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STANDARDIZED CPUE OF BLUE SHARK IN THE PORTUGUESE PELAGIC LONGLINE FLEET OPERATING IN THE NORTH ATLANTIC

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SUMMARY

This working document analyzes the catch, effort and standardized CPUE trends for the north Atlantic blue shark captured by the Portuguese pelagic longline fleet. Nominal annual CPUE were calculated as kg/1000 hooks and were standardized with Generalized Linear Models (GLM) and Generalized Linear Mixed Models (GLMM) using year, quarter, area, gear type, targeting effects and area:quarter interactions as fixed factors, and year:area as random effects. Sensitivity analyzes were carried out for the model type (lognormal, tweedie, gamma or delta lognormal), the definition of targeting effects (based on ratios or cluster analysis), and definition of areas. Model goodness-of-fit and comparison was carried out with AIC and the pseudo coefficient of determination (R^2), and model validation with a residual analysis. The final standardized CPUE trend shows a general increase over the studied period, between 1997 and 2014, with some inter-annual oscillations. This paper presents the first index of abundance for the blue shark estimated from captures from the Portuguese pelagic longline fleet in the North Atlantic, and can be used in future stock assessments models.

RÉSUMÉ

Le présent document de travail analyse les tendances de la prise, de l'effort et de la CPUE standardisée pour le requin peau bleue du Nord capturé par la flottille pélagique palangrière portugaise. Les CPUE nominales annuelles ont été calculées en tant que kg/1000 hameçons et ont été standardisées au moyen de modèles linéaires généralisés (GLM) et de modèles mixtes linéaires généralisés (GLMM) en utilisant l'année, le trimestre, la zone, le type d'engin, les effets du ciblage et les interactions zone-trimestre en tant que facteurs fixes et l'année-zone en tant qu'effets aléatoires. Des analyses de sensibilité ont été réalisées pour le type de modèle (lognormal, tweedie, gamma ou delta lognormal), la définition des effets du ciblage (reposant sur des ratios ou l'analyse de regroupement) et la définition des zones. La qualité de l'ajustement du modèle et une comparaison ont été réalisées au moyen de AIC et le pseudo coefficient de détermination (R2) et la validation du modèle avec une analyse résiduelle. La tendance de la CPUE standardisée finale présente une augmentation générale pendant la période étudiée, entre 1997 et 2014, avec quelques oscillations interannuelles. Ce document présente le premier indice d'abondance pour le requin peau bleue estimé à partir des captures de la flottille palangrière pélagique portugaise dans l'Atlantique Nord et peut être utilisé dans de futurs modèles d'évaluations des stocks.

RESUMEN

Este documento analiza las tendencias de captura, esfuerzo y CPUE estandarizada para la tintorera del Atlántico norte capturada por la flota de palangre pelágico portuguesa. Las CPUE nominales anuales se calcularon como kg/1000 anzuelos y se estandarizaron con modelos lineales generalizados (GLM) y modelos lineales mixtos generalizados (GLMM) utilizando año, trimestre, área, tipo de arte, efectos de la especie objetivo e interacciones área:trimestre como factores fijos y año:área como factores aleatorios. Se llevaron a cabo análisis de sensibilidad para el tipo de modelo (lognormal, tweedie, gamma o delta lognormal), la definición de los efectos de la especie objetivo (basándose en la ratio o en un análisis de conglomerados) y la definición de las áreas. La comparación y la bondad del ajuste del modelo se llevaron a cabo con AIC y el pseudo coeficiente de determinación (R2) y la validación del modelo con un análisis residual. La tendencia de la CPUE estandarizada final muestra un aumento general durante el periodo estudiado, entre 1997 y 2014, con algunas oscilaciones interanuales. Este documento presenta el primer índice de abundancia para la tintorera estimado a partir de capturas de la flota de palangre pelágico portuguesa en el Atlántico norte y puede utilizarse en futuros modelos de evaluación de stock.

KEYWORDS

Blue shark, catch/effort, CPUE standardization, fishery indicators, generalized linear models, generalized linear mixed models, longline fisheries, north Atlantic, prionace glauca

1. Introduction

Fisheries management is usually based on stock assessment models that require data on the abundance of the species under assessment (Hilborn and Walters 1992). Ideally, data for such models should be fishery-independent but, when assessing pelagic and migratory species that cover wide geographical areas (e.g. tunas, billfishes and pelagic sharks) this type of fisheries-independent data is usually not available. Therefore, most stock assessments currently carried out for pelagic species are based on fishery-dependent data, available from the commercial fisheries that capture those species.

The data usually gathered from the commercial fisheries and analyzed is the catch per unit of effort (CPUE, either in number or biomass), and it is important to standardize those CPUEs to account for effects (consequence of the fishery-dependence) other than the annual abundance effects that are being analyzed. By standardizing the CPUEs, the effects of the covariates considered are removed from the annual CPUE values, and those standardized CPUEs can be used as annual indexes of abundance.

Following a preliminary working document presented to ICCAT analyzing catch at size of sharks by the Portuguese fleet in the Atlantic (Santos *et al*. 2014a), this study now provides the standardized blue shark (BSH – *Prionace glauca*) CPUE index for the Portuguese pelagic longline fishery in the North Atlantic Ocean.

2. Material and methods

2.1 Data collection

The data used for this study was collected by fishery observers onboard Portuguese pelagic longline vessels, interviews of skippers during landings and from skippers logbooks (self reporting) voluntarily provided to IPMA, for the period 1995-2014. The information on the total catch was provided by the Portuguese Fisheries authorities (DGRM). The percentage of the catch covered in the analysis (as regards to the overall yearly catch) varied between years, ranging from minimums of 3.6% to maximums of 30.5% per year (excluding the 1995-1996 that were not included in the CPUE standardization process) (**Table 1**). Data from a total of 1,573 trips or sub-trip (consecutive sets in the same trip, area and month) were used, which amounted to a total fishing effort of 13,934,075 hooks.

The spatial catch and effort used in the analysis was mapped and plotted in order to identify the major areas of operation of the fleet in the North Atlantic. The blue shark CPUE, measured in blue shark (BSH) 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 CPUE standardization

The available catch data started in 1995 and was available until 2014. The data from the first two years of the series (1995 and 1996) were excluded from the model runs due to low number of observations, so the final CPUE time series was analyzed for the period 1997 to 2014. For the CPUE standardization, the response variable considered was catch per unit of effort (CPUE), measured as biomass of live fish (kg) per 1000 hooks deployed. The standardized CPUE series was estimated with Generalized Linear Models (GLM) and Generalized Linear Mixed Models (GLMM).

There were some trips or sub-trips (11.1% of the data) 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, three different methodologies were used and compared, specifically tweedie, gamma, lognormal and delta 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 1997 and 2014;
- Quarter of the year: 4 categories: 1 = January to March, 2 = April to June, 3 = July to September, 4 = October to December;
- Area: using the areas represented in **Figure 1** and considering the aggregations previously mentioned, and using alternative areas in a sensitivity analysis;
- Gear type: multifilament (old Spanish style) or monofilament (Florida style);
- Targeting: based on the SWO/SWO+BSH ratio of the captures or based on a cluster analysis and used as a sensitivity;
- Quarter - Area interactions.
- Year - Area interactions (used as a random variable in GLMM)

The Portuguese fleet introduced the semi-automatic Florida style (using a monofilament mainline) between 2000-2004. Therefore a gear factor (multifilament or monofilament) was considered, based on the date when this changed occurred at each vessel. The information was obtained directly from skippers or from DGRM records. For those vessels for which such information was not available, it was considered the use of the semi-automatic Florida style from the 1st January 2004.

Differences in fishing strategy reflect the increased economic importance of sharks among the Portuguese pelagic longline fleets which traditionally targeted swordfish almost exclusively. These changes in target species were incorporated into the model by a proxy based on the ratio of the swordfish retained catch and the combined swordfish and blue shark retained catches by trip (or sub-trip). 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 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*. 2013; Santos *et al*. 2014b; Coelho *et al*. 2014). The ratio factor was calculated for each set and then divided into ten categories using the 0.1 or the 0.25 quantiles (used as a sensitivity analysis).

Another approach used to incorporate targeting effects into the CPUE standardization process is based on cluster analysis. For this analysis, the catch composition was grouped in 10 species or species-groups that represent the major groups of catches by the Portuguese pelagic longline fleet, specifically BSH, SWO, SMA, BET, YFT, BUM, Other billfishes, Other tunas, Other sharks and Other bony fishes. The analysis was carried out as suggested by He *et al*. (1997) and as applied for CPUE standardization of other fleets such as the case of the Taiwanese fleet in the Indian Ocean (Wang and Nishida 2014). The analysis was divided into two steps: 1) a non-hierarchical cluster analysis (*K-means* method) used to group all data sets into fewer clusters taking into account the mixture of fishing operations and 2) a hierarchical cluster analysis (Ward minimum variance method using squared Euclidean distances) calculated from the non-hierarchical clusters. In the case of the Portuguese pelagic longline fishery in the North Atlantic whose catches are comprise mainly SWO and BSH, the two minimum clusters would represent swordfish or blue shark targeting, while other clusters would represent either a mixed SWO + BSH targeting or other target species in some specific sets. Therefore, and as suggested by He *et al*. (1997) additional clusters were considered until the smaller one accounted for less than 10% of the sets.

The catches were assigned to the fishing areas (**Figure 1**) defined by Mejuto *et al*. (2008) based on oceanographic conditions, which have been used before by Santos *et al*. (2014b) for swordfish CPUE standardization. In this specific study some of these areas were aggregated (specifically 1+2, 9+10 and 13+14) into larger zones, due to the low number of trips or sub-trips in some of the areas. Even though those areas were defined originally for SWO, they were also tested for these BSH models, as the SWO and BSH are the main components of the Portuguese fleet. Another option in terms of area definitions that was used as a sensitivity analysis was to use the areas as defined by Mejuto and García-Cortés (2005) based on biological observations of BSH in the Atlantic.

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 pseudo coefficient of determination (R^2). Model validation was carried out with a residual analysis.

Once a final candidate model was selected, several sensitivity analyzes were carried out to test the influence of the model type, the ratio variable and geographical areas to 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, 3) a gamma model and 4) a delta log-normal approach.
- Sensitivity to the targeting effect: 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, 2) using targets based on cluster analysis, and 3) by removing the target effects from the model.
- Sensitivity to the area effects: The base case model based on the sea temperature at 50m depth as used by Mejuto *et al*. (2008) was compared with alternative BSH areas as defined by Mejuto and Garcia-Cortés (2005), and a model without spatial effects.

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

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 (Venables and Ripley 2002; Wickham 2007, 2009; Fox and Weisberg 2011; Gross and Ligges 2012; Højsgaard and Halekoh 2012; Becker *et al*. 2013; Bivand and Lewin-Koh 2013; Dunn 2013; Pinheiro *et al*. 2013; Smyth *et al*. 2013; Stabler *et al*. 2013; Lenth 2014). The mixed effects models were run in R using ADMB (Fournier *et al*. 2012; Skaug *et al*. 2014).

3. Results and discussion

3.1 Catch and effort

3.1.1 Spatial distribution of the catch and effort

The BSH catches in the North Atlantic were mostly concentrated in the tropical and temperate northeast region (**Figure 1**). Likewise, most of the sampling effort also took place in that region of the tropical and temperate eastern Atlantic (**Figure 2**), as those are the major areas of operation of the Portuguese pelagic longline fleet in the North Atlantic.

3.1.2 Yearly and seasonal variability in the catch and effort

The total effort of the Portuguese longline fleet in the North Atlantic analyzed for this work increased in the first years of the series, and slightly decreased for the more recent years (**Figure 3**), and this is related with the total fishing effort from the Portuguese pelagic longline fleet in the Atlantic Ocean and also with the annual coverage of the sampling effort. The analyzed blue shark catches did not directly follow this trend, as there was an increase in the catches until 2008, followed by a decrease for the more recent years (**Figure 3**). In terms of swordfish compared to the swordfish + blue shark catches, the two initial years of the series had very high ratios and were followed by a decrease for the remaining years (**Figure 3**). Some of the decreases observed in the more recent year, after 2008, might be related with a change in the fishing gear (nylon monofilament by wire leaders) and bait (mackerel alternating with squid) in areas/periods of higher shark abundance. Several authors have demonstrated that higher blue shark catch rates are obtained with wire leaders (e.g., Ward *et al*. 2009; Vega and Licandeo 2009; Afonso *et al*. 2012), and fish bait (Coelho *et al*. 2012; Amorim *et al*. 2015).

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 2nd and 3rd quarters of the year, and lower CPUEs both in the beginning and towards the end of the year (**Figure 4**).

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 North Atlantic Ocean is presented in **Figure 5**. There was a peak in the start of the series in 1997, followed by a sharp decrease in 1999, then a progressive increase until 2011 and finally a slight decrease in the more recent years from 2011 to 2014 (**Figure 5**). The nominal blue shark CPUE distribution was highly skewed to the right and become more normal shaped in the log-transformed scale (**Figure 6**).

3.2.2 Model construction

For the base case lognormal models, all the explanatory variables tested for the blue shark CPUE standardization were significant and contributed significantly for explaining part of the deviance. 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**). The inclusion of a random interaction between year and quarter in a GLMM only produced a very slight decrease in AIC (Delta AIC = 2.2), and the variability of the random effect was very low (variance = 0.0045). As such, the random effects of the year:quarter interaction were not included in the final models. On all models (with and without spatial:seasonal interactions; with and without random year:quarter interactions), the factors that contributed most for the deviance explanation were the ratio factor followed by the area and the year effects (**Table 3**).

In terms of model validation, the 3 models seemed adequate for this particular situation with a relatively low quantity of zeros. However, in the residual analysis, including the residuals distribution along the fitted values, the QQ plots and the residuals histograms, it was possible to detect the presence of some outliers (**Figure 7**).

For those lognormal models the resulting relative indexes of abundance were very similar, showing a general increasing trend along the entire time series, with some oscillations in some of the year (**Figure 8**).

3.2.3 Sensitivity to the model type

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

The comparison of those models with the base case lognormal, resulted in relatively similar patterns for all cases, even thought there were some differences. Specifically, the most similar trends were given by the lognormal and gamma models, while the tweedie and delta lognormal showed some slight differences in some of the years (**Figure 9**).

Like in the base cases, the factors that contributed most for the deviance explanation were the ratio factor followed by area and year effects (**Table 4**). In some cases, specifically in the lognormal with c=1 and the tweedie models the gear type and quarter:area interactions were not significant. In terms of goodness-of-fit, specifically using the R^2 comparison, the best fitted model was the gamma model using c=10% of the mean. Note that in this case the AIC values are not comparable between models because the response variable (CPUE, CPUE+*c* and CPUE+1) is not the same for all models. After the gamma, the best fitted model was the lognormal with *c*=1, while the tweedie had the poorest fit (**Table 4**).

In terms of residual analysis there were some problems with the lognormal model with constant *c*=1 (Mod 4) and also with the tweedie model (Mod5), while for the gamma model the residual analysis produced better results (**Figure 10**).

3.2.4 Sensitivity to the area definitions

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 was compared to a model using the areas defined by Mejuto and Garcia Cortés (2005) and a model without the area effects. This analysis revealed very little differences in the standardized CPUE series, even when the area factor was removed (**Figure 11**). This may be occurring because most of the fishing region for the Portuguese pelagic longline fishery in the North Atlantic occurs in the tropical and temperate NE Atlantic, in a region where the spatial effects influencing the blue shark CPUE are smaller. In terms of goodness-of-fit, the best fitted model was the gamma using the original area definitions, as the AIC was lower and the R^2 was higher (**Table 5**). In terms of residual analysis there were no major differences in the models using different areas (**Figure 12**).

3.2.5 Sensitivity to the targeting effects

A final sensitivity analysis was run for testing the influence of the targeting effects, specifically by either using the ratios (swordfish / swordfish + blue shark) factor on the CPUE series, or various candidate models with alternative approaches. The original model using the ratios categorized by the 0.1 quantiles was compared with a model using the ratios categorized by the 0.25 quantiles, with a model using targets effects based on a cluster analysis, and with a model without target effects.

In terms of species composition it is noteworthy that the two dominant catches of the Portuguese fleet for the entire time series were SWO and BSH, with some inter-annual variability (**Figure 13**). He *et al*. (1997) and Wang and Nishida (2014) noted that the choice for the number of clusters to produce with multivariate statistics was largely subjective, and in the case of the mixed tuna fisheries in the Pacific and Indian Oceans, both mentioned that at least two clusters are expected (from tuna and swordfish sets), and that more may be produced to allow other targeting categories. The case of the Portuguese pelagic longline fishery is different, as it is clear from the catch composition that the major species are SWO and BSH, while the tunas represent a very small component of the catch (**Figure 13**). As such, in the Portuguese fishery the two minimum clusters would represent swordfish or blue shark targeting, while the other clusters would represent either a mixed SWO + BSH targeting, or other target species in a few specific sets.

From the non-hierarchical cluster analysis (*k-means*) it was possible to reduce the overall number of trips or sub-trips into 45 groups, which were then clustered in the hierarchical analysis (**Figure 14**). The selection of clusters for the hierarchical analysis followed He *et al*. (1997) suggestion of reducing the number until the smallest cluster contained less than 10% of the observations, and in the case of the Portuguese fleet this was achieved with four clusters. The catch composition of those four clusters, representing four targeting strategies of the fleet is presented in **Figure 15**, and are summarized as: 1) targeting mainly SWO (45.4% of trips or sub-trips), 2) targeting mainly BSH (26.2% of trips or sub-trips), mixed strategy targeting both SWO and BSH (26.5% of trips or sub-trips) and 4) mixed strategy targeting mainly SWO and capturing other sharks, mainly SMA (1.8% of trips or sub-trips).

This sensitivity analysis revealed some differences in the standardized BSH CPUE series, but the general trends remained very similar for all tested scenarios (**Figure 16**). In terms of goodness-of-fit, the best fitted model was the original base case 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 6**).

Using targeting effects from the cluster analysis also produced a slightly worse fit than using ratios. As the data for the cluster analysis was only available until 2012, the AIC of the base case model using ratios and the alternative model using clusters cannot be directly compared. As such, a new base case model was run using data only until 2012 to allow those comparisons, and in that case the AIC increased from 1680.5 when using ratios to 2652.5 when using clusters, and the R^2 decreased from 84.5% when using ratios to 69.1% when using clusters. In terms of residual analysis there were no major differences in the models using or not the ratio variable, even though a larger dispersion in the residuals was observed when the ratio factor was removed (**Figure 17**).

4. Conclusions

The standardized blue shark CPUE index (kg/1000 hooks) for the Portuguese pelagic longline fishery in the North Atlantic between 1997-2014, suggested to be used in future BSH stock assessments is presented in **Table** 7.

Given the goodness-of-fit and residual analysis of the various candidate models, including the sensitivity analysis for the model type, targeting effects and areas considered, the final standardized CPUE series recommended is derived from Model 6 (GLM Gamma with area:season interaction). Besides the main simple effects year, quarter, area, ratio and gear type, this model also accounts for area:season interactions, allowing for different seasonal effects in the CPUEs to take place within each of the areas considered.

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6. References

Afonso A.S., Hazin F.H.V., Carvalho F., Pacheco J.C., Hazin H., Kerstetter D.W., Murie D., Burgess G.H. 2011. Fishing gear modifications to reduce elasmobranch mortality in pelagic and bottom longline fisheries off Northeast Brazil. Fish. Res. 108: 336–343.

Amorim S., Santos M.N., Coelho R., Fernandez-Carvalho J. 2015. Effects of 17/0 circle hooks and bait on fish catches in a Southern Atlantic swordfish longline fishery. Aquatic Conserv: Mar. Freshw. Ecosyst. 25: 518–533.

Becker R.A., Wilks A.R., Brownrigg R., Minka T.P. 2013. maps: draw geographical maps, R package version 2.3-6. http://CRAN.R-project.org/package=maps.

Bivand R., Lewin-Koh N. 2013. maptools: tools for reading and handling spatial objects. R package version 0.8-27. http://CRAN.R-project.org/package=maptools.

Campbell R.A. 2004. CPUE standardisation and the construction of indices of stock abundance in a spatially varying fishery using general linear models. Fish Res. 70: 209–227.

Coelho R., Santos M.N, Amorim S. 2012. Effects of hook and bait on targeted and bycatch fishes in an equatorial Atlantic pelagic longline fishery. Bull. Mar. Sci. 88: 449–467.

Coelho R., Santos M.N., Lino P.G. 2014. Blue shark catches by the Portuguese pelagic longline fleet between 1998-2013 in the Indian Ocean: Catch, effort and standardized CPUE. IOTC-2014-WPEB10-24. 32pp.

Dunn P.K. 2013. tweedie: Tweedie exponential family models. R package version 2.1.7.

Fournier D.A., Skaug H.J., Ancheta J., Ianelli J., Magnusson A., Maunder M., Nielsen A., Sibert J. 2012. AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. Optim. Methods Softw. 27: 233-249.

Fox J., Weisberg S. 2011. An {R} Companion to Applied Regression, 2nd Edition. Sage, Thousand Oaks CA.

Gross J, Ligges U. 2012. nortest: tests for normality. R package version 1.0-2. http://CRAN.R-project.org/package=nortest.

He X., Bigelow K.A., Boggs C.H. 1997. Cluster analysis of longline sets and fishing strategies within the Hawaii-based fishery. Fish. Res., 31: 147-158.

Hilborn R., Walters C.J. 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman and Hall: New York. 570 pp.

Højsgaard S., Halekoh U. 2012. doBy: groupwise summary statistics, general linear contrasts, population means (least-squares-means), and other utilities. R package version 4.5.0. http://CRAN.R-project.org/package=doBy.

Lenth R.V. 2014. lsmeans: least-squares means. R package version 2.11. http://CRAN.R-project.org/package=lsmeans.

Mejuto J., García-Cortés B. 2005. Reproductive and distribution parameters of the blue sharks *Prionace glauca*, on the basis of on-board observations at sea in the Atlantic, Indian and Pacific Oceans. Col. Vol. Sci. Pap. ICCAT 58(3): 951-973.

Mejuto J., García-Cortés B., Ramos-Cartelle A. 2008. Standardized catch rates in biomass for the swordfish (*Xiphias gladius*) caught by the Spanish longline fleet in the Indian Ocean for the period 1993-2007. IOTC Working Document. IOTC-2008-WPB-06.

Mejuto, J., García-Cortés, B., Ramos-Cartelle, A., De la Serna, J.M., González-González, I. 2013. Standardized catch rates of shortfin mako (*Isurus oxyrinchus*) caught by the Spanish surface longline fishery targeting swordfish in the Atlantic Ocean during the period 1990-2010. Col. Vol. Sci. Pap. ICCAT 69(4): 1657-1669.

Pinheiro J., Bates D., DebRoy S., Sarkar D. 2013. nlme: linear and nonlinear mixed effects models. R package version 3.1-113.

R Core Team. 2013. R: A language and environment for statistical computing. Version 3.0.1. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org.

Ramos-Cartelle A., García-Cortés B., Fernández-Costa J., Mejuto J. 2011. Standardized catch rates for the swordfish (*Xiphias gladius*) caught by the Spanish longline in the Indian Ocean during the period 2011-2012. IOTC-2011-WPB09-23. 19pp.

Santos M.N., Coelho R., Lino P.G., Fernandez-Carvalho J. 2014a. Preliminary observations on elasmobranchs bycatch-at-size and sex ratios on the Portuguese pelagic longline fishery in the Atlantic Ocean. Col. Vol. Sci. Pap. ICCAT 70(5): 2416-2432.

Santos M.N., Coelho R., Lino P.G. 2014b. Standardized CPUE for swordfish (*Xiphias gladius*) caught by the Portuguese pelagic longline fishery in the North Atlantic. Col. Vol. Sci. Pap. ICCAT 70(4): 1783-1791.

Shono H. 2008. Application of the Tweedie distribution to zero-catch data in CPUE analysis. Fish. Res. 93: 154–162.

Skaug H., Fournier D., Bolker B., Magnusson A., Nielsen A. 2014. Generalized linear mixed models using AD model builder. R package version 0.8.0.

Smyth G., Hu Y., Dunn P., Phipson B., Chen Y. 2013. statmod: statistical modeling. R package version 1.4.18. http://CRAN.R-project.org/package=statmod.

Stabler B. 2013. shapefiles: read and write ESRI shapefiles. R package version 0.7. http://CRAN.R-project.org/package=shapefiles.

Vega R., Licandeo R. 2009. The effect of American and Spanish longline systems on target and non-target species in the eastern South Pacific swordfish fishery. Fish. Res. 98: 22-32.

Venables W.N., Ripley B.D. 2002. Modern Applied Statistics with S. 4th Edition. Springer, New York.

Wang S-P., Nishida T. 2014. CPUE standardization with targeting analysis for swordfish (*Xiphias gladius*) caught by Taiwanese longline fishery in the Indian Ocean. IOTC–2014–WPB12–22. 25pp.

Ward P., Lawrence E., Darbyshire R., Hindmarsh S. 2008. Large-scale experiment shows that nylon leaders reduce shark bycatch and benefit pelagic longline fishers. Fish. Res. 90: 100-108.

Wickham H. 2007. Reshaping data with the reshape package. J. Stat. Softw. 21:1-20.

Wickham H. 2009. ggplot2: elegant graphics for data analysis. Springer, New York.

Table 1. Annual blue shark catch (MT) by the Portuguese pelagic longline fishery in the North Atlantic (> 5ºN) with a summary of the data coverage in this analysis: Catch (MT), relative percentage of the catch covered in the analysis, number of trips (or sub-trips) and effort (number of hooks). Data below the dotted line was used in the CPUE standardization for the Portuguese pelagic longline fleet in the North Atlantic.

Year	*Total catch*	*Covered in the analysis*			
		Catch	*%*	*Trips/Sub-trips*	*Effort*
1995	4,722	4.7	0.1	8	75,200
1996	4,843	25.8	0.5	4	83200
1997	2,630	368.8	14.0	28	367,500
1998	2,440	332.7	13.6	42	494,400
1999	2,227	205.0	9.2	66	918,800
2000	2,081	363.0	17.4	142	1,418,610
2001	2,110	320.3	15.2	139	1,034,908
2002	2,265	425.0	18.8	92	783,850
2003	4,819	432.3	9.0	113	851,102
2004	1,458	444.0	30.5	125	876,482
2005	3,289	490.9	14.9	109	1,048,178
2006	3,867	140.5	3.6	72	522,917
2007	4,891	316.0	6.5	95	567,790
2008	5,630	511.0	9.1	92	640,946
2009	5,795	507.7	8.8	89	730,782
2010	6,305	836.9	13.3	94	817,542
2011	5,879	404.7	6.9	50	482,839
2012	3,008	437.1	14.5	69	712,567
2013	3,353	495.4	14.8	95	1,001,193
2014	-	305.7	-	49	505,269

Table 2. Specifications of the candidate models run for the blue shark CPUE standardization in the North Atlantic for 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 type*	*Explanatory variables*	*Comments*
Base cases	Mod1	GLM Lognormal (*c*=10%mean)	Year + Quarter + Area + Ratio + Geartype	Full simple effect model (35 pars)
	Mod2	GLM Lognormal (*c*=10%mean)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Model with area:season interaction (47 pars)
	Mod3	GLMM Lognormal (*c*=10%mean)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area + random(Year:Area)	Model with year:area interaction as a random effect (48 pars)
Sensitivity to model type	Mod4	GLM Lognormal (*c*=1)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Lognormal GLM with area:season interaction (47 pars)
	Mod5	GLM Tweedie (link=log)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Tweedie GLM with area:season interaction (47 pars)
	Mod6	GLM Gamma (link=log; *c*=10%mean)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Gamma GLM with area:season interaction (47 pars)
	Mod7	GLM Delta-lognormal (Binomial with logit link and lognormal for positives)	Year + Quarter + Area + Vessel + Ratio + Geartype	Delta-lognormal (binomial: 28 pars; lognormal: 35 pars)
Sensitivity to area	Mod8	GLM Gamma (link=log; *c*=10%mean)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Using Mejuto (2005) areas (51 pars)
	Mod9	GLM Gamma (link=log; *c*=10%mean)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Model without spatial effects (31 pars)
Sensitivity to targeting	Mod10	GLM Gamma (link=log; *c*=10%mean)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Ratio factor categorized by the 0.25 quantiles (41 pars)
	Mod11	GLM Gamma (link=log; *c*=10%mean)	Year + Quarter + Area + Vessel +Cluster + Geartype + Quarter:Area	Targeting based on cluster analysis (39 pars)
	Mod12	GLM Gamma (link=log; *c*=10%mean)	Year + Quarter + Area + Vessel + Geartype + Quarter:Area	Model without target effects (37 pars)

Table 3. Deviance table (anova type II) of the parameters used for the blue shark CPUE standardization models for the North Atlantic, using a lognormal error distribution with *c*=10% of the mean. For each parameter it is indicated the degrees of freedom (Df), the sum of squares (SS), the F test statistic and the significance (*p-value*). For each model it is also indicated the goodness-of-fit in terms of AIC and R^2.

Model	*Variables*	*Df*	*SS*	*F-stat.*	*p-value*
Mod 1: Full simple effects model (AIC=1879.9; R^2=85.8%)	Year	17	29.14	8.99	< 0.001
	Quarter	3	5.71	9.99	< 0.001
	Area	4	40.32	52.85	< 0.001
	Ratio	9	981.08	571.58	< 0.001
	Geartype	1	0.94	4.94	0.026
Mod 2: Model with area:quarter interaction (AIC=1863.3; R^2=86.0%)	Year	17	30.59	9.61	< 0.001
	Quarter	3	5.71	10.17	< 0.001
	Area	4	40.32	53.82	< 0.001
	Ratio	9	823.65	488.67	< 0.001
	Geartype	1	0.95	5.05	0.025
	Quarter:Area	12	7.50	3.34	< 0.001
Mod 3: GLMM with random year:area effects (AIC=1861.1; R^2=NA)	Year	17	-	12.22	< 0.001
	Quarter	3	-	3.93	0.008
	Area	4	-	8.39	< 0.001
	Ratio	9	-	1136.98	< 0.001
	Geartype	1	-	5.11	0.024
	Quarter:Area	12	-	2.57	0.002

Table 4. Deviance table (anova type II) of the parameters for the sensitivity analysis of the model types for the blue shark CPUE standardization in the North Atlantic Ocean. For each parameter it is indicated the degrees of freedom (Df), the sum of squares (SS), the F test statistic and the significance (*p-value*). For each model it is also indicated the goodness-of-fit in terms of R^2.

Model	*Variables*	*Df*	*SS*	*F-stat.*	*p-value*
Mod 4: Lognormal (cons=1) (R^2=86.4%)	Year	17	71.00	6.71	< 0.001
	Quarter	3	5.30	2.83	0.037
	Area	4	78.80	31.71	< 0.001
	Ratio	9	3848.60	687.84	< 0.001
	Geartype	1	1.50	2.40	0.122
	Quarter:Area	12	10.40	1.39	0.164
Mod 5: Tweedie (R^2=83.7%)	Year	17	290.30	5.42	< 0.001
	Quarter	3	48.50	5.13	0.002
	Area	4	244.50	19.39	< 0.001
	Ratio	9	8124.10	286.34	< 0.001
	Geartype	1	6.20	1.96	0.162
	Quarter:Area	12	51.20	1.35	0.182
Mod 6: Gamma (cons=c) (AIC=1778.3, R^2=87.9%)	Year	17	30.48	10.99	< 0.001
	Quarter	3	7.08	14.48	< 0.001
	Area	4	27.78	42.58	< 0.001
	Ratio	9	791.72	539.31	< 0.001
	Geartype	1	0.65	3.99	0.046
	Quarter:Area	12	6.36	3.25	< 0.001
Mod 7.1: Delta lognormal (binomial) (R^2=50.4%)	Year	17	148.14	22.59	< 0.001
	Quarter	3	4.75	4.11	0.006
	Area	4	2.79	1.81	0.124
	Ratio	3	333.91	288.56	< 0.001
Mod 7.2: Delta lognormal (positives only) (R^2=85.8%)	Year	17	58.40	12.88	< 0.001
	Quarter	3	11.72	14.64	< 0.001
	Area	4	38.33	35.92	< 0.001
	Ratio	9	1134.23	472.41	< 0.001
	Geartype	1	0.71	2.66	0.103

Table 5. Deviance table (anova type II) of the parameters for the sensitivity analysis of the area variable for the blue shark CPUE standardization in the North Atlantic Ocean. For each parameter it is indicated the degrees of freedom (Df), the sum of squares (SS), the F test statistic and the significance (*p-value*). For each model it is also indicated the goodness-of-fit in terms of R^2.

Model	*Variables*	*Df*	*SS*	*F-stat.*	*p-value*
Mod 8: Alternative BSH areas (AIC=1792.6; R^2=76.8%)	Year	17	0.69	7.18	< 0.001
	Quarter	3	0.17	10.17	< 0.001
	Area	4	0.62	27.56	< 0.001
	Ratio	9	28.15	553.79	< 0.001
	Geartype	1	0.02	3.82	0.051
	Quarter:Area	16	0.15	1.65	0.051
Mod 9: Removing areas (AIC=1925.6; R^2=74.6%)	Year	17	0.64	6.08	< 0.001
	Quarter	3	0.03	1.67	0.1718
	Ratio	9	47.12	848.10	< 0.001
	Geartype	1	0.01	2.13	0.1449

Table 6. Deviance table (anova type II) of the parameters for the sensitivity analysis of the targeting effects for the blue shark CPUE standardization in the North Atlantic Ocean. For each parameter it is indicated the degrees of freedom (Df), the sum of squares (SS), the F test statistic and the significance (*p-value*). For each model it is also indicated the goodness-of-fit in terms of R^2.

Model	*Variables*	*Df*	*SS*	*F-stat.*	*p-value*
Mod 10: Ratio categorization (AIC=2379.0; R^2=79.6%)	Year	17	0.48	3.33	< 0.001
	Quarter	3	0.21	8.34	< 0.001
	Area	4	1.16	34.13	< 0.001
	RatioCategory	3	23.57	925.53	< 0.001
	Geartype	1	0.01	1.61	0.204
	Quarter:Area	12	0.35	3.46	< 0.001
Mod 11: Cluster analysis (AIC=2652.5; R^2=69.1%)	Year	15	0.70	3.98	< 0.001
	Quarter	3	0.25	7.03	< 0.001
	Area	4	1.20	25.58	< 0.001
	Clusters	3	12.66	361.22	< 0.001
	Geartype	1	0.00	0.23	0.633
	Quarter:Area	12	0.59	4.18	< 0.001
Mod 12: Removing targeting (AIC= 3966.5; R^2=43.6%)	Year	17	2.09	5.22	< 0.001
	Quarter	3	1.00	14.17	< 0.001
	Area	4	16.23	172.43	< 0.001
	Geartype	1	0.09	3.91	0.048
	Quarter:Area	12	4.10	14.52	< 0.001

Table 7. Standardized BSH CPUE index (kg/1000 hooks) for the Portuguese pelagic longline fleet in the North Atlantic between 1997 and 2014, suggested to be used in future stock assessments. The 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*
1997	182.1	221.0	148.8	7.4
1998	172.5	204.2	144.7	7.8
1999	152.7	176.5	131.4	8.2
2000	217.2	239.1	197.0	8.4
2001	227.5	251.8	205.2	8.9
2002	204.8	230.1	181.8	8.2
2003	253.2	279.2	229.2	7.9
2004	278.3	305.8	252.9	8.1
2005	226.7	252.1	203.5	8.2
2006	220.0	250.6	192.6	8.2
2007	258.6	288.8	231.1	8.2
2008	266.7	298.7	237.6	8.3
2009	279.8	314.0	248.9	8.4
2010	323.2	361.0	288.9	8.4
2011	269.3	311.8	231.8	8.0
2012	368.8	416.7	325.9	8.1
2013	381.0	426.5	339.8	8.8
2014	320.4	370.0	276.6	7.9

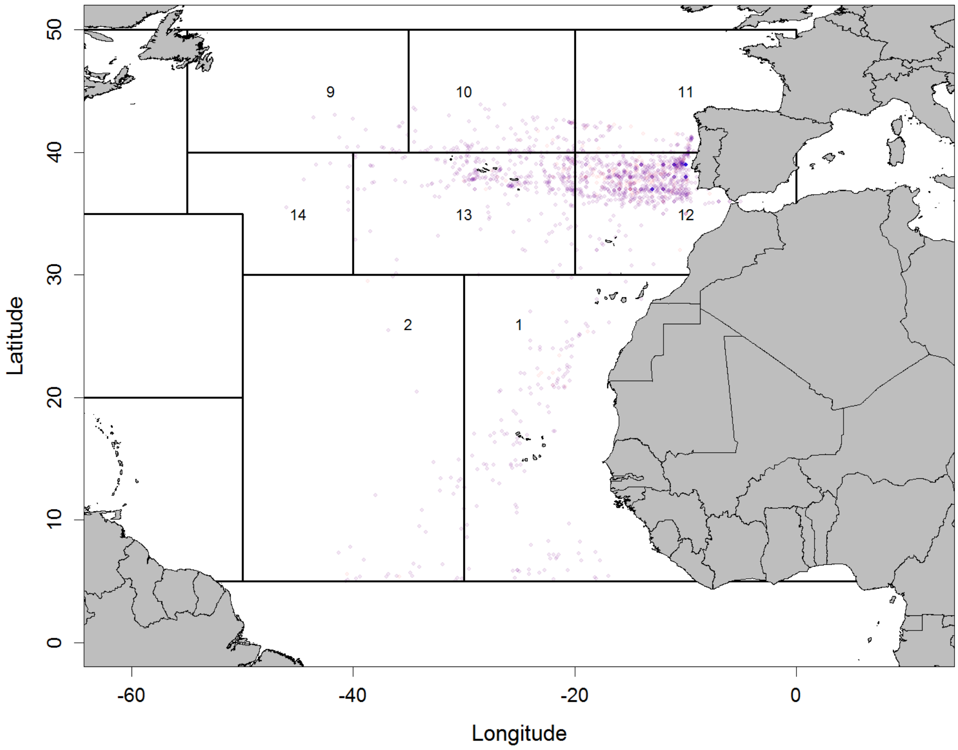

Figure 1. Sampling locations with the definition of fishing areas of the North Atlantic used in this study for the base case scenario (according to the area definitions by Mejuto *et al*. 2008). Due to small sample sizes, the areas 1+2, 9+10 and 13+14 were joined for the models.

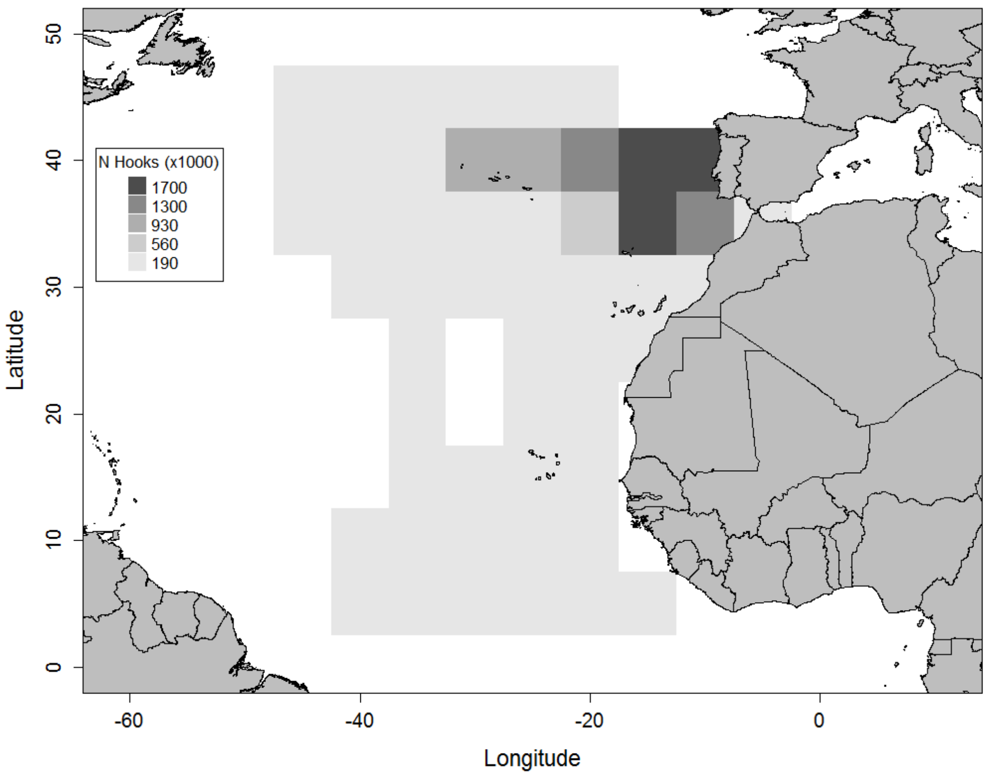

Figure 2. Effort distribution of the sampling in the North Atlantic used in this study for the period between 1995 and 2014. The effort is represented in number of hooks (x1000) in 5x5 grids.

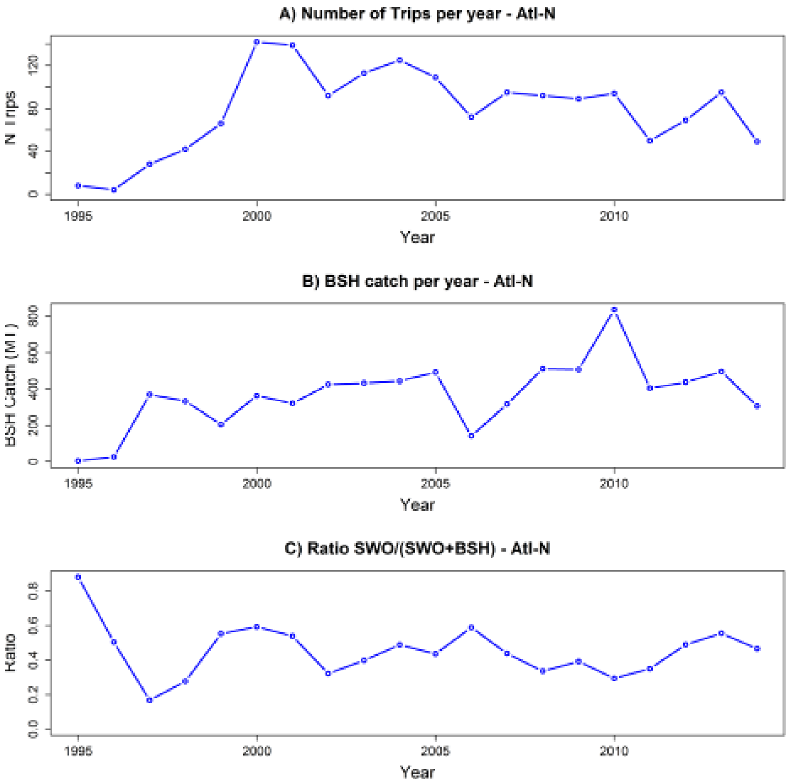

Figure 3. Descriptive plots of the sample used in this study in terms of total effort in sets (A), total catch of blue shark (B), and ratio of swordfish compared to the swordfish and blue shark catches (C), for the Portuguese longline fleet operating in the North Atlantic.

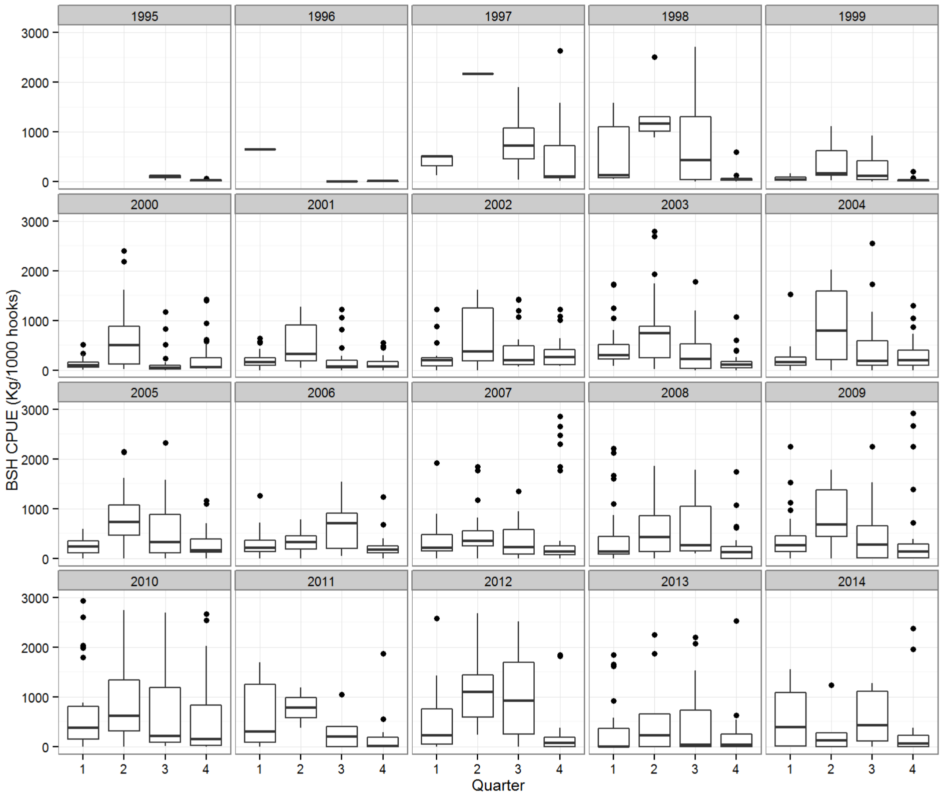

Figure 4. Quarterly blue shark CPUE (kg/1000 hooks) by the Portuguese pelagic longline fleet in the North Atlantic, per year. In the boxplots the middle lines represents the median, the box the quartiles, the whiskers the non-outlier range and the points the outliers.

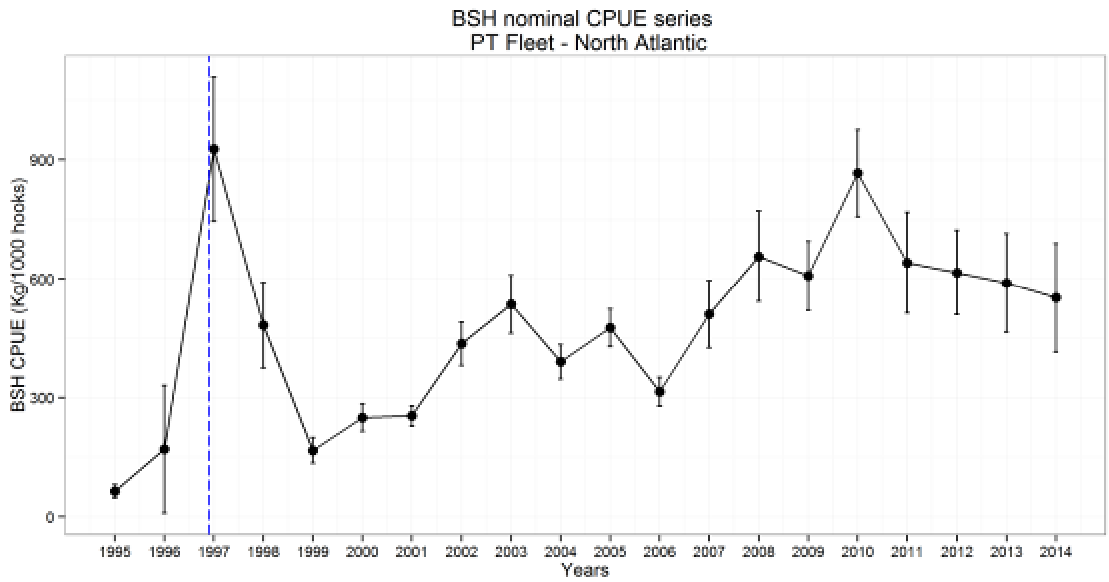

Figure 5. Nominal CPUE series (kg/1000 hooks) for blue shark caught by the Portuguese pelagic longline fishery in the North Atlantic between 1995 and 2014. The error bars refer to the standard errors and the vertical dotted blue line refers to the start of the data series for the CPUE standardization analysis.

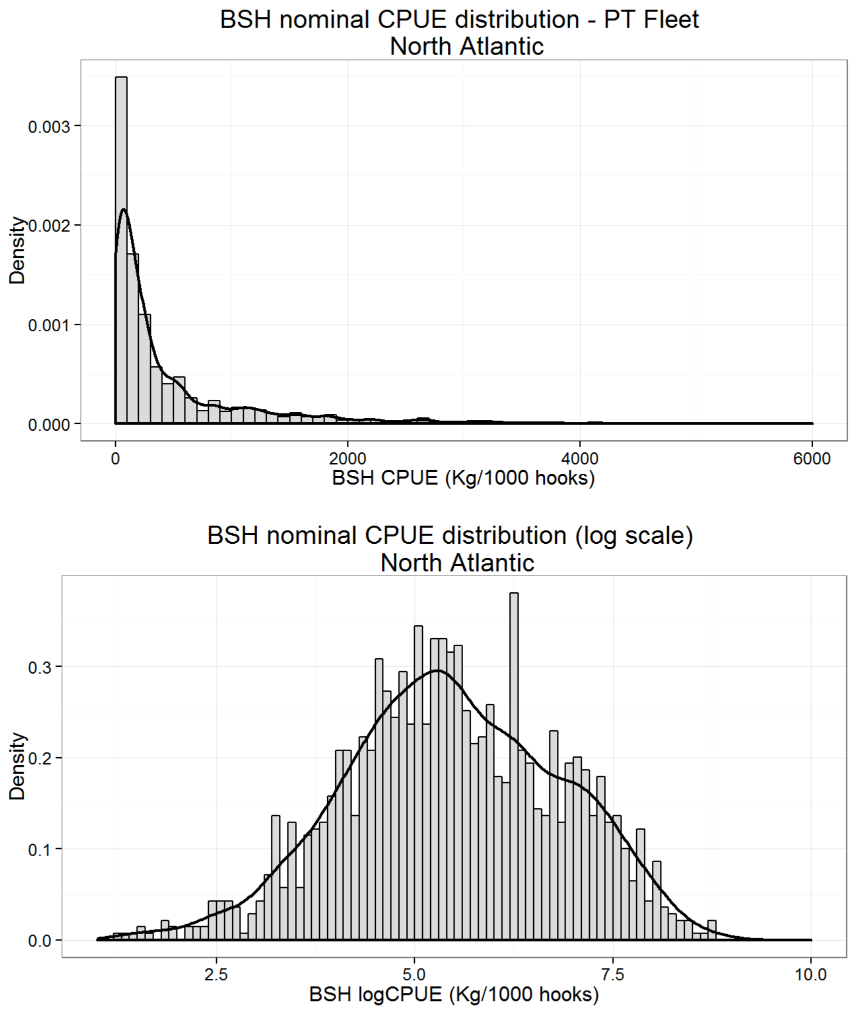

Figure 6. Distribution of the nominal blue shark CPUE captured by the Portuguese longline fleet in the North Atlantic Ocean in non-transformed (top plot) and log-transformed (bottom plot) scales.

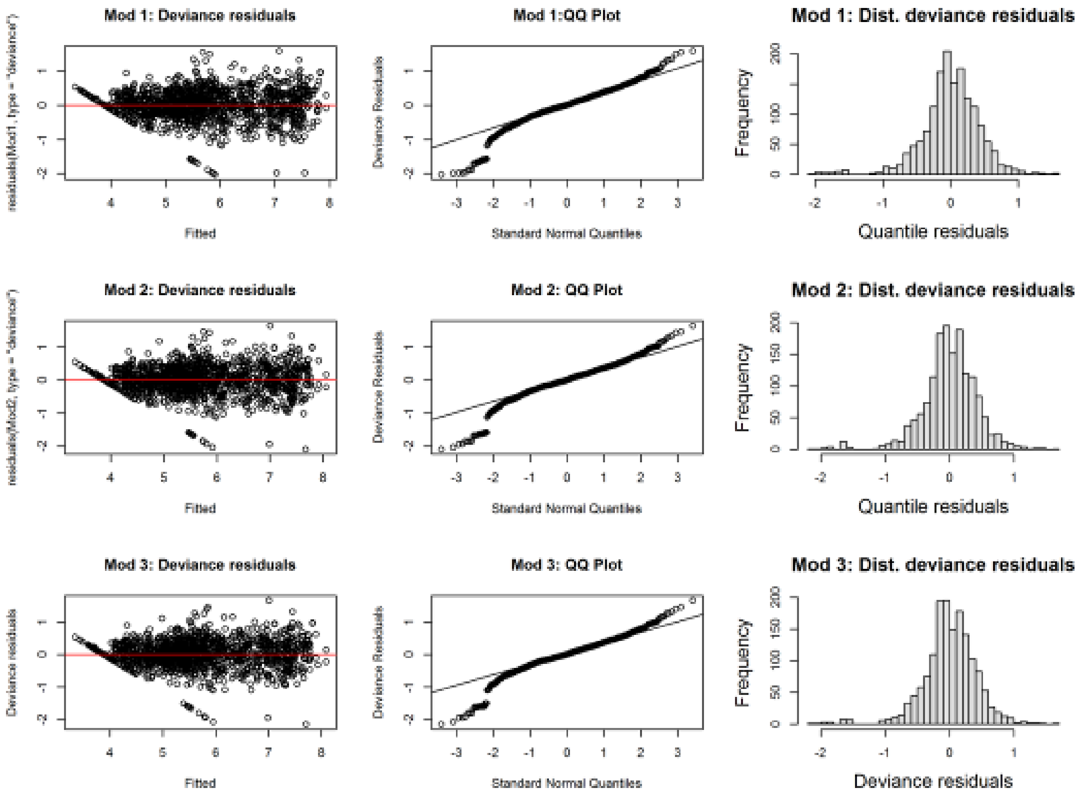

Figure 7. Residual analysis for the lognormal models tested for the blue shark CPUE standardization in the North Atlantic Ocean, specifically a GLM with simple effects only (Mod1), a GLM with quarter/area interactions (Mod2), and a GLMM with random year:area interactions. For each model it is presented the residuals along the fitted values (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).

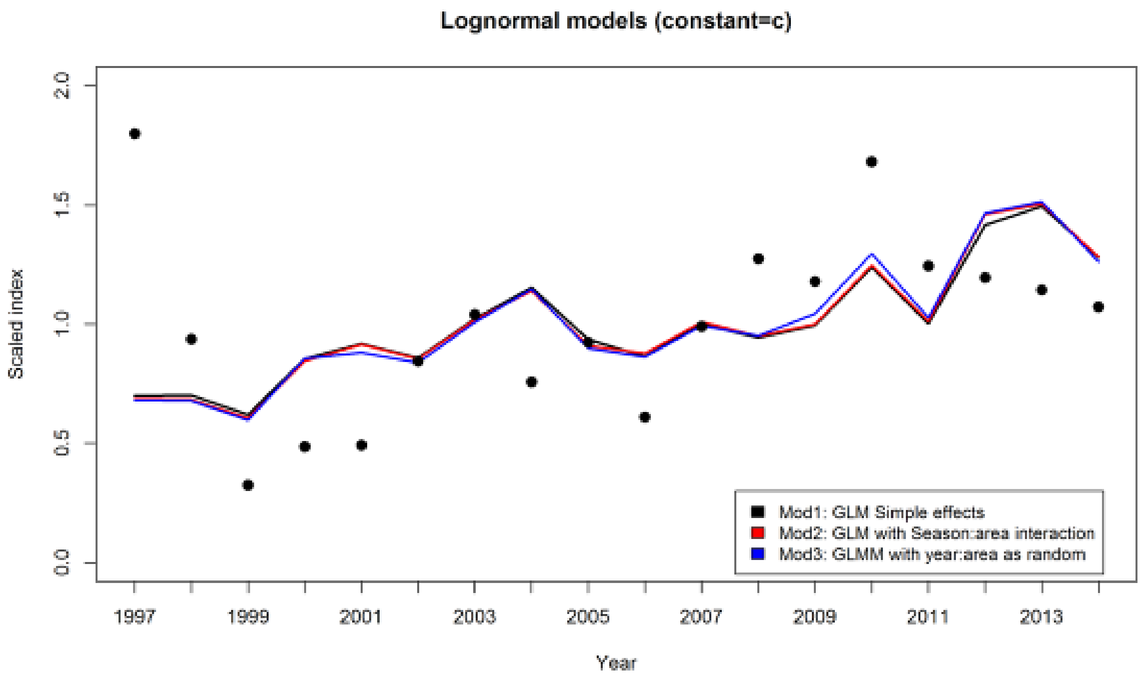

Figure 8. Standardized CPUE series for blue shark captured by the Portuguese pelagic longline fleet in the North Atlantic Ocean using lognormal GLM with and without season:area interactions, and a lognormal GLMM with random year.area interactions. The solid lines and the black dots refer respectively to the standardized and nominal CPUE series scaled by the mean.

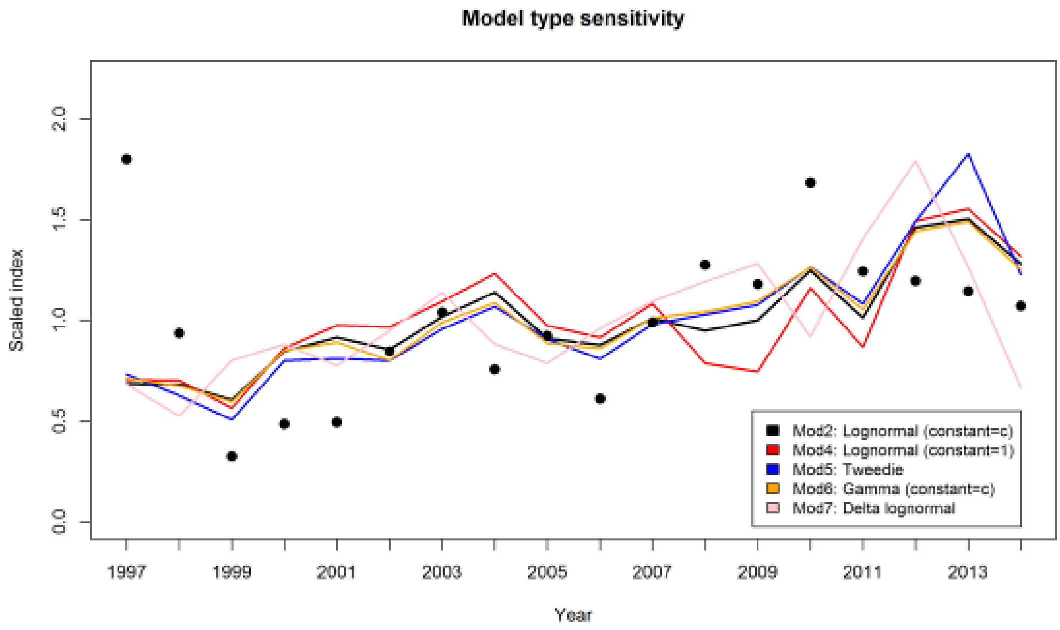

Figure 9. Sensitivity analysis to the model type for the blue shark CPUE standardization from the Portuguese pelagic longline fleet in the North Atlantic Ocean. The scaled annual indexes of abundance of the final model selected (Mod2) is represented in black, and compared to alternative models, specifically: Mod4: lognormal with constant=1 (red); Mod5: tweedie model (blue); Mod6: gamma model (orange) and Mod7: Delta lognormal (pink).

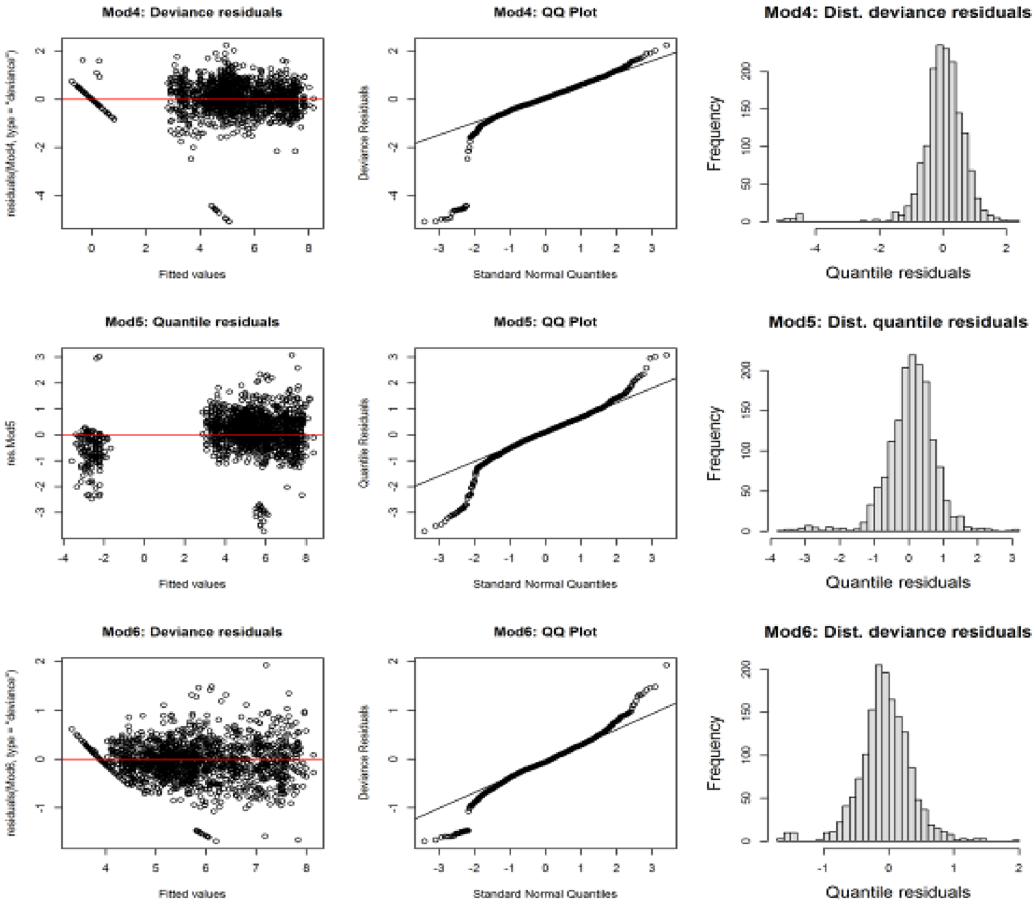

Figure 10. Residual analysis for the various model types (sensitivity analysis) tested for the blue shark CPUE standardization in the North Atlantic, specifically a lognormal with constant *c*=1 (Mod 3), a tweedie model (Mod4) and a gamma model (Mod 5). For each model it is presented the residuals along 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).

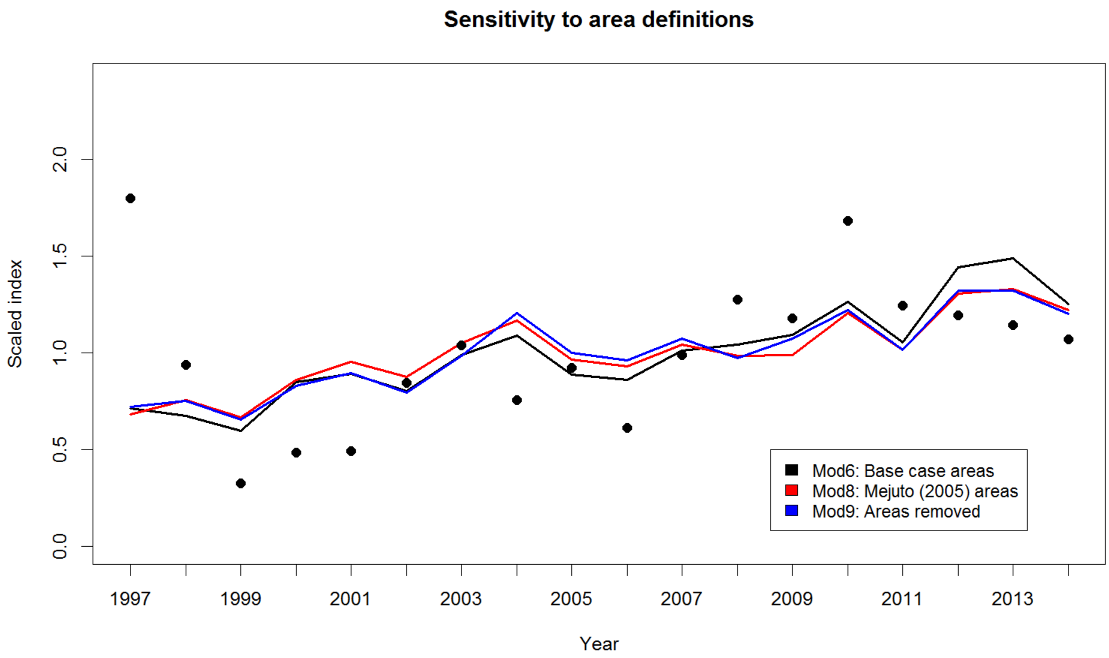

Figure 11. Model sensitivity to the area factor for the blue shark CPUE standardization from the Portuguese pelagic longline fleet in the North Atlantic Ocean. The scaled annual indexes of abundance of the final model selected (Mod6) is represented in black, and the alternative models in red (Mod8: using areas as defined by Mejuto and Garcis-Cortés, 2005) and blue (Mod9: model without area effects).

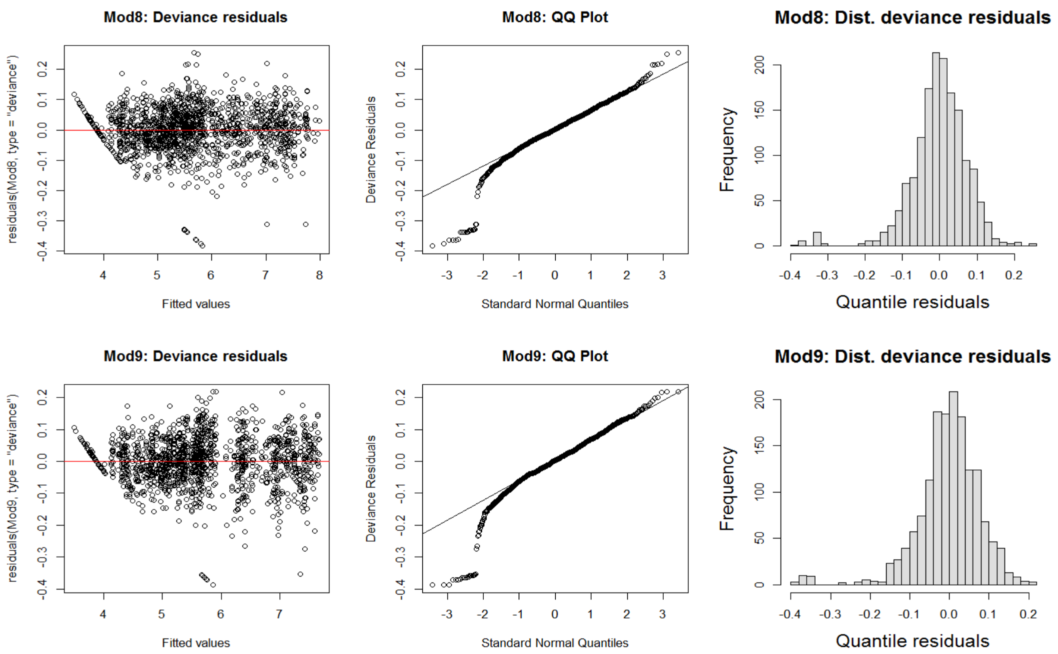

Figure 12. Residual analysis for the model tested for the sensitivity to the area factor for the blue shark CPUE standardization in the North Atlantic Ocean. Mod 8 uses areas as defined by Mejuto and García-Cortés (2005) and Mod 9 does not include the area factor. For each model it is presented the residuals 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).

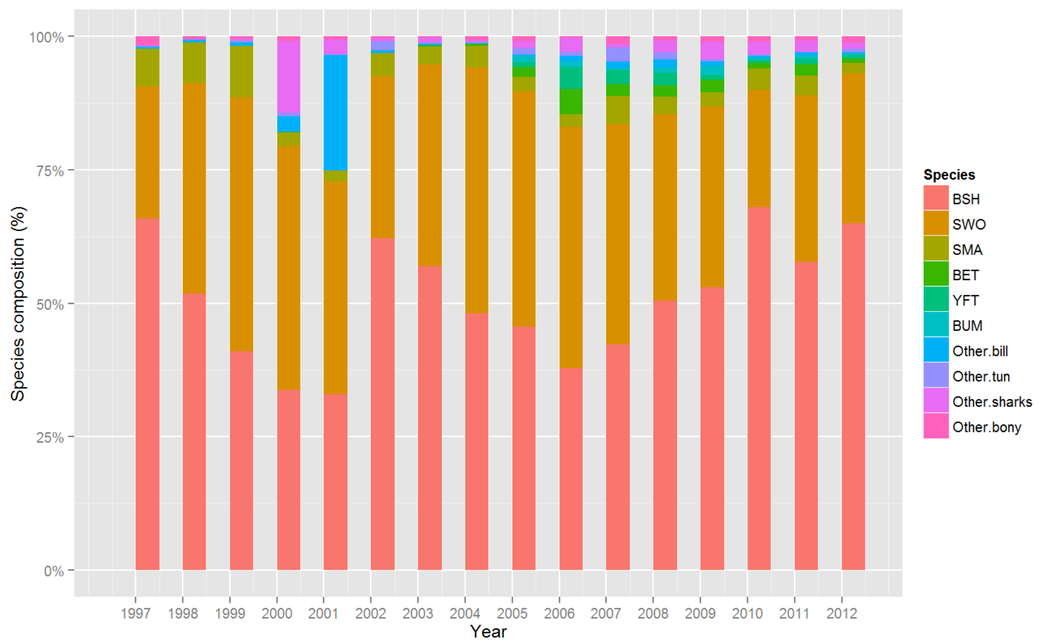

Figure 13. Catch composition of the Portuguese pelagic longline fleet operation in the North Atlantic between 1997 and 2014.

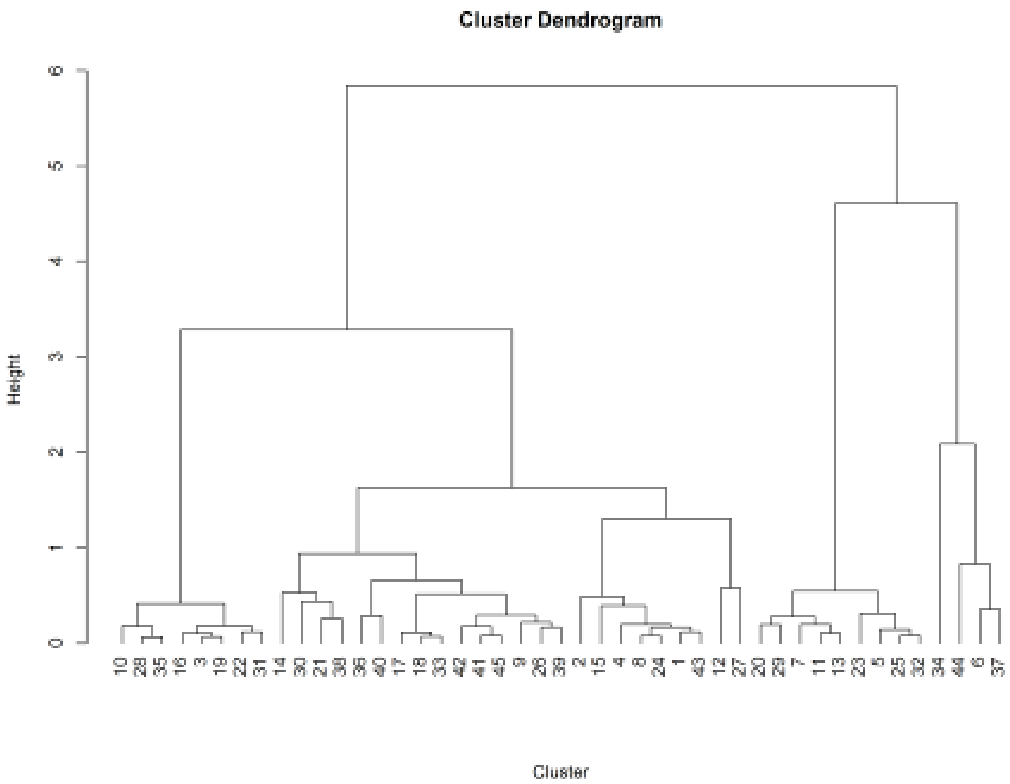

Figure 14. Hierarchical cluster analysis classifying the groups formed with the non-hierarchical analysis (*k-means*) for the Portuguese pelagic longline fleet in the North Atlantic Ocean.

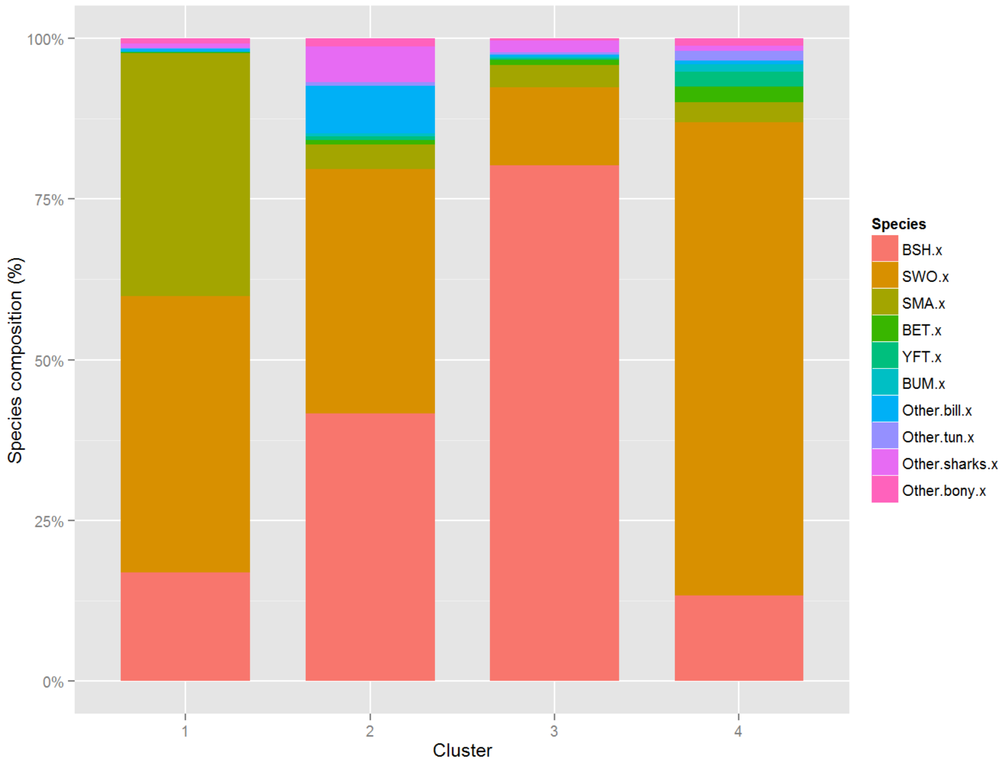

Figure 15. Catch composition of the 4 clusters defined for the Portuguese pelagic longline fleet operating in the North Atlantic.

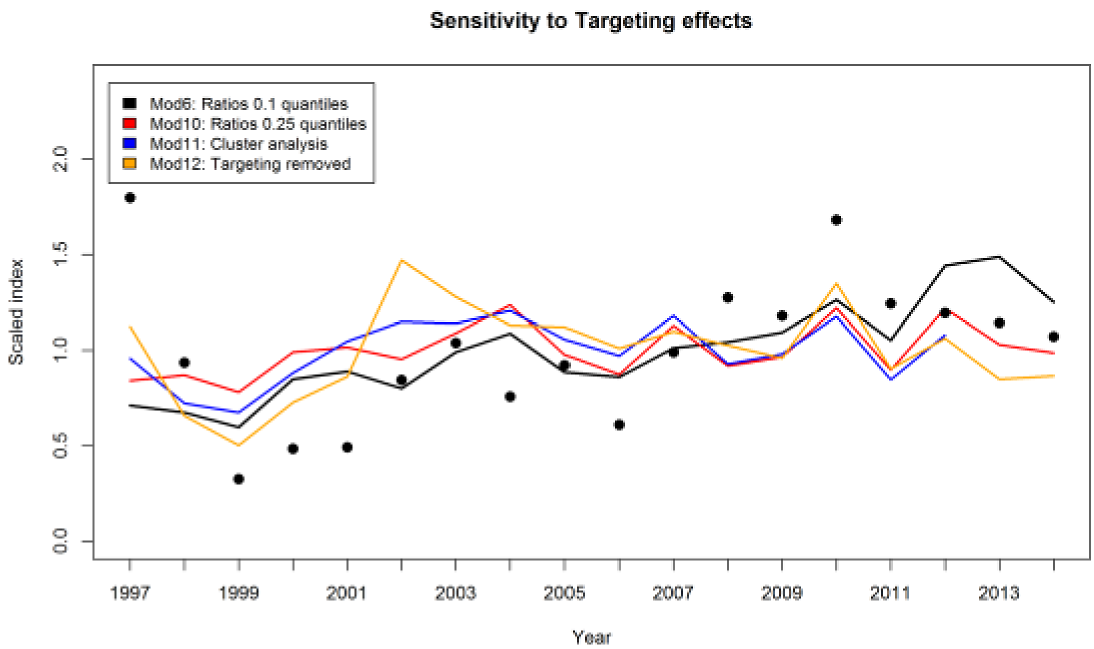

Figure 16. Model sensitivity to the targeting effects for the blue shark CPUE standardization from the Portuguese pelagic longline fleet in the North Atlantic Ocean. The scaled annual indexes of abundance of the final model selected (Mod6) is represented in black, and the alternative models in red (Mod10: using a different ratio categorization), blue (Mod11: targeting effects from the cluster analysis) and orange (Mod12: removing targeting effects).

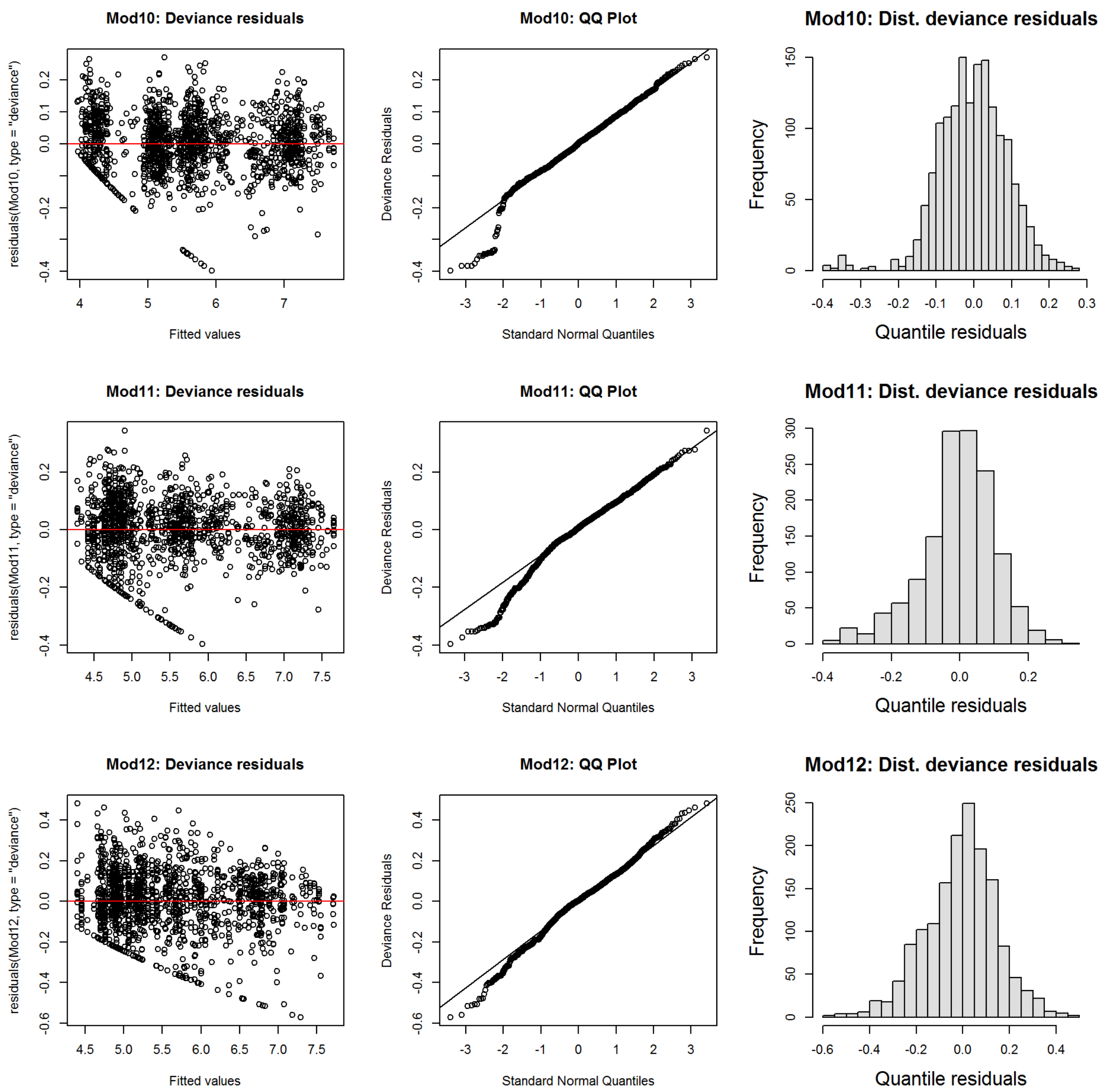

Figure 17. Residual analysis for the various model tested for the sensitivity to the targeting effects for the blue shark CPUE standardization in the North Atlantic. Mod 10 uses a different ratio categorization (0.25 quantiles), Mod 11 uses targeting based on a cluster analysis, and Mod 12 does not include targeting effects. 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).