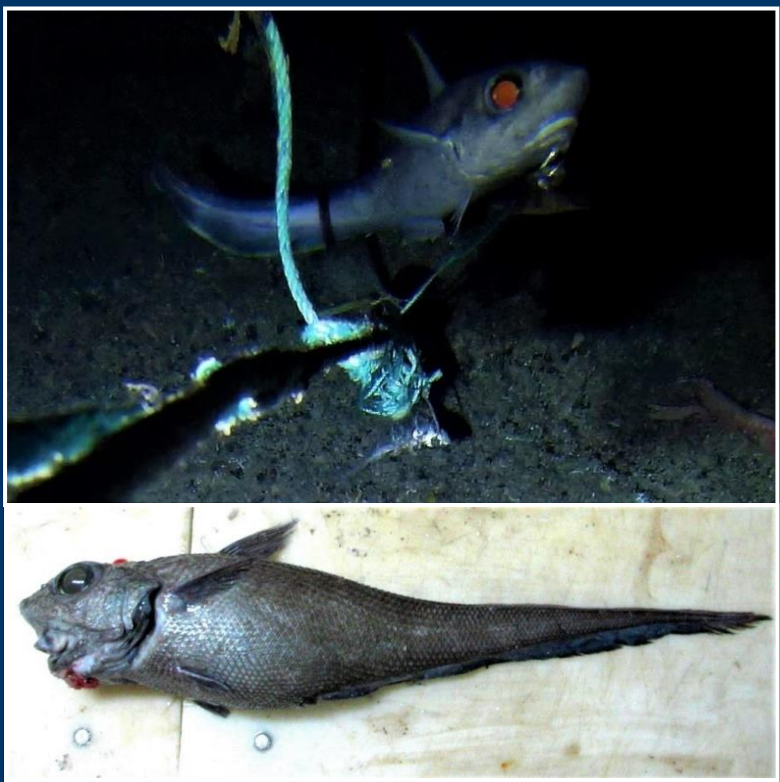
Stock assessment of bigeye grenadier (*Macrourus holotrachys*) in the Falkland Islands to 2024



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Director of Natural Resources

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Summary

1. This report presents an updated stock assessment of bigeye grenadier (*Macrourus holotrachys*) in Falkland Islands waters, using data up to the end of 2024. The assessment was conducted using the Bayesian surplus production model framework JABBA.
2. This assessment incorporates several updates, the most notable being the inclusion of data from 2000 to 2001, which altered the perceived stock status.
3. Five scenarios with different *r* priors led to similar stock trajectories and status. The B/B_{MSY} ratio declined steadily from 2000 to 2017, falling below 1 in 2005, and levelled off from 2018 onwards. The F/F_{MSY} ratio exhibited an overall downward trend from 2000 to 2017, followed by a slight increase until 2024. It remained above 1 throughout this period, except in 2017.
4. All five scenarios indicated a high probability (67.6 - 79.9%) that the stock was both overfished ($B/B_{MSY} < 1$) and subject to overfishing ($F/F_{MSY} > 1$) in 2024.

1. Introduction

Bigeye grenadier (*Macrourus holotrachys*) is a long-lived, slow-growing and late-matured deep-sea species distributed over the continental slopes of South America. Its range in the southwest Atlantic extends from the Patagonian slope, north of the Falkland Islands, to the North Scotia Ridge and South Georgia (Morley et al. 2004). In the southeastern Pacific, it is distributed along the coast of Chile (Ñacari et al. 2022).

The bigeye grenadier represents the main bycatch species in the Falkland Islands Patagonian toothfish (*Dissostichus eleginoides*) longline fishery, which began in 1992 as an exploratory fishery and became established in 1994 (Laptikhovsky and Brickle 2005). It is caught throughout the longline fishing area. The 'Spanish' longline system was historically used in this fishery before being progressively replaced by the 'umbrella' (or 'Chilean') system between 2007 and 2009, in an effort to reduce whale depredation. This system consists of hooks set in clusters with a buoyant netting umbrella attached above each cluster. While the gear is on the seabed, the umbrella floats above the cluster of hooks, but it folds over the cluster and the hooked fish during hauling to prevent depredation (Moreno et al., 2008; Brown et al., 2010).

Since the transition to the umbrella system in 2008, the toothfish longline fishery has had a relatively low aggregated bycatch rate of ~10% (Farrugia and Winter 2019, Saulnier and Skeljo, 2024). The largest bycatch category (accounting for around 5% of the total annual catch) is 'grenadiers', comprising two species that are not distinguished in the fishery catch reports: the bigeye grenadier and the ridge-scaled rattail (*Macrourus carinatus*). The ridge-scaled rattail is found at depths between 350 and 1,000 m, while the bigeye grenadier is generally found below 900 m (Laptikhovsky et al., 2008). Because the longline fishing effort is distributed almost entirely below 900 m, the bigeye grenadier represents over 95% of the grenadier bycatch (Farrugia and Winter 2019). Most of the grenadier bycatch is discarded, but about 10 t of bigeye grenadier are retained, processed and landed in the Falkland Islands each year for local consumption (Farrugia and Winter 2019).

Bigeye grenadier is thought to be vulnerable to fishing due to its life-history characteristics. In 2018, the impact of fishing on the bigeye grenadier population in Falkland Islands waters was highlighted during the Marine Stewardship Council (MSC) re-certification of the fishery (Acoura Marine 2018). With a bycatch level above 5% of the total catch by weight, the bigeye grenadier was considered a '*main primary*' bycatch species under the MSC Fisheries Certification Requirements v2.0, necessitating dedicated monitoring and assessment. The first bigeye grenadier stock assessment in Falkland Islands waters was conducted in 2019 (Farrugia and Winter 2019), using the Bayesian surplus production model framework JABBA (Winker et al. 2018). Surplus production models represent a data-moderate approach requiring few inputs, making them suitable for assessing stocks such as the bigeye grenadier, for which age-structured data are not readily available. This modelling approach has been used ever since (Skeljo and Winter 2020, 2021, 2022, 2023), with the recommendation to update the stock assessment at least biennially.

This report presents an updated JABBA stock assessment of bigeye grenadier in Falkland Islands waters, using data up to the end of 2024. As very little is known about the connectivity and the spatial structure of bigeye grenadier populations across the region, the population exploited around the Falkland Islands was assumed to be a single stock, distinct from those fished in other parts of the Southern Atlantic and Pacific Oceans.

2. Material and Methods

2.1. Assessment updates

The previous assessment (Skeljo and Winter 2023) was updated as follows:

a. Time-series of catch and effort were extended with data reported from 2000 to 2001 (Spanish system) and from 2023 to 2024 (umbrella system).
b. Catch and effort data reported outside Falkland Islands waters from 2005 to 2008 were removed from the analysis, resulting in lower total removal estimates for those four years.
c. Catch-per-unit-effort (CPUE) was standardised using spatial Generalised Additive Models (spatial GAMs, sensu Hoyle et al. 2024) rather than Generalised Linear Mixed Models (GLMMs).
d. CPUE data from longlines set with the umbrella system in 2007 were excluded. Furthermore, CPUE was standardised line by line from 2008 to 2024, rather than being aggregated per day.
e. A catch observation error with a coefficient of variation of 0.1 (JABBA default value, Winker et al. 2023) was used, rather than assuming catches to be known without error.
f. A sensitivity analysis was conducted to assess the robustness of the model outputs to the prior used for the intrinsic rate of population growth.
g. Stock projections were performed for various catch levels between 2025 and 2035.

The rationale for these updates is provided in the corresponding sections of the present report.

2.2. Data

Three datasets were used in the assessment: (i) total annual removals by the toothfish longline fishery from 2000 to 2024, (ii) CPUE time series for the Spanish system from 2000 to 2007 and (iii) CPUE time-series for the umbrella system from 2008 to 2024.

<u>Removals</u>

Grenadier catch reports in the toothfish longline fishery first appeared in 1997, but most of the bycatch was still reported as 'unidentified fish' until 1999. This practice was reversed in 2000, marked by the highest annual grenadier catches reported in the fishery (253 t, 12.0% of the total catch) and a relatively low level of bycatch reported as 'unidentified fish' (69 t, 3.3% of the total catch). The amount of bycatch reported as 'unidentified fish' was negligible in 2001 (5 t, 0.3% of the total catch) and equal to zero from 2002 onwards. Although the total annual grenadier catches reported by the longliners were known to be slightly to moderately underestimated between 2000 and 2003 (see the 'CPUE' section below), they were deemed sufficiently accurate to be included in the assessment. Accordingly, grenadier catches from 2000 onwards were included in the current assessment. Catches reported outside Falkland Islands waters from 2005 to 2008 were removed from the analysis because the impact on the local population is virtually unknown due to a lack of knowledge regarding the connectivity and spatial structure of grenadier populations in the region.

Total annual removals were calculated by summing the reported bigeye grenadier catches taken in the longline fishery and the catches assumed to be taken by *Illegal, Unreported and*

Unregulated (IUU) fishing in Falkland Islands waters since 2000 (Fig. 1). Assuming that the level of IUU fishing was similar between bigeye grenadier and Patagonian toothfish, bigeye grenadier IUU catches were calculated as a percentage of reported bigeye grenadier catches equal to 7% from 2000 to 2003 and to 5% from 2004 to 2024 (Agnew et al. 2009, Skeljo 2025).

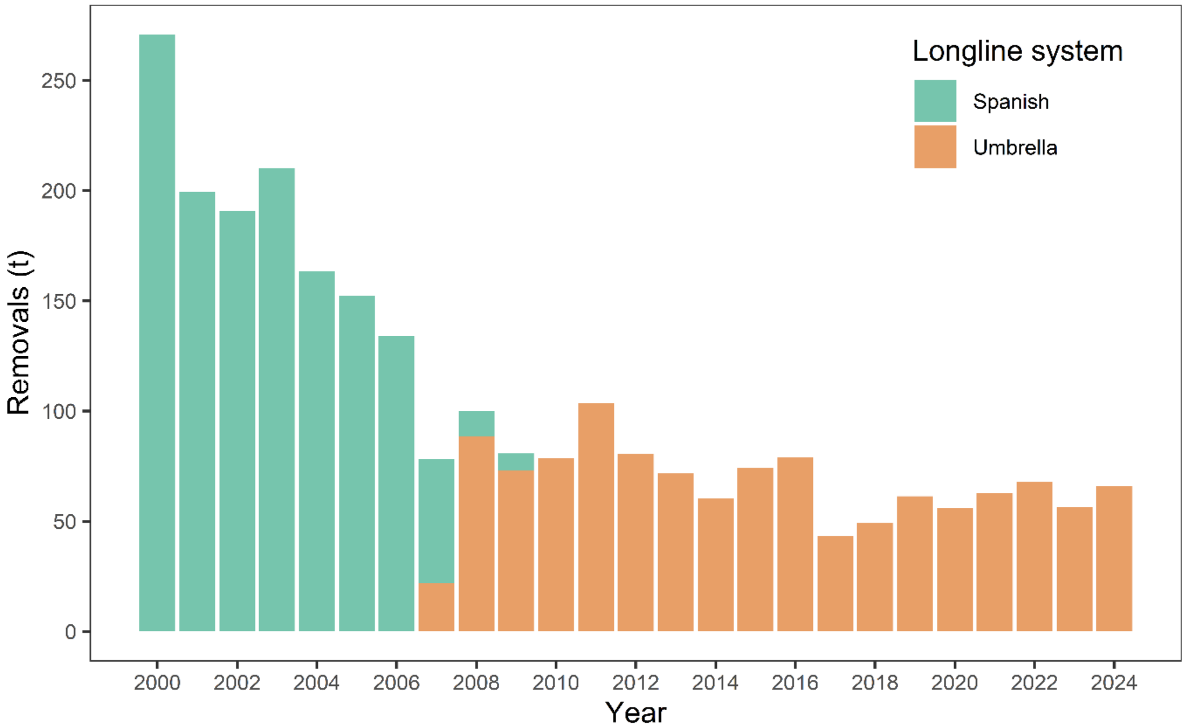

Figure 1. Total removals (t) of bigeye grenadier in Falkland Islands waters from 2000 to 2024.

<u>CPUE</u>

CPUE data were divided between the Spanish and the umbrella systems to account for the difference in catchability and reporting practice between the two (Brown et al. 2010). For the Spanish system, catch and effort were reported daily for each 0.5° x 0.25° grid square in paper logbooks (Fig. 2). In contrast, for the umbrella system, catch and effort data were reported line-by-line in electronic logbooks.

From 2000 to 2001, three fishing vessels reported zero grenadier catches on 32-100% of their fishing days. In contrast, all other vessels recorded zero catches on ≤5% of fishing days. Therefore, the three vessels were deemed to have severely underreported grenadier catches and were excluded from the CPUE standardisation. One of the excluded vessels was suspected of continuing to misreport catches in the following two years, with its proportion of zeros declining from 38% in 2001 to 15% in 2002, and ultimately reaching 0% in 2003—yet its mean annual catch rate remained consistently lower than that of other vessels throughout this period. As this vessel did not operate during the remainder of the time series, it was also excluded from the CPUE standardisation. Between 2003 and 2007, daily grenadier catches were strictly positive, except for one vessel which reported three zero-catch days (out of 75 total; 4%) in 2007. A fourth vessel was also excluded because it operated in Falkland Islands waters for only a few days in 2003.

Since the onset of the umbrella system, the fishery has been dominated by a single Falkland Islands vessel (*CFL Gambler*, replaced by *CFL Hunter* in 2017), occasionally assisted by up to two chartered Chilean vessels. None of the chartered vessels has participated in the Falkland Islands fishery for more than two years since 2007, resulting in inconsistent CPUE data. Moreover, at least one of the chartered vessels had restrictions imposed on its fishing practice (e.g. a limit on the number of fishing days in the 'best' fishing grounds) that were not in place for the Falkland Islands vessel.

Therefore, CPUE data from the chartered Chilean vessels were removed from the analysis. Data from dedicated toothfish tagging trips were also removed because they potentially involved different fishing strategies. Longlines set at depths <600 m were excluded because they corresponded to experimental fishing conducted to collect broodstock for the toothfish rearing facility (commercial longlining is prohibited at depths <600 m). Finally, longlines set using the umbrella system in 2007 were excluded as they were deemed unreliable for CPUE standardisation; including them would have resulted in a suspiciously low annual index (Skeljo and Winter, 2023).

Nominal (i.e, raw) CPUE was calculated using day-by-day catch reports and was expressed in kg-per-hook from 2000 to 2007 (Spanish system, Fig. 2). From 2008 to 2024, nominal CPUE was calculated using line-by-line catch reports and was expressed in kg-per-umbrella (umbrella system, Figs. A1-A2). Finally, nominal CPUE was standardised using spatial GAMs, providing a relative abundance time series for each longline system (see Appendix 2 for details on CPUE standardisation).

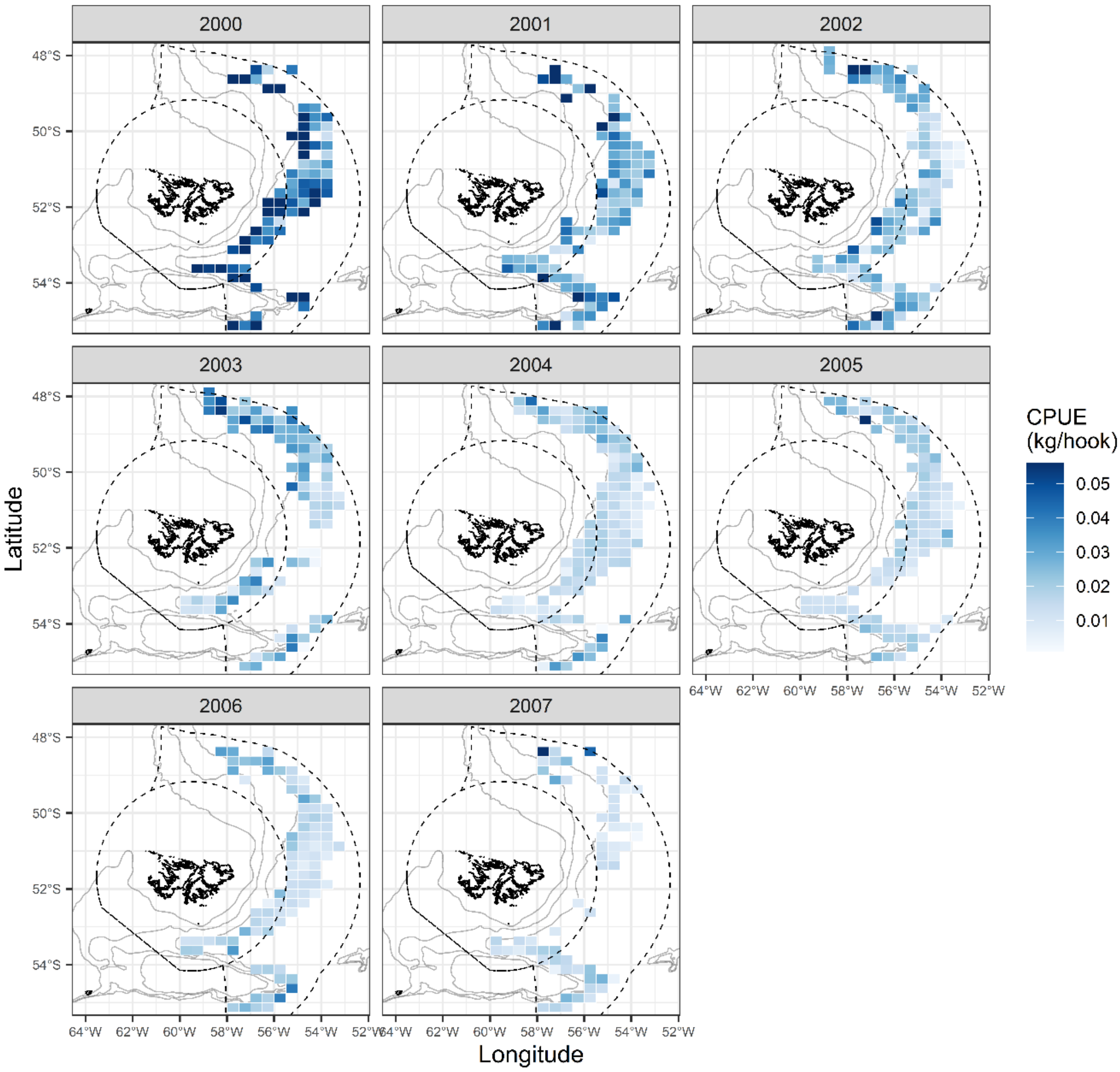

Figure 2. Distribution of bigeye grenadier nominal catch per unit effort (CPUE) in Falkland Islands waters from 2000 to 2007. The mean annual CPUE, expressed in kg/hook, is displayed for each 0.5° x 0.25° grid square in which longline fishing occurred. The dashed lines represent the inner and outer Falkland Islands conservation zones. See Figs. A1-A2 for the spatial distribution of nominal CPUEs from 2008 to 2024.

2.3. JABBA model setup

JABBA is a Bayesian state-space surplus production model framework, based on the generalised Pella-Tomlinson surplus production function (Pella and Tomlinson 1969) of the form:

$$SP_t = \frac{r}{m-1} B_t \left(1 - \left(\frac{B_t}{K}\right)^{m-1}\right),$$

where *r* is the intrinsic rate of population growth at time *t*, *K* is the carrying capacity, *B* is stock biomass at time *t*, and *m* is a shape parameter that determines at which *B/K* ratio maximum surplus production is attained (hereafter B_{MSY}/K) (Winker et al. 2018). The Pella-Tomlinson function reduces to the Schaefer function if the shape parameter *m* equals 2, and to the Fox function if *m* approaches 1. In the current model, surplus production was assumed maximized at B_{MSY}/K = 0.478, as reported by Thorson et al. (2012) for the taxonomic order Gadiformes, which includes grenadiers (Macrouridae). This ratio was converted into Pella-Tomlinson shape parameter *m* = 1.785, according to the equation (Winker et al. 2018):

$$\frac{B_{MSY}}{K} = m^{\left(\frac{1}{1-m}\right)}.$$

JABBA estimates fisheries reference points, relative stock biomass and exploitation using catch and abundance indices time series, while incorporating priors for the intrinsic rate of population increase *r*, the carrying capacity *K*, and the relative biomass *B/K* at the start of the available catch time series. It can also estimate process variance σ^2_{proc} and additional observation variance for the abundance indices time series σ^2_{est}. The total observed variance σ^2_{obs} is separated into three components that are additive in their squared form (Francis et al. 2003), with the total observation variance for abundance index *i* and year *y* given by:

$$\sigma^2_{obs,y,i} = \hat{\sigma}^2_{SE,y,i} + \sigma^2_{fix} + \sigma^2_{est,i}$$

where $\hat{\sigma}_{SE}$ are standard error estimates associated with the abundance indices and derived externally from the CPUE standardisation model, σ^2_{fix} is a fixed input variance, and σ^2_{est} is a model estimable variance. In the current assessment, $\hat{\sigma}_{SE}$ for each annual abundance index were provided to the model, and σ_{fix} was set to 0.2, a commonly used value suggested by Francis et al. (2003). Adding a fixed observation error σ_{fix} to externally estimated standard errors for abundance indices $\hat{\sigma}_{SE}$ is common practice to account for additional sampling errors associated with abundance indices (Maunder and Piner 2017), such as those caused by year-to-year variation in catchability (Francis et al. 2003).

The key priors used in the model (*r*, *K* and B_{2000}/K) were stock-specific and defined based on expert knowledge of the stock for *K* and B_{2000}/K and estimated based on the species life-history for *r* (Table 1). The prior for *r* was estimated using the R package *FishLife* (Thorson, 2019, 2023), version 3.0.0 (https://github.com/James-Thorson-NOAA/FishLife). *FishLife* estimates *r* for the selected species and/or higher taxonomic levels based on an integrated analysis of all life history parameters from FishBase (http://www.fishbase.org; Froese and Pauly 2025) and spawning-recruitment relationship data series from the RAM Legacy Database (http://www.ramlegacy.org; Ricard et al. 2012). Following Skeljo and Winter (2023), *r* was estimated at the genus level (*Macrourus)*, as species-specific data for *M. holotrachys* were not available. To better reflect the large uncertainty of this parameter, a standard deviation approximately twice as high as the value used in Skeljo and Winter (2023) was assumed in this assessment. Finally, priors for variances (σ^2_{proc}, σ^2_{est}) and catchability coefficients ($q_{Spanish}$, $q_{umbrella}$) were set to the default JABBA settings (Table 1). A catch observation error with a coefficient of variation of 0.1 (the default value) was used, as this seemed more realistic than assuming the catch was known without error.

The Bayesian state-space surplus production model was run using the package JABBA (Winker et al. 2023), version 2.2.9 (https://github.com/jabbamodel/JABBA) in R version 4.5.0 (R Core Team, 2025). The Bayesian posterior distributions of all quantities of interest were estimated using a Markov Chains Monte Carlo (MCMC) simulation. Three MCMC chains with 60,000 iterations each were used, with a burn-in of 10,000 for each chain and a thinning rate of ten iterations. Parameter values were defined as the medians of the three combined chains.

A full JABBA model description, including formulation and state-space implementation, prior specification options and diagnostic tools is available in Winker et al. (2018).

Table 1. Prior used for each parameter in the assessment model (base case scenario). For log-normal priors, the mean (μ) and the coefficient of variation (*CV)* are given on natural scale while the standard deviation *(sd)* is provided on log scale. *: Scaling parameters of the inverse-gamma distributions; **: range of the uniform distribution.

Parameter	Prior	Source / Justification
r	log-normal; μ = 0.058, *sd* = 0.3	μ: Estimated at genus level using the *FishLife* R package; sd: assumed to be ~ twice as high as the value used in Skeljo and Winter (2023)
K	log-normal; μ = 5,000, *cv* = 1	Skeljo and Winter 2023
B_{2002}/K	log-normal; μ = 0.75, *cv* = 0.25	Skeljo and Winter 2023
σ^2_{proc}	inverse-gamma (4, 0.01) *	Model default
σ^2_{est}	inverse-gamma (0.001, 0.001) *	Model default
$q_{Spanish}, q_{umbrella}$	uniform (1e-30, 1e3) **	Model default

2.4. Model diagnostics

Model convergence was investigated using MCMC trace-plots (visual assessment), single-chain convergence tests of Geweke (1992) and the stationarity and half-width tests of Heidelberger and Welch (1983) (with p>0.05 indicating convergence) as implemented in the *coda* R package (Plummer et al. 2006).

To evaluate the model goodness-of-fit, the residual patterns were visually inspected, and the Root-Mean-Squared-Error (RMSE) was calculated. A RMSE ≤ 0.3 was assumed to indicate a reasonably precise model fit to the relative abundance indices (Winker et al. 2018).

To check for systematic bias in stock status estimates, a retrospective analysis was finally performed by removing one year of data at a time (n = 5 peels), refitting the model and comparing the quantities of interest (e.g., B/B_{MSY}) to those estimated with the model fitted to the full time series (2000–2024). The magnitude of retrospective pattern was assessed using Mohn's rho statistic (Mohn 1999, Hurtado-Ferro et al. 2014).

2.5. Sensitivity analysis

A previous assessment of the bigeye grenadier stock showed that the outputs of the JABBA model were robust to the prior used for the carrying capacity *K* and the value of the Pella-Tomlinson shape parameter *m*, but sensitive to the prior used for the intrinsic rate of population growth *r* (Skeljo and Winter, 2020). To account for this sensitivity, and following the approach used in Kapur et al. (2019), the JABBA model was refitted using alternative intrinsic growth rate prior means equal to 0.5, 0.75, 1.25, and 1.5 times the base case mean. The standard error was assumed to be 0.3 in all scenarios (Table 2).

To evaluate the impact of incorporating catch and effort data from 2000-2001 and to facilitate comparison with the previous assessment (Skeljo and Winter, 2023), the nominal CPUE was re-standardised, and the JABBA model was re-run excluding either the first two years or the first and last two years of the time-series (Table 2).

Table 2. Description of the sensitivity analysis, indicating the prior for the intrinsic growth rate (*r*) and the catch and CPUE time-series used in each scenario. The mean (μ) of the log-normal prior distribution is provided on natural scale and its standard deviation (*sd*) on log scale.

Sensitivity scenario	Catch and CPUE	*r* (μ)	*r* (*sd*)
r prior mean reduced 50%	2000-2024	0.029	0.3
r prior mean reduced 25%	2000-2024	0.044	0.3
r prior mean increased 25%	2000-2024	0.073	0.3
r prior mean increased 50%	2000-2024	0.087	0.3
shortened time-series (2002-2024)	2002-2024	0.058	0.3
shortened time-series (2002-2022)	2002-2022	0.058	0.3

2.6. Stock projections

Projection analyses were performed using posterior distributions from the base case model to estimate the stock trajectory from 2025 to 2035 under alternative future catches. Projections were conducted for each scenario assuming a constant catch level, as implemented in the *fw_jabba()* function of the JABBA R package. The projected catch scenarios ranged from 40 t to 80 t in 5-t increments, corresponding to the range of total removals observed during the past ten years (2015-2024).

3. Results

3.1. Model diagnostics

Visual inspection of trace plots indicates an adequate convergence and good mixing of the MCMC chains (Fig. A12). The MCMC diagnostics tests of Geweke (1992) and Heidelberger and Welch (1983) were passed by all estimated parameters.

Predicted CPUE from the JABBA model fitted the standardised CPUE time-series reasonably well for both the Spanish and the umbrella system (RMSE = 0.16, Fig. A13-14). However, visual assessment of the residuals indicated that the model failed to fully capture the sharp initial decline in standardised CPUE from 2000 to 2003, underestimating CPUE in 2000 and 2001 and overestimating it in the next four years (Fig. A14). No pattern in the residuals was detected for the umbrella system.

The comparison of posterior distributions and prior densities showed that the carrying capacity (*K)* had a relatively low posterior to prior means ratio (PPMR) and a low posterior to prior variances ratio (PPVR), indicating that the data were to some extent informative with respect to *K* (Fig. A15). In contrast, the intrinsic growth rate (*r),* the initial depletion ratio *(B_{2000}/K)* and the process error variance (σ^2_{proc}) had PPMR values close to 1 and much higher PPVR values than *K*, indicating that the posterior was largely informed by the prior for these parameters.

3.2. Model estimates

The carrying capacity of the bigeye grenadier stock in Falkland Islands waters was estimated to be 3,524 t (95% CI: 2,241 - 6,434) (Table 3). Absolute biomass and biomass relative to B_{MSY} declined steadily from 2000 to 2017, levelling off from 2018 onwards (Fig. 3). The decreasing trend in *B* and B/B_{MSY} was much steeper between 2000 and 2006 than between 2007 and 2017. Overall, the biomass halved between the first and the last years of the time-series. The biomass fell below B_{MSY} between 2004 and 2005, and the B/B_{MSY} ratio has remained below 1 ever since. Fishing mortality relative to F_{MSY} showed an overall downward trend from 2000 to 2017, falling by a factor of three during this period, before increasing progressively until 2024 (Fig. 3). The F/F_{MSY} ratio has remained equal to or above 1 from 2000 to 2024.

Taking into account the uncertainty in the estimates of B_{2024}/B_{MSY} and F_{2024}/F_{MSY} (grey credibility intervals on the Kobe plot), there is a 79.9% probability that the bigeye grenadier stock was both overfished ($B < B_{MSY}$) and experiencing overfishing ($F > F_{MSY}$) in 2024 (red area on the Kobe plot, Fig. 4). There is a 85.9% probability that the stock was overfished (the red and yellow areas combined), and a 84.4% probability that it was experiencing overfishing (the red and orange areas combined) that year.

B_{MSY} and *MSY* were estimated to be 1,685 t (95% CI: 1,071 - 3,075) and 62 t (95% CI: 36 - 105), respectively. All the parameter and stock status estimates were associated with relatively high uncertainty, as indicated by their wide 95% credible intervals (Table 3, Fig. 3).

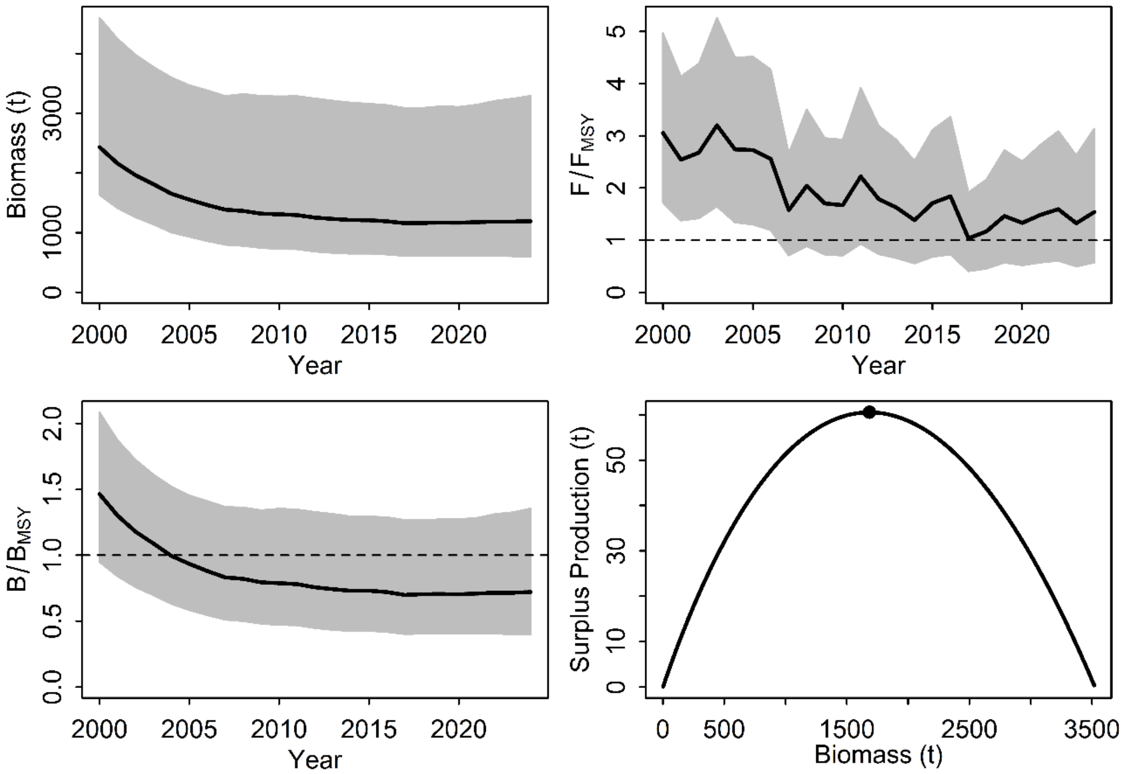

Figure 3. Estimated trajectories of the absolute biomass (top left), fishing mortality relative to F_{MSY} (top right) and biomass relative to B_{MSY} (bottom left), and surplus production curve (bottom right) for the base case scenario. Solid black lines indicate posterior estimates (medians) and grey shaded areas represent their 95% credible intervals. Horizontal dashed lines indicate overfished (B/B_{MSY} < 1) and overfishing (F/F_{MSY} > 1) limits, respectively.

Table 3. Summary of posterior estimates (medians), lower 95% credible intervals (LCI) and upper 95% credible intervals of model parameters and stock status for the base case scenario.

Parameter	Median	95% LCI	95% UCI
K	3,524	2,241	6,434
r	0.064	0.036	0.111
B_{2000}/K	0.700	0.454	0.996
B_{2024}/K	0.344	0.190	0.648
F_{MSY}	0.036	0.020	0.062
B_{MSY}	1,685	1,071	3,075
MSY	62	36	105
B_{2024}/B_{MSY}	0.720	0.397	1.355
F_{2024}/F_{MSY}	1.541	0.571	3.137

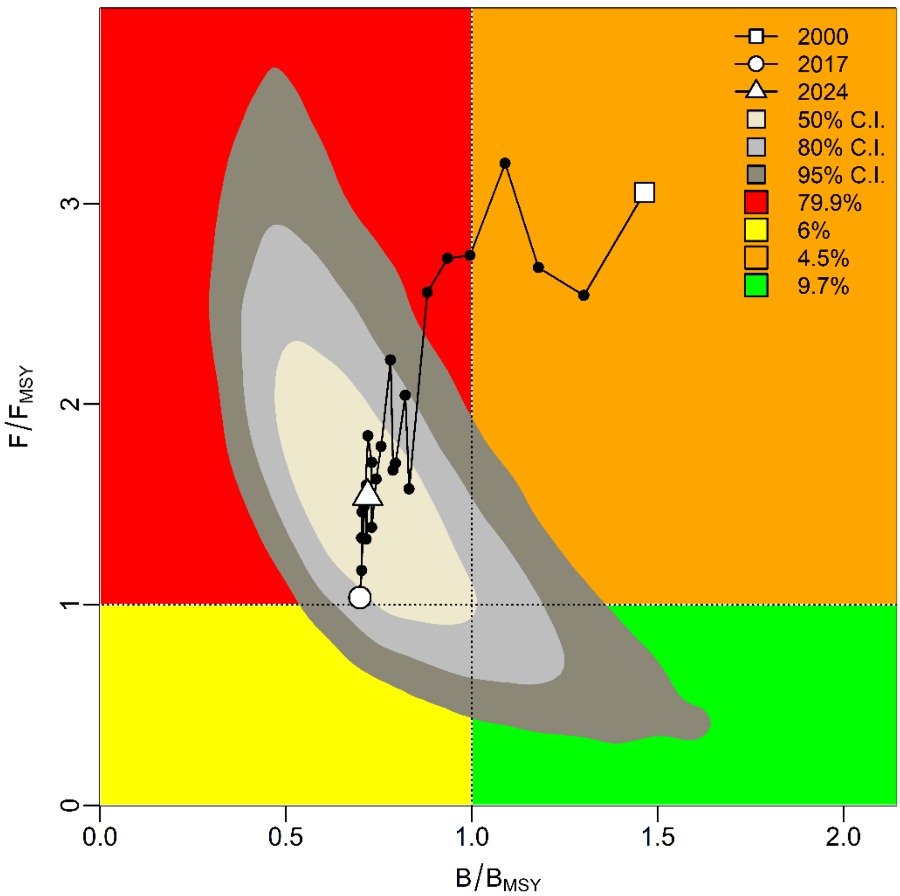

Figure 4. Kobe plot showing the estimated trajectory of B/B_{MSY} and F/F_{MSY} from 2000 to 2024 for the base case scenario. Grey-shaded areas denote the 50, 80, and 95% credible intervals of the stock status in the final year. The probability of the final-year stock status falling within each quadrant is indicated in the figure legend.

3.3. Retrospective analysis

The retrospective analysis revealed no systematic deviation from the 2024 model for any of the key estimated parameters (Fig. 5). The estimated Mohn's rho for all stock quantities was within the acceptable range of -0.15 and 0.20 (Hurtado-Ferro et al. 2014, Carvalho et al. 2017), which confirms the absence of an undesirable retrospective pattern.

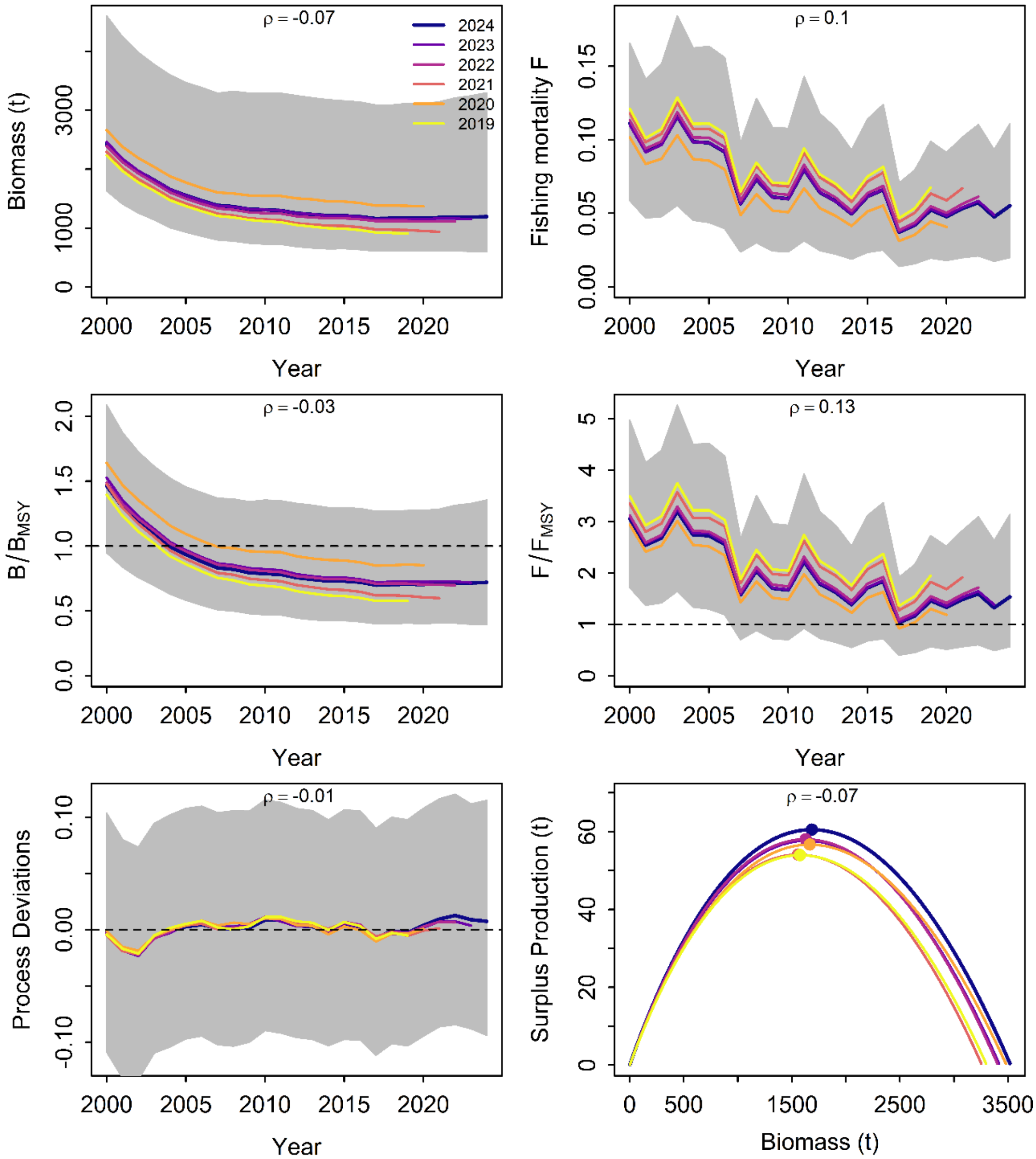

Figure 5. Retrospective analysis conducted for the base case scenario, showing the trajectories of the absolute biomass (top left), fishing mortality (top right), biomass relative to B_{MSY} (middle left) and fishing mortality relative to F_{MSY} (middle right), along with process deviations (bottom left) and surplus production curves (bottom right) for five retrospective model runs (coloured lines). Estimates from the model fitted to the full time series (2000–2024) are shown in dark blue (solid lines), and their 95% credible intervals are shown in grey (shaded areas). The numeric label indicates the year up to which the individual retrospective model was run (inclusive). ρ: Mohn's rho index.

3.4. Sensitivity analysis

MCMC diagnostics tests of Geweke (1992) and Heidelberger and Welch (1983) and visual inspection of trace plots indicate an adequate convergence and good mixing of the MCMC chains for all sensitivity scenarios (not shown). Similarly, JABBA model fits to the standardised CPUE were reasonably good for all scenarios (RMSE range: 0.13-0.17) and no major pattern in the residuals was detected. Comparison of posterior distributions and prior densities led to similar results to those obtained for the base case scenario (not shown). No major retrospective pattern was detected, and the estimated Mohn's rho for the key parameters was within the acceptable range of -0.15 and 0.20 for all scenarios, except for *F* (0.20) and F_{MSY} (0.23) for the scenario with the lowest r prior mean ("r reduced 50%"), and for *B* (0.22) for the scenario excluding the first and last two years of the time-series.

While the prior mean used for *r* affected the estimates and the trajectories of most of the stock quantities (Figs. 6-7), it had a negligible effect on B/B_{MSY} and *B/K*, a slight effect on F/F_{MSY} (except in the scenario with the lowest *r* prior mean), and virtually no effect on the trends of *B*, B/B_{MSY}, *B/K*, *F* and F/F_{MSY}. All scenarios using the full time-series indicated that the stock was both overfished and experiencing overfishing in 2024 (67.6 – 79.1% probability; Fig. A16). Reducing the prior mean for *r* resulted in higher posterior medians for *K*, *B*, B_{MSY}, F/F_{MSY}, and lower posterior medians for *r*, *MSY*, *F* and F_{MSY} (Figs. 6-7).

Excluding the first two years of the catch and CPUE time-series had a major impact on the posterior medians of most stock quantities and considerably increased their 95% credible intervals (Figs. A17-18). Most importantly, it impacted the trajectories of B/B_{MSY} and F/F_{MSY} significantly and led to a much more optimistic and uncertain stock status in 2024 (51.5% and 28% probability that the stock status fell within the green and red quadrant of the Kobe plot in 2024, respectively; Fig. A19). Excluding the first and last two years of the time-series had a similar impact on stock estimates and status as excluding only the first two years (Figs. A17-19).

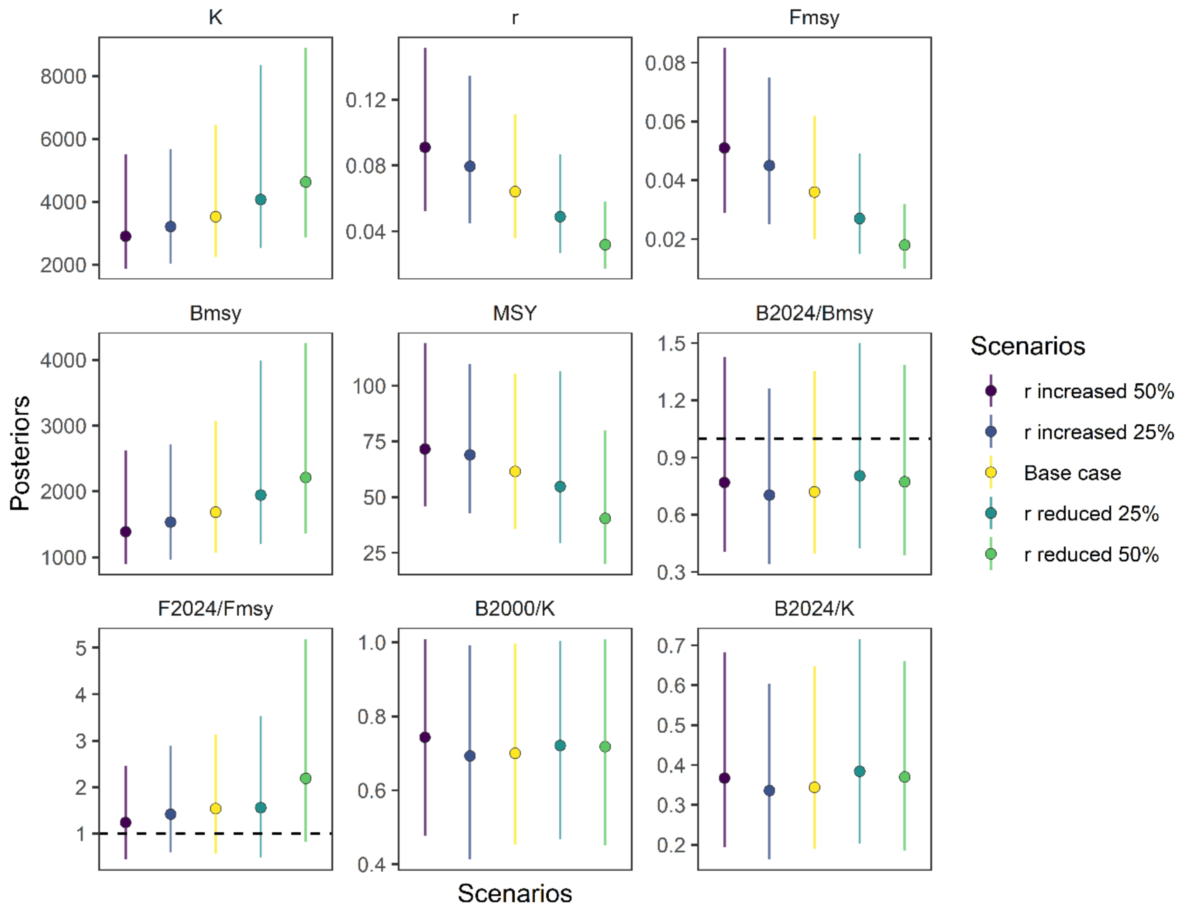

Figure 6. Posterior estimates (medians) and 95% credible intervals (vertical bars) of model parameters and stock status for the base case and the four sensitivity scenarios. Horizontal dashed lines indicate overfished (B/B_{MSY} < 1) and overfishing (F/F_{MSY} > 1) limits, respectively.

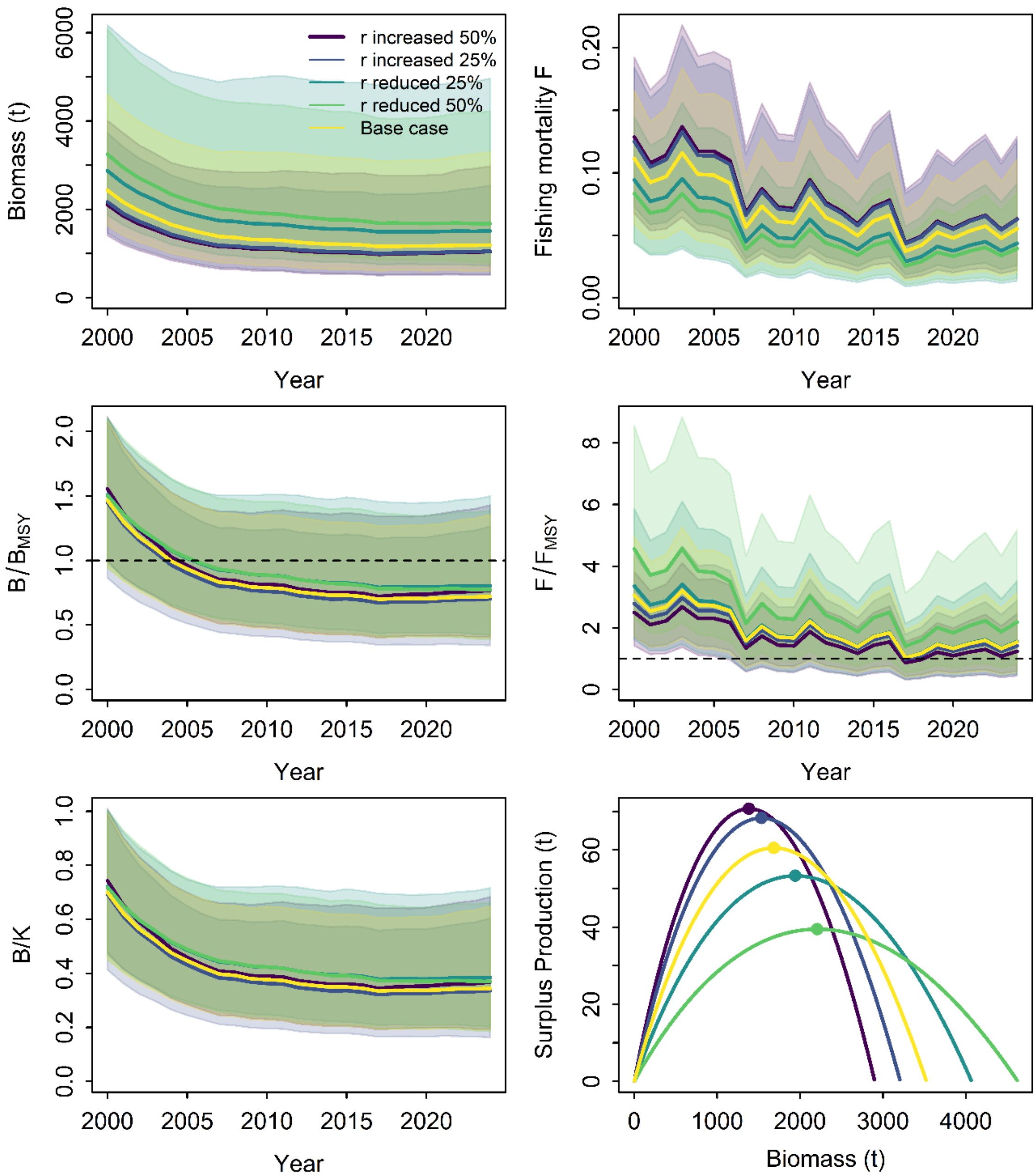

Figure 7. Sensitivity analysis showing the influence of the prior for the intrinsic rate of population growth (*r*) on the estimated trajectories of the absolute biomass (top left), fishing mortality (top right), biomass relative to B_{MSY} (middle left), fishing mortality relative to F_{MSY} (middle right) and biomass relative to *K* (bottom left), and on the surplus production curve (bottom right).

3.5. Stock projections

Projections from the base case model suggest that the bigeye grenadier stock will remain overfished ($B/B_{MSY} < 1$) through 2035 across all tested catch scenarios (Fig. 8). However, the stock is projected to begin a slow recovery if annual removals are reduced to 50 t or less. Annual removals of 45 t or less would end overfishing ($F/F_{MSY} \leq 1$) within ten years (Fig. 8). Conversely, removals of 60 t or more are expected to lead to further depletion, indicated by a continued decline in B/B_{MSY}.

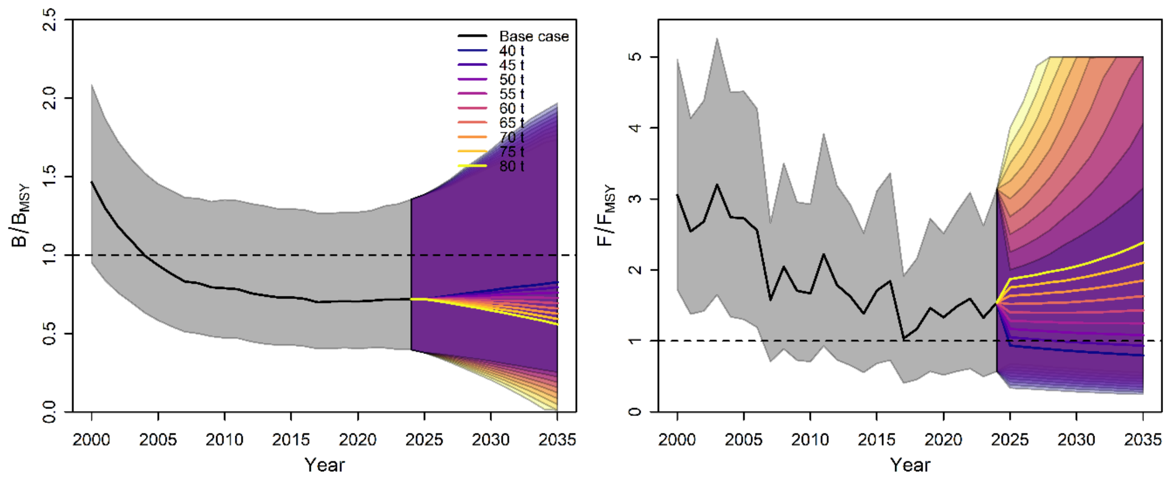

Figure 8. Projected trajectories of biomass relative to B_{MSY} (left panel) and fishing mortality relative to F_{MSY} (right panel), based on the base case model for various future catch levels between 2025 and 2035. Black lines denote model estimates, while coloured lines represent projected stock quantities under constant catch scenarios.

4. Discussion

This report provides an updated assessment of the bigeye grenadier stock in Falkland Islands waters, using the Bayesian surplus production model framework JABBA. Surplus production models (SPMs) are among the least data-demanding population models that can produce estimates of MSY and associated fisheries reference points, and despite a number of limitations (Maunder 2003, Punt and Szuwalski 2012), they remain an integral tool for data-moderate stock assessments (Dichmont et al. 2016, Punt et al. 2015). Furthermore, SPMs have been considerably enhanced by the introduction of Bayesian state-space modelling approaches, which reduce uncertainty in stock estimates and status by using reasonably informative priors and accounting for both process and observation errors (Winker et al. 2018). However, even Bayesian state-space SPMs, such as JABBA, can produce biased and uncertain estimates if the stock has been lightly exploited, or if the available data do not reflect the range of exploitation levels experienced by the stock (Hilborn and Walters 1992, Kokkalis et al., 2024).

Previous assessments of the bigeye grenadier stock highlighted a lack of contrast in the CPUE time-series and the sensitivity of the model outputs to the prior used for the intrinsic rate of population growth, which both led to large uncertainty around the stock status (Skeljo and Winter 2021, 2022, 2023). The present assessment addressed these concerns by (i) including two years with high CPUE at the beginning of the time-series (2000-2001) and (ii) running alternative scenarios with different *r* values to account for the effect of this key but poorly known parameter on the assessment results.

The re-analysis of the catch and effort data from the early years of the fishery confirmed that bigeye grenadier catches were severely underreported from 1994 to 1999 (Skeljo and Winter, 2021). However, it revealed that those reported from 2000 to 2001 could be considered accurate enough to be included in the assessment. This exploratory analysis also indicated that the associated CPUE could serve as a relative abundance index after careful exclusion of a few fishing vessels. Incorporating these two years of data into the assessment increased the contrast in the CPUE time series, leading to a less optimistic status estimate for the bigeye grenadier stock in Falkland Islands waters. It also considerably reduced the uncertainty surrounding stock estimates and status, which nonetheless remains relatively high. This could be explained by the unidirectional trend in biomass (“one-way downhill trip”), which typically contains limited information about the stock productivity and prevent the independent estimation of intrinsic growth rate and carrying capacity parameters (Fig. 6; Hilborn 1979, Hilborn and Walters 1992). By contrast, the retrospective analysis showed that removing the last few years of the catch and CPUE time series had a negligible impact on the stock trajectory and status. This came as no surprise, as increasing the length of a time series generally affects SPM outputs and reduces uncertainty only if it increases contrast in the data (Kokkalis et al. 2024). This was not the case with the data reported over the past few years, as bigeye grenadier has been caught exclusively in the longline fishery and at a consistently low proportion of the annual toothfish catch, which has remained stable during this period.

Although the total removals of bigeye grenadier accounted for potential IUU catches in the present assessment, alternative scenarios with different levels of IUU fishing could be tested, particularly at the beginning of the time-series (e.g., Winker et al. 2020). This catch reconstruction could be extended to the early years of the fishery (1994-1999), for example using an approach based on ratios of bycatch to target species (Coelho and Rosa, 2017; Gertseva and Matson, 2021). While reconstructing historical removals is notoriously difficult, even rough catch estimates can be useful for SPMs, as they may contain additional information and increase the contrast in the data, ultimately contributing to reducing uncertainty around stock estimates and status (Kokkalis et al., 2024). In particular, such a catch reconstruction could potentially lead to a more realistic estimate of the carrying capacity for the exploitable part of the bigeye grenadier population, which consistently appeared to be relatively low across all tested scenarios.

The uncertainty about the intrinsic rate of population growth and the sensitivity of many estimated stock quantities to the prior used for this parameter remain a matter of concern. It is therefore recommended that future assessments of the bigeye grenadier stock continue to perform sensitivity runs with different *r* values. However, the fact that all scenarios using the full time-series led to the same stock status strengthens our confidence in the results obtained in the base case scenario.

This assessment indicates that the bigeye grenadier stock is more depleted than previously thought and remains subject to overfishing. However, projections from the base case model suggest that the stock will rebuild slowly if annual removals do not exceed 50 t. Reducing grenadier bycatch is challenging because bigeye grenadier are distributed throughout the fishing area and have been caught on virtually every line set around the Falkland Islands. Introducing a move-on rule was found to be ineffective in reducing grenadier bycatch and was therefore not recommended at the time of the study (Skeljo, 2021). In the present assessment, CPUE standardisation revealed historical hotspots in the northern part of the fishing area and the eastern part of Burdwood Bank (Figs. A1-2, A4-5). Therefore, a more detailed analysis of the spatiotemporal distribution of bigeye grenadier, in relation to that of Patagonian toothfish, would be useful for evaluating whether temporal closures of specific grid squares could help reduce grenadier bycatch in the toothfish longline fishery.

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Appendix 1. Spatial distribution of bigeye grenadier CPUE from 2008-2024

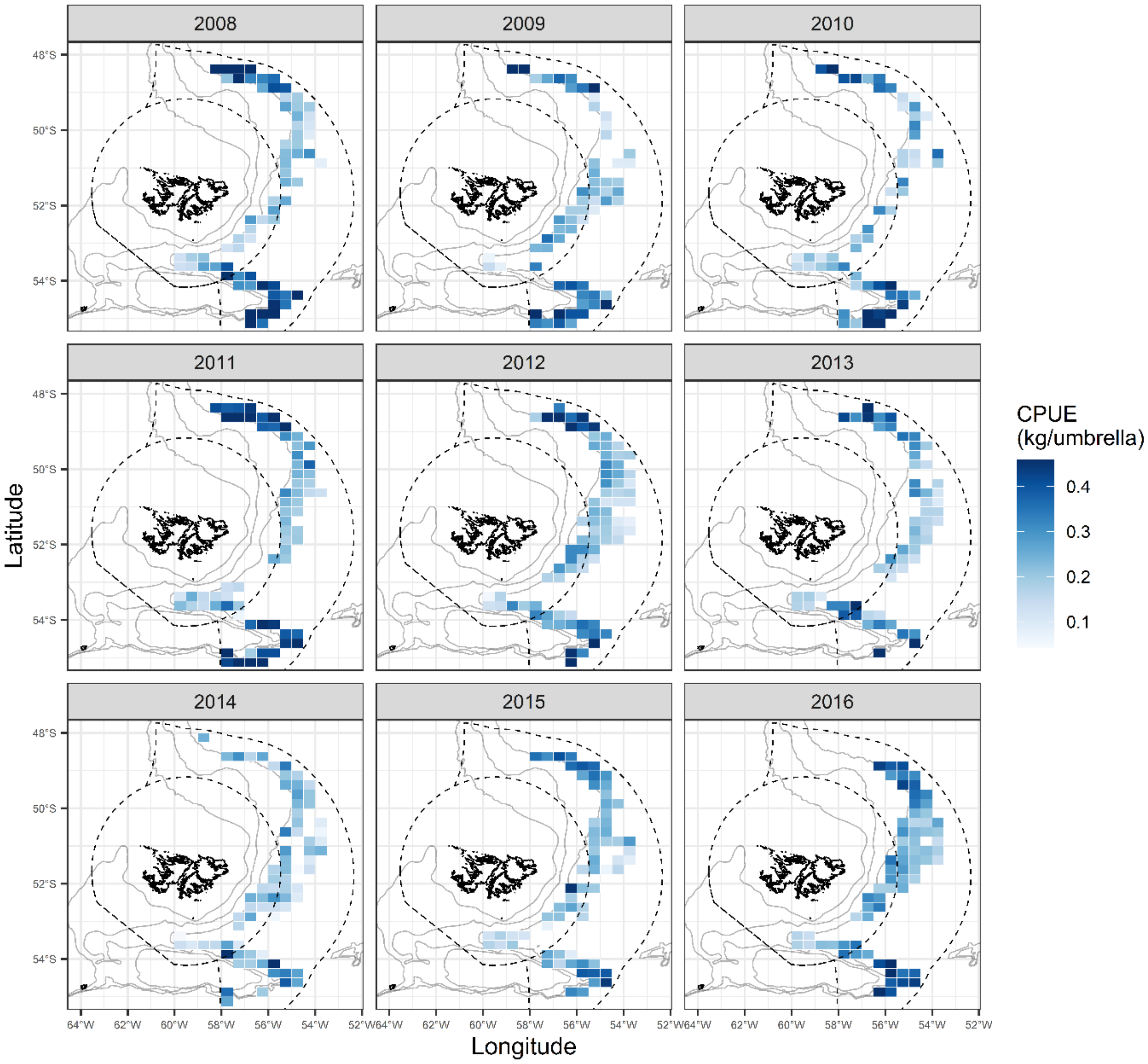

Figure A1. Distribution of bigeye grenadier nominal catch per unit effort (CPUE) in Falkland Islands waters from 2008 to 2016. The mean annual CPUE, expressed in kg/umbrella, is displayed for each 0.5° x 0.25° grid square in which longline fishing occurred. The dashed lines represent the inner and outer Falkland Islands conservation zones.

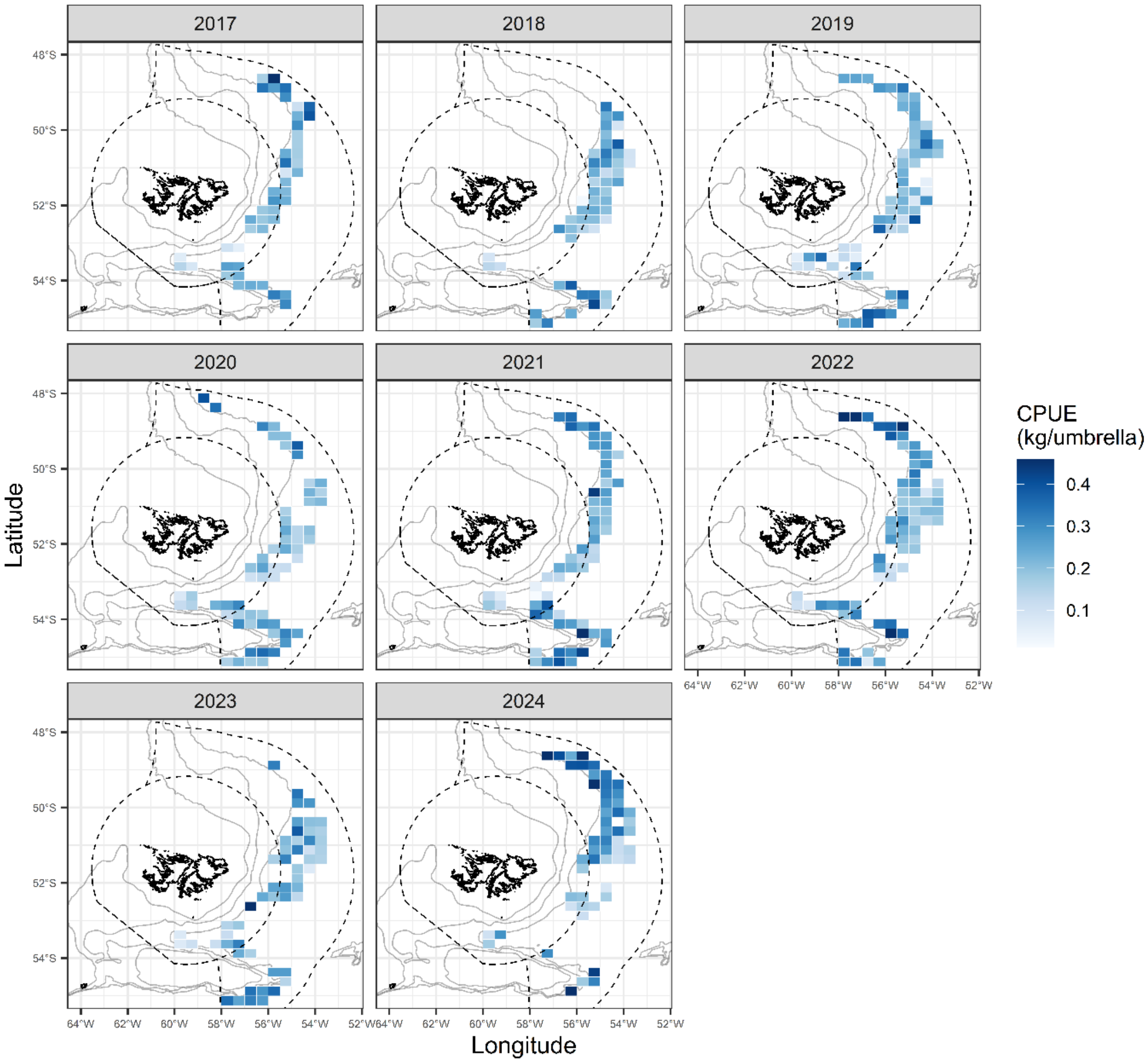

Figure A2. Distribution of bigeye grenadier nominal catch per unit effort (CPUE) in Falkland Islands waters from 2017 to 2024. The mean annual CPUE, expressed in kg/umbrella, is displayed for each 0.5° x 0.25° grid square in which longline fishing occurred. The dashed lines represent the inner and outer Falkland Islands conservation zones.

Appendix 2. CPUE standardisation

CPUE was standardised using Generalised Additive Models (GAMs) fitted with the *mgcv* package (Wood 2011) in R version 4.5.0 (R Core Team, 2025). GAMs represent a flexible alternative to Generalised Linear (Mixed) Models (GL(M)Ms) and tend to outperform the latter by predicting more realistic relationships between CPUE and continuous variables (Grüss et al. 2019, Hoyle et al. 2024).

The response variable was defined as bigeye grenadier CPUE expressed in kg-per-hook for the Spanish system (day-by-day catch reports) and in kg-per-umbrella for the umbrella system (line-by-line catch reports). CPUE was modelled using a Gamma distribution with a log link function for both time series. Seven explanatory variables were selected as potential covariates (Table A1). Contrary to the previous assessment (Skeljo and Winter 2023), toothfish CPUE was excluded from the list because its inclusion in any given model may remove time trends in grenadier catch rate which should be attributed to the year effect, as both species are being caught on the same longlines (Maunder and Punt, 2004).

Table A1. Explanatory variables considered in the CPUE standardisation. The asterisk (*) indicates variables included in the final model.

Explanatory variables		Variable type
Spanish system	Umbrella system	
Year*	Year*	Categorical
Month*	Month	Continuous
Longitude*	Longitude*	Continuous
Latitude*	Latitude*	Continuous
Depth*	Depth*	Continuous
-	Soak-time*	Continuous
Vessel*	-	Categorical

The *Year* effect is the quantity of interest and was included as a categorical variable (Spanish system: 8 levels; umbrella system: 17 levels) in all models. The *Vessel* variable (categorical, 5 levels) was included in the Spanish-system CPUE standardisation to account for the dependency among CPUE values from the same vessel. It was treated as a fixed effect due to the small number of levels. Conversely, it was excluded from the umbrella-system CPUE standardisation because the dataset included only two vessels which never fished concurrently during the same year, making the *Vessel* and *Year* effects indistinguishable. The other explanatory variables were added by forward stepwise selection and retained in the final model only if they increased the deviance explained by at least 0.5%. All continuous variables were fitted with the smooth function s(), using the cyclic cubic spline (bs = “cc”) for the *Month* covariate and the default thin-plate regression spline (bs = “tp”) for the other covariates. The *Longitude* and *Latitude* variables were fitted as a two-dimensional spline to account for spatial autocorrelation among CPUE values. The *Soak-time* variable, defined as the soak time of individual lines, was only considered as a candidate covariate in the umbrella-system CPUE standardisation. This variable was not available in a suitable format for the Spanish system (Skeljo, 2025). The *Depth* variable was defined as the mean depth of each line (umbrella system) or the mean depth of multiple lines set the same day in a given grid square (Spanish system). Before modelling, exploratory analyses were conducted following the protocol described by Zuur et al. (2010). A few vessels that fished inconsistently and/or that were suspected of underreporting were excluded from the analysis (see section 2.2. for details). The remaining catch reports with zero bigeye grenadier were assumed to represent erroneous entries or broken sets and were thus excluded (0.7% of daily catch reports and 0.1% of line-by-line catch reports with the Spanish and the umbrella systems, respectively). Grid squares with less than three catch reports across each time series represented areas that were fished infrequently and were all located at the edge of the fishery. Therefore, these areas were excluded, resulting in the removal of 2% of the catch reports for the Spanish system (n =

67 daily reports), and 0.2% for the umbrella system (n=17 longlines). Explanatory variables were inspected for outliers using visual assessments and checked for concurvity (generalization of collinearity) using the 'concurvity' function of the *mgcv* package. Residuals of the final GAMs were visually inspected (Figs. A6-A11). All models were fitted with restricted maximum likelihood (REML) instead of generalized cross-validation (GCV) to avoid overfitting (Wood, 2017).

The final GAM fitted to the Spanish-system data included the effects of *Year, Month*, *Depth*, *Vessel* and the interaction between *Longitude* and *Latitude*; together, they explained 48.0% of the deviance. The annual CPUE index (standardised CPUE) decreased considerably from 2000 to 2002 and then remained fairly stable until 2007 (Fig. A3). The final GAM fitted to the umbrella-system data included the effects of *Year, Depth*, *soak-time* and the interaction between *Longitude* and *Latitude*, which together explained 39.9% of the deviance. From 2008 to 2016, the annual CPUE index fluctuated without displaying any clear trend. It reached its lowest value in 2019 before increasing progressively until 2024. Standardisation removed the downward trend observed in the nominal CPUE time series from 2008 to 2014 (Fig. A3).

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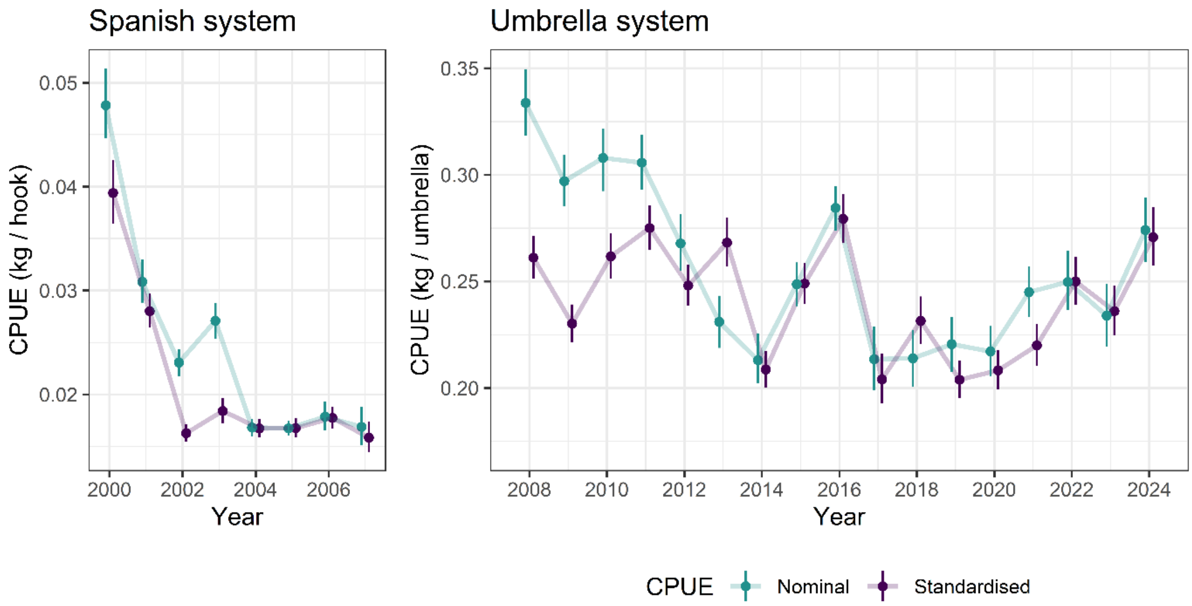

Figure A3. Nominal and standardised CPUE time series for the Spanish (left panel) and the umbrella (right panel) longline systems. Yearly CPUE estimates (coloured dots) and their 95% confidence intervals (vertical bars) are slightly jittered for clarity.

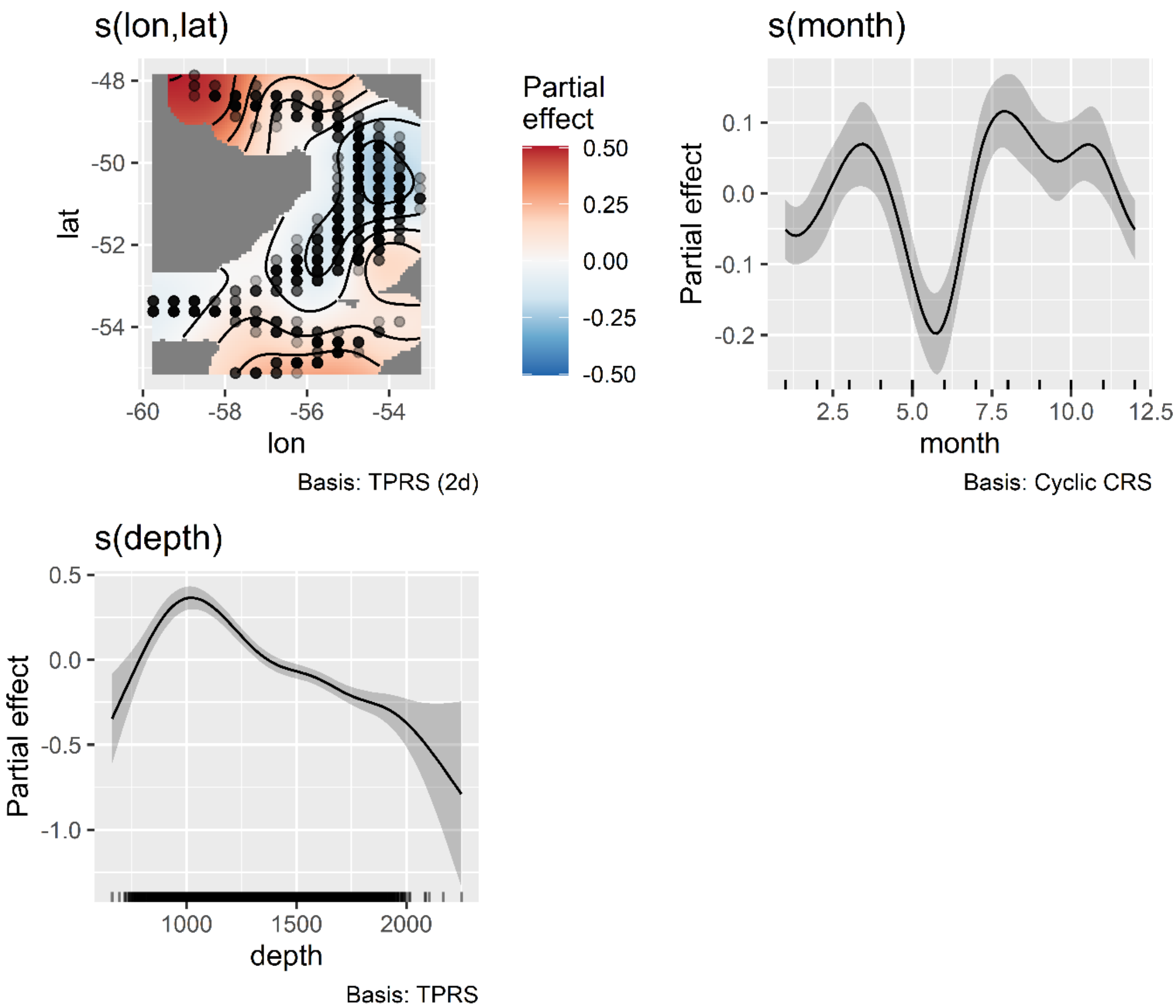

Figure A4. Partial effects of longitude and latitude (top-left), month (top-right) and depth (bottom-left) on Spanish-system CPUE (2000-2007). Lat: latitude, lon: longitude, TPRS: thin plate regression splines, CRS: cubic regression splines.

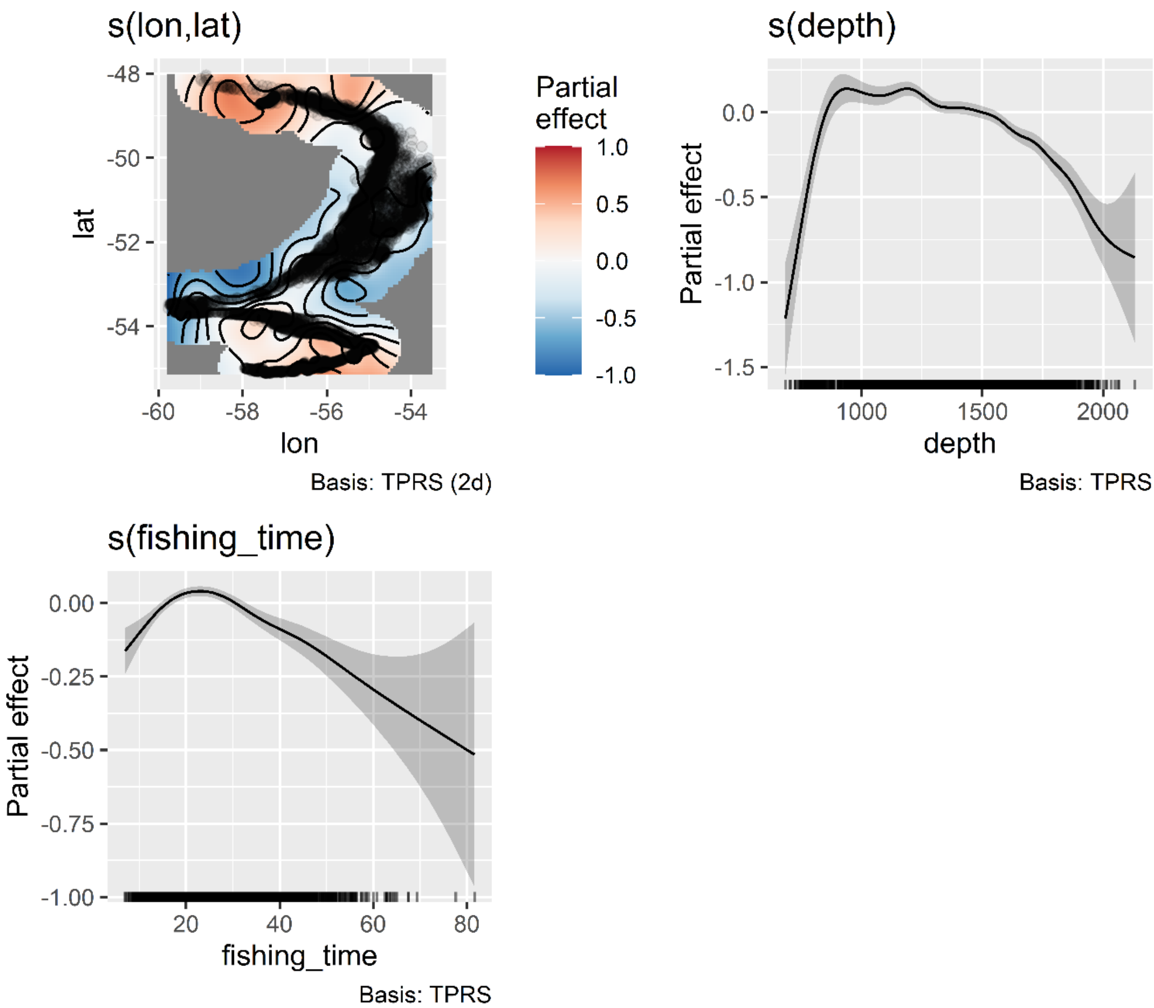

Figure A5. Partial effects of longitude and latitude (top-left), depth (top-right) and soak time ('fishing_time', bottom-left) on umbrella-system CPUE (2008-2024). Lat: latitude, lon: longitude, TPRS: thin plate regression splines.

Diagnostic plots for the final GAM fitted to Spanish-system CPUE (2000-2007)

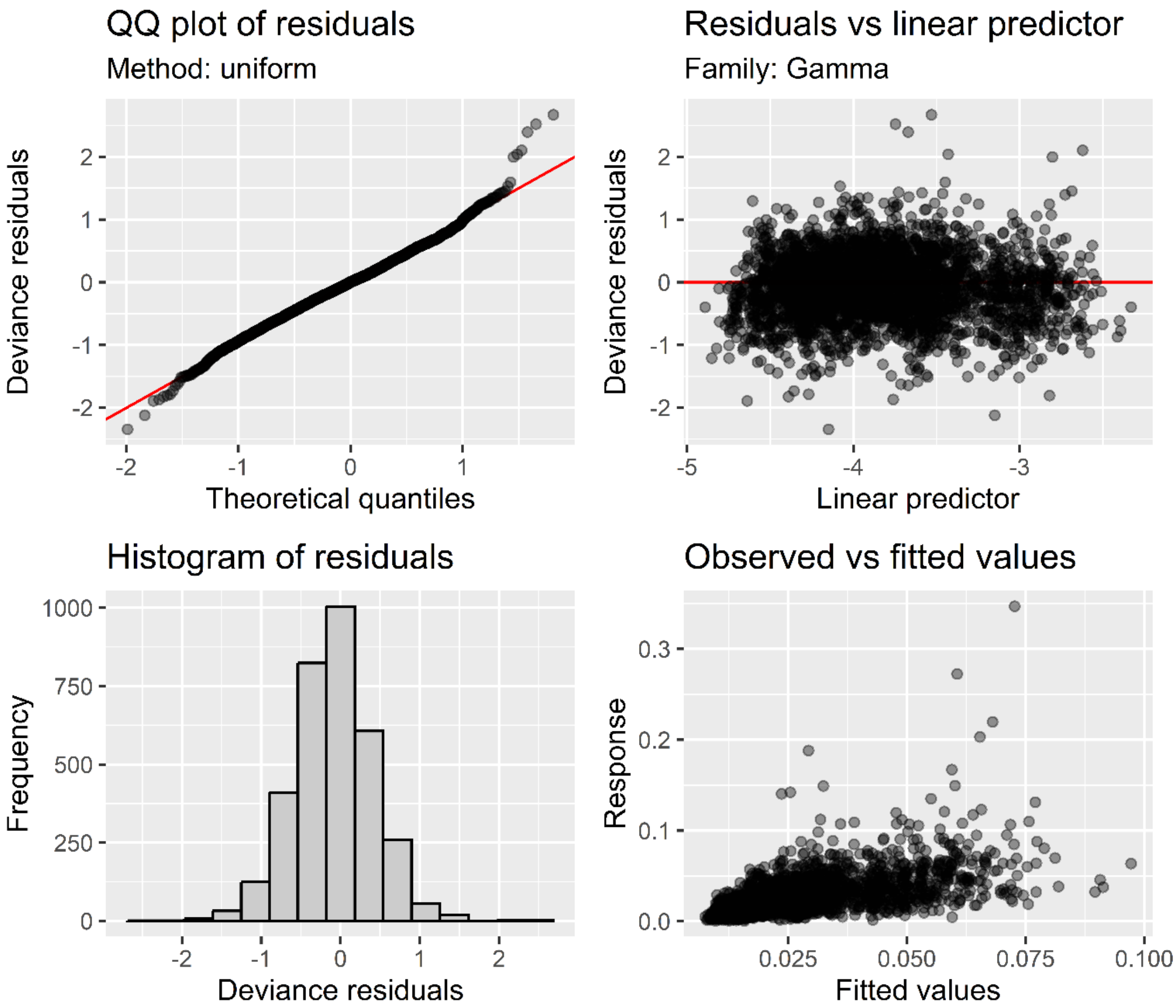

Figure A6. Standard diagnostic plots for the final GAM used to standardise Spanish-system CPUE (2000-2007).

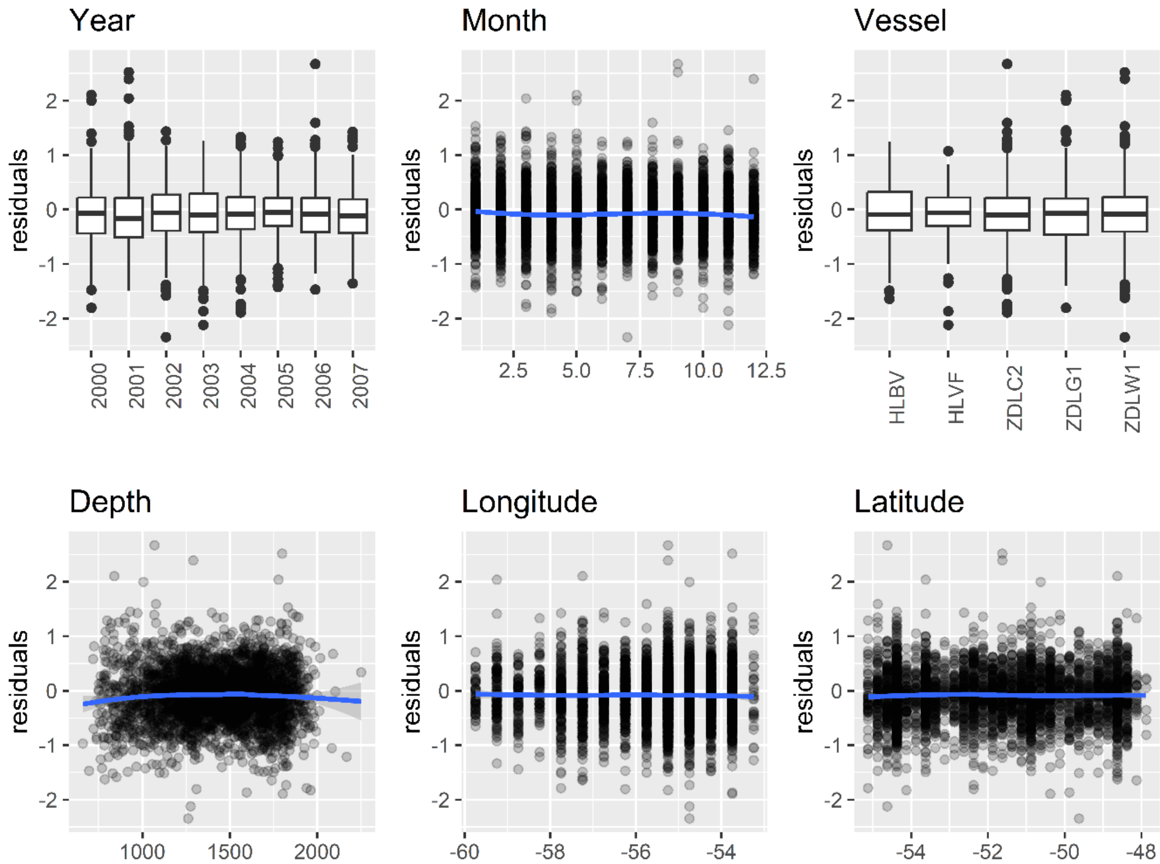

Figure A7. Residuals against each predictor for the final GAM used to standardise Spanish-system CPUE (2000-2007).

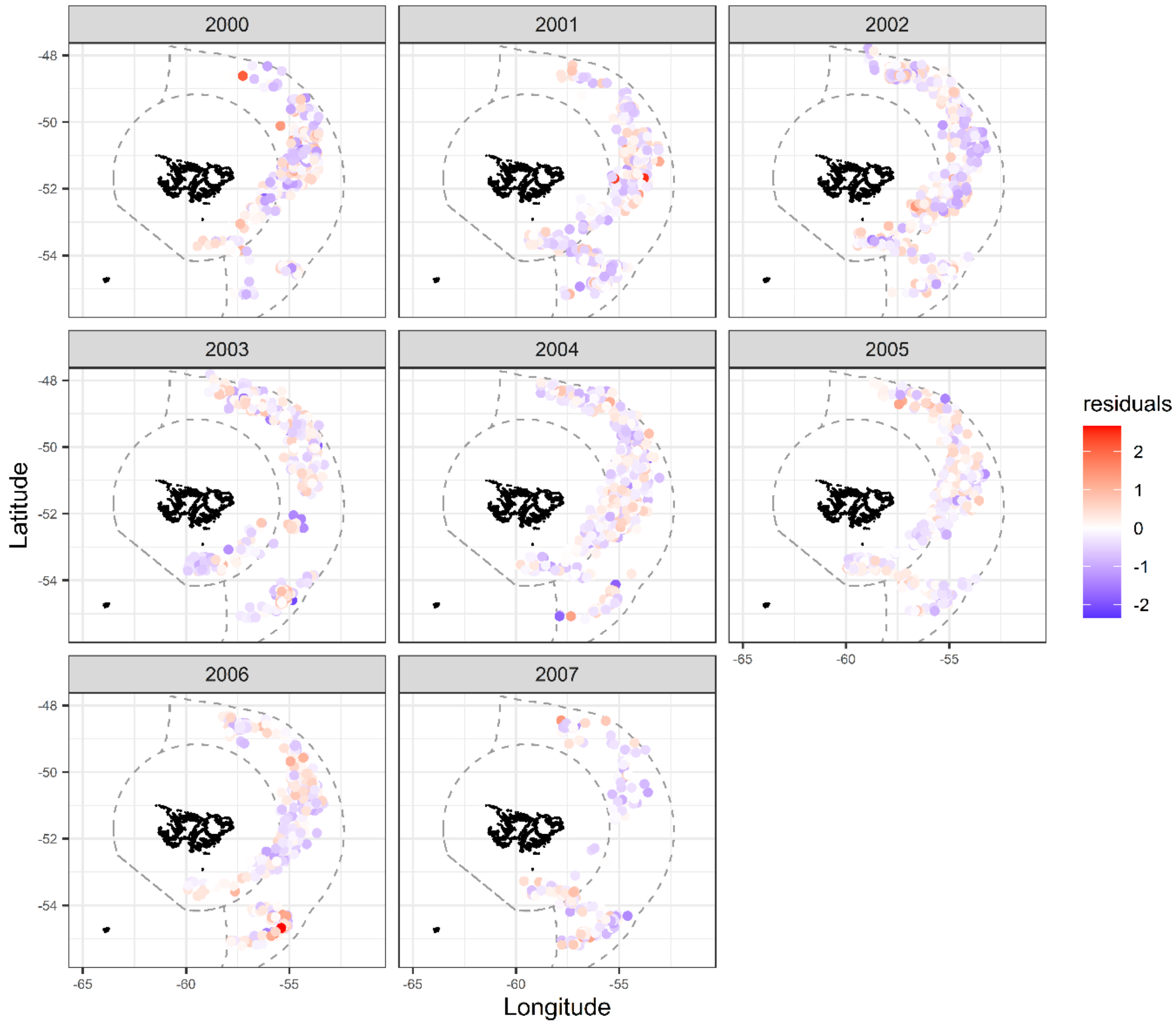

Figure A8. Spatial distribution of the residuals for the final GAM used to standardise Spanish-system CPUE (2000-2007).

Diagnostic plots for the final GAM fitted to umbrella-system CPUE (2008-2024)

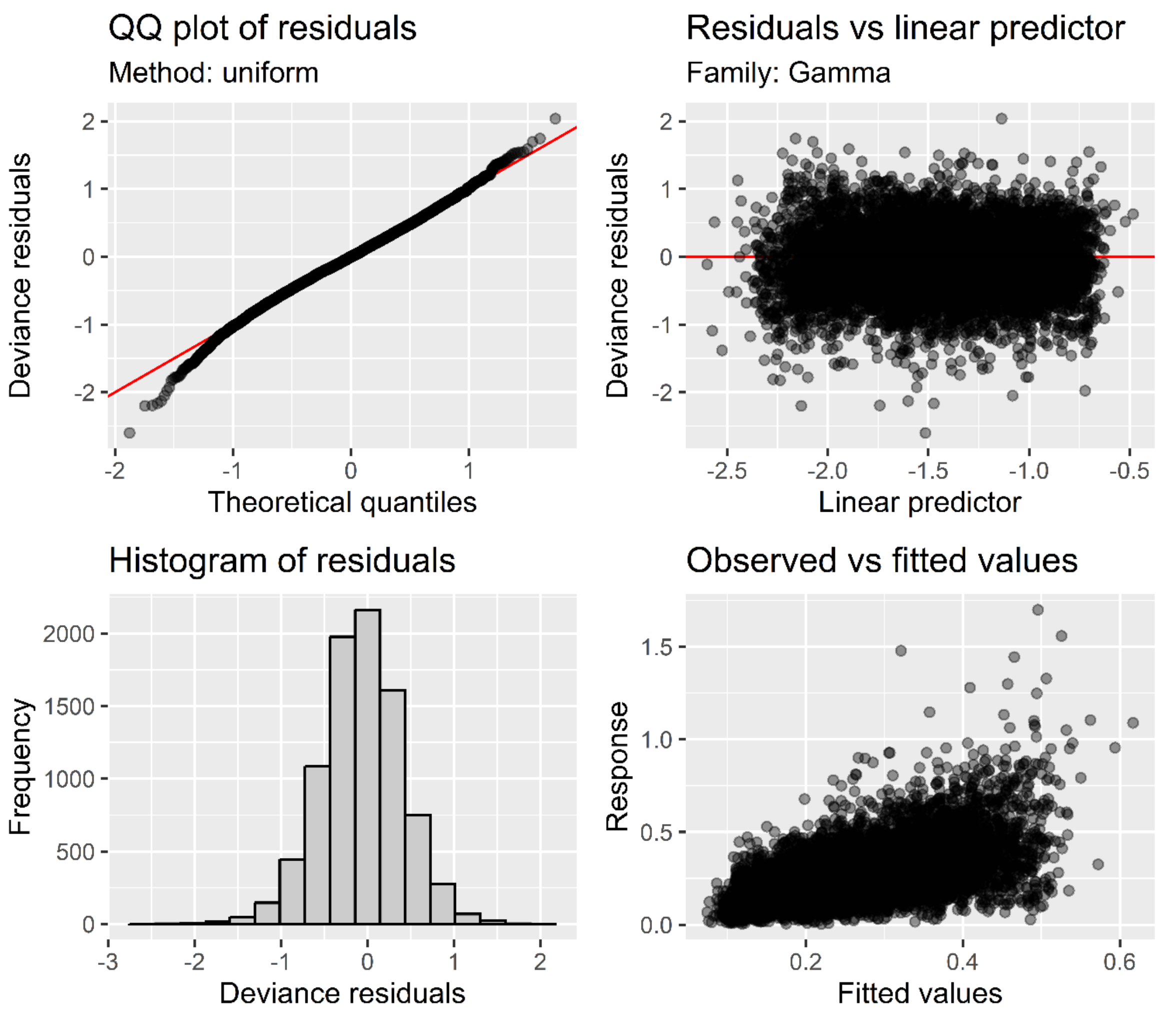

Figure A9. Standard diagnostic plots for the final GAM used to standardise umbrella-system CPUE (2008-2024).

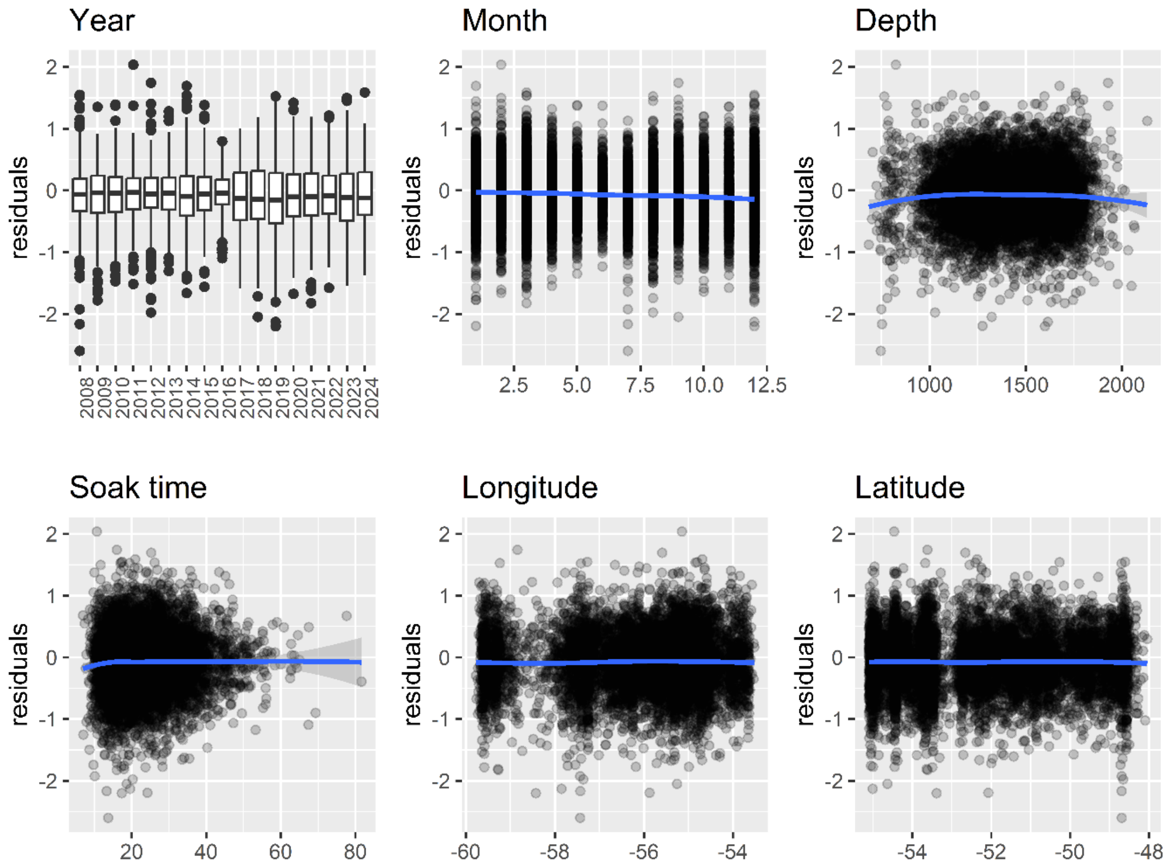

Figure A10. Residuals against each predictor for the final GAM used to standardise umbrella-system CPUE (2008-2024). Although the 'month' covariate was not included in the final GAM, no seasonal pattern was found in the residuals.

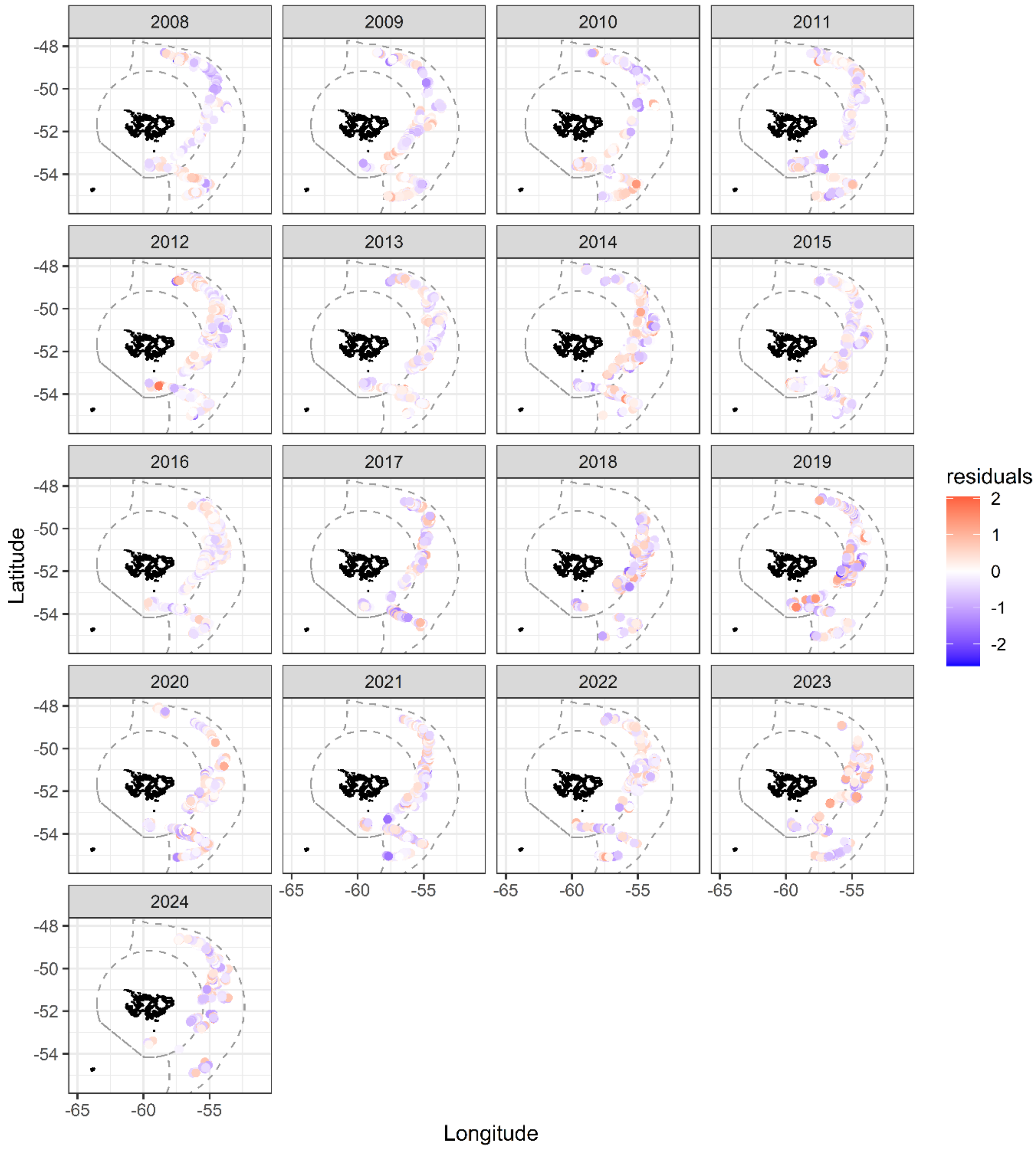

Figure A11. Spatial distribution of the residuals for the final GAM used to standardise umbrella-system CPUE (2008-2024).

Appendix 3. JABBA diagnostic plots for the base case scenario

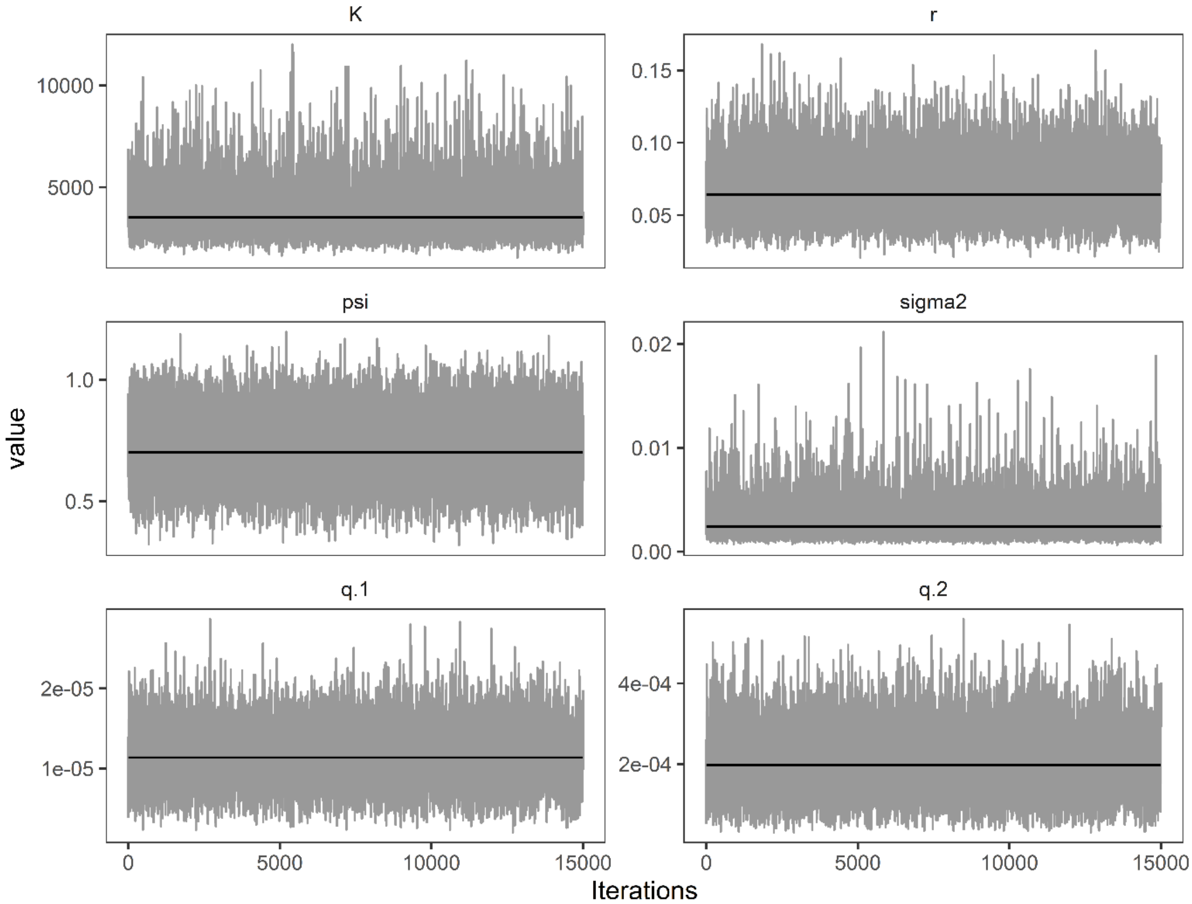

Figure A12. MCMC posterior trace plots for all estimated parameters. The black lines denote the medians. *K*: carrying capacity; *r*: intrinsic growth rate; *psi*: B_{2000}/K; *sigma2*: process error variance (σ^2_{proc}); *q.1*: catchability of the Spanish system; *q.2*: catchability of the umbrella system.

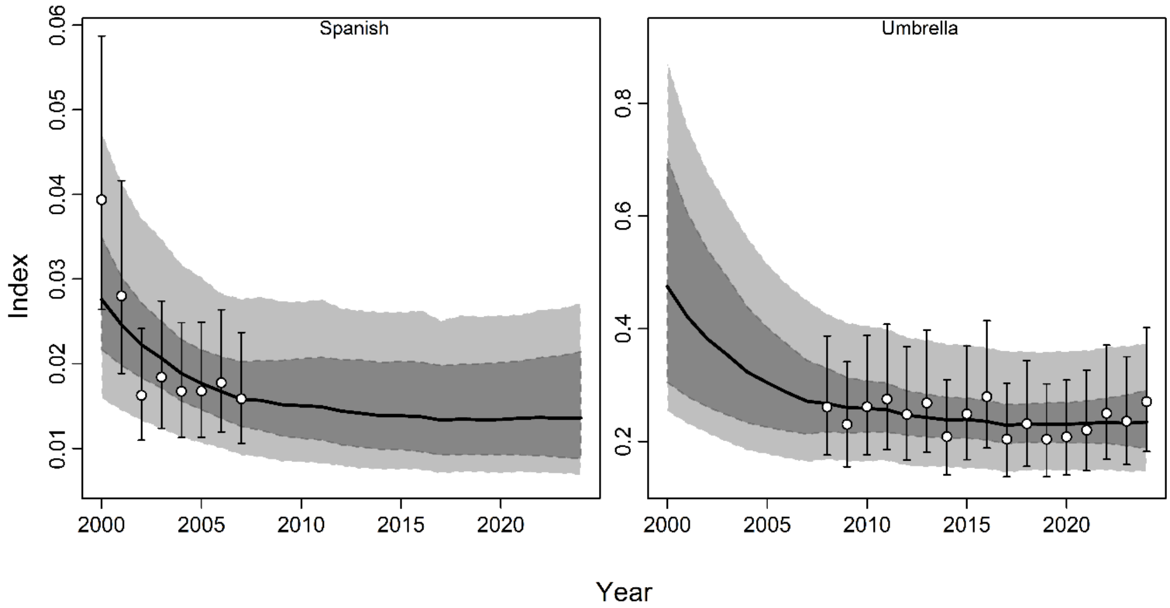

Figure A13. Model fits (black lines) to the standardised CPUE indices (white dots) for the Spanish system (CPUE in kg/hooks, left panel) and the umbrella system (CPUE in kg/umbrella, right panel). The vertical bars denote the 95% confidence intervals of the standardised CPUE indices. The dark grey shaded areas denote the 95% credible intervals of the expected mean CPUEs, and the light grey shaded areas denote the 95% posterior predictive distribution intervals.

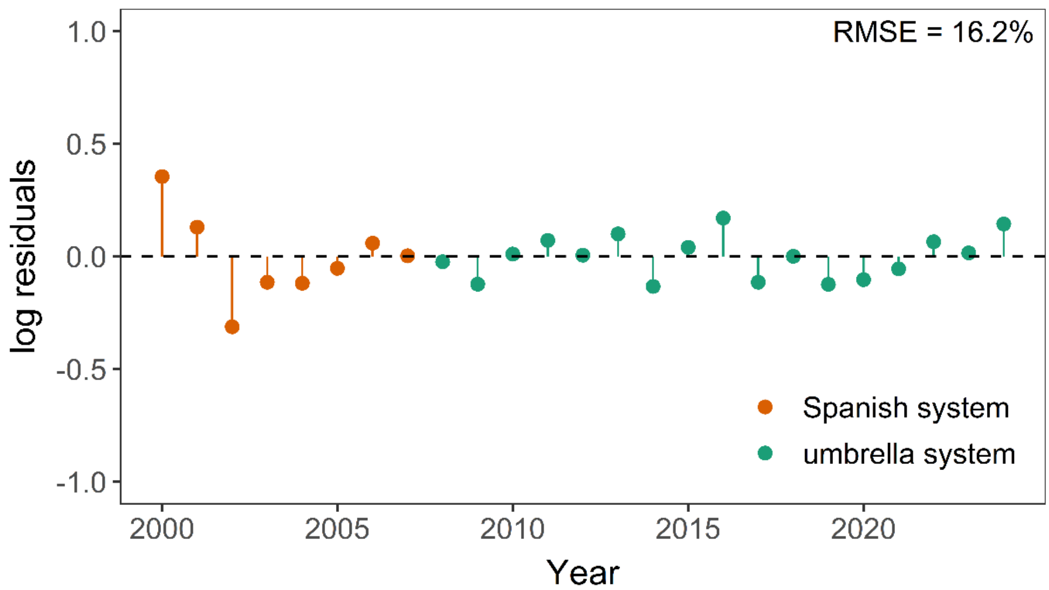

Figure A14. JABBA residual diagnostic plot for the Spanish and the umbrella CPUE indices. RMSE: root-mean-squared-error.

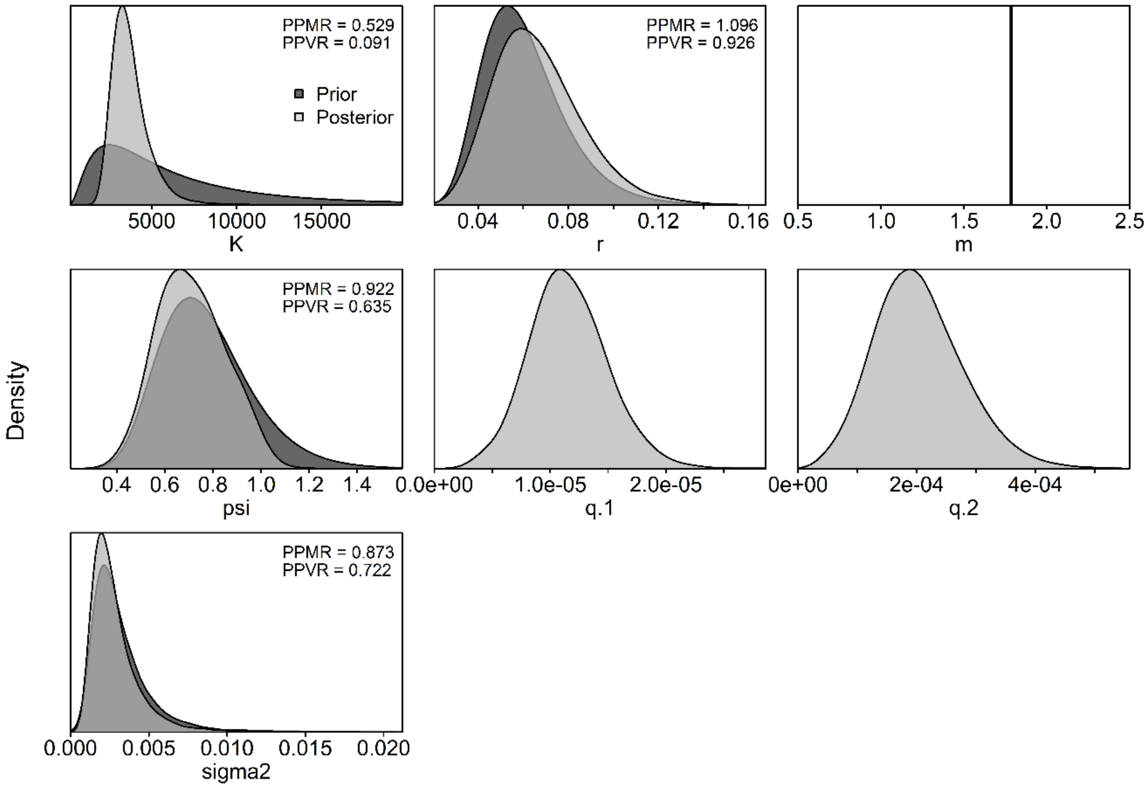

Figure A15. Prior (dark grey) and posterior (light grey) distributions of key model parameters. *PPMR*: Posterior to Prior Means Ratio; *PPVR*: Posterior to Prior Variances Ratio; *K*: carrying capacity; *r*: intrinsic growth rate; *m*: Pella-Tomlinson shape parameter; *psi*: B_{2000}/K; *q.1*: catchability of the Spanish system; *q.2*: catchability of the umbrella system; *sigma2*: process error variance (σ_{proc}^2). The vertical black line represents the fixed value used for *m* in this assessment (see section 2.3. for details).

Appendix 4. Supplementary figures for the sensitivity scenarios

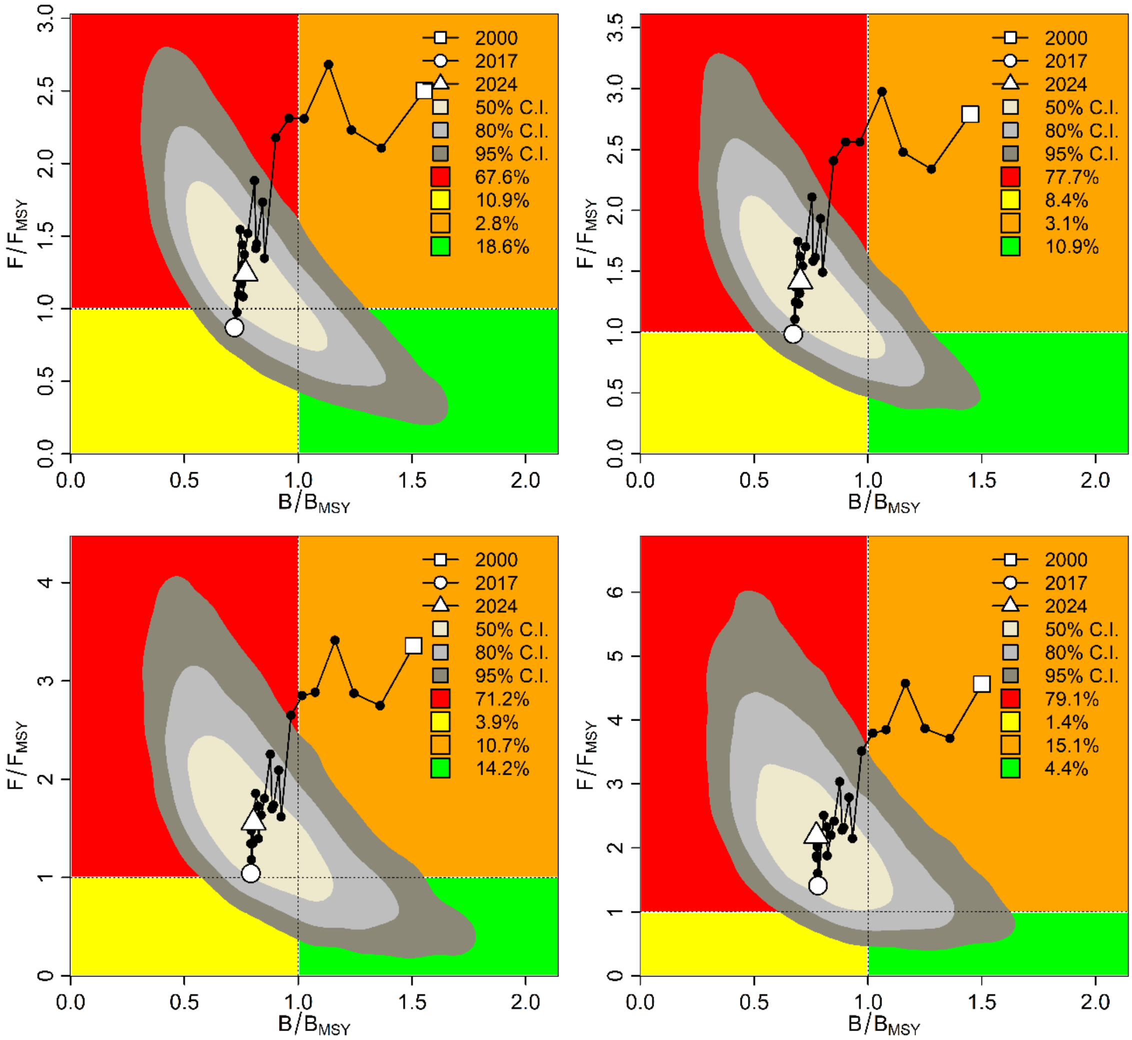

Figure A16. Kobe plots showing the estimated trajectory of B/B_{MSY} and F/F_{MSY} from 2000 to 2024 for four sensitivity scenarios with different intrinsic growth rate (*r*) priors (top left: "*r* increased 50%", top right: "*r* increased 25%", bottom left: "*r* reduced 25%", bottom right: "*r* reduced 50%"). Grey-shaded areas denote the 50, 80, and 95% credible intervals of the stock status in the final year. The probability of the final-year stock status falling within each quadrant is indicated in the figure legend.

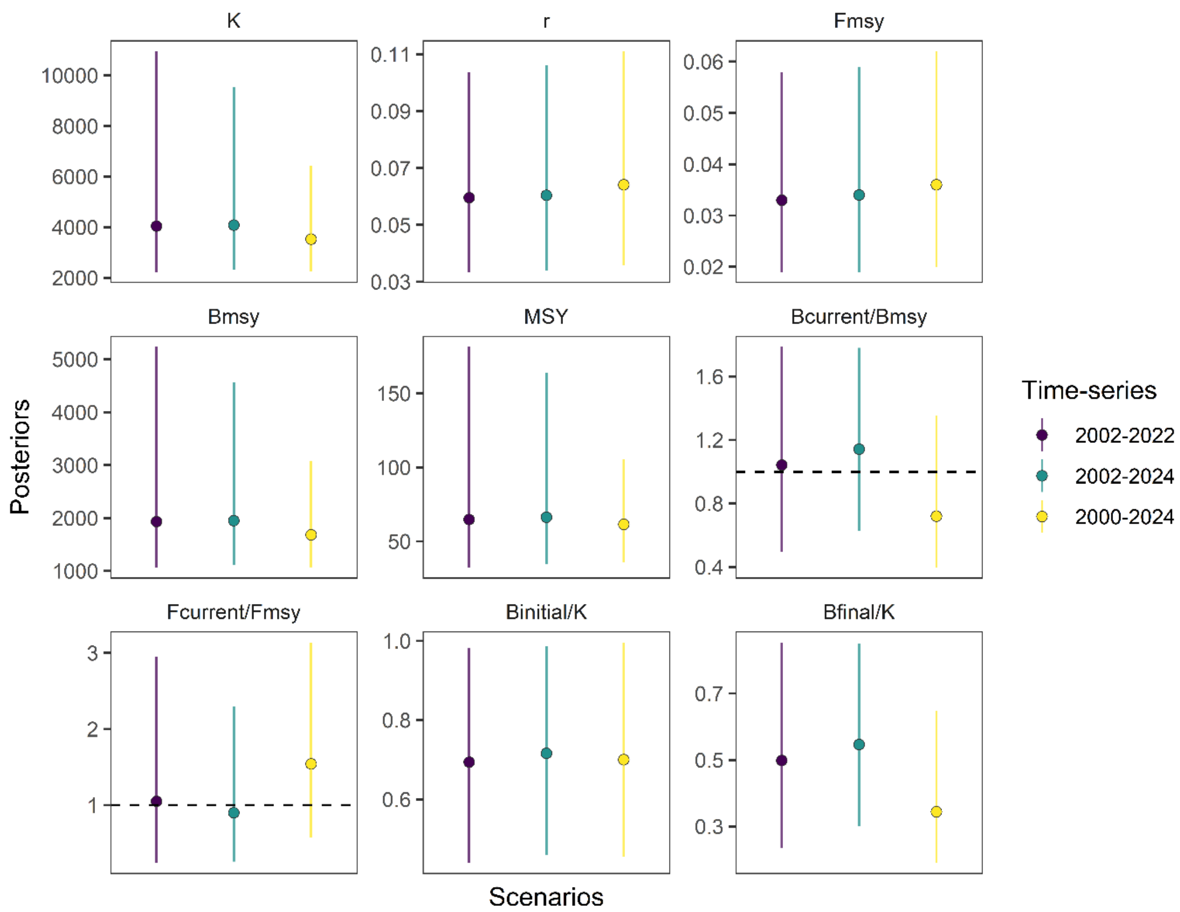

Figure A17. Posterior estimates (medians) and 95% credible intervals (vertical bars) of model parameters and stock status for the two sensitivity scenarios with shortened time-series (2002-2022 and 2002-2024) and the base case scenario (2000-2024). Horizontal dashed lines indicate overfished ($B_{current}/B_{MSY}$ < 1) and overfishing ($F_{current}/F_{MSY}$ > 1) limits, respectively.

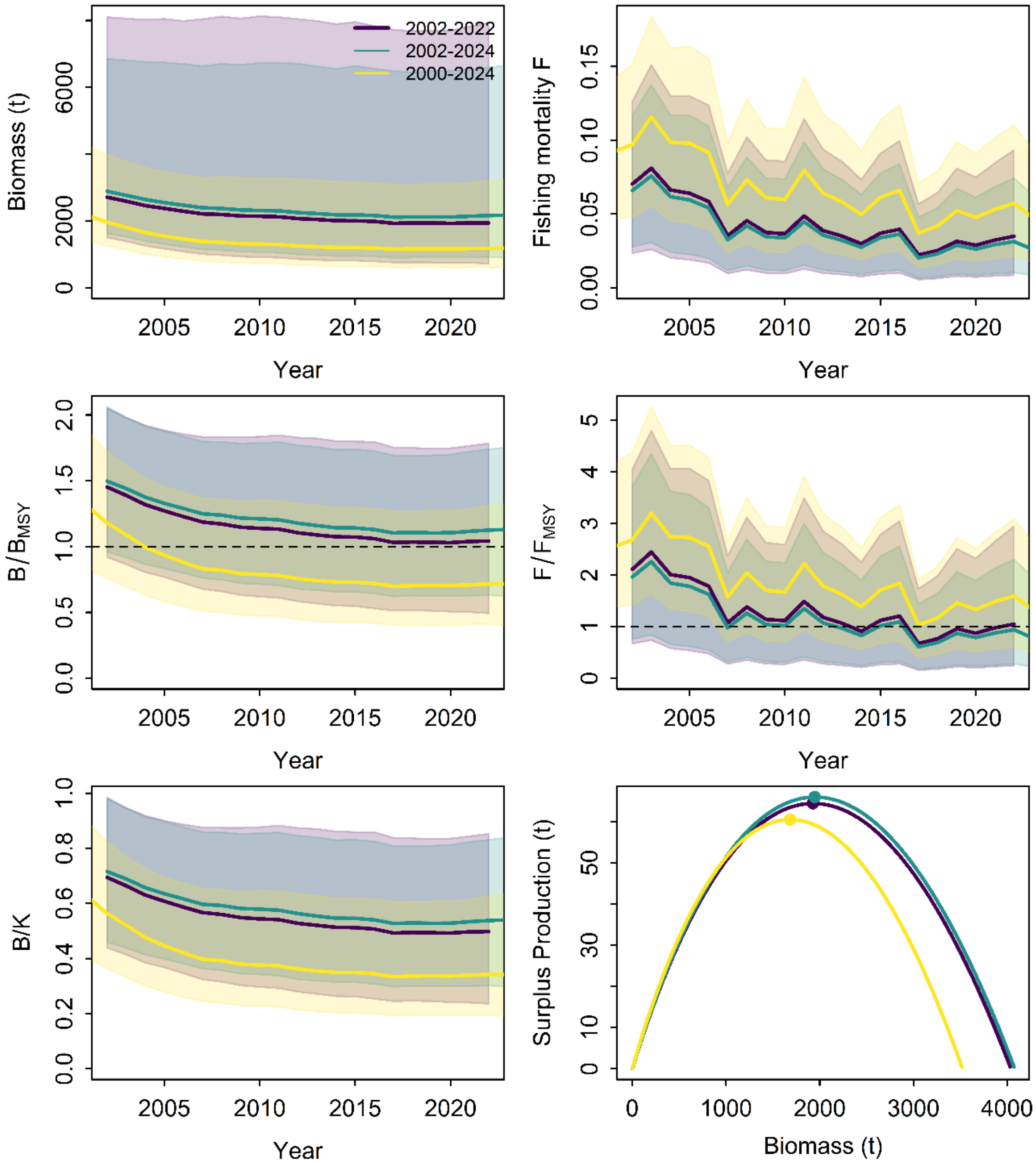

Figure A18. Sensitivity analysis showing the impact of shortening the catch and CPUE time-series on the estimated trajectories of the absolute biomass (top left), fishing mortality (top right), biomass relative to B_{MSY} (middle left), fishing mortality relative to F_{MSY} (middle right) and biomass relative to K (bottom left), and on the surplus production curve (bottom right). The full time-series (2000-2024) represents the base case scenario and is displayed in yellow.

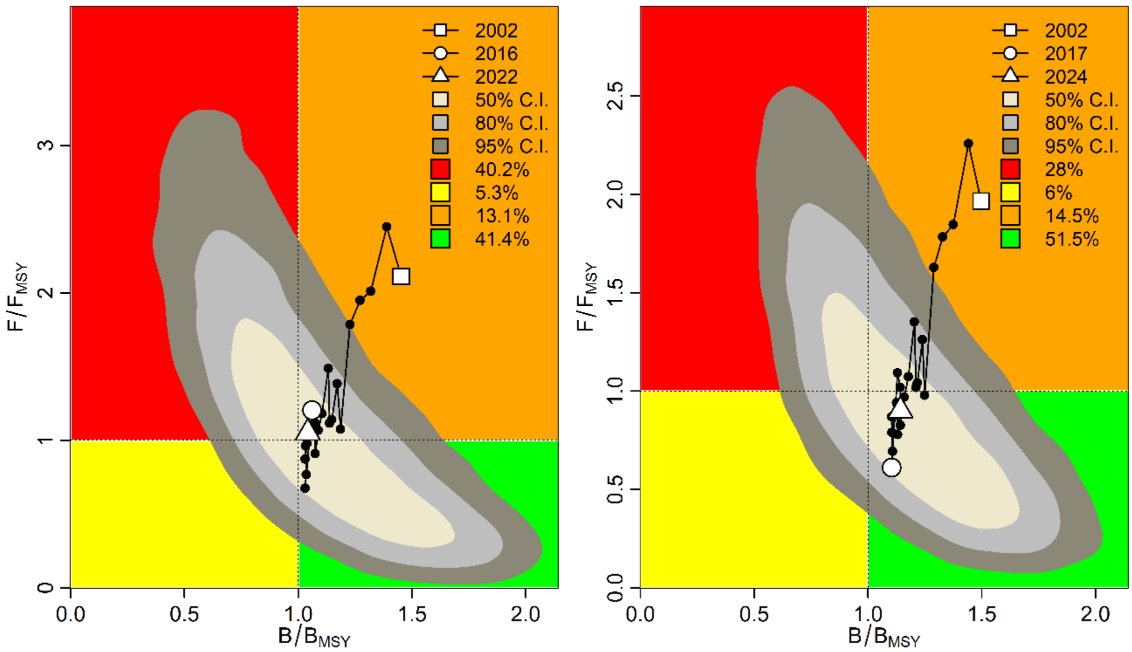

Figure A19. Kobe plots showing the estimated trajectory of B/B_{MSY} and F/F_{MSY} for the two sensitivity scenarios with shortened catch and CPUE time-series (left panel: 2002-2022, right panel: 2002-2024). Grey-shaded areas denote the 50, 80, and 95% credible intervals of the stock status in the final year. The probability of the final-year stock status falling within each quadrant is indicated in the figure legend.