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Circle hook effectiveness for the mitigation of sea turtle bycatch and capture of target species in a Brazilian pelagic longline fishery

GILBERTO SALES[a], BRUNO B. GIFFONI[b], FERNANDO N. FIEDLER[a], VENÂNCIO G. AZEVEDO[c], JORGE E. KOTAS[d], YONAT SWIMMER[e] and LEANDRO BUGONI[f,*]
[a]*Centro TAMAR/ICMBio and Fundação Pró-TAMAR, Av. Ministro Victor Konder 374, 88301-700, Itajaí, SC, Brazil*
[b]*Projeto Tamar – Fundação Pró-Tamar, Rua Antônio Athanazio da Silva 273, 11680-000, Ubatuba, SP, Brazil*
[c]*Instituto de Pesca/APTA/SAA, Estrada Joaquim Lauro de Monte Claro Neto 2275, 11680-000, Ubatuba, SP, Brazil*
[d]*Centro de Pesquisa e Gestão de Recursos Pesqueiros do Litoral Sudeste e Sul — CEPSUL/ICMBio, Av. Ministro Victor Konder 374, 88301-700, Itajaí, SC, Brazil*
[e]*US NOAA Fisheries, Pacific Islands Fisheries Science Center, 2570 Dole Street, Honolulu, Hawaii 96822, USA*
[f]*UFPel, Instituto de Biologia, Campus Universitário Capão do Leão, CP 354, 96010-900, Pelotas, RS, Brazil*

ABSTRACT

1. Incidental catches by the pelagic longline fishery is a major global threat for loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) sea turtles.
2. The reduction of incidental capture and post-release mortality of sea turtles in the Brazilian pelagic longline fishery, operating in the south-western Atlantic Ocean, was investigated by comparing the performance of 18/0 circle hooks with 9/0 J-type (control) hooks. Hook selectivity experiments were performed between 2004 and 2008, in a total of 26 trips, 229 sets and 145 828 hooks. The experimental design included alternating control and experimental hooks along sections of the mainline.
3. An overall decrease in capture rates for loggerhead turtles of 55% and for leatherbacks of 65% were observed when using circle hooks. In addition, deep-hooking in loggerheads decreased significantly from 25% using J-hooks to 5.8% with circle hooks, potentially increasing post-release survival.
4. Circle hooks increased catch rates of most of the main target species, including tunas (bigeye *Thunnus obesus* and albacore *T. alalunga*), and sharks (blue *Prionace glauca* and requiem sharks of the genus *Carcharinus*), with no difference in the capture rates of yellowfin tuna (*T. albacares*), shortfin mako shark (*Isurus oxyrinchus*), hammerhead sharks (*Sphyrna lewini* and *S. zygaena*), and dolphinfish or mahi mahi (*Coryphaena hippurus*). On the other hand, a significant decrease in the capture rate of swordfish (*Xiphias gladius*) was detected when using circle hooks.
5. Overall, results support the effectiveness of using circle hooks for the conservation of loggerhead and leatherback sea turtles, with positive effects on capture of most target species of the south-western Atlantic longline fishery. Copyright © 2010 John Wiley & Sons, Ltd.

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KEY WORDS: loggerhead sea turtle; leatherback sea turtle; incidental capture; mitigation measures; circle hook

INTRODUCTION

Most marine fisheries around the world are not 100% selective with respect to catching only targeted species, and often result in unintentional capture of fishes, mammals, seabirds and sea turtles (Kelleher, 2005; Werner *et al*., 2006), with an estimated 7.3 million tonnes of discards from marine fisheries every year (Kelleher, 2005). A range of bycatch species, especially those with K-selected life strategies, i.e. long-lived, low fertility, delayed maturity, and high adult survival, are threatened with extinction owing to unsustainable levels of incidental mortality (Lewison *et al*., 2004). The pelagic longline fishery is commonly used throughout the world to catch large predatory fishes such as tuna, billfish, and shark (Brothers

*Correspondence to: L. Bugoni, UFPel, Instituto de Biologia, Campus Universitário Capão do Leão, CP 354, 96010-900, Pelotas, RS, Brazil.
E-mail: lbugoni@yahoo.com.br

et al., 1999; Watson and Kerstetter, 2006). The fishery is considered relatively selective with respect to capturing targeted fish by species and size compared with gillnetting and trawling (Alverson *et al*., 1996; Bjordal and Løkkeborg, 1996; but see Ovetz, 2007). However, pelagic longlines are frequently referred to as a major threat to sea turtles and seabirds worldwide (Brothers *et al*., 1999; Lewison and Crowder, 2007), and in the south-western Atlantic Ocean (Domingo *et al*., 2006; Bugoni *et al*., 2008; Sales *et al*., 2008; Jiménez *et al*., 2009).

In this context, fishing companies, researchers, governments and Regional Fishing Management Organizations (RFMOs) are urged to find practical ways to minimize sea turtle capture in longline fisheries. An ideal mitigation measure would be one that accomplishes all of the following: (1) reduce captures of sea turtles to negligible levels; (2) has minimal effects or even increase capture of target-species, if not overexploited; (3) has minimal or beneficial effects on other threatened bycatch species (e.g. albatross, billfish, some sharks); (4) provides operational benefits; (5) has low costs of implementation (especially important in developing countries); and (6) does not increase safety hazards.

Several measures to mitigate the incidental capture of sea turtles in pelagic longline fisheries have been proposed or implemented in different fisheries (Gilman *et al*., 2006; Werner *et al*., 2006). For instance, in the Hawaii-based longline fishery, shallow sets (<100 m) were banned for parts of 2001 to 2004, which eliminated captures of shallow-dwelling loggerhead sea turtles (*Caretta caretta*) (Polovina *et al*., 2003). In the Hawaiian swordfish (*Xiphias gladius*) fishery, following a closure of four years, the fishery was reopened with a number of conditions such as a maximum annual quota for the entire fleet of 17 loggerhead and 16 leatherback (*Dermochelys coriacea*) sea turtles, restricted annual fishing effort, prescribed use of fish bait and large 18/0 circle hooks instead of squid bait and 9/0 J-hooks, and 100% observer coverage (Gilman *et al*., 2006, 2007; Pradhan and Leung, 2006). In the US Atlantic fishery, circle hooks are also mandatory, while the International Commission for the Conservation of Atlantic Tunas (ICCAT), encourage their use throughout the Atlantic Ocean (Watson and Kerstetter, 2006). Other strategies for mitigation have shown limited ability to avoid or reduce incidental capture (e.g. blue-dyed bait, Swimmer *et al*., 2005; Yokota *et al*., 2009); are in preliminary stages (e.g. sensory-based experiments, Southwood *et al*., 2008), or have resulted in economic losses and social conflicts (e.g. area closures, banning the fishery, reduction of fishing effort, Pradhan and Leung, 2006).

In addition to reducing sea turtle captures in some fisheries, it has been suggested that circle hooks increase post-release survivorship of captured turtles by reducing the number of deep-hooking events (Watson *et al*., 2005; Read, 2007). Their efficiency in catching target species has encouraged testing and implementation in several fisheries (e.g. Yokota *et al*., 2006; Read, 2007; Piovano *et al*., 2009). Nevertheless, in recent reviews Gilman *et al*. (2006) and Read (2007) suggested that mitigation measures for sea turtles in general, and circle hooks in particular, will not be effective in every pelagic longline fishery and each case needs to be tested locally before this measure is adopted.

Despite being tested in several fisheries around the globe (Read, 2007), peer-reviewed publications with data on experiments designed to test the effectiveness of circle hooks for sea turtles are limited to the western north Atlantic (Watson *et al*., 2005), the Hawaiian-based fleet in the north Pacific (Gilman *et al*., 2007) and the Mediterranean Sea (Piovano *et al*., 2009). In this study, the performance of 18/0 10° offset circle-hooks was compared with 9/0 J-type hooks (control) in terms of reduction in the capture of sea turtles and the incidence of deep-hooking, and the effect on target species catches in the Brazilian pelagic longline fleet operating in the south-western Atlantic Ocean.

METHODS

Fishing grounds and fleet

In this study, monitored longline sets occurred over a wide area from 20 to 38°S and from 30 to 53°W (Figure 1). Throughout the year this area is the fishing ground for the Brazilian pelagic longline fleet departing from Santos, Itajaí and Rio Grande harbours. Core area for this fishing fleet is the continental slope, mainly over isobaths 200 to 2000 m, within the southern Brazilian Exclusive Economic Zone. However, gear is also frequently deployed over the Rio Grande Rise and international waters in between. The current study was carried out in such areas where most fishing effort occurs (Figure 1). In 2005, the Brazilian-owned plus the foreign-chartered vessels deployed 12.6 million hooks from 99 vessels (Sales *et al*., 2008).

Oceanography is complex in the south-western Atlantic Ocean. The warm, high salinity, oligotrophic waters of the Brazilian Current flowing southward meet the cold, low salinity, nutrient-rich waters of the Malvinas/Falkland Current flowing northward (Olson *et al*., 1988; Seeliger *et al*., 1998). The front formed by both currents is the Subtropical Convergence, which varies seasonally from 30 to 46°S (Olson *et al*., 1988; Campos *et al*., 2000). Frontal vortices and meanders are particularly common. The branch formed by the meeting of both currents flowing eastward (Stramma and England, 1999) and the mixing of water masses play an important role in physical and biotic processes (Campos *et al*., 2000), supporting important fish stocks and a considerable number of top predators (Seeliger *et al*., 1998).

Along the Subtropical Convergence there is an important longline fishery for tuna, swordfish and sharks, operated since the 1950s by coastal nations (Brazil and Uruguay), as well as distant water fleets such as Japan, China, Spain, and Taiwan (Hazin *et al*., 2008).

Fishing gear, sampling design and data collection

The fishing gear used during the study was a typical American-style monofilament polyamide longline (for a description see Watson and Kerstetter, 2006). Circle hooks 18/0 10° offset, one type made in Brazil (Anzóis Mendes Ltda.) and another in South Korea (OPI, Lindgren-Pitman design) were compared with straight 'J-style' hooks 9/0 0° offset without ring (Mustad design), traditionally used by the Brazilian fleet targeting tuna, sharks and swordfish (Figure 2). The term 'offset' refers to the deviation, in degrees, in the plane of the hook point relative to that of the hook shank. Gangion length varied according to the vessel, captain and target species, and swivels were placed about 2 m from the hook. Because sharks are an important target group, a 0.5 m length multifilament steel cable was

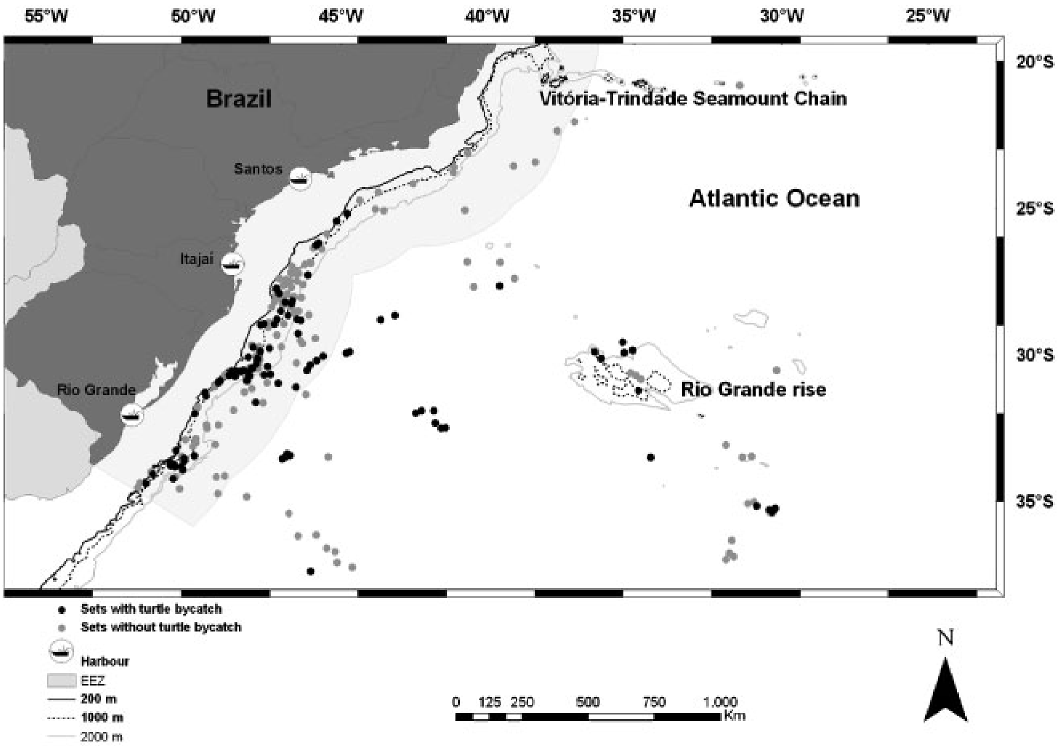

Figure 1. Fishing grounds and distribution of pelagic longline sets carried out from 2004 to 2008 in the south-western Atlantic Ocean to test 18/0 circle hooks and 9/0 J-type hooks. Sets with and without capture of sea turtles are indicated.

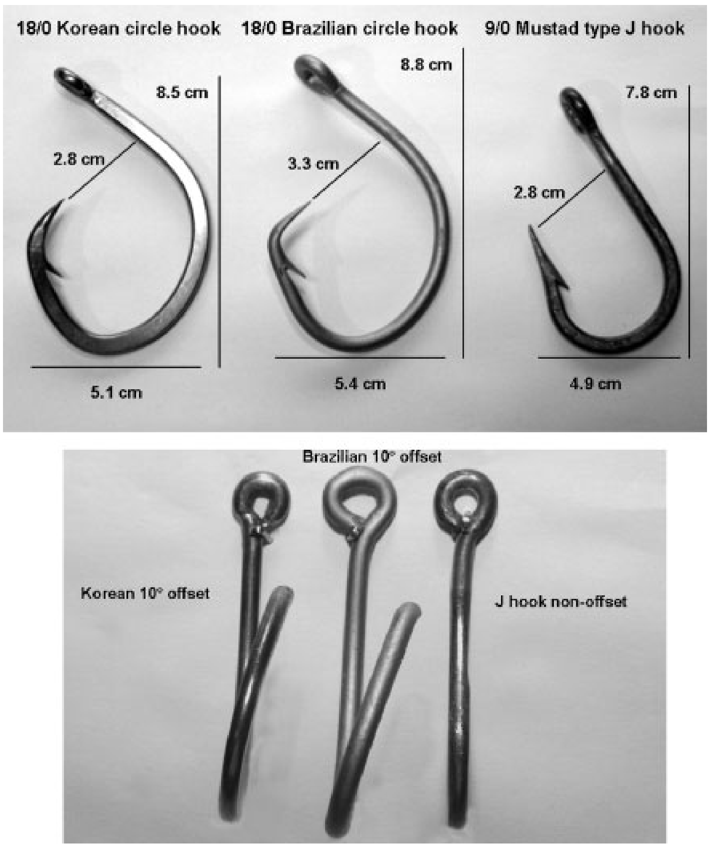

Figure 2. Lateral (above) and frontal (below) views of circle hooks 18/0, 10° offset (Korean – left, Brazilian – centre) and Mustad type 'J' hook 9/0, 0° offset – right. Photos: V. Fonseca.

attached at the terminal section of the gangions, near the hook. Five hooks (sometimes six) were deployed between buoys, and the position of the hook which caught a turtle within a section between floats was recorded (positions 1 to 5). Bait used throughout the study was whole mackerel (*Scomber* spp.).

Data were collected by onboard scientific observers whose main task was to collect biological data on sea turtles and test hook performance. Twenty-two trips undertaken by four different vessels of the commercial fleet and four trips by the R/V Soloncy Moura were carried out from 2004 to 2008, covering all months. It is possible that because the trials were conducted on different vessels, this could add confounding variables, such as differences in fishing gear and operational procedures. As such, the aim was to minimize these effects by conducting the trials such that control and experimental hooks were alternated in a subset of the mainline (see Figure 3 in Piovano *et al*., 2009). By using such a design the purpose was to have every J hook as a control for the adjacent circle hook, diluting potential effects from the position of every hook type along the mainline. The number of hooks between floats was usually five (six in a few sets), thus differences in depth according to hook type was minimized. A variable number of hooks, usually J-type, but also tuna hooks, were used outside the experimental section, with different baits, but data was not collected in this section. During operation of a similar vessel and gear configuration in the same fishery, recorded hook depth varied from 33 to 100 m (Olavo *et al*., 2005), justifying the assumption that during the current study hooks were deployed within this range.

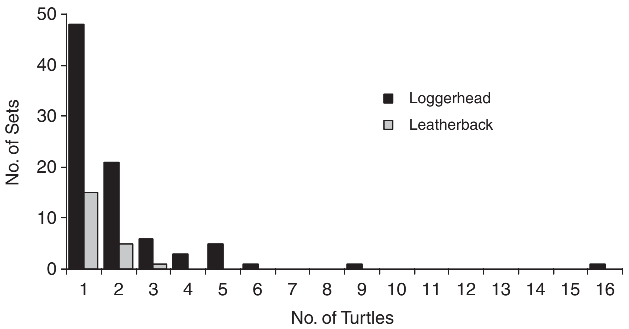

Figure 3. Number of loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) sea turtles captured per set, excluding sets with no captures.

In total, 145 828 hooks were deployed (mean = 636.8 ± 280.1 hooks per set, range = 300 to 1450 hooks, $n = 229$ sets). Hooks were usually set near dusk and hauling started early morning. At the start of sets, sea state in Beaufort scale varied from 0 to 5, mode = 2. Mean depth at the start of setting was 1757.3 ± 1370.2 m (range 254–5000 m), similar to the end of the sets (1802.3 ± 1461.7, range 140–5000 m), with large depth variation when sets were deployed over the shelf break (Figure 1). Mainline was 33.6 ± 10.0 nautical miles (nm) long (range 10–46 nm).

Every sea turtle captured was identified and curved carapace length (CCL) was measured to the nearest 0.5 cm. Hook type and location where it was inserted were recorded (deep hooking = esophagus or deeper; light hooking = mouth; and external/entangled or flipper-hooked). Also recorded were the sea turtle condition (alive, dead or in comatose state), and if the hook and terminal gear was removed or not. Live turtles were tagged with metallic inconel tags on every front flipper (hard-shelled turtles) or on hind flippers (leatherback turtles) (Model 681, National Band and Tag Company, Newport, KY, USA) before they were released.

Data analysis

Comparison of the captures of circle vs J hooks for sea turtles, fish and shark target species or group of species (Table 1) was carried out using the Mantel–Haenszel χ^2 test. This test has been designed to test the association between two dichotomous variables using information from several 2×2 tables, when events (in this case captures) are rare (Agresti, 2002). Number of hooks and turtles captured per set was inserted in 2×2 tables to run analysis ($n = 229$ sets).

Table 1. Capture rates (individuals per1000 hooks) and number of sea turtles, bony fishes and sharks captured by pelagic longline using J-type and circle hooks in the south-western Atlantic Ocean. Total fishing effort 145 828 hooks (equal number of circle and J-type hooks set alternated). M-H – Mantel-Haenszel χ^2 test

	J hook Capture rate (No. individuals)	Circle hook Capture rate (No. individuals)	M-H χ^2	*P* value	Odds-ratio
Sea turtles	1.893 (138)	0.837 (61)	25.44	<0.001	2.17
Loggerhead turtle *Caretta caretta*	1.605 (117)	0.727 (53)	23.40	<0.001	2.21
Leatherback turtle *Dermochelys coriacea*	0.274 (20)	0.096 (7)	25.44	<0.001	2.00
Green turtle *Chelonia mydas*	0.014 (1)	0.014 (1)	—	—	—
Bony fishes					
Swordfish *Xiphias gladius*	11.424 (833)	9.806 (715)	10.10	0.001	1.18
All tuna	3.950 (288)	6.830 (498)	15.63	<0.001	1.34
Bigeye tuna *Thunnus obesus*	0.315 (23)	0.631 (46)	0.002	0.008	0.96
Yellowfin tuna *Thunnus albacares*	1.152 (84)	1.591 (116)	2.04	0.153	1.24
Albacore tuna *Thunnus alalunga*	2.482 (181)	4.608 (336)	22.21	<0.001	1.55
Dolphinfish *Coryphaena hippurus*	3.058 (223)	2.688 (196)	1.73	0.188	0.09
Sharks					
Blue shark *Prionace glauca*	20.421 (1489)	23.919 (1744)	25.53	<0.001	1.19
Carcharinus sharks	1.125 (82)	1.701 (124)	7.77	0.005	1.50
Hammerhead sharks *Sphyrna lewini*/*S. zigaena*	1.550 (113)	1.659 (121)	0.21	0.647	1.07
Shortfin mako shark *Isurus oxyrinchus*	1.221 (89)	1.742 (127)	0.355	0.551	1.10

All comparisons have degrees of freedom (df) = 1. — Not calculated.

The effect of hook type on size of loggerheads captured was tested by t-test. The influence of the position of the hook within a section between floats (basket) in the capture of loggerhead turtles was tested for sets with five hooks between floats, and hook type pooled, through chi-square goodness-of-fit test. To test if the location of hooking in loggerhead turtles differed between hook types the χ^2 test of heterogeneity was used. Finally, tests were made to determine if the number of loggerheads with hook and lines completely removed before releasing them differed between circle and J hooks through a χ^2 test with Yates correction for continuity (Fowler *et al.*, 1998).

Results are presented for sea turtles, main bony fish and shark target species. A complete analysis and discussion of teleosts, sharks and rays captured during this experiment will be reported elsewhere. All species or groups with over 10 individuals were analysed statistically. Parametric tests were used after checking for normality of residuals by Kolmogorov–Smirnov test, and for homoscedasticity by Levene's test, both at $P<0.05$. When necessary, data were 'log' or 'log $n+1$' transformed looking for normality and homocedasticity, or nonparametric tests were used. Capture rates are reported as number of individuals (turtles, fish or sharks) caught per 1000 hooks deployed. Values are given as mean ± 1 standard deviation, except when indicated.

RESULTS

Sea turtle captures

A total of 200 sea turtles of three species were captured. Loggerheads comprised 85% of sea turtles captured, followed by leatherback (14%), and only two juvenile green turtles *Chelonia mydas* (Table 1). One green turtle was caught with a J-hook (CCL = 30.5 cm) and another with a circle hook (CCL = 34.5 cm). Both were hooked in the mouth and were dead when recovered.

Most sets did not capture loggerheads (62.4% of sets) or leatherbacks (90.8%). Among the 86 sets with loggerheads captured, 48 sets captured a single specimen, 21 sets captured two, and a maximum of 16 loggerheads were captured in a single set. Similarly, among the 21 sets with leatherbacks captured, 15 sets captured a single individual, five sets captured two and a single set captured three leatherbacks (Figure 3).

Effect of hook type on turtle capture

Loggerheads

Capture rate of loggerhead turtles decreased from 1.605 turtles per 1000 hooks with J-type hooks to 0.727 turtles per 1000 hooks with circle hooks. The probability of capturing a loggerhead increased by a factor of 2.2 with J hooks (odds-ratio in Table 1). Circle hooks captured larger loggerheads than J hooks (CCL = 60.5 ± 6.7 cm, range 50–81 cm vs 57.9 ± 7.9 cm, range = 37.5–96 cm, $t=2.36$, df = 118, $P=0.02$). Based on measurements of CCL of nesting females in Brazilian rookeries (minimum CCL in Espírito Santo State 83 cm, mean = 102.7 cm, Baptistotte *et al.*, 2003; Bahia State, mean 102.8 cm, Marcovaldi and Laurent, 1996), most loggerhead turtles captured by the pelagic longline fleet were immatures, with only two individuals over 81 cm.

Most loggerheads were captured and released alive (92.9%). The proportion of loggerheads released dead did not differ among hook types (circle hook = 5.8%; J hook = 7.7%, $\chi^2_{\text{Yates}}=0.004$, df = 1, $P=0.9$). Among loggerheads released alive, 2.1% of those caught with circle hooks were released with hooks remaining in the digestive tract due to difficulty in removing them without causing excessive damage. For turtles caught on J hooks, 7.5% were released with the hook remaining in the turtle with as much line as possible removed. The number of turtles released with the hook remaining was similar between hook types ($\chi^2_{\text{Yates}}=0.9$, df = 1, $P=0.3$). However, deep-hooking (esophagus) more commonly involved J hooks than circle hooks (J = 25.0%, circle = 5.8%; $\chi^2=9.0$, df = 2, $P=0.01$). Hooking in the mouth accounted for 73 and 61% for circle and J hooks, respectively, while external hooking/entanglement was 21 and 14% for circle and J hooks, respectively. Captures of loggerheads did not differ according to the location of the hook between floats (positions 1 to 5), hook type pooled and excluded sets with six hooks between floats (chi-square goodness-of-fit test $\chi^2=7.8$, df = 4, $P=0.1$, $n=95$ turtles).

Capture of loggerheads was higher during spring and autumn and lower during summer and winter. The pattern of reduction of capture rates with circle hooks in comparison with J hooks occurred in all seasons, and varied between 41 and 62%. This seasonal reduction in capture rates with circle hooks was significant in the autumn and approached significance in winter and spring (both $P=0.06$; Table 2; Figure 4).

Leatherbacks

Twenty-eight leatherbacks were captured during the study, and hook type was recorded for 27 turtles. Most (94.7%) were captured alive, one turtle was dead and one with condition not recorded by the observer. Similar to loggerheads, capture of leatherbacks decreased using circle hooks, from 0.274 leatherbacks per 1000 hooks to 0.096, with 2.0 times more

Table 2. Seasonal capture rates using circle and J-type hooks (turtles per 1000 hooks) and number of individuals of loggerhead sea turtles (*Caretta caretta*) in the pelagic longline fishery off the Brazilian coast

	Summer		Autumn		Winter		Spring	
	J-hook	Circle	J-hook	Circle	J-hook	Circle	J-hook	Circle
No. of turtles	11	5	51	19	16	6	39	23
Capture rates	0.831	0.378	2.435	0.907	0.622	0.233	2.994	1.766
No. of hooks	13 230	13 230	20 944	20 944	25 715	25 715	13 025	13 025
χ^2_{Yates}	1.56	13.73	3.68	3.63				
p value	0.21	0.002[a]	0.06	0.06				

[a]Significant after Bonferroni correction (significance at $P=0.05/4$, so that $P_{\text{adj}}=0.013$).

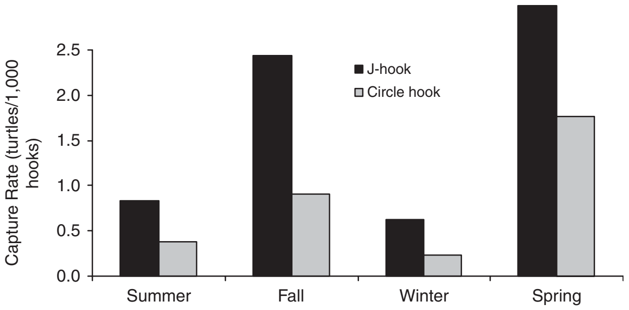

Figure 4. Seasonal variation in capture rates of loggerhead sea turtles (*Caretta caretta*) with J-type and circle hooks in the pelagic longline fishery of Brazil.

likelihood of capturing a leatherback with J hooks (Table 1). Twenty-two leatherbacks had hooks attached externally or were entangled (circle and J pooled); four were hooked in the mouth and two unidentified. Thus, hook location was not evenly distributed ($\chi^2_{\text{Yates}} = 11.1$, df $= 1$, $P = 0.0009$, $n = 26$), but difference between hook types was not tested owing to the small number of leatherbacks caught. On six occasions the observer could not determine if the turtle was in comatose state. For a sample of seven leatherbacks, the mean CCL was 138.1 ± 7.9 cm, range 127–149 cm. This sample represents animals that were small enough to be hauled on board and does not include significantly larger animals that are also vulnerable to this fishing gear but too large to be measured. Leatherbacks were also caught in all seasons.

Target species of bony fish and shark

Among the target species or group of species analysed, capture rates were significantly increased for four target species when using circle hooks, measured in terms of number of individuals per 1000 hooks (Table 1). These include main target species for the Brazilian longline fishery, such as the blue shark (*Prionace glauca*), requiem sharks of the genus *Carcharhinus*, and tunas (bigeye *Thunnus obsesus* and albacore *T. alalunga*). Capture of hammerheads (*Sphyrna lewini* and *S. zygaena*) and shortfin mako (*Isurus oxyrinchus*) sharks, and yellowfin tuna (*T. albacares*) increased slightly with circle hooks, but the difference was not significant. For the dolphinfish (*Coryphaena hippurus*) there was a non-significant decrease in captures when using circle hooks (12.1%). The only species with significant decrease in captures with circle hooks (14.2%) in comparison with J hooks was the swordfish, with probability of capture increasing 1.2 times with J-hooks (Table 1). Overall, circle hooks resulted in an additional 5.6 individuals per 1000 hooks deployed in comparison with J hooks (target capture rate with circle hook = 47.001 per 1000 hooks vs J-hook = 41.432 individuals per 1000 hooks). This difference was due to a substantial increase in tuna and blue shark catches with circle hooks (42.2% and 14.6%, respectively). Additional non-target sharks and bony fish species, which are usually landed when captured (e.g. oilfish *Ruvettus pretiosus*, escolar *Lepidocybium flavobrunneum*, Istiophoridae billfishes, thresher sharks *Alopias vulpinus* and *Alopias superciliosus*), as well as the fishing productivity in terms of weight of target species were not analysed or assessed here.

DISCUSSION

Sea turtle capture rates

Capture of sea turtles by pelagic longline has been confirmed to be a 'rare event' in many fisheries (Gilman *et al*., 2007), which was also true in this study whereby 62% and 91% of sets had 'zero' captures of loggerhead and leatherback turtles, respectively. Notwithstanding, the overall capture rates of sea turtles of 0.837 turtles per 1000 circle hooks and 1.893 turtles per 1000 J-hooks were higher than those measured in previous studies in the area (Sales *et al*., 2008), but much lower than those based on a limited number of sets and number of hooks (Kotas *et al*., 2004; Pinedo and Polacheck, 2004). On the other hand, we confirm previous studies in the area and elsewhere that immature loggerheads are the main species and life stage captured, followed by leatherbacks (but see Watson *et al*., 2005), while green turtles are rarely caught. In the current study most leatherbacks became entangled, while ingesting hooks was rare, the main difference in comparison with loggerheads, which actively ingest the hook and bait (Watson *et al*., 2005; Read, 2007). The current study also confirms an overall reduction in capture rates of sea turtles with circle hooks in comparison with other hook types (Watson *et al*., 2005; Read, 2007; Piovano *et al*., 2009).

Hooks near the floats in a given basket, and consequently shallower than mid-basket hooks, did not have higher capture rates of loggerhead turtles. Probably all hooks were within depths used by immature loggerheads. The Brazilian pelagic longline, targeting a range of species from sharks to swordfish and tunas, tends to set hooks shallower than in the Indian and Pacific Oceans, where the number of hooks between floats is higher, or than the several fleets that operate in the south Atlantic and target mainly tuna, such as Japan and Taiwan. The potential for interaction with loggerheads, which remain for 90% of their time at depths <40 m (Polovina *et al*., 2004) is thus high for all hooks within a basket in the Brazilian fishery.

Circle hooks as a tool for improving the post-release survival of sea turtles

Despite controversies of post-release survival of sea turtles hooked by longline fisheries (Hays *et al*., 2004; Bradshaw, 2005) it is sensible to assume that deep hooking (i.e. where the hook has been swallowed) increases mortality in comparison with light hooking (in the upper or lower jaw) and external hooking/entanglement (Gilman *et al*., 2007). It is generally agreed that removing the hook and line is beneficial for the survival chances of turtles (Valente *et al*., 2007), except in cases of deep hooking. This is probably even more important in the current fishery where a steel cable is used instead of nylon and so could potentially cause more severe lesions. In addition, a larger proportion of loggerheads are released with terminal gear still attached when captured on J hooks compared with circle hooks (7.5 vs 2.1%, respectively), similar to other findings (Gilman *et al*., 2007). Thus, it can be concluded that using circle hooks benefits sea turtles in three ways: (1) decreased capture rates; (2) decreased deep hooking rates; (3) decreased proportion of turtles released with terminal gear attached.

Reduction of deep hooking is related to the larger size of hook and shape of circle hooks, which facilitates hooking at the jaw corner, so hooks are less likely to be swallowed. Read (2007) argued that circle hooks are more likely to reduce turtle mortality by preventing swallowing, rather than avoiding hooking of turtles. Results presented here demonstrate that in addition to reduced direct mortality, circle hooks also significantly reduced capture rates of both loggerheads and leatherbacks, which is a clear major benefit for both sea turtle species. The larger size of loggerheads captured with circle hooks could be related to the larger width of the circle hooks, which precluded smaller individuals ingesting the hook, suggesting that hook size, irrespective of hook design, plays a role in loggerhead captures (Watson *et al*., 2005; Read, 2007).

Bony fish and shark target capture rates

It has also been advocated that circle hooks are more efficient in retaining fish after hooking, thus increasing captures. By preventing swallowing, fish are hauled fresher than with traditional J or tuna hooks in both recreational hook-and-line (Cooke and Suski, 2004) and commercial longline fisheries (Kerstetter *et al*., 2007), which can provide a higher quality and subsequently higher price for fish sold at market (Watson *et al*., 2005).

It is not clear why swordfish captures decreased with circle hooks in the current study. Piovano *et al*. (2009) found a non-significant decrease in capture rates of swordfish with 16/0 circle hooks (by number and weight per 1000 hooks) compared with Mustad J- hooks No. 2 in the Mediterranean, similar to the non-significant decrease in Australia comparing 14/0 circle hooks with tuna-hook (Ward *et al*., 2009). In the North Atlantic Ocean, Watson *et al*. (2005) also found a 25% decrease of capture, by weight, using non-offset 18/0 circle hooks with squid bait, and a nominal increase of bigeye tuna. However, these authors, using mackerel as bait and 10° offset 18/0 circle hooks (exactly the same treatment in the current study), found a 19% increase in swordfish capture by weight, and 80% decrease in capture rates of the bigeye tuna in comparison with 25° offset 9/0 J hook (we used non-offset J hooks here). Moreover, circle hooks in recreational Istiophoridae billfishes fisheries had captures comparable with or higher than J hooks (Prince *et al*., 2002). For the Hawaiian swordfish fishery, a pool of regulations, including use of 10° offset 18/0 circle hooks have proved very effective in reducing sea turtle captures, as well as increasing swordfish capture rates (Gilman *et al*., 2007). Preliminary results (26 sets, 16 624 hooks) of a study carried out onboard Brazilian longliners operating in equatorial waters showed increase captures of swordfish and yellowfin tuna, and decreased mortality of fish hauled onboard (Kerstetter *et al*., 2007). This study used a similar design as here, with alternated hook types, but 18/0 non-offset hooks, and a range of baits in different sets (mackerel, squid and mix).

Shark captures in the North Atlantic increased by 8–9% with circle hooks compared with J hooks, where both were baited with squid, but there was a significant reduction in captures with both hooks when using mackerel bait (Watson *et al*., 2005). In the same area post-release survival increased when using circle hooks in the Canadian longline fleet (Carruthers *et al*., 2009). In the north-west Pacific and Australia there were negligible differences between blue shark captures with circle and tuna hooks (Yokota *et al*., 2006; Ward *et al*., 2009), and in Hawaii there was a significant 36% decrease in shark captures between pre- and post-regulations (Gilman *et al*., 2006). While sharks are considered bycatch and their capture undesirable in several fisheries around the world (Gilman *et al*., 2008; Ward *et al*., 2008), they are target species and frequently comprise the bulk of captures in the Brazilian pelagic longline fishery (Hazin *et al*., 2008). Thus, increase in captures reported in this study is a welcome result for the fishing companies and is beneficial for sea turtles by increasing the probability of the acceptance of circle hooks by the fishing industry.

Despite capture rates reported here being based on number of individuals per effort, rather than weight per fishing effort or economic returns, the increased capture of tuna and sharks probably outweigh the losses caused by the reduction in swordfish catches. Fishermen reported that size of target specimens increase with circle hooks, due to improvements in fish retention once hooked, an issue which deserves further investigation.

Implications for fishery management and conservation

Overall, most sea turtles were caught alive (93% of loggerheads; 95% of leatherbacks), which highlights the critical role of fishermen in increasing post-hooking survival, by correctly hauling, handling and releasing sea turtles (Carruthers *et al*., 2009). Educational campaigns, formal courses, or informal training through onboard observers, and increased awareness are essential tools for the conservation of sea turtles at sea. Increasing post-release survival could be greatly improved through the use of dehooking devices for removal of hooks, and line-cutters, instruments with blades and a long handle to assist in the removal of line and disentangling leatherbacks and large loggerheads not hauled onboard. Dipnets will probably reduce injuries in most loggerheads, as their relatively small size makes it feasible for them to be hauled onboard for hook removal.

However, even with the significant reduction of capture rates and potential reduction in mortality for both loggerhead and leatherback turtles with the use of circle hooks, capture rates are still relatively high and an even greater reduction would improve the selectivity of the fishing gear. Watson *et al*. (2005) and Yokota *et al*. (2009) have demonstrated that the use of squid bait instead of fish can also increase the capture rate of loggerhead sea turtles. Because squid is frequently used as bait in the pelagic longline fishery in the south-west Atlantic Ocean, capture rates by fleets in this region are probably higher that those reported in the current study where hooks were baited with fish. Testing additional mitigation measures such as the use of fish instead of squid as bait, or operational shifts, such as increasing depth of hooks set (Shiode *et al*., 2005; Beverly *et al*., 2009), reducing daylight soak time (Watson *et al*., 2005), or restricting the use of lightsticks (Wang *et al*., 2007), should also be tested in combination with circle hooks to further reduce turtle capture rates. Use of such measures, alone or in combination, can greatly enhance the selectivity of the fishing gear, which could benefit a range of other non-target species.

In the longline fishery studied here, the capture rate of dolphinfish was similar between hook types, which is similar to trials in Australia where small 14/0 circle hooks were tested against tuna hooks (Ward *et al*., 2009). On the other hand, preliminary results from the eastern Pacific show a marked decrease in dolphinfish captures using a range of circle hooks (see Read, 2007 and references therein).

Genetic and tag recovery data have shown that leatherbacks and loggerheads incidentally captured in fisheries or stranded on adjacent south-west Atlantic beaches are of mixed stocks, with individuals from nesting populations from Brazil, east Atlantic–Africa, Indian Ocean, Australia, North Atlantic and unknown origins (Billes *et al*., 2006; Sales *et al*., 2008; Vargas *et al*., 2008), making sea turtle conservation in south-west Atlantic waters of global importance.

Before circle hooks are made compulsory in a given fishery, they should be field tested first to ensure that they are effective both for reducing turtle bycatch and for not adversely affecting fishery landings (Read, 2007). Here we provide substantial evidence of their effectiveness in the Brazilian pelagic longline fishery. The current study shows that, more than any other fishery studied to date, circle hooks are a viable option for the mitigation of sea turtle bycatch in the Brazilian pelagic longline fishery. Specifically, circle hooks (1) reduced capture rates of loggerheads and leatherbacks, (2) reduced deep hooking of loggerheads, and (3) increased capture of several target species, thereby remaining economically viable and more likely to be adopted by the fishing industry. However, if circle hooks are adopted in this fishery, their effects on other species, such as seabirds, sharks and billfishes should be considered. Despite not reducing bycatch of sea turtles to negligible levels, circle hook adoption is an important step forward, being the simplest and most effective mitigation measure currently available to minimize sea turtle bycatch and reduce post-release mortality. The increased replacement of J and tuna hooks in favour of circle hooks can contribute greatly towards recovering trends of loggerhead and leatherback populations inhabiting the south-west Atlantic Ocean and nesting on Brazilian beaches (Marcovaldi and Chaloupka, 2007; Thomé *et al*., 2007).

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