UPDATED FISHERY INDICATORS FOR SHORTFIN MAKO SHARK (*Isurus oxyrinchus*) CAUGHT BY THE PORTUGUESE PELAGIC LONGLINE FISHERY IN THE INDIAN OCEAN, BETWEEN 1999-2022: CATCH, EFFORT AND STANDARDIZED CPUES

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SUMMARY

This working document provides updated fishery indicators for the shortfin mako shark captured by the Portuguese pelagic longline fishery in the Indian Ocean, in terms of catches, effort and standardized CPUEs. The analysis was based on data collected from fishery observers, skipper's logbooks (self-sampling) and official electronic logbooks collected between 1999 and 2022. 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 CPUE trends, especially in the earlier years, with the standardized CPUEs relatively similar to the nominal trend. There was a general increasing trend until 2012, followed by a more stable period for the more recent years, between 2012-2022.

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

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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) and in a smaller proportion and frequency the shortfin mako (*Isurus oxyrinchus*, SMA) (e.g, Santos et al., 2013, 2014; Coelho et al., 2014).

The Portuguese fishing vessels operating in the IOTC area consist of pelagic longliners, setting shallow night sets targeting swordfish. Those tend to be large sized vessels, traditionally ranging in size from 35 to about 50m. 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 only two or three in recent years.

Standardized shortfin mako CPUE indices from EU.Portugal have been presented to the IOTC Working Party on Ecosystems and Bycatch (WPEB) in 2013, 2017 and 2020 (Coelho et al., 2013, 2017, 2020). In 2014, a thorough revision was made on the modeling approach, including sensitivity analyses for the model type, using the ratio SWO/SWO+BSH factor as a proxy for targeting, and the definition of areas in the Indian Ocean (Coelho et al., 2014), and a similar approach has been carried out since then.

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 1999 and 2022, including information on the catch, effort and CPUE trends, including providing a standardized CPUE for consideration in the upcoming 2024 SMA IOTC stock assessment.

2. Materials and methods

2.1. Data collection

Data used includes information on catches, fishing effort in number of hooks per set and geographical location integrated from VMS data and covers close to 100% of the entire fishery (**Table 1**).

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 1999 and 2022 and used for this analysis. Note that the first year of the series (1999) was not used for the CPUE standardization due to low effort and poor representation of the data.

Year	Number of sets (N)
1999	147
2000	275
2001	631
2002	687
2003	575
2004	370
2005	143
2006	1801
2007	1325
2008	238
2009	482

2010	457
2011	633
2012	516
2013	1312
2014	863
2015	1302
2016	1449
2017	1413
2018	833
2019	767
2020	564
2021	584
2022	532
Total	**17899**

2.2. Data analysis

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 1999 and was available until 2022. However, the first 1 year of the series (1999) was not used in the models because there was limited information in that initial year. 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 Models (GLMs).

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 result in a response variable of CPUE=0. As these zeros can cause mathematical problems when fitting the models, a tweedie model was used, as described in Coelho et al. (2012b and 2017) 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 2022;
- 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, in this case with 7 areas selected;
- 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 and by using variable influence plots and 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, a work from (He et al., 1997) suggested the use of cluster analysis to define target effects as explanatory variables in the standardization models. 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.

Data analysis for this paper was carried out in the R language for statistical computing 3.6.1 (R Core Team, 2019). 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), "lsmeans" (Lenth, 2015) and “influ” (Bentley, 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 1999 and 2022, 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 CPUEs are also spread throughout the Indian Ocean, but also follow the general trend of a higher concentration in the southwest region, especially southern of South Africa (**Figure 2**).

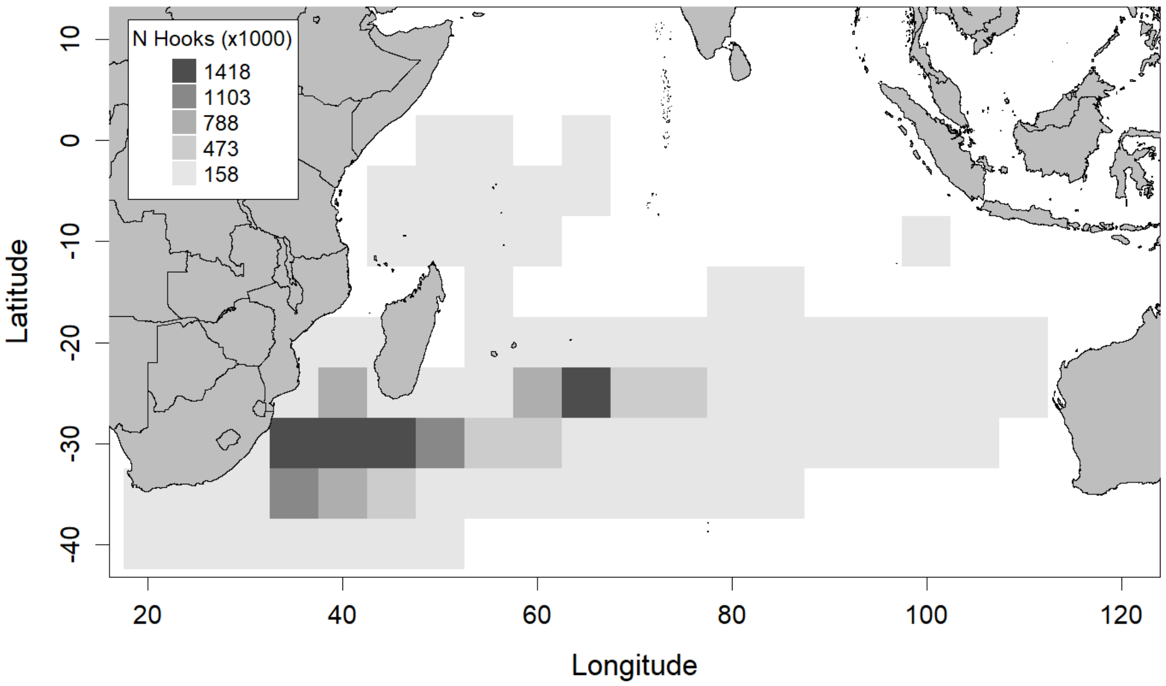

Figure 1. Effort distribution of the Portuguese pelagic longline fleet for the 1999-2022 period in the Indian Ocean. The effort is represented in 5°x5° grids with darker colors representing areas with more effort in number of hooks.

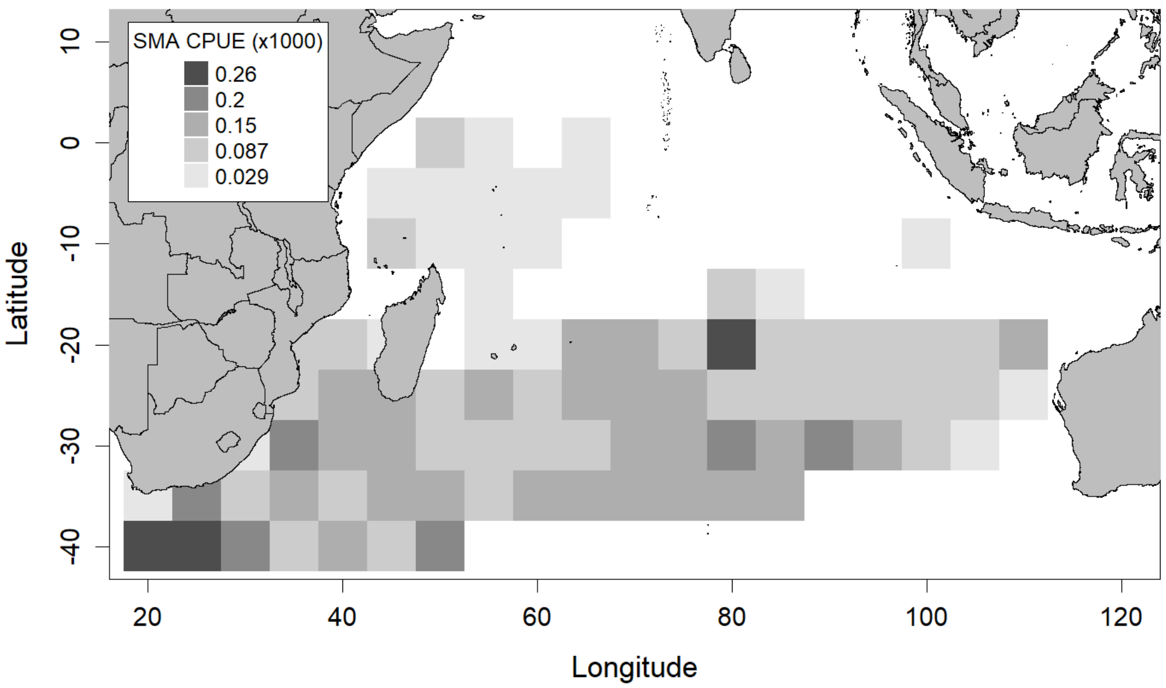

Figure 2. Distribution of SMA CPUEs in the Portuguese pelagic longline fleet for the 1999-2022 period in the Indian Ocean. The catch-per-unit-of-effort is represented in 5°x5° grids with darker colors representing areas with higher SMA CPUEs in biomass (kg/1000 hooks).

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 3A**). Since then, and for the most recent years (2009 to 2022) the effort has been increasing to values higher than in the early 2000's and closer to the 2006-2007 period (**Figure 3A**). 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 until 2015, followed by stable period for the more recent years (**Figure** 3B).

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 3C). The increase after 2004 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 2009 is probably related to 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; Santos et al., 2024).

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**).

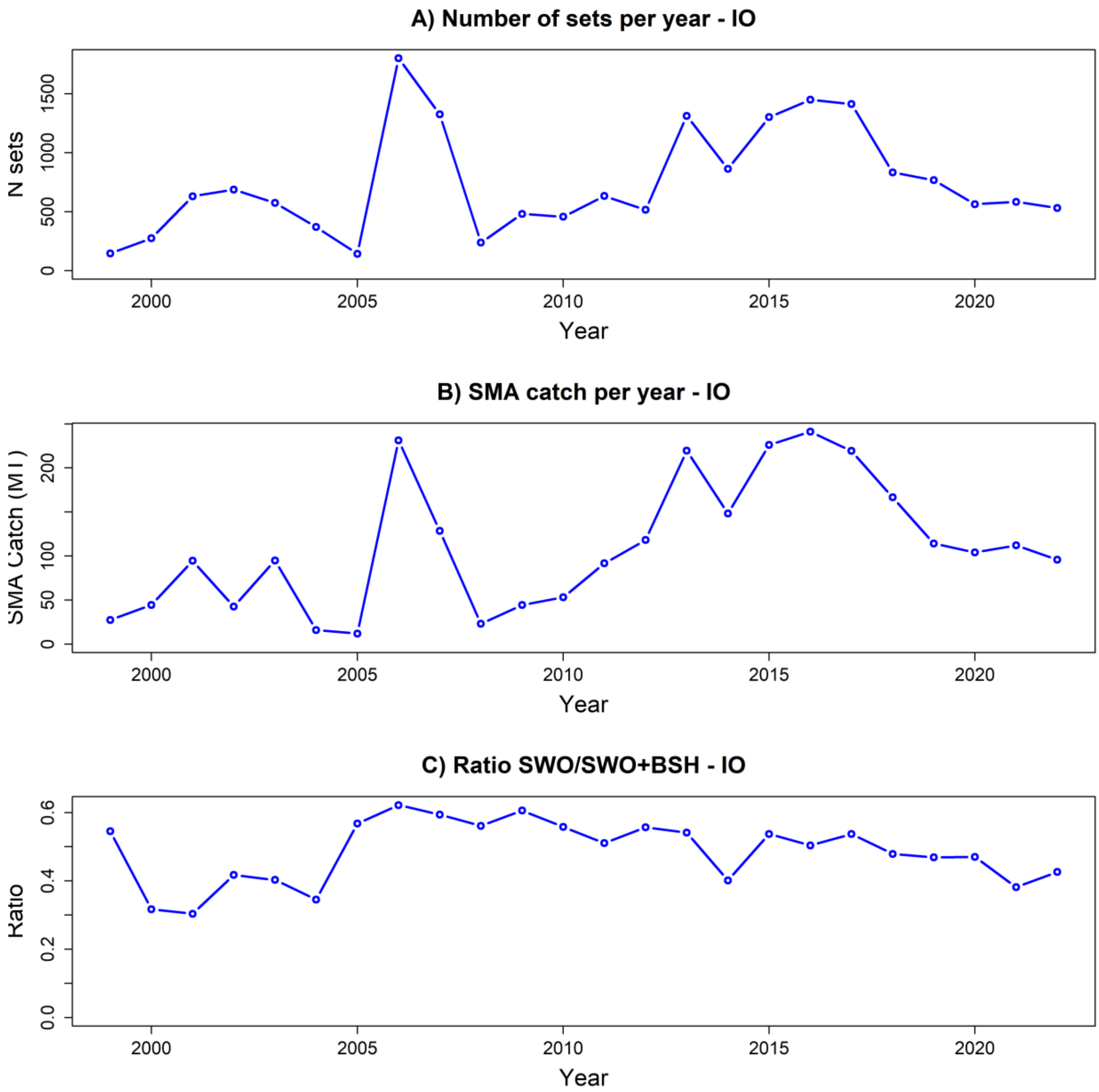

Figure 3. Descriptive plots of the total effort in sets (A), the total catch of shortfin mako shark (B), and the ratio of swordfish compared to the swordfish and blue shark catches used as a proxy for the fleet targeting (C), for the Portuguese longline fleet operating in the Indian Ocean.

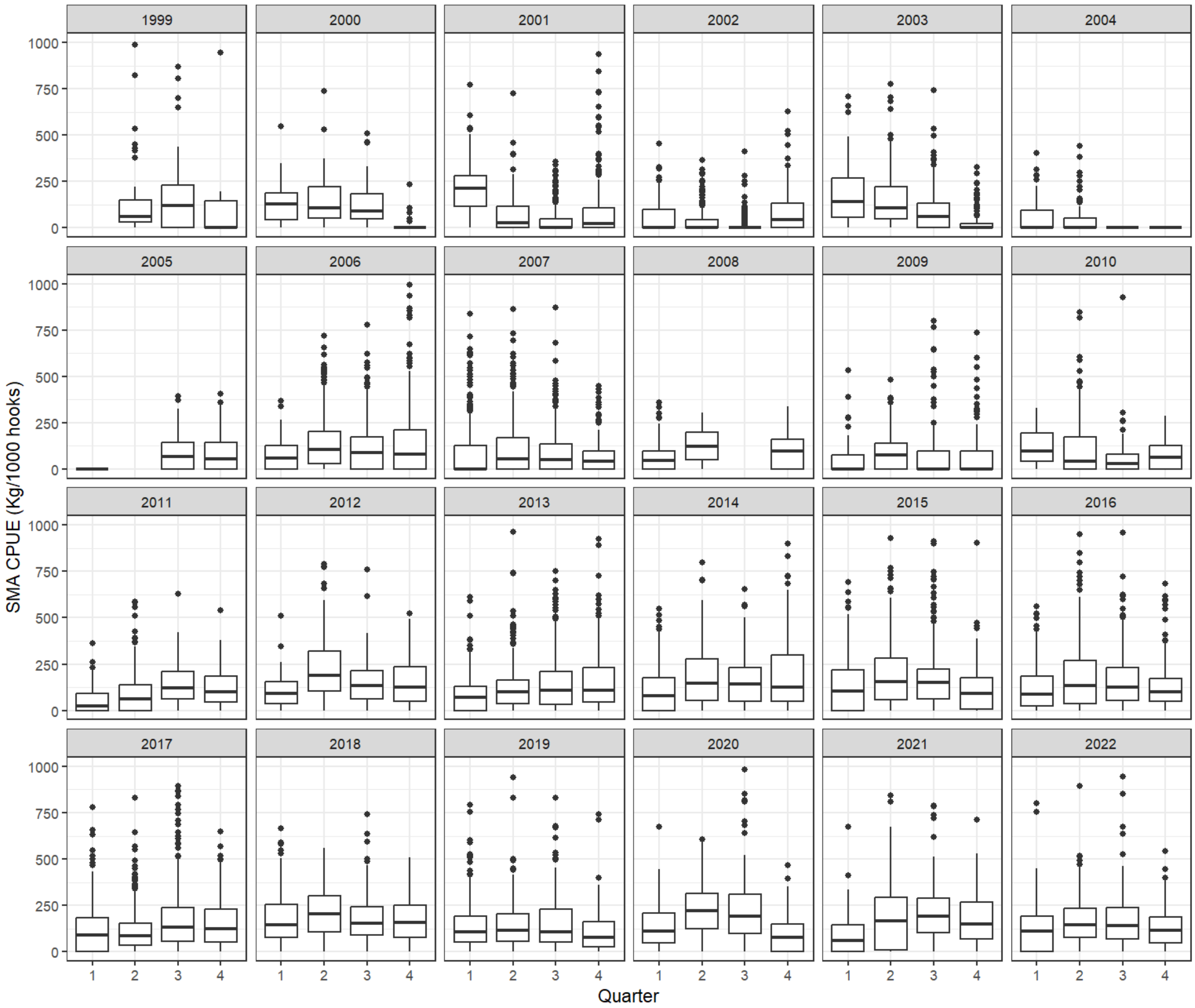

Figure 4. Quarterly shortfin mako shark CPUE (kg/1000 hooks) by the Portuguese pelagic longline fleet in the Indian Ocean, per year. In the boxplots the middle lines represent the median, the box the quartiles, the whiskers the non-outlier range and the points the outliers.

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 were some large oscillations in the earlier period, and a general increasing trend in the more recent years, followed by a relatively more stable period from 2012 to 2022 (**Figure 5**).

The percentage of fishing sets with zero catches of SMA in the Indian Ocean was relatively high, specifically 26.9% of the sets. In general, there were higher proportions of sets with zero SMA catches in the earlier years and the proportion of sets with zero SMA catches 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**).

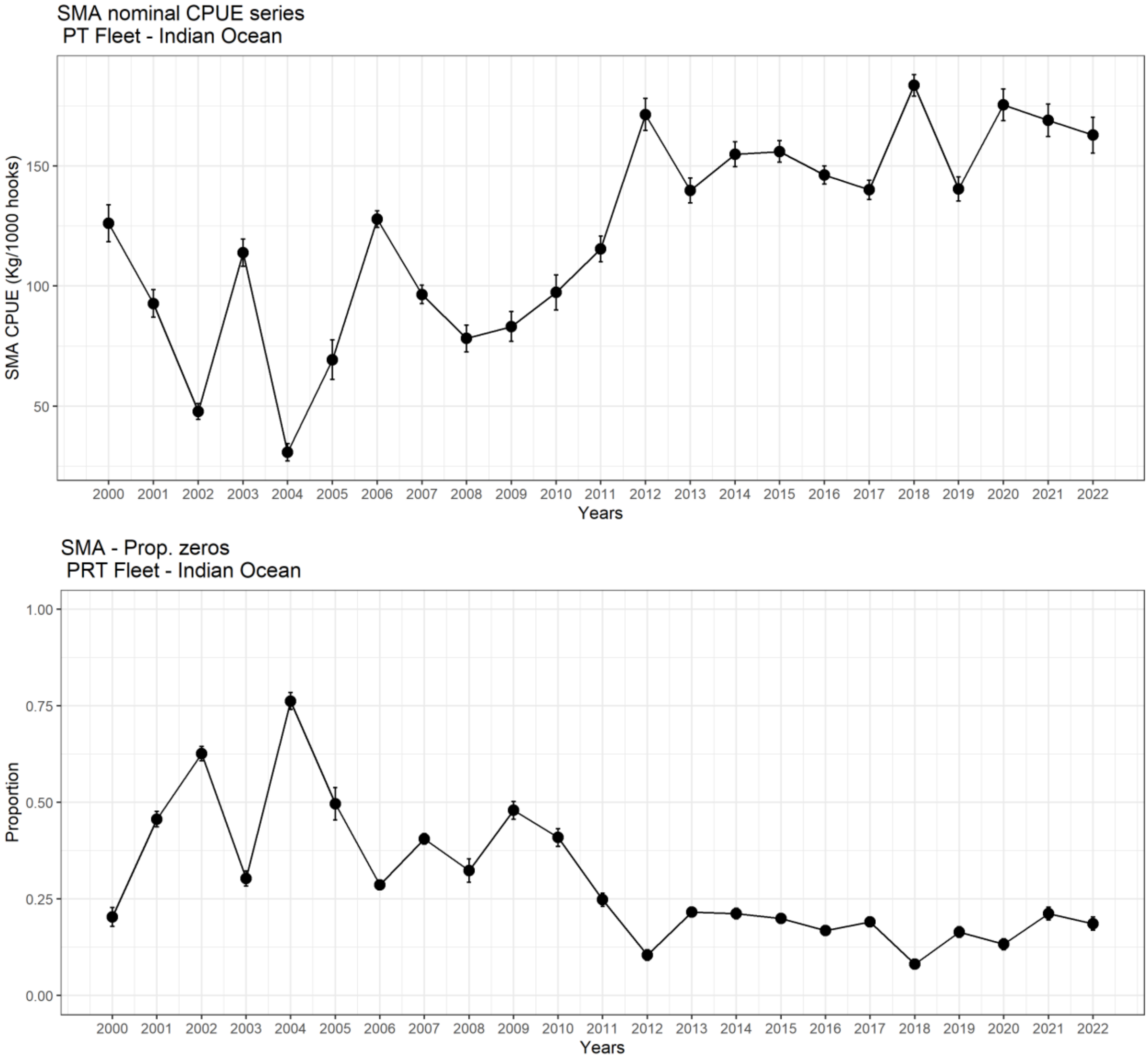

Figure 5. Nominal CPUE series (kg/1000 hooks) and proportion of zeros for SMA caught by the Portuguese pelagic longline fishery in the Indian Ocean between 2000 and 2022. The error bars refer to the standard errors.

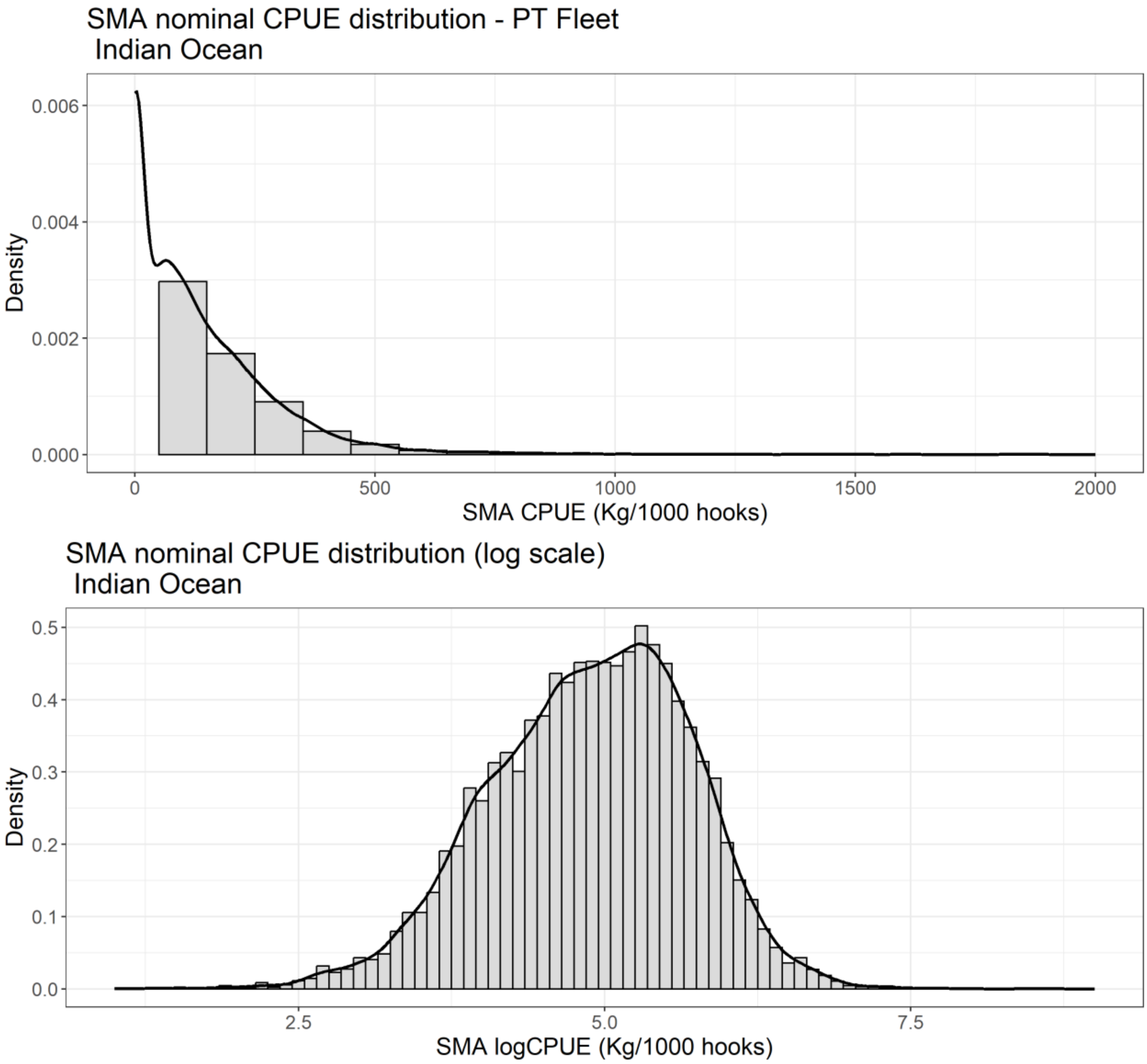

Figure 6: Distribution of the nominal shortfin mako shark CPUE captured by the Portuguese longline fleet in the Indian Ocean in non-transformed (top) and log-transformed (bottom) scales.

3.2.2. CPUE standardization models

The base case model was based on the best case as tested by Coelho et al. (2013, 2017, 2020) 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) were updated to incorporate the most recent data until 2022, and are shown in **Figure 7**.

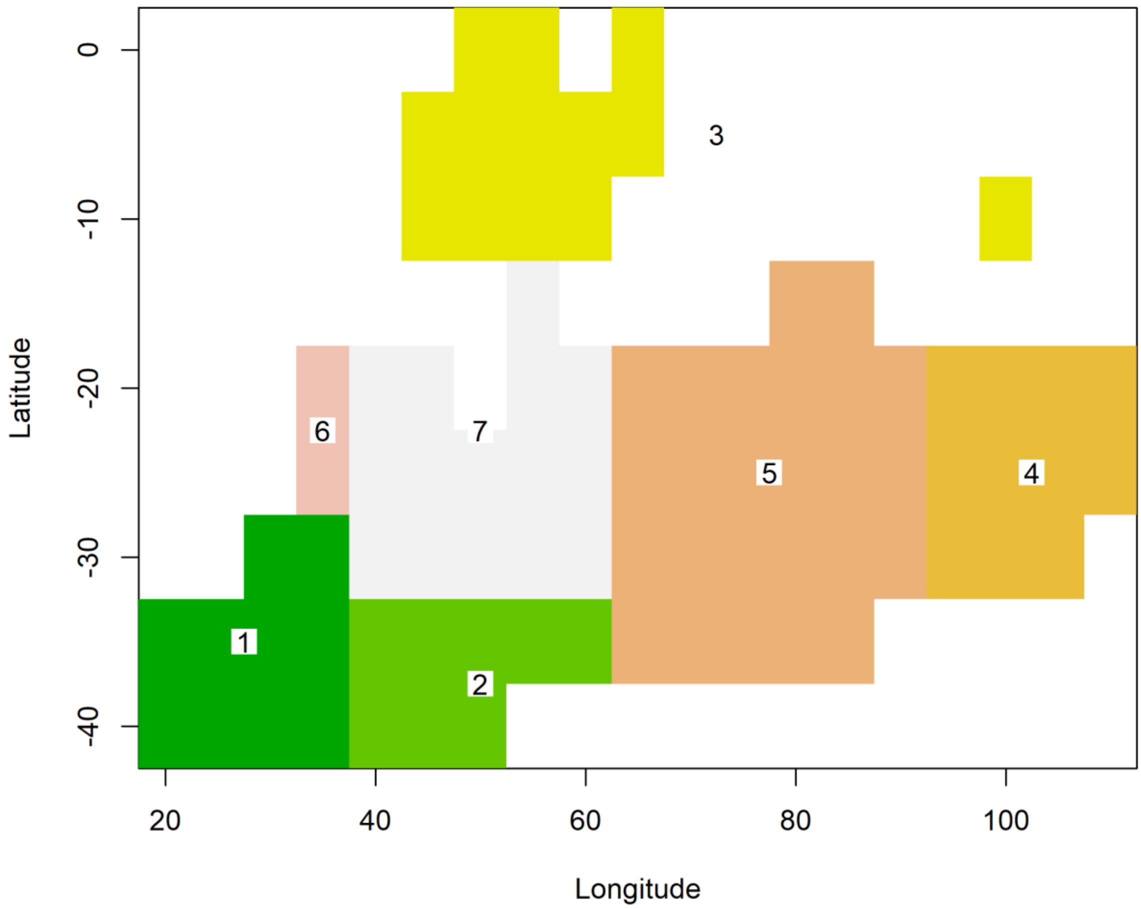

Figure 7. Spatial area stratification for the SMA CPUE captured by the Portuguese longline fleet in the Indian Ocean for the period 1999-2022.

The factors that contributed most for the deviance explanation were the year, followed by the area, and then the quarter:area interaction (**Table 2**).

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			17750	607294			
Year	22	37889	17728	569405	55.2593	< 2.2e-16	***
Quarter	3	2069	17725	567336	22.1263	2.543e-14	***
AreaCat7.2	4	10520	17721	556816	84.3879	< 2.2e-16	***
RatioFac	9	3068	17712	553748	10.9384	< 2.2e-16	***
Quarter:AreaCat7.2	12	5384	17700	548364	14.3946	< 2.2e-16	***
Quarter:RatioFac	27	3079	17673	545286	3.6586	4.076e-10	***
AreaCat7.2:RatioFac	36	2050	17637	543236	1.8272	0.00177	**

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

3.2.3. Residual analysis and model validation

The residual analysis used for model validation showed no major problems, with the histogram of the distribution of the residuals close to a normal shape, even though it was evident the presence of some outliers along the fitted values (**Figure 8**).

For this final model, we also calculated the influence of each variable in the estimation of the parameters. **Figures 9, 10 and 11** represent the coefficients, residuals, and influence of each of the main effect variables for the final standardized CPUE series.

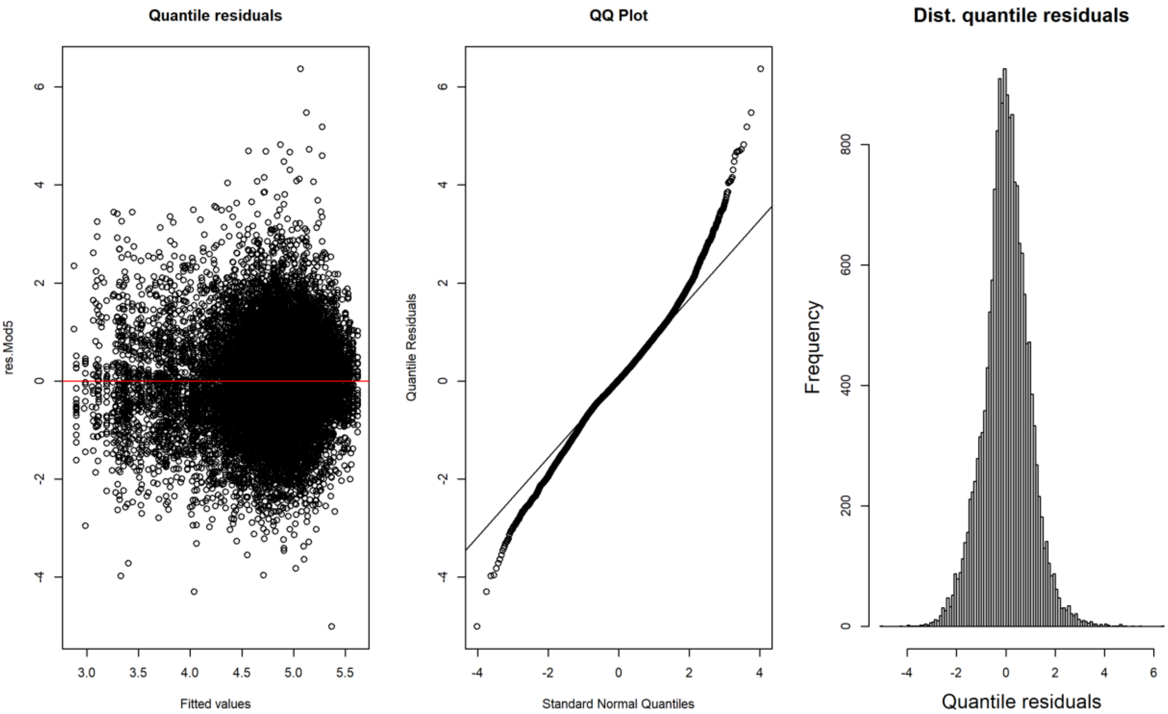

Figure 8. Residual analysis for the final Tweedie GLM model for the SMA CPUE standardization in the Indian Ocean. In the plot it is presented the histogram of the distribution of the residuals, the QQPlot and the residuals along the fitted values on the log scale.

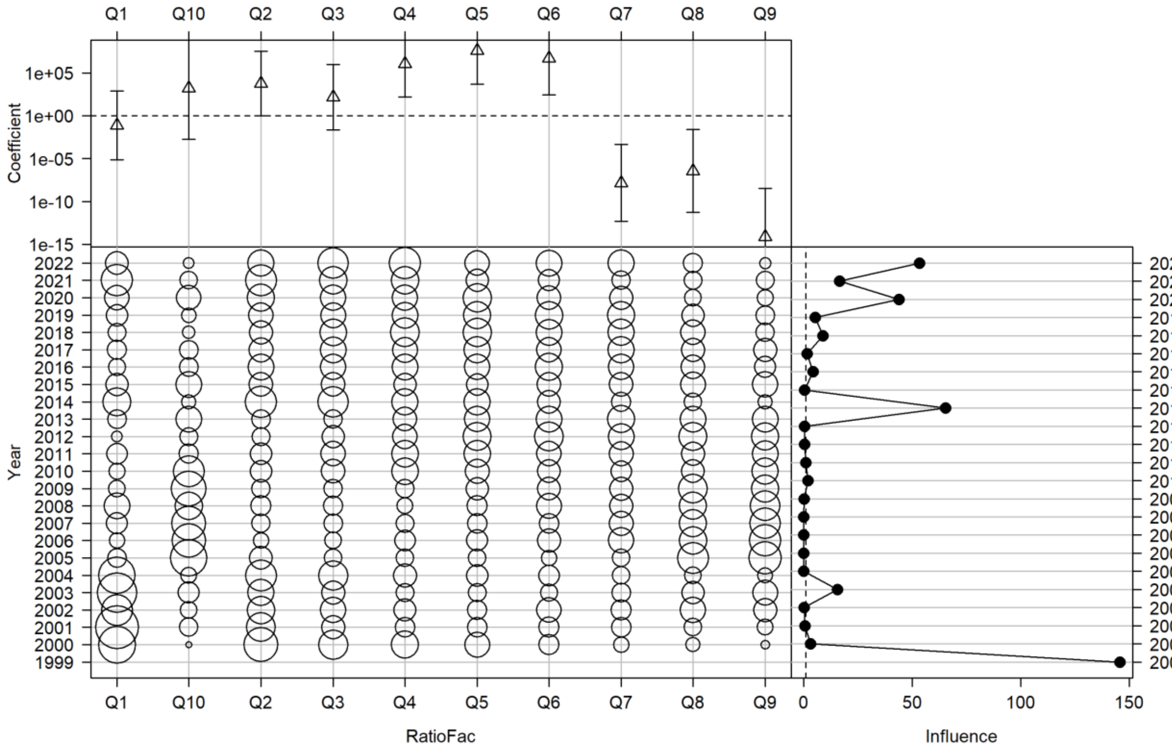

Figure 9. Coefficients, residuals and influence of the variable Ratio (proxy for targeting) in the final model for the SMA CPUE series.

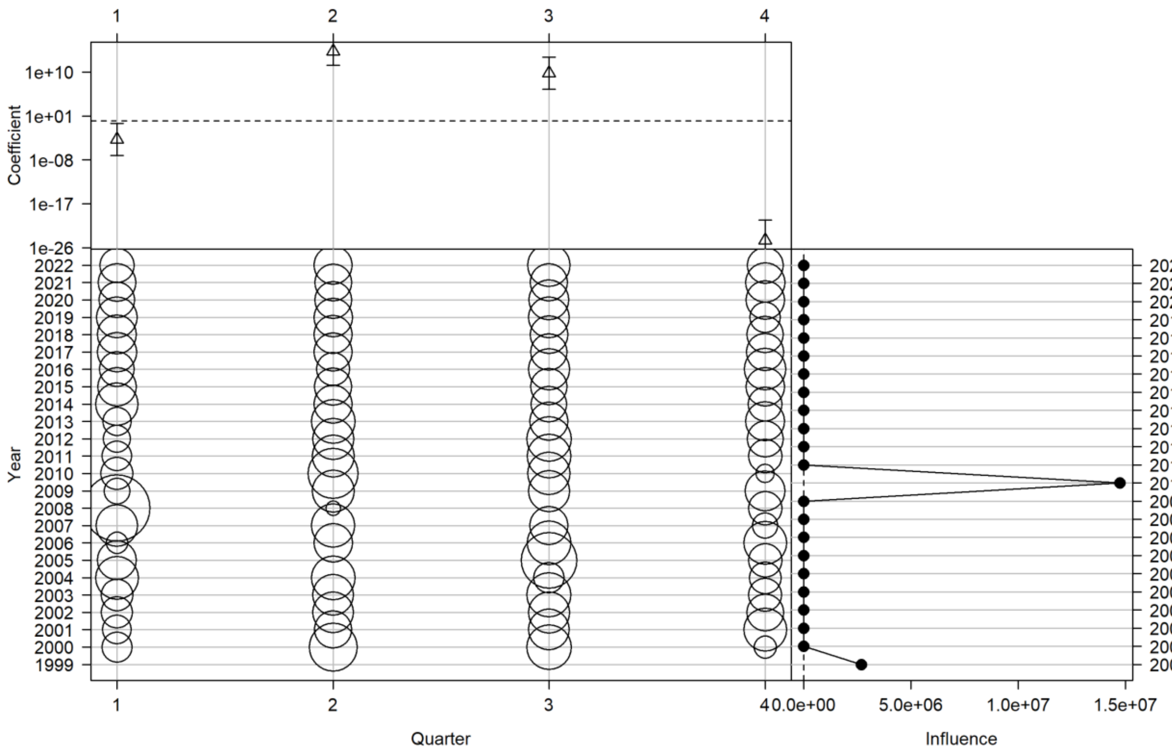

Figure 10. Coefficients, residuals and influence of the variable Quarter in the final model for the SMA CPUE series.

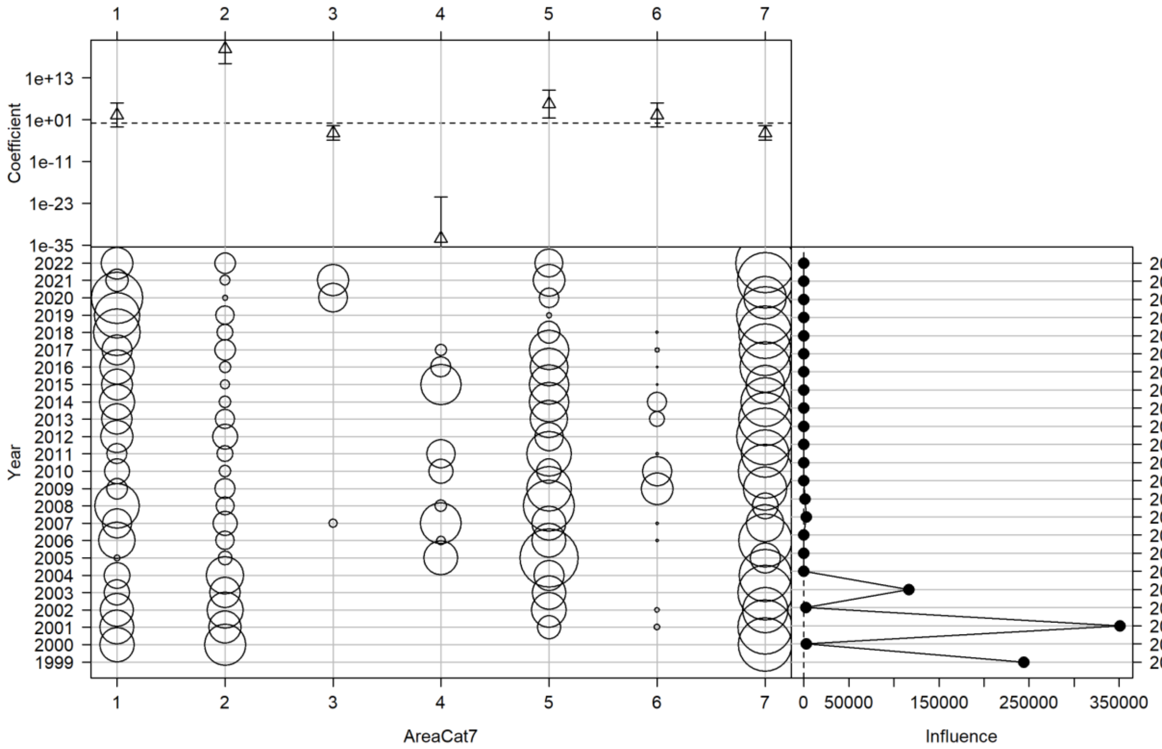

Figure 11. Coefficients, residuals and influence of the variable Area in the final model for the SMA CPUE series.

3.2.4. 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 and 2020), the final standardized CPUE series recommended to be used as indicator of relative abundance for shortfin mako is shown in **Figure 12**. This model accounts for the main 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 2000-2022, suggested to be used as a relative abundance index, is shown in **Figure 12** 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 until 2012, and a more stable period in the more recent years, between 2012 and 2022 (**Figure 12**). This index could be considered to be used in future stock assessments for this species.

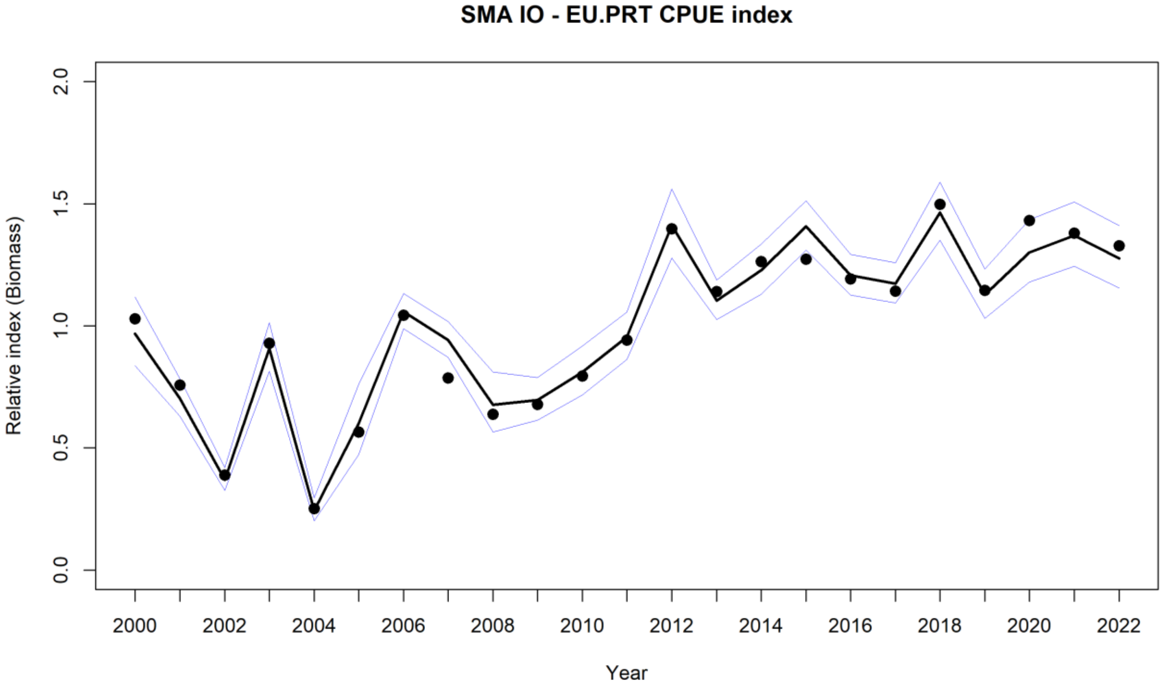

Figure 12. Standardized CPUE series for SMA captured by the Portuguese pelagic longline fleet in the Indian Ocean using a Tweedie GLM. The solid black line refers to the standardized index, the blue lines refer to 95% confidence intervals and the black dots to the nominal CPUE series. Both series are shown in relative values (scaled to 1) for comparison purposes.

Table 3. Standardized SMA CPUE index (kg/1000 hooks) for the Portuguese pelagic longline fleet in the Indian Ocean between 2000 and 2022, for use as a relative biomass index indicator. The table includes the standardized CPUE index value, the 95% confidence intervals (CI) and the coefficient of variation (CV, %).

Year	Estimate	Upper CI (95%)	Lower CI (95%)	CV (%)
2000	100.0	115.6	86.6	26.9
2001	72.6	81.0	65.1	30.7
2002	38.2	43.4	33.7	36.9
2003	93.8	104.6	84.1	29.2
2004	25.2	30.5	20.9	41.0
2005	62.0	78.6	49.0	31.7
2006	109.4	117.1	102.2	32.4
2007	97.3	105.2	90.1	31.6
2008	70.0	83.8	58.4	31.2
2009	72.0	81.5	63.5	30.6
2010	83.9	94.9	74.2	29.5
2011	98.7	109.2	89.1	28.6
2012	145.9	161.2	132.1	25.3
2013	114.1	122.8	106.0	29.8
2014	126.9	138.0	116.7	27.5
2015	145.4	156.2	135.4	28.9
2016	124.7	133.7	116.3	29.6
2017	121.2	130.1	113.0	29.6
2018	151.3	164.2	139.5	26.2

2019	116.5	127.5	106.5	27.9
2020	134.4	148.2	122.0	25.9
2021	141.5	155.8	128.5	26.0
2022	132.0	145.8	119.5	25.7

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