Updated standardized CPUE of blue shark bycaught by the French Reunion-based pelagic longline fishery (2007-2020)

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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 2020, we propose a standardized CPUE series for blue shark for 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 2020 where the monitoring effort has been consequent in comparison with previous years. Throughout 2011-2020, the standardized CPUE for the blue shark shows a significant decreasing trend.

Keywords

Blue shark | CPUE standardization | Longline | Western Indian Ocean

1. Introduction

Primary indices of abundance of target species (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 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 37% of the bycatch in number of individuals caught (Sabarros et al., 2013).

In 2017 we presented an index of abundance for the blue shark (standardized CPUE) for the period 2007-2016 (Sabarros et al., 2017). We provide now 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 2007-2020.

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 (2009-2020; Reg 199/2008 and 665/2008). The coverage in number of hooks monitored is presented in Figure 1. We retained a total of 3602 fishing operations monitored between 2007 and 2020 from the core fishing area that consists of 5°x5° squares with more than 100 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). 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 2020
  - *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).
  - *soakingtime* (continuous): time in hours from when the first hook is deployed to when the last hook retrieved.
  - *settingstarttime* (continuous): time (hh:mm) when the first buoy is deployed.
  - *haulingendtime* (continuous): time (hh:mm) when the last buoy is retrieved.
  - *hooksperbasket* (continuous): number of hooks per basket as a relative index of fishing depth range/targeting.
  - *percentagecirclehooks* (continuous): relative proportion of circle hooks to other types of hooks (J-hooks, tuna hooks, Teracima hooks).
  - *percentagesquidbait* (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* + *soakingtime* + *settingstarttime* + *haulingandtime* + *hooksperbasket* + *percentagecirclehooks* + *percentagesquidbait* + (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. 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).

3. Results

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

Mod 1: *year* + *quarter* + *region* + *quarter:region* + *latitude* + *soakingtime* + *hooksperbasket* + *percentagecirclehooks* + (1 | *vessel*)

The blue shark standardized CPUE series obtained using Mod 0 et Mod 1 are extremely similar (Figure 6).

According to the ANOVA table of the retained model (Mod 1; Table 2), all covariates have significant effects. Weights (sum of squares) show that *latitude* (28.72) and *year* (27.88) have a larger influence, followed by *quarter* (9.75) and *region* (8.08), and then the rest of the covariates (2.35-4.56).

Overall, the retained standardized CPUE (Mod 1) follows the nominal CPUE except for the first years (2007-2010) and 2019. Throughout 2011-2020, the trend is decreasing and the significance of the slope was checked using a linear model (b = -0.11, p-value < 0.01).

4. Discussion

Significant effects on blue shark CPUE

The year, quarter, region (west and east of 52°E, roughly corresponding to the EEZ of 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 the Malagasy EEZ in the second quarter and mostly the third for vessels above 12 meters (length overall) that can reach that far, 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.

The overall soaking time has a positive effect on 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.

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.

The percentage of circle hooks tends to slightly increase blue shark observable captures as demonstrated in the Australian (Ward et al., 2009) and Taiwanese longline fisheries (Huang et al., 2015).

The percentage of squid bait tends to have a slight positive effect of blue shark catch rates contrastingly to the general pattern found in the literature where mackerel-baited hooks catch more blue sharks than squid-baited hooks (e.g. Fernandez-Carvalho et al., 2015).

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 Mozambique Channel and faraway international waters 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 1; 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 1), the resulting standardized CPUE series of Mod 0 and Mod 1 are extremely similar (the difference cannot 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 1 selected covariates) fitted to the 2011-2020 period showed extremely similar standardized CPUE values than those of Mod 1 (not shown).

The standardized CPUE series exhibits is relatively steady decrease throughout 2011-2020 with a rate of 11% per year, going from approximately 2.5 to 1.5 over this ten-year period.

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 and can be used for stock assessment, at least for the 2011-2020 period.

6. Acknowledgments

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

7. References

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8. Tables

Table 1. Deviance table (Type III ANOVA with Satterthwaite's method) of the covariates in lognormal GLMM Mod 0 (full model) and Mod 1 (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 = 3602 R2c = 0.3365 AIC = 6744	as.factor(*year*)	13	27.82	2.14	6.11	<0.001
	quarter	3	9.63	3.21	9.16	<0.001
	region	1	8.1	8.1	23.13	<0.001
	latitude	1	28.53	28.53	81.43	<0.001
	soakingtime	1	1.15	1.15	3.29	0.07
	settingstarttime	1	0.03	0.03	0.07	0.788
	haulingendtime	1	0.01	0.01	0.04	0.851
	hooksperbasket	1	4.39	4.39	12.52	<0.001
	percentagecirclehooks	1	4.38	4.38	12.5	<0.001
	percentagesquidbait	1	3.51	3.51	10.03	0.002
	quarter:region	3	4.39	1.46	4.18	0.006
Mod 1 (retained model) Lognormal GLMM Random effect: *vessel* N = 3602 R2c = 0.3342 AIC = 6725	as.factor(*year*)	13	27.88	2.14	6.12	<0.001
	quarter	3	9.75	3.25	9.28	<0.001
	region	1	8.08	8.08	23.06	<0.001
	latitude	1	28.72	28.72	81.99	<0.001
	soakingtime	1	2.35	2.35	6.7	0.01
	hooksperbasket	1	4.56	4.56	13.01	<0.001
	percentagecirclehooks	1	4.36	4.36	12.45	<0.001
	percentagesquidbait	1	3.51	3.51	10.01	0.002
	quarter:region	3	4.37	1.46	4.16	0.006

Table 2. Summary table of the retained lognormal GLMM (Mod 1).

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

REML criterion at convergence: 6669.2

Scaled residuals:
    Min      1Q  Median      3Q     Max
-2.9776 -0.6073  0.0860  0.6753  3.6383

Random effects:
 Groups   Name        Variance Std.Dev.
 vessel   (Intercept) 0.1302   0.3609
 Residual             0.3503   0.5918
Number of obs: 3602, groups:  vessel, 40

Fixed effects:
                        Estimate  Std. Error        df  t value  Pr(>|t|)
(Intercept)           -4.082e-01  2.458e-01  9.135e+02  -1.660 0.097164 .
as.factor(year)2008   -2.453e-01  2.181e-01  1.392e+03  -1.125 0.260958
as.factor(year)2009   -3.743e-01  2.303e-01  3.734e+02  -1.625 0.104922
as.factor(year)2010   -2.919e-02  2.215e-01  4.552e+02  -0.132 0.895220
as.factor(year)2011   -4.227e-02  1.745e-01  5.267e+02  -0.242 0.808642
as.factor(year)2012    1.351e-02  1.674e-01  4.851e+02   0.081 0.935729
as.factor(year)2013   -1.673e-01  1.682e-01  4.762e+02  -0.995 0.320337
as.factor(year)2014   -1.852e-01  1.690e-01  4.847e+02  -1.096 0.273826
as.factor(year)2015   -1.754e-01  1.685e-01  4.780e+02  -1.041 0.298453
as.factor(year)2016   -5.241e-02  1.695e-01  4.931e+02  -0.309 0.757259
as.factor(year)2017   -2.224e-01  1.693e-01  4.965e+02  -1.314 0.189570
as.factor(year)2018   -2.871e-01  1.715e-01  5.128e+02  -1.675 0.094611 .
as.factor(year)2019   -3.944e-01  1.709e-01  5.128e+02  -2.308 0.021388 *
as.factor(year)2020   -3.349e-01  1.702e-01  5.087e+02  -1.968 0.049605 *
quarterQ2             -4.000e-02  4.998e-02  3.557e+03  -0.800 0.423580
quarterQ3             -1.328e-01  4.872e-02  3.553e+03  -2.725 0.006466 **
quarterQ4              9.825e-02  6.647e-02  3.550e+03   1.478 0.139422
regionREU              7.619e-02  5.232e-02  3.573e+03   1.456 0.145426
latitude              -6.133e-02  6.773e-03  3.468e+03  -9.055  < 2e-16 ***
soakingtime            1.104e-02  4.265e-03  3.566e+03   2.589 0.009663 **
hooksperbasket        -2.008e-02  5.567e-03  3.563e+03  -3.607 0.000314 ***
percentagecirclehook   1.721e-03  4.877e-04  2.860e+03   3.529 0.000424 ***
percentagesquidbait    1.943e-03  6.140e-04  3.480e+03   3.165 0.001566 **
quarterQ2:regionRE    -9.517e-03  6.674e-02  3.575e+03  -0.143 0.886614
quarterQ3:regionREU    1.818e-01  6.614e-02  3.567e+03   2.749 0.006015 **
quarterQ4:regionREU    6.345e-02  7.577e-02  3.566e+03   0.837 0.402412
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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	**2.56**	1.54	3.99
2008	1.86	**1.79**	1.01	2.86
2009	2.47	**1.45**	0.76	2.41
2010	4.87	**2.46**	1.56	3.68
2011	2.86	**2.42**	1.91	3.01
2012	3.36	**2.61**	2.14	3.15
2013	2.67	**2.01**	1.63	2.45
2014	2.45	**1.96**	1.57	2.41
2015	2.50	**1.99**	1.60	2.44
2016	3.00	**2.38**	1.93	2.90
2017	2.38	**1.85**	1.47	2.29
2018	1.97	**1.67**	1.29	2.12
2019	2.01	**1.40**	1.06	1.80
2020	1.92	**1.55**	1.19	1.96

9. Figures

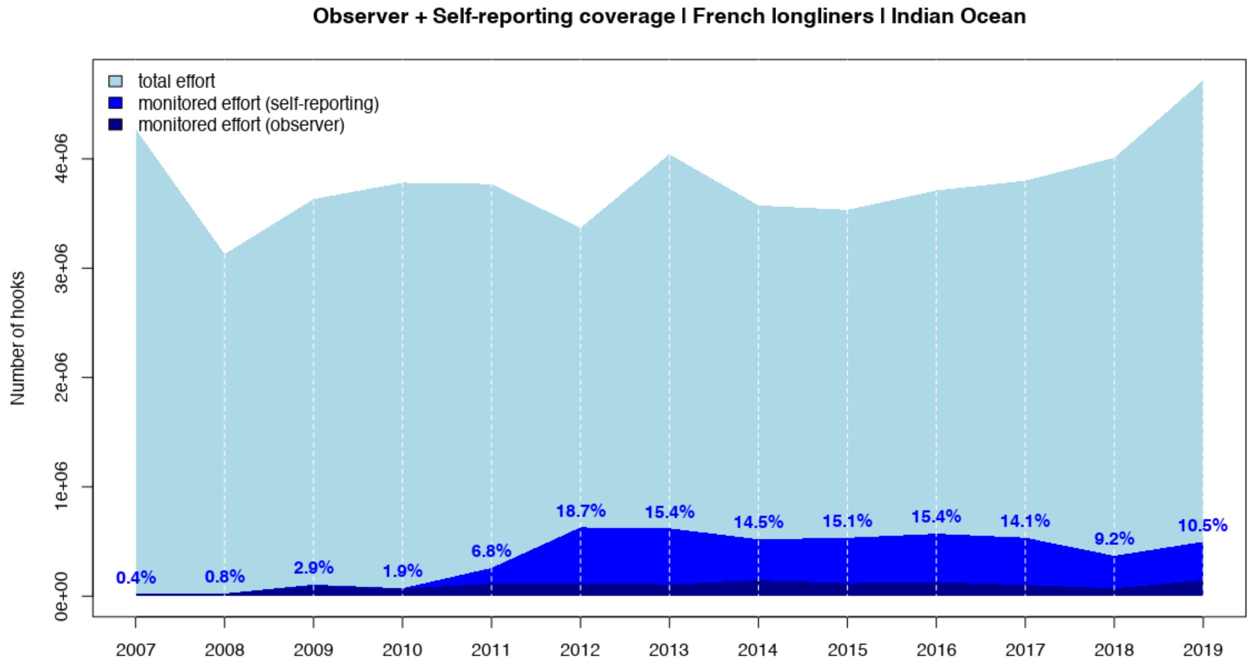

Figure 1. Observer and self-reporting effort coverage in number of hooks deployed in the French longline fishery operating in the south-west Indian Ocean between 2007 and 2019.

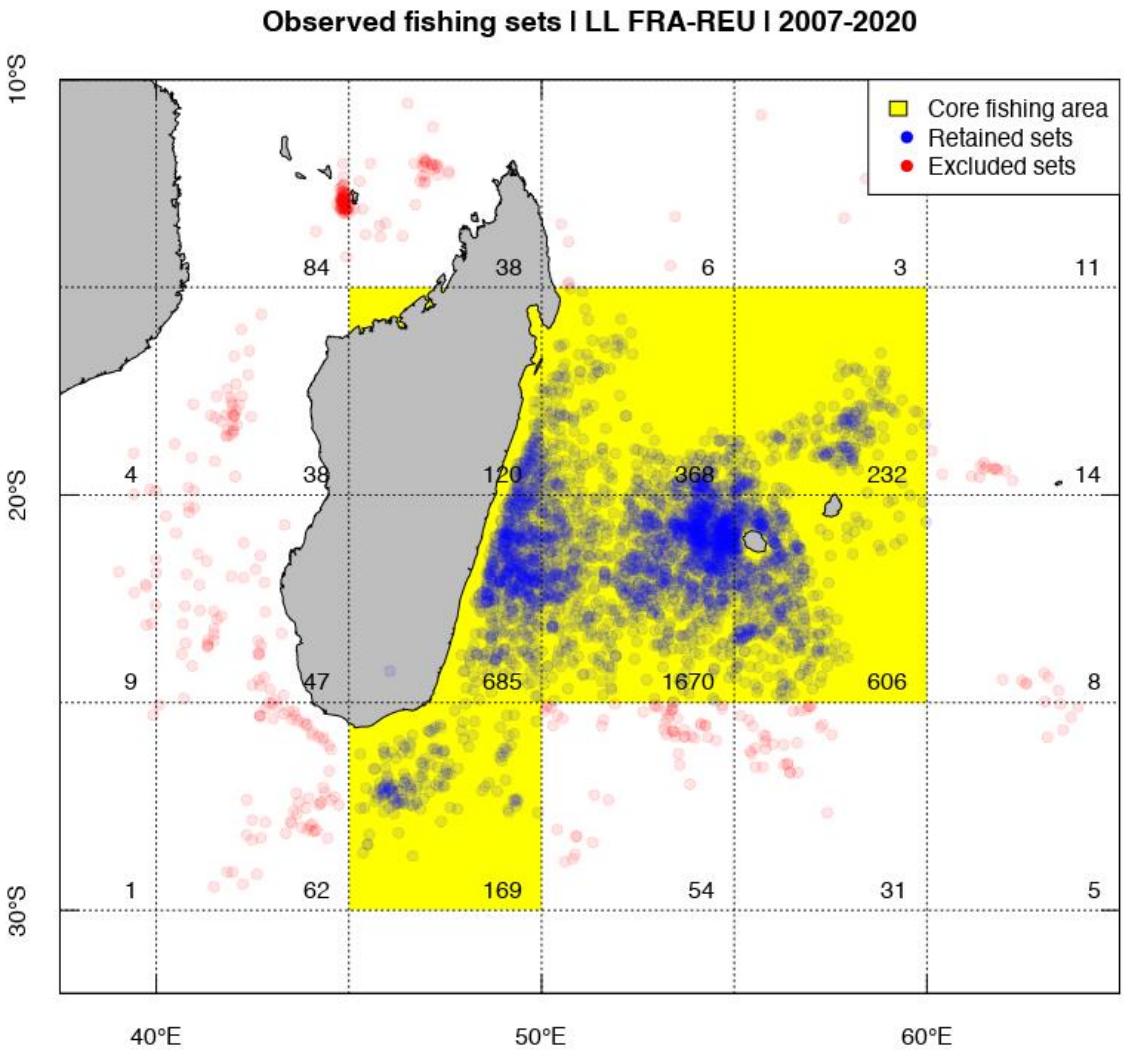

Figure 2. Distribution of fishing sets (hauling start position) between 2007 and 2020. The yellow area represents the core fishing area with retained sets in blue. Excluded sets are shown in red. Numbers in the corners of 5°x5° squares are the number of sets.

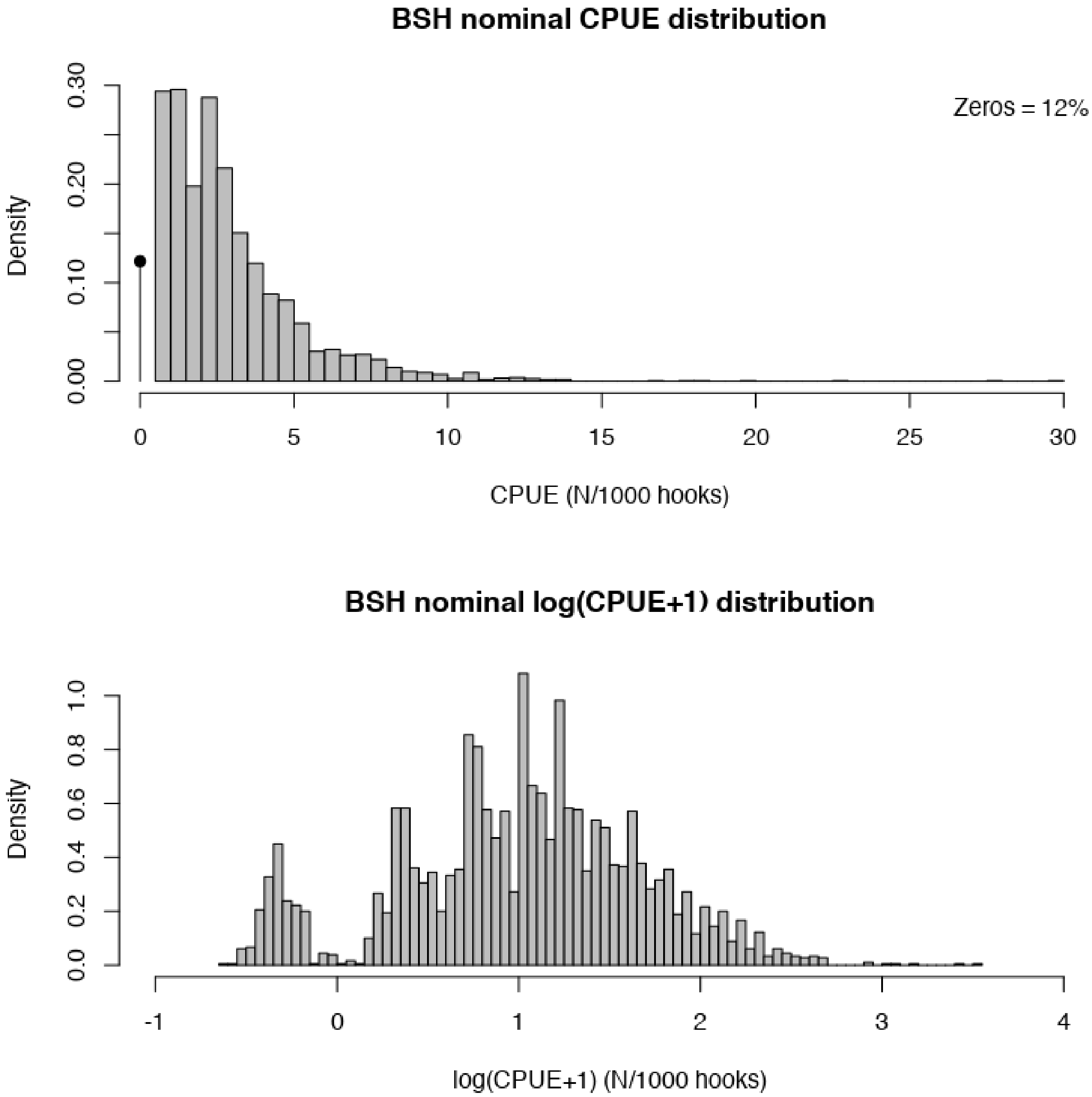

Figure 3. Blue shark nominal CPUE (N/1000 hooks; top panel) and log(CPUE+1) (bottom panel) distributions.

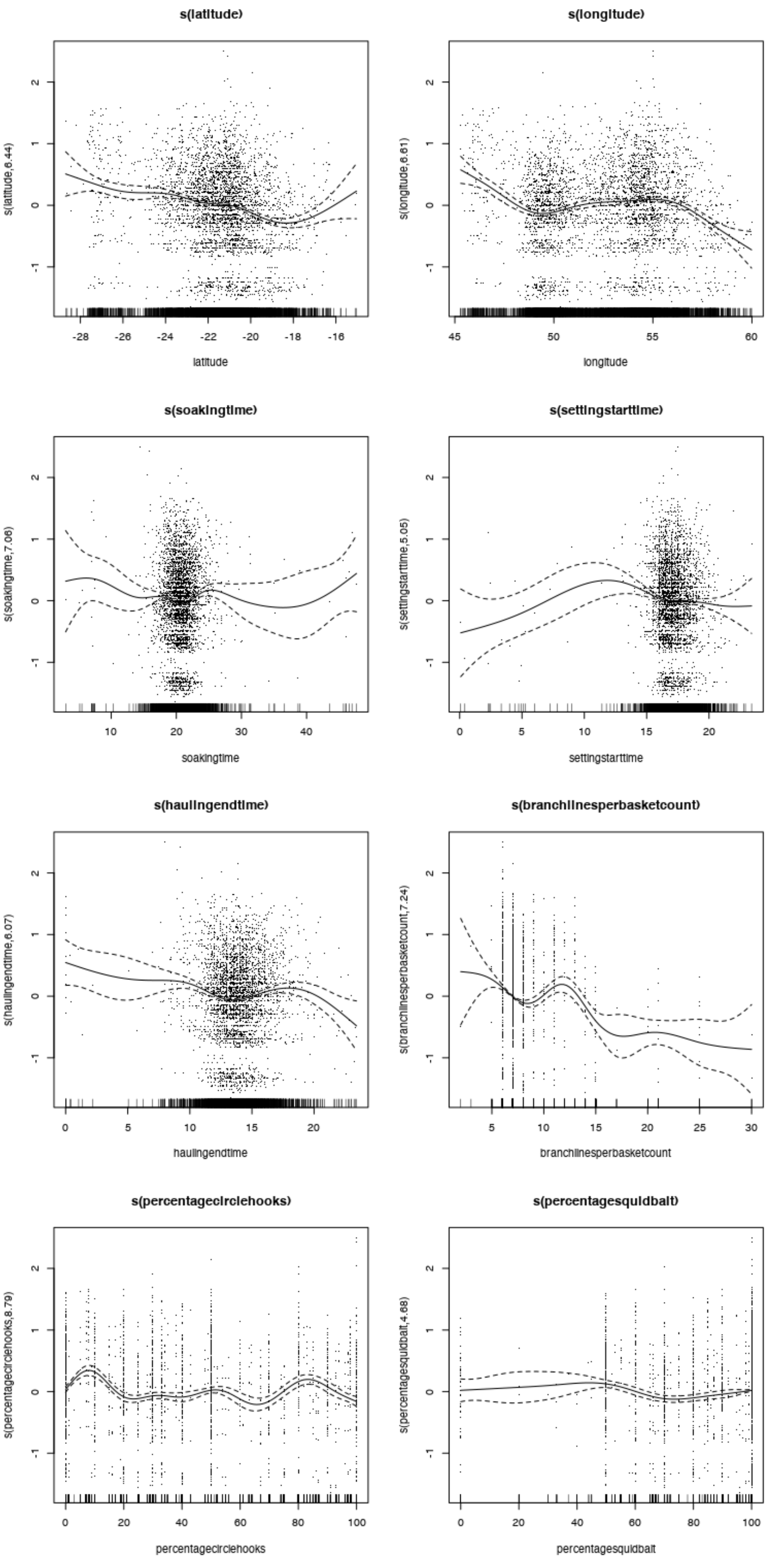

Figure 4. Individual univariate GAMs for each continuous covariates used to explain log(CPUE+1).

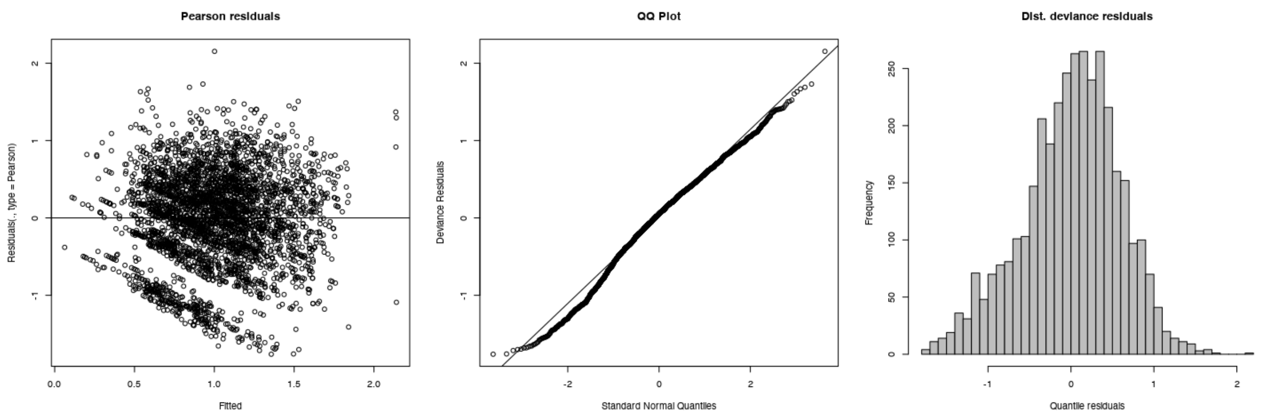

Figure 5. Residual analysis of lognormal GLMM Mod 1 selected for blue shark CPUE standardization including the covariates selected by the backward-stepwise model selection.

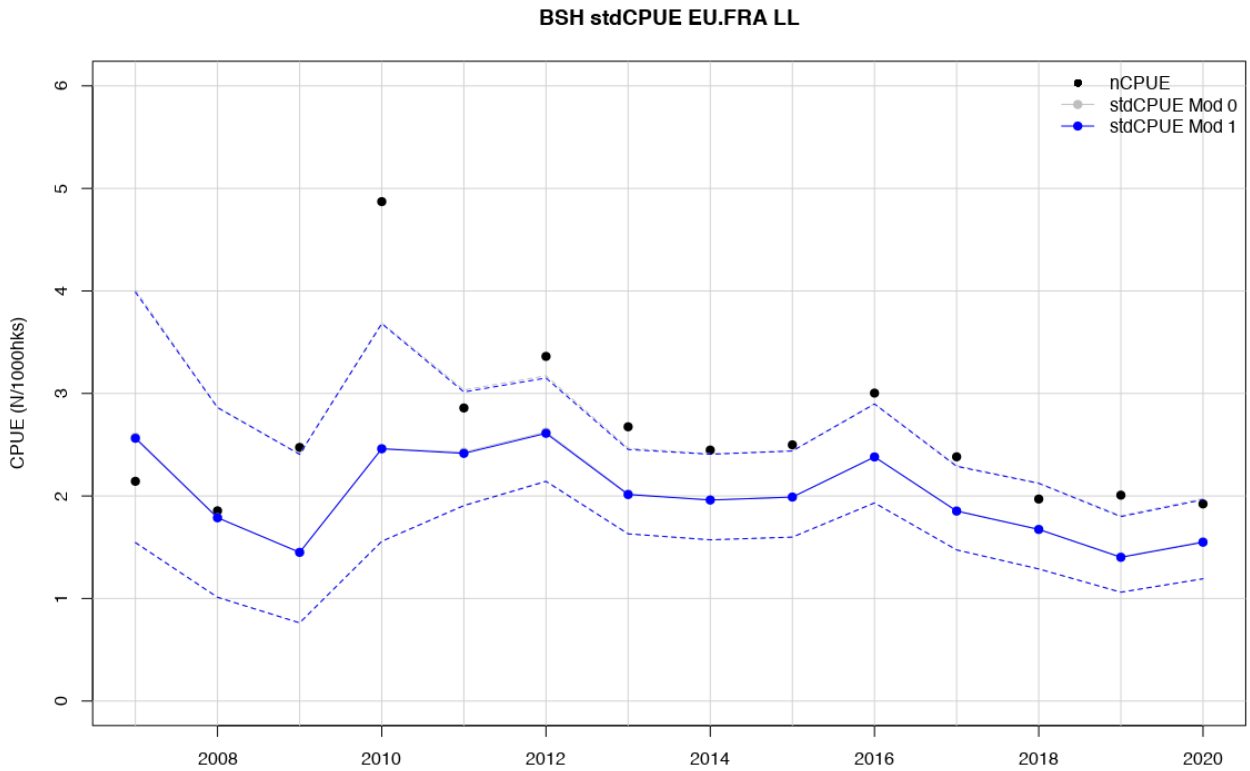

Figure 6. Nominal and standardized CPUE (N/1000 hooks) time series for Mod 0 and Mod 1 for the French longline fishery based in Reunion Island (EU.FRA LL) for the period 2007-2020.

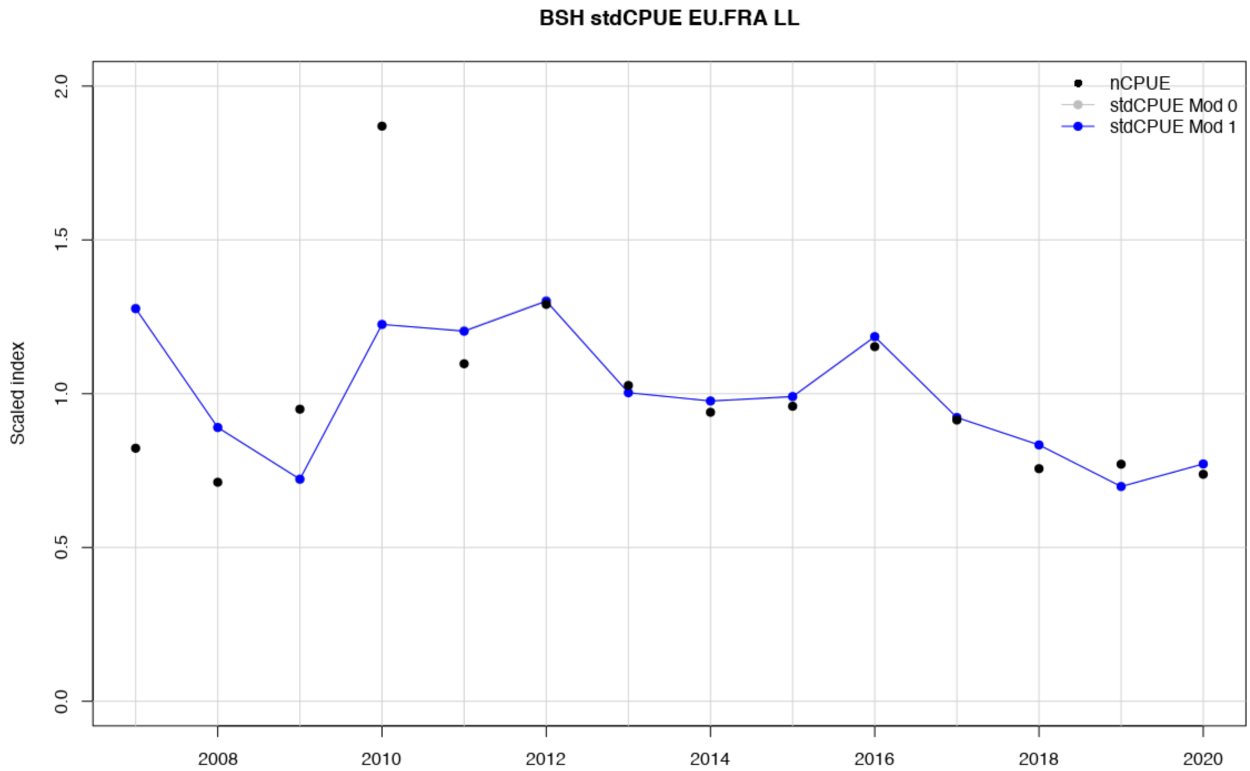

Figure 7. Scaled (by the mean) nominal and standardized CPUE time series of Mod 0 and Mod 1 for the French longline fishery based in Reunion Island (EU.FRA LL) for the period 2007-2020.