Stock assessment of bigeye grenadier (*Macrourus holotrachys*) in the Falkland Islands to 2022

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Summary

1. This report provides an updated stock assessment of bigeye grenadier (*Macrourus holotrachys*) in Falkland Islands waters, using data up to the end of 2022. The model structure and assumptions were the same as in the previous assessment. The assessment was done in the Bayesian surplus production model framework JABBA (Winker *et al.* 2018).
2. Overall, the model showed a negative trend in stock status in 2002-2006, followed by a transitional period in 2007-2008 and a positive trend in 2009-2022. The estimated current biomass B_{2022} is 27.7% above B_{MSY}, and the current fishing mortality F_{2022} is 34.4% below F_{MSY}; taking into account the uncertainty of this estimate, there is a 72.2% probability that bigeye grenadier stock was not overfished ($B > B_{MSY}$) and not experiencing overfishing ($F < F_{MSY}$).
3. Since 2009, bigeye grenadier catch has been at or below the estimated maximum sustainable yield (MSY) in all years except 2011, indicating sustainable exploitation of the stock.

1. Introduction

The Falkland Islands toothfish longline fishery began in 1992 as an exploratory fishery and became an established fishery in 1994 (Laptikhovsky and Brickle 2005). Fishing was traditionally conducted using the 'Spanish' longlining system until the 'umbrella' system was introduced in 2007 to reduce the loss of hooked toothfish to depredation. The umbrella system consists of hooks set in clusters, with an umbrella of buoyant netting attached above each cluster. The umbrella floats above the cluster whilst the gear is on the seabed but folds over the cluster and hooked fish during hauling, preventing depredation (Brown *et al.* 2010).

Toothfish longline fishery has had a relatively low aggregated bycatch rate of 10.4% since the transition to the umbrella system in 2008 (8.5 - 13.5% annually). The largest bycatch category (5.5% of the total catch; 3.6 - 7.1% annually) is 'grenadiers', a mix of two species not distinguished in the fishery catch reports: the ridge scaled rattail (*Macrourus carinatus*) found from 350 to 1,000 m depth, and the bigeye grenadier (*M. holotrachys*), generally found below 900 m (Laptikhovsky *et al.* 2008). Because the longline fishing effort is distributed almost entirely deeper than 900 m, over 95% of grenadier caught is bigeye grenadier (Farrugia and Winter 2019). Bigeye grenadier is caught throughout the longline fishery area (Figure 1); most of the catch is discarded, but about 10 t per year are retained, processed and landed in the Falkland Islands for local consumption (Farrugia and Winter 2019).

The Falkland Islands toothfish longline fishery is certified by the Marine Stewardship Council (MSC). The issue of grenadier bycatch was highlighted during the fishery MSC re-certification in 2018 (Acoura Marine 2018); at a bycatch level above 5% of the total catch by weight, bigeye grenadier was considered a '*main primary'* bycatch species under the MSC Fisheries Certification Requirements v2.0 and required dedicated monitoring and assessment. With this in mind, the initial bigeye grenadier stock assessment in Falkland Islands waters was done in 2019 (Farrugia and Winter 2019) using a Bayesian surplus production model framework JABBA (Winker *et al.* 2018). The surplus production models are a data-moderate approach requiring few inputs and suitable for the assessment of stocks for which reliable age-structured data are not readily available. The same approach to bigeye grenadier stock assessment has been used ever since (Skeljo and Winter 2020, 2021, 2022), with the recommendation to be updated annually.

This report presents an updated JABBA stock assessment of bigeye grenadier in Falkland Islands waters, using data up to the end of 2022.

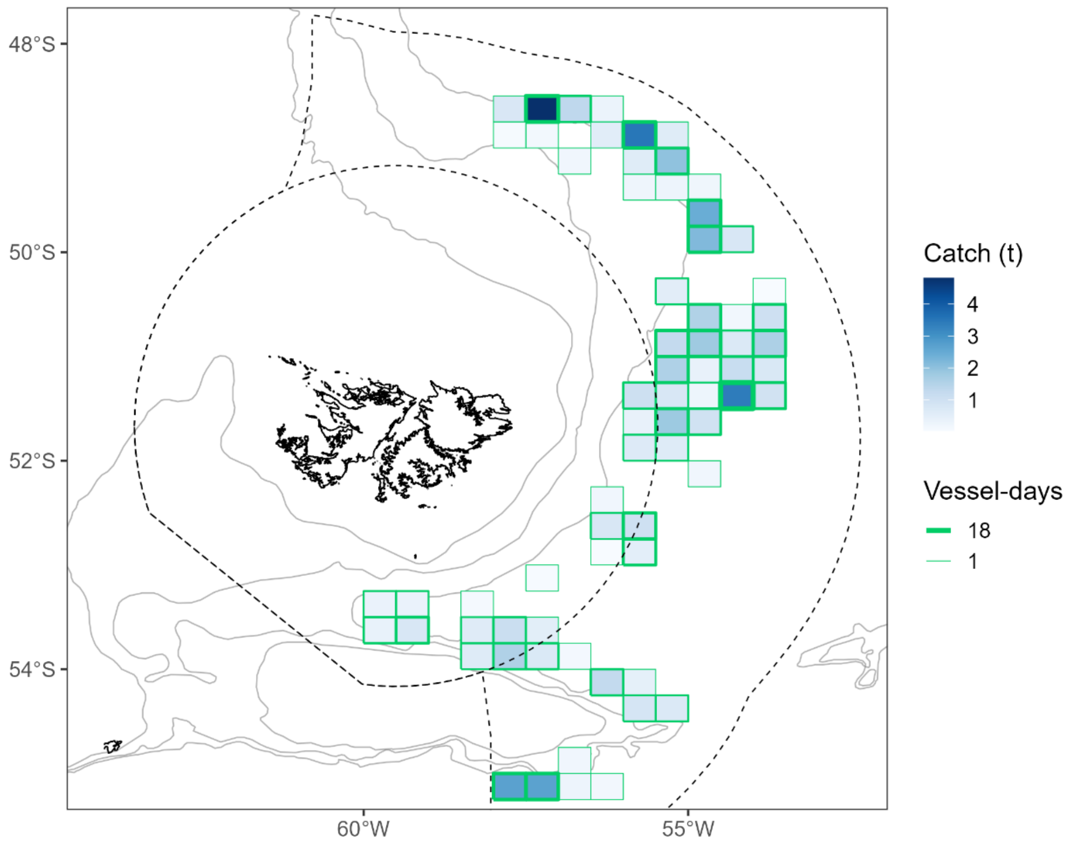

Figure 1. Distribution of bigeye grenadier catch and effort in the Falkland Islands waters in 2022. The thickness of grid lines is proportional to the number of vessel days. Blue-scale is proportional to the catch biomass.

2. Methods

2.1. Data

Three datasets were used to inform the assessment: total annual removals by longline fisheries (2002-2022) and catch-per-unit-effort (CPUE) time series for Spanish- (2002-2007) and umbrella-system (2007-2022) longline fisheries.

As in the previous assessment, the catch and CPUE data prior to 2002 were considered unrepresentative and thus excluded from the model. Grenadier catch reports in longline fishery first appeared in 1997, but at that time, a portion of the bycatch was still commonly reported as 'unidentified fish'. From 1997, catches were increasingly reported at the species level (or species group, e.g. grenadiers or skates), leaving fewer fish unidentified; a negligible amount in 2002, and none afterwards. Years with a high proportion of unidentified catches had a relatively low proportion of grenadier catches, suggesting grenadiers were pooled with unidentified bycatch occasionally. The practice seems to have been vessel-specific in 1997-2001, making it difficult to get reliable annual catch and CPUE estimates. For example, CPUE estimates might be biased if certain vessels only reported grenadier when the catches were large but pooled it with the unidentified bycatch otherwise. Therefore, data used in the current assessment was limited to the years with reliable grenadier catch reports, i.e. years with no 'unidentified fish' catches.

CPUE

The longline CPUE data were divided between the Spanish- and umbrella systems to allow for different catchability between the two, as suggested in the work of Brown *et al.* (2010). During the transition from the Spanish- to the umbrella system (2007-2009), both were used concurrently, sometimes by the same vessel on the same day. Catch reports from this period were inspected and showed a gradual transition between the two systems. The proportion of daily hooks set in an umbrella system started low and gradually increased to ~50%, followed by a rapid switch to fully adopting the umbrella system (however, timing differed between vessels). Because our analysis uses data aggregated by day, daily catch reports with both types of lines set by the same vessel had to be resolved; we assigned daily catch reports with >90% of hooks set in an umbrella system to the corresponding fishery and excluded the remaining 'mixed' daily catch reports from the analysis (with ~10-50% of hooks set in an umbrella-system), as it was not clear how to classify them.

For the umbrella-system longline fishery, only catch reports belonging to Falkland Islands vessels were used. Since the onset of the umbrella system, the fishery was dominated by a 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 participated in the Falkland Islands fishery in more than two years since 2007, resulting in inconsistent CPUE data; and leading to the conclusion that only the Falkland Islands vessels' CPUE should be used as an index of abundance. Data from the longlines set at depths <600 m were excluded from the analysis because these were experimental fishing to collect brood stock for the toothfish rearing facility (commercial longlining is prohibited at depths <600 m).

CPUE was calculated from the selected catch reports, for each fishing day, as reported bigeye grenadier catch in kg-per-hook (Spanish system) or kg-per-umbrella (umbrella system). Finally, CPUE was standardised using a generalised linear mixed modelling approach (GLMM), providing a time series of CPUE values as relative abundance indices (Appendix 1).

Removals

Total removals were calculated by adding the reported catches in the Falkland Islands waters and the catches assumed to be taken by *Illegal, Unreported and Unregulated* (IUU) fishing in the Falkland Islands waters (Appendix 2).

The reported bigeye grenadier catches taken in the longline fishery since 2002 were used, as explained in the previous section. For IUU catches, we assumed that bycatch such as grenadier would experience an equivalent level of IUU fishing to the targeted catch (toothfish). Therefore, we used the same approach as in the recent toothfish stock assessment (Skeljo *et al.* 2023), i.e. annual bigeye grenadier IUU catches were calculated as a percentage of reported catches: 7% in years 2002-2003 and 5% in years 2004-2021.

2.2. JABBA model setup

JABBA is a Bayesian state-space surplus production model framework, based on the generalized 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). 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 taxonomic order Gadiformes which includes grenadiers (Macrouridae). This ratio was converted into Pella-Tomlinson shape parameter m = 1.785, according to the equation:

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

JABBA estimates fisheries reference points, relative stock biomass and exploitation from the catch and abundance indices time series and the 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}. In JABBA, 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 standardization 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).

Priors used in the model are provided in Table 1. Key priors (*r*, *K* and B_{2002}/K) are stock-specific and were defined based on expert knowledge of the stock status (*K* and B_{2002}/K) or estimated from the species life-history parameters (*r*). The same priors were used as in the previous assessment (Skeljo and Winter 2022), with *r* prior estimated using R package *FishLife*, version 3.0.0 (available online at https://github.com/James-Thorson-NOAA/FishLife). *FishLife* produces *r* estimates for 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 2000) and spawning-recruitment relationship data series from *RAM Legacy Database* (http://www.ramlegacy.org; Ricard *et al.* 2012). A full description of the *FishLife* model is available in Thorson (2019). In our case, the estimate of *r* was provided at the *Macrourus* genus level, as species-specific data for *M. holotrachys* were unavailable. Finally, priors for variances (σ^2_{proc}, σ^2_{est}) and catchability coefficients ($q_{Spanish}$, $q_{umbrella}$) were set to the default JABBA settings.

Once the priors were defined, the model was executed in the R environment (R Core Team 2022) using the package JABBA (R package version 2.1.6. https://github.com/jabbamodel/JABBA; Winker *et al.* 2021). The Bayesian posterior distributions of all quantities of interest are estimated using a Markov Chains Monte Carlo (MCMC) simulation. Two MCMC chains with 30,000 iterations each were used, with a burn-in of 5,000 for each chain and a thinning rate of five iterations; parameter values were defined as the medians of the two combined chains. MCMC chains were investigated for evidence of non-convergence using trace plots, and single-chain convergence tests of Geweke (1992) and the stationarity and half-width tests of Heidelberger and Welch (1983) as implemented in the *coda* R package (Plummer *et al.* 2006).

To evaluate the model goodness-of-fit, the residual patterns were inspected visually, and the Root-Mean-Squared-Error (RMSE) was calculated; a relatively small RMSE (≤ 0.3) indicates a reasonably precise model fit to relative abundance indices (Winker *et al.* 2018). 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. Parameter priors used in the assessment model, with a brief description of the selection criteria.

Parameter	Prior	Description
r	log-normal; μ = 0.058, *sd* = 0.163	Estimated at genus level (*Macrourus*) using the *FishLife* R package (Thorson 2019)
K	log-normal; μ = 5,000, *cv* = 1	Used in the previous assessment (Skeljo and Winter 2022)
B_{2002}/K	log-normal; μ = 0.75, *cv* = 0.25	Used in the previous assessment (Skeljo and Winter 2022)
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

* inverse-gamma distribution was defined by the two scaling parameters; ** uniform distribution was defined by the range

3. Results

3.1. Model diagnostics

The model diagnostics plots are given in Appendix 3. The MCMC diagnostics tests of Geweke (1992) and Heidelberger and Welch (1983) were passed by all estimated parameters. An adequate convergence of the MCMC chains was corroborated by visual inspection of trace plots, which showed good mixing in general (Figure A.4).

The model fit to standardized CPUE data was reasonably good for both Spanish- and umbrella-system fisheries, except for a notable outlier in the first year of the umbrella-system fishery (Figure A.5). The residuals pattern showed that the model overestimated CPUE in 2007 and underestimated in the next six years (Figure A.6); this trend was likely due to a large magnitude of the 2007 outlier, which may have prevented good fit to the data in the years immediately following. The goodness-of-fit statistic indicated an adequate model fit (RMSE = 22.2%).

The comparison of posterior distributions and prior densities of key estimated parameters is given in Figure A.7. K was the parameter with the lowest PPMR (posterior to prior means ratio) and PPVR (posterior to prior variances ratio), suggesting that the data are to some extent informative with respect to K. In contrast, r had PPMR and PPVR values close to 1, suggesting that the posterior was largely informed by the prior.

3.2. Model estimates

The key model parameters and stock status estimates are summarised in Table 2. The carrying capacity was estimated at K = 5,181 t, and the estimated biomass declined from 0.686K in 2002 to 0.610K in 2022. The absolute biomass B and the relative biomass B/K and $B/BMSY$ trends showed a slight to moderate decline in 2002-2007 and were levelled afterwards. Estimated biomass trends were related to a high level of relative fishing mortality in 2002-2006, followed by a decline to a sustainable level in 2008 ($F/F_{MSY} < 1$) and a fluctuating but overall decreasing trend since (Figure 2).

The relationship between B/B_{MSY} and F/F_{MSY} is illustrated using the Kobe plot (Figure 3), showing that the overfishing in 2002-2006 led to a slight decrease in biomass, which stopped once the F/F_{MSY} decreased in 2008. Since 2009 the biomass remained almost the same, above B_{MSY}, and the fishing mortality remained below F_{MSY} in all years. The estimated current biomass B_{2022} is 27.7% above B_{MSY}, and the current fishing mortality F_{2022} is 34.4% below F_{MSY}. Taking into account the uncertainty of this estimate (grey credibility intervals on the Kobe plot), there is a 72.2% probability that bigeye grenadier stock was not overfished ($B > B_{MSY}$) and not experiencing overfishing ($F < F_{MSY}$)

in 2022 (green area on the Kobe plot). Considering only fishing mortality, the probability of stock not experiencing overfishing in 2021 is 77.4% (green plus yellow areas on the Kobe plot).

According to the Pella-Tomlinson surplus production function, biomass that would produce maximum surplus production (i.e. maximum sustainable yield, MSY) was estimated at B_{MSY} = 2,477 t, with the corresponding *MSY* = 82 t (Figure 4). Since 2009, catches have been at or below the median MSY in all years except 2011 (Figure A.3). Most of the parameters and stock status estimates in the current assessment were associated with high uncertainty, as indicated by their wide 95% credible intervals (Table 2, Figures 2-4).

Table 2. Summary of model parameters and stock status estimates.

Parameter	Median	MCMC 95% CI
r	0.059	0.043 - 0.082
K	5,181 t	2,686 - 13,738 t
B_{2002}/K	0.686	0.450 - 0.967
B_{2022}/K	0.610	0.319 - 0.913
MSY	82 t	41 - 221 t
B_{MSY}	2,477 t	1,284 - 6,657 t
F_{MSY}	0.033	0.024 - 0.046
B_{2022}/B_{MSY}	1.277	0.666 - 1.909
F_{2022}/F_{MSY}	0.656	0.188 - 1.879

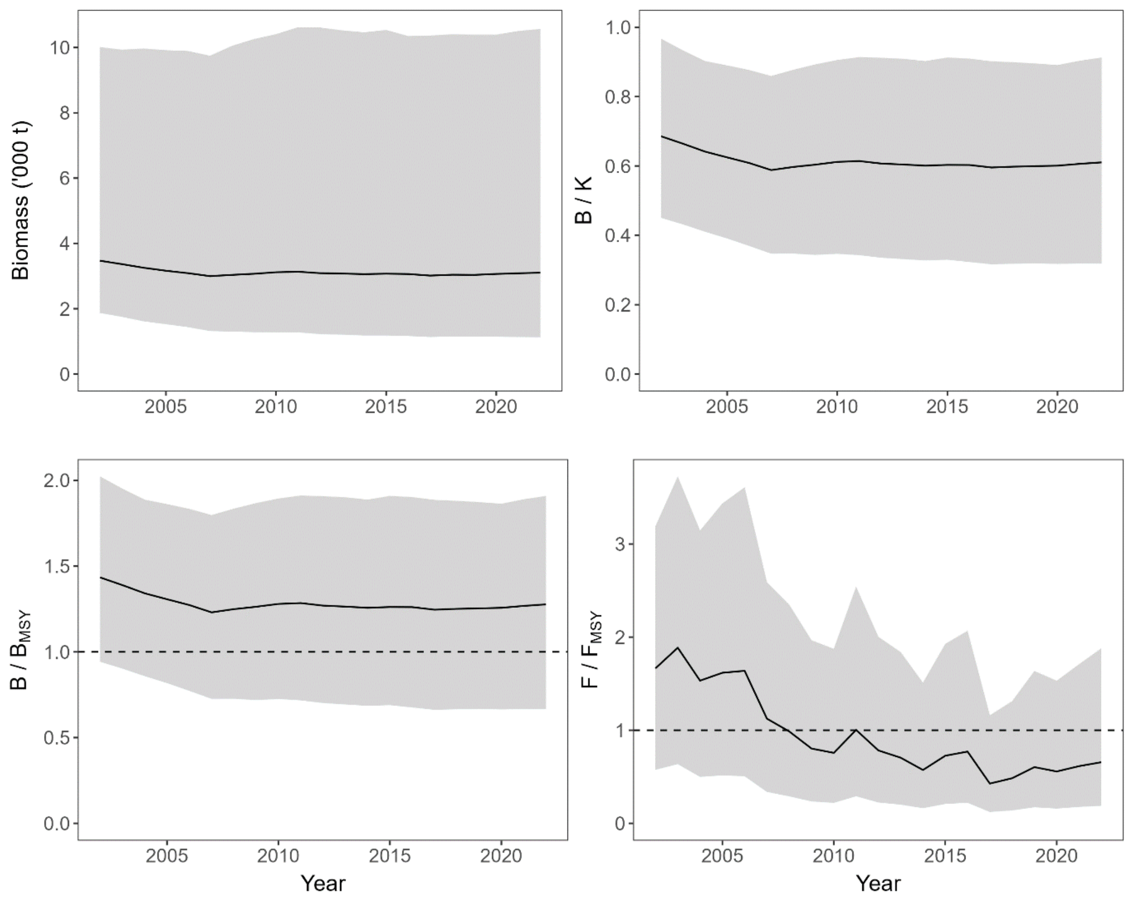

Figure 2. Estimated trends in absolute biomass (top left), biomass relative to *K* (top right), biomass relative to B_{MSY} (bottom left) and fishing mortality relative to F_{MSY} (bottom right). Solid black lines are medians, and shaded areas denote MCMC 95% credible intervals.

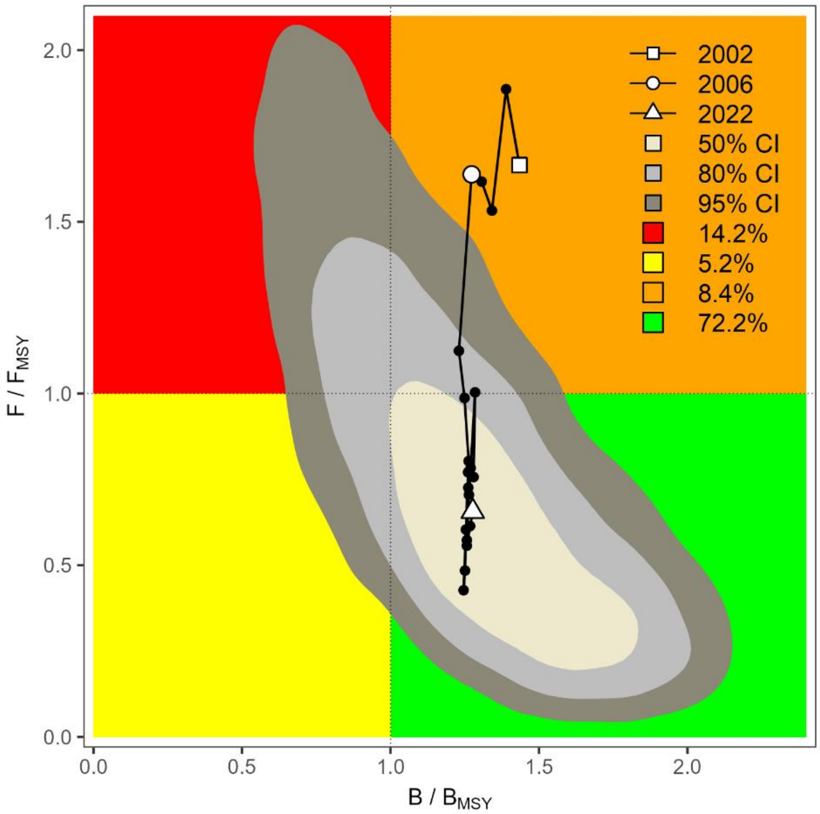

Figure 3. Kobe phase plot showing the estimated trajectory of *B/BMSY* and *F/FMSY* for bigeye grenadier stock in 2002-2022. Grey-shaded areas denote the 50, 80, and 95% credible intervals of the stock status in the final year. The probability of the final-year stock status falling within each quadrant is indicated in the figure legend.

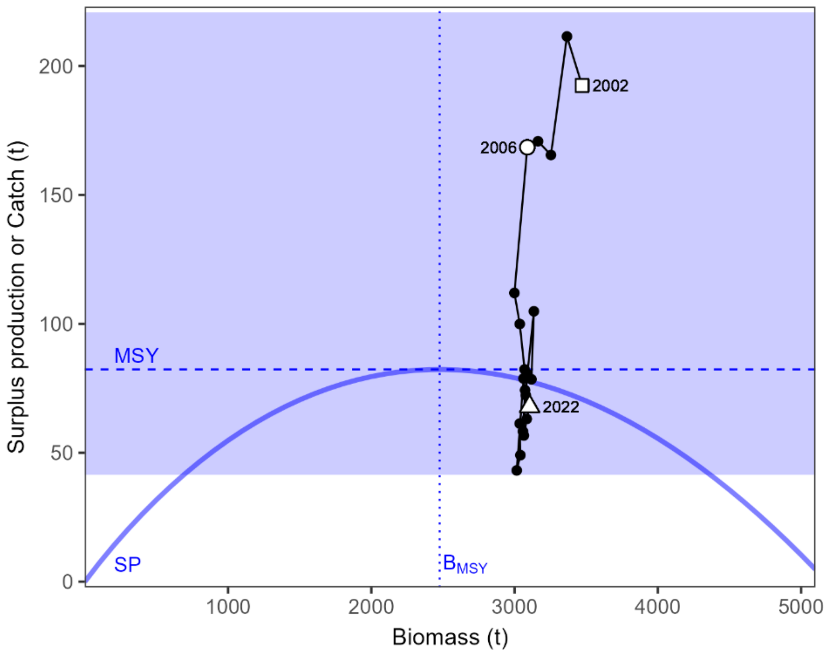

Figure 4. Surplus-production phase plot showing Pella-Tomlinson curve *SP* (solid blue line) and catch/biomass trajectory for the bigeye grenadier stock in 2002-2022 (black line). Catches on the *SP* curve would maintain the biomass, catches above the curve will shrink future biomass, and catches below the curve allow future biomass to increase. The year 2006 (white dot) marks the introduction of the TAC system to the longline fishery. Estimated *MSY* (dashed blue line) and B_{MSY} (dotted blue line) are added for reference. Blue-shaded area denotes 95% credible intervals of the *MSY*.

3.3. Retrospective analysis

The retrospective analysis was conducted by successively removing one to six final years of data from the 2022 model and rerunning the analysis to evaluate how data availability affects model results. *Mohn's rho* statistic was used to quantify the bias between models (Mohn 1999, Hurtado-Ferro *et al.* 2014). The estimated Mohn's rho for *B* (0.001), *B/K* (0.008), *B/BMSY* (0.008) and *F/FMSY* (-0.003) was within the acceptable range of -0.15 and 0.20 (Hurtado-Ferro *et al.* 2014, Carvalho *et al.* 2017), and indicated negligible retrospective pattern. Retrospective plots showed no systematic trend in departures from the 2022 model (Figure 5).

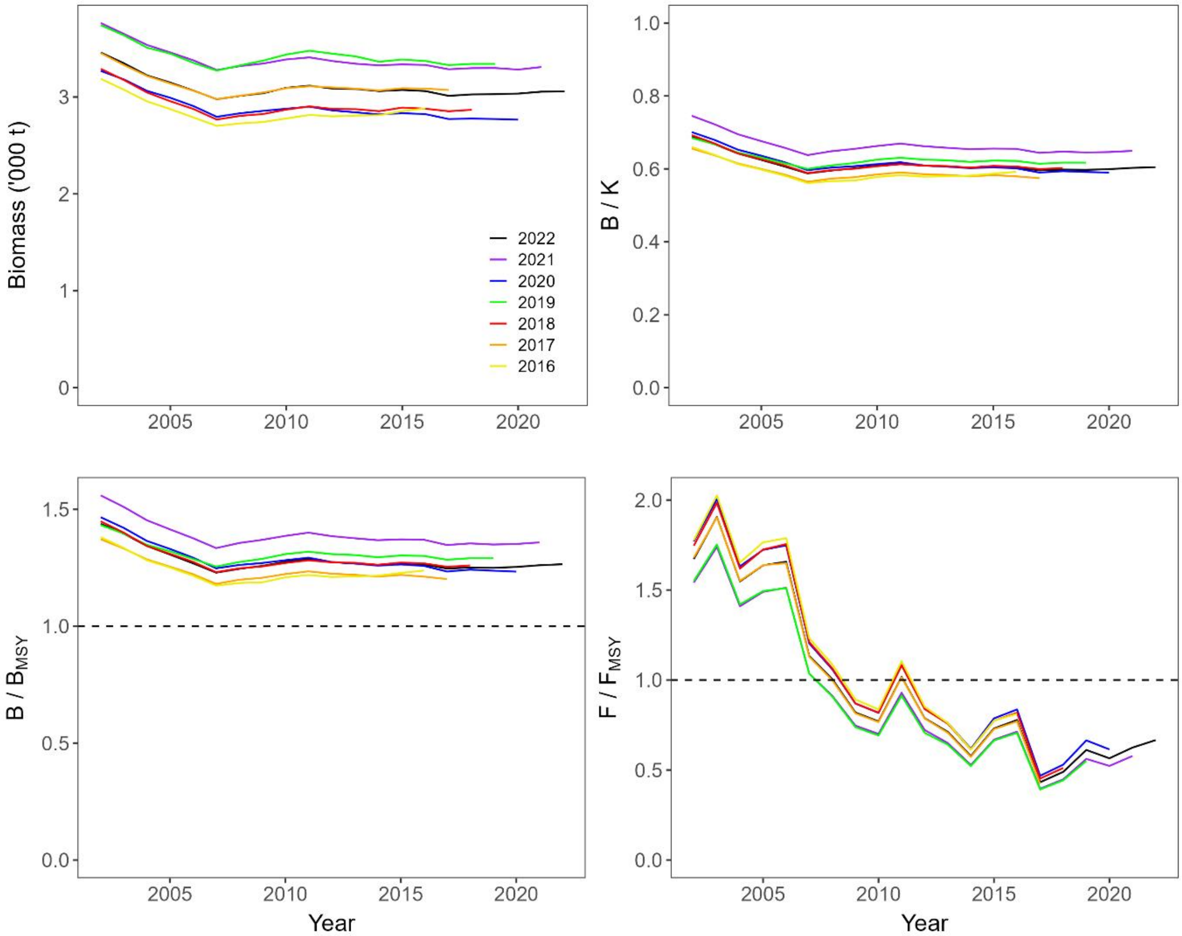

Figure 5. Estimated trends in biomass, *B/K*, *B/B$_{MSY}$* and *F/F$_{MSY}$* for the 2022 model (black line) and six retrospective model runs. The numeric label indicates the year up to which the individual retrospective model was run (inclusive).

4. Discussion

This report provides an updated stock assessment of bigeye grenadier (*Macrourus holotrachys*) in Falkland Islands waters, using a Bayesian surplus production model implemented in JABBA framework. 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), remain an integral tool for data-limited to -moderate stock assessments (Dichmont *et al.* 2016, Punt *et al.* 2015). The main limitation of SPMs is that they ignore the stock's size/age structure and therefore fail to account for dynamics in gear selectivity (Wang *et al.* 2014) and lagged effects of recruitment and mortality (Aalto *et al.* 2015, Punt and Szuwalski 2012), which can both lead to biased assessment results. However, SPMs have been considerably enhanced by the introduction of Bayesian methods with improved prior formulations, the development of frameworks that allow incorporating both observation and process errors, and Bayesian state-space modelling approaches (Winker *et al.* 2018). Given the available data, we considered SPM appropriate for bigeye grenadier stock assessment.

Besides the catch and CPUE data updates for 2022, no further changes were made to the model structure and assumptions. The updated model resulted in almost identical estimates of *r* and *K*, and consequently of *MSY*, B_{MSY} and F_{MSY}, to the previous assessment. Overall, the stock was estimated to be healthy, with a low probability of being overfished or experiencing overfishing. Since 2009, annual bigeye grenadier catches have either been at or below the estimated MSY in all years but one, adding a measure of confidence that the stock was exploited sustainably.

The main shortcomings of the model were: 1) a considerable uncertainty of parameter and stock status estimates and 2) data being largely uninformative on *r*. Both can be attributed to the difficulties faced by SPMs when assessing lightly exploited stocks; SPMs perform better if the stock has historically passed through a wide variety of sizes, reflected in the CPUE. If the CPUE time series lack contrast (as in our case, with levelled to slowly decreasing trend), the interplay between catch and biomass contains less information about *r*, and the estimates will be more uncertain (Hilborn 1979, Hilborn and Walters 1992, Haddon 2011, Froese *et al.* 2017, Sant'Ana *et al.* 2020). Light exploitation and levelled CPUE time series of bigeye grenadier in the Falkland Islands waters are due to being (by)caught exclusively in the longline fishery and at a low and almost constant proportion of the annual toothfish TAC. Because the data proved uninformative, the model estimate of *r* was largely informed by the assumed prior; this is a cause for some concern, as the model was found sensitive to the choice of *r* prior (Skeljo and Winter 2020). Obtaining an appropriate *r* prior for bigeye grenadier proved challenging due to the scarcity of species-specific life-history data. Instead, we utilised the package *FishLife* to calculate *r* and the associated variability at the *Macrourus* genus level and used it as a prior in the current assessment.

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Appendix 1. CPUE standardization

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CPUE was standardized using Generalized Linear Mixed Models (GLMMs; Pinheiro and Bates 2000); GLMMs were fitted using package glmmTMB (Brooks *et al.* 2017, Magnusson *et al.* 2017) implemented in R version 4.1.3 (R Core Team, 2022). Before modelling, data were explored following the protocol described by Zuur *et al.* (2010); explanatory variables were inspected for outliers and collinearity using visual assessments, Pearson correlation coefficients (>0.5) and variance inflation factors (>3). Continuous explanatory variables were scaled by subtracting the mean and dividing by the standard deviation. Daily catch reports with zero bigeye grenadier catch were presumed to represent erroneous entries or broken sets and excluded from the analysis (0.5% of daily catch reports in the Spanish system and none in the umbrella system fishery).

The response variable was defined as daily bigeye grenadier CPUE expressed in kg-per-hook (Spanish system) or kg-per-umbrella (umbrella system) and modelled using Gamma distribution with a log link function. The explanatory variables considered in the model as either fixed or random effects are given in Table A.1.

Table A.1. Explanatory variables considered in the CPUE standardization.

Explanatory variables		Variable type	Effect
Spanish-system	umbrella-system		
Year*	Year*	Categorical	Fixed
Month*	Month*	Categorical	Random
Area*	Area*	Categorical	Random
Depth*	Depth*	Continuous	Fixed
$CPUE_{TOO}$	$CPUE_{TOO}$	Continuous	Fixed
Soak-time	Soak-time	Continuous	Fixed
Vessel*	-	Categorical	Random
-	Hooks-per-umbrella	Categorical	Fixed

* Variables included in the final model.

The *Year* effect is the quantity of interest and had to be included in the final model; the remaining explanatory variables were added to the *Year* by forward stepwise selection and included in the final model only if they improved pseudo-R^2 by at least 0.5%. Pseudo-R^2 was calculated based on the likelihood-ratio test, as implemented in the R package MuMIn (Barton 2009). The *Month* and *Area* variables were treated as random effects, attempting to capture temporal or spatial dependency in CPUE; the spatial resolution was 1° Lon x 1° Lat. The *Depth* variable is the average fishing depth, and *Soak-time* is the sum of soak times of the lines belonging to a single response CPUE value (usually multiple lines were set by a given vessel on a given day). The $CPUE_{TOO}$ variable is toothfish CPUE expressed in the same units as the corresponding bigeye grenadier CPUE. The *Vessel* variable was treated as a random effect in the Spanish-system standardization to account for dependence in CPUE values belonging to the same vessel due to e.g. vessel fishing power and skipper/crew skills and behaviour. The *Vessel* variable was excluded from the umbrella-system CPUE standardization because only two vessels appeared in the model (too few to treat it as a random effect) and never fished concurrently in a year, making the *Vessel* and *Year* effect indistinguishable. The umbrella system had an additional variable, the number of *Hooks-per-umbrella*, which progressively decreased from 10 hooks initially to 8 hooks in December 2007, to 7 hooks in March 2014, and to 6 hooks in June 2016).

The final GLMM fitted to the Spanish-system data included *Year* and *Depth* as fixed effects and *Month*, *Region* and *Vessel* as random effects; the model explained 41.2% of the overall variation in CPUE. Unstandardized CPUE time series showed higher annual CPUE in 2002-2003 followed by much lower values in 2004-2007; standardization removed this trend as it reflected differences in CPUE between vessels rather than years (Figure A.1). The final GLMM fitted to the umbrella-system data included *Year* and *Depth* as fixed effects and *Month* and *Area* as random effects; the model explained 48.1% of the overall variation in CPUE. Standardized and unstandardized CPUE time series were similar and showed no clear trend; a notable outlier was a low CPUE in 2007 (Figure A.2). In 2007, the transition from the Spanish- to umbrella-system longline started, and the number of days fished under the umbrella-system was limited.

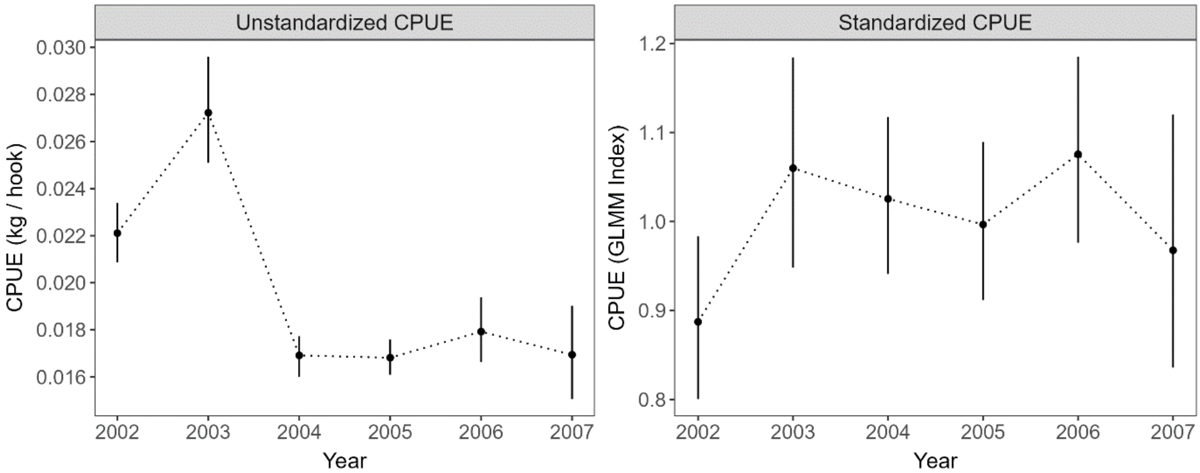

Figure A.1. Spanish-system longline fishery unstandardized and standardized CPUE time series; black vertical lines denote 95% confidence intervals.

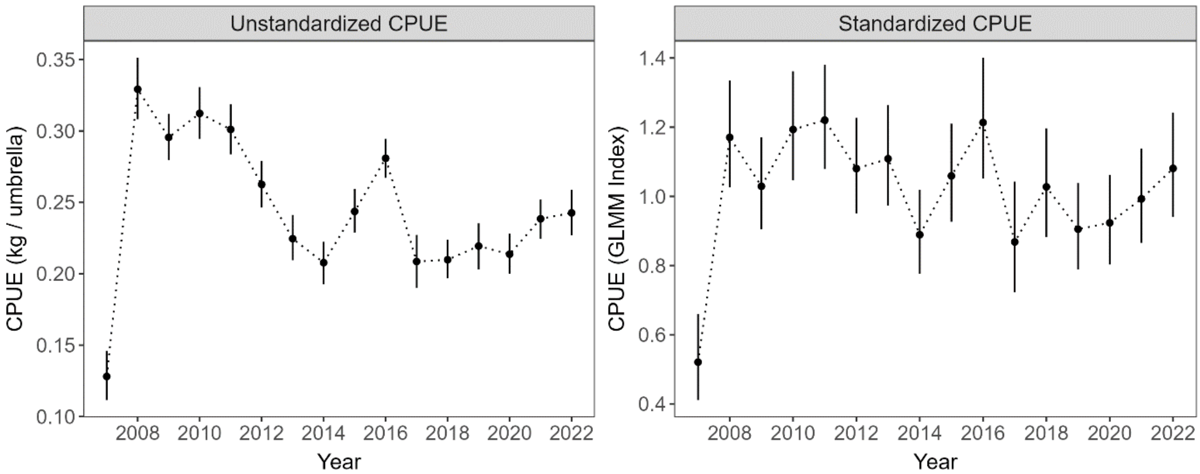

Figure A.2. Umbrella-system longline fishery unstandardized and standardized CPUE time series; black vertical lines denote 95% confidence intervals.

Appendix 2. Removals

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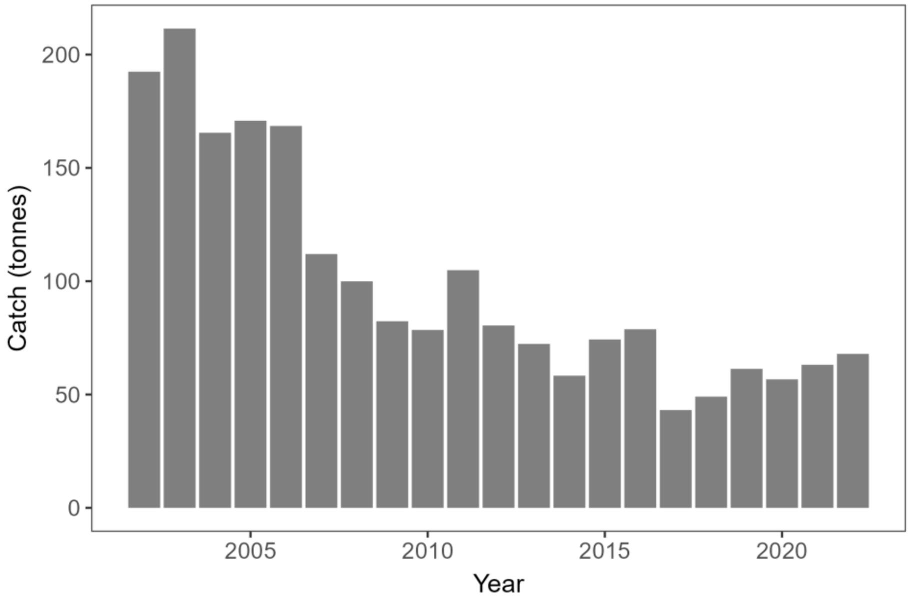

Figure A.3. Time-series of bigeye grenadier total removals in the Falkland Islands waters.

Appendix 3. Diagnostics plots

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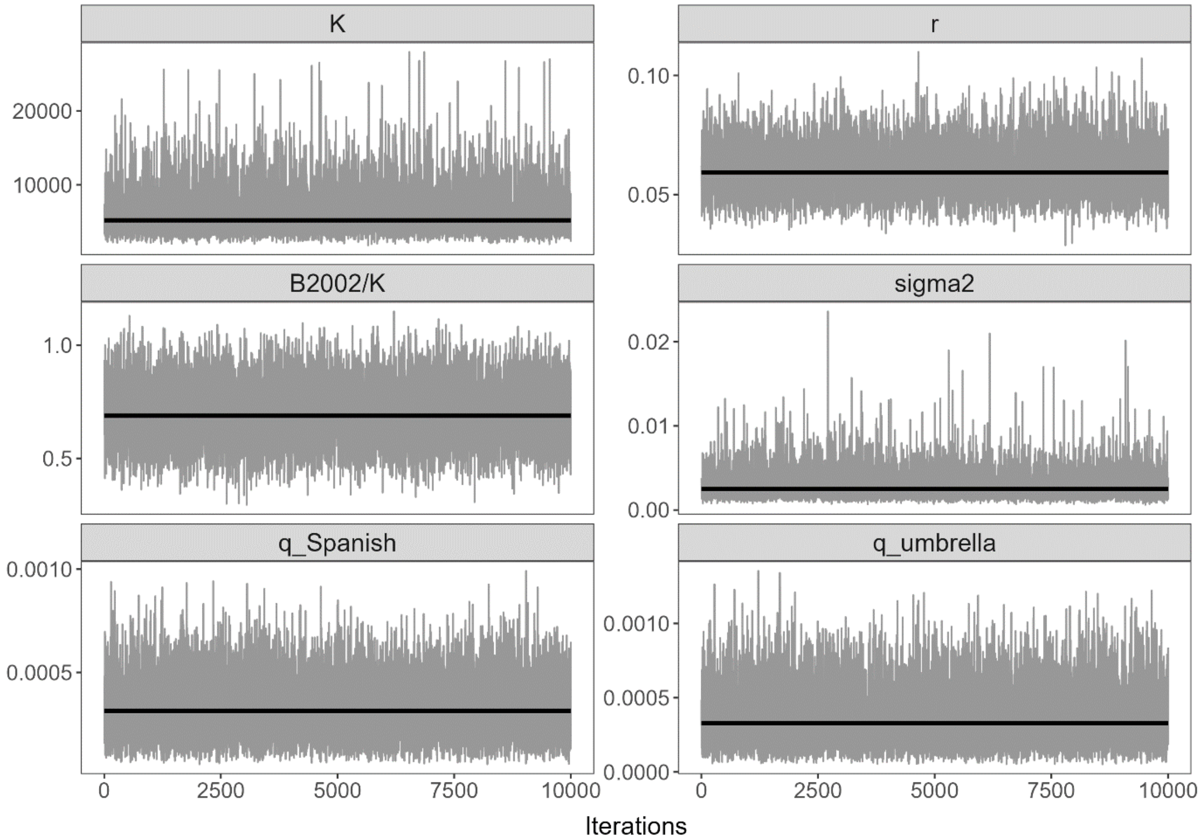

Figure A.4. MCMC posterior trace plots for all estimated parameters. Black line denotes the median.

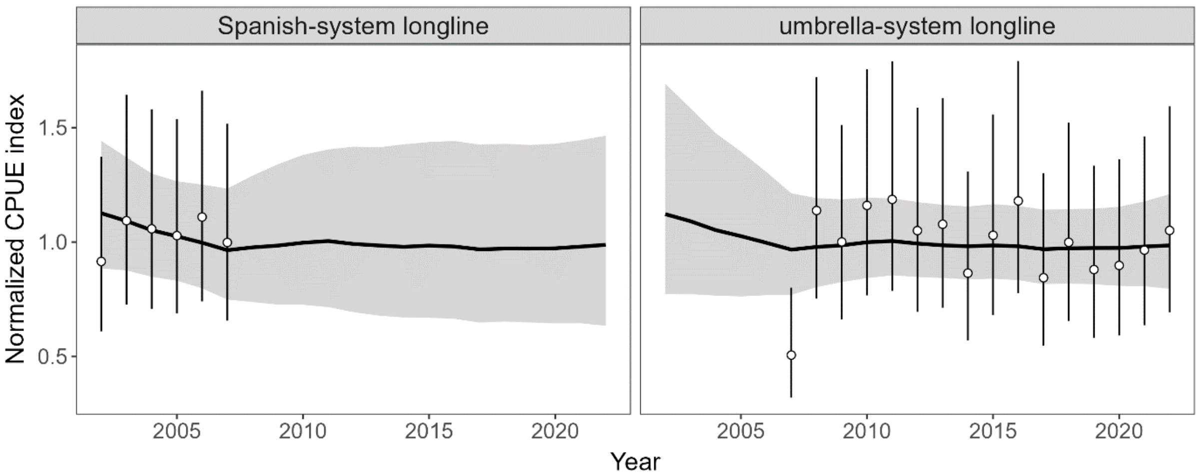

Figure A.5. Model fit (black line) to standardised CPUE indices (white dots) for Spanish- and umbrella-system longline fishery. Vertical lines denote 95% confidence intervals of standardized CPUE indices; shaded areas denote MCMC 95% credible intervals of model fit.

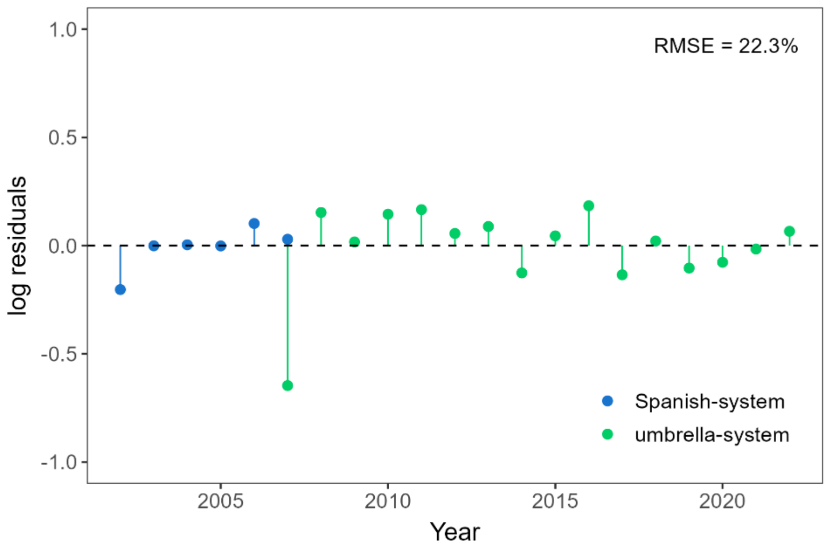

Figure A.6. Residuals from model fit to standardised CPUE indices; for Spanish-system (blue dots) and umbrella-system longline fishery (green dots). RMSE: root-mean-squared-error.

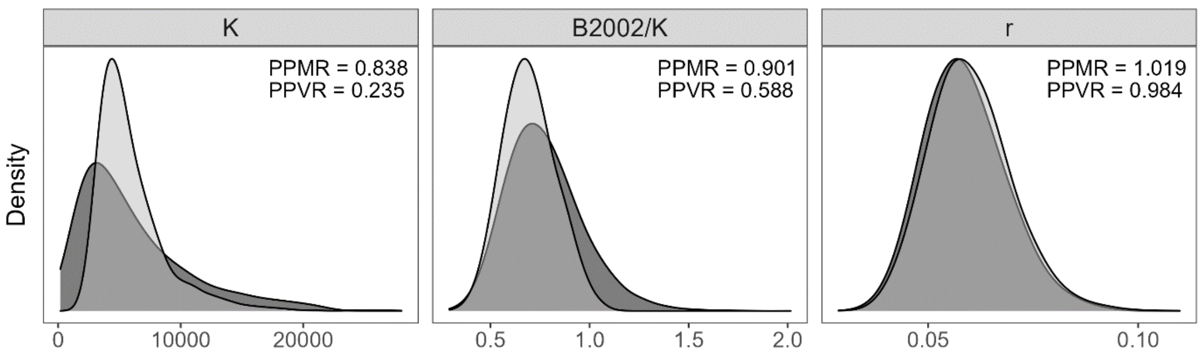

Figure A.7. Prior (dark grey) and posterior distributions (light grey) of key estimated parameters. PPMR: Posterior to Prior Means Ratio; PPVR: Posterior to Prior Variances Ratio.