Received: 29 September 2014

SWORDFISH CATCHES BY THE PORTUGUESE PELAGIC LONGLINE FLEET BETWEEN 1998-2013 IN THE SOUTHWEST INDIAN OCEAN: EFFORT, STANDARDIZED CPUE AND CATCH-AT-SIZE.

Miguel N. Santos, Rui Coelho & Pedro G. Lino

SUMMARY

The Portuguese pelagic longline fishery in the Indian Ocean started in the late 1990's, targeting mainly swordfish in the southwest. A recent effort by the *Portuguese Institute for the Ocean and Atmosphere* (IPMA) was made to collect of historical catch and effort data on this fishery since the late 1990's to the present date, as well as vessel monitoring system (VMS) data. This working document analyses the catch and effort, catch-at-size, and standardized CPUE trends for that period. The trends in the swordfish catch-at-size were analyzed annually and compared between seasons, revealing a decrease in the sizes in the first period of the time series (up to 2009) followed by an increase in the median sizes in the more recent years. Nominal annual CPUEs were calculated as kg/1000 hooks, and were standardized with Generalized Linear Models (GLM) using year, quarter, area, gear type, vessel, swordfish/blue shark ratio and regional:seasonal interactions. Sensitivity analyses were carried out for the model type used (lognormal, tweedie or gamma), to the inclusion of the ratio factor in the models, and to the definition of the areas. Model goodness-of-fit and comparison was carried out with AIC and the coefficient of determination (R^2), and model validation with a residual analysis. The final standardized CPUE trends show an increase in the first years of the series, followed by a general decrease until 2005, then followed by a peak in 2008, and then a general decrease for the more recent years. The final results present an updated annual index of abundance for the swordfish captured by the Portuguese pelagic longline fleet in the southwest Indian Ocean that can be integrated in stock assessment models for that species in that region.

KEYWORDS: Southwest Indian Ocean, swordfish, Xiphias gladius, fishery indicators, CPUE standardization, generalized linear models, pelagic longline fisheries.

Authors Addresses: Instituto Português do Mar e da Atmosfera (IPMA, I.P.), Av. 5 de Outubro s/n, 8700-305 Olhão, PORTUGAL

*: Corresponding author e-mail: mnsantos@ipma.pt

1. Introduction

The Portuguese pelagic longline fishery in the Indian Ocean started in the late 1990's and has traditionally targeted swordfish (*Xiphias gladius*, SWO) even though, in certain areas and seasons, it also catches relatively high quantities of sharks as bycatch (particularly the blue shark *Prionace glauca*, BSH).

The Portuguese fishing vessels operating in the IOTC area of competence consist only of pelagic longliners 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 5 years, the active vessels in the convention area decreased to as low as three (in 2009, 2012), with a slight increase in 2013. The reasons beyond such decrease of active fishing units in the IOTC convention area were related with the increase of exploitation costs (particularly oil in late 2000's), but also due to piracy related problems in the SW Indian Ocean, which has been traditionally the fishing area for the Portuguese fleet.

Given the objective of conducting a swordfish stock assessment for the Indian Ocean in 2014, and following the working documents presented by the authors in 2012 and 2013 (Santos et al., 2012, 2013), this study provides an updated overview of the swordfish catches by the Portuguese pelagic longline fishery operating in the Southwest Indian Ocean between 1998 and 2013. Specific objectives are to present new information on the catch and effort, catch-at-size, and CPUE trends (nominal and standardized) that can contribute to the stock assessment of swordfish in the Indian Ocean.

2. Material and methods

2.1. Catch and effort

In a recent effort by the *Portuguese Institute for the Ocean and Atmosphere* (*IPMA, I.P.)*, the historical catch and effort data from the Portuguese longliners targeting swordfish in the southwest Indian Ocean were compiled and analyzed. This included information on the catches, fishing effort in number of hooks per set and geographical location integrated from VMS data (**Table 1**). This data mining exercise allowed us to recover the entire time series for the Portuguese pelagic longline fleet operating in SW Indian Ocean.

Table 1: Number of fishing sets with catch, effort and location information carried out by the Portuguese pelagic longline fleet in the southwest Indian Ocean between 1998 and 2013. The percentage of sets per year analyzed for this paper is also indicated.

Year	Sets (N)	Sets with effort (hooks)	Sets with locations (VMS)	Sets used for analysis (%)
1998	106	106	106	100.0
1999	133	133	133	100.0
2000	270	270	270	100.0
2001	554	554	554	100.0
2002	480	480	480	100.0
2003	335	335	335	100.0
2004	297	297	297	100.0
2005	27	27	27	100.0
2006	1391	1391	1391	100.0
2007	637	637	637	100.0
2008	122	122	122	100.0
2009	269	269	269	100.0
2010	361	361	361	100.0
2011	292	292	292	100.0
2012	416	416	416	100.0
2013	922	922	922	100.0
Total	**6612**	**6612**	**6612**	**100.0**

The spatial catch and effort was mapped and plotted in order to identify the major areas of operation of the fleet in the SW Indian Ocean. The CPUE, measured in swordfish (SWO) biomass per 1000 hooks (kg/1000 hooks), was plotted along the quarters of the year, in order to describe the patterns of the catches of this species by the fleet in that region and seasons.

2.2. Catch-at-size

The catch-at-size data (LJFL, lower-jaw-fork-length in cm) came from the skippers logbooks that voluntarily provided these to IPMA, as well as from information collected by the Portuguese Fishery Observer program. However, most of the information used in this study comes from the first data source, as the Portuguese Fishery Observer program in the Indian Ocean only started collecting these data in 2011. A total of 42,015 individual swordfish specimens were measured and included in this analysis between 2001 and 2013.

For the catch-at-size analysis, histograms with the yearly swordfish catch-at-size distributions were created, and the mean sizes and boxplots were plotted by year and quarters. The mean sizes were compared with Kruskal-Wallis non-parametric rank sum tests, that were chosen instead of the parametric approaches (e.g. ANOVA), because the data was not normally distributed (tested with Kolmogorov Smirnov tests with Lilliefors correction) and was heterogeneous between groups (tested with Levene tests). Generalized Additive Models (GAMs) were also run to analyze and plot the non-linear effects of latitude and longitude in the sizes of the captured SWO specimens. For these models the response variable considered was the lower-jaw-fork-length (LJFL) and the explanatory variables were the latitude, longitude, month and year. The error distribution was assumed to follow a Gamma distribution and the link function used was the *log*. A residual analysis was conducted to validate these catch-at-size models.

2.3. CPUE standardization

The CPUE analysis was carried out using the official fisheries statistics collected by the Portuguese Fisheries authorities, 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 swordfish captured per fishing set. The available catch data started in 1998 and was analyzed until 2013. 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 CPUE were estimated with Generalized Linear Models (GLM).

There were some fishing sets with zero swordfish catches that result in a response variable of CPUE=0. As these zeros can cause mathematical problems for fitting the models, three different methodologies were used and compared, specifically tweedie, gamma and lognormal models. For the tweedie models the nominal CPUE was used directly for the response variable, given that this distribution can handle a certain proportion of zeros. For the gamma and lognormal models, the response variable was defined as the nominal CPUE + constant (*c*), with *c* set to 10% of the overall mean catch rate or to 1 (used in a sensitivity analysis). The value of *c*=10% of the mean has been recommended by Campbell (2004), as it 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%), the method of adding a constant to the response variable performs relatively well.

The covariates considered and tested in the models were:

- Year: analyzed between 1998 and 2013;
- Quarter of the year: 4 categories: 1 = January to March, 2 = April to June, 3 = July to September, 4 = October to December;
- Area: Using areas divided into 4 quadrants to account for finer scale spatial effects, or Longhust ecological regions (Longhurst, 2007); see **Figures 1 and 2 of the Annexes** for maps with the locations of the areas used;
- Vessel ID;
- Gear type: multifilament (old Spanish style) or monofilament (Florida style);
- Ratio: based on the SWO/SWO+BSH ratio of the captures;

- Quarter - Area interactions.

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) and the coefficient of determination (R^2). 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 factor ratio 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 *vs.* a more diffuse fishing strategy aimed at the two main species (SWO and BSH). Moreover, it has 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). The ratio factor was calculated each fishing set and then divided into ten categories using the 0.1 quantiles.

Once a final candidate model was selected, several sensitivity analyses were carried out to test the influence of the model type and the ratio variable on the final model:

- Sensitivity to model type: The base case model using a lognormal distribution with a constant of 10% of the mean was compared to 1) a lognormal model with a c=1, 2) a tweedie model and 3) a gamma model.
- Sensitivity to the ratio factor: The base model using the ratios categorized by the 0.1 quantiles was compared to 1) a model with a different ratio categorization of 0.25 instead of 0.1 quantiles, and 2) by removing the ratio factor from the model.
- Sensitivity to the area categorization: The base case model using the SW Indian Ocean region divided in 4 quadrants was compared to 1) the use of the Longhurst ecological regions (Longhurst, 2007) and 2) a model without spatial effects. **Figures 1 and 2 of the Annexes** provides maps with the definition of the areas used and tested in the models.

The various model specification and characteristics considered in this comparative approach are listed in detail in **Table 2**.

Table 2: Specifications of the candidate models run for the swordfish CPUE standardization for the SW Indian Ocean by the Portuguese pelagic longline fleet. The model types, specifications and explanatory variables are described, as well as some additional comments including the number of estimated parameters (pars). In the model characteristics, the "*c*" refers to the constant that was added to the response variable in the lognormal and gamma models.

	Model	Model characteristics	Explanatory variables	Comments
Base cases	Mod1	GLM lognormal (c=10% mean)	Year + Quarter + Area + Vessel + Ratio + Gear type	Full simple effect model (54 pars)
	Mod2	GLM lognormal (c=10% mean)	Year + Quarter + Area + Vessel + Ratio + Quarter:Area	Model with area:season interaction (62 pars)
Sensitivity to model type	Mod3	GLM lognormal (c=1)	Year + Quarter + Area + Vessel + Ratio + Quarter:Area	Lognormal GLM with area:season interaction (62 pars)
	Mod4	GLM tweedie (link=log)	Year + Quarter + Area + Vessel + Ratio + Quarter:Area	Tweedie GLM with area:season interaction (62 pars)
	Mod5	GLM gamma (link=log; c=10% mean)	Year + Quarter + Area + Vessel + Ratio + Quarter:Area	Gamma GLM with area:season interaction (62 pars)
Sensitivity to ratio factor	Mod6	GLM lognormal	Year + Quarter + Area + Vessel + Ratio + Quarter:Area	Model with ratio factor categorized by the 0.25 quantiles (56 pars)
	Mod7	GLM lognormal	Year + Quarter + Area + Vessel + Quarter:Area	Model without ratio factor (53 pars)
Sensitivity to Area	Mod8	GLM lognormal	Year + Quarter + AreaLongh + Vessel + Ratio + Quarter:AreaLongh	Using Longhurst ecological areas (54 pars)
	Mod9	GLM lognormal	Year + Quarter + Vessel + Ratio	Model without Area effects (50 pars)

Statistical analysis for this paper was carried out with the R Project for Statistical Computing version 3.0.1 (R Core Team, 2013) using several additional libraries (Wickham, 2009; Fox and Weisberg, 2011; Dunn, 2011; Højsgaard and Halekoh, 2012; Bivand and Lewin-Koh, 2013; Lenth, 2014).

3. Results and Discussion

3.1. Catch and effort

3.1.1. Spatial distribution of the catch and effort

The areas of operation in the SW Indian Ocean in terms of fishing effort for the Portuguese pelagic longline fleet, for the period between 1998 and 2013, is shown in **Figure 1**. Most of the effort took place throughout the region, but was mainly concentrated in the area south of Madagascar Island and closer to South Africa and south Mozambique (**Figure 1**).

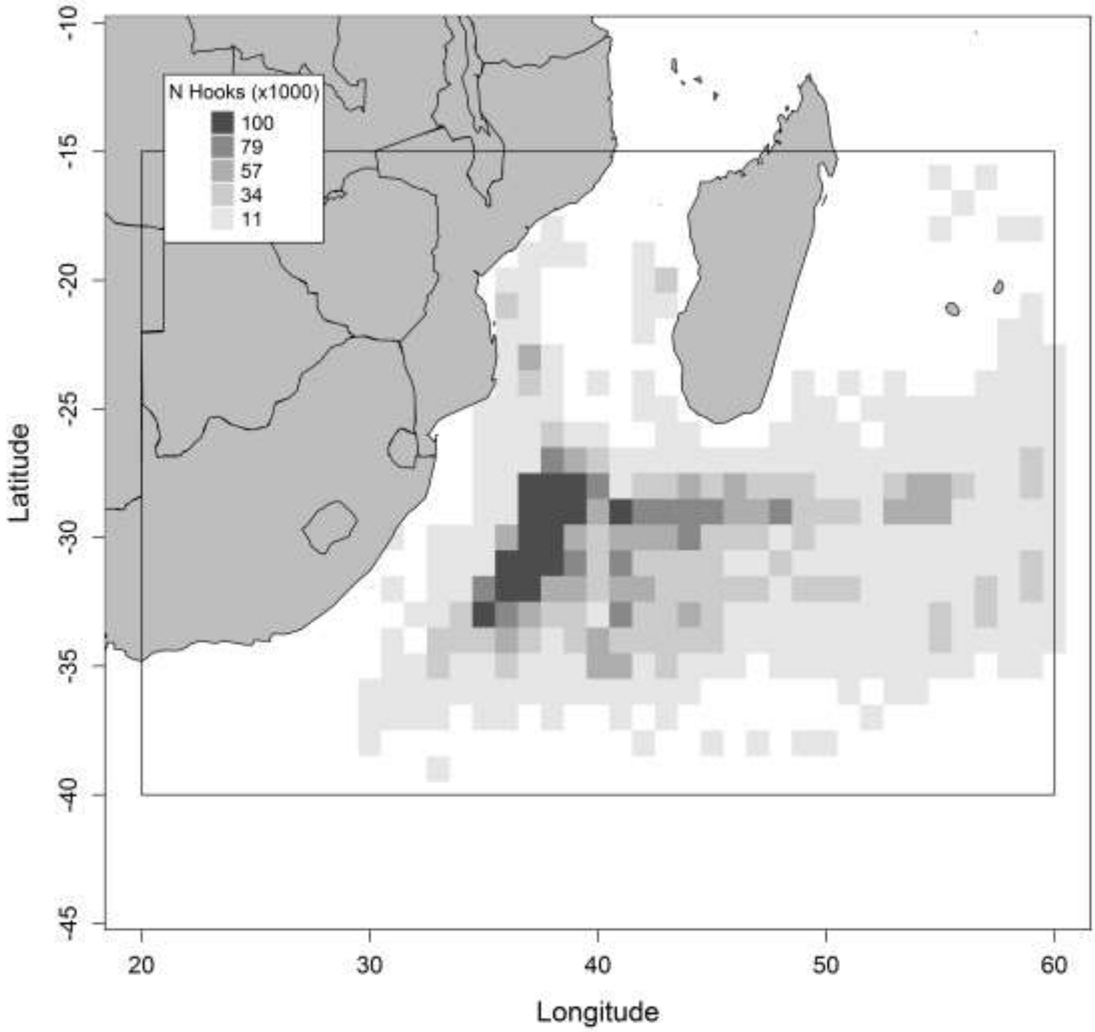

Figure 1. Effort distribution of the Portuguese pelagic longline fleet for the 1998-2013 period in the SW Indian Ocean. The effort is represented in 1°x1° grids with darker and lighter colors representing respectively to areas with more and less effort in number of hooks.

The SWO catches are also spread throughout the southwest Indian Ocean region, but also follow this general trend of a higher concentration south of Madagascar Island and closer to South Africa and south Mozambique (**Figure 2**).

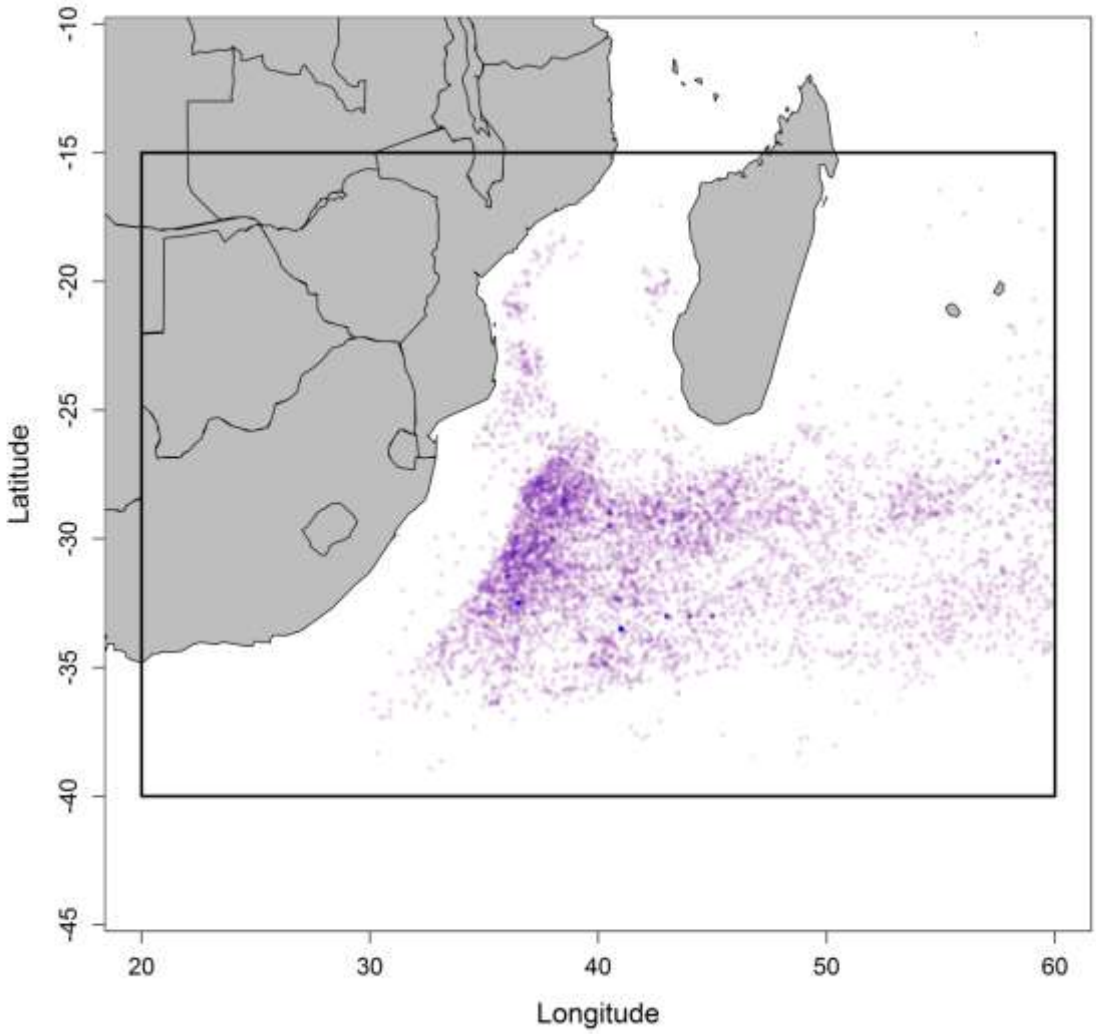

Figure 2. Location of the Portuguese pelagic longline sets reported by the fleet with logbooks between 1998 and 2013 for the southwest Indian Ocean. Full color saturation indicates higher swordfish CPUEs, while the lighter red color represents sets with zero SWO catches.

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 2006-2007and then a sharp decrease in the 2008 (**Figure 3**). Since then, and for the more recent years (2009 to 2013) the effort has been increasing again to values higher than in the early 2000's (**Figure 3**).

The total swordfish 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 for the more recent period (**Figure 3**). In terms of ratios of swordfish compared to the swordfish + blue shark catches, the ratios tended to be lower between 2000 and 2005, and higher in the more recent period between 2005 and 2013 (**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 by wire leaders) and bait (mackerel alternating with of squid, or instead of, in areas/periods of higher shark abundance). Several authors (Ward et al., 2009; Vega and Licandeo, 2009; Afonso et al., 2012) have demonstrated that higher blue shark catch rates are obtained when wire leaders are used.

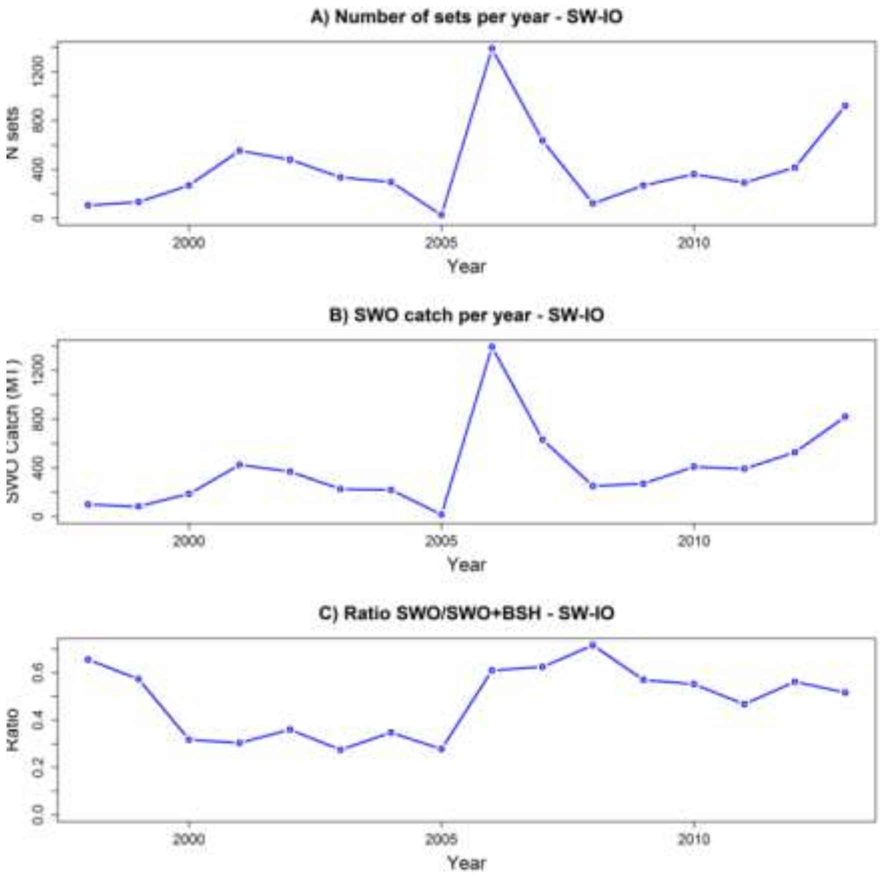

Figure 3: Descriptive plots of the total effort in sets (A), the total catch of swordfish (B), and the ratio of swordfish compared to the swordfish and blue shark catches (C), for the Portuguese longline fleet operating in the SW Indian Ocean.

No major pattern or trend was observed in the swordfish CPUE along the quarters of the year, that showed a high inter- and intra-annual variability (**Figure 4**).

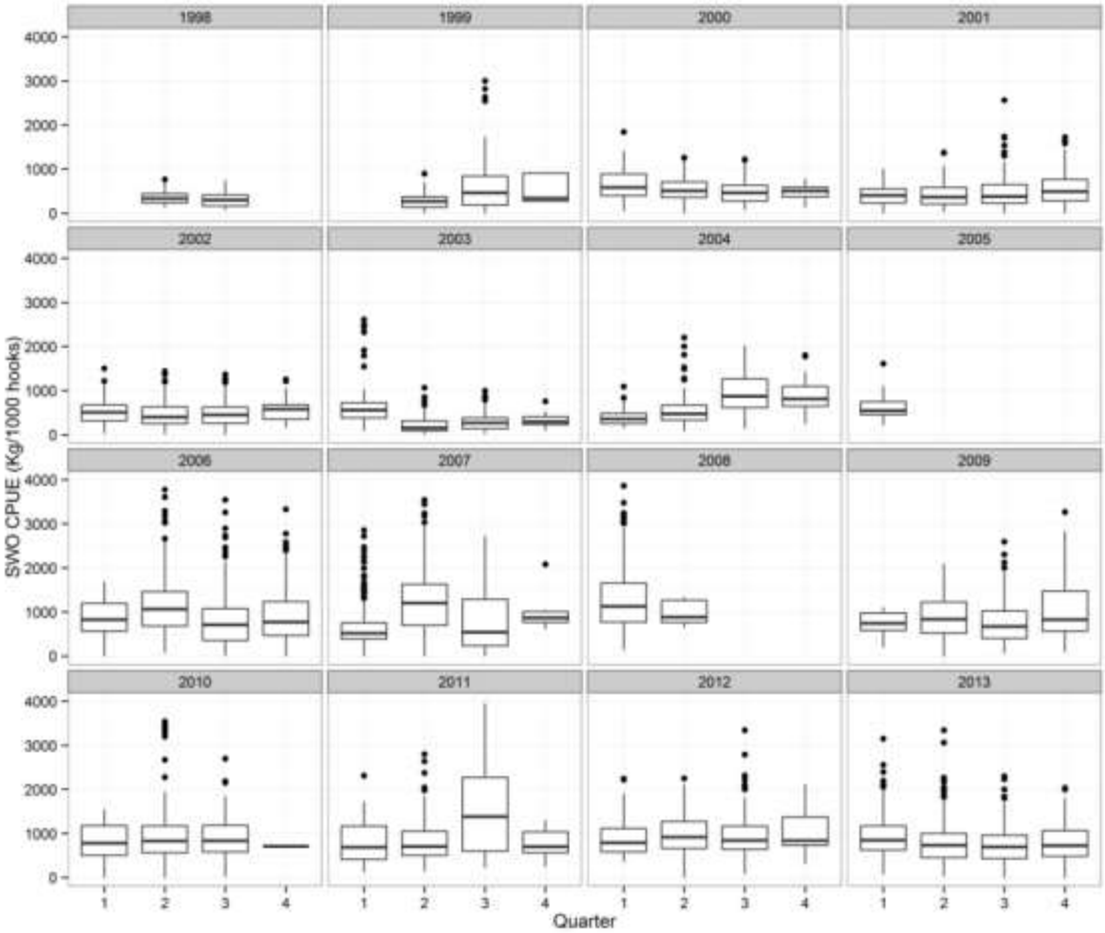

Figure 4. Quarterly swordfish CPUE (kg/1000 hooks) by the Portuguese pelagic longline fleet in the SW Indian Ocean, per year. In the boxplots the middle lines represents the median, the box the quartiles, the whiskers the non-outlier range and the points the outliers.

3.2. Catch-at-size

3.2.1. Yearly variability in the catch-at-size

The size distribution of the swordfish captured in the southwest Indian Ocean by the Portuguese fleet showed a relatively decreasing trend in the initial years between 2001 and 2007, and a general increasing trend in the more recent year until 2013 (**Figure 5** and **Figure 6**), with those differences being statistically significant (Kruskal-Wallis: chi-square = 2368.3, df = 11, p-value < 0.001).

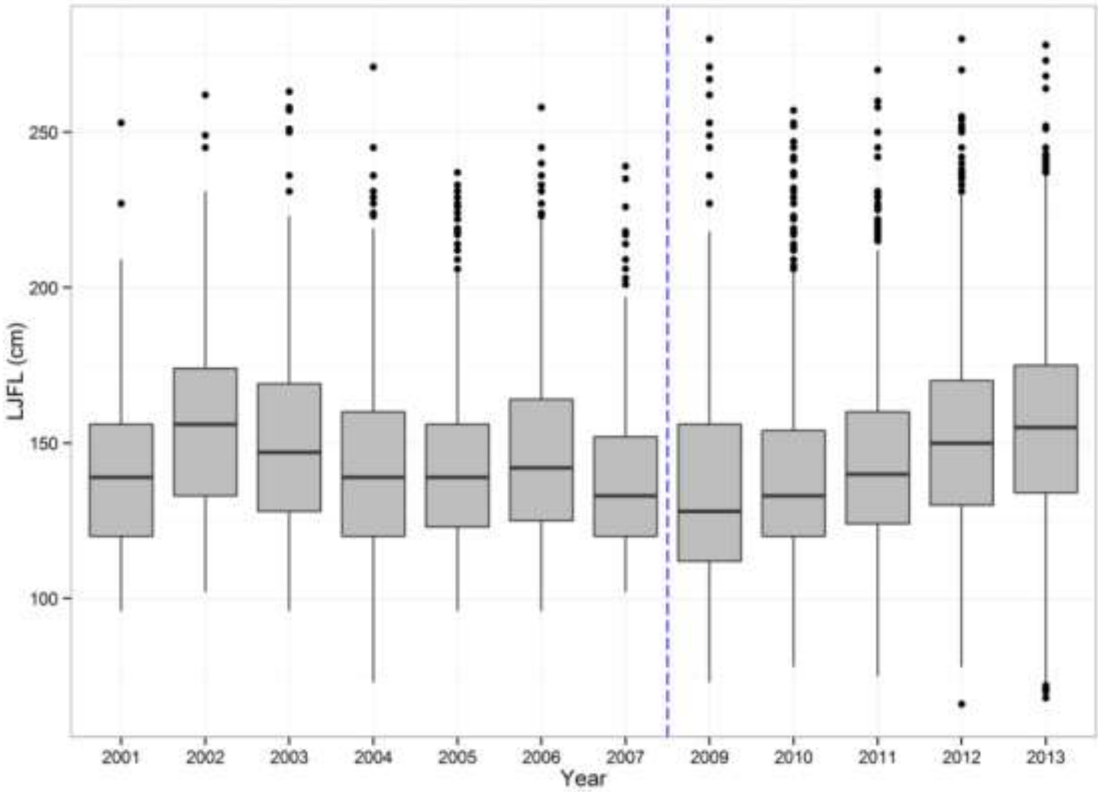

Figure 5. Yearly boxplots with the catch-at-sizes for the swordfish (LJFL, lower-jaw-fork-length in cm) reported by the Portuguese pelagic longline fishery in the SW Indian Ocean. In the boxplots the middle lines represents the median, the box the quartiles, the whiskers the non-outlier range and the points the outliers. Note that there is a break in 2008 for which catch-at-size data is not available.

The analysis of **Figures 5** and **6** shows that during the 2000's the catches were mostly composed of juveniles, but being particularly noted on the second half of that decade. This was probably due to strong recruitment in that period, namely on the mid-2000, which cohort could be followed until 2013. However, such high recruitment seems not to be occurring in the most recent years. In fact, although the catch-at-size distribution showed a constant size range, it is more skewed to the right and consequently an increase of median size was observed. However, we cannot exclude that this trends are not a consequence of the re-distribution of the effort, rather than a recruitment issue (see **Figure 3 of the Annex** for yearly effort maps).

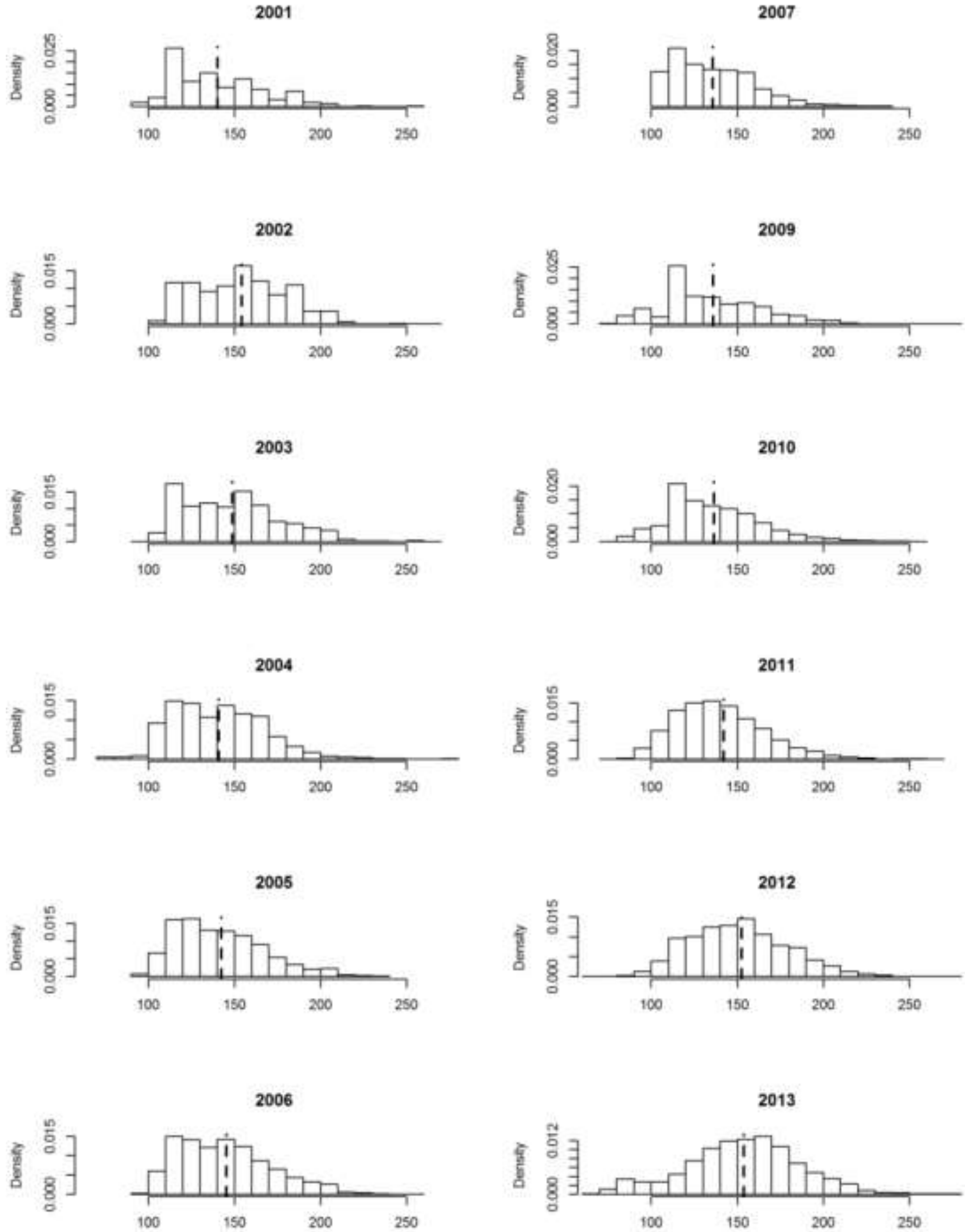

Figure 6. Frequency distribution of swordfish captured by the Portuguese longline fleet in the SW Indian Ocean between 2001 and 2013. The dotted vertical lines represent the yearly mean swordfish catch-at-size (LJFL, lower-jaw-fork-length in cm).

3.2.2. Seasonal and spatial variability in the catch-at-size

In terms of seasonal variability some differences were detected in the catch-at-size, but in general all quarters followed the same general size trend along the time series (**Figure 7**), with the differences between the quarters being statistically significant (Kruskal-Wallis: chi-square = 192.2, df = 3, p-value < 0.001).

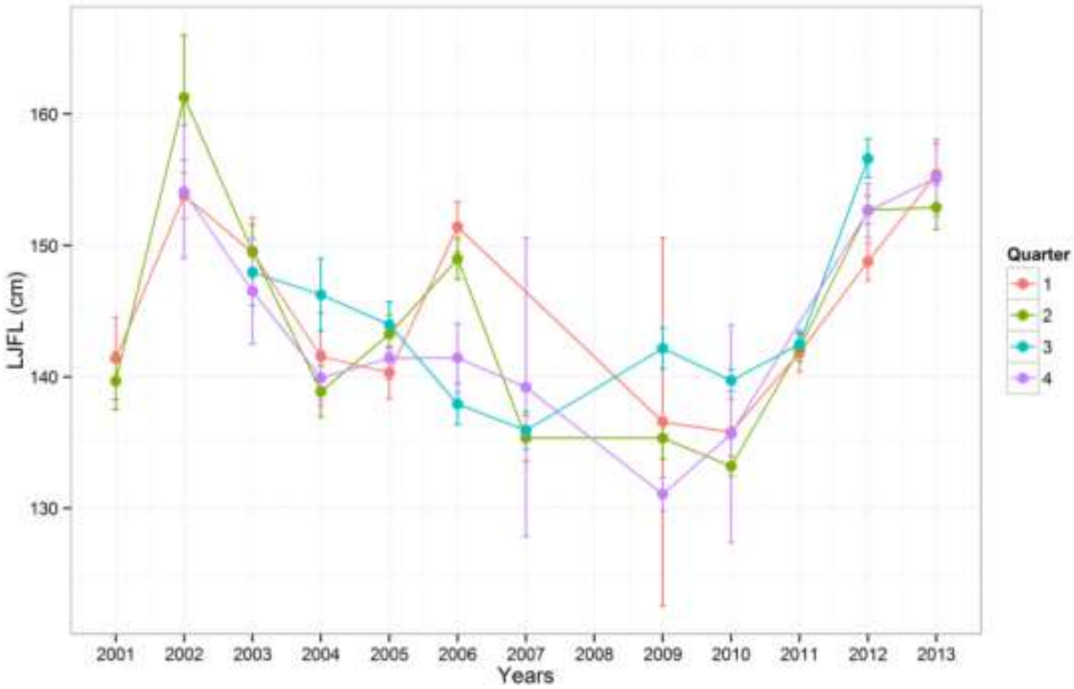

Figure 7. Mean yearly catch-at-size for the swordfish reported by the Portuguese pelagic longline fishery in the SW Indian Ocean in each quarter of the year. The error bars represent the 95% confidence intervals.

The spatial effects were investigated by plotting the non-linear effects of the latitude and longitude in a GAM model using year, month, latitude and longitude. It was possible to observe a tendency for larger swordfish specimens being captured towards southern latitudes, both at eastern and western longitudes of the SW Indian Ocean region (**Figure 8**). In the same model, it was also possible to observe the partial effects of year and month. In terms of years, the sizes decreased until the middle of the time series and then increased in the more recent years, while in terms of months the sizes tended to be larger in the 2nd semester of the year (**Figure 8**).

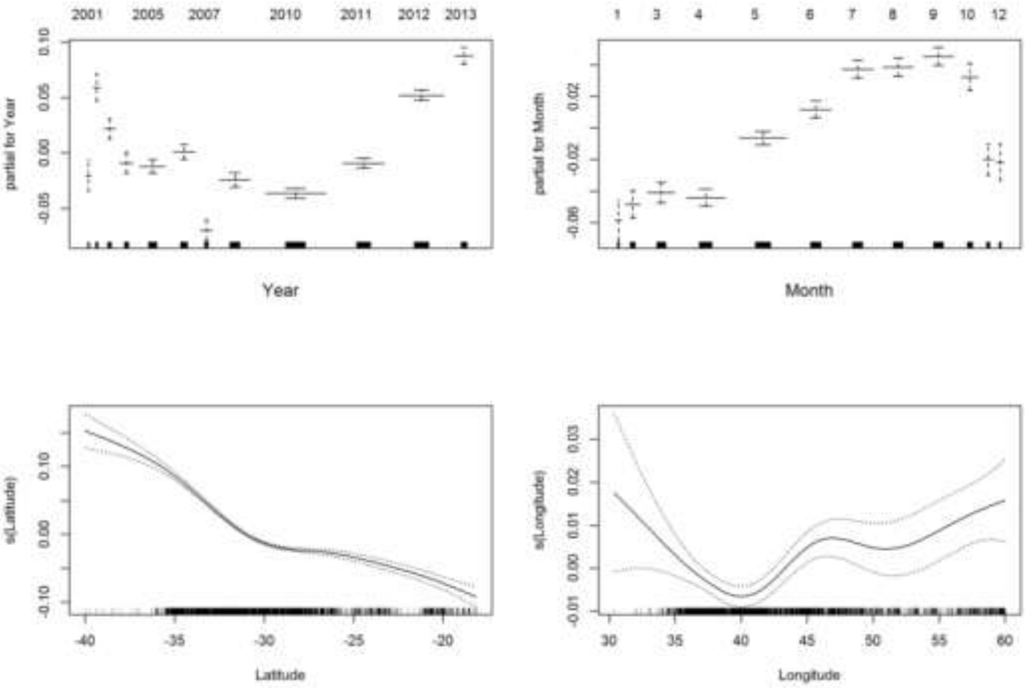

Figure 8. GAM plots with the partial effects of year, month, latitude and longitude on the swordfish catch-at- sizes in the SW Indian Ocean by the Portuguese pelagic longline fleet, in a model using a Gamma distribution with a log link function.

3.3. CPUE standardization

3.3.1. CPUE data characteristics

The nominal time series of the swordfish CPUE for the Portuguese pelagic longline fleet operating in the SW Indian Ocean is presented in **Figure 9**. There was a tendency for the CPUE to increase substantially in the first years of the fishery between 1998 and 2008, followed by a general decreasing trend in the more recent period between 2008 and 2013 (**Figure 9**).

The percentage of fishing sets with zero catches of SWO in the SW Indian Ocean was very low, specifically 0.55%. This level of low percentages of fishing sets with zero SWO catches are similar, for example, to what has been previously reported by the Spanish fleet targeting swordfish in the same area, which reported values of fishing sets with zero catches generally lower than 1% (Ramos-Cartelle et al., 2011), and also for the Portuguese fleet operating along wider areas of the Indian Ocean (Santos et al., 2013). The nominal swordfish CPUE distribution was highly skewed to the right and become more normal shaped in the log-transformed scale (**Figure 10**).

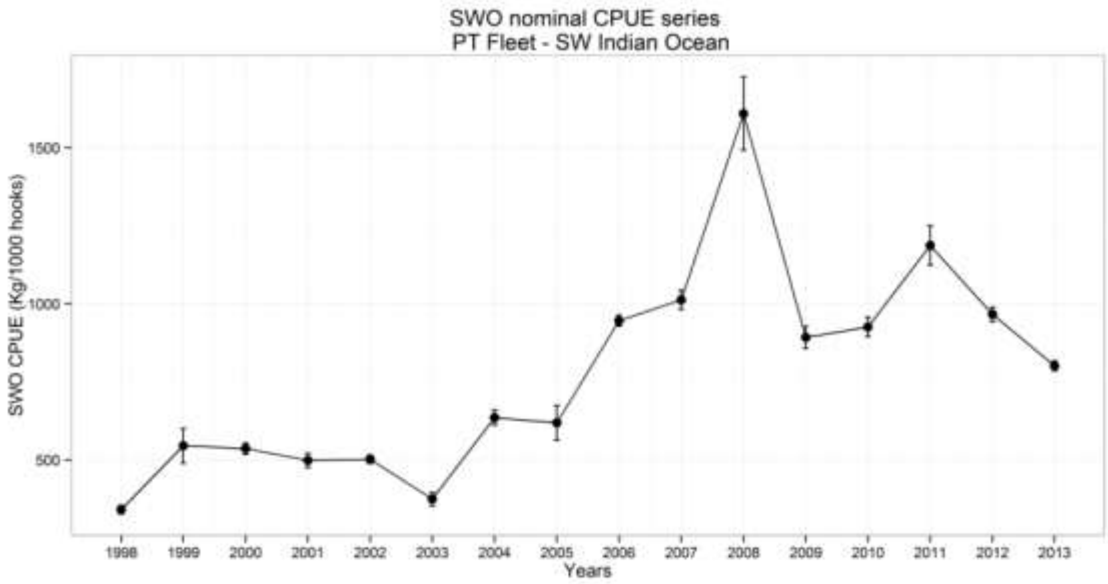

Figure 9. Nominal CPUE series (kg/1000 hooks) for swordfish caught by the Portuguese pelagic longline fishery in the southwest Indian Ocean, between 1998 and 2013. The error bars refer to the standard errors.

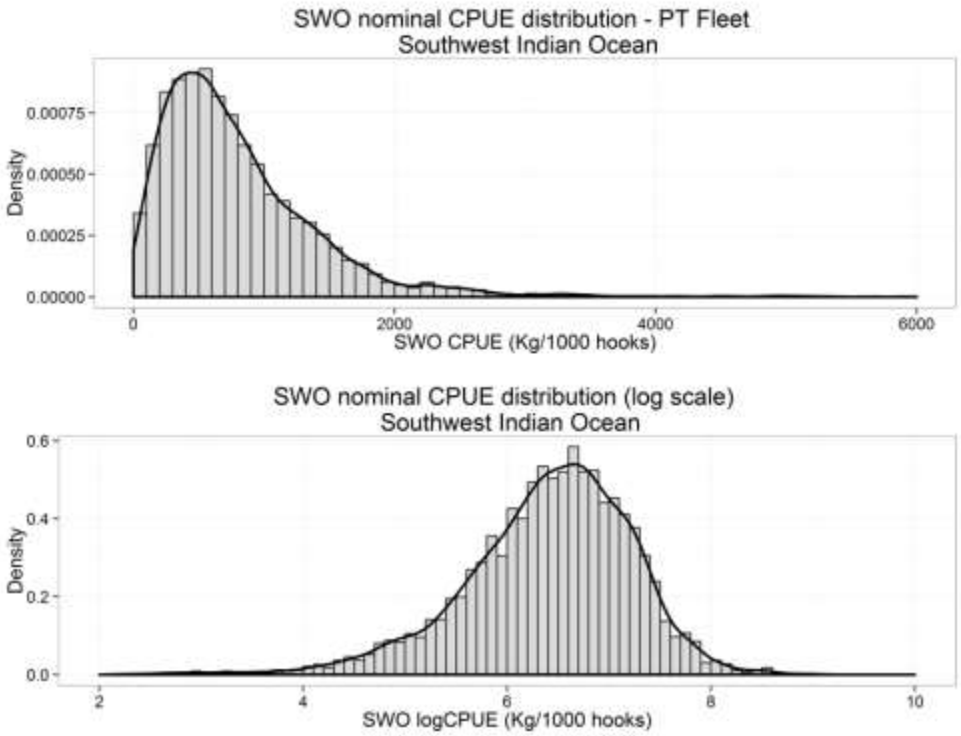

Figure 10: Distribution of the nominal swordfish CPUE captured by the Portuguese longline fleet in the SW Indian Ocean in non-transformed (top plot) and log-transformed (bottom plot) scales.

The lower nominal CPUE in the early years of the time series was most probably related to the use of the traditional Spanish style longline gear in the period. It is known that the currently used monofilament gear (Florida style) is more efficient (see Vega and

Licandeo, 2009; and references therein). It is worth noting that the entire Portuguese fleet shifted to the new gear by the mid-2000.

3.3.2. Model construction

For the base case lognormal models, all the explanatory variables tested for the swordfish CPUE standardization were significant and contributed significantly for explaining part of the deviance, except the gear type that was not significant and was therefore removed from the final models. This is likely due to the fact that most vessels changed to the modern gear type around the same time period, and therefore there is a lack of contrasts of both gear types on all the years and this creates modeling problems. The interaction between area and quarter was significant and improved the goodness-of-fit (decrease in AIC and increase in R^2) and was therefore included in the models (**Table 3**).

On both models (with and without spatial:seasonal interactions), the factors that contributed most for the deviance explanation were the ratio factor followed by the year and the vessel effects (**Table 3**). In terms of model validation both models seemed adequate for this particular situation with a low quantity of zeros, as the residual analysis, including the residuals distribution along the fitted values, the QQ plots and the residuals histograms, did not identified any major problems in the models (**Figure 11**).

Table 3. Deviance table of the parameters used for the swordfish CPUE standardization models for the SW Indian Ocean using a lognormal error distribution with c=10% of the mean. For each parameter it is indicated the degrees of freedom used (Df), the deviance explained (Dev), the residual degrees of freedom (Resid Df) and deviance (Resid Dev) after incorporating sequentially each variable. The significance (F-stat and p-value) of each variable is also indicated as well as the goodness-of-fit values (AIC and R^2).

Model	Variables	Df	Dev	Resid Df	Resid Dev	F-stat	*p-value*
Mod 1: Full simple effects model (AIC=7712; R^2=61.2%)	Intersept only			6605	3179.9		
	Year	15	600.1	6590	2579.8	214.4	< 0.001
	Year + Quarter	3	6.2	6587	2573.6	11.1	< 0.001
	Year + Quarter + Area	3	8.5	6584	2565.1	15.2	< 0.001
	Year + Quarter + Area + Vessel	23	555.7	6561	2009.4	129.5	< 0.001
	Year + Quarter + Area + Vessel + Ratio	9	787.2	6552	1222.2	468.8	< 0.001
	Year + Quarter + Area + Vessel + Ratio + Gear type	1	0.01	6551	1222.2	0.05	0.823
Mod 2: Model with spatial/seasonal interaction (AIC=7579; R^2=62.1%)	Intersept only			6605	3179.9		
	Year	15	600.1	6590	2579.8	219.1	< 0.001
	Year + Quarter	3	6.2	6587	2573.6	11.4	< 0.001
	Year + Quarter + Area	3	8.5	6584	2565.1	15.5	< 0.001
	Year + Quarter + Area + Vessel	23	555.7	6561	2009.4	132.3	< 0.001
	Year + Quarter + Area + Vessel + Ratio	9	787.2	6552	1222.2	478.9	< 0.001
	Year + Quarter + Area + Vessel + Ratio + Quarter:Area	9	27.3	6543	1194.9	16.6	< 0.001

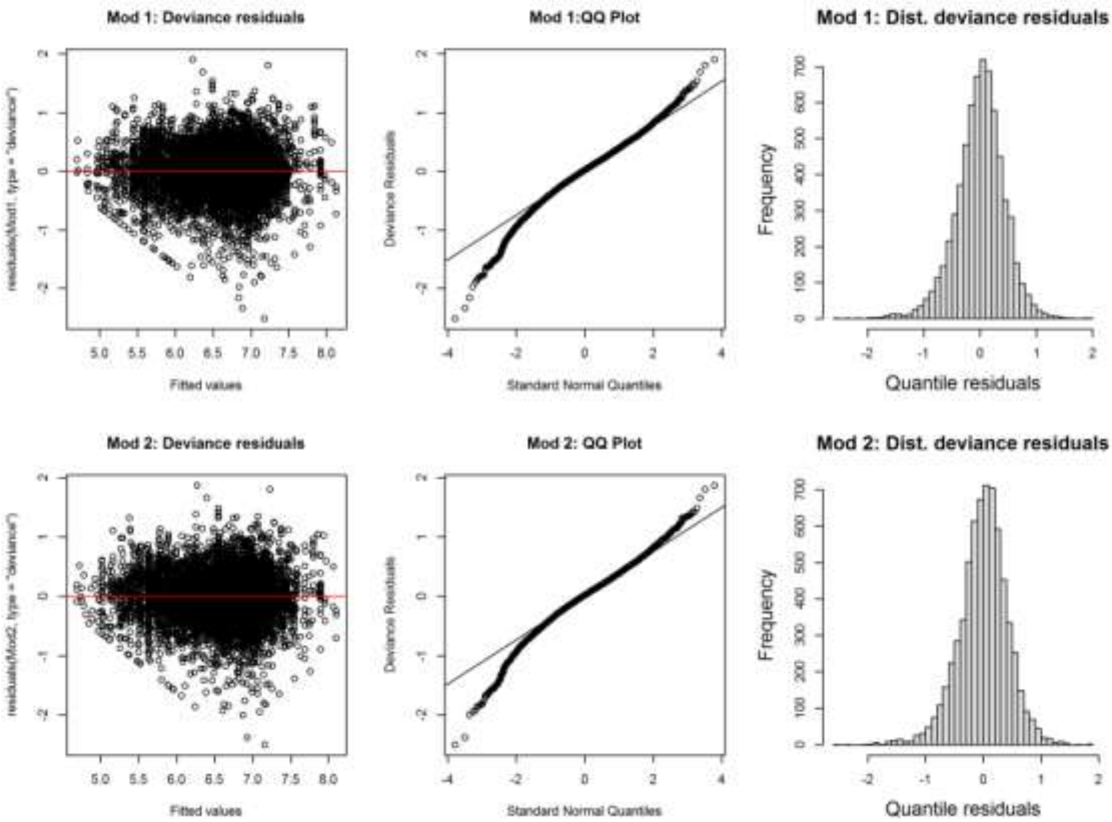

Figure 11. Residual analysis for the lognormal models tested for the swordfish CPUE standardization in the SW Indian Ocean, specifically a model with simple effects only (Mod 1) and a model with quarter/area interactions (Mod 2). For each model it is presented the residuals along the fitted values on the log scale (graphics on the left), the QQPlot (graphics on the middle) and the histogram of the distribution of the residuals (graphics on the right).

For those two first models using a lognormal error distribution with and without season:area interaction, the relative indexes of abundance were relatively similar. On both cases the index showed an increase in the initial years between 1998 and 2000, followed by a decreasing period between 2000 and 2005, then another increase until 2008, and finally a general decrease in the more recent years until 2013 (**Figure 12**). This overall trend followed, in general, the patterns observed in the nominal CPUE series (**Figure 9**).

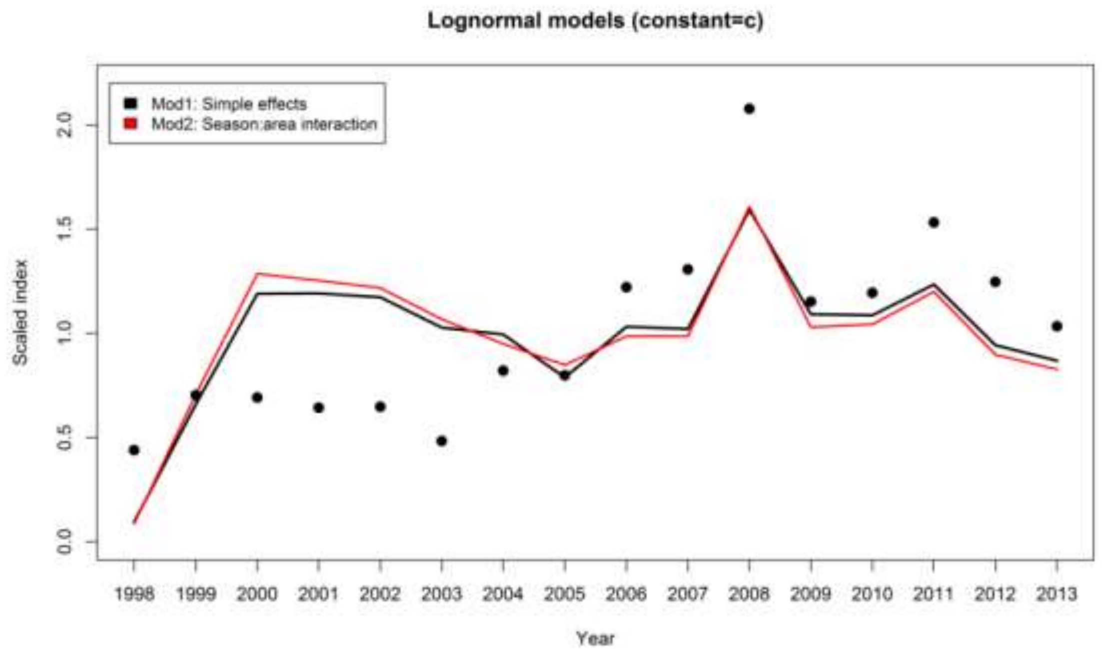

Figure 12. Standardized CPUE series for swordfish captured by the Portuguese pelagic longline fleet in the SW Indian Ocean using a lognormal GLM with and without interactions. The solid lines and the black dots refer respectively to the standardized and nominal CPUE series.

3.3.3. Sensitivity to the model type

A sensitivity analysis was run for testing various candidate model types that were compared to the original lognormal (adding a constant *c*=10% of the mean). Specifically, the tested models were a lognormal with constant c=1, a tweedie model and a gamma with constant *c*=10% of the mean.

The comparison of those models with the base case lognormal, resulted in relatively similar results between all cases, except for the lognormal adding *c*=1 (**Figure 13**). In this last case, the values of the index were higher than in the other models for the first years of the series, and lower at the end of the series (**Figure 13**).

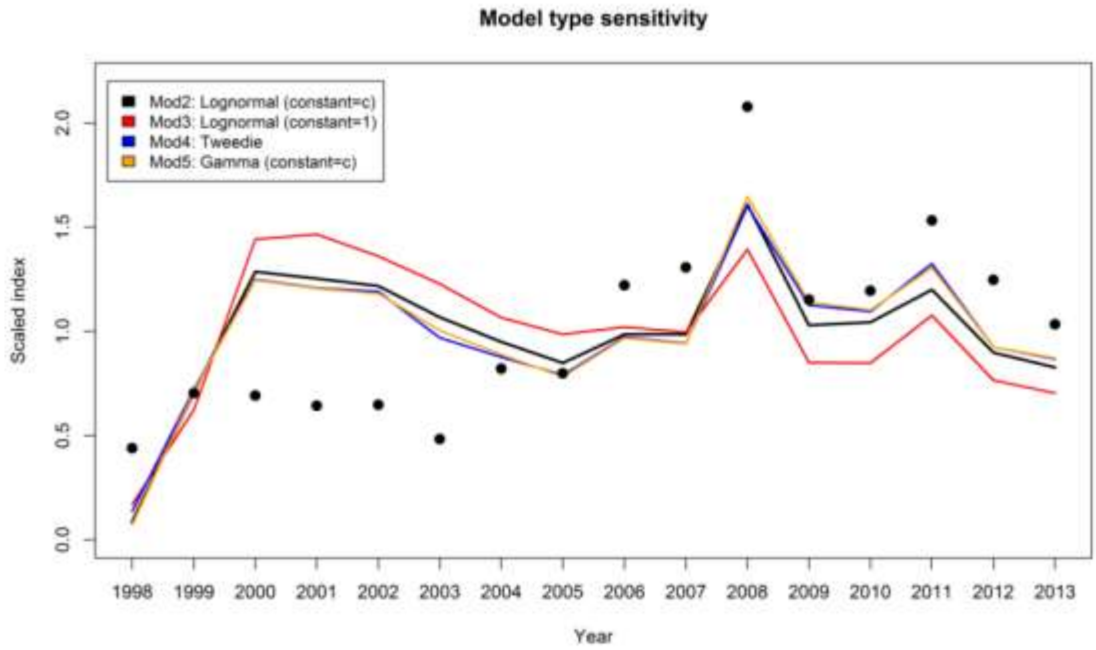

Figure 13. Sensitivity analysis to the model type for the swordfish CPUE standardization from the Portuguese pelagic longline fleet in the SW Indian Ocean. The scaled annual indexes of abundance of the final model selected (Mod2) is represented in black, and compared to alternative models in red (Mod3: lognormal with constant=1), blue (Mod4: tweedie model) and orange (Mod5: gamma model).

Like in the base case, the factors that contributed most for the deviance explanation were the ratio factor followed by the year and the vessel effects (**Table 4**). In terms of R^2 comparison, the best fitted model was the original lognormal using a constant of 10% of the mean (Mod2: R^2=62.1%). Note that in this case the AIC values are not compared because the response variable (CPUE, CPUE+c and CPUE+1) is not the same for all models.

Table 4. Deviance table of the parameters for the sensitivity analysis of the model types for the swordfish CPUE standardization in the SW Indian Ocean. For each parameter it is indicated the degrees of freedom used (Df), the deviance explained (Dev), the residual degrees of freedom (Resid Df) and deviance (Resid Dev) after incorporating sequentially each variable. The significance (F-stat and p-value) of each variable is indicated as well as the R^2 values.

Model	Variables	Df	Dev.	Resid. Df	Resid. Dev	F-stat.	*p-value*
Mod 3: lognormal (cons=1) (R^2=56.3%)	Intersept only			6605	5951		
	Year	15	885.3	6590	5066	150.0	< 0.001
	Year + Quarter	3	7.1	6587	5059	6.0	< 0.001
	Year + Quarter + Area	3	28.4	6584	5031	24.0	< 0.001
	Year + Quarter + Area + Vessel	23	844.2	6561	4186	93.3	< 0.001
	Year + Quarter + Area + Vessel + Ratio	9	1547.4	6552	2639	437.1	< 0.001
	Year + Quarter + Area + Vessel + Ratio + Quarter:Area	9	65.2	6543	2574	18.4	< 0.001
Mod 4: tweedie (R^2=58.9%)	Intersept only			6605	27678		
	Year	15	5022.8	6590	22656	208.6	< 0.001
	Year + Quarter	3	28.7	6587	22627	6.0	< 0.001
	Year + Quarter + Area	3	70.6	6584	22556	14.6	< 0.001
	Year + Quarter + Area + Vessel	23	4932.3	6561	17624	133.6	< 0.001
	Year + Quarter + Area + Vessel + Ratio	9	6141.0	6552	11483	425.1	< 0.001
	Year + Quarter + Area + Vessel + Ratio + Quarter:Area	9	220.0	6543	11263	15.2	< 0.001
Mod 5: gamma (cons=c) (R^2=61.8%)	Intersept only			6605	3000		
	Year	15	576.4	6590	2424	216.9	< 0.001
	Year + Quarter	3	2.3	6587	2421	4.4	< 0.001
	Year + Quarter + Area	3	9.4	6584	2412	17.6	< 0.001
	Year + Quarter + Area + Vessel	23	553.6	6561	1858	135.9	< 0.001
	Year + Quarter + Area + Vessel + Ratio	9	700.2	6552	1158	439.2	< 0.001
	Year + Quarter + Area + Vessel + Ratio + Quarter:Area	9	24.0	6543	1134	15.0	< 0.001

In terms of residual analysis there were some problems with the lognormal model with constant *c*=1 (Mod 3) that were particularly noticeable in the QQPlot (**Figure 14**). For the tweedie (Mod4) and gamma (Mod5) models the residual analysis produced better and very similar results (**Figure 14**).

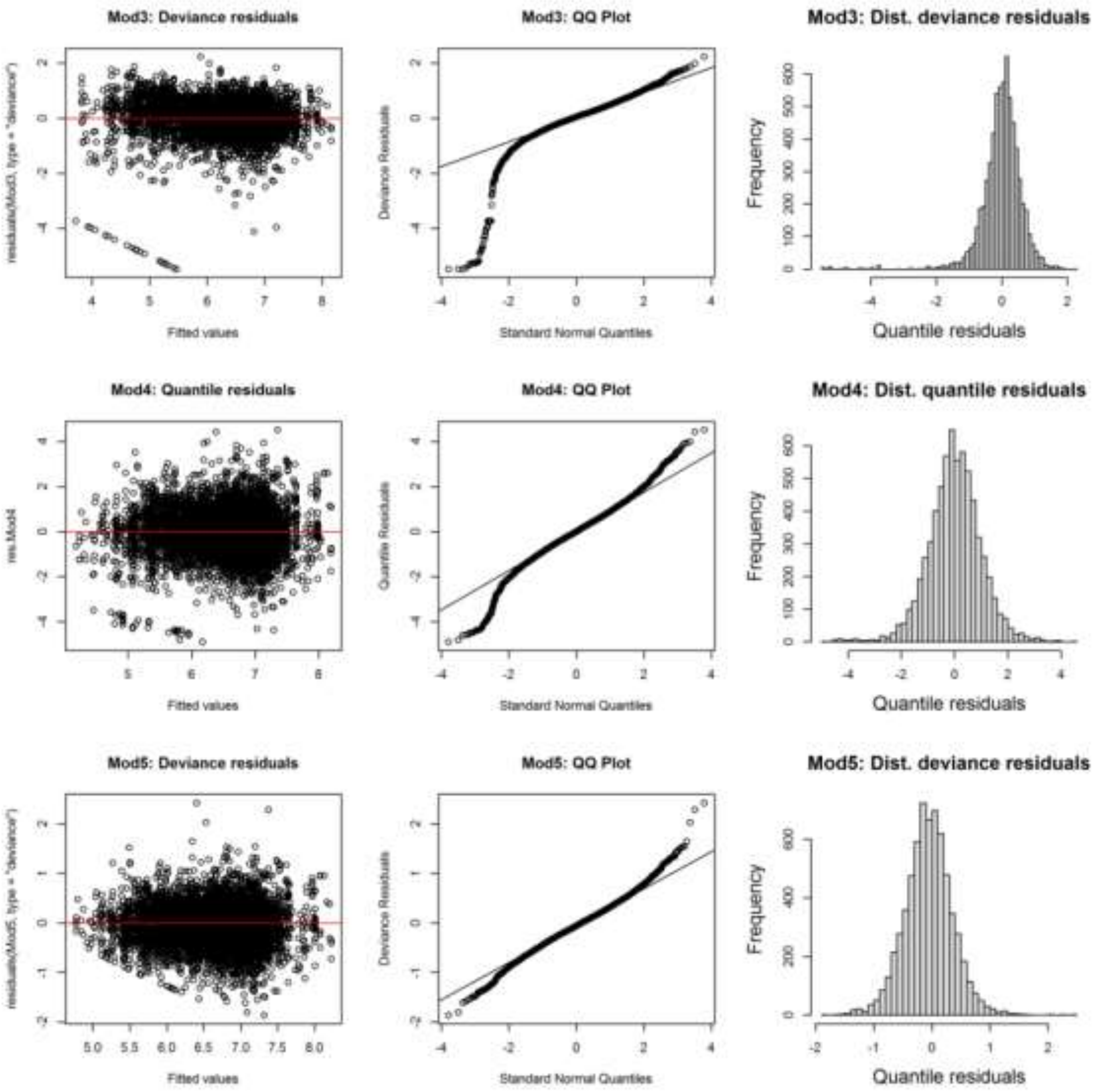

Figure 14. Residual analysis for the various model types (sensitivity analysis) tested for the swordfish CPUE standardization in the SW Indian Ocean, specifically a lognormal with constant c=1 (Mod 3), a tweedie model (Mod4) and a gamma model (Mod 5). For each model it is presented the residuals along the fitted values on the log scale (graphics on the left), the QQPlot (graphics on the middle) and the histogram of the distribution of the residuals (graphics on the right).

3.3.4. Sensitivity to the Ratio factor

Another sensitivity analysis was run for testing the influence of the ratio (swordfish/swordfish + blue shark) factor on the CPUE series and various candidate models were compared to the original model. Specifically, the original model that was using the ratios categorized by the 0.1 quantiles was compared to a model using the ratios categorized by the 0.25 quantiles and with another model without the ratio factor. This analysis revealed some differences in the standardized CPUE series, particularly when the ratio variable was removed from the model (**Figure 15**). However, the general pattern of the CPUEs remained similar even when the ratio factor was removed, with an increase in the first few years of the series, followed by a general decrease until 2005, then followed by an increase until 2008 and then a general decrease for the more recent years (**Figure 15**).

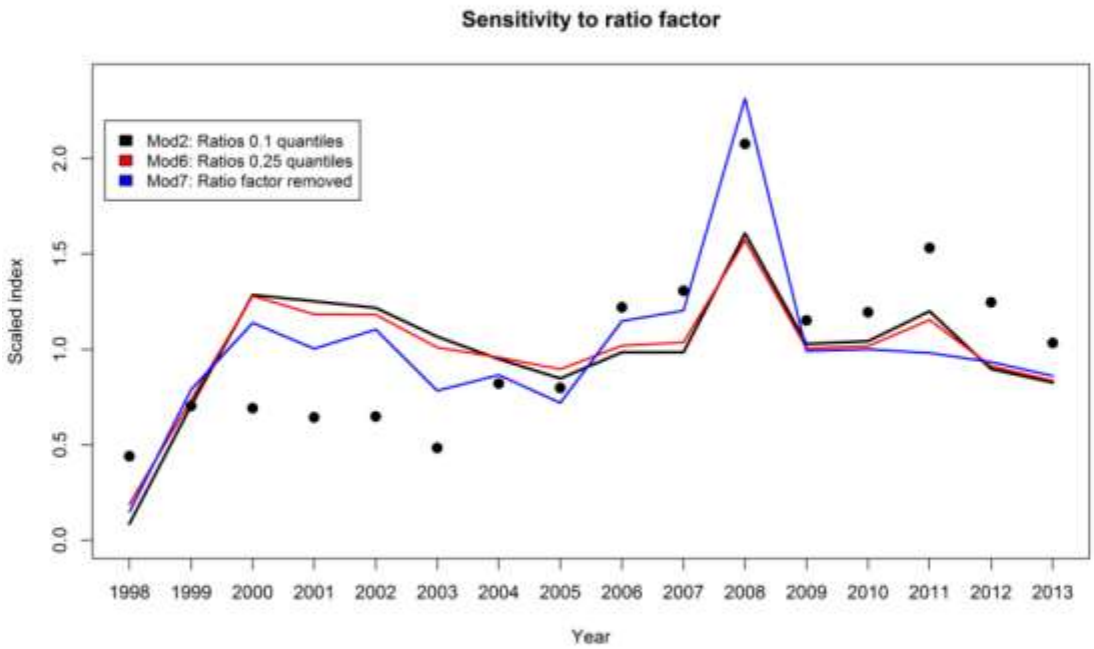

Figure 15. Model sensitivity to the factor ratio for the swordfish CPUE standardization from the Portuguese pelagic longline fleet in the SW Indian Ocean. The scaled annual indexes of abundance of the final model selected (Mod2) is represented in black, and the alternative models in red (Mod6: using a different ratio categorization) and blue (Mod7: removing the ratio factor).

In terms of goodness-of-fit, the best fitted model was the original one that used the ratios categorized by the 0.1 quantiles. Using a different categorization produced a slightly worse fit, and by removing the ratio factor the fit was much worse with a high decrease in the R^2 and a high increase in the AIC (**Table 5**). In terms of residual analysis, there were no major differences in the models using or not the ratio variable (**Figure 16**).

Table 5. Deviance table of the parameters for the sensitivity analysis of the ratio variable for the swordfish CPUE standardization in the SW Indian Ocean. For each parameter it is indicated the degrees of freedom used (Df), the deviance explained (Dev), the residual degrees of freedom (Resid Df) and deviance (Resid Dev) after incorporating sequentially each variable. The significance (F-stat and p-value) of each variable is indicated as well as the R^2 values.

Model	**Variables**	**Df**	**Dev.**	**Resid. Df**	**Resid. Dev**	**F-stat.**	***p-value***
Mod 6: Ratio categorization (AIC=8329; R^2=57.5%)	Intersept only			6605	3179.9		
	Year	15	600.1	6590	2580	195.4	< 0.001
	Year + Quarter	3	6.2	6587	2574	10.1	< 0.001
	Year + Quarter + Area	3	8.5	6584	2565	13.9	< 0.001
	Year + Quarter + Area + Vessel	23	555.7	6561	2009	118.0	< 0.001
	Year + Quarter + Area + Vessel + Ratio	3	640.6	6558	1369	1042.8	< 0.001
	Year + Quarter + Area + Vessel + Ratio + Quarter:Area	9	27.7	6549	1341	15.0	< 0.001
Mod 7: Removing ratio variable (AIC=10809; R^2=38.1%)	Intersept only			6605	3179.9		
	Year	15	600.1	6590	2579.8	134.2	< 0.001
	Year + Quarter	3	6.2	6587	2573.6	7.0	< 0.001
	Year + Quarter + Area	3	8.5	6584	2565.1	9.5	< 0.001
	Year + Quarter + Area + Vessel	23	555.7	6561	2009.4	81.0	< 0.001
	Year + Quarter + Area + Vessel + Quarter:Area	9	55.6	6552	1953.8	20.7	< 0.001

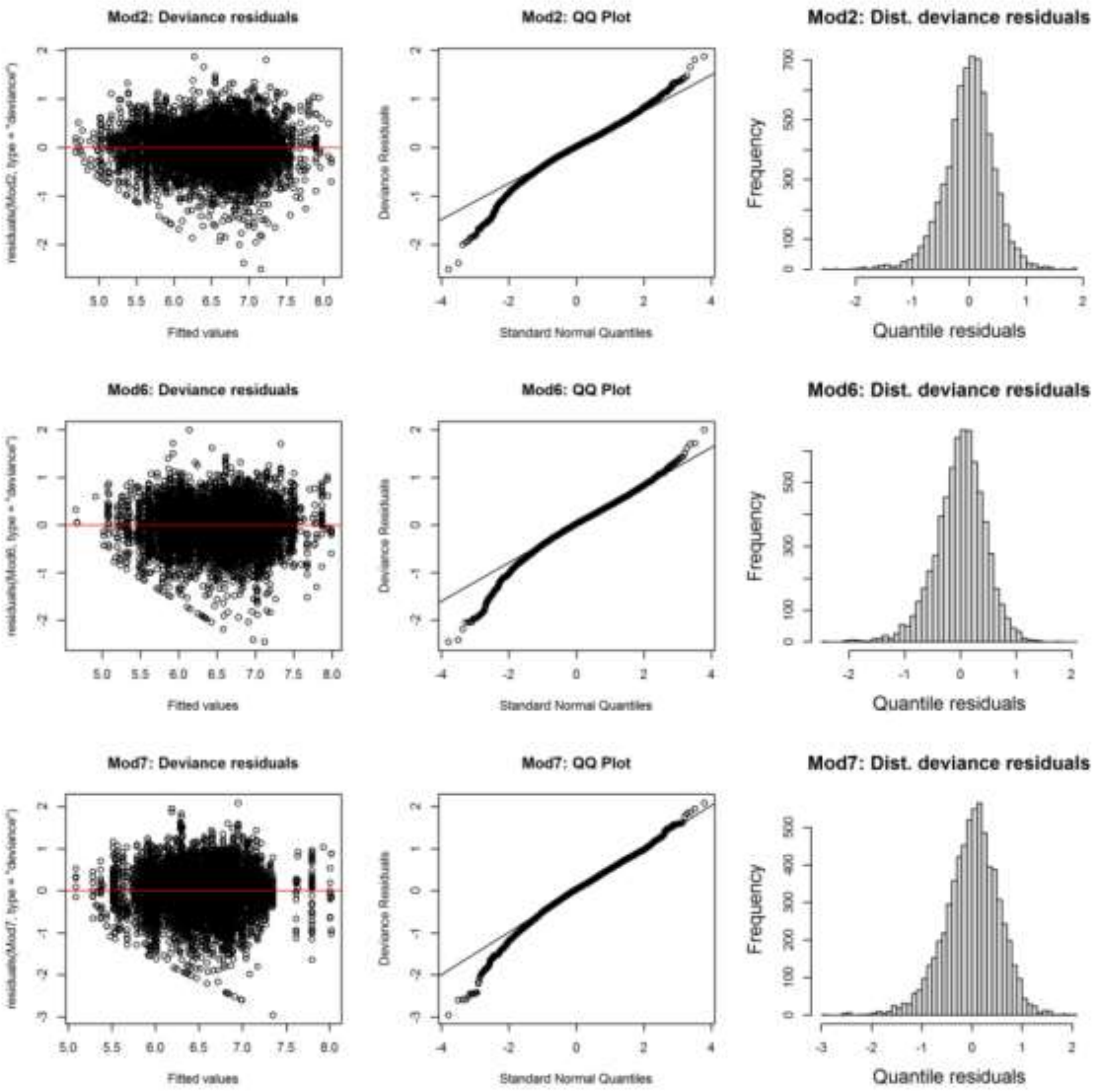

Figure 16. Residual analysis for the various model tested for the sensitivity to the ratio factor for the swordfish CPUE standardization in the SW Indian Ocean. Mod 2 is the base case model with the ratios categorized by the 01 quantiles, Mod 6 uses a different ratio categorization (0.25 quantiles) and Mod 7 does not include the ratio factor. For each model it is presented the residuals along the fitted values on the log scale (graphics on the left), the QQPlot (graphics on the middle) and the histogram of the distribution of the residuals (graphics on the right).

3.3.5. Sensitivity to the Area

Another sensitivity analysis was run for testing the influence of the areas used on the CPUE series and various candidate models were compared to the original model. Specifically, the original model that was using the SW Indian Ocean divided in quadrants was compared to a model using the Longhurst areas and another model without the area effects. This analysis revealed very little differences in the standardized CPUE series, even when the area factor was removed (**Figure 17**). This may be occurring, as those models are only for the SW Indian ocean region here the spatial effects influencing the swordfish CPUE are smaller.

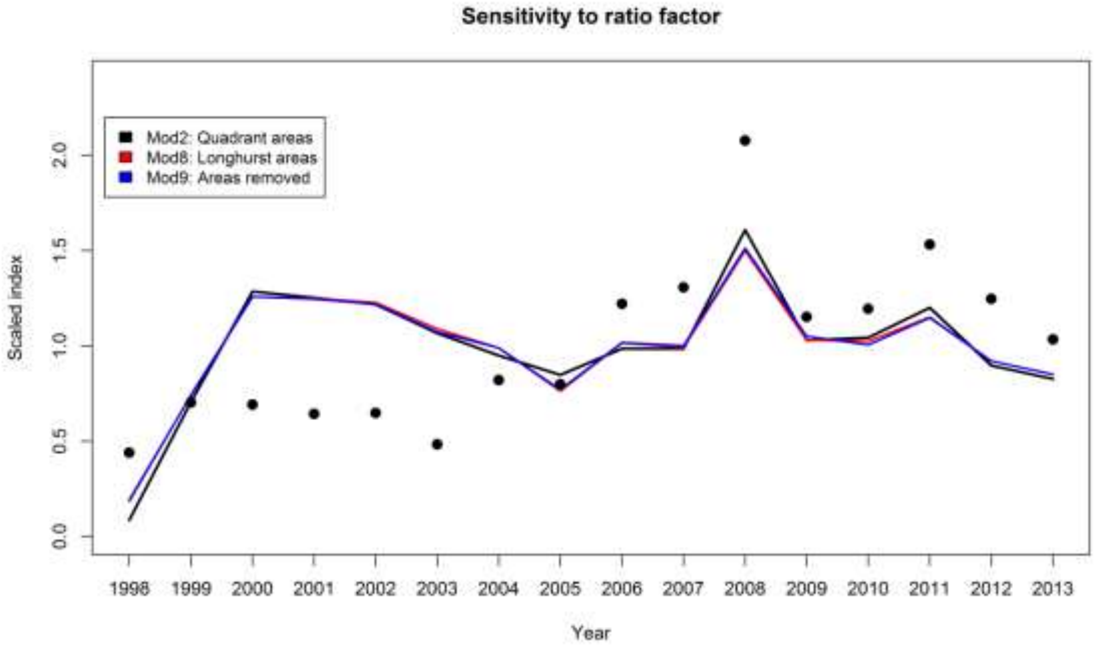

Figure 17. Model sensitivity to the area factor for the swordfish CPUE standardization from the Portuguese pelagic longline fleet in the SW Indian Ocean. The scaled annual indexes of abundance of the final model selected (Mod2) is represented in black, and the alternative models in red (Mod8: using the Longhurst ecological regions) and blue (Mod9: model without area effects).

In terms of goodness-of-fit, the best fitted model was the original one that used the SW area divided into four quadrants. However, using the Longhurst ecological regions produced very similar results, with the R^2 decreasing only from 61.2% in Mod2 to 60.9% in Mod8 (**Table 6**). The AIC was also worse in Mod 8; however, it should be noted that the AIC are not entirely comparable between models as the response variable was not exactly the same. Specifically, 12 data points from the SSTC ecological region had to be removed from Mod 8 due to the low representativeness of that region to the fishery. The model without the spatial effects produced much worse results, with a lower R2 and higher AIC (**Table 6**). In terms of residual analysis, there were no major differences in the models using different areas (**Figure 18**).

Table 6. Deviance table of the parameters for the sensitivity analysis of the area variable for the swordfish CPUE standardization in the SW Indian Ocean. For each parameter it is indicated the degrees of freedom used (Df), the deviance explained (Dev), the residual degrees of freedom (Resid Df) and deviance (Resid Dev) after incorporating sequentially each variable. The significance (F-stat and p-value) of each variable is indicated as well as the R^2 values.

Model	Variables	Df	Dev.	Resid. Df	Resid. Dev	F-stat.	*p-value*
Mod 8: Longhurst areas (AIC=7733; R2=60.9%)	Intersept only			6593	3164.8		
	Year	15	597.7	6578	2567	212.4	< 0.001
	Year + Quarter	3	6.1	6575	2561	10.9	< 0.001
	Year + Quarter + Area	1	0.6	6574	2560	3.1	0.077
	Year + Quarter + Area + Vessel	23	560.2	6551	2000	129.9	< 0.001
	Year + Quarter + Area + Vessel + Ratio	9	764.4	6542	1236	452.8	< 0.001
	Year + Quarter + Area + Vessel + Ratio + Quarter:Area	3	9.4	6539	1226	16.8	< 0.001
Mod 9: Removing area effects (AIC=7840; R2=60.5%)	Intersept only			6605	3179.9		
	Year	15	600.1	6590	2579.8	210.2	< 0.001
	Year + Quarter	3	6.2	6587	2573.6	10.9	< 0.001
	Year + Quarter + Vessel	23	561.2	6564	2012.4	128.2	< 0.001
	Year + Quarter + Vessel + Ratio	9	765.0	6555	1247.4	446.6	< 0.001

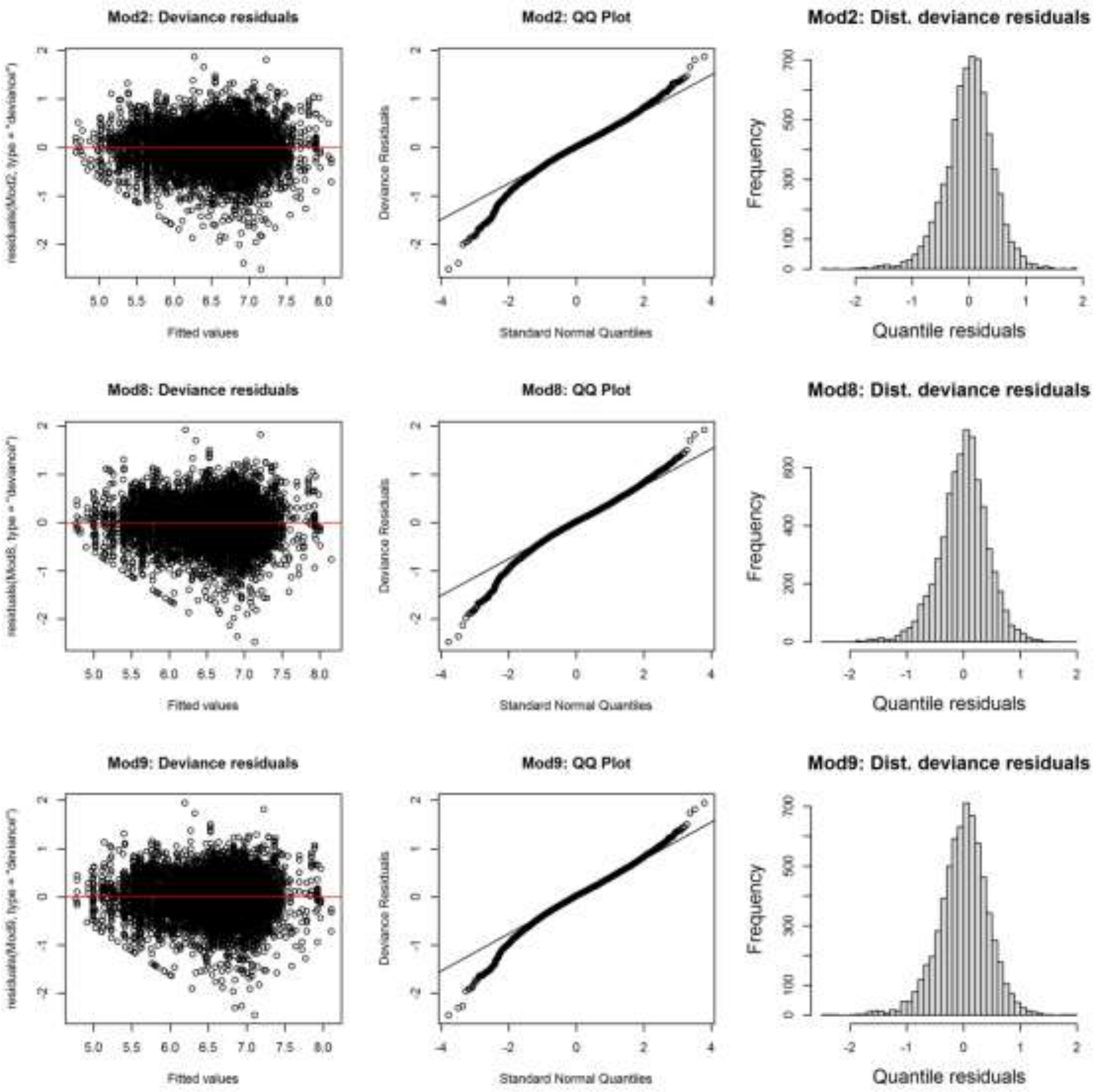

Figure 18. Residual analysis for the various model tested for the sensitivity to the area factor for the swordfish CPUE standardization in the SW Indian Ocean. Mod 2 is the base case model with SW Indian Ocean region divided into quadrants, Mod 8 uses the Longhurst ecological regions and Mod 9 does not include the area factor. For each model it is presented the residuals along the fitted values on the log scale (graphics on the left), the QQPlot (graphics on the middle) and the histogram of the distribution of the residuals (graphics on the right).

3.3.6. Final standardized CPUE series

Given the goodness-of-fit of the various candidate models and the comparisons from the sensitivity analysis for the model type, the use of the ratio factor, and the areas considered, the final standardized CPUE series recommended to be used is derived from Mod2. Besides the main simple effects Year, Quarter, Area, Vessel and Ratio, this model also accounts for a Quarter:Area interaction, allowing for different seasonal effects in the CPUEs to take place within each of the areas considered.

The standardized swordfish CPUE index (in kg/1000 hooks) for the Portuguese pelagic longline fishery in the SW Indian Ocean between 1998-2013, suggested to be used in future stock assessments, is presented in **Table 7**. Overall, the general trend of the series followed the same general pattern of the nominal series, with an increase in the first years of the series, followed by a general decrease until 2005, then followed by a peak in 2008, and then a general decrease for the more recent years.

Table 7: Standardized SWO CPUE index (kg/1000 hooks) for the Portuguese pelagic longline fleet in the SW Indian Ocean between 1998 and 2013, suggested to be used in future stock assessments. This table includes the index value, the 95% confidence intervals (CI) and the coefficient of variation (CV, %).

Year	Estimate	Upper 95%CI	Lower 95%CI	CV (%)
1998	54.9	80.1	33.7	13.8
1999	447.4	497.4	401.9	8.2
2000	813.7	875.6	755.8	8.6
2001	793.2	843.6	745.5	10.4
2002	770.8	819.5	724.6	9.6
2003	675.4	725.9	628.2	9.3
2004	601.3	647.5	558.0	8.9
2005	536.8	657.0	436.1	7.3
2006	624.0	651.4	597.7	11.2
2007	624.0	658.9	590.7	9.5
2008	1018.1	1164.9	888.6	10.9
2009	651.5	719.9	588.9	11.5
2010	660.7	723.5	602.9	12.1
2011	759.7	830.1	694.8	10.8
2012	568.1	620.1	520.0	12.3
2013	523.4	559.5	489.4	13.8

4. Acknowledgments

All the data used in this study was collected within the EU Data Collection Framework. VMS data was provided by *Direcção de Serviços de Inspecção, Monitorização e Controlo das Actividade Marítimas* (DSMC/DGRM). Rui Coelho was supported with a grant from FCT, the *Portuguese Foundation for Science and Technology* (Ref: SFRH/BPD/93936/2013). Special thanks are due to all skippers that voluntarily provided data from their fishing activities in the IOTC convention area.

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Annexes

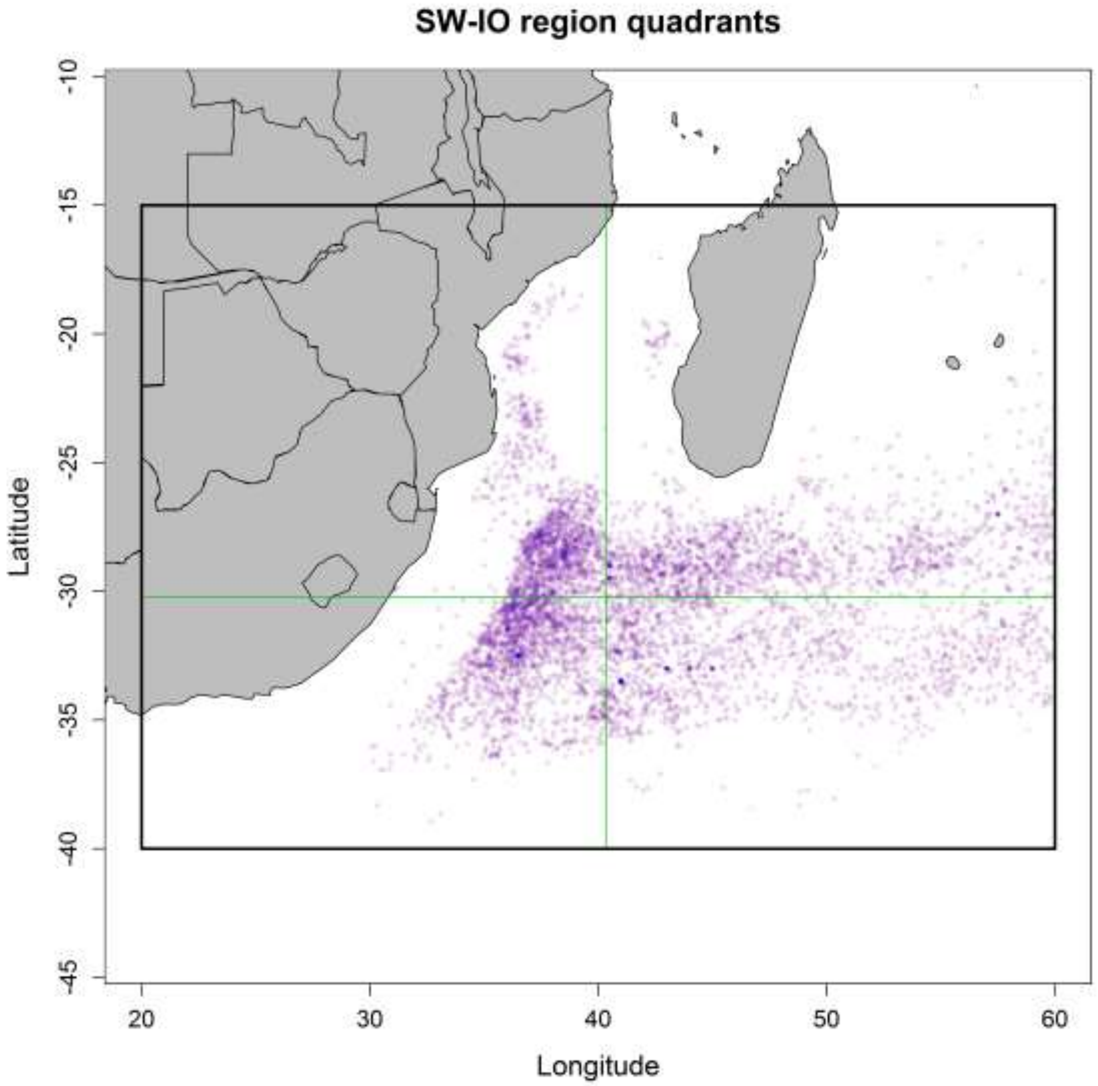

Figure 1: Regional quadrants in the SW Indian Ocean, with the location of the Portuguese pelagic longline sets reported by the fleet with logbooks between 1998 and 2013. Full color saturation indicates higher swordfish CPUEs, while the lighter red color represents sets with zero SWO catches.

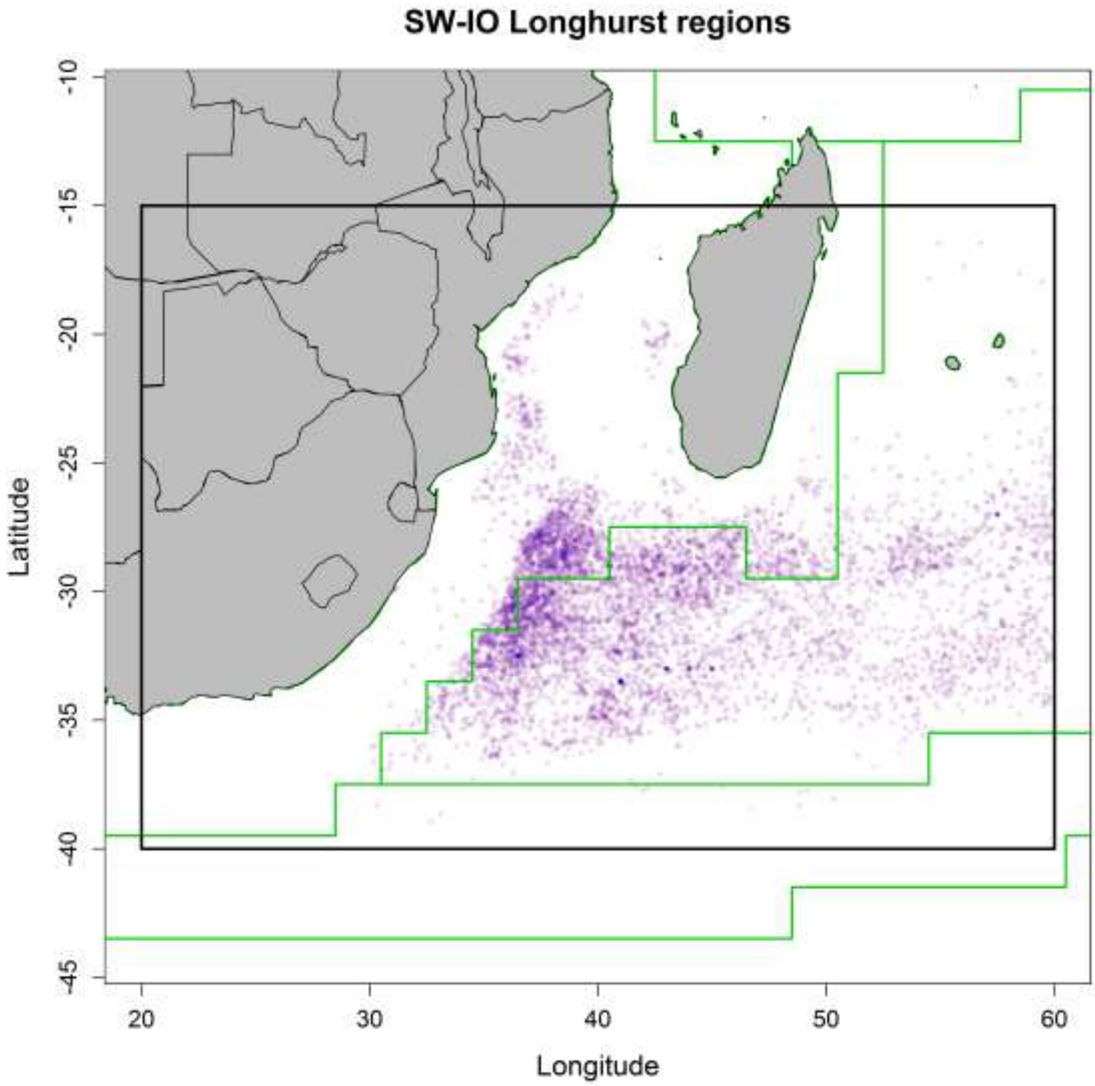

Figure 2: Longhurst ecological regions (Longhurst, 2007) in the SW Indian Ocean, with the location of the Portuguese pelagic longline sets reported by the fleet with logbooks between 1998 and 2013. Full color saturation indicates higher swordfish CPUEs, while the lighter red color represents sets with zero SWO catches.

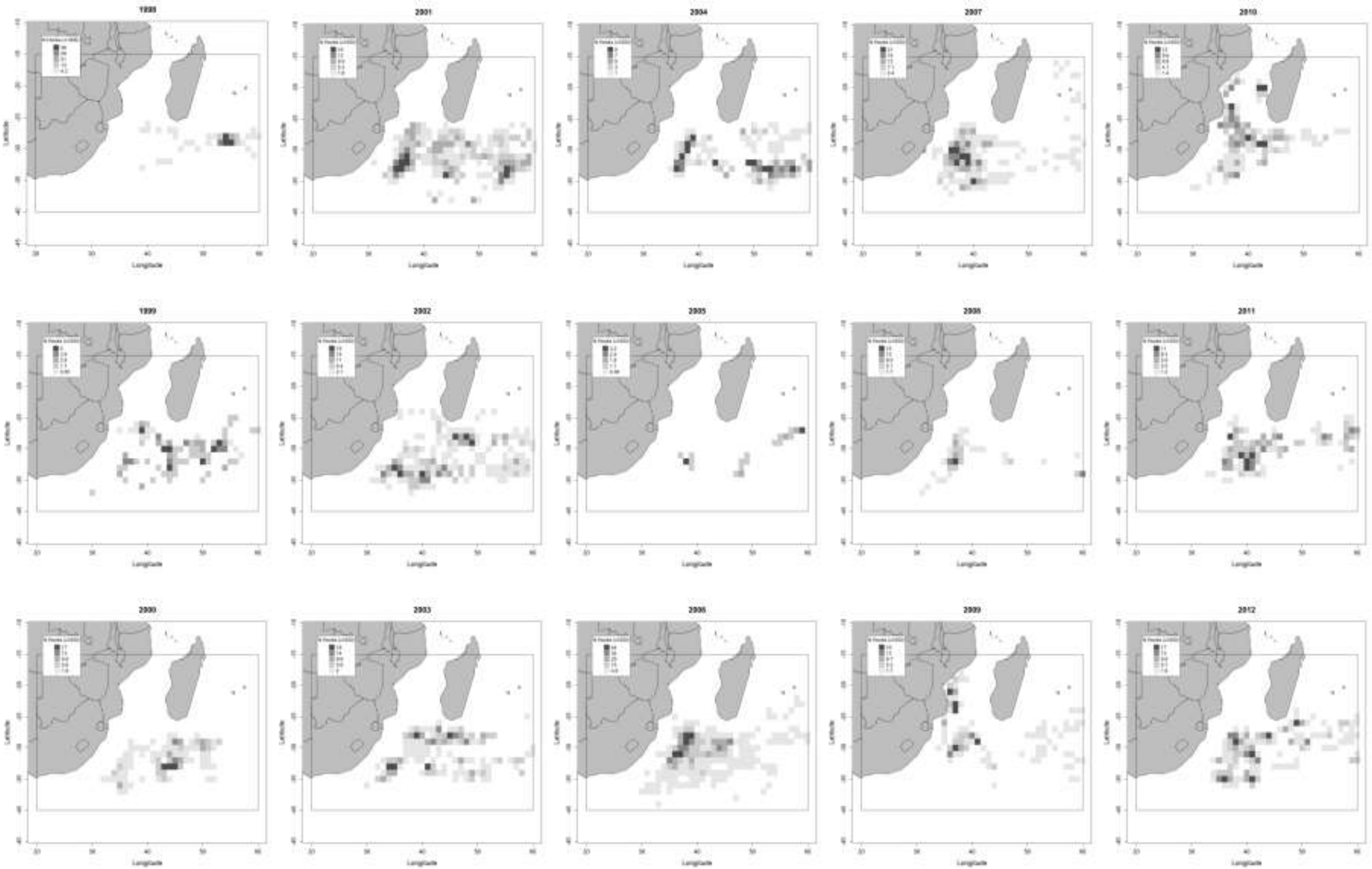

Figure 3: Effort distribution of the Portuguese pelagic longline fleet in the SW Indian Ocean between 1998 and 2013. The effort is represented in 1°x1° grids with darker and lighter colors representing respectively to areas with more and less effort in number of hooks.

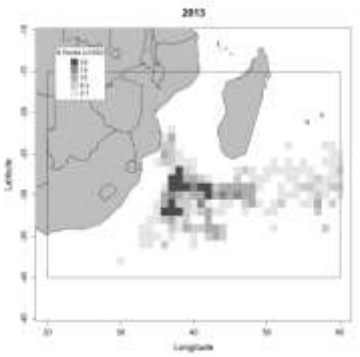

Figure 3 (continued): Effort distribution of the Portuguese pelagic longline fleet in the SW Indian Ocean between 1998 and 2013. The effort is represented in 1°x1° grids with darker and lighter colors representing respectively to areas with more and less effort in number of hooks.