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Effects of 17/0 circle hooks and bait on sea turtles bycatch in a Southern Atlantic swordfish longline fishery

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ABSTRACT

1. The incidental catch of marine turtles is a major problem in commercial pelagic longline fisheries. The present paper reports marine turtle bycatch composition and rates from a Portuguese commercial longline fishery targeting swordfish in the South Atlantic, and investigates the effects of changes in hook style and bait type.

2. In total, 310 longline sets were carried out between 2008 and 2012. Three different hook styles were tested, traditional J hook (9/0) and two 17/0 circle hooks (a non-offset and a 10º offset), but only one bait type was used in each set (*Scomber* spp. or *Illex* spp.).

3. Two species of sea turtles were caught, the leatherback *Dermochelys coriacea*, and the loggerhead *Caretta caretta*, the latter comprising the majority of the catches. The highest mean bycatch per unit of effort values for both species combined (1.693/1000 hooks) and for the individual species (1.505/1000 hooks for loggerheads) occurred with J-style hooks baited with squid. Changing from J-style to one of the circle hooks was only significant when using squid bait (with the odds-ratios decreasing between 54% and 63%).

4. Hooking location was species-specific, with most loggerheads hooked by the mouth, while leatherbacks were mostly hooked externally by the flippers. Overall, 65% of all sea turtles were released alive (85% for leatherbacks compared with 63% for loggerheads).

5. Significant reduction of sea turtle accidental catches on the swordfish longline fisheries can be achieved by changing the J hooks to circle hooks, especially if baited with mackerel. However, such gain is species-specific and area dependent.

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KEY WORDS: ocean; protected species; fishing; long-lining; hook style; circle hooks; bait types

INTRODUCTION

Fisheries bycatch, the unintended capture of non-target organisms during fisheries operations, is a major problem worldwide as it occurs in virtually all fishing fleets, resulting in a global issue for the management of marine resources (Hall *et al*., 2000; Soykan *et al*., 2008). Despite the differences in bycatch types and the magnitude of their effects from one fishery to another, bycatch can be a major driver of marine megafauna population declines (Lewison *et al*., 2004; Read *et al*., 2006; Wallace *et al*., 2010), particularly in the case of the bycatch of species that have long life-cycles and low productivity, as is the case for the sea turtles.

Sea turtle bycatch occurs in a wide range of fisheries, from small- to large-scale fishing fleets, using many gear types such as trawls, longlines, gill and pound nets, dredges, and to a lesser extent, pots and traps (De Metrio and Megalofonu, 1988; Magnuson *et al*.,

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1990; Poiner and Harris, 1996; Julian and Beeson, 1998; Chuenpagdee *et al*., 2003; Lewison and Crowder, 2007; Moore *et al*., 2009; Wallace *et al*., 2010; Casale, 2011). Sea turtle bycatch is of special concern as five of the seven species living in the world's oceans have been listed as either critically endangered (e.g. leatherback – *Dermochelys coriacea* (Vandelli 1761)) or endangered (e.g. loggerhead – *Caretta caretta* (Linnaeus 1758)) (IUCN, 2012). Moreover, one of the main causes for the worldwide failure of most sea turtle populations to recover is their incidental capture in fisheries (Hillestad *et al*., 1995; Lutcavage *et al*., 1996). Even though longline sea turtle bycatch is only one of many threats faced by these species, it has been gaining international attention in recent years (FAO, 2009).

Several measures to mitigate the incidental capture of sea turtles have been proposed and/or implemented in different fisheries. These include management measures (e.g. time/area closures, fishery bans, limitation of fishing effort, maximum annual quota), but also technical measures (gear technology approaches), such as the use of turtle excluding devices on trawl fisheries; deterrents, including sonic 'pingers', shark silhouettes, lights or chemical repellents on set and drift nets; and use of specific circle style hooks (FAO, 2009 and reference therein). As regards the mitigation of longlines bycatch, a number of research initiatives have focused on testing several technological and methodological changes, all aiming at increasing the fishing gear selectivity and reducing bycatch mortality of sea turtles (Polovina *et al*., 2003; Swimmer *et al*., 2005; Werner *et al*., 2006; Gilman *et al*., 2007; Yokota *et al*., 2009). Particular attention has been given to the use of circle hooks – a hook with the point turned perpendicularly back toward the shank, as a means to reduce bycatch mortality (see reviews by Read, 2007; Wallace *et al*., 2010; Serafy *et al*., 2012). However, in the Atlantic Ocean these studies were mostly limited to the Northern Hemisphere. To the authors' best knowledge, only a few studies were conducted in recent years in the Southern Atlantic Ocean (Anon, 2008; Domingo *et al*., 2009; Sales *et al*., 2010; Pacheco *et al*., 2011), but these were limited in terms of the number of sets and/or geographical area covered, as well as in terms of the baits used and tested.

The Portuguese pelagic longline fishery targeting swordfish began in the 1970s and the fishing method has remained almost unchanged since then. Some modifications have been incorporated in the last decade though, specifically shifting from the traditional to the so-called 'modern gear' (for gear description see Watson and Kerstetter, 2006), making use of mainlines and branch lines of monofilament, using battery flashlights and J hooks baited with squid. Before this study, which is part of an ongoing project (SELECT-PAL – *Redução das capturas acessórias na pescaria de palangre de superfície*), no circle hooks were used or tested commercially by the Portuguese fleet, apart from some experiments supported by the US Government between 2000 and 2002 in the Azores (Bolten and Bjorndal, 2005), and the initial results of the SELECT–PAL Project for the Atlantic Equatorial area (Santos *et al*., 2012).

In order to increase the area covered for such circle hook studies in the Atlantic Ocean, the SELECT-PAL Project aims to test the influence of different hook and bait combinations on the catch of target and non-target species caught by the Portuguese pelagic longline fishery operating in three major areas in the Atlantic Ocean: North-eastern Tropical, Equatorial and Southern Temperate. The present paper reports the results for the Southern area, comparing in particular, the sea turtle catch composition and rates, hooking location and status at haulback, throughout the experimental use of different combinations of hook styles and bait types.

MATERIAL AND METHODS

Experimental design and data collection

For this study, 310 longline sets were carried out during five trips along the Southern Atlantic region (Figure 1) that took place between October 2008 and February 2012. A commercial fishing vessel from the Portuguese pelagic longline fleet participated in the study, with experimental fishing taking place along wide latitudinal (11º to 34º S) and longitudinal (044º W to 007º E) ranges. The fishing gear consisted of a standard monofilament polyamide mainline of 3.6 mm diameter (approximately 62 nautical miles long), with five branch lines between floats. Each branch line was 18 m in length, the first part consisting of 2.5 mm monofilament (9 m long) connected by a swivel to a 2.2 mm monofilament gangion (9 m in length) with a hook in the terminal tackle. A battery flashlight (green colour) was attached to each gangion. On each set, 1440 hooks were used, fishing at depths of approximately 20–50 m. Gear deployment began traditionally at 17:00 hours, with

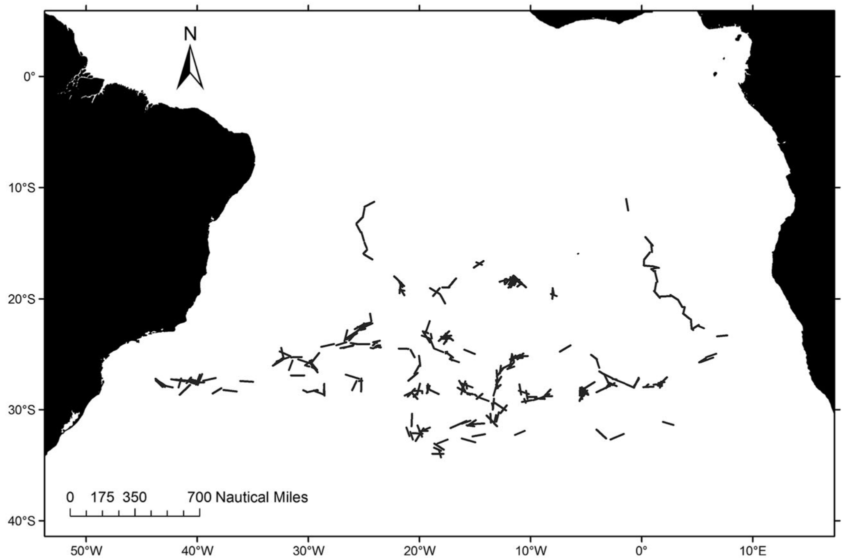

Figure 1. Location of the 310 experimental longline sets in the Southern Atlantic region.

haulback starting the next day from about 06:00 hours. Three different stainless steel hook styles (produced by WON YANG, Korea) were used in each longline set. The control corresponding to the traditional J hook on the fishery (EC-9/0-R), and the treatments corresponding to: G hook, a non-offset circle hook (H17/0-M-S); and Gt hook, a 10º offset circle hook (H17/0-M-R). The characteristics of the different hooks are summarized in Table 1. Hook style was alternated section by section of the longline (each section containing 80 hooks), to minimize the potential confounding effects specific to a set (e.g. location, water temperature, turtle density, or other factors). Moreover, the hook style of the first section in the water changed every set, following a fixed scheme (i.e. J:G:Gt:J:G:Gt, and so on). Two different bait types were used, mackerel (*Scomber* spp.) and squid (*Illex* spp.), but only one bait was used in each set to avoid possible interaction effects, as suggested by Watson *et al.* (2005). Standardized bait sizes were used in all longline sets (squid 27.8 ± 0.97 cm and mackerel 35.1 ± 1.19 cm; based on the measurement of 200 individuals of each genus). All characteristics of the fishing gear and practices (e.g. hook placement, setting time, flashlight colour, bait size, and hook) were standardized throughout the study.

Table 1. Details of the different hook styles used in the study. Standard deviation is indicated between parentheses

	Hook style		
Parameter	J (EC-9/0-R)	G (H17/0-M-S)	Gt (H17/0-M-R)
Total length (mm)	87.2 (±1.11)	77.7 (±0.92)	
Front length (mm)	40.4 (±1.10)	43.9 (±0.45)	
Maximum width (mm)	43.3 (±0.64)	49.4 (±0.88)	
Gap (mm)	33.2 (±0.59)	27.0 (±0.51)	
Arm diameter (mm)	5.0 (±0.00)	5.0 (±(0.00)	
Offset angle	10º	0º	10º

Whenever a sea turtle was caught in the longline, the onboard observer identified the species, recorded the hook style and bait type used, the condition/status of the turtle at haulback (alive/dead), the type of interaction (i.e. location of the hook: flippers, mouth, oesophagus or entangled) and the condition when released (alive/dead). When possible, turtles were boated with a large dip net. Further, and whenever possible, observers and crew attempted to remove fishing gear using long-handled de-hookers and line cutters. Observers attempted to remove all gear immediately. They were instructed to remove all external hooks and those in the mouth, as well as hooks in the oesophagus when the insertion point of the barb could be seen. Whenever possible the sex of the specimen was determined and the curved carapace length (CCL) was measured to the nearest lower 1 cm. However, due to the size and weight of leatherback turtles, *Dermochelys coriacea*, only a limited number of specimens of this species were measured, with most specimens being immediately released by cutting-off the line without bringing the turtle onboard. Sea surface temperature (SST) was collected for each experimental set, being recorded at the beginning of haulback.

Following Watson *et al.* (2005), power tests were carried out in order to estimate the experimental fishing effort required to determine a fishing method that has different degrees of effectiveness in reducing bycatch of sea turtles in comparison with the control fishing method. The control fishing method was assumed to be the combination most commonly used in the fishery, specifically J type hooks baited with squid, and the power calculations were based on the necessary number of hooks required to provide a 25% and 50% reduction in bycatch rate in the case of loggerheads and leatherbacks, respectively.

Data analysis

Catch rates were expressed as BPUE, calculated as the number of specimens caught per 1000 hooks. Given the lack of normality of the BPUE data, verified with Kolmogorov–Smirnov tests with Lilliefors correction (Lilliefors, 1969), and heterogeneity in the variances (verified with Levene tests), Kruskal–Wallis tests were used to compare BPUE between different hook types, and Mann–Whitney tests were used to compare BPUE between the two baits.

A logistic-binomial GLM was used to determine the influence of hook style and bait type on turtle bycatch. Owing to the small sample sizes, this model was applied only to the loggerheads. For this model, the response variable was the proportion of loggerhead catches in each longline set, calculated as the number of catches given the number of hooks used in each set. A binomial error distribution and a logit link function were used in the model. The explanatory variables tested were the hook style (J, G or Gt) and the bait type (squid or mackerel), with their significance verified by the Wald statistic. The interaction between the two variables was tested with a likelihood ratio test and by comparing the AIC values of the models. This interaction was used in the final model because it was considered significant and relevant for interpreting the results. The odds-ratios of the parameters, with their respective 95% confidence intervals, were calculated considering the model parameters and the interaction.

With regard to the size structure of the sea turtles caught, only the most abundant species (loggerheads) was analysed, while the CCL of leatherbacks was not compared owing to the small sample size. Loggerhead CCL was tested for normality and homogeneity of variances, and the skewness and kurtosis were calculated. Considering the results of these analyses, the application of parametric tests seemed reasonable, and therefore the mean CCLs for the two different baits were compared with student t-test, while the mean CCLs for the three different hook styles were compared with ANOVAs. In addition, the mean CCLs for the different hooking locations were also compared using ANOVAs. When the ANOVA results were significant, Schefee *post hoc* multiple comparisons were carried out.

The relationship between hooking location and hook style was assessed using contingency tables and chi-square tests of independence. Analyses were conducted for the two species combined, as well as for the loggerhead separately. For this analysis, the hooking location was re-categorized into three categories: mouth, oesophagus and external (combining flippers and entangled) due to the existence of very low values in some of the combinations using the original categories. Chi-square proportions tests were also used to assess differences in the proportions of live/dead sea turtles between hook styles, bait type, and hooking locations. This analysis was only carried out for the loggerheads, as the contingency table analysis assumptions could not be validated for the leatherback species because of their very low bycatch rates. Non-parametric tests were used when *a priori* assumptions were not fulfilled.

All statistical analyses were performed using the R Project for Statistical Computing 2.14.1 (R Development Core Team, 2011), using mainly functions available in the core R program. Exceptions were the Levene tests for the homogeneity of variances that is available in library 'car' (Fox and Weisberg, 2011), contingency table analysis that was carried out using library 'gmodels' (Warnes *et al.*, 2011), and the plots of means that are available in 'Rcmdr' (Fox *et al.*, 2011).

RESULTS

Overall, 446 400 hooks were used during the 310 experimental fishing sets, corresponding to 148 800 hooks of each style. According to the power analysis carried out, the number of hooks required to detect a 25% reduction in the loggerheads bycatch per unit of effort (BPUE) (with 95% confidence interval) was 166 597 (corresponding to 116 fishing sets). Comparative efforts required to detect a 50% reduction in the leatherback BPUE was 333 632, corresponding to 232 sets. The sea surface temperatures (SST) ranged between 16.5°C and 28.3°C, with an average of 21.9 ± 2.76°C. A correlation between SST and latitude and longitude was observed, with higher SSTs tending to be mainly recorded towards northern latitudes (Pearson correlation = 0.225, t = 4.0;, df = 299, $P < 0.001$) and for the western regions of the sampling area (Pearson correlation = −0.498, t = −9.9, df = 299, $P < 0.001$).

Bycatch rates

In total, 286 sea turtles were caught during this study; specifically 260 loggerheads and 26 leatherbacks. Most of the experimental fishing sets had zero (78.4%) or very limited catches of sea turtles. The maximum number of specimens caught in a single set was 20, but for most of the sets (95%) less than five sea turtles were caught. The specific proportions of fishing sets with zero catches of sea turtles also varied for each hook/bait combinations, with a tendency for more sets with zero catches when mackerel bait was used (Table 2).

The highest BPUEs were observed in the western part of the study area, between 37ºW and 44ºW, both for species combined, but also for loggerheads (Figure 2). Overall, the highest mean BPUE values for the leatherback tended to occur with J style hooks ($J_{mackerel} = 0.040$ and $J_{squid} = 0.188$ per 1000 hooks) rather than circle hooks ($Gt_{mackerel} = 0.013$ and $Gt_{squid} = 0.054$ per 1000 hooks). For the loggerhead such a tendency was not so evident, although the traditional combination still showed the highest value ($J_{squid} = 1.505$/1000 hooks, see Figure 3). These differences between the three hook styles were significant for the species combined, but also for the leatherbacks (Kruskal–Wallis: species combined – chi-square = 9.86, df = 2, $P = 0.007$; leatherback – chi-square = 9.33, df = 2, $P = 0.009$) and loggerheads (chi-square = 6.07, df = 2, $P = 0.048$). The BPUE tended to be significantly lower when mackerel bait was used instead of squid for the two species combined, as well as for the two species individually (Figure 3) (Mann–Whitney: species combined: W = 94766, $P < 0.001$; loggerhead – W = 96921, $P < 0.001$; leatherback – W = 104398, $P < 0.001$). The ratio between the standard fishing practice and the other hook:bait combinations tested showed reductions in BPUE between 1.7–6.4, 1.5–7.1 and 3.5–14.0 times, for species combined, loggerhead and leatherback turtles, respectively (Table 3).

For the loggerhead sea turtle, and using the binomial modelling analysis, both the hook style and the bait type were significant for explaining the BPUE rates. In addition, the interaction between hook style and bait type was marginally significant (likelihood ratio test: diff. residual deviance = 5.32, $P = 0.07$), and produced a slightly lower AIC value (simple effects model AIC = 1404.3; model with hook:bait interaction AIC = 1402.9). When changing the bait type from squid to mackerel the odds-ratios of catching loggerhead sea turtles decreased significantly regardless of the hook style used, with these decreases ranging from 64–82% (Table 4). However, and due to the interaction observed, changing from J-style to one of the circle hooks was significantly different when using squid bait (with the odds-ratios decreasing between 54% and 63%), but not when using mackerel bait (with the 95% confidence intervals of the odds-ratios ranging between reductions of 65% to increases of 86%).

Table 2. Percentage of sets with zero sea turtle incidental catches obtained with the different combination of hook style (J – traditional 10º off set 9/0 hook used on the fishery; G – 0º offset 17/0 circle hook; Gt – 10º offset 17/0 circle hook) and bait type (S – squid; and M – mackerel) tested, for species combined and for the two sea turtle species incidentally caught

Hook style: bait type	Loggerhead	Leatherback	Combined species
J_S	78.0%	92.2%	73.6%
J_M	92.2%	98.8%	91.0%
G_S	87.8%	97.4%	85.9%
G_M	93.6%	100%	93.6%
Gt_S	85.2%	98.0%	83.8%
Gt_M	94.8%	99.4%	94.2%

Bycatch at size and hooking location

Loggerheads ranged in CCL from 41 to 78 cm and averaged 61.5 (±6.09) cm (N = 260, n = 234). Only 42% (N = 26) of leatherback turtles (CCL from 48 to 140 cm and averaged 92.9.5 (±33.82) cm) were measured.

For both species combined, the mouth was the most frequent hooking location (65.7%) regardless of the hook type used (Figure 4). However, when the species were analysed separately it was possible to determine species-specific patterns of hooking locations. Leatherbacks were almost exclusively hooked by the flippers (73.1%) or entangled (19.2%) on the lines, whereas most loggerhead turtles bit the bait, with 71.5% hooked in the mouth and 17.7% hooked in the oesophagus (Figure 4).

The relative proportions of the different hooking locations were statistically different between hook styles (Figure 4), as confirmed by chi-square tests between the two factors. This analysis was carried out for species combined (chi-square = 17.80, df = 4, $P = 0.001$) and for the loggerhead (chi-square = 20.87, df = 4, $P < 0.001$). On the contrary, the relative proportions of the different hooking locations were

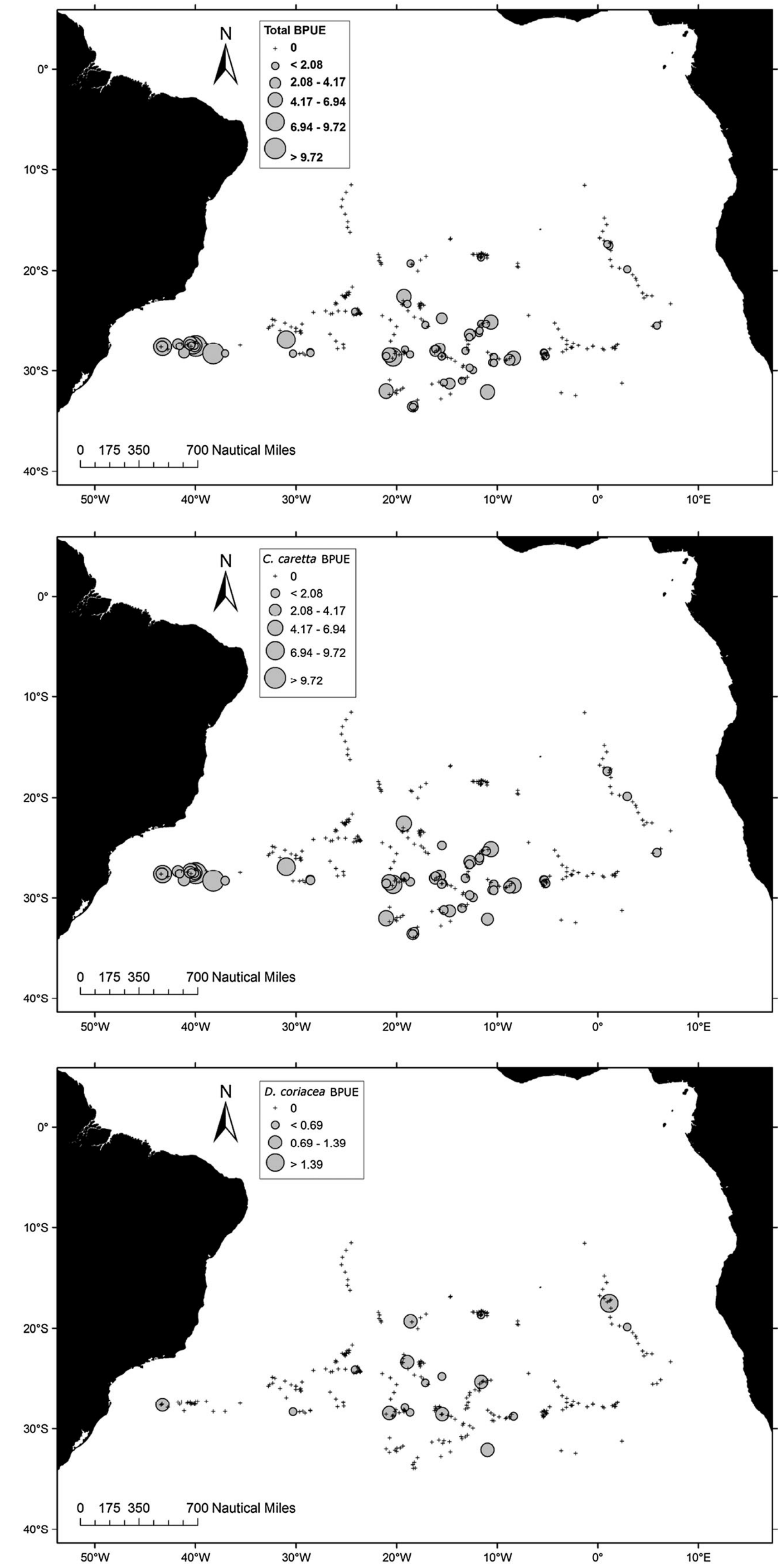

Figure 2. Spatial distribution of BPUE by longline experimental set, for turtle species combined (top), loggerhead (TTL - *C. caretta*, middle) and leatherback (DKK - *D. coriacea*, bottom). The size of the circles is proportional to the BPUE and the dark crosses represent fishing sets with 0 catches.

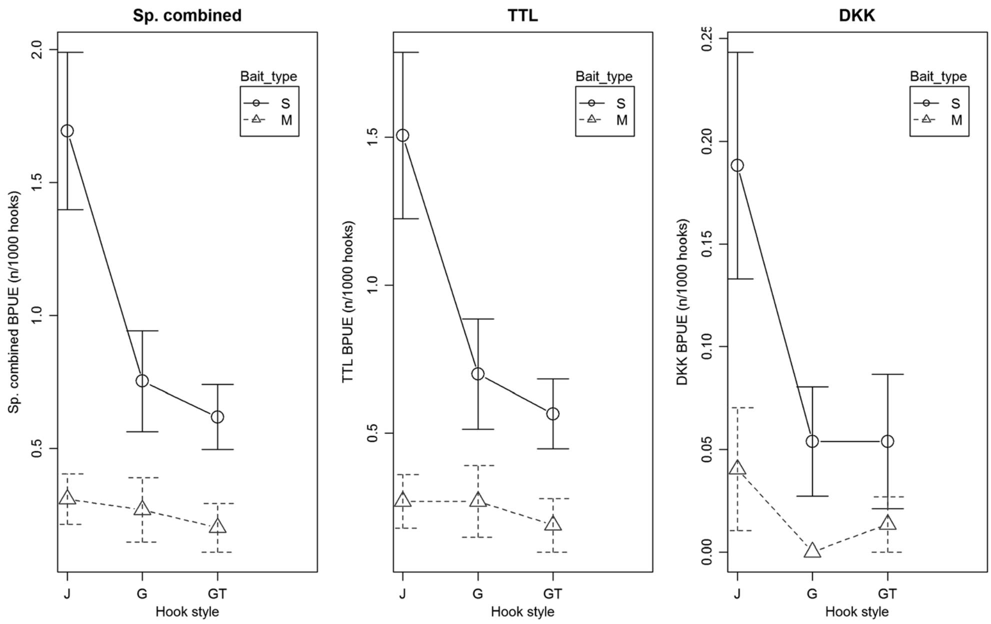

Figure 3. Plot of the mean BPUE (with the respective standard errors) observed with the different hook styles (G, Gt and J) and bait combinations, for the species combined, loggerheads (TTL - *C. caretta*) and leatherbacks (DKK - *D. coriacea*). On the bait type, M refers to mackerel and S refers to squid.

Table 3. Ratio between the mean BPUE obtained with the standard fishing gear (J hook baited with squid - control) and the different combinations of hook style (J – traditional 10º offset 9/0 hook used on the fishery; G – 0º offset 17/0 circle hook; Gt – 10º offset 17/0 circle hook) and bait type (S – squid; and M – mackerel) tested, for species combined and for the two sea turtle species caught

Comparison	Loggerhead	Leatherback	Combined species
J_S vs. G_S	1.5	3.5	1.7
J_S vs. Gt_S	1.8	3.5	2.0
J_S vs. G_M	3.8	-	4.9
J_S vs. Gt_M	4.5	14.0	5.3
J_S vs. J_M	7.1	4.7	6.4

not statistically different between bait types for species combined (chi-square = 1.72, df = 2, $P = 0.424$) and the loggerhead (chi-square = 1.74, df = 2, $P = 0.418$) (Figure 4). These analyses were not performed for the leatherback as most specimens were captured by the flippers, and the contingency tables had cells with zero values for most of the other combinations.

For loggerheads the size distribution did not significantly vary depending on the bait type (t-student: t = 1.19, df = 232, $P = 0.236$) (Figure 5). However, significant differences in the size distributions were detected between hook styles (ANOVA: F = 7.73, df = 2, $P < 0.001$), and hooking locations (ANOVA: F = 8.71, df = 3, $P < 0.001$) (Figure 5). Using Shefee *post hoc* multiple comparison tests for hook styles, it was noted that significant differences occurred only between Gt hooks and the other two hook styles (J and G), with Gt hooks capturing significantly larger specimens. With regard to the hooking location, significant differences were found between entangled and the remaining hooking locations, with the entangled specimens significantly smaller (Figure 5).

Mortality

Overall, 65% of all sea turtles were alive at haulback and were, therefore, released alive. The overall percentage of alive specimens at haulback was higher for leatherbacks (85%) than for loggerheads (63%). The hooking location seems to have a great impact

Table 4. Odds-ratios, with the respective 95% confidence intervals, for the effects of changing hook styles and bait types in the loggerhead (*Caretta caretta*) BPUE, accounting for the model interactions

Interaction	Main factor	Estimate	Lower 95%CI	Upper 95% CI
Using squid bait	Change from J to G	0.46	0.33	0.64
	Change from J to Gt	0.37	0.26	0.53
Using mackerel bait	Change from J to G	1.00	0.54	1.86
	Change from J to Gt	0.70	0.35	1.39
Using J-style hook	Change from squid to mackerel	0.18	0.11	0.29
Using G-style hook	Change from squid to mackerel	0.38	0.23	0.64
Using Gt-style hook	Change from squid to mackerel	0.33	0.18	0.61

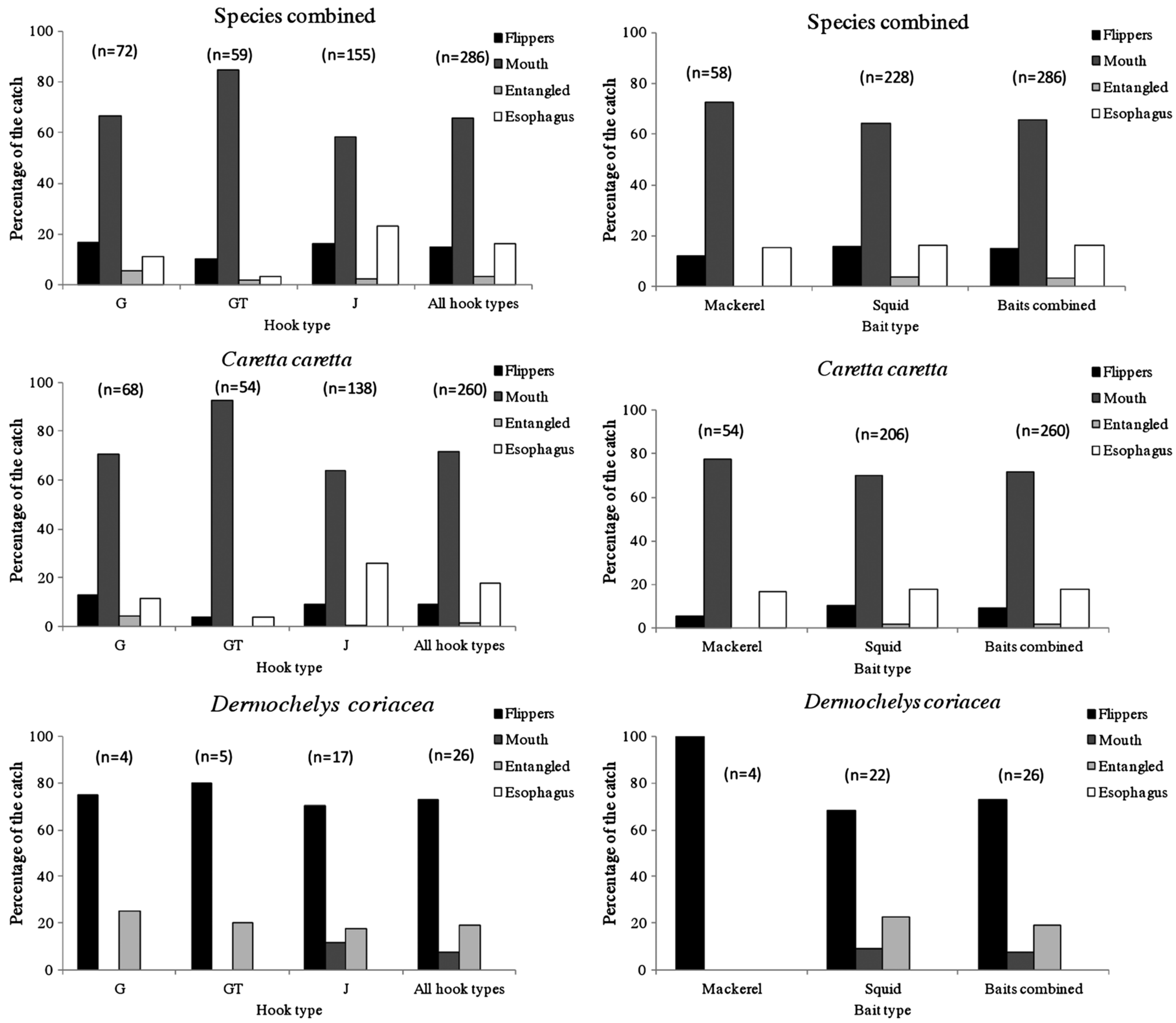

Figure 4. Hooking location per hook style (left) and bait type (right) for all species combined, loggerhead (*C. caretta*) and leatherback (*D. coriacea*). The bars refer to the percentage of each hooking location within each hook style or bait type. Numbers between brackets refer to the corresponding nominal catch of each hook style or bait type.

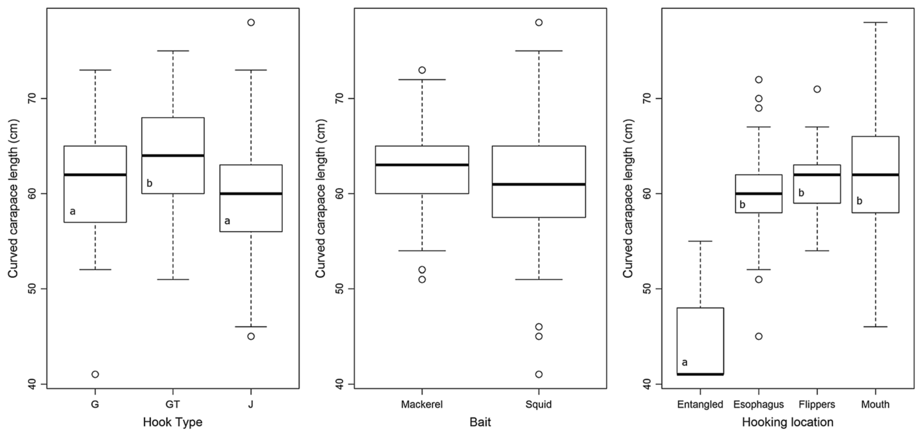

Figure 5. Boxplots with the size distribution (median, inter-quartil range, non-outliers range and outliers) for loggerhead (*C. caretta*), for each of the three factors considered (hook style, bait type and hooking location).

on mortality with most specimens caught by the flippers being alive at the time of haulback (88%), while the specimens entangled or hooked in the oesophagus and in the mouth had lower percentages of alive specimens (22%, 48% and 66% alive at the time of haulback, respectively) (Figure 6). Because

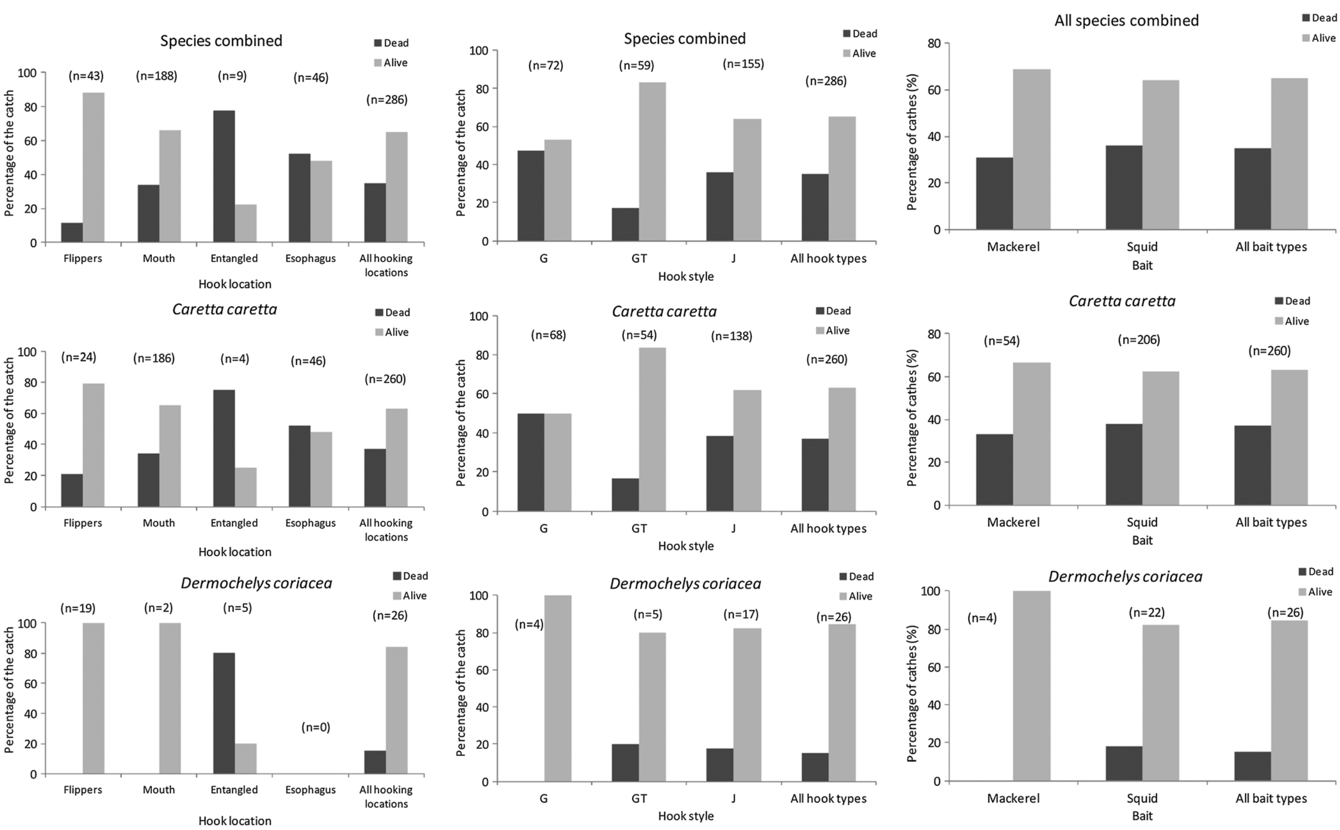

Figure 6. Percentage of fishing mortality at-haulback per hooking location (left), hook style (centre) and bait type (right), for all species combined (top), loggerhead (*C. caretta*, middle) and leatherback (*D. coriacea*, bottom). The numbers between brackets refer to the corresponding number captured for each hooking location (n).

the two species tended to be hooked in different ways, hooking location reflected the species-specific mortality.

For the factor hook style, and considering species combined, the Gt-style hook had proportionally more turtles alive (83%) than dead (17%), with the percentage of alive specimens decreasing substantially for the J-style hooks (64%) and even more with the G hooks (53%), with those differences statistically significant (chi-square proportion test: chi-square = 13.27, df = 2, $P = 0.001$). When the loggerhead data were analysed separately, the proportion of alive specimens was 83%, 62% and 50% for hook types Gt, J and G, respectively (Figure 6), which was again statistically significant (chi-square proportion test: chi-square = 14.64, df = 2, $P < 0.001$). For leatherbacks, the proportions of live specimens were very high for all hook styles; 100%, 82% and 80% for hook types G, J and Gt, respectively (Figure 6). For the factor bait type, the observed versus expected frequencies of dead and alive turtles were not significantly different for species combined (proportion chi-square with Yates correction: chi-square = 0.49, df = 1, $P = 0.48$), nor for loggerheads individually (proportion chi-square with Yates correction: chi-square = 0.21, df = 1, $P = 0.65$).

DISCUSSION

The overall mean sea turtle BPUE observed in this study using the traditional gear configuration (1.694/1000 hooks) was similar to that reported by Sales *et al*. (2010) for another pelagic longline fishery targeting swordfish off southern Brazil (1.893/1000 hooks). However, the observed overall BPUE was higher than those reported by Pinedo and Polacheck (2004) off southern Brazil (1.48/1000 hooks), Pons *et al*. (2010) off Uruguay (average of 1.001 loggerheads/1000 hooks between 1998 and 2007), Petersen *et al*. (2009) off South Africa (0.04/1000 hooks) and Afonso *et al*. (2012) off northern Brazil (0.47–0.94/1000 hooks). Major interactions (22% of the sets) of loggerhead, and to a smaller extent leatherback sea turtles, seem to exist with the Southern Atlantic Portuguese pelagic swordfish longline fishery, particularly between 37°W and 44°W of longitude, as shown by the present study. A similar trend was found by Pinedo and Polacheck (2004) and Sales *et al.* (2010) in the South Atlantic, with loggerheads followed by leatherbacks also being the most captured species by the Brazilian and Uruguayan pelagic longline fleets. In the Equatorial Atlantic, the olive ridley *Lepidochelys olivacea* was the sea turtle species that interacted the most with the pelagic swordfish longline fishery, although other sea turtles were also present (Carranza *et al.*, 2006; Sales *et al.*, 2008; Santos *et al.*, 2012). In comparison, for the North-west Atlantic region the loggerheads and leatherbacks seem to be the species most commonly caught in pelagic longlines (Watson *et al.*, 2005; Foster *et al.*, 2012). Hence, and as suggested by Gardner *et al.* (2008), the incidental capture of sea turtles seems to vary considerably by region, with the water temperature possibly playing a major role in this variability.

The present study shows that sea turtle interactions can be significantly reduced by using mackerel in place of squid bait, and to a lesser extent by employing circle hooks. A combination of circle hooks baited with mackerel can result in a reduction in sea turtle catches by 87.5% and 100% for loggerheads and leatherbacks, respectively. Still, the reductions observed in this study for leatherbacks should be interpreted with care, as the catches of that species in particular were very low. Similar findings were presented for the South-east Atlantic (Anon., 2008), where it was suggested that bait type had the greatest influence on loggerhead turtle bycatch. Previous studies have also shown that changing the bait type from squid to mackerel (or other fish) and/or the traditional J to circle hooks, were effective measures to reduce sea turtle bycatch in different oceanic areas: in the North-west Atlantic (Watson *et al.*, 2005; Foster *et al.*, 2012); in the North-west Pacific (Yokota *et al.*, 2009); in the Equatorial Atlantic (Pacheco *et al.*, 2011; Santos *et al.*, 2012); and South Atlantic (Domingo *et al.*, 2009; Sales *et al.*, 2010). However, these comparisons should be analysed carefully because the cited studies used slightly different hooks (in terms of sizes and shapes), covered different seasons and areas (with different ranges of temperature), and were based on substantially different numbers of sets.

As loggerhead and leatherback turtles have different life histories, pelagic longlines affect both species differently, which can influence the size distribution of the captures. Leatherback sea turtles are pelagic/oceanic during all stages of their life (Bjorndal, 1997), thus a wide size range was observed in the captures, including adult specimens. It must be noted that the largest specimens captured were probably not measured because of difficulty in handling and boarding, thus no statistical inference should be made with regards to the sizes of the catches for this species. On the other hand, loggerheads typically frequent open waters feeding on pelagic invertebrates, where the juvenile development takes place, and after a decade or longer, sub-adults and adults move to neritic habitats near the continental coastline and start feeding upon benthic invertebrates (e.g. molluscs) and fish (Bjorndal, 1997). As a result, based upon the information reported by Domingo *et al.* (2006) on the size at maturity for the South-western Atlantic Ocean, the captured loggerheads in the present study were mostly juveniles. Similar catch-at-size of loggerheads were reported by other studies in the South Atlantic (Pinedo and Polacheck, 2004; Domingo *et al.*, 2009; Sales *et al.*, 2010). While bait type did not influenced loggerheads size distribution, significant differences were found in the size distribution between hook styles, with Gt hooks capturing larger specimens. Stokes *et al.* (2012) points out that when comparing hook type effects in size distribution, a potential hook-size effect may be masked due to the fact that most commonly used J hooks (7/0, 8/0, and 9/0) are slightly smaller than 16/0 and 18/0 circle hooks. Sales *et al.* (2010) also found significant differences in the sizes of captured loggerheads, with circle hooks capturing larger specimens, compared with those reported by Domingo *et al.* (2009) and Anon. (2008), who found no differences in the size distribution between hook types and bait in the same region. Likewise, no differences were found for the olive ridley sea turtles caught in the Equatorial Atlantic by the Portuguese fishery (Santos *et al.*, 2012).

Hooking location seemed to be mainly species-specific, which may be related to each species feeding behaviour. While leatherbacks were almost exclusively hooked externally, mainly by the flippers (with all hook types), loggerheads were mostly hooked by the mouth in all treatments. Significant differences were found for this species in the relative proportions of the different hooking locations between hook styles, with J hooks showing a higher proportion of loggerheads hooked in the oesophagus, while the bait showed no significant differences. Likewise, in the North-west

Atlantic, Watson *et al.* (2005) and Epperly *et al.* (2012) found no significant differences in hooking location for both loggerheads and leatherbacks upon switching between mackerel and squid bait. Anon. (2008) and Sales *et al.* (2010) also noted that deep-hooking involved more often J hooks than circle hooks, in the South Atlantic. In the North Atlantic, Stokes *et al.* (2012) also found significant differences in hooking location in loggerheads when comparing offset J hooks and non-offset and 10° offset circle hooks, with the latter hooking mostly loggerheads by the mouth while offset J hooks were swallowed more often. In contrast, Carruthers *et al.* (2009) found no significant differences in hooking location for loggerheads when comparing 16/0 circle hooks, non-offset J hooks, and offset (20–30°) J hooks in the Canadian longline fishery for swordfish and tuna in the North Atlantic.

The main factor that seemed to influence at-haulback mortality of sea turtles was the hooking location. Turtles hooked externally (by the flippers or entangled) showed a large proportion of specimens that were alive at haulback, while specimens that were hooked in the mouth or deep hooked in the oesophagus had a higher proportion of dead specimens at time of haulback. Hence, the type of circle hook appears to be an important factor in the mortality rate as well, as there were statistical differences between the three hook types tested. In loggerheads the Gt hook showed the lowest at-haulback mortality, followed by J hook and G hook, whereas Sales *et al.* (2010) found no differences in loggerhead mortality among hook types. In the Equatorial Atlantic Santos *et al.* (2012) also found differences in mortality between the same three hook types although, contrary to this study, for both sea turtle species (olive ridley and leatherback) the J hook had the highest mortality. The reported mortality results represent the short-term at-haulback mortality, and should be interpreted as minimum mortality estimates, as post-release mortality may occur.

Overall, the present study supports previous reported results on the reduction of sea turtle accidental catches in the swordfish longline fisheries, by changing the traditional configuration of J hook baited with squid to circle hooks baited with mackerel. It is important to note, however, that in this study the bait seemed to have more influence on the level of bycatch reduction than the hook style itself, and that in the case of mortality the effect of the hook style is not so evident (Gt vs G instead of Gt/G vs J). A high variability between results seems to exist in the literature, highlighting the influence of different aspects (e.g. region and consequently the species, season, fishery, etc.) in sea turtle accidental captures. For this reason extreme caution must be used when interpreting the results of these kinds of studies. For example, Anon. (2008) reports a remark of one observer noting the fact that circular hooks were much more difficult to remove than J-type hooks whether hooked in the mouth or internally. In addition, the observer stated that more traction was caused in the oesophagus, producing tissue tears and haemorrhages when removing ingested circle hooks compared with J hooks. Parga (2012) illustrates another example of the uncertainty about the benefits of the use of circle hooks, stating that even though hooks in the mouth are generally considered low risk, sensitive structures are present in the mouth, such as the glottis or the jaw joint, and that if damaged may cause death due to infection. The oesophagus, on the other hand, has a strong muscular wall and is somewhat resistant to lesions, unless the hook lodges close to the heart or large blood vessels. The same author further noted that cutting short the branch line close to the mouth enables some deep hooked sea turtles to swallow and even expel the hooks without major harm. Therefore, gear removal seems to play a crucial role in turtle survival/mortality, and training vessel crews for onboard turtle management is essential for improving turtle survival at sea and maximizing possible positive effects of gear change.

It is clear that circle hooks baited with mackerel significantly reduce sea turtle incidental catch on the Portuguese pelagic swordfish longline fishery in the Southern Atlantic. However, from the fisheries management point of view, it is essential to assess the consequences of such gear modifications in a wider scale, before implementing them. The human dimensions of such modifications also have to be addressed (Campbell and Cornwell, 2008) and the economic impacts in the fishery have to be considered. For instance, in some cases, possible reductions in the target species catches may occur (Largarcha *et al.*, 2005; Báez *et al.*, 2010; Domingo *et al.*, 2012), while in other cases the reductions in the target species catches are balanced by the gains in other marketable species (Coelho *et al.*, 2012). Increases in target species catches, while decreasing sea turtle bycatch, also have been observed in some fisheries when changing to circle hooks baited with mackerel (Pacheco *et al.*, 2011; Foster *et al.*, 2012). Besides the economics, other factors to reflect on when considering gear changes are the impacts on other vulnerable species. As an example, Coelho *et al.* (2012) observed that when changing from squid to mackerel, although sea turtles bycatch decreased, the catch rates of some large pelagic sharks, like the vulnerable bigeye thresher, increased significantly.

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