2019 Stock Assessment Report

Bigeye grenadier
(*Macrourus holotrachys*)

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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 2019. Several changes regarding the input data and model assumptions were introduced in the 2019 model, and are outlined in the report. In addition, sensitivity of the model outputs to alternative priors was investigated.
2. Assessment was done using a Bayesian surplus production model JABBA (Winker et al. 2018) and the stock was estimated to be healthy, with low probability of currently being overfished or experiencing overfishing. The annual catches have not surpassed the estimated maximum sustainable yield (MSY) of 99 tonnes per year since 2007, 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 10.0% since the transition to the umbrella-system. The largest bycatch category (5.4%) 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 in this fishery is bigeye grenadier (Farrugia and Winter 2019), therefore this species is the focus of this report. Bigeye grenadier is caught throughout the longline fishery area, although some areas yield noticeably higher catch-per-unit-effort (CPUE) than others (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 JABBA (Winker et al. 2018). This is a data-limited model with few input requirements, suitable for the assessment of stocks for which reliable age-structured data are not readily available.

The current report provides an updated JABBA stock assessment of bigeye grenadier in Falkland Islands waters, using data through year 2019. Several changes regarding the input data and model assumptions were introduced in the 2019 model, and are outlined in the report. In addition, sensitivity of the model outputs to alternative modelling assumptions was investigated.

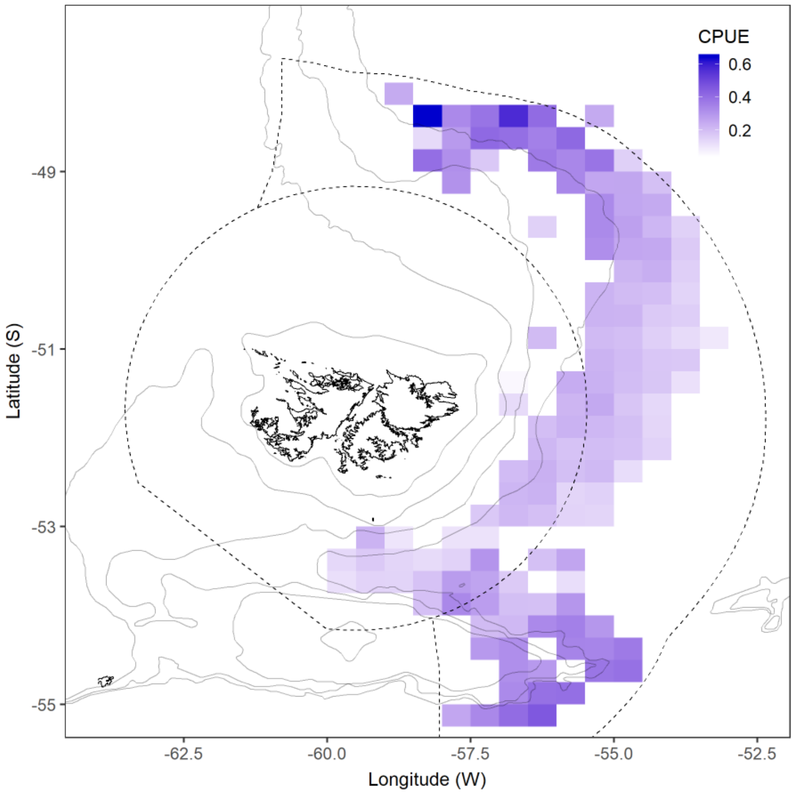

Figure 1. Spatial distribution of bigeye grenadier catch-per-unit-effort (CPUE, expressed in kg-per-umbrella) in the Falkland Islands waters during the last ten years (2010-2019).

2. Methods

2.1. Data

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

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). Spanish-system CPUE data were available for the period 1997-2007, and umbrella-system CPUE data for the period 2007-2019.

For the umbrella-system longline, additional data selection had to be performed in order to avoid introducing bias in the CPUE estimates. The most substantial decision, compared to the previous year's assessment, was to use only the CPUE data from Falkland Islands flagged vessels. The reason is that the fishing was predominantly done by a single Falkland Islands vessel at a time since the onset of the umbrella-system (*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 as an index of abundance if only Falkland Islands vessels data were used. With a similar goal, data from the longline sets at depths <600 m were removed from the analysis. Fishing in shallow waters was excluded because longlining is prohibited at depths <600 m, and the corresponding sets were not regular commercial fishing (they were experimental fishing, aiming to collect toothfish brood stock for the rearing facility).

The selected CPUE data were prepared for modelling in two steps. First, unstandardized CPUE values were calculated for each longline set as the reported bigeye grenadier catch in kg-per-hook (Spanish-system) or kg-per-umbrella (umbrella-system). Second, CPUE was standardised using a generalised linear model (GLM), providing a time series of CPUE values (with the associated standard errors) which were assumed to be relative abundance indices. The standardization procedure is described in more detail in Appendix 1, and standardized CPUE indices with standard errors are given in Appendix 2.

Removals

Total bigeye grenadier removals by the fishery were assumed equal to the reported longline catches in Falkland Islands waters, available for the period 1997-2019 (Appendix 2).

2.2. JABBA model setup

JABBA is a Bayesian state-space surplus production model, 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 our base-case model we assumed surplus production is 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 catch and abundance indices time series and 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 our base-case model we used the same priors for r, K and B_{1997}/K as in the previous year's bigeye grenadier assessment (Farrugia and Winter 2019), and default JABBA priors for σ^2_{proc} and σ^2_{est} (Table 1). However, alternative priors for r and K were tested as a part of the sensitivity analyses.

Once the priors were defined, JABBA was executed in R environment using the most updated version *v1.5beta* (available online at https://github.com/Henning-Winker/JABBAbeta). 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. A full description of the JABBA model, 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 base-case JABBA model run, with a brief description of the selection criteria.

Parameter	Prior	Description
r	log-normal; range = 0.05 - 0.5*	Used in the previous assessment (Farrugia and Winter 2019), corresponds to the '*low*' species resilience (Froese et al. 2017); alternative values are explored in sensitivity analyses
K	log-normal; μ = 5,000, c*v* = 1	Used in the previous assessment (Farrugia and Winter 2019); alternative values are explored in sensitivity analyses
B_{1997}/K	log-normal; μ = 1, *cv* = 0.25	Used in the previous assessment (Farrugia and Winter 2019); Stock is assumed to have been '*nearly unexploited*' at this time, based on the very low reported catches
σ^2_{proc}	inverse-gamma (4, 0.01)**	Model default
σ^2_{est}	inverse-gamma (0.001, 0.001)**	Model default

* range was converted into a lognormal prior in the model; ** inverse-gamma distribution was defined by two scaling parameters

3. Results

3.1. JABBA model estimates

The key output parameters and stock status estimated by JABBA for the base-case model are summarised in Table 2. The carrying capacity was estimated as K = 2,228 t, and the estimated biomass declined from 0.884 K in the beginning of the time series (1997) to 0.643 K in the last assessed year (2019). The absolute biomass B and the relative biomass B/K and B/B_{MSY} trends showed a moderate decline starting in 2000, reaching its minimum in 2007, and reverting to a slow increase afterwards. This was related to the sharp increase in fishing pressure F/F_{MSY} to an unsustainable level ($F/F_{MSY} > 1$) in 2000-2006, followed by a decline to a sustainable level in 2007 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 increase in fishing pressure in early 2000s led to a biomass decline, which has stopped once the fishing pressure decreased in 2006, and reverted to a slow biomass increase afterwards. The fishing pressure decline in 2006 coincided with the introduction of TAC system to the longline fishery, which limited the targeted toothfish catches and consequently reduced the bigeye grenadier bycatch as well. The estimated current biomass B_{2019} is 34.4% above B_{MSY}, and the current fishing mortality F_{2019} is only 44.6% of the F_{MSY}. Taking into account the uncertainty of this estimate (grey credibility intervals on the Kobe plot), there is 77.1% probability that the bigeye grenadier stock was not overfished ($B > B_{MSY}$) and not experiencing overfishing ($F < F_{MSY}$) in 2019 (green area on the Kobe plot). If we consider the fishing pressure only, as this is something that we can regulate, the cumulative probability of stock not being subjected to overfishing in 2019 is 86.5% (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} = 1,065 t, with the corresponding *MSY* = 99 t. In 2000-2006 catches were above the estimated median MSY, leading to a decline in bigeye grenadier biomass, although never below the B_{MSY} (Figure 4). Since 2007 catches have been below the MSY in each year, therefore the biomass was estimated to be slowly increasing and will continue to do so if catches remain at current levels, considering that the surplus production is larger than the removals by the fishery.

It is important to note that parameter and stock status estimates in the current assessment are 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 for the base-case model.

Parameter	median	95% CI
K	2,228 t	1,303 - 4,793 t
r	0.165	0.058 - 0.464
B_{1997}	1,899 t	990 - 3,668 t
B_{2019}	1,303 t	501 - 2,949 t
B_{1997}/K	0.884	0.624 - 1.033
B_{2019}/K	0.643	0.289 - 0.932
MSY	99 t	47 - 225 t
B_{MSY}	1,065 t	623 - 2,291 t
F_{MSY}	0.093	0.033 - 0.26
B_{2019}/B_{MSY}	1.344	0.605 - 1.951
F_{2019}/F_{MSY}	0.446	0.141 - 1.661

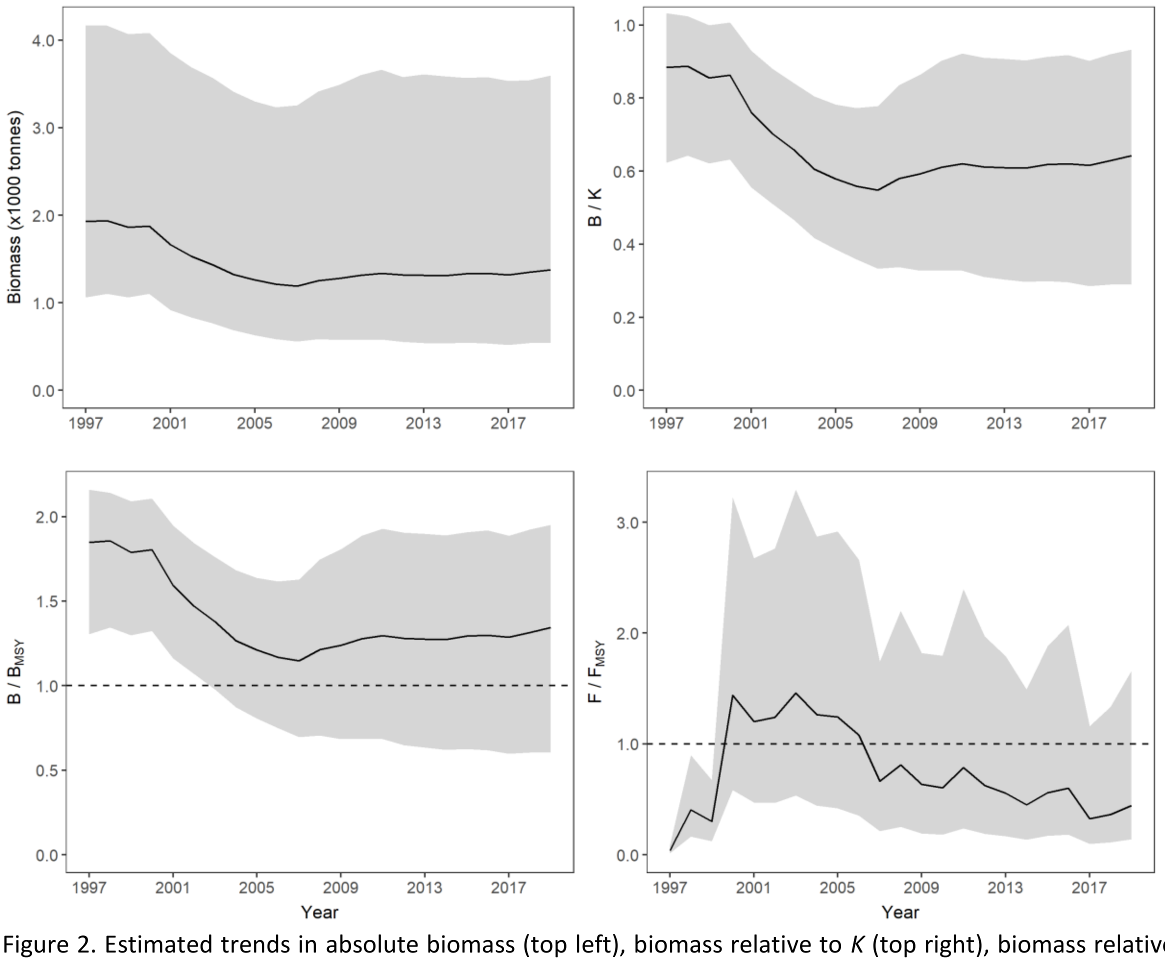

Figure 2. Estimated trends in absolute biomass (top left), biomass relative to *K* (top right), biomass relative to B_{MSY} (bottom left) and fishing mortality relative to F_{MSY} (bottom right) for the base-case model. Solid lines are medians and shaded areas denote 95% confidence intervals.

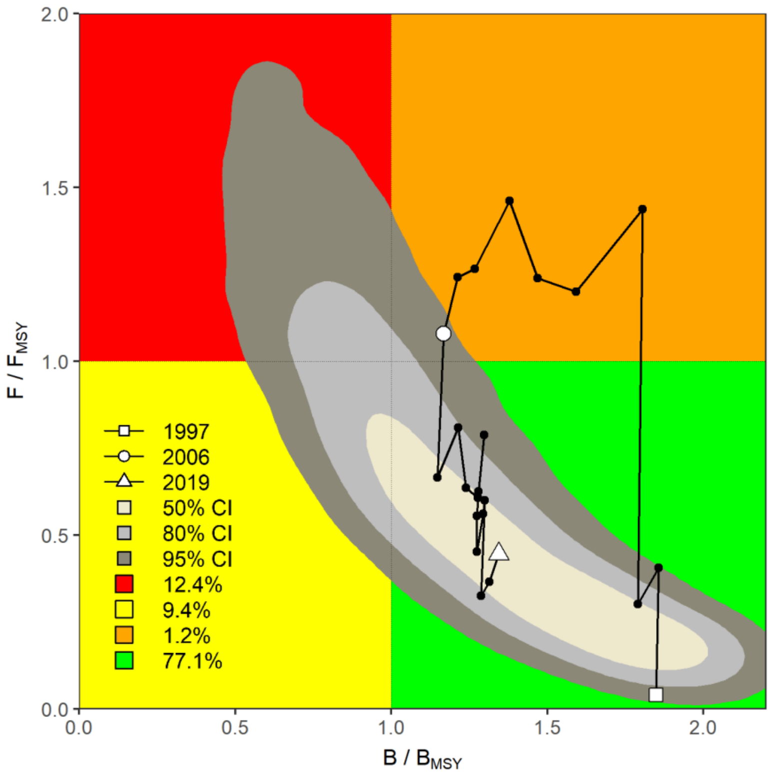

Figure 3. Kobe phase plot showing estimated trajectory of B/B_{MSY} and F/F_{MSY} for the bigeye grenadier stock in 1997-2019. Grey shaded areas denote the 50%, 80%, and 95% credibility intervals for the last assessment year. The probability of the last year estimate falling within each quadrant is indicated in the figure legend.

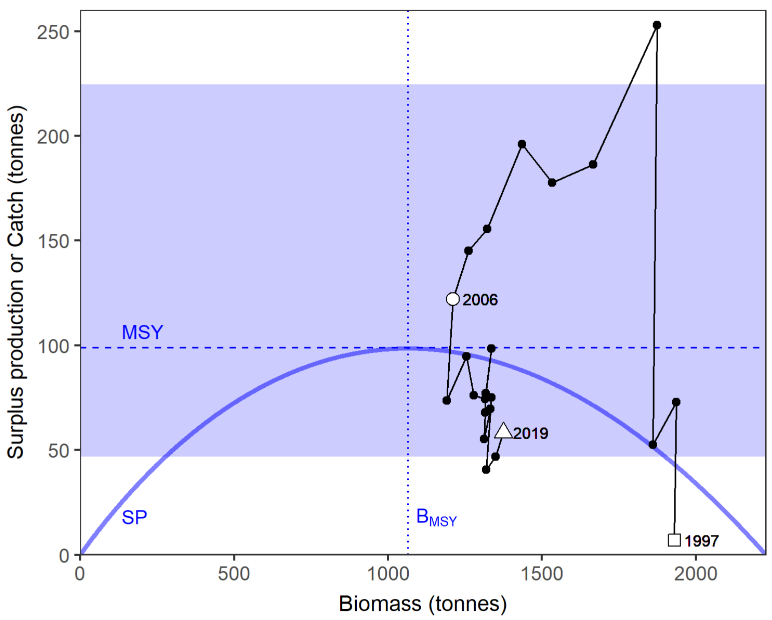

Figure 4. Surplus-production phase plot showing estimated Pella-Tomlinson surplus production curve *SP* (solid blue line) and catch/biomass trajectory for the bigeye grenadier stock in 1997-2019 (black line). Catches on the *SP* curve would maintain the biomass, catches above the curve will shrink future biomass, and catches below the curve allow future biomass to increase. Year 2006 (circle) 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% confidence intervals of the *MSY*.

3.2. Retrospective analysis

The retrospective analysis was done by successively removing one to six final years of data from the base-case model and rerunning the analysis. This allowed us to evaluate whether there were any strong changes in model results based on data availability. All six runs produced similar estimates as the base-case model, and no systematic trend in departures from the base-case model was evident, providing a degree of confidence in the predictive capabilities of the model (Figure 5).

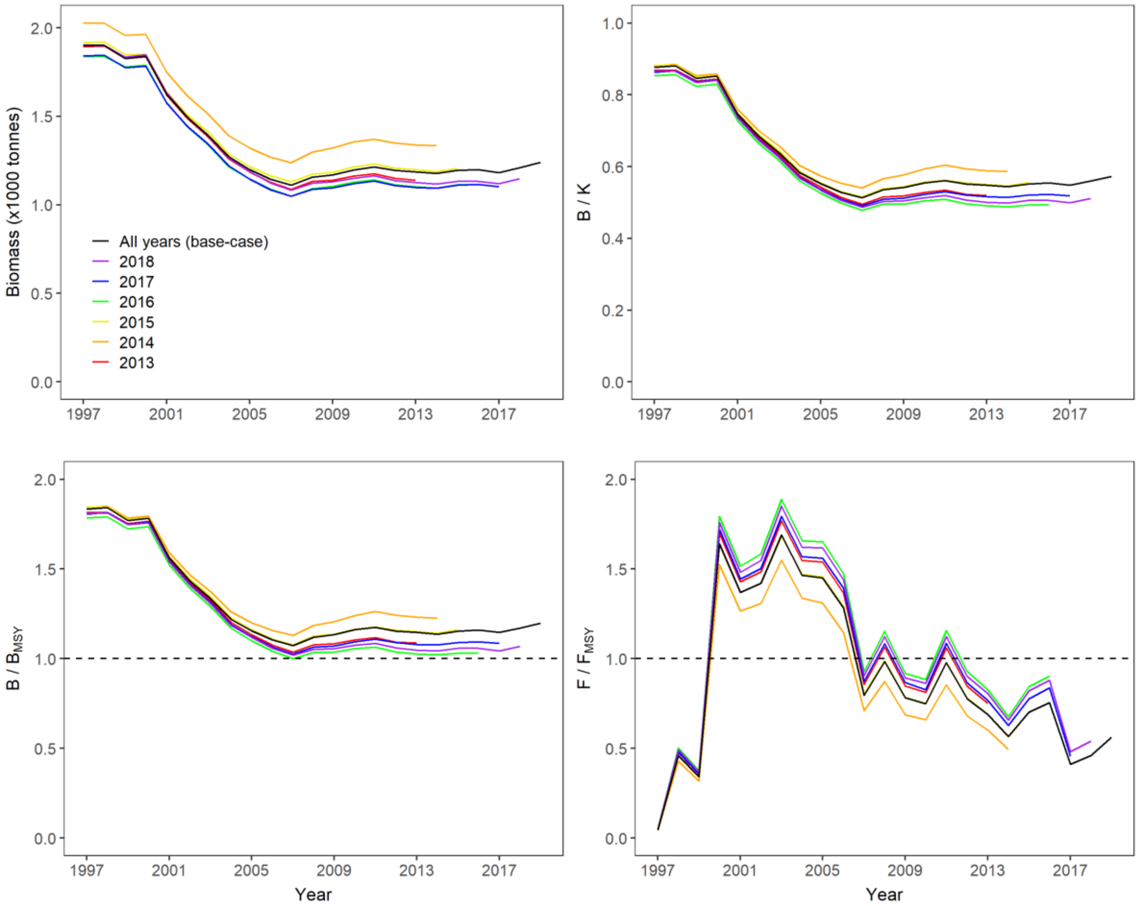

Figure 5. Estimated trends in biomass, *B/K*, B/B_{MSY} and F/F_{MSY} for the base-case model (black line) and six retrospective model runs. The numeric label indicates the year up to which individual retrospective model was run (inclusive).

3.3. Sensitivity analysis

Priors for key estimated parameters need to be specified before JABBA model can be run. Priors used in the base-case scenario are given in the methods section, and here we explored the effect of different prior settings of *K* and *r* on the model outcomes. Additionally, we tested the effect of using different values of Pella-Tomlinson shape parameter *m* in the model; it should be noted that *m* was not specified as a prior and estimated by the model, but instead entered as a user-defined fixed input value.

In the first sensitivity test we analysed the model outcomes when different mean values of the lognormal prior for carrying capacity *K* were used. Specifying different prior values for *K* had relatively small effect on the model estimates of *K* and biomass (higher priors leading to higher estimates and vice versa), and even less effect on estimates of *B/K*, B/B_{MSY} and F/F_{MSY} trends (Figure 6). The range of tested *K* priors was quite wide (3,000 - 20,000 t), but none of these values significantly altered the assessment outcomes, indicating a low model sensitivity to the assumptions about *K*.

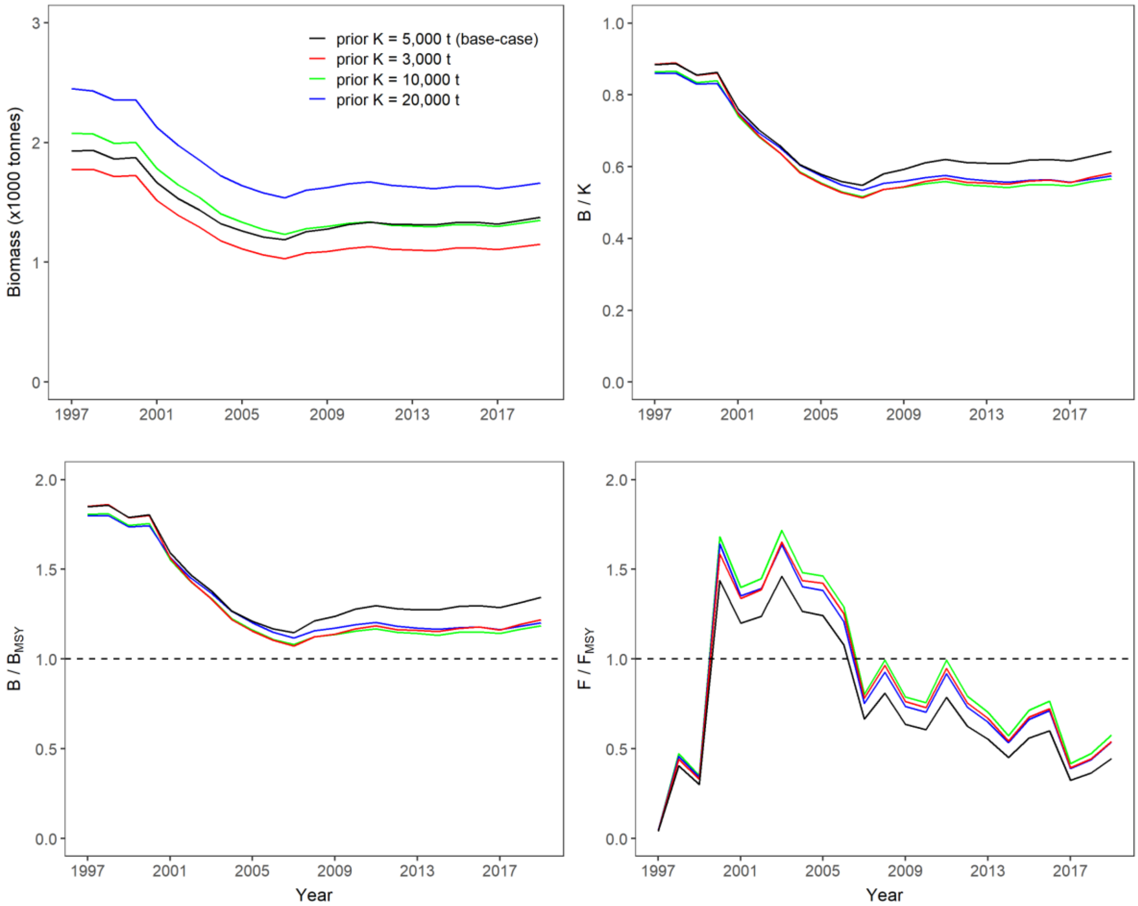

Figure 6. Estimated trends in biomass, *B/K*, B/B_{MSY} and F/F_{MSY} for the base-case model (black line) and three alternative model runs with different assumed priors for *K*.

In the second sensitivity test we analysed the model outcomes when different priors for intrinsic population growth rate *r* were used. We used two forms of priors: in the base-case model and two alternative models *r* was defined as range of values, corresponding to broad species resilience categories proposed by Froese et al. (2017) (Table 3). However, same 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, independent of these categories. Following this advice, for the third alternative model we defined *r* by lognormal mean and *sd* estimated using an R package *FishLife*, release 2.0 (available online at (https://github.com/James-Thorson/FishLife/releases/tag/2.0.0). The *FishLife2.0* can produce *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) and spawning-recruitment relationship data series from the *RAM Legacy Database* (Ricard et al. 2012). A full description of the *FishLife2.0* model is available in Thorson (2019). In our case, estimate of *r* was provided at *Macrourus* genus level, as data specific for *M. holotrachys* were not available.

Specifying different prior values for *r* had very high effect on the model estimates of *r* (i.e. model estimates were almost the same as provided priors), indicating that the actual CPUE and catch data were not very informative when fitting the model, and the prior information heavily influenced the outcomes. This is far from ideal situation, and is most likely a consequence of difficulties faced by surplus production models in estimating stock productivity from lightly exploited stocks, and/or from CPUE time series lacking contrast (Froese et al. 2017, Haddon 2011). There is not much that can be done to change this, and the most reasonable course of action is to utilize the best possible prior estimates of *r*. Different priors tested in this sensitivity analysis led to a substantially different estimates of stock biomass, *B/K*, B/B_{MSY} and F/F_{MSY} trends (Figure 7), highlighting the model sensitivity to assumptions about *r*. However, it should be noted that we tested a very wide range of prior *r* values in order to estimate their effect on the model outcomes, which does not mean that they are all equally realistic (e.g. it is unlikely that the bigeye grenadier is a *medium* resilience species). Since the life history data on this species is very scarce, using *FishLife2.0* to produce prior *r* based on the data available for other species of genus *Macrourus* seems like a reasonable approach. This prior produced similar stock status estimates as the *low* resilience prior used in our base-case scenario and the last years' assessment and should be considered as a preferred approach in future assessment.

Table 3. Description of the alternative models' assumptions about intrinsic population growth rate *r*.

Model run	*r* prior	Description
base-case	0.05 - 0.5*	*r* corresponding to '*low*' species resilience (Froese et al. 2017)
prior r = medium	0.2 - 0.8*	*r* corresponding to '*medium*' species resilience (Froese et al. 2017)
prior r = very low	0.015 - 0.1*	*r* corresponding to '*very low*' species resilience (Froese et al. 2017)
prior r = FishLife	μ = 0.124, *sd* = 0.164	*r* estimated for genus *Macrourus* using *FishLife2.0* R package (Thorson 2019)

* range is converted into a lognormal prior μ and *sd* in the model

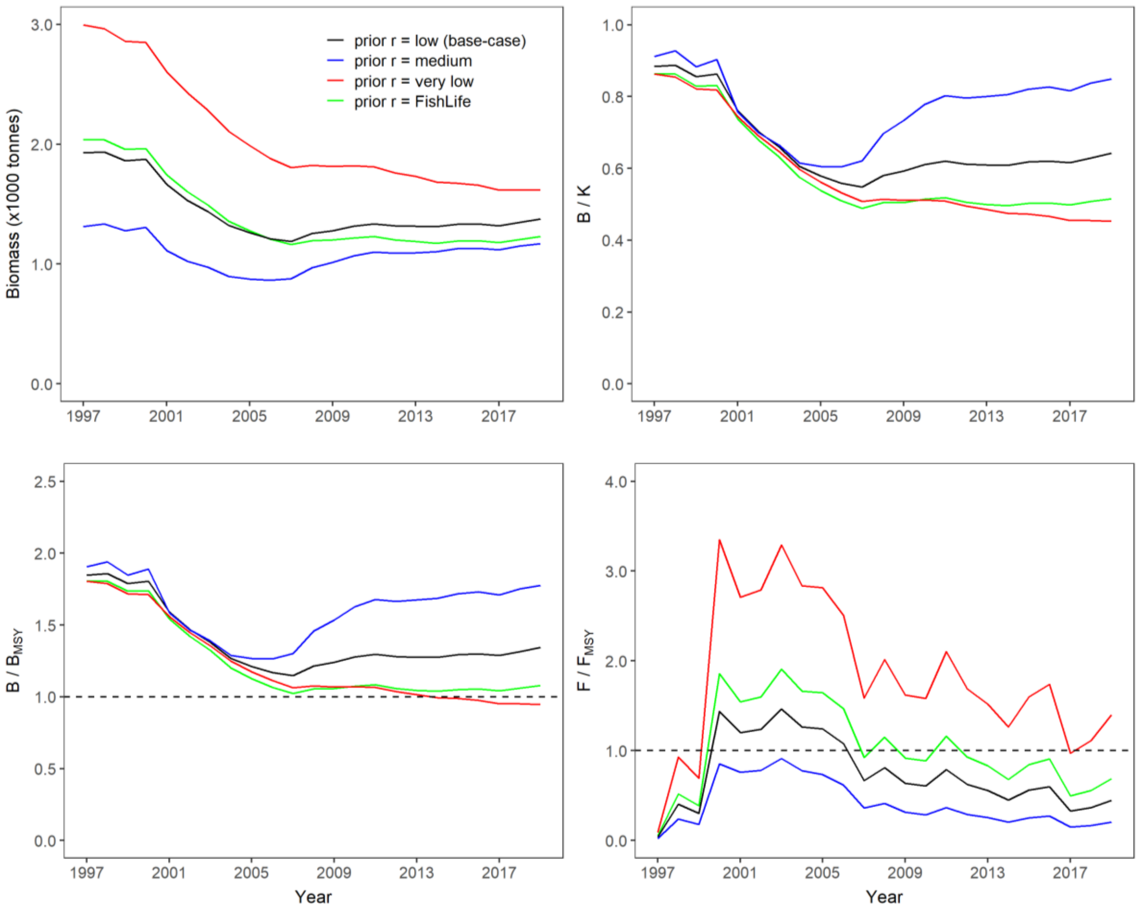

Figure 7. Estimated trends in biomass, *B/K*, B/B_{MSY} and F/F_{MSY} for the base-case model (black line) and three alternative model runs with different assumed priors for *r*.

In the final sensitivity test, we analysed the model outcomes when different values of Pella-Tomlinson shape parameter *m* are used. In our base-case model we assumed surplus production is maximized at B_{MSY}/K = 0.478 (as reported by Thorson et al. (2012) for taxonomic order Gadiformes) and converted this into *m* = 1.785. In our alternative models we tested another value reported by the same authors, but pertaining to the spawning stock biomass, and the JABBA default value for Pella-Tomlinson curve, used in the last year's assessment (Table 4). Overall, sensitivity of the model to the alternative *m* values was low, with substantially different assumptions leading to similar outcomes (Figure 8). Nevertheless, one important qualitative difference is that the model with the lowest *m* value (as used in the last year's assessment) estimated barely any overfishing (F/F_{MSY} > 1) during the time series. It is of note that the value used in our base-case scenario produces the most conservative results, as it assumes that the maximum surplus production occurs at higher biomass compared to the alternative models.

Table 4. Description of the alternative models' assumptions about Pella-Tomlinson shape parameter *m*.

Model run	*m* prior	Description
base-case	1.785	*m* corresponding to maximum surplus production at B_{MSY}/K = 0.478 (Thorson et al. 2012, supplementary data)
m = 1.458	1.458	*m* corresponding to maximum surplus production at B_{MSY}/K = 0.439* (Thorson et al. 2012)
m = 1.188	1.188	*m* corresponding to maximum surplus production at B_{MSY}/K = 0.4 (Model default)

* in this case B_{MSY} and *K* pertain to the spawning stock biomass, instead of total biomass

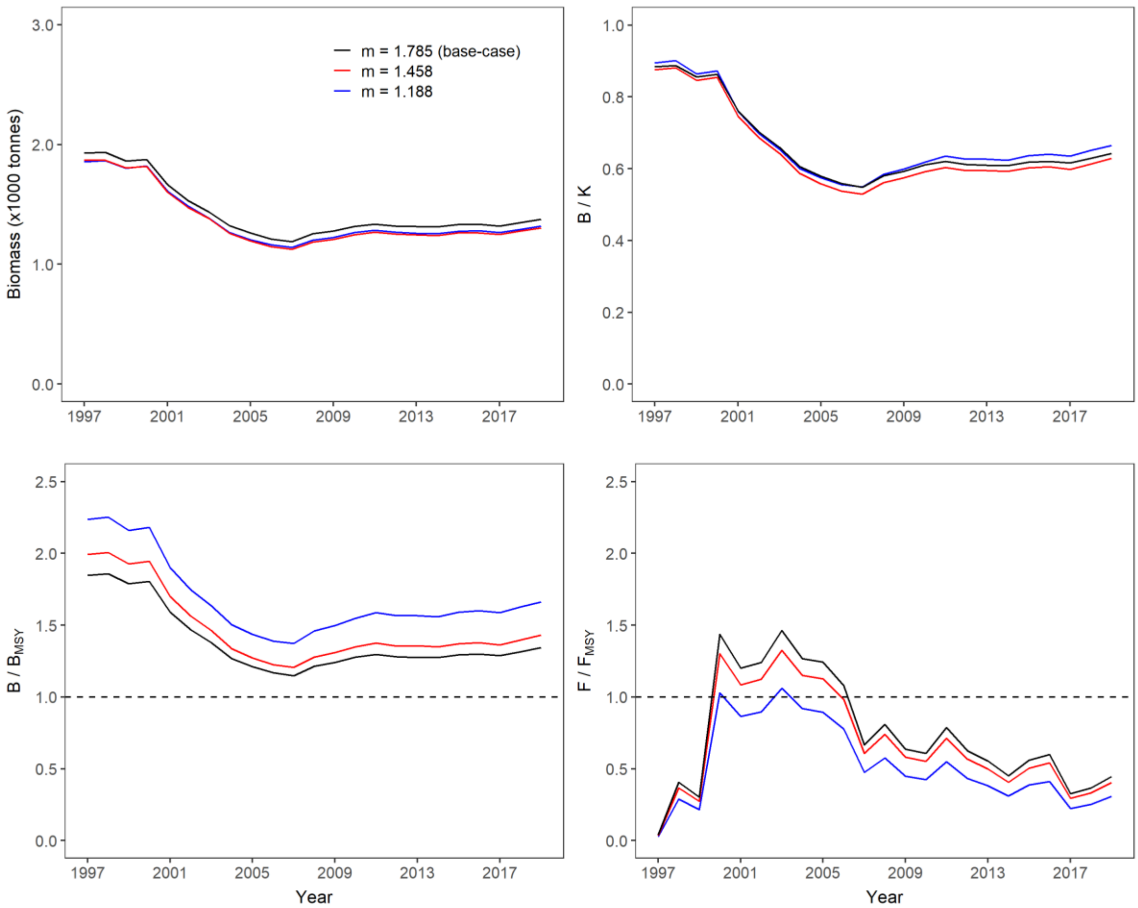

Figure 8. Estimated trends in biomass, *B/K*, B/B_{MSY} and F/F_{MSY} for the base-case model (black line) and two alternative model runs with different assumed value of Pella-Tomlinson shape parameter *m*.

4. Discussion

The first bigeye grenadier stock assessment in Falkland Islands waters was done in 2019, by fitting JABBA model to the catch data for the period 1997-2018 and the umbrella-system longline CPUE data for 2008-2018 (Farrugia and Winter 2019). JABBA belongs to the surplus production models (SPMs), which 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 limitations 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 the JABBA model appropriate for the level of information we have about bigeye grenadier (no reliable age-structured data is available) and used it in the current assessment as well. However, compared to last year we have introduced some changes to the input data and priors used in the analysis. The most substantial decision regarding the input data was inclusion of the Spanish-system longline CPUE data for the period 1997-2007 in the analysis. This informed the model about the stock abundance in the early years of the fishery, and notably reduced the uncertainty of the estimates; successively rerunning the model now produced more consistent outcomes, coupled with narrower confidence intervals on most of the estimated parameters. Other notable changes from the previous assessment, like excluding the non-Falkland vessels from the umbrella-system CPUE analysis and using the Pella-Tomlinson shape parameter *m* suggested for order Gadiformes by Thorson et al. (2012), had less impact on the model outcomes.

The current assessment produced somewhat less optimistic estimates of the bigeye grenadier stock status then the previous one, but the stock was nevertheless estimated to be healthy, with low probability of being overfished or experiencing overfishing. Since the onset of the umbrella-system fishery in 2007, annual bigeye grenadier catches fluctuated between 41 and 98 t (mean = 70 t) and have never surpassed the estimated MSY of 99 t, adding a measure of confidence that the stock was exploited in a sustainable manner.

The sensitivity analysis showed that the prior for carrying capacity *K*, and the value of Pella-Tomlinson shape parameter *m*, have small effects on the model outcomes, while the retrospective analysis showed that the model outcomes are not overly influenced by the most recent data; together, these findings indicate the model robustness and reliability for future projections. However, model sensitivity to the prior for the intrinsic population growth rate *r* 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 current 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 best possible prior estimates 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 can provide estimates of *r* for higher taxonomic levels, based on the data available for related species (e.g. at genus level).

5. Conclusion and recommendations

The results presented in this report indicate that the bigeye grenadier stock in Falkland Islands waters is currently not overfished nor experiencing overfishing, that it has been exploited sustainably since 2007, and that the recent catch levels could continue in the future without endangering the population. Our recommendations regarding its future assessment and management are:

- Stock assessment using JABBA model should be continued in the future, and conducted annually. We consider the model appropriate to the level of information available for bigeye grenadier, although some of its limitations have been outlined. More reliable assessment of stock status might be obtained using an age-structured model; this requires collecting more extensive data on the life history (e.g. age estimates) and stock structure of bigeye grenadier in Falkland Islands waters.
- R package *FishLife2.0* proved useful in producing informative *r* prior for the assessment, by supplementing the life history knowledge gap about bigeye grenadier with data available for the related species of the same genus. Therefore, its utilization in the future assessment is advised.
- Close monitoring of the bigeye grenadier bycatch should continue in order to ensure that the annual catch does not surpass estimated MSY; if the cumulative catch approaches MSY, it may be possible for the fishery to decrease the bycatch rate of this species by avoiding its CPUE 'hot spots' (Figure 1).

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Appendix 1. CPUE standardization

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Spanish- and umbrella-system longline CPUE was standardized using generalized linear model (GLM), with a log link function and normally distributed error (Maunder and Starr 2003, Maunder and Punt 2004). Individual longline haul CPUE values (expressed as bigeye grenadier catch in kg per 1000 hooks for Spanish-system, and per umbrella for the umbrella-system) were the response variable, and the explanatory variables considered in the model are given in Table A.1.

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

Explanatory variables		Variable type
Spanish-system	umbrella-system	
Year*	Year*	Categorical
Month*	Month*	Categorical
Region	Region*	Categorical
Depth*	Depth*	Continuous
Soak-time*	Soak-time	Continuous
Toothfish-catch	Toothfish-catch	Continuous
Vessel*	-	Categorical
-	Hooks-per-umbrella	Categorical
-	Umbrella-spacing	Categorical

* Variables which were found statistically significant and included in the final model.

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 within the Falklands conservation zone: south of 53.5° S (Burdwood Bank spawning area), and north of 53.5° S. *Toothfish-catch* variable is the weight of the caught toothfish per longline set (in kg). *Depth* variable is the average fishing depth at which longline is set (in meters). *Soak-time* was calculated in hours-per-hook for Spanish-system longline, and hours-per-umbrella for the umbrella-system. *Vessel* variable was excluded from the umbrella-system longline CPUE standardization, as the only two vessels used in the assessment never fished concurrently in the same year, making the *Vessel* and *Year* effects indistinguishable. The umbrella-system had two additional variables: *Umbrella-spacing* (which was changed from 40 m between umbrellas to 22 m between umbrellas after November 2014) and 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).

Year effect is the quantity of interest so it must be a part of the final CPUE model, and the remaining explanatory variables were added to the *Year* by forward stepwise selection, and included in the final model only if they improved R^2 by at least 0.5%.

Fitting GLM to the Spanish-system data showed that the explanatory variables *Year*, *Month*, *Depth*, *Soak-time* and *Vessel* are statistically significant, and the model explained 40.1% of the overall variation in CPUE. Standardized and unstandardized CPUE time series showed very similar trends, with overall higher and more variable catches in the first years of fishery, followed by the lower, but relatively steady values in the late years (Figure A.1).

Fitting GLM to umbrella-system data showed that the explanatory variables *Year*, *Month*, *Region* and *Depth* are statistically significant, and the model explained 30.1% of the overall variation in CPUE. Comparison of the umbrella-system standardized and unstandardized annual CPUE indices is shown in Figure A.2. They exhibit a similar trend, although the standardized indices have noticeably wider confidence intervals. The most prominent feature of both unstandardized and standardized umbrella-system data is a significantly lower CPUE in 2007; this is likely related to the facts that 2007 was the first year of umbrella-system trials, and that this fishing gear /technique was used only in the second part of the year, possibly leading to an uncharacteristic fishing practice.

The distribution of the residuals from the GLM fit to Spanish- and umbrella-system data was consistent with the assumption of normality, although a few larger residuals were noticed for the Spanish-system data (Figure A.3).

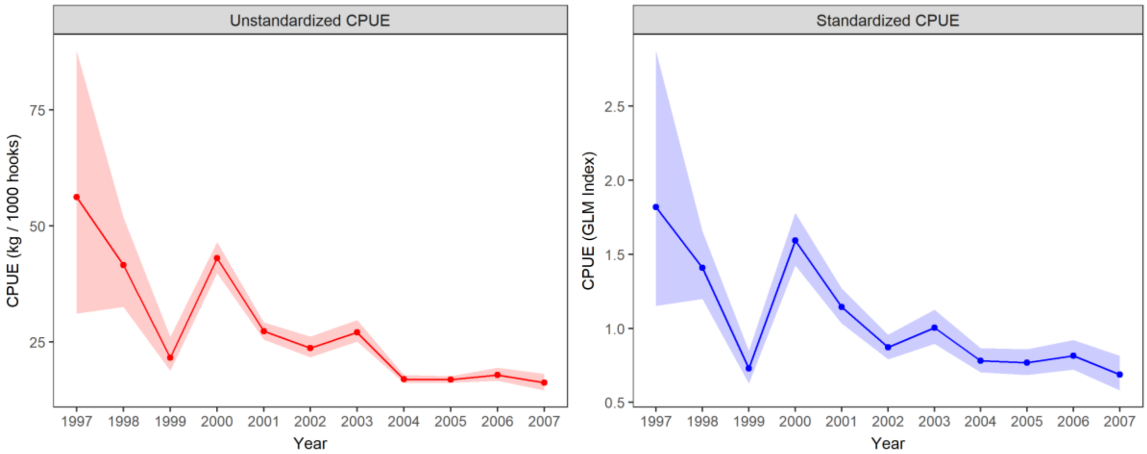

Figure A.1. Spanish-system longline CPUE time series: unstandardized CPUE expressed as toothfish catch in kg per 1000 hooks (left), and standardized CPUE indices from the GLM (right); shaded areas correspond to 95% confidence intervals.

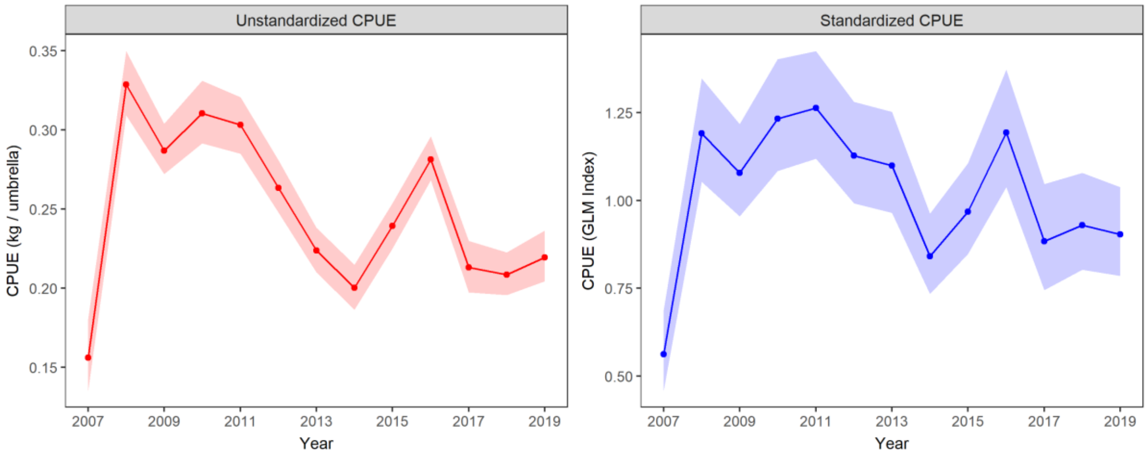

Figure A.2. Umbrella-system longline CPUE time series: unstandardized CPUE expressed as toothfish catch in kg per umbrella (left), and standardized CPUE indices from the GLM (right); shaded areas correspond to 95% confidence intervals.

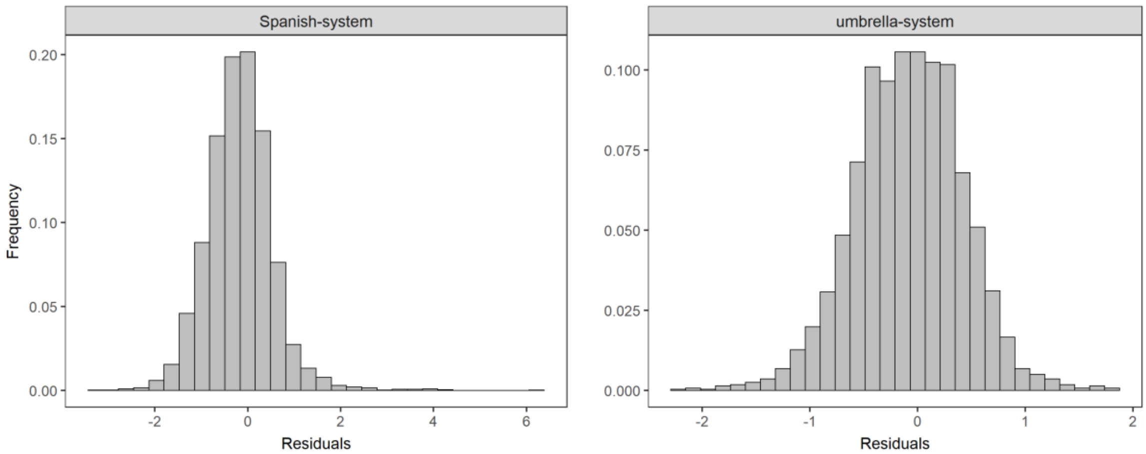

Figure A.3. Density histograms of residuals from the generalized linear model (GLM) fitted to the Spanish- and umbrella-system longline CPUE data.

Appendix 2. Input parameters

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Table A.2. Total bigeye grenadier removals for combined logline fishery, and standardized CPUE indices with standard errors for Spanish- and umbrella-system longline fisheries.

Year	Removals (tonnes)	CPUE indices		CPUE standard errors	
		Spanish-system	umbrella-system	Spanish-system	umbrella-system
1997	7.1	1.817	-	0.228	-
1998	73.0	1.408	-	0.081	-
1999	52.4	0.730	-	0.076	-
2000	252.9	1.592	-	0.056	-
2001	186.3	1.145	-	0.051	-
2002	177.6	0.871	-	0.048	-
2003	196.1	1.003	-	0.057	-
2004	155.6	0.781	-	0.052	-
2005	145.1	0.768	-	0.056	-
2006	122.1	0.815	-	0.061	-
2007	73.8	0.688	0.562	0.085	0.101
2008	94.8	-	1.191	-	0.062
2009	76.1	-	1.078	-	0.061
2010	74.5	-	1.232	-	0.064
2011	98.4	-	1.263	-	0.060
2012	77.0	-	1.127	-	0.064
2013	67.9	-	1.099	-	0.065
2014	55.2	-	0.840	-	0.068
2015	69.7	-	0.968	-	0.066
2016	75.1	-	1.193	-	0.070
2017	40.6	-	0.883	-	0.085
2018	46.8	-	0.930	-	0.074
2019	58.4	-	0.903	-	0.069