Conservation Biology

Contributed Paper

Trends in the exploitation of South Atlantic shark populations

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Abstract: *Approximately 25% of globally reported shark catches occur in Atlantic pelagic longline fisheries. Strong declines in shark populations have been detected in the North Atlantic, whereas in the South Atlantic the situation is less clear, although fishing effort has been increasing in this region since the late 1970s. We synthesized information on shark catch rates (based on 871,177 sharks caught on 86,492 longline sets) for the major species caught by multiple fleets in the South Atlantic between 1979 and 2011. We complied records from fishing logbooks of fishing companies, fishers, and onboard observers that were supplied to Brazilian institutions. By using exploratory data analysis and literature sources, we identified 3 phases of exploitation in these data (Supporting Information). From 1979 to 1997 (phase A), 5 fleets (40 vessels) fished mainly for tunas. From 1998 to 2008 (phase B), 20 fleets (100 vessels) fished for tunas, swordfishes, and sharks. From 2008 to 2011 (phase C), 3 fleets (30 vessels) fished for multiple species, but restrictive measures were implemented. We used generalized linear models to standardize catch rates and identify trends in each of these phases. Shark catch rates increased from 1979 to 1997, when fishing effort was low, decreased from 1998 to 2008, when fishing effort increased substantially, and remained stable or increased from 2008 to 2011, when fishing effort was again low. Our results indicate that most shark populations affected by longlines in the South Atlantic are currently depleted, but these populations may recover if fishing effort is reduced accordingly. In this context, it is problematic that comprehensive data collection, monitoring, and management of these fisheries ceased after 2012. Concurrently with the fact that Brazil is newly identified by FAO among the largest (and in fastest expansion) shark sub-products consumer market worldwide.*

Keywords: fishing logbooks, longline fisheries, pelagic sharks, South Atlantic Ocean, threatened species

Tendencias en la Explotación de las Poblaciones de Tiburones del Atlántico Sur

Resumen: *Aproximadamente el 25% de las capturas de tiburones reportadas a nivel mundial suceden en las pesquerías de palangre del Atlántico. Se han detectado fuertes declinaciones en el Atlántico Norte, mientras que en el Atlántico Sur la situación es menos clara, aunque los esfuerzos de pesca han incrementado en esta región desde finales de la década de 1970. Sintetizamos la información sobre las tasas de captura de tiburones (basadas en 871, 177 tiburones capturados en 86, 492 series de palangre) para las principales especies atrapadas por múltiples flotas en el Atlántico Sur entre 1979 y 2011. Compilamos los registros, que fueron suministrados a instituciones brasileñas, de las bitácoras de pesca de las compañías pesqueras, los pescadores y los observadores abordo. Con el uso de análisis exploratorios de datos y fuentes literarias identificamos tres fases de explotación en estos datos. De 1979 a 1997 (fase A), cinco flotas (40 navíos) pescaron principalmente atún. De 1998 a 2008 (fase B), 20 flotas (100 navíos) pescaron atún, peces espada y tiburones. De 2008 a 2011 (fase C), tres flotas (30 navíos) pescaron múltiples especies, pero se implementaron medidas restrictivas. Usamos modelos lineales generalizados para estandarizar las tasas de captura e identificar las tendencias*

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Paper submitted February 11, 2015; revised manuscript accepted November 29, 2015.

Conservation Biology, Volume 00, No. 0, 1–13

DOI: 10.1111/cobi.12663

en cada una de estas fases. Las tasas de captura de tiburones incrementaron de 1979 a 1997, cuando el esfuerzo de pesca era bajo; disminuyeron de 1998 a 2008, cuando los esfuerzos de pesca incrementaron sustancialmente; y permanecieron estables o incrementaron de 2008 a 2011, cuando el esfuerzo de pesca de nuevo fue bajo. Nuestros resultados indican que la mayoría de las poblaciones de tiburones afectadas por palangres en el Atlántico Sur actualmente se encuentran mermadas, pero estas poblaciones pueden recuperarse si el esfuerzo de pesca se reduce adecuadamente. En este contexto, es un problema que la colecta de datos, el monitoreo y el manejo de estas pesqueras hayan cesado después de 2012. Simultáneamente con el hecho de que Brasil ha sido recientemente identificado per la FAO entre los más grandes (y en más rápida expansión) mercados de consumo de sub-productos de tiburones in el mundo.

Palabras Clave: bitácoras de pesca, especies amenazadas, Océano Atlántico Sur, pesqueras de palangre, tiburones pelágicos

Introduction

Twenty-four percent of all known species of elasmobranchs (sharks, skates, and rays) that are not data deficient are currently threatened with extinction (Dulvy et al. 2014). The cumulative extinction risk for these species is substantially higher than for most other marine vertebrates due to their life history (slow growth, late maturity, and low fecundity) (Smith et al. 2008). These features make sharks and other elasmobranchs particularly vulnerable to increased mortality from fisheries (Smith et al. 2008).

Historically, however, most shark species have been a low priority for regional fisheries management organizations (RFMOs). Consequently, there is a paucity of data for many species and regions. Existing data are often sourced from fisheries logbooks (reported by fishers and onboard observers and taken from landing reports), which may be incomplete (Pauly et al. 1998; Worm et al. 2013), have low taxonomic resolution, and be influenced by technological changes in fishing gear and preferences for target species (Harley et al. 2001; Baum et al. 2003; Burgess et al. 2005).

Surveying sharks over large ocean regions is expensive and impractical (Baum et al. 2003; Jensen et al. 2012), and in many cases, fisheries-dependent data are often the only available source of information to estimate trends in relative abundance and spatial distribution of oceanic sharks. Although more problematic than survey data (Bishop 2006; Jensen et al. 2012), fisheries-dependent data in some cases can be used to estimate abundance indices with standardization and appropriate statistical methods (Harley et al. 2001; Maunder & Punt 2004; Bishop 2006).

Over the last few decades, population declines of oceanic sharks have been attributed largely to longline fishing in the North Atlantic, Pacific, and Indian Oceans (Clarke et al. 2013; Worm et al. 2013; Dulvy et al. 2014). High-seas longline fishing in the Atlantic generates about 25% of reported global shark catches (Clarke 2008). Fishing effort has been high in the northern and southern Atlantic and intensified after the 1990s (Camhi et al. 2008). However, most of the information on the effect of fishing on large pelagic sharks comes from the North Atlantic, whereas data analyses from the South Atlantic (SAO) are fragmented and pertain only to the most abundant species (Tolotti et al. 2013; Carvalho et al. 2014).

There is international concern over the conservation status of pelagic sharks with respect to shark bycatch by a multinational fishing fleet operating in the SAO. Since 2008, the International Commission for the Conservation of Atlantic Tunas (ICCAT), the main RFMO managing pelagic fisheries in the Atlantic, has recommended no retention, catch, or commercialization of some of the species exploited by these fisheries, including all sphyrnids (hammerhead sharks) and bigeye thresher, oceanic white-tip, and silky sharks (*Alopias superciliosus*, *Carcharhinus longimanus*, and *C. falciformis* respectively) (Tolotti et al. 2015). The Brazilian Ministry of the Environment has attempted to protect these species by including them in the national list of endangered species (ICMBio 2014). However, there is strong opposition from the fishing industry, and some ordinances guaranteeing protection to endangered species in the country have been rescinded (Chao et al. 2015).

According to Hazin et al. (2008), the simultaneous exploitation of the SAO by several fishing fleets (which may lead to high levels of underreporting) and the migratory patterns of the major species have hampered data collection in the SAO. Furthermore, coastal nation such as Brazil, Uruguay, South Africa, and Namibia have historically allowed their ports to be used by international fleets from Asia and the European Union (Domingo et al. 2014) so as to build their own fleets and meet quotas established by RFMOs, particularly the ICCAT. These fleets changed their target strategies over time due to market demands, technological advancements, and declines in abundance of commercial species (Hazin et al. 2008).

To address the information gap, we assembled a large database of longline catch and effort data on multiple species of large pelagic sharks recorded in logbooks of 21 fishing fleets operating in the southwestern Atlantic over 33 years (1979–2011). All the species we analyzed are listed in Annex 1 of the UN Convention on the Law of the Sea (UNCLOS) as highly migratory. Highly migratory species usually move great distances at particular life stages and thus occur both in the open ocean and within EEZs (Maguire et al. 2006). Recent studies suggest that there is a single stock of *Prionace glauca* in each hemisphere of the Atlantic and that these sharks use a large tropical and subtropical area of these oceans during their life cycle (Queiroz et al. 2010; Carvalho et al. 2011; Vandeperre et al. 2014). Habitat use of *Isurus oxyrinchus*, *Sphyrna* spp., *Carcharhinus longimanus*, and other pelagic charcharhinids is expected to occur on similar scales (Camhi et al. 2008). Yet, because there is no evidence of marked populations structure in SAO, we assumed our results would be indicative of broader populations trends across the SAO. The data, however, were provided only by Brazilian institutions and cover mainly the western and central part of the SAO (Fig. 1).

We extracted trends in standardized catch rates for the major species and used these data and information from the literature and other sources to infer changes in patterns of exploitation and their effect on the species population abundance. This work is timely because Brazil will reassess the conservation status of marine fauna in the next few years (ICMBio 2014), despite the fact that onboard observer programs have been cancelled and national data collection from fisheries has mostly ceased as of 2012. Our work may contribute to a baseline population assessment for globally threatened oceanic shark species and inform further data collection and management and conservation decisions.

Methods

Data

Our database is a compilation of data from fishing logbooks reported by fishing companies, fishers, and onboard observers from different fleets. We obtained these data from Brazilian institutions monitoring longline fisheries in the western and central SAO. We screened all sources of data to identify common logbook errors (i.e., set coordinates on land, typographical errors) and created an identification code for each set (identified by the combination of coordinates, boat name, flag name, institutional source, and date). Suspect or repeated sets were discarded.

Because we used fishing logbooks collected from different sources, the number of variables and the level of detail varied temporally. For example, old logbooks (late 1970s, reported by fishing companies) had fewer technical details than the most recent logbooks (onboard observers). Common variables useful for catch-rate stan-

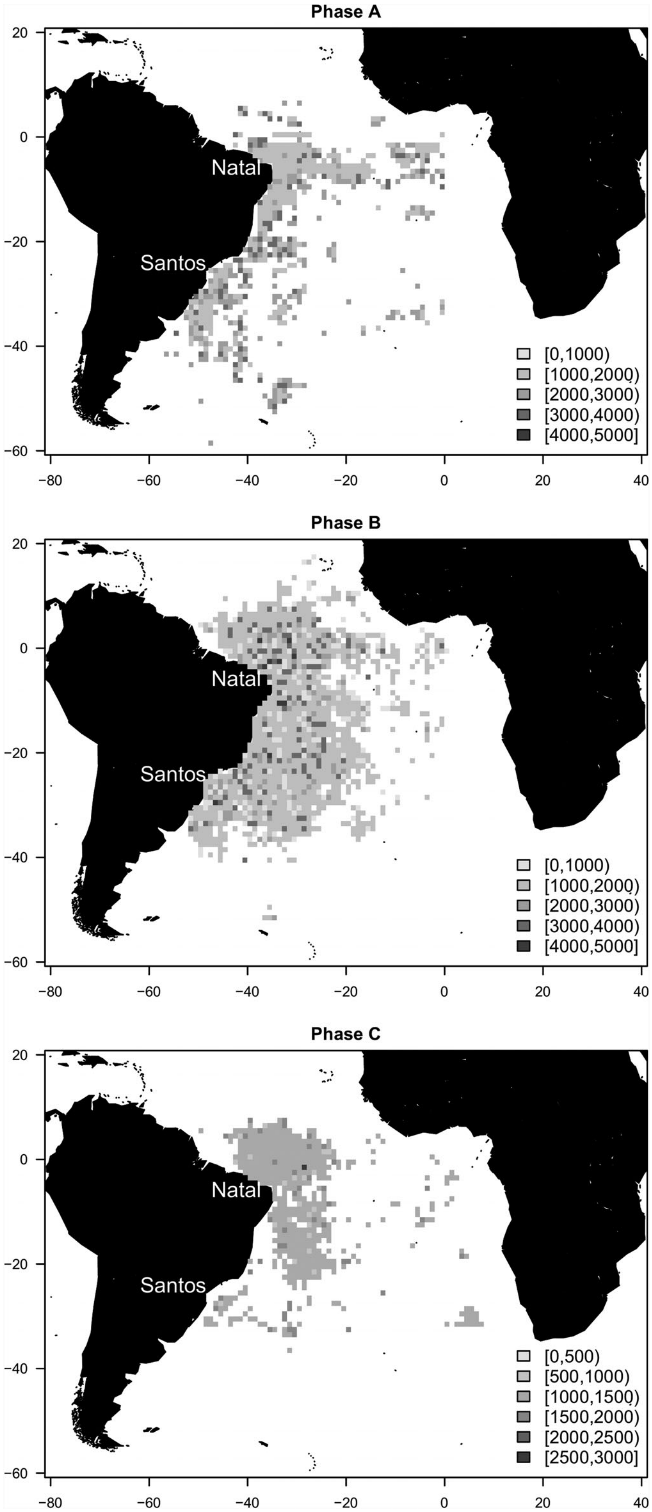

Figure 1. Spatial distribution of reported longline fishing effort (gray scale, sum of number of hooks in pixels degrees of 1× 1) in the 3 identified exploitation phases (A, 1979–1998; B, 1998–2007; C, 2008–2011).

dardization were retained from the source data sets and merged in a new database (Supporting Information). The resulting database included counts of sharks caught in individual sets (n), number of hooks used on individual sets (H), identity of the fishing fleet (flag), year of the set (Y), month of the set (m), and geographic coordinates. We incorporated a variable that accounted for seasonal differences in the sinusoidal function of month (m):

$$f\ (m) = \text{smonth} + \text{cmonth} = \sin\left(\frac{2 \times \pi \times m}{12}\right) + \cos\left(\frac{2 \times \pi \times m}{12}\right).$$

Species

Because fishers and observers sometimes incorrectly or inconsistently identify sharks, we combined some sharks into broad groups. *Prionace glauca*, *Isurus oxyrhinchus*, *Carcharhinus falciformis*, *C. longimanus*, and *Alopias superciliosus* were analyzed at the species level because they tend to be identified reliably. We categorized sharks of the genus *Sphyrna* as *Sphyrna* spp., sharks of the genus *Carcharhinus* (all carcharhinids except *P. glauca*) as grey sharks (a term used by the ICCAT reporting guidelines for sharks of the *Carcharhinus* genera), and the remaining unidentified sharks as other sharks (Table 1).

Phases of Exploitation

In the southwestern Atlantic, significant changes have occurred over time in total fishing effort, species targeting, and catch reporting. Changes in fishing methods were associated with the introduction of new technologies, management measures, and market demands. Furthermore, even within fleets there were mixed fishing strategies (Supporting Information).

We first performed an exploratory data analysis, initially using catches for all fleets referring to all shark species (Supporting Information). The total number of sharks caught, hooks used, and nominal catch rates recorded (number of sharks divided by the number of hooks) each month were plotted over time (Fig. 2). Then we used the number of sets deployed by each fishing fleet each year to build a mosaic plot of fishing operations showing the relative proportion of fishing effort deployed by all fleets in our data base (Supporting Information). From these results and information from the literature, we identified 3 distinct exploitation phases (Fig. 2; Table 2; Supporting Information): A, 1979–1997; B, 1998–2007; and C, 2008–2011.

In phase A, data on shark catches were reported by 5 fleets and 40 vessels. Of these, 28 vessels came from Japan and 2 operated under multiple flags (Figs. 1 & 3). Overall, fleets used similar gear configuration (Supporting Information). Vessels operated during the early morning and using deep multifilament longlines (>200 m) with J hooks and small fish as bait target tunas (Hazin et al. 2008). Logbooks had a high incidence of zeros but fewer missing values (Table 2).

In phase B (1998–2007), 20 fleets reported data, of which 18 recorded shark catches (Fig. 2). Out of these fleets, data from 10 were retained for modeling. We excluded fleets reporting data for <3 years (see below). Of the 100 vessels reporting data in this phase, at least 10 changed flags during this phase, most of these were Spanish. Fishing practices also changed during this phase, mainly because of the introduction of monofilament lines and circle hooks that target swordfishes and sharks (Supporting Information). Nominal catch rates of sharks during this period were considerably higher than for the other phases (Table 2). This was an effect of an increased use of swordfish longlines that have a greater shark bycatch than tuna longlines and an indication of more directed shark fishing, probably due to the increasing demand for shark fins from Asian markets in the 1990s (Clarke et al. 2006). We detected that although the proportion of zeros decreased, the proportion of missing values increased relative to phase A (Table 2).

The ICCAT banned the shark fin fishery in 2004, and from 2008 to 2011 a series of recommendations were made for nonretention and commercialization of several endangered oceanic sharks (Tollotti et al. 2015). Since 2006, Brazil has required that all foreign vessels host onboard observers. Concurrently, the landing port of the foreign fleets shifted from southern to northeastern Brazil. Thirty vessels from 3 fleets (Spain, Brazil, and Honduras) reported shark data in phase C. These vessels used different gear configurations to target multiple species (Supporting Information). Catch rates were in general considerably lower than in phase B but slightly higher than in phase A (Table 2). Because of onboard observers on foreign fleets, we expected this phase would be the most reliable over the entire period. However, the proportion of missing values (Table 2) was considerably higher than for phases A and B.

Modeling Trends in Catch Rates

Our database had a large portion of zeros and missing values (Table 2). Zeros could be missing values, unreported catches replaced by zeros in the logbooks, or true zero catches. Nonetheless, logbooks seem fairly accurate for positive catches (Baum et al. 2003). Because it was impossible to distinguish between real zeros and missing values in our database, we removed them and used zero-truncated negative binomial distributions to model only the positive catches (Baum et al. 2003; Martin et al. 2005).

We fitted zero-truncated negative binomial generalized linear models to the data of each species for each fishing phase. All covariates were used to build an initial model. We included the logarithm of the number of hooks as an offset term to model catch rates while still retaining the

Table 1. Description of the data set (species) used to estimate trends in sharks catch rates in the South Atlantic Ocean.

Family	*Species*	*Code*[a]	*Common name*	*Number reported*[b]	*IUCN status*[c]	*Brazil (MMA)*[c]
Lamnidae	*Isurus oxyrinchus*[d]	SMA	shortfin mako	35,411	VU	NT
	Isurus paucus	LMA	longfin mako	3	VU	DD
Alopidae	*Alopias supercilosus*[d]	BTH	bigeye thresher shark	5114	VU	VU
	Alopias vulpinus	ALV	common thresher shark	1	VU	VU
Pseudocarchariidae	*Pseudocarcharias kamoharaii*	PSK	crocodile shark	30	NT	DD
Sphyrnidae	*Sphyrna lewini*	SPL	scalloped hammerhead	50,900	EN	CR
	Sphyrna zygaena	SPZ	smooth hammerhead	1	VU	CR
	Sphyrna mokarran	SPK	great hammerhead	1	EN	EN
	Sphyrna spp.[d,e]	SPX	hammerhead sharks	63,989	–	–
Carcharhinidae	*Prionace glauca*[d]	BSH	blue shark	445,587	NT	NT
	Carcharhinus falciformis[d]	FAL	silky shark	26,177	NT	NT
	Carcharhinus longimanus[d]	OCS	oceanic whitetip shark	3288	VU	VU
	Carcharhinus signatus	CCS	night shark	132	VU	VU
	Galeocerdo cuvier	TIG	tiger shark	15	NT	NT
	Carcharhinus spp.[d,f]	CAX	grey sharks	135,345	–	–
Not identified	other sharks	OTHSHARKS	other sharks	105,183	–	–
All sharks	–	–	–	871,177	–	–

[a] *International Commission for the Conservation of Atlantic Tunas task 1 codes broadly used in fisheries logbooks from South Atlantic.*
[b] *Total number of sharks reported by multiple fleets in the western and central South Atlantic from 1979 to 2011.*
[c] *International Union for Conservation of Nature status abbreviations: EX, extinct; RE, regionally extinct; EW, extinct in the wild; CR, critically endangered; EN, endangered; VU, vulnerable; NT, near threatened; LC, least concern; DD, data deficient.*
[d] *Species used for modeling trends in catch rates.*
[e] *All sharks identified as Sphyrna spp., plus S. lewini.*
[f] *All sharks identified as Carcharhinus spp., plus C. falciformis, C. signatus, and C. longimanus.*

Table 2. Catch rates, zero observations, and missing values in the data set used to estimate trends in sharks catch rates in the South Atlantic Ocean.

Species	*Phase*[a]	*Mean annual catch rate*[b]	*Longline sets with zero catches (%)*	*Longline set with missing values (%)*
Prionace glauca	A	0.97	61.62	0.03
	B	26.06	44.27	0.48
	C	10.16	6.48	9.84
Isurus oxyrinchus	A	0.08	90.39	0.91
	B	2.07	76.97	5.18
	C	0.35	21.46	62.21
Sphyrna spp.	A	0.06	94.7	0.96
	B	4.31	83.58	7.12
	C	0.17	23.19	71.93
Alopias superciliosus	A	0.01	96.56	2.22
	B	0.35	88.1	8.63
	C	0.05	23.97	75.32
Carcharhinus longimanus	A	0.02	97.95	1.22
	B	0.13	88.53	9.79
	C	0.19	19.81	71.47
Carcharhinus falciformis	A	0.44	91.02	1.22
	B	0.55	88.22	9.76
	C	0.36	22.82	71.15
Other sharks	A	0.8	78.84	0
	B	5.24	79.68	0.02
	C	0.43	22.51	64.84

[a] *3 identified exploitation phases (A, 1979–1998; B, 1998–2007; C, 2008–2011).*
[b] *Unstandardized, including sets with zero catches.*

probabilistic nature of the response variable. The basic model structure was

$$\log(\mu) = \mathbf{X}\beta + \log(\mathbf{H_v}),$$

where **X** is the matrix of explanatory variables, β is the vector of parameters (explanatory variables, fixed effects), $\mathbf{H_v}$ is a vector of the number of hooks (treated as an offset), and μ is the expected catch (response variable).

We then refined our models by iteratively selecting the most appropriate combination of explanatory variables according to their statistical significance (Table 3). Year (Y) was modeled both as a continuous

Table 3. Results of the generalized linear models of trends in shark catch rates (assumed zero truncated negative binomial distribution) with year as a continuous variable in each of the 3 phases of shark exploitation the South Atlantic Ocean (SAO). Further information are available in Supporting Information (i.e Standard errors [S.E] for year coefficients).

Phase	*Covariates*[a]	*P. glauca*	*I. oxyrinchus*	*C. falciformis*	*C. longimanus*	*A. superciliosus*	*Sphyrna* spp	*Grey sharks*	*Other sharks*
A, 1978–1997	Intercept (BRA)	−44.751	233.301	95.805	−215.000	20.588	−124.021	−34.231	−143.000
	Year	0.020	0.113	−0.052	0.105	−0.021	0.057	0.014	0.069
	BLZ	−0.447	−0.063	−2.301	–[b]	– [b]	−1.596	−2.700	−2.990
	JPN	−0.467	−0.523	−1.473	−0.242	12.729	−0.059	−1.639	−1.560
	KOR	−0.336	−0.717	−0.717	–[b]	–[b]	−1.892	−1.709	−2.680
	TAI	−0.613	−0.339	−1.125	–	12.801	−0.867	−2.192	−2.460
	Smonth	−0.076	−0.108	−0.581	−0.114	0.157	−0.352	−0.395	−0.236
	Cmonth	0.032	0.209	−0.116	−0.385	−0.129	0.110	0.076	0.187
	Lat	–[b]	–[b]	–[b]	0.011	–[b]	–[b]	−0.011	−0.005
	Long	0.007	–[b]	–[b]	0.004	–[b]	–[b]	–[b]	–[b]
	number of observations (>0)	6007[c]	1419[c]	1275[c]	122[c]	159[c]	660[c]	4773[c]	3543[c]
	negative binomial dispersion parameter	0.393[c]	0.163[c]	0.007[c]	2.055[c]	2.054[c]	0.007[c]	0.044[c]	0.114[c]
	SE	0.023[c]	0.066[c]	0.000[c]	2.271[c]	0.133[c]	0.000[c]	0.017[c]	0.023[c]
	log likelihood	−16562.60[c]	−2428.02[c]	−3889.80[c]	−136.45[c]	−284.46[c]	−1314.57[c]	−13375.400[c]	−9439.83[c]
B, 1998–2007	Intercept (BRA)	54.094	153.000	607.893	152.771	−79.100	201.410	740.375	752.279
	Year	−0.029	−0.082	−0.309	−0.083	0.033	−0.107	−0.375	−0.381
	BLZ	−0.245	−0.412	–[b]	–[b]	–[b]	–[b]	−2.419	−2.431
	BOL	−2.022	3.250	–[b]	–[b]	–[b]	–[b]	−1.506	−1.505
	CAN	−0.485	−33.000	–[b]	–[b]	–[b]	–[b]	−1.586	−1.661
	ESP	−0.400	0.675	−0.309	1.060	−0.142	0.933	−0.118	−0.046
	HND	−0.076	0.410	0.619	1.957	0.677	0.861	−0.117	−0.297
	ISL	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	−0.207	−0.199
	KIT	−1.917	−1.650	–[b]	–[b]	–[b]	–[b]	−1.304	−0.991
	MAR	−0.439	−1.280	–[b]	–[b]	–[b]	–[b]	−0.004	0.038
	PAN	−0.919	−1.090	1.087	0.602	1.170	1.969	−1.022	−1.045
	PRT	−0.256	1.030	−1.317	1.130	−1.360	0.803	−0.641	−0.581
	TAI	−1.364	0.459	−2.352	–[b]	−16.100	−2.709	−1.765	−1.738
	UK	−1.181	−2.510	–[b]	–[b]	–[b]	–[b]	−1.344	−1.254
	URY	0.385	−0.115	1.313	3.455	4.980	3.026	0.032	−0.150
	USA	−0.073	−0.552	0.924	–[b]	–[b]	−1.204	1.006	0.967
	VCT	−0.780	0.153	0.148	–[b]	−1.750	−1.699	−1.251	−1.390
	VUT	−0.952	−1.150	−1.339	–[b]	−0.247	−1.500	−2.015	−3.174
	smonth	−0.080	−0.058	−0.351	−0.166	−0.097	−0.242	0.132	0.161
	cmonth	−0.251	−0.079	0.311	−0.015	−0.127	0.584	0.125	0.108
	Lat	−0.055	−0.030	−0.014	−0.042	−0.175	0.008	−0.007	−0.008
	lon	0.037	–[b]	−0.035	−0.064	0.006	−0.068	−0.036	−0.033
	number of observations (>0)	35071[c]	11284[c]	1208[c]	1001[c]	1955[c]	5478[c]	15331[c]	13067[c]
	negative binomial dispersion parameter	0.705[c]	0.007[c]	0.007[c]	0.054[c]	0.007[c]	0.007[c]	0.00[c]	0.007[c]
	SE	0.011[c]	0.000[c]	0.000[c]	0.112[c]	0.000[c]	0.000[c]	0.000[c]	0.000[c]
	log likelihood	−103005.00[c]	−17556.20[c]	−2533.67[c]	−1084.76[c]	−2254.82[c]	−11232.80[c]	−33504.50[c]	−29303.80[c]

Continued

Table 3. Continued.

Phase	*Covariates*[a]	*P. glauca*	*I. oxyrinchus*	*C. falciformis*	*C. longimanus*	*A. superciliosus*	*Sphyrna* spp	*Grey sharks*	*Other sharks*
C, 2008–2011	Intercept (BRA)	−508.000	−197.000	−1190.000	95.328	−1204.814	1006.353	−471.071	−749.599
	Year	0.251	0.092	0.581	−0.051	0.596	−0.510	0.226	0.365
	ESP	0.106	−0.311	−1.540	−2.321	−3.903	−1.619	−0.616	−0.392
	HND	0.290	1.400	1.380	−1.854	−19.461	−0.034	−0.053	−0.746
	smonth	−0.662	−0.694	0.363	−0.012	–^{b}	0.855	−0.014	−0.073
	cmonth	0.019^{c}	0.163^{c}	−0.804^{c}	−0.593^{c}	–^{b}	−1.278^{c}	−0.356^{c}	−0.333^{c}
	lat	−0.021	−0.035	−0.121	−0.071	–^{b}	0.057	–^{b}	–^{b}
	lon	0.044	0.017	−0.262	−0.027	–^{b}	−0.247	−0.174	−0.159
	number of observations (>0)	5270^{c}	1030^{c}	380^{c}	550^{c}	45^{c}	308^{c}	1606^{c}	798^{c}
	negative binomial dispersion parameter	1.349^{c}	0.007^{c}	0.007^{c}	0.963^{c}	0.007^{c}	0.007^{c}	0.007^{c}	0.007^{c}
	SE	0.045^{c}	0.000^{c}	0.000^{c}	0.375^{c}	0.000^{c}	0.000^{c}	0.000^{c}	0.000^{c}
	log likelihood	−15570.50^{c}	−994.18^{c}	−585.309^{c}	−583.28^{c}	−72.36^{c}	−307.73^{c}	−2404.62^{c}	−1129.77^{c}

[a] *Abbreviations: BLZ, Belize; BOL, Bolivia; BRA, Brazil; CAN, Canada; ESP, Spain; GUY, Guyana; HND, Honduras; ISL, Iceland; JPN, Japan; KIT, Saint Kitts and Nevis; KOR, Korea; MAR, Morocco; PAN, Panama; PRT, Portugal; TAI, China-Taipei; UK, United Kingdom; URY, Uruguay; USA, United States of America; VCT, Saint Vincent and Grenadines; VUT, Vanuatu; smonth, Sine function of month; cmonth, Cosine function of month.*

[b] *Covariate dropped from the final model.*

[c] *Nonsignificant values. All other values are significant covariates ($P < 0.05$). Seasonal differences significant when both cmonth and smonth coefficients were significant.*

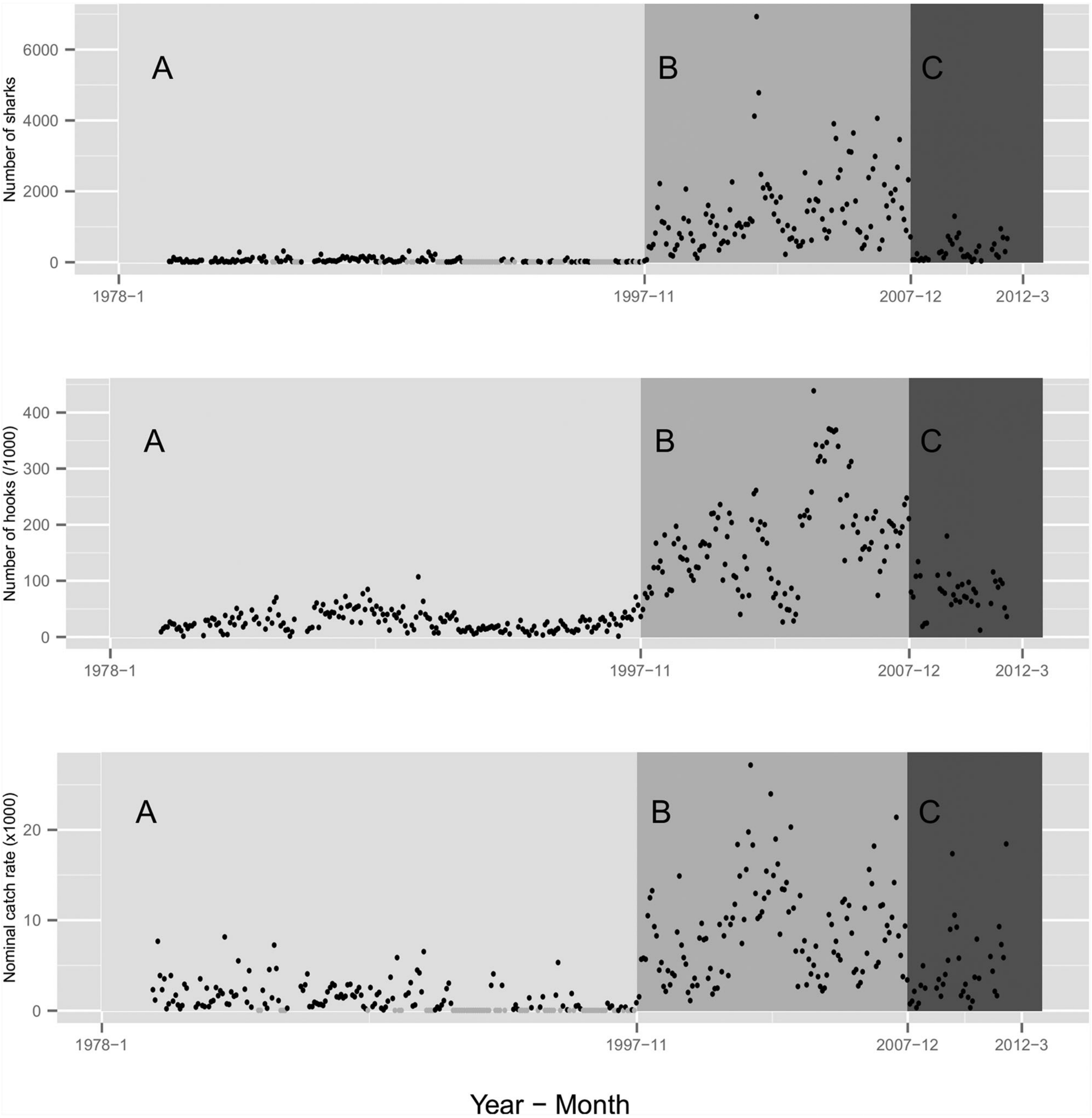

Figure 2. Monthly total number of sharks (sum), fishing effort (number of hooks), and nominal catch rates (total number of sharks divided by total number of hooks multiplied by 1000) from 1979 to 2012 reported by multiple fleets to Brazilian institutions, including longline sets with 0 sharks reported (black dots, observations sets in which sharks were caught; gray dots, months without reported shark catches).

(to obtain overall estimates and percentage rate of change) and categorical explanatory variable (to detect annual variability). Annual mean catch rates were predicted by fixing the explanatory variables at their median values and standardizing per 1000 hooks. Percent changes in catch rates were estimated by comparing the predicted catch rates of the initial and final year of the series.

Because fleets fished in different ways, we kept fleet in the model structure (Supporting information) even though this process reduced the amount of data we could analyze (i.e., fleets with <2 years of shark data were excluded). To further justify this decision, we explored the outcome of using our models with the exclusion of this variable and by creating fleets-specific models (Supporting Information). When the fleet variable was excluded,

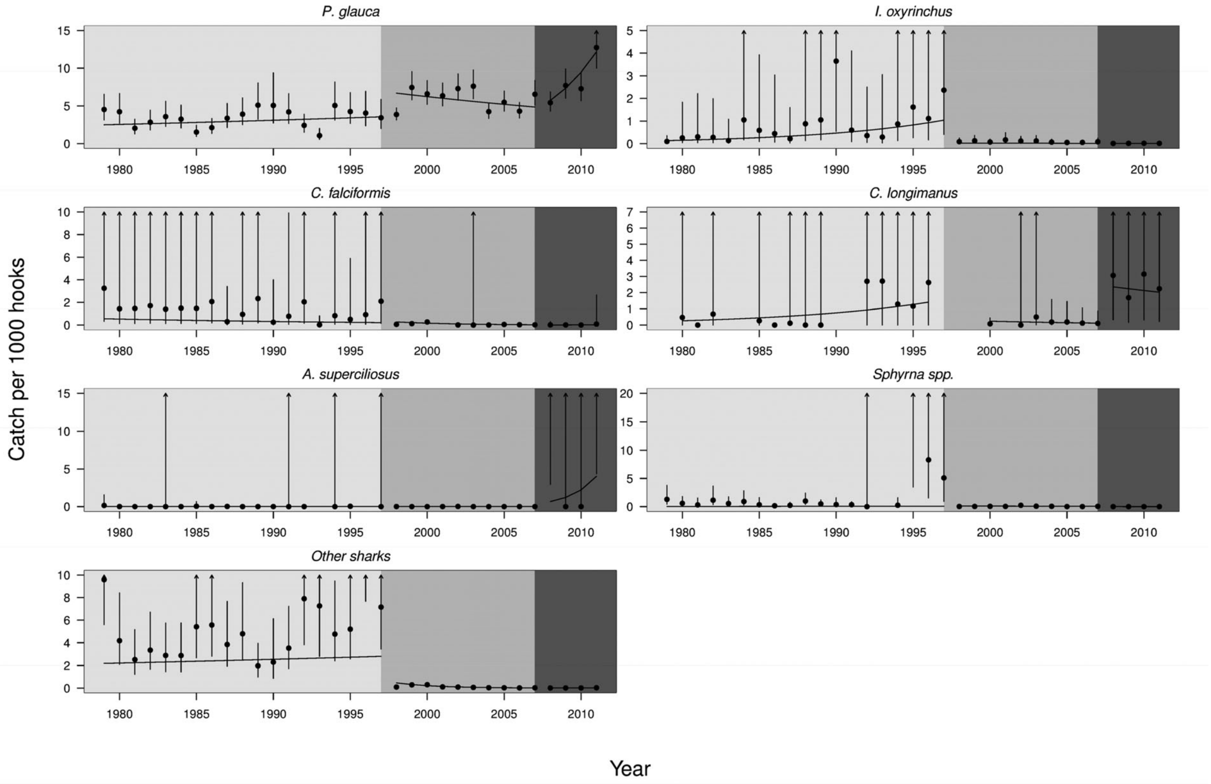

Figure 3. Trends in standardized catch rates of sharks (estimated from generalized linear models with a zero truncated negative binomial distribution) in 3 fishing phases (shadings) (solid lines, overall trends with year as continuous variable; dots, individual year estimates with year as factor; vertical lines, 95% CI; arrows, CIs larger than the y-axis scale in a particular year).

catch rates fluctuated with the number of fleets fishing in any particular year.

To test the sensitivity of our models to the timing of the identified phases we refit the models to alternative phases (increasing and decreasing their cutoffs by 2 years) and by excluding phases (Supporting information).

Results

From 1979 to 2011, 871,177 sharks of 13 species were reported on 86,492 longline sets. These sets were deployed by 339 vessels of 20 different fleets using a total of 142,450,304 hooks. The number of sharks caught, effort deployed, and resulting catch rates for all species changed considerably across phases (Figs. 1 & 2, Table 2). These changes were influenced by changes in reporting and variation in fishing strategies (Supporting Information).

In phase A (1979–1997), pelagic shark catch rates increased for most species (range 1.4-fold for *P. glauca* to 8-fold for *I. oxyrinchus*). Decreasing trends were detected for *C. falciformis* and *A. superciliosus* (–61% and –63%, respectively). In general, fleets caught an average of 5.11 sharks per thousand hooks in 1979 and 12.62 sharks per thousand hooks in 1997. Yet there were statistically significant differences in catch rates among the 3 fleets; Brazil generally reported the highest catches (Table 3).

In phase B (1998–2007), all sharks showed decreasing trends in catch rates except *A. superciliosus*. Changes ranged from a 90% catch-rate decline for *C. falciformis* and a 96% decline for all other requiem sharks (grey sharks) to an estimated 61%, 55%, and 27% catch-rate decline for *Sphyrna* spp., *I oxyrinchus*, and *P. glauca*, respectively (Fig. 3). Except for *P. glauca*, catch rates for all species were considerably lower than in phase A (average 1.58 sharks per thousand hooks in 1998 and 0.2 in 2007 [Supporting information]). Catch rates for *I. oxyrinchus* and the groups other and grey sharks differed substantially from catch rates detected in phase A (Supporting information). Specifically for *I. oxyrinchus*, models using year as factor and continuous did not converge at this phase. When year was analyzed as factor, catch rates were generally higher. Thus in a conservative way, we use year as continuous to extract the percent rate of change, which fits easily to the data and was the standard process for all other species. Uruguay, Honduras, and Panama had generally higher catch rates than other fleets (Table 3). The spatial (latitude and longitude in all models) and seasonal components (smonth and cmonth in all models) had significant effects on all species (Table 3).

In phase C (2008–2011), catch rates for most species increased (range 6-fold for *C. falciformis* and *A. superciliosus* to 1.3-fold for *I. oxyrinchus*). Catch rates of *Sphyrna* spp. (–80%) and *C. longimanus* (–14%) decreased. Except for *P. glauca* and *C. longimanus*, all species were caught at very low catch rates throughout this phase (Supporting Information). Conversely, catch rates of *P. glauca* were at their highest level ever (about 12 sharks per thousand hooks in 2011) (Fig. 3). All fleets differed significantly in catch rates, and Brazil recorded higher shark catch rates than other fleets (Table 3). It is important to take into consideration that the Brazilian vessels, were unique vessels (at this phase) without mandatory presence of onboard observers. Spatial terms were statistically significant for all species except *A. superciliosus* and greys and other sharks (Table 3).

Discussion

Catch rates for most of the species we analyzed declined precipitously, particularly in phase B, which in turn exhibits best modeling performance in comparison with other phases (narrow CIs [Supporting information]). These declines coincided with significant fishing effort expansion, a lack of regulatory measures to deal with shark bycatch, finning, and directed fishing for sharks by some fleets. Based on the percentage of change (Supporting Information) between the last year of phase A and the last year of the phase B, with exception of *P. glauca* and *A. superciliosus*, catch rates of all species declined by over 85%. Assuming that in the absence of directed management, observed declines in catch rates often indicate declining abundance (Davidson et al. 2015), and following IUCN Red List criterion A (population size reduction of ≥50% over the last 10 years or 3 generations), our results suggest that *I. oxyrinchus* and *C. falciformis* may be endangered. Both species were recently assessed as near threatened in Brazil (Table 1) and thus have no restrictions for catches in the study area (Fig. 1).

Our analyses of different phases allowed us to model catch-rate trajectories in generally homogeneous fishing regimes. This approach allowed us to cope with differences in catchability across phases, major gear modifications (e.g., introduction of monofilament longlines in phase B), and implementation of more restrictive monitoring (e.g., introduction of onboard observers on foreign vessels in phase C). Yet, we could not completely control for temporal changes in target strategies within some fleets and phases. Moreover, quotas and fishing licenses can be traded among signatory members of ICCAT, masking the real identity of some fleets. China-Taipei, for example, fished under flags from St. Vincent, Grenadines, and Belize, targeting tunas, billfishes, and sharks (ICCAT 2013). In models that included boats and fleets as fixed and random effects, estimates improved when we used boats and flags as nested random effects (Supporting Information). However, these models converged only for the most data-rich species (*P. glauca*).

During the initial period of industrial exploitation (phase A), fishing was relatively moderate. Only Japan and Brazil reported data regularly. Target species were mainly albacore (*Thunnus alalunga*) and bigeye tunas (*T. obesus*) (Hazin et al. 2008). Except for *C. falciformis* and *A. superciliosus*, standardized catch rates for this phase increased for all species (Fig. 3 & Table 3). We hypothesize that the increases detected for these species were partly an effect of changes in reporting. Sharks were not commercially important in South America until the late 1980s, and ICCAT imposed consistent reporting of shark catches only from the 1990s (Hazin et al. 2008). Thus, our results for phase A are probably influenced by a systematic increase in the recording of sharks in logbooks and should be interpreted in this light.

After the 1990s, significant declines in some high-value North Atlantic target species such as bluefin tuna (*Thunnus thynnus*) and swordfish (*Xiphias gladius*) led ICCAT and other North American and European fisheries management bodies to impose quota restrictions and tighter fisheries regulations, which resulted in a significant displacement of fishing effort from the North to the South Atlantic (Hazin et al. 2008); such north-south shifts may be part of a more global phenomenon of fishing effort displacement (Worm et al. 2009; Worm & Branch 2012). In the SAO, this expansion of fishing effort coincided with the introduction of new technologies and the rise of a global shark fin market, which incentivized directed fishing for sharks. Furthermore, from the mid-1990s, especially in the SAO, swordfish fisheries developed faster than any other sectors (Maguire et al. 2006). Swordfish fisheries tend to record higher bycatch of sharks than tuna fisheries because they use shallow lines and nighttime operations. Yet, in phase B, all shark species showed decreasing trends, except for *A. superciliosus* (Table 3).

When fishing effort decreased again (phase C) and restrictive measures were adopted (finning ban, recommendations for nonretention of some species), catch rates increased or stabilized. Onboard observers covered 45% of the fishing vessels we examined in this phase (from Spain and Honduras), and we cannot exclude the possibility that catch rates were influenced by changes in reporting. Particularly for *I. oxyrinchus* and *C. falciformis*, increasing trends in catch rates were observed in phase C; however, when absolute estimates were compared with those from previous phases these species were systematically declining (Fig. 3; Supporting Information). During phase C, most species had standardized catch rates close to 0, but in general they increased (Table 3). This result suggests that the high level of longline fishing observed in phase B likely led to significant changes in the shark assemblage in the SAO. Moreover, this marked increase for most shark species may in part reflect directed fisheries on already overexploited stocks. Brazil was recently identified by the FAO as one of the largest and most rapidly expanding shark-meat consumer markets and the world's largest shark meat importer in 2011 (Dent & Clarke 2015).

P. glauca is one of the few species of pelagic sharks species caught in the SAO for which there is a considerable amount of information (Montealegre-Quijano & Vooren 2010; Carvalho et al. 2014). Stock assessment models fitted to *P. glauca* catches recorded by the Brazilian longline fisheries concluded that the stock of *P. glauca* in the SAO was below biomass levels at which maximum sustainable yield is achieved (Carvalho et al. 2014). Likewise, the ICCAT (2015) found that the SAO stock might be slightly overexploited. Pons and Domingo (2008), analyzing data from Uruguay from 1992 to 1998, concluded that catch per unit effort (CPUE) dropped by 30%, a trend similar to our estimate for phase B. In the North Atlantic, Blue sharks declined by 30% from 1957 to 2000 and by 53% from 1992 to 2005 (Baum & Blanchard 2010). In light of these findings, the recent catch-rate increase detected in phase C needs to be further investigated. This could reflect increasing abundance, increasing influence of the fleets targeting swordfish (Spain and Honduras), or increased *P. glauca* retention due to market demands or reduced availability of higher value species (Aires da Silva et al. 2008; Fredou et al. 2015).

According to recent ICCAT ecological risk assessment, *I. oxyrinchus* are predicted to be more vulnerable than other pelagic species (Cortes et al. 2010). Although contrasting trends were previously observed in the SAO (Hazin et al. 2007; Mourato et al. 2008), the species declined significantly in other areas. In the North Atlantic, catch rates of *I. oxyrinchus* declined by about 35% from 1992 to 2005 (Baum & Blanchard 2010). The extremely low catch rates we observed in phases B and C suggest that population of *I. oxyrinchus* are depleted in the SAO. Unlike other sharks, this species is targeted for its fins and meat, especially by Spanish vessels (Hazin et al. 2008).

Species of the genus *Carcharhinus* are often combined into generic groups because of challenges in species identification. This practice hampers the identification of species-specific trends in catch rates. For example, in the North Atlantic, *C. falciformis* were grouped with other sharks (*C. signatus* and *C. obscurus*), which declined by over 75% from 1992 to 2005 (Baum & Blanchard 2010). We were able to estimate a species-specific trend for the species and found a significant decline, which was similar to trends for the other sharks and grey sharks groups (which mostly consisted of carcharhinids, especially *C. falciformis* and *C. signatus*). Consistent with Tolotti et al. (2013), our results were inconclusive for *C. longimanus*. In the North Atlantic, this species declined by 50% from 1992 to 2005 (Baum & Blanchard 2010) and is currently protected by several RFMOs, including ICCAT (Tolotti et al. 2015). Our results are generally supported by independent assessment and approaches, such as demographic and productivity and susceptibility analysis, which indicate that some Carcharhinidae species are at great risk of extinction in the SAO, specifically *Carcharhinus signatus*, *C. galapagensis*, C. *falciformis*, and *C. longimanus* (Santana et al. 2009; Cortes et al. 2010; Luiz & Edwards 2011).

Similar to our results for the SAO, hammerhead sharks (*S. lewini*, *S. zygaena*, *S. mokarran*) have declined by over 75% in the North Atlantic (Baum & Blanchard 2010). *S. lewini* composes most of the catches for this group, at least in southern Brazil (around 80%). However, not being able to extract species-specific trends for these 3 vulnerable species of large sharks (Gallagher et al. 2014) is a problem. *A. superciliosus* was the least frequently encountered species among those analyzed and was often discarded according to the data collected by onboard observers. Like *I. oxyrinchus*, *A. superciliosus* also has a more vulnerable life history and is currently depleted in several locations (Cortes et al. 2010).

We conclude that the SAO experienced significant levels of depletion during the mid-1990s and mid-2000s gold rush on sharks and other pelagic species, likely driven by increasing marked demands for shark fins and expansion of large industrial tuna and swordfish fisheries on previously lightly exploited grounds. Decreasing fishing effort and increasing regulation may set the stage for species to recover from previous depletion, as has been noted for other species and regions (Lotze et al. 2011). In light of these findings, we are very concerned about the end of systematic data collection from fleets fishing over Brazilian jurisdiction since 2012 and about the cancellation of onboard observer programs, which renders any further monitoring of SAO shark populations difficult or impossible (Chao et al. 2015; Dario et al. 2015). This exacerbates a more general scarcity of fisheries statistics from neighboring jurisdictions, including Uruguay, South Africa, Namibia, and Argentina (Hazin et al. 2008), and makes an integrated management plan among nations of the SAO difficult.

Although countries such as Brazil, Uruguay, and South Africa have been creating favorable conditions for many fishing fleets to expand in the area, proper monitoring of these fleets has been inconsistent. This situation severely impedes proper stock assessment and hence the evaluation of current conservation status for threatened species in SAO waters. In this respect, it is significant that a number of other shark species of South America (e.g., *Carcharhinus plumbeus*, *C. porosus*, *C. galapagensis*, *Sphyrna tudes*, *S. tiburo*, *S. lewini*, *S. media*, *S. tudes*, *S. zygaena*, *Isogomphodon oxyrhynchus*, *Galeorhinus galeus*, and *Mustelus fasciatus*) are at even greater risk from unregulated and unobserved fishing and may be close to extirpation in Brazilian waters (ICMBio 2014).

Nowadays, there are 750 longline fishing vessels with specific permission to catch *P. glauca*, *I. oxyrhinchus*, and *C. falciformis* in Brazilian waters (SINPESQ 2015). For comparison, in our database, over more than 30 years, about 300 vessels reported data. In accordance with the recently implemented Brazilian National Plan of Action for the Conservation and Management of Sharks (NPOA-ICMBio 2014), we suggest that further actions focus primarily on improving monitoring and fisheries statistics to inform proper recovery strategies for heavily affected shark populations in the South Atlantic Ocean.

Acknowledgments

We thank the Universidade Federal Rural de Pernambuco (UFRPE) and the Fisheries and Aquaculture Department (DEPAq) of the same institution; The Ministry of Environment, Ministry of Fisheries and Aquaculture, and the Institute of Fisheries of the State of Sao Paulo for supplying data; University of Dalhousie (WormLab), Hopkins Marine Station of Stanford University (Dra. Fiorenza Michelli and FioLab Staff), the Shark Baselines Project for R,B,'s internship and for help with data analyses. We give special thanks to CAPES, CNPq, and FACEPE for the doctoral scholarship to R.B. and Productivity Grant to R.L, to the NSERC for a discovery grant to J.M.F., and to the Lenfest Ocean Program for a grant to F.F.

Supporting Information

Further information on fishing phases and fleets (literature review, empirical and statistical rationale) (Appendix S1), sensitivity analyses of the effects of timing for the identified phases (Appendix S2) and of the effects of including a vessel flag variable (Appendix S3), data sources (Appendix S4), and observed rates of change in catch rates (Appendix S5) are available online. The authors are solely responsible for the content and functionality of these materials. Queries should be directed to the corresponding author.

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