BULLETIN OF MARINE SCIENCE. 88(3):683–701. 2012
http://dx.doi.org/10.5343/bms.2011.1065

EFFECTS OF HOOK AND BAIT ON SEA TURTLE CATCHES IN AN EQUATORIAL ATLANTIC PELAGIC LONGLINE FISHERY

Miguel N Santos, Rui Coelho, Joana Fernandez-Carvalho, and Sérgio Amorim

ABSTRACT

Here we report a component of the results of the SELECT-PAL project, namely marine turtle bycatch composition and rates, hooking location, and status at haulback and at release for several hook-bait combinations in a Portuguese commercial longline fishery targeting swordfish in the Atlantic equatorial region. In total, 221 longline sets were deployed during the fishing season (February–October) by the Portuguese fleet operating in the area. Three different hook types were tested, traditional J-hook (9/0) and two 17/0 circle hooks (non-offset and 10° offset), but only one bait type was used in each set (*Scomber* spp. or *Illex* spp.). Four species of sea turtle were caught, most consisting of the olive ridley, *Lepidochelys olivacea* (Eschscholtz, 1829), and leatherback, *Dermochelys coriacea* (Vandelli, 1761). The highest mean bycatch per unit effort (BPUE) values for both species combined and for the individual species occurred with the J-hook. The 10° offset circle hook baited with mackerel provided a reduction of 88% and 85% on the bycatch rates, for all turtles combined and olive ridleys, respectively. Although hook location was species-specific and only bait appeared to be driving bycatch rate differences, most sea turtles were caught in the mouth, except for leatherbacks. Only hook type contributed significantly to haulback mortality, with J-hooks associated with slightly higher mortality rates.

Marine fishery resources are a primary source of protein for human consumption (FAO 2010). As a consequence, marine fisheries now have a major influence on marine systems worldwide, affecting marine animal populations and ecosystem function, and warranting urgent and comprehensive management in many places (Jackson et al. 2001, Pauly et al. 2005, Halpern et al. 2008). Among the different key issues in marine fisheries, bycatch—the unintended capture of non-target organisms during fishery operations—is a major problem (Hall et al. 2000, Soykan et al. 2008). Despite the existence of bycatch in all fisheries and differences in their types and amount, many of the bycatch species have long life-cycles and low productivity. This is the case for the pelagic drift longline, which despite being more selective than many other fishing gears, catches a wide range of megafauna, such as: sharks, mammals, seabirds, and sea turtles (Brothers and Cooper 1999, Lewison et al. 2004, Huang 2011). These groups of animals occupy broad geographic ranges spanning geopolitical boundaries and oceanographic regions that support different fisheries (Wallace et al. 2010). Among the marine megafauna, which are commonly caught incidentally, sea turtles are of special concern. In fact, five of the seven species of sea turtle living in the world's oceans have been listed as either critically endangered or endangered, and their international trade is prohibited according to the Convention on International Trade in Endangered Species (CITES). One of the

main causes for the worldwide failure of many sea turtle populations to recover is their continued incidental capture in fisheries (Hillestad et al. 1995, Lutcavage et al. 1996). Apart from longlines, other fishing gears are known to interact with sea turtles worldwide, including trawls (Magnuson et al. 1990, Poiner and Harris 1996, Lewison and Crowder 2007) and gill nets (De Metrio and Megalofonu 1988, Julian and Beeson 1998).

A number of research initiatives have focused on the mitigation of longline bycatch by testing several technological and methodological changes, all aiming at increasing fishing gear selectivity and reducing bycatch mortality. Particular attention has been directed at the use of circle hooks—a hook with the point turned perpendicularly toward the shank—as a means to reduce bycatch mortality. With regard to sea turtles, a number of such studies have been conducted worldwide (see reviews by Read 2007 and Wallace et al. 2010). In the Atlantic Ocean, these studies have been mostly limited to the Northern Hemisphere, with only a few studies conducted in the equatorial areas (Carranza et al. 2006, Pacheco et al. 2011). However, these efforts have been limited in terms of the number of sets, geographical area covered, and bait used.

The Portuguese pelagic longline fishery targeting swordfish began in the 1970s and the fishing method has remained almost unchanged since. A few changes have been incorporated in the last decade: (1) fishers shifted 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 and using lightsticks or flashlights; (2) in some areas and seasons, pelagic sharks are a major component of the catch thus the branch line material is multifilament steel, with mackerel bait. The fleet has traditionally used the J-hook with squid bait. Prior to the present study, no circle hooks had been used or tested commercially by the Portuguese fleet, apart from some experiments supported by the US Government between 2000 and 2002 in the Azores (Bolden and Bjørndal 2005). To date, however, none of those results have been published in the peer-reviewed literature.

The Portuguese Fisheries and Aquaculture Directorate and a private fishing company are funding an ongoing project (SELECT-PAL: "Redução das capturas acessórias na pescaria de palangre de superfície"). The aim is 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: Northeastern Tropical, Equatorial, and Southern Temperate. Here we report the first results of the SELECT-PAL project. Specifically, we compare sea turtle bycatch composition and rates, hooking location, and status at haulback, resulting from experimental fishing with different combinations of hook style and bait type in the Equatorial area.

Material and Methods

Experimental Design and Data Collection.—For the present study, a total of 221 long-line sets were deployed along the equatorial Atlantic region (Fig. 1), between January 2009 and March 2011. Two commercial fishing vessels from the Portuguese pelagic longline fleet participated in the experiment. Experimental fishing took place along a wide longitudinal range (42°W–9°E), but in a restricted latitudinal range (7°N–7°S). The fishing gear was similar for both vessels consisting of a standard monofilament polyamide mainline of 3.6 mm diameter (approximately 55 nm long), with five branch lines between floats. Each branch line

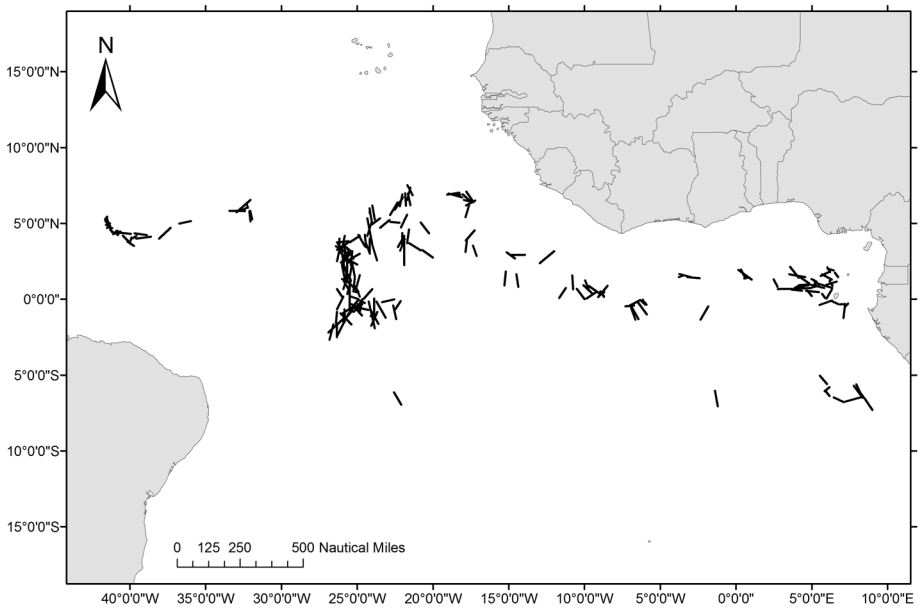


Figure 1. Location of the 221 experimental longline sets in the equatorial Atlantic region.

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 as the terminal tackle. A battery-powered flashlight (green light) was attached to each gangion. On average, 1382 hooks (SD = 133, min = 1260, max = 1728) were used per set, fishing at depths of 20–50 m. Gear deployment typically began at 17:00 hrs, with haulback starting the next day from about 06:00 hrs. Three different stainless steel hook styles (manufactured by WON YANG, Korea) were used in each longline set. The control corresponding to the traditional J-hook of 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 10° offset circle hook (H17/0-M-R; Table 1, Fig. 2). Hook style was alternated section by section of the longline (each section containing between 70 and 80 hooks), to reduce the potential for 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

Table 1. Details of the different hook styles used in the study. Standard deviation is indicated within parentheses. J is traditional hook used in fishery, G and Gt are circle hooks with no offset and 10° offset, respectively.

	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)	77.7 (± 0.92)
Front length (mm)	40.4 (± 1.10)	43.9 (± 0.45)	43.9 (± 0.45)
Maximum width (mm)	43.3 (± 0.64)	49.4 (± 0.88)	49.4 (± 0.88)
Gap (mm)	33.2 (± 0.59)	27.0 (± 0.51)	27.0 (± 0.51)
Arm diameter (mm)	5.0 (± 0.00)	5.0 (± 0.00)	5.0 (± 0.00)
Offset angle	10°	0°	10°

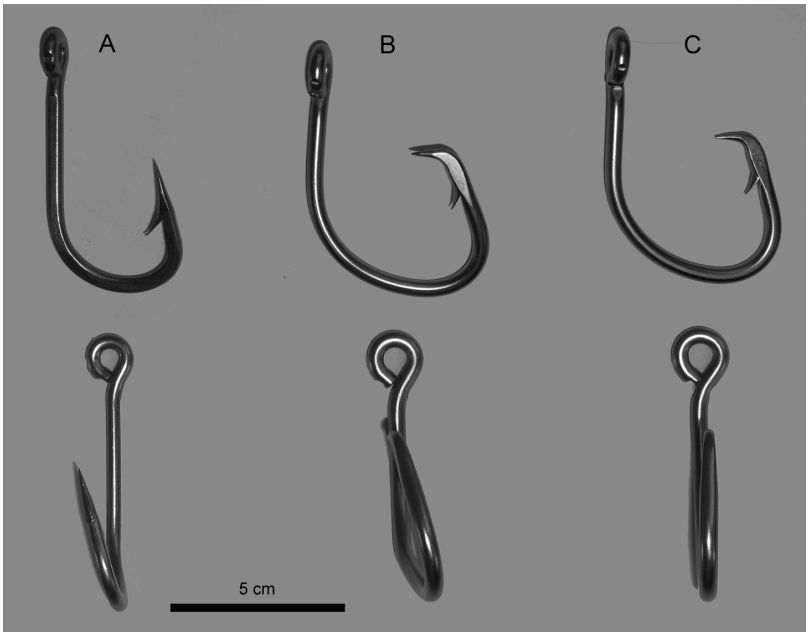


Figure 2. Photograph of the three hook styles used during this study: (A) J-hook 10° offset; (B) Gt circle hook 10° offset; and (C) G non-offset circle hook. Hook measurements in Table 1.

al. (2005). Standardized bait was used in all longline sets (squid 27.8 ± 0.97 cm and mackerel 35.1 ± 1.19 cm).

All characteristics of the fishing gear and fishing practices (e.g., hook placement, setting time, use of light, bait size, and hook manufacturer) were standardized between the two vessels. However, length of mainline and number of hooks were allowed to vary among vessels to take into consideration vessel operating capacity and sea conditions.

Whenever a sea turtle was caught by 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, esophagus, or entangled), and the condition when released (alive/dead). When possible, turtles were boated with a large dip net. Further, observers and crew attempted to remove fishing gear immediately using long-handled dehookers and line cutters. They were instructed to remove all external hooks and those in the mouth, as well as hooks in the esophagus when the insertion point of the barb could be seen. Whenever possible, the sex of the specimen was determined and the carapace curved length and width were measured to the nearest 1 cm. However, due to the size and weight of leatherback sea turtles, *Dermochelys coriacea* (Vandelli, 1761), only a limited number of specimens of this species were measured, with most specimens being immediately released by cutting-off the line.

Following Watson et al. (2005), power analyses were performed to estimate the experimental fishing effort required to detect differences among hook-bait combinations for sea turtle bycatch reduction. The control fishing method was 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 detect a 25% reduction in each of the species bycatch rates. The calculations were based on the mean catch rates of sea turtles previously observed for that region that had been recorded by fishery observers over the period 2005–2008 (IPIMAR, unpubl data).

Data Analysis.—Bycatch rates were expressed as BPUE, calculated as the number of specimens caught per 1000 hooks. Given the lack of normality of the BPUE data and homogeneity of the variances, Kruskal-Wallis tests were used to compare BPUE among different hook types and Mann-Whitney tests were used to compare BPUE between the two baits (due to lack of normality and homogeneity of the variances).

A logistic-binomial GLM was used to determine the influence of hook style and bait type on sea turtle bycatch. Due to small sample sizes, this model was only applied to the olive ridley, *Lepidochelys olivacea* (Eschscholtz, 1829). For this model, the response variable was the proportion of olive ridley catches in each longline set, calculated as the number of catches within 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 indicated by the Wald statistic. Interactions between the two explanatory variables were tested with a likelihood ratio test. With the final model, the odds-ratios of the parameters with their respective 95% confidence intervals were calculated.

Regarding the size structure of the sea turtles caught, only the most abundant species (olive ridley) was considered. Data were tested for normality using a Kolmogorov-Smirnov test (with Lilliefors correction, Lilliefors 1969) and a Levene test for homogeneity of variances, between the different levels of each factor under consideration. The skewness and the kurtosis of the size data were calculated to assess departures from normality. Results of these analyses indicated that parametric tests were appropriate to compare mean sizes among treatments. The bait type effect was tested using a student *t*-test and the hook style and hooking location interaction effects were compared using one-way ANOVA.

The relationship between hooking location and hook type was assessed using contingency tables and chi-square tests of independence. Analyses were conducted for all species combined and for the olive ridley separately. Due to the existence of zero values in some of the combinations using the original four categories, hooking location data were placed into three categories: mouth, esophagus, and external (combining hooked flippers and entangled). Chi-square tests were computed to assess differences in the proportions of live/dead sea turtles between hook styles, bait type, and hooking location. This analysis was performed for species combined and for olive ridley separately, as the contingency table analysis assumptions could not be met for the remaining species due to their low bycatch rates.

All statistical analyses were performed using the R Project for Statistical Computing 2.13.0 (R Development Core Team 2011), primarily using functions available in the core R program. Exceptions were the Levene tests for the homogeneity of variance that is available in library "car" (Fox and Weisberg 2011), contingency table analysis that was performed with library "gmodels" (Warnes et al. 2011), and the plots of means that are available with "Rcmdr" (Fox et al. 2011).

Results

In total, 305,352 hooks were used during the experimental fishing sets (221 sets), corresponding to 101,784 hooks of each hook type. The vessels fished an average of 1381 hooks per set; the minimum number of hooks fished in a set was 1260 and the maximum was 1728 hooks. In terms of bait, an overall 143,136 hooks were baited with mackerel, while the remainder (162,216) were baited with squid. The minimum and the maximum number of hooks used in each of the different hook style-bait type combinations were 47,712 and 54,072, respectively. According to the power analysis, the number of hooks required to detect a 25% reduction in the olive ridley bycatch per unit effort (BPUE) was 17,997; that for leatherback sea turtles was 33,486 hooks. The sea surface temperatures (SST) ranged from 21 to 29 °C, with a mean of 26.6 °C and a standard deviation of 1.97 °C. A correlation between

SST and longitude was observed (Pearson's value of –0.60613), with higher SST recorded toward the western region.

Bycatch Rates.—In total, 231 sea turtles were caught during the present study: 161 olive ridley, 58 leatherbacks, 10 loggerheads, *Caretta caretta* (Linnaeus, 1758), and 2 Kemp's ridley, *Lepidochelys kempii* (Garman, 1880). Of 221 sets, 150 (67.9%) had zero sea turtle bycatch. The maximum number of specimens caught in a single set was 18; for most of the positive sets, fewer than four sea turtles were caught. The highest BPUE was observed in the central part of the study area, between 8°W and 27°W, both for species combined and the two most numerous species caught (Fig. 3).

Because of the high number of sets with zero catches, mean BPUE values were generally very low. Overall, the highest mean BPUE values for species combined and for the individual species occurred with the J-hook, while the catches with both circle hooks tended to be much lower (Fig. 4). Significant differences were detected in the BPUEs among the three hook styles (Kruskal-Wallis: species combined: chi-square = 20.01, df = 2, $P < 0.01$; olive ridley: chi-square = 9.61, df = 2, $P < 0.01$; leatherback: chi-square = 11.35, df = 2, $P < 0.01$). The Kruskal-Wallis rank sum test was performed instead of a parametric ANOVA due to the lack of normality of the data (Lilliefors: $P < 0.01$) and the lack of homogeneity of the variance (Levene: $P < 0.01$). Regarding the bait type (Fig. 4), the BPUE was significantly higher when squid was used (Mann-Whitney: species combined: W = 48,191, $P < 0.01$; leatherback: W = 52,788, $P < 0.01$; olive ridley: W = 49,801, $P < 0.01$). The ratio between the standard fishing practice (J-hook baited with squid) and the other tested combinations indicated 2.0–8.4, 2.1–6.8, and 1.4–11.0 BPUE reductions, for species combined, olive ridley, and leatherback sea turtles, respectively (Table 2).

Both hook style and bait type were significant factors contributing for the olive ridley sea turtle BPUE (Table 3). The interaction between hook style and bait was not significant (likelihood ratio test: diff. residual deviance = 0.583, $P = 0.747$), and therefore the simpler model without interactions was applied. When changing the bait type from squid to mackerel, the odds-ratio of catching olive ridley sea turtles decreased 56% (with 95% CI of 38%–69%). When changing the hook from J-hook to both circle hooks the odds-ratio of catching olive ridleys also decreased. For specific hook types, changing from J to G resulted in the odds-ratio decreasing 54% (with 95% CI of 33%–68%), and changing from J to Gt resulted in the odds-ratios decreasing 65% (with 95% CI of 48%–77%).

Bycatch at Size and Hooking Location.—Olive ridleys ranged in size from 43 to 71 cm total curved length and averaged 60.4 (±5.81) cm (Table 4). Only 26% of leatherback sea turtles were measured due to their large size, as most specimens were released by the crew without being brought to the fishing vessel (particularly the larger specimens). The size statistics for the other species caught are shown in Table 4.

For all species combined, the mouth was the most frequent hooking location (58.4%) regardless of the hook type used (Fig. 5). However, when species were analyzed separately it was possible to determine species-specific patterns of hooking locations. Leatherbacks were almost exclusively hooked on the flippers (63.8%) or entangled (32.8%) on the lines, whereas most olive ridley sea turtle apparently bit the bait, with 77.0% hooked in the mouth and 17.4% in the esophagus (Fig. 5). Even

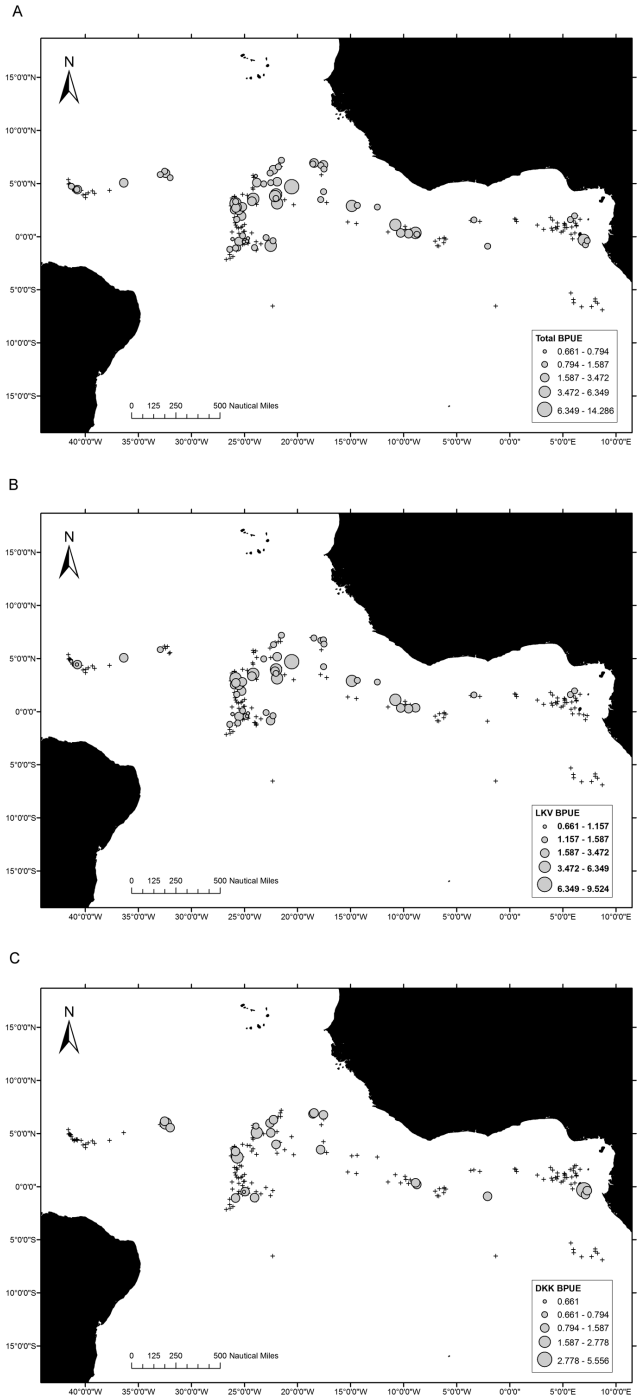


Figure 3. Spatial distribution of bycatch per unit effort (BPUE) by longline experimental set, for (A) sea turtle species combined, (B) olive ridley (LKV, *Lepidochelys olivacea*), (C) and leatherback (DKK, *Dermochelys coriacea*). The size of the circles is proportional to the BPUE and the dark crosses represent fishing sets with 0 catches.

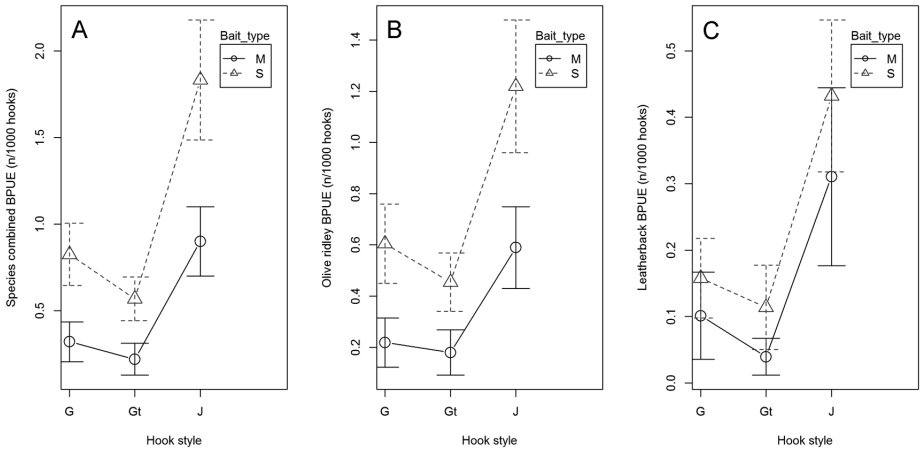


Figure 4. Plot of the mean BPUE (with the respective standard errors) observed with the different hook styles (G, Gt and J) and bait combinations, for (A) all species combined and the two most abundant species, (B) olive ridley (*Lepidochelys olivacea*) and (C) leatherback turtle (*Dermochelys coriacea*). M = mackerel (solid lines with circles), S = squid (dotted lines with triangles).

though only 10 loggerheads were caught, this species seems to have a similar behavior to the olive ridley, as 75% were hooked in the mouth and the remainder in the esophagus.

The relative proportions of the different hooking locations did not differ significantly among hook styles (Fig. 5), as confirmed by chi-square proportion tests between the two factors. This analysis was carried out for species combined (chi-square test of independence: chi-square = 8.89, df = 6, $P = 0.180$) and for olive ridley (chi-square test of independence: chi-square = 1.24, df = 4, $P = 0.871$), but not for leatherback due to low sample sizes. Unlike with hooks, the relative proportions of the different hooking locations differed significantly among baits (Fig. 5). The mouth was always the most frequent hooking location, but when mackerel was used the proportions of the other hooking locations tended to increase (for species combined: chi-square = 24.02664, df = 3, $P < 0.001$; olive ridley: chi-square = 18.7908, df = 2, $P < 0.001$). Corresponding analyses were not carried out for leatherback due to the prevalence of cells with zero values in the contingency table. For olive ridley, the hooking

Table 2. 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 10° offset 9/0 hook used on the fishery, G = 0° offset 17/0 circle hook, Gt = 10° offset 17/0 circle hook) and bait type (S = squid, M = mackerel) tested, for species combined and for the two most abundant sea turtle species caught.

Comparison	Olive ridley	Leatherback	Combined species
J_S vs G_S	2.2	2.7	2.2
J_S vs Gt_S	3.2	3.8	3.2
J_S vs G_M	5.6	4.3	5.7
J_S vs Gt_M	6.8	11.0	8.4
J_S vs J_M	2.1	1.4	2.0

Table 3. Parameter estimation with the respective standard error and statistical significance (Wald statistic and respective *P*-value) for the effects of hook style and bait type in the olive ridley (*Lepidochelys olivacea)* BPUE. The odds-ratios (with the respective 95% confidence intervals) are given for each parameter.

		Odds-ratios 95% CI					
Coefficients	Odds-ratios	Lower	Upper	Estimate	SE	Wald stat	*P*
Mackerel bait	0.439	0.311	0.620	–0.822	0.176	–4.681	< 0.001
G hook	0.460	0.318	0.667	–0.776	0.189	–4.108	< 0.001
Gt hook	0.349	0.231	0.524	–1.055	0.209	–5.059	< 0.001

locations "entangled" and "flippers" were grouped into one category ("hooked externally") due to low sample sizes.

For olive ridley, size distribution did not vary much with bait type or hook style. However, some differences in the sizes were observed depending on the hooking location (Fig. 6), mostly with regard to the entangled specimens that tended to be larger than the others. Statistically, no differences in sea turtle sizes were detected between the bycatch rates with the two baits types (*t*-student: $t = 1.384$, df = 146, $P = 0.169$), nor with the three hook styles (ANOVA: $F = 0.326$, df = 2145, $P = 0.723$). However, the sea turtle sizes varied significantly depending on the hooking location (ANOVA: $F = 4.415$, df = 3144, $P = 0.005$).

Mortality.—Overall, 76.6% of all sea turtles were alive at haulback and released. The hooking location appeared to have substantial impact on mortality with most specimens caught by the flippers or entangled being live at the time of haulback (100% and 90.5% alive at the time of haulback, respectively), while the specimens hooked in the esophagus and in the mouth had lower percentages of alive specimens (70.0% and 68.1% alive at the time of haulback, respectively; Fig. 7). Because the different species tended to be hooked in specific ways, species-specific mortality reflected this specificity in hooking location. Thus, most leatherbacks (that tended to be hooked by the flippers or entangled in the longline) were alive at haulback (96.6%), while olive ridley sea turtles, which tended to be hooked in the mouth or the esophagus, suffered higher mortality (68.3% alive at haulback).

For the factor hook style, and considering all species combined, the G-hook had proportionally more sea turtles alive (84.2%) than dead (15.3%), with the percentage of live specimens decreasing slightly for the J-hooks (78.5%) and substantially more with the Gt-hooks (59.0%; chi-square Proportion test: chi-square = 8.88, df = 2, $P = 0.011$). When the olive ridley data were analyzed separately, the proportion of live

Table 4. Statistics of the size structure of the four sea turtle species caught. *N* = total number of specimens caught; *n* = number of specimens measured; Min = minimum; Max = maximum; SD = standard deviation. Measurements refer to the total carapace curve length (cm).

			Total curve length (cm)			
Species	*N*	*n*	Min	Max	Mean	SD
Olive ridley turtle (*Lepidochelys olivacea)*	161	148	43	71	60.35	5.81
Leatherback (*Dermochelys coriacea*)	58	15	46	151	101.80	43.45
Loggerhead (*Caretta caretta*)	10	10	73	77	74.70	1.25
Kemp's ridley (*Lepidochelys kempii)*	2	2	58	59	58.50	0.71

A

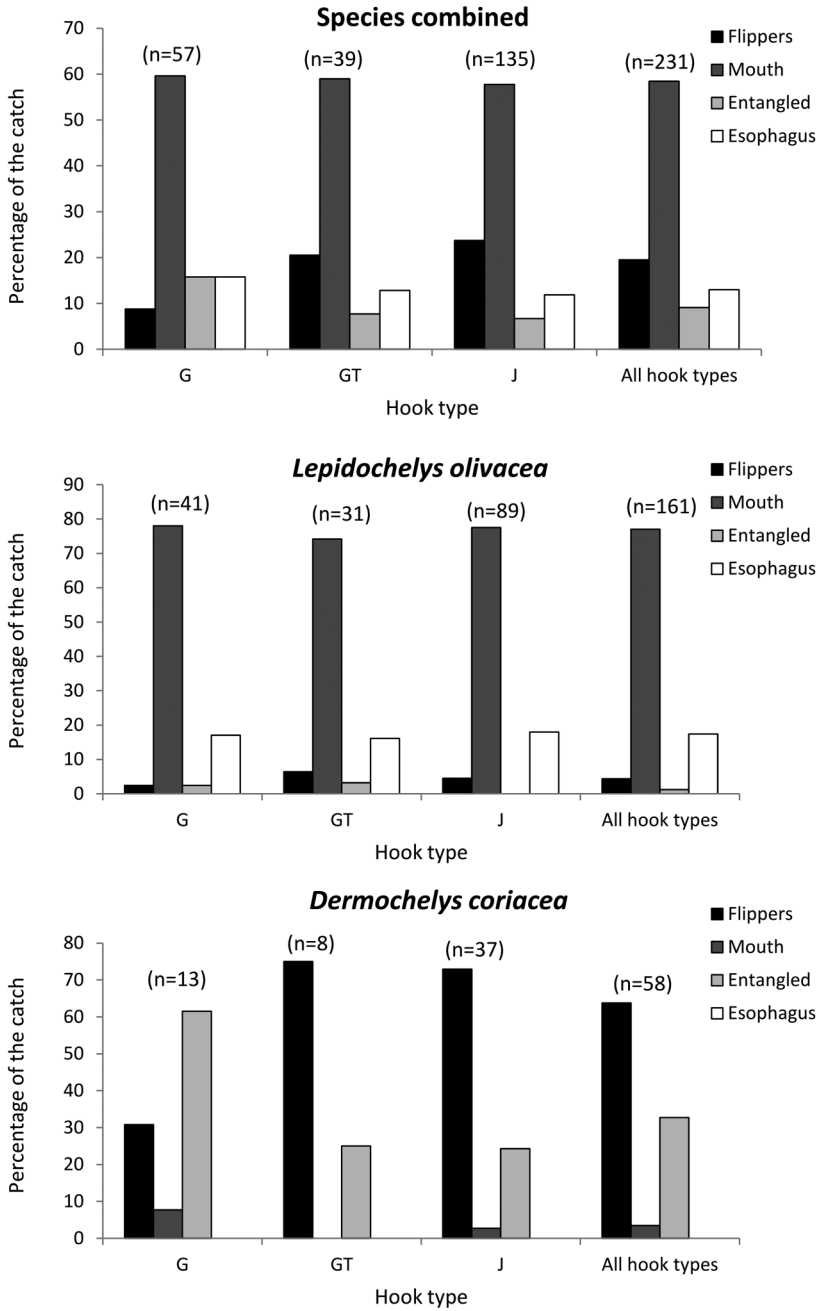
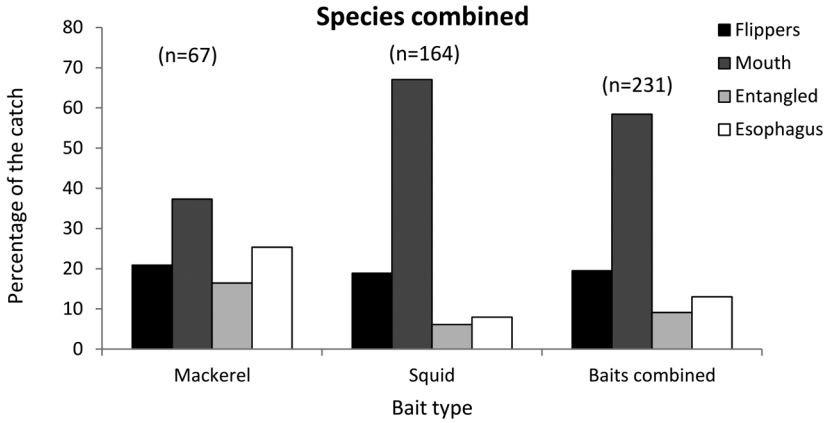
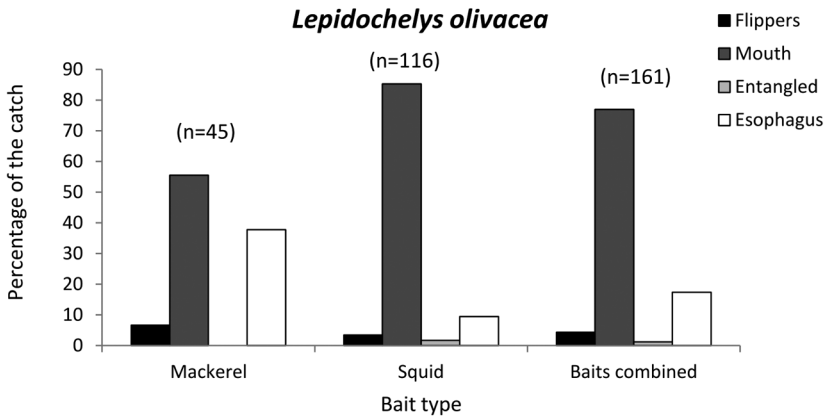
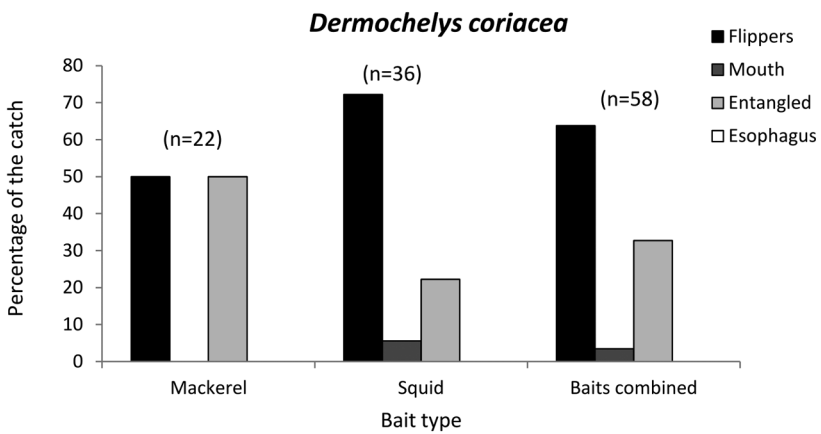


Figure 5. Hooking location per (A) hook style and (B) *(opposite page)* bait type for all species combined, olive ridley (*Lepidochelys olivacea*), and leatherback (*Dermochelys coriacea*). The bars refer to the percentage of each hooking location within each hook style or bait type. Numbers between brackets refer to the corresponding nominal catch of each hook style or bait type.

B


Species combined
(n=67)
(n=164)
(n=231)
Flippers
Mouth
Entangled
Esophagus
Percentage of the catch
80
70
60
50
40
30
20
10
0
Mackerel
Squid
Baits combined
Bait type


Lepidochelys olivacea
(n=45)
(n=116)
(n=161)
Flippers
Mouth
Entangled
Esophagus
Percentage of the catch
90
80
70
60
50
40
30
20
10
0
Mackerel
Squid
Baits combined
Bait type


Dermochelys coriacea
(n=22)
(n=36)
(n=58)
Flippers
Mouth
Entangled
Esophagus
Percentage of the catch
80
70
60
50
40
30
20
10
0
Mackerel
Squid
Baits combined
Bait type

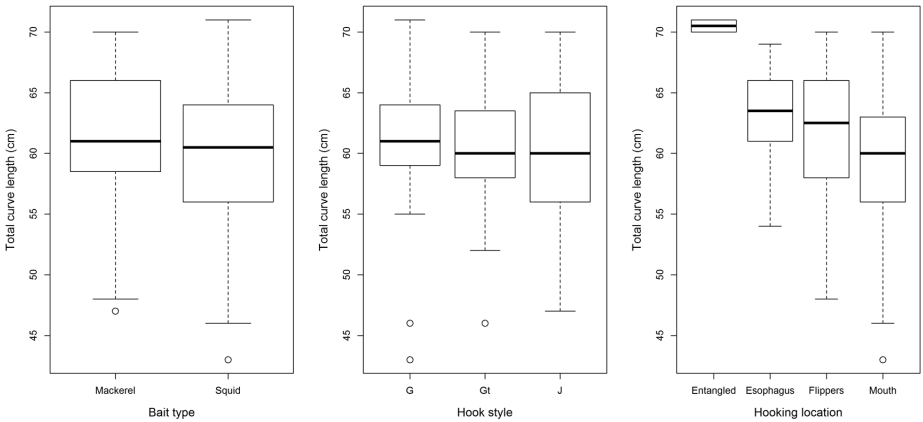


Figure 6. Size distribution (median, inter-quartil range, non-outliers range, and outliers) for olive ridley (*Lepidochelys olivacea*), for each of the three factors considered (bait type, hook style, and hooking location).

specimens differed by hook type: 80.5%, 48.4%, and 69.7% for hook types G, Gt, and J, respectively (Fig. 8; chi-square proportion test: chi-square = 8.57, df = 2, $P = 0.014$). For leatherback sea turtles, the proportions of live specimens were very high for all hook types, specifically 92.3%, 100%, and 97.3% for hook types G, Gt, and J, respectively (Fig. 8; low and zero sample sizes for some of the combinations precluded statistical tests). When the factor bait was analyzed separately for all species combined, the bait type by itself did not significantly influence mortality. Overall, many more sea turtles were caught when squid was used as bait than with mackerel, but the observed vs expected frequencies of dead and live sea turtles caught with each bait type did not differ significantly (proportion chi-square with Yates correction: chi-square = 0.40, df = 1, $P = 0.53$). For olive ridley, the proportions of live specimens (71.6% and 60.0% using squid and mackerel, respectively) did not differ significantly (proportion chi-square with Yates correction: chi-square = 1.50, df = 1, $P = 0.22$).

Discussion

Although a number of studies on sea turtle bycatch of pelagic longline fisheries have been conducted worldwide (see reviews by Read 2007, Wallace et al. 2010), only a few studies have been conducted in the Atlantic equatorial area (Carranza et al. 2006, Pacheco et al. 2011), and these have been limited in terms of the number of sets, geographical area covered, and bait type used. The present study is the most extensive effort to date that followed a strict experimental design and aimed to assess sea turtle bycatch on pelagic longline gear in the Atlantic Equatorial area.

Our results demonstrate that olive ridley, and to a lesser extent, leatherback sea turtles, frequently interact (33% of all sets) with the Equatorial Atlantic Portuguese pelagic swordfish longline fishery, particularly between 8°W and 27°W. However, these can be significantly reduced by using mackerel bait in place of squid bait and/or by employing circle hooks. The combination of circle hooks baited with mackerel resulted in a reduction in sea turtle interactions of 85% for olive ridleys and 91% for leatherbacks. Previous studies have shown that changing the bait type from squid to

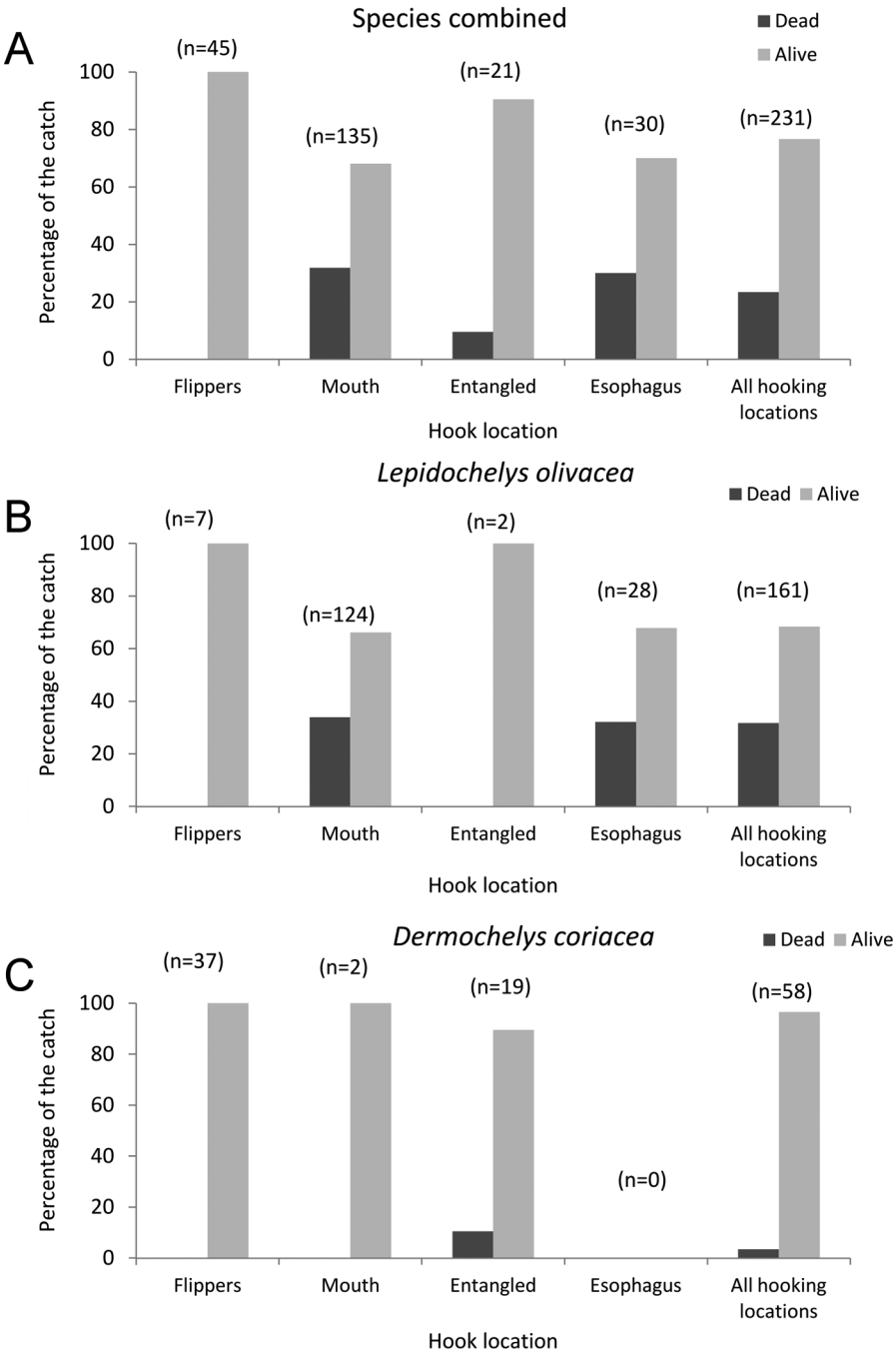


Figure 7. Percentage of fishing mortality at-haulback per hooking location, for (A) all species combined, (B) olive ridley (*Lepidochelys olivacea*), and (C) leatherback (*Dermochelys coriacea*). The numbers between brackets refer to the corresponding number captured for each hooking location (n).

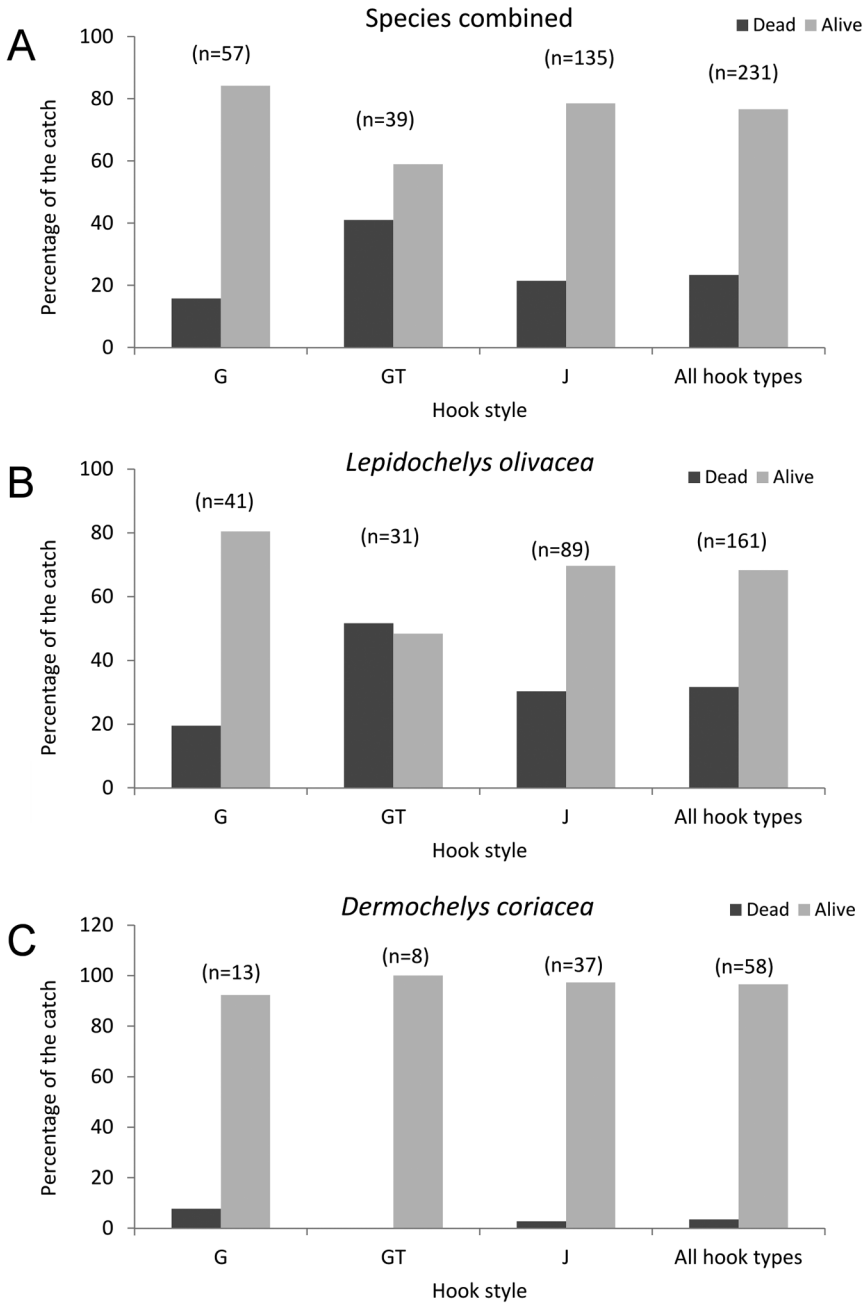


Figure 8. Percentage of fishing mortality at haulback for all sea turtles (A) combined, (B) olive ridley (*Lepidochelys olivacea*), and (C) leatherback (*Dermochelys coriacea*). In each case, mortality is presented separately for each hook type (G, GT, and J) and for hook styles combined. Numbers between brackets refer to the number captured for each hook type (n).

mackerel (or other fish) and/or the traditional J- to circle hooks were efficient measures to reduce sea turtle bycatch (e.g., in the northwest Atlantic, Watson et al. 2005; in northwest Pacific, Yokota et al. 2009; in the equatorial west Atlantic, Pacheco et al. 2011). An additional measure that has been tested in the past that has the potential to influence sea turtle bycatch rates is the use of dye to color bait. Yokota et al. (2009) tested squid and mackerel dyed blue; however, they concluded that this color did not significantly reduce sea turtle bycatch.

The overall BPUE observed in our study using the traditional gear configuration was similar to other pelagic longline fisheries targeting Atlantic swordfish, including those reported by Pinedo and Polacheck (2004) off southern Brazil, Brazner and McMillan (2008) off Canada, and Pacheco et al. (2011) off northwestern Brazil. However, our observed overall BPUE was higher than those reported by Carranza et al. (2006) for the Gulf of Guinea and the St. Helena area and by Watson et al. (2005) for the northwestern Atlantic. When circle hooks were used in western equatorial area of the Atlantic, olive ridley catch rates increased by 300% (based on a small number of specimens caught, baited with squid), whereas catch rates of leatherbacks were reduced by 70% (Pacheco et al. 2011). Watson et al. (2005) reported that circle hooks baited with mackerel resulted in a reduction of 65% of leatherback CPUE in the northwestern Atlantic. However, these comparisons should be carefully analyzed as the cited studies used slightly different hooks (in terms of size and shape), covered different seasons (different ranges of temperature), and were based on substantially different numbers of sets.

Olive ridley and leatherback sea turtles have different life histories. While the latter are pelagic/oceanic during all stages of their life, olive ridley sub-adults and adults use both neritic and oceanic habitats (Musick and Limpus 1997), feeding both in deep water (80–110 m) and relatively shallow benthic habitats (Bjorndal 1997). Thus, the pelagic longlines impact these species differently. For this reason, leatherbacks of a wide size range were captured, including big animals comparable in size to nesting females of the western North Atlantic (Boulon et al. 1996). However, it is likely that the leatherbacks do not represent a random sample of the total catch as the largest and heaviest individuals were not measured. Therefore, caution should be exercised when considering the size data for this species. Captured olive ridley were mostly sub-adults and adults, based upon the carapace length at maturity (66 cm) reported by Miller (1997).

Hooking location patterns were species-specific and hook style was not a significant determining factor. Regardless of the hook style used, leatherback sea turtles were almost exclusively hooked in the flippers or entangled on the lines, whereas most olive ridley sea turtles were hooked in the mouth. This may be related to each species' feeding behavior. In Hawaiian waters, Gilman et al. (2007) found a significant reduction in the proportion of sea turtles that swallowed the hooks (instead of being hooked in the mouth or body or entangled) when switching from J-hook with squid to circle hooks with fish bait. Watson et al. (2005) presented similar results for the loggerhead in the northwest Atlantic. However, Watson et al. (2005) showed a higher proportion of leatherbacks hooked in the mouth when using circles hooks than when using J-hooks, although the majority of the sea turtles were hooked externally in both treatments. Similarly, for leatherbacks a slight switch was observed from being hooked externally (flippers) to the mouth when changing from J-hooks to 0° offset circle hooks. On the other hand, hooking location differed significantly

between bait types. Kiyota et al. (2005) hypothesized that loggerheads were more likely to swallow entire squid bait because of its flexible and tough muscle texture whereas they tended to ingest smaller pieces of fish after biting and cutting the fish baits. Results of the present study indicated that as changing bait type from squid to mackerel resulted in lower proportions of olive ridley sea turtles hooked in the mouth and higher proportions of deep hooking (hooked in the esophagus). In the northwest Atlantic, Watson et al. (2005) found no significant differences in hooking location for both loggerheads and leatherbacks upon switching between mackerel and squid bait.

The main factor appearing to influence mortality at-haulback was hooking location. Sea turtles hooked externally (by the flippers or entangled) were mostly alive, while specimens that were hooked in the mouth or deep hooked in the esophagus were more likely to be dead at time of haulback. Gilman et al. (2007) reported similar results for the Hawaii-based longline swordfish fishery. Moreover, the latter study suggested that this was because pelagic longline fisheries targeting swordfish operate with relatively shallow-set gear (which is the case of the Portuguese fleet). As a result, captured sea turtles are able to reach the surface to breathe during gear soak. Deeper-setting longline fisheries, which tend to use heavier gear (e.g., Japanese and Korean longliners targeting tuna), have a higher proportion of drowned sea turtles. The type of circle hook (G vs Gt) appears to be significant in terms of mortality, particularly for olive ridley, with higher mortality rates associated with the Gt hook.

Our reported mortality results represent the short term at-haulback mortality, and should be interpreted as minimum estimates. We attempted to remove all gear based on recommendations of Watson et al. (2005) because they noted that "Harm from gear left in place may include tissue damage, infection, and digestive track lockage. Hooks may perforate internal organs or vessels; in some cases, hooks become encapsulated or are expelled. Trailing line can encircle a limb, restrict circulation, and cut deeply into the tissue, and eventually cause loss of function. Ingested line may irritate the lining of the gastrointestinal tract and cause death by torsion (involution) or intussusceptions (telescoping of the gut tube, cutting off its cirrculation)." However, Parga (2012) observed that as long as the branch line was cut short (close to the mouth), some deep hooked sea turtles could swallow and even expel the hooks without major harm.

Our results indicate that the adoption of management measures requiring the use of circle hooks with finfish bait in the Portuguese longline fishery would likely reduce sea turtle bycatch mortality. However, as suggested by Campbell and Cornwell (2008), prior to implementing any bycatch reduction device or gear modification in a fishery to try to reduce bycatch, the human dimensions of such changes need to be addressed. In particular, economic impacts of such gear modifications in the fishery need to be estimated because in some cases, significant reductions in the target species may hinder the application of such devices or gear modifications. Such was the case described by Largarcha et al. (2005) for the mahi-mahi fishery in Ecuador, where changing from traditional to circle hooks was efficient in reducing sea turtle bycatch and mortality, but also reduced the target species catch rates by such levels (ca. 30%) that implementation of such gear modification was not economically viable. Another example was presented by Báez et al. (2010) for the Spanish Mediterranean surface longline fishery, where sea turtle captures could be reduced via changing the bait, but due to profit losses, fishers preferred the used of squid instead of fish bait

particularly when targeting swordfish. More recently, Coelho et al. (2012) reported that in the same equatorial longline fishery, the catch rates of the main target species (swordfish) decreased significantly when changing from J-hooks to circle hooks, and when changing from squid to mackerel bait. However, the hook change did not lead to significant economic losses, as there were some gains in other marketable species.

As an overall conclusion, the present study reinforces previous reported results on the reduction of sea turtle bycatch in swordfish longline fisheries by changing the traditional combination of hook and bait. Moreover, it highlights that such gain is species-specific and time-area dependent. Thus, from the management point of view it is important to continue to assess the consequences of such gear modifications on a wider scale.

Acknowledgments

This study was carried out within the scope of the SELECT-PAL project (Programa PROMAR Proj. 31-03-05-FEP-1). Thanks are due to the crews of fishing vessels Alma Lusa (PM-1269-N) and Príncipe das Marés (PM-1218-C) for their cooperation and commitment during the course of the study. Thank are also due to technicians I Ribeiro and J Táta Regala for collecting the data. We are also grateful to the three anonymous referees for their valuable comments that greatly improved the manuscript. R Coelho was supported in part by a grant from FCT (Ref: BDP 40523/2007) co-funded by "POCI-2010 Programa Operacional Ciência e Inovação 2010" and "FSE Fundo Social Europeu." During part of this work J Fernandez-Carvalho was supported by a grant from FCT (Ref: BD 60624/2009).

Literature Cited

Báez JC, Real R, Mácias D, Serna JM, Bellido JJ, Camiñas JA. 2010. Captures of swordfish *Xiphias gladius* Linnaeus, 1758 and loggerhead sea turtles *Caretta caretta* (Linnaeus, 1758) associated with different bait combinations in the western Mediterranean surface longline fishery. J Appl Ichthyol. 26:126–127. http://dx.doi.org/10.1111/j.1439-0426.2009.01342.x

Brazner JC, McMillan J. 2008. Loggerhead turtle (*Caretta caretta*) bycatch in Canadian pelagic longline fisheries: relative importance in the western North Atlantic and opportunities for mitigation. Fish Res. 91:310–324. http://dx.doi.org/10.1016/j.fishres.2007.12.023

Bjorndal KA. 1997. Foraging ecology and nutrition of sea turtles. *In:* Lutz PL, Musick JA, editors. The biology of sea turtles. New York: CRC Press. p. 199–231.

Bolten AB, Bjorndal KA. 2005. Experiment to evaluate gear modification on rates of sea turtle bycatch in the swordfish longline fishery in the Azores — phase 4. Final project report, NOAA award number NA03NMF4540204, Archie Carr Center for Sea Turtle Research, Univ Florida.

Boulon RH, Dutton PH, McDonald DL. 1996. Leatherback turtles (*Dermochelys coriacea*) on St. Croix, US Virgin Islands: fifteen years of conservation. Chelonian Conserv Biol. 2:141–147.

Brothers NP, Cooper JSL. 1999. The incidental catch of seabirds by longline fisheries: worldwide review and technical guidelines for mitigation. Rome: FAO.

Carranza A, Domingo A, Estrades A. 2006. Pelagic longlines: a threat to sea turtles in the Equatorial Eastern Atlantic. Biol Conserv. 131:52–57. http://dx.doi.org/10.1016/j.biocon.2006.02.003

Campbell LM, Cornwell ML. 2008. Human dimensions of bycatch reduction technology: current assumptions and directions for future research. Endang Species Res. 5:325–334. http://dx.doi.org/10.3354/esr00172

Coelho R, Santos MN, Amorim S. 2012. Effects of hook and bait on targeted and bycatch fishes in an equatorial atlantic pelagic longline fishery. Bull Mar Sci. 88:449–467. http://dx.doi.org/10.5343/bms.2011.1064

De Metrio G, Megalofonu P. 1988. Mortality of marine turtles (*Caretta caretta* L., and *Dermochelys coriacea* L.) consequent to accidental capture in the Gulf of Taranto. Rapp P-V Reun Comm Int Explor Sci Mer Mediterr Monaco. 31:285.

FAO Fisheries and Aquaculture Department. 2010. The state of world fisheries and aquaculture. Rome: FAO.

Fox J, Andronic L, Ash M, Boye T, Calza S, Chang A, Grosjean P, Heiberger R, Jay Kerns G, Lancelot R, et al. 2011. Rcmdr: R Commander. R package version 1.6-4. Available from: http://CRAN.R-project.org/package=Rcmdr

Fox J, Weisberg S. 2011. An {R} companion to applied regression. 2nd ed. Thousand Oaks CA: Sage.

Gilman E, Kobayashi D, Swenarton T, Brothers N, Dalzell P, Kinan-Kelly I. 2007. Reducing sea turtle interactions in the Hawaii-based longline swordfish fishery. Biol Conserv. 139:19–28. http://dx.doi.org/10.1016/j.biocon.2007.06.002

Hall MA, Alverson DL, Metuzals KI. 2000. Bycatch: problems and solutions. Mar Poll Bull. 41:204–219. http://dx.doi.org/10.1016/S0025-326X(00)00111-9

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, et al. 2008 A global map of human impact on marine ecosystems. Science. 319:948–952. PMid:18276889. http://dx.doi.org/10.1126/science.1149345

Hillestad HO, Richardson JI, McVea Jr C, Watson Jr JM. 1995. Worldwide incidental capture of sea turtles. *In:* Biology and conservation of sea turtles. Revised edition. Bjorndal KA, editor. Washington DC: Smithsonian Institute Press. p. 489–495.

Huang HW. 2011. Bycatch of high sea longline fisheries and measures taken by Taiwan: actions and challenges. Mar Policy. 35:712–720. http://dx.doi.org/10.1016/j.marpol.2011.02.012

Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, et al. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science. 293:629–638. PMid:11474098. http://dx.doi.org/10.1126/science.1059199

Julian F, Beeson M. 1998. Estimates of marine mammal, turtle, and seabird mortality for two California gillnet fisheries: 1990–1995. Fish Bull. 96(2):271–284.

Kiyota M, Yokota K, Nobetsu T, Minami H, Nakano H. 2005. Assessment of mitigation measures to reduce interactions between sea turtles and longline fishery. Proceedings of the International Symposium on SEASTAR2000 and Bio-logging Science (The 5th SEASTAR2000 Workshop). p. 24–29.

Largarcha E, Parrales M, Rendón L, Velasquez V, Orozco M, Hall M. 2005. Working with the Ecuadorian fishing community to reduce the mortality of sea turtles in longlines: the first year Match 2004–March 2005. Western Pacific Regional Fishery Management Council. 57 p.

Lewison RL, Crowder LB. 2007. Putting longline bycatch of sea turtles into perspective. Conserv Biol. 21(1):79–86. PMid:17298513. http://dx.doi.org/10.1111/j.1523-1739.2006.00592.x

Lewison RL, Freeman SA, Crowder LB. 2004. Quantifying the effects of fisheries on threatened species: the impact of pelagic longlines on loggerhead and leatherback sea turtles. Ecol Lett. 7:221–231. http://dx.doi.org/10.1111/j.1461-0248.2004.00573.x

Lilliefors HW. 1969. On the Kolmogorov-Smirnov test for the exponential distribution with mean unknown. J Amer Statistical Assoc. 64:387–389.

Lutcavage ME, Plotkin P, Witherington B, Lutz P. 1996. Human impacts on sea turtle survival. *In:* Lutz PL, Musick JA, editors. The biology of sea turtles. New York: CRC Press. p. 387–409.

Magnuson JJ, Bjorndal KA, Dupaul WA, Graham GL, Owens FW, Peterson CH, Pritchard PCH, Richardson JI, Saul GE, West CW. 1990. Decline of the sea turtles: causes and prevention. 1st ed. Washington DC: National Academy Press.

Miller JD. 1997. Reproduction in sea turtles. *In:* Lutz PL, Musick JA, editors. The biology of sea turtles. New York: CRC Press. p. 51–81.

Musick JA, Limpus CJ. 1997. Habitat utilization and migration inn juvenile sea turtles. *In:* Lutz PL, Musick JA, editors. The biology of sea turtles. New York: CRC Press. p. 137–163.

Pacheco JC, Kerstetter DW, Hazin FH, Hazin H, Segundo RSSL, Graves JE, Carvalho F, Travassos PE. 2011. A comparison of circle hook and J hook performance in a western equatorial Atlantic Ocean pelagic longline fishery. Fish Res. 107:39–45. http://dx.doi.org/10.1016/j.fishres.2010.10.003

Parga ML. 2012. Hooks and sea turtles: a veterinarian's perspective. Bull Mar Sci. 88:731–741. http://dx.doi.org/10.5343/bms.2011.1063

Pauly DP, Watson R, Alder J. 2005. Global trends in world fisheries: impacts on marine ecosystems and food security. Philos T Roy Soc B. 360:5–12. PMid:15713585. PMCid:1636108. http://dx.doi.org/10.1098/rstb.2004.1574

Pinedo MC, Polacheck T. 2004. Sea turtle bycatch in pelagic longline sets off southern Brazil. Biol Conserv. 119:335–339. http://dx.doi.org/10.1016/j.biocon.2003.11.016

Poiner IR, Harris ANM. 1996. Incidental capture, direct mortality and delayed mortality of sea turtles in Australia's northern prawn fishery. Mar Bio. 125:813–825. http://dx.doi.org/10.1007/BF00349264

R Development Core Team. 2011. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available from: http://www.R-project.org/

Read A. 2007. Do circle hooks reduce the mortality of sea turtles in pelagic longlines? A review of recent experiments. Biol Conserv. 135:155–169. http://dx.doi.org/10.1016/j.biocon.2006.10.030

Soykan CU, Moore JE, Zydelis R, Crowder LB, Safina C, Lewison RL. 2008. Why study bycatch? An introduction to the theme section on fisheries bycatch. Endang Species Res. 5:91–102. http://dx.doi.org/10.3354/esr00175

Wallace BP, Lewison RL, McDonald SL, McDonald RK, Kot CY, Kelez S, Bjorkland RK, Finkbeiner EM, Helmbrecht S, Crowder LB. 2010. Global patterns of marine turtle bycatch. Conserv Lett. 3(3):131–142. http://dx.doi.org/10.1111/j.1755-263X.2010.00105.x

Warnes GR, Bolker B, Lumley T, Johnson RC. 2011. gmodels: various R programming tools for model fitting. R package version 2.15.1. Available from: http://CRAN.R-project.org/package=gmodels

Watson JW, Epperly S, Shah A, Foster DG. 2005. Fishing methods to reduce sea turtle mortality associated with pelagic longlines. Can J Fish Aquat Sci. 62:965–981. http://dx.doi.org/10.1139/f05-004

Watson JW, Kerstetter DW. 2006. Pelagic longline fishing gear: a brief history and discussion of research efforts to improve selectivity and sustainability. Mar Tech Soc J. 40(3):5–10. http://dx.doi.org/10.4031/002533206787353259

Yokota K, Kiyota M, Okamura H. 2009. Effect of bait species and color on sea turtle bycatch and fish catch in a pelagic longline fishery. Fish Res. 97(1–2):53–58. http://dx.doi.org/10.1016/j.fishres.2009.01.003

Date Submitted: 11 July, 2011.
Date Accepted: 3 April, 2012.
Available Online: 20 April, 2012.

Addresses: (MNS) *Instituto Nacional dos Recursos Biológicos (INRB I.P./IPIMAR), Avenida 5 de Outubro s/n, 8700-305 Olhão, Portugal.* (RC) *Instituto Nacional dos Recursos Biológicos (INRB I.P./IPIMAR), Avenida 5 de Outubro s/n, 8700-305 Olhão, Portugal. Centre of Marine Sciences, University of Algarve (CCMAR), FCT Ed. 7, Campus de Gambelas, 8005-139 Faro, Portugal.* (JFC) *Instituto Nacional dos Recursos Biológicos (INRB I.P./IPIMAR), Avenida 5 de Outubro s/n, 8700-305 Olhão, Portugal.* (SA) *Instituto Nacional dos Recursos Biológicos I.P./IPIMAR, Avenida 5 de Outubro s/n, 8700-305 Olhão, Portugal.* Corresponding Author: (MNS) *Email: <mnsantos@ipimar.pt>.*