2020 Stock Assessment Report

Bigeye grenadier (*Macrourus holotrachys*)

Skeljo F
Winter A

Fisheries Department
Directorate of Natural Resources
Falkland Islands Government
Stanley, Falkland Islands

23 July 2021

SA – 2020 – GRH

DESIRE THE RIGHT

Participating Scientific Staff

Frane Skeljo (PhD, Stock Assessment Scientist)
Andreas Winter (PhD, Senior Stock Assessment Scientist)

Comments provided by: Alexander Arkhipkin

Acknowledgements

We thank all of the observers and researchers that have contributed to the data used in this stock assessment report. We also thank Consolidated Fisheries Ltd., and the Captain and crew of the *CFL Hunter* for their continued assistance and support.

For citation purposes this publication should be referenced as follows:

Skeljo F, Winter A. 2021. 2020 Stock assessments for Bigeye grenadier (*Macrourus holotrachys*). Fisheries Report SA-2020-GRH. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 17 p.

Distribution: Public Domain

Reviewed and approved by:

Andrea Clausen
Director of Natural Resource

Date: 23 July 2021

Table of Contents

Summary

1. This report provides an updated stock assessment of bigeye grenadier (*Macrourus holotrachys*) in Falkland Islands waters, using data through year 2020. Several changes regarding the input data and model assumptions were introduced in the 2020 model and are outlined in the report. Assessment was done using a Bayesian surplus production model framework JABBA (Winker et al. 2018).
2. Overall, the model showed negative stock status trend in 2002-2006, followed by a transitional period in 2007-2008 and a positive trend in 2009-2020. Since 2009, bigeye grenadier catches have either been very close to or well below the estimated maximum sustainable yield (MSY) in all but one year, indicating sustainable exploitation of the stock.
3. We recommend that the assessment using JABBA model be continued in the future, and conducted annually. Close monitoring of the bigeye grenadier bycatch should continue in order to ensure that the annual catches do not surpass estimated MSY.

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 10.1% since the transition to the umbrella-system (8.7 - 13.5% annually). The largest bycatch category (5.4% 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 and landed in the Falkland Islands for local consumption (Farrugia and Winter 2019).

The toothfish fishery is certified by the Marine Stewardship Council (MSC), and the issue of bigeye grenadier bycatch was highlighted in the recent recertification 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 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 was used in grenadier stock assessment in 2020 (Skeljo and Winter 2020), with the recommendation to be updated on an annual basis.

The current report provides an updated JABBA stock assessment of bigeye grenadier in Falkland Islands waters, using data through year 2020. Several changes regarding the input data and model assumptions were introduced in the 2020 model and are outlined in the report.

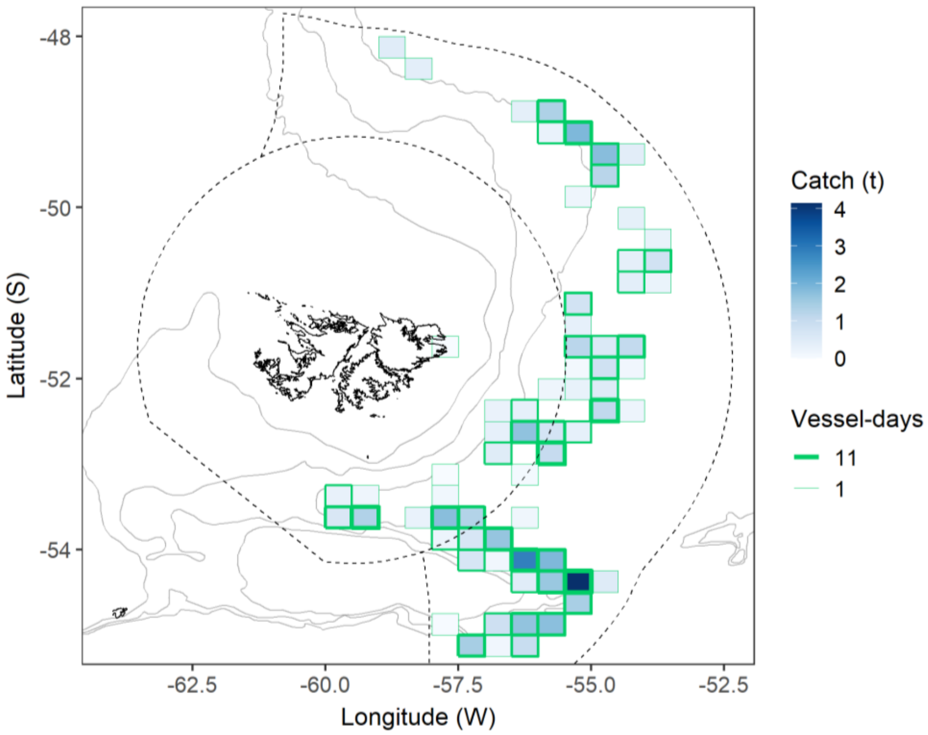

Figure 1. Spatial distribution of bigeye grenadier catches and longline fishery effort in the Falkland Islands waters in 2020. Thickness of grid lines is proportional to vessel days; blue-scale is proportional to bigeye grenadier catch biomass.

2. Methods

2.1. Data

Three datasets were used as information for the JABBA stock assessment model: total annual removals by combined longline fisheries (2002-2020) and catch-per-unit-effort (CPUE) time series for Spanish- (2002-2007) and umbrella-system (2007-2020) longline fisheries.

The main change compared to the previous year's assessment was exclusion of pre-2002 catch and CPUE data from the analysis (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 species. Additionally, 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, in the current assessment dataset was limited to the years with reliable grenadier catch reports, i.e. years without 'unidentified fish' catches.

CPUE

The CPUE data were treated separately for Spanish- and umbrella-system longline, according to the documented difference in the grenadiers' CPUE (*M. holotrachys* and *M. carinatus* pooled) between these two fishing gears/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 assessment (Skeljo and Winter 2020). 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 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 (with the associated standard errors) 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.

Reported bigeye grenadier catches taken in longline fisheries going back to 2002 were used, as explained in the previous section. IUU catches were introduced into grenadier assessment for the first time; we utilized the data for the Antarctic region from Table 2 in Agnew et al. (2009), which give estimates of IUU fishing as a percentage of reported catch in 1980-2003. Bycatch such as grenadier would be expected to have the equivalent IUU percentage as the target catch (toothfish). For years since 2003, we took grey-literature estimates (e.g. CCAMLR 2010) that IUU fishing in the southern oceans has decreased significantly and assumed IUU to be 5% of the reported catch. The same IUU data were used in the most recent toothfish stock assessment (Skeljo and Winter 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^2_{proc}, and additional observation variance for the abundance indices time series σ^2_{est}. In JABBA, the total observation 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 the expert knowledge of the stock status (*K* and B_{2002}/K) or estimated from the species life-history parameters (*r*). Prior of *K* was the same as in the previous assessment, while the mean of prior of B_{2002}/K was moderately reduced to account for the change of the initial year in the model from 1997 to 2002, when stock was already exploited for at least several years. Change was also made to the prior of *r*, which was previously defined in terms of broad species resilience categories proposed by Froese et al. (2017). However, those authors recommend these categories as a starting point but advise the users to carefully consider all available information and then select the most suitable prior of *r* for the stock in question. Following their advice, in the current assessment prior of *r* was 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* (www.fishbase.org; Froese and Pauly 2000) and spawning-recruitment relationship data series from *RAM Legacy Database* (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^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 R environment (R Core Team 2020) using the most recent version of 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 convergence tests of Geweke (1992) and 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 2020)
B_{2002}/K	log-normal; μ = 0.75, *cv* = 0.25	μ was reduced from 1.00 (Skeljo and Winter 2020) to 0.75, as initial year changed from 1997 to 2002, when the stock was already exploited for several years
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 Appendix 2. The MCMC convergence tests of Geweke (1992) and Heidelberger & 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.3).

The model fit to the standardized CPUE data was reasonably good for both Spanish- and umbrella-system fisheries, with the exception of notable outlier in the first year of the umbrella-system fishery (Figure A.4). The residuals pattern showed that the model overestimated CPUE in 2007, and underestimated it in the next six years (Figure A.5); 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 = 27.0%).

The comparison of posterior distributions and prior densities of key estimated parameters is given in Figure A.6. *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 = 4,908 t, and the estimated biomass declined from 0.662K in 2002 to 0.556K in 2020. 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 2009 ($F/F_{MSY} < 1$) 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 but one year. The estimated current biomass B_{2020} is 16.3% above B_{MSY}, and the current fishing mortality F_{2020} is 37.1% below F_{MSY}. Taking into account the uncertainty of this estimate (grey credibility intervals on the Kobe plot), there is 66.8% probability that the bigeye grenadier stock was not overfished ($B > B_{MSY}$) and not experiencing overfishing ($F < F_{MSY}$) in 2020 (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 2020 is 80.3% (green and 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} = 2,346 t, with the corresponding MSY = 78 t. Since 2009, catches have either been very close to or well below the median MSY in all but one year (2011).

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 - 0.081
K	4,908 t	2,622 - 12,496 t
B_{2002}	3,196 t	1,793 - 8,008 t
B_{2020}	2,707 t	1,029 - 8,199 t
B_{2002}/K	0.662	0.416 - 0.963
B_{2020}/K	0.556	0.275 - 0.850
MSY	78 t	40 - 198 t
B_{MSY}	2,346 t	1,253 - 5,973 t
F_{MSY}	0.033	0.024 - 0.045
B_{2020}/B_{MSY}	1.163	0.575 - 1.778
F_{2020}/F_{MSY}	0.629	0.199 - 1.763

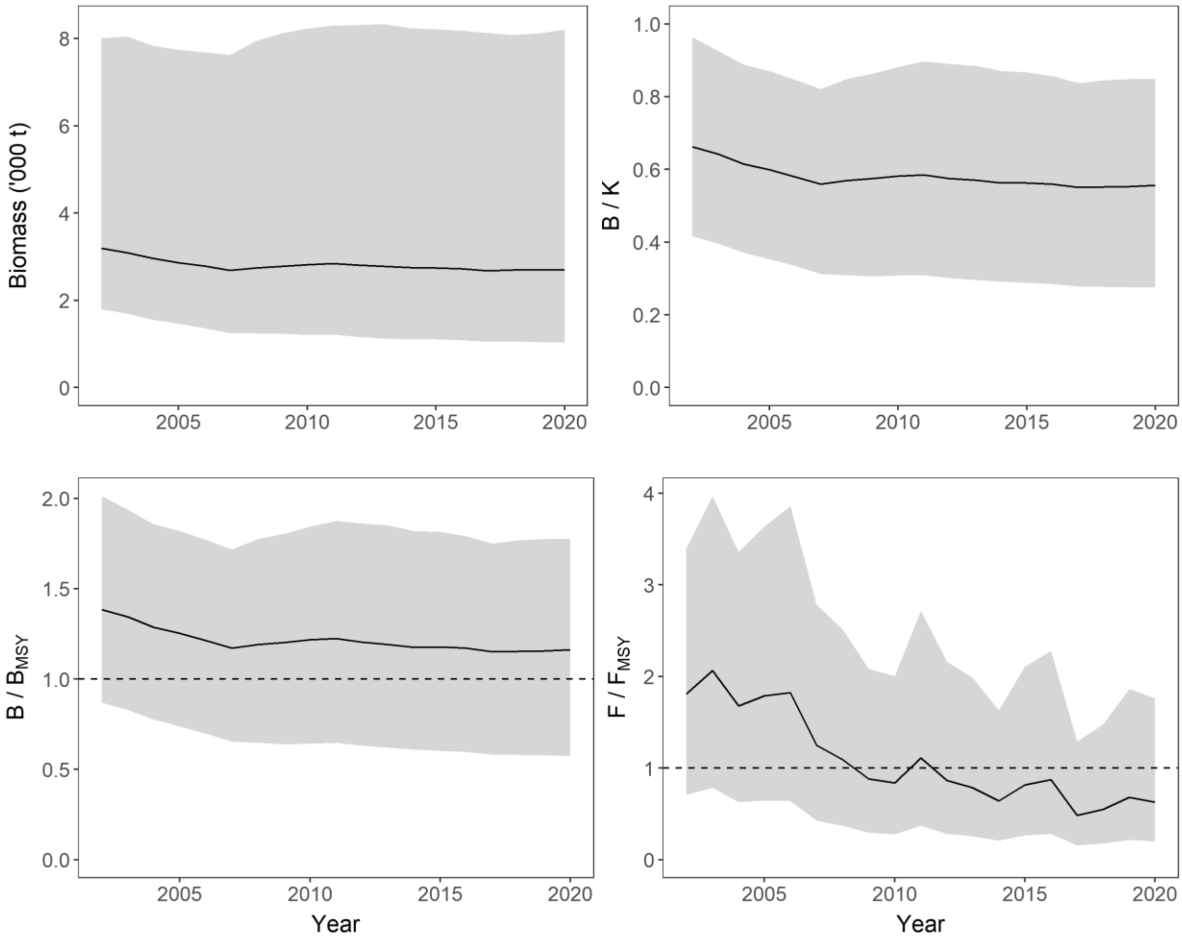

Figure 2. Estimated trends in absolute biomass (top left), biomass relative to *K* (top right), biomass relative to B_{MSY} (bottom left) and fishing mortality relative to F_{MSY} (bottom right). Solid black lines are medians and shaded areas denote 95% credibility intervals.

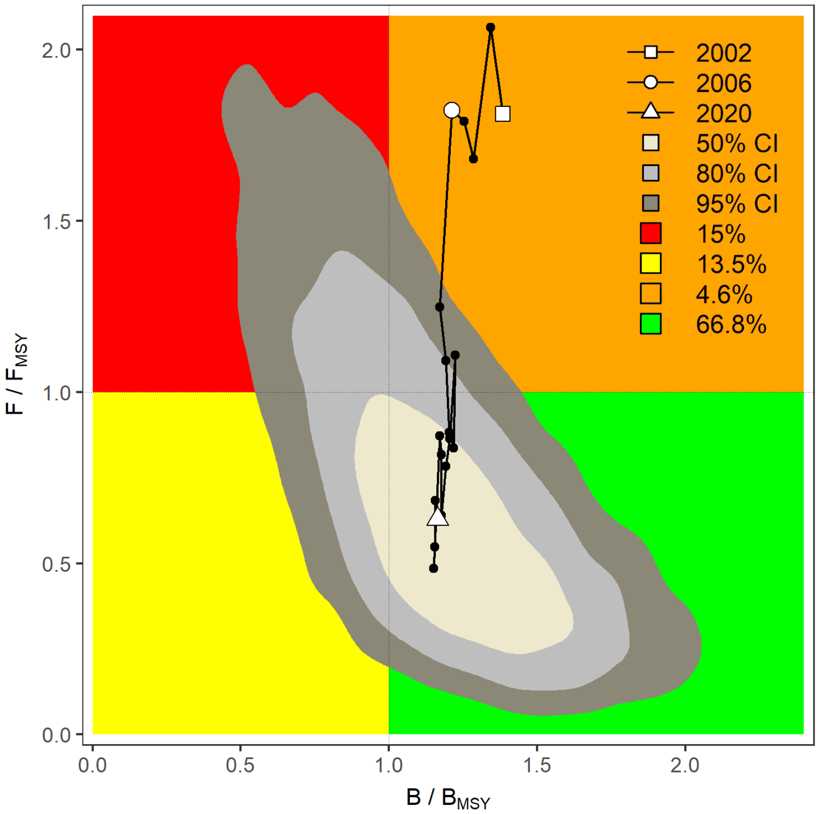

Figure 3. Kobe phase plot showing estimated trajectory of *B/B_{MSY}* and *F/F_{MSY}* for the bigeye grenadier stock in 2002-2020. Grey shaded areas denote the 50%, 80%, and 95% credibility intervals for the last assessment year. The probability of the last year estimate falling within each quadrant is indicated in the figure legend.

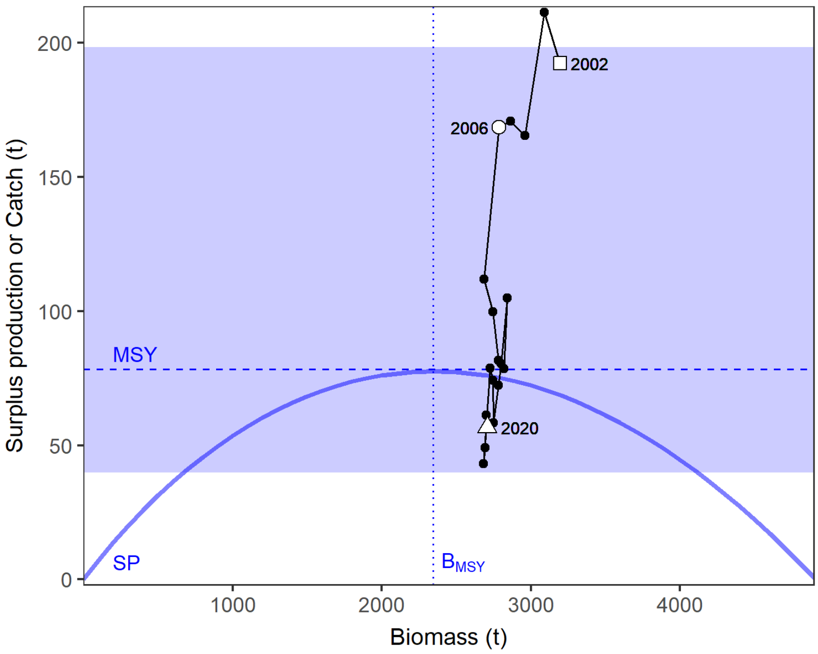

Figure 4. Surplus-production phase plot showing Pella-Tomlinson curve *SP* (solid blue line) and catch/biomass trajectory for the bigeye grenadier stock in 2002-2020 (black line). Catches on the *SP* curve would maintain the biomass, catches above the curve will shrink future biomass, and catches below 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 2020 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* (0.10), *B/K* (0.06), B/B_{MSY} (0.06) and F/F_{MSY} (-0.09) 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 relatively small. Retrospective plots showed no systematic trend in departures from the 2020 model, and five out of six retrospective models produced more optimistic estimates than the current model.

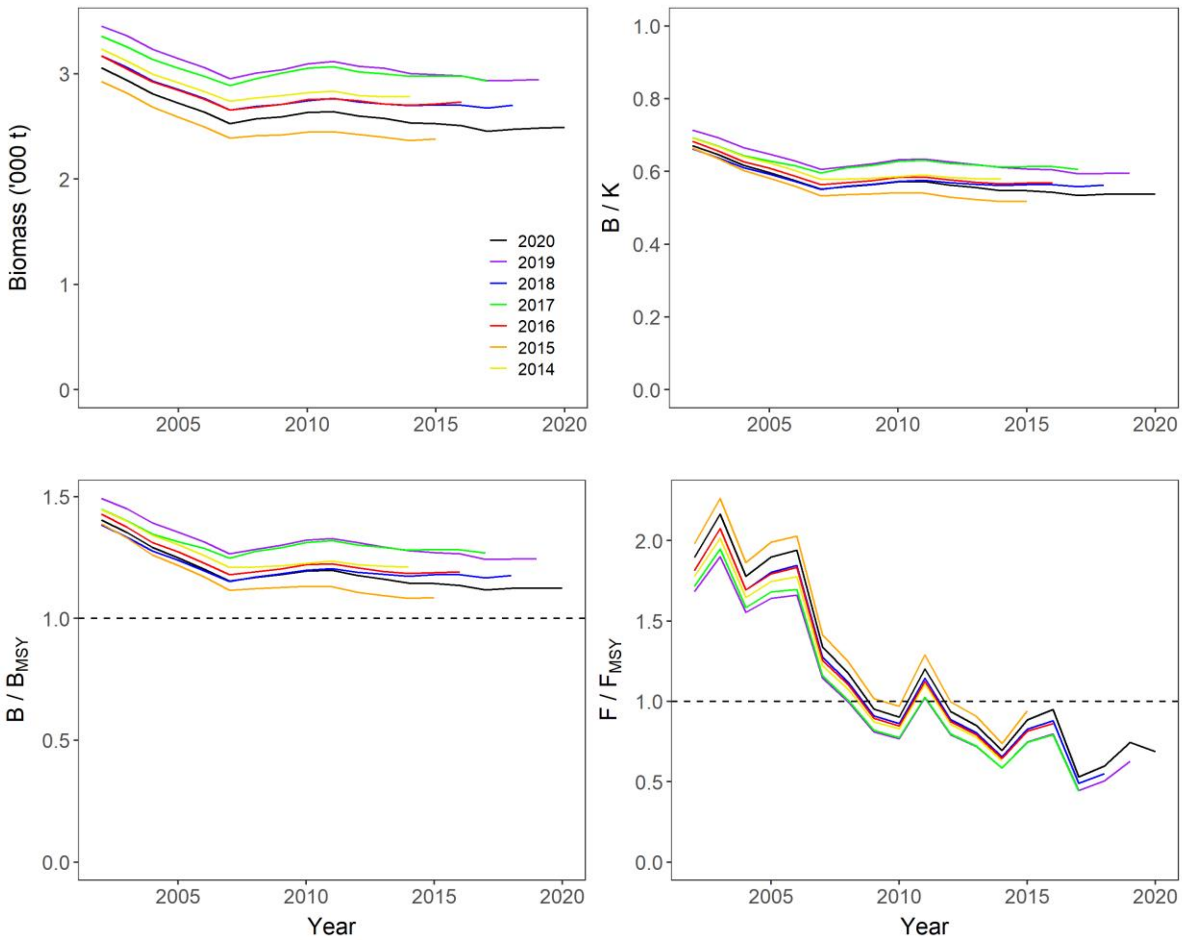

Figure 5. Estimated trends in biomass, *B/K*, B/B_{MSY} and F/F_{MSY} for the 2020 model (black line) and six retrospective model runs. The numeric label indicates the year up to which individual retrospective model was run (inclusive).

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.

Compared to the previous year's assessment, several changes were introduced to the input data and priors used in the analysis. The most substantial decision regarding the input data was exclusion of the 1997-2001 catch and CPUE data from the analysis, as bigeye grenadier catch reports for this period were possibly biased (for details see Methods section). Regarding priors, small adjustment was made to the prior of B_{2002}/K (relative biomass at the start of the available catch time series), to account for changing of the initial year in the model from 1997 to 2002. The more influential change was made to the prior of r, with new prior being more precautionary in the sense that it assumed a lower intrinsic population growth rate.

The revised and updated data resulted in somewhat less optimistic estimates of bigeye grenadier stock status compared to the previous assessment; this was expected as we used a less optimistic prior of r, and it was already demonstrated that the prior of r has high influence on the overall model outcomes (Skeljo and Winter 2020). Nevertheless, the stock was still estimated to be healthy, with low probability of experiencing overfishing. Since 2009, annual bigeye grenadier catches have either been very close to or well below the estimated MSY of 78 t in all but one year, adding a measure of confidence that the stock was exploited in a sustainable manner.

The high influence of the prior of r on model outcomes is 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.

5. References

Aalto EA, Dick EJ, MacCall AD. 2015. Separating recruitment and mortality time lags for a delay-difference production model. Canadian Journal of Fisheries and Aquatic Sciences 165, 161-165.

Acoura Marine. 2018. MSC sustainable fisheries certification: Falkland Islands toothfish. Final Report Certificate Code F-ACO-0033. Edinburgh, Scotland, United Kingdom.

Agnew DJ, Pearce J, Pramod G, Peatman T, Watson R, Beddington JR, Pitcher TJ. 2009. Estimating the worldwide extent of illegal fishing. PLoS ONE 4, e4570.

Barton K. 2009. Mu-MIn: Multi-model inference. R Package Version 0.12.2/r18. http://R-Forge.R-project.org/projects/mumin/.

Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Maechler M, Bolker BM. 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modelling. *The R Journal* 9(2), 378-400.

Brown J, Brickle P, Hearne S, French G. 2010. An experimental investigation of the 'umbrella' and 'Spanish' system of longline fishing for the Patagonian toothfish (*Dissostichus eleginoides*) in the Falkland Islands: Implications for stock assessment and seabird by-catch. Fisheries Research 106, 404-412.

Candy SG. 2004. Modelling catch and effort data using generalised linear models, the Tweedie distribution, random vessel effects and random stratum-by-year effects. CCAMLR Science 11, 59-80.

Carvalho F, Punt AE, Chang YJ, Maunder MN, Piner KR. 2017. Can diagnostic tests help identify model misspecification in integrated stock assessments? Fisheries Research 192, 28-40.

CCAMLR. 2010. Estimation of IUU catches of toothfish inside the convention area during the 2009/10 fishing season. Document WG-FSA-10/6 Rev. 1, 12 p.

Dichmont CM, Deng RA, Punt AE, Brodziak J, Chang YJ, Cope JM, Ianelli JN, Legault CM, Methot RD, Porch CE, Prager MH, Shertzer KW. 2016. A review of stock assessment packages in the United States. Fisheries Research 183, 447-460.

Farrugia TJ, Winter A. 2019. 2018 Stock assessment report for Bigeye grenadier (*Macrourus holotrachys*). Fisheries Report SA-2018-GRH. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 18 p.

Francis RICC, Hurst RJ, Renwick JA. 2003. Quantifying annual variation in catchability for commercial and research fishing. Fisheries Bulletin 101, 293-304.

Froese R, Demirel N, Coro G, Kleisner KM, Winker H. 2017. Estimating fisheries reference points from catch and resilience. Fish and Fisheries 18(3), 506-526.

Froese R, Demirel N, Coro G, Kleisner KM, Winker H. 2017. Estimating fisheries reference points from catch and resilience. Fish and Fisheries 18(3), 506-526.

Froese R, Pauly D (Eds.). 2000. FishBase 2000: concepts, design and data sources. ICLARM, Los Baños, Laguna, Philippines, 344 p.

Geweke J. 1992. Evaluating the accuracy of sampling-based approaches to calculating posterior moments. In: Bernardo JM, Berger JO, David AP, Smith AFM (Eds.). Bayesian Statistics, 4. Clarendon Press, Oxford, 169-194.

Haddon M. 2011. Modelling and quantitative methods in fisheries, 2nd Edition. Chapman & Hall/CRC, Boca Raton.

Heidelberger P, Welch P. 1983. Simulation run length control in the presence of an initial transient. Operations Research 31, 1109-1144.

Hilborn R, Walters CJ. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Chapman & Hall, London.

Hilborn R. 1979. Comparison of fisheries control systems that utilize catch and effort data. Journal of the Fisheries Research Board of Canada 36, 1477-1489.

Hurtado-Ferro F, Szuwalski CS, Valero JL, Anderson SC, Cunningham CJ, Johnson KF, Licandeo R, McGilliard CR, Monnahan CC, Muradian ML, Ono K, Vert-Pre KA, Whitten AR, Punt AE. 2014.

Looking in the rear-view mirror: Bias and retrospective patterns in integrated, age-structured stock assessment models. ICES Journal of Marine Science 72(1), 99-110.
Laptikhovsky VV, Arkhipkin AI, Brickle P. 2008. Biology and distribution of grenadiers of the family Macrouridae around the Falkland Islands. American Fisheries Society Symposium 63, 261-284.
Laptikhovsky VV, Brickle P. 2005. The Patagonian toothfish fishery in Falkland Islands' waters. Fisheries Research 74, 11-23.
Magnusson A, Skaug HJ, Nielsen A, Berg CW, Kristensen K, Maechler M, van Bentham KJ, Bolker BM, Brooks ME. 2017. glmmTMB: Generalized Linear Mixed Models using Template Model Builder. R package version 0.1.3. https://github.com/glmmTMB/.
Maunder MN, Piner KR. 2017. Dealing with data conflicts in statistical inference of population assessment models that integrate information from multiple diverse data sets. Fisheries Research 192, 16-27.
Maunder MN, Punt AE. 2004. Standardizing catch and effort data: A review of recent approaches. Fisheries Research 70, 141-159.
Maunder MN. 2003. Is it time to discard the Schaefer model from the stock assessment scientist's toolbox? Fisheries Research 61, 145-149.
Mohn R. 1999. The retrospective problem in sequential population analysis: An investigation using cod fishery and simulated data. ICES Journal of Marine Science 56, 473-488.
Pella JJ, Tomlinson PK. 1969. A generalized stock production model. Inter-American Tropical Tuna Commission Bulletin 13, 421-458.
Pinheiro JC, Bates DM. 2000. Mixed-effects Models in S and S-plus. Springer, New York, 528 p.
Plummer M, Best N, Cowles K, Vines K. 2006. CODA: Convergence Diagnosis and Output Analysis for MCMC. R News 6, 7-11.
Punt AE, Su N-J, Sun C-L. 2015. Assessing billfish stocks: a review of current methods and some future directions. Fisheries Research 166, 103-118.
Punt AE, Szuwalski C. 2012. How well can FMSY and BMSY be estimated using empirical measures of surplus production? Fisheries Research 134-136, 113–124.
R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.
Ricard D, Minto C, Jensen OP, Baum JK. 2012. Examining the knowledge base and status of commercially exploited marine species with the RAM Legacy Stock Assessment Database. Fish and Fisheries 13, 380-398.
Sant'Ana R, Mourato B, Kimoto A, Walter J, Winker H. 2020. Atlantic yellowfin tuna stock assessment: an implementation of Bayesian state-space surplus production model using JABBA. Collective Volume of Scientifics Papers ICCAT 76(6), 699-724.
Skeljo F, Winter A. 2020. 2019 Stock assessments report for Bigeye grenadier (*Macrourus holotrachys*). Fisheries Report SA-2019-GRH. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 16 p.
Skeljo F, Winter A. 2021. 2020 Stock assessment report for Patagonian toothfish (*Dissostichus eleginoides*). Fisheries Report SA-2020-TOO. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 38 p.
Thorson JT, Cope JM, Branch TA, Jensen OP. 2012. Spawning biomass reference points for exploited marine fishes, incorporating taxonomic and body size information. Canadian Journal of Fisheries and Aquatic Sciences 69(9), 1556-1568.
Thorson JT. 2019. Predicting recruitment density dependence and intrinsic growth rate for all fishes worldwide using a data-integrated life-history model. Fish and Fisheries 21(2), 237-251.
Thorson JT. 2019. Predicting recruitment density dependence and intrinsic growth rate for all fishes worldwide using a data-integrated life-history model. Fish and Fisheries 21(2), 237-251.
Wang S-P, Maunder MN, Aires-da-Silva A. 2014. Selectivity's distortion of the production function and its influence on management advice from surplus production models. Fisheries Research 158, 181-193.

Winker H, Carvalho F, Kapur M .2021. JABBA: Just Another Bayesian Biomass Assessment. R package version 2.1.6. https://github.com/jabbamodel/JABBA/.

Winker H, Carvalho F, Kapur M. 2018. JABBA: Just another Bayesian biomass assessment. Fisheries Research 204, 275-288.

Zuur AF, Ieno EN, Elphick CS. 2010. A protocol for data exploration to avoid common statistical problems. Methods in Ecology and Evolution 1, 3-14.

Appendix 1. CPUE standardization

back to text

CPUE data belonging to the commercial Spanish- and umbrella-system longline fisheries are the main source of information on stock abundance available to the current 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 has been slightly modified this year by employing a generalized linear mixed modelling approach (GLMM; Pinheiro and Bates 2000), an extension of the generalized linear modelling approach (GLM) used in the previous 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 where 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 (Maunder and Punt 2004). 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 34.1% 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 33.2% 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, possibly due to the small sample size available (Figure A.2). In 2007 the transition from the Spanish- to the umbrella-system longline commenced and both techniques were used concurrently, sometimes by the same vessel on the same day. As the database currently holds only day-by-day data for this period, some catch reports had to be omitted from the analysis because it was not clear to which system they should be attributed. Once the line-by-line data for 2007 are entered into the database (in progress), it should be possible to clearly delineate catches taken by both systems, giving us a better insight into the CPUE time-series.

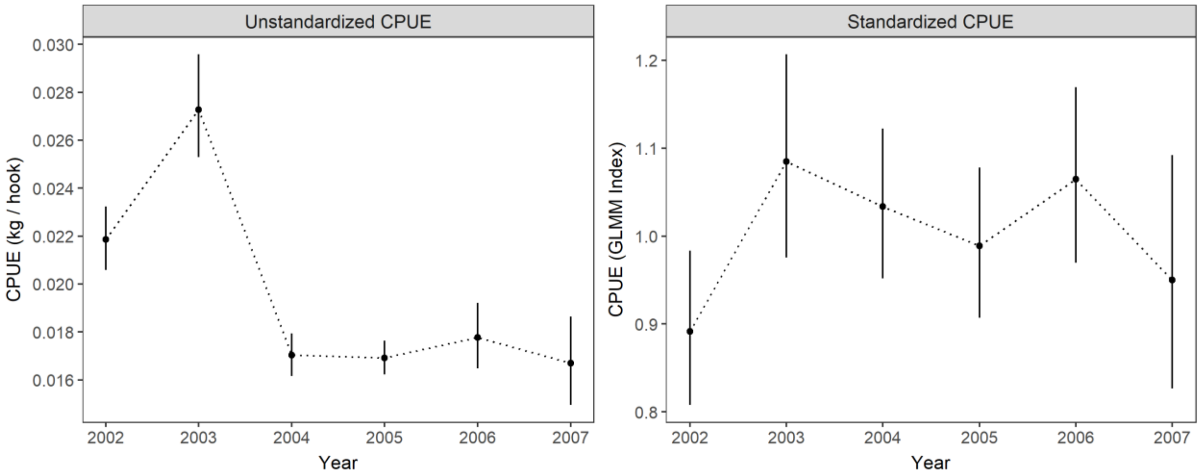

Figure A.1. Spanish-system longline unstandardized and standardized CPUE time series; black vertical lines correspond to 95% confidence intervals.

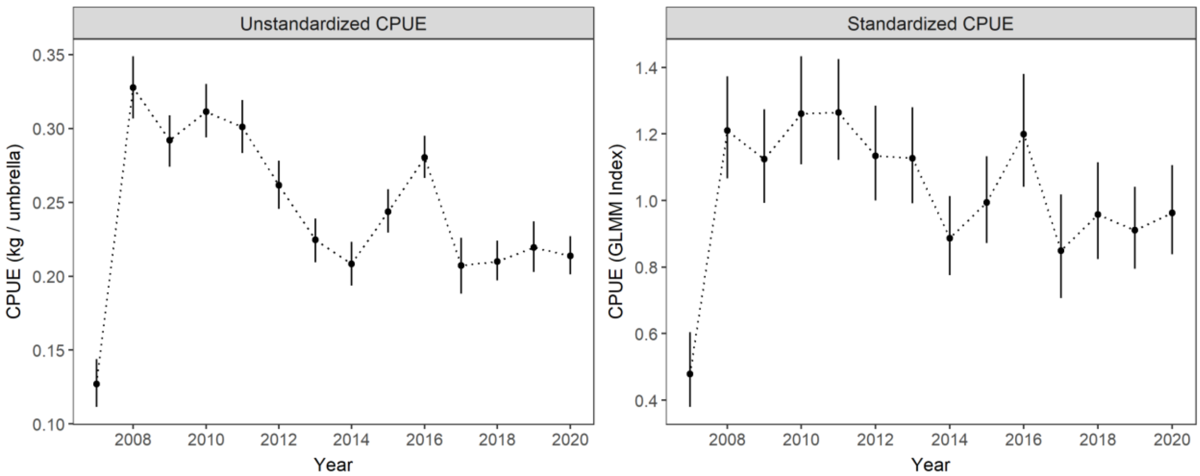

Figure A.2. Umbrella-system longline unstandardized and standardized CPUE time series; black vertical lines correspond to 95% confidence intervals.

Appendix 2. Diagnostics plots

back to text

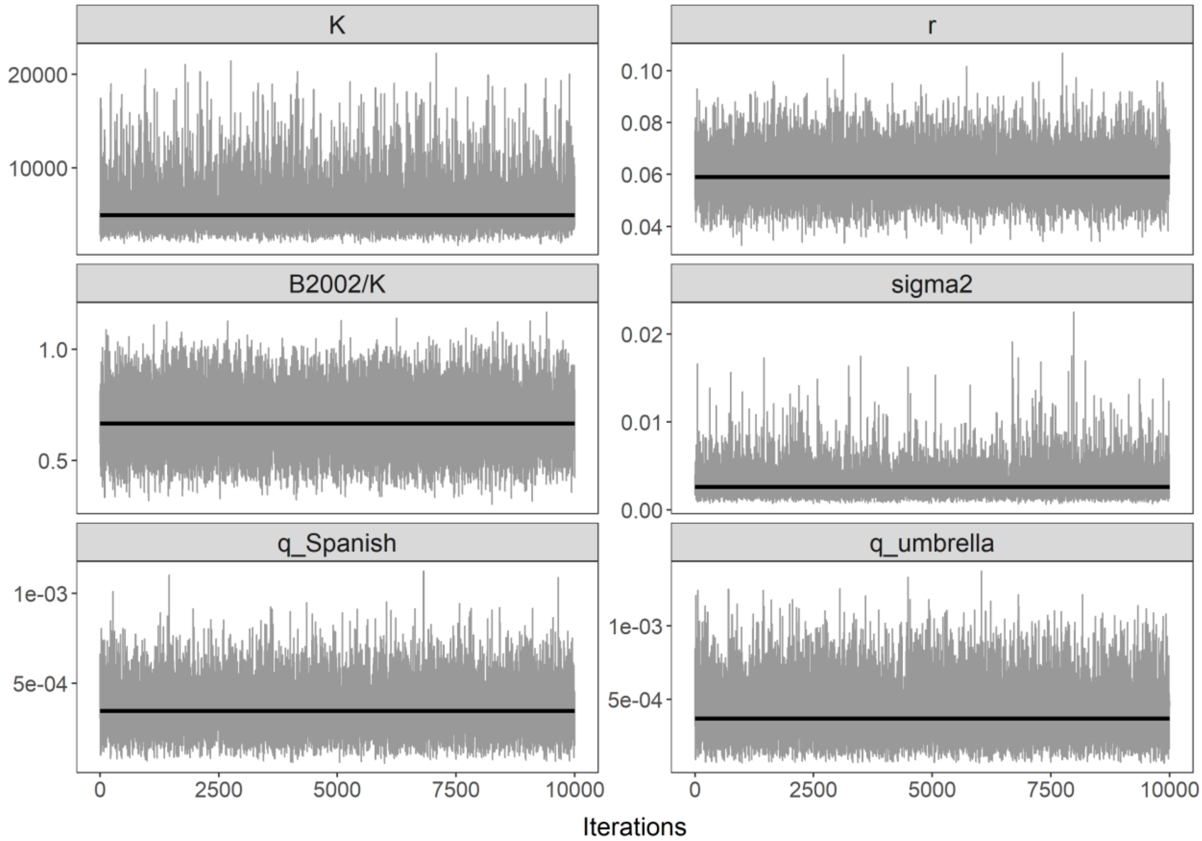

Figure A.3. MCMC posterior trace plots for the estimated parameters. Black line denotes the median.

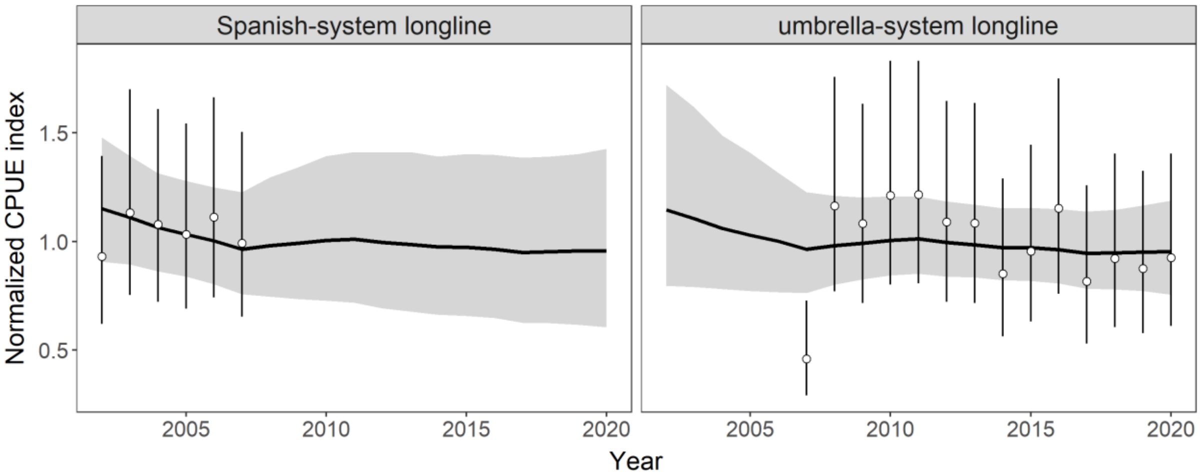

Figure A.4. Model fit (black line) to the normalised CPUE indices (white dots) for Spanish- and umbrella-system longline. Vertical lines denote 95% confidence intervals of the normalised CPUE indices; shaded areas denote 95% credibility intervals of the model fit.

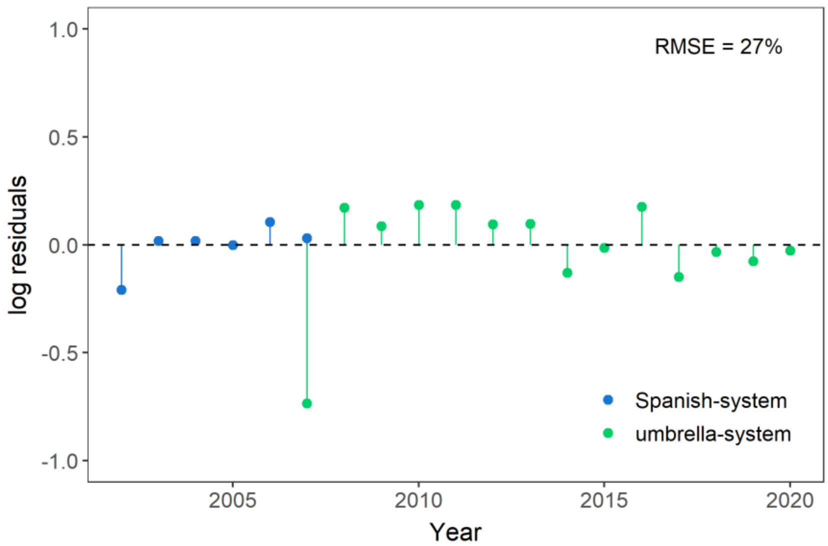

Figure A.5. Residuals from the model fit to the observed CPUE indices; for Spanish-system (blue dots) and umbrella-system longline (green dots). Solid black line denotes a loess smoother through all residuals. RMSE: root-mean-squared-error.

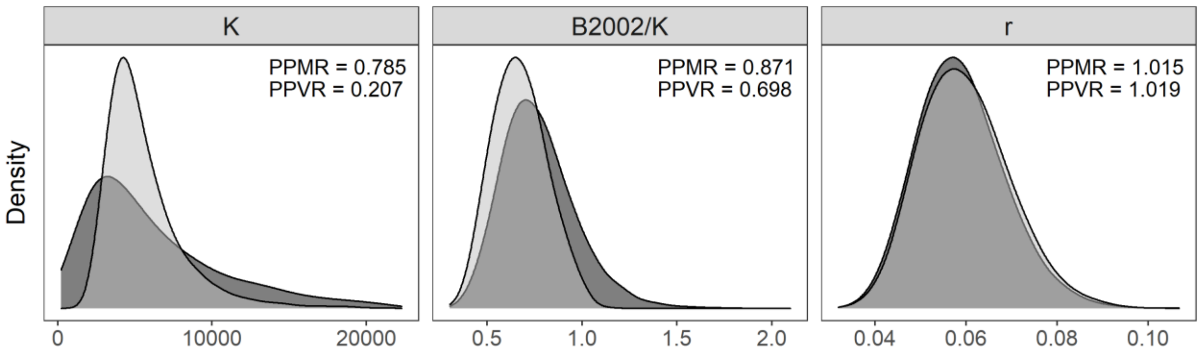

Figure A.6. Prior (dark grey) and posterior distributions (light grey) of key estimated parameters. PPMR: Posterior to Prior Means Ratio; PPVR: Posterior to Prior Variances Ratio.