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FEATURE PAPER

A *green* strategy for shark attack mitigation off Recife, Brazil

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Abstract

Shark attacks on humans have prompted the implementation of shark control programs aiming at reducing local populations of potentially aggressive species using mostly gillnets. However, shark meshing produces ecological disturbances by inflicting severe mortality not only to sharks but also to several harmless, frequently endangered taxa, including cetaceans, sirenians and chelonids. A different methodological approach to mitigate shark peril off Recife combines bottom longlining and drumlines with comparably better results. This region has been experiencing an abnormally high shark attack rate since 1992, but the protective fishing strategy was developed in 2004 only. Unlike traditional shark control programs, the Shark Monitoring Program of Recife (SMPR) aims at removing dangerous sharks not from their populations but from the hazardous area instead, which is achieved by capturing, transporting and releasing sharks offshore. During 8 years, the SMPR caught fish and turtles only and showed high selectivity for sharks compared with shark meshing. Target species comprised carcharhinids and sphyrnids and accounted for 7% of total catch. The fishing mortality of abundant taxa was generally low except for *Carcharhinus acronotus* and *Gymnothorax* spp., and protected species had ~100% survival. The shark attack rate diminished about 97% while fishing operations were being conducted ($W = 1108.5$, $P < 0.001$), whereas no-fishing periods and the period prior to the implementation of the SMPR had similar shark attack rates. Overall, the SMPR seems to be less detrimental than shark meshing strategies while clearly contributing for enhancing bather safety; thus, it may provide an effective, ecologically balanced tool for assisting in shark attack mitigation.

Introduction

Although shark attacks on humans are rare (64 attacks·year^{-1} worldwide) (Burgess *et al.*, 2010), they produce deleterious socioeconomic impacts (Bullion, 1976; Dudley, 1997). Large-scale shark control programs operating for decades in Australia and South Africa aim at mitigating shark peril by reducing shark populations around hazardous shores using mostly gillnets (Dudley, 1997), but they also inflict severe mortality to several harmless, frequently endangered taxa, including cetaceans, pinnipeds, sirenians, chelonids, batoids, teleosts and birds (Dudley & Cliff, 1993, 2010; Krogh & Reid, 1996; Gribble *et al.*, 1998*a*,*b*; Green, Ganassin & Reid, 2009). Evidence of ecological damage resulting from shark meshing (Dudley & Simpfendorfer, 2006; Dudley & Cliff, 2010; Reid, Robbins & Peddemors, 2011) have raised serious concerns about the poor performance of gillnet-based programs regarding both selectivity toward potentially dangerous sharks and survival of accessory species (Paterson, 1990; Sumpton *et al.*, 2011). Not surprisingly, shark meshing has been listed as a key threatening process by the Australian Fisheries Scientific Committee (http://www.dpi.nsw.gov.au/fisheries/species-protection/conservation/what-current/key/shark-meshing; accessed 4 July 2012). The sustainable use of protective fishing gear to mitigate shark peril at specific shores thus depends on curtailing environmental impacts, especially as coastal ecosystems are already depleted (Jackson *et al.*, 2001).

The Metropolitan Region of Recife (MRR), Pernambuco, Brazil, has been experiencing an abnormally high shark attack rate, with 55 incidents (36% fatalities) occurring within an ~20-km stretch of coastline between 1992 and 2011. Surprisingly, despite intense recreational use of these beaches since the early 1950s, there had been no confirmed records of shark attacks in this region before 1992. Also, no incidents have been reported in other regions of this littoral. The attack outbreak coincided with the construction of a port complex to the south of the MRR and had great influence upon the local economy and social welfare. A detailed description of this situation can be found in Hazin, Burgess & Carvalho (2008).

In May 2004, the State Government of Pernambuco created the Committee for the Monitoring of Shark Attack Incidents (CEMIT) in order to address the several components of the shark attack problem by a multidisciplinary approach. As a CEMIT permanent member, the Universidade Federal Rural de Pernambuco (UFRPE) has been assigned with scientific development on this subject. One of UFRPE goals was to raise biological information on the species involved in the attacks as there was virtually no knowledge of the coastal ecosystem off Recife. The main objective of UFRPE was ultimately to develop a protective strategy to significantly reduce the shark attack rate with minimum ecological disturbance, which included minimizing both the catch of harmless species and the mortality of all species. The combination between shark surveying and beach protection evolved to a shark attack mitigation policy, which, unlike shark meshing programs, endeavors to remove sharks not from their populations but from the area of risk instead. If adequate, such strategy would further minimize environmental impacts because it would not promote any structural changes to coastal communities. This is essential for conservation purposes because shark attack protective programs are typically conducted at fixed locations during extensive periods of time.

This study introduces and characterizes an innovative, ecologically balanced protective fishing strategy for shark attack mitigation off Recife and examines several aspects of the catch composition and mortality. An appraisal of the performance of the protective fishing strategy regarding the mitigation of the local shark attack rate is also included.

Material and methods

Protective fishing strategy

The Shark Monitoring Program of Recife (SMPR) focused on developing a protective fishing strategy aimed at selecting potentially aggressive sharks (PAS) among the marine fauna present in this region and remove them from the hazardous area. For this, hook-based fishing gear was used due to expectedly higher survival rates compared with gillnets (Hyatt *et al*., 2012). PAS removal was achieved by accommodating captured sharks in a tank measuring ~3 m in length and ~1 m in width that was readily assembled on the deck of the R/V Sinuelo (13 m in length) when the shark was first sighted. The tank was filled with running seawater to a depth just enough to cover most of the body of the shark. Measures taken to reduce shark stress and injury during handling and transportation toward offshore included setting the gunwale of the boat so that it could be removed in order to haul the shark from the water directly into the tank, placing soft, impact-absorbing material underneath the shark to minimize internal damage and covering its eyes with dark tissue. The duration of transport varied with the location of capture, the health of the shark and oceanographic conditions, but sharks were typically released at isobaths ≥25 m after being sampled and tagged. This procedure started in October 2007. Non-aggressive taxa were readily released at the site of capture.

Fishing operations in the study area off the Metropolitan Region of Recife (MRR; 8°10′S, 34°53′W; Fig. 1) began in May 2004 and continued until December 2011, with interruptions in August 2004, March–April 2006, May–October 2007, September–November 2008, February–June 2009 and June 2011 due to discontinuity of funding. Until August 2005, fishing trips generally consisted of seven consecutive fishing sets and were conducted during the new and full moon phases. After September 2005, the chronogram was modified in order to carry out four consecutive fishing sets per fishing trip scheduled on a weekly basis so that fishing operations were continuous from Fridays through Tuesdays. This modification was due to the necessity of synchronizing fishing operations with the weekly distribution of both recreational beach usage (Silva *et al*., 2008) and shark attacks (Hazin *et al*., 2008).

A combination of bottom longline gear and drumlines was used as a fishing strategy. Longlines were composed of

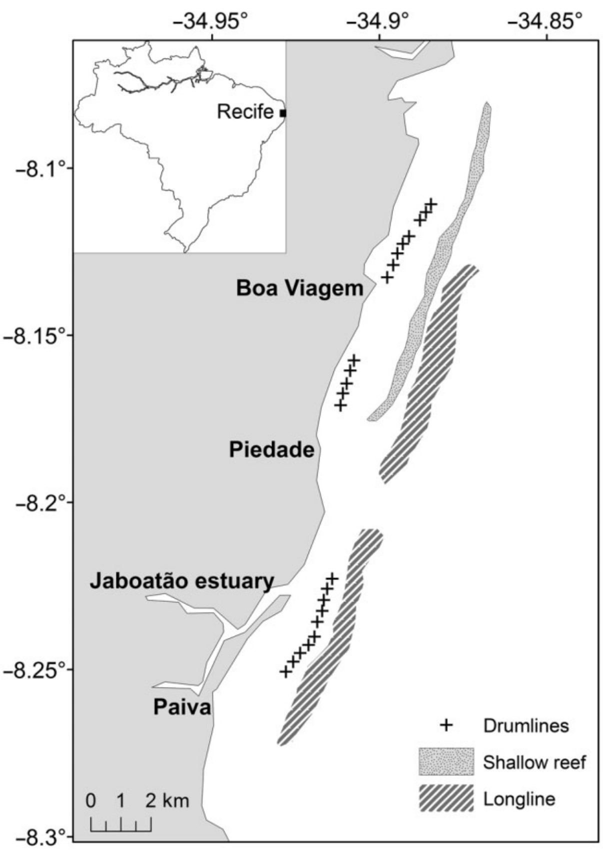

Figure 1 Shark Monitoring Program of Recife. Map of the study area depicting the locations of a shallow reef and both longline and drumline deployments at two surveyed sites. Adapted from Ferreira *et al.* (2012).

a 4-km long, 8-mm diameter, multifilament, polyamide mainline with five moorings, which subdivided the mainline in four similar sections. Each section comprised 25 branch lines that were composed of a snap followed by an 8-m long, 3.2-mm diameter, monofilament, polyamide line crimped to a 2-m long, 2-mm diameter, stainless steel leader, a 60-g swivel and a hook. Thus, each longline had 100 hooks. Until August 2005, a Styrofoam float (200 g in flotation) was attached to the proximal end of the leader of about half of the secondary lines for longline selectivity assessment (Afonso *et al.*, 2011). After September 2005, all secondary lines were equipped with such floats in order to suspend all hooks in the water column. Similarly, both J-style (9/0, 0% offset) and circle (17/0, 10% offset) hooks were used until May 2006 for performance comparison (Afonso *et al.*, 2011), but only circle hooks were used afterward. Drumlines consisted of an 18-m long, 6-mm diameter, multifilament, polyamide mainline that was vertically stretched by an anchor and a float and equipped with two 4-m long, 3.2-mm diameter branch lines. The configuration of terminal tackles in drumlines was similar to longlines. Moray eels, *Gymnothorax* spp., were generally used as bait (~300 g) because they were low-priced and readily accessible, but occasionally, the oilfish *Ruvettus pretiosus* was also used, especially during the full and new moon phases. Both bait types yielded high catch rates of target species in preliminary field testing (Hazin, Wanderley Jr & Mattos, 2000).

The survey area was divided into two contiguous, nearshore fishing sites: Boa Viagem/Piedade (BV), to the north, corresponding to a densely urbanized beach off which most attacks occurred (Hazin *et al.*, 2008) and that includes a ~6.4-m deep, ~437-m wide, alongshore channel-like structure delimited seawardly by a shallow reef (Supporting Information Figure S1); and Paiva (PA), to the south, a comparatively undeveloped region that includes the Jaboatão estuary and where no channel-like structure is present. Two longlines were deployed alongshore ~1.5–3 km away from the coastline at each site (Fig. 1), corresponding to mean (±SD) depths of 13.5 (±1.0) m at BV and 13.2 (±0.8) m at PA. In BV, the longline was located seaward to the channel. Drumlines were deployed ~0.5–1 km from shore, at depths averaging 6.4 (±1.5) m in BV and 10.2 (±2.5) m in PA. In BV, 13 drumlines were positioned inside the channel, whereas 10 drumlines were deployed in PA. The purpose of such spatial configuration was not only to form an outer barrier for intercepting sharks before they entered the area of risk but also to increase the probability of sharks being lured away from the channel to the baited longline. On the contrary, the drumline setting would provide a second barrier to any shark that entered the channel, although using a much lower fishing effort to avoid luring sharks into the area of risk by the effect of bait. Additionally, some longline sets (200 hooks per set) were occasionally conducted offshore at the middle continental shelf (CS), usually in the last set of some fishing trips. The longlines were routinely deployed during the afternoon and hauled back during early morning. At BV, such schedules averaged 15:58 (±1:16) and 07:05 (±1:24), respectively, while they averaged 16:13 (±1:28) and 06:22 (±1:32) at PA. Longline soak time averaged 15.04 (±1.86) h at BV and 14.05 (±2.07) h at PA. Drumlines were allowed to fish continuously and were hauled daily at dawn for bait replacement.

Statistical analyses

Target species are herein considered as PAS, and bycatch is interpreted as all the remaining species. PAS were defined as large species in the catch composition which had previously been implicated in unprovoked attacks on humans by the International Shark Attack File (http://www.flmnh.ufl.edu/fish/sharks/ISAF/ISAF.htm; accessed 3 March 2013). Catch rates were interpreted as catch-per-unit-effort (CPUE), defined by the number of individuals caught per 100 hooks. Statistical analyses were conducted on the most abundant species ($n > 30$) and pertain to longlines only. Drumlines were excluded from the analyses because distinct spatial arrangements and effort densities prevented a direct comparison with longlines. The period between May 2004 and August 2005 was not included in the analyses because of the distinct fishing gear configurations, which significantly influenced longline catch rate (Afonso *et al.*, 2011).

Annual variations in the proportion of the most abundant species were assessed with a Pearson's chi-square test with simulated *P*-value (based on 20 000 replicates). Changes in methods and seasonal coverage limit the number of years that can be directly compared; thus, this analysis included only the years 2006, 2008, 2010 and 2011. The proportions of individuals caught in the four fishing sets of each fishing trip were compared for each species with a chi-square test for equal probabilities with simulated *P*-value (based on 20 000 replicates) for the period between October 2007 and December 2011. At-vessel relative mortality, as the proportion of dead individuals caught, was assessed for all taxa for the period between October 2007 and December 2011. Also, the hooking location was recorded and categorized as (1) internal, for gut-hooking; (2) external, for jaw-hooking; (3) other, for individuals hooked in body parts other than gut or mouth.

For analyzing the effect of the SMPR on the shark attack rate, the period between January 2004 and December 2011 was discriminated according to the status (fishing/no-fishing) of the SMPR, and the monthly number of attacks occurring during fishing and no-fishing periods were compared with a one-tailed Mann–Whitney rank sum test. This comparison has an unavoidable caveat because fishing and no-fishing periods are mutually exclusive in time, implying that temporal variability in the shark attack rate cannot be accounted for in the comparison. Yet, this is the only plausible means to assess the direct effect of the SMPR on the shark attack rate. Also, the correlation between the absolute monthly frequency of attacks and the mean monthly catch rate of all potentially aggressive sharks combined was inspected using both Pearson's product-moment correlation, r, and Spearman's rank correlation, ρ. The alleged shark attack in September 2009 was not included in statis-

Table 1 Catches of the Shark Monitoring Program of Recife. Taxa identification with discriminated potentially aggressive sharks (PAS), number of individuals caught (*n*) and catch-per-unit-effort (CPUE), as the number of individuals caught per 100 hooks, in a longline (LL) and drumline (DL) survey off Recife between 2004 and 2011

Family	Species	PAS	n_{LL}	$CPUE_{LL}$	n_{DL}	$CPUE_{DL}$
Elasmobranchii						
Carcharhinidae			192	0.082 (±0.41)	10	0.065 (±0.56)
	Carcharhinus acronotus		118	0.051 (±0.32)	7	0.047 (±0.48)
	Carcharhinus falciformis	X	2	0.001 (±0.04)		
	Carcharhinus leucas	X	9	0.004 (±0.06)	2	0.011 (±0.23)
	Carcharhinus limbatus	X	6	0.003 (±0.05)		
	Carcharhinus perezi	X	1	0.000 (±0.02)		
	Galeocerdo cuvier	X	55	0.023 (±0.20)	1	0.007 (±0.18)
	Rhizoprionodon lalandii		1	0.000 (±0.02)		
Dasyatidae	*Dasyatis* spp.		71	0.031 (±0.25)	5	0.032 (±0.39)
Ginglymostomatidae	*Ginglymostoma cirratum*		141	0.062 (±0.28)	8	0.049 (±0.47)
Mobulidae	*Mobula* spp.		16	0.007 (±0.10)		
Myliobatidae	*Aetobatus narinari*		4	0.002 (±0.04)		
Sphyrnidae			2	0.001 (±0.04)		
	Sphyrna mokarran	X	1	0.000 (±0.02)		
	Sphyrna lewini	X	1	0.000 (±0.02)		
Teleostei						
Ariidae			476	0.214 (±0.67)	38	0.208 (±0.95)
Echeneidae			3	0.001 (±0.05)		
Ephippidae	*Chaetodipterus faber*		1	0.000 (±0.02)		
Haemulidae	*Conodon nobilis*		3	0.001 (±0.04)		
Lutjanidae			37	0.018 (±0.16)	1	0.007 (±0.18)
	Lutjanus analis		4	0.002 (±0.04)		
	Lutjanus jocu		8	0.003 (±0.09)		
	Lutjanus spp.		25	0.012 (±0.12)	1	0.007 (±0.18)
Megalopidae	*Megalops atlanticus*		5	0.002 (±0.06)		
Muraenidae	*Gymnothorax* spp.		74	0.033 (±0.27)	8	0.047 (±0.48)
Pomacanthidae	*Pomacanthus paru*		1	0.000 (±0.02)		
Serranidae	*Epinephelus itajara*		9	0.004 (±0.06)	3	0.018 (±0.28)
Sphyraenidae			1	0.000 (±0.02)		
Tetraodontidae			1	0.000 (±0.02)		
n. id.			2	0.001 (±0.04)		
Turtles						
Cheloniidae			8	0.004 (±0.07)	1	0.007 (±0.18)

tical analysis because a number of testimonies in local media stated that the victim actually drowned and it should correspond to a misidentified incident. All statistical analyses were conducted in R version 2.14.0 (R Development Core Team, 2011).

Results

Fishing effort and catch composition

A total of 2247 longlines were evenly deployed in BV and PA between 2004 and 2011, totaling 221 694 hooks (Supporting Information Table S1). Analogously, 2247 drumline settings totaling 51 796 hooks were deployed in both sites, but the number of hooks was ~30% higher in BV. Thus, a total of 273 490 hooks were deployed in the study area and longlines accounted for 81% of total effort. Thirty-eight additional longline sets conducted in CS accounted for 6589 hooks, raising the overall total effort to 280 079 deployed hooks. Sampling effort was highest in 2006, 2010 and 2011, and lowest in 2004 (Supporting Information Table S1). Some seasonality in sampling effort was noted as it was greater during summer, between November and January, and smaller during winter, especially between June and July. Yet, every Julian day was sampled at least once (Supporting Information Figure S2a).

A total of 1121 individuals were caught in both fishing gears between May 2004 and December 2011, yet the longline was responsible for the vast majority (92.6%) of the catch (Table 1). Teleosts corresponded to 59.1% of the overall catch, while elasmobranchs and marine turtles represented 40.1 and 0.8%, respectively. Seven PAS were identified, namely tiger *Galeocerdo cuvier*, bull, *Carcharhinus leucas*, blacktip, *C. limbatus*, silky, *C. falciformis*, Caribbean reef, *C. perezi*, and both scalloped, *Sphyrna lewini*, and great hammerhead, *S. mokarran*, sharks. These species accounted for 7.0% of the overall catch, with tiger and bull sharks being most represented among PAS (~73 and ~13%, respectively). Drumlines caught only three of such sharks. Regarding bycatch, at least 22 species were caught

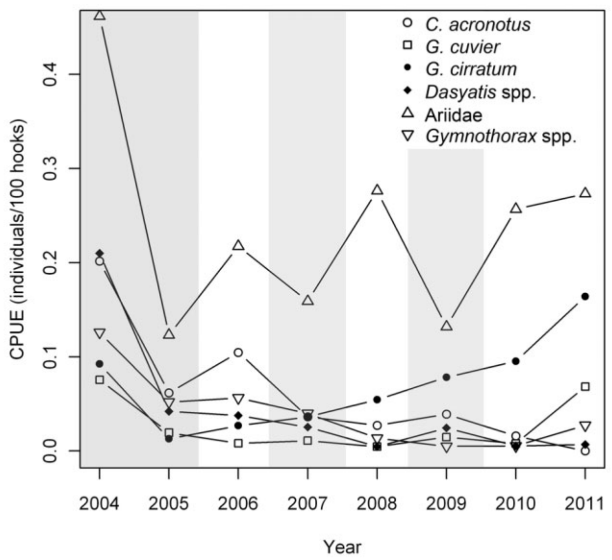

Figure 2 Annual trends of taxa caught in a longline survey off Recife. Yearly catch rates, as the number of individuals caught per 100 hooks, of *Carcharhinus acronotus*, *Galeocerdo cuvier*, *Ginglymostoma cirratum*, *Dasyatis* spp., ariids and *Gymnothorax* spp. Methods and seasonal coverage differed in the shaded years rendering catch-per-unit-effort (CPUE) in these years not directly comparable to CPUE in the non-shaded years where standard protocols were followed.

(Table 1). Individuals other than fish were restricted to a few chelonids comprising at least the green, *Chelonia mydas*, and the hawksbill, *Eretmochelys imbricata*, turtles. Ariid catfishes were by far the most represented taxa (45.9% of the overall catch) and comprised three species: *Bagre bagre*, *B. marinus* and *Sciades proops*. However, all ariids were grouped because they were not identified at species level before 2009. Similarly, most lutjanids were grouped as *Lutjanus* spp. because a recently described species, *L. alexandrei*, has been often misidentified as the gray snapper *L. griseus* or the schoolmaster *L. apodus* in this region (Moura & Lindeman, 2007). Dasyatids were also grouped and were represented mostly by the Southern stingray *Dasyatis americana* and, to a lesser extent, by *D. marianae* and *D. centroura*. Other common, inoffensive taxa included both the nurse, *Ginglymostoma cirratum*, and the blacknose, *Carcharhinus acronotus*, sharks, and moray eels *Gymnothorax* (Table 1).

Catch and mortality rates

The catch rate of tiger sharks showed no trend throughout the study period, but both blacknose shark and dasyatid stingray catches declined, whereas nurse shark catches increased steadily (Fig. 2). In accordance, the annual relative frequencies of captured taxa varied significantly ($\chi^2 = 142.806$, $P < 0.001$) (Supporting Information Figure S3). Caught species exhibited distinct occurrence patterns throughout the year and PAS were present in the study area in all seasons, although tiger sharks seemed to be most common between January–March and June–September (Supporting Information Figure S2b). Also, virtually all species were more frequently caught in the first longline set of each fishing trip (Supporting Information Figure S4), with significant differences being detected for nurse sharks ($\chi^2 = 13.168$, $P = 0.004$), stingrays ($\chi^2 = 8.00$, $P = 0.049$) and catfish ($\chi^2 = 11.994$, $P = 0.009$).

The relative mortality of all PAS combined equaled 30%, yet tiger sharks experienced low mortality (Table 2). As for bycatch, the relative mortality of all species combined equaled 22% but such value was mostly shaped by ariid mortality due to their greater abundance (Table 2). Species protected by Brazilian legislation such as the goliath grouper *Epinephelus itajara*, the nurse shark and marine turtles (Brazilian Ministry of the Environment, Normative Instruction #5, 21 May 2004) had virtually zero mortality. However, blacknose sharks and moray eels experienced high, > 80%, mortality. Furthermore, most species were hooked exclusively in the jaw and only a small number of individuals had swallowed the hook by gear retrieval (Table 2).

Mitigation of the shark attack rate

Between 1992 and the creation of the SMPR, the shark attack rate off the MRR averaged 0.289 (±0.607) attacks·month^{-1}, with as many as 10 attacks occurring every year except one (Supporting Information Table S2). From 2004 to 2011, the SMPR was interrupted in five occasions of varied spans due to funding discontinuity (Fig. 3), which provided the opportunity to compare shark attack rates between fishing and no-fishing periods. Between 2004 and 2011, the SMPR operated during 73 months and spent 23 months (~24% of the whole period) inactive. A single attack occurred off Recife during fishing periods (Fig. 3), resulting in an event rate of 0.014 (±0.119) attacks·month^{-1}. On the contrary, 10 attacks were verified while the SMPR was inactive, equaling 0.435 (±0.728) attacks·month^{-1}, which is significantly higher than the former (W = 1108.5, $P < 0.001$). Thus, an ~97% reduction in the monthly shark attack rate was observed while the program was in commission. Also, from 1992 to 2003 (12 years), a single year (=92%) elapsed with no attacks off Recife, but from 2004 to 2011 (8 years), as many as four years (=50%) elapsed with no incidents (Supporting Information Table S2). However, an increase in the frequency of shark attacks at beaches northward from Recife has been noted since 2004. Moreover, the monthly distribution of the catch rate of PAS off Recife seems to follow the same trend as the monthly frequency of shark attacks (Fig. 4). However, statistical tests were not able to detect a significant correlation between the two variables (Pearson's r = 0.51, t = 1.87, $P = 0.090$; Spearman's $\rho = 0.49$, S = 146.54, $P = 0.107$), although statistical significance and a considerable rise in correlation coefficients were achieved after discarding the month of October from the analysis (Pearson's r = 0.68, t = 2.70, $P = 0.024$; Spearman's $\rho = 0.69$, S = 67.55, $P = 0.018$).

Table 2 Fishing mortality in the Shark Monitoring Program of Recife. Number of specimens monitored (*n*), relative fishing mortality (RelMor) and hooking location as gut-hooked (internal), jaw-hooked (external), and hooked in other anatomical regions other than gut or mouth (other) between October 2007 and December 2011

		Fishing mortality		Hooking location			
Taxa	Common name	*n*	Relative mortality	*n*	Internal	External	Other
Aetobatus narinari	Spotted eagle ray	4	0.000	4	0.000	0.250	0.750
Ariidae	Marine catfish	244	0.250	190	0.032	0.911	0.058
Carcharhinus acronotus	Blacknose shark	26	0.885	18	0.000	1.000	0.000
Carcharhinus falciformis[a]	Silky shark[a]	2	0.500	1	0.000	1.000	0.000
Carcharhinus leucas[a]	Bull shark[a]	4	0.500	2	0.000	1.000	0.000
Carcharhinus limbatus[a]	Blacktip shark[a]	3	0.667	1	0.000	1.000	0.000
Carcharhinus perezi[a]	Caribbean reef shark[a]	1	1.000	1	0.000	1.000	0.000
Chelonidae	Marine turtles	4	0.000	3	0.000	0.333	0.667
Conodon nobilis	Barred grunt	3	0.333	2	0.000	1.000	0.000
Dasyatis spp.	Sting rays	14	0.071	11	0.000	1.000	0.000
Epinephelus itajara	Goliath grouper	13	0.000	10	0.000	1.000	0.000
Galeocerdo cuvier[a]	Tiger shark[a]	34	0.176	32	0.000	1.000	0.000
Ginglymostoma cirratum	Nurse shark	130	0.008	85	0.047	0.953	0.000
Gymnothorax spp.	Moray eels	11	0.818	7	0.000	1.000	0.000
Lutjanus spp.	Snappers	6	0.333	5	0.000	1.000	0.000
Mobula spp.	Devil rays	6	0.500	3	0.000	0.667	0.333
Rhizoprionodon lalandii	Brazilian sharpnose shark	1	1.000				
Total		506	0.227	375	0.027	0.928	0.045

[a]Potentially aggressive sharks.

Discussion

The study area off Recife corresponds to a seashore with heterogeneous bathymetry included in a region with many estuaries and mangrove habitats, which urban development depleted to a great extent (Braga, Uchoa & Duarte, 1989). The sudden shark attack outbreak coincided with the nearby construction of a commercial port (Hazin *et al*., 2008), suggesting that anthropogenic disturbance may have increased the probability of sharks encountering and interacting with bathers and surfers. Protective gillnets were not considered for shark attack mitigation because they could promote further environmental damage due to the removal of a diversity of large-bodied animals from these waters. Instead, because shark attacks in this region are highly localized, a combination of longlines and drumlines was designed to reduce shark peril. The whole operation required a four-person crew plus a scientific member, and soak time could be kept reasonably low to maximize survival.

PAS included five carcharhinids and two sphyrnids, but higher catch rates of tiger and bull sharks suggest these species to be responsible for most of the incidents, agreeing with previous forensic analyses (Gadig & Sazima, 2003; Hazin *et al*., 2008). Ariid fish dominated the catch composition, probably due to their great abundance in tropical coastal habitats (Yáñez-Arancibia & Lara-Domínguez, 1988). Nevertheless, carcharhinids and ginglymostomids were highly represented, suggesting that the selectivity of the fishing gear was reasonably optimized for sharks. In 9 years, shark meshing off Natal, South Africa, caught a total of 68 harmless species comprising birds, turtles, cetaceans, elasmobranchs, teleosts and crustaceans (Dudley & Cliff, 1993), a much greater diversity than the one found in this study, which comprised 27 harmless species corresponding to teleosts, elasmobranchs and turtles, despite the occurrence of other large-bodied taxa such as cetaceans and sirenians in this region. Recent replacements of gillnets by drumlines in South Africa effectively reduced the diversity of bycatch, particularly regarding cetaceans, birds, and rays (Cliff & Dudley, 2011), whereas drumlines were reported to catch significantly more tiger sharks (Sumpton *et al*., 2011) and less cetaceans, turtles, batoids and birds (Gribble, McPherson & Lane, 1998*a*; Cliff & Dudley, 2011) than gillnets in Australia. All these findings confirm that hook-based fishing gear is more selective for sharks than gillnets.

The mortality produced by the SMPR seems to be of minor importance for most taxa except the blacknose shark. This delicate species experienced high relative mortality, yet the observed decline in annual catch rate should not be ascribed solely to the SMPR because only 125 specimens were caught during an 8-year period (mean = 15.6 sharks·year^{-1}). Blacknose shark populations are known to be decreasing throughout their range since the last decade (Morgan *et al*., 2009), which may have contributed to the observed trend. In addition, concomitant variations in the annual catch rate of blacknose and nurse sharks and stingrays suggest a possible shift in the local elasmobranch community structure, with nurse sharks replacing blacknose sharks as the most abundant species and stingrays becoming less frequent throughout the study span. Yet, further research is required to understand the magnitude of such abundance variations and the underlying ecological processes. It should be noted that a sharp decline in catch rates

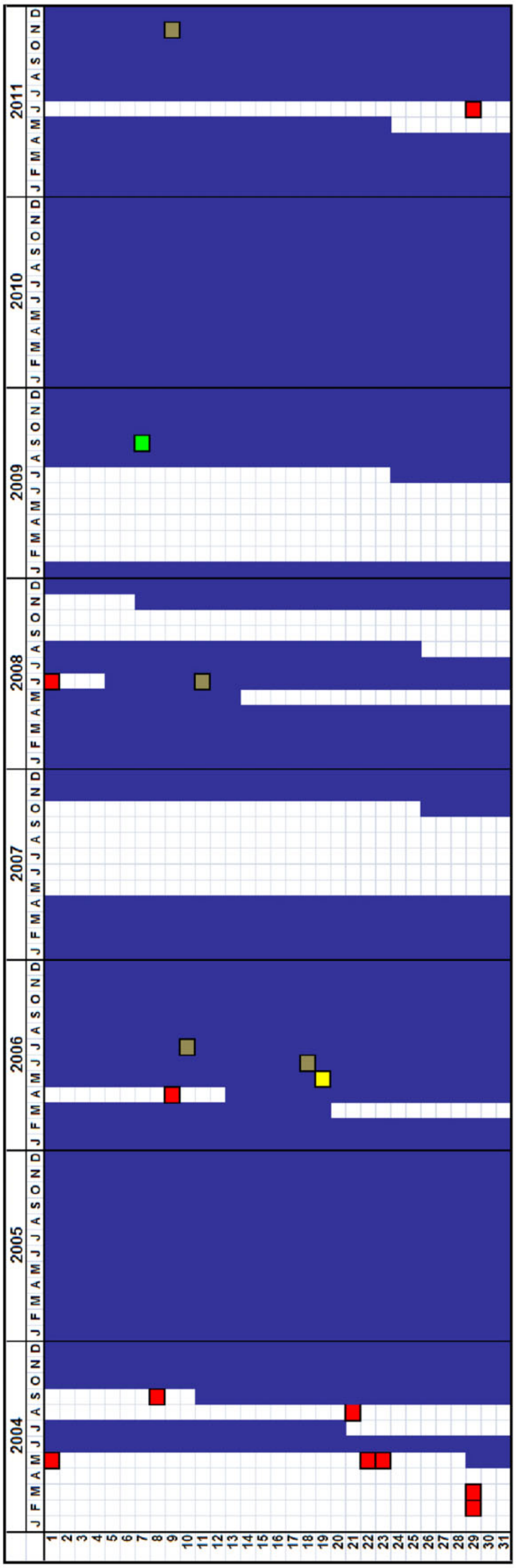

Figure 3 Calendar of the monitoring activities of the Shark Monitoring Program of Recife. Included are the fishing periods (blue fields), attacks off Recife during no-fishing (red squares), attack off Recife during fishing (yellow square), a likely misidentified attack (green square) and attacks in other regions of the State of Pernambuco (gray squares) from 2004 to 2011. For clarity sake, blue fields were depicted continuously including non-existing dates at the end of some months despite consecutive fishing trips being generally separated by 3 resting days.

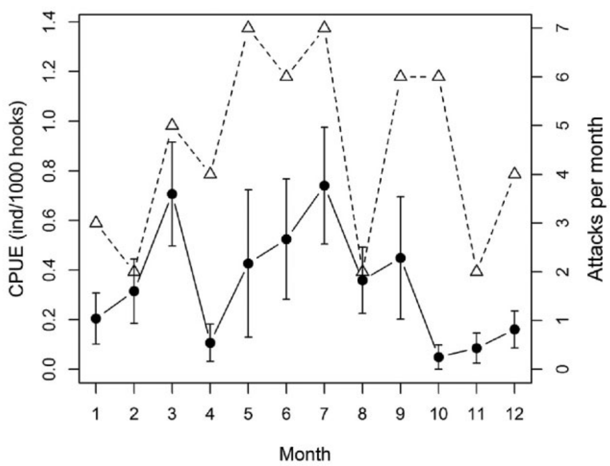

Figure 4 Monthly variation of shark attacks and shark abundance off Recife. Mean (±SE) catch-per-unit-effort (CPUE) of potentially aggressive sharks, as the number of individuals caught per 1000 hooks between 2004 and 2011 (solid circles with solid line), and total number of shark attacks between 1992 and 2011 (blank triangles with dashed line).

from 2004 to 2005 is likely ascribed to changes to the fishing gear that significantly reduced the catchability of bycatch such as blacknose sharks (Afonso *et al*., 2011). Further efforts to reduce blacknose shark mortality, for example, by using shorter soak times, have been hindered by a general absence of this species from the catch composition in more recent years.

Notwithstanding the methodological improvements required to further reduce the mortality of less resilient species, the SMPR appears yet to be less detrimental than traditional shark meshing because fishing mortality in gillnet-based shark control programs is substantially higher. In South Africa, tiger sharks had the highest survival rate (40%) among target species (Cliff & Dudley, 2011), whereas ~82% of tiger sharks in this study were released alive. The same authors report survival rates of bycatch equaling 42–49%, with rays being among the most resilient species (45–75% released) and other vulnerable or endangered taxa such as turtles and dolphins experiencing low survival rates (33 and 0–5%, respectively). Similar values have been observed in Australian shark control programs (Gribble *et al*., 1998*a*; Green *et al*., 2009). Drumlines have been introduced in some gillnet-based programs to reduce environmental impacts (Gribble, McPherson & Lane, 1998*b*; Cliff & Dudley, 2011), but survival rates are yet low due to the continued use of gillnets (Dudley & Cliff, 2010) and long soak times (Dudley, 1997). In the SMPR, mortalities were lessened by the use of circle hooks as most specimens were hooked by the jaw. A previous study showed that circle hooks could be effective in preventing harmful gut-hooking compared with the traditional J-style hooks (Afonso *et al*., 2011), which is crucial for enhancing post-release survival.

The spatial configuration of the protective fishing gear off the MRR seems to be effective in preventing PAS from accessing the hazardous area as drumline catch composition barely included such species. Previous concerns regarding baited lines attracting more sharks to the shore (Paterson, 1990) have not been verified as the fishing effort was strategically arranged in order to lure sharks away from the hazardous area. The fact that most taxa were more frequent in the first of the four fishing sets could be an effect of fishing periodicity involving 3 resting days between consecutive fishing trips, thus allowing more time for emigration into the study area to occur. As demonstrated by satellite tracking, removing dangerous sharks from the hazardous area seems to effectively reduce shark peril off the MRR because sharks do not return to this region after being released. On the contrary, tiger sharks tend to move to deep, oceanic waters within the first day at-liberty and further move through great distances, generally toward north, along north-eastern Brazil (Afonso, 2013; Hazin *et al*., 2013), hence posing no additional threats to beach users off the MRR. Such behavioral pattern also indicates that translocating tiger sharks to deeper waters from the CS should not have any significant impact on their populations because they exhibit no site-attachment to the MRR and will have plentiful habitat available throughout their extensive home ranges. Ongoing research should allow to further understanding the post-release behavior of infrequently caught PAS. Yet, the results so far obtained indicate shark culling as a shark attack mitigation strategy to be apparently unnecessary in Recife, as indicated by a greater reduction (97%) in the shark attack rate off the MRR compared with those achieved in shark meshing programs (88–91%) (Dudley, 1997), although direct comparisons between these programs require caution because the magnitude of the SMPR is considerably smaller. Moreover, similar shark attack rates during no-fishing periods and before the creation of the SMPR suggest that the protective fishing gear was the prime contributor for the reduction in the number of incidents. Also, seemingly coinciding trends in the monthly distributions of PAS catch rate and shark attack frequency suggest that the catch composition of the SMPR reflects the abundance of the species implicated in the incidents. The fact that this hypothesis lacked a clear statistical support could be ascribed to the distinct scales of the two variables (shark attacks are ordinal and catch rates are continuous) and to the influence of a single month represented by one of the largest numbers of attacks and the smallest catch rate of PAS in the dataset.

Altogether, the SMPR seems to provide an effective tool to reduce shark peril at local beaches with lessened ecological disturbance. The protective strategy herein introduced, combined with ongoing bioecological research (e.g. mark-recapture, telemetry, environmental control), should allow future refinements of preventive measures and contribute to further mitigating shark peril off the MRR. The sustainable use of protective fishing gear for shark attack prevention may require adequate selectivity toward PAS and optimized survival rates; thus, the SMPR could endow researchers and governments with a valuable framework for developing ecologically balanced shark attack mitigation measures. The success of the SMPR in shark attack prevention may, however, depend on site-specific features as a discontinued, longline-based shark control program off Hawaii showed no measurable effect on the shark attack rate (Wetherbee, Lowe & Crow, 1994).

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Figure S1. The coastal area off Recife. Bathymetric chart with 1-m isobaths depicting an alongshore channel next to the coastline between Boa Viagem and Piedade beaches. The red dots represent tentative estimates of some shark attack locations.

Figure S2. Intensity of fishing effort and seasonality of catches. Chart depicting (a) fishing effort, as the total number of hooks deployed per Julian day, and (b) Julian days with positive capture for taxa caught in a longline survey off Recife. Data correspond to combined years (2004–2011). Note the logarithmic scale of the *y*-axis in (a).

Figure S3. Proportion trends in the catch composition. Annual variation in the proportion of taxa caught in a longline survey off Recife between 2004 and 2011. O. elasm. and O. teleo. comprise all infrequently caught elasmobranchs and teleosts combined, respectively. Numbers in bars correspond to the number of individuals caught in the respective period. Ph1 corresponds to the period between May 2004 and August 2005 using a different fishing methodology. Asterisks (*) denote years with little valid sampling effort (~4–7 months) not included in statistical analysis.

Figure S4. Relative catchability by fishing set. Proportion of captures per each of the four longline sets of all fishing trips between October 2007 and December 2011. Bar widths are logarithmically proportional to the number of individuals caught. Horizontal dashed lines represent the 25, 50 and 75% quartiles. LEU = *Carcharhinus leucas*; CUV = *Galeocerdo cuvier*; LIM = *Carcharhinus limbatus*; ACR = *Carcharhinus acronotus*; CIR = *Ginglymostoma cirratum*; DAS = *Dasyatis* spp.; MOB = *Mobula* spp.; NAR = *Aetobatus narinari*; ARI = ariids; GYM = *Gymnotorax* spp.; LAN = *Lutjanus analis*; LUT = other lutjanids; NOB = *Conodon nobilis*; ITA = *Epinephelus itajara*; CHE = chelonids.

Table S1. Fishing effort in the Shark Monitoring Program of Recife. Distribution of fishing sets and deployed hooks in a longline and drumline survey between 2004 and 2011.

Table S2. Monthly frequencies of shark attacks off the Metropolitan Region of Recife every year between 1992 and 2011. Years in bold correspond to the period after the creation of the Shark Monitoring Program. Note that the attack in September 2009 should actually correspond to a drowning followed by scavenging by sharks.