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UPDATED STANDARDIZED CPUES OF BLUE SHARK IN THE PORTUGUESE PELAGIC LONGLINE FLEET OPERATING IN THE NORTH ATLANTIC (1997-2021)

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SUMMARY

This document updates the catch, effort and standardized CPUE for the north Atlantic blue shark captured by the Portuguese pelagic longline fleet. Nominal annual CPUE were calculated in biomass (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), targeting effects (ratios or cluster analysis), and definition of areas. Model goodness-of-fit was carried out with AIC and the pseudo R^2, and model validation with residual analysis. This paper updates the previous index from the Portuguese fleet to be considered for use in the 2023 ICCAT blue shark stock assessment. The final standardized CPUE results show an overall increasing trend from the start of the time series in 1997 until 2015, and then a relatively stable period between 2015 and 2021 with yearly oscillations.

RÉSUMÉ

Ce document met à jour la prise, l'effort et la CPUE standardisée pour le requin peau bleue de l'Atlantique Nord capturé par la flottille de palangriers pélagiques portugais. Les CPUE nominales annuelles ont été calculées en biomasse (kg/1000 hameçons) et ont été standardisées avec des modèles linéaires généralisés (GLM) et des modèles mixtes linéaires généralisés (GLMM) utilisant l'année, le trimestre, la zone, le type d'engin, les effets de ciblage et les interactions zone : trimestre comme facteurs fixes, et zone : année comme effets aléatoires. Des analyses de sensibilité ont été effectuées pour le type de modèle (lognormal, tweedie, gamma ou delta lognormal), les effets de ciblage (ratios ou analyse de grappes) et la définition des zones. La qualité de l'ajustement du modèle a été établie au moyen de AIC et du pseudo R^2 et la validation du modèle a été réalisée avec une analyse résiduelle. Ce document met à jour l'indice précédent de la flottille portugaise à prendre en compte dans l'évaluation du stock de requin peau bleue de l'ICCAT en 2023. Les résultats finaux de la CPUE standardisée montrent une tendance globale à la hausse depuis le début de la série temporelle en 1997 jusqu'en 2015, puis une période relativement stable entre 2015 et 2021 avec des oscillations annuelles.

RESUMEN

Este documento actualiza la captura, esfuerzo y CPUE estandarizada para el tiburón azul del Atlántico norte capturado por la flota de palangre pelágico portuguesa. Las CPUE nominales anuales se calcularon sobre la biomasa (kg/1.000 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), efectos de la especie objetivo (la ratio o en un análisis de conglomerados) y definición de las áreas. La bondad del ajuste del modelo se llevó a cabo con AIC y el pseudo R^2 y la validación del modelo con análisis residual. Este documento actualiza el índice anterior de la flota portuguesa para que se considere su uso en la evaluación del stock de tiburón azul de 2023 de ICCAT. Los

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resultados finales de la CPUE estandarizada muestran una tendencia creciente global desde el inicio de la serie temporal en 1997 hasta 2015, y luego un período relativamente estable entre 2015 y 2021 con oscilaciones anuales.

KEYWORDS:

Blue shark, Prionace glauca, fishery indicators, CPUE standardization, generalized linear models, generalized linear mixed models, longline fisheries

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.

A first blue shark (*Prionace glauca*) standardized CPUE from the Portuguese pelagic longline fleet operating in the North Atlantic was presented to ICCAT in 2015 (Coelho et al., 2016) and was used in the latest stock assessment carried out in that same year. This paper updates that index, to be considered for use in the blue shark stock assessment that will be carried out by ICCAT in 2023.

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 1995-2021. The information on the total catch and effort 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 3.2% to maximums of 21.9% per year (excluding the years of 1995-1996 that were not included in the CPUE standardization process, and also excluding 2020 that had very little sampling due to Covid-19 related restrictions) (**Table 1**). Data from a total of 1,981 trips or sub-trip (consecutive sets in the same trip, area and month) were used, which amounted to a total fishing effort of 18,670 fishing sets, with 22,640,260 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 months/quarters of the year, in order to describe the patterns of the catches of this species by the fleet in that region and month or quarter.

2.2 CPUE standardization

The available catch and effort data started in 1995 and was available until 2021. The data from the first two years of the series (1995 and 1996) was excluded from the model runs due to low number of observations, so the final CPUE time series was analyzed for the period 1997 to 2021. 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 with zero blue shark catches (10.4% of the data) that result in a response variable of CPUE=0. As these zeros can cause mathematical problems for fitting the models, four different methodologies were used and compared, specifically tweedie, gamma, lognormal and delta lognormal models. For the tweedie based 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 based 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 2021;
- 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 change 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 1 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., 2012; Santos et al., 2013b; 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 comprised mainly of 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 were used before by Santos et al. (2013b) 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 SWO and BSH are the main components of the Portuguese longline fleet catches. 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 targeting 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 1) alternative BSH areas as defined by Mejuto and Garcia-Cortés (2005), and 2) 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 4.0.5 (R Core Team, 2021) 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**). Most of the sampling effort took place in the temperate northeast Atlantic (**Figure 2**) as that is one of the major areas of operation of the Portuguese pelagic longline fleet in the North Atlantic. In contrast, the higher concentration of BSH CPUEs (in biomass) was observed in areas of the tropical northeast Atlantic (**Figure 3**).

3.1.2 Yearly and quarterly variability in the catch and effort

The observed 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 4**), and this is related with the total fishing effort from the Portuguese pelagic longline fleet in the Atlantic Ocean. The analyzed blue shark sampled catch did not directly follow this trend, as there was a general increase in the sampled catches until 2010, followed by a decrease in the more recent years (**Figure 4**). In terms of swordfish compared to the swordfish + blue shark catches, the initial year of the series had a very high ratio which was followed by a decrease for the remaining years, even though there were some more recent years with higher ratios (**Figure 4**). Some of the decreases observed in the more recent years, after 2008, might be related with changes in the fishing gear (nylon monofilament leaders 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 quarterly variability 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 5**).

3.3 CPUE standardization

3.3.1 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 6**. There was a peak in the start of the series in 1997, followed by a sharp decrease in 1999, then a progressive increase until 2010 and 2015, and finally a slight decrease in the more recent years from 2015 to 2021 (**Figure 6**). The nominal blue shark CPUE distribution was highly skewed to the right and became more normal shaped in the log-transformed scale (**Figure 7**).

3.3.2 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 increased the AIC, and the variability of the random effect was very low (variance = 0.014), as such, the random effects of the year:quarter interaction were not included in the final models. On all models (with and without spatial:quarter 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 some outliers (**Figure 8**).

For the 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 years (**Figure 9**).

3.3.3. 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, gamma and tweedie models, while the delta lognormal showed differences in some of the years (**Figure 10**).

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 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 tweedie model (Mod5), while for the lognormal and gamma model the residual analysis produced better results (**Figure 11**).

3.3.4 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 12**). 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, while removing the area effect produced much worse fits (**Table 5**). In terms of residual analysis there were no major differences in the models using different areas (**Figure 13**).

3.3.5. Sensitivity to the targeting effects

A final sensitivity analysis was run for testing the influence of the targeting effects, 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, a model using targets effects based on a cluster analysis, and 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 14**). 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 14**). 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 15**). 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 4 clusters. The catch composition of those 4 clusters, representing four targeting strategies of the fleet is presented in **Figure 16**, and are summarized as: 1) targeting mainly SWO (38.0% of trips or sub-trips), 2) mixed strategy targeting mainly SWO and capturing other sharks, mainly SMA (1.1% of trips or sub-trips, 3) targeting mainly BSH (26.9% of trips or sub-trips), and 4) mixed strategy targeting both SWO and BSH (34.0% of trips or sub-trips) and). Those proportions of targeting clusters had some variations over time which are represented in **Figure 17**.

This sensitivity analysis revealed some differences in the standardized BSH CPUE series, but the general trends remained very similar for all tested scenarios (**Figure 18**). 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. Using targeting effects from the cluster analysis also produced a worse fit than using ratios (**Table 6**). 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 19**).

4. Conclusions

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:quarter interaction). Besides the main simple effects year, quarter, area, ratio and gear type, this model also accounts for area:quarter interactions, allowing for different seasonal effects in the CPUEs to take place within each of the areas considered.

The standardized blue shark CPUE index (kg/1000 hooks) for the Portuguese pelagic longline fishery in the North Atlantic between 1997-2021 estimated from this model and suggested to be used in the 2023 BSH stock assessments is presented in **Table 7**. A plot with the respective CIs of this index is provided in **Figure 20**. The final standardized index shows an overall increasing trend from the start of the time series in 1997 until 2015, and then a relatively stable period between 2015 and 2021 with yearly oscillations.

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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 sampled (MT), relative percentage of the catch covered in the analysis, number of trips (or sub-trips) and effort covered in number of sets and hooks. Only the data below the dashed line was used in the CPUE standardization modelling.

Year	*BSH total catch*	*Covered in the analysis*				
		Catch sampled	*% covered*	*Trips/Sub-trips*	*Sets*	*Hooks*
1995	4 722.0	4.7	0.1	8	47	75 200
1996	4 843.0	25.8	0.5	4	52	83 200
1997	2 630.0	368.8	14.0	28	181	367 500
1998	2 440.4	332.7	13.6	42	257	494 400
1999	2 226.6	205.0	9.2	66	512	918 800
2000	2 081.0	363.0	17.4	142	928	1 418 610
2001	2 109.9	320.3	15.2	139	802	1 034 908
2002	2 264.6	425.0	18.8	92	647	783 850
2003	5 642.8	432.3	7.7	113	734	851 102
2004	2 024.6	444.0	21.9	125	792	876 482
2005	4 027.0	490.9	12.2	109	902	1 048 178
2006	4 337.9	140.5	3.2	72	464	522 917
2007	5 283.3	316.0	6.0	95	562	567 790
2008	6 166.8	511.0	8.3	92	619	640 946
2009	6 251.6	507.7	8.1	89	695	730 782
2010	8 261.1	836.9	10.1	94	783	817 542
2011	6 509.1	404.7	6.2	50	470	482 839
2012	3 767.8	437.1	11.6	69	663	712 567
2013	3 694.4	564.4	15.3	81	958	973 168
2014	3 059.5	323.4	10.6	46	489	515 191
2015	3 859.2	534.4	13.8	59	558	541 854
2016	7 819.0	430.8	5.5	81	785	747 120
2017	5 664.2	382.2	6.7	66	650	621 411
2018	5 194.6	366.3	7.1	65	630	599 478
2019	4 507.3	317.1	7.0	55	554	539 026
2020	3 836.3	54.0	1.4	39	284	264 990
2021	4 299.8	286.2	6.7	60	546	526 968

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 (54 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 (54 pars)
Sensitivity to model type	Mod4	GLM Lognormal (c=1)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Lognormal GLM with area:season interaction (54 pars)
	Mod5	GLM Tweedie (link=log)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Tweedie GLM with area:season interaction (54 pars)
	Mod6	GLM Gamma (link=log; c=10%mean)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Gamma GLM with area:season interaction (54 pars)
	Mod7	GLM Delta-lognormal (Binomial with logit link and lognormal for positives)	Year + Quarter + Area + Vessel + Ratio + Geartype	Delta-lognormal (binomial: 35 pars; lognormal: 42 pars)
Sensitivity to area effects	Mod8	GLM Gamma (link=log; c=10%mean)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Using Mejuto (2005) areas (58 pars)
	Mod9	GLM Gamma (link=log; c=10%mean)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Model without spatial effects (38 pars)
Sensitivity to target effect	Mod10	GLM Gamma (link=log; c=10%mean)	Year + Quarter + Area + Vessel + Ratio + Geartype + Quarter:Area	Ratio factor categorized by the 0.25 quantiles (48 pars)
	Mod11	GLM Gamma (link=log; c=10%mean)	Year + Quarter + Area + Vessel +Cluster + Geartype + Quarter:Area	Targetting based on cluster analysis (48 pars)
	Mod12	GLM Gamma (link=log; c=10%mean)	Year + Quarter + Area + Vessel + Geartype + Quarter:Area	Model without target effects (45 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 variable 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	SS	Df	F-stat.	*p-value*
Mod 1: Full simple effects model (AIC=2308; R2=85.5%)	Year	65.76	24	14.82	< 0.001
	Quarter	7.18	3	12.94	< 0.001
	Area	46.43	4	62.77	< 0.001
	Ratio	1215.16	9	730.20	< 0.001
	Geartype	0.98	1	5.31	0.021
Mod 2: Model with area:quarter interaction (AIC=2280; R2=85.8%)	Year	66.34	24	15.26	< 0.001
	Quarter	7.18	3	13.20	< 0.001
	Area	46.43	4	64.06	< 0.001
	Ratio	1024.55	9	628.23	< 0.001
	Geartype	1.02	1	5.63	0.018
	Quarter:Area	9.3	12	4.28	< 0.001
Mod 3: GLMM with random year:area effects (AIC=2479; R2=NA)	Year	50.71	24	12.10	< 0.001
	Quarter	81.16	3	154.92	< 0.001
	Area	224.38	4	321.23	< 0.001
	Ratio	1152.59	9	733.36	< 0.001
	Geartype	0.97	1	5.58	0.016
	Quarter:Area	8.61	12	4.11	< 0.001

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 variable 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	SS	Df	F-stat.	*p-value*
Mod 4: Lognormal (cons=1) (R2=85.8%)	Year	66.34	24	15.26	< 0.001
	Quarter	7.18	3	13.20	< 0.001
	Area	46.43	4	64.06	< 0.001
	Ratio	1024.55	9	628.23	< 0.001
	Geartype	1.02	1	5.63	0.018
	Quarter:Area	9.3	12	4.28	< 0.001
Mod 5: Tweedie (R2=82.0%)	Year	483.7	24	7.79	< 0.001
	Quarter	60.7	3	7.82	< 0.001
	Area	270.5	4	26.14	< 0.001
	Ratio	9708.3	9	416.90	< 0.001
	Geartype	8.2	1	3.17	0.075
	Quarter:Area	59.6	12	1.92	0.028
Mod 6: Gamma (cons=c) (AIC=2160, R2=86.1%)	Year	1.692	24	13.29	< 0.001
	Quarter	0.203	3	12.75	< 0.001
	Area	1.001	4	47.18	< 0.001
	Ratio	34.751	9	727.96	< 0.001
	Geartype	0.021	1	4.04	0.045
	Quarter:Area	0.229	12	3.60	< 0.001
Mod 7.1: Delta lognormal (binomial) (R2=50.2%)	Year	174.54	24	19.09	< 0.001
	Quarter	4.26	3	3.73	0.011
	Area	2.63	4	1.73	0.141
	Ratio	411.26	3	359.89	< 0.001
Mod 7.2: Delta lognormal (lognormal for positives) (R2=85.3%)	Year	107.93	24	17.73	< 0.001
	Quarter	13.18	3	17.32	< 0.001
	Area	48.02	4	47.33	< 0.001
	Ratio	1368.24	9	599.30	< 0.001
	Geartype	0.78	1	3.09	0.079

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 variable 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	SS	Df	F-stat.	*p-value*
Mod 8: Mejuto and Garcia-Cortés (2005) areas (AIC=2176; R2=86.0%)	Year	1.714	24	13.39	< 0.001
	Quarter	0.203	3	12.67	< 0.001
	Area	0.648	4	30.38	< 0.001
	Ratio	35.094	9	730.81	< 0.001
	Geartype	0.024	1	4.48	0.034
	Quarter:Area	0.185	16	2.16	0.005
Mod 9: Removing areas (AIC=2341; R2=84.7%)	Year	1.333	24	9.55	< 0.001
	Quarter	0.061	3	3.52	0.015
	Ratio	55.842	9	1067.36	< 0.001
	Geartype	0.015	1	2.54	0.111

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 variable 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	SS	Df	F-stat.	*p-value*
Mod 10: Ratio categorization (AIC=3001; R2=78.6%)	Year	1.8588	24	9.22	< 0.001
	Quarter	0.2208	3	8.76	< 0.001
	Area	1.2812	4	38.13	< 0.001
	RatioCategory	28.9052	3	1146.99	< 0.001
	Geartype	0.0127	1	1.51	0.219
	Quarter:Area	0.4394	12	4.36	< 0.001
Mod 11: Cluster analysis (AIC=3733; R2=69.1%)	Year	2.6504	24	9.19	< 0.001
	Quarter	0.3837	3	10.64	< 0.001
	Area	1.298	4	27.00	< 0.001
	Clusters	21.4606	3	595.17	< 0.001
	Geartype	0.0037	1	0.31	0.580
	Quarter:Area	0.7292	12	5.06	< 0.001
Mod 12: Removing targeting (AIC= 4987; R2=41.6%)	Year	4.636	24	8.44	< 0.001
	Quarter	1.619	3	23.57	< 0.001
	Area	17.532	4	191.42	< 0.001
	Geartype	0.094	1	4.12	0.043
	Quarter:Area	4.789	12	17.43	< 0.001

Table 7. Standardized BSH CPUE index (kg/1000 hooks) for the Portuguese pelagic longline fleet in the North Atlantic between 1997 and 2021, suggested to be used in the 2023 BSH stock assessments. The table includes the index value, the 95% confidence intervals (CI) and the coefficient of variation (CV, %).

Year	*Pop means*	*UppIC*	*LowIC*	*CV*
1997	160.9	199.0	128.7	7.9
1998	163.9	191.8	139.2	7.1
1999	141.5	161.3	123.7	7.2
2000	189.4	207.3	172.8	7.7
2001	215.6	237.2	195.6	8.3
2002	191.1	214.5	169.7	8.0
2003	229.9	253.4	208.2	7.7
2004	262.0	287.5	238.5	7.9
2005	217.8	242.1	195.4	8.2
2006	213.1	241.9	187.1	7.9
2007	235.1	262.5	210.2	8.0
2008	223.6	250.3	199.3	8.0
2009	233.1	261.6	207.3	8.1
2010	274.0	306.9	244.2	8.4
2011	245.0	281.5	212.4	7.4
2012	310.1	348.8	275.1	7.6
2013	309.6	345.0	277.3	7.6
2014	288.3	329.9	251.2	7.1
2015	383.1	435.3	336.6	7.8
2016	373.4	419.3	332.1	8.3
2017	344.2	390.9	302.4	8.2
2018	330.2	375.2	290.0	8.1
2019	340.9	390.7	296.7	8.0
2020	373.1	432.3	321.3	7.3
2021	345.7	394.2	302.5	8.0

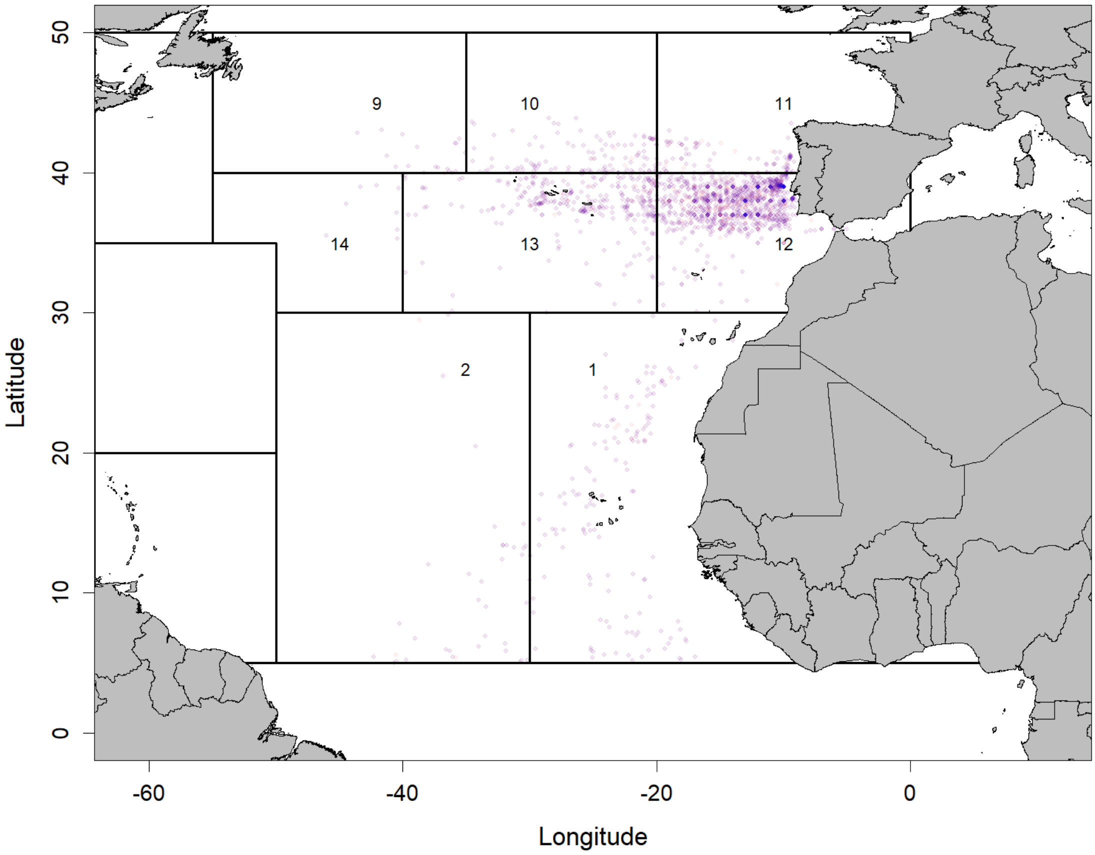

Figure 1. Sampling locations with the definition of fishing areas of the North Atlantic used in this study for the base case scenario (according to the area definitions by Mejuto et al., 2008). Due to small sample sizes, the areas 1+2, 9+10 and 13+14 were joined for the models.

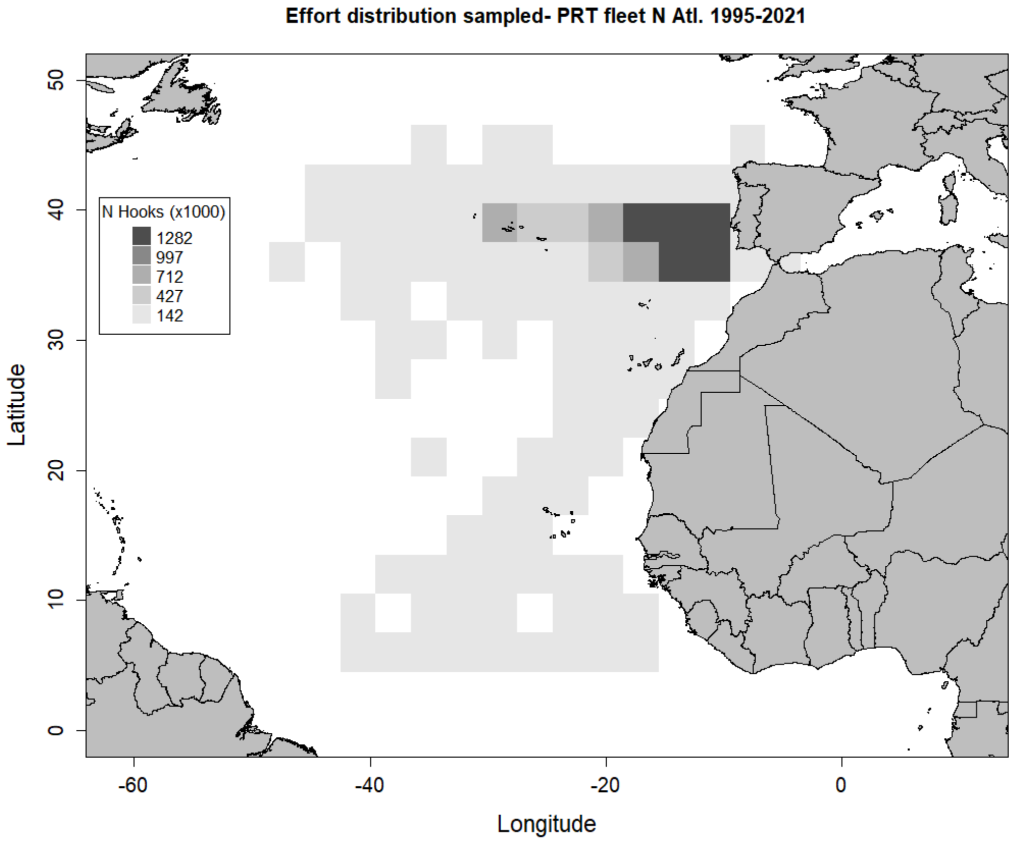

Figure 2. Sampled effort distribution in the North Atlantic used in this study for the period between 1995 and 2021. The effort is represented in number of hooks (x1000) in 3x3 degrees grids.

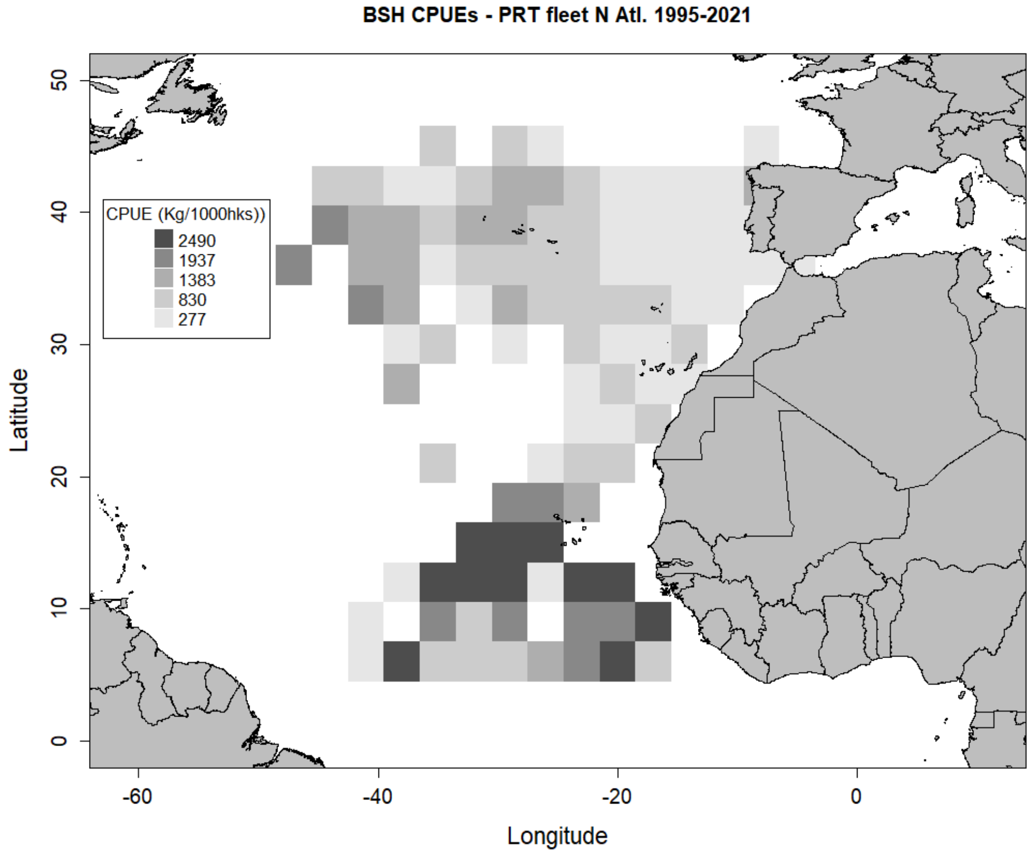

Figure 3. Distribution of CPUEs of BSH (biomass) in the North Atlantic used in this study for the period between 1995 and 2021. The distribution is represented in 3x3 degrees grids.

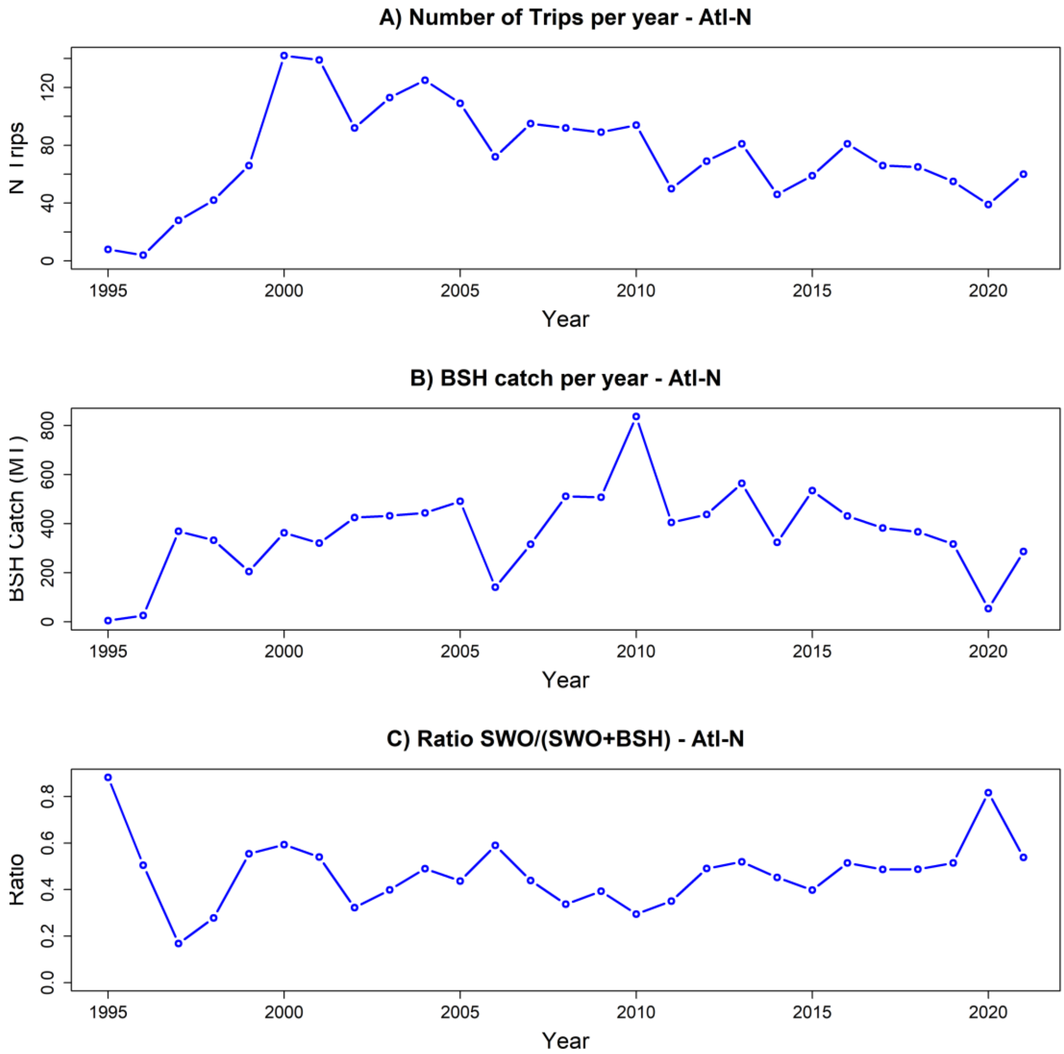

Figure 4. Descriptive plots of the sample used in this study in terms of observed effort in sets (A), total catch of blue shark (B), and ratio of swordfish compared to the swordfish and blue shark catches (C), for the Portuguese longline fleet operating in the North Atlantic.

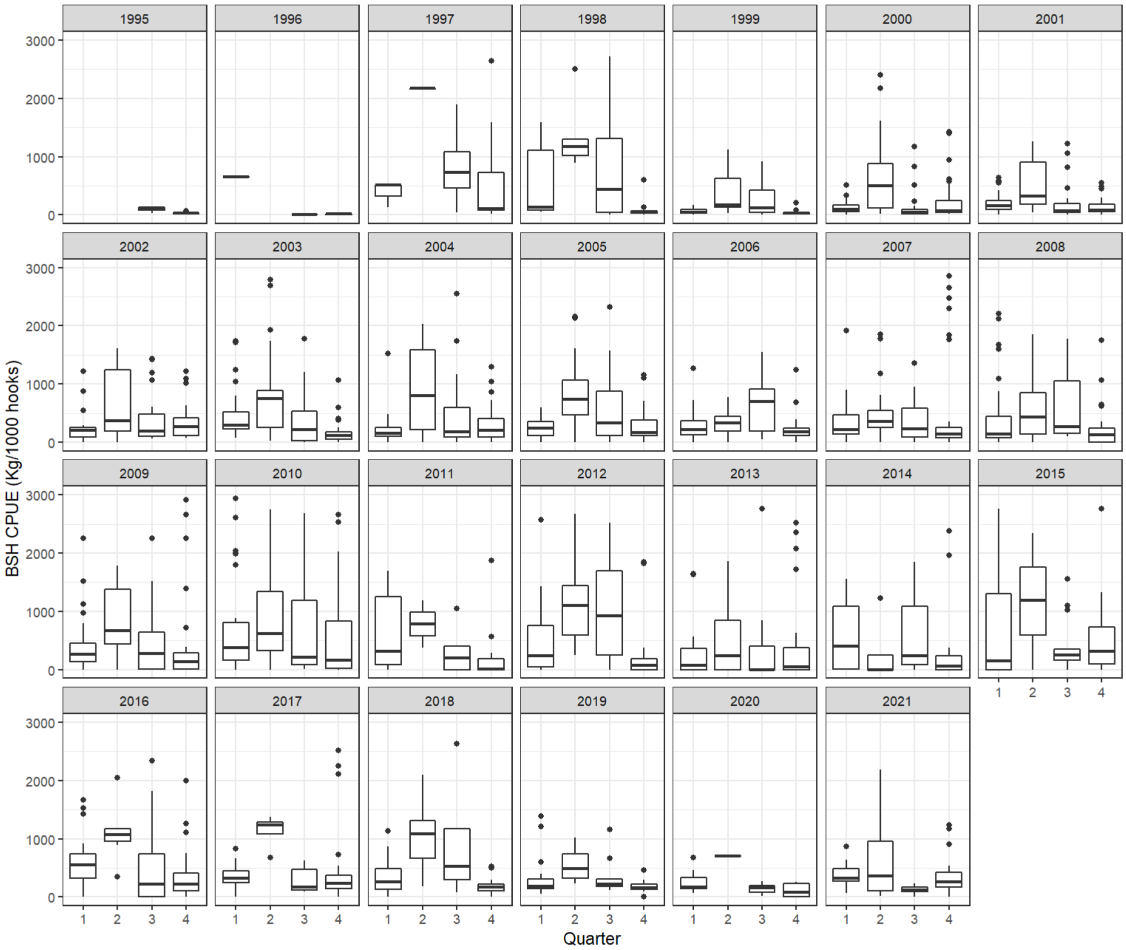

Figure 5. Quarterly blue shark CPUE (kg/1000 hooks) by the Portuguese pelagic longline fleet in the North Atlantic, per year. In the boxplots the middle lines represents the median, the box the quartiles, the whiskers the non-outlier range and the points the outliers.

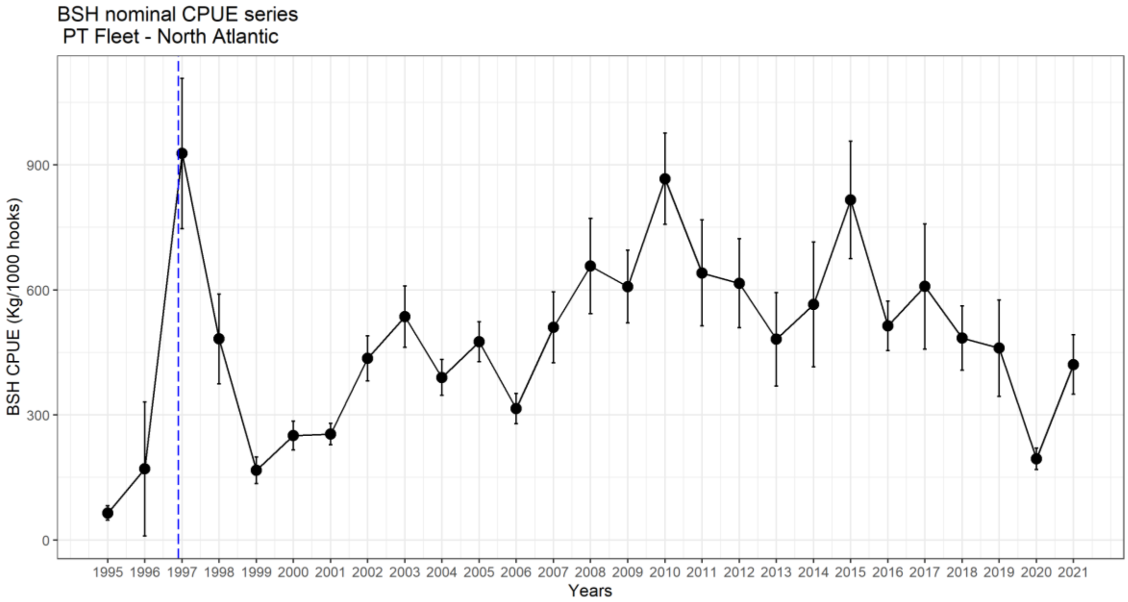

Figure 6. Nominal CPUE series (kg/1000 hooks) for blue shark caught by the Portuguese pelagic longline fishery in the North Atlantic between 1995 and 2021. The error bars refer to the standard errors and the vertical dashed blue line refers to the start of the data series for the CPUE standardization analysis.

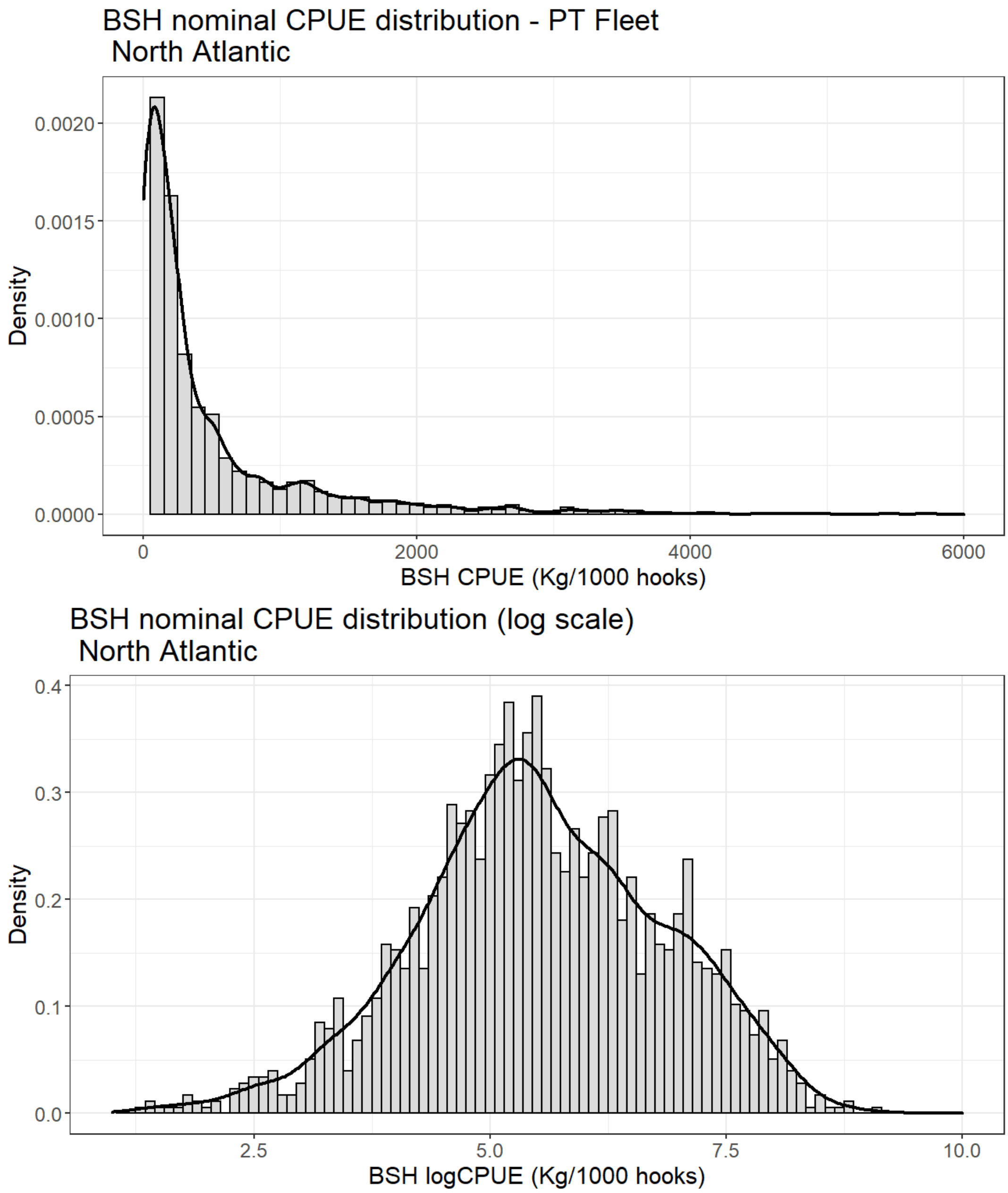

Figure 7. Distribution of the nominal blue shark CPUE captured by the Portuguese longline fleet in the North Atlantic Ocean in non-transformed (top plot) and log-transformed (bottom plot) scales.

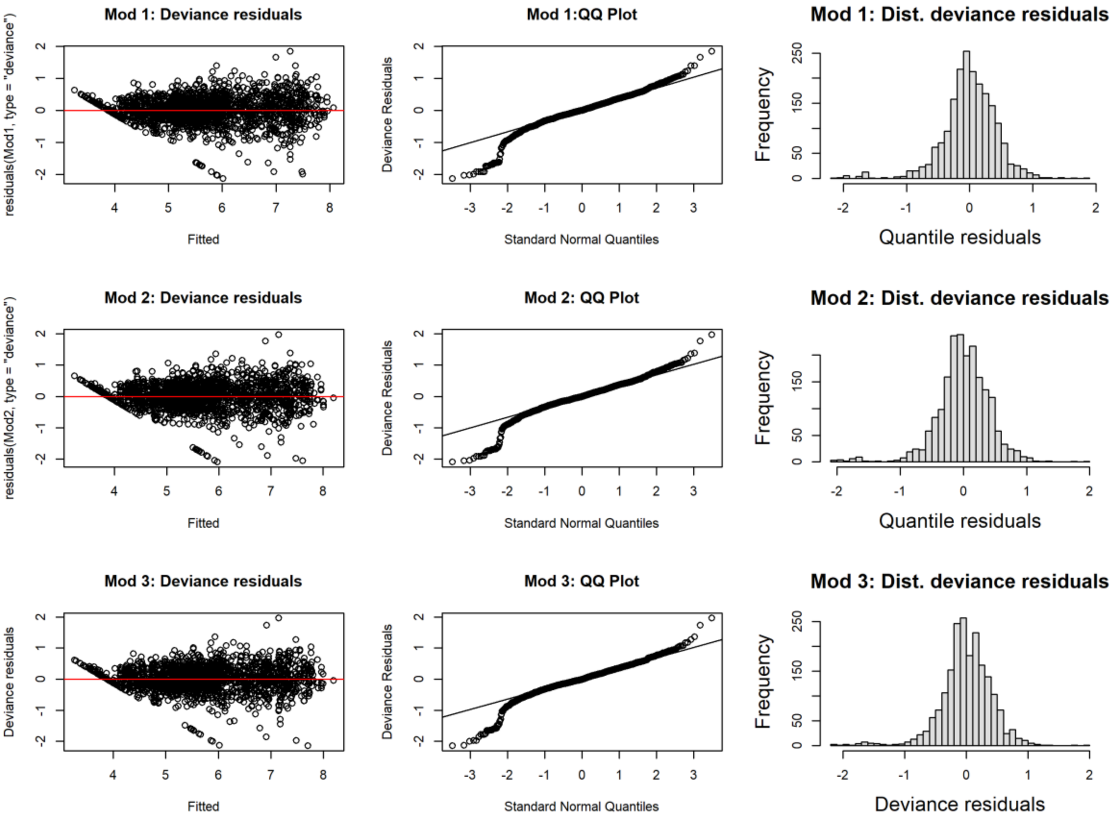

Figure 8. Residual analysis for the lognormal models tested for the blue shark CPUE standardization in the North Atlantic Ocean, specifically a GLM with simple effects only (Mod1), a GLM with quarter/area interactions (Mod2), and a GLMM with random year:area interactions. For each model it is presented 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).

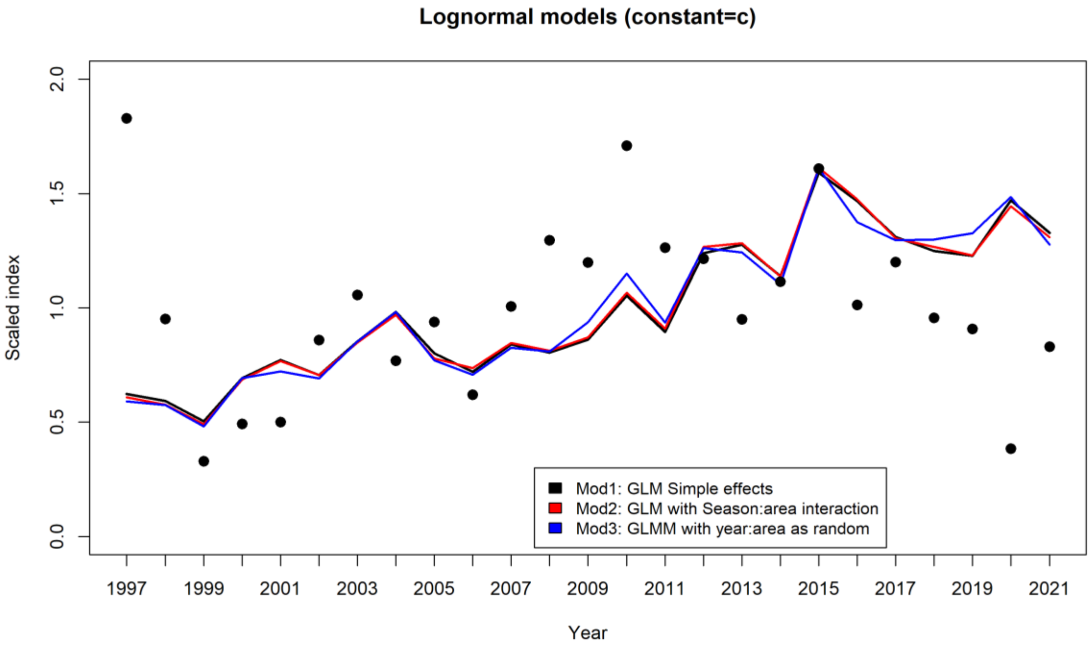

Figure 9. Standardized CPUE series for blue shark captured by the Portuguese pelagic longline fleet in the North Atlantic Ocean using lognormal GLM with and without quarter:area interactions, and a lognormal GLMM with random year:area interactions. The solid lines and the black dots refer respectively to the standardized and nominal CPUE series scaled by the mean.

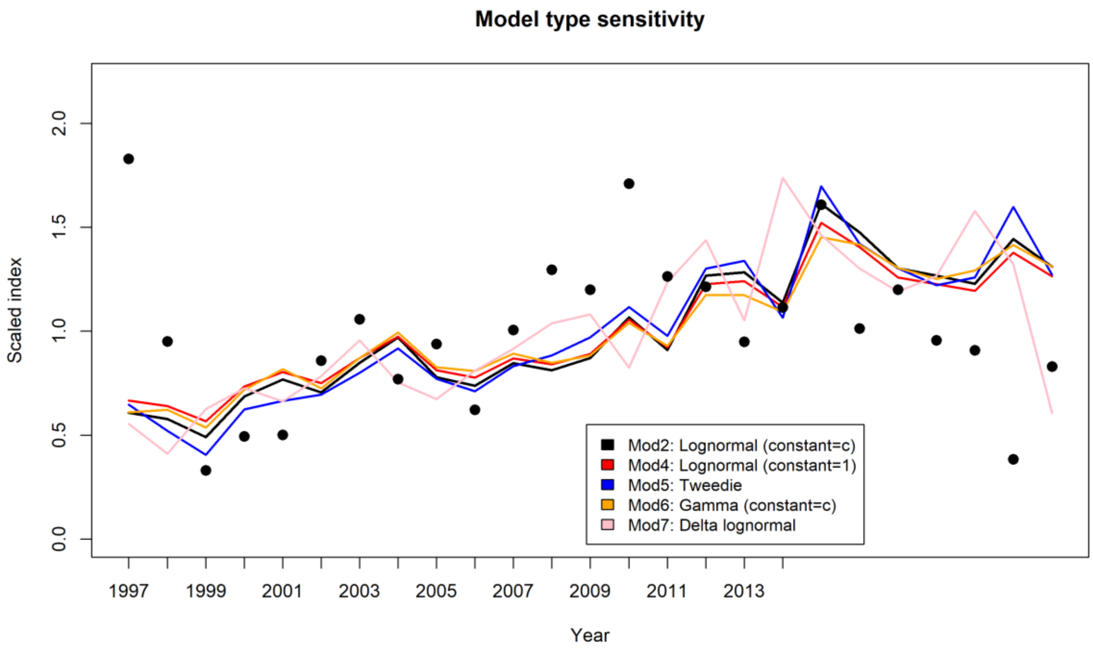

Figure 10. Sensitivity analysis to the model type for the blue shark CPUE standardization from the Portuguese pelagic longline fleet in the North Atlantic Ocean. The scaled annual indexes of abundance of the final model selected (Mod2) is represented in black, and compared to alternative models, specifically: Mod4: lognormal with constant=1 (red); Mod5: tweedie model (blue); Mod6: gamma model (orange) and Mod7: Delta lognormal (pink). The black dots refer to the nominal CPUE series scaled by the mean.

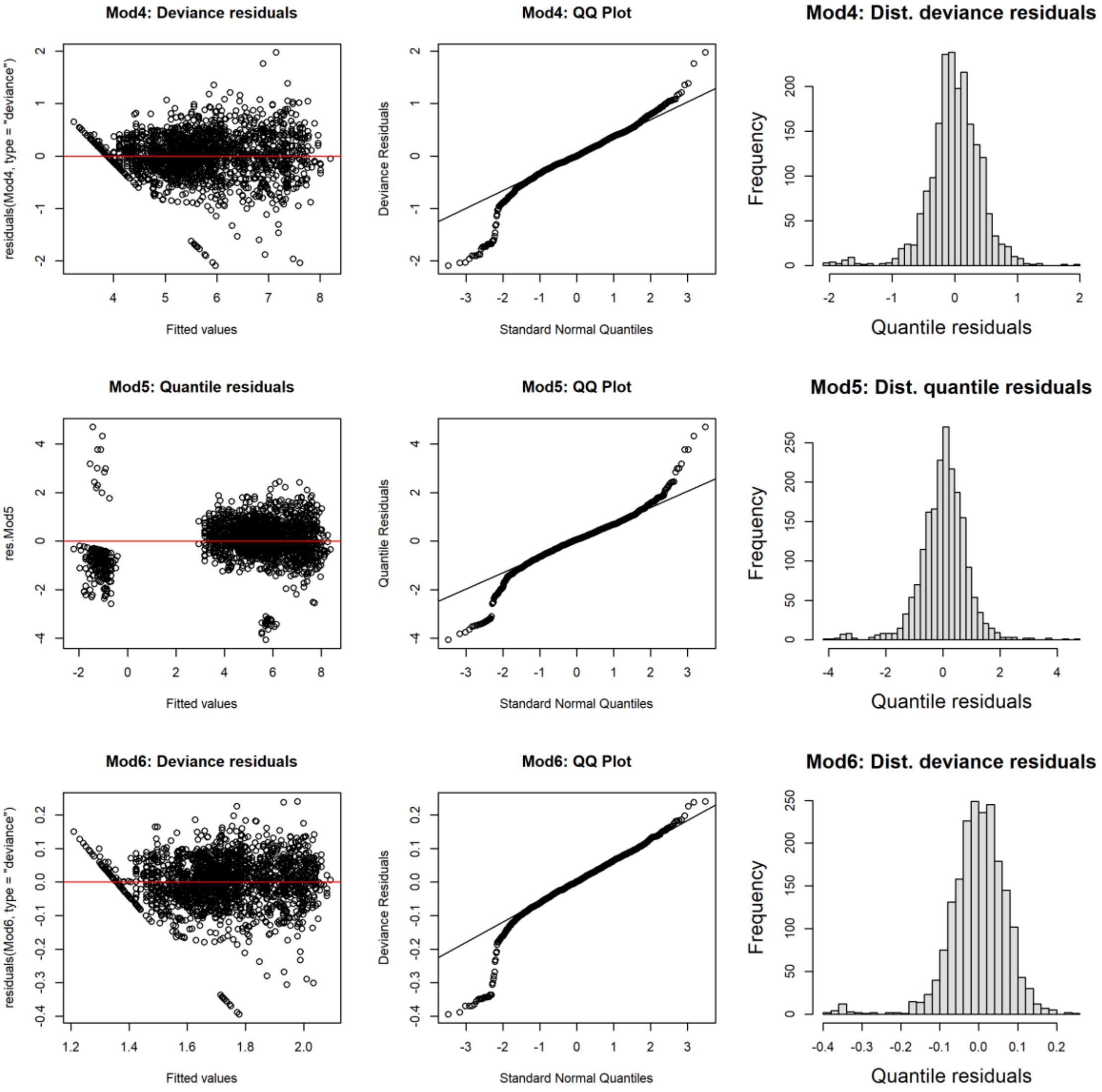

Figure 11. Residual analysis for the various model types (sensitivity analysis) tested for the blue shark CPUE standardization in the North Atlantic, specifically a lognormal with constant *c*=1 (Mod 3), a tweedie model (Mod4) and a gamma model (Mod 5). For each model it is presented the residuals along 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).

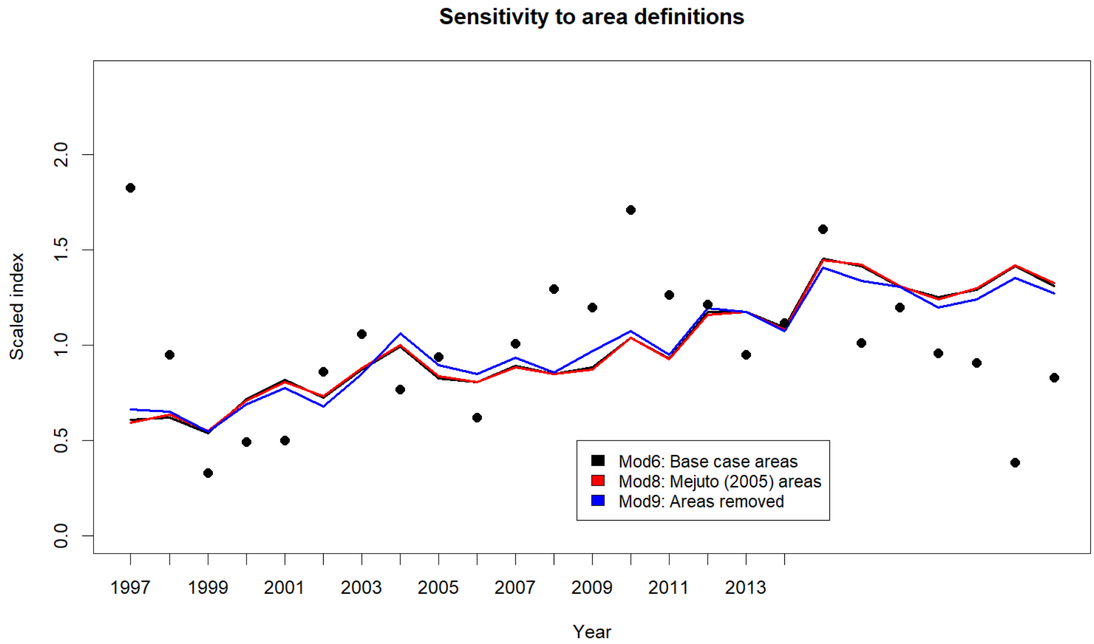

Figure 12. Model sensitivity to the area factor for the blue shark CPUE standardization from the Portuguese pelagic longline fleet in the North Atlantic Ocean. The scaled annual indexes of abundance of the final model selected (Mod6) is represented in black, and the alternative models in red (Mod8: using areas as defined by Mejuto and Garcis-Cortés, 2005) and blue (Mod9: model without area effects). The black dots refer to the nominal CPUE series scaled by the mean.

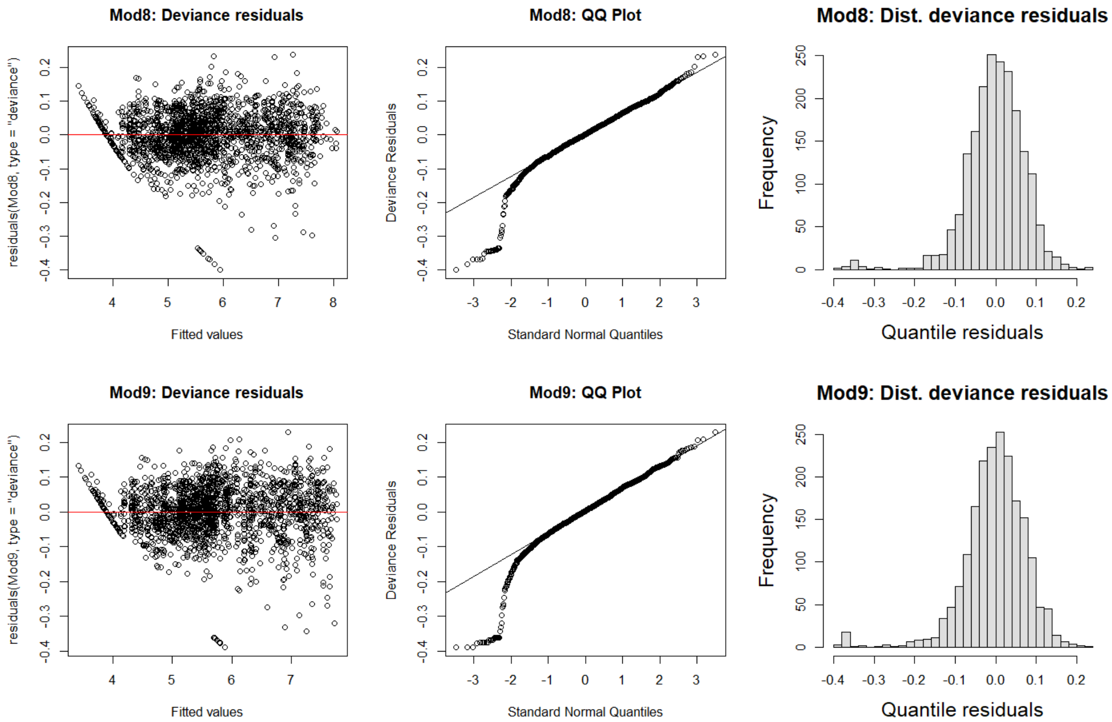

Figure 13. Residual analysis for the model tested for the sensitivity to the area factor for the blue shark CPUE standardization in the North Atlantic Ocean. Mod 8 uses areas as defined by Mejuto and García-Cortés (2005) and Mod 9 does not include the area factor. For each model it is presented the residuals 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).

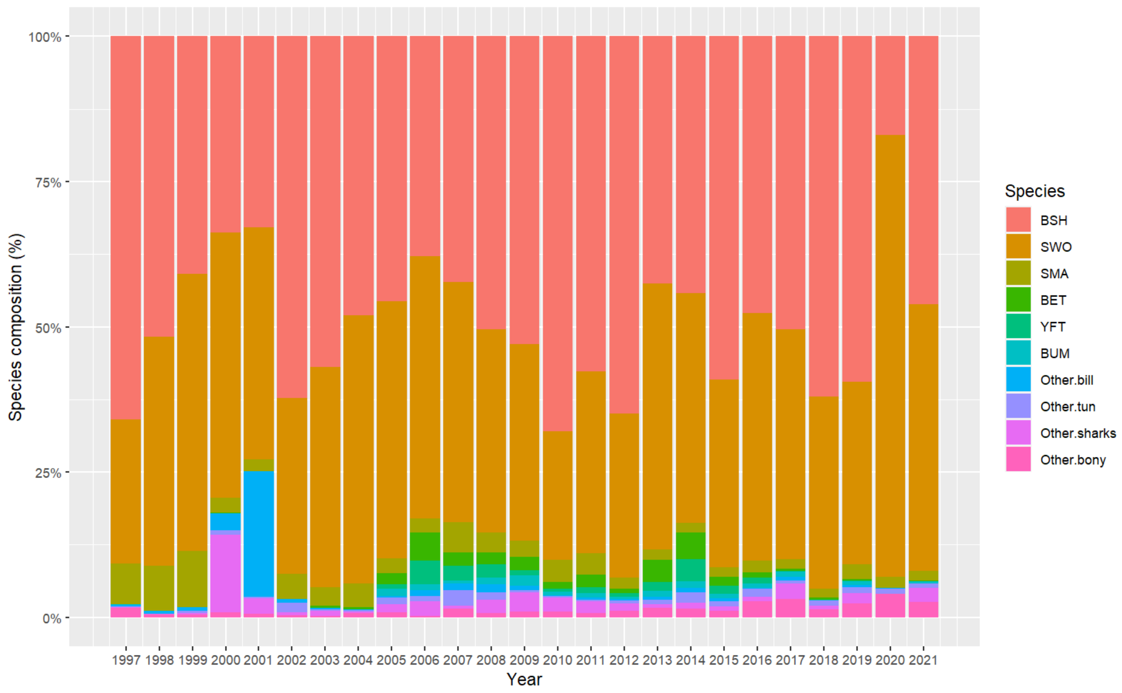

Figure 14. Catch composition of the Portuguese pelagic longline fleet operation in the North Atlantic between 1997 and 2021.

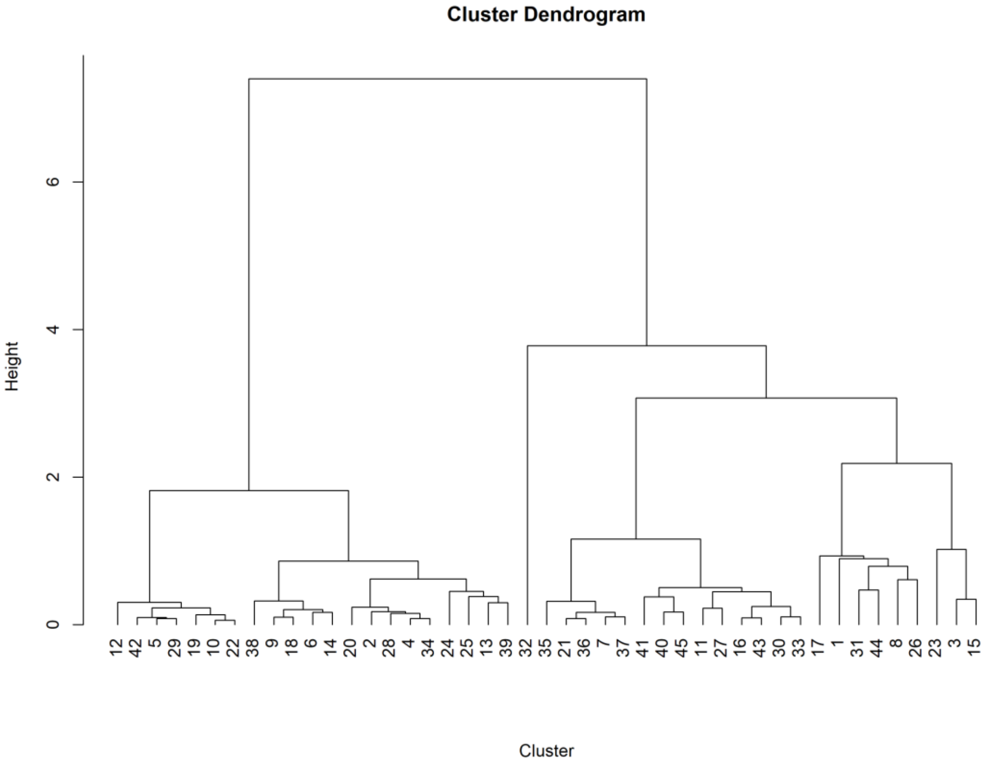

Figure 15. Hierarchical cluster analysis classifying the groups formed with the non-hierarchical analysis (*k-means*) for the Portuguese pelagic longline fleet in the North Atlantic Ocean.

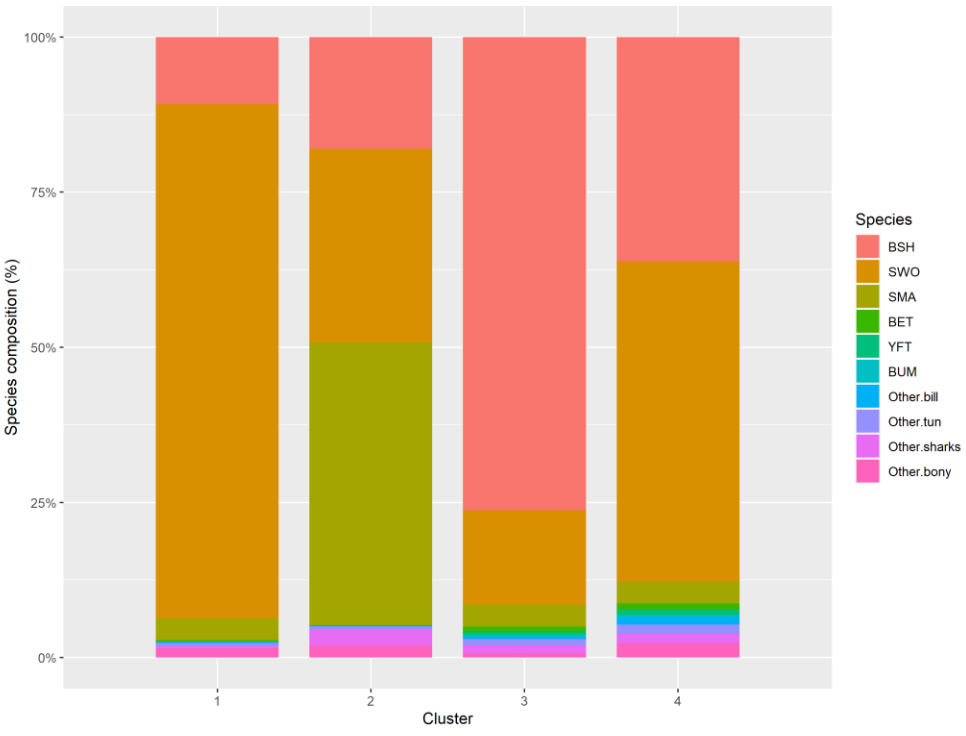

Figure 16. Catch composition of the 4 clusters defined for the Portuguese pelagic longline fleet operating in the North Atlantic.

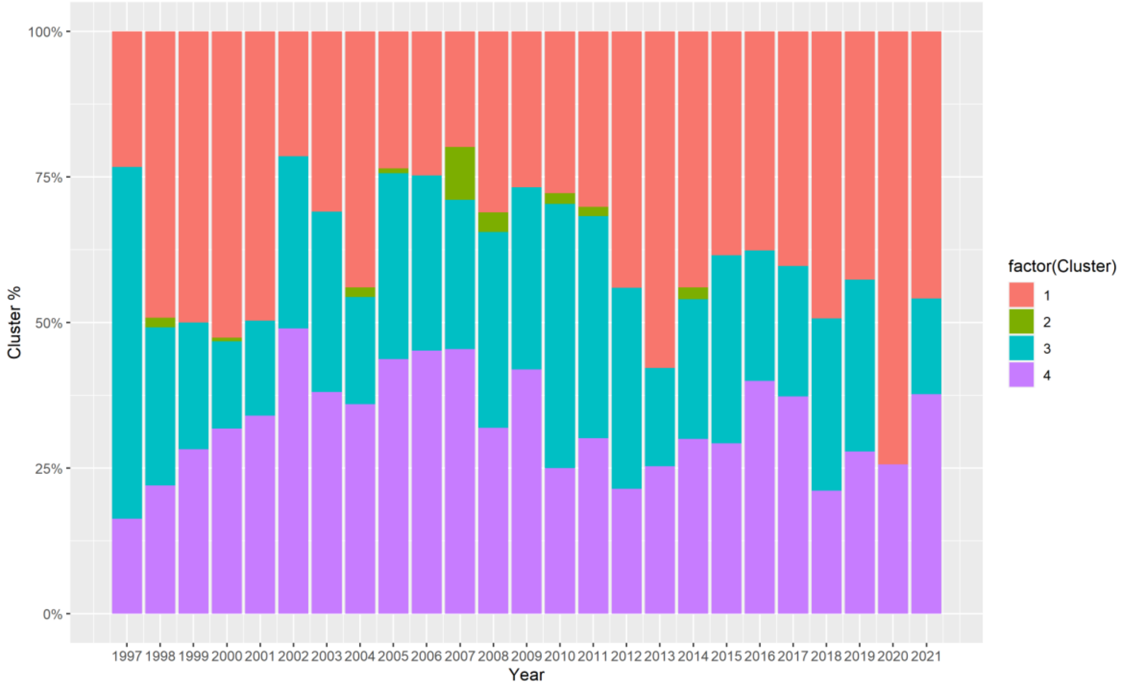

Figure 17. Yearly percentage of the targeting clusters defined for the Portuguese pelagic longline fleet operating in the North Atlantic.

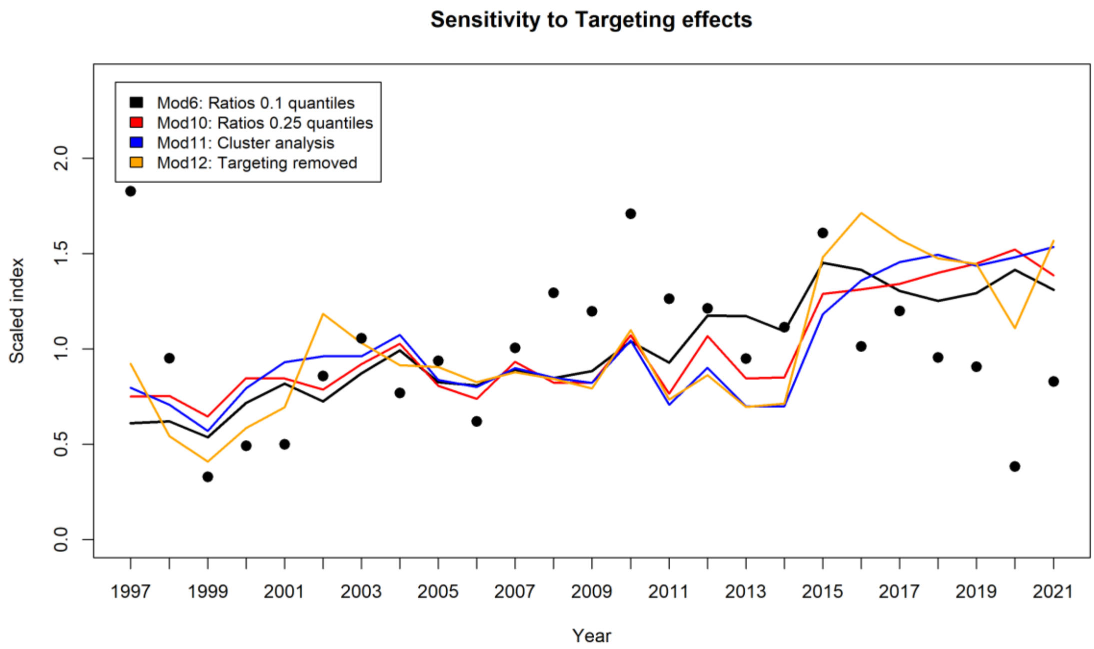

Figure 18. Model sensitivity to the targeting effects for the blue shark CPUE standardization from the Portuguese pelagic longline fleet in the North Atlantic Ocean. The scaled annual indexes of abundance of the final model selected (Mod6) is represented in black, and the alternative models in red (Mod10: using a different ratio categorization), blue (Mod11: targeting effects from the cluster analysis) and orange (Mod12: removing targeting effects). The black dots refer to the nominal CPUE series scaled by the mean.

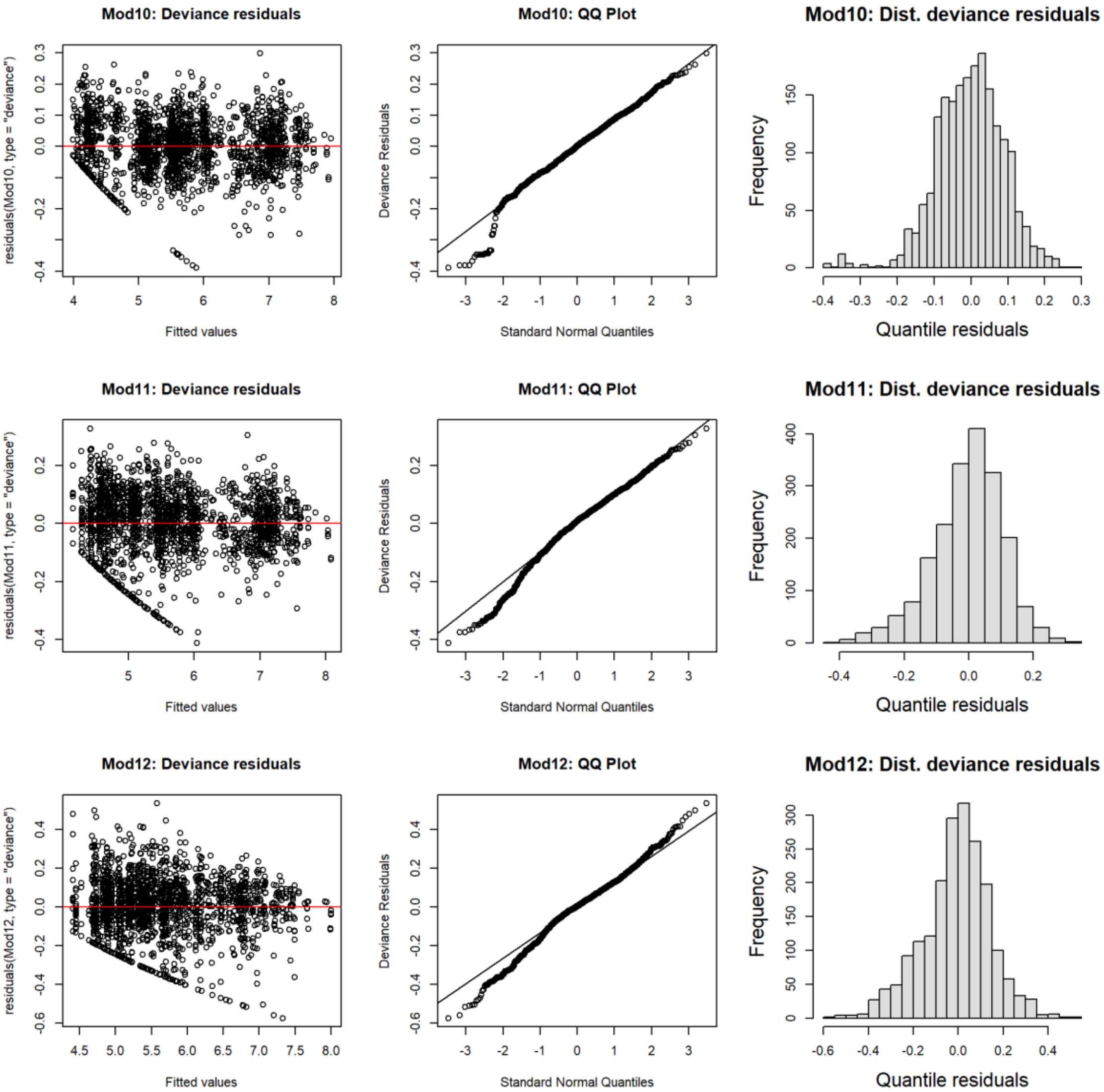

Figure 19. Residual analysis for the various model tested for the sensitivity to the targeting effects for the blue shark CPUE standardization in the North Atlantic. Mod 10 uses a different ratio categorization (0.25 quantiles), Mod 11 uses targeting based on a cluster analysis, and Mod 12 does not include 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).

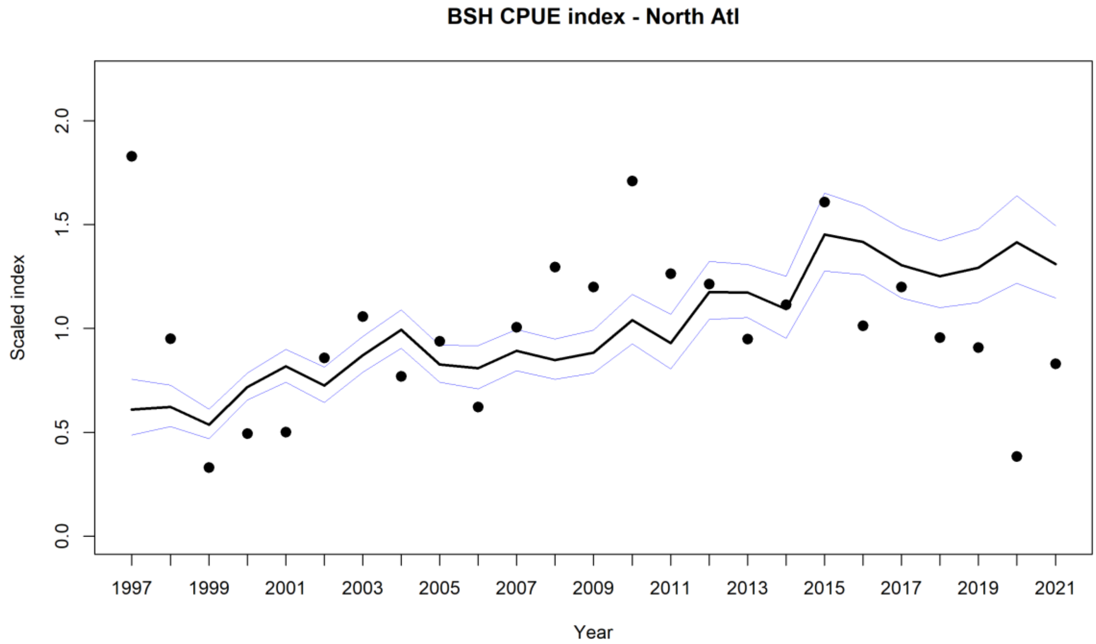

Figure 20. Time series of the standardized BSH CPUE index in biomass (scaled by the means) for the Portuguese pelagic longline fleet in the North Atlantic between 1997 and 2021, suggested to be used in the 2023 BSH stock assessment. The blue lines represent the 95% confidence intervals (CIs).