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UPDATED CATCH, EFFORT AND STANDARDIZED CPUE OF BLUE SHARK (*Prionace glauca*) CAPTURED BY THE PORTUGUESE PELAGIC LONGLINE FISHERY IN THE INDIAN OCEAN

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SUMMARY

The Portuguese pelagic longline fishery in the Indian Ocean started in the late 1990's, targeting mainly swordfish in the southwest region. This working document analyses catch, effort and standardized CPUE trends for blue shark captured by this fishery. Nominal annual CPUEs were calculated in biomass (kg/1000 hooks), and were standardized with Generalized Linear Mixed Models (GLMMs) using year, quarter, season and targeting as fixed effects, and vessel as random effects. The standardized CPUE trends show an overall decrease in the initial years between 2000 and 2014, followed by a more stable period with oscillations until 2020, and a slight increase in the more recent years until 2023. A comparison is made with a standardization without the targeting effects. These results present an updated annual index of abundance for the blue shark captured by the Portuguese pelagic longline fleet in the Indian Ocean with data until 2023, that can now be considered for use in the 2025 IOTC blue shark stock assessment.

KEYWORDS: Blue shark, CPUE standardization, generalized linear mixed models (GLMM), Indian Ocean, pelagic longline fisheries.

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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, mostly ranging in size from about 25 to 45m. 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), and then decreased to a low of 3 (in 2009, 2012), with another increase in 2013 and 2014 (Santos et al., 2013, 2014). In more recent years (2018-2024) only 2 or 3 vessels have been active in the IOTC area. 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 blue shark CPUE indices for EU.Portugal were presented to the IOTC Working Party on Ecosystems and Bycatch (WPEB) in 2011, 2012 and 2013 (Coelho et al., 2011, 2012, 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). Updated indices were created for use in the 2015, 2017 and 2021 BSH stock assessments, which also used the effects of targeting based on ratios *versus* cluster analysis (Coelho et al., 2015a, 2017, 2021).

In this work, we update the standardized BSH CPUE index using the best case as defined by Coelho et al. (2014) and as recommended by the WPEB in 2014 (IOTC WPEB, 2014), and that have been used since then. We also take into consideration the recommendations from the targeting effects study by Coelho et al. (2015a).

The objectives of this study were therefore to provide an updated description of the BSH catches by the Portuguese pelagic longline fishery operating in the Indian Ocean between 1998 and 2023, including information on the catch, effort and CPUE trends (nominal and standardized) that can contribute for the 2025 IOTC BSH stock assessment in the Indian Ocean.

2. Material and methods

2.1. Catch and effort

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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.

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 2000 and 2023, used for this study.

Year	Number of sets (N)
2000	275
2001	631
2002	647
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	534
2023	590
Total	**18304**

2.3. CPUE standardization

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 blue shark captured per fishing set. 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 BSH 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 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 behaviors in this particular fleet (fleet targeting mainly SWO but with BSH as a secondary target). Therefore, this update of the BSH CPUE is based on the base case from those previous studies.

There were some fishing sets with zero blue shark catches that result in a response variable of CPUE=0. As these zeros can cause mathematical problems for fitting the models, Coelho et al. (2014) tested three different methodologies, specifically tweedie, gamma and lognormal models. The best fit was achieved using lognormal models with the response variable defined as the nominal CPUE + constant (c), with c set to 10% of the overall mean catch rate (as recommended by Campbell, 2004), as that is the value that seems to minimize the bias for this type of adjustments. Further, and in a comparative study, Shono (2008) showed that when the percentage of zeros in the dataset is low (<10%, as is the case in this dataset), the method of adding a constant to the response variable performs relatively well.

Based on the sensitivities and tests reported by Coelho et al. (2014) and the standardization carried out by Coelho et al. (2017), the covariates considered and tested in the base case models for this work were:

- Year: analyzed between 2000 and 2023;
- 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;
- Vessel ID: used as a random variable in the GLMM.

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).

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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. By further requests of the WPEB in previous years when presenting this index, a sensitivity analysis was carried out for a standardized series without the use of targeting effects as a covariate.

All statistical analysis for this paper was carried out with the R Project for Statistical Computing version 3.6.1 (R Core Team, 2019) using several additional libraries (Wickham, 2007, 2009; Fox and Weisberg, 2011; Højsgaard and Halekoh, 2012; Bivand and Lewin-Koh, 2013; Bates et al., 2014; Lenth, 2014).

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 2000 and 2023, 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 BSH catches are also spread throughout the Indian Ocean region, but also follow this general trend of a higher concentration in the southwest region, south of Madagascar Island and closer to South Africa and south Mozambique (**Figure 2**).
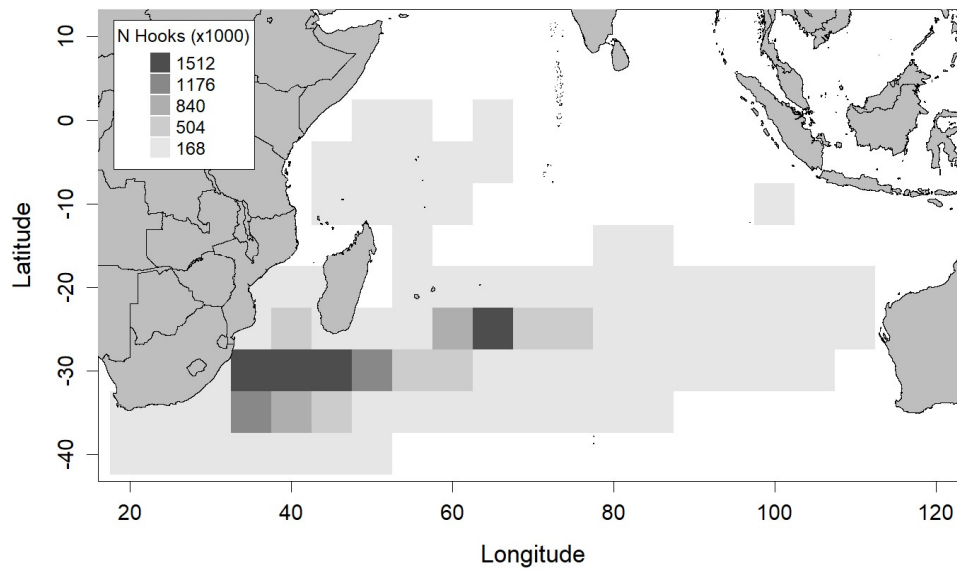
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Figure 1. Effort distribution of the Portuguese pelagic longline fleet for the 1998-2019 period in the Indian Ocean. The effort is represented in 5°x5° grids with darker and lighter colors representing respectively areas with more and less effort in number of hooks.
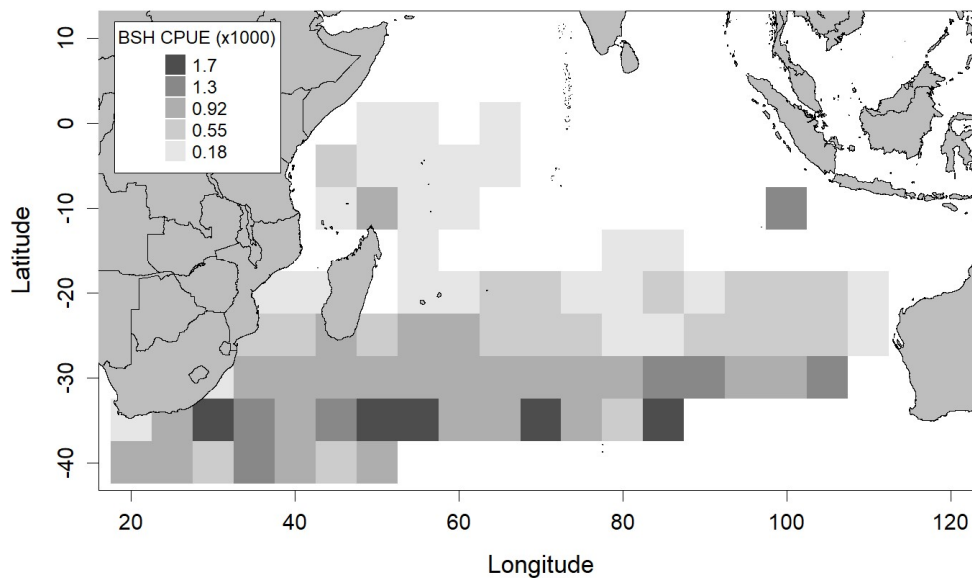

Figure 2. Distribution of BSH CPUEs in the Portuguese pelagic longline fleet for the 1998-2019 period in the Indian Ocean. The effort is represented in 5°x5° grids with darker and lighter colors representing respectively areas with more and less BSH CPUEs in biomass (kg/1000 hooks).

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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 2005, followed by an increase during 2006-2007 and then a sharp decrease in 2008 (**Figure 3**). Then, in the period between 2009 to 2017 there was an increase, and followed by a decrease in the more recent years (**Figure 3**).

The total blue shark catches also tended to follow this general trend, with a peak during 2006-2007, followed by a sharp decrease in 2008, and then a more steady and progressive increase until 2017, followed by lower values since then (**Figure 3**).

In terms of ratios of swordfish compared to the swordfish + blue shark catches, the ratios were lower until 2004, and then tended to be higher since then, even though they have been progressively decreasing over time (**Figure 3**). Those changes over time 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. Additionally, 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).
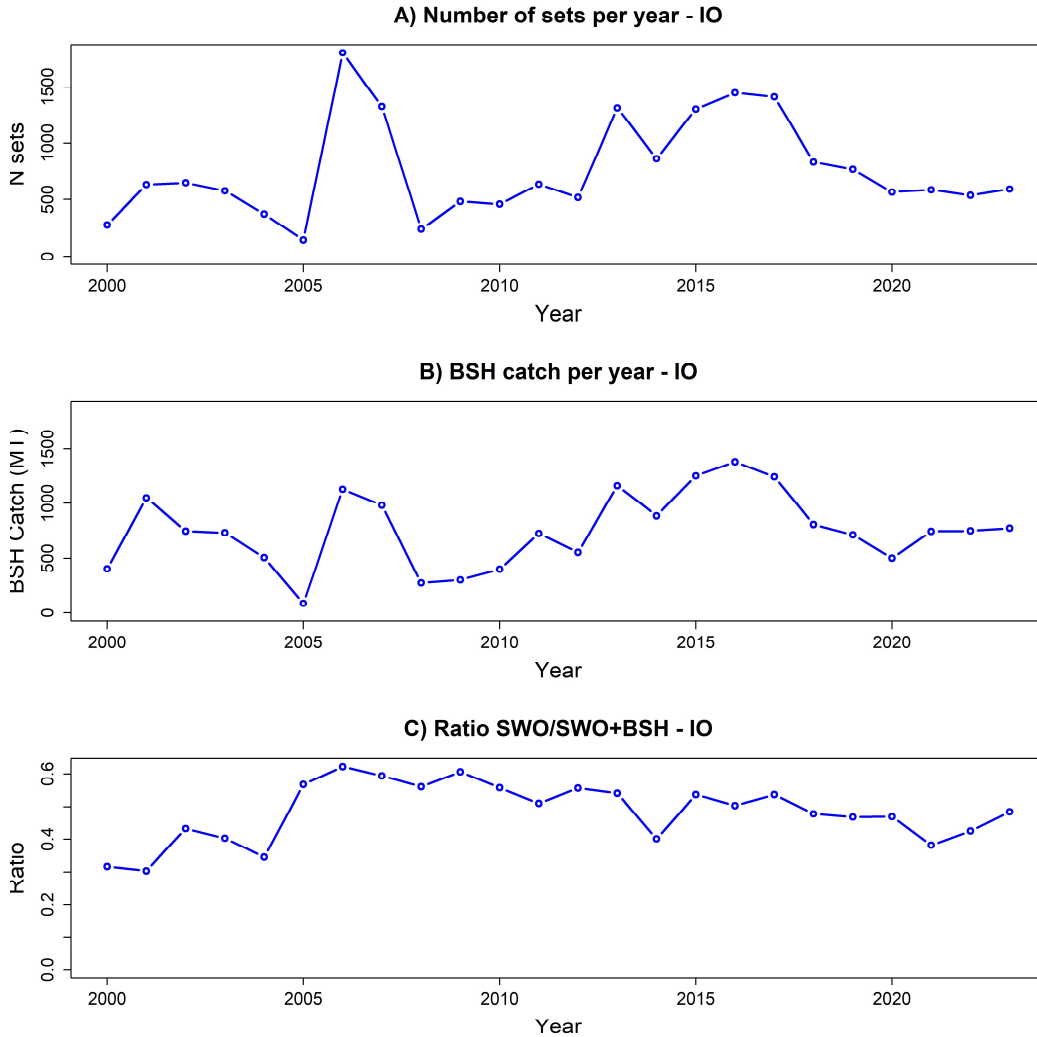
Figure 3. Descriptive plots of the total effort in sets (A), the total catch of blue shark (B), and the ratio of swordfish compared to the swordfish and blue shark catches (C), for the Portuguese longline fleet operating in the Indian Ocean.

In terms of seasonality in the CPUE, and even though there was some considerable inter-annual variability, it was possible to observe a general trend of higher CPUEs in the 1st half of the year followed by lower CPUEs towards the middle of the year, and then higher CPUEs again later in the year (**Figure 4**). Santos et al. (2002) reported a similar trend for the Portuguese pelagic longline blue shark catches in the North Atlantic, with a peak occurring in May-June.
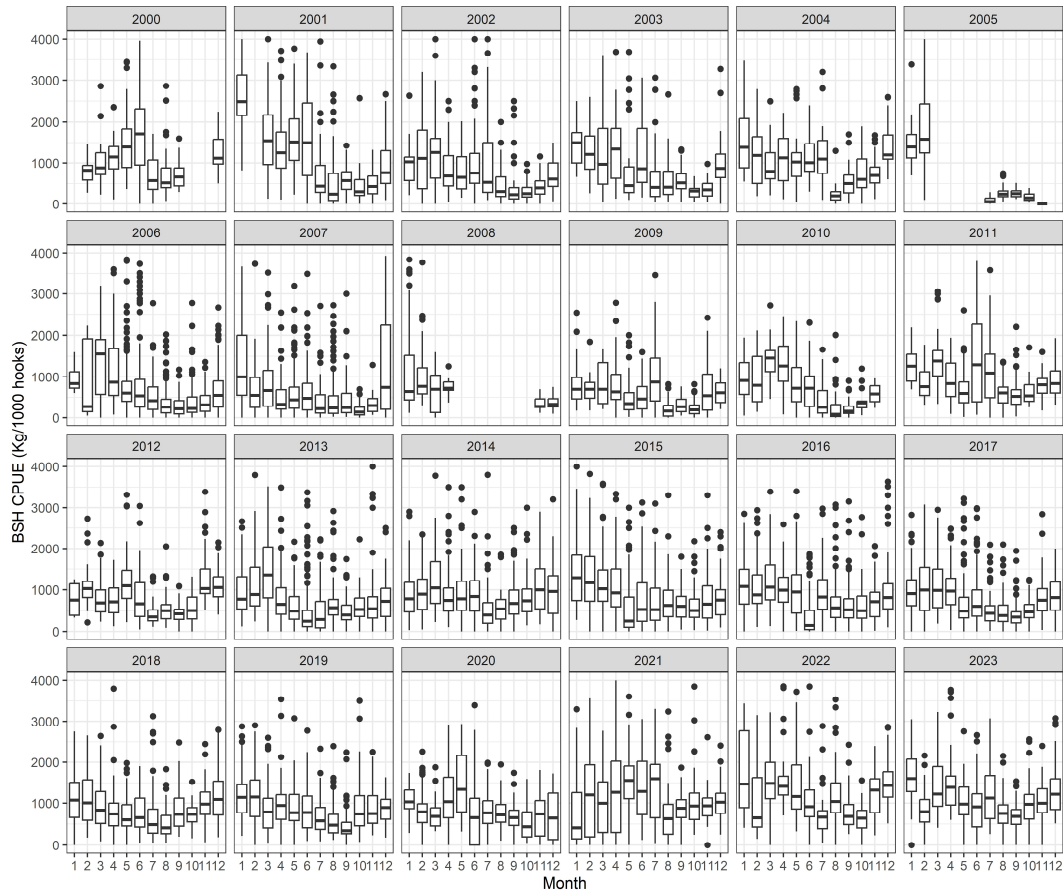
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Figure 4. Monthly blue shark CPUE (kg/1000 hooks) by the Portuguese pelagic longline fleet in the Indian Ocean, per year. In the boxplots the middle lines represent the median, the box the quartiles, the whiskers the non-outlier range and the points the outliers.

3.2. CPUE standardization

3.2.1. CPUE data characteristics

The nominal time series of the blue shark CPUE for the Portuguese pelagic longline fleet operating in the Indian Ocean is presented in **Figure 5**. In general, there was a decreasing tendency between 2000 and 2009 with oscillations, and then an increasing trend since then until the last data year of 2023, also with oscillations (**Figure 5**).

The percentage of fishing sets with zero catches of BSH in the Indian Ocean was low, specifically 2.7%. The nominal blue shark CPUE distribution was highly skewed to the right and became more normal shaped in the log-transformed scale (**Figure 6**).
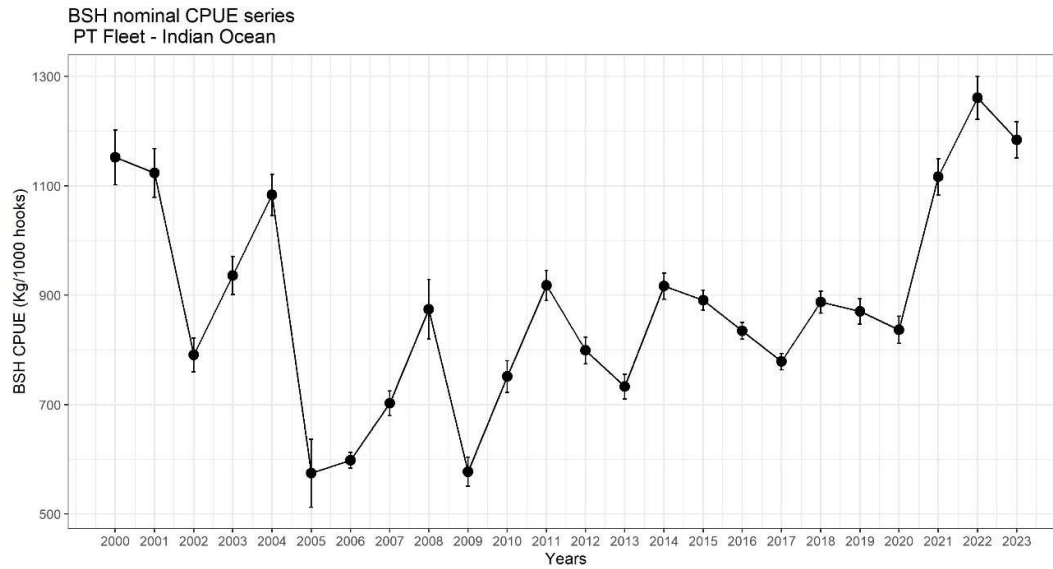
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Figure 5. Nominal CPUE series (kg/1000 hooks) for BSH caught by the Portuguese pelagic longline fishery in the Indian Ocean between 2000 and 2023. The error bars refer to the standard errors.
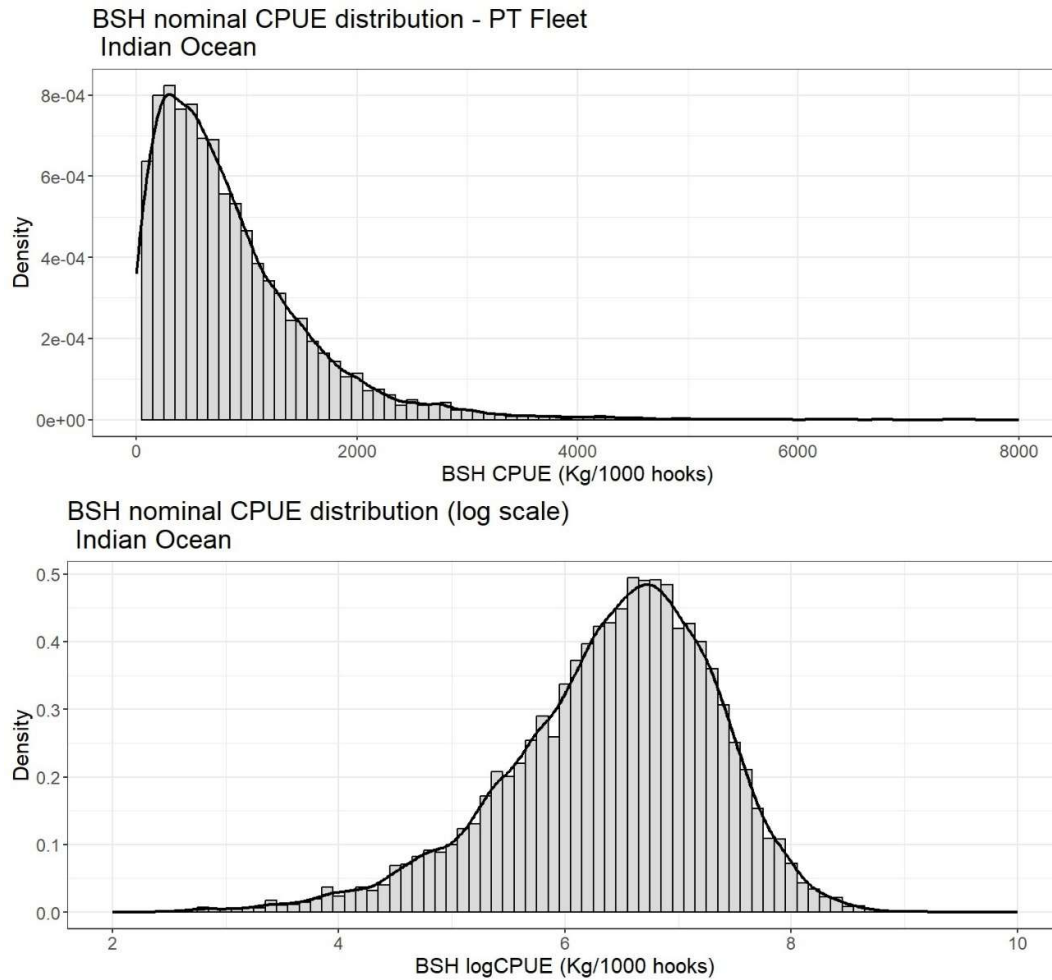
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Figure 6: Distribution of the nominal blue shark CPUE captured by the Portuguese longline fleet in the Indian Ocean in non-transformed (top) and log-transformed (bottom) scales.

3.2.2. Area stratification

The area stratifications used in the standardization models followed a GLM tree approach for optimization based on the AIC drop. The final areas selected (7 areas) are shown in **Figure 7**.
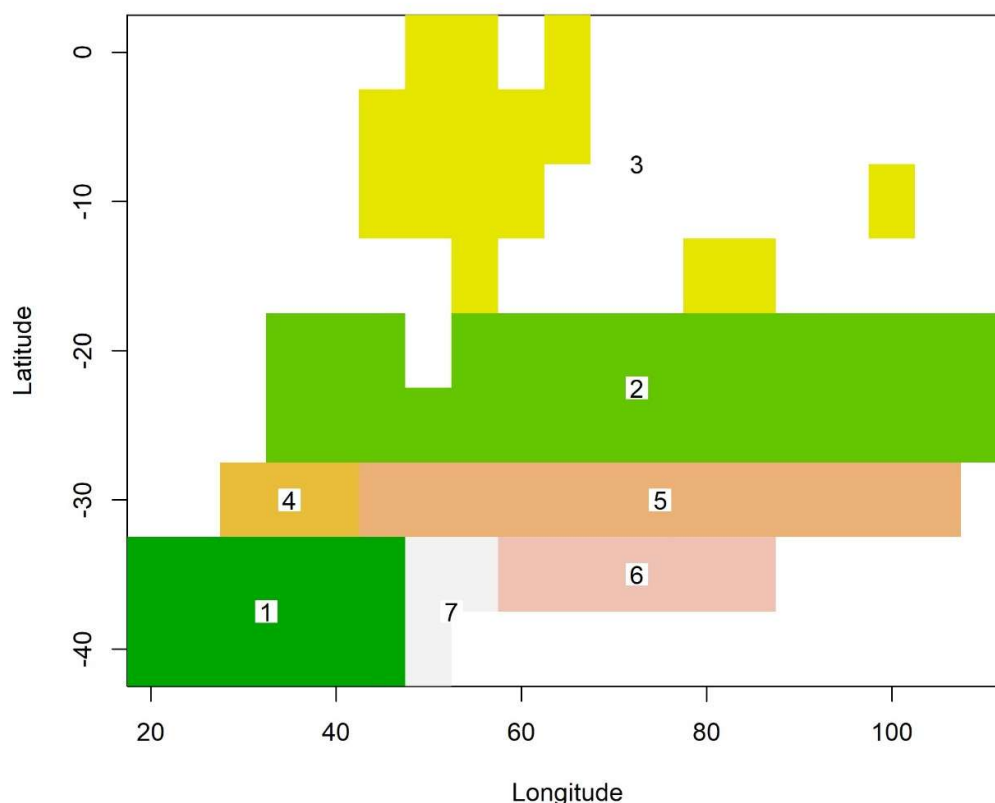
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Figure 7: Spatial area stratification for the BSH CPUE captured by the Portuguese longline fleet in the Indian Ocean.

3.2.3. Base case CPUE model with targeting/ratio effects

The base case model was based on the best case as tested by Coelho et al. (2014) using the explanatory variables that were selected then. The factors that contributed most to the deviance explanation were the ratio, followed by the quarter, year and area (**Table 2**).

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

Table 2. Deviance table (type II Anova) of the parameters used for the BSH CPUE standardization in the Indian Ocean from the Portuguese pelagic longline fleet. For each parameter it is indicated the degrees of freedom used (Df), the sum of squares (Sum sq.), the mean squares (Mean sq.) the F statistic (F value).

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```
Analysis of Variance Table
          npar Sum Sq Mean Sq F value
Year        23  436.7   18.99  107.06
Quarter      3  826.0  275.34 1552.53
AreaCat7     6  423.9   70.65  398.39
RatioFac     9 5218.9  579.88 3269.69
```
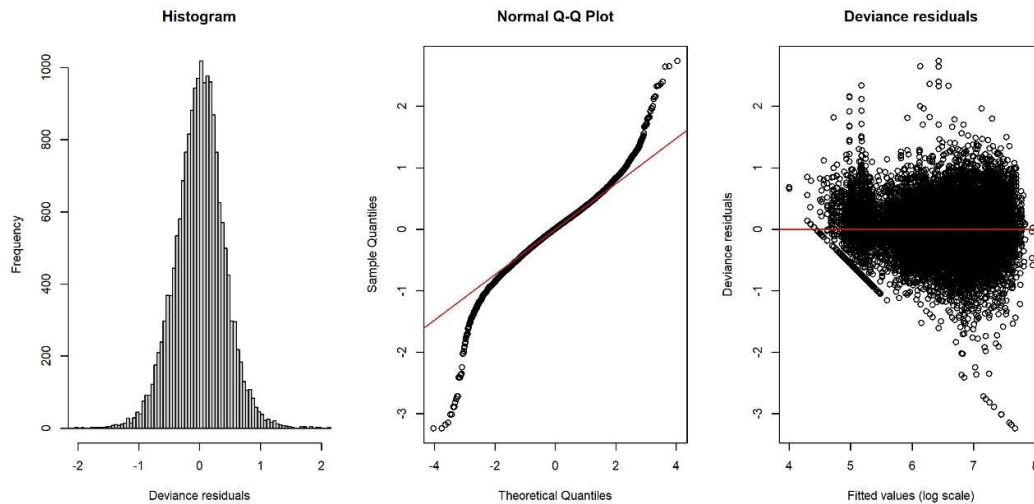

Figure 8. Residual analysis for the final lognormal GLMM model for the BSH CPUE standardization in the Indian Ocean. In the plot it is presented the histogram of the distribution of the residuals (left), the QQPlot (middle) and the residuals along the fitted values on the log scale (right).

3.2.4. Sensitivity to targeting effects

After a request from the WPEB in previous years, a model without targeting effects was also considered. In this case, the factors that contributed most to the deviance explanation were the quarter, followed by year and area (**Table 3**).

The residual analysis showed no major problems and was in fact even better than in the original model with the targeting effects, also with the histogram of the residuals close to a normal shape and with the presence of some outliers along the fitted values (**Figure 9**).

Table 3. Deviance table (type II Anova) of the parameters used for the BSH CPUE standardization in the Indian Ocean from the Portuguese pelagic longline fleet. For each parameter it is indicated the degrees of freedom used (Df), the sum of squares (Sum sq.), the mean squares (Mean sq.) the F statistic (F value).
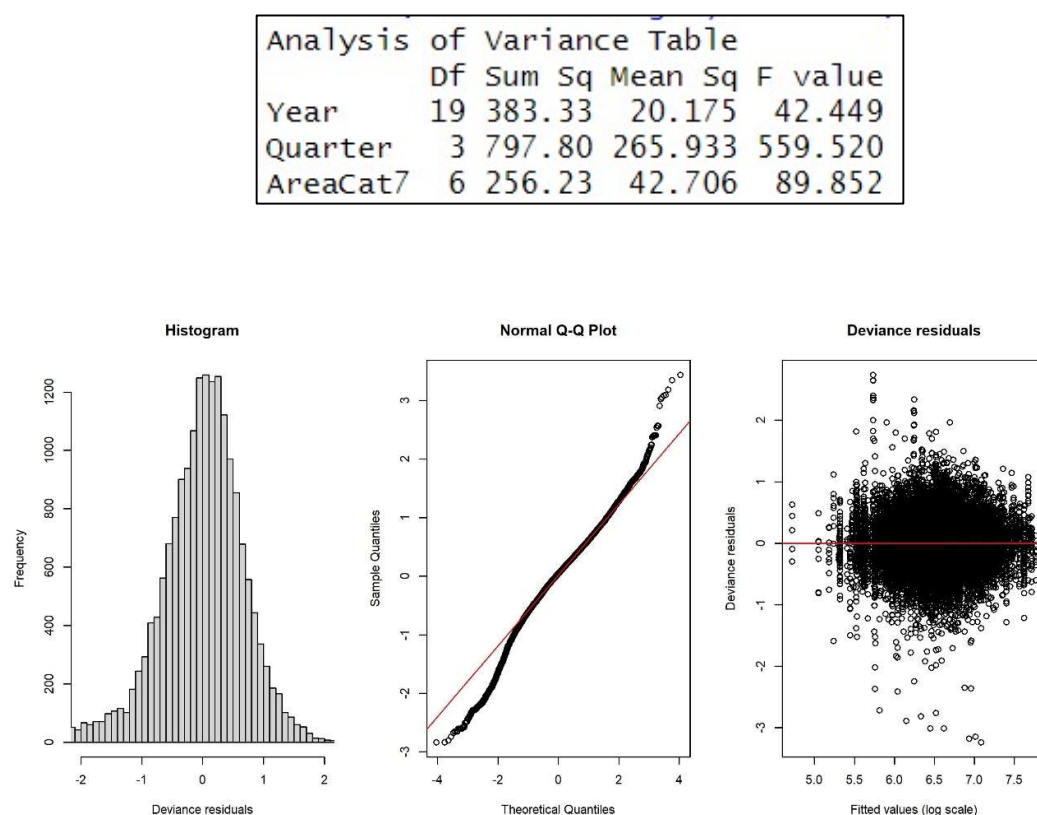
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```
Analysis of Variance Table
          Df Sum Sq Mean Sq F value
Year      19 383.33  20.175  42.449
Quarter    3 797.80 265.933 559.520
AreaCat7   6 256.23  42.706  89.852
```


Figure 9. Residual analysis for the lognormal GLMM model for the BSH CPUE standardization in the Indian Ocean, without using targeting effects. In the plot it is presented the histogram of the distribution of the residuals (left), the QQPlot (middle) and the residuals along the fitted values on the log scale (right).

3.2.5. Model comparison

The goodness of fit was much better in the original model with targeting effects (**Table 4**), but the residuals look better in the model without targeting (**Figures 8 and 9**).

A comparison of the 2 standardized series is provided in **Figure 10**. Both series follow similar overall trends, but the series with the targeting effects is smoother than the series without the targeting effects. The main difference in the model without targeting is in the initial period, with the reduction in the original years larger than in the original base model (**Figure 10**).

Table 4. Comparison of goodness-of-fit of the base case model using targeting, and (Mod2.2) with the sensitivity model without using targeting/cluster effects (Mod2.2.no.target).

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                     Df   AIC   BIC   logLik deviance Chisq Chi Df Pr(>Chisq)
Mod2.2.no.target 31 33737 33975 -16837.5    33675
Mod2.2           40 18129 18436  -9024.4    18049 15626     9  < 2.2e-16 ***
```
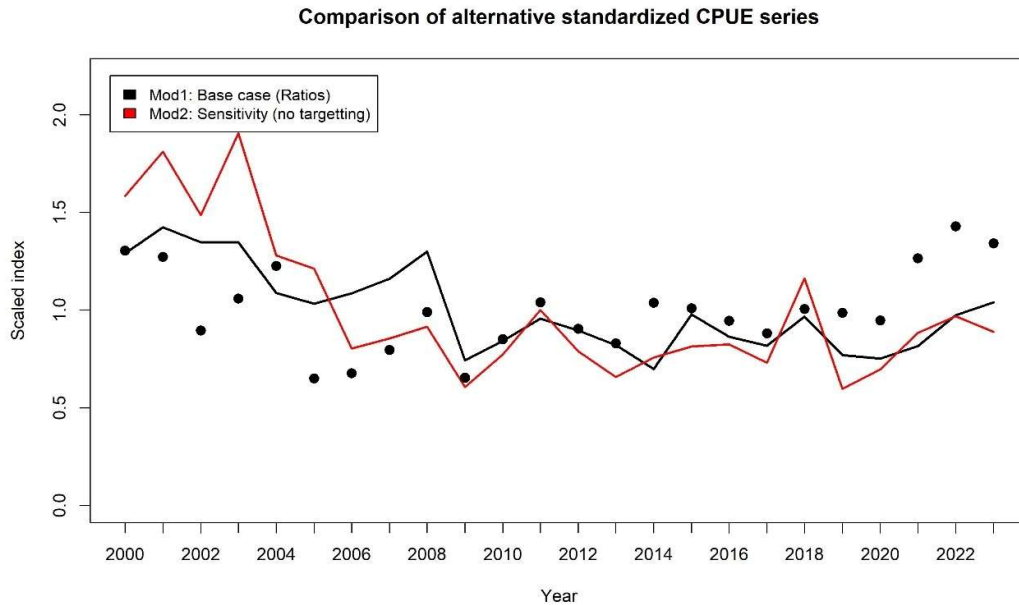

Comparison of alternative standardized CPUE series

Figure 10. Comparison of the CPUE base case series (using targeting ration) compared to an optional series used as sensitivity analysis (without targeting ratios effects).

3.3. Final standardized CPUE series

Given the goodness-of-fit and the comparisons from the sensitivity analysis for the target effects, as well as the previous sensitivity runs described by Coelho *et al.* (2014) and standardization carried out by Coelho et al. (2017), we suggest to use a final GLMM model that incorporates a random vessel effect, allowing the variability inherent to the different vessels to be considered in the models, and the covariates year, quarter, area and target effects.

On this model, the relative index of abundance showed an overall decrease in the initial years between 2000 and 2014 with oscillations, followed by a more stable period also with some oscillations until 2020, and then a slight increase in the more recent years until 2023 (**Figure 11**). The values to be considered for the 2025 IOTC BSH stock assessment are provided in **Table 5**.
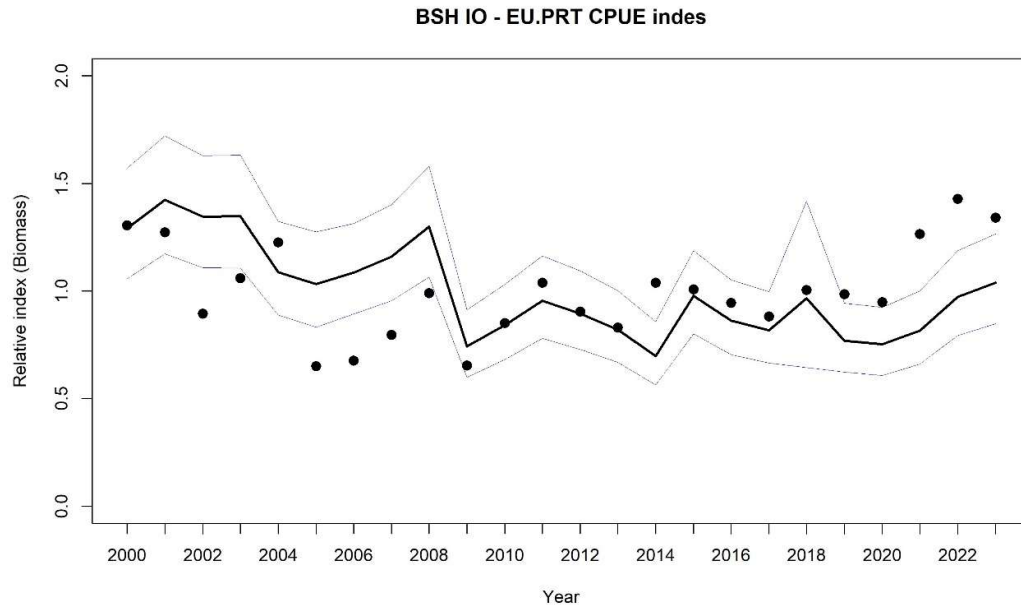
Figure 11. Standardized CPUE series for BSH captured by the Portuguese pelagic longline fleet in the Indian Ocean using a lognormal GLMM for the final selected model. The black line refers to the standardized index, the blue lines to the 95% confidence interval and the black dots to the nominal CPUE series.

Table 5. Standardized BSH CPUE index (kg/1000 hooks) for the Portuguese pelagic longline fleet in the Indian Ocean between 2000 and 2023. The table includes the standardized index value, the 95% confidence intervals (CI) and the coefficient of variation (CV, %).

Year	Nominal CPUEs	Standardized CPUEs			
		Standardized CPUEs	Upper CI (95%)	Lower CI (95%)	CV (%)
2000	1151.8	665.4	809.4	544.6	23.3
2001	1123.5	733.4	886.7	604.3	34.5
2002	790.7	694.1	839.7	571.4	34.9
2003	935.7	694.2	841.4	570.4	33.2
2004	1083.1	560.3	681.9	458.0	26.6
2005	574.5	532.3	657.1	428.5	17.6
2006	597.8	559.8	677.0	460.7	56.7
2007	702.4	597.8	722.1	492.6	48.7
2008	874.2	669.7	814.3	548.4	21.6
2009	576.9	382.7	470.4	308.9	30.2
2010	751.1	433.7	531.4	351.6	29.5
2011	917.7	492.4	599.6	401.9	34.3
2012	798.9	461.7	564.0	375.6	31.2
2013	732.9	423.0	516.0	344.4	48.8

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2014	916.5	359.7	441.9	290.4	39.9
2015	890.5	504.1	612.3	412.8	48.7
2016	834.7	445.0	542.1	363.0	51.2
2017	778.6	421.5	514.1	343.2	50.5
2018	887.3	498.2	730.5	332.1	77.4
2019	870.1	396.7	486.2	321.3	37.8
2020	836.7	387.8	476.1	313.5	32.5
2021	1116.3	420.5	515.3	340.6	33.3
2022	1261	501.5	611.8	408.7	31.9
2023	1183.8	535.6	652.1	437.6	33.4

4. Acknowledgments

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