

2021 Alternative Stock Assessments Report

Patagonian toothfish (*Dissostichus eleginoides*)



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15 September 2022



SA - 2021 - TOO

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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.

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For citation purposes this publication should be referenced as follows:

Skeljo F, Winter A. 2022. 2021 Alternative stock assessment for Patagonian toothfish (*Dissostichus eleginoides*). Fisheries Report SA-2021-TOO. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 21 p.

Distribution: Public Domain

Reviewed and approved by:



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Date: 15 September 2022

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Summary

1. This report provides an updated alternative stock assessment of Patagonian toothfish in Falkland Islands waters, using data through year 2021. Assessment was done using a Bayesian surplus production model framework JABBA (Winker *et al.* 2018).
2. Overall, the model showed a negative stock status trend in ~1995-2005, which reverted to a levelled trend following the introduction of the TAC system in 2006. The estimated current biomass B_{2021} is 5.1% above B_{MSY} , and the current fishing mortality F_{2021} is 26.9% below F_{MSY} . Since 2006, annual catches have fluctuated narrowly around the estimated maximum sustainable yield (MSY) of 1,507 t, indicating sustainable exploitation of the stock.
3. JABBA produced lower estimates of absolute biomass, relative biomass and MSY compared to the CASAL assessment, but the model still suggested that the stock was exploited sustainably in recent years, with total fishery removals lower than the surplus production.
4. The age-structured model in CASAL remains a preferred approach to toothfish stock assessment in Falkland Islands as it integrates a wider range of data, i.e. takes explicitly into account somatic growth, reproduction, lagged effects of recruitment, natural mortality and multiple fishery-specific selectivities.
5. Findings of this report provide insight into the usefulness of the JABBA data-moderate approach for other species /stocks managed by FIFD, where data limitations prevent the use of integrated age-structured assessment (e.g. rock cod *Patagonotothen ramsayi*).

1. Introduction

Patagonian toothfish (*Dissostichus eleginoides*) is a large notothenioid fish found on the shelves and slopes of South America and around the sub-Antarctic islands of the Southern Ocean. It is a long-lived species (>50 years), which initially grows rapidly in shallow shelf areas, before undertaking an ontogenetic migration into deeper waters (Collins *et al.* 2010). In Falkland Islands waters, Patagonian toothfish spawn on the slopes of Burdwood Bank at ca. 1000 m depth with a minor peak in May, and a major peak from July to August (Laptikhovsky *et al.* 2006). The eggs, larvae, and small juveniles (<10 cm TL) develop and grow in epipelagic layers of the Falkland Current, with early juveniles of 10-12 cm TL (<1 year old; Lee 2017) occurring on the Patagonian shelf at depths ~100 m (Arkhipkin and Laptikhovsky 2010). Immature toothfish remain on the shelf for 3-4 years, and then, upon reaching 60-70 cm TL, they migrate into deeper waters over the Patagonian slope and deep-water plains at depths >1000 m (Arkhipkin and Laptikhovsky 2010).

The Falkland Islands toothfish longline fishery began in 1992 as an exploratory fishery and became an established fishery in 1994 (Laptikhovsky and Brickle 2005). Fishing was traditionally conducted using the Spanish system of longlining (although in the beginning a few vessels used the *Mustad Autoline* system), 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. The umbrella floats above the hooks whilst the gear is on the seabed, but when the gear is recovered, it folds over the hooks and hooked fish, protecting it from depredation (Brown *et al.* 2010). Following initial trials in 2007, since 2008 the umbrella system has been adopted by all vessels operating in the Falkland Islands longline fishery.

Although longlining is the only fishery targeting toothfish in Falkland Islands waters, notable quantities are taken as a bycatch in finfish and calamari trawl fisheries. In finfish fishery toothfish is a commercially valuable bycatch, while in calamari fishery it is usually discarded, due to the small size of the specimens (20-40 cm TL). These fisheries exploit different parts of the toothfish population in different areas: longlining occurs on the slope and in deep water, finfish trawling on the shelf primarily

north and west of the Falkland Islands, and calamari trawling on the shelf south and east of the Falkland Islands (Figure 1).

Management of the Falkland Islands toothfish fishery has relied on an integrated age-structured stock assessment implemented in CASAL software (Bull *et al.* 2012) since 2012. Although CASAL has become a standard approach to toothfish stock assessment in the Southern Ocean (Earl and Readdy 2021a, 2021b; Ziegler 2021; Massiot-Granier *et al.* 2021a, 2021b; Grüss *et al.* 2021), examining alternative models can provide a useful comparison (Cadrin and Dickey-Collas 2015), and either increase our confidence in CASAL outputs, or prompt re-evaluation of its assumptions. The current report provides an updated stock assessment of toothfish in Falkland Islands waters using a Bayesian surplus production model framework JABBA (Winker *et al.* 2018), using data through year 2021. The JABBA outputs are compared with the results of integrated age-structured toothfish stock assessment done in CASAL for year 2021 (Skeljo and Winter 2022).

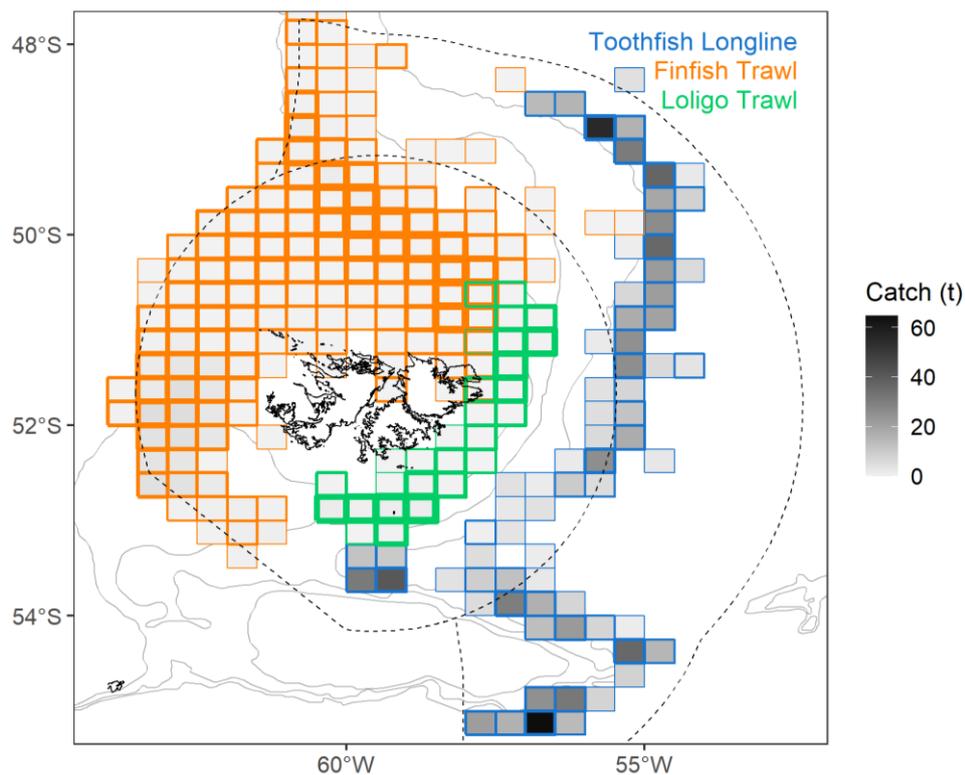


Figure 1. Spatial distribution of toothfish catch and effort by fisheries in 2021. Thickness of grid lines is proportional to the number of vessel days; greyscale is proportional to the toothfish catch biomass in tonnes.

1.1. Stock structure and assumptions

Many questions still remain surrounding the stock structure of Patagonian toothfish in the southwest Atlantic. On a larger spatial scale, there is well-documented genetic differentiation between toothfish found on the Patagonian Shelf and around South Georgia and South Sandwich Islands (Shaw *et al.* 2004; Rogers *et al.* 2006; Canales-Aguirre *et al.* 2018, Arkhipkin *et al.* 2022). However, toothfish population structure across the Patagonian Shelf is less certain in the context of where it fits into a possible stock structure continuum, extending across possible sympatric discrete, spatially complex (e.g. metapopulation or source-sink) and panmictic population structures (Ciannelli *et al.* 2013, Hawkins *et al.* 2016, Cadrin 2020).

The existence of separate spawning populations south of Diego Ramirez Islands in Chilean waters and the eastern Burdwood Banks in Falkland Islands waters have been identified (Laptikhovskiy *et al.* 2006, Arana 2009); with otolith microchemistry analysis suggesting that larvae settling on the

Falkland Shelf originate from a combination of these two spatially distinct areas (Ashford *et al.* 2012). Annual spawning migrations have been inferred for Patagonian toothfish from foraging areas on the Patagonian shelf and slope located in the north and east of the Falkland Islands to spawning areas on the Burdwood Bank (Laptikhovsky *et al.* 2006). However, early satellite-tagging work undertaken in Falkland Islands waters showed high site fidelity and limited movement of adult toothfish (Brown *et al.* 2013), leading to the conclusion that the part of the stock targeted by the longline fishery (primarily older, adult individuals) is most likely confined to Falkland Islands waters.

Results from a recent genetic study suggests two independent evolutionary lineages within the '*D. eleginoides*' complex and their differentiation into two distinct taxonomic entities as separate species based on genomic and morphometric data (Arkhipkin *et al.* 2022). Results of Arkhipkin *et al.* (2022) also implied a complex level of restricted connectivity between local populations of Patagonian toothfish, specifically between fish captured from (1) southern Chile and the Falkland Islands; and (2) Falkland Islands and the high seas (North of Falkland Islands), illustrating the Falkland Islands as an intermediate zone of mixing.

Otolith shape analyses revealed high site fidelity across their distribution, and possible stock separation among early adult fish within localised areas on the Patagonian Shelf (Lee *et al.* 2018). Based on these results limited mixing appeared to occur between southern Chile and Burdwood Bank spawning areas; and feeding grounds off the continental slope and deep-sea plains to the north-east of the Falkland Islands (Lee *et al.* 2018).

Analyses of abundance distributions were undertaken to assess the spatial-temporal persistence (stability) of toothfish nursery area hotspots around the Falkland Islands and to describe their subsequent ontogenetic migration pathways into their adult deep-water habitats (Lee *et al.* 2021). Results indicate spatially discrete hotspots exhibiting high temporal variability. This variability is defined through oceanographic influence that drives larval dispersal and survival on the Shelf. Juvenile toothfish appear to follow persistent ontogenetic migrations, linking distinct recruitment areas with their respective component of the adult population on the Patagonian slope. Evidence of mixing among cohort groups during their ontogenetic migration into deep-sea adult habitats was limited, reflecting a mixed population based on oceanographically defined egg and larval dispersal.

A large-scale tag-recapture program using conventional and satellite tags was established in June 2016 (Randhawa and Lee 2016) to improve understanding of the movement patterns of toothfish within the region; and to quantify the exchange between adults on the northern and eastern slope, and the spawning grounds on the Burdwood Bank (and possible southern Chile). Analyses based on results over the first 6 years of data were used to elucidate the movement patterns as well as the extent that these are driving connectivity during the adult life-history stages of Patagonian toothfish in the region (Lee *et al.* 2022). Tagging and recapture results indicated that the majority of individuals (78%) displayed high site fidelity (<50 km). However, 10% of individuals undertook long-distance movements across oceanographic and physical boundaries. These movements were undertaken by large (>120 cm) fish inhabiting the slope and deep-sea plains (north of 52°S) moving southward (direction = 150 - 240°) to spawning areas on the Burdwood Bank, North Scotia Ridge and southern Chile.

Otolith microstructure and trace element analysis were applied to infer time-resolved elemental profiles that reflect the early ontogeny of juvenile Patagonian toothfish from key nursery areas on the Patagonian Shelf (Lee 2022). Results revealed significant ontogenetic shifts in elemental profiles across the early life-history of Patagonian toothfish. From these, key biological benchmarks were identified, including (i) the hatch date distribution (mid-September to late October; mean = 3 October); (ii) the dispersal period of pelagic larvae until their entry onto the Patagonian shelf (0 to 40 days post-hatch); (iii) the transition phase from the shelf extent to inshore waters (<100 m depth; 40 to 75 days post-hatch); (iv) settlement into a demersal habitat (100 days post-hatch); and (v) subsequent migration into juvenile nursery areas (<150 m depth; 120 days post-hatch). Finally, these benchmarks were shown to occur significantly earlier in fish sampled in discrete nursery areas to the west of the Falkland Islands.

Overall, the results provide important considerations in terms of the complexity and protracted nature of early life-history stages, the reliance of recruitment upon stable environmental patterns and the potential for a mixed stock origin on the Patagonian Shelf. Results highlighted further monitoring and research priorities with a focus on the identification of reproductive potential, egg and larval dispersal pathways and settlement patterns of stock contingents to inform the dynamics of mixed stock origins across the Patagonian region.

Research on the stock structure of Patagonian toothfish on the Patagonian Shelf reveals complex patterns. High levels of uncertainty remain in terms of understanding the extent of connectivity during the early life-history phases of egg and larval dispersal. Further, evidence of connectivity across the region through the active migration of adults appears to occur on a relatively small scale (<8%). Current results demonstrate that the stock structure arising from the retention of juveniles across the Falklands Shelf remains discrete (within the Falkland Islands Conservation Zone) until adult life-history stages. Therefore, considering the currently available information, for the purpose of this assessment we assumed that there is one discrete toothfish stock present in Falkland Islands waters.

2. Methods

2.1. Data

Three datasets were used as information for the JABBA stock assessment model: total annual removals by combined fisheries (1987-2021) and catch-per-unit-of-effort (CPUE) time series for Spanish- (1996-2007) and umbrella-system (2007-2021) longline fisheries.

CPUE

Although CPUE data were available for all four fisheries (Spanish longline, umbrella longline, finfish trawl, calamari trawl), only longline CPUE were used as a relative abundance index. This is motivated by the inconsistency of the toothfish CPUE in trawl fisheries, where this species is not targeted, and its bycatch may change due to factors other than stock abundance (e.g. fisheries are switching targets or areas). The longline CPUE data were treated separately for Spanish- and umbrella-system longline, according to the documented difference in the toothfish CPUE between these two fishing techniques (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. Also, in this period vessels that fished in Falkland Islands waters would sometimes report to FIFD their catches taken in other 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. Moreover, at least one of these vessels had restrictions imposed on its fishing practice (e.g. limit on the number of fishing days in the 'best' fishing grounds), which were not in place for the Falkland Islands vessel. All of this led to a conclusion that the CPUE would be a more representative as an index of abundance if only Falkland Islands vessels data were used. With a similar goal, data from 'tagging trips' and from longline sets at depths <600 m were removed from the analysis. Tagging trips were removed because part of the actual catch was not reported (corresponding to the tagged and released fish), leading to a biased, lower estimates of CPUE. Fishing in shallow waters was excluded because longlining is prohibited at depths <600 m, 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 toothfish 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 three distinct catch components: (a) reported catches in Falkland Islands waters, (b) catches taken by *Illegal, Unreported and Unregulated* (IUU) fishing from areas adjacent to Falkland Islands waters, and (c) catches lost to undetected whale depredation.

All reported toothfish catches taken in longline (targeted catch) and trawl fisheries (bycatch) were used, going back to 1992 and 1987, respectively.

IUU fishing is inherently difficult to estimate (Pitcher *et al.* 2002, Ainsworth and Pitcher 2005), and no reliable information specific to the Falkland Islands waters was found. Therefore, 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. 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 catches taken from the Falkland Islands stock (e.g. by foreign-licenced vessels fishing near the Falkland Islands waters) to be 5% of the reported toothfish catch in Falkland Islands waters. The same IUU data were used in the previous JABBA assessment (Skeljo and Winter 2021) and in the most recent CASAL assessment (Skeljo and Winter 2022).

Whale depredations are included in longline catch reports when they are evident as toothfish hauled up damaged or destroyed by bite-marks. However, toothfish taken entirely by whales before hauling are not seen and not accounted for in the catch reports. In order to quantify this cryptic depredation, Winter and Pompert (2016) developed a model-differencing algorithm between catches predicted from all observer-monitored longlines, and catches predicted only from observer-monitored longlines without sign of whale depredation. Models included parameters longline position, fishing depth, year, month, numbers of hooks and soak time. The model-difference could then be projected onto all commercial longlines to estimate the amount of toothfish lost. The algorithm has recently been revised by modelling Spanish-system and umbrella-system longline fishing separately, as for stock assessment, and by projecting the depredation ratios of the models rather than the models themselves, which improved the avoidance of outlier extrapolations.

The above-mentioned catch components (reported catches, IUU catches and whale depredation) were added together into total removals and used in the assessment model run.

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 surplus production was assumed maximized at $B_{MSY}/K = 0.4$, the default setting for the Pella-Tomlinson function and the same value used in the previous year's assessment. This ratio was converted into Pella-Tomlinson shape parameter $m = 1.188$, 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_{1987}/K) are stock-specific and were defined based on the expert knowledge of the stock status (K and B_{1987}/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 available at species level (*D. eleginoides*). 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 model parameters and management quantities of

interest (r , K , B_{1987}/K , B_{2021}/K , MSY , B_{MSY} , F_{MSY} , B_{2021}/B_{MSY} , F_{2021}/F_{MSY}) were 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. MCMC chains were investigated for evidence of non-convergence using trace plots, and single-chain convergence tests of Geweke (1992) and the stationarity and half-width tests of Heidelberger and Welch (1983) as implemented in the *coda* R package (Plummer *et al.* 2006).

To evaluate model goodness-of-fit, the residual patterns were inspected visually, and the Root-Mean-Squared-Error (RMSE) was calculated; a small RMSE (≤ 0.3) indicates a reasonable 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; $\mu = 0.143$, $sd = 0.105$	Used in the previous assessment (Skeljo and Winter 2021). Estimated at species level (<i>D. eleginoides</i>) using <i>FishLife2.0</i> R package (Thorson 2019)
K	log-normal; $\mu = 60,000$, $cv = 1$	Used in the previous assessment (Skeljo and Winter 2021); Defined to be roughly comparable with the prior used in CASAL assessment
B_{1987}/K	log-normal; $\mu = 1$, $cv = 0.1$	Used in the previous assessment (Skeljo and Winter 2021); Stock is assumed to have been nearly unexploited at this time (1987), based on the very low reported catches
σ_{proc}^2	inverse-gamma (4, 0.01) *	Model default
σ_{est}^2	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

Model diagnostics plots are given in [Appendix 2](#). The MCMC convergence 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.3).

The model fit to the standardized CPUE data was very good for both Spanish- and umbrella-system fisheries (Figure A.4). No patterns were observed in the residuals (Figure A.5), and the goodness-of-fit statistic indicated good model fit (RMSE = 12.2%).

The comparison of posterior distributions and prior densities of key estimated parameters is given in Figure A.6. Posterior distribution of K was much narrower compared to its prior, and the resulting small PPVR (posterior to prior variances ratio) indicates that the input data were very informative about K . The opposite is true of r , with both PPMR (posterior to prior means ratio) and PPVR 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 $K = 31,350$ t, and the estimated biomass declined from $0.945K$ (29,626 t) in 1987 to $0.421K$ (13,198 t) in 2021. The absolute biomass B and the relative biomass B/K and B/B_{MSY} trends showed a sharp decline in 1995-2001, followed by a moderate decline in 2001-2006, and reverting to a roughly levelled trend afterwards. This was related to the sharp increases in relative fishing mortality F/F_{MSY} in 1994 and more prominently in 1996-1999, followed by a period of sustained high F/F_{MSY} in 2000-2005. Since 2006, F/F_{MSY} has been fluctuating around the sustainable level baseline ($F/F_{MSY} = 1$), on an overall slightly decreasing trend (Figure 2).

Relationship between B/B_{MSY} and F/F_{MSY} is illustrated using the Kobe plot (Figure 3), showing that overfishing ($F/F_{MSY} > 1$) in 1999-2005 (orange area on the plot) quickly reduced the biomass to a level slightly above B_{MSY} . Since 2006, F/F_{MSY} has fluctuated close to the sustainable baseline, and the biomass consequently remained roughly the same until 2021. The fishing mortality decline in 2006 coincided with the introduction of the TAC system to the toothfish longline fishery (the TAC was initially set to 1,500 t in 2006, and progressively reduced to 1,200 t in 2008, to 1,040 t in 2015). The estimated current biomass B_{2021} is 5.1% above B_{MSY} , and the current fishing mortality F_{2021} is 26.9% below F_{MSY} . Taking into account the uncertainty of this estimate (grey credibility intervals on the Kobe plot), there is 57.1% probability that the toothfish 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 was 81.7% (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 $B_{MSY} = 12,539$ t, with the corresponding $MSY = 1,507$ t. In 1994-1995 and 1998-2005 catches were above the MSY, leading to a decline in toothfish biomass; since 2006 catches have been fluctuating narrowly around the median MSY (Figure 4). Biomass is expected to increase if catch were maintained at current levels, considering that surplus production is larger than recent catches.

Table 2. Summary of parameters and stock status estimates.

Parameter	median	95% CI
r	0.143	0.117 - 0.173
K	31,350 t	25,271 - 48,486 t
B_{1987}/K	0.945	0.815 - 1.030
B_{2021}/K	0.421	0.253 - 0.705
MSY	1,507 t	1,257 - 2,281 t
B_{MSY}	12,539 t	10,108 - 19,394 t
F_{MSY}	0.120	0.099 - 0.146
B_{2021}/B_{MSY}	1.051	0.633 - 1.763
F_{2021}/F_{MSY}	0.731	0.297 - 1.340

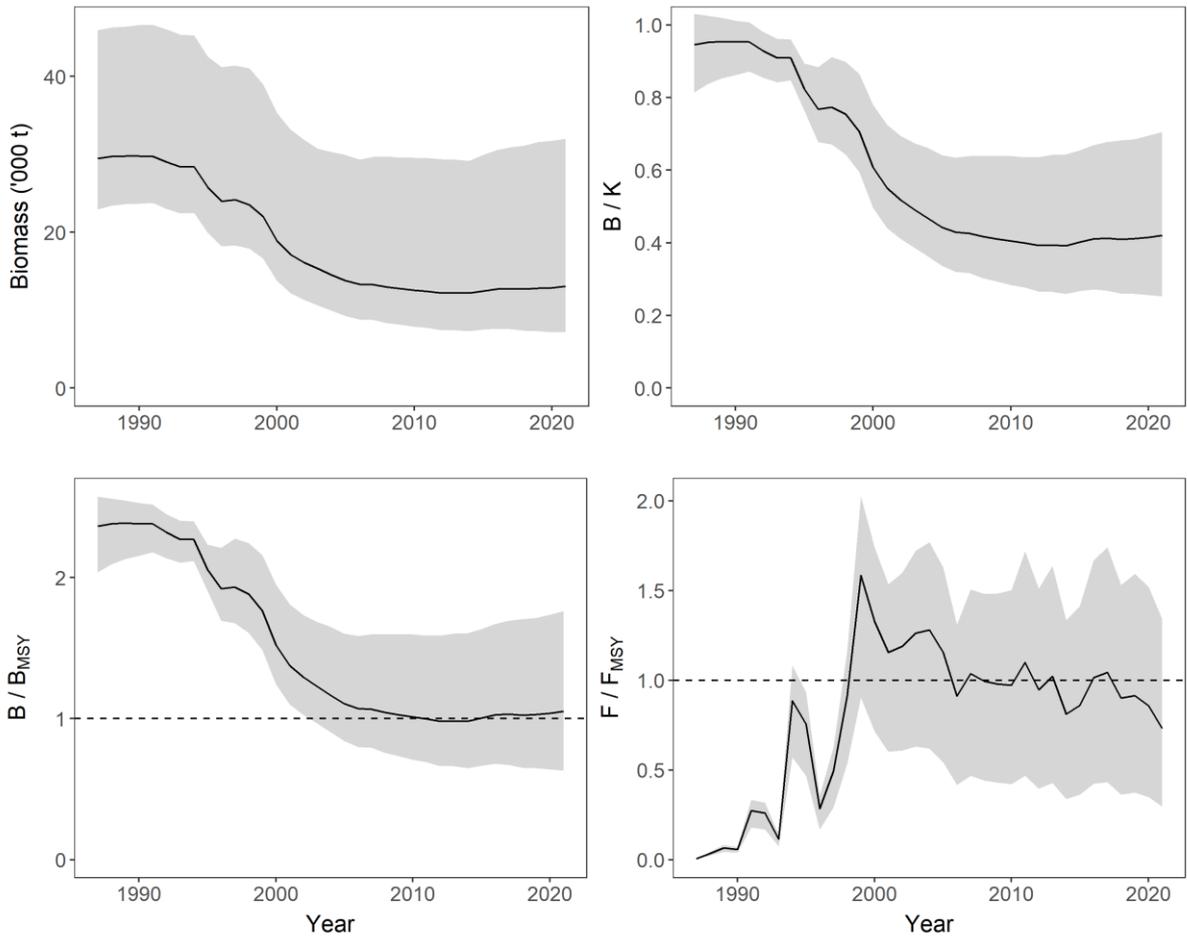


Figure 2. Estimated trends in absolute biomass (top left), biomass relative to K (top right), biomass relative to B_{MSY} (bottom left) and fishing mortality relative to F_{MSY} (bottom right). Solid black lines are medians and shaded areas denote 95% confidence intervals.

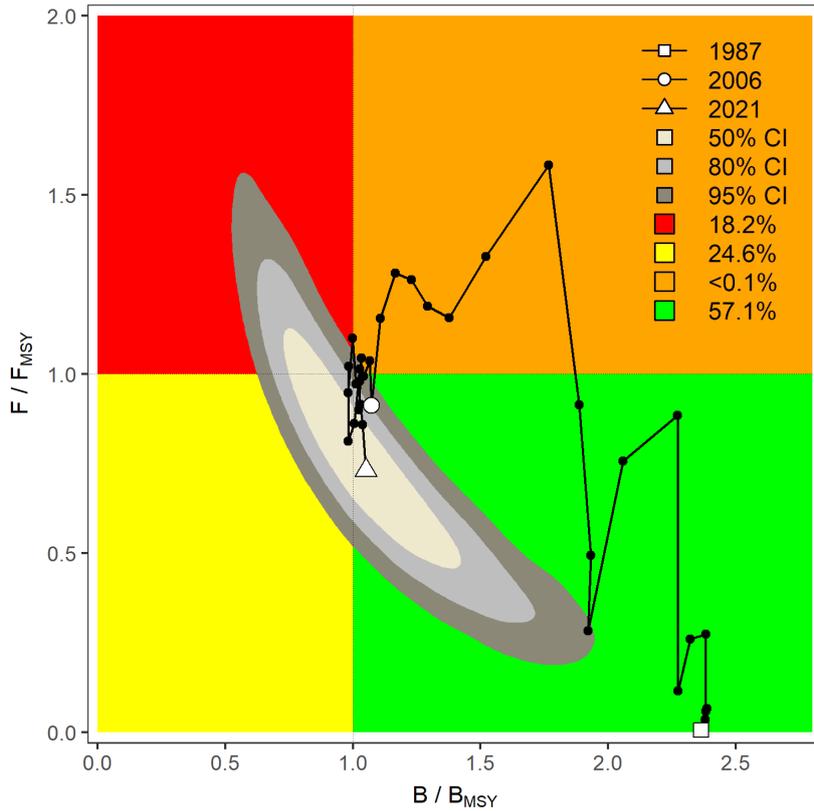


Figure 3. Kobe phase plot showing estimated trajectory of B/B_{MSY} and F/F_{MSY} for the toothfish stock in 1987-2021. Grey shaded areas denote the 50%, 80%, and 95% credibility intervals for the last assessment year. The probability of the last year estimate falling within each quadrant is indicated in the figure legend.

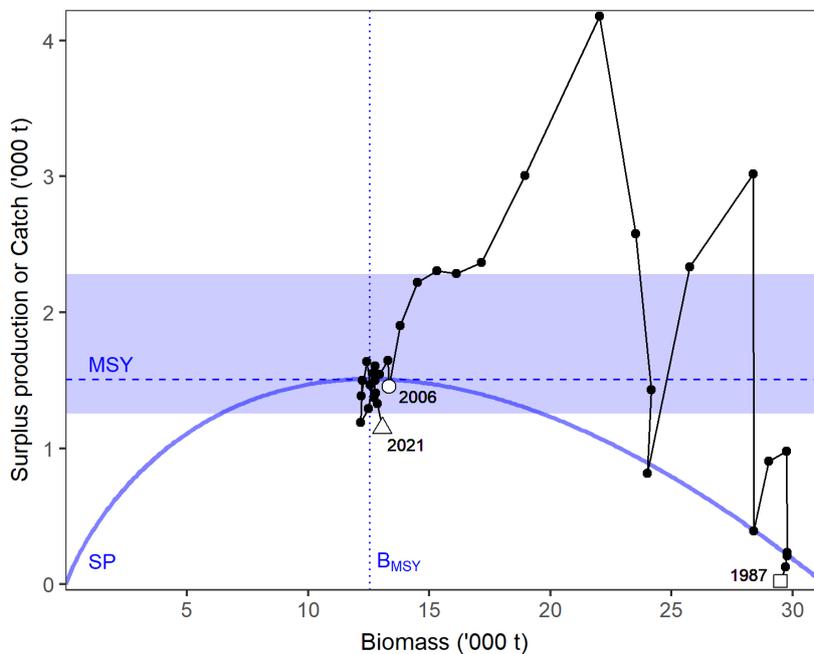


Figure 4. Surplus-production phase plot showing Pella-Tomlinson curve SP (solid blue line) and catch/biomass trajectory for the toothfish stock in 1987-2021 (black line). Catches on the SP curve would maintain the biomass, catches above the curve will shrink future biomass, and catches below the curve 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% confidence 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 (-0.10), B/K (-0.07), B/B_{MSY} (-0.07) and F/F_{MSY} (0.12) 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 effect was relatively small. Retrospective plots showed no systematic trend in departures from the 2021 model (Figure 5).

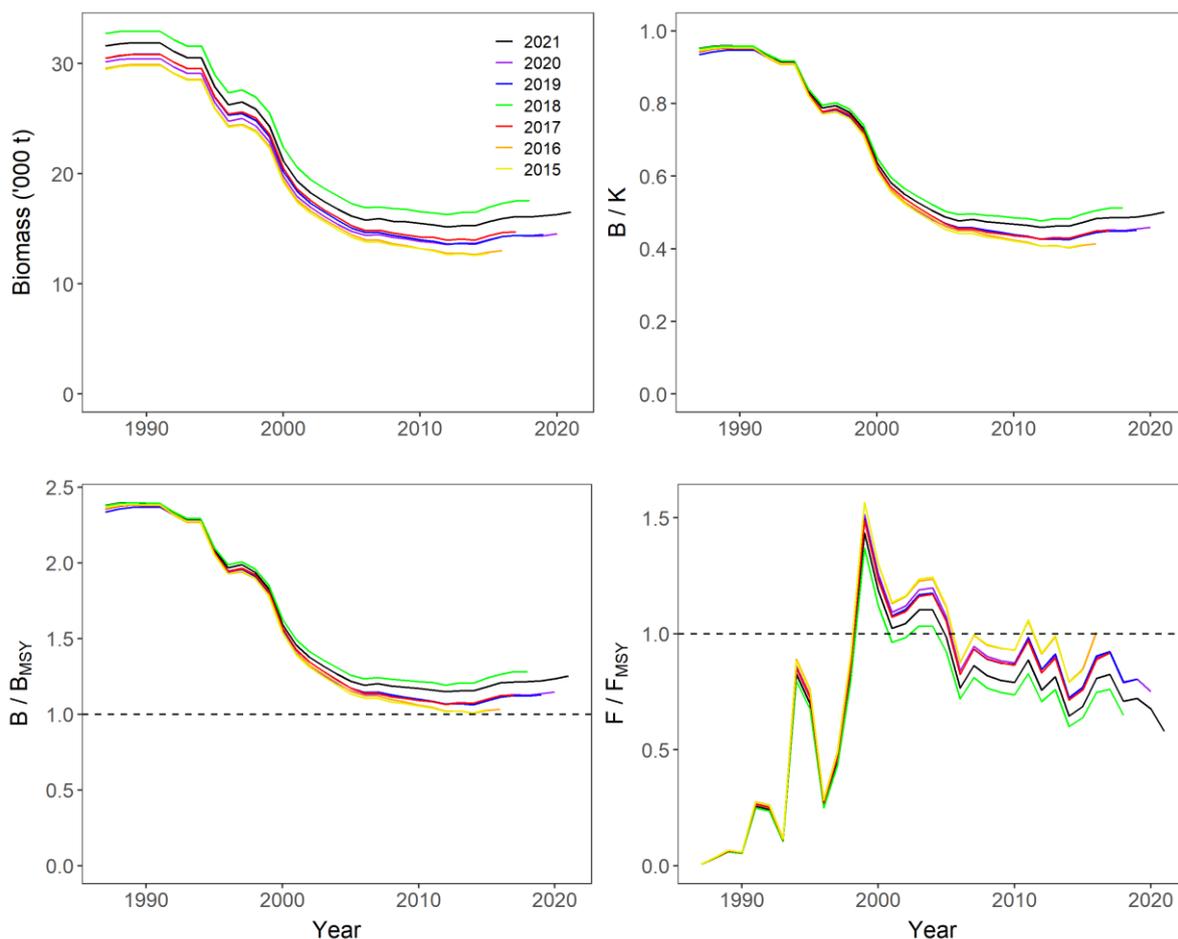


Figure 5. Estimated trends in biomass, B/K , B/B_{MSY} and F/F_{MSY} for the 2021 model (black line) and six retrospective model runs. The numeric label indicates the year (inclusive) up to which individual retrospective model was run.

3.4. Comparison of JABBA and CASAL assessment

As CASAL does not provide estimate of K , the comparison with JABBA was approximated by setting K equivalent to B_{1987} for the CASAL model (i.e. total biomass in 1987 was assumed to be at carrying capacity). Overall, JABBA estimated substantially lower absolute biomass values compared to CASAL (Table 3); however, time-series trends had similar shape, as both models captured the steeper decline in biomass up to approximately 2005 followed by a more levelled trend afterwards (Figure 6.A). The relative biomass estimates and trends were expressed as proportion of the pre-exploitation (virgin) biomass estimated by the corresponding models; compared to the absolute biomass, the relative biomass estimates were more similar between the two models, with CASAL estimates falling within the 95% credible intervals of JABBA estimates (Table 3, Figure 6.B).

Table 3. Comparison of the selected output parameters estimated by CASAL and JABBA stock assessment models for Patagonian toothfish in Falkland Islands waters (1987-2021). All biomass estimates are given in tonnes.

Parameter	CASAL	JABBA
K	$\sim B_{1987}$	31,350 (25,271 - 48,486)
B_{1987}	69,319 (61,242 - 95,571)	29,493 (22,938 - 45,932)
B_{2021}	36,612 (29,616 - 65,080)	13,055 (7,143 - 31,967)
B_{2021}/K	0.528 *	0.421 (0.253 - 0.705)
MSY	1,728 (1,529 - 2,383) **	1,507 (1,257 - 2,281)

* Calculated as B_{2021}/B_{1987}

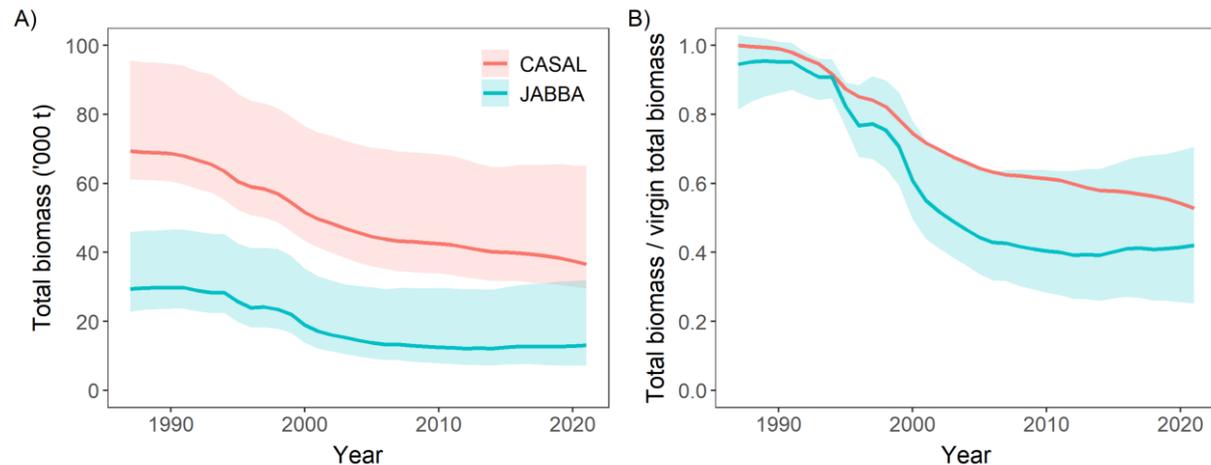


Figure 6. A) Absolute and B) relative total biomass trends estimated by statistical-catch-at-age model in CASAL (red) and surplus production model in JABBA (blue). Solid lines are MPD (mode of posterior density) estimates in case of CASAL and median estimates in case of JABBA. Shaded areas are MCMC 95% credible intervals of the corresponding model fits.

4. Discussion

In this assessment, the JABBA (*Just Another Bayesian Biomass Assessment*) framework was used to fit a generalised Bayesian surplus production model to the catch and CPUE data of the Falkland Islands toothfish 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 data-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).

Compared to the previous year's JABBA assessment, updated model resulted in almost identical estimates of r and initial depletion (B_{1987}/K), and a slightly higher (by 3.5%) estimate of K , leading to slightly more optimistic stock status estimates. Overall, the stock was estimated to be healthy, with low probability of being overfished or experiencing overfishing. Sensitivity analysis from the earlier assessment showed high influence of r prior on model outcomes (Skeljo and Winter 2020), and the current assessment's model diagnostics showed that estimate of r was poorly informed by the input data, and strongly by the specified prior. We suggest this is a consequence of difficulties faced by SPMs when estimating r from CPUE time series lacking contrast. In our case, CPUE data are roughly continuously declining; a so called 'one-way trip', both the most common and the most difficult to interpret type of CPUE time-series (Hilborn 1979, Hilborn and Walters 1992). This highlights the need to provide a well-informed species-specific r prior, and in this respect R package *FishLife2.0* proved useful. However, high influence of r prior on model outcomes suggests caution when interpreting the results.

One of the main reasons for conducting alternative toothfish stock assessment in JABBA was to provide a comparison with the age-structured integrated stock assessment in CASAL. Overall, JABBA produced lower estimates of absolute biomass, relative biomass and MSY, but the model still suggested that the stock was exploited sustainably in recent years, with total fishery removals fluctuating narrowly around the MSY. The discrepancy between the two models was not surprising, as the type of data used can influence model estimates. In this case, the main difference in data used was the absence of composition data (i.e. catch-at-age) in the JABBA surplus production model, exempting the JABBA model from estimating fishery-specific selectivity patterns and optimizing population trends only on the abundance index. Catch-at-age data can be highly influential on the estimated biomass trajectory and may not be consistent with the overall trend in the abundance index (Wetzel and Punt 2011), which was indeed the case in the integrated CASAL model used for comparison here (Skeljo and Winter 2022). We suggest two main reasons for lower absolute biomass estimates produced by JABBA: (i) the surplus production abundance index reflects vulnerable biomass only and may particularly have caused the JABBA model to underestimate the potential of the juvenile year classes, and (ii) interplay between r and K , coupled with relatively uninformative catch and CPUE data, allowed the JABBA model to describe the stock in terms of lower K (i.e. lower biomass) and higher r ; this was driven mainly by the r prior, derived from an integrated analysis of life history parameters via package *FishLife2.0*. In general, including multiple types of data such as composition data along with abundance indices allows for more complex population dynamics models as the basis of stock assessments, and has previously been shown to improve estimation performance (Magnusson and Hilborn 2007).

In conclusion, the age-structured model in CASAL should be a preferred approach to toothfish stock assessment in Falkland Islands, as it integrates wider range of data, i.e. takes explicitly into account somatic growth, reproduction, lagged effects of recruitment, natural mortality and multiple fishery-specific selectivities. However, findings of this report provide an insight into the usefulness of

JABBA data-moderate approach for other species/stocks managed by FIFD, where data limitations prevent the use of integrated CASAL 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.
- 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.
- Ainsworth CH, Pitcher TJ. 2005. Estimating illegal, unreported and unregulated catch in British Columbia's marine fisheries. *Fisheries Research* 75, 40-55.
- Arana P. 2009. Reproductive aspects of the Patagonian toothfish (*Dissostichus eleginoides*) off southern Chile. *Latin American Journal of Aquatic Research* 37, 381-394.
- Arkhipkin AI, Brickle P, Lee B, Shaw PW, McKeown NJ. 2022. Taxonomic re-appraisal for toothfish (*Dissostichus*: Notothenioidea) across the Antarctic Polar Front using genomic and morphological studies. *Journal of Fish Biology*, 1-13.
- Arkhipkin AI, Laptikhovskiy VV. 2010. Convergence in life-history traits in migratory deep-water squid and fish. *ICES Journal of Marine Science* 67, 1444-1451.
- Ashford JR, Fach BA, Arkhipkin AI, Jones CM. 2012. Testing early life connectivity supplying a marine fishery around the Falkland Islands. *Fisheries Research* 121-122, 144-152.
- 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.
- Brown J, Brickle P, Scott BE. 2013. Investigating the movements and behaviour of Patagonian toothfish (*Dissostichus eleginoides* Smitt, 1898) around the Falkland Islands using satellite linked archival tags. *Journal of Experimental Marine Biology and Ecology* 443, 65-74.
- Bull B, Francis RICC, Dunn A, McKenzie A, Gilbert DJ, Smith MH, Bian R, Fu D. 2012. CASAL (C++ algorithmic stock assessment laboratory): CASAL User Manual v2.30-2012/03/21. NIWA Technical Report 135, 275 p.
- Cadrin SX, Dickey-Collas M. 2015. Stock assessment methods for sustainable fisheries. *ICES Journal of Marine Science* 72, 1-6.
- Cadrin SX. 2020. Defining spatial structure for fishery stock assessment. *Fisheries Research* 221, 105397.
- Canales-Aguirre CB, Ferrada-Fuentes S, Galleguillos R, Oyarzun FX, Hernández CE. 2018. Population genetic structure of Patagonian toothfish (*Dissostichus eleginoides*) in the Southeast Pacific and Southwest Atlantic Ocean. *PeerJ* 6, e4173.
- 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.

- Ciannelli L, Fisher JAD, Skern-Mauritzen M, Hunsicker ME, Hidalgo M, Frank KT, Bailey KM. 2013. Theory, consequences and evidence of eroding population spatial structure in harvested marine fishes: A review. *Marine Ecology Progress Series* 480, 227-243.
- Collins MA, Brickle P, Brown J, Belchier M. 2010. The Patagonian toothfish: biology, ecology, and fishery. *Advances in Marine Biology* 58, 227-300.
- 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.
- Earl T, Readdy L. 2021a. Assessment of Patagonian toothfish (*Dissostichus eleginoides*) in Subarea 48.3. CCAMLR working document WG-FSA-2021/59, CCAMLR, Hobart, Australia.
- Earl T, Readdy L. 2021b. Assessment of Patagonian toothfish (*Dissostichus eleginoides*) in Subarea 48.4. CCAMLR working document WG-FSA-2021/61, CCAMLR, Hobart, Australia.
- Francis RICC, Hurst RJ, Renwick JA. 2003. Quantifying annual variation in catchability for commercial and research fishing. *Fisheries Bulletin* 101, 293-304.
- 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.
- Grüss A, Dunn A, Parker S. 2021. Assessment model for Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea region to 2020/21. CCAMLR working document WG-FSA-2021/26, CCAMLR, Hobart, Australia.
- Hawkins SJ, Bohn K, Sims DW, Ribeiro P, Faria J, Presa P, Pita A, Martins GM, Neto AI, Burrows MT, Genner MJ. 2016. Fisheries stocks from an ecological perspective: Disentangling ecological connectivity from genetic interchange. *Fisheries Research* 179, 333-341.
- 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.
- Laptikhovskiy VV, Arkhipkin AI, Brickle P. 2006. Distribution and reproduction of the Patagonian toothfish *Dissostichus eleginoides* Smitt around the Falkland Islands. *Journal of Fish Biology* 68, 849-861
- Laptikhovskiy VV, Brickle P. 2005. The Patagonian toothfish fishery in Falkland Islands' waters. *Fisheries Research* 74, 11-23.
- Lee B, Arkhipkin A, Randhawa H. 2021. Environmental drivers of Patagonian toothfish (*Dissostichus eleginoides*) spatial-temporal patterns during an ontogenetic migration on the Patagonian Shelf. *Estuarine, Coastal and Shelf Science* 259, 107473.
- Lee B, Brewin PE, Brickle P, Randhawa H. 2018. Use of otolith shape to inform stock structure in Patagonian toothfish (*Dissostichus eleginoides*) in the south-western Atlantic. *Marine and Freshwater Research* 69, 1238-1247.
- Lee B, Skeljo F, Randhawa HS, Arkhipkin A. 2022. Deep-sea movement patterns of the Patagonian toothfish *Dissostichus eleginoides* Smitt in the Southwest Atlantic. *Marine and Freshwater Research*, 1-13.

- Lee B. 2017. Age structure for Patagonian toothfish *Dissostichus eleginoides* from Falkland Island waters: January - December 2017. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, 16 p.
- Lee B. 2022. Stock structure of Patagonian toothfish *Dissostichus eleginoides* (Smitt 1898, family Nototheniidae) in the southwest Atlantic. PhD Thesis, Rhodes University.
- Magnusson A, Hilborn R. 2007. What makes fisheries data informative? *Fish and Fisheries* 8, 337-358.
- 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/>.
- Massiot-Granier F, Landru S, Peron C. 2021a. Updated stock assessment model for the Kerguelen Island EEZ Patagonian toothfish (*Dissostichus eleginoides*) fishery in Division 58.5.1 for 2021. CCAMLR working document WG-FSA-2021/46, CCAMLR, Hobart, Australia.
- Massiot-Granier F, Péron C. 2021b. An integrated stock assessment for the Crozet Islands Patagonian toothfish (*Dissostichus eleginoides*) fishery in Subarea 58.6. CCAMLR working document WG-FSA 2021/45, CCAMLR, Hobart, Australia.
- 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.
- Pitcher TJ, Watson R, Forrest R, Valtýsson HP, Guénette S. 2002. Estimating illegal and unreported catches from marine ecosystems: a basis for change. *Fish and Fisheries* 3, 317-339.
- 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/>.
- Randhawa HS, Lee B. 2016. Toothfish tagging cruise. Scientific Report ZDLC2-06-2016. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands, 20 p.
- 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.
- Rogers AD, Morley S, Fitzcharles E, Jarvis K, Belchier M. 2006. Genetic structure of Patagonian toothfish (*Dissostichus eleginoides*) populations on the Patagonian shelf and Atlantic and western Indian Ocean sectors of the Southern Ocean. *Marine Biology* 149, 915-924.
- Shaw PW, Arkhipkin AI, Al-Khairulla H. 2004. Genetic structuring of Patagonian toothfish populations in the southwest Atlantic Ocean: the effect of the Antarctic polar front and deep-water troughs as barriers to genetic exchange. *Molecular Ecology* 13, 3293-3303.

- Skeljo F, Lee B, Winter A. 2022. 2021 Stock assessment report for Patagonian toothfish (*Dissostichus eleginoides*). Fisheries Report SA-2021-TOO. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 44 p.
- Skeljo F, Winter A. 2021. 2020 Alternative stock assessments for Patagonian toothfish (*Dissostichus eleginoides*). Fisheries Report SA-2020-TOO. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 19 p.
- Skeljo F, Winter A. 2020. 2019 Alternative Stock Assessments for Patagonian toothfish (*Dissostichus eleginoides*). Fisheries Report SA-2019-TOO. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, Stanley, Falkland Islands. 22 p.
- 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.
- Wetzel CR, Punt AE. Performance of a fisheries catch-at-age model (Stock Synthesis) in data-limited situations. *Marine and Freshwater Research* 62, 927-936.
- 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.
- Winter A, Pompert J. 2016. Initial analysis of whale depredation in the Falkland Islands toothfish longline fishery. Fisheries Department, Directorate of Natural Resources, Falkland Islands Government, 18 p.
- Ziegler P. 2021. Draft integrated stock assessment for the Heard Island and McDonald Islands Patagonian toothfish (*Dissostichus eleginoides*) fishery in Division 58.5.2. CCAMLR working document WG-FSA-2021/21, CCAMLR, Hobart, Australia.
- 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

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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 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. Daily catch reports with zero toothfish catches were presumed to represent erroneous entries or broken sets and were excluded from the analysis.

The response variable in the model was daily longline CPUE, expressed as toothfish 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
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 added to the *Year* by forward stepwise selection and included in the final model only if they improved pseudo- R^2 by at least 0.5%. Pseudo- R^2 was calculated based on the likelihood-ratio test, as implemented in R package *MuMIn* (Barton 2009). 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). *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 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 the explanatory variables *Year*, *Month*, *Region* and *Vessel*, and the model explained 17.4% of the overall variation in CPUE. Standardized and unstandardized CPUE time series showed overall similar declining trend (Figure A.1). Fitting GLMM to umbrella-system data included the explanatory variables *Year*, *Month*, *Region* and *Soak-time*, and the model explained 14.0% of the overall variation in CPUE. Standardized and unstandardized CPUE time series were similar and showed no clear trend (Figure A.2). The *hooks-per-umbrella* variable wasn't significant, indicating that the gradual reduction in the number of hooks per umbrella from 8 to 7 to 6 didn't significantly affect the CPUE; this was expected, as the change was fishery driven, presumably to simplify the work and possibly reduce the amount of bait while maintaining the catches. This could be achieved because hooks are set in tight clusters, with each hook on a ~30 cm snood, and all snoods tied together at the free end; therefore, reducing the number of hooks doesn't necessarily reduce the catchability of the cluster as a whole.

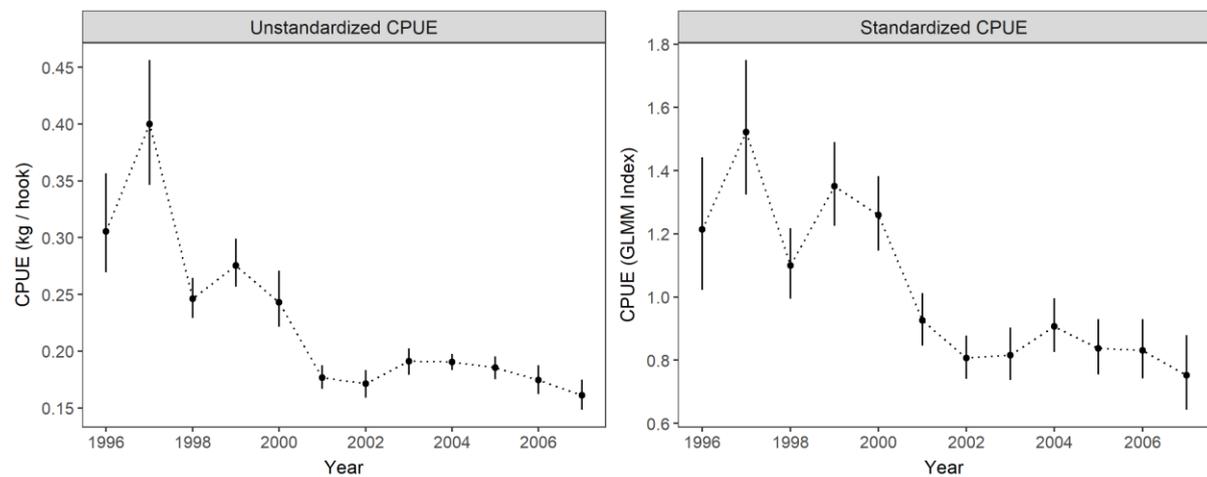


Figure A.1. Spanish-system longline unstandardized and standardized CPUE time series; black vertical lines correspond to 95% confidence intervals.

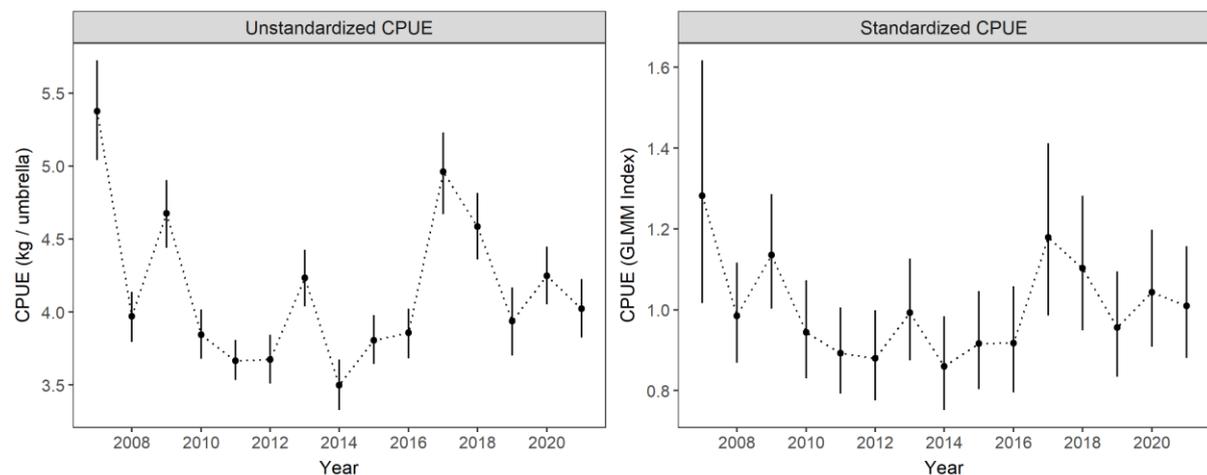


Figure A.2. Umbrella-system longline unstandardized and standardized CPUE time series; black vertical lines correspond to 95% confidence intervals.

Appendix 2. Diagnostics plots

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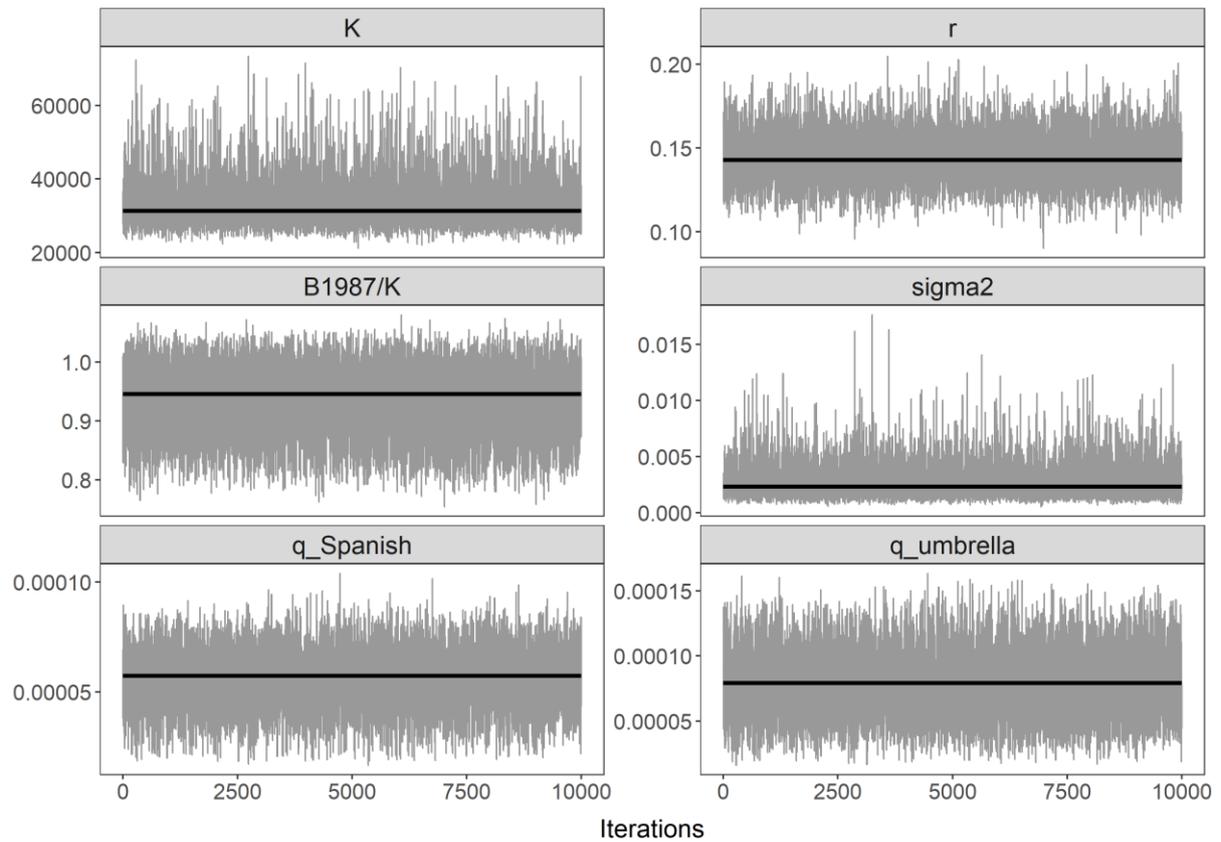


Figure A.3. MCMC posterior trace plots for the estimated parameters. Black line denotes the median.

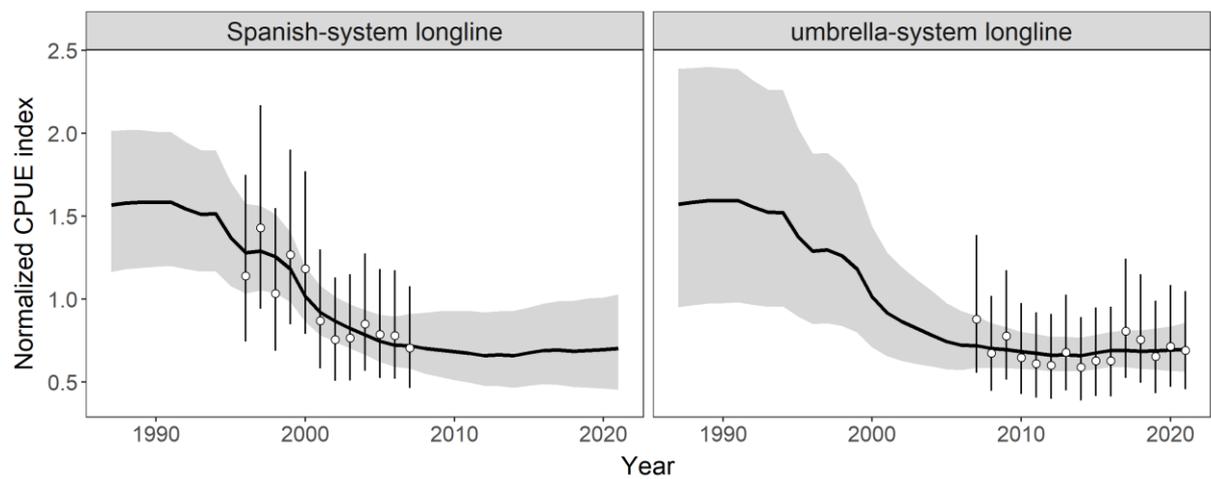


Figure A.4. Model fit (black line) to the normalised CPUE indices (white dots) for Spanish- and umbrella-system longline. Vertical lines denote 95% confidence intervals of the normalised CPUE indices; shaded areas denote 95% credibility intervals of the model fit.

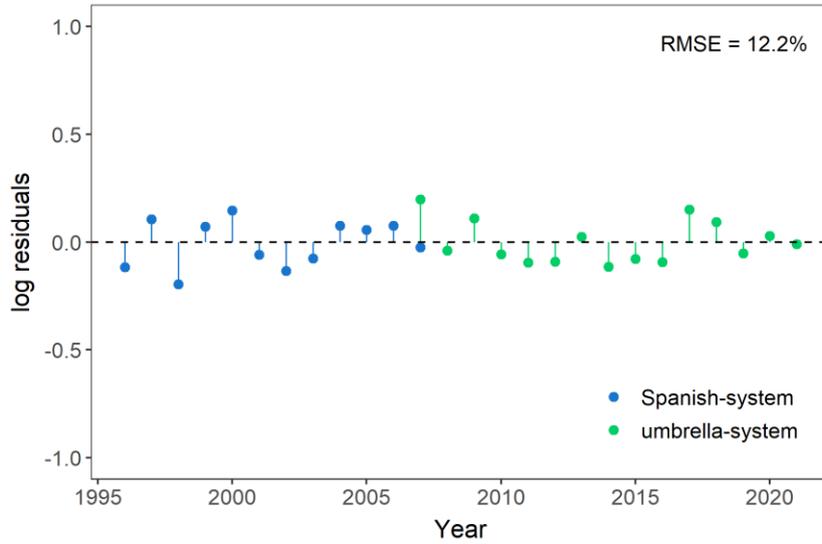


Figure A.5. Residuals from the model fit to the observed CPUE indices; for Spanish-system (blue dots) and umbrella-system longline (green dots). RMSE: root mean square error.

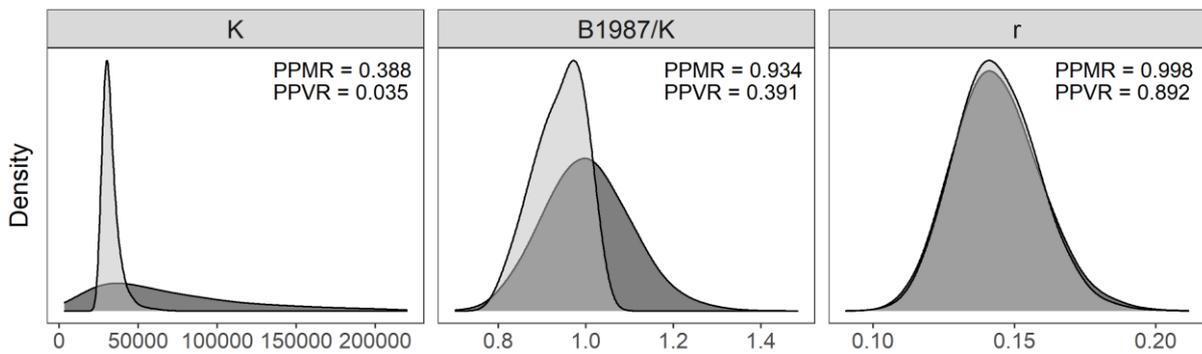


Figure A.6. Prior (dark grey) and posterior distributions (light grey) of key estimated parameters. PPMR: Posterior to Prior Means Ratio; PPVR: Posterior to Prior Variances Ratio.