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STANDARDIZED CATCH RATES OF SHORTFIN MAKO SHARKS CAUGHT BY THE BRAZILIAN TUNA LONGLINE FLEET (1978-2016) USING GENERALIZED LINEAR MIXED MODELS (GLMM)[1]

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SUMMARY

Catch and effort data from the Brazilian tuna longline fleet (national and chartered) in the equatorial and southwestern Atlantic Ocean from 1978 to 2016, including more than 90,000 sets, were analyzed. The CPUE of Shortfin Mako was standardized by a Generalized Linear Mixed Models (GLMM) using a Delta Lognormal approach. The factors initially considered in the models were: quarter, year, area, length of boats, hook per basket, sea surface temperature, bathymetry and fishing strategy. The final model, however, included only quarter, year, area, and fishing strategy. The standardized CPUE series shows an oscillation over time, but with a relative stability, with a few peaks (1993, 2009) and drops (2006). Except for these extreme values, however, the scaled index has fluctuated from 0.5 to 1.5 throughout almost the entire period. In the most recent years, the standardized CPUE has been unusually stable, around 1.5 (1.4 to 1.6), with a drop, however, in 2016, back to a value a bit lower than 1 (0.85).

RÉSUMÉ

Les données de prise et d'effort provenant de la flottille palangrière brésilienne (nationale et affrétée) ciblant les thonidés dans l'océan Atlantique équatorial et du Sud-Ouest entre 1978 et 2016, incluant plus de 90.000 opérations, ont été analysées. La CPUE du requin taupe bleu a été standardisée en utilisant des modèles mixtes linéaires généralisés (GLMM) au moyen d'une approche delta log-normale. Les facteurs initialement considérés dans les modèles étaient les suivants : trimestre, année, zone, longueur des bateaux, hameçon par panier, température de la surface de la mer, bathymétrie et stratégie de pêche. Le modèle final n'incluait toutefois que le trimestre, l'année, la zone et la stratégie de pêche. Les séries de CPUE standardisées montrent une oscillation dans le temps, mais avec une stabilité relative, avec quelques pics (1993, 2009) et des baisses (2006). À l'exception de ces valeurs extrêmes, l'indice échelonné a fluctué de 0,5 à 1,5 pendant presque toute la période. Dans les années les plus récentes, la CPUE standardisée a été exceptionnellement stable, autour de 1,5 (1,4 à 1,6), avec toutefois une baisse en 2016, revenant à une valeur légèrement inférieure à 1 (0,85).

RESUMEN

Se analizaron los datos de captura y esfuerzo de la flota atunera de palangre brasileña (nacional y fletada) en el Atlántico suroccidental y ecuatorial entre 1978 y 2016, incluyendo más de 90.000 lances. Se estandarizó la CPUE de marrajo dientuso mediante modelos mixtos lineales generalizados (GLMM) utilizando un enfoque delta lognormal. Los factores inicialmente considerados en los modelos fueron: trimestre, año, área, eslora de los barcos, anzuelos por cesta, temperatura de la superficie del mar, batimetría y estrategia de pesca. Sin embargo, el modelo final incluía solo trimestre, año, área y estrategia de pesca. Las series de CPUE estandarizada mostraban una oscilación en el tiempo, pero con una estabilidad relativa, con unos pocos picos (1993, 2009) y caídas (2006). Sin embargo, con la excepción de estos valores extremos, el índice escalado ha fluctuado desde 0,5 hasta 1,5 a lo largo de casi todo el periodo.

[1] This is an updated version of the paper submitted in 2016, to the shark group meeting, which included data up to 2012, with an expansion of the time series up to 2016.

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En los años más recientes, la CPUE estandarizada se ha mantenido inusitadamente estable en torno a 1,5 (1,4 a 1,6), con una caída, no obstante, en 2016, hasta un valor algo inferior a 1 (0,85).

KEYWORDS

Mako, Generalized linear mixed models, Brazilian tuna longline

1. Introduction

In recent decades, there has been a growing concern with the status of several shark populations worldwide, mainly because of an increased mortality resulting from fishing. Among the pelagic sharks, the blue shark and the mako shark are two of the most common and widely distributed species, being mainly caught by the tuna longline fishery targeting tunas and swordfish. Although they were initially caught exclusively as bycatch, their status in the fishery has gradually changed over time, with an increased number of boats and fleets starting to target them, together with tunas and swordfish. The increased fishing pressure on these species has prompted Regional Fisheries Management Organizations, such as the International Commission for the Conservation of Atlantic Tunas-ICCAT, to assess the condition of their stocks and the impact of the tuna fishery on them, aiming at designing and implementing management and conservation measures required to ensure their conservation.

The first attempt to assess the status of the mako shark stocks in the Atlantic Ocean was led by the Standing Committee on Research and Statistics of ICCAT (SCRS), in 2004. At that time, the main hindrance for the assessment was the lack of adequate data. Subsequent attempts to assess the condition of the mako stocks in the Atlantic Ocean were undertaken by ICCAT/SCRS in 2008 and 2012, but the results were again rather inconclusive, particularly in the case of the South Atlantic Population. As noted in the SCRS report of the 2008 assessment, it resulted in an estimate of unfished biomass that was biologically implausible, and thus the Committee could not draw any conclusion about the status of the southern stock. During the 2012 shortfin mako shark stock assessment, different standardized CPUE series were presented, both for the southern and for the northern stocks, but conflicting trends of CPUE and catch tendencies again casted doubt on the accuracy of the results. According to the report of the stock assessment meeting, the increase in CPUE values could be due to several reasons, including an increase in abundance, an increase in catchability, a change in fishing strategy, or a better data reporting for the species. Finally, in 2015, a new stock assessment was required by the Commission, to be done in 2017, preceded by a data preparatory meeting in 2016.

The assessment was done as planned and concluded that the probability of the southern stock of the mako shark being overfished was 32.5%, while the probability of overfishing happening was 41.9%. Again, however, the Committee considered the results to be highly uncertain owing to the conflict between catch and CPUE data. In 2017, ICCAT adopted a new recommendation on the conservation of North Atlantic stock of shortfin mako caught in association with ICCAT fisheries, requesting the SCRS to review, in 2019, the effectiveness of the measures contained in it and to provide the Commission with additional scientific advice on conservation and management measures for the North Atlantic shortfin mako. Although the southern stock was not included in that recommendation, the SCRS will likely address both stocks, as it has done in the past. With a view, therefore, to contribute information on the South Atlantic stock of the mako shark, in the present paper the standardized series of CPUE for the species, caught by the Brazilian tuna longline fleet, including both national and chartered vessels, was updated, spanning for 39 years, from 1978 to 2016.

Material and Methods

In the present study, catch and effort data from 99,376 tuna longline sets obtained from logbooks reported by the Brazilian tuna longline fleet, including both national and foreign chartered vessels, from 1978 to 2016, were analyzed (**Table 1**). The longline sets were distributed along a wide area of the equatorial and southwestern Atlantic Ocean, ranging from 003ºW to 052ºW of longitude, and from 11ºN to 50ºS of latitude **(Figure 1)**. The resolution of 1º x 1º, per fishing set, was used for the analysis of the geographical distribution of fishing effort and catches.

Due to the high proportion of sets with zero catches of shortfin mako (93.0%), a GLMM using a Delta Lognormal approach was used for the standardization of CPUE. In the Delta Lognormal model, the catch rates are assumed to be the result of two dependent processes: a) the probability of catching at least one fish; and b) the conditional expected mean catch rate given that there is a positive probability of capture. In this case, the probability of capture was assumed to follow a binomial distribution, while the mean catch rate was assumed to follow a normal error distribution of the log-transformed CPUE. A GLMM model was applied with the logit function being used as the link between the linear predictor and the binomial error response variable.

GLMM models are generally non-orthogonal and the order of entry of explanatory variables affects the contribution of each variable in the final model (McCullagh & Nelder, 1989). For the final model, the selection of factors and interactions was carried out by analysis of deviance tables (Ortiz and Arocha 2004). Briefly, main factors and interactions were included in the model if: a) the percent of total deviance explained by a given factor/interaction was 5% or greater; and b) the Chi-square probability was 0.05 or less for the test of deviance explained versus the number of additional parameters estimated for a given factor or interaction. In the case of a statistically significant interaction between the year factor and any other factor, they were considered as random interactions in the final model.

Once the fixed factors and interactions were selected, all interactions involving the factor year and strategy were evaluated as random variables to obtain the estimated index per year, transforming the GLMs in GLMMs (Generalized Linear Mixed Models) (Cooke 1997). Selection of the final mixed model was based on the Akaike's Information Criterion (AIC), Schwarz's Bayesian Information Criterion (BIC), and a chi-square test of the difference between the [-2 log likelihood statistic] successive model formulations (Littell et al. 1996). Relative indices for the delta model formulation were calculated as the product of the year effect least square means (LSmeans) from the binomial and the lognormal model components. The LSmeans estimates use a weighted factor of the proportional observed margins in the input data to account for the un-balanced characteristics of the data. The factors considered as explanatory variables were: "Year" (39), "Quarter" (4), "Area" (A1>20ºS; A2<20ºS), "Fishing Strategy" (S1= ALB, S2= YFT, BET, SWO; and S3= SWO, BSH), LOA of fishing boat (10-15m, 15-20m, 20-25m, 25-30m and >35m), Hook per Basket- HPB (3-10, 10-15, >15), BAT (20-1000,1000-3000, >3000m) , and SST (<20, 20-25, >25). SST data were obtained from the "Physical Oceanography Distributed Active Archive Center", do "Jet Propulsion Laboratory"- NASA, pelo "Geophysical Fluid Dynamics Lab./ ocean data from the IRI/ ARCS/ Ocean assimilation", e pelo "Centre ERS d'Archivage et de Traitement (CERSAT)", do (IFREMER). Bathymetry data were obtained from ETOPOS.

The fishing strategy was defined in two steps. In the first step, a multivariate cluster analysis was conducted to identify the different Targeting Strategies (TS) by combining clusters of predominant species that were internally coherent and externally isolated (MathSoft, 1995). A total of 99,376 fishing sets with approximately 25 species reported in the observer logbooks were analyzed. The Targeting Strategy typology was then built using the "CLARA (Clustering for Large Applications)" method. This approach is widely applied among non-hierarchical clustering techniques and is well adapted to very large datasets. Each cluster (of fishing sets) can be considered as a Targeting Strategy (He *et al*., 1997; Pelletier and Ferraris, 2000; Hazin *et al.*, 2007; Mourato *et al*., 2011). For a given number of clusters, the final value of the criterion is given. Analyses were conducted with different numbers of clusters, among which the most realistic solution was chosen when considering the evolution of the criterion value. The Targeting Strategy can be described by the mean values obtained (centroids) (Fall *et al*., 2006). In the second step, a matrix was constructed considering aggregated catches by vessels with a given Targeting Strategy. Then, a PCA method was applied to find coherent patterns that may discriminate clusters of vessels (Fishing Fleets= Strategy) with similar fishing strategies.

All statistical and data analyses developed on this study were performed using the software R-3.5.0 (R Core Team, 2016) with the aid of packages *dplyr* (Wickham and Francois, 2015), *ggplot2* (Wickham, 2016), *lme4* (Bates, 2016), *lsmeans* (Lenth, 2016), *lmerTest* (Kuznetsova et al., 2016).

Results and Discussion

The proportion of null catches of shortfin mako sharks for the Brazilian fleet during the period of the present study was 93%. However, the proportion of positive catches varied during the period of study, with a minimum of 2%, in 2007, and a maximum of 21%, in 1993 (**Table 1; Figure 2**). The proportion of positive sets was relatively uniform for quarters, but showed a higher value in strategy 1, in the area 1, SST 3, BAT 1 and in boats larger than 20 m (**Figure 2**).

Table 2 presents a summary of the deviance analysis for the two stages of the Delta model, with a description for Lognormal and Binomial models. In both cases, all interactions explained more than 8% of the total deviance. Thus, all interactions were tested in the GLMM as random variables. Comparisons of models considering different combinations of interactions were conducted and the selected models for the Lognormal and Binomial components are presented in **Table 3**. Variables related to fishing operations and environment (LOA, HPB, BAT and SST) were not included in the GLMM models, since they were not significant in the binomial model and presented a contribution lower than 5% of the total variance when added to the model. The absence in the model of operational and environmental variables indicates that the variable fishing strategy probably incorporates their effects.

Diagnostic plot showed that the assumption of the lognormal distribution for the positive dataset seems to be adequate, as indicated by the QQ-plots (**Figure 3**). Residuals were homoscedastic at least in the case of the positive dataset. There were no temporal trends in the residuals on a yearly basis, so the assumption of independence of the samples was considered to be acceptable, as well (**Figure 4**).

The standardized CPUE series shows an oscillation over time, but with a relative stability, with a few peaks (1993, 2009) and drops (2006). Except for these extreme values, however, the scaled index has fluctuated from 0.5 to 1.5 throughout almost the entire period. In the most recent years, the standardized CPUE has been unusually stable, around 1.5 (1.4 to 1.6), with a drop, however, in 2016, back to a value a bit lower than 1 (0.85).

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Table 1. Number of sets and proportion of positive sets for shortfin mako shark catch of the Brazilian longline fleet from 1978 to 2016.

Year	Positive sets	Zero	Total	%Zero	%positive
1978	44	449	493	91%	9%
1979	22	460	482	95%	5%
1980	78	500	578	87%	13%
1981	29	436	465	94%	6%
1982	71	815	886	92%	8%
1983	31	580	611	95%	5%
1984	59	652	711	92%	8%
1985	63	397	460	86%	14%
1986	121	865	986	88%	12%
1987	59	868	927	94%	6%
1988	178	1036	1214	85%	15%
1989	106	924	1030	90%	10%
1990	8	108	116	93%	7%
1991	81	690	771	89%	11%
1992	70	731	801	91%	9%
1993	5	19	24	79%	21%
1994	114	790	904	87%	13%
1995	66	1013	1079	94%	6%
1996	40	679	719	94%	6%
1997	29	541	570	95%	5%
1998	335	1737	2072	84%	16%
1999	201	3730	3931	95%	5%
2000	232	4076	4308	95%	5%
2001	96	2232	2328	96%	4%
2002	77	1409	1486	95%	5%
2003	103	1910	2013	95%	5%
2004	211	2668	2879	93%	7%
2005	27	1433	1460	98%	2%
2006	57	3286	3343	98%	2%
2007	60	2467	2527	98%	2%
2008	57	1051	1108	95%	5%
2009	28	580	608	95%	5%
2010	27	727	754	96%	4%
2011	111	782	893	88%	12%
2012	131	913	1044	87%	13%
2013	22	383	405	95%	5%
2014	123	1490	1613	92%	8%
2015	50	647	697	93%	7%
2016	105	2017	2122	95%	5%
Total	**3327**	**46091**	**49418**	**93%**	**7%**

Table 2. Deviance analysis table of positive catch rates (Lognormal) and proportion of positive sets (Binomial) models.

Models	*Residual Deviance*	*Chance in Deviance*	*% of total Deviance*
Model Positive			
NULL	1762,1	NA	NA
Y	1389,3	372,9	55,0
Y + S	1351,3	38,0	5,6
Y + S + Q	1343,2	8,1	1,2
Y + S + Q + A	1342,6	0,6	0,1
*Y + S + Q + A + fLOA	1275,8	66,8	9,9
*Y + S + Q + A + fLOA + fhpb	1250,9	24,9	3,7
*Y + S + Q + A + fLOA + fhpb + fbat	1246,9	4,0	0,6
*Y + S + Q + A + fLOA + fhpb + fbat + fsst	1246,3	0,5	0,1
Y + S + Q + A + fLOA + fhpb + fbat + fsst + Y:Q	1084,7	161,6	23,9
Y + S + Q + A + fLOA + fhpb + fbat + fsst + Y:S	1153,2	-68,5	-10,1
Y + S + Q + A + fLOA + fhpb + fbat + fsst + Y:A	1189,0	-35,8	-5,3
Model binomial			
NULL	791,2	NA	NA
Y	739,8	51,5	23,8
Y + S	702,1	37,7	17,4
Y + S + Q	691,6	10,5	4,9
Y + S + Q + A	672,2	19,3	8,9
*Y + S + Q + A + fLOA	662,3	10,0	4,6
*Y + S + Q + A + fLOA + fhpb	656,0	6,3	2,9
*Y + S + Q + A + fLOA + fhpb + fbat	655,6	0,4	0,2
*Y + S + Q + A + fLOA + fhpb + fbat + fsst	645,9	9,7	4,5
Y + S + Q + A + fLOA + fhpb + fbat + fsst + Y:Q	574,9	71,0	32,8
Y + S + Q + A + fLOA + fhpb + fbat + fsst + Y:S	576,4	-1,6	-0,7
Y + S + Q + A + fLOA + fhpb + fbat + fsst + Y:A	610,5	-34,1	-15,7

* Not used in the model because they were not significant in the binomial model.

Table 3. Summary table of analyses of Delta Lognormal Mixed Model formulations for blue marlin catch rates from Brazilian pelagic longline fisheries from 1978 to 2016.

Model Positive sets	**AIC**	**BIC**	**logLik**	**LRT**
Y + S + A + Q + (1 | Y:Q)	6380,2	6667,4	-3143,1	NA
Y + S + A + Q + (1 | Y:A)	6467,2	6754,3	-3186,6	1,0
Y + S + A + Q + (1 | Y:S)	6381,1	6668,3	-3143,6	0,0
Y + S + A + Q + (1 | Y:Q) + (1 | Y:A)	6336,8	6630,0	-3120,4	0,0
Y + S + A + Q + (1 | Y:Q) + (1 | Y:S)	6250,3	6543,6	-3077,1	0,0
Model binomial	**AIC**	**BIC**	**logLik**	**LRT**
Y + S + A + Q + (1 | Y:Q)	7756,9	8022,0	-3832,4	NA
Y + S + A + Q + (1 | Y:A)	7614,4	7879,5	-3761,2	0,0
Y + S + A + Q + (1 | Y:S)	7464,5	7729,5	-3686,2	0,0
Y + S + A + Q + (1 | Y:Q) + (1 | Y:A)	7397,0	7667,9	-3651,5	0,0
Y + S + A + Q + (1 | Y:Q) + (1 | Y:S)	7229,8	7500,6	-3567,9	0,0

Table 4. Nominal and standardized index of relative abundance shortfin mako caught by Brazilian pelagic longline fishery fleet between the years of 1978 to 2016.

Year	*OBS*	*index*	*cv.index*	*lower.index*	*upper.index*	*scaled.index*	*scaled.lower*	*scaled.upper*
1978	0,050	0,020	0,339	0,007	0,034	0,311	0,105	0,517
1979	0,028	0,018	0,295	0,008	0,029	0,282	0,119	0,445
1980	0,118	0,070	0,242	0,037	0,103	1,066	0,560	1,572
1981	0,056	0,035	0,282	0,016	0,054	0,537	0,240	0,834
1982	0,064	0,060	0,253	0,031	0,090	0,925	0,467	1,383
1983	0,032	0,022	0,267	0,011	0,034	0,338	0,161	0,516
1984	0,132	0,066	0,240	0,035	0,097	1,010	0,535	1,485
1985	0,155	0,090	0,240	0,047	0,132	1,371	0,726	2,015
1986	0,122	0,073	0,260	0,036	0,110	1,119	0,549	1,689
1987	0,057	0,026	0,279	0,012	0,041	0,405	0,184	0,626
1988	0,193	0,075	0,269	0,035	0,114	1,145	0,541	1,750
1989	0,135	0,054	0,281	0,024	0,084	0,827	0,371	1,282
1990	0,091	0,057	0,401	0,012	0,102	0,874	0,187	1,561
1991	0,087	0,050	0,277	0,023	0,077	0,766	0,350	1,183
1992	0,060	0,061	0,274	0,028	0,094	0,940	0,435	1,446
1993	0,135	0,193	0,373	0,052	0,333	2,946	0,792	5,100
1994	0,134	0,103	0,264	0,050	0,156	1,577	0,761	2,393
1995	0,093	0,050	0,278	0,023	0,078	0,771	0,351	1,191
1996	0,133	0,042	0,341	0,014	0,070	0,642	0,213	1,072
1997	0,089	0,095	0,264	0,046	0,144	1,457	0,704	2,210
1998	0,133	0,054	0,255	0,027	0,081	0,823	0,412	1,235
1999	0,078	0,048	0,236	0,026	0,070	0,730	0,393	1,068
2000	0,057	0,033	0,257	0,016	0,050	0,507	0,252	0,762
2001	0,050	0,052	0,234	0,028	0,076	0,795	0,430	1,160
2002	0,067	0,057	0,248	0,029	0,085	0,877	0,451	1,303
2003	0,067	0,052	0,252	0,026	0,077	0,791	0,400	1,182
2004	0,082	0,089	0,255	0,045	0,134	1,365	0,682	2,048
2005	0,062	0,039	0,298	0,016	0,062	0,602	0,250	0,954
2006	0,065	0,014	0,309	0,005	0,022	0,212	0,084	0,340
2007	0,063	0,044	0,269	0,021	0,067	0,674	0,318	1,030
2008	0,097	0,077	0,275	0,036	0,119	1,184	0,546	1,821
2009	0,059	0,129	0,285	0,057	0,201	1,970	0,871	3,070
2010	0,078	0,048	0,332	0,017	0,079	0,737	0,257	1,216
2011	0,072	0,102	0,263	0,049	0,155	1,561	0,757	2,364
2012	0,104	0,093	0,233	0,050	0,135	1,416	0,768	2,064
2013	0,087	0,107	0,288	0,047	0,168	1,639	0,713	2,564
2014	0,084	0,094	0,243	0,049	0,139	1,437	0,752	2,121
2015	0,083	0,100	0,269	0,047	0,152	1,526	0,721	2,330
2016	0,055	0,055	0,247	0,029	0,082	0,845	0,437	1,254

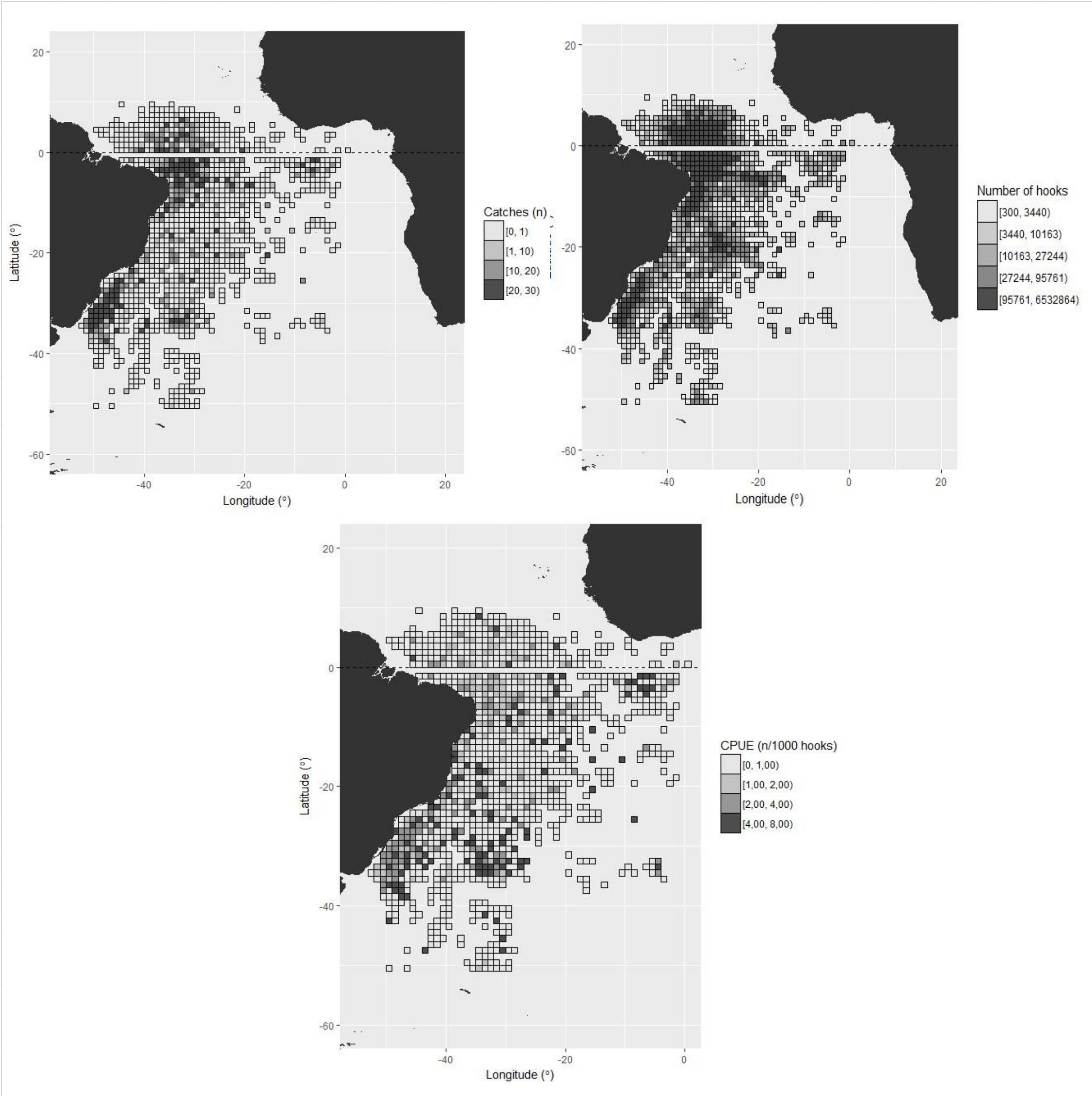

Figure 1. Distribution of catches (upper left panel), fishing effort (upper right panel), and CPUE (lower panel) of the shortfin mako shark caught by the Brazilian tuna longline fishery in the Atlantic Ocean, from 1978 to 2016.

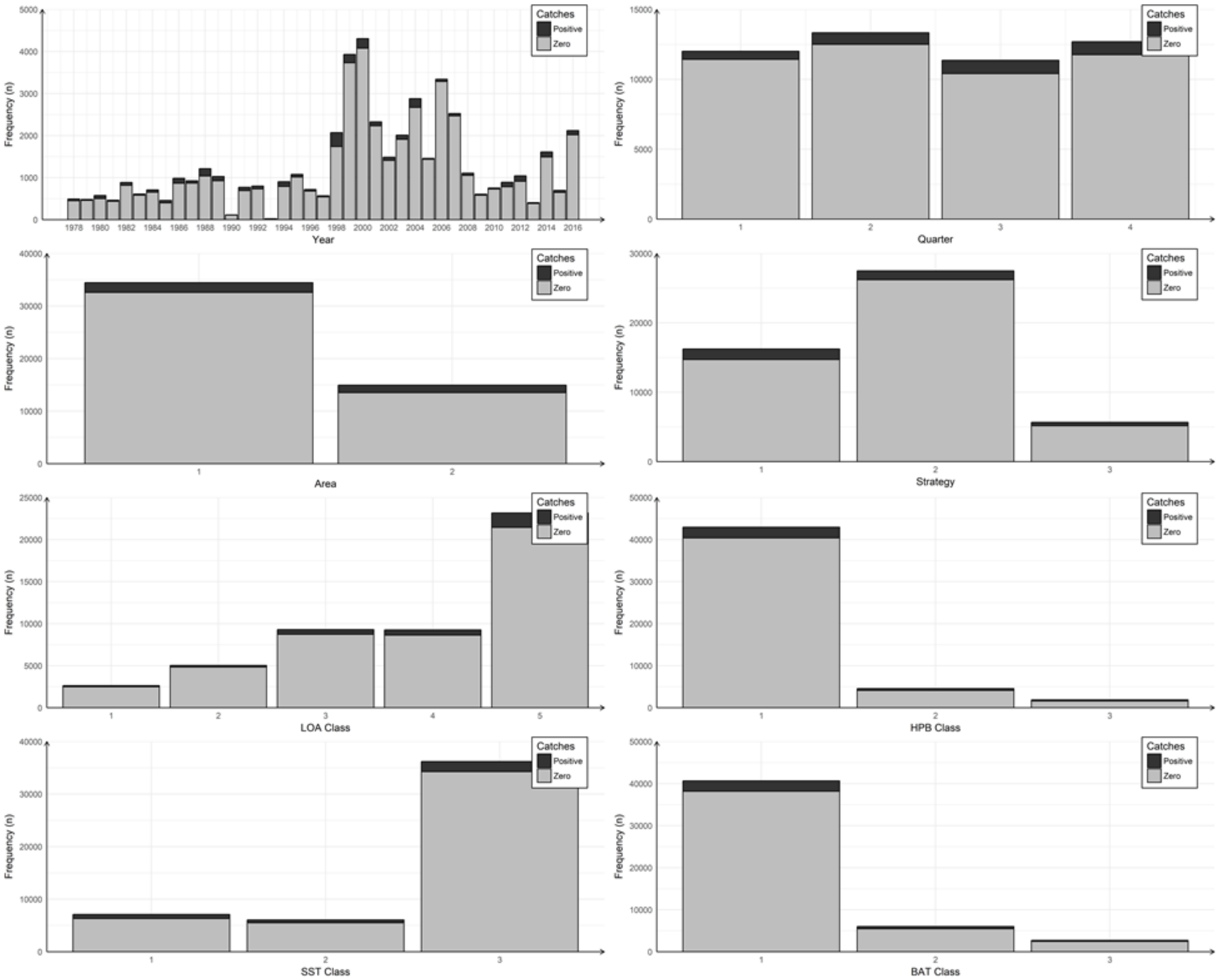

Figure 2. Proportion of positive catches and negative sets by year, quarter, area, strategy, hook per basket, SST and LOA for shortfin mako caught by the Brazilian tuna longline fleet 1978 to 2016.

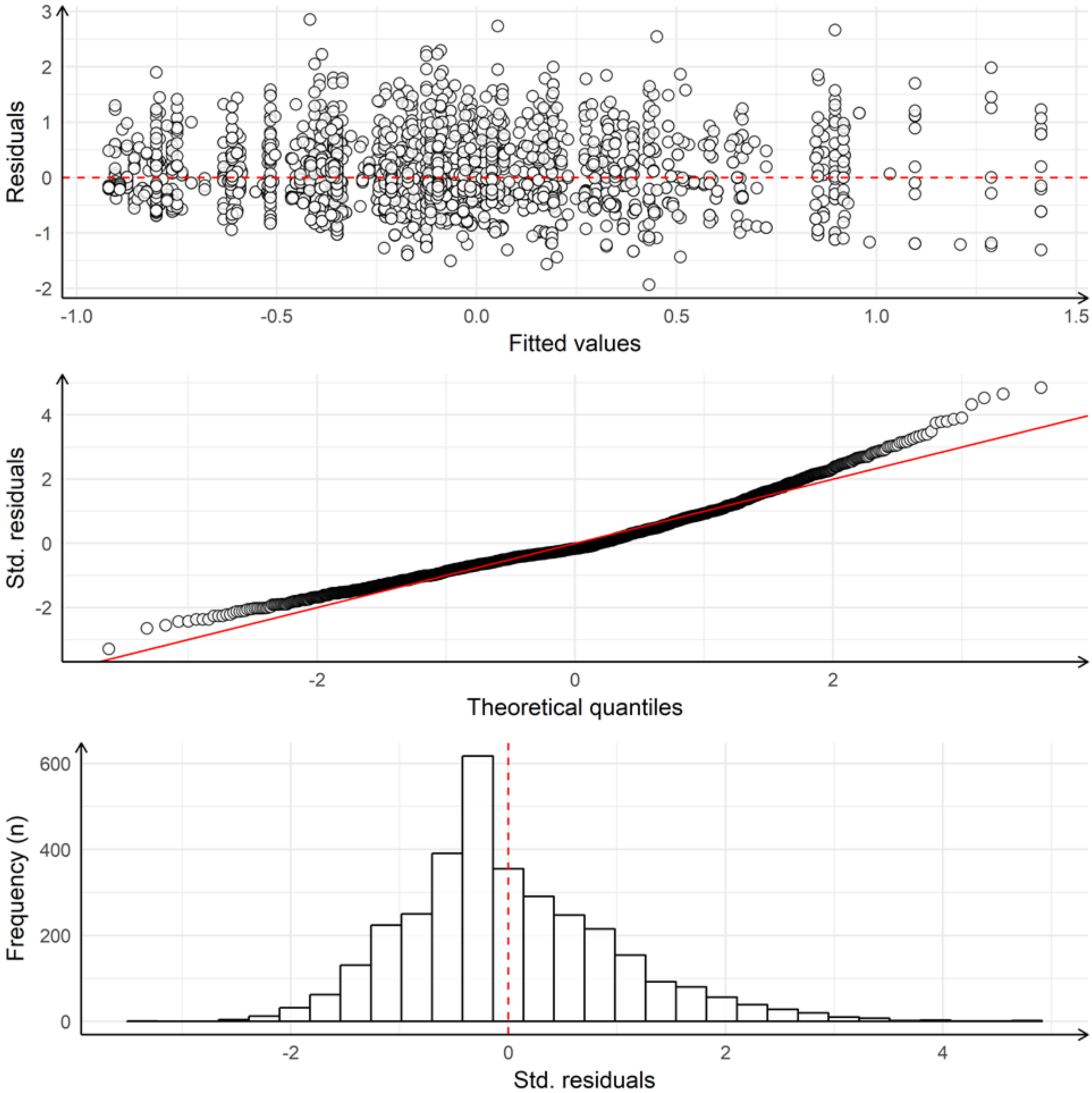

Figure 3. Residual analysis of the lognormal model final fitting of the CPUE of shortfin mako shark caught by the Brazilian tuna longline fleet, from 1978 to 2016.

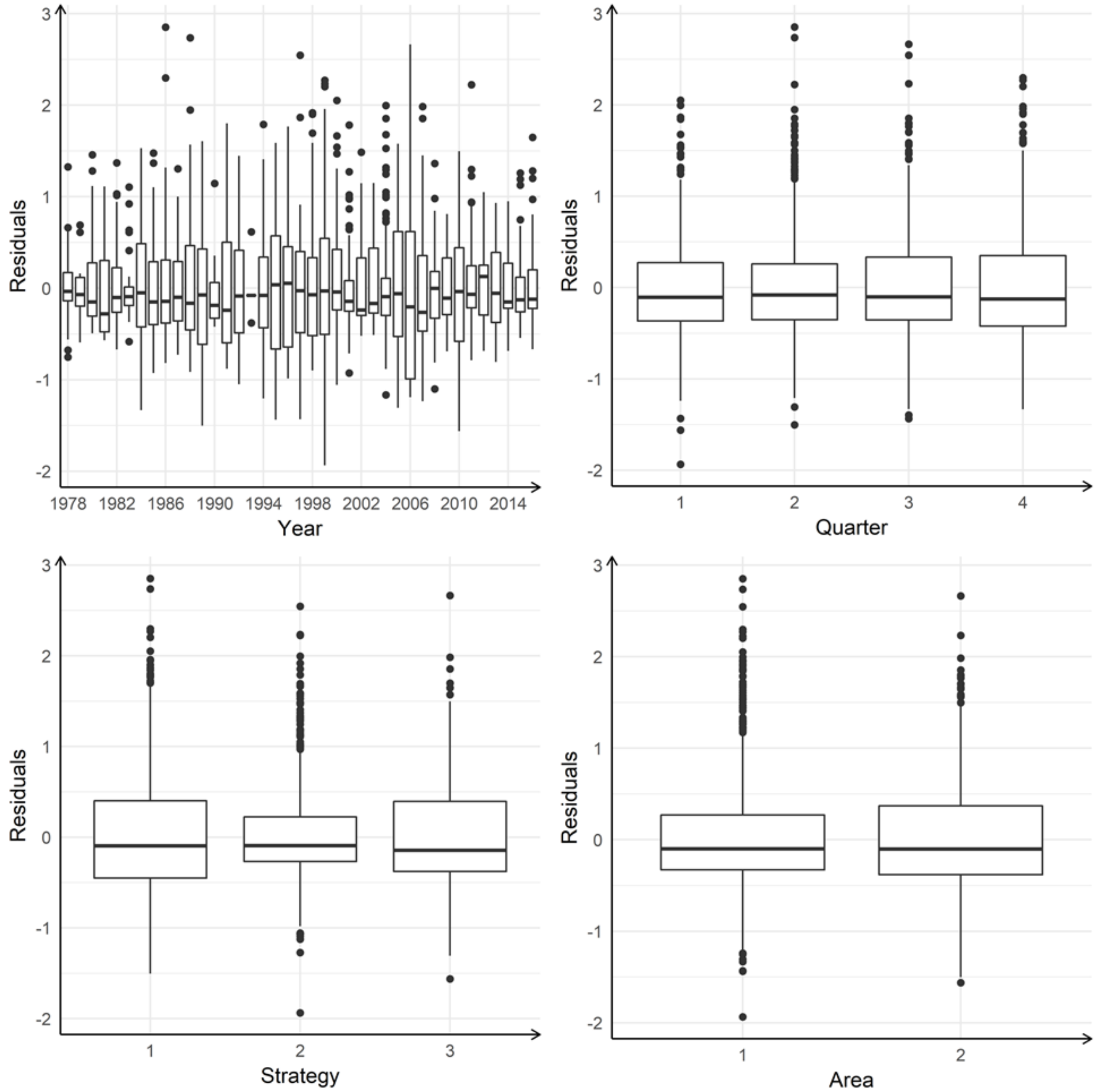

Figure 4. Residual analysis by factors of the lognormal model fitting of the CPUE of the shortfin mako shark caught by the Brazilian tuna longline fleet, from 1978 to 2016.

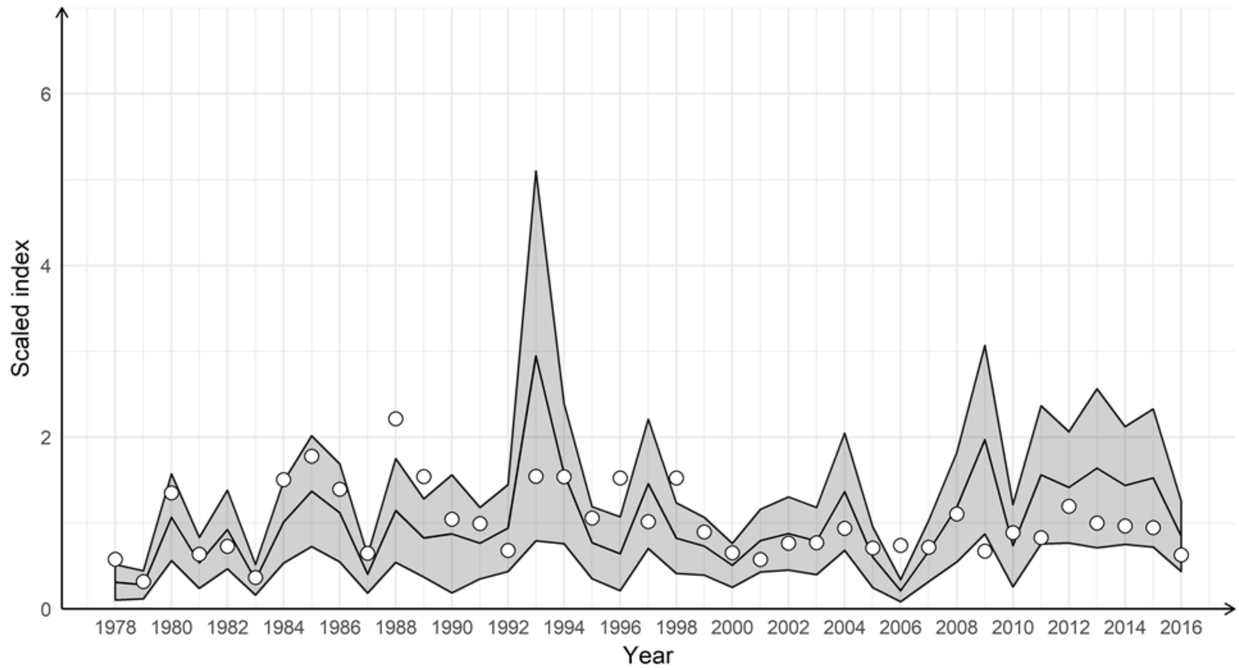

Figure 5. Catch rates (CPUE) of shortfin mako sharks for Brazilian tuna longliners, from 1978 to 2016. Central black line represents the standardized CPUE and grey area depicts the associated confidence intervals estimates (95%). White circles are the nominal catch rates.