STANDARDIZATION OF SWORDFISH CPUE FROM THE RÉUNION LONGLINE FISHERY LOGBOOK DATA

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Purpose, expectation and action intended

Discussions (for information and open discussion)

The paper presents the first standardized swordfish (*Xiphias gladius*) CPUE index for the Réunion pelagic longline fleet using logbook data, covering 2005–2025, and invites discussion of the observed increase in relative abundance since 2019, as set out in Sections 3 and 4.

Feedback (to collect input and suggestions)

The paper is to request review and comments on the three standardization frameworks evaluated (Delta-Lognormal GAM, Tweedie GAM and spatiotemporal sdmTMB), on the treatment of fishing métier and effort reconstruction, and on the operational variables that could not be included, as set out in Section 2.

Recommendation (to ask the meeting to endorse a recommendation)

The paper is to seek endorsement of the Tweedie-GAM index as the operational abundance index for the Réunion pelagic longline fishery, for inclusion in future IOTC swordfish stock assessments, as set out in Section 4.4. This CPUE index should be treated as a sensitivity analysis of the stock assessment regarding the strong limitations of the produced CPUE index.

Abstract

The Réunion pelagic longline fleet has operated in the southwest Indian Ocean since the late 1990s and constitutes one of the longest continuously monitored swordfish fisheries in the region. This paper presents the first standardized swordfish CPUE index for this fleet, based on 155,959 fishing sets recorded in the SACROIS logbook database between 2005 and 2025, representing approximately 220.6 million hooks and 14,700 t of swordfish. Because raw effort records contained implausible values, the number of hooks per set was reconstructed from an auxiliary vessel-year hook database. Three standardization frameworks were evaluated and compared: a Delta-Lognormal generalized additive model separating encounter probability from positive catch rates, a single-stage Tweedie GAM, and a spatiotemporal generalized linear mixed model fitted with sdmTMB. All models accounted for year, quarter, fishing métier, vessel identity and spatial location. The three approaches produced closely convergent abundance trajectories (pairwise correlations of 0.956–0.991) describing three phases: an initial decline to 2008, a decade of relative stability to 2018, and a sustained increase thereafter. Relative to the 2005 baseline, standardized CPUE approximately doubled by 2025. The persistence of this trend after accounting for changes in fishing strategy, fleet composition and spatial distribution indicates that it cannot be attributed solely to changes in fishing practices, and is consistent with increased swordfish availability to the Réunion fleet. Standardized CPUE nevertheless remains an index of availability to the gear rather than a direct measure of stock biomass, and operational variables known to influence catchability – hook depth, bait and hook type, soak duration and light-stick use – were unavailable in the logbook records. The convergence of results across three conceptually distinct frameworks supports the robustness of the index and its suitability as a regional abundance indicator for Indian Ocean swordfish stock assessment but only for sensitivity analyses with respect to the strong limitations of the standardization process identified in the document.

Keywords: swordfish, *Xiphias gladius*, CPUE standardization, pelagic longline, Réunion, southwest Indian Ocean, Tweedie GAM, sdmTMB

1. Introduction

The Réunion pelagic longline fishery developed during the late 1990s and early 2000s as part of efforts to diversify the island's offshore fisheries and exploit oceanic tuna and billfish resources in the southwest Indian Ocean. The fishery is composed of locally based vessels operating from Réunion and targeting a range of highly migratory species, principally swordfish (*Xiphias gladius*), albacore tuna (*Thunnus alalunga*), yellowfin tuna (*T. albacares*), and bigeye tuna (*T. obesus*). Since the mid-2000s, the fleet has consisted of approximately 20–30 active vessels annually and has operated over a large area of the southwest Indian Ocean, extending from tropical to subtropical waters. The fishery represents one of the longest continuously monitored swordfish fisheries in the southwestern Indian Ocean

2. Materials and methods

2.1 Data available

Catch and effort data were extracted from the SACROIS database, which compiles logbook information from Réunion-based pelagic longliners operating throughout the southwest Indian Ocean. Records are available at the fishing-set level and include vessel identity, trip and set identifiers, fishing date, fishing métier, spatial location (1° × 1° statistical cells), species-specific catch weights, and operational information associated with each set.

The analysis focused on the two principal longline métiers used by the Réunion fleet: the swordfish-directed longline fishery (LLDSWO) and the deep pelagic longline fishery (LLDLPF). Although these métiers differ in their primary target species, both contribute substantially to swordfish catches and are operated by the same fleet using similar fishing gears and fishing grounds. Excluding LLDLPF records would therefore omit a substantial proportion of swordfish catches and effort from the fishery.

Over the study period, the database contained records from 32 vessels operating between 2000 and 2026. Annual fishing activity ranged from fewer than 100 sets during the earliest years of the series to more than 10,000 sets during periods of peak fleet activity. Swordfish represented the dominant species in the LLDSWO métier, accounting for approximately 55% of total reported catch weight, followed by albacore tuna, yellowfin tuna, and bigeye tuna. In contrast, catches reported under the LLDLPF métier were more evenly distributed among yellowfin tuna, bigeye tuna, albacore tuna, and swordfish.

The spatial extent of the fishery expanded considerably during the development of the fleet, with annual fishing activity covering between 12 and 205 statistical cells. The number of active vessels varied from 17 to 29 during the main period of commercial operation (2005–2025), while annual fishing effort exceeded 11 million hooks in the most active years. A summary of the principal characteristics of the fishery and dataset by year is provided in Table 1.

Table 1: Main information about the Réunion pelagic longline fishery and available SACROIS dataset by year, including the number of active vessels, fishing sets, hooks deployed, total catches, swordfish catches, and spatial coverage.

Year	Vessels	Sets	Cells	Hooks (million)	SWO catch (t)	Total catch (t)	Positive sets	Positive prop.
2,000	9	768	61	0.99	5.9	14.9	754	0.982
2,001	1	69	12	0.07	11.3	18.3	67	0.971
2,002	3	148	44	0.21	45.1	80.4	146	0.986
2,004	4	579	76	0.78	0.0	0.0	0	0.000
2,005	24	4,519	148	6.17	389.4	1,146.7	2,346	0.519
2,006	24	6,152	141	8.55	505.9	1,636.2	4,428	0.720
2,007	29	7,988	155	11.39	596.1	1,953.8	6,189	0.775
2,008	29	7,559	165	10.69	465.7	1,395.2	5,087	0.673
2,009	28	10,410	183	14.80	809.4	2,080.9	5,869	0.564
2,010	26	9,529	209	13.39	859.1	1,928.3	5,927	0.622
2,011	24	9,769	196	13.90	877.5	2,253.0	6,023	0.617
2,012	22	7,928	162	11.18	559.4	1,215.5	4,124	0.520
2,013	18	6,536	90	9.32	531.3	1,324.1	4,374	0.669
2,014	19	6,623	123	9.69	617.4	1,673.5	5,240	0.791
2,015	19	6,848	146	10.02	588.7	1,564.7	5,086	0.743
2,016	19	6,799	144	9.93	611.7	1,502.8	4,971	0.731
2,017	17	5,890	92	8.61	512.0	1,192.9	4,430	0.752
2,018	19	6,458	143	9.41	572.1	1,381.9	4,722	0.731
2,019	19	7,013	110	10.24	682.8	1,460.7	4,448	0.634
2,020	18	7,368	111	10.74	789.9	1,644.9	4,786	0.650
2,021	19	6,634	82	9.71	865.2	1,836.6	4,631	0.698
2,022	21	7,171	89	10.49	849.6	1,783.4	4,854	0.677
2,023	20	6,890	111	10.08	941.2	2,039.7	5,079	0.737
2,024	21	6,655	91	9.69	1,016.3	2,170.0	5,046	0.758
2,025	21	6,382	115	9.32	963.3	2,212.0	4,709	0.738
2,026	21	2,577	82	3.76	270.8	894.6	1,872	0.726

The Réunion pelagic longline fishery expanded rapidly during the mid-2000s following the development of the local longline fleet. Annual swordfish catches increased from negligible levels in the early 2000s to approximately 600–900 t per year during most of the study period, with peaks exceeding 1,000 t in recent years (Figure 1). Swordfish remained one of the dominant species landed by the fleet throughout the time series.

Although two métiers were reported in the SACROIS database—LLDSWO (swordfish-directed longline) and LLDLPF (large pelagic longline)—both contributed substantially to total swordfish catches. The LLDSWO métier consistently accounted for the majority of swordfish landings, generally representing 75–85% of annual catches, whereas LLDLPF contributed a smaller but non-negligible fraction. Because swordfish catches are regularly recorded in both métiers and many vessels operated under both classifications during the study period, analyses were conducted using the combined LLDSWO and LLDLPF dataset.

Figure 1 illustrates the temporal evolution of swordfish catches by métier and highlights the increasing importance of swordfish in the Réunion pelagic longline fishery over the last two decades.

Years 2000–2004 were excluded because of limited fleet participation and spatial coverage. Year 2026 was excluded because data were incomplete.

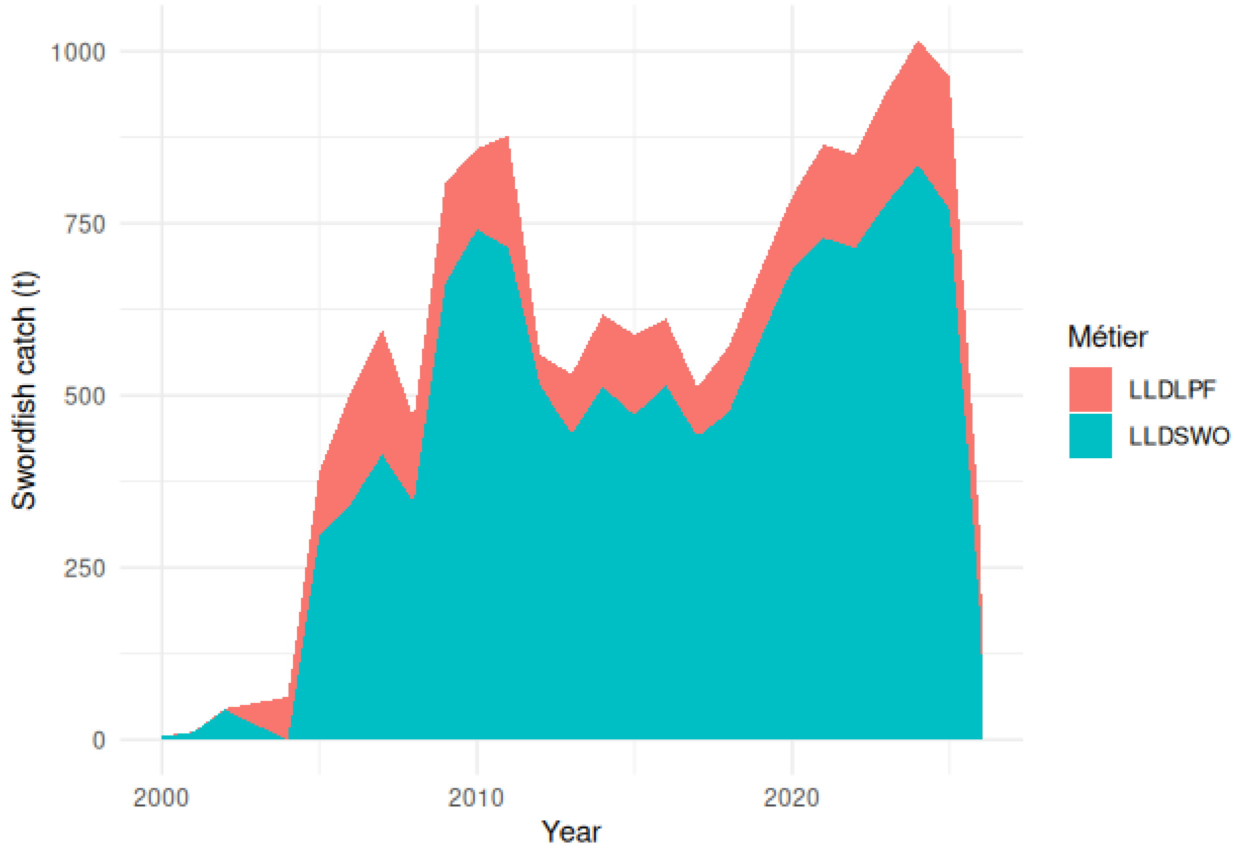

Figure 1: Temporal evolution of swordfish catches by métier (LLDSWO and LLDLPF) in the Réunion pelagic longline fishery. Swordfish catches increased substantially over the study period, reflecting the growing importance of swordfish within the fishery and the contribution of both métiers to total landings.

Figure 2 summarizes the evolution of catch composition in the Réunion pelagic longline fishery between 2000 and 2025. Total annual catches increased substantially following the development of the fleet during the early 2000s, reaching more than 1,300 t in several recent years (Panel A). Swordfish (*Xiphias gladius*; SWO) consistently represented the dominant component of the catch throughout the study period and accounted for approximately 50–60% of total landings in most years (Panel B).

The fishery also retained significant quantities of tropical tunas, primarily yellowfin tuna (YFT), albacore tuna (ALB), and bigeye tuna (BET), which together represented approximately 25–35% of annual catches. Other regularly encountered species included dolphinfish (*Coryphaena hippurus*; DOL), blue marlin (*Makaira nigricans*; BUM), sailfish (*Istiophorus platypterus*; SFA), black marlin (*Istiompax indica*; BLM), blue shark (*Prionace glauca*; BSH), and aggregated billfishes (BIL), although each contributed a relatively small proportion of total catches.

A substantial number of records (33,808) contained no species code. These records were associated with zero reported catch and were interpreted as empty catch records rather than unidentified species. They were retained during the reconstruction of set-level fishing operations but did not contribute to swordfish catch estimates.

Despite interannual variability in total catch, the overall species composition remained relatively stable through time, with swordfish consistently dominating landings and no major shifts in target assemblages being apparent (Figure 2 B). This stability suggests that changes in nominal CPUE are unlikely to be driven by large changes in species targeting and supports the use of a common standardization framework across the study period.

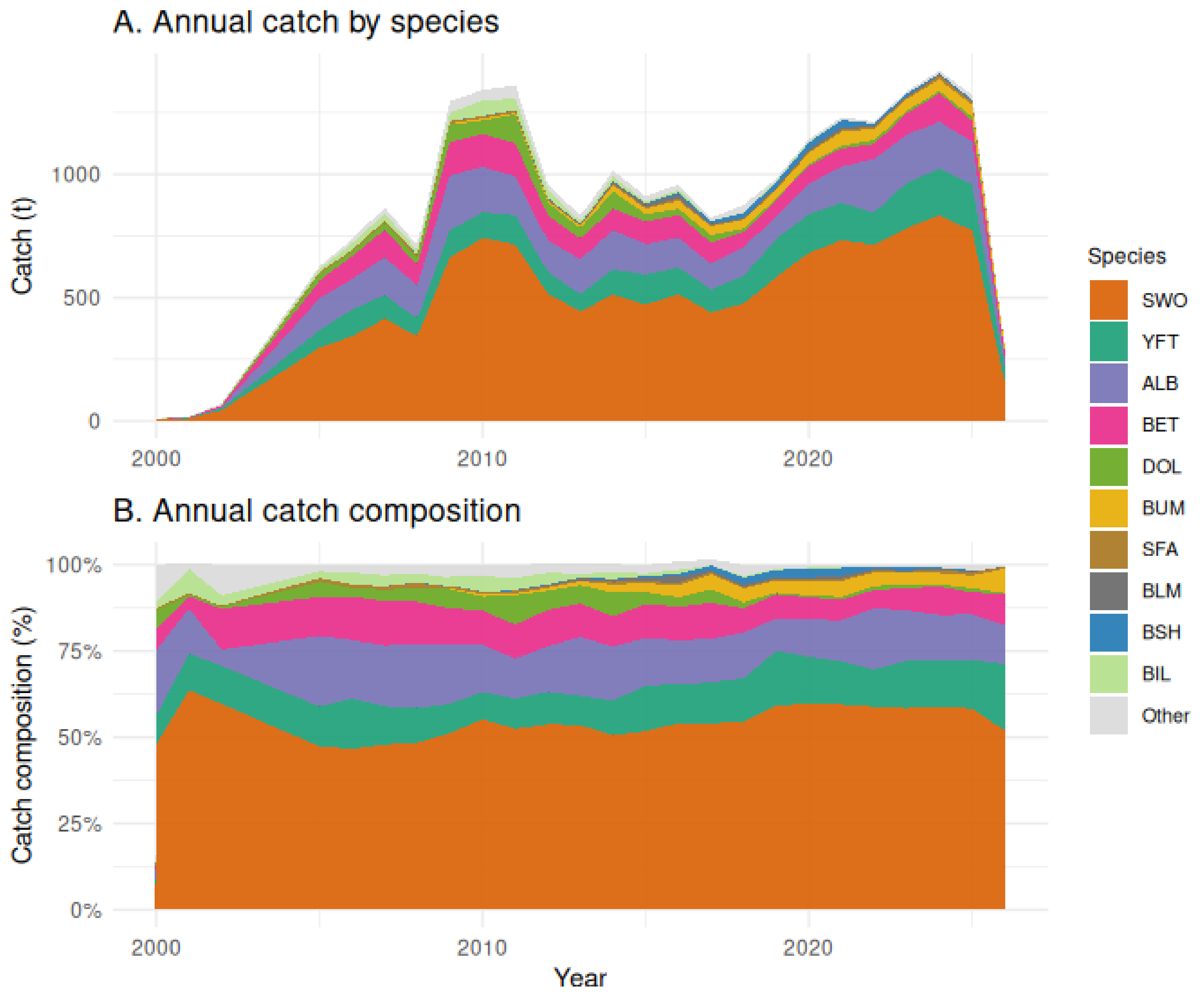

Figure 2: Annual catches and catch composition of the Réunion pelagic longline fishery from 2000 to 2026. As 2026 is the current year, this dataset is incomplete. Panel A shows annual catches (t) by species group, while Panel B presents the relative contribution of each species group to total annual catches. Swordfish (SWO) consistently dominated landings throughout the study period, although substantial catches of yellowfin tuna (YFT), albacore tuna (ALB), and bigeye tuna (BET) were also recorded.

The number of hooks per set was reconstructed using an auxiliary vessel-year hook database specific to the longline fleet (i.e. the activity calendar database whenever available). Raw effort information contained in the SACROIS "DIMENSION" field (i.e., number of hooks per set) included numerous implausible values and was therefore not used directly. Instead, effort was estimated from vessel-year records when available and supplemented using vessel-specific or fleet-level averages when necessary.

The reconstructed effort series indicated a relatively stable fishing strategy throughout the study period (Figure 12). Median hook numbers generally ranged between 1,400 and 1,500 hooks per set, with limited interannual variation after 2007. Some years exhibited a small number of observations with substantially lower hook counts, reflecting either atypical fishing operations or uncertainty in the reconstruction process. However, these observations represented a small fraction of the total number of sets and did not materially affect annual mean effort estimates.

The overall stability of hook deployment suggests that major temporal changes in nominal CPUE are unlikely to be driven solely by changes in the number of hooks deployed per set.

Overall, the reconstructed effort series suggests that the Réunion pelagic longline fleet maintained relatively stable fishing practices over time, providing a robust basis for standardizing catch rates using hooks as the primary measure of fishing effort.

Fishing activity expanded rapidly during the early development of the Réunion pelagic longline fishery before stabilizing during the mid-2000s (Figure 13). The number of active vessels increased from fewer than 10 vessels in 2000 to approximately 30 vessels by 2007–2008, after which the fleet gradually declined and stabilized at around 18–21 vessels from 2013 onwards.

A similar pattern was observed for fishing effort. The annual number of sets increased substantially during the expansion phase of the fishery, reaching more than 10,000 sets in 2009 before declining and stabilizing at approximately 6,000–7,500 sets per year in recent years. Spatial coverage followed a comparable trajectory, with the number of occupied fishing cells (IOTC 1°x1° grid) increasing from fewer than 50 cells during the earliest years of the fishery to more than 200 cells around 2009–2010, before contracting and stabilizing at approximately 80–150 occupied cells per year thereafter.

In contrast, the mean number of hooks per set remained relatively stable throughout the study period, generally ranging between 1,350 and 1,500 hooks per set. This indicates that temporal changes in fishing effort were primarily driven by changes in the number of vessels, sets, and fishing locations rather than major modifications to gear configuration. The observed variability in fleet size, fishing effort, and spatial coverage highlights the importance of accounting for these factors during CPUE standardization.

2.2 Data screening, validation, and curation

Fishing activity expanded rapidly during the early development of the Réunion pelagic longline fishery before stabilizing during the mid-2000s (Figure 14). The number of active vessels increased from fewer than 10 vessels in 2000 to approximately 30 vessels by 2007–2008, after which the fleet gradually declined and stabilized at around 18–21 vessels from 2013 onwards.

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The proportion of fishing sets catching at least one swordfish varied substantially throughout the study period (Figure 15). Positive-set frequency increased rapidly during the development of the fishery, fluctuated between approximately 50% and 80% during the 2005–2015 period, and remained relatively high thereafter. From 2013 onwards, more than two-thirds of sets generally recorded swordfish catches, with several years exceeding 75%.

Temporal variation in positive-set frequency indicates that changes in nominal CPUE may arise from both variation in swordfish encounter rates and variation in catch rates among positive sets. This pattern supports the use of modelling approaches that account separately for occurrence and abundance components when standardizing swordfish CPUE.

To better characterize temporal changes in nominal swordfish catch rates, annual CPUE was decomposed into two components: (1) the proportion of positive sets (encounter rate) and (2) the mean catch rate among positive sets (positive CPUE) (Figure 3).

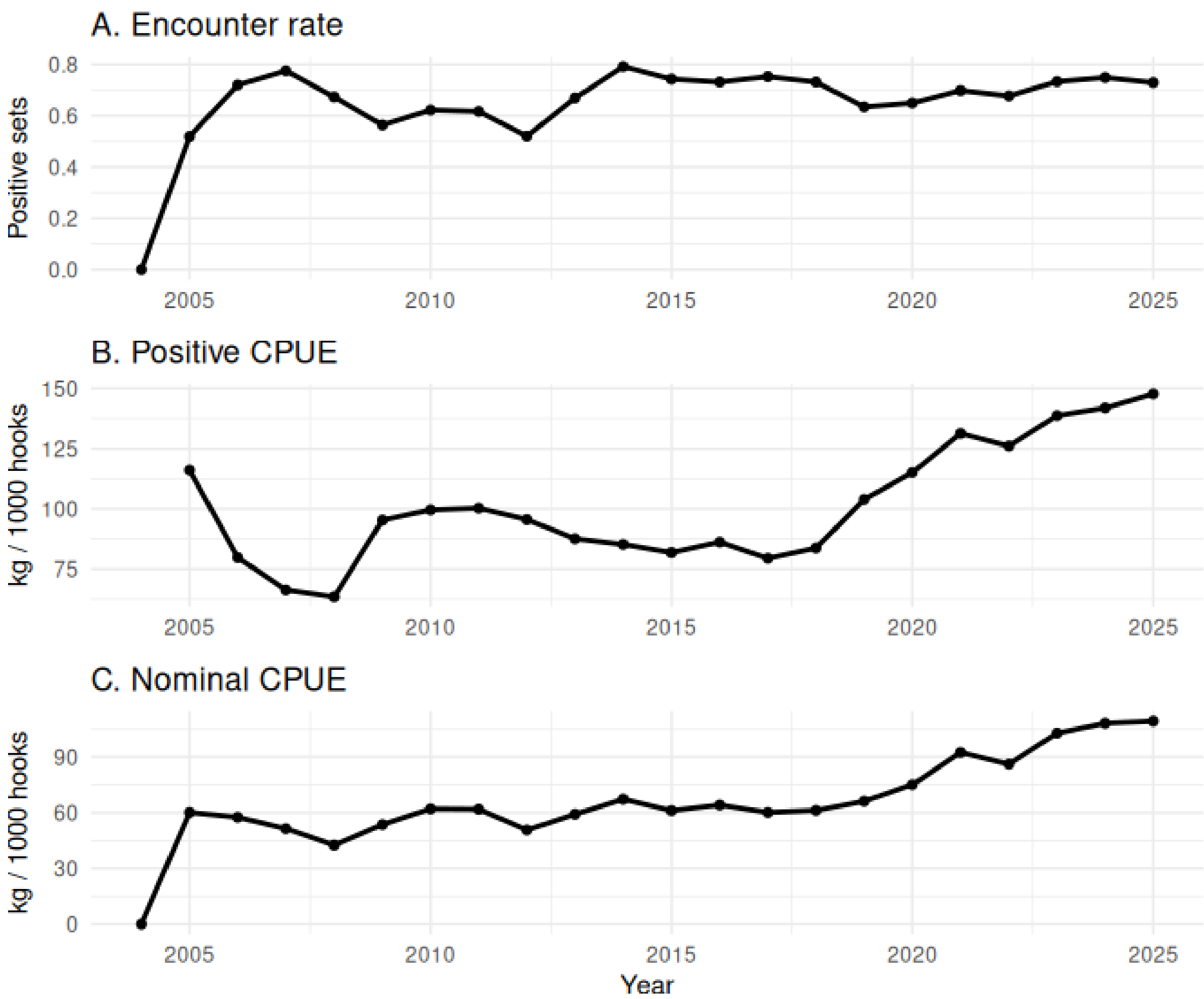

Figure 3: Annual trends in (A) encounter rate (proportion of positive sets), (B) positive CPUE (mean catch rate among sets catching at least one swordfish), and (C) nominal CPUE in the Réunion pelagic longline fishery between 2004 and 2025. Nominal CPUE reflects the combined influence of encounter probability and catch rates among positive sets. The increase observed during recent years was driven primarily by increasing positive CPUE, while encounter rates remained comparatively stable.

The encounter rate increased rapidly during the establishment of the fishery and remained relatively high thereafter, generally fluctuating between 0.6 and 0.8. In contrast, positive CPUE exhibited stronger long-term variation. Positive CPUE declined during the mid-2000s, remained relatively stable between 2009 and 2018, and increased markedly after 2019. Consequently, the increase observed in nominal CPUE during recent years appears to be driven primarily by higher catches in successful sets rather than by substantial changes in encounter probability.

Nominal swordfish CPUE increased from approximately 60–80 kg per 1,000 hooks during 2005–2019 to more than 120 kg per 1,000 hooks after 2023. This increase was accompanied by a rise in CPUE among positive sets and a decline in the proportion of zero-catch sets, suggesting that both encounter rates and catches conditional on encounter contributed to the observed increase in nominal CPUE.

These results indicate that temporal variation in swordfish abundance is reflected both in the occurrence of positive sets and in catch rates among successful fishing operations, supporting the use of modelling approaches capable of accounting for both processes.

The spatial distribution of fishing effort remained broadly consistent throughout the study period, with most fishing activity concentrated between approximately 40–65°E and 15–30°S, encompassing the waters surrounding Réunion Island, Madagascar, Mauritius, and the southwestern Indian Ocean (Figure 4). While some interannual fluctuations in the extent of fishing operations were observed, the core fishing grounds remained relatively stable over time.

Nominal swordfish CPUE exhibited substantial spatial heterogeneity within the fishing area. Elevated catch rates were consistently observed along the western and southern margins of the fishing grounds, whereas lower catch rates generally occurred within the central portion of the fishing area. Although some high-CPUE cells appeared intermittently through time, the overall spatial pattern remained broadly similar across periods.

The relative stability of both fishing grounds and CPUE hotspots suggests that the long-term increase observed in nominal CPUE is unlikely to be solely attributable to large-scale shifts in fishing location. Nevertheless, the presence of persistent spatial gradients highlights the importance of accounting for spatial variation during CPUE standardization.

2.2.1 In a nutshell

The proportion of positive swordfish sets varied substantially among years, ranging from approximately 42% in 2005 to more than 75% in 2014, with no consistent long-term trend. In contrast, CPUE among positive sets increased progressively throughout the series, particularly after 2019, rising from approximately 100–120 kg per 1,000 hooks during the mid-2010s to nearly 180 kg per 1,000 hooks by 2024–2025. This suggests that the recent increase in nominal CPUE was driven primarily by higher catches in successful sets, rather than by a substantial increase in encounter rates.

Encounter and positive-catch components

The proportion of positive swordfish sets varied between approximately 0.5 and 0.75 throughout the study period, with no clear long-term trend. In contrast, CPUE among positive sets increased steadily, particularly after 2019, rising from approximately 100–120 kg per 1,000 hooks during the mid-2010s to nearly 180 kg per 1,000 hooks by 2024–2025. These exploratory analyses suggest that the increase in nominal CPUE is primarily associated with higher catches in successful sets rather than major changes in encounter probability (Figure 16).

Spatial and temporal coverage

The number of active vessels remained relatively stable throughout the analysis period, ranging between 17 and 29 vessels annually. Mean effort per set also remained relatively constant, averaging approximately 1,350–1,500 hooks per set. In contrast, the spatial extent of the fishery varied substantially among years, with the number of occupied fishing cells ranging from 81 to 205. These changes in spatial coverage highlight the importance of accounting for spatial effects during CPUE standardization.

Annual fishing effort concentration, expressed as the number of sets per occupied spatial cell. Values increased from approximately 23 sets per cell in 2005 to more than 50 sets per cell after 2020, indicating a progressive concentration of fishing effort within a smaller spatial footprint.

The final analytical dataset comprised 155,959 fishing sets conducted by 32 vessels between 2004 and 2025 (Table 2). These sets represented approximately 220.6 million hooks and yielded 14,700 t of swordfish from a total catch of 36,229 t. Swordfish were recorded in 66.3% of all fishing sets, indicating a substantial proportion of zero-catch observations that should be considered during CPUE standardization. Fishing activity was distributed across 435 occupied 1° spatial cells throughout the southwestern Indian Ocean, reflecting the broad geographic extent of the fishery.

The large temporal and spatial coverage of the dataset provides a robust basis for investigating trends in swordfish catch rates while accounting for changes in fishing practices, fleet dynamics, and fishing location through time.

Table 2: Summary of the Réunion pelagic longline dataset used for swordfish CPUE standardization. The dataset comprises all fishing sets retained for analysis after effort reconstruction and data screening.

Metric	Value
Study period	2004–2025
Fishing sets	155,959
Vessels	32
Swordfish catch (t)	14,700
Total catch (t)	36,229
Total hooks	220,649,883
Mean hooks per set	1,415
Positive sets (%)	66.3%
Occupied 1° cells	435

2.3 Standardization models

Three alternative approaches were evaluated for standardizing swordfish CPUE in the Réunion pelagic longline fishery. These models differ in their treatment of zero catches, distributional assumptions, and capacity to account for spatial variation.

First, a Delta-Lognormal model was fitted to explicitly account for the high proportion of zero-catch observations. The Delta approach decomposes CPUE into two processes: (1) the probability of obtaining a positive catch and (2) the magnitude of the catch conditional on a positive observation. The encounter component was modelled using a binomial distribution, while positive catch rates were modelled using a Gaussian distribution applied to log-transformed positive CPUE values. The standardized index was obtained by multiplying the predicted probability of occurrence by the predicted positive CPUE. This approach is widely used in fisheries assessments when catch data contain many zeros.

Second, a Tweedie generalized additive model (GAM) was evaluated as an alternative single-stage model. The Tweedie distribution accommodates continuous positive observations together with exact zeros within a unified likelihood framework, thereby avoiding the need to model occurrence and abundance separately. Tweedie models have become increasingly popular in fisheries CPUE standardization because they often provide comparable results to Delta models while requiring fewer modelling steps.

Finally, a spatiotemporal generalized linear mixed model was fitted using the sdmTMB framework. This approach extends the previous models by explicitly accounting for spatial and temporal autocorrelation in catch rates. The model incorporates fixed effects describing year, season, vessel effects, and fishing effort, together with spatial and spatiotemporal random fields that capture persistent and annually varying patterns in swordfish distribution. Because the Réunion longline fleet operates over a large and changing area of the southwestern Indian Ocean, spatial shifts in fishing activity may influence nominal CPUE trends. Spatiotemporal models are therefore expected to provide the most robust abundance index by separating changes in fish availability from changes in fishing location.

The performance of the three approaches was compared using model diagnostics, residual analyses, goodness-of-fit metrics, and the resulting standardized annual indices. Particular attention was given to the consistency of temporal trends among models and to the ability of each approach to account for the substantial spatial variability observed in the fishery.

2.3.1 Delta-Lognormal generalized additive model

Swordfish catch data contained a substantial proportion of zero-catch observations (Table 2; Figure 3), indicating that catch rates were generated by two distinct processes: the probability of encountering swordfish and the magnitude of catches when swordfish were present. To account for this characteristic, CPUE was standardized using a Delta-Lognormal modelling framework.

The Delta approach decomposes CPUE into two model components. The first component models the probability of obtaining a positive catch using a binomial distribution:

$$P(Y_i > 0)$$

where (Y_i) represents the swordfish catch rate for set (i). The second component models the magnitude of positive catch rates conditional on a positive catch:

$$E(Y_i \mid Y_i > 0)$$

Positive CPUE values were calculated as:

$$CPUE_i = \frac{C_i}{H_i} \times 1000$$

where (C_i) is the swordfish catch weight (kg) and (H_i) is the number of hooks deployed in set (i). Positive CPUE values were log-transformed prior to modelling to improve normality and stabilize variance.

Both model components were fitted using generalized additive models (GAMs) implemented in the R package *mgcv* using the *bam()* function. The occurrence component was fitted using a binomial error distribution with a logit link function, while the positive component was fitted using a Gaussian distribution applied to log-transformed positive CPUE values.

The predictor structure included year and quarter as fixed effects, a vessel random effect, and a two-dimensional spatial smoother:

$$\eta_i = \text{Year}_i + \text{Quarter}_i + s(\text{Vessel}_i) + s(\text{Longitude}_i, \text{Latitude}_i)$$

where ($s()$) denotes a smooth function estimated from the data. Vessel effects were modelled as random effects to account for differences in fishing practices and vessel performance, while the spatial smoother accounted for persistent geographic variation in swordfish availability.

The annual standardized index was derived by multiplying predictions from the two model components:

$$I_t = \hat{P}_t \times \widehat{CPUE}_t^+$$

where ($\hat{P}_t$) is the predicted probability of a positive catch and ($\widehat{CPUE}_t^+$) is the predicted positive catch rate for year (t). Standardized indices were scaled relative to the first year of the analysis period to facilitate comparison among modelling approaches.

2.3.2 Model 2: Tweedie model

As an alternative to the Delta-GAM framework, swordfish CPUE was standardized using a generalized additive model (GAM) with a Tweedie error distribution. The Tweedie family is particularly well suited to fisheries catch-rate data because it can accommodate a mixture of exact zeros and positive continuous observations within a single modelling framework.

CPUE for set (i) was calculated as:

$$CPUE_i = \frac{C_i}{H_i} \times 1000$$

where (C_i) is the swordfish catch weight (kg) and (H_i) is the number of hooks deployed in set (i). Unlike the Delta approach, both zero and positive observations were modelled simultaneously.

The Tweedie distribution belongs to the exponential dispersion family and is characterized by a variance function of the form:

$$Var(Y_i) = \phi \mu_i^p$$

where (μ_i) is the expected CPUE, (ϕ) is the dispersion parameter, and (p) is the Tweedie power parameter. For values of $1 < p < 2$, the distribution represents a compound Poisson-Gamma process capable of generating both zero and positive observations, making it appropriate for fisheries CPUE data.

The model was fitted using the *bam()* function from the R package *mgcv* with a log-link function. The predictor structure was identical to that used in the Delta-GAM:

$$\eta_i = \text{Year}_i + \text{Quarter}_i + s(\text{Vessel}_i) + s(\text{Longitude}_i, \text{Latitude}_i)$$

where *year* and *quarter* were included as fixed effects, *vessel* was included as a random effect, and a two-dimensional smoother was used to account for spatial variation in swordfish availability.

Standardized annual indices were obtained from model predictions by averaging predicted CPUE across all observations while holding explanatory variables at their observed values. Annual indices were subsequently scaled relative to the first year of the analysis period to facilitate comparison with the Delta-GAM and spatiotemporal modelling approaches.

Compared with the Delta-GAM, the Tweedie model offers a simpler modelling framework because occurrence and positive catch processes are estimated simultaneously. Similar trends between the two approaches would provide evidence that the resulting abundance index is robust to alternative distributional assumptions.

2.3.3 Spatiotemporal generalized linear mixed model (*sdmTMB*)

To explicitly account for spatial and temporal variation in swordfish catch rates, CPUE was standardized using spatiotemporal generalized linear mixed models fitted with the R package sdmTMB. Unlike conventional GAM approaches, which account for spatial variation through smooth functions of latitude and longitude, spatiotemporal models estimate latent spatial processes that can vary through time and therefore provide a more realistic representation of fish distributions and fishing dynamics.

Swordfish CPUE was modelled as a function of year, quarter, vessel effects, and spatial location. The linear predictor can be expressed as:

$$\eta_{s,t} = \mathbf{X}s, t\boldsymbol{\beta} + \omega_s + \epsilon s, t$$

where ($\mathbf{X}s, t\boldsymbol{\beta}$) represents the fixed effects, (ω_s) is a spatial random field describing persistent spatial differences in swordfish abundance, and ($\epsilon s, t$) is a spatiotemporal random field describing annual deviations from the average spatial pattern.

The spatial random fields were estimated using the stochastic partial differential equation (SPDE) approach, which approximates Gaussian random fields on a triangulated mesh covering the fishing grounds. This framework allows spatial autocorrelation to be modelled efficiently while accommodating large fisheries datasets.

Several candidate model formulations were evaluated, including models with spatial random fields only and models including both spatial and spatiotemporal random fields. Alternative observation distributions were also considered to accommodate the large number of zero catches observed in the dataset. Model selection was based on residual diagnostics, predictive performance, and information-theoretic criteria.

Standardized annual indices were derived from model predictions averaged over a common spatial domain. By predicting abundance across the same geographic region each year, the resulting indices are less sensitive to shifts in fishing locations than conventional CPUE standardizations. This approach is particularly relevant for the Réunion pelagic longline fishery, whose spatial footprint has varied substantially through time (Figure 4).

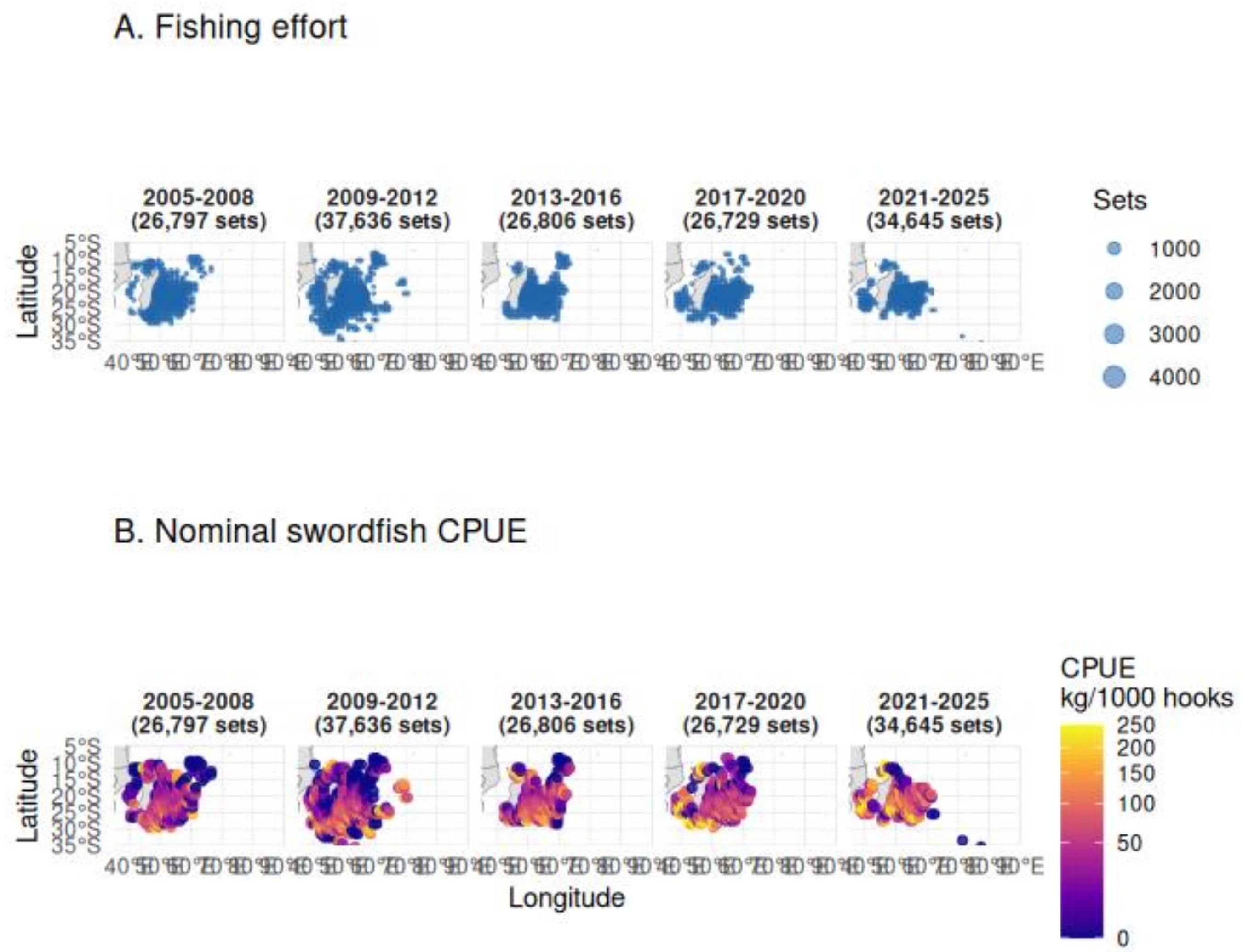

Figure 4: Spatial distribution of fishing effort and nominal swordfish CPUE in the Réunion pelagic longline fishery. (A) Fishing effort aggregated by 5° × 5° spatial cell for successive four- to five-year periods, with symbol size proportional to the number of fishing sets. (B) Mean nominal swordfish CPUE (kg·1000 hooks^{-1}) by spatial cell and period. Fishing activity remained concentrated in the southwestern Indian Ocean throughout the study period, while spatial variation in CPUE was consistently observed across the fishing grounds.

The spatiotemporal modelling framework was expected to provide the most robust abundance index because it explicitly accounts for both spatial heterogeneity and temporal changes in the distribution of swordfish and fishing effort. Comparisons with the Delta-GAM and Tweedie GAM indices were used to assess the sensitivity of standardized CPUE trends to alternative modelling assumptions.

3. Results

3.1 Fishery dynamics and changes in fishing practices

3.1.1 Fleet and effort

The final dataset comprised 144,105 longline sets collected between 2005 and 2025 from 21–29 active vessels annually. Mean hooks per set remained relatively stable throughout the study period (approximately 1,300–1,470 hooks per set), indicating that fishing power associated with set size changed little over time (Table 3).

Table 3: Annual summary of the Réunion pelagic longline fishery used for swordfish CPUE standardization, including the number of fishing sets, active vessels, occupied 1° spatial cells, mean number of hooks per set, and nominal swordfish CPUE.

Year	Sets	Vessels	Cells	Mean hooks per set	Nominal CPUE (kg/1000 hooks)
2005	4519	24	148	1432.3	60.2
2006	6152	24	141	1428.2	57.6
2007	7973	29	154	1451.2	51.5
2008	7559	29	165	1447.5	42.6
2009	10359	28	182	1450.5	53.7
2010	9521	26	208	1452.4	62.0
2011	8707	24	195	1457.2	68.3
2012	6660	22	161	1425.2	58.6
2013	6238	18	89	1398.3	60.7
2014	6555	18	122	1385.9	67.2
2015	6703	19	145	1402.0	62.4
2016	6655	19	143	1398.2	65.6
2017	5790	17	91	1444.8	60.4
2018	5982	19	142	1441.9	64.3
2019	6248	19	109	1473.5	73.9
2020	6528	18	110	1429.5	83.9
2021	5804	19	81	1419.8	104.6
2022	6294	21	88	1382.8	97.1
2023	6769	20	110	1298.1	108.9
2024	6739	21	90	1381.9	111.2
2025	6350	21	114	1361.1	114.0

3.1.2 Spatial distribution of effort

The spatial distribution of fishing effort varied substantially over the study period (Figure 4). The fleet occupied between 82 and 220 one-degree grid cells annually, with the broadest spatial coverage occurring during 2008–2011. After 2020, fishing effort became progressively concentrated within fewer spatial cells, although the number of sets per occupied cell increased. These temporal shifts in fishing distribution provide a strong rationale for applying spatially explicit CPUE standardization methods.

3.1.3 Fishing strategy

Two principal fishing strategies were represented in the dataset. Swordfish-targeting trips (LLDSWO) accounted for approximately 70% of all longline sets, whereas mixed large-pelagic trips (LLDLPF) comprised the remainder (Figure 1). Mean nominal swordfish CPUE was substantially higher for LLDSWO sets (81.3 kg·1000 hooks^{-1}) than for LLDLPF sets (44.3 kg·1000 hooks^{-1}), reflecting differences in targeting strategy rather than underlying abundance (Table 4). Positive swordfish catches occurred in 65.9% of LLDSWO sets and 84.1% of LLDLPF sets. These differences justify the inclusion of fishing métier as an explanatory variable in subsequent standardization models.

Table 4: Summary of fishing effort and nominal swordfish catch rates by fishing métier (LLDSWO: swordfish-directed longline; LLDLPF: deep pelagic longline).

Métier	Sets	Sets (%)	Positive sets (%)	Nominal CPUE (kg/1000 hooks)
LLDLPF	41319	28.7	84.1	44.5
LLDSWO	102786	71.3	65.9	82.1

Nominal swordfish CPUE exhibited considerable interannual variability, with a pronounced increase after 2018 (Figure 5). However, this trend coincided with substantial changes in both fishing distribution and fishing strategy, emphasizing the need for statistical standardization before interpreting temporal changes in abundance.

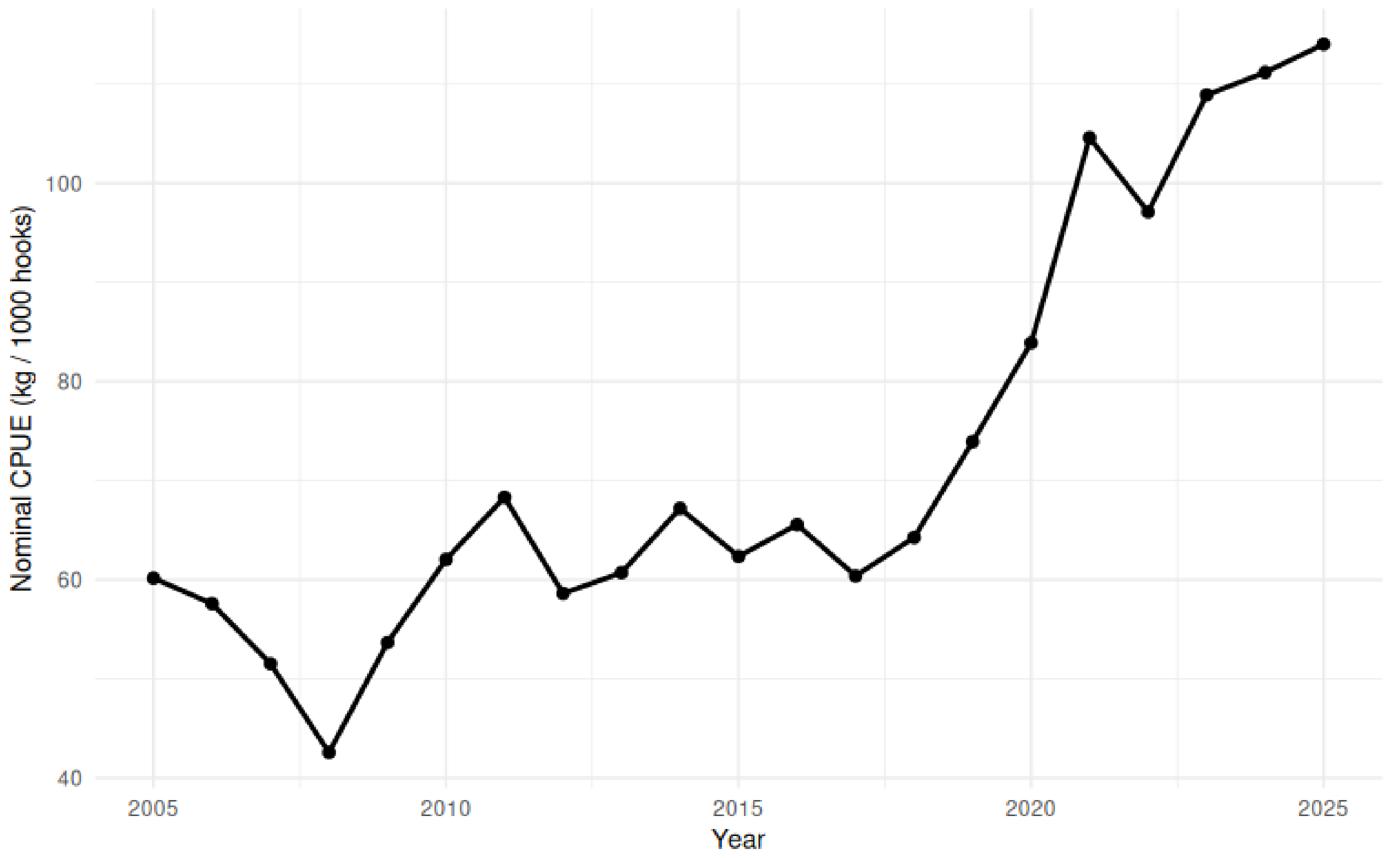

Figure 5: Annual nominal swordfish CPUE (kg per 1,000 hooks) in the Réunion pelagic longline fishery between 2005 and 2025, expressed relative to 2005 (=1).

3.2 Model performance

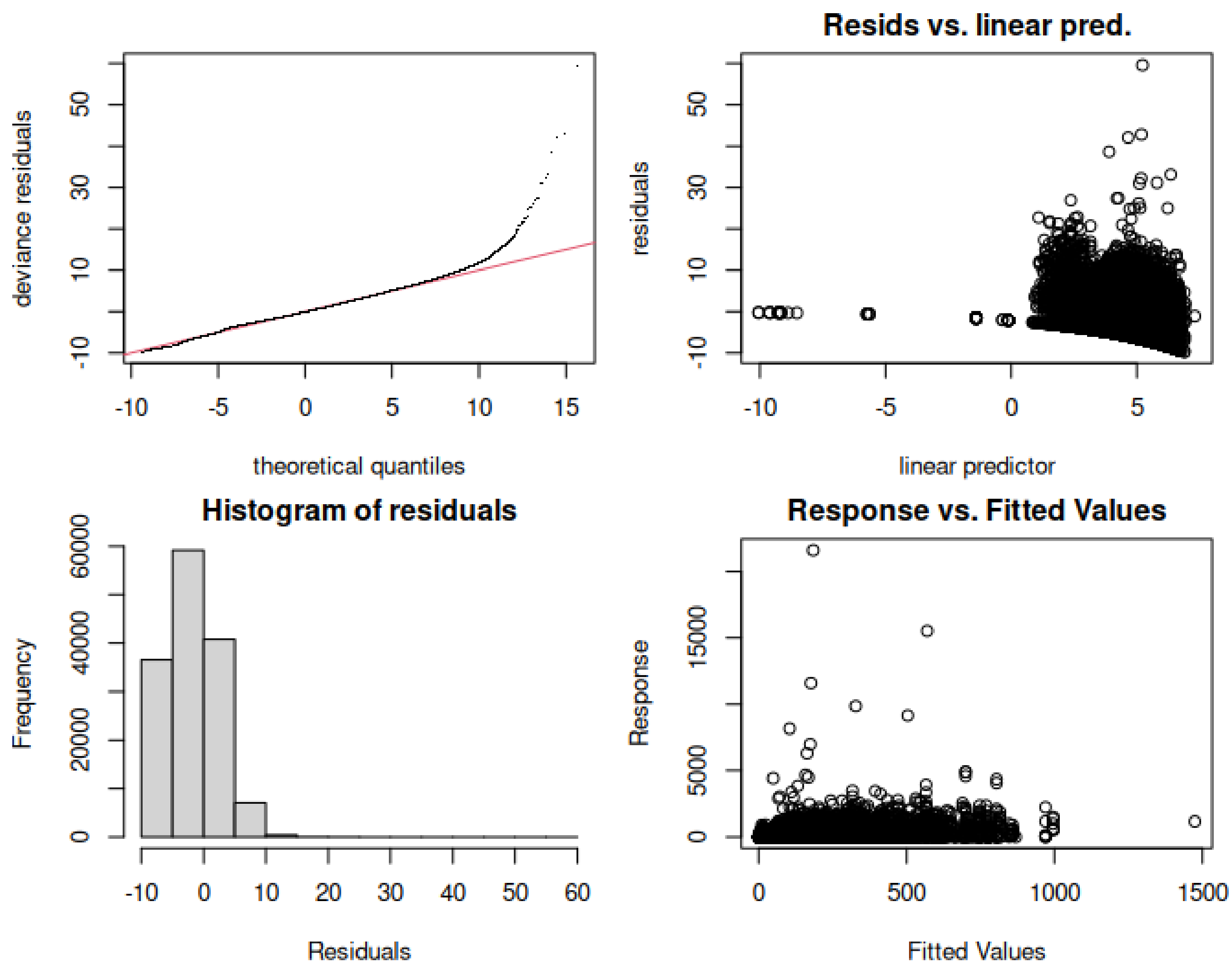

Figure 6: Residual diagnostics for the Tweedie-GAM. Panels show the quantile-quantile plot of deviance residuals, residuals against the linear predictor, the histogram of residuals, and the response plotted against fitted values.

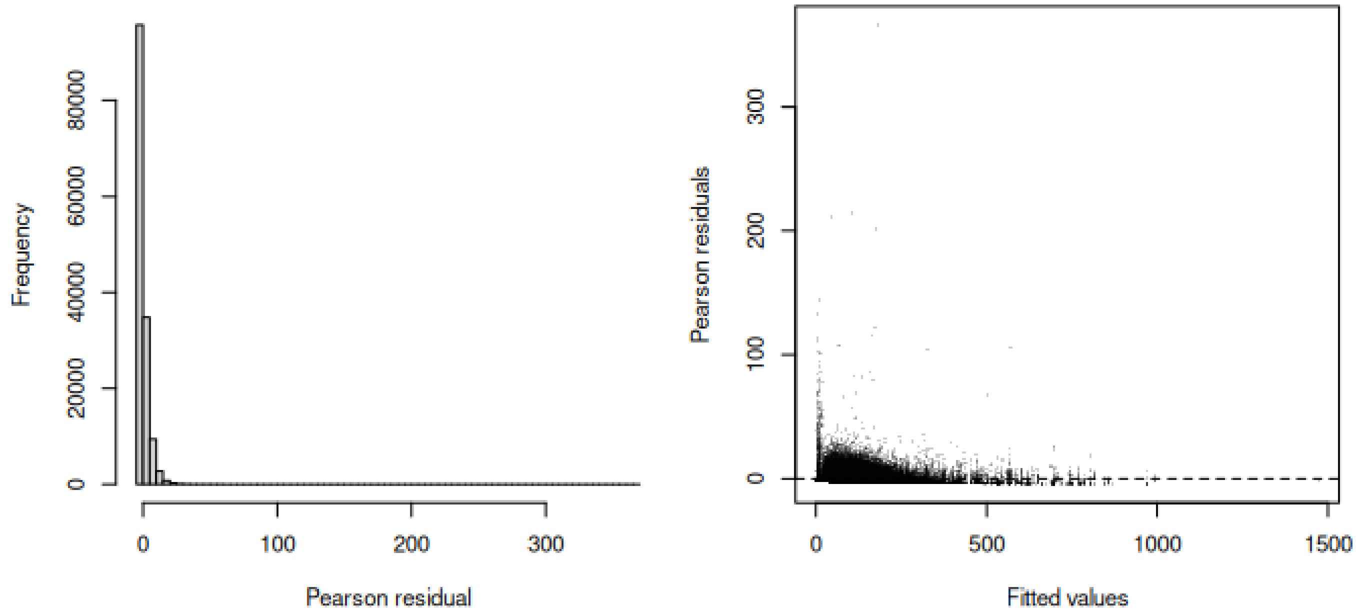

Figure 7: Distribution of Pearson residuals from the Tweedie-GAM (left) and Pearson residuals plotted against fitted values (right). The dashed line indicates zero residual.

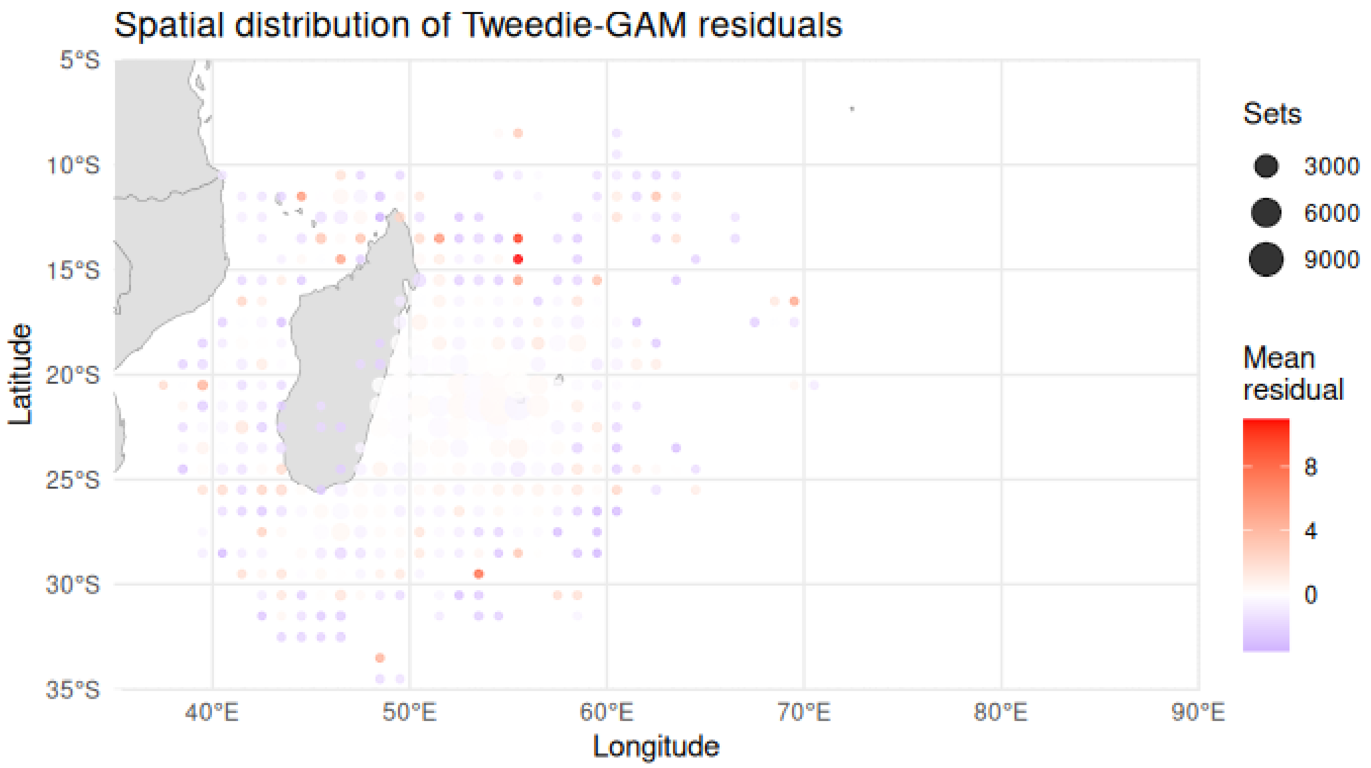

Figure 8: Spatial distribution of mean Tweedie-GAM Pearson residuals by 1° spatial cell. Symbol size is proportional to the number of fishing sets and colour indicates the mean residual. The absence of large-scale spatial structure indicates that the spatial smoother adequately captured persistent geographic variation in swordfish catch rates.

3.2.1 Model comparison

Four alternative standardization approaches were evaluated: a Delta-GAM, a Tweedie-GAM, an sdmTMB model with a spatial random field, and an sdmTMB model including both spatial and spatiotemporal random fields. Model performance was compared using Akaike's Information Criterion (AIC). The inclusion of fishing métier substantially improved model fit for both the encounter and positive Delta-GAM components (ΔAIC = 4951 and 9420, respectively), supporting its retention in all subsequent analyses. Likewise, the Tweedie-GAM including métier provided a substantially better fit than the corresponding model without métier (ΔAIC = 2952). Within the sdmTMB framework, the inclusion of an IID spatiotemporal random field further improved model fit relative to the purely spatial model (ΔAIC = 3050), indicating that both spatial structure and year-specific spatial variability contributed to explaining catch variability.

3.2.2 Significance of explanatory variables

Quarter, fishing métier, vessel identity, and spatial location all contributed significantly to explaining variation in swordfish catch rates (all $P < 0.001$). The estimated Tweedie dispersion parameter was 13.39 with an estimated Tweedie power parameter of 1.56, indicating an appropriate compound Poisson–Gamma distribution for the observed catch data.

3.2.3 Diagnostic evaluation

Residual diagnostics indicated generally satisfactory model performance (Figure 6). Quantile–quantile plots showed good agreement with the theoretical distribution over most of the residual range, with moderate deviations confined to the upper tail owing to a small number of exceptionally large catches. Residuals displayed no systematic relationship with fitted values, although increasing variance at higher predicted catches reflected the inherent heteroscedasticity of fisheries catch data (Figure 7). Spatial aggregation of residuals revealed no large-scale geographic patterns (Figure 8), suggesting that the spatial smooth adequately captured the principal spatial structure.

3.2.4 Robustness of annual index

The annual standardized indices obtained from the Delta-GAM and Tweedie-GAM approaches were highly consistent (Pearson's $r = 0.959$), while both were strongly correlated with the nominal CPUE series ($r = 0.956–0.991$). Despite differences in model formulation, all approaches identified the same temporal pattern characterized by relatively stable abundance until approximately 2018 followed by a marked increase thereafter (Figure 11). This consistency indicates that the estimated temporal trend is robust to model choice.

The Delta-GAM framework consisted of a binomial encounter model and a Gaussian model fitted to positive catch rates. Both model components identified significant effects of year, quarter, fishing métier, vessel identity, and spatial location ($p < 0.001$). The encounter model explained 7.4% of the deviance.

3.3 Standardized abundance trends

3.3.1 Overall trend

The final standardized abundance index derived from the Tweedie-GAM revealed substantial changes in swordfish catch rates over the study period (Figure 9; Table 6). Following an initial decline between 2005 and 2008, standardized CPUE remained relatively stable until approximately 2018 before increasing markedly during the final years of the time series. Relative to the 2005 baseline, the standardized index reached 2.18 in 2025, corresponding to more than a two-fold increase in standardized swordfish abundance.

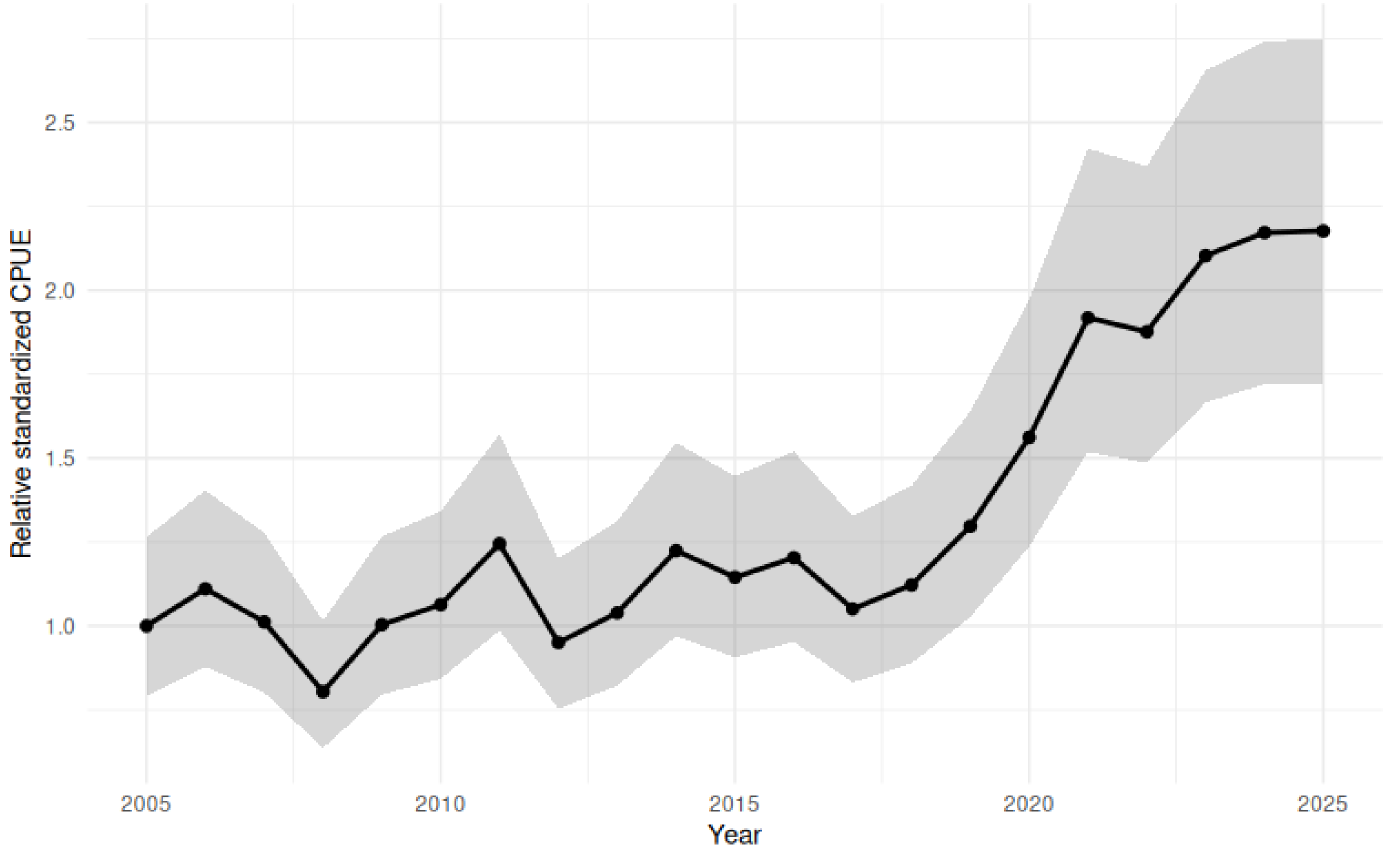

Figure 9: Tweedie-GAM standardized swordfish CPUE index for the Réunion pelagic longline fishery, expressed relative to 2005 (=1). The shaded ribbon represents approximate 95% confidence intervals.

3.3.2 Focus on the recent increase

The most pronounced increase occurred after 2018. Between 2018 and 2025, the standardized index increased by approximately 94%, rising from 1.12 to 2.18. The increase was progressive rather than abrupt, with standardized abundance exceeding 1.5 by 2020 and remaining above 2.0 from 2023 onwards (Figure 9). Confidence intervals showed limited overlap between the earliest and latest years of the series, supporting a sustained long-term increase rather than short-term interannual variability.

3.3.3 Biological interpretation

Although annual fluctuations were evident throughout the time series, no persistent long-term decline was detected. Instead, the standardized abundance index suggests a period of relatively stable swordfish availability between approximately 2009 and 2018 followed by a sustained increase during the last seven years of the study. The potential biological and fishery-related drivers of this recent increase are considered in the Discussion.

3.4 Interannual changes in standardized abundance

The annual effects estimated by the Tweedie-GAM were generally consistent with the standardized abundance index, but provide a formal statistical comparison of each year relative to the 2005 baseline (Figure 10; Table 5).

Standardized abundance was significantly lower in 2008, with an estimated relative effect of 0.8 (95% CI: 0.76–0.85), corresponding to approximately 20% lower catch rates than in 2005. Between 2009 and 2018, annual effects fluctuated around the baseline, with most years remaining within approximately ±25% of the 2005 level despite several statistically significant deviations (Figure 10).

A sustained increase in standardized abundance began in 2019. Relative effects increased from 1.30 in 2019 to 1.56 in 2020 and exceeded 1.85 from 2021 onwards. The largest effects were estimated for 2023–2025, during which standardized catch rates were approximately 2.1–2.2 times higher than in 2005 (Table 5). All annual effects from 2019 onwards were highly significant ($p < 0.001$), indicating that the recent increase in standardized abundance represents a persistent shift rather than isolated interannual fluctuations.

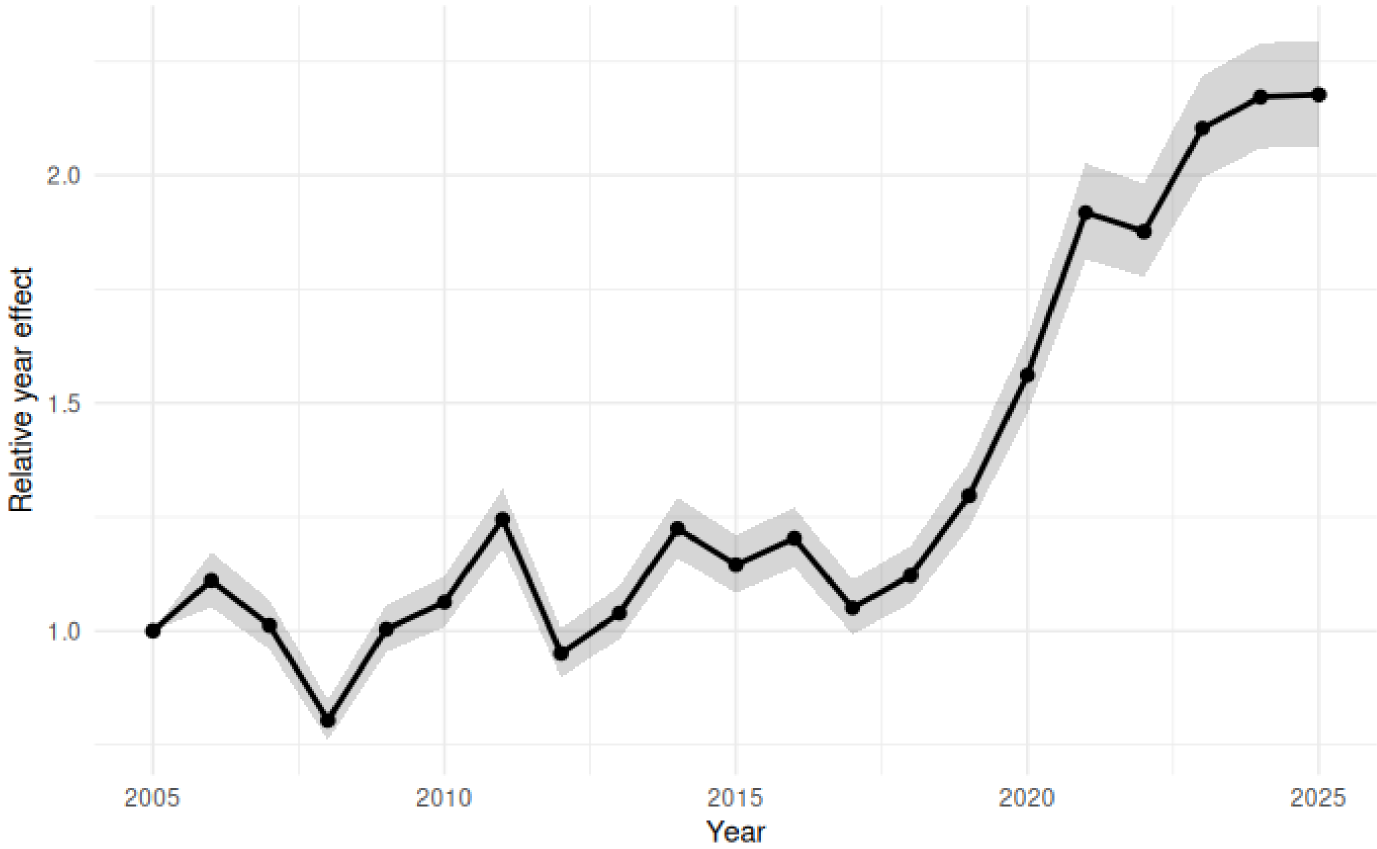

Figure 10: Annual effects estimated by the Tweedie-GAM, expressed relative to the 2005 baseline (=1). Points show the estimated relative effect for each year and the shaded ribbon shows approximate 95% confidence intervals.

Table 5: Annual effects estimated by the Tweedie-GAM relative to the 2005 baseline, with approximate 95% confidence intervals and the significance of each annual coefficient.

Year	Relative effect	2.5%	97.5%	Estimate	Std. error	p-value
2005	1.000	1.000	1.000	0.000	0.000	NA
2006	1.111	1.052	1.173	0.105	0.028	0.000
2007	1.012	0.959	1.068	0.012	0.027	0.662
2008	0.804	0.761	0.849	-0.218	0.028	0.000
2009	1.004	0.953	1.057	0.004	0.026	0.892
2010	1.063	1.009	1.120	0.061	0.027	0.021
2011	1.245	1.181	1.313	0.219	0.027	0.000
2012	0.950	0.899	1.005	-0.051	0.028	0.074
2013	1.039	0.982	1.099	0.038	0.029	0.182
2014	1.224	1.159	1.294	0.202	0.028	0.000
2015	1.145	1.084	1.210	0.135	0.028	0.000
2016	1.203	1.139	1.271	0.185	0.028	0.000
2017	1.051	0.993	1.112	0.049	0.029	0.088
2018	1.122	1.061	1.187	0.115	0.029	0.000
2019	1.297	1.227	1.371	0.260	0.028	0.000
2020	1.562	1.478	1.650	0.446	0.028	0.000
2021	1.918	1.815	2.026	0.651	0.028	0.000
2022	1.876	1.777	1.981	0.629	0.028	0.000
2023	2.103	1.994	2.218	0.743	0.027	0.000
2024	2.172	2.060	2.290	0.776	0.027	0.000
2025	2.177	2.064	2.295	0.778	0.027	0.000

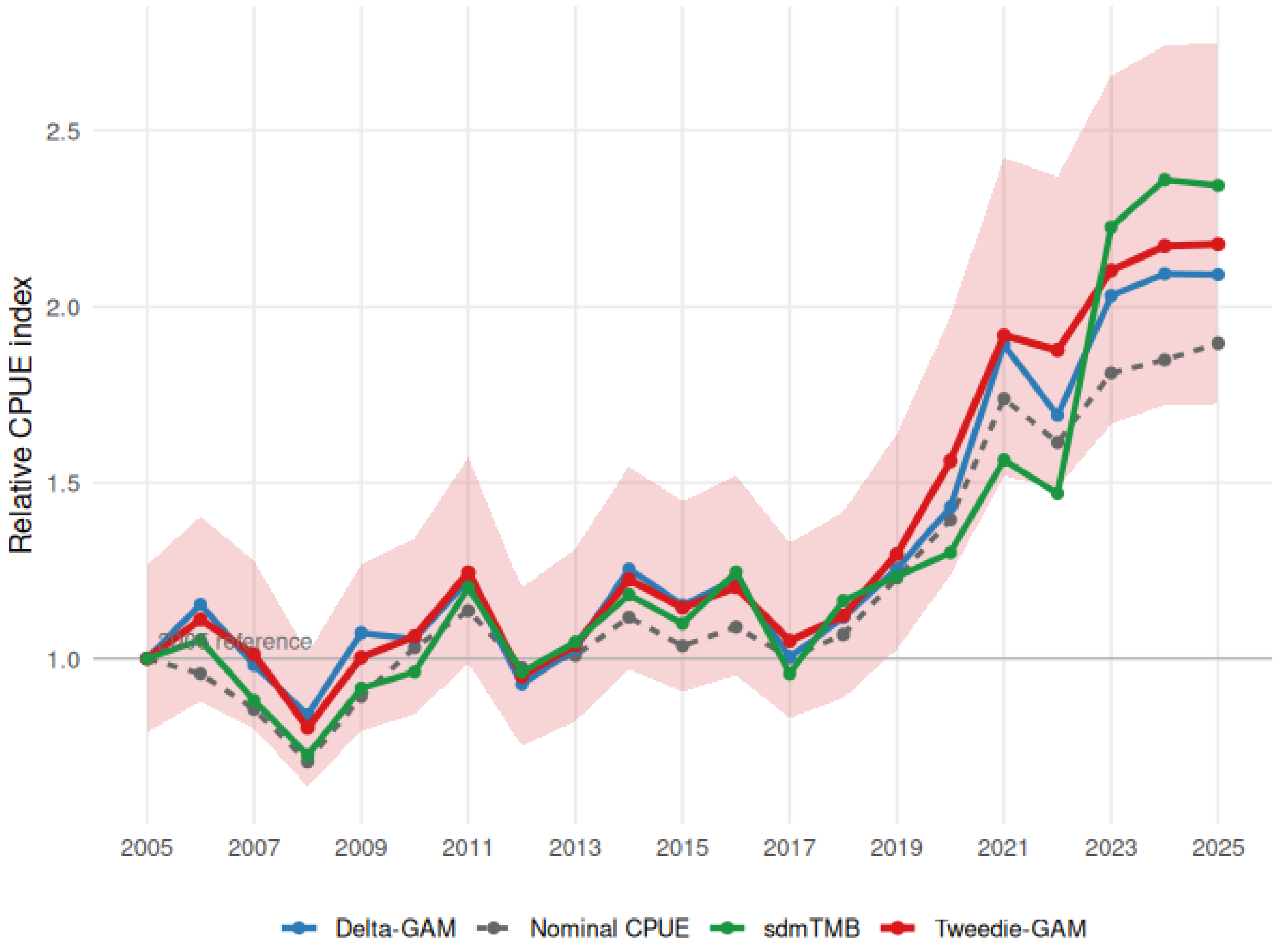

Figure 11: Comparison of nominal and standardized annual swordfish CPUE indices estimated using alternative modelling approaches. All indices were standardized relative to 2005 (=1). The shaded ribbon represents approximate 95% confidence intervals for the Tweedie-GAM.

Overall, the annual-effect estimates support the interpretation of three broad phases in the time series: (i) an initial decline culminating in 2008, (ii) a decade of relatively stable standardized abundance, and (iii) a sustained increase beginning around 2019.

3.5 Robustness of standardized abundance trends

The standardized abundance trends obtained from the Delta-GAM, Tweedie-GAM and spatiotemporal sdmTMB models were highly consistent (Figure 11). Pairwise correlations among standardized indices ranged from 0.959 to 0.991, indicating that the inferred temporal trend was largely insensitive to model formulation.

All three approaches identified the same principal features of the time series, namely an initial decline between 2005 and 2008, relative stability until approximately 2018, and a marked increase thereafter. The final standardized abundance index estimated in 2025 ranged from approximately 2.0 to 2.2 times the 2005 baseline across the different modelling approaches.

The spatiotemporal sdmTMB model substantially improved model fit relative to the spatial-only model (ΔAIC = 3427), indicating the presence of year-specific spatial variation in swordfish availability. Nevertheless, the resulting abundance trajectory remained highly consistent with the Tweedie-GAM index, suggesting that the observed increase cannot be explained solely by changes in fishing location or spatial redistribution of the stock.

3.6 Annual effects from the Tweedie-GAM

The annual effects estimated by the Tweedie-GAM indicated relatively modest departures from the 2005 baseline during the first part of the time series. Standardized catch rates were significantly lower in 2008 (relative effect = 0.80) and significantly higher in 2011 (1.24), 2014 (1.22), and 2016 (1.20), but generally remained within ±25% of the baseline level.

A marked increase in standardized swordfish catch rates began in 2019 (relative effect = 1.30) and strengthened thereafter. Relative effects reached 1.56 in 2020 and exceeded 1.85 from 2021 onwards. The highest annual effects were observed during 2023–2025, with standardized catch rates approximately 2.1–2.2 times higher than those estimated for 2005. All annual effects from 2019 onwards were highly significant ($p < 0.001$).

These results indicate a sustained increase in standardized swordfish catch rates beginning around 2019, rather than a short-lived fluctuation associated with a single year or localized event.

Collectively, the different standardization approaches consistently identified three phases in the Réunion swordfish fishery: (*i*) an initial decline in standardized abundance until 2008, (*ii*) a prolonged period of relative stability, and (*iii*) a marked increase beginning around 2019. The similarity of the standardized indices across model formulations indicates that these temporal patterns are robust to alternative assumptions regarding zero catches and spatial structure. The values for the standardized CPUE using the Tweedie model and the nominal cpue are available in Table 6. The comparison of the nominal CPUE and the different CPUE is available on @.

Table 6: Annual nominal and Tweedie-GAM standardized swordfish CPUE indices relative to 2005.

Year	Nominal	Standardized	2.50%	97.50%
2005	1.000	1.000	0.791	1.265
2006	0.957	1.111	0.879	1.404
2007	0.856	1.012	0.801	1.278
2008	0.708	0.804	0.636	1.015
2009	0.892	1.004	0.795	1.267
2010	1.031	1.063	0.842	1.342
2011	1.136	1.245	0.986	1.571
2012	0.974	0.950	0.752	1.201
2013	1.009	1.039	0.822	1.313
2014	1.117	1.224	0.969	1.546
2015	1.037	1.145	0.906	1.446
2016	1.090	1.203	0.953	1.520
2017	1.004	1.051	0.831	1.328
2018	1.068	1.122	0.888	1.417
2019	1.229	1.297	1.027	1.638
2020	1.395	1.562	1.236	1.972
2021	1.739	1.918	1.519	2.422
2022	1.614	1.876	1.486	2.370
2023	1.811	2.103	1.666	2.655
2024	1.849	2.172	1.720	2.742
2025	1.896	2.177	1.724	2.748

4. Discussion

4.1 Standardization successfully disentangled changes in fishing practices from abundance

The Réunion pelagic longline fishery underwent substantial changes over the two decades covered by this study. Fleet composition evolved, fishing effort became more spatially concentrated, and the relative importance of the two principal métiers (LLDSWO and LLDLPF) changed markedly through time. In addition, nominal catch rates were influenced by seasonal variability, individual vessel characteristics, and heterogeneous fishing grounds. Such changes are expected to affect catchability independently of stock abundance, making nominal CPUE an unreliable indicator of population trends when interpreted in isolation.

The objective of CPUE standardization is precisely to account for these sources of variation so that the remaining temporal signal more closely reflects changes in fish availability to the fishery. Across all modelling approaches, year remained a highly significant predictor of swordfish catches after accounting for season, fishing métier, vessel effects and spatial structure. The persistence of a strong temporal trend following standardization indicates that the recent increase in CPUE cannot be explained solely by shifts in fishing strategy or fleet composition.

Several results support this interpretation. First, inclusion of fishing métier significantly improved model fit for both components of the Delta-GAM (ΔAIC = 4951 and ΔAIC = 9420 for the encounter and positive-catch models, respectively), confirming that targeting strategy influences swordfish catch rates. Likewise, both the spatial smooth and vessel random effect explained significant variation in catches, demonstrating the importance of accounting for heterogeneous fishing grounds and vessel-specific fishing efficiency. Nevertheless, correcting for these factors produced only modest changes in the overall temporal trajectory relative to the nominal index. Instead, all standardized approaches converged on the same general pattern of an initial decline, a prolonged period of relative stability, and a pronounced increase beginning around 2019.

The close agreement among the Delta-GAM, Tweedie-GAM and spatiotemporal sdmTMB models further strengthens confidence in the robustness of the inferred trend. Although these approaches differ substantially in their statistical assumptions and treatment of zero catches and spatial correlation, they all produced highly correlated standardized indices (correlations ranging from 0.959 to 0.991. Moreover, the inclusion of spatiotemporal random fields improved model fit (ΔAIC = 3427), yet resulted in only minor changes to the estimated annual abundance trajectory. Collectively, these findings indicate that the observed increase is not an artefact of the particular standardization method selected.

Despite these encouraging results, standardized CPUE should still be interpreted as an index of relative availability to the fishery, rather than a direct measure of stock biomass. Standardization can account only for variables that are observed and included in the model. Operational characteristics such as hook depth, bait type, branchline configuration, soak duration, light-stick use, and other changes in fishing practices were not available in the present dataset and therefore could not be evaluated. These factors may influence catchability and should be considered when interpreting long-term CPUE trends.

4.2 Robustness of the standardized index

An important objective of this study was to evaluate whether the inferred temporal trend depended on the choice of statistical standardization method. Although the Delta-GAM, Tweedie-GAM, and spatiotemporal sdmTMB models differ substantially in their treatment of zero catches, error distributions, and spatial dependence, they produced remarkably similar standardized abundance trajectories. Pairwise correlations among the standardized indices exceeded 0.959, and all approaches identified the same three broad phases of the time series: an initial decline between 2005 and 2008, a relatively stable period extending until approximately 2018, and a sustained increase thereafter. This convergence provides strong evidence that the inferred temporal signal is robust to alternative statistical assumptions.

Delta models have long been considered the standard approach for standardizing fisheries catch-per-unit-effort data containing large numbers of zero catches because they explicitly separate encounter probability from the distribution of positive catches (Lo et al., 1992; Stefánsson, 1996; Maunder & Punt, 2004). More recently, Tweedie distributions have gained increasing acceptance as a one-stage alternative capable of modelling zero and positive catches simultaneously within a compound Poisson–Gamma framework, while often providing comparable or improved statistical performance [Shono2008]. In the present study, the Tweedie-GAM produced a standardized abundance index that was almost indistinguishable from the Delta-GAM despite its simpler formulation. This result suggests that, for the Réunion swordfish fishery, the additional complexity associated with modelling encounter probability and positive catches separately provides little practical benefit for estimating annual abundance indices.

Similarly, incorporating explicit spatial and spatiotemporal random fields through sdmTMB significantly improved statistical fit, indicating that residual spatial dependence remained after accounting for the principal explanatory variables. Spatially explicit models have become increasingly important in fisheries stock assessment because they account for spatial autocorrelation and shifting fishing distributions that may bias conventional CPUE standardization (Thorson et al., 2015; Anderson et al., 2024). Nevertheless, despite the improved likelihood of the spatiotemporal model, the resulting abundance trajectory closely matched those obtained from both GAM-based approaches. This suggests that broad-scale changes in fishing location are unlikely to explain the observed increase in standardized CPUE.

Comparative evaluations of multiple standardization frameworks on the same fishery dataset remain relatively uncommon, particularly those incorporating both traditional Delta approaches and modern spatiotemporal mixed-effects models. By comparing three conceptually distinct modelling strategies within a common analytical framework, this study demonstrates that the inferred temporal trend is remarkably insensitive to the statistical formulation adopted. The convergence of the standardized indices across models therefore provides stronger evidence for the robustness of the estimated abundance trajectory than would be obtained from a single modelling approach alone.

From an operational perspective, the Tweedie-GAM offers an attractive compromise between statistical performance, computational efficiency, and ease of implementation. Given its one-stage formulation, strong diagnostic performance, and close agreement with both the Delta-GAM and spatiotemporal sdmTMB models, it appears particularly well suited for routine CPUE standardization within future IOTC swordfish stock assessments. At the same time, the agreement with the spatially explicit model provides additional confidence that the standardized index is not unduly influenced by residual spatial structure, strengthening its suitability for long-term monitoring of swordfish abundance.

4.3 Evidence for increasing swordfish availability in the southwest Indian Ocean

The standardized CPUE indices consistently indicate that swordfish availability to the Réunion pelagic longline fleet has increased substantially during the last two decades, with the most pronounced increase occurring after approximately 2018. Because this trend remained evident after accounting for seasonality, fishing métier, vessel effects, and spatial distribution of fishing effort, it is unlikely to be explained solely by changes in fishing practices. Instead, the results suggest that swordfish have become increasingly available to the Réunion fishery during recent years.

The present findings are broadly consistent with the current understanding of Indian Ocean swordfish stock status. The most recent IOTC stock assessment concluded that the stock is not overfished and not subject to overfishing, and the recently adopted Management Procedure indicates that current catches remain below the recommended total allowable catch for 2026–2028. Although the regional stock assessment integrates information from multiple fisheries operating across the entire Indian Ocean, whereas the present study represents a single regional fishery, the agreement between these independent sources of evidence increases confidence that the observed increase in standardized CPUE reflects a genuine change in stock status or availability rather than a statistical artefact.

Nevertheless, standardized CPUE remains an index of fish availability to the fishing gear rather than a direct estimate of population biomass. Increased availability may arise through several mechanisms, including higher stock abundance, redistribution of the population, or changes in habitat use that increase the overlap between fish and fishing gear. Environmental variability may also influence vertical behaviour and horizontal distribution of swordfish, thereby modifying catchability independently of changes in stock size. Consequently, the increasing standardized CPUE reported here should be interpreted as evidence of increased availability to the Réunion fleet rather than unequivocal evidence of proportional increases in total stock biomass.

An additional consideration is the possibility of CPUE hyperstability, whereby catch rates remain stable or increase despite declining abundance because fish become concentrated in predictable habitats or because fishers progressively improve their ability to locate aggregations (Hilborn & Walters, 1992; Harley et al., 2001; Erisman et al., 2011). The collapse of the northern Atlantic cod stock is perhaps the best-known example of this phenomenon, where commercial catch rates remained relatively high despite severe reductions in spawning biomass owing to the persistence of dense spawning aggregations (Rose & Kulka, 1999). Similar processes could, in principle, affect pelagic fisheries if oceanographic features concentrate swordfish or if fishers increasingly target predictable productive areas. Although the present analyses incorporated spatial effects and demonstrated that the increasing trend persisted after spatial standardization, they cannot completely exclude more localized forms of hyperstability operating at spatial scales finer than those represented in the available data.

The absence of detailed operational information represents another important limitation. Historical logbook records did not include variables such as bait type, hook type, branchline configuration, longline fishing depth, soak duration, light-stick use, or other technological changes that may have occurred progressively through the study period. Among these factors, longline fishing depth is likely to be particularly important because swordfish undertake pronounced diel vertical migrations and relatively small changes in hook depth may substantially modify encounter rates (Carey & Robison, 1981; Abascal et al., 2010). Likewise, gradual improvements in fishing practices or targeting efficiency could increase catchability without corresponding changes in stock abundance. The lack of observer data or detailed gear information therefore limits the ability to explicitly quantify changes in fishing efficiency through time.

Despite these uncertainties, several observations suggest that changes in catchability alone are unlikely to explain the magnitude of the observed increase. First, three statistically distinct modelling frameworks converged on remarkably similar abundance trajectories. Second, explicit correction for spatial distribution, fishing métier, vessel-specific effects, and seasonal variability altered the absolute magnitude of the index but not its temporal pattern. Finally, the increase developed progressively over multiple years rather than occurring as an abrupt shift associated with a specific technological innovation or management change. Collectively, these observations support the interpretation that the Réunion longline fishery has experienced a sustained increase in swordfish availability since approximately 2019, although future work integrating observer data, environmental covariates, and regional stock assessment outputs will be required to determine the relative contributions of changes in abundance, distribution, and catchability.

4.4 Implications for stock assessment

Reliable abundance indices are fundamental components of integrated stock assessments because they provide information on temporal changes in stock availability that cannot be inferred from catch statistics alone (Maunder & Punt, 2004). The standardized index developed in this study represents the first comprehensive CPUE series for the Réunion pelagic longline fishery that explicitly accounts for changes in fishing strategy, spatial distribution, vessel-specific effects, and seasonal variability over more than two decades of operation. As such, it provides a valuable new source of information for future assessments of Indian Ocean swordfish and contributes an independent regional perspective to the suite of abundance indices currently available to the IOTC.

An additional strength of the present study is the duration and consistency of the time series. The standardized CPUE series spans 21 consecutive years, covering multiple recruitment cycles, changes in fleet composition, and evolving fishing strategies. Long-term abundance indices are particularly valuable in integrated stock assessments because they improve the estimation of productivity, recruitment variability, and long-term stock dynamics, while helping to distinguish persistent biological trends from short-term environmental or operational fluctuations. Maintaining continuity in such indices is therefore essential for reliable stock assessment and management advice.

The close agreement among the Delta-GAM, Tweedie-GAM, and spatiotemporal sdmTMB approaches further increases confidence in the suitability of this index for stock assessment applications. Although the spatiotemporal model provided the best statistical fit, it produced an abundance trajectory that was remarkably similar to those obtained from the simpler GAM-based approaches. This suggests that the principal temporal signal is robust and that routine annual updates can be achieved using a computationally efficient Tweedie-GAM without compromising biological interpretation. From an operational perspective, the Tweedie-GAM therefore offers an attractive balance between statistical performance, transparency, reproducibility, and ease of implementation, making it particularly well suited for annual CPUE standardization within the IOTC assessment framework.

The standardized index presented here should be viewed as complementary to the multiple abundance indices currently incorporated into the Indian Ocean swordfish assessment rather than as a replacement for existing datasets. Because it originates from a geographically restricted fishery operating primarily in the southwestern Indian Ocean, it provides regional information that complements indices derived from fleets exploiting different areas of the stock distribution or employing different fishing strategies. Such independent fishery-specific indices are particularly valuable because they allow consistency among abundance trends to be evaluated across fleets, reducing dependence on any single fishery or modelling approach. If future research confirms greater regional population structuring within the Indian Ocean than is currently assumed, regional indices such as the one developed here may become even more informative for detecting geographically specific changes in stock dynamics.

The present study also highlights the importance of maintaining detailed operational information within commercial fisheries. Although the available logbook data were sufficient to construct a robust standardized index, several variables known to influence catchability—including hook depth, bait type, branchline configuration, soak duration, light-stick use, and other gear characteristics—were unavailable. Observer programmes, electronic monitoring systems, and enhanced electronic logbooks would allow these variables to be incorporated into future standardization models, improving the separation of abundance and catchability processes. Likewise, integrating environmental covariates such as sea surface temperature, chlorophyll concentration, dissolved oxygen, mixed-layer depth, and mesoscale oceanographic features may further improve CPUE standardization by accounting for environmentally driven changes in swordfish distribution and availability.

More broadly, this study demonstrates the value of evaluating multiple statistical standardization frameworks within a common analytical framework. While the Tweedie-GAM was selected as the preferred operational model because of its simplicity and strong statistical performance, the agreement among three conceptually distinct approaches provides additional confidence that the inferred temporal trend is not an artefact of model specification. Comparative evaluations of alternative standardization methods remain relatively uncommon in fisheries CPUE studies, yet they provide a powerful means of assessing the robustness of abundance indices before they are incorporated into stock assessments. We therefore recommend that sensitivity analyses comparing alternative statistical frameworks become routine practice when developing long-term CPUE indices for fisheries management.

4.5 Limitations and future work

Several limitations should be considered when interpreting the standardized abundance index developed in this study. First, the analyses were based exclusively on commercial logbook data. Although these data provide extensive temporal coverage and represent the best available information for the Réunion pelagic longline fishery, they lack several operational variables known to influence catchability. Information on hook depth, branchline configuration, bait type, hook type, soak duration, setting time, light-stick use, and other aspects of fishing operations was unavailable. Changes in these factors through time may influence fishing efficiency independently of changes in swordfish abundance and therefore could not be explicitly incorporated into the standardization models.

Second, the spatial resolution of the available fishing location data was limited to approximately 1° × 1° cells. While sufficient for modelling broad-scale spatial variation, this resolution does not capture finer-scale oceanographic processes that are known to influence swordfish distribution. Mesoscale features such as eddies, fronts, thermal gradients, and productivity hotspots may alter swordfish availability over relatively short temporal and spatial scales. Future analyses integrating high-resolution environmental datasets and precise set-by-set GPS positions could improve the representation of habitat-driven variability in catchability.

The absence of independent fishery observations also limits the interpretation of standardized CPUE. Observer programmes and electronic monitoring systems provide information on gear deployment, fishing behaviour, bycatch, and environmental conditions that cannot be reconstructed from historical logbooks alone. Integrating these complementary data sources would improve the ability to distinguish changes in fishing efficiency from genuine changes in stock abundance. Likewise, fishery-independent information, such as electronic tagging, survey data, or environmental DNA, could provide valuable external validation of long-term abundance trends.

The present study focused on correcting for observed sources of variation affecting catchability, but did not explicitly model technological development or behavioural adaptation by fishers. Improvements in navigation systems, oceanographic forecasting, fish-finding technology, or accumulated skipper experience may progressively increase fishing efficiency over time. Similarly, adaptive fishing behaviour may lead vessels to increasingly target predictable areas of high swordfish density. Developing models that explicitly account for technological creep and fisher behaviour remains an important challenge for long-term CPUE standardization.

Future work should also explore more integrated spatiotemporal modelling approaches. Although the sdmTMB model presented here was used primarily as a sensitivity analysis, it demonstrated the potential value of explicitly modelling spatial and temporal dependence simultaneously. Extensions incorporating environmental covariates, dynamic habitat models, or time-varying catchability processes may further improve the interpretation of abundance indices, particularly under changing oceanographic conditions associated with climate variability and climate change.

Finally, this study highlights the value of maintaining long-term, standardized fishery-dependent monitoring programmes. Consistent data collection protocols, improved recording of operational variables, and routine evaluation of alternative standardization frameworks will increase confidence in future abundance indices and strengthen their contribution to regional stock assessments. Continued collaboration between fishers, scientists, and management organizations will therefore be essential for improving the quality and reliability of fisheries-dependent indicators used in ecosystem-based fisheries management.

Climate-driven changes in ocean temperature, oxygen concentration, and productivity may alter swordfish distribution and vertical habitat independently of changes in population size. Future standardization frameworks should therefore seek to explicitly separate environmentally driven changes in availability from changes in abundance by integrating habitat models and environmental covariates into CPUE standardization.

5. Conclusion

This study developed the first standardized swordfish CPUE index for the Réunion pelagic longline fishery using 21 years of commercial logbook data. Three alternative modelling approaches (Delta-GAM, Tweedie-GAM and spatiotemporal sdmTMB) produced highly consistent abundance trajectories despite their different statistical assumptions. After accounting for changes in fishing practices, spatial distribution and vessel effects, standardized swordfish CPUE approximately doubled between 2005 and 2025, with the strongest increase occurring after 2018. The agreement among modelling approaches indicates that this trend is robust and suitable for use as an abundance index in future Indian Ocean swordfish stock assessments. More broadly, the study illustrates how combining complementary standardization frameworks can improve confidence in fisheries-dependent abundance indicators while providing a transparent basis for long-term monitoring under changing environmental conditions.

6. Supplementary information

6.1 Stable effort over time

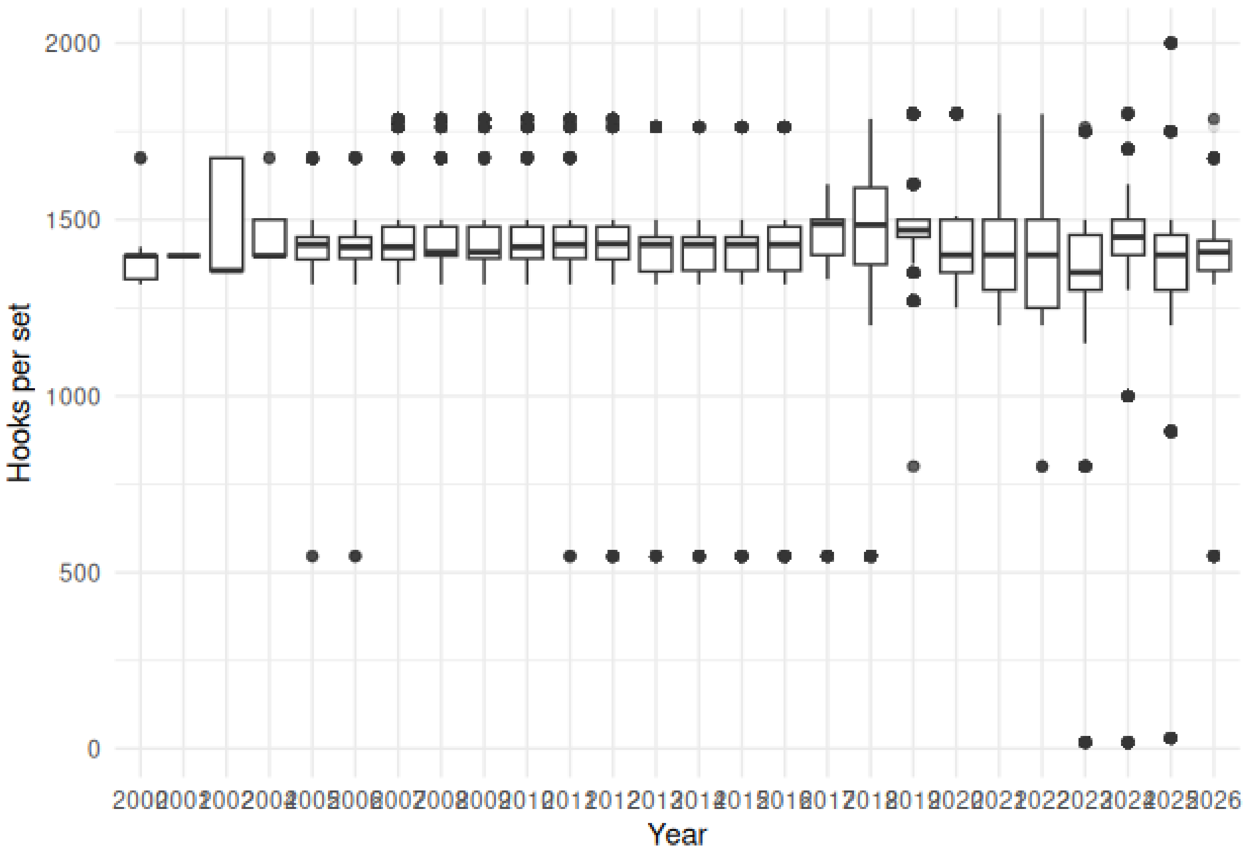

Figure 12: Distribution of reconstructed hooks per set by year for Réunion pelagic longliners between 2000 and 2026. Boxplots show the median, interquartile range, and distribution of hooks per set after effort reconstruction using vessel-year information from the auxiliary hook database. Median hook numbers remained relatively stable throughout the study period, generally ranging between 1,400 and 1,500 hooks per set.

6.2 Comparison

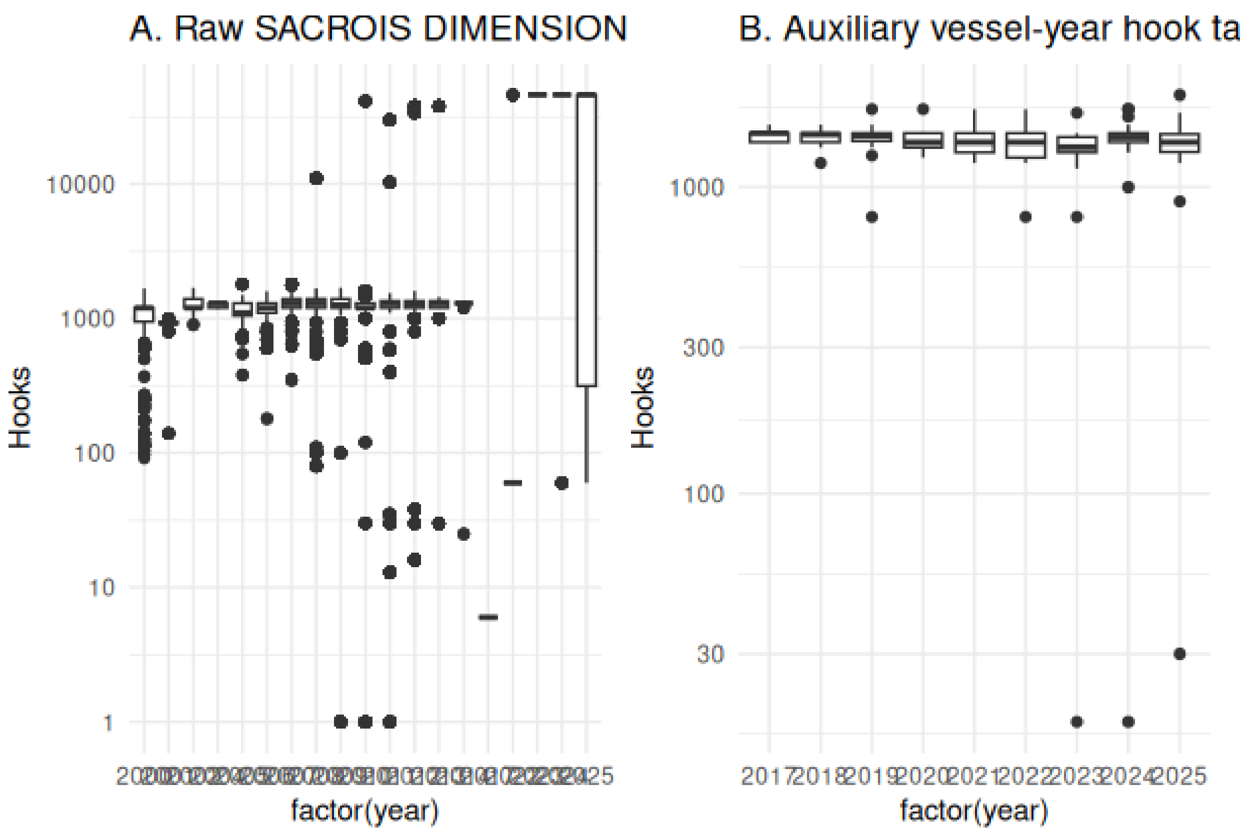

Figure 13: Comparison of the two sources of effort information by year, on a logarithmic scale. (A) Raw hook numbers recorded in the SACROIS DIMENSION field, which contain numerous implausible values. (B) Hook numbers from the auxiliary vessel-year hook database used to reconstruct effort. The comparison motivates the use of the auxiliary source rather than the raw field.

Fleet dynamics

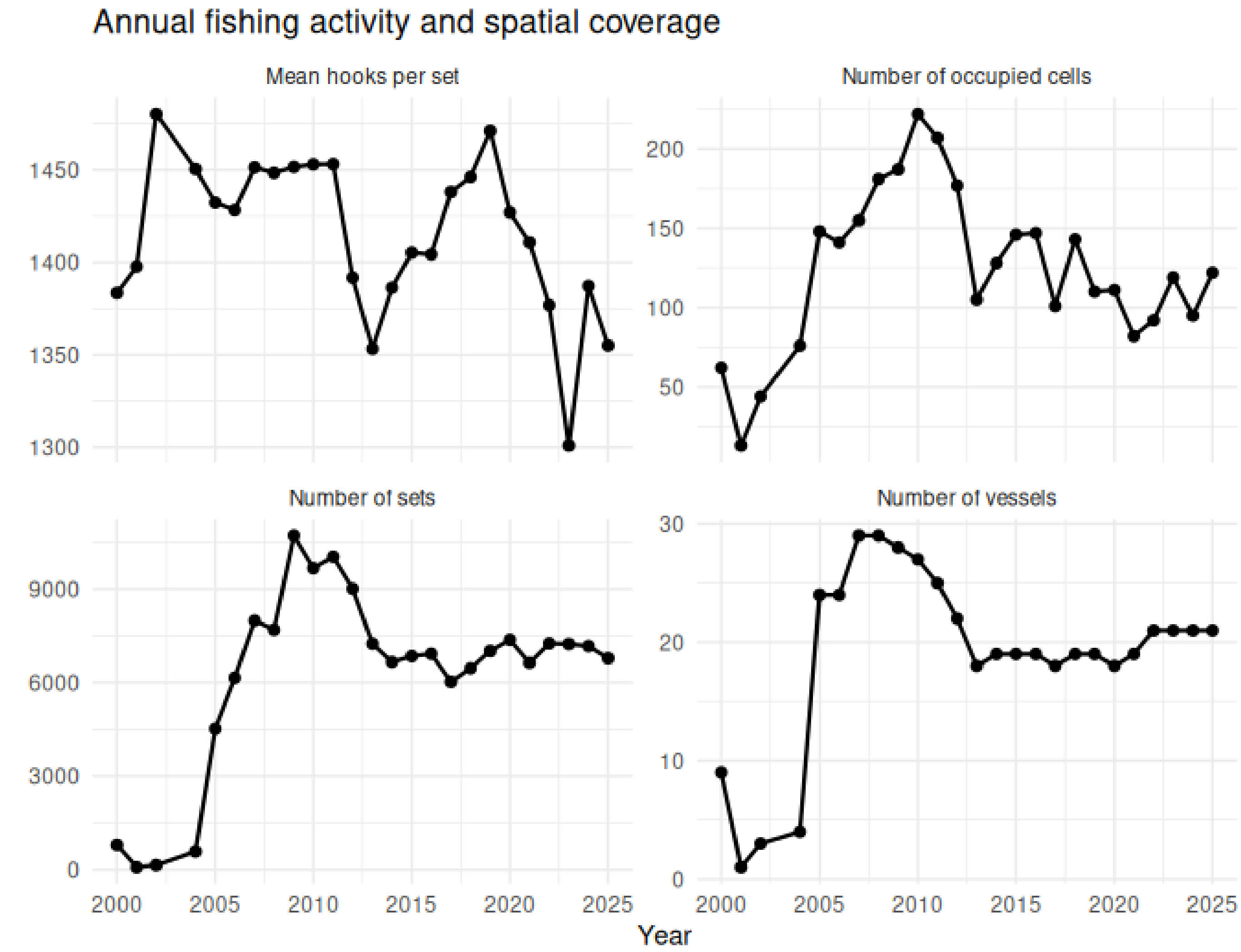

Figure 14: Annual indicators of fishing activity and spatial coverage in the Réunion pelagic longline fishery between 2000 and 2025. Panels show the mean number of hooks per set, number of occupied 1°×1° spatial cells, number of fishing sets, and number of active vessels by year. Together, these metrics describe temporal changes in fleet size, fishing effort, and spatial distribution throughout the study period.

6.3 Positive proportion

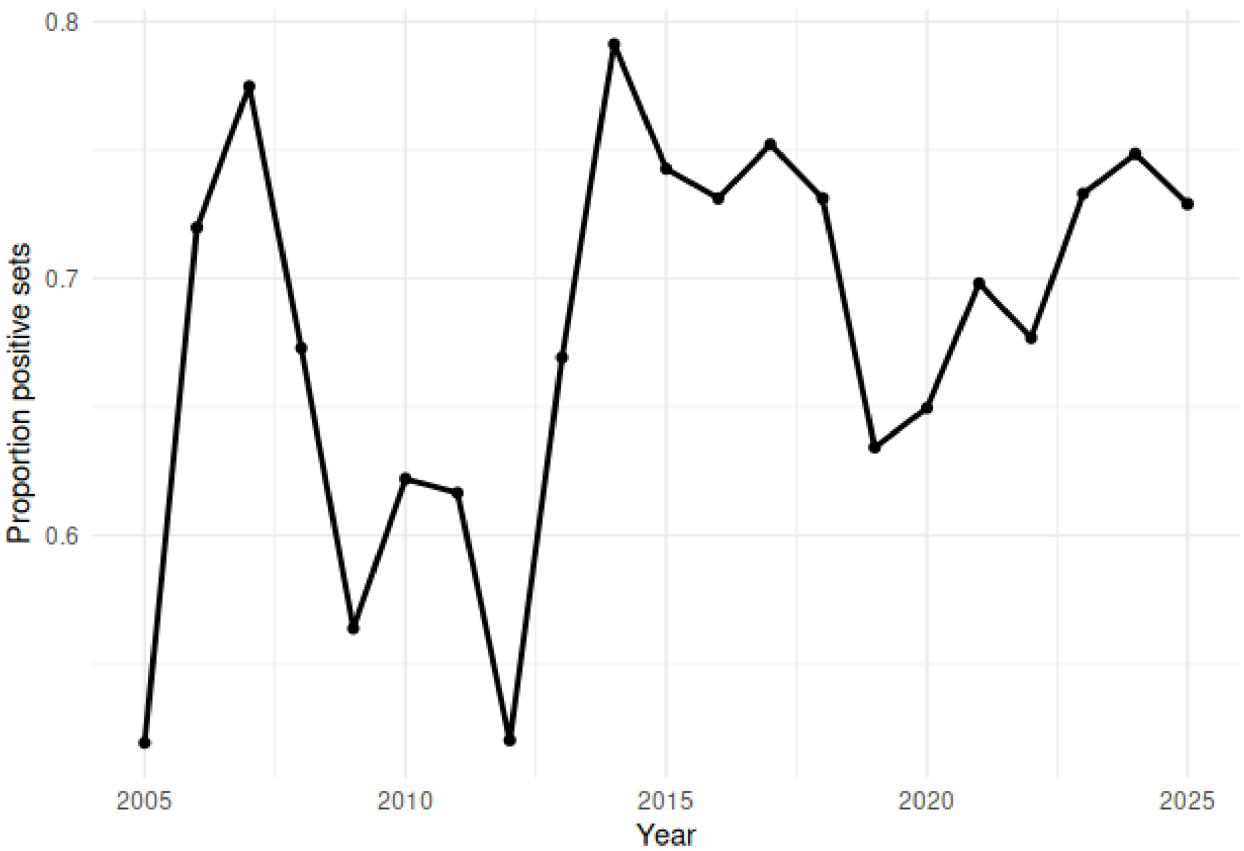

Figure 15: Annual proportion of positive fishing sets (sets catching at least one swordfish) in the Réunion pelagic longline fishery between 2005 and 2025. Positive-set frequency increased during the development of the fishery and remained relatively high during recent years, indicating temporal variation in swordfish encounter rates.

6.4 Fishery development

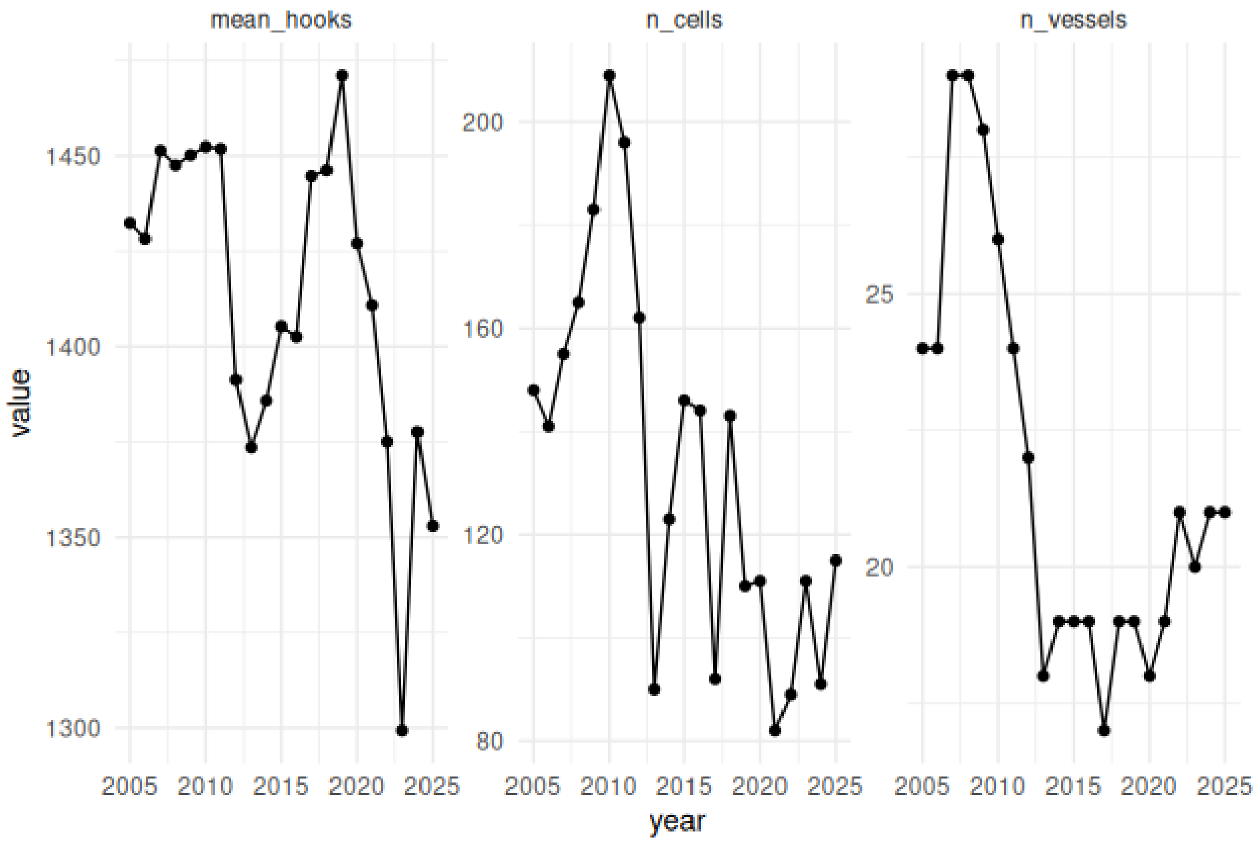

Figure 16: Annual indicators describing the development of the Réunion pelagic longline fishery between 2005 and 2025. Panels show (A) mean number of hooks per set, (B) number of occupied 5° × 5° spatial cells, and (C) number of active vessels. The figure illustrates temporal changes in fishing practices, fleet size, and spatial distribution that may influence nominal catch rates and should therefore be considered during CPUE standardization.

6.5 Delta marginal

The marginal Delta-GAM standardized index is compared with the nominal series in Figure 17. The two series follow the same temporal pattern, indicating that standardization changed the amplitude of the index rather than its overall trajectory.

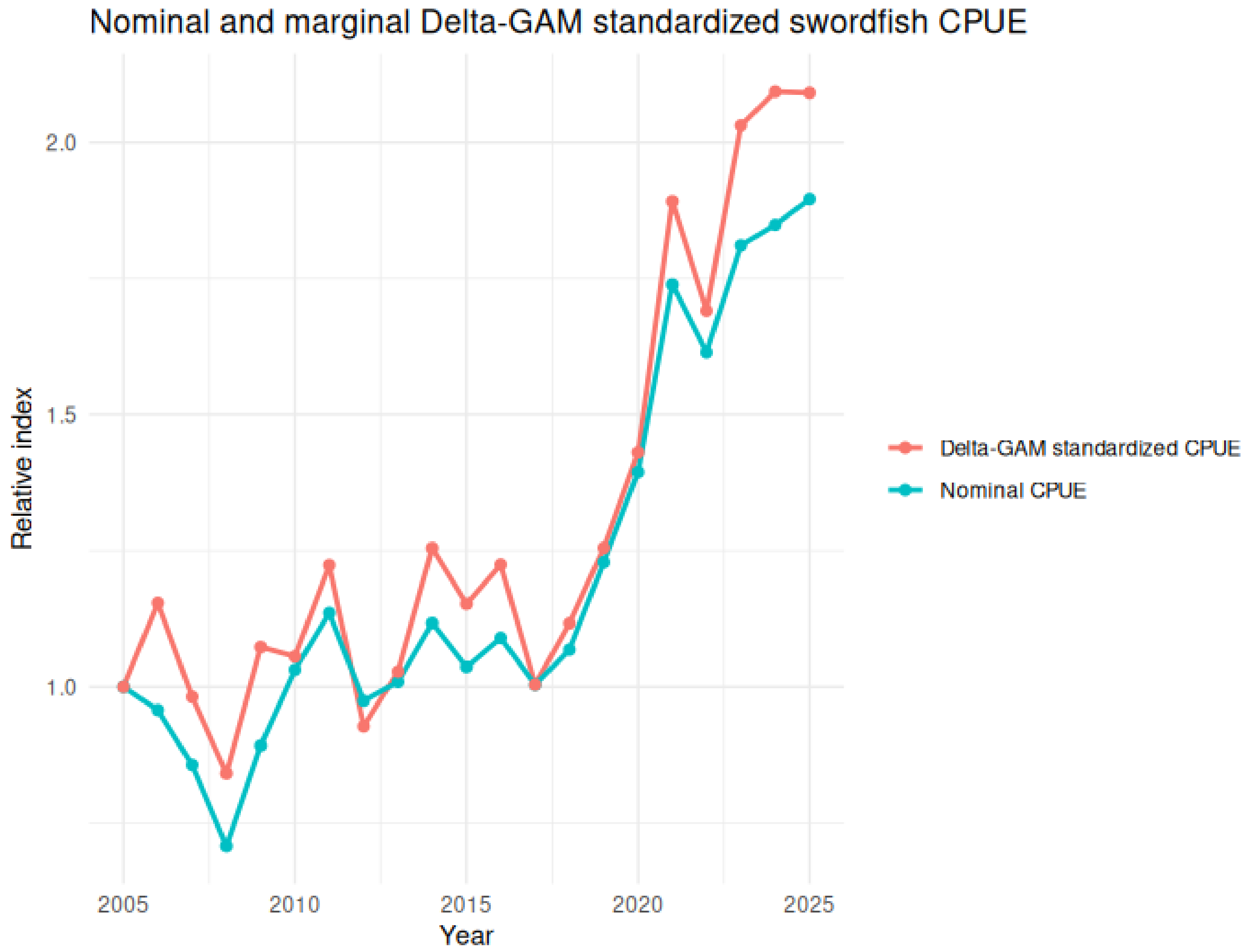

Figure 17: Nominal and marginal Delta-GAM standardized swordfish CPUE indices for the Réunion pelagic longline fishery, expressed relative to 2005 (=1). The standardized series is obtained by marginal prediction over a common reference dataset, combining the binomial encounter and lognormal positive-catch components.

6.6 Delta marginal métiers compare

The sensitivity of the Delta-GAM index to the inclusion of fishing métier is shown in Figure 18. Indices estimated with and without the métier term remain closely aligned throughout the series, although models including métier provided a substantially better fit (see the AIC comparison below).

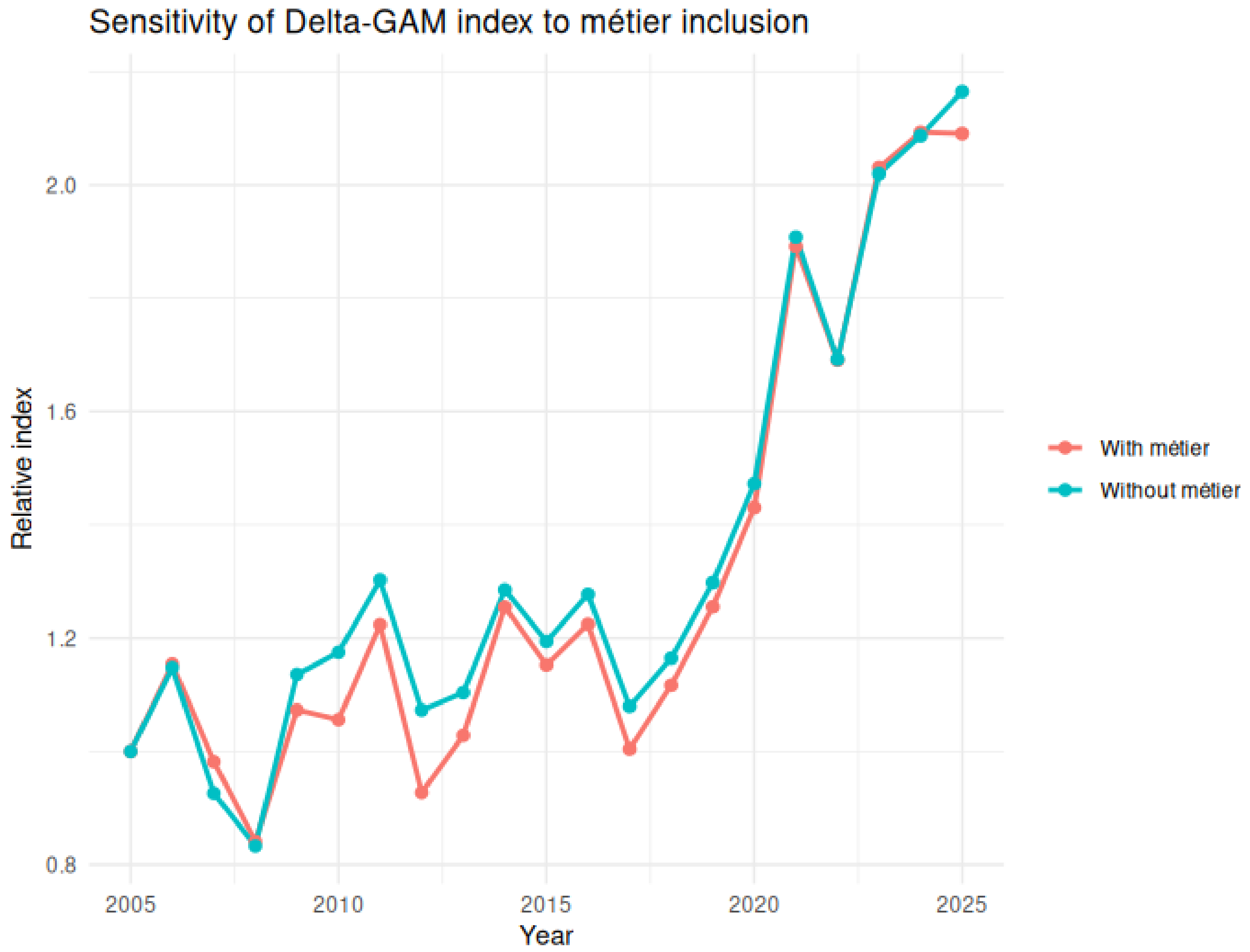

Figure 18: Sensitivity of the Delta-GAM standardized index to the inclusion of fishing métier. Indices estimated from models fitted with and without the métier term are shown relative to 2005 (=1); the two series remain closely aligned throughout the time period.

```
Family: binomial
Link function: logit

Formula:
I(swo_wt > 0) ~ year_f + quarter_f + s(vessel_f, bs = "re") +
    s(lon, lat, k = 100)

Parametric coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept) -0.38875    0.11389  -3.413 0.000642 ***
year_f2006   0.89660    0.04266  21.018  < 2e-16 ***
year_f2007   1.27189    0.04267  29.807  < 2e-16 ***
year_f2008   0.80887    0.04119  19.638  < 2e-16 ***
year_f2009   0.31139    0.03841   8.107 5.19e-16 ***
year_f2010   0.50950    0.03948  12.906  < 2e-16 ***
year_f2011   0.83103    0.04106  20.240  < 2e-16 ***
year_f2012   0.48017    0.04208  11.410  < 2e-16 ***
year_f2013   0.80841    0.04330  18.668  < 2e-16 ***
year_f2014   1.36703    0.04530  30.177  < 2e-16 ***
year_f2015   1.10566    0.04357  25.374  < 2e-16 ***
year_f2016   1.04947    0.04342  24.169  < 2e-16 ***
year_f2017   1.04523    0.04512  23.166  < 2e-16 ***
year_f2018   1.18878    0.04540  26.186  < 2e-16 ***
year_f2019   0.84827    0.04397  19.291  < 2e-16 ***
year_f2020   1.00519    0.04390  22.898  < 2e-16 ***
year_f2021   1.34498    0.04697  28.632  < 2e-16 ***
```

```
year_f2022   1.25459    0.04507  27.838  < 2e-16 ***
year_f2023   1.32505    0.04461  29.704  < 2e-16 ***
year_f2024   1.31198    0.04458  29.427  < 2e-16 ***
year_f2025   1.23409    0.04460  27.667  < 2e-16 ***
quarter_f2  -0.18562    0.01774 -10.462  < 2e-16 ***
quarter_f3   0.07197    0.01847   3.896 9.77e-05 ***
quarter_f4   0.18047    0.01775  10.168  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
              edf Ref.df Chi.sq p-value
s(vessel_f) 30.26  31.00   1729  <2e-16 ***
s(lon,lat)  69.90  82.08   1231  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.0568   Deviance explained = 4.54%
fREML = 2.1545e+05  Scale est. = 1         n = 144105

Family: gaussian
Link function: identity

Formula:
log_cpue ~ year_f + quarter_f + s(vessel_f, bs = "re") + s(lon,
    lat, k = 100)

Parametric coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  4.147180   0.077744  53.344  < 2e-16 ***
year_f2006  -0.148075   0.034445  -4.299 1.72e-05 ***
year_f2007  -0.437086   0.033447 -13.068  < 2e-16 ***
year_f2008  -0.447890   0.034509 -12.979  < 2e-16 ***
year_f2009   0.008675   0.033963   0.255 0.798398
year_f2010  -0.021835   0.033844  -0.645 0.518820
year_f2011  -0.005871   0.034163  -0.172 0.863563
year_f2012  -0.103673   0.035871  -2.890 0.003851 **
year_f2013  -0.166105   0.035311  -4.704 2.55e-06 ***
year_f2014  -0.124854   0.034379  -3.632 0.000282 ***
year_f2015  -0.152550   0.034475  -4.425 9.65e-06 ***
year_f2016  -0.073753   0.034533  -2.136 0.032702 *
year_f2017  -0.241442   0.035246  -6.850 7.42e-12 ***
year_f2018  -0.193353   0.034970  -5.529 3.23e-08 ***
year_f2019  -0.013525   0.035637  -0.380 0.704311
year_f2020   0.077471   0.035282   2.196 0.028111 *
year_f2021   0.273707   0.035436   7.724 1.14e-14 ***
year_f2022   0.168866   0.035040   4.819 1.44e-06 ***
year_f2023   0.333910   0.034600   9.651  < 2e-16 ***
year_f2024   0.368779   0.034568  10.668  < 2e-16 ***
year_f2025   0.418660   0.034761  12.044  < 2e-16 ***
quarter_f2  -0.371943   0.012715 -29.252  < 2e-16 ***
quarter_f3   0.064326   0.012729   5.054 4.34e-07 ***
quarter_f4   0.307045   0.012202  25.164  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
              edf Ref.df     F p-value
s(vessel_f) 30.13  31.00 93.75  <2e-16 ***
s(lon,lat)  70.90  79.47 37.79  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.113   Deviance explained = 11.4%
fREML = 1.7408e+05  Scale est. = 1.7418    n = 102452
```

AIC comparison of Delta-GAM components fitted with and without fishing métier.

Model	df	AIC
m_encounter	125.9	160723.3
m_encounter_nom	125.0	165673.8
m_positive	127.9	338309.3
m_positive_nom	126.5	347729.2

6.7 Tweedie results

The full Tweedie-GAM model summary is reproduced below. Figure 19 shows the nominal, Delta-GAM and Tweedie-GAM indices on a common scale, and Figure 20 shows the retained Tweedie-GAM index with its approximate 95% confidence intervals.

```
Family: Tweedie(p=1.56)
Link function: log

Formula:
swo_wt ~ year_f + quarter_f + metier_f + s(vessel_f, bs = "re") +
    s(lon, lat, k = 100) + offset(log(hooks_final))

Parametric coefficients:
                Estimate Std. Error t value Pr(>|t|)
(Intercept)    -3.651587   0.100505 -36.332  < 2e-16 ***
year_f2006      0.104981   0.027802   3.776 0.000159 ***
year_f2007      0.011991   0.027433   0.437 0.662040
year_f2008     -0.218301   0.028124  -7.762 8.40e-15 ***
year_f2009      0.003578   0.026293   0.136 0.891744
year_f2010      0.061313   0.026594   2.305 0.021141 *
year_f2011      0.219000   0.027041   8.099 5.59e-16 ***
year_f2012     -0.050828   0.028491  -1.784 0.074421 .
year_f2013      0.038180   0.028575   1.336 0.181514
year_f2014      0.202421   0.028061   7.214 5.47e-13 ***
year_f2015      0.135295   0.028022   4.828 1.38e-06 ***
year_f2016      0.185013   0.027937   6.622 3.54e-11 ***
year_f2017      0.049363   0.028893   1.708 0.087555 .
year_f2018      0.114994   0.028604   4.020 5.82e-05 ***
year_f2019      0.260012   0.028422   9.148  < 2e-16 ***
year_f2020      0.445673   0.027991  15.922  < 2e-16 ***
year_f2021      0.651225   0.028093  23.181  < 2e-16 ***
year_f2022      0.629348   0.027777  22.657  < 2e-16 ***
year_f2023      0.743423   0.027202  27.330  < 2e-16 ***
year_f2024      0.775510   0.027016  28.705  < 2e-16 ***
year_f2025      0.777775   0.027068  28.734  < 2e-16 ***
quarter_f2     -0.341393   0.011448 -29.822  < 2e-16 ***
quarter_f3      0.116833   0.011067  10.556  < 2e-16 ***
quarter_f4      0.392848   0.010429  37.668  < 2e-16 ***
metier_fLLDSWO  0.482750   0.008808  54.811  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
              edf Ref.df      F p-value
s(vessel_f) 30.42  32.00 172.23  <2e-16 ***
s(lon,lat)  85.20  92.55  47.96  <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.0986   Deviance explained = 14.8%
fREML = 4.0765e+05  Scale est. = 13.386    n = 144105
```

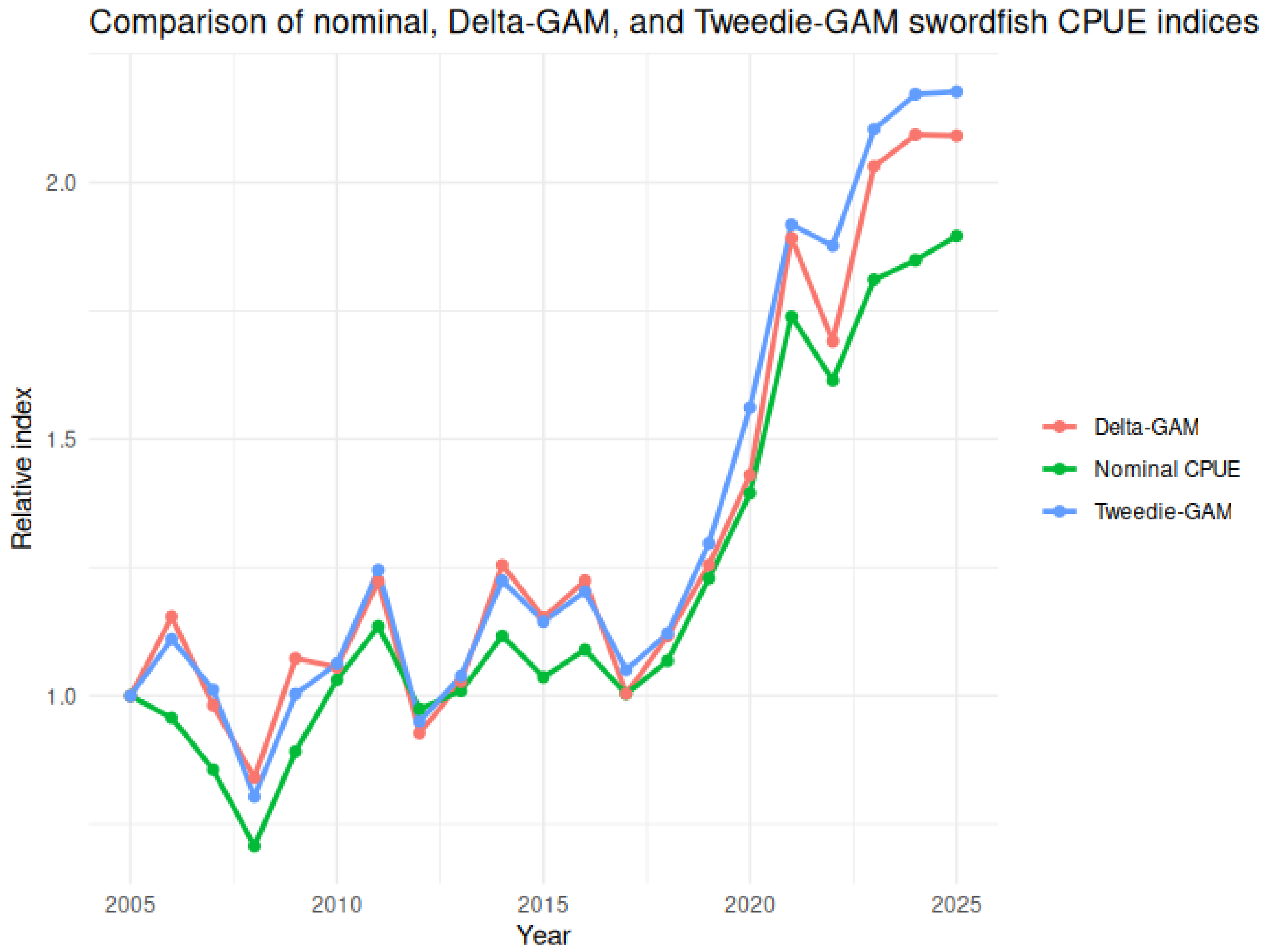

Figure 19: Nominal, Delta-GAM and Tweedie-GAM standardized swordfish CPUE indices plotted together, each expressed relative to 2005 (=1).

Comparison of nominal, Delta-GAM, and Tweedie-GAM swordfish CPUE indices.

Year	Nominal CPUE	Nominal index	Delta CPUE	Delta index	Tweedie CPUE	Tweedie index
2005	60.154	1.000	52.997	1.000	87.829	1.000
2006	57.580	0.957	61.169	1.154	97.551	1.111
2007	51.521	0.856	52.026	0.982	88.889	1.012
2008	42.561	0.708	44.563	0.841	70.605	0.804
2009	53.659	0.892	56.866	1.073	88.144	1.004
2010	62.041	1.031	55.955	1.056	93.383	1.063
2011	68.316	1.136	64.844	1.224	109.333	1.245
2012	58.616	0.974	49.142	0.927	83.477	0.950
2013	60.703	1.009	54.475	1.028	91.248	1.039
2014	67.197	1.117	66.499	1.255	107.535	1.224
2015	62.351	1.037	61.077	1.152	100.554	1.145
2016	65.555	1.090	64.894	1.224	105.679	1.203
2017	60.383	1.004	53.213	1.004	92.274	1.051
2018	64.256	1.068	59.175	1.117	98.533	1.122

Year	Nominal CPUE	Nominal index	Delta CPUE	Delta index	Tweedie CPUE	Tweedie index
2019	73.922	1.229	66.515	1.255	113.910	1.297
2020	83.890	1.395	75.808	1.430	137.149	1.562
2021	104.588	1.739	100.242	1.891	168.447	1.918
2022	97.110	1.614	89.604	1.691	164.802	1.876
2023	108.914	1.811	107.630	2.031	184.716	2.103
2024	111.195	1.849	110.921	2.093	190.739	2.172
2025	114.034	1.896	110.806	2.091	191.172	2.177

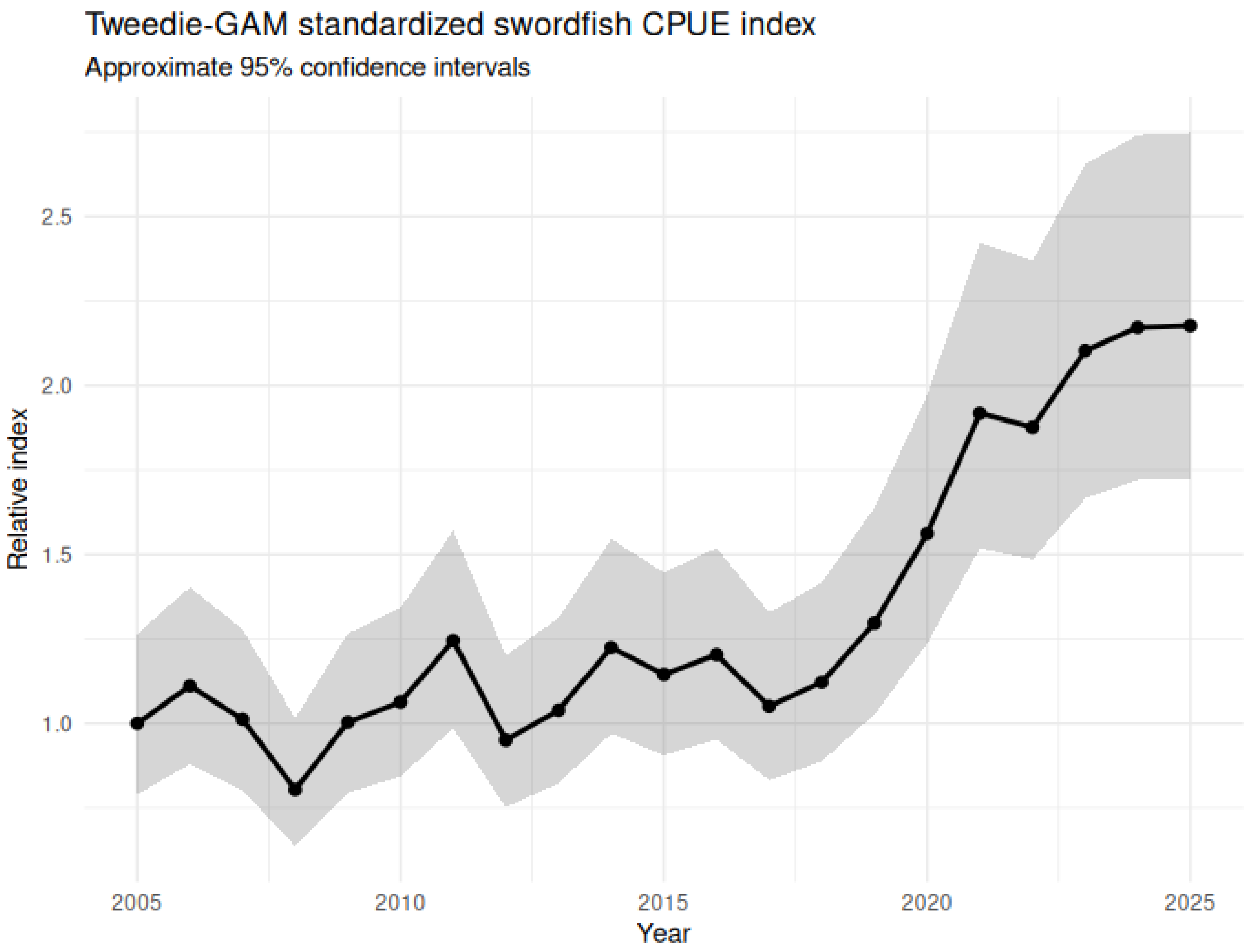

Figure 20: Tweedie-GAM standardized swordfish CPUE index with approximate 95% confidence intervals, expressed relative to 2005 (=1).

Correlation among nominal and standardized CPUE indices.

comparison	correlation
Nominal vs Delta-GAM	0.956
Nominal vs Tweedie-GAM	0.991
Delta-GAM vs Tweedie-GAM	0.959

Nominal, Delta-GAM and Tweedie-GAM standardized swordfish CPUE indices.

Year	Nominal index	Delta index	Tweedie index	2.5%	97.5%
2005	1.000	1.000	1.000	0.791	1.265

Year	Nominal index	Delta index	Tweedie index	2.5%	97.5%
2006	0.957	1.057	1.111	0.879	1.404
2007	0.856	0.840	1.012	0.801	1.278
2008	0.708	0.747	0.804	0.636	1.015
2009	0.892	0.956	1.004	0.795	1.267
2010	1.031	1.051	1.063	0.842	1.342
2011	1.136	1.166	1.245	0.986	1.571
2012	0.974	0.977	0.950	0.752	1.201
2013	1.009	1.023	1.039	0.822	1.313
2014	1.117	1.210	1.224	0.969	1.546
2015	1.037	1.107	1.145	0.906	1.446
2016	1.090	1.175	1.203	0.953	1.520
2017	1.004	0.977	1.051	0.831	1.328
2018	1.068	1.087	1.122	0.888	1.417
2019	1.229	1.170	1.297	1.027	1.638
2020	1.395	1.217	1.562	1.236	1.972
2021	1.739	1.689	1.918	1.519	2.422
2022	1.614	1.431	1.876	1.486	2.370
2023	1.811	2.112	2.103	1.666	2.655
2024	1.849	2.220	2.172	1.720	2.742
2025	1.896	2.191	2.177	1.724	2.748

Annual effects estimated by the Tweedie-GAM relative to the 2005 baseline.

Year	Estimate	Std. error	t value	p-value	Relative effect
2006	0.105	0.028	3.776	0.000	1.111
2007	0.012	0.027	0.437	0.662	1.012
2008	-0.218	0.028	-7.762	0.000	0.804
2009	0.004	0.026	0.136	0.892	1.004
2010	0.061	0.027	2.305	0.021	1.063
2011	0.219	0.027	8.099	0.000	1.245
2012	-0.051	0.028	-1.784	0.074	0.950
2013	0.038	0.029	1.336	0.182	1.039
2014	0.202	0.028	7.214	0.000	1.224
2015	0.135	0.028	4.828	0.000	1.145
2016	0.185	0.028	6.622	0.000	1.203
2017	0.049	0.029	1.708	0.088	1.051
2018	0.115	0.029	4.020	0.000	1.122
2019	0.260	0.028	9.148	0.000	1.297
2020	0.446	0.028	15.922	0.000	1.562
2021	0.651	0.028	23.181	0.000	1.918
2022	0.629	0.028	22.657	0.000	1.876
2023	0.743	0.027	27.330	0.000	2.103
2024	0.776	0.027	28.705	0.000	2.172
2025	0.778	0.027	28.734	0.000	2.177

AIC comparison of the spatial and spatiotemporal sdmTMB models.

Model	df	AIC
m_sdm_spatial	29	1381280
m_sdm_st	30	1377853

sdmTMB standardized swordfish CPUE index.

Year	sdmTMB CPUE	sdmTMB index
2005	55.556	1.000
2006	58.505	1.053
2007	48.963	0.881
2008	40.337	0.726
2009	50.888	0.916
2010	53.456	0.962
2011	66.746	1.201
2012	53.437	0.962
2013	58.190	1.047
2014	65.650	1.182
2015	61.073	1.099
2016	69.247	1.246
2017	53.158	0.957
2018	64.728	1.165
2019	68.494	1.233
2020	72.287	1.301
2021	86.894	1.564
2022	81.599	1.469
2023	123.671	2.226
2024	131.129	2.360
2025	130.239	2.344

The standardized index estimated by the spatiotemporal sdmTMB model is shown in Figure 21.

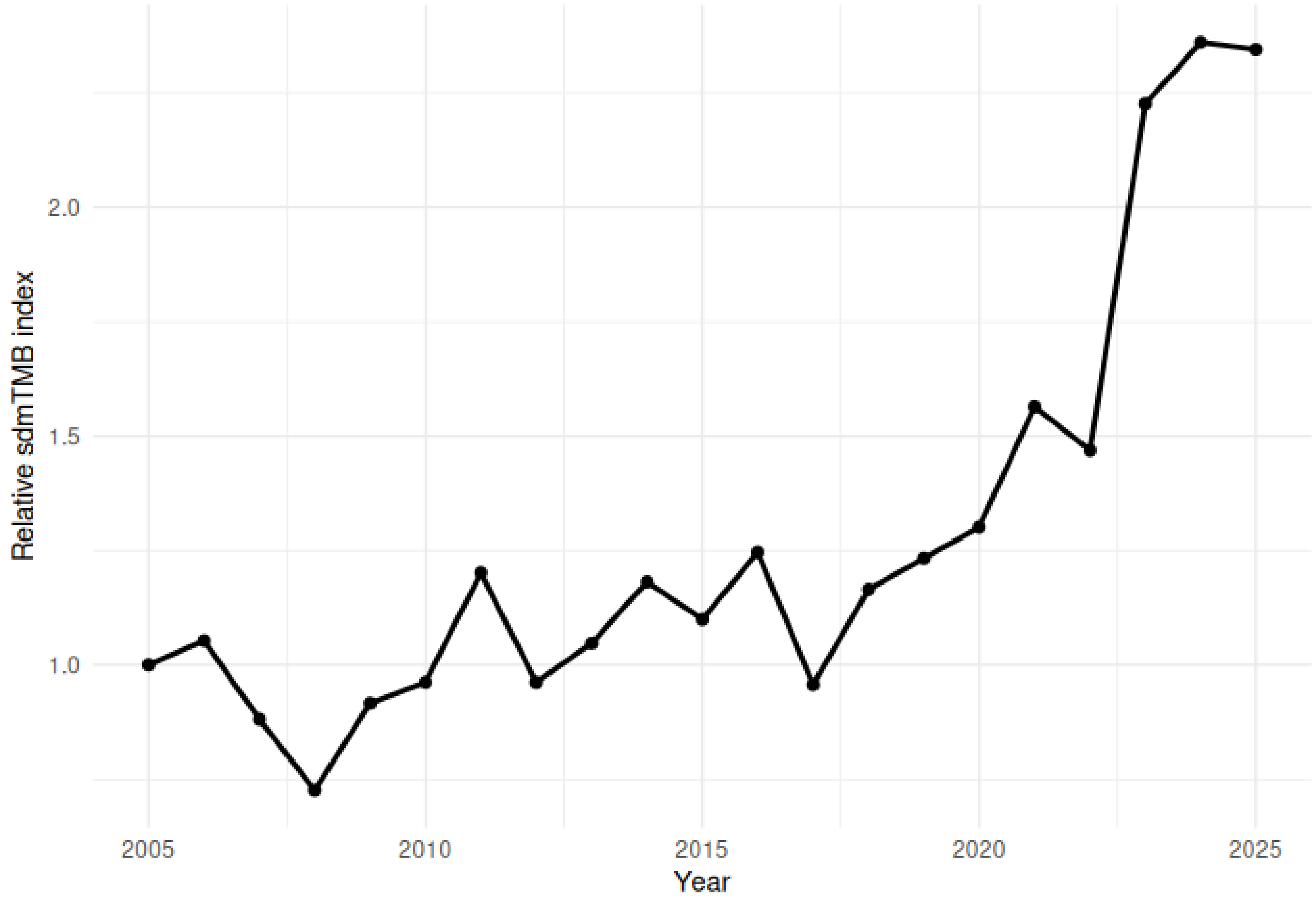

Figure 21: Standardized swordfish CPUE index estimated by the spatiotemporal sdmTMB model, expressed relative to 2005 (=1). Predictions are averaged over a common spatial domain each year, so the index is less sensitive to shifts in fishing location than the GAM-based indices.

6.8 Tweedie effect

The annual year effects estimated by the Tweedie-GAM, expressed relative to the 2005 baseline, are shown in Figure 22 together with their approximate 95% confidence intervals.

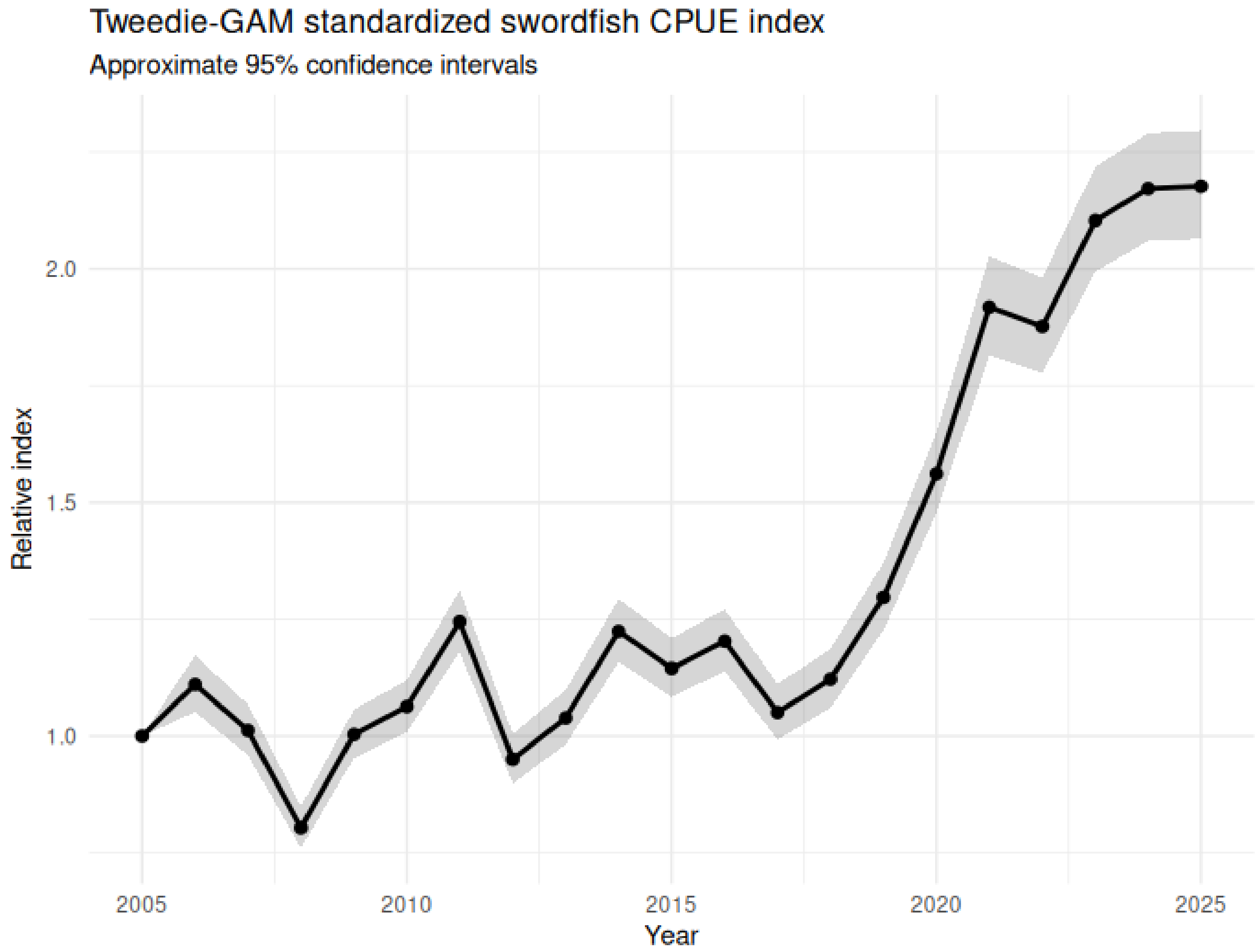

Figure 22: Annual year effects estimated by the Tweedie-GAM, expressed relative to the 2005 baseline (=1). The shaded ribbon shows approximate 95% confidence intervals derived from the standard errors of the year coefficients.

6.8.1 Supplementary files

- Table S1. Annual standardized CPUE index

7. References