



STANDARDIZED SWORDFISH CPUE BASED ON OBSERVER AND SELF-REPORTED DATA FROM THE FRENCH REUNION-BASED PELAGIC LONGLINE FISHERY IN THE SOUTH- WEST INDIAN OCEAN (2007-2025)

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Purpose, expectation and action intended (select one or more and include corresponding text)

Discussions (for information and open discussion):

This paper presents a standardized CPUE series for swordfish, for the upcoming stock assessment of this species. This standardization is based on observer and self-reported data collected between 2007 and 2025 for the French Reunion-based pelagic longline fishery operating in the southwestern Indian Ocean. It will be presented in Section 5.2.

Abstract

For the upcoming stock assessment of swordfish (*Xiphias gladius*), we developed a standardized catch-per-unit-effort (CPUE) series based on observer and self-reported data for the French Reunion-based pelagic longline fishery operating in the southwestern Indian Ocean. This observer- and self-reporting-based series is intended to be compared with a standardized CPUE derived from logbook data. Observer and self-reporting data provide more detailed information for standardization, whereas logbook data provide broader fishery coverage. Comparing the trends derived from these two data sources will provide an opportunity to assess the consistency of the resulting indices of relative abundance. Temporal, spatial, operational and environmental covariates were considered during model selection. A Generalized Linear Mixed Model (GLMM) framework was used, with three alternative random effect structures: conventional vessel-level random effect only, vessel-level random effect combined with a spatial random field, and vessel-level random effect combined with a spatiotemporal random field. The latter two models were fitted using the *sdmTMB* R package. Poisson and Negative Binomial distributions were also compared. The retained index was estimated using a GLMM with a spatiotemporal random effect and a Negative Binomial distribution, which provided the best fit to the overdispersed data. For the upcoming swordfish stock assessment, we recommend using the standardized CPUE series for the period 2011-2025, during which monitoring coverage was substantially higher than in the earlier years. Throughout this period, the standardized swordfish CPUE shows a slight but statistically significant increasing trend.

Keywords

Swordfish | CPUE standardization | Longline | Observer data | Western Indian Ocean | sdmTMB | GLMM

1. Introduction

Fishery-dependent CPUE indices are commonly used as indices of relative abundance for both target species, such as tunas and billfishes, and non-target species, such as sharks, particularly when fishery-independent abundance indicators are unavailable. However, observed catch rates may be influenced by a range of factors unrelated to changes in population abundance, including changes in fishing effort, fishing practices and strategies, fishing gear, vessel characteristics, spatial and temporal fishing patterns, and the overlap between fishing operations and the distribution of the species. CPUE data therefore need to be standardized to account for these sources of variability before being used as indices of relative abundance in stock assessments ([Maunder and Punt, 2004](#)).

The French Reunion-based pelagic longline fishery operates mainly in the southwestern Indian Ocean, including waters around Reunion Island, Mauritius, Madagascar and the Mozambique Channel. Swordfish (*Xiphias gladius*) is the main target species of this fishery, although substantial catches of tuna species are also recorded. Fishing operations mainly consist of relatively shallow longline sets deployed in the evening, left to fish overnight, and retrieved the following morning ([Bach et al., 2014](#)).

The spatial distribution of both fishing effort and swordfish catch rates may vary over time. Consequently, changes in the spatial distribution of the fishing effort may affect observed catch rates independently of changes in swordfish abundance. In addition to conventional generalized linear modelling approaches, spatial and spatiotemporal models provide a framework for accounting for spatial structure in catch rates and for potential changes in this structure through time.

The objective of this study is to develop a standardized CPUE series for swordfish caught by the French Reunion-based pelagic longline fleet over the period 2007-2025. Observer and self-reported data collected from this fishery were used to evaluate the effects of temporal, spatial, operational and environmental covariates on swordfish catch rates. Generalized Linear Mixed Models (GLMMs) with three alternative random effect structures were compared: vessel-level random effect only, vessel-level random effect combined with a spatial random field, and vessel-level random effect combined with a spatiotemporal random field. The resulting standardized CPUE series is intended to provide an index of relative abundance for consideration in the upcoming stock assessment of swordfish in the Indian Ocean.

2. Material and methods

2.1. Data

We used data collected by sea-going observers on French longline vessels ([Bach et al., 2008](#)) as well as data collected by fishermen themselves called “self-reporting data” ([Bach et al., 2013](#)). Data were collected through CAPPER (2007-2008) and EU Data Collection Framework (2009-2025; Reg 199/2008 and 665/2008). The coverage in number of hooks monitored is presented in [Figure 1](#). We retained a total of 5784 fishing

operations monitored between 2007 and 2025 from the core fishing area that consists of 5°x5° squares with more than 120 fishing operations ([Figure 2](#)).

2.2. Covariate selection

The list of candidate covariates for standardization was determined based on previous work of CPUE standardization for swordfish ([da Silva et al., 2025](#)) and other species carried out with the same dataset ([Sabarros et al., 2017](#); [Sabarros et al., 2021](#); [Sabarros et al., 2025](#); [Tellier and Sabarros, 2025](#)). Candidate covariates included temporal, spatial, operational and environmental variables.

Candidate covariates were:

- Fixed effects:
 - *year* (factor): year of the fishing operation, from 2007 to 2025. Year is included in all models to estimate interannual variations.
 - *quarter* (factor): calendar quarter, from Q1 to Q4.
 - *month* (factor): calendar month, from January to December. *month* and *quarter* are considered as alternative temporal covariates and are therefore mutually exclusive during model selection.
 - *longitude* (continuous): longitude of the fishing operation, specifically the longitude where the fishing gear starts being retrieved (hauling).
 - *latitude* (continuous): latitude of the fishing operation, specifically the latitude where the fishing gear starts being retrieved (hauling).
 - *soaking_time* (continuous): time in hours between when the first hook is deployed and when the last hook is retrieved.
 - *setting_start_time* (continuous): time (hh:mm) when the first buoy is deployed.
 - *hauling_end_time* (continuous): time (hh:mm) when the last buoy is retrieved.
 - *branchlines_per_basket_count* (continuous): number of hooks per basket as a proxy index of fishing depth range/targeting.
 - *percentage_circle_hooks* (continuous): relative proportion of circle hooks to other types of hooks, i.e., J-hooks, tuna hooks, and Teracima hooks.
 - *percentage_squid_bait* (continuous): proportion of squid bait relatively to other bait used (mackerel, etc.).
 - *moon_illumination* (continuous): lunar illumination, expressed as an index ranging from 0 to 100. A value of 0 corresponds to minimum lunar illumination, corresponding to the new moon, whereas a value of 100 corresponds to maximum lunar illumination, corresponding to

the full moon. Lunar illumination was calculated using the *lunar.illumination* function from the *lunar* R package.

- Random effects:
 - *vessel* (factor): the vessel name is used as a random effect given that we wanted to incorporate the vessel effect variability in the model, without estimating specific parameters for each vessel.

A forward stepwise covariate selection procedure was applied to identify covariates improving model fit. At each step, each remaining candidate covariate was added separately to the current model, and the resulting models were compared using the Akaike Information Criterion (AIC). The candidate covariate producing the greatest reduction in AIC was selected at each step. A covariate was retained only when its inclusion reduced the AIC by at least two units compared with the current model. The procedure was repeated until no remaining candidate covariate resulted in an AIC reduction of at least two units.

Additionally, in this forward stepwise model selection procedure, alternative functional shapes were evaluated for continuous covariates, including a linear effect and non-linear spline representations with varying numbers of degrees of freedom (2 to 5). The partial effect associated with the lowest AIC was retained for each candidate covariate.

2.3. Comparison of models

The response variable for the standardization is the number of swordfish caught per fishing operation (*nb_caught*). Fishing effort, defined as the total number of hooks deployed during each fishing operation (*total_hooks_count*) is included as a log-transformed offset. This allowed swordfish catches to be modelled while accounting for differences in fishing effort among operations, thereby providing standardized estimates of catch rates, using a distribution adapted to overdispersed count data.

We compared several models: conventional GLMMs, GLMMs with a spatial random effect, and a GLMM with a spatiotemporal random effect.

2.3.1. Conventional GLMMs

Standardized swordfish CPUE was first estimated using GLMMs fitted with the *glmmTMB* R package (Brooks et al., 2017). Candidate covariates were selected using the forward stepwise procedure described above. The covariate *year* was included as a categorical fixed effect in all models to estimate annual changes in standardized catch rates, while *vessel* was included as a random effect.

For each selected continuous covariate showing a non-linear relationship with catch rates, the representation with the number of degrees of freedom associated with the lowest AIC was retained and was used in subsequent models adjusted with *sdmTMB* (see sections 2.3.2 and 2.3.3).

An exception was made for *percentage_circle_hooks*, for which only a linear representation was considered. This choice was based on the expected nature of the relationship between the proportion of circle hooks and catch rates, and to avoid fitting an unnecessarily complex non-linear relationship.

Poisson and Negative Binomial distributions were compared. A zero-inflated component was not considered because only approximately 3% of the fishing operations had zero swordfish catches (Figure 3). The distribution which provided the better fit was retained for subsequent analyses.

The best models fitted using the conventional GLMM approach are hereafter referred to as Mod 1a (Poisson distribution) and Mod 1b (Negative Binomial distribution).

2.3.2. GLMMs with a spatial random effect

Spatial GLMMs were fitted using *sdmTMB* R package (Anderson et al., 2022), by incorporating a spatial random field as random effect. The spatial effect accounts for residual spatial structure in swordfish catch rates that is not explained by the fixed effects included in the model.

In *sdmTMB*, the spatial field is built using a triangular mesh covering the study area. Rather than estimating a separate spatial effect at every fishing location, the spatial process is estimated at the mesh knots and interpolated between them. This approach substantially reduces the computational complexity of the spatial model while retaining the ability to take into account spatial variations in catch rates.

The influence of mesh resolution was tested by fitting models using meshes containing 50, 80, 100 and 150 knots. Coarser meshes reduce computational time but may fail to capture fine-scale spatial variation, whereas finer meshes provide a more detailed representation of the spatial field at the expense of increased computational time. Mesh resolution influences the fit of the model, and consequently its AIC. The different meshes evaluated are presented in Figure 4, and the standardized CPUE series obtained using each mesh are compared in Figure 5. Based on this sensitivity analysis, the mesh associated with the lowest AIC was retained.

The best GLMM including a spatial effect is hereafter referred to as Mod 2.

2.3.3. GLMM with a spatiotemporal random effect

A spatiotemporal GLMM was also fitted using *sdmTMB* R package, by adding a spatiotemporal random field. While the spatial field captures persistent spatial variations in swordfish catch rates, the spatiotemporal field allows the spatial structure of catch rates to vary among years.

This approach can account for temporal changes in the spatial distribution of swordfish, including potential shifts in areas with relatively high and low catch rates through time. It can therefore help account for temporal changes in spatial patterns of catch rates that may otherwise contribute to differences in observed CPUE among years.

The GLMM including a spatiotemporal effect is hereafter referred to as Mod 3.

2.3.4. Selection of the final model

Mod 1a, Mod 1b, Mod 2 and Mod 3 were compared using AIC. The standardized annual CPUE series estimated by the three approaches (conventional GLMM, GLMM with a spatial random field, and GLMM with a spatiotemporal random field) were also compared and are presented in [Figure 6](#). The model with the lowest AIC was retained as the final model for standardization of swordfish CPUE. Diagnostic and model evaluation results for Mod 1a, Mod 1b, Mod 2 and Mod 3 are presented in [Table 1](#). A summary of the retained model is provided in [Table 2](#). The estimated partial effects of the selected continuous covariates are presented in [Figure 7](#) while the estimated effect of the selected categorical covariate is presented in [Figure 8](#). The graphical analysis of scaled residuals obtained using the *DHARMa* R package ([Hartig et al., 2024](#)) is shown in [Figure 9](#), [Figure 10](#), [Figure 11](#) and [Figure 12](#).

2. 4. Standardized CPUE predictions

Annual standardized CPUE estimates were derived from predictions of the retained model. A prediction dataset was created containing one observation for each year of the study period, i.e., 2007-2025. The year factor was used to produce annual predictions, while all selected continuous covariates were held constant at their median values calculated over the complete dataset. The month effect was fixed to January (month = 1), hence corresponding to the reference conditions used for the standardized predictions. Fishing effort was standardized to 1000 hooks by setting the log-transformed offset to $\log(1000)$.

Predictions were obtained on the link scale using the *predict* function from the *sdmTMB* R package. Random effects and spatial and spatiotemporal random fields were excluded from the predictions in order to estimate annual standardized CPUE under constant fishing conditions. Predicted values were then exponentiated to obtain standardized CPUE estimates expressed as the expected number of swordfish caught per 1000 hooks.

Confidence intervals of 95% were calculated on the link scale using the estimated standard errors:

$$CI_{lower} = \exp(\eta - 1.96 \times SE_{\eta})$$

$$CI_{upper} = \exp(\eta + 1.96 \times SE_{\eta})$$

where η is the predicted value for a given year on the link scale and SE_{η} its associated standard error.

For comparison, nominal annual CPUE is calculated as:

$$\text{Nominal } CPUE_y = \frac{\sum \text{Swordfish caught}_y}{\frac{\sum \text{Hooks deployed}_y}{1000}}$$

where the sums were calculated across all fishing operations monitored during year y .

The annual standardized CPUE estimates from the retained model are presented in [Table 3](#) and [Figure 13](#). Standardized annual CPUE values scaled by their overall mean are also presented in [Table 3](#) and [Figure 14](#).

3. Results

3.1. Model selection and comparison

The results of the model selection procedure and the characteristics of the final models are presented in [Table 1](#).

The Negative Binomial distribution provided a better fit than the Poisson distribution ([Table 1](#); AIC of 36251.2 for Poisson distribution, vs 32458.62 for Negative Binomial distribution), consistent with the presence of overdispersion in the catch data (variance >> expected value), and was therefore retained.

For the conventional GLMM approach with a Negative Binomial link (Mod 1b), the selected covariates include *month*, *hauling_end_time*, *latitude*, *longitude*, *moon_illumination*, *setting_start_time*, *branchlines_per_basket_count*, *soaking_time* and *percentage_circle_hooks*. Covariates selection with the GLMMs with spatial or spatiotemporal random effects (Mod 2 and Mod 3) retains the same covariates, except for latitude and longitude, as spatial variation is accounted for by spatial and spatiotemporal random fields ([Table 1](#)).

For the GLMMs with a spatial random effect, mesh sensitivity was evaluated using 50, 80, 100 and 150 knots. The corresponding AIC values are 32419.40, 32403.92, 32391.46 and 32391.81, respectively. The mesh containing 100 knots provides the lowest AIC and was therefore retained for GLMMs including spatial or spatiotemporal random effect. The standardized CPUE series obtained using the different mesh resolutions are quite similar ([Figure 5](#)).

The three models (Mod 1b, Mod 2, Mod 3) also produced quite similar standardized CPUE trends ([Figure 6](#)), indicating that the estimated annual indices are relatively robust to the choice of modelling framework. The final models have AIC values of 32458.62 for Mod 1b, 32391.46 for Mod 2 and 32194.77 for Mod 3 ([Table 1](#)). The GLMM with a spatiotemporal random effect therefore provides the best fit according to AIC and is retained as the final model. The final retained model (Mod 3) is therefore:

$$nb_caught \sim year + month + s(hauling_end_time) + s(moon_illumination) + s(setting_start_time) + s(soaking_time) + s(branchlines_per_basket_count) + percentage_circle_hooks + (1|vessel) + offset(\log(total_hooks_count))$$

where the notation $s()$ represents the spline terms described above.

3.2. Characteristics of the retained model

A summary of the retained GLMM (Mod 3), that includes a spatiotemporal random field, is presented in [Table 2](#).

For non-linear effects, the degrees of freedom retained are 3 for *hauling_end_time*, 3 for *moon_illumination*, 5 for *setting_start_time*, 3 for *soaking_time* and 2 for *branchlines_per_basket_count*. A linear effect was imposed for *percentage_circle_hooks* ([Table 1](#)).

The estimated standard deviation associated with the vessel random effect is 0.21 on the log scale, indicating variability in swordfish catch rates among vessels after accounting for the other covariates included in the model.

The annual coefficients represent differences in catch rates relative to 2007, which is used as the reference year. For example, the coefficient estimated for 2025 is 0.21, corresponding to an expected catch rate of $\exp(0.21) = 1.23$ times the one estimated for 2007 under otherwise identical conditions.

The estimated *month* effect is presented in [Figure 8](#). It shows seasonal variations in standardized catch rates. Indicated values are relative to January, which is used as the reference month. For example, the coefficient estimated for February is -0.08, corresponding to an expected catch rate of $\exp(-0.08) = 0.92$ times the value of January, all other covariates being held constant. Catch rates are generally higher between November and January and lower between April and August.

The estimated partial effects of the six selected continuous covariates are presented in [Figure 7](#). The figures show the estimated spline effects and their approximate 95% confidence intervals, together with histograms representing the distribution of observations in the dataset used.

The timing of fishing operations influences swordfish catches. The effect of *setting_start_time* ([Figure 7B](#)) increases progressively over most of the observed range and reaches its maximum around 19:00. Concerning the effect of *hauling_end_time* ([Figure 7A](#)), catch rates are relatively stable until approximately 12:00–13:00, followed by a slight increase around 14:00–15:00 and a marked decrease at later hauling times. Soaking time ([Figure 7C](#)) shows a positive effect on swordfish catch rates over the range represented by the majority of observations (16–24 hours).

The proportion of circle hooks ([Figure 7D](#)) has a negative effect on swordfish catches. The model suggests a gradual decrease in catch rates as the proportion of circle hooks increased.

The number of branchlines per basket ([Figure 7E](#)) shows a non-linear effect. In the range containing most observations (6–11), the estimated effect is negative, with catches decreasing as the number of branchlines per basket increased.

Moon illumination ([Figure 7F](#)) shows a non-linear relationship with swordfish catch rates. According to the estimated spline effect, catch rates are highest at intermediate to relatively high levels of lunar illumination, with a maximum around 70% illumination, whereas lower catch rates are estimated around the new and full moon. These periods also correspond to the ranges of lunar illumination with the highest number of observed fishing operations.

The dispersion parameter of the Negative Binomial model is estimated at 6.48 ([Table 2](#)). The catch data are overdispersed relative to the assumptions of a Poisson distribution, supporting the use of the Negative Binomial distribution selected during model comparison.

The estimated spatiotemporal correlation is 0.56 ([Table 2](#)), indicating moderate temporal persistence in the spatiotemporal random field: the residual spatial structure in swordfish catch rates shows partial continuity between successive years, rather than changing independently from one year to the next.

3.3. CPUE trends

The annual nominal and standardized swordfish CPUE series are presented in [Table 3](#) and [Figure 13](#). For comparison of relative annual changes, the nominal and standardized CPUE series scaled by their respective overall means are presented in [Figure 14](#). Overall, the standardized CPUE series follows a similar trend compared to the nominal CPUE series, although differences are observed in the magnitude of these annual indices.

Observer coverage was low (< 3%) between 2007 and 2010 while it increased substantially from 2011 with the implementation of self-reporting data collection, reaching an average coverage of 13.6% (range: 6.4-17.8%) between 2011 and 2025 ([Figure 1](#)). During the latter period (2011-2025), the standardized CPUE series exhibited an increasing trend: standardized CPUE increased from 6.69 swordfish per 1000 hooks in 2011 to 8.72 swordfish per 1000 hooks in 2025. The highest standardized CPUE during this period is observed in 2024, with 9.48 swordfish per 1000 hooks. Throughout 2011-2025, the trend of the standardized CPUE is weak but significantly positive (linear regression: $b = 0.25214$, $p\text{-value} = 1.11\text{e-}05$, $r^2 = 0.7847$).

3.4. Residual analysis

Residual diagnostics for the final model were performed using the *DHARMA* R package. The diagnostic plots and associated tests are presented in [Figure 9](#), [Figure 10](#), [Figure 11](#) and [Figure 12](#). Overall, the graphical diagnostics indicate no major systematic patterns, although several formal tests detect minor but statistically significant deviations from the model assumptions.

The QQ-plot of the simulated scaled residuals ([Figure 9A](#)) shows an overall close agreement with the expected uniform distribution. However, the Kolmogorov–Smirnov test detects a statistically significant deviation from uniformity ($D = 0.0257$, $p\text{-value} < 0.05$). The magnitude of this deviation is nevertheless limited.

The residuals plotted against the fitted values ([Figure 9B](#)) show no strong systematic structure. Residuals are distributed across the range of fitted values, and the fitted quantile regression curve remains close to the expected value of 0.5, suggesting no pronounced bias related to the magnitude of the model predictions.

The *DHARMA* dispersion test indicates significant underdispersion (dispersion = 0.82, $p\text{-value} < 0.05$), indicating that the variability of the observed residuals is lower than that expected from simulations under the fitted model ([Figure 10A](#)). This suggests that the fitted model does not reproduce all aspects of the variability present in the data.

The zero-inflation test also detects a significant deviation between the observed and simulated numbers of zero catches (ratioObsSim = 1.36, $p\text{-value} < 0.05$; [Figure 10B](#)). The ratio is greater than one and therefore indicates that the observed dataset contains more zero catches than expected under the fitted model. However, the absolute difference remains limited: among the 5784 observations, the number of zero catches simulated under the fitted model ranges from 104 to 186, compared with 193 observed zero catches in the original dataset.

Finally, the bootstrapped outlier test detects a significant excess of extreme residuals (**Figure 10C**). Fifteen observations, corresponding to approximately 0.26% of the dataset, are classified as outliers, compared with an expected frequency of approximately 0.15% ($p\text{-value} < 0.05$). Although statistically significant, the absolute number of observations concerned remains low.

Residuals were also examined in relation to the covariates retained in the final model. No major systematic patterns are observed for the continuous covariates (**Figure 11**), with residual quantile regression curves generally remaining close to the expected value of 0.5. For the categorical covariates (**Figure 12**), no significant within-group deviations from uniformity are detected for either *month* or *year*. Residual variance is homogeneous among years but differed significantly among months according to Levene's test, indicating some remaining heterogeneity in residual dispersion across months.

4. Discussion

4.1. Significant effects on swordfish CPUE

The final standardization model identified several covariates that influence swordfish catch rates, retained by the AIC-based selection procedure.

The vessel random effect indicates the presence of inter-vessel differences in fishing efficiency. Such differences may reflect variations in vessel characteristics, fishing practices, gear configuration, fishermen's experiences or other vessel-specific factors not explicitly represented by the available covariates. Accounting for this variability is essential to avoid biased estimates and to ensure that the observed effects are not confounded by vessel-specific fishing practices.

Month was the temporal covariate retained during model selection, in preference to quarter. It reveals a clear seasonal pattern in swordfish catch rates (**Figure 8**). Seasonal changes in catch rates could result from intra-annual changes in the availability and spatial distribution of swordfish, in combination with seasonal changes in the spatial distribution of fishing operations.

The proportion of circle hooks is negatively correlated with swordfish catch rates (**Figure 7D**). A lower proportion of circle hooks generally corresponds to a higher proportion of J-hooks in the fishing gear, even though other hooks (tuna hooks, Teracima hooks for instance) are also used, but in lesser proportion. Compared with circle hooks, J-hooks are more likely to result in internal hooking, which may increase the probability of retaining swordfish. In contrast, circle hooks tend to lodge in the mouth rather than internally, a characteristic generally considered beneficial for reducing the severity of hooking on bycatch species ([Reinhardt et al., 2018](#)). The negative relationship observed here is therefore consistent with differences in hooking location and catchability between hook types, indicating that swordfish catch rates are reduced with circle hooks and they increase with J-hooks. The relatively wide confidence intervals, particularly at high proportions of circle hooks, should nevertheless be considered when interpreting the magnitude of this effect.

The positive effect of soaking time on swordfish catch rates ([Figure 7C](#)) could be expected, as a longer period during which hooks remain available to fish may increase the probability of encountering and catching swordfish. Although the total number of hooks is already accounted for through the offset, soaking time represents an additional dimension of fishing effort and catchability that may vary among operations. Its inclusion in the model therefore helps account for differences in effective fishing conditions that are not captured by the number of hooks deployed alone. The timing of fishing operations also influences swordfish catch rates, but the separate effects of *hauling_end_time* ([Figure 7A](#)) and *setting_start_time* ([Figure 7B](#)) are more difficult to interpret. These patterns may reflect changes in swordfish behavior and vertical distribution over the course of the night. Relatively few observations are available at the extremes of the distribution, and the confidence intervals are consequently wider in these areas. Because *setting_start_time*, *hauling_end_time* and *soaking_time* are intrinsically related, the partial effects of these variables should nevertheless be interpreted with caution. However, each covariate effect informs of some relationships with catch rates after accounting for the other variables included in the model.

The number of branchlines per basket can be considered as a proxy for the depth at which hooks are deployed, where more hooks per basket correspond to deeper sets. The number of branchlines (or hooks) per basket is retained as a non-linear operational covariate, however, fishermen from Reunion Island mostly deploy between 6 and 9 branchlines per basket, and within this range the effect of branchlines per basket on swordfish catches is negative ([Figure 7E](#)). This is consistent with the predominantly shallow fishing strategy of the Reunion Island longline fishery, where hooks are typically deployed from approximately 10 m below the surface to around 120 m during night sets ([Bach et al., 2014](#)). Results suggest that lower catch rates are made in deeper sets while shallower sets catch more swordfish. The increase in the estimated effect at the highest values should be interpreted cautiously because these configurations are relatively uncommon and are associated with greater uncertainty.

Moon illumination is also retained as an important environmental covariate influencing swordfish catch rates. Catch rates are highest at intermediate levels of lunar illumination, with a maximum around 70% illumination, and lowest around 0% and 100%, corresponding respectively to the new and full moon ([Figure 7F](#)). Similar patterns in the same fishery have been reported previously in [Guyomard et al. \(2004\)](#) and [Poisson et al. \(2010\)](#), both reporting higher swordfish catch rates under intermediate levels of lunar illumination. [Bach et al. \(2014\)](#) and [Sabarros et al. \(2014\)](#) also reported a similar bell-shaped spline effect of lunar illumination, although the relationship reached its maximum at approximately 50% lunar illumination. Lunar illumination influences on the vertical distribution of micronekton and swordfish prey, and ultimately swordfish. Under low illumination, around the new moon, swordfish will be found close to the surface, while under higher lunar illumination, around the full moon, they will occur deeper. According to [Bach et al. \(2014\)](#), fishermen only make limited adjustments to the fishing depth of the longline according to lunar phase. Changes in swordfish vertical distribution may consequently modify the overlap between swordfish and the depth range of the longline, resulting in a targeting mismatch, which explains that the higher catch rates are observed under intermediate levels of lunar illumination, where the overlap between swordfish and hooks is maximum. An additional mechanism to explain the low catch rates when the lunar illumination is maximal could be the ability of swordfish to detect and avoid fishing gear under higher levels of ambient light. [Ortega-Garcia et al. \(2008\)](#) suggested that increased lunar illumination may allow swordfish to better detect and avoid gillnets, which could potentially also apply to longline gear.

There are some concerns and limitations with the present model structure. The effects of the selected covariates were evaluated individually during the forward selection procedure, and potentially relevant interactions between covariates were not tested. In particular, an interaction between *branchlines_per_basket_count* and *moon_illumination* could be biologically meaningful, in the light of findings reported by [Bach et al. \(2014\)](#) and explained above. Also, an interaction between *setting_start_time* and *hauling_end_time* could potentially account for combined effects of the temporal configuration of fishing operations. Such interactions could be represented using tensor-product smooths in a Generalized Additive Modelling framework. Although the construction of a tensor-product basis can be done manually prior to model fitting in *sdmTMB*, this requires additional implementation and makes the specification and penalization of tensor-product smooths less straightforward. Consequently, only the main effects of the candidate covariates were evaluated in the present analysis. Future analyses could investigate whether the inclusion of biologically motivated interactions improves model fit and further reduces unexplained variability.

4.2. Relevance of the retained standardized CPUE series

This standardization is based exclusively on the core fishing grounds of the Reunion Island longline fleet ([Figure 2](#)). Restricting the analysis to this area avoided the potential biases associated with the inclusion of a small number of sets conducted in peripheral regions such as the northern Mozambique Channel or the high seas, where different environmental conditions and fishing strategies may influence catch rates. This conservative approach, which was also adopted in previous CPUE standardization analyses conducted for other species caught by the same fleet ([Sabarros et al., 2025](#); [Tellier and Sabarros, 2025](#)), ensures that the resulting index is more representative and reliable.

Some individuals were measured and/or sexed by observers. The length-frequency distribution and the temporal evolution of observed sizes between 2007 and 2025 are presented in [Annex 1](#). The overall length-frequency follows a normal distribution centered around 140 cm LJFL, with 95% of individuals ranging between 75 and 210 cm LJFL. No major temporal pattern is observable in the evolution of swordfish sizes over the study period. Size-frequency distributions differed between females and males ([Annex 2](#)), with mature individuals accounting for 45% of females and 65% of males in the observed catches. The observed size distributions covered a broad size range including immature and mature individuals, with females generally occurring over a wider size range than males.

The comparison of the three GLMM random-effect structures further supports the robustness of the resulting annual CPUE series. Although the best conventional GLMM (Mod 1b), the best GLMM with spatial random field (Mod 2) and the GLMM with spatiotemporal random field (Mod 3) differed in their ability to account for residual spatial structure, the standardized CPUE trends obtained from these approaches are quite similar ([Figure 6](#)). Similarly, the standardized indices obtained using different mesh resolutions showed only limited differences ([Figure 5](#)). This indicates that the main temporal pattern of the standardized CPUE is relatively robust to the choice of modelling framework and mesh resolution. The spatiotemporal model nevertheless provided the lowest AIC and was therefore retained as the final model. Its improved fit is consistent with the presence of spatial variation in swordfish catch rates that changes through time and that is not fully accounted for by the fixed effects.

Residual diagnostics show several minor but statistically significant deviations between the observed residual patterns and those expected under the fitted model. The tests of residual uniformity, dispersion, zero inflation and outliers all detect significant deviations. However, the graphical diagnostics show no major systematic patterns, and the magnitude of the detected deviations is limited. In particular, the deviation from residual uniformity is minor, with a Kolmogorov-Smirnov statistic of only 0.0257. Similarly, although the zero-inflation test indicates more observed zero catches than expected under the fitted model, the absolute difference is limited: 193 zero catches were observed among 5784 fishing operations, compared with between 104 and 186 zero catches in simulations from the fitted model. The excess of outliers is also minor in absolute terms, with 15 observations classified as outliers, corresponding to approximately 0.26% of the dataset, compared with an expected frequency of approximately 0.15%. The significant underdispersion indicates that the residual variability is somewhat lower than expected under the fitted model, although the magnitude of this deviation does not appear sufficient to compromise the overall standardization. These diagnostics support the use of the retained model for deriving the standardized CPUE index while acknowledging that further improvements to the model structure could be investigated in future analyses.

However, some caution is warranted for the early years of the series. Observer coverage was relatively low (<3% of effort in hooks observed) between 2007 and 2010 ([Figure 1](#)), raising concerns about data representativeness. For this reason, we recommend discarding this initial period and focusing on the 2011-2025 series for stock assessment purposes. Within this period, the standardized CPUE shows an overall significant increasing trend, suggesting an increase in the abundance of swordfish in the south-west Indian Ocean.

The standardized CPUE index follows a temporal pattern that is relatively similar to the nominal CPUE but smoother than the latter ([Figure 13](#)), which is expected for a standardized index. This index is therefore considered a more appropriate index of relative abundance than nominal catch rates for use in stock assessment.

This series based on observer and self-reported data is intended to be compared with another standardized CPUE series, derived from logbook data, for the same fishery. Comparing the trends derived from these two data sources will allow to assess the consistency of the increase in the relative abundance of swordfish.

5. Conclusion

This study provides a standardized swordfish CPUE series for the French Reunion-based pelagic longline fishery in the southwestern Indian Ocean, based on observer and self-reported data collected between 2007 and 2025. This series is intended for comparison with another standardized CPUE series based on logbook data from the same fishery. Given the limited monitoring coverage during 2007-2010, we recommend that only the 2011-2025 portion of the series be considered for stock assessment purposes. Among the models evaluated, the Negative Binomial GLMM with a spatiotemporal random effect provides the best fit and was retained to derive the annual abundance index. The standardized CPUE series is robust to the choice of modelling framework and mesh resolution, and residual diagnostics indicate that the retained model



provides an adequate basis for CPUE standardization despite minor deviations between the observed residual patterns and those expected. Over the period 2011-2025, the standardized CPUE shows a slight but statistically significant increasing trend.

Acknowledgements

We thank the observers and captains that collected data through CAPPER and EU DCF data collection programs.

References

- Anderson, S.C., Ward, E.J., English, P.A., Barnett, L.A.K., Thorson, J.T., 2022. sdmTMB: An R Package for Fast, Flexible, and User-Friendly Generalized Linear Mixed Effects Models with Spatial and Spatiotemporal Random Fields. <https://doi.org/10.1101/2022.03.24.485545>
- Bach, P., Rabearisoa, N., Filippi, T., Hubas, S., 2008. The first year of SEALOR: Database of SEA-going observer surveys monitoring the local pelagic longline fishery based in La Reunion, IOTC-2008-WPEB08-13. 8th IOTC Working Party on Ecosystems and Bycatch – Bangkok, Thailand.
- Bach, P., Sabarros, P.S., Le Foulgoc, L., Richard, E., Lamoureux, J.P., Romanov, E., 2013. Self-reporting data collection project for the pelagic longline fishery based in La Reunion, IOTC-2013-WPEB09-42. 9th IOTC Working Party on Ecosystems and Bycatch – La Réunion, France.
- Bach, P., Sabarros, P.S., Romanov, E., Puech, A., Capello, M., Lucas, V., 2014. Patterns of swordfish capture in relation to fishing time, moon illumination and fishing depth, IOTC-2014-WPB12-14. 12th IOTC Working Party on Billfish – Yokohama, Japan.
- Brooks, M.E., Kristensen, K., Van Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Mächler, M., Bolker, B.M., 2017. Modeling zero-inflated count data with glmmTMB. <https://doi.org/10.1101/132753>
- da Silva, C., West, W., Kerwath, S., 2025. CPUE Standardisation of Swordfish caught in South African waters, IOTC-2025-WPB23-22. 23th Session of the IOTC Working Party on Billfish – Sète, France.
- Guyomard, D., Desruisseaux, M., Poisson, F., Petit, M., Taquet, M., 2004. GAM analysis of operational and environmental factors affecting swordfish (*Xiphias gladius*) catch and CPUE of the Reunion Island longline fishery, in the South Western Indian Ocean, IOTC-2004-WPB-04. 4th Session of the IOTC Working Party on Billfish – Albion Fisheries Research Centre, Mauritius.
- Hartig, F., 2020. Package “DHARMa.”
- Maunder, M.N., Punt, A.E., 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research 70, 141–159. <https://doi.org/10.1016/j.fishres.2004.08.002>
- Ortega-Garcia, S., Ponce-Diaz, G., O'Hara, R., Merilä, J., 2008. The relative importance of lunar phase and environmental conditions on striped marlin (*Tetrapturus audax*) catches in sport fishing. Fisheries Research 93, 190–194. <https://doi.org/10.1016/j.fishres.2008.04.005>
- Poisson, F., Gaertner, J.-C., Taquet, M., Durbec, J.-P., Bigelow, K., 2010. Effects of lunar cycle and fishing operations on longline-caught pelagic fish: fishing performance, capture time, and survival of fish. Fishery Bulletin. 108 (3). 268-281. <https://archimer.ifremer.fr/doc/00011/12237/>
- Reinhardt, J.F., Weaver, J., Latham, P.J., Dell'Apa, A., Serafy, J.E., Browder, J.A., Christman, M., Foster, D.G., Blankinship, D.R., 2018. Catch rate and at-vessel mortality of circle hooks versus J-hooks in pelagic

longline fisheries: A global meta-analysis. *Fish and Fisheries* 19, 413–430.
<https://doi.org/10.1111/faf.12260>

Sabarros, P.S., Romanov, E., Dagorne, D., Foulgoc, L.L., Ternon, J.-F., Bach, P., 2014. Environmental drivers of swordfish local abundance in the south-west Indian Ocean, IOTC-2014-WPB12-15. 12th Session of the IOTC Working Party on Billfish – Yokohama, Japan.

Sabarros, P.S., Coelho, R., Bach, P., 2017. Standardized CPUE of blue shark caught by the French swordfish fishery in the south-west Indian Ocean (2007-2016), IOTC-2017-WPEB13-27. 13th Session of the IOTC Working Party on Ecosystems and Bycatch – San Sebastián, Spain.

Sabarros, P.S., Coelho, R., Romanov, E.V., Guillon, N., Bach, P., 2021. Updated standardized CPUE of blue shark bycaught by the French Reunion-based pelagic longline fishery (2007-2020), IOTC-2021-WPEB17(DP)-08_Rev1. 17th Session of the IOTC Working Party on Ecosystems and Bycatch – Data Preparatory, Online.

Sabarros, P.S., Tellier, C., Bach, P., Coelho, R., Romanov, E.V., 2025. Updated standardized CPUE of blue shark bycaught by the French Reunion-based pelagic longline fishery (2007-2024), IOTC-2025-WPEB21(DP)-05. 21th Session of the IOTC Working Party on Ecosystems and Bycatch – Data Preparatory, Online.

Tellier, C., Sabarros, P.S., 2025. Standardized CPUE of oceanic whitetip shark bycaught by the French Reunion-based pelagic longline fishery operating in the South West Indian Ocean (2007-2024), IOTC-2025-WPEB21(AS)-18. 21th Session of the IOTC Working Party on Ecosystems and Bycatch – Sète, France.

Tables

Table 1. Model comparison: the best conventional GLMM with a Poisson Distribution (Mod 1a), the best conventional GLMM with a Negative Binomial Distribution (Mod 1b), the best GLMM with a spatial effect (Mod 2), and the best GLMM with a spatiotemporal effect (Mod 3).

GLMM	Covariates selected (in order of selection)	Degrees of freedom (for quantitative covariates)	Mesh	AIC
Mod 1a: Distribution: Poisson Random effect: <i>vessel</i>	<i>hauling_end_time</i>	4	/	36251.2
	<i>month</i>	11		
	<i>latitude</i>	3		
	<i>longitude</i>	5		
	<i>moon_illumination</i>	4		
	<i>setting_start_time</i>	5		
	<i>branchlines_per_basket_count</i>	2		
	<i>soaking_time</i>	5		
Mod 1b: Distribution: Negative Binomial Random effect: <i>vessel</i>	<i>month</i>	11	/	32458.62
	<i>hauling_end_time</i>	3		
	<i>latitude</i>	3		
	<i>longitude</i>	5		
	<i>moon_illumination</i>	3		
	<i>setting_start_time</i>	5		
	<i>branchlines_per_basket_count</i>	2		
	<i>soaking_time</i>	3		
	<i>percentage_circle_hooks</i>	1		
Mod 2: Distribution: Negative Binomial Random effects: <i>vessel, spatial random field</i>	<i>month</i>	11	100 knots	32391.46
	<i>hauling_end_time</i>	3		
	<i>moon_illumination</i>	3		
	<i>setting_start_time</i>	5		
	<i>soaking_time</i>	3		
	<i>branchlines_per_basket_count</i>	2		
	<i>percentage_circle_hooks</i>	1		
Mod 3: Distribution: Negative Binomial Random effects: <i>vessel, spatiotemporal random field</i>	<i>month</i>	11	100 knots	32194.77
	<i>hauling_end_time</i>	3		
	<i>moon_illumination</i>	3		
	<i>setting_start_time</i>	5		
	<i>soaking_time</i>	3		
	<i>branchlines_per_basket_count</i>	2		
	<i>percentage_circle_hooks</i>	1		

Table 2. Summary of the retained model (Mod 3).

Spatiotemporal model fit by ML ['sdmTMB']

Formula:

$\text{nb_caught} \sim 1 + \text{factor}(\text{month}) + \text{hauling_end_time_spl1} + \text{hauling_end_time_spl2} +$
 $\text{hauling_end_time_spl3} + \text{moon_illumination_spl1} + \text{moon_illumination_spl2} +$
 $\text{moon_illumination_spl3} + \text{setting_start_time_spl1} + \text{setting_start_time_spl2} +$
 $\text{setting_start_time_spl3} + \text{setting_start_time_spl4} + \text{setting_start_time_spl5} +$
 $\text{soaking_time_spl1} + \text{soaking_time_spl2} + \text{soaking_time_spl3} +$
 $\text{branchlines_per_basket_count_spl1} + \text{branchlines_per_basket_count_spl2} +$
 $\text{percentage_circle_hooks_spl1} + \text{year} + (1 \mid \text{vessel})$

Mesh: mesh (isotropic covariance)

Time column: character

Data: data

Family: nbinom2(link = 'log')

Random intercepts and/or slopes:

Conditional model:

Groups	Name	Variance	Std.Dev.
vessel	(Intercept)	0.04	0.21

Conditional model:

	coef.est	coef.se
(Intercept)	-4.90	0.42
factor(month)2	-0.08	0.04
factor(month)3	-0.09	0.04
factor(month)4	-0.23	0.05
factor(month)5	-0.44	0.04
factor(month)6	-0.54	0.04
factor(month)7	-0.44	0.04
factor(month)8	-0.28	0.05
factor(month)9	-0.09	0.04
factor(month)10	-0.09	0.04
factor(month)11	-0.03	0.04
factor(month)12	0.04	0.04
hauling_end_time_spl1	0.26	0.16
hauling_end_time_spl2	-0.55	0.46
hauling_end_time_spl3	-0.80	0.21
moon_illumination_spl1	0.21	0.04
moon_illumination_spl2	0.10	0.06
moon_illumination_spl3	-0.02	0.02
setting_start_time_spl1	0.71	0.22
setting_start_time_spl2	0.70	0.23
setting_start_time_spl3	0.89	0.17
setting_start_time_spl4	0.70	0.48
setting_start_time_spl5	0.44	0.24
soaking_time_spl1	1.05	0.26
soaking_time_spl2	-0.62	0.64
soaking_time_spl3	0.20	0.22
branchlines_per_basket_count_spl1	-0.92	0.21



branchlines_per_basket_count_spl2	-0.05	0.16
percentage_circle_hooks_spl1	-0.09	0.05
year2008	-0.13	0.25
year2009	-0.28	0.25
year2010	0.36	0.26
year2011	-0.06	0.22
year2012	-0.18	0.22
year2013	-0.23	0.22
year2014	-0.34	0.22
year2015	-0.16	0.22
year2016	-0.04	0.22
year2017	0.01	0.23
year2018	-0.10	0.22
year2019	-0.01	0.23
year2020	0.04	0.23
year2021	0.10	0.23
year2022	0.18	0.23
year2023	0.19	0.22
year2024	0.29	0.23
year2025	0.21	0.22

Dispersion parameter: 6.48

Spatiotemporal AR1 correlation (ρ): 0.56

Matérn range: 4.03

Spatial SD: 0.25

Spatiotemporal marginal AR1 SD: 0.24

ML criterion at convergence: 16044.384

See ?tidy.sdmTMB to extract these values as a data frame.

Table 3. Standardized CPUE (stdCPUE) time series for swordfish caught in the French longline fishery for the period 2007-2025. nCPUE designates the nominal CPUE. The stdCPUE is provided with 95% confidence interval (CI).

Year	nCPUE	stdCPUE	Lower CI	Upper CI	Std Error
2007	4.9750	7.1000	4.5980	10.9634	0.2217
2008	7.6667	6.2545	3.9549	9.8909	0.2338
2009	6.3829	5.3415	3.6211	7.8793	0.1983
2010	13.6694	10.2245	6.8096	15.3521	0.2074
2011	7.0905	6.6910	4.9339	9.0737	0.1554
2012	5.3682	5.9402	4.3932	8.0318	0.1539
2013	4.7521	5.6310	4.1334	7.6710	0.1577
2014	4.2576	5.0577	3.7160	6.8838	0.1573
2015	5.0111	6.0241	4.4585	8.1395	0.1536
2016	5.9489	6.8233	5.1093	9.1124	0.1476
2017	5.1648	7.1914	5.3271	9.7081	0.1531
2018	4.4568	6.4183	4.7922	8.5962	0.1491
2019	5.2494	7.0122	5.1882	9.4775	0.1537
2020	6.3366	7.4218	5.4704	10.0694	0.1556
2021	7.0798	7.8811	5.7911	10.7255	0.1572
2022	8.7639	8.4859	6.2796	11.4674	0.1536
2023	9.3295	8.6046	6.4383	11.4998	0.1480
2024	8.2596	9.4795	6.9877	12.8598	0.1556
2025	7.4010	8.7184	6.5585	11.5897	0.1452

Figures

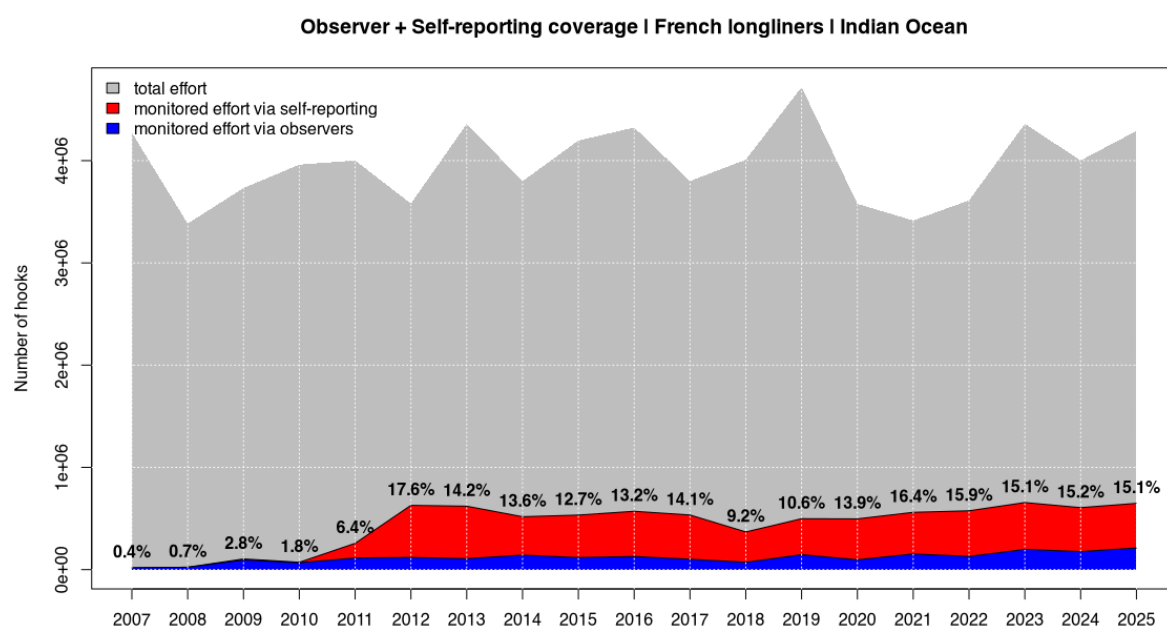


Figure 1. Observer and self-reporting effort coverage in number of hooks deployed in the French longline fishery operating in the south-west Indian Ocean between 2007 and 2025.

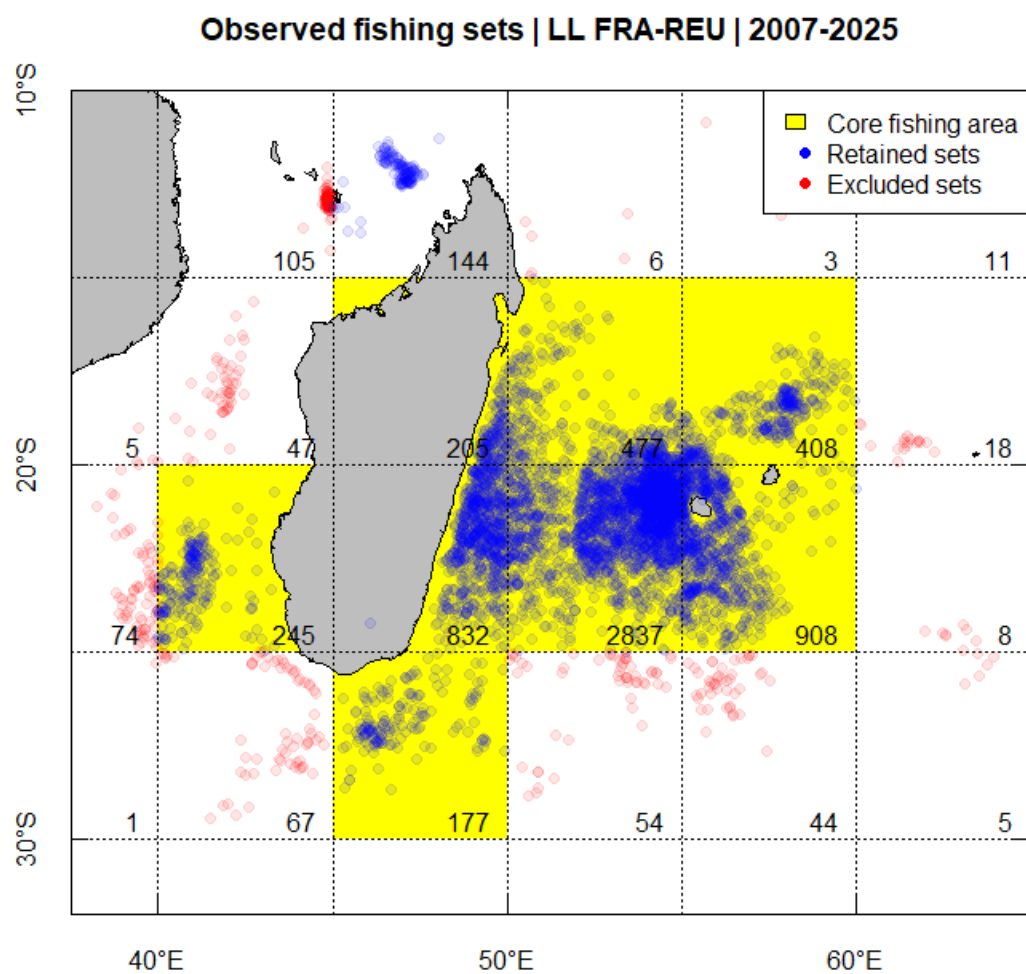


Figure 2. Distribution of fishing sets (hauling start position) between 2007 and 2025. The yellow area represents the core fishing area with retained sets in blue. Excluded sets are shown in red. Numbers in the corners of 5°x5° squares are the number of sets.

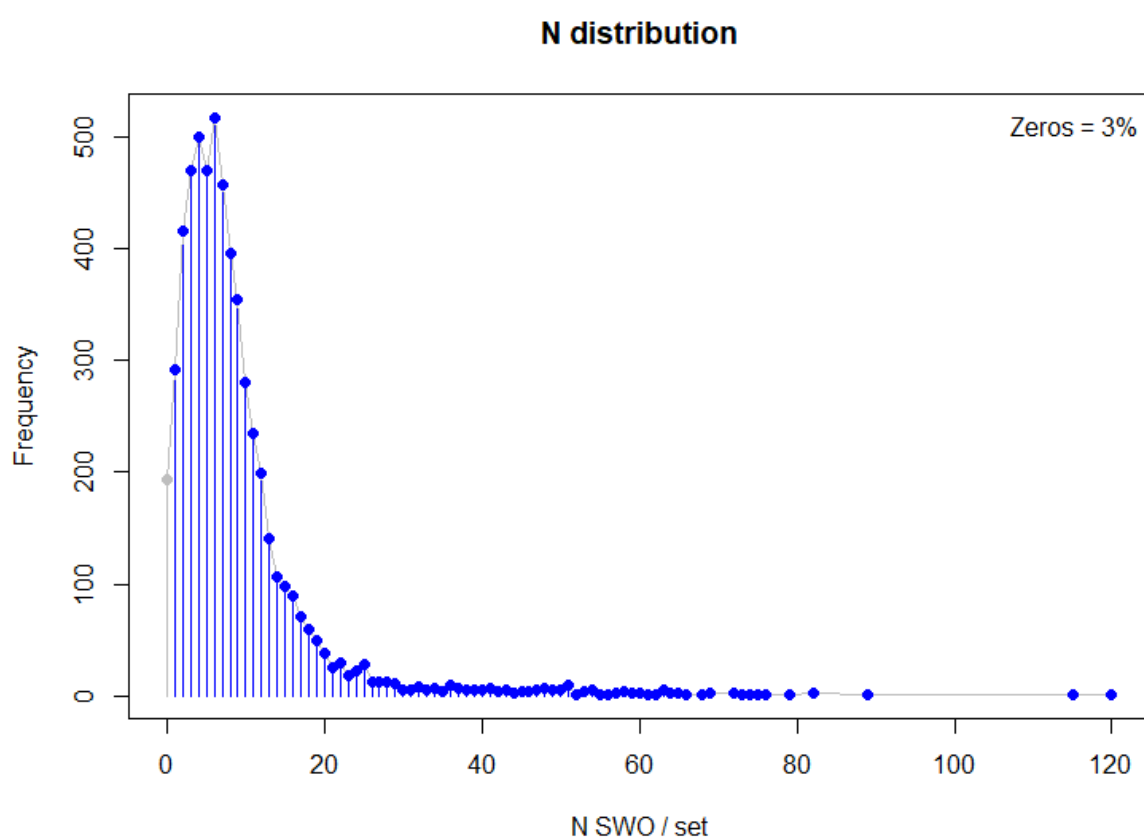


Figure 3. Frequency distribution of swordfish catches per set. The proportion of zero-catch in sets is 3%.

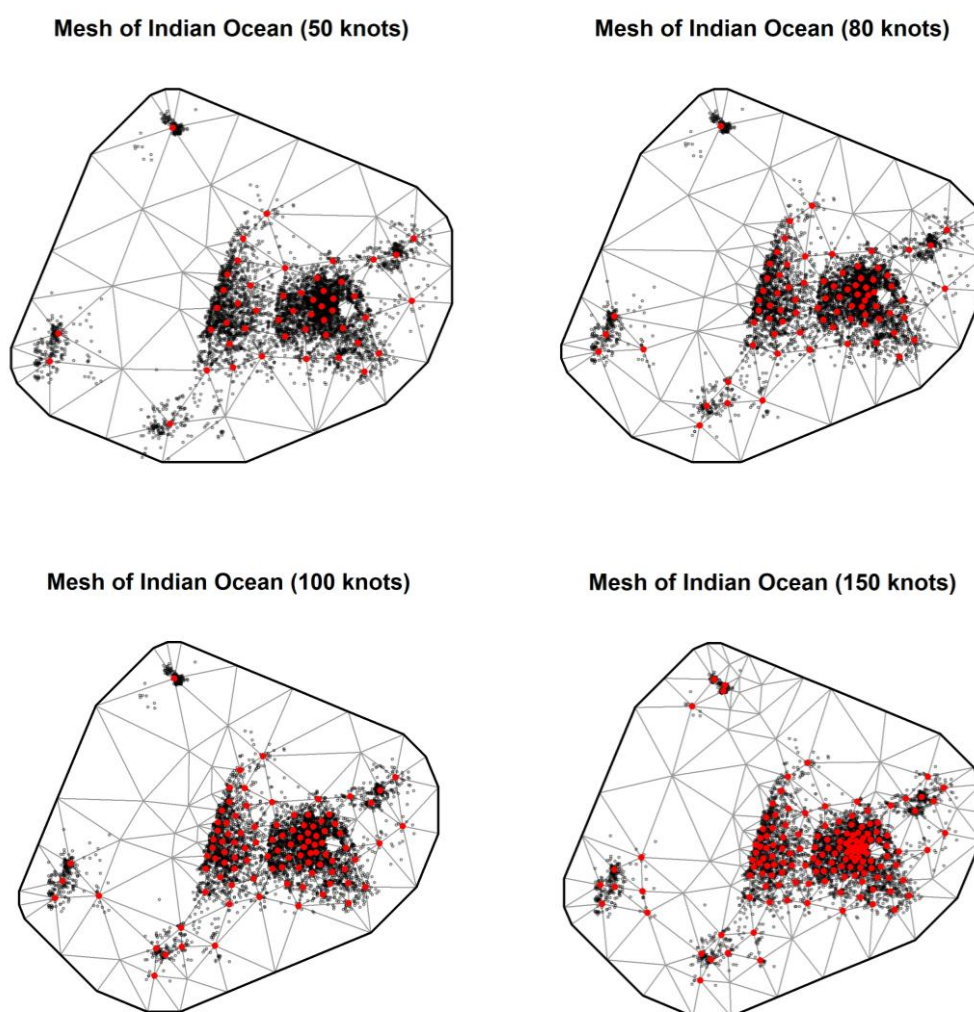


Figure 4. Spatial meshes (50, 80, 100, and 150 knots) tested for GLMMs with a spatial random field.

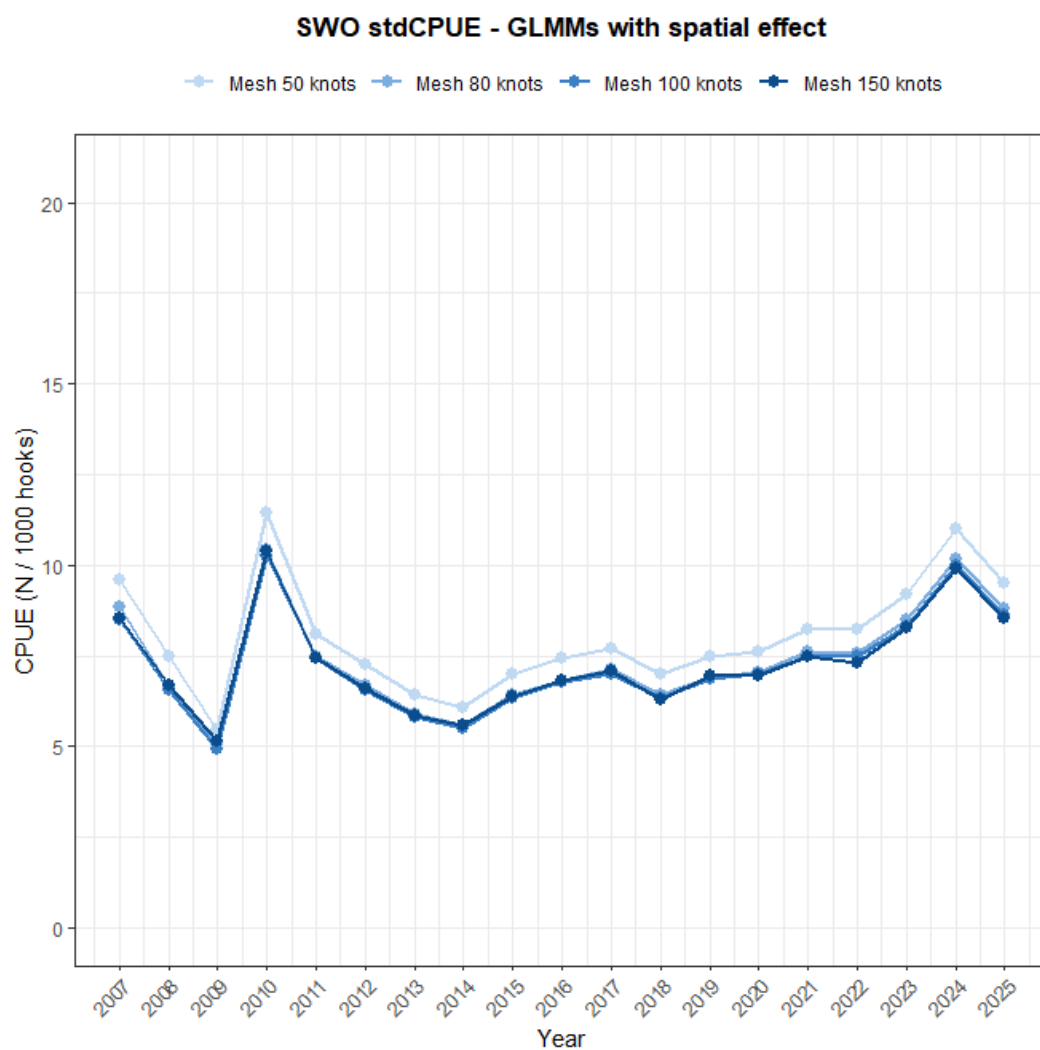


Figure 5. Swordfish standardized CPUE time series, estimated from GLMMs with a spatial random effect, using four mesh resolutions: 50, 80, 100, and 150 knots.

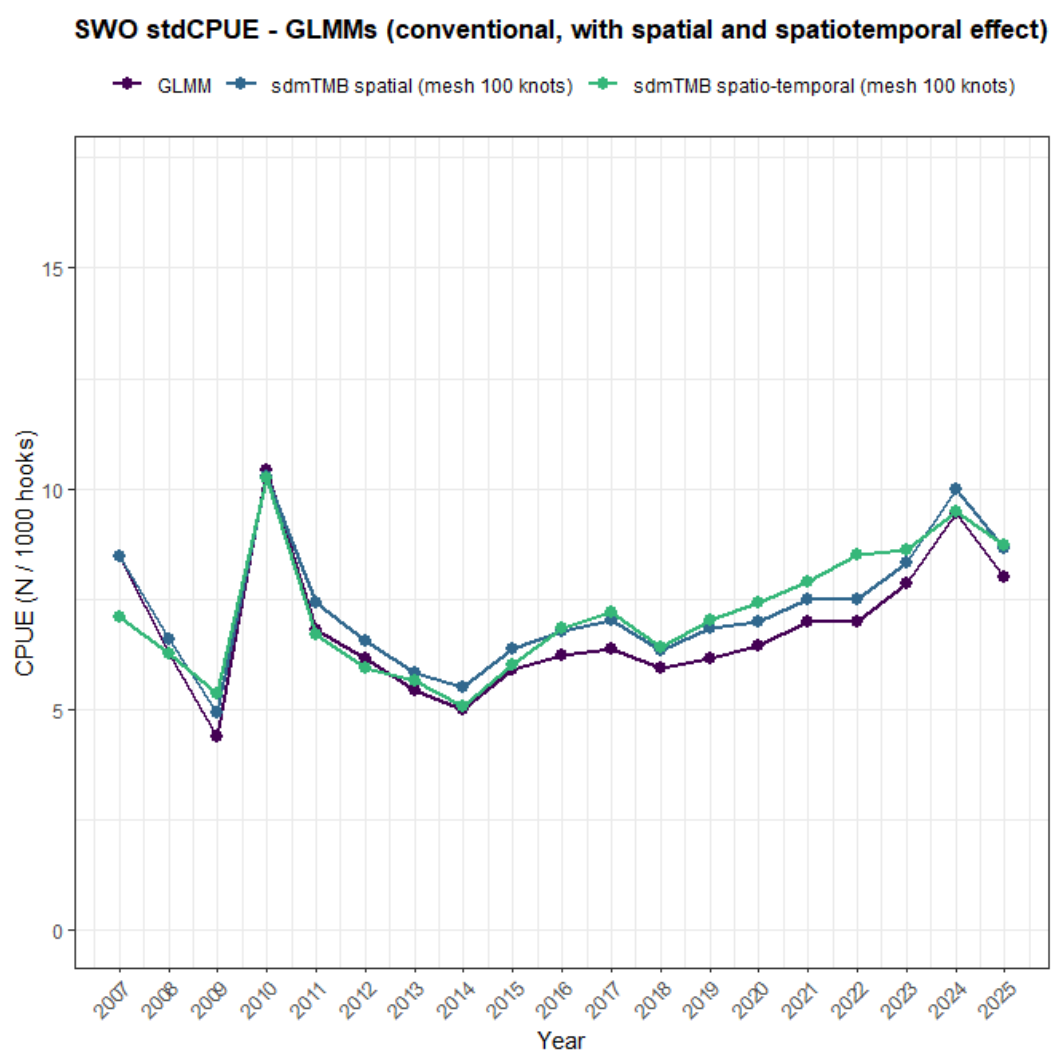


Figure 6. Swordfish standardized CPUE time series, estimated with the best conventional GLMM (Mod 1b), the best GLMM with a spatial random field (Mod 2), and the GLMM with a spatiotemporal random field (Mod 3).

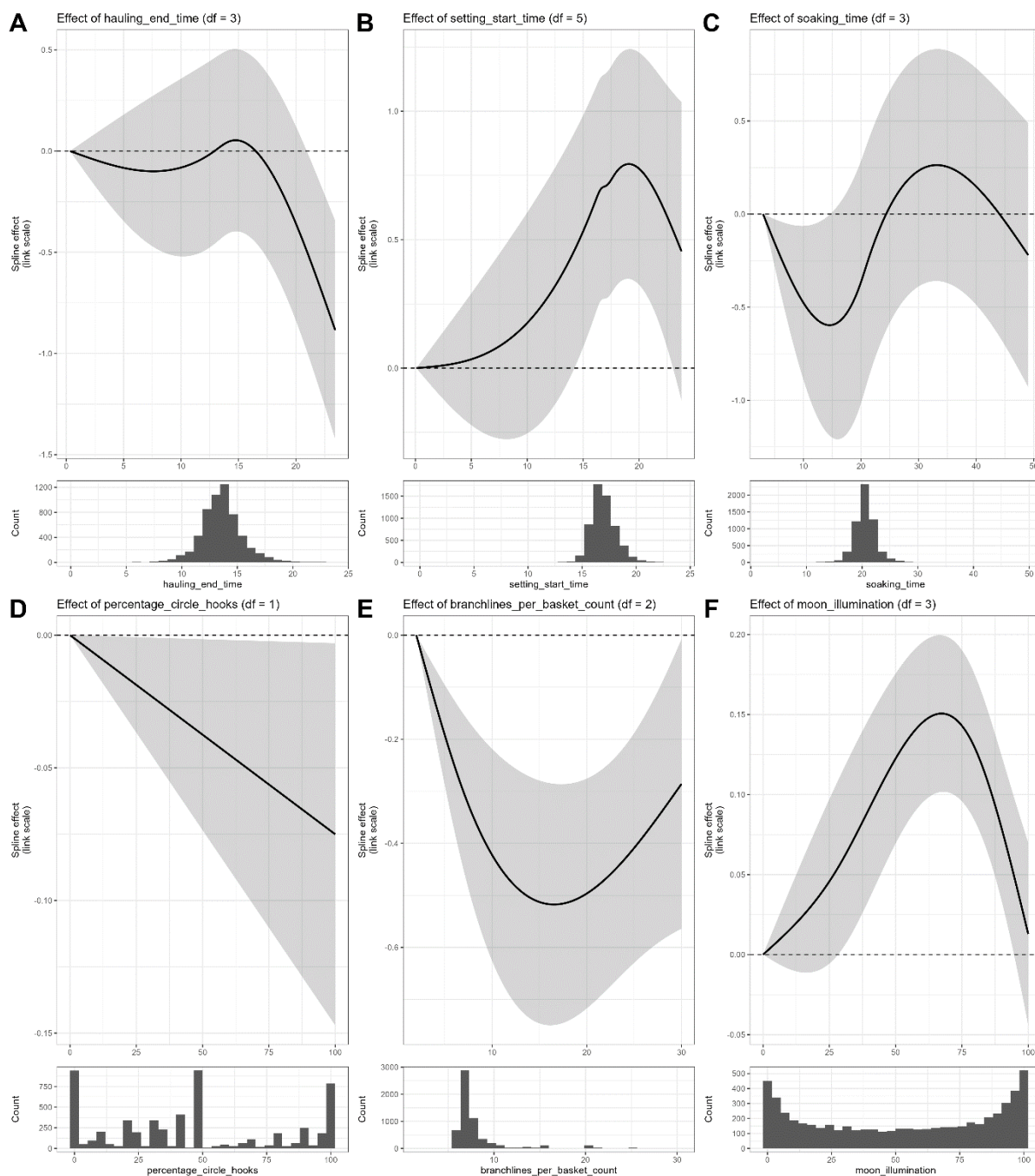


Figure 7. Partial effects (splines) of the continuous covariates used to explain CPUE in the retained model (Mod 3): *hauling_end_time* (A), *setting_start_time* (B), *soaking_time* (C), *percentage_circle_hooks* (D), *branchlines_per_basket_count* (E) and *moon_illumination* (F).

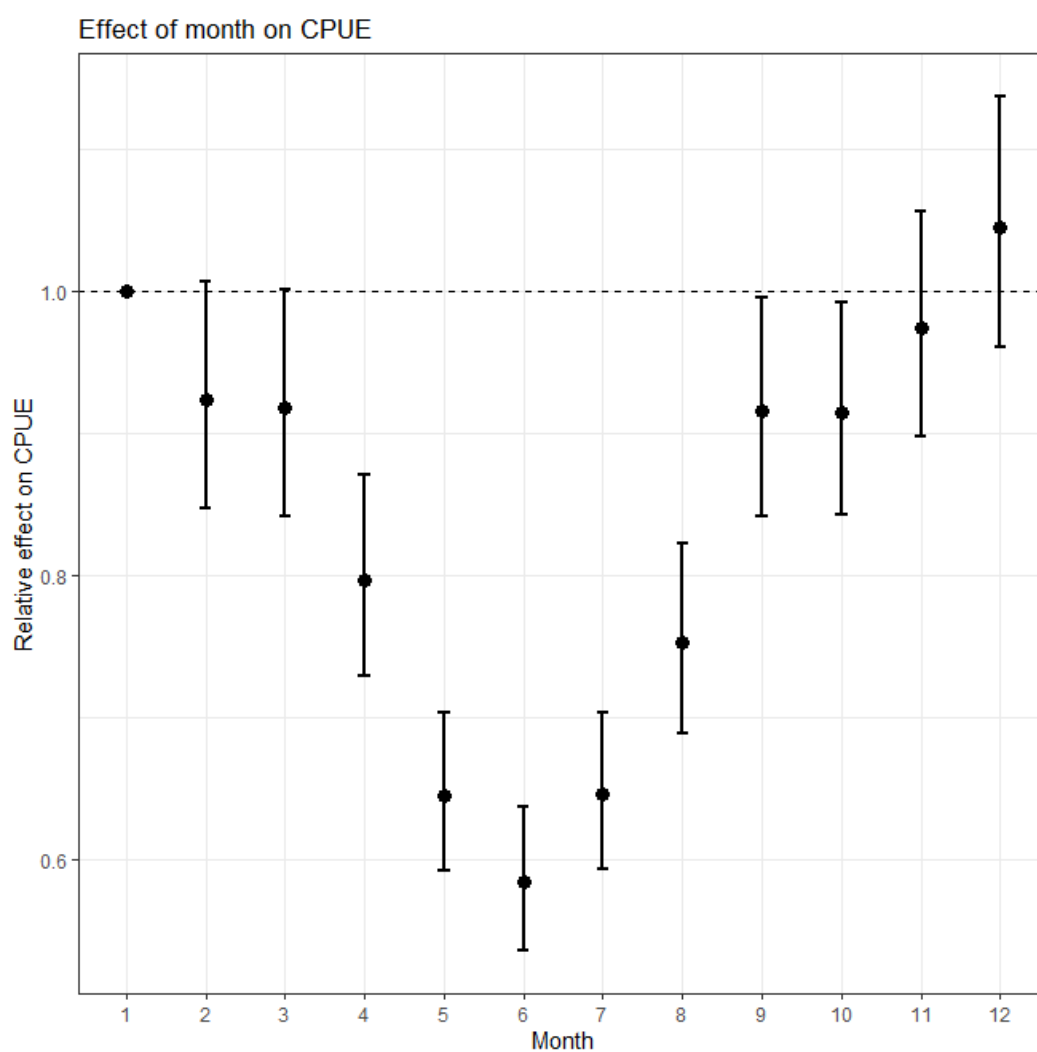


Figure 8. Effect of the factor covariate month used to explain CPUE in the retained Negative Binomial GLMM with a spatiotemporal random field (Mod 3).

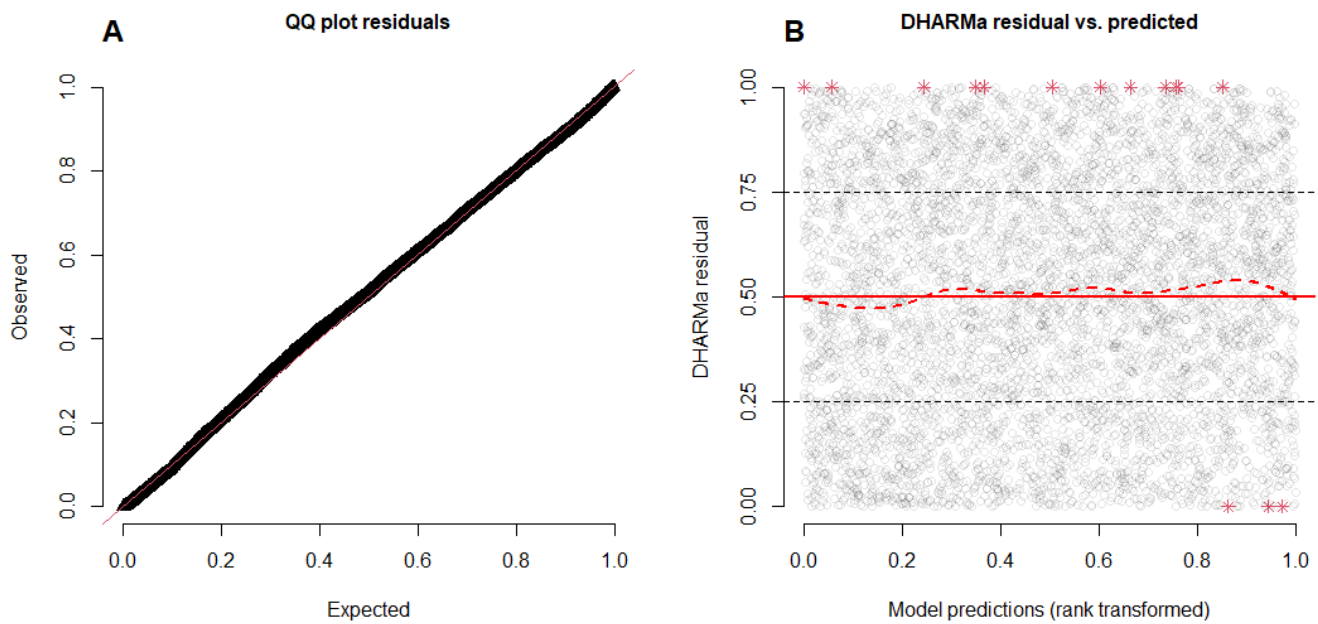


Figure 9. Residual analysis of model selected for swordfish CPUE standardization: QQ plot of the simulated scaled residuals (A) and residuals plotted against fitted values (B).

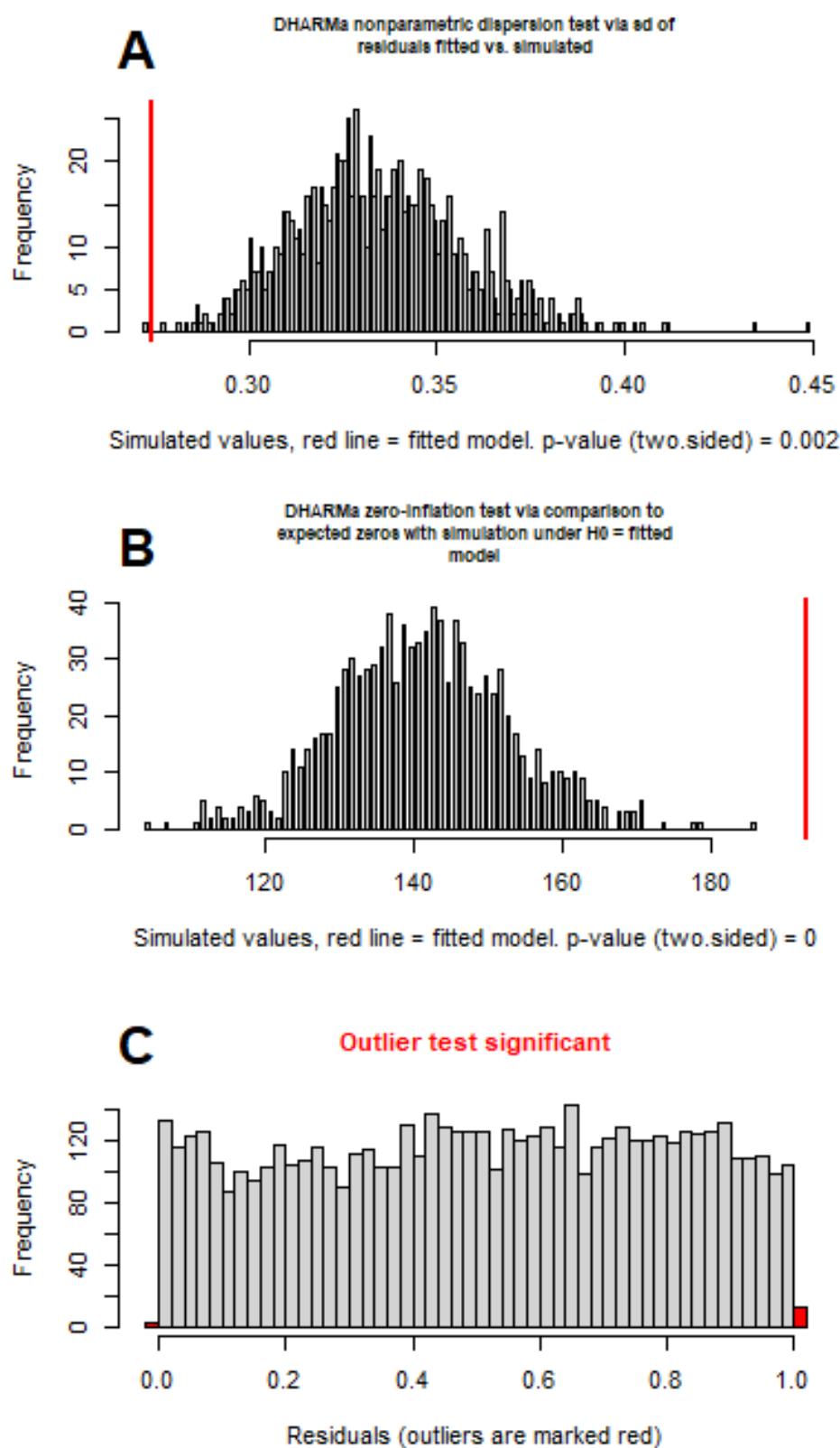


Figure 10. Residual analysis of model selected for swordfish CPUE standardization: dispersion test (A), zero-inflation test (B) and outliers test (C).

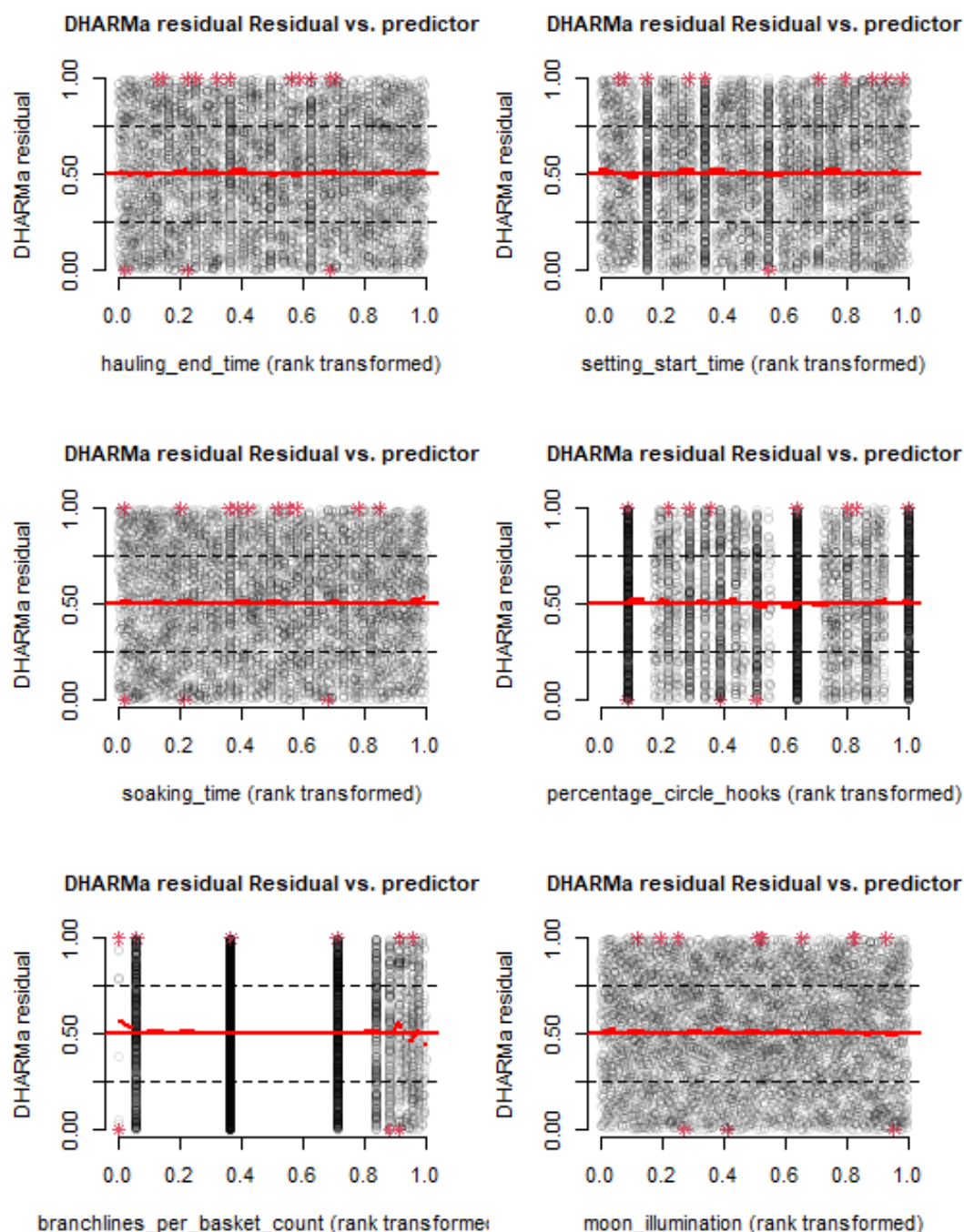


Figure 11. Residuals of model selected for swordfish CPUE standardization (Mod 3), for each quantitative covariate selected.

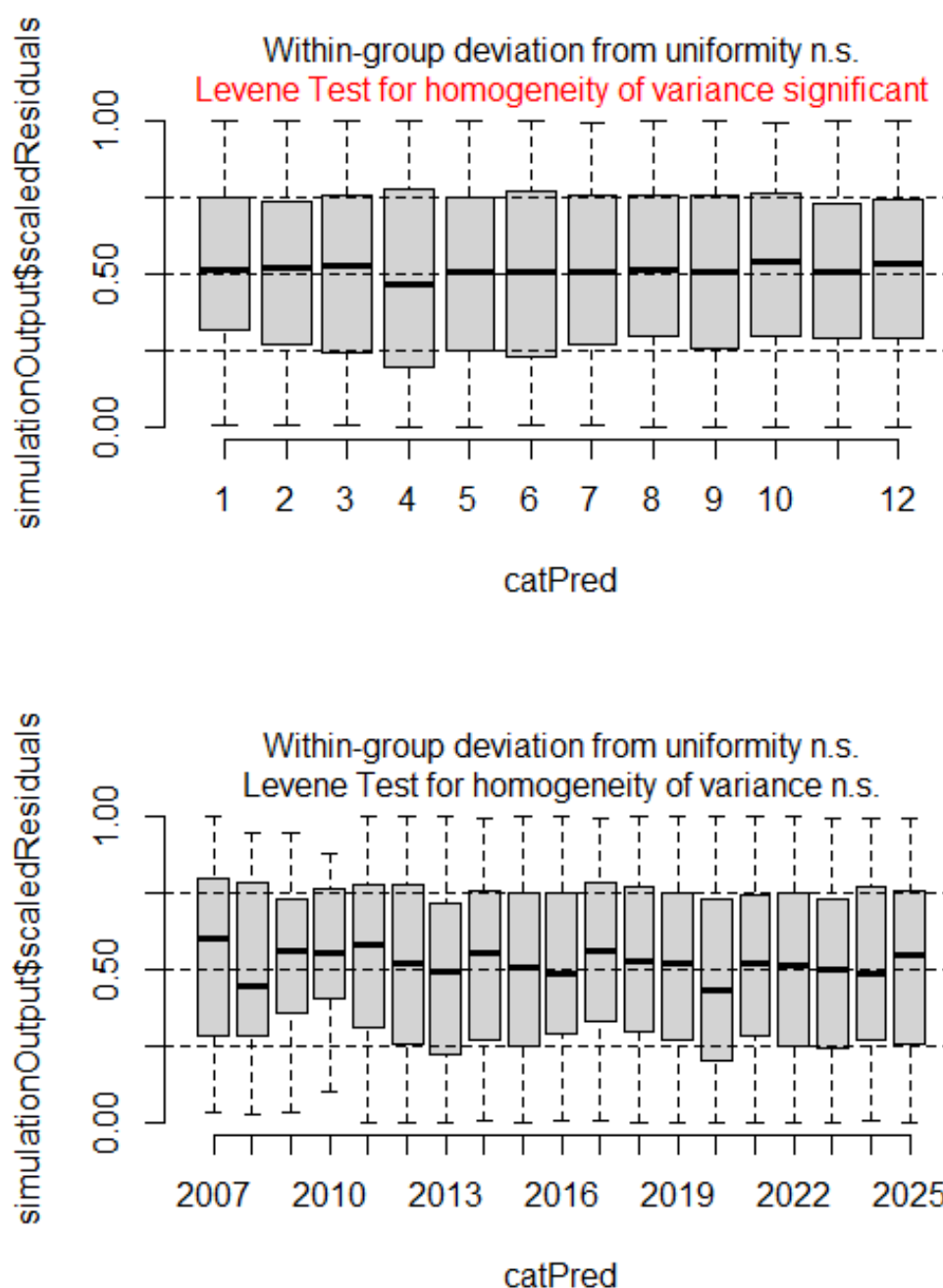


Figure 12. Residuals of model selected for swordfish CPUE standardization (Mod 3), for covariates *month* and *year*.

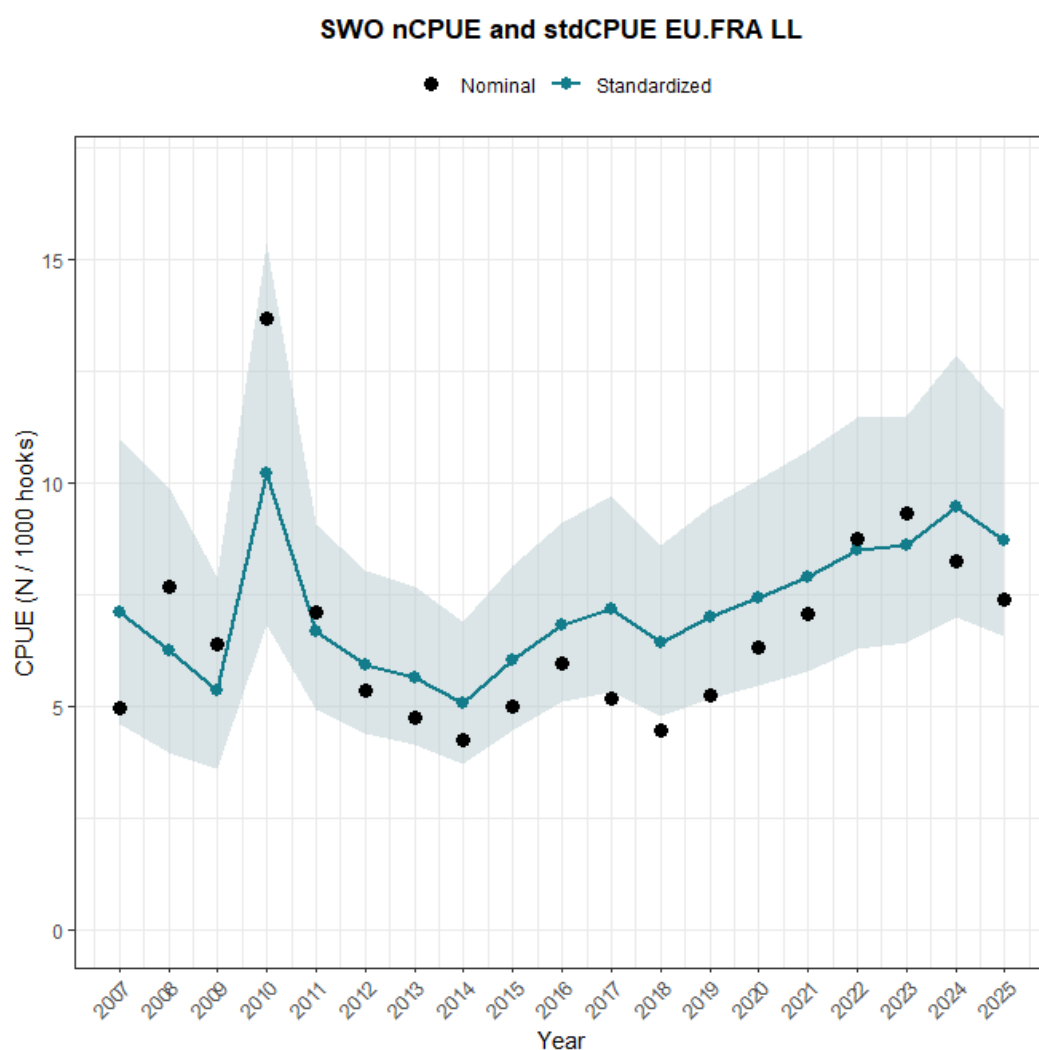


Figure 13. Nominal and standardized CPUE (N/1000 hooks) time series for the swordfish (SWO) caught by the French longline fishery based in Reunion Island (EU.FRA LL) for the period 2007-2025. The standardized index is derived from the final GLMM with a spatiotemporal random field, fitted with *sdmTMB*. The gray envelope represents the 95% confidence intervals.

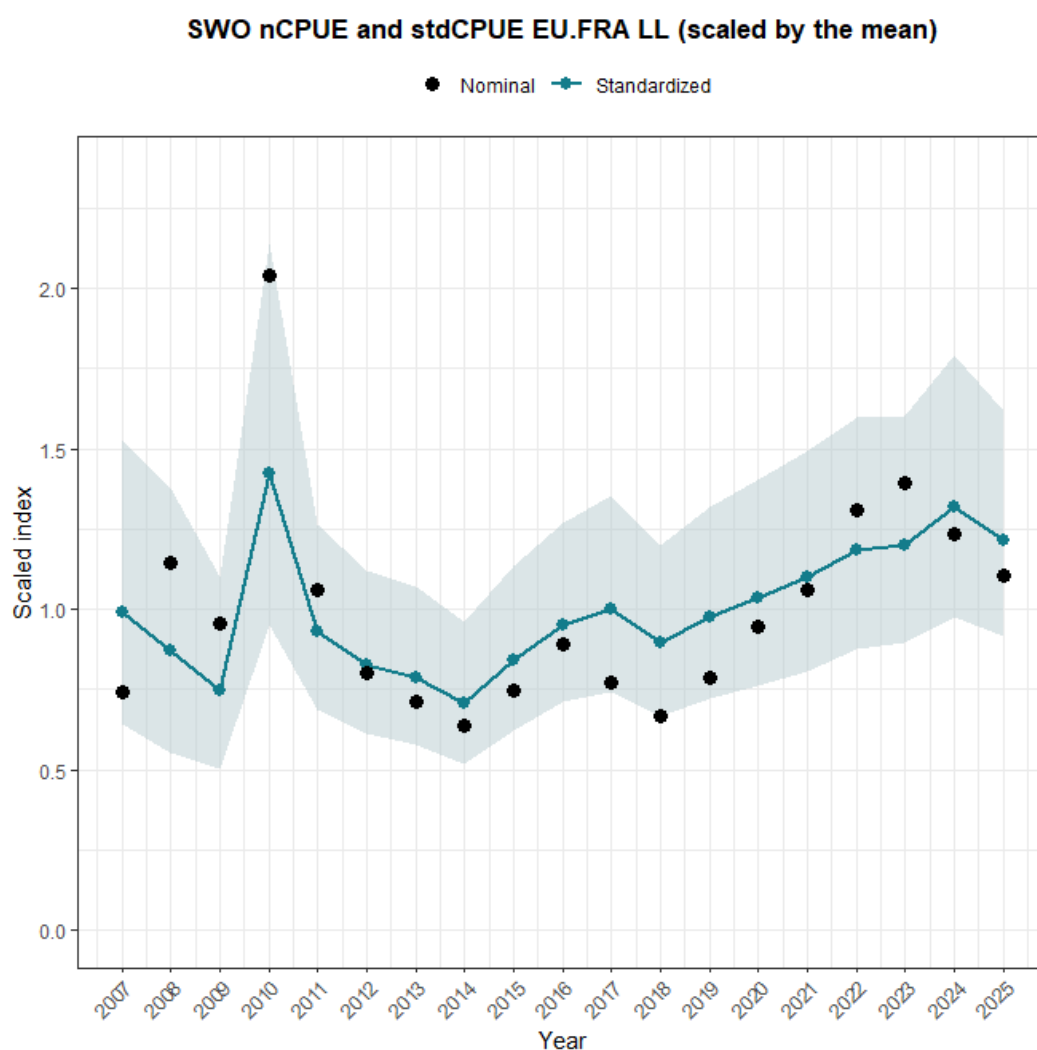
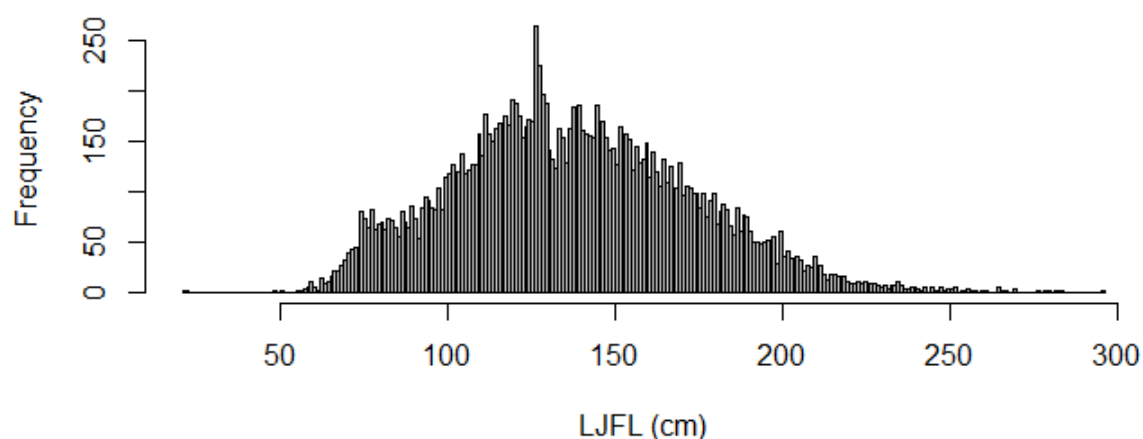


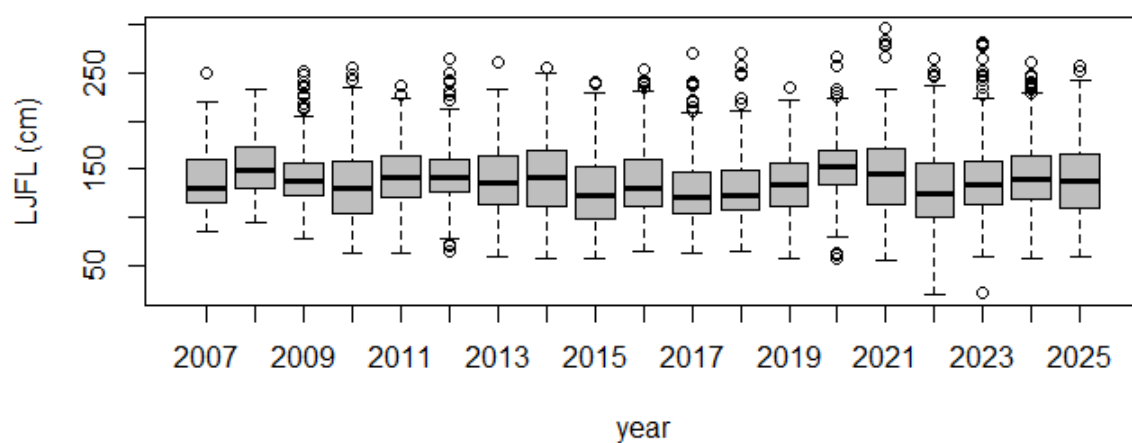
Figure 14. Scaled (by the mean) nominal and standardized CPUE time series for the swordfish (SWO) caught by the French longline fishery based in Reunion Island (EU.FRA LL) for the period 2007-2025. The standardized index is derived from the final GLMM with a spatiotemporal random field, fitted with *sdmTMB*. The gray envelope represents the 95% confidence intervals.

Annexes

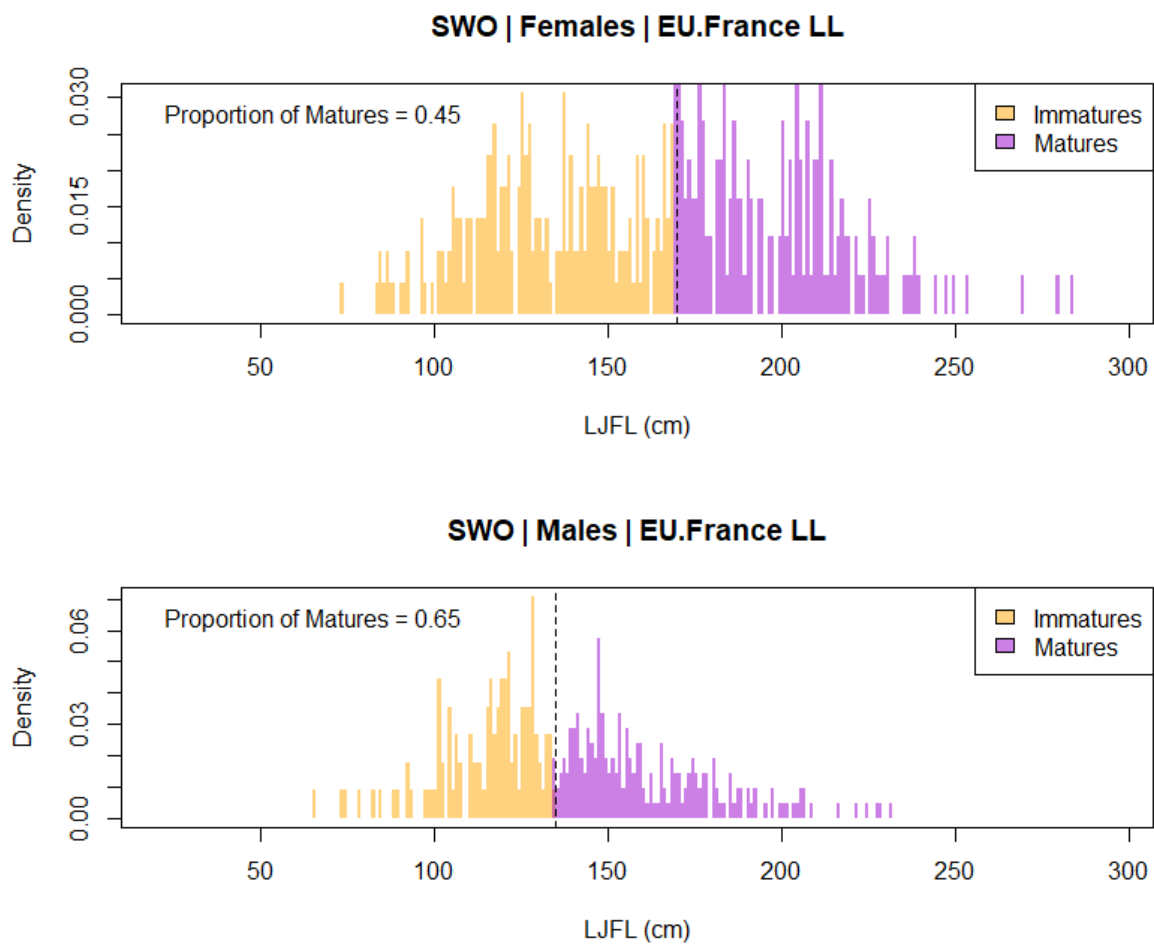
SWO size distribution | LL | EU.France



SWO size distribution | LL | EU.France



Annex 1. Length-frequency distribution of swordfish, and evolution of the sizes between 2007 and 2025.



Annex 2. Length-frequency distribution of swordfish by sex, showing immature and mature individuals according to maturity thresholds (170 cm LJFL for females, 135 cm LJFL for males).