Updated standardized CPUE of blue shark bycaught by the French Reunion-based pelagic longline fishery (2007-2024)

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Abstract

The blue shark *Prionace glauca* is the main bycatch species of the French swordfish-targeting longline fishery operating in the south-west Indian Ocean. Using observer and self-reported data collected aboard commercial longliners between 2007 and 2024, we present a standardized CPUE series for blue shark bycaught in this fishery estimated with a lognormal generalized linear mixed model (GLMM) to be used for the upcoming stock assessment. We propose to use the standardized CPUE for the period comprised between 2011 and 2024 where the monitoring effort has been consequent in comparison with previous years. Throughout 2011-2024, the standardized CPUE for the blue shark shows a slight decreasing trend, more precisely a substantial decrease between 2011 and 2019 followed by a stabilization since 2019.

Keywords

Blue shark | CPUE standardization | Longline | Western Indian Ocean

1. Introduction

Primary indices of abundance of target (e.g. tunas) and non-target species (e.g. sharks) are based on catch and effort data from commercial fisheries in the absence of fishery-independent abundance indicators. Fishery-based indices need to be standardized in order to remove the influence of various fishery-dependent factors such as the fishing effort variability, fishing strategy, habitat overlap, etc., so they can be used for stock assessment (Maunder and Punt, 2004).

The French longline fishery based in Reunion Island operates in the south-west Indian Ocean around Reunion Island, Mauritius, and Madagascar and mainly targets swordfish (*Xiphias gladius*) with relatively shallow night sets. The blue shark *Prionace glauca* is the main bycatch species and represents about 40% of the bycatch in number of individuals caught (Sabarros et al., 2013).

We previously presented an index of abundance for the blue shark (standardized CPUE) for the period 2007-2016 (Sabarros et al., 2017) and 2007-2020 (Sabarros et al., 2021). We now provide an updated index of abundance for this species based on observer and self-reported data of the French swordfish-targeting fishery based in Reunion Island for the period 2007-2024.

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-reported data" (Bach et al., 2013). Data were collected through CAPPER (2007-2008) and EU Data Collection Framework (2009-2024; Reg 199/2008 and 665/2008). The coverage in number of hooks monitored is presented in Figure 1. We retained a total of 5487 fishing operations monitored between 2007 and 2024 from the core fishing area that consists of 5°x5° squares with more than 120 fishing operations (Figure 2).

2.2. CPUE standardization

The response variable considered was the catch per unit of effort (CPUE) in number of individuals per 1000 hooks deployed. The proportion of zeros was 12% with a CPUE right-skewed distribution (Figure 3). By adding a constant (c = 1) and log-transforming the CPUE, the log(CPUE+1) transformation exhibits a Gaussian shape (Figure 3).

We estimated the standardized CPUE with lognormal Generalized Linear Mixed Models (GLMM) using the *lmer* function from *lmerTest* R package (Kuznetsova et al., 2020). According to the distribution of log(CPUE+1), we chose a Gaussian distribution for the residuals (link function: identity).

The list of candidate covariates was determined based on previous work on the characterization of blue shark hotspots in the south-west Indian Ocean (Selles et al., 2014) as well as the standardized CPUE presented in 2017 (Sabarros et al., 2017) and 2021 (Sabarros et al., 2021). Potential non-linearity of continuous candidate covariates was checked by performing univariate Generalized Additive Models (GAM; Figure 4). We first fitted a full model (Mod 0; Table 1) with the following covariates:

- Fixed effects:
  - *year* (factor): 2007 to 2024
  - *quarter* (factor): Q1 to Q4
  - *region* (factor): west and east of 52°E, it roughly corresponds to the EEZ of Madagascar (MDG) and Reunion Island (REU) respectively.
  - *quarter:region* (factor): interaction between quarter and region.
  - *latitude* (continuous): latitude of the fishing operation, specifically the latitude where the line starts being retrieved (hauling).
  - *soaking_time* (continuous): time in hours from when the first hook is deployed to when the last hook 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.
  - *hooks_per_basket* (continuous): number of hooks per basket as a relative index of fishing depth range/targeting.
  - *percentage_circle_hooks* (continuous): relative proportion of circle hooks to other types of hooks (J-hooks, tuna hooks, Teracima hooks).
  - *percentage_squid_bait* (continuous): proportion of squid bait relatively to other bait used (mackerel, etc.).
- Random effects:
  - *vessel* (factor): the vessel name was used as a random effect given that we wanted to incorporate the vessel effect variability in the model but without estimating specific parameters for each vessel.

Mod 0: *year* + *quarter* + *region* + *quarter:region* + *latitude* + *soaking_time* + *setting_start_time* + *hauling_end_time* + *hooks_per_basket* + *percentage_circle_hooks* + *percentage_squid_bait* + (1 | *vessel*)

We then ran a backward-stepwise model selection using the *step* function in *lmerTest* R package (Kuznetsova et al., 2020) to select for relevant and significant covariates, hereafter called Mod 2 (retained model). The deviance tables (Type III ANOVA with Satterthewaite's method) of the full and retained models are provided in Table 1, the summary table of the retained model is Table 2, and the graphical analysis of residuals of the retained model is presented in Figure 5.

Finally, we present the yearly standardized CPUE series from the retained model computed using the *lsmeans* function from *lsmeans* R package (Lenth, 2018; Table 3; Figure 6) as well as the scaled (by the mean) standardized CPUEs series (Figure 7).

For continuity with the standardized CPUE presented in 2021 (Sabarros et al., 2021), we also show the results of the model using the variables selected in this paper (Table 1; Figure 6; Figure 7), hereafter called Mod 1 (continuity model):

Mod 1: *year* + *quarter* + *region* + *quarter:region* + *latitude* + *soaking_time* + *hooks_per_basket* + *percentage_circle_hooks* + *percentage_squid_bait* + (1 | *vessel*)

3. Results

The model selection procedure based on the Akaike Information Criterion (AIC) score retained a lognormal GLMM with fewer covariates (Mod 2) than the full model Mod 0 (Table 1 and Table 2):

Mod 2: *year* + *quarter* + *region* + *quarter:region* + *latitude* + *hauling_end_time* + *hooks_per_basket* + (1 | *vessel*)

The blue shark standardized CPUE series obtained using Mod 0 (full model), Mod 1 (continuity model), and Mod 2 (retained model) are extremely similar (Figure 6; Figure 7).

According to the ANOVA table of the retained model (Table 1), all covariates have significant effects. Weights (sum of squares) show that *latitude* (58.67) and *year* (36.41) have a larger influence, followed by *quarter* (19.61) and then the rest of the covariates (4.88-7.76).

Overall, the retained standardized CPUE (Mod 2) follows the nominal CPUE except for the first years (2007-2010).

Throughout 2011-2024, the overall trend of the standardized CPUE is significantly decreasing (linear regression: b = -0.05165, p-value = 0.0102). Between 2011 and 2019, the decrease is significant and more pronounced (b = -0.095, p-value = 0.0257) while it is not significant between 2019 and 2024 (b = 0.01371, p-value = 0.798).

4. Discussion

Significant effects on blue shark CPUE

The year, quarter, region (west and east of 52°E, roughly corresponding to Mozambique Channel/Madagascar and Reunion Island respectively) have a significant effect on blue shark catch rates. This is also the case for the interaction between the quarter and region that was originally considered to account for the fact that the fishing effort is concentrated in Madagascar EEZ in the second and third quarters for vessels above 12 meters (length overall) that are able reach those waters, while most vessels stay in the Reunion Island EEZ during the fourth and first quarters of the year (Sabarros et al., 2013). We can note that blue shark catch rate is particularly high for vessels that remained in Reunion Island EEZ during the fourth quarter (Table 2).

To account for additional spatial effects (other than the west and east regions), the latitude was considered in this standardization work instead of the 5°x5° squares that were previously used (Sabarros et al., 2017). The latitude exhibits a strong negative effect (noting that the latitude sign is negative) of blue shark rates similarly to Selles et al. (2014). Blue shark catch rates increase across the north-south gradient.

Hauling end time has a positive effect in blue shark bycatch rate as previously demonstrated by Auger et al. (2015). Indeed, during typical swordfish-targeting fishing operations with line setting during sunset and hauling time starting at sunrise, the longer the line stays in the water and later is it hauled, more bycatch and notably blue sharks will be caught. In the standardized CPUE presented in 2021 (Sabarros et al., 2021), soaking time was selected instead of hauling end time; both variables are however indicative of late gear retrieval which tends to increase blue shark catch rates.

The number of hooks per basket is a proxy of fishing depth and displays a negative effect suggesting blue shark CPUE decreases with fishing depth. In Reunion Island longline fishery, hooks are generally set between 10 meters from the surface down to 120 meters for night fishing (Bach et al., 2014) but deeper sets probably for targeting tunas during the day (with an increased number of hooks between floats) will reach deeper layers, which results in a lower blue shark CPUE. Such pattern would need to be further investigated.

Compared to the model selected in 2021 (Sabarros et al., 2021), the percentage of circle hooks and squid bait are no longer retained through the backward step model selection.

Relevance of the retained standardized CPUE series

The data considered in this standardization work only concern the core fishing area of the Reunion-based pelagic longline fishery (see Figure 2). This was a safer approach than considering the total dataset that includes scarce sets located in the northern Mozambique Channel and high seas that might exhibit different patterns in terms of blue shark catch rates than those in the core fishing area.

The residual analysis of the retained lognormal GLMM (Mod 2; Figure 3) used to standardized blue shark CPUE did not exhibit violation of normality nor heteroscedasticity which suggests that the log transformation of the CPUE and chosen distribution (Gaussian with identity link) in the model are satisfactory.

Despite the selection of a model with fewer covariates (Mod 2), the resulting standardized CPUE series of Mod 0, Mod 1 and Mod 2 are extremely similar (the difference cannot barely be seen on Figure 6 and Figure 7). Compared to the nominal CPUE series, the retained standardized CPUE series is smoother but still shows variations over time.

Acknowledging the relatively low coverage rate (< 3%) in number of hooks observed in the first years of implementation of the observation programs (Figure 1) we should consider discarding the early part of the standardized time series before 2011. Moreover, a standardization model (using Mod 2 selected covariates) fitted to the 2011-2024 period showed extremely similar standardized CPUE values than those of Mod 1 (not shown).

The standardized CPUE series exhibits a relatively steady decrease throughout 2011-2024 with a rate of 5% per year, going from approximately 2.5 to 1.7 over this fourteen-year period. However, we can also consider that there is a more pronounced decrease between 2011 and 2019 with a rate about 10% per year, followed by a period of relative stability between 2019 and 2024.

5. Conclusion

According to the assessment of the retained standardization model, we believe that the updated standardized CPUE time series presented in this paper for blue sharks bycaught by the French pelagic longline fishery of the south-west Indian Ocean is reliable between 2011 and 2024 and can be used for stock assessment. Over this period, the standardized CPUE exhibits an overall slight decreasing trend, more precisely a decreasing trend between 2011 and 2019 and a stabilization since 2019.

6. Acknowledgments

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

7. References

Auger, L., Trombetta, T., Sabarros, P.S., Rabearisoa, N., Romanov, E.V., Bach, P., 2015. Optimal fishing time window: an approach to mitigate bycatch in longline fisheries, IOTC–2015–WPEB13–15. 11th Session of the IOTC Working Party on Ecosystems and Bycatch, Olhão, Portugal.

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.

Kuznetsova, A., Brockhoff, P.B., Haubo Bojesen Christensen, R., Pødenphant Jensen, S., 2020. lmerTest: Tests in Linear Mixed Effects Models. R package.

Lenth, R., 2018. lsmeans: Least-Squares Means. R package.

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

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 Sabastián, 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., Romanov, E., Le Foulgoc, L., Richard, E., Lamoureux, J.P., Bach, P., 2013. Commercial catch and discards of pelagic longline fishery of Reunion Island based on the self-reporting data collection program, IOTC-2013-WPEB09-37. 9th IOTC Working Party on Ecosystems and Bycatch, La Réunion, France.

Selles, J., Sabarros, P.S., Romanov, E., Dagorne, D., Le Foulgoc, L., Bach, P., 2014. Characterisation of blue shark (*Prionace glauca*) hotspots in the South-West Indian Ocean, IOTC-2014-WPEB10-23. 10th IOTC Working Party on Ecosystem and Bycatch, Yokohama, Japan.

8. Tables

Table 1. Deviance table (Type III ANOVA with Satterthwaite's method) of the covariates in lognormal GLMM Mod 0 (full model), Mod 1 (continuity model), and Mod 2 (retained model). For each covariate, we indicate the degrees of freedom (Df), the sum of squares (Sum Sq), the mean squares (Mean Sq), the F test statistic (F value) and the significance (P value).

Models	Covariates	Df	Sum Sq	Mean Sq	F value	P value
Mod 0 (full model) Lognormal GLMM Random effect: *vessel* N = 5211 R2c = 0.3245 AIC = 9724	as.factor(*year*)	17	36.72	2.16	6.1	<0.001
	quarter	3	19.39	6.46	18.25	<0.001
	region	1	5.3	5.3	14.98	<0.001
	latitude	1	58.71	58.71	165.86	<0.001
	soaking_time	1	0.52	0.52	3.29	0.226
	setting_start_time	1	0	0	0.01	0.928
	hauling_end_time	1	2.59	2.59	7.31	0.007
	hooks_per_basket	1	7.38	7.38	20.86	<0.001
	percentage_circle_hooks	1	0.21	0.21	0.59	0.442
	percentage_squid_bait	1	0.58	0.58	1.63	0.202
	quarter:region	3	4.84	1.61	4.56	0.003
Mod 1 (continuity model) Lognormal GLMM Random effect: *vessel* N = 5211 R2c = 0.3122 AIC = 9712	as.factor(*year*)	17	36.21	2.13	6.01	<0.001
	quarter	3	19.97	6.66	18.77	<0.001
	region	1	4.72	4.72	13.32	<0.001
	latitude	1	60.25	60.25	169.91	<0.001
	soaking_time	1	4.77	4.77	13.46	<0.001
	hooks_per_basket	1	7.83	7.83	22.07	<0.001
	percentage_circle_hooks	1	0.21	0.21	0.58	0.446
	percentage_squid_bait	1	0.59	0.59	1.67	0.196
	quarter:region	3	4.61	1.54	4.33	0.005
Mod 2 (retained model) Lognormal GLMM Random effect: *vessel* N = 5211 R2c = 0.3242 AIC = 9675	as.factor(*year*)	17	36.41	2.14	6.05	<0.001
	quarter	3	19.61	6.54	18.47	<0.001
	region	1	5.44	5.44	15.36	<0.001
	latitude	1	58.67	58.67	165.73	<0.001
	hauling_end_time	1	7.08	7.08	20.01	<0.001
	hooks_per_basket	1	7.76	7.76	21.93	<0.001
	quarter:region	3	4.88	1.63	4.6	0.003

Table 2. Summary table of the retained lognormal GLMM (Mod 2).

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: logcpue ~ as.factor(year) + quarter + region + quarter:region +
    latitude + hauling_end_time + branchlines_per_basket_count +      (1 | vessel)
   Data: catch.bsh

REML criterion at convergence: 9615.6

Scaled residuals:
    Min      1Q  Median      3Q     Max
-4.2253 -0.6235  0.0738  0.6786  3.7294

Random effects:
 Groups   Name        Variance Std.Dev.
 vessel   (Intercept) 0.1247   0.3531
 Residual             0.3540   0.5950
Number of obs: 5211, groups:  vessel, 44

Fixed effects:
                              Estimate  Std. Error  df          t value Pr(>|t|)
(Intercept)                  -5.756e-01  1.887e-01  1.679e+03  -3.050  0.00233 **
as.factor(year)2008          -1.156e-01  1.913e-01  5.039e+03  -0.604  0.54561
as.factor(year)2009          -3.208e-01  2.015e-01  6.847e+02  -1.592  0.11179
as.factor(year)2010          -1.937e-03  1.899e-01  1.096e+03  -0.010  0.99186
as.factor(year)2011           1.855e-02  1.319e-01  4.145e+03   0.141  0.88815
as.factor(year)2012           1.338e-01  1.256e-01  4.130e+03   1.065  0.28712
as.factor(year)2013          -6.777e-02  1.263e-01  4.047e+03  -0.536  0.59167
as.factor(year)2014          -9.269e-02  1.277e-01  4.083e+03  -0.726  0.46811
as.factor(year)2015          -2.941e-02  1.273e-01  4.087e+03  -0.231  0.81725
as.factor(year)2016           5.503e-02  1.283e-01  4.141e+03   0.429  0.66800
as.factor(year)2017          -1.131e-01  1.277e-01  4.143e+03  -0.885  0.37611
as.factor(year)2018          -2.240e-01  1.299e-01  4.226e+03  -1.725  0.08459 .
as.factor(year)2019          -2.051e-01  1.287e-01  4.145e+03  -1.593  0.11116
as.factor(year)2020          -1.873e-01  1.284e-01  4.172e+03  -1.459  0.14452
as.factor(year)2021          -2.683e-02  1.269e-01  4.115e+03  -0.211  0.83260
as.factor(year)2022          -1.937e-01  1.273e-01  4.153e+03  -1.521  0.12833
as.factor(year)2023          -1.620e-01  1.248e-01  4.152e+03  -1.298  0.19445
as.factor(year)2024          -1.465e-01  1.246e-01  4.160e+03  -1.176  0.23986
quarterQ2                    -2.805e-02  3.111e-02  5.181e+03  -0.902  0.36733
quarterQ3                     8.163e-03  3.479e-02  5.178e+03   0.235  0.81453
quarterQ4                     1.668e-01  2.958e-02  5.183e+03   5.637 1.82e-08 ***
regionWSWIO                  -2.491e-02  4.629e-02  5.182e+03  -0.538  0.59057
latitude                     -7.502e-02  5.828e-03  5.082e+03 -12.873  < 2e-16 ***
hauling_end_time              2.217e-02  4.956e-03  5.154e+03   4.473 7.88e-06 ***
branchlines_per_basket_count -2.019e-02  4.312e-03  5.069e+03  -4.683 2.90e-06 ***
quarterQ2:regionWSWIO        -2.129e-02  5.558e-02  5.166e+03  -0.383  0.70177
quarterQ3:regionWSWIO        -1.787e-01  5.649e-02  5.167e+03  -3.162  0.00157 **
quarterQ4:regionWSWIO        -9.016e-02  6.166e-02  5.159e+03  -1.462  0.14373
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Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Table 3. Standardized CPUE (stdCPUE) time series for blue shark caught in the French longline fishery for the period 2007-2020. nCPUE designates the nominal CPUE. The stdCPUE is provided with 95% confidence interval (CI).

Year	nCPUE	stdCPUE	Lower CI	Upper CI
2007	2.14	**2.20**	1.46	3.16
2008	1.86	**1.85**	1.07	2.92
2009	2.47	**1.32**	0.68	2.21
2010	4.87	**2.19**	1.38	3.28
2011	2.86	**2.26**	1.81	2.79
2012	3.36	**2.66**	2.21	3.17
2013	2.67	**1.99**	1.63	2.40
2014	2.45	**1.92**	1.56	2.33
2015	2.49	**2.11**	1.73	2.54
2016	3.14	**2.38**	1.96	2.86
2017	2.38	**1.86**	1.50	2.27
2018	2.09	**1.56**	1.22	1.95
2019	2.25	**1.61**	1.27	2.00
2020	2.00	**1.65**	1.31	2.05
2021	2.78	**2.12**	1.73	2.56
2022	2.18	**1.64**	1.30	2.03
2023	2.66	**1.72**	1.38	2.11
2024	2.23	**1.76**	1.42	2.15

9. Figures

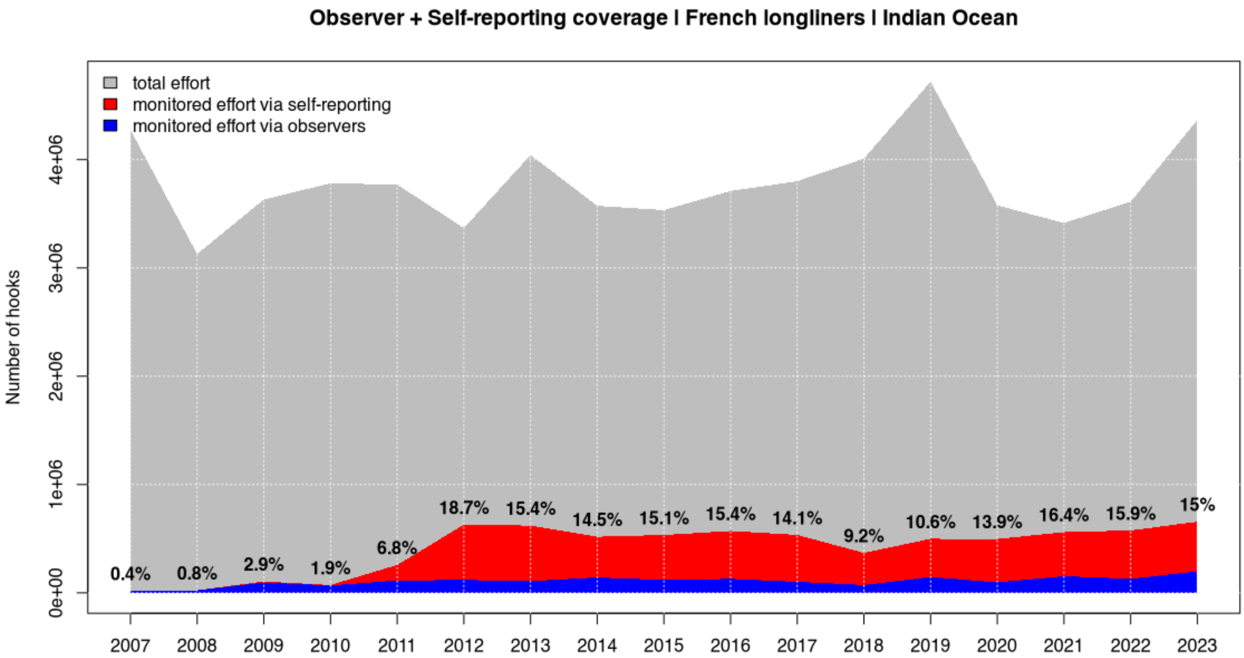

Figure 1. Observer and self-reporting effort coverage in number of hooks deployed in the French longline fishery operating in the south-west Indian Ocean between 2007 and 2023.

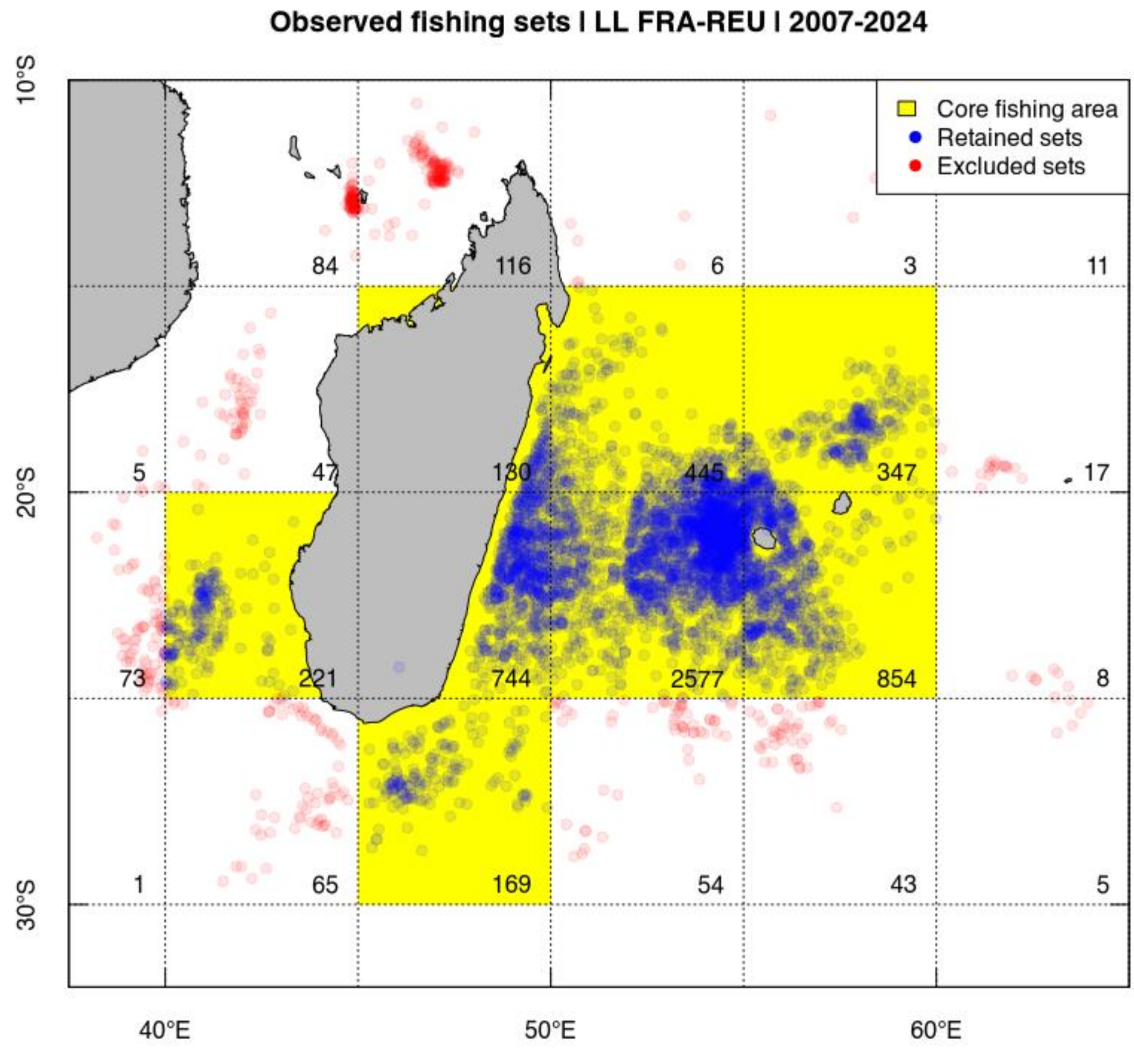

Figure 2. Distribution of fishing sets (hauling start position) between 2007 and 2024. The yellow area represents the core fishing area with retained sets in blue. Excluded sets are shown in red. Numbers in the corners of 5°x5° squares are the number of sets.

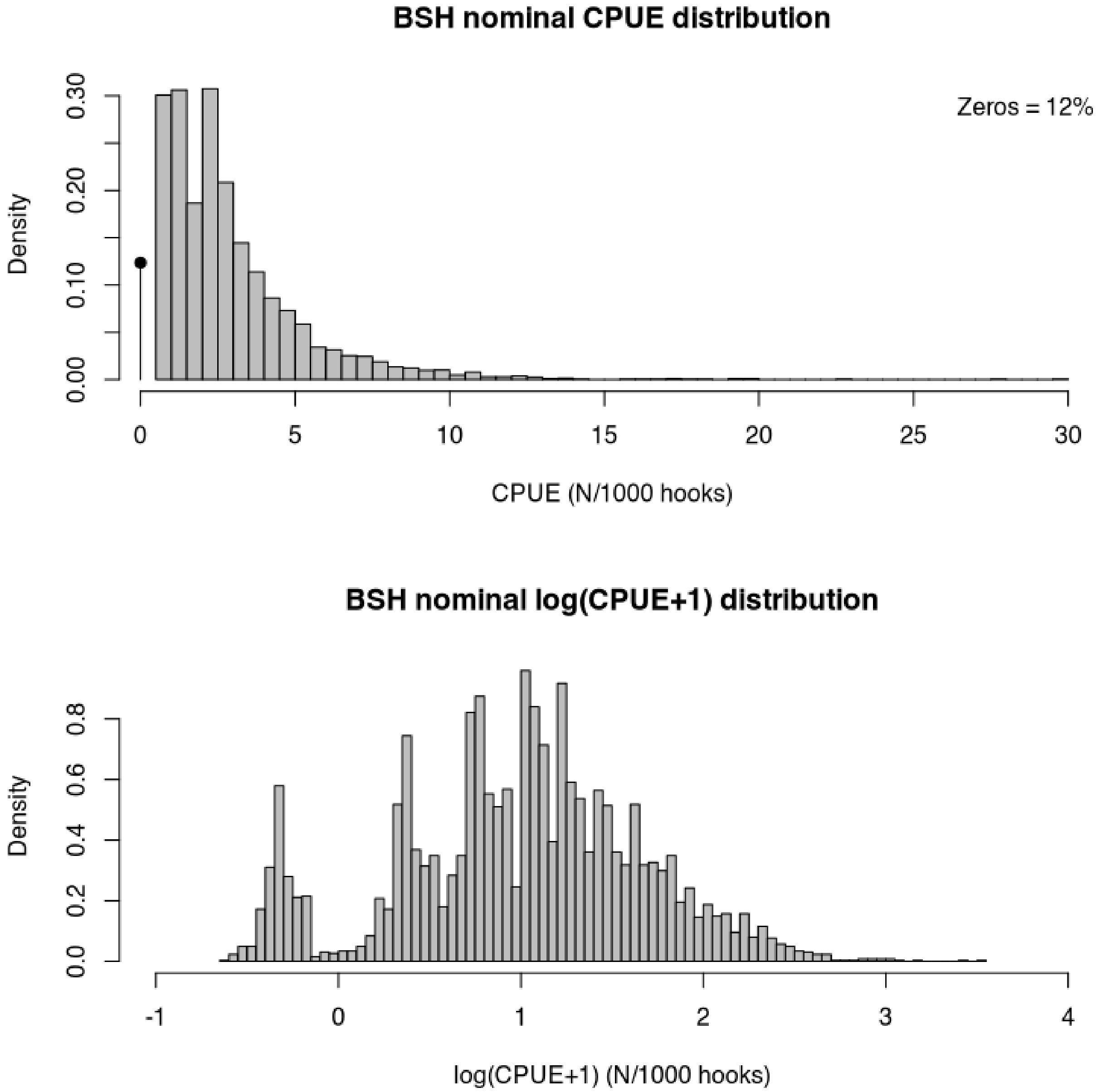

Figure 3. Blue shark nominal CPUE (N/1000 hooks; top panel) and log(CPUE+1) (bottom panel) distributions.

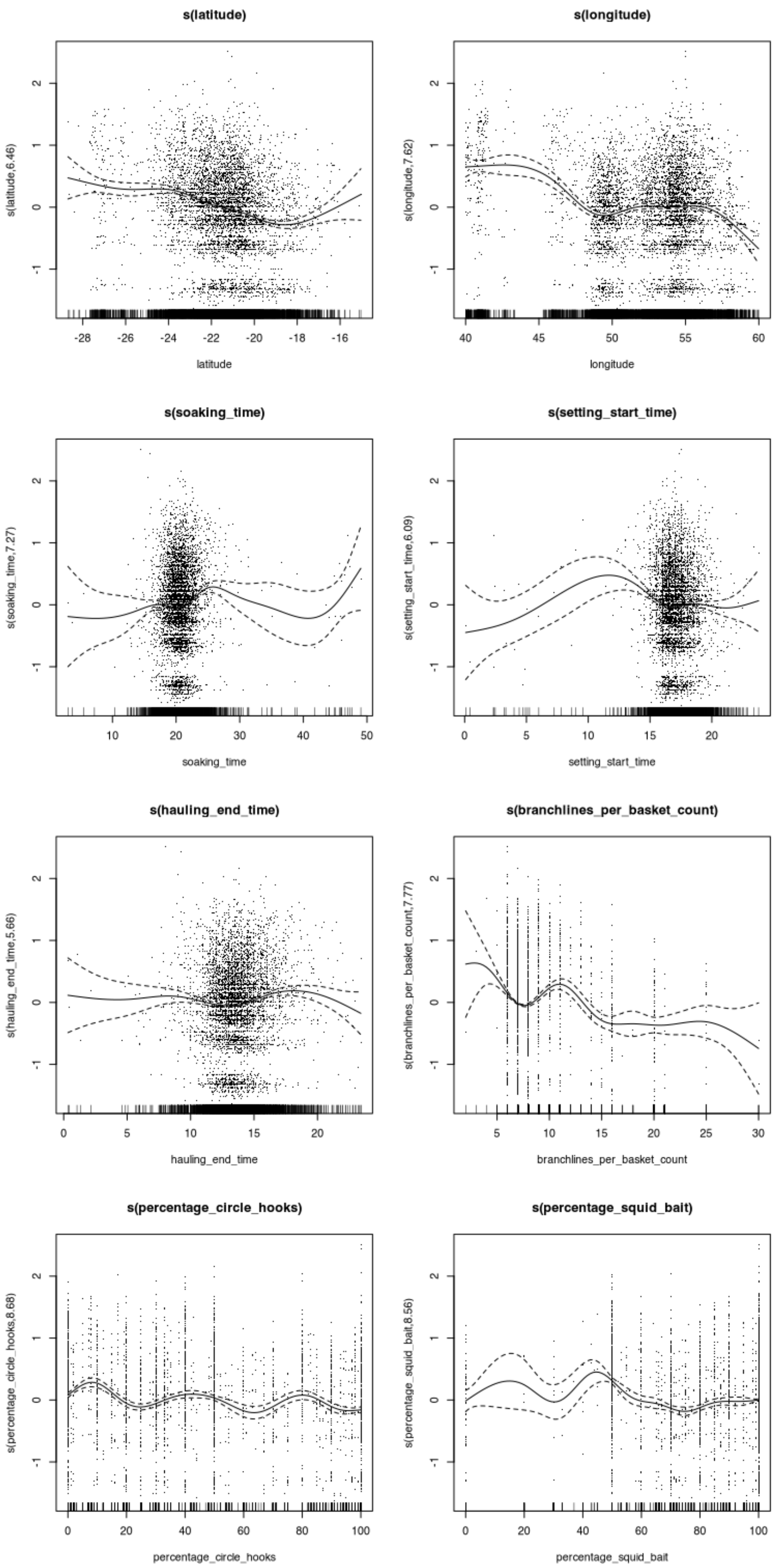

Figure 4. Individual univariate GAMs for each continuous covariates used to explain log(CPUE+1).

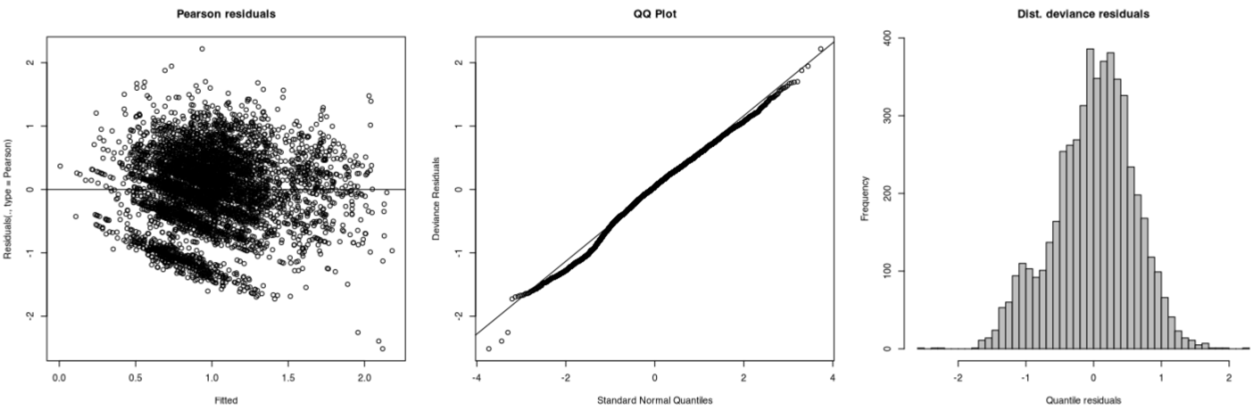

Figure 5. Residual analysis of lognormal GLMM Mod 2 selected for blue shark CPUE standardization including the covariates selected by the backward-stepwise model selection.

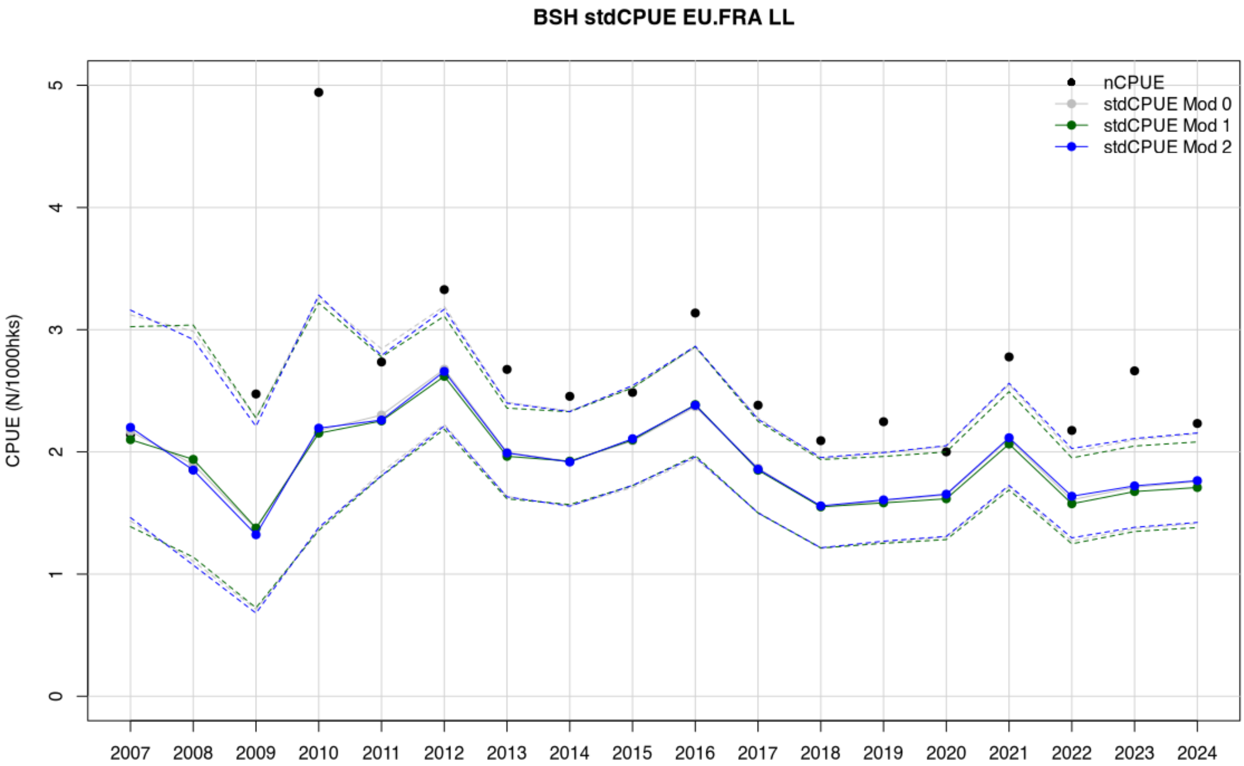

Figure 6. Nominal and standardized CPUE (N/1000 hooks) time series for Mod 0, Mod 1 and Mod 2 for the French longline fishery based in Reunion Island (EU.FRA LL) for the period 2007-2024.

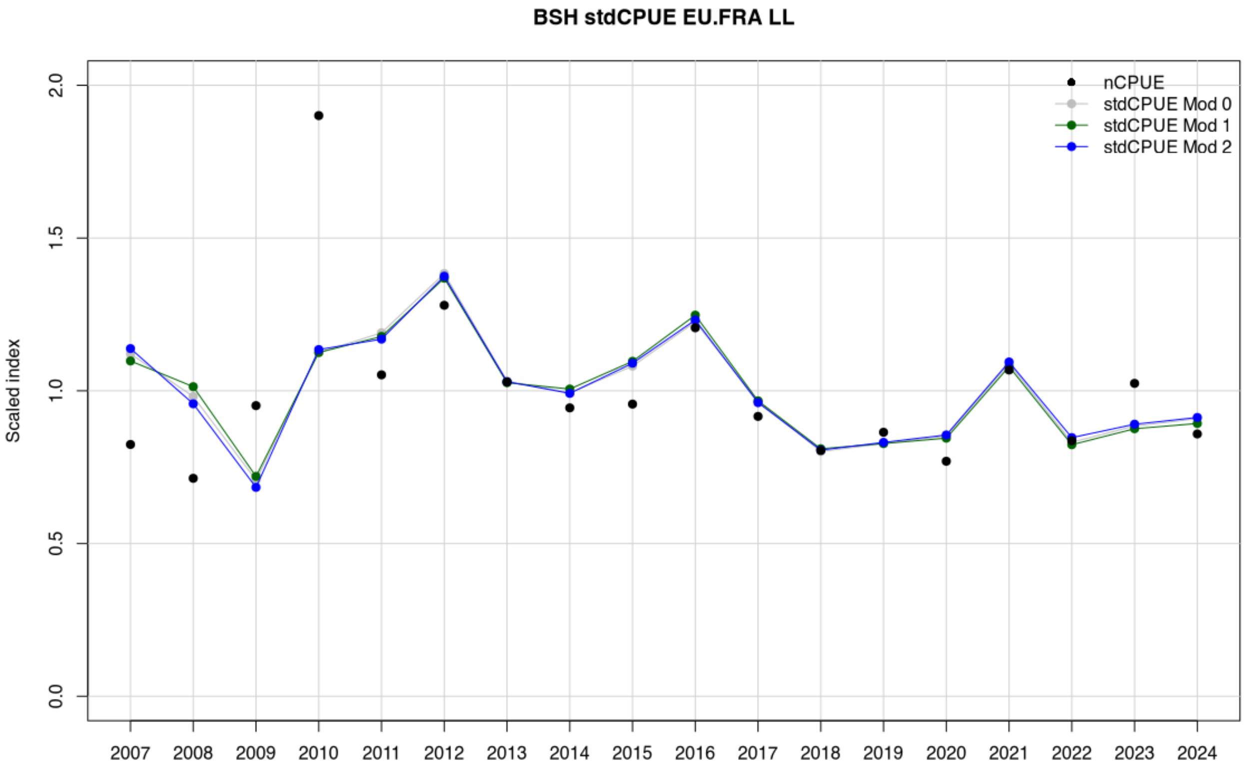

Figure 7. Scaled (by the mean) nominal and standardized CPUE time series of Mod 0, Mod 1 and Mod 2 for the French longline fishery based in Reunion Island (EU.FRA LL) for the period 2007-2024.