FISHERY INDICATORS FOR SHORTFIN MAKO SHARK (*Isurus oxyrinchus*) CAUGHT BY THE PORTUGUESE PELAGIC LONGLINE FISHERY IN THE INDIAN OCEAN: CATCH, EFFORT, SIZE DISTRIBUTION AND STANDARDIZED CPUES

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SUMMARY

This working document provides fishery indicators for the shortfin mako shark captured by the Portuguese pelagic longline fishery in the Indian Ocean, in terms of catches, effort, standardized CPUEs and size distribution. The analysis was based on data collected from fishery observers, skipper's logbooks (self sampling) and official logbooks collected between 1998 and 2016. The mean sizes were compared between years and seasons (quarters). The CPUEs were analyzed for the Indian Ocean and compared between years, and were modeled with tweedie GLM models for the CPUE standardization procedure. In general, there was a large variability in the nominal CPUE trends with the standardized CPUEs relatively similar to the nominal trends. In terms of size distributions there were some spatial trends with larger specimens tending to occur in the central and eastern areas and smaller specimens in the southwest Indian Ocean. The size distribution time series showed slight increases in mean sizes through time.

KEYWORDS: Bycatch, fishery indicators, standardized CPUEs, pelagic longline fishery, shortfin mako shark, size distribution.

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1. Introduction

The Portuguese pelagic longline fishery in the Indian Ocean started in the late 1990's in the southwest area (SW-IO) and has traditionally targeted swordfish (*Xiphias gladius*, SWO). However, in certain areas and seasons this fishery also catches relatively high quantities of sharks, particularly blue shark (*Prionace glauca*, BSH) (Santos et al., 2013, 2014; Coelho et al., 2014).

The Portuguese fishing vessels operating in the IOTC area consist only of pelagic longliners setting shallow night sets targeting swordfish, traditionally ranging in size from 35 to about 50m. On recent years the mean vessel size was 40 m of total length. The number of vessels licensed increased from the beginning of the fishery in 1998 (five vessels) until 2009 (24 vessels). The number of active vessels followed a similar trend, with a peak in 2006 (17 vessels). However, during the last years, the active vessels in the convention area decreased to as low as three (in 2009, 2012), with another increase in 2013 and 2014 (Santos et al., 2013, 2014). The reasons behind this decrease of active fishing vessels in the IOTC area is related mainly with an increase of the exploitation costs, particularly the increase in fuel prices in the late 2000's, but also to piracy related problems in the SW Indian Ocean, which has traditionally been the fishing area for the Portuguese fleet (Santos et al., 2013, 2014).

Preliminary standardized shortfin mako CPUE indices for EU.Portugal were presented to the IOTC Working Party on Ecosystems and Bycatch (WPEB) in 2013 (Coelho et al., 2013). In 2014, a thorough revision was made on the modeling approach, including sensitivity analyses for the model type, using the ratio factor as a proxy for targeting, and the definition of areas in the Indian Ocean (Coelho et al., 2014).

In this work, we update fishery indicators for the shortfin mako from the EU.Portugal fleet. The objectives of this study were therefore to provide an updated description of the SMA catches by the Portuguese pelagic longline fishery operating in the Indian Ocean between 1998 and 2016, including information on the catch, effort, CPUE trends (nominal and standardized) and size distributions, that can contribute as fishery indicators for this species in the Indian Ocean.

2. Materials and methods

2.1. Data collection

A continuous effort over the last years has been made by the Portuguese Institute for the Ocean and Atmosphere (IPMA) to collect current and historical catch and effort data from the Portuguese longliners targeting swordfish in the Indian Ocean. This includes information on the catches, fishing effort in number of hooks per set and geographical location integrated from VMS data (**Table 1**). This data mining effort allowed us to recover most of the time series for the Portuguese pelagic longline fleet operating in Indian Ocean, which can now be used in this work. It should be noted that thanks to this effort, the overall coverage available and used for the BSH CPUE analysis has increased from 39.1% in 2011 (Coelho et al., 2011) to 99.7% in this work (**Table 1**).

The size data comes mainly from fishery observers onboard Portuguese pelagic longline vessels and skipper's logbooks (self sampling) voluntarily provided to IPMA. The fishery observer data is usually the most complete and detailed, apart from set data there is also the collection of individual information on the catch sizes and sex for all specimens. The skippers' logbooks have the data recorded and reported voluntarily by the vessel skippers, and usually also have detailed information regarding the catch, effort and location of the fishing sets. For some species, including the major fishery species (i.e. swordfish, tunas and sharks as blue and shortfin mako) detailed individual specimen information is usually recorded, including individual specimen sizes or weights.

Table 1: Number of fishing sets with catch, effort and location information carried out by the Portuguese pelagic longline fleet in the Indian Ocean between 1998 and 2016. The percentage of sets per year analyzed for this

paper is also indicated. Note that the 2 first years of the series (1998 and 1999) were not used for the CPUE standardization analysis due to lower effort in the Indian Ocean.

Year	Sets (n)	Sets with effort (Hooks)	Sets with locations (VMS)	Sets used for analysis (%)
1998	113	113	113	100.0
1999	147	147	147	100.0
2000	275	275	275	100.0
2001	631	631	631	100.0
2002	687	687	647	94.2
2003	575	575	575	100.0
2004	370	370	370	100.0
2005	143	143	143	100.0
2006	1801	1801	1801	100.0
2007	1325	1325	1325	100.0
2008	238	238	238	100.0
2009	482	482	482	100.0
2010	457	457	457	100.0
2011	633	633	633	100.0
2012	516	516	516	100.0
2013	1312	1312	1312	100.0
2014	863	863	863	100.0
2015	1302	1302	1302	100.0
2016	1445	1445	1445	100.0
Total	**13315**	**13315**	**13275**	**99.7**

2.2. Data analysis

The CPUE analysis was carried out using the official fisheries statistics collected by the Portuguese Fisheries authorities (DGRM), to which VMS and skippers logbook data was added. Operational data at the fishing set level was used, with the catch data referring to the total (round) weight of shortfin makos captured per fishing set. The available catch data started in 1998 and was available until 2016. However, the first 2 years of the series (1998 and 1999) were not used for the models because there was more limited information in those initial years of the fisheries. For the CPUE standardization, the response variable considered for this study was catch per unit of effort (CPUE), measured as biomass of live fish (kg) per 1000 hooks deployed. The standardized CPUEs were estimated with Generalized Linear Mixed Models (GLMMs).

Coelho et al. (2014) tested 10 sensitivity runs in blue shark CPUE standardization models, including sensitivities to the model type, the use of ratio factor and the definition of the area effects. The base case used for the present work is based on the best model approaches selected in that work. Additionally, Coelho et al. (2015a) tested targeting effects to this fleet by using ratios and cluster analysis, demonstrating that both had very similar behaviours in this particular fleet (fleet targeting mainly SWO but with blue shark as a secondary target).

As the shortfin mako shark is a bycatch from the fishery, there were considerable trips or sub-trips with zero catches that results in a response variable of CPUE=0. As these zeros can cause mathematical problems for fitting the models, a tweedie model was used, as described in Coelho et al. (2012b) for the SMA CPUE standardization for the Portuguese fleet in the Atlantic Ocean.

The tweedie model uses an approach in which only one model is fitted to the data, with that model handling the mixture of continuous positive values with a discrete mass of zeros. The tweedie distribution is part of the exponential family of distributions, and is defined by a mean (μ) and a variance (φμp), in which φ is the dispersion parameter and p is an index parameter. In this study, the index parameter (p-index) was calculated by maximum likelihood estimation (MLE).

Based on the sensitivities and tests reported by Coelho et al (2014), the covariates considered and tested in the base case models for this work were:

- Year: analyzed between 2000 and 2016;
- Quarter of the year: 4 categories: 1 = January to March, 2 = April to June, 3 = July to September, 4 = October to December;
- Area: Using a GLM Tree area stratification based on Ichinokawa & Brodziak (2010) approach;
- Ratio: based on the SWO/SWO+BSH ratio of captures;
- Interactions: first order interactions were tested and would be used if significant with the AIC criteria;

Interactions were considered and tested in the models. Specifically, interactions not involving the year factor were considered as fixed factors in the GLM, while interactions involving the year factor were considered as random variables within GLMMs.

The significance of the explanatory variables was assessed with likelihood ratio tests comparing each univariate model to the null model (considering a significance level of 5%), and by analyzing the deviance explained by each covariate. Goodness-of-fit and model comparison was carried out with the Akaike Information Criteria (AIC). Model validation was carried out with a residual analysis. The final estimated indexes of abundance were calculated by Least Square Means (marginal means), that for comparison purposes were scaled by the mean standardized CPUE in the time series.

The ratio factor was defined as the percentage of swordfish catches related to combined swordfish and blue shark catches. This ratio is in general considered a good proxy indicator of target criteria more clearly directed at swordfish versus a more diffuse fishing strategy aimed at the two main species (SWO and BSH). Moreover, it has been consistently applied to other fleets that have a similar method of operation, such as the Spanish fleet, with applications both to the Atlantic and the Indian Ocean (e.g., Ramos-Cartelle et al., 2011; Mejuto et al., 2012; Santos et al., 2013; Coelho et al., 2015a). The ratio factor was calculated for each set and then divided into ten categories using the 0.1 quantiles. However, recent works have also suggested the use of cluster analysis to define target effects as explanatory variables in the standardization models (He et al., 1997). This approach has been used with success in the Indian Ocean by Wang and Nishida (2014) for swordfish, and has also been tested in blue shark both in the North Atlantic by Coelho et al. (2015b) and Indian Ocean by Coelho et al. (2015a). In those later studies, this approach was tested as a sensitivity analysis but not selected in the final model as the EU.Portugal fleet consistently targets SWO and to a less extent BSH, and as such the information obtained with the cluster analysis is very similar to using SWO/BSH ratios.

In terms of sizes, the data was analyzed with exploratory size frequency plots and time series of the mean sizes in each stock. Size data was tested for normality with Kolmogorov-Smirnov tests with Lilliefors correction (Lilliefors, 1967) and for homogeneity of variances with Levene tests (Levene, 1960). Catch sizes were compared between years, quarters, sampling areas and stocks using non-parametric k-sample permutation tests (Manly, 2007) given that the data was not normally distributed and the variances were heterogeneous.

Data analysis for this paper was carried out in the R language for statistical computing 3.4.0 (R Core Team, 2016). The plots were designed using library "ggplot2" (Wickham, 2009) and the maps using libraries "maps" (Richard et al., 2014), "maptools" (Bivand and Lewin-Koh, 2013), "mapplots" (Gerritsen, 2014) and "shapefiles" (Stabler, 2013). Additional libraries used in the analysis included "classInt " (Bivand, 2013), "nortest" (Gross and Ligges, 2012), "car" (Fox and Weisberg, 2011), "perm" (Fay and Shaw, 2010), "doBy" (Højsgaard et al., 2014), "tweedie" (Dunn, 2014), "statmod" (Smyth et al., 2015) and "lsmeans" (Lenth, 2015).

3. Results and Discussion

3.1. Catch and effort

3.1.1. Spatial distribution of the catch and effort

The area of operation in the Indian Ocean in terms of fishing effort for the Portuguese pelagic longline fleet, for the period between 1998 and 2016, is shown in **Figure 1**, where it is possible to see that most of the effort took place in the southwest region of the Indian Ocean. However, part of the effort also takes place in more eastern areas of the South Indian Ocean.

The SMA catches are also spread throughout the Indian Ocean region, but also follow this general trend of a higher concentration in the southwest region, especially southern of South Africa (**Figure 2**).

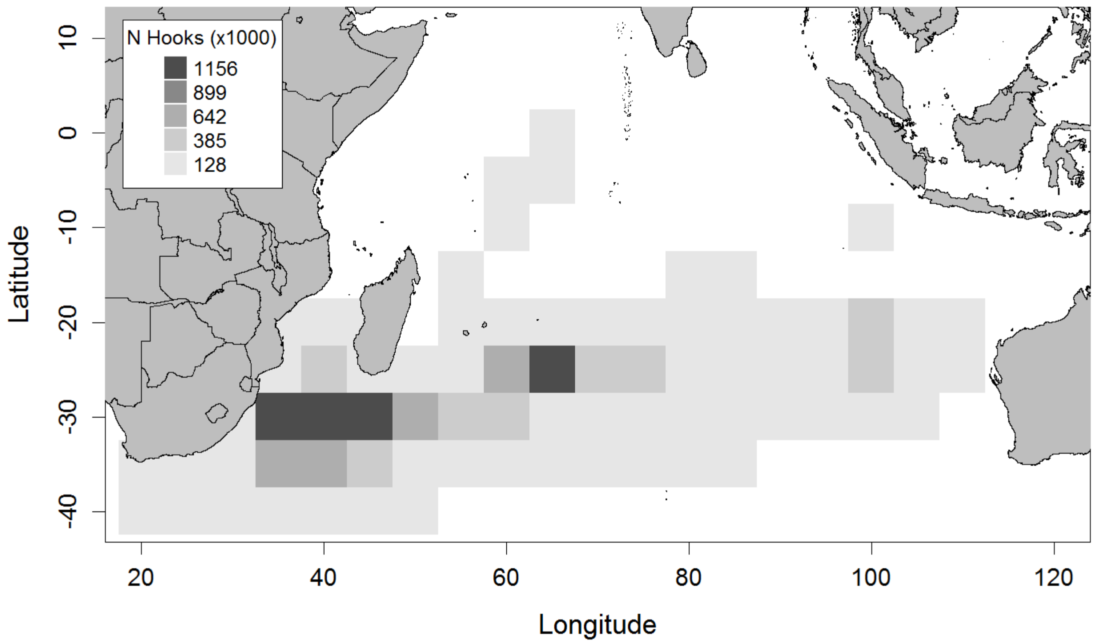

Figure 1. Effort distribution of the Portuguese pelagic longline fleet for the 1998-2016 period in the Indian Ocean. The effort is represented in 1°x1° grids with darker and lighter colors representing respectively areas with more and less effort in number of hooks.

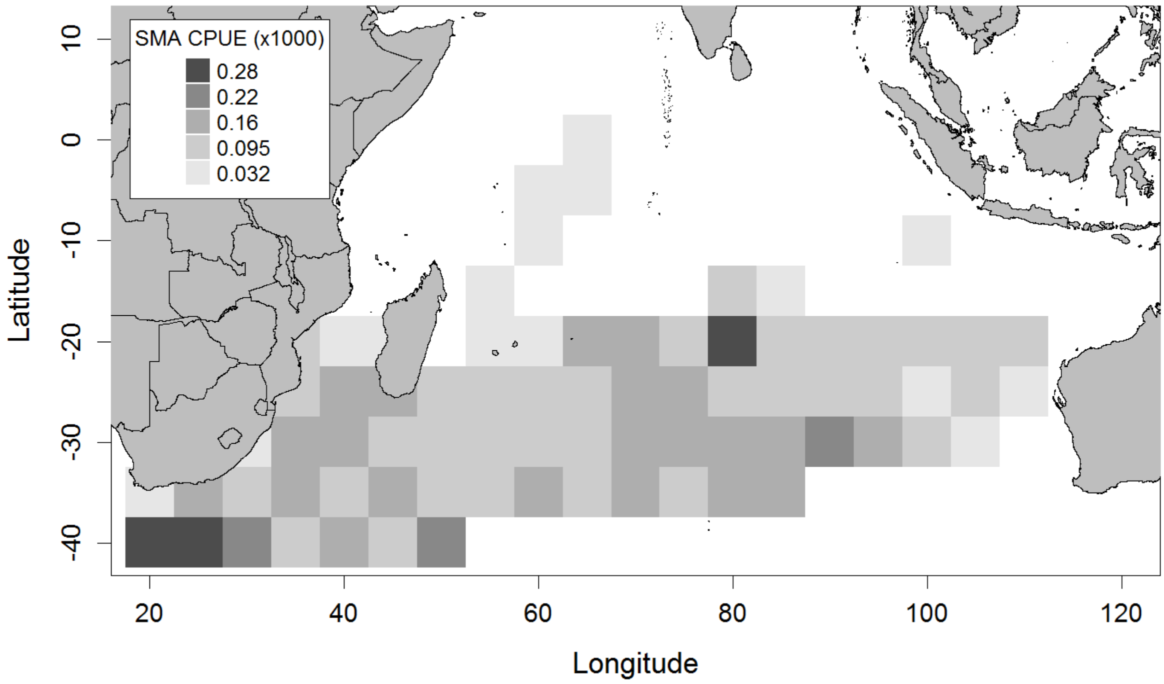

Figure 2. Distribution of SMA CPUEs in the Portuguese pelagic longline fleet for the 1998-2016 period in the Indian Ocean. The effort is represented in 5°x5° grids with darker and lighter colors representing respectively areas with more and less SMA CPUEs in biomass (kg/1000 hooks).

3.1.2. Yearly and seasonal variability in the catch and effort

The total effort of the Portuguese longline fleet in the Indian Ocean remained relatively constant between 1999 and 2004, followed by an increase during 2006-2007 and then a sharp decrease in 2008 (**Figure 3**). Since then, and for the most recent years (2009 to 2016) the effort has been increasing to values higher than in the early 2000's and closer to the 2006-2007 period (**Figure 3**).

The total shortfin mako shark catches also tended to follow this general trend, with a peak in 2006, followed by a sharp decrease in 2008, and then a more steady and progressive increase for the more recent period (**Figure** 3). In terms of ratios of swordfish compared to the swordfish + blue shark catches, the ratios were higher in the first 2 years of the time series, then tended to be lower between 2000 and 2005, followed by a higher period between 2005 and 2013, and then a decrease in 2014 (**Figure 3**).

The increase after 2005 might be a result of a change in the fishery, namely in terms of gear material, i.e. the replacement of the traditional multifilament by nylon monofilament gear which provides higher swordfish catches. Whereas, the slight decrease after 2008 is probably related by another change in the fishing gear (nylon monofilament replaced by wire leaders) and bait (mackerel alternating with squid, or instead of, in areas/periods of higher shark abundance). Several authors have demonstrated that higher blue shark catch rates are obtained when wire leaders are used (e.g., Ward et al., 2009; Vega and Licandeo, 2009; Afonso et al., 2012).

In terms of seasonality in the CPUE, and even though there was some considerable inter-annual variability, there were no major seasonal trends in the CPUEs (**Figure 4**).

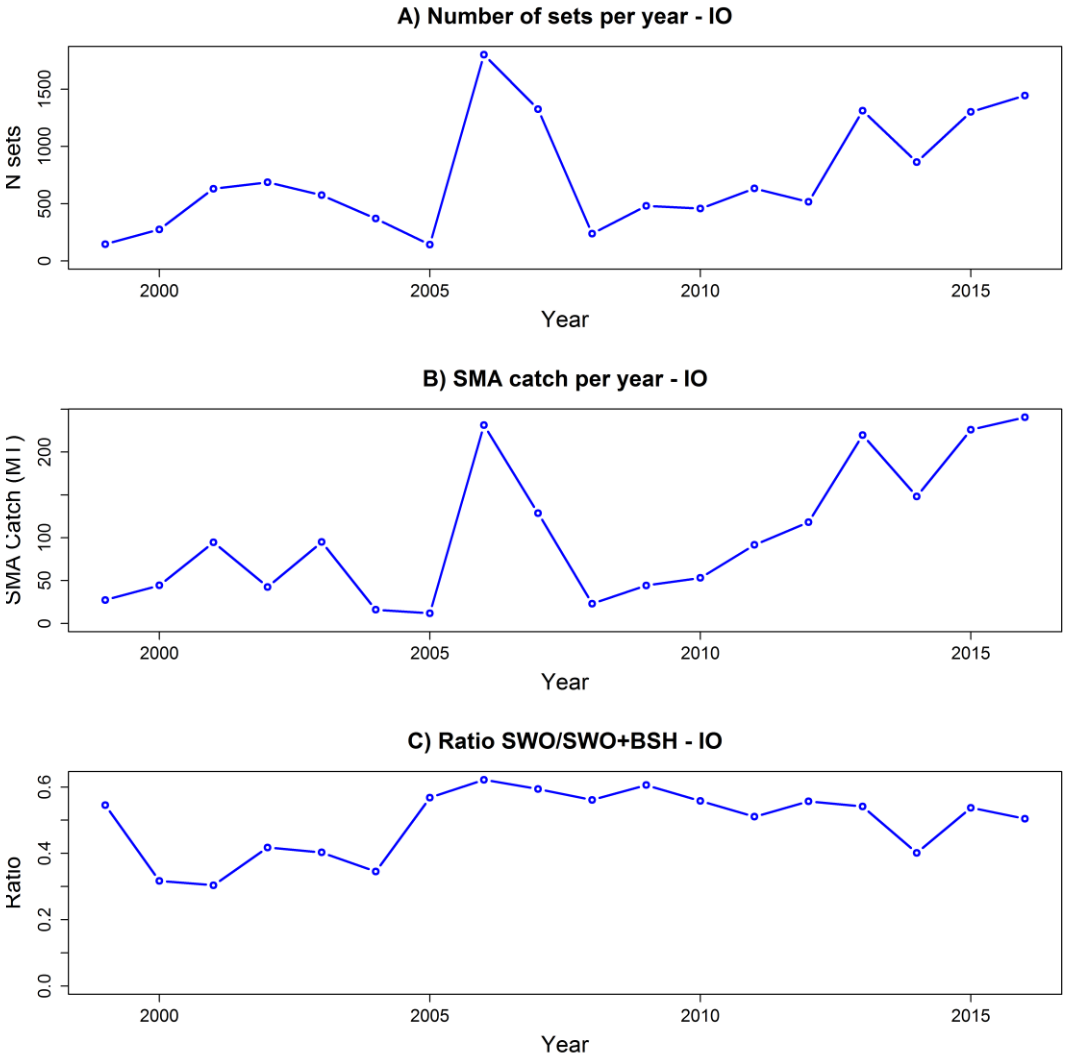

Figure 3. Descriptive plots of the total effort in sets (A), the total catch of shortfin mako shark (B), and the ratio of swordfish compared to the swordfish and blue shark catches (C) for the Portuguese longline fleet operating in the Indian Ocean.

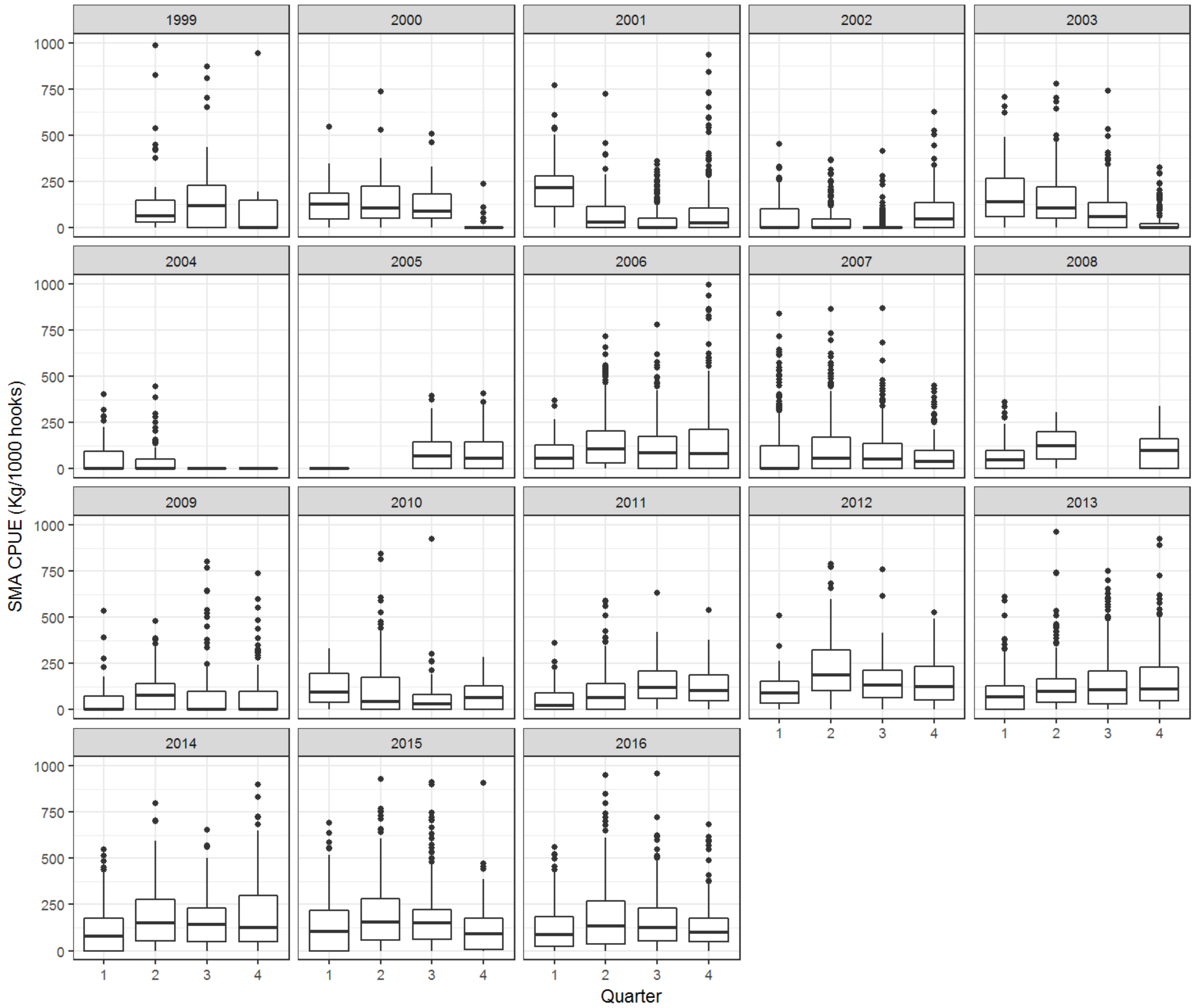

Figure 4. Quarterly shortfin mako shark CPUE (kg/1000 hooks) by the Portuguese pelagic longline fleet in the Indian Ocean, per year. In the boxplots the middle lines represents the median, the box the quartiles, the whiskers the non-outlier range and the points the outliers.

3.2. CPUE trends and standardization

3.2.1. CPUE data characteristics

The nominal time series of SMA CPUE for the Portuguese pelagic longline fleet operating in the Indian Ocean is presented in **Figure 5**. In general there was some large oscillations in the earlier period, and a general increasing trend in the more recent years ((**Figure 5**).

The percentage of fishing sets with zero catches of SMA in the Indian Ocean was relatively high, specifically 30.6% of the sets, ranging from 10.5% in 2012 to 76.2% in 2004 (**Figure 5**). In general, the higher proportions of sets with zero SMA catches were more observed in the earlier years and decreased for the more recent period (**Figure 5**).

The nominal SMA CPUE distribution was highly skewed to the right and became more normal shaped in the log-transformed scale (**Figure 6**).

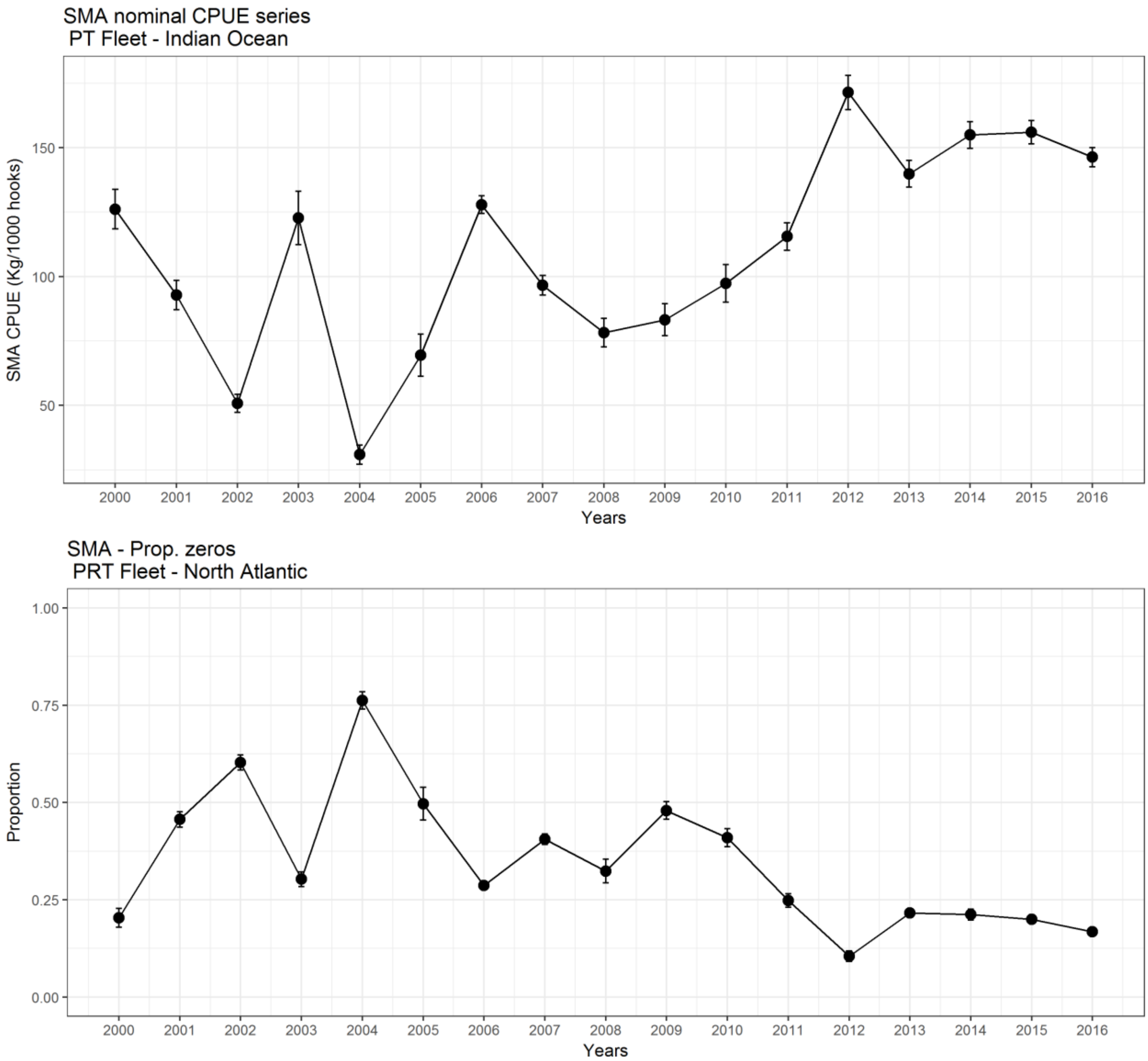

Figure 5. Nominal CPUE series (kg/1000 hooks) and proportion of zeros for SMA caught by the Portuguese pelagic longline fishery in the Indian Ocean between 2000 and 2016. The error bars refer to the standard errors.

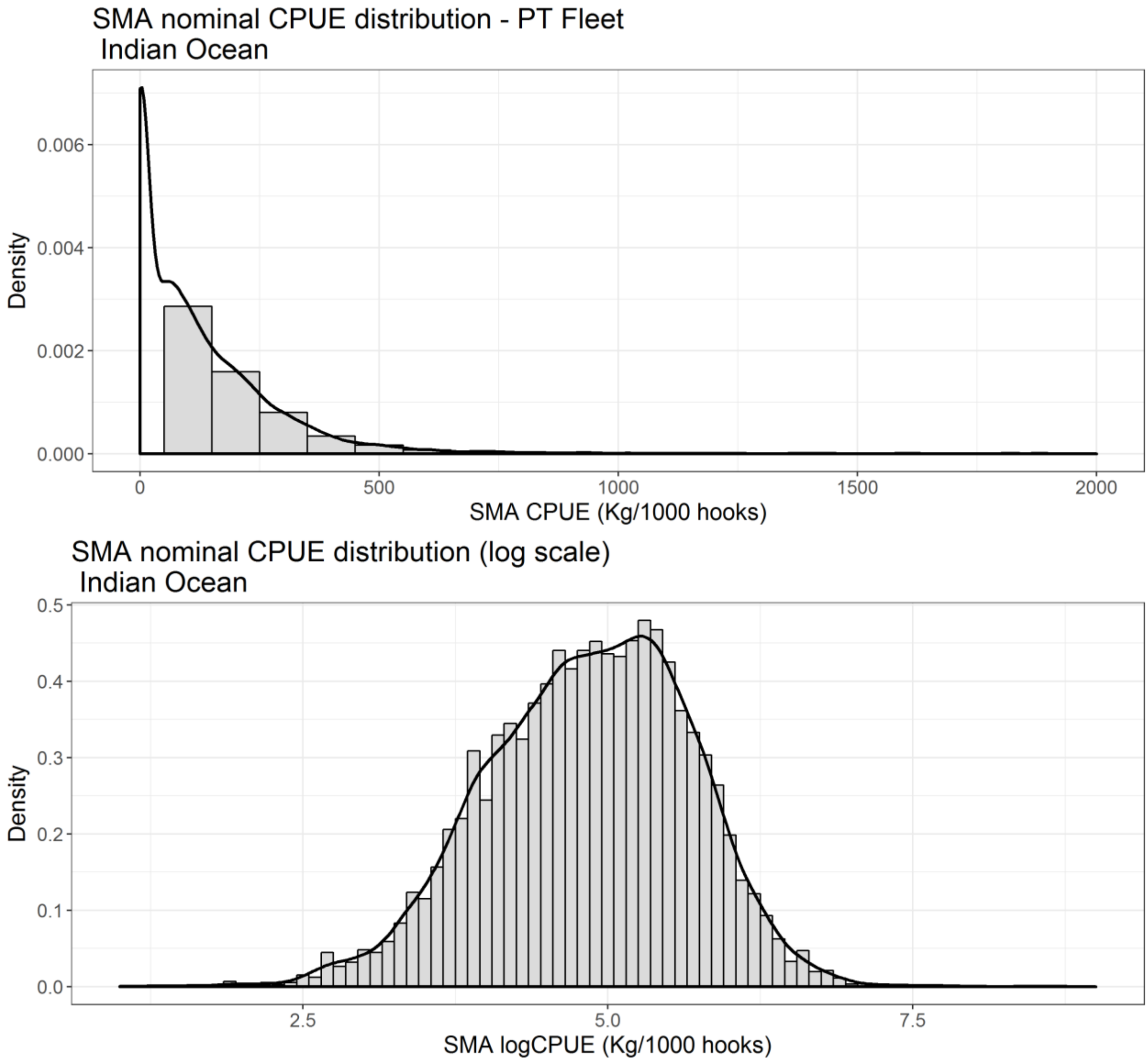

Figure 6: Distribution of the nominal shortfin mako shark CPUE captured by the Portuguese longline fleet in the Indian Ocean in non-transformed (top) and log-transformed (bottom) scales.

3.2.2. CPUE standardization models

The base case model was based on the best case as tested by Coelho et al. (2013) using the explanatory variables that were selected then. The area stratifications followed a GLM tree approach for optimization based on the AIC drop. The final areas selected (7 areas) are shown in **Figure 7**.

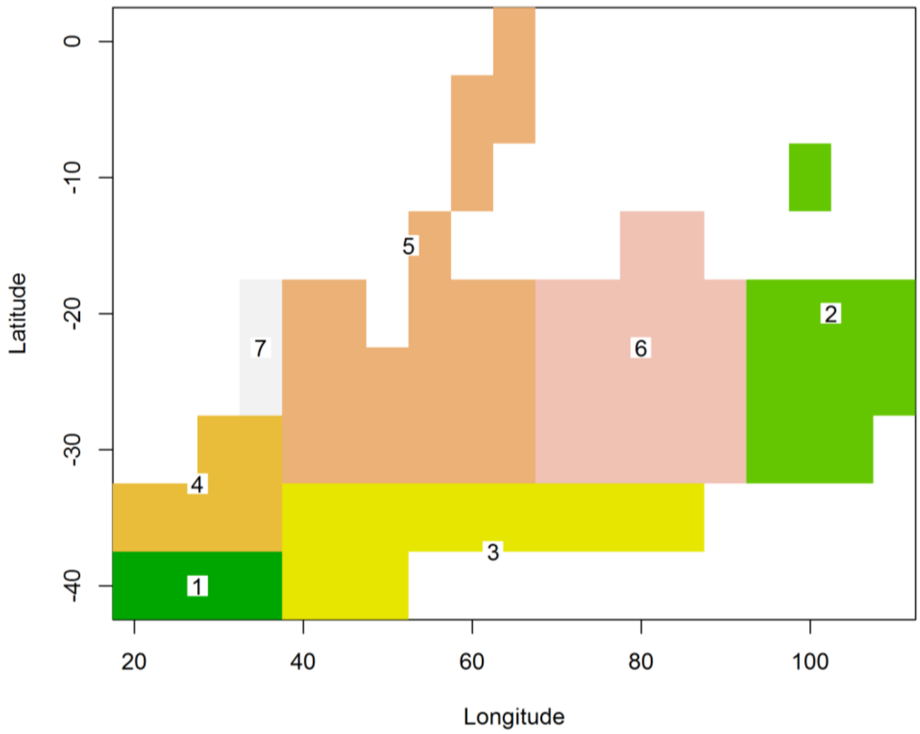

Figure 7. Spatial area stratification for the SMA CPUE captured by the Portuguese longline fleet in the Indian Ocean.

The factors that contributed most for the deviance explanation were the year, followed by the area, and then the quarter:area interaction (**Table 2**). The residual analysis showed no major problems, with the histogram of the residuals distribution being very close to a normal shape, even thought it was evident the presence of some outliers along the fitted values (**Figure 8**).

Table 2. Deviance table of the parameters used for the SMA CPUE standardization in the Indian Ocean from the Portuguese pelagic longline fleet. For each parameter it is indicated the deviance, the degrees of freedom used (Df), the residual degrees of freedom, the residual deviance, the F statistic and the significance (p-value).

	Df	Deviance	Resid. Df	Resid. Dev	F	Pr(>F)	
NULL			13014	415266			
Year	16	24213.4	12998	391053	49.4575	< 2.2e-16	***
Quarter	3	1340.9	12995	389712	14.6069	1.707e-09	***
AreaCat7.2	4	7653.9	12991	382058	62.5348	< 2.2e-16	***
RatioFac	9	2626.0	12982	379432	9.5357	1.260e-14	***
Quarter:AreaCat7.2	12	5282.4	12970	374149	14.3862	< 2.2e-16	***
Quarter:RatioFac	27	3209.7	12943	370940	3.8851	4.508e-11	***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

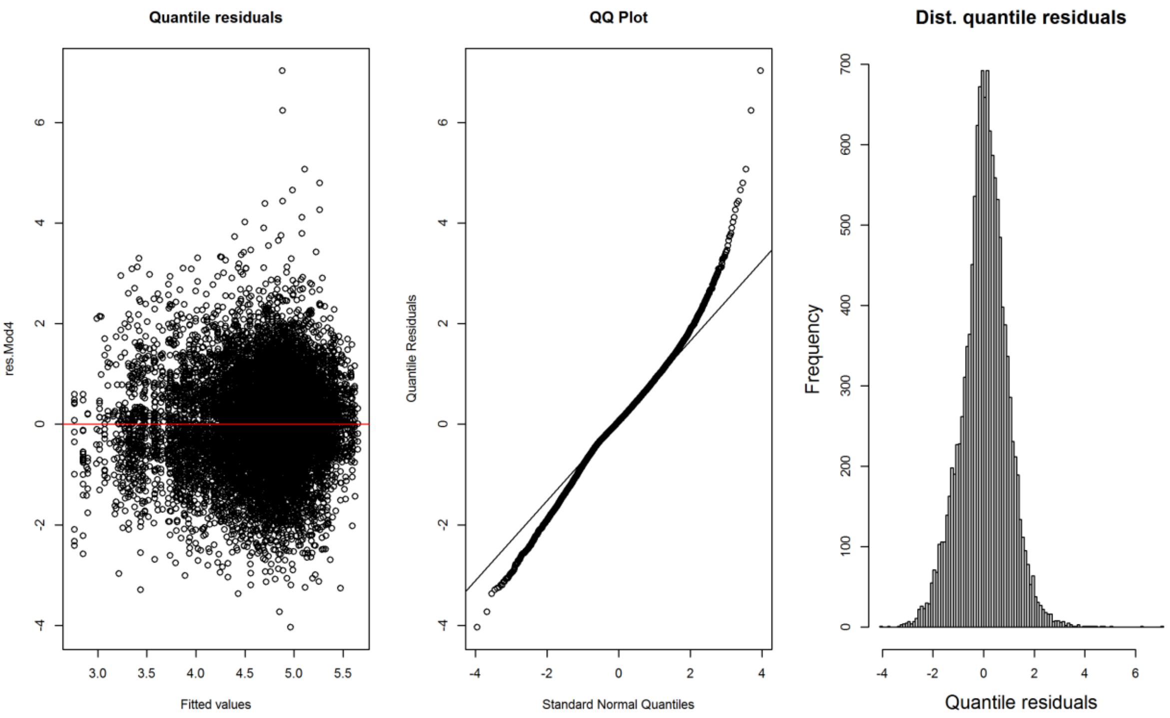

Figure 8. Residual analysis for the final Tweedie GLM model for the SMA CPUE standardization in the Indian Ocean. In the plot it is presented the histogram of the distribution of the residuals, the QQPlot and the residuals along the fitted values on the log scale.

3.2.3. SMA standardized CPUE series

Given the goodness-of-fit of the various candidate models and the comparisons from the sensitivity analysis for the target effects, as well as the previous sensitivity runs described by Coelho et al. (2013, 2014), the final standardized CPUE series recommended to be used as indicator of relative abundance for shortfin mako in shown in **Figure 9**. This model accounts for the main simple effects Year, Quarter, Area and Ratio, as well as interactions between Quarter : Area and Quarter : Ratio.

The final standardized SMA CPUE index (kg/1000 hooks) for the Portuguese pelagic longline fishery in the Indian Ocean between 2000-2016, suggested to be used as a relative abundance index, is shown in **Figure 9** and **Table 3**. On this final model, the relative index showed high variability in the earlier years until 2008, followed by a general increasing trend in the more recent years until 2016 (**Figure 9**). This index could also be used in future stock assessments for this species.

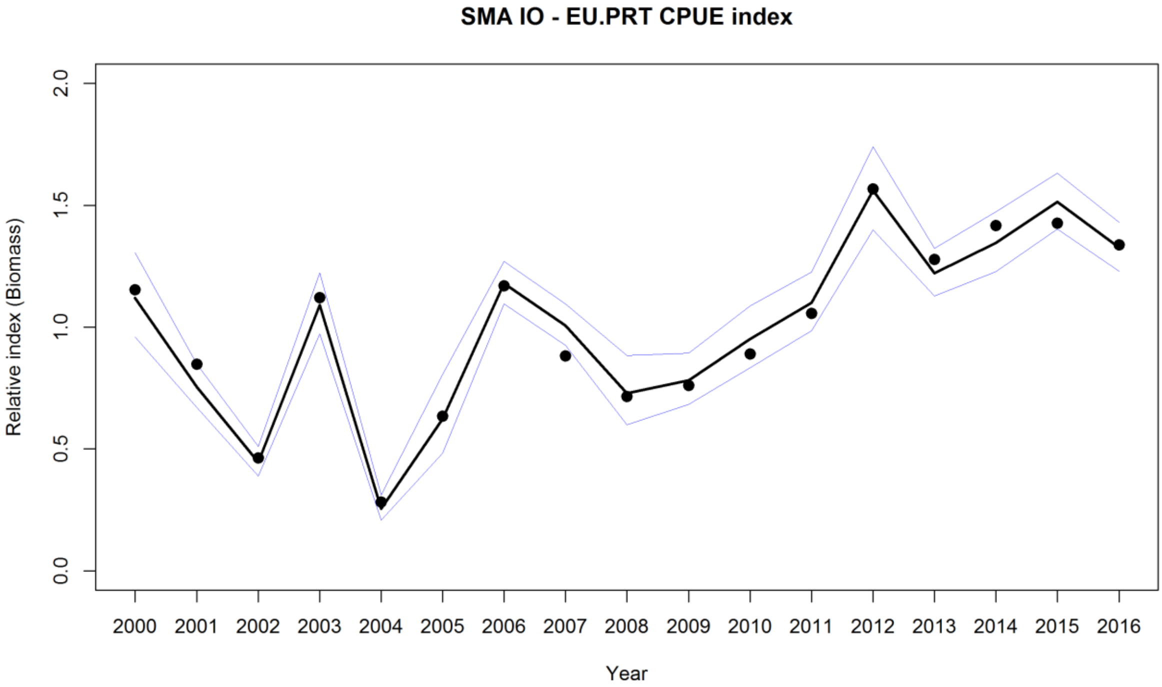

Figure 9. Standardized CPUE series for SMA captured by the Portuguese pelagic longline fleet in the Indian Ocean using a Tweedie GLM as the final selected model. The solid line refers to the standardized index and the black dots to the nominal CPUE series.

Table 3. Standardized SMA CPUE index (kg/1000 hooks) for the Portuguese pelagic longline fleet in the Indian Ocean between 2000 and 2016, for use as a relative biomass index indicator. The table includes the standardized index value, the 95% confidence intervals (CI) and the coefficient of variation (CV, %).

Year	Estimate	Upper CI (95%)	Lower CI (95%)	CV (%)
2000	109.5	127.6	94.0	28.8
2001	73.8	83.0	65.6	33.5
2002	43.6	49.9	38.1	39.0
2003	106.6	119.6	95.1	31.2
2004	24.9	30.5	20.3	44.0
2005	61.1	78.9	47.3	34.7
2006	115.4	124.3	107.1	35.7
2007	98.5	107.1	90.6	34.5
2008	71.2	86.4	58.7	33.8
2009	76.4	87.4	66.9	33.3
2010	93.1	106.4	81.5	32.2
2011	107.6	119.9	96.5	31.0
2012	152.6	170.2	136.9	28.1
2013	119.5	129.5	110.3	32.9
2014	131.6	144.1	120.2	30.3
2015	148.1	159.7	137.3	31.0
2016	129.7	140.0	120.3	32.7

3.3. Size distribution and trends

Size data for shortfin mako sharks was available for 2,690 specimens, with the sizes ranging between 64 and 350 cm FL. Of those, sex specific information was available on 1,487 specimens. The size and sex data was collected exclusively from fishery observers and the self-sampling program between 2011 and 2016.

The size distribution data was not normally distributed (Lilliefors test: D = 0.065, p-value < 0.001) and there was heterogeneity of variances between sexes (Levene test: F = 58.76; df = 1; p-value < 0.001), years (Levene test: F = 20.242; df = 5; p-value < 0.001), and quarters (Levene test: F = 19.71; df = 3; p-value < 0.001). Significant differences in the size distributions were detected between years (Permutation test: chi^2 = 346.04; df = 5; p-value < 0.001), quarters (Permutation test: chi^2 = 16.76; df = 3 p-value < 0.001) and sex (Permutation test: chi^2 = 284.58; df = 1, p-value < 0.001).

Mapping the catch by size classes seems to indicate that the smaller specimens occur mostly in more western waters closer to mainland Africa, in the southwest Indian Ocean, while the larger specimens seems to occur more in the central south Indian Ocean (**Figure 10**).

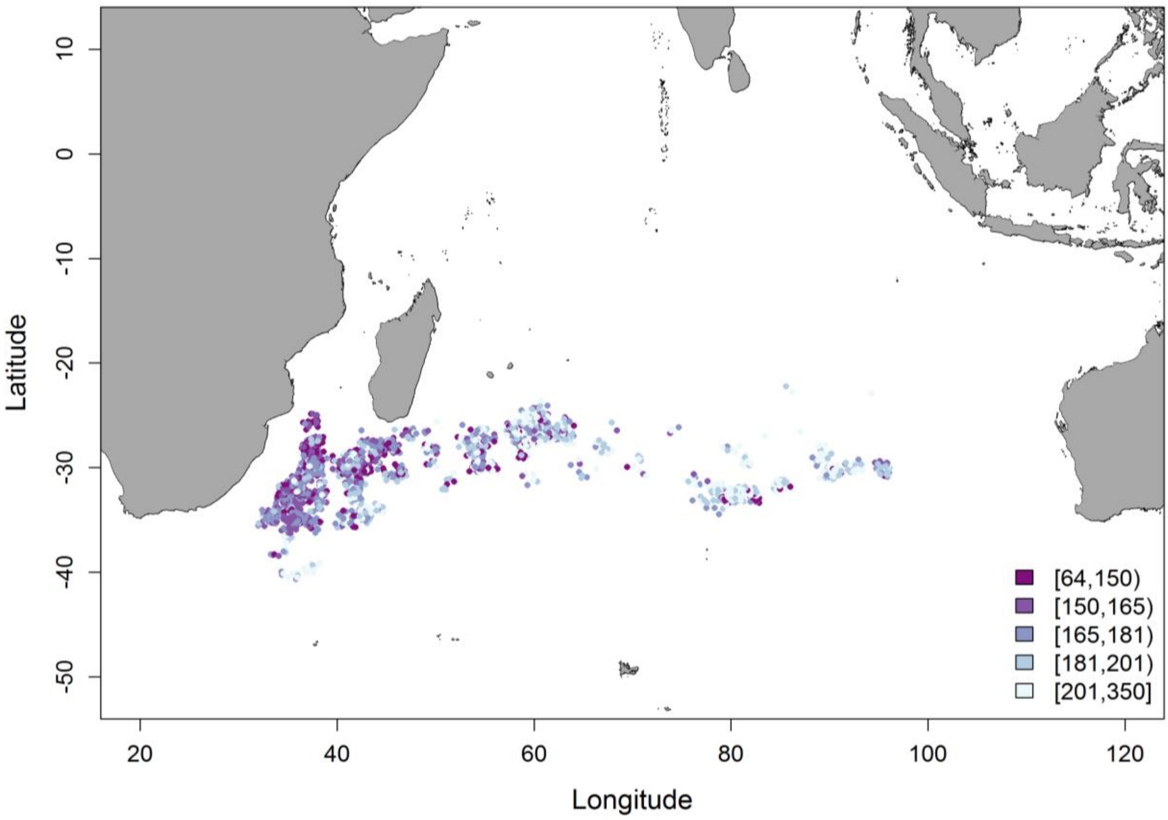

Figure 10. Distribution of the size samples of SMA from the Portuguese pelagic longline fleet in the Indian Ocean for the 2011-2016 period. The points are jittered by up to 0.5 degrees Lat and 0.5 degrees Long to facilitate visualization of spatially overlapped points.

There was some considerable variability observed in the size frequency distribution of shortfin mako sharks along the longitude gradient in the south Indian Ocean. In areas closer to Africa the size distribution were smaller specimens, and the sizes tended to be larger for more eastern longitudes in the central Indian Ocean (**Figure 11**). However, in this later area, there was also the concentration of smaller specimens (**Figure 11**). This is an issue that will need further investigation in the future, in order to full understand the spatial dynamics of this species in the Indian Ocean.

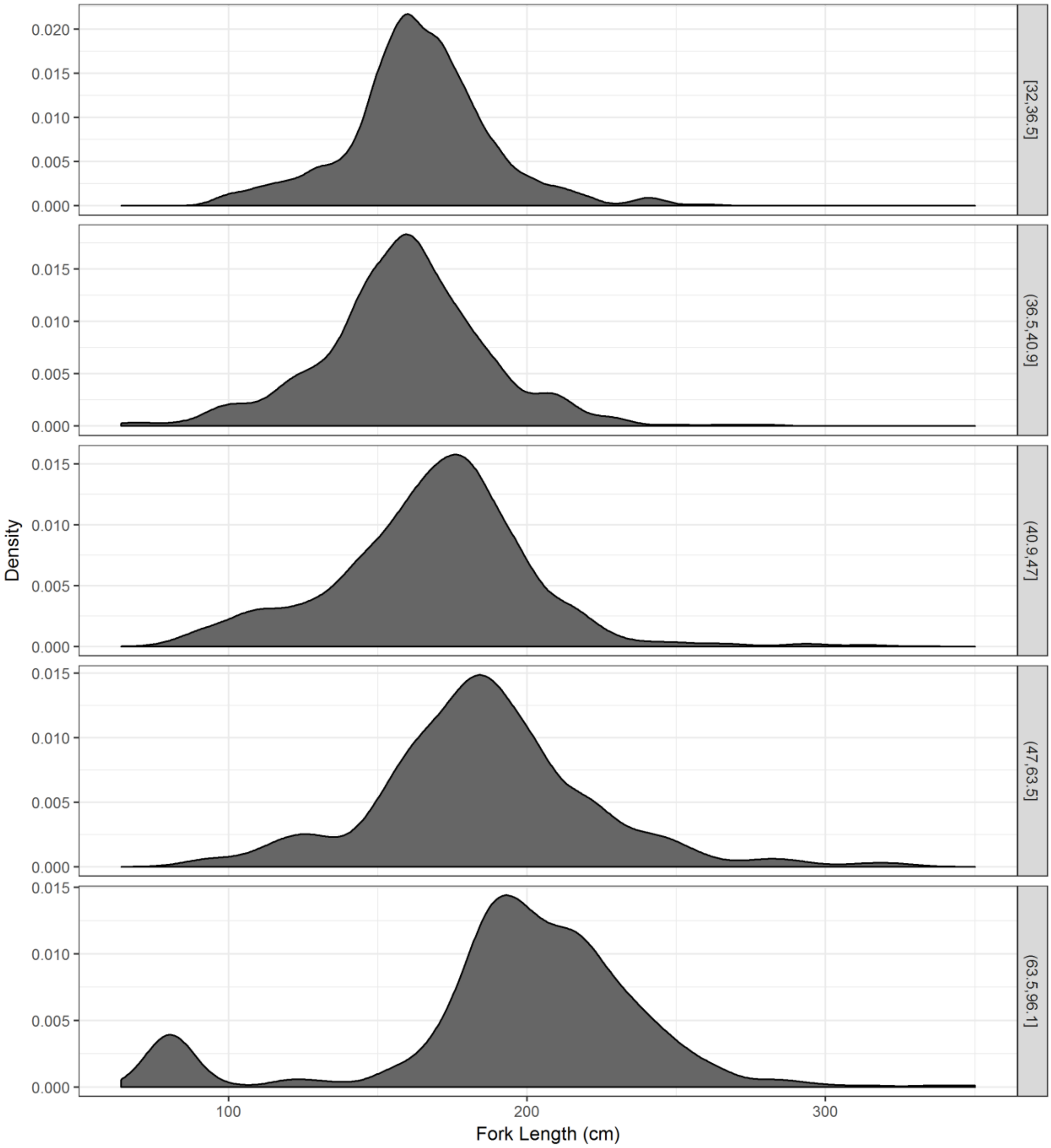

Figure 11. Size-frequency distributions of SMA caught by the Portuguese fleet in the IOTC along the longitude gradient in the South Indian Ocean, between 2011-2016.

The size frequency distribution and time series trends of SMA captured by the Portuguese fleet in the Indian Ocean was mostly stable in 2011 and 2012, and then increased between 2013 and 2015, followed by a slight decrease in 2016 (**Figures 12 and 13**). However, this trend seems to be mostly related with the fishing operations areas of the fleet, than in 2011 and 2012 was operating mainly in the southwest Indian Ocean, and then in the more recent years started to expand more to the central and eastern regions (**Figure 14**).

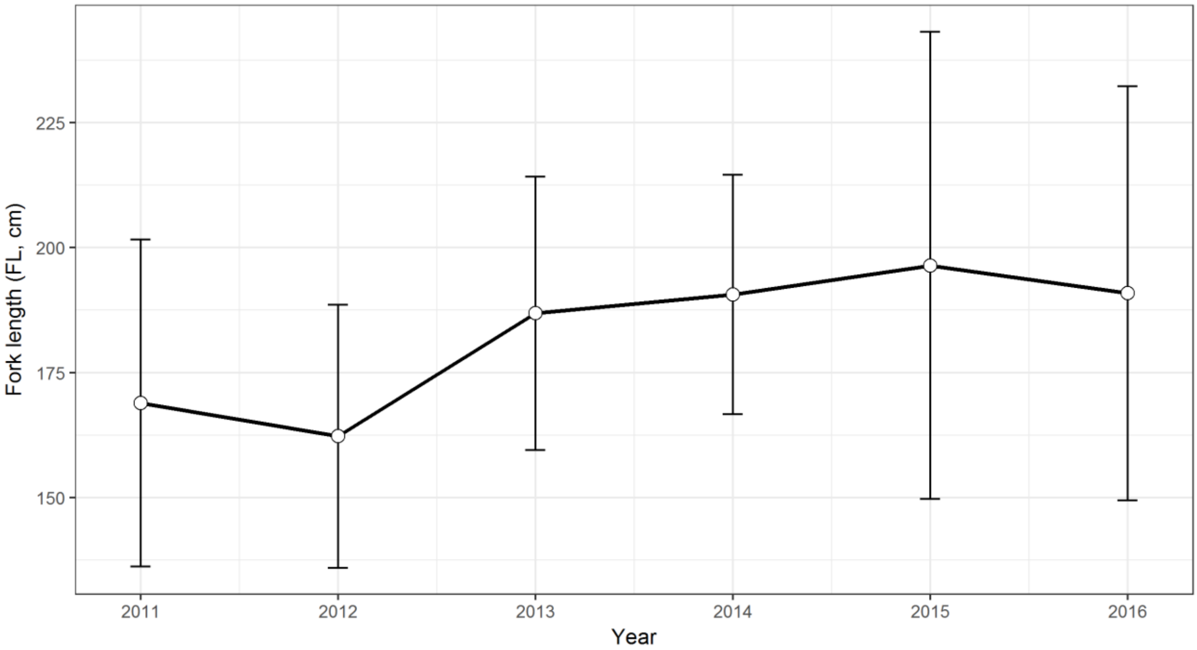

Figure 12. Time series of the mean sizes of SMA caught by the Portuguese pelagic longline fleet in the IOTC area. The error bars are ± 1 standard deviation.

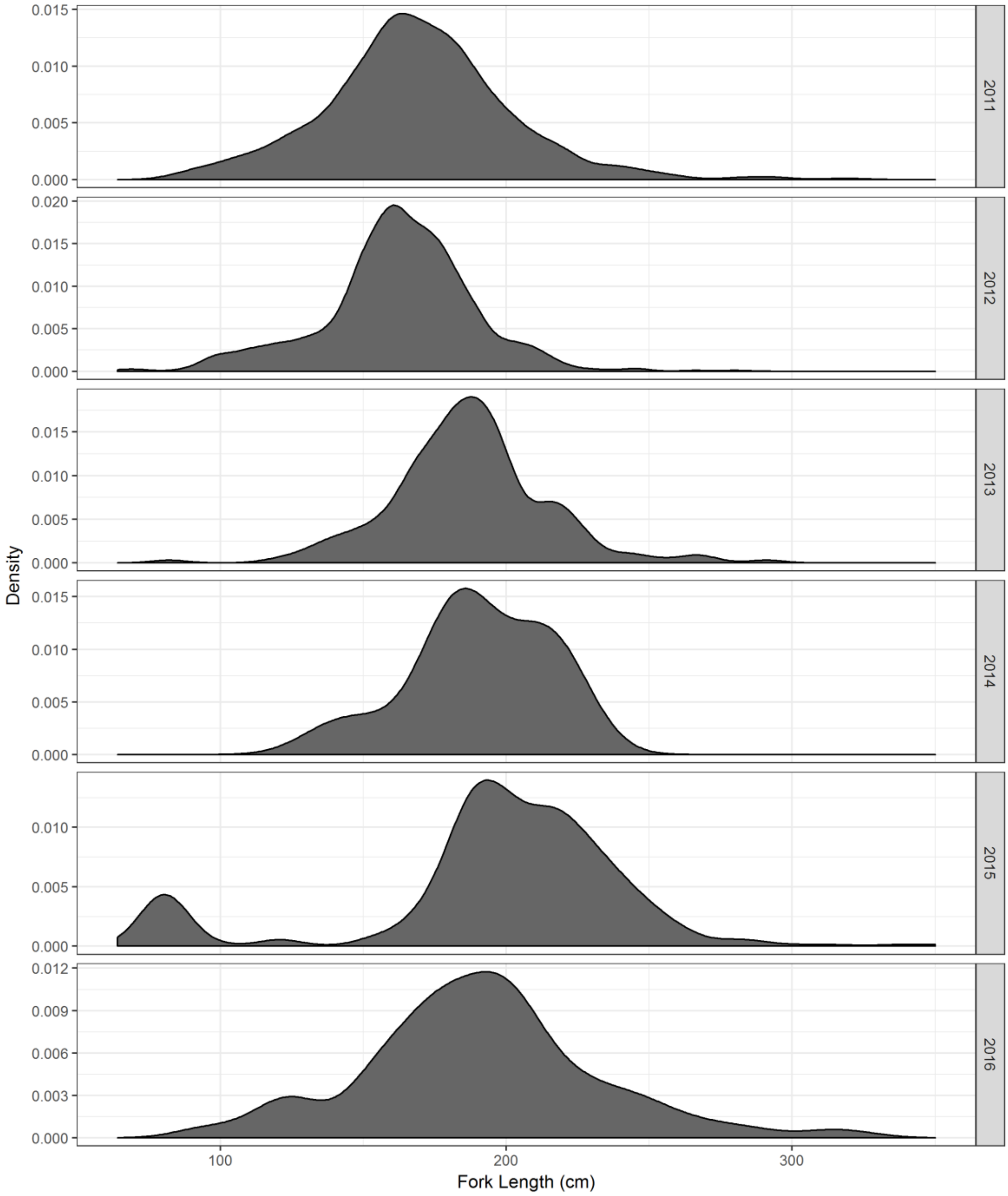

Figure 13. Size frequency distribution of SMA caught by the Portuguese pelagic longline fleet in the IOTC area, between 2011 and 2016.

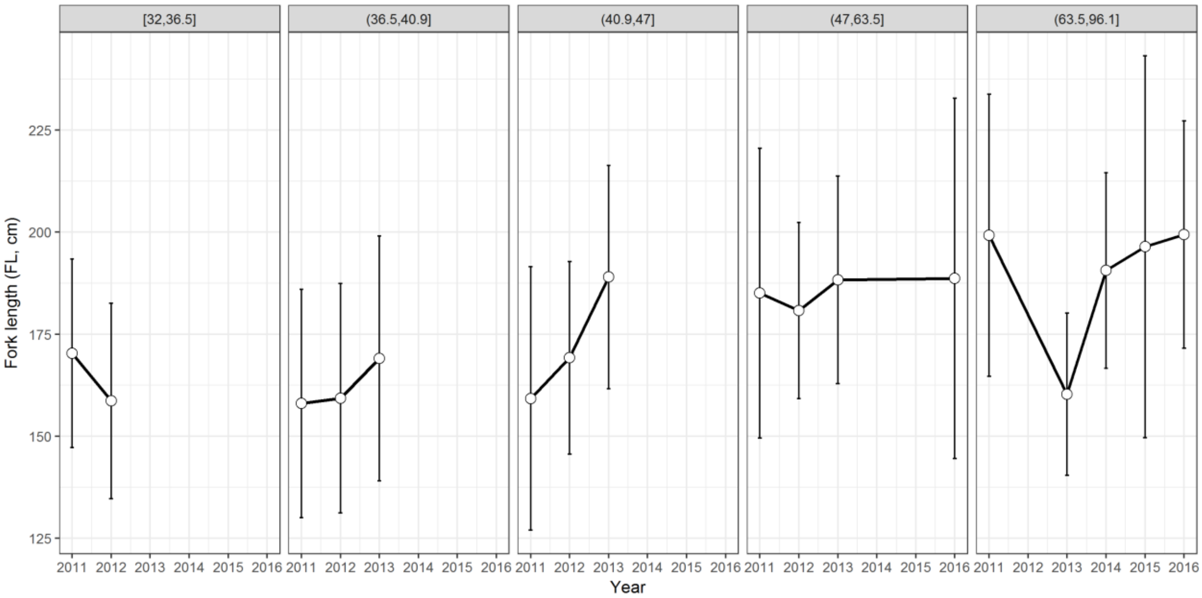

Figure 14. Time series of the mean sizes of SMA caught by the Portuguese pelagic longline fleet in the IOTC area by longitude class. The error bars are ± 1 standard deviation.

In conclusion, this means that the interpretation of the SMA size distributions and time series is limited in terms of fishery indicator, as in this case the trends are much more reflective of the fleet patterns rather than eventual changes in the size distribution of the population.

Future work to address this issue could include:

1) Create a standardized size distribution series accounting for fishery dependent effects.

2) Start collaborative work to include data from other fleets and fisheries, much like was recently done in collaborative scientific work for BSH in the ICCAT and IOTC areas (see Coelho et al, 2017 - *In press*).

4. Acknowledgments

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