STANDARDIZED CATCH PER UNIT EFFORT OF SWORDFISH (*XIPHIAS GLADIUS*) FOR THE SOUTH AFRICAN LONGLINE FISHERY

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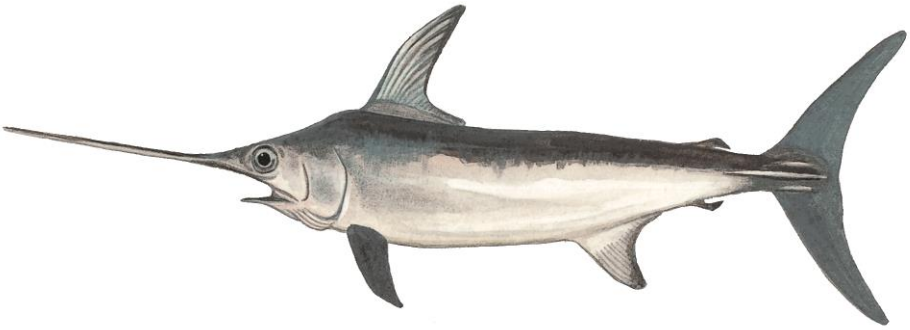

SUMMARY

Swordfish, *Xiphias gladius,* is a target species in the South African pelagic longline fleet operating along the west and east coast of South Africa. A standardization of the CPUE of the South African swordfish directed longline fleet for the time series 2004-2019 was carried out with a Generalized Additive Mixed Model (GAMM) with a Tweedie distributed error. Explanatory variables of the final model included *Year, Month,* geographic position (*Lat, Long*) and a targeting factor *(Fishing Tactic)* with two levels, derived by clustering of PCA scores of the root-root transformed, normalized catch composition. *Vessel* was included as a random effect. Swordfish CPUE had a definitive seasonal trend, with catch rates higher in winter (July - October) than the rest of the year. Standardized CPUE peaked in 2008 (530kg/1000 hooks) and was lowest in 2014 (262kg/1000 hooks). The results indicate that the swordfish catch rates in the South African pelagic longline fishery have recently stabilized after an initial period of decline during 2004 to 2012.

KEYWORDS

Swordfish, standardized cpue, longline, GAMM, targeting, PCA cluster, random effect

AFFILIATIONS

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INTRODUCTION

Commercial fishing for large pelagic species in South Africa dates back to the 1960s (Welsh, 1968; Nepgen, 1970). Exploitation of large pelagic species in South Africa can be divided into four sectors, 1) pelagic longline, 2) tuna pole-line 3) commercial linefishing (rod and reel) and 4) recreational line-fishing. Pelagic longline vessels are the only vessels that target swordfish, with negligible bycatch being caught in other fisheries. Pelagic longline fishing by South African vessels began in the 1960s with the main target being southern bluefin tuna (*Thunnus maccoyii*) and albacore (*Thunnus alalunga*) (Welsh, 1968; Nepgen, 1970). This South African fishery ceased to exist after the mid 1960's, as a result of a poor market for low quality southern bluefin and albacore (Welsh, 1968). However, foreign vessels, mainly from Japan and Chinese-Taipei, continued to fish in South African waters from the 1970s until 2002 under a series of bilateral agreements. Interest in pelagic longline fishing re-emerged in 1995 when a joint venture with a Japanese vessel confirmed that tuna and swordfish could be profitably exploited within South Africa's waters. Thirty experimental longline permits were subsequently issued in 1997 to target tuna, though substantial catches of swordfish were made during that period (Penney and Griffiths, 1999).

The commercial fishery was formalised in 2005 with the issuing of 10-year long term rights to swordfish- and tuna-directed vessels. The fishery is coastal and swordfish-oriented effort concentrates in the southwest Indian Ocean region (20°- 30°S, 30°- 40°E) and along the South African continental shelf in the southeast Atlantic (30°- 35°S, 15°- 18°E). As such, the fishery straddles two ocean basins, the Indian and Atlantic Ocean (Fig. 1). The jurisdictions of the Indian Ocean Tuna Commission (IOTC) and International Commission for the Conservation of Atlantic Tuna (ICCAT) are separated by a management boundary at 20°E. The South African caught swordfish originate from an Indian and an Atlantic ocean stock, with a broad admixture zone between 17°E and 30°E, hence the artificial split at 20°E in reporting stock indices requires further investigation. South Africa's overall swordfish catches reached a peak in 2002 at 1 187 t. However, within the IOTC area of competence (Longitude > 20 degrees), South Africa's swordfish catches peaked in 2011 at 488 t, and steadily declined to only 57 t in 2017.

Here, we present an update of the standardised catch-per-unit-effort (CPUE) time series for swordfish caught in the South African longline fishery. The methodology follows that first introduced by da Silva et al. (2017), and uses a generalised additive mixed model (GAMM) applied to catch and effort data from the South African pelagic longline fleet operating during the period 2004 - 2019. The GAMM was fitted using a Tweedie distribution and included *year, month, latitude, longitude, fishing tactic* (targeting) as fixed factors and *vessel* as random effect. Targeting was determined by clustering PCA scores of the root-root transformed, normalized catch composition.

MATERIALS AND METHODS

CATCH AND EFFORT DATA PREPARATION

Catch and effort data for the period 2004-2019 were extracted from the South African longline logbook database. Each record included the following information: (1) date, (2) unique vessel number, (3) catch position at a 1 x 1 degree latitude and longitude resolution and (4) mandatory catch reports in kilogram per set and (5) hooks per set. Data were subset to only include sets in which > 500 hooks were deployed, and only data from east of 29 degrees (Longitude > 29) was considered to exclude the area of admixture, where stock originating in the two ocean basins cannot be distinguished(West 2016). The final dataset contained 4 724 sets and 6 485 449 hooks.

MODEL FRAMEWORK

Swordfish CPUE was standardized using Generalized Additive Mixed Models (GAMMs), which included the covariates *year*, *month*, 1 x 1 degree latitude (*Lat*) and longitude (*Long*) coordinates and *vessel* as random effect. In an attempt to account for variation in fishing tactics, we considered an additional factor for targeting derived from a cluster analysis of the catch composition (He *et al.*, 1997; Carvalho *et al.*, 2010; Winker *et al.*, 2013). For the clustering analysis, all CPUE was modelled as catch in metric tons per species per vessel per day. All of the following analysis was conducted within the statistical environment R. The R package ‘cluster’ was used to perform the CLARA analysis, while all GAMMs were fitted using the ‘mgcv’ and ‘nlme’ libraries described in Wood (2006).

Clustering of the catch composition data was conducted by applying a non-hierarchical clustering technique known as CLARA (Struyf *et al.*, 1997) to the catch composition matrix. To obtain the input data matrix for CLARA, we transformed the $CPUE_{i,j}$ matrix of record *i* and species j into its Principal Components (PCs) using Principal Component Analysis (PCA). For this purpose, the data matrix comprising the $CPUE_{i,j}$ records for all reported species was extracted from the dataset. The CPUE records were normalized into relative proportions by weight to eliminate the influence of catch volume, fourth-root transformed and PCA-transformed. Subsequently, the identified cluster for each catch composition record was aligned with the original dataset and treated as categorical variable (FT) in the model (Winker *et al.*, 2013). To select the number of meaningful clusters we followed the PCA-based approach outlined and simulation-tested in Winker et al. (2014). This approach is based on the selection of non-trivial PCs through non-graphical solutions for Catell’s Scree test in association with the Kaiser-Guttman rule (Eigenvalue > 1), called Optimal Coordinate test, which available in the R package ‘nFactors’ (Raiche *et al.*, 2013). The optimal number of clusters considered is then taken as the number of retained PCs plus one (Winker *et al.*, 2014). The results suggest that only the first PC is non-trivial (Fig. 2) and correspondingly two clusters were selected as optimal for the CLARA clustering.

The CPUE records were fitted by assuming Tweedie distribution (Tascheri *et al.*, 2010; Winker *et al.*, 2014). The Tweedie distribution belongs to the family of exponential dispersion models and is characterized by a two-parameter power mean-variance function of the form $Var(Y) = \phi\mu p$, where ϕ is the dispersion parameter, μ is the mean and p is the power parameter (Dunn and Smyth, 2005). Here, we considered the case of 1 < p < 2, which represents the special case of a Poisson ($p = 1$) and gamma ($p = 2$) mixed distribution with an added mass at 0. This makes it possible to accommodate high frequencies of zeros in combination with right-skewed continuous numbers in a natural way when modelling CPUE data (Winker *et al.*, 2014; Ono *et al.*, 2015). As it is not possible to estimate the optimal power parameter p internally within GAMMs, p was optimized by iteratively maximizing the profile log-likelihood of the GAMM for 1 < p < 2 (Fig. 3). This resulted in a power parameter p = 1.3 with an associated dispersion parameter of ϕ = 5 for the full GAMM. The full GAMM expressed swordfish CPUE as:

$$CPUE = exp(\beta_0 + Year + s_1(Month) + s_2(Long, Lat) + FT + \alpha_V)$$

where $s_1()$ denotes cyclic cubic smoothing function for *Month*, $s_2()$ a thin plate smoothing function for the two-dimensional covariate of *Lat* and *Long*, *FT* is the vector of cluster numbers treated as categorical variable for *'Fishing Tactic'*, and α_v is the random effect for *Vessel v* (Helser *et al.*, 2004). The inclusion of individual vessels as random effects term provides an efficient way to combine CPUE recorded from various vessels (*n* = 17) into a single, continuous CPUE time series, despite discontinuity of individual vessels over the time series (Helser *et al.*, 2004). The main reason for treating vessel as a random effect was because of concerns that multiple CPUE records produced by the same vessel may violate the assumption of independence caused by variations in fishing power, skipper skills and behaviour, which can result in overestimated precision and significance levels of the predicted CPUE trends if not accounted for (Thorson and Minto, 2014). The significance of the random-effects structure of the GAMM was supported by both Akaike's Information Criterion (AIC) and the more conservative Bayesian Information Criterion (BIC). Sequential F-tests were used to determine the covariates that contributed significantly (*p* < 0.001) to the deviance explained.

Annual CPUE was standardized by fixing all covariates other than *Year* and *Lat* and *Long* to a vector of standardized values X_0. The choices made were that *Month* was fixed to July (*Month* = 7), representative of the high catch quarter and *FT* was fixed to the fishing tactic the produced highest average catch rates (FT = 1). The expected yearly mean $CPUE_y$ and standard-error of the expected $log(CPUE_y)$ for the vector of standardized covariates X_0 were then calculated as average across all *Lat-Long* combinations (here forth grid cells) *a*, such that:

$$E[CPUE_y(X_0^T\hat{\beta})] = \frac{1}{A}\sum_{a}^{A} e\,xp(\hat{\mu}_{y,a})$$

and

$$\hat{\sigma}_y(X_0^T\hat{\beta}) = \sqrt{\frac{1}{A}\sum_{a}^{A} \hat{\sigma}_{y,a}^2}$$

where $\hat{\mu}_{y,a}$ is the standardized, model-predicted $log(CPUE_{y,a})$ for *Year y* and *Lat* and *Long* for grid cell *a*, $\hat{\sigma}_{y,a}$ is the estimated model standard error associated with $log(CPUE_{y,a})$, *A* is the total number of grid cells and *T* denotes the matrix in which *X* is transposed.

RESULTS AND DISCUSSION

The analysis of deviance for the step-wise regression procedure showed that all of the covariates considered were highly significant ($p < 0.001$) and the inclusion of all considered fixed effects were supported by both the AIC and BIC (Table 1). Seasonality (*Month*) accounted for the majority of the deviance explained by the model (Table 1), followed by the inclusion of the effect of targeting other species (*Fishing tactic*), particularly tuna (Fig. 2). Swordfish CPUE was approximately halved when vessels were deemed not to be targeting this species (Fig. 6b). The inclusion of targeting, and the justifiable use of the Tweedie distribution (Figs. 3 & 5) have improved the model fit, however, further analyses could be considered. The amendment of the catch return forms to include the target per catch day, sea surface temperature, bait type, hooks between floats and soak time could further improve the standardization of the CPUE data in this fishery.

Determining the vessel specifications according to crew size and trip length are both deemed to be poor indicators of vessel type (Leslie *et al.*, 2004; Smith and Glazer, 2007). It is challenging to obtain this vessel information (gross registered tonnage (GRT), length, use of live bait and sonar information) for the entire fleet, but a classification into vessel type was attempted in the past (Kerwath *et al.*, 2012) based on maximum and average number of crew. However, there was no significant improvement in explanatory power by including vessel type as categorical variable or by using a subset of vessels from each class as indicator vessels. To include vessel as a random effect was deemed the most appropriate solution. There was notable variation among vessels (Fig. 4) and the inclusion of the random vessel effect produced the most parsimonious error structure. However, the random effect did not have a large effect on the confidence intervals.

In accordance with the previous analyses (da Silva *et al.*, 2017), swordfish CPUE from the South African pelagic longline fishery displayed a definitive seasonal trend, with higher catch rates in austral winter (July - October) than the rest of the year (Fig. 6a). This may in part be due to the seasonal operations of Joint-Venture vessels operating predominantly off the East coast of South Africa, which predominantly fish in the South African EEZ during the winter period. Standardized catch rates were relatively high in the first half of the time series (2004-2012) and normalized CPUE values were generally > 1 for this period (Fig. 7). Standardized CPUE peaked in 2008 at 530kg/1000 hooks. After 2012, CPUE was relatively low and all normalized values remained < 1, with the exception of the final year, 2019. The lowest standardized CPUE estimate was observed in 2014 at 262kg/1000 hooks; approximately half of the highest observed catch rates. These results suggest that swordfish catch rates in the South African pelagic longline fishery have recently stabilized after an initial period of decline during 2004 to 2012.

TABLES

Table 1. Results from the GAMM applied to swordfish (*Xiphias gladius*) indicating the deviance explained by parameters selected for the final model.

	DF	AIC	BIC	Deviance	Deviance Explained	% Deviance Explained	P-Value
Null Model	2	61785.14	61798.06	128108.30	0.000	0.00	
Year	17	61401.49	61511.32	119870.42	−8237.882	22.44	< 0.001
Month	23	60550.23	60697.37	103761.79	−16108.630	43.88	< 0.001
Latitude/Longitude	31	60314.91	60517.28	99330.96	−4430.826	12.07	< 0.001
Fishing Tactic	32	59845.11	60053.55	91398.89	−7932.069	21.61	< 0.001

Table 2. Nominal and standardised CPUE values (kg/1000 hooks), including standard error (SE) and confidence intervals (LCI, UCI) for swordfish (*Xiphias gladius*) for the period 2004 - 2019.

Year	Nominal	CPUE	CV	LCI	UCI
2004	329	462	0.09	390	547
2005	373	453	0.09	383	537
2006	350	446	0.08	378	525
2007	298	375	0.08	318	442
2008	346	530	0.08	453	622
2009	226	352	0.08	299	414
2010	319	446	0.08	382	521
2011	330	473	0.08	406	552
2012	282	401	0.08	342	470
2013	261	382	0.08	327	447
2014	149	262	0.09	219	313
2015	284	377	0.09	319	446
2016	319	338	0.11	271	421
2017	154	298	0.17	211	419
2018	227	352	0.1	292	426
2019	208	441	0.09	368	529

FIGURES

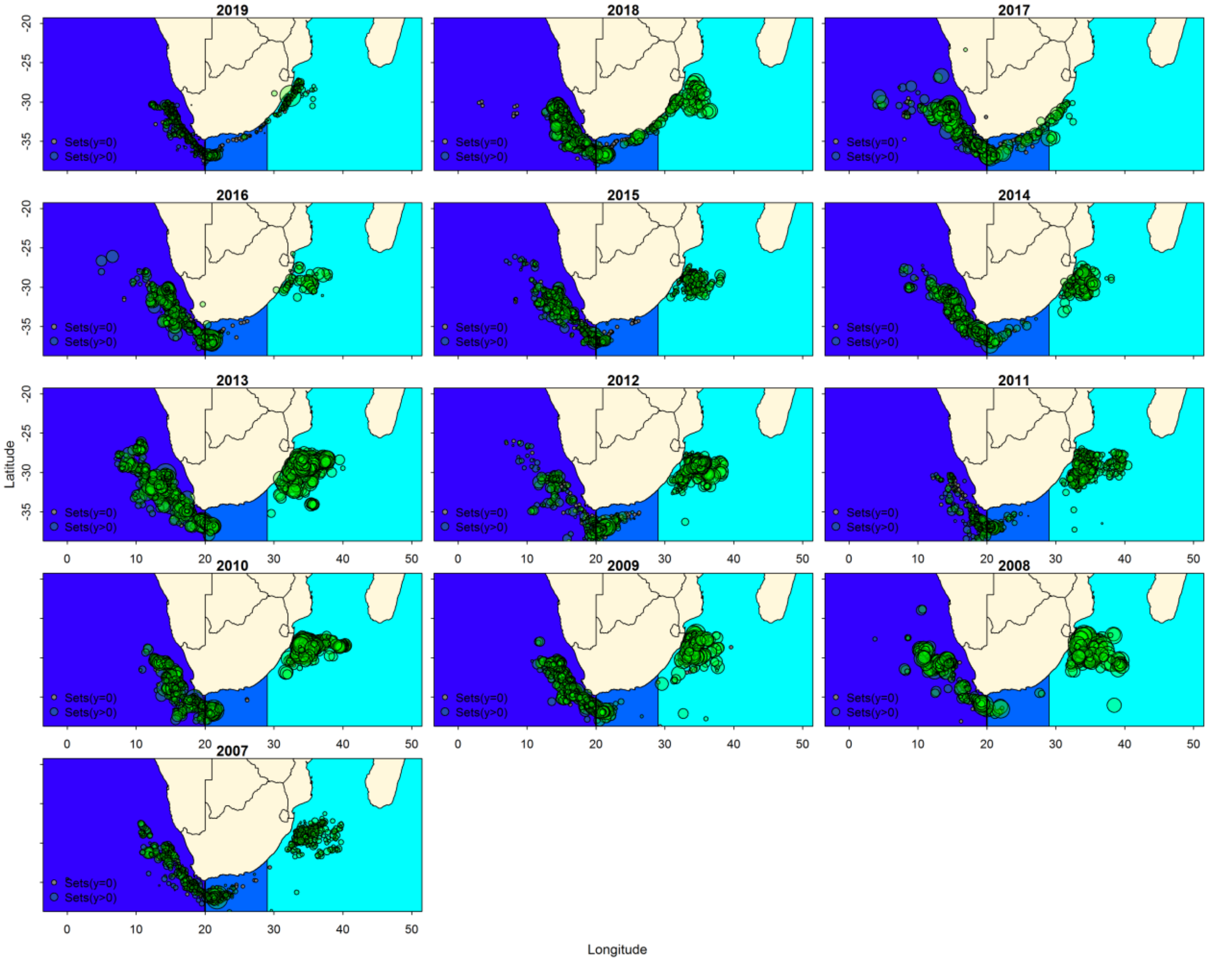

Figure 1. Annual effort distribution for the South African longline fleet. Longline sets that did not encounter a swordfish are the smallest circles, and the circle diameter increases proportional to the weight of swordfish caught per set. The black line indicates the ICCAT/IOTC boundary.

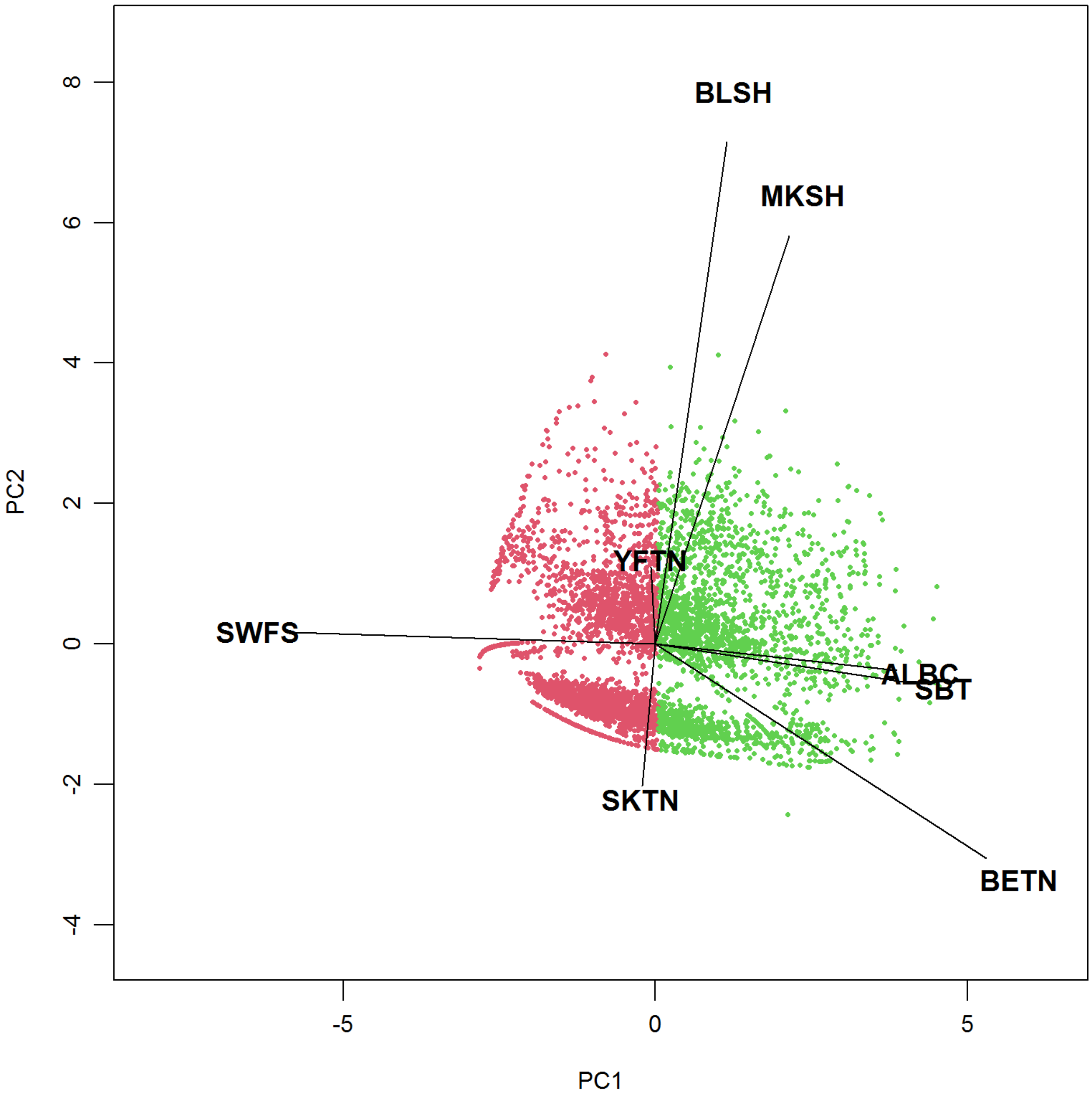

Figure 2. A graphical representation of the two clusters that characterise the different fishing tactics projected over the first two Principal Components (PCs), where only PC1 was determined to be non-trivial. FT 1: Cluster one (red) is predominantly swordfish catches. FT 2: Cluster two (green) is predominantly tuna (ALB, BETN, SBT) with a mixture shark (blue and shortfin mako) catches.

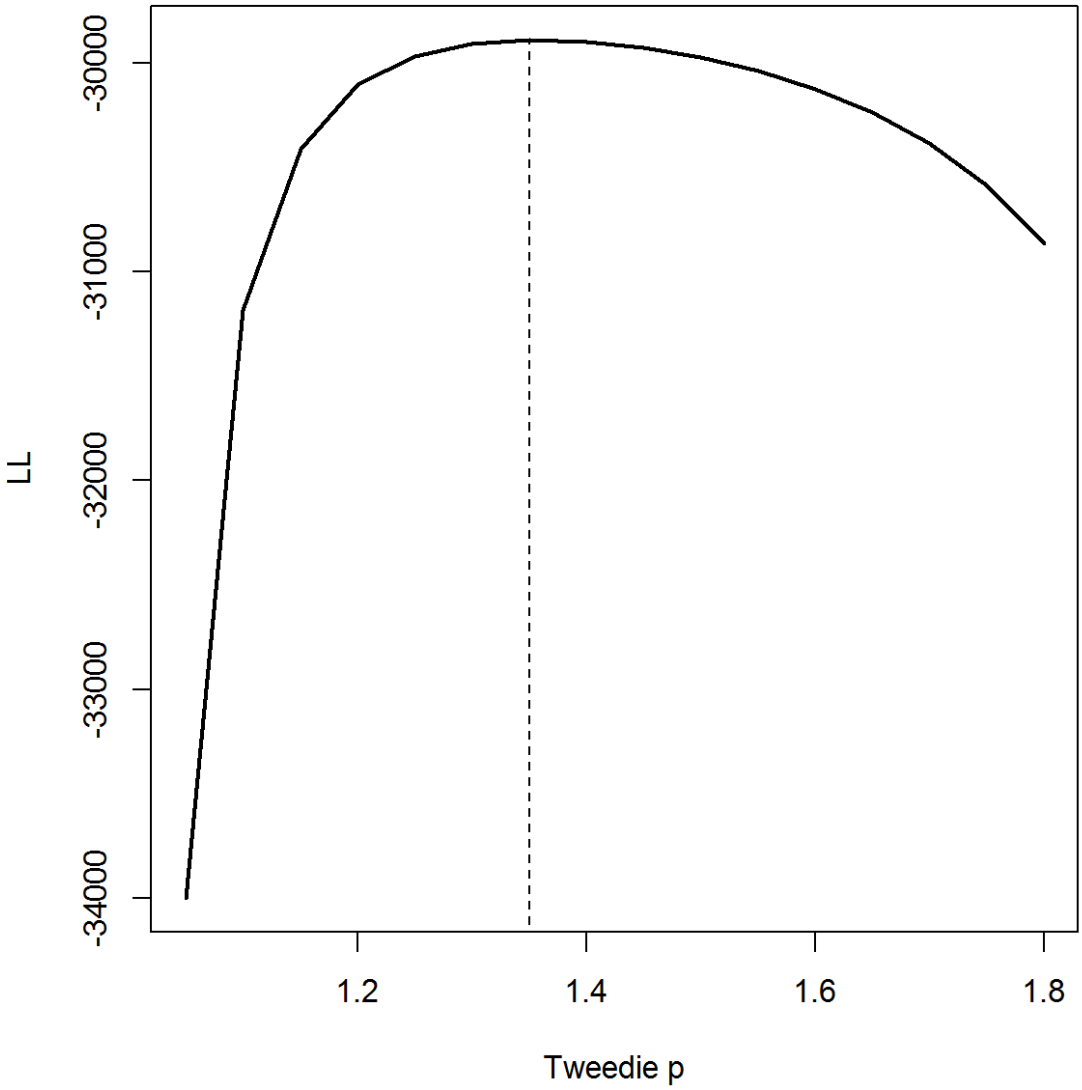

Figure 3. Log-likelihood profile for over the grid of power parameters values (1 < p < 2) of the Tweedie distribution. The vertical dashed line denote the optimized p used in the final standardization GAMM.

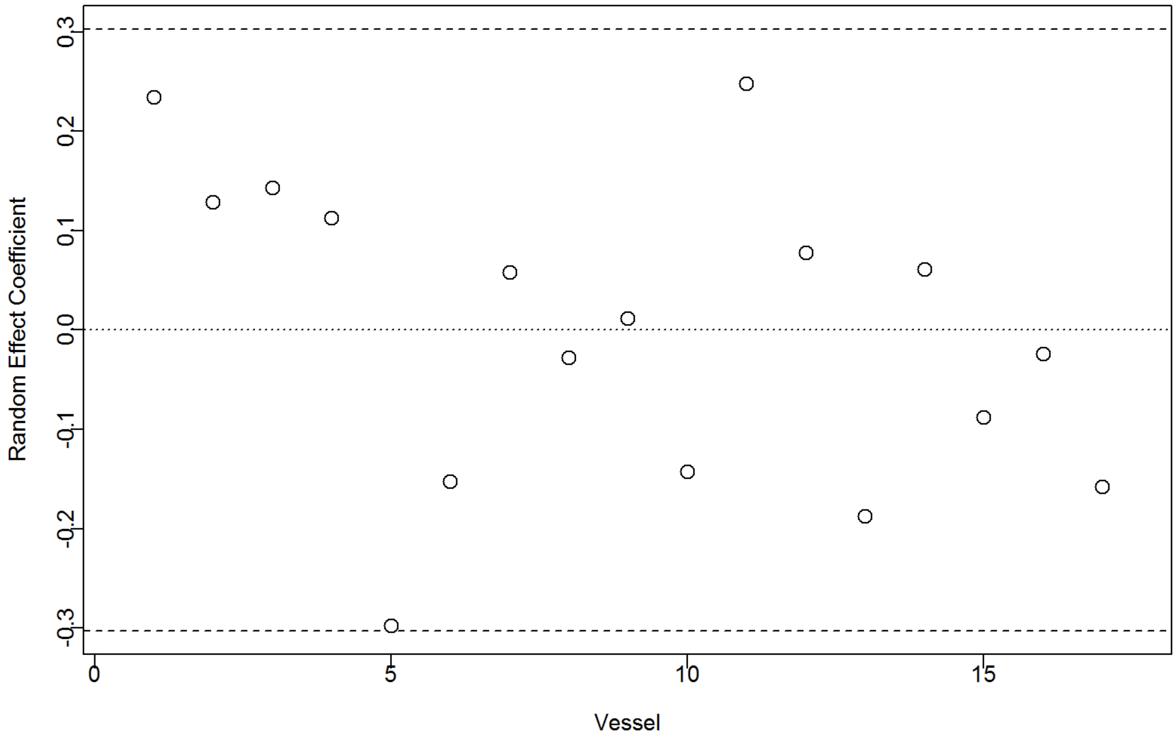

Figure 4. Random effects coeffients (dots) illustrating the deviation from the mean of zero across the 17 vessels retained for the analysis. Dashed lines denote the 95% confidence interval of the mean.

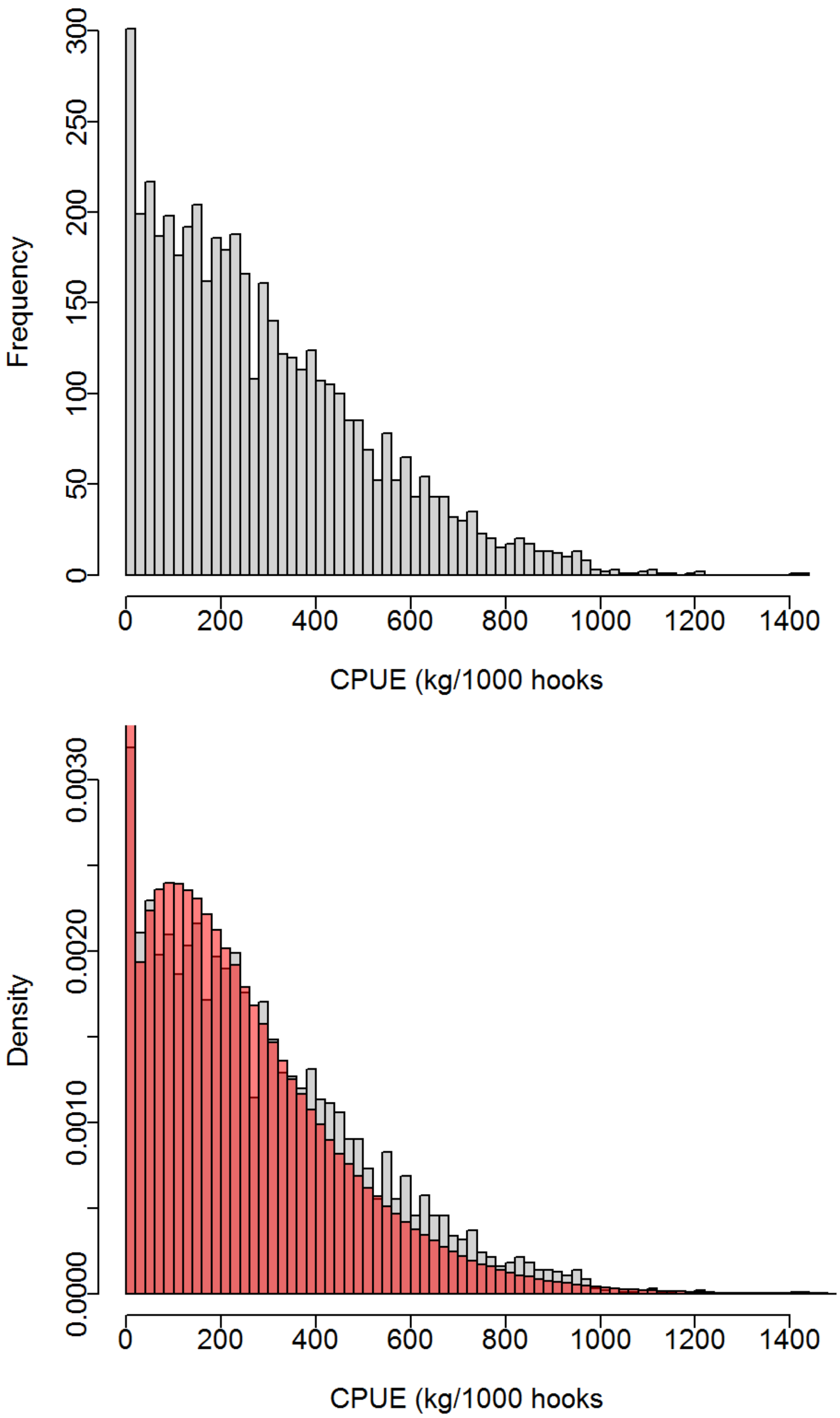

Figure 5. CPUE frequency, and density, distributions for the South African swordfish directed long-line fishery. The red shaded density denotes the expected density of the response for the Tweedie GAMM, and supports the use of the Tweedie distribution form in the GAMMs.

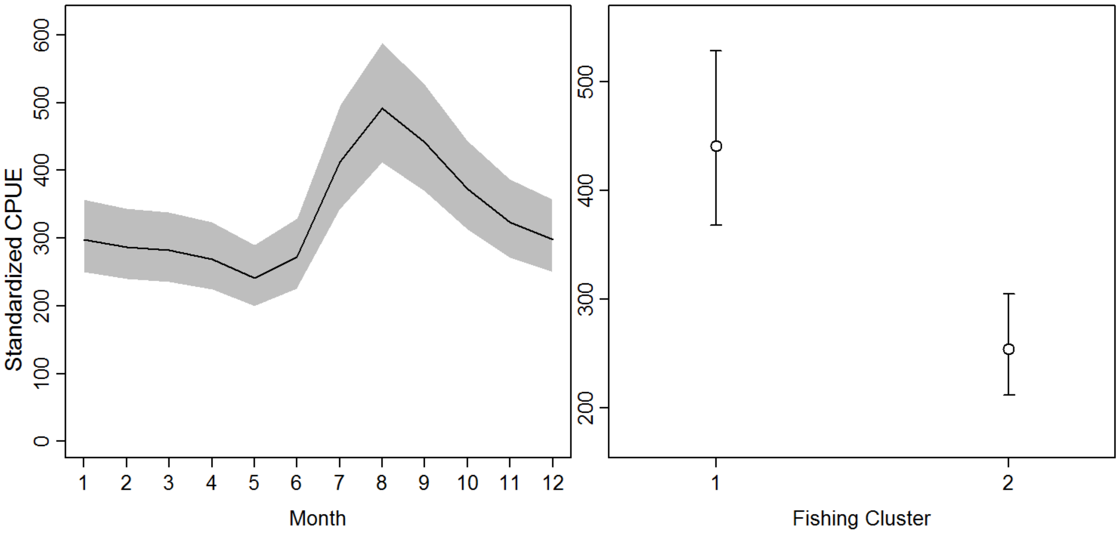

Figure 6. The influence of the fixed effects *Month* and *Fishing Tactic* on the CPUE of swordfish when modelled using the GAMM applied to the South African swordfish directed longline data.

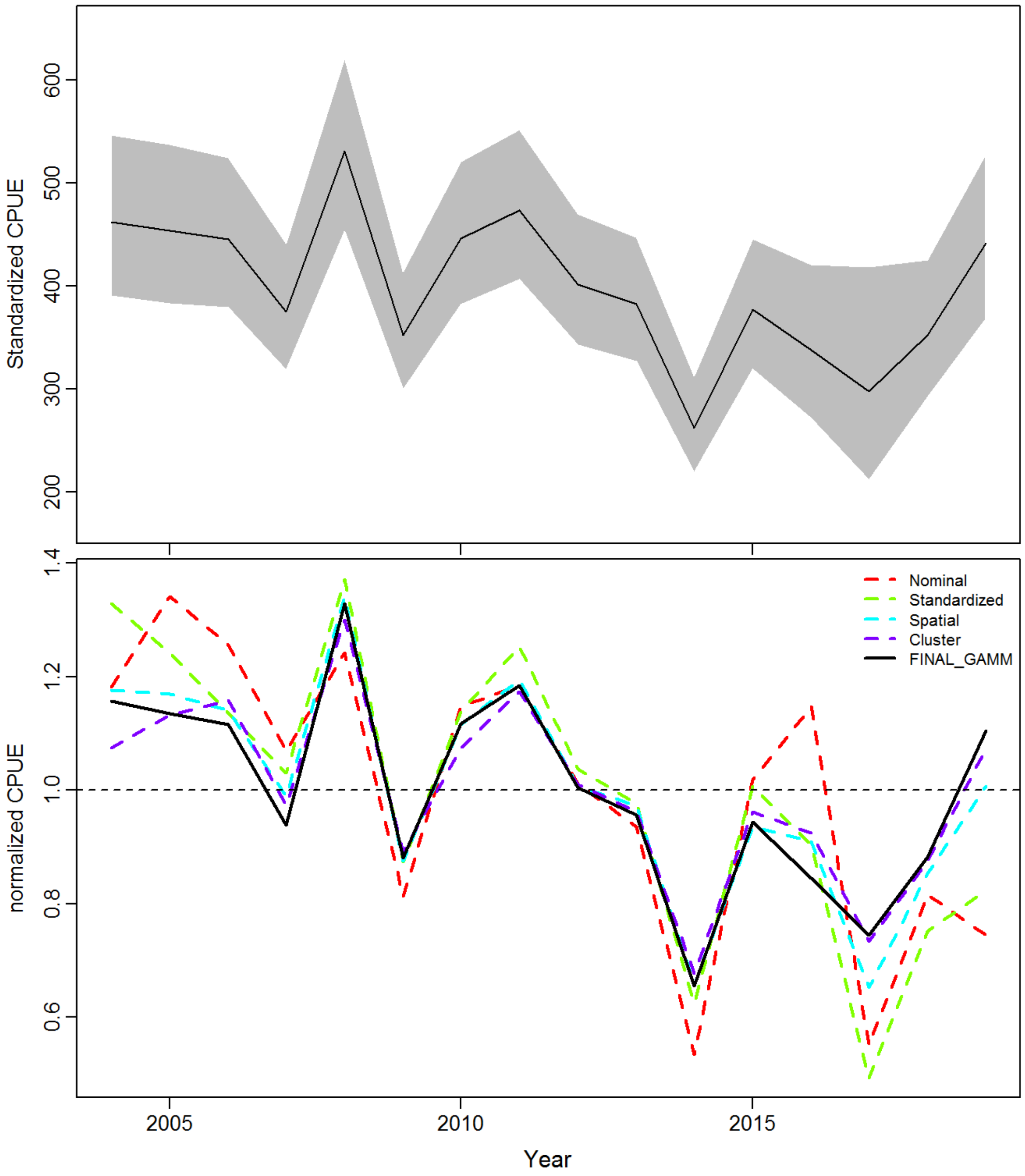

Figure 7. Standardized swordfish CPUE for the South African pelagic longline fishery for the period 2004 to 2019 (upper panel). The 95% confidence intervals for the nominal CPUE are denoted by grey shaded areas. A comparison of nominal and the various alternative standardized CPUE models (lower panel).

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