2021 Stock Assessment Report

Bigeye grenadier
(*Macrourus holotrachys*)

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DESIRE THE RIGHT

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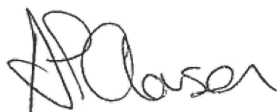
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Summary

1. This report provides an updated stock assessment of bigeye grenadier (*Macrourus holotrachys*) in Falkland Islands waters, using data through year 2021. Besides the inclusion of catch and catch-per-unit-effort data for 2021, no further changes were made to the model structure and assumptions. Assessment was done using a Bayesian surplus production model framework JABBA (Winker *et al.* 2018).
2. Overall, the model showed negative trend in stock status in 2002-2006, followed by a transitional period in 2007-2008 and a positive trend in 2009-2021. Since 2009, bigeye grenadier catches have either been very close to or well below the estimated maximum sustainable yield (MSY) in all years, indicating sustainable exploitation of the stock.
3. We recommend that the assessment using JABBA model be continued in the future, and conducted annually.

1. Introduction

The Falkland Islands longline fishery targeting Patagonian toothfish (*Dissostichus eleginoides*) began in 1992 and became an established fishery in 1994 (Laptikhovsky and Brickle 2005). Fishing was traditionally conducted using the Spanish system of longlining, until the 'umbrella' system was introduced in 2007. The latter system was developed to reduce the loss of hooked toothfish to depredation by cetaceans, with hooks set in clusters and an 'umbrella' of buoyant netting set above each cluster (Brown *et al.* 2010).

The longline fishery has had a relatively low aggregated bycatch rate of 10.2% since the transition to the umbrella-system (8.5 - 13.5% annually). The largest bycatch category (5.3% of the total catch; 3.7 - 7.1% annually) are 'grenadiers', a mix of two species not distinguished in the fishery catch reports: the ridge scaled rattail (*Macrourus carinatus*), occurring generally 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), therefore this species is the focus of the current report. 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), and the issue of bigeye grenadier bycatch was highlighted in the recent re-certification process (Acoura Marine 2018); at a bycatch level above 5% of the total catch by weight, bigeye grenadier is considered as the '*main primary' bycatch species* under the MSC Fisheries Certification Requirements v2.0 and therefore requires specific monitoring and analysis. With this in mind, the first assessment of bigeye grenadier stock status in Falkland Islands waters was done in 2019 (Farrugia and Winter 2019), using a Bayesian surplus production model framework JABBA (Winker *et al.* 2018). This is a data-limited approach with few input requirements, suitable for the assessment of stocks for which reliable age-structured data are not readily available. The same approach to grenadier stock assessment was used in the following years (Skeljo and Winter 2020, 2021), with the recommendation to be updated annually.

The current report provides an updated JABBA stock assessment of bigeye grenadier in Falkland Islands waters, using data through year 2021. Besides the inclusion of 2021 data, no further changes were made to the model structure and assumptions.
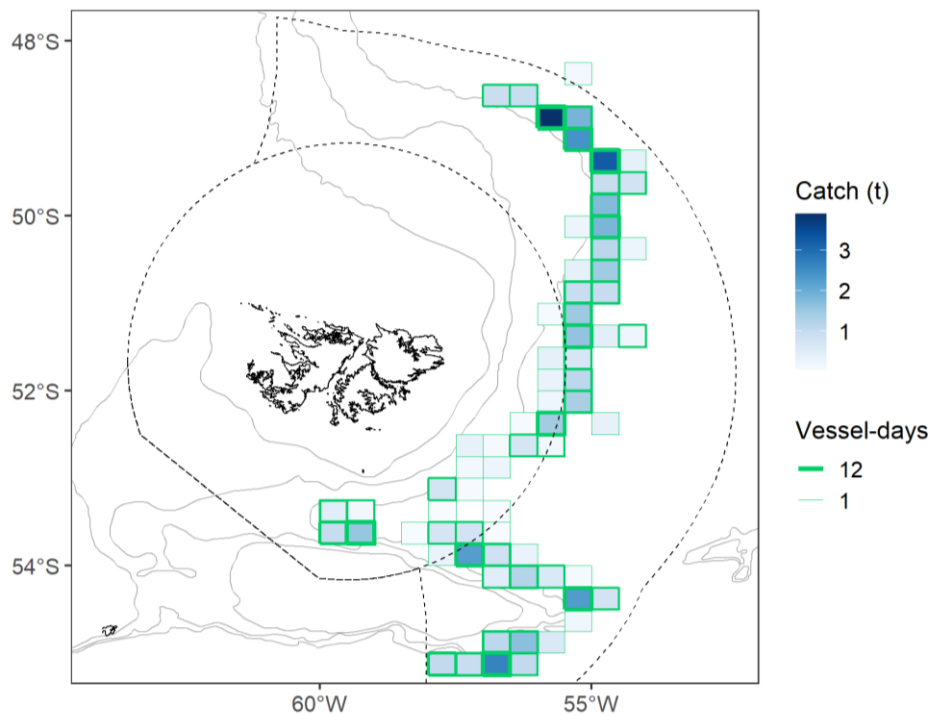
Figure 1. Spatial distribution of bigeye grenadier catches and longline fishery effort in the Falkland Islands waters in 2021. Thickness of grid lines is proportional to vessel days; blue-scale is proportional to bigeye grenadier catch biomass.

2. Methods

2.1. Data

Three datasets were used as information for the JABBA stock assessment model: total annual removals by combined longline fisheries (2002-2021) and catch-per-unit-effort (CPUE) time series for Spanish- (2002-2007) and umbrella-system (2007-2021) longline fisheries.

Following the approach from the previous year's assessment, pre-2002 catch and CPUE data were omitted from the model (i.e. data from 1997-2001). Although the first reports of grenadier catch in longline fishery started in 1997, at the same time large portions of the catch were still reported as 'unidentified fish'. Starting from 1997, reported annual catches of unidentified fish kept decreasing, as the catches were increasingly reported at species level (or group, e.g. grenadiers or skates); in 2002, only a negligible amount was reported as unidentified fish, and following 2002 this category hasn't been used at all. In general, years with higher proportion of unidentified catches had relatively lower proportion of grenadier catches, suggesting that the grenadiers were pooled with the other unidentified bycatch. Also, grenadier reporting practices seem to have been vessel-specific in 1997-2001, making it difficult to get reliable annual catch and CPUE estimates. For example, bias might be introduced into CPUE estimates if certain vessels only reported grenadier when the catches were large, or if vessel-specific differences in reporting translated into year-specific differences, as not all vessels fished in all years. Therefore, dataset used for the current assessment was limited to the years with reliable grenadier catch reports, i.e. years without 'unidentified fish' catches.

2

CPUE

The CPUE data were treated separately for Spanish- and umbrella-system longline, according to the documented difference in grenadiers' CPUE (*M. holotrachys* and *M. carinatus* pooled) between these two fishing techniques in Falkland Islands waters (Brown *et al.* 2010). During the transition period from the Spanish- to umbrella-system (2007-2009), both techniques 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 as an umbrella-system started low and gradually increased to ~50%, at which point there was a rapid switch to full (100%) umbrella-system (however, timing differed between vessels). Since data aggregated by day were used in the current analysis, daily catch reports with both types of lines set by the same vessel needed to be resolved; we decided to assign daily catch reports with >90% of hooks set in an umbrella-system to the corresponding fishery, and to exclude 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 correctly classify them.

For the Spanish-system longline, data were inspected and 95 daily catch reports pertaining to remote areas (outside the region 47°W - 70°W and 40°S - 57°S) were removed. These records belong exclusively to the early years of the fishery (1998-2002) when presumably more exploratory fishing took place, and the vessels fishing in Falkland waters would occasionally report to FIFD the catches taken in remote areas as well.

For the umbrella-system longline, data selection followed the same reasoning outlined in the previous year's assessment (Skeljo and Winter 2021). In order to avoid introducing bias to the CPUE estimates, only the catch reports belonging to Falkland Islands flagged vessels were used. Since the onset of the umbrella-system the fishing was predominantly done by a single Falkland Islands vessel (*CFL Gambler*, replaced by *CFL Hunter* in 2017), assisted occasionally by one or two chartered Chilean vessels. None of the chartered vessels fished in Falkland Islands waters in more than two years since 2007 and their CPUE data were inconsistent, leading to a conclusion that the CPUE would be a more representative index of abundance if only Falkland Islands vessels data were used. With a similar goal, data from the longline sets deployed at depths <600 m were removed, as commercial longlining is prohibited at these depths and the corresponding sets were experimental fishing aiming to collect brood stock for the toothfish rearing facility.

For the selected catch reports, CPUE data were calculated 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 model (GLMM), providing a time series of CPUE values which were assumed relative abundance indices (Appendix 1).

Removals

Total removals were calculated by adding two catch components: (a) reported catches in Falkland Islands waters and (b) catches taken by *Illegal, Unreported and Unregulated* (IUU) fishing in Falkland Islands waters (Appendix 2).

Reported bigeye grenadier catches taken in longline fisheries going back to 2002 were used, as explained in the previous section. For IUU catches, we assumed that bycatch such as grenadier would experience equivalent level of IUU fishing as the target catch (toothfish). Therefore, we utilised the same approach as in the most recent toothfish stock assessment (Skeljo *et al.* 2022), i.e. bigeye grenadier IUU annual catches were calculated as a percentage of reported annual 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 = 2, and to the Fox function if m approaches 1. In the current model the 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_{proc}^2, and additional observation variance for the abundance indices time series σ_{est}^2. In JABBA, the total observation variance σ_{obs}^2 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:

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

where $\hat{\sigma}_{SE}$ are standard error estimates associated with the abundance indices and derived externally from the CPUE standardization model, σ_{fix}^2 is a fixed input variance, and σ_{est}^2 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 2021), with r prior estimated using R package *FishLife*, release 2.0 (available online at (https://github.com/James-Thorson/FishLife/releases/tag/2.0.0). *FishLife2.0* 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 *FishLife2.0* model is available in Thorson (2019). In our case, estimate of r was provided at *Macrourus* genus level, as species-specific data for *M. holotrachys* were not available. Finally, priors for variances (σ_{proc}^2, σ_{est}^2) and catchability coefficients ($q_{Spanish}$, $q_{umbrella}$) were set to the default JABBA settings.

Once the priors were defined, the model was executed in R environment (R Core Team 2020) 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 by means

of 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 & Welch (1983) as implemented in the *coda* R package (Plummer *et al.* 2006).

To evaluate 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 JABBA model run, 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 *FishLife2.0* R package (Thorson 2019)
K	log-normal; μ = 5,000, *cv* = 1	Used in the previous assessment (Skeljo and Winter 2021)
B_{2002}/K	log-normal; μ = 0.75, *cv* = 0.25	Used in the previous assessment (Skeljo and Winter 2021)
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 two scaling parameters; ** uniform distribution was defined by range

3. Results

3.1. Model diagnostics

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

The model fit to the standardized CPUE data was reasonably good for both Spanish- and umbrella-system fisheries, with the exception of 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 it in the next six years (Figure A.6); this trend was likely caused by the large magnitude of the 2007 outlier, which might have prevented good fit to the data in the years immediately following. The goodness-of-fit statistic indicated that the model fit was nevertheless adequate (RMSE = 25.9%).

The comparison of posterior distributions and prior densities of key estimated parameters is given in Figure A.7. *K* had the lowest PPMR (posterior to prior means ratio) and PPVR (posterior to prior variances ratio), which indicates that this parameter was most informed by the data. In contrast, for *r* both PPMR and PPVR were close to 1, which suggests that the posterior was largely informed by the prior rather than the input data.

3.2. Model estimates

The key output parameters and stock status estimated by JABBA are summarised in Table 2. The carrying capacity was estimated as K = 4,958 t, and the estimated biomass declined from 0.720K in 2002 to 0.624K in 2021. The absolute biomass B and the relative biomass B/K and B/B_{MSY} trends showed a slight to moderate decline in 2002-2007, followed by a levelled trend afterwards. This was 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).

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 has 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_{2021} is 30.5% above B_{MSY}, and the current fishing mortality F_{2021} is 39.2% below F_{MSY}. Taking into account the uncertainty of this estimate (grey credibility intervals on the Kobe plot), there is 78.4% probability that the bigeye grenadier stock was not overfished ($B > B_{MSY}$) and not experiencing overfishing ($F < F_{MSY}$) in 2021 (green area on the Kobe plot). If only the fishing mortality is considered, as this is something that can be regulated, the cumulative probability of stock not being subjected to overfishing in 2021 is 82.8% (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} = 2,370 t, with the corresponding MSY = 79 t. Since 2009, catches have either been very close to or well below the median MSY in all but one year (2011) (Figure A.3).

It is important to note that most of the parameter and stock status estimates in the current assessment were associated with high uncertainty, as indicated by their wide 95% confidence intervals (Table 2, Figures 2-4). This may be partially explained by the fact that surplus production models produce less reliable estimates when assessing lightly exploited stocks, as the interplay between catch and biomass contains less information about stock productivity (Froese *et al.* 2017). Surplus production models perform better if the stock has historically passed through a wide variety of sizes, which should be reflected in the available CPUE; if the estimated CPUE indices time series lack contrast (as in our case, with levelled to slowly decreasing trend), the information available to the model is limited and the estimates will be more uncertain (Hilborn 1979, Hilborn and Walters 1992, Haddon 2011, Sant'Ana *et al.* 2020).

Table 2. Summary of parameters and stock status estimates.

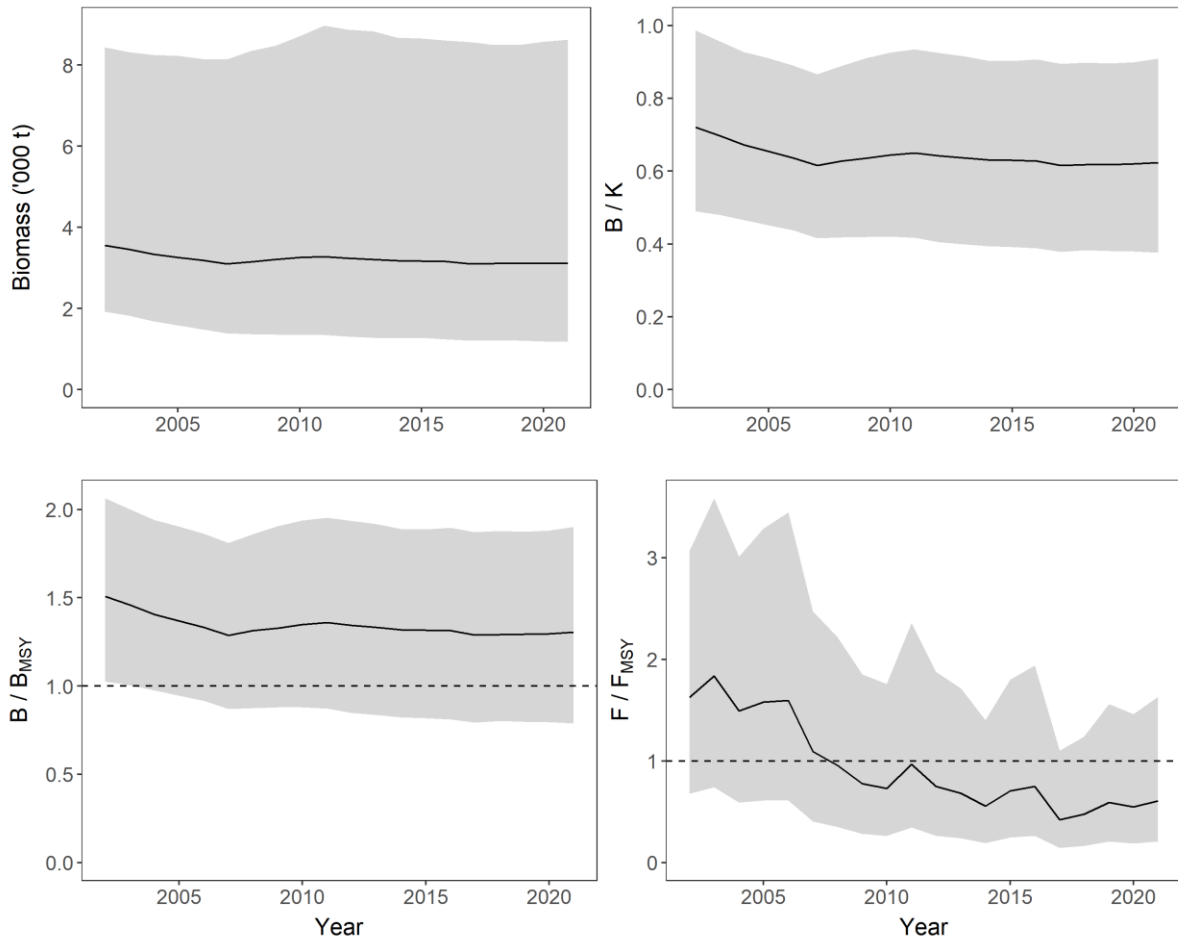| Parameter	median	95% CI
r	0.059	0.043 - 0.082
K	4,958 t	2,543 - 12,331 t
B_{2002}/K	0.720	0.490 - 0.986
B_{2021}/K	0.624	0.377 - 0.909
MSY	79 t	40 - 199 t
B_{MSY}	2,370 t	1,216 - 5,894 t
F_{MSY}	0.033	0.024 - 0.046
B_{2021}/B_{MSY}	1.305	0.789 - 1.902
F_{2021}/F_{MSY}	0.608	0.209 - 1.630

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 95% credibility intervals.
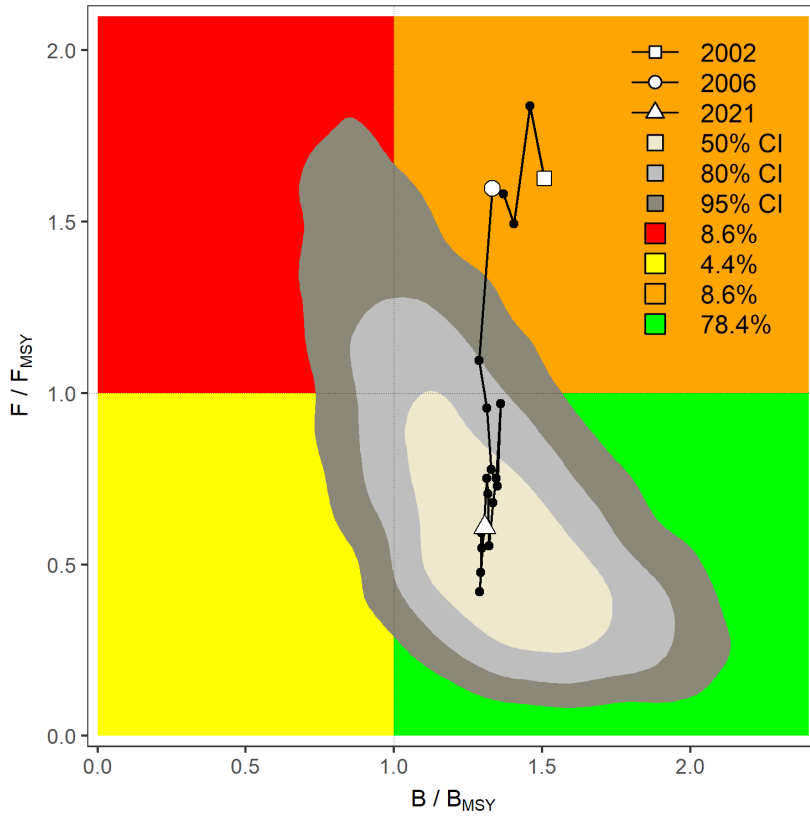
Figure 3. Kobe phase plot showing estimated trajectory of B/B_{MSY} and F/F_{MSY} for the bigeye grenadier stock in 2002-2021. Grey shaded areas denote the 50%, 80%, and 95% credibility intervals for the last assessment year. The probability of the last year estimate falling within each quadrant is indicated in the figure legend.
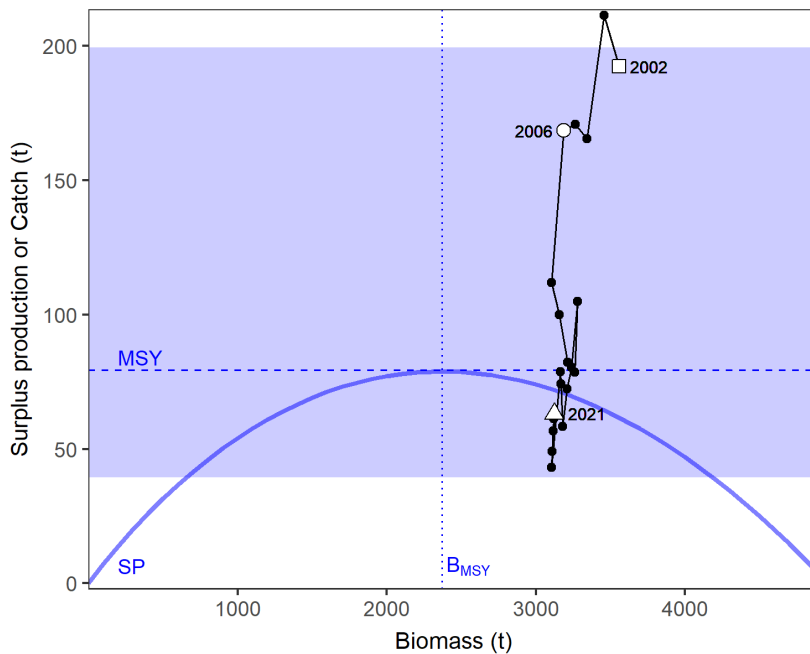

Figure 4. Surplus-production phase plot showing Pella-Tomlinson curve *SP* (solid blue line) and catch/biomass trajectory for the bigeye grenadier stock in 2002-2021 (black line). Catches on the *SP* curve would maintain the biomass, catches above the curve will shrink future biomass, and catches below the curve allow future biomass to increase. 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% credibility 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 2021 model and rerunning the analysis, in order to evaluate whether there were any strong changes in model results based on data availability. To quantify the bias between the models, the commonly used formulation of *Mohn's rho* statistic (Mohn 1999) was computed (Hurtado-Ferro *et al.* 2014). The estimated Mohn's rho for *B* (-0.01), *B/K* (-0.02), B/B_{MSY} (-0.02) and F/F_{MSY} (0.02) fell within the acceptable range of -0.15 and 0.20 (Hurtado-Ferro *et al.* 2014, Carvalho *et al.* 2017) and consequently indicated that the retrospective pattern was small. Retrospective plots showed no systematic trend in departures from the 2021 model (Figure 5).
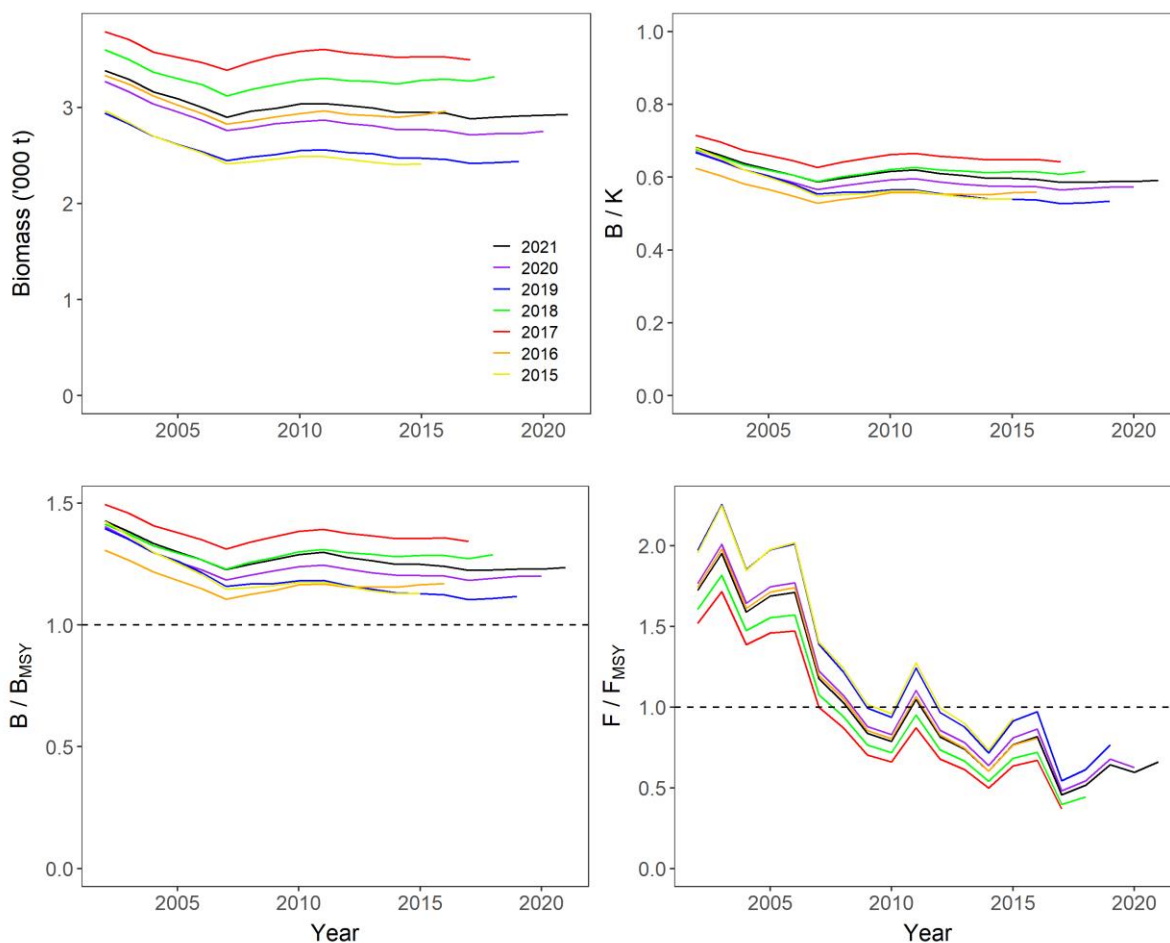

Figure 5. Estimated trends in biomass, *B/K*, B/B_{MSY} and F/F_{MSY} for the 2021 model (black line) and six retrospective model runs. The numeric label indicates the year up to which individual retrospective model was run (inclusive).

4. Discussion

In this assessment, JABBA (*Just Another Bayesian Biomass Assessment*) framework was used to fit a generalised Bayesian surplus production model to the catch and CPUE data belonging to the Falkland Islands bigeye grenadier stock. 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, development of frameworks that allow incorporating both observation and process errors, and Bayesian state-space modelling approaches (Winker *et al.* 2018). We considered SPMs appropriate for bigeye grenadier stock assessment, given the available data.

Besides the regular data updates for the most recent year (catch and CPUE for 2021), no further changes were made to the model structure and assumptions. Compared to the previous assessment, updated model resulted in almost identical estimates of r and K, and consequently of MSY, B_{MSY} and F_{MSY}. However, the relative biomass estimate at the beginning of time series B_{2002}/K was ~10% higher, resulting in slightly more optimistic estimates of stock status. Overall, the stock was estimated to be healthy, with low probability of being overfished or experiencing overfishing. Since 2009, annual bigeye grenadier catches have either been very close to or well below the estimated MSY of 79 t in all years, adding a measure of confidence that the stock was exploited in a sustainable manner. However, it is important to emphasize a high uncertainty associated with stock status estimates; a consequence of limited information content in the available catch and CPUE data.

The high influence of r prior on model outcomes (Skeljo and Winter 2020; 2021) remains a cause for some concern, especially coupled with the fact that this parameter was poorly informed by the input data, and strongly by the specified prior. We suggest that this is a consequence of difficulties faced by SPMs in estimating r from lightly exploited stocks, and/or from CPUE time series lacking contrast (Hilborn 1979, Hilborn and Walters 1992, Froese *et al.* 2017, Haddon 2011), as is the case in the bigeye grenadier assessment. This should not be considered as deficiency of the data, as both light exploitation and stable CPUE time series since 2008 can be explained by the fact that bigeye grenadier is a bycatch species caught at a very low and stable annual rate in a TAC regulated longline fishery, operated predominantly by a single vessel. Under the circumstances, effort should be taken to provide the model with the well-informed prior of r for bigeye grenadier, a challenging task given the scarcity of life history data for this species. In this respect R package *FishLife2.0* proved useful, as it provided estimate of r at *Macrourus* genus level, which was in turn used to construct a prior of r in the current assessment.

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Appendix 1. CPUE standardization

CPUE data belonging to the commercial Spanish- and umbrella-system longline fisheries are the main source of information on stock abundance available to our stock assessment model. In order to provide unbiased indices of relative stock abundance, these CPUE data had to be standardized to remove the impact of explanatory variables other than abundance (Maunder and Punt 2004). CPUE standardization employed a generalized linear mixed modelling approach (GLMM; Pinheiro and Bates 2000), an extension of the generalized linear modelling approach (GLM) used in the earlier assessments. GLMMs were fitted using package glmmTMB (Brooks *et al.* 2017, Magnusson *et al.* 2017) implemented in R (R Core Team 2020).

Prior to modelling, data exploration was applied following the protocol described in Zuur *et al.* (2010). Variables were inspected for outliers and collinearity. Continuous explanatory variables were scaled, i.e. mean was subtracted from the individual values, and the values were divided by its standard deviation.

The response variable in the model was daily longline CPUE, expressed as bigeye grenadier catch in kg-per-hook (Spanish-system) or kg-per-umbrella (umbrella-system). As the response variable was continuous and didn't include any zeroes, it was assumed gamma distributed around the mean, and the relationship between the linear predictor and the mean of the distribution was described by a canonical log link function. The explanatory variables considered in the model are given in Table A.1.

Table A.1. Explanatory variables considered in the CPUE standardization GLMM, by fishery and type.

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

* Variables included in the final model

Year effect is the quantity of interest so it must be a part of the final CPUE model; the remaining explanatory variables were included in the final model only if they improved the deviance explained by the model by at least 0.5%. The *Month* variable accounts for the seasonal variability in CPUE, and the *Region* variable attempts to capture the spatial distribution of CPUE, divided into two broad areas: (a) Falkland Islands waters south of 53.5°S (Burdwood Bank spawning area) and (b) Falkland Islands waters north of 53.5°S. *Depth* variable is the average fishing depth, and *Soak-time* the sum of soak times, of the lines pertaining to a single response CPUE value (usually multiple lines were set by a given vessel on a given day). $CPUE_{TOO}$ variable is the toothfish CPUE, expressed in the same units as the corresponding bigeye grenadier CPUE. *Vessel* variable was excluded from the umbrella-system longline CPUE standardization, as the only two vessels included in the assessment never fished concurrently in the same year, making the *Vessel* and *Year* effects indistinguishable. The umbrella-system had one additional variable, number of *Hooks-per-umbrella* (which was progressively decreased from 10 hooks initially to 8 hooks in December 2007, to 7 hooks in March 2014, to 6 hooks in June 2016).

The *vessel* and *month* variables were treated as random effects, thus imposing a correlation among CPUE values belonging to the same vessel or the same month. Random vessel effect accommodates variation between vessels in their ability to catch fish which will depend on the

attributes of the vessel, its crew, and the total extent of fishing grounds that they target (Candy 2004). The *Month* random effect was used to account for the short-term temporal dependency.

Fitting GLMM to the Spanish-system data included explanatory variables *Year*, *Month*, *Region*, *Depth* and *Vessel*, and the model explained 34.4% 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 (Figure A.1). Standardization removed this trend, as it reflected the differences in CPUE between the vessels, rather than actual differences in biomass between the years.

Fitting GLMM to umbrella-system data included explanatory variables *Year*, *Month*, *Region* and *Depth*, and the model explained 33.3% of the overall variation in CPUE. Standardized and unstandardized CPUE time series were similar and showed no clear trend; one notable outlier is a very low CPUE value for year 2007, likely due to the small sample size available (Figure A.2). In 2007 the transition from the Spanish- to the umbrella-system longline commenced and the number of days fished under the umbrella-system was limited.
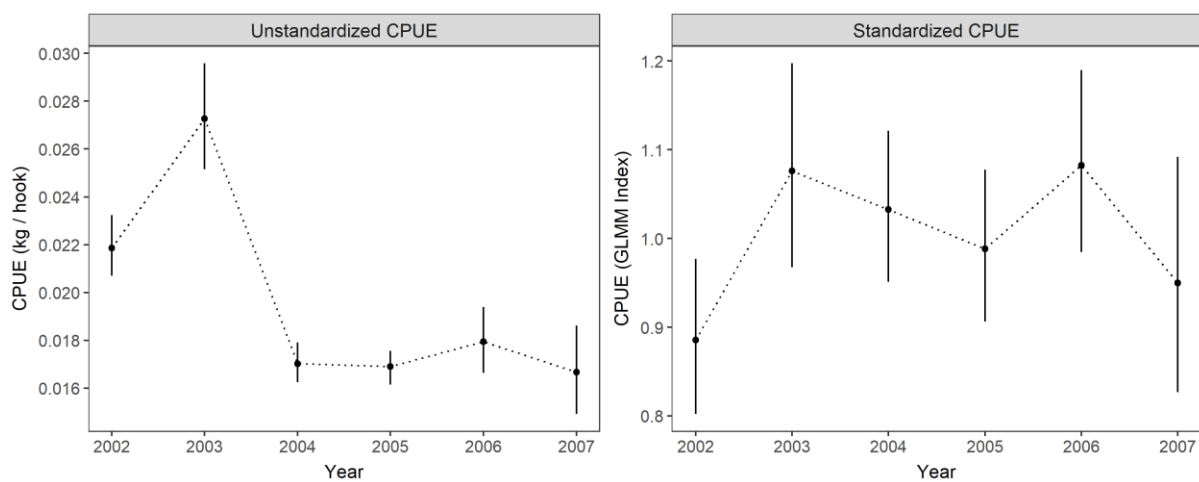

Figure A.1. Spanish-system longline unstandardized and standardized CPUE time series; black vertical lines correspond to 95% confidence intervals.
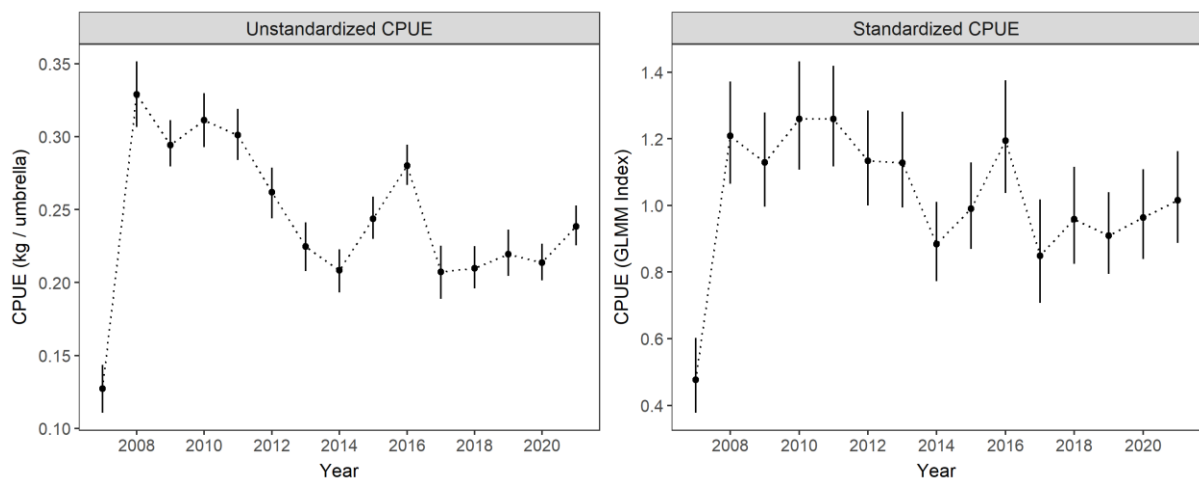

Figure A.2. Umbrella-system longline unstandardized and standardized CPUE time series; black vertical lines correspond to 95% confidence intervals.
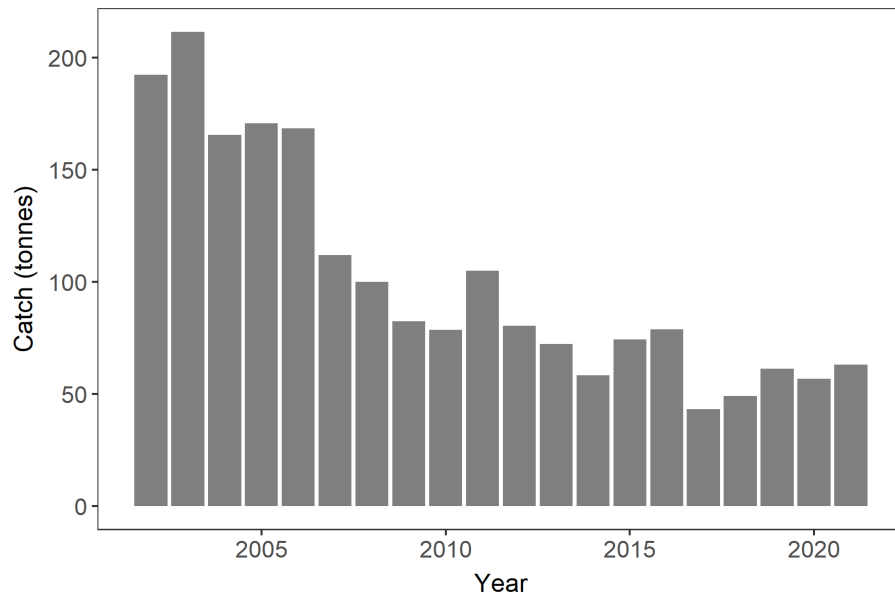
Appendix 2. Removals

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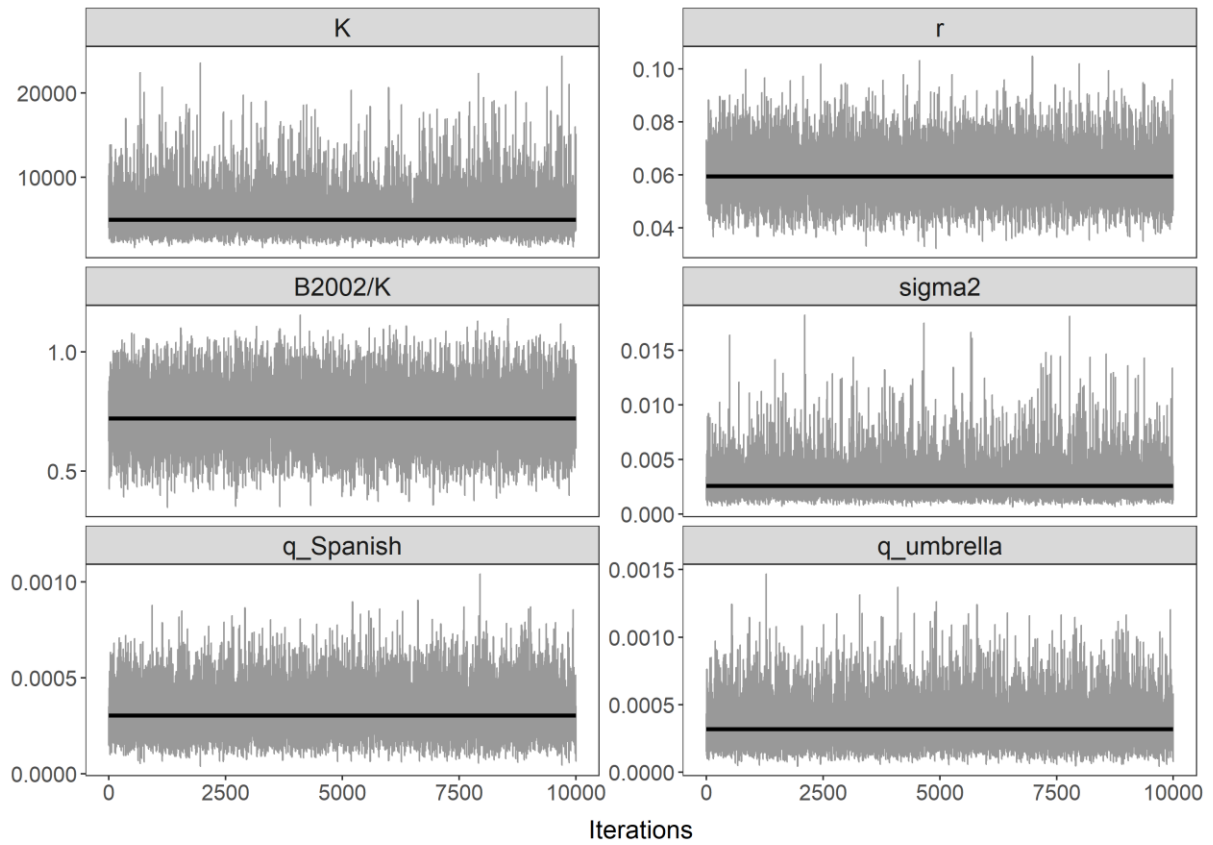
Appendix 3. Diagnostics plots

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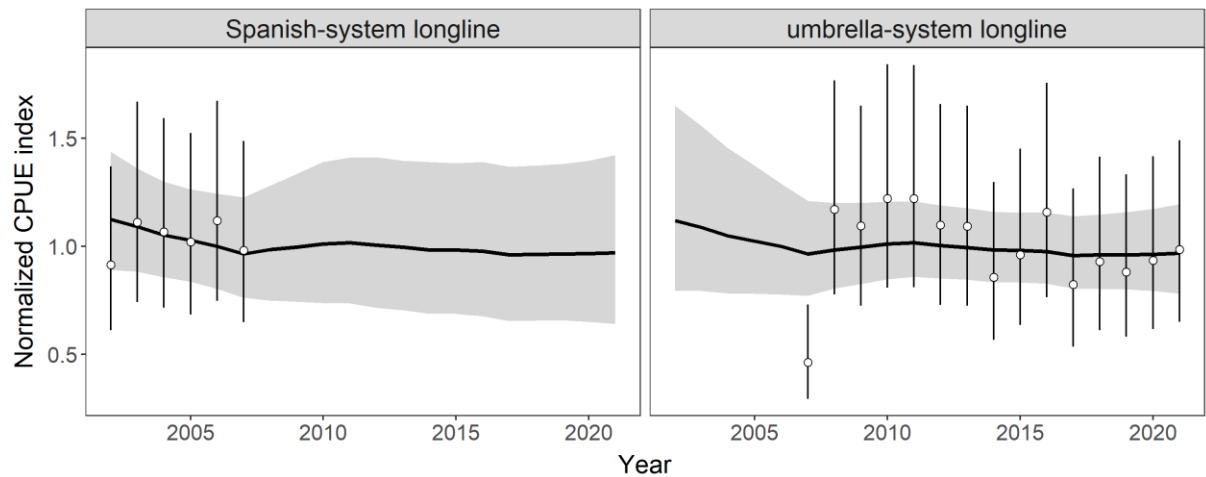

Figure A.5. Model fit (black line) to the normalised CPUE indices (white dots) for Spanish- and umbrella-system longline. Vertical lines denote 95% confidence intervals of the normalised CPUE indices; shaded areas denote 95% credibility intervals of the model fit.
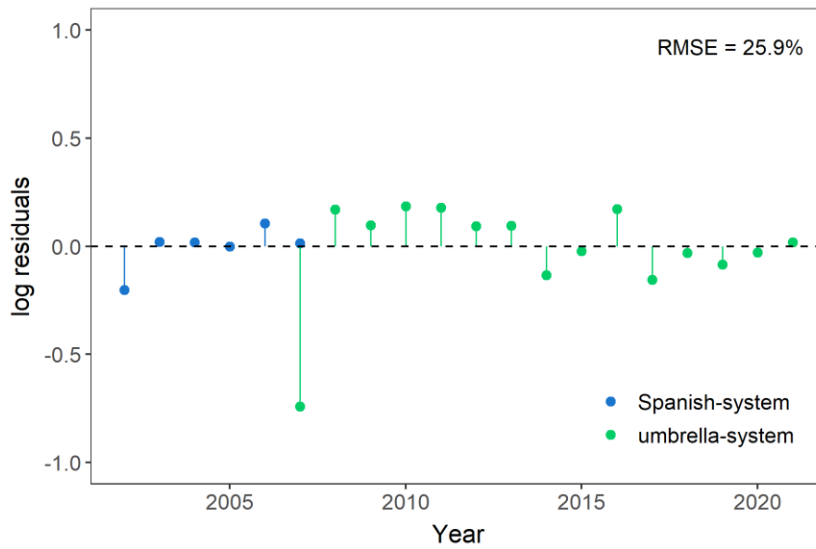
Figure A.6. Residuals from the model fit to the observed CPUE indices; for Spanish-system (blue dots) and umbrella-system longline (green dots). RMSE: root-mean-squared-error.
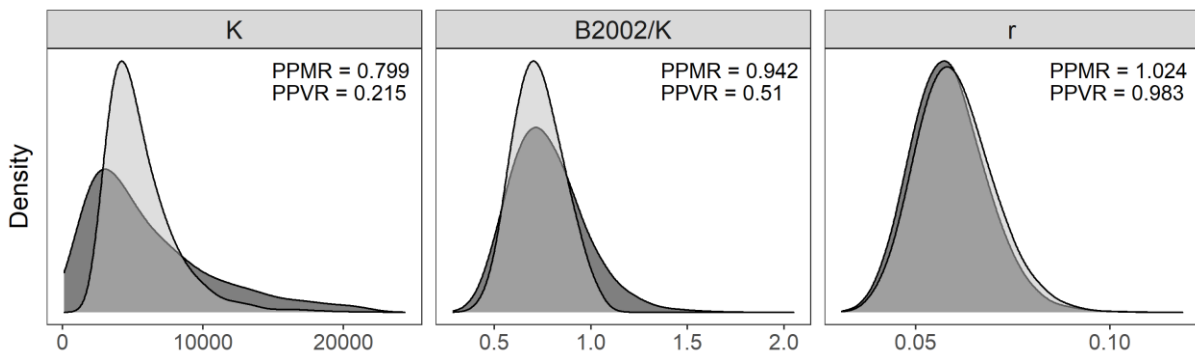

Figure A.7. Prior (dark grey) and posterior distributions (light grey) of key estimated parameters. PPMR: Posterior to Prior Means Ratio; PPVR: Posterior to Prior Variances Ratio.