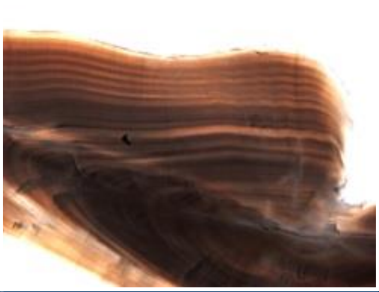
2020 Stock Assessment Report

Patagonian toothfish
(*Dissostichus eleginoides*)



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Summary

1. This report provides an updated Bayesian age-structured stock assessment of *Dissostichus eleginoides* in Falkland Islands waters, using data through year 2020. Several changes were introduced in the 2020 model regarding both data treatment and model assumptions, following the recommendations of the external review (Bergh 2018).
2. Current spawning stock biomass (SSB_{2020}) was estimated at 11,056 tonnes and the ratio of current spawning stock biomass to initial spawning stock biomass (SSB_{2020}/SSB_0) at 0.477, both values slightly higher than in the previous year's assessment. According to the established harvest control rules (HCR), the SSB_{2020}/SSB_0 ratio places the stock in the *expansion range*.
3. Projection from the current model indicated that the SSB/SSB_0 ratio will likely remain in the HCR expansion range, on a slightly increasing trend before levelling out by the end of the projection period. Maximum sustainable yield (MSY) was estimated at 1,850 tonnes, slightly lower than in the previous year.
4. Based on the HCR, the recommendation for the toothfish longline fishery is to maintain the total allowable catch (TAC) at 1,040 tonnes, same as the previous year.

1. Introduction

Patagonian toothfish (*Dissostichus eleginoides*) is a large notothenioid fish found on the southern sea 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 on the 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 abundance peak in May, and a major peak in 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, and when juveniles attain 10-12 cm TL (<1 year old; Lee 2017), they start to migrate towards the Patagonian shelf and are found at depths <100 m (Arkhipkin & Laptikhovsky 2010). Immature toothfish remain there for 3-4 years, and then, on reaching 60-70 cm TL, they migrate into deeper water over the Patagonian slope (Laptikhovsky et al. 2008).

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 (20-30 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).

This report provides an updated Bayesian age-structured stock assessment of *D. eleginoides* in Falkland Islands waters, using data through year 2020.

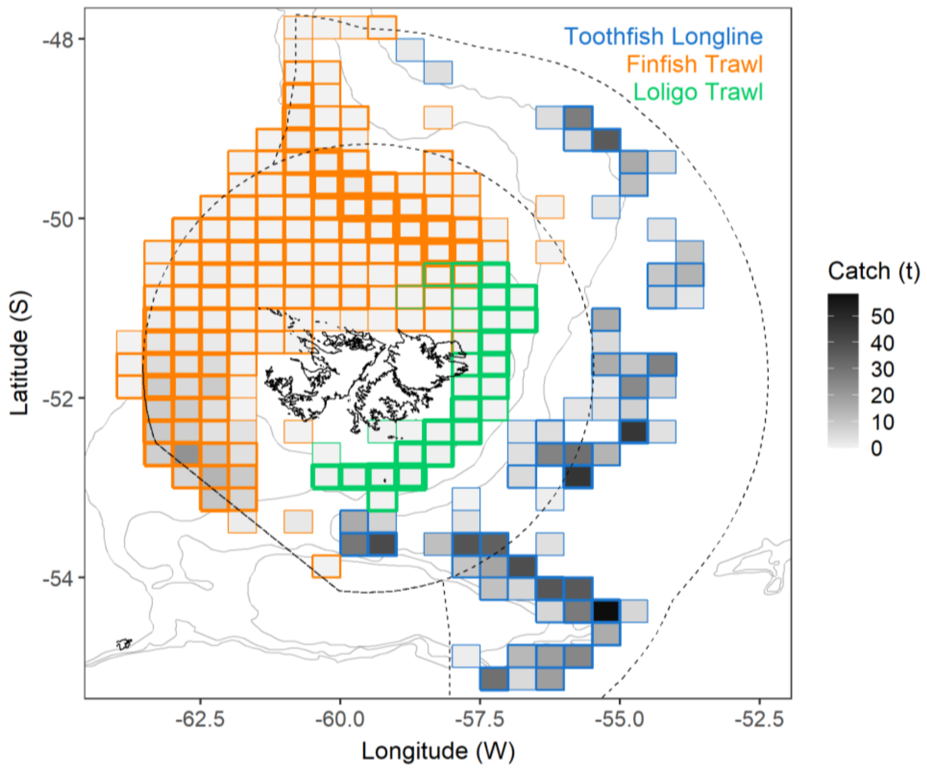

Figure 1. Spatial distribution of toothfish catch and effort by fisheries in 2020. Thickness of grid lines is proportional to the number of vessel days; greyscale is proportional to the toothfish catch biomass in tonnes.

1.1. Stock structure and assumptions

The stock structure of Patagonian toothfish in the Southwest Atlantic is still poorly understood. On a larger spatial scale, there is a 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). However, toothfish population structure across the Patagonian Shelf is less certain, and it is not yet clear whether there are several separate self-sustaining populations or one large meta-population (Parker 2015). The existence of separate spawning populations south of Diego Ramirez Islands in Chilean waters and the eastern Burdwood Banks in Falkland Islands waters has been proposed (Laptikhovsky et al. 2006, Arana 2009); with otolith microchemistry analysis indicating that larvae settling on the Falkland Shelf originate from a combination of these two spatially distinct areas (Ashford et al. 2012). Early 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.

In order to build on these early studies and to get a better understanding of the toothfish stock structure within Patagonian Shelf (and especially Falkland Islands waters) a range of methodologies were employed by FIFD, most notably: otolith shape analysis, life-history aspects, otolith microchemistry analysis and the re-establishment of a large-scale tag-recapture program using conventional and satellite tags (Randhawa and Lee 2016).

Results obtained from otolith shape analyses revealed high site fidelity of adult fish across localised regions of the Patagonian Shelf, including southern Chile, the Burdwood Bank, and the continental slope to the north-east of the Falkland Islands (Lee et al. 2018). However, the extent to which these groups functioned as discrete stocks remained unclear. Recent work was therefore 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 - under review). 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. Results highlighted further research objectives aimed at (1) the identification of the extent of any potential adult migratory behaviour from non-spawning to spawning areas amongst the adult component of the population, and (2) the extent that temporally variable discrete spatial groups in the shelf-based population arise from a single or multiple spawning areas.

The primary aim of the tag-recapture program that was re-established in June 2016 was to improve our understanding of the movement patterns of toothfish within the region; and to quantify the exchange taking place between adults on the northern and eastern slope, and the spawning grounds on the Burdwood Bank. While the initial medium term (3-years) aim to tag 3000 fish was achieved, the program was extended for a further 4-year time period (Lee and Skeljo, 2020). The most recent tagging survey took place in January 2021, with ~700 toothfish tagged (Skeljo and Pearman 2021). Preliminary analyses based on results over the first 5-years of data are to be undertaken during 2021-2022 in order to improve our understanding of objective 1 defined above.

In order to meet objective 2, otolith microstructures and associated trace elemental composition are being analysed for newly settled age 0+ toothfish from three regions of abundance between 2014 and 2017. Otoliths extracted from progressive cohorts of age 1+ (2015-2018) and 2+ (2016-2019) year old toothfish were also sampled from four key regions of abundance that overlap with the recruitment areas and processed for elemental analyses in the same way (Lee, FIFD, in progress). The results of this study should provide us with an improved understanding of the population structure of Patagonian toothfish across the shelf regions around the Falkland Islands.

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

In this assessment we use an integrated statistical catch-at-age model implemented in CASAL (Bull et al. 2012), a general stock assessment software capable of integrating a variety of different types of input data in parameter estimation. The model assumes a single area with four distinct fisheries: Spanish-system longline, umbrella-system longline, finfish trawl and calamari trawl. Information from these fisheries covers varying time periods and areas and gives us an insight into the variety of issues that need to be addressed in toothfish stock assessment.

2.1. Model updates

The current assessment incorporates new data collected in 2020, including (a) catch and effort data for the umbrella-system longline fishery, (b) catch data for the finfish and calamari trawl fisheries, (c) ageing data, and (d) length frequencies and maturity data.

Besides the regular data updates, several model changes were introduced compared to the previous year's assessment, following the recommendations of the external review (Bergh 2018). These are listed here for reference, and explained in more detail further in the text:

Catch-per-unit-effort (CPUE) data

- Revised the assignment of individual longline daily catch reports between Spanish- and umbrella-system longline fishing for the period when these two fisheries overlapped (2007-2010)
- Removed a small number of Spanish-system catch reports pertaining to remote areas
- Introduced mixed effects in CPUE modelling, i.e. used generalised linear mixed modelling approach (GLMM)

Catch-at-age (CAA) data

- Introduced the catch and CAA data from two research surveys (groundfish and calamari pre-season surveys in 2015-2020) in the assessment model
- Excluded pre-2008 CAA data belonging to calamari trawl fishery

Removals data

- Revised the whale depredation estimates for longline fishery

Age data

- Included revised age readings from otoliths collected and aged in 2014 in the age-length key (ALK) (Lee 2014)

New model output included in the report

- Included Markov chain Monte-Carlo (MCMC) convergence diagnostics and between-sample autocorrelations (ACF) in the report

2.2. Data

Several datasets were used as information in the assessment, either as *observations* or *input parameters* (Table 1). Observations appear in the objective function and are used to fit the model - in our case these include two CPUE and four catch-at-age time series from the commercial fisheries, and two catch-at-age time series from the research surveys. Input parameters were estimated outside the model, and then treated as fixed parameters within the model (e.g. von Bertalanffy growth coefficients). Input parameters were assumed known without error.

Table 1. Data used in the stock assessment.

Data type	Data	Time series
Observations	**CPUE**	
	Spanish-system longline	1996-2007
	umbrella-system longline	2007-2020
	CAA	
	Spanish-system longline	1992, 1994-2010, 2013
	umbrella-system longline	2007-2020
	finfish trawl	1988-1994, 1997-1999, 2002-2020
	calamari trawl	2008-2020
	groundfish survey	2015-2020
	calamari pre-season survey	2015-2020
Input parameters	**Removals**	
	Spanish-system longline	1992-2010, 2013
	umbrella-system longline	2007-2020
	finfish trawl	1987-2020
	calamari trawl	1987-2020
	groundfish survey	2015-2020
	calamari pre-season survey	2015-2020
	Length-weight relationship	
	all fisheries combined	1989-2020
	Von Bertalanffy growth	
	all fisheries combined	2014-2020
	Maturity	
	all fisheries combined	1988-2020

Catch-per-unit-effort (CPUE)

Although CPUE data were available for all four fisheries, only longline CPUE was 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 we use data aggregated by day in our 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. 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 more representative as an index of abundance if only Falkland Islands vessels data were used. With a similar goal, data from the 'tagging trips' and from the 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 the 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 which were assumed relative abundance indices (Appendix 1). Observation error of the CPUE indices was accounted for in the assessment model by using the coefficient of variation (CV) estimates obtained directly from a GLMM. To account for any additional variance on top of observation error, which may arise from the differences between model simplifications and real-world variation, a process error CV = 0.2 was added (Francis et al. 2003). The CPUE indices were assumed to be log-normally distributed about the model-predicted vulnerable biomass, via a catchability parameter.

Catch-at-age (CAA)

As in the previous assessment, CAA distributions were treated separately for each of the four fisheries. The longline CAA data had to be split between Spanish- and umbrella-system fishery in the same way as CPUE data (this is a model requirement), while the trawl data were split between finfish and calamari fisheries due to the differences in legal net mesh size and fishing grounds, leading to distinct CAA distributions. One change, compared to the previous year, was exclusion of the pre-2008 CAA data for the calamari trawl fishery from the analysis. The poor model fit to these data, and the potential reasons behind it, have already been reported (Skeljo and Winter 2020); in brief, pre-2008 data were few (more toothfish were sampled in 2008 alone then in the previous 15 years combined). We suspect this bias reflects different sampling protocols pre- and post-2008, i.e. different levels of attention given to accounting for the juvenile toothfish (which can be difficult to distinguish from certain other species in the juvenile stage). Therefore, we decided to treat pre-2008 data as questionable and exclude them from the current model.

In addition to the commercial fisheries data, the CAA data from two research trawl surveys conducted by FIFD (groundfish and calamari pre-season surveys in parallel) have been included in the model for the first time. Both surveys now cover 6-year time spans (2015-2020) (Ramos and Winter 2021), which was deemed sufficiently long period for the analysis.

Toothfish ageing data used in the stock assessment were restricted to the otoliths sampled in 2014-2020. Age readings from the otoliths collected and aged in 2014 have been revised during 2020 and are a new addition compared to the previous assessment. Otoliths collected in 2020 have been partially processed, with ~300 age readings available at the time of the assessment. All the otoliths from the period 2014-2020 were processed at FIFD, and the corresponding age readings are the most reliable toothfish age estimates available at the time of this assessment (Lee 2015, 2016, 2017, 2018, 2019). In total 4,952 toothfish age estimates were used to construct a single age-length key. Next, 156,523 toothfish length measurements (sampled randomly by the observers from commercial catches in 1988-2020) were split between the four corresponding fisheries, and age was assigned to each fish by conditional probability of the age-length key. Ages ≥31 years were assigned to a plus group. Finally, CAA datasets were constructed as fish counts per age class for each year and fishery, and then expressed as catch proportions-at-age. Ageing error was accounted for in the model by deriving an error misclassification matrix from a normal distribution with CV = 0.1. The CAA data were assumed independently multinomially distributed about the model-predicted CAA.

An important consideration in integrated models is to ensure that the observations are given appropriate weights in the objective function (Francis 2011), and for the CAA data this was achieved by estimating effective sample size for each fishery and year combination. The effective sample sizes were estimated by a two-stage weighting approach: in stage 1 the weights appropriate for the observation error are assigned outside the model, and in stage 2 those weights are adjusted within the model to allow for the process error (Francis 2011). In our assessment, in stage 1 the effective sample sizes were calculated based on the data fit to the multinomial distribution, using the function *neff.obs* from R package *DataWeighting* (Francis 2013). The initial model fit was then run, and the information from that run was used in the stage-2 adjustment of the effective sample sizes, multiplying them by a weighting factor calculated as:

$$w_j = 1/var_i\left[\left(O_{ij} - E_{ij}\right)/\left(v_{ij} - N_{ij}\right)^{0.5}\right]$$

where N_{ij} is the number of multinomial cells, O_{ij} is the observed proportions for age class i in year j, E_{ij} is the expected proportions, and v_{ij} is the variance of the expected age distribution (Method TA1.8 in Table A.1, Francis 2011). The model was then run again with the adjusted effective sample sizes. The most important consequence of the described procedure was down-weighting of CAA data, as otherwise large sample sizes determined as the number of fish measured would give it disproportionate weight, potentially swamping CPUE data in the analysis (Francis 2011).

<u>*Removals*</u>

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, and (c) catches lost to undetected whale depredation.

Catch reports from all available years for the four fisheries and two research surveys were used, going back to 1987. Catch reports that list the fishing effort as *trawl and jig time* (listed under various licenses until 1996) were considered trawls if the unit of effort was ≤1440, the number of minutes in 24 hours. Trawls catch reports without licence information were considered calamari trawls if the dominant species in the catch was *Doryteuthis gahi*. Otherwise, they were considered finfish trawls.

The 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 estimations (e.g. CCAMLR 2010) that IUU fishing in the southern oceans has decreased significantly and assumed IUU to be 5% of the reported catch. The same IUU data was used in the previous year's baseline assessment model.

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. Since removals are treated as input parameters and not as observations in CASAL, they were assumed known without error.

Length-weight relationship

The length-weight relationship was calculated as $W = aL^b$, based on the length and weight measurements of 35,540 toothfish sampled randomly by the observers from commercial catches in 1989-2020. Individual fish weights were expressed in tonnes (to be compatible with the removals in CASAL), lengths in cm, and parameters *a* and *b* are summarized in Table 2.

Von Bertalanffy growth

The length-at-age relationship was described by the von Bertalanffy growth model $L = L_{inf}\left(1 - e^{-k(age - t_o)}\right)$, based on age estimates and length measurements of 4,952 toothfish sampled randomly by observers from commercial catches in 2014-2020. Parameters L_{inf}, k and t_0 are summarized in Table 2.

Maturity

Maturity-at-age vector was based on the maturity stage data estimated by the observers for 155,578 toothfish, sampled randomly from commercial catches in 1988-2020. Maturity was scored on an 8-point scale, and toothfish are considered mature from stage 3 (Laptikhovsky et al. 2006). However, mature toothfish occasionally enter a ‘resting’ stage, and they can skip annual spawning (Collins et al. 2010, Boucher 2018). While in this resting stage, the gonads look very similar macroscopically to stage 2 gonads that are considered immature. Analysis of the available maturity data strongly indicated that due to this, some older fish were erroneously assigned as immature (stage 2) when observed. To address this inaccuracy, a generalized additive model (GAM) was used to predict the expected number of older fish at stage 2, and the maturity data were corrected accordingly, as outlined in Farrugia and Winter (2019). Finally, instead of the more typical logistic function, the maturity ogive was fitted using GAM, resulting in a maturity-at-age vector with proportion of mature fish in each age class from 1 to 31+ (plus group). Parameters of the maturity-at-age vector are summarized in Table 2.

Table 2. Biological input parameters assumed in the model.

Relationship	Parameter	Value				
Length-weight	a ($t \cdot cm^{-1}$)	6.15e-9				
	b	3.115				
Von Bertalanffy growth	L_{inf} (cm)	167.968				
	k (y^{-1})	0.070				
	t_0 (y)	-2.238				
	CV	0.151				
Maturity *(proportion mature at age)*	Age 1	0	Age 12	0.472	Age 23	0.654
	Age 2	0.017	Age 13	0.503	Age 24	0.666
	Age 3	0.056	Age 14	0.530	Age 25	0.681
	Age 4	0.102	Age 15	0.553	Age 26	0.698
	Age 5	0.154	Age 16	0.572	Age 27	0.714
	Age 6	0.209	Age 17	0.587	Age 28	0.728
	Age 7	0.265	Age 18	0.601	Age 29	0.737
	Age 8	0.316	Age 19	0.613	Age 30	0.742
	Age 9	0.362	Age 20	0.624	Age 31+	0.744
	Age 10	0.403	Age 21	0.634		
	Age 11	0.439	Age 22	0.643		

2.3. CASAL model setup

<u>*Population dynamics*</u>

Toothfish population dynamics were described by an age-structured model, with age classes from 1 to 31+ years, the last one being a plus group. It is a single-sex, single-area model, with the annual cycle split into three time-steps. Recruitment, fishing mortality from all concurrent fisheries, and the first half of the year's natural mortality occur in time step 1; spawning and the second half of natural mortality in time step 2; and ageing in time step 3. Since both fishing and natural mortality occur in time step 1, the process was to apply half time step's natural mortality, then fishing mortality instantaneously, then the remaining half of the time step's natural mortality.

Recruitment to the population was calculated by multiplying average recruitment (R_0) with estimated year class strength multipliers (YCS) and a stock-recruitment relationship. Stock-recruitment was assumed to follow a Beverton-Holt relationship:

$$R = \frac{SSB}{SSB_0} \Big/ \left(1 - \frac{5h-1}{4h}\left(1 - \frac{SSB}{SSB_0}\right)\right)$$

where R is the recruitment, SSB is the spawning stock biomass, SSB_0 is the pre-exploitation equilibrium spawning stock biomass, and h is the steepness parameter, defined as the fraction of recruitment from the unfished population when the spawning stock biomass declines to 20% of its unfished level (Mangel et al. 2013). Recruitment was fixed, rather than being estimated, as suggested for example by He et al. (2006) and Kenchington (2014), and the steepness parameter was set to the commonly used reference value h = 0.75 (Punt 2005, Brandão and Butterworth 2009, Dunn and Hanchet 2010, Mormede et al. 2014, Dunn and Parker 2019).

The initial year in the model was set to 1987, the first year of recorded data by the FIFD, and it was run up to 2020. Projections from the model extended for another 35 years, up to 2055. Conditions in the initial year were assumed to be an equilibrium age structure at an unexploited equilibrium biomass.

Estimation method
Model parameters were estimated by minimising the total objective function, which is the sum of the negative log-likelihoods from the observations, the negative-log Bayesian priors, and the penalty functions applied to constrain the parameterisations. The estimated parameter values presented in the report are MPD (mode of the posterior density) point estimates (Bull et al. 2012).

To estimate the joint posterior distribution of the parameters in a Bayesian analysis, the Monte-Carlo Markov Chain (MCMC) method was used. Starting point of each chain was set to the corresponding MPD, length of the burn-in period was set to 1,100,000 iterations, and from the next 10,000,000 iterations every 10000th value was taken. The resulting 1,000 values represent a systematic sample from the Bayesian posterior distribution for the parameter of interest. Chains were investigated for evidence of non-convergence using trace plots, chain autocorrelation plots, and single-chain convergence tests of Geweke (1992) and the stationarity and half-width tests of Heidelberger & Welch (1983).

Estimated parameters
The parameters estimated by the model, their priors, starting values and bounds are given in Table 3, and detailed further in the text.

Table 3. Number of parameters (N), priors, starting values and bounds for the free parameters estimated by the model

Estimated parameter/s		N	Prior	Start value	Lower bound	Upper bound
SSB_0		1	uniform-log	40,000	10,000	100,000
YCS		33	lognormal	1	0.001	20
M		1	uniform	0.13	0.05	0.75
Selectivity $_{LLH}$	a_{50}	1	uniform	10	1	50
	a_{to95}	1	uniform	5	0.05	50
Selectivity $_{LLU}$	a_{50}	1	uniform	10	1	50
	a_{to95}	1	uniform	5	0.05	50
Selectivity $_{FIN}$	a_1	1	uniform	2	1	50
	S_L	1	uniform	1	0.05	50
	S_R	1	uniform	2	0.05	500
Selectivity $_{LOL}$		8	uniform	0.5	0	1
Selectivity $_{RFIN}$		6	uniform	0.5	0	1
Selectivity $_{RLOL}$		6	uniform	0.5	0	1
q_{LLH}		1	uniform-log	-	1e-9	0.1
q_{LLU}		1	uniform-log	-	1e-9	0.1

LLH - Spanish-system longline, LLU - umbrella-system longline, FIN - finfish trawl, LOL - calamari trawl, RFIN - groundfish survey, RLOL - calamari pre-recruitment survey.

SSB_0 is the estimated pre-exploitation equilibrium spawning stock biomass, defined as the spawning stock biomass that would exist with average recruitment in the absence of fishing. For SSB_0, a uniform-log prior was used (Hillary et al. 2006, Dunn and Hanchet 2010, Mormede et al. 2014, Dunn 2019). Year class strength multipliers (YCS) were estimated for the period 1986-2019 (33 parameters, one for each year), using the *Haist parameterisation* to make the YCS parameters average to 1 over the period 1986-2015 (for the Haist method description see Bull et al. 2012). For YCS, a lognormal prior with μ = 1 and CV = 1.1 was used (Constable et al. 2006a, 2006b). Natural mortality (M) was assumed to be constant across all age classes, and the start value of 0.13 year^{-1} was set (Dunn and Hanchet 2010, Mormede et al. 2011, 2013, 2014). Catchability coefficients (q) were estimated for the two CPUE series separately. They were treated as 'nuisance' parameters (default in CASAL), so no starting values had to be provided. For q's, log-uniform priors were considered appropriate (Hillary et al. 2006).

Selectivity-at-age was estimated separately for each fishery and survey to reflect the different age distributions of fish in the catch. Three types of selectivity ogives were used: logistic for longline fisheries, double-normal for finfish trawl fishery, and CASAL *allvalues* for calamari trawl fishery and both surveys. Logistic ogive is defined by two parameters: a_{50} (age at 50% selectivity) and a_{to95} (difference in age at 50% and 95% selectivity), where the value of selectivity at age *x* is given by

$$f(x) = 1/\left[1 + 19^{(a_{50}-x)/a_{to95}}\right].$$

Double-normal ogive is defined by three parameters: a_1 (the mode), S_L (increasing left-hand limb shape parameter) and S_R (decreasing right-hand limb shape parameter), where the value of selectivity at age *x* is given by

$$\begin{aligned} f(x) &= 2^{-[(x-a_1)/S_L]^2}, \quad (x \le a_1) \\ &= 2^{-[(x-a_1)/S_R]^2}, \quad (x > a_1). \end{aligned}$$

The *allvalues* ogive is defined by one selectivity parameter for each age class, meaning that for our CAA data we would have 31 parameters. Since negligible numbers of toothfish older than 8 years were recorded in the calamari fishery, selectivity parameters were estimated only for ages 1-8 and set to zero for the remaining age classes, to reduce the number of estimable parameters. The same procedure was applied to the research surveys, but for ages 1-6. The empirical *allvalues* ogive was used for calamari trawl fishery and research surveys because standard selectivity curves, such as logistic or double-normal, could not fit well the CAA patterns observed in the data, with the highest proportions in the catch corresponding to the lowest age classes (descending ogive).

Selectivities were assumed to remain constant throughout the modelled period. For all selectivity parameters uniform priors were used (Dunn and Hanchet 2010, Mormede et al. 2011, 2013, 2014). It is important to note that what we term 'selectivity' is a combination of *gear selectivity* and *availability* of the fish to the gear (Candy and Constable 2008). For example, trawl gear selectivity most likely doesn't decrease with toothfish age, but the fish availability does, as older individuals leave the trawling grounds for deeper waters. This is the reason toothfish selectivity in trawl fisheries was described by double-normal, instead of logistic ogive. In this report we use the term selectivity because it is consistent with CASAL terminology, but it should be interpreted as *vulnerability*.

Penalties

Besides the observations and priors, final components of the objective function are penalties. Two types of penalties were included in the model: catch limit penalty and vector average penalty. Catch limit penalty was applied to each fishery, to ensure that the model doesn't estimate abundances so low that the recorded removals could not have been taken. Vector average penalty was used to encourage YCS to average to 1. Penalty multipliers were set to 100 for catch limits and 20 for YCS vector average (for details on penalty calculations see Bull et al. 2012).

Yield calculations

MSY was calculated by projecting the estimated current stock status into the future, under a constant hypothetical catch split between the fisheries. For the yield calculations, recruitment for 2016-2055 was assumed to be log-normally distributed with standard deviation σ_R = 0.6 (Dunn and Hanchet 2006, Mormede et al. 2011, 2013, 2014). The future toothfish catch split between fisheries was assumed according to the recent catch history and the current longline catch quota: Spanish-system longline (0 t; 0%), umbrella-system longline (1,040 t; 75.9%), finfish trawl (300 t; 21.9%) and calamari trawl (30 t; 2.2%).

3. Results

Model fits

Diagnostics plots of the model fits to the different observation datasets are provided in Appendix 2. The model fit to the standardized CPUE data for the umbrella-system longline was moderately good, with 95% CI of the observations and estimates overlapping in all analysed years. However, fit to the Spanish-system data was rather poor; although the model approximately followed the overall trend, it underestimated CPUE in the earlier years, and overestimated it in the later years of the fishery (Figure A.3). Corresponding trends in normalised residuals for both longline fisheries are shown in Figure A.4.

The model fit to the catch proportion-at-age data was very good for all four fisheries and both research surveys (Figures A.5 - A.10). The corresponding residual bubble plots show no clear patterns, with the possible exception of longline fisheries, where the model tends to slightly overestimate the proportion of 1-3 year old fish and slightly underestimate the proportions of 4-6 year old fish (Figure A.11). The model fit to the observed mean toothfish age was good in all cases except the Spanish-system longline fishery (Figure A.12).

Likelihood profiles were carried out by fixing SSB_0 over a range of plausible values (10,000 - 100,000 t), while the remaining parameters were estimated. All CAA observations and umbrella-system CPUE observations suggested that low biomass levels were less likely, whilst Spanish-system CPUE observations suggested that the high biomass estimates were less likely (Figures A.13, A.14).

MCMC trace plots showed no evidence of lack of convergence in the most of the estimated parameters, but there was weak evidence of potential non-convergence in the selectivity parameters for ages 5-6 in groundfish survey, and 4-6 in calamari pre-season survey (Figure A.15). The convergence test of Geweke (1992) and the Heidelberger & Welch (1983) stationarity and half-width tests also suggested the failure to converge for these selectivity parameters. Autocorrelations in the MCMC samples for mentioned parameters were high, indicating slow mixing (Figure A.16).

Model estimates

The key output parameters estimated by the stock assessment model are summarised in Table 4, and detailed further in the text.

Table 4. Key output parameters estimated by the model.

Parameter	MPD value	MCMC 95% CI
SSB_0	23,169 t	20,516 - 94,602 t
SSB_{2020}	11,056 t	8,895 - 85,530 t
SSB_{2020}/SSB_0	0.477	0.425 - 0.944
MSY	1,850 t	1,637 - 7,550 t
M	0.192 y^{-1}	0.180 - 0.261 y^{-1}

Overall the MPD estimate of the initial spawning stock biomass (SSB_0) was lower than in the previous year's assessment ($SSB_{0\ in\ 2019}$ = 24,199 t), while the current spawning stock biomass (SSB_{2020}) and the ratio SSB_{2020}/SSB_0 were somewhat higher (SSB_{2019} = 10,637 t, $SSB_{2019}/SSB_{0\ in\ 2019}$ = 0.440). According to the existing harvest control rules (HCR) (Farrugia and Winter 2018, 2019), the current SSB_{2020}/SSB_0 of 0.477 places the stock in the *expansion range*. The estimated historical SSB trend is shown in Figure 2, and the detailed HCR decision matrix used to manage Falkland Islands longline toothfish fishery is given in Appendix 3.

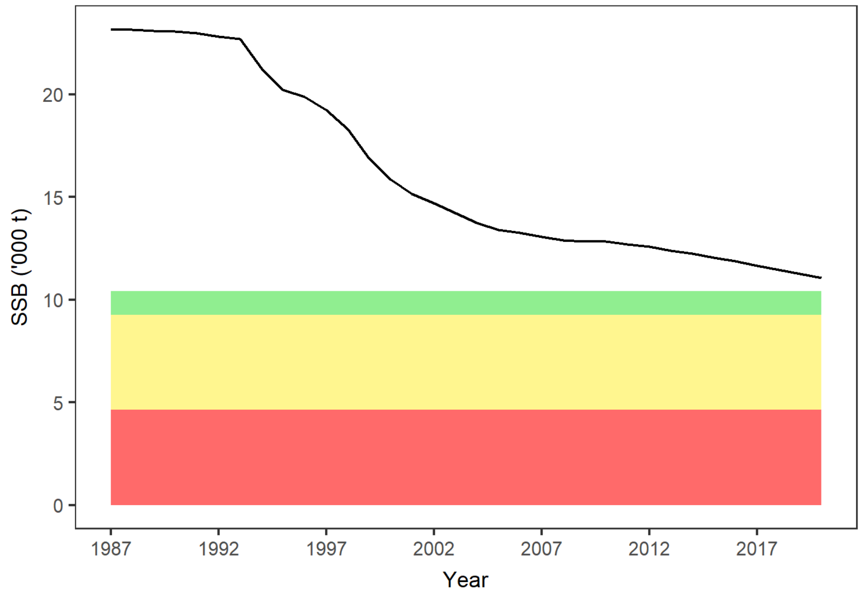

Figure 2. MPD estimate of the historical spawning stock biomass trajectory (black line). Harvest control rule ranges are colour coded for reference: *target range* in green (SSB/SSB_0 = 0.45-0.40), *trigger range* in yellow (SSB/SSB_0 = 0.40-0.20) and *closure range* in red (SSB/SSB_0 < 0.20).

Maximum sustainable yield (MSY), estimated under the assumption of a constant future catch partition, was slightly lower than in 2019 (MSY_{2019} = 1,890 t). Deducting from the MSY 300 t for finfish trawl and 30 t for calamari trawl fishery leaves 1,520 t, well above the current longline toothfish TAC (1,040 t).

MCMC posterior distributions of SSB_0 and SSB_{2019} displayed positive skewness with narrow lower bounds and wide upper bounds (Figure 3). Neither parameter was strongly constrained by the model to an upper limit, but at the same time both are naturally lower bounded at zero as biomass cannot be negative, resulting in asymmetrical 95% confidence intervals.

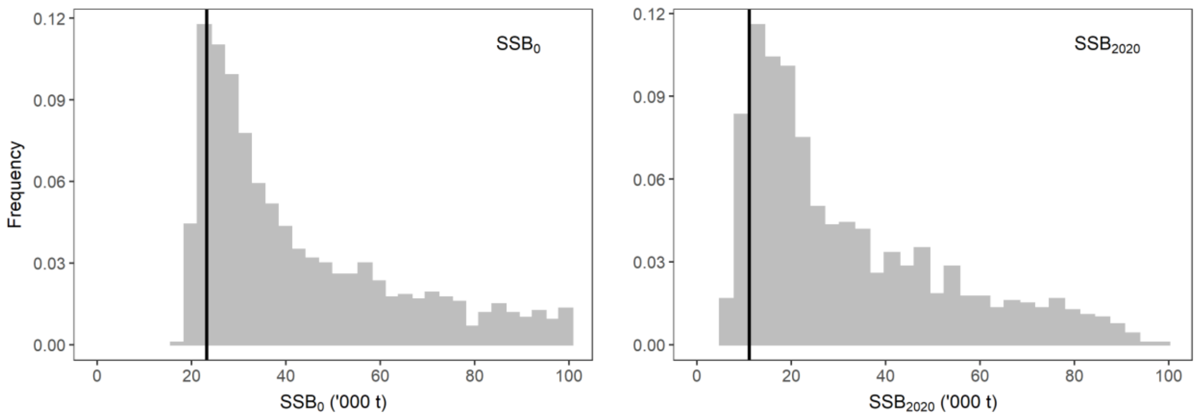

Figure 3. MCMC samples from the posterior distribution of the initial (SSB_0) and current (SSB_{2020}) spawning stock biomass; MPD point estimates are added as a reference (vertical black lines).

The estimated selectivity ogives appeared reasonable, showing the distinct differences in how the longline and trawl fisheries interact with the stock (Figure 4). The calamari trawl fishery catches the youngest fish, as a combination of fishing in shallower waters (=young fish is available) and using small mesh size (=low gear selectivity), which results in the descending right limb selectivity ogive with maximum selectivity for 1-year old fish. Finfish trawl fishery has domed selectivity with maximum for 2-year old fish, and lower selectivity for younger (=presumably escapes due to the gear selectivity) and older fish (=unavailable at trawling grounds). As could be expected, the two longline fisheries have almost identical selectivity curves, catching predominantly older fish available in deeper waters. Selectivity of both research surveys closely resembles the calamari trawl fishery selectivity, which is expected as survey samples are collected using trawls with small cod-end mesh size, comparable to the commercial calamari fishery.

For the selectivity ogives with descending right limb (trawl fisheries and research surveys), MCMC 95% credible intervals were notably asymmetrical, and in the case of surveys, very wide. This is a consequence of previously mentioned MCMC convergence issues for research surveys selectivity parameters at ages 4-6. In general, right-hand limb descending ogives often cause convergence issues in CASAL (Dunn 2013, SAERI CASAL workshop, personal communication).

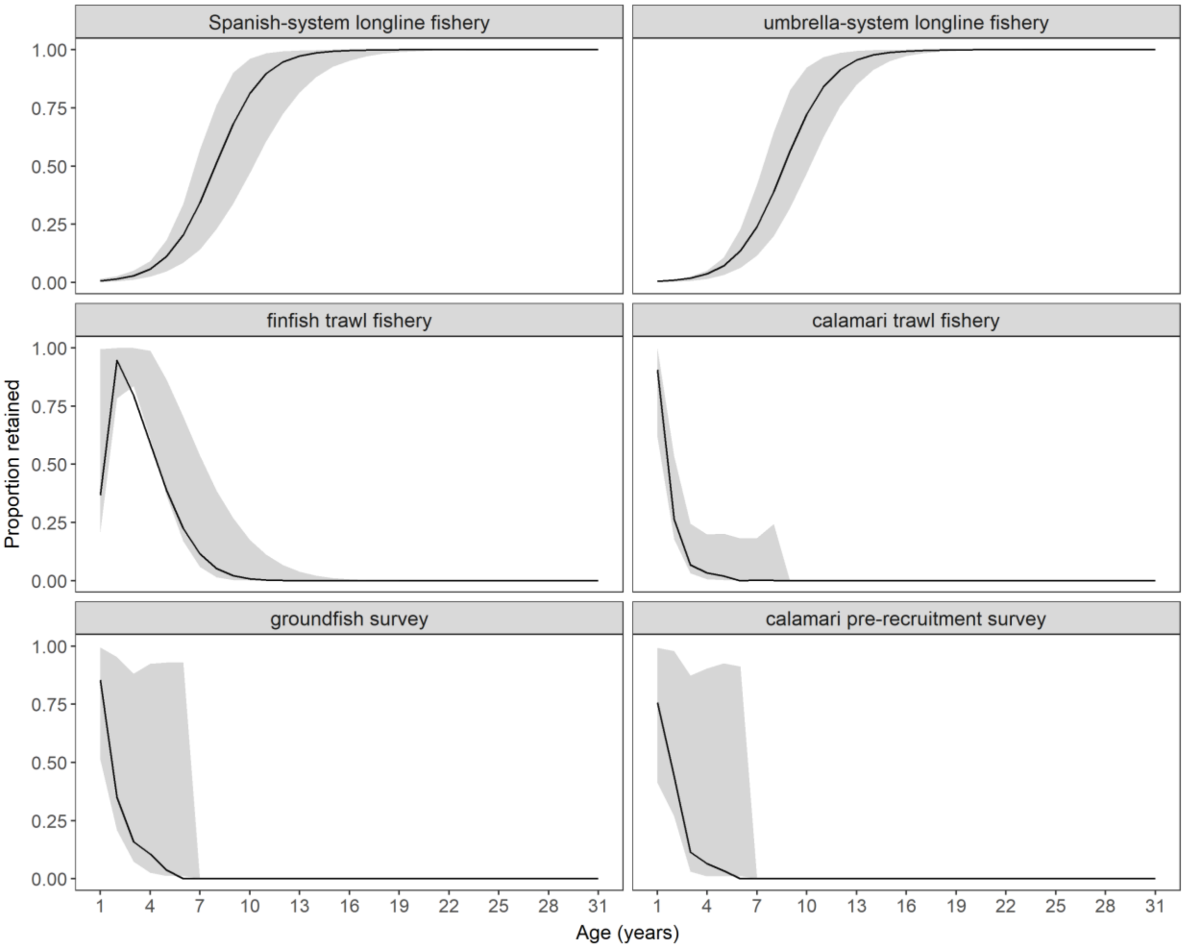

Figure 4. MPD estimates of selectivity ogives for four fisheries and two surveys (lines); shaded areas denote MCMC 95% credible intervals of the model fit.

Year class strength estimates for the most recent years (2015-2019) corresponded well to the CAA data from both research surveys introduced to the model, as well as recruitment estimates independent of the model (Lee, FIFD, personal communication), with strong recruitment peak in 2015, followed by years of low recruitment, interrupted only by a small peak in 2017 (Figure 5). No independent survey data was available for the earlier years, making it difficult to confirm the model estimated YCS trend.

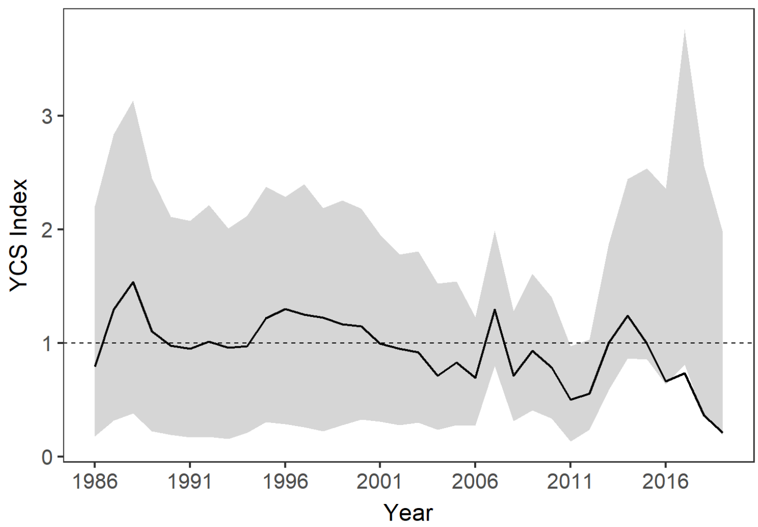

Figure 5. MPD estimates of year-class strengths (solid black line); shaded areas denote MCMC 95% credible intervals of the model fit.

Model projections

The future trend of SSB/SSB_0 was projected based on 5000 MCMC runs, with random lognormal recruitment from 2016-2055 and constant annual catches from 2021-2055 (umbrella-system longline 1,040 t, finfish trawl 300 t, calamari trawl 30 t) (Figure 6). The median SSB/SSB_0 ratio was estimated to remain in the HCR *expansion range*, on a slightly increasing trend, expected to level out by the end of the projection period. The probability of SSB/SSB_0 ratio falling below existing management thresholds, corresponding to the upper bounds of HCR ranges, is shown in Figure 7; the probability of falling below 0.45, 0.40 and 0.20 thresholds during the projection period levels out at ~30%, ~18% and ~0.3%, respectively.

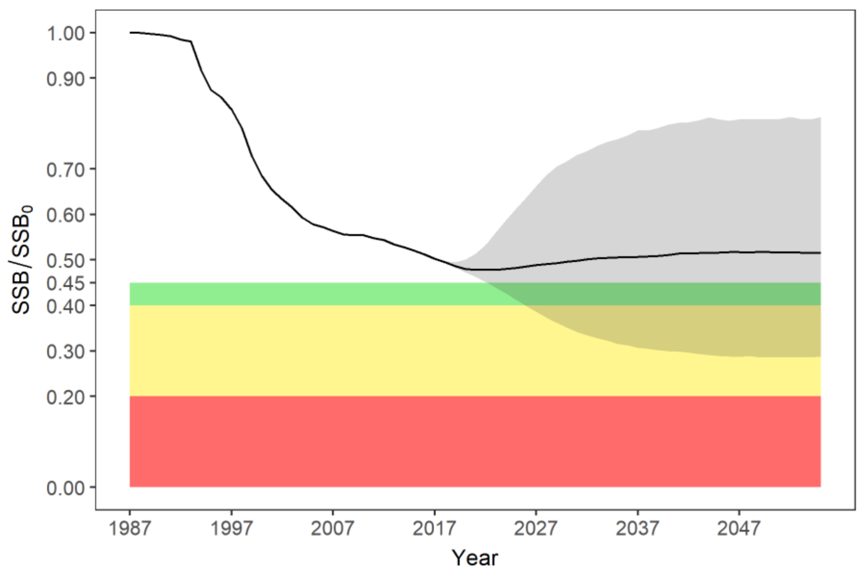

Figure 6. Projected SSB/SSB_0 trend based on 5000 MCMC runs, assuming random lognormal recruitment from 2016-2055 and constant annual catches from 2021-2055. Black line denotes MCMC median, and shaded area MCMC 95% credible intervals of the projection. Harvest control rule ranges are colour coded for reference: *target range* in green (SSB/SSB_0 = 0.45-0.40), *trigger range* in yellow (SSB/SSB_0 = 0.40-0.20) and *closure range* in red (SSB/SSB_0 < 0.20).

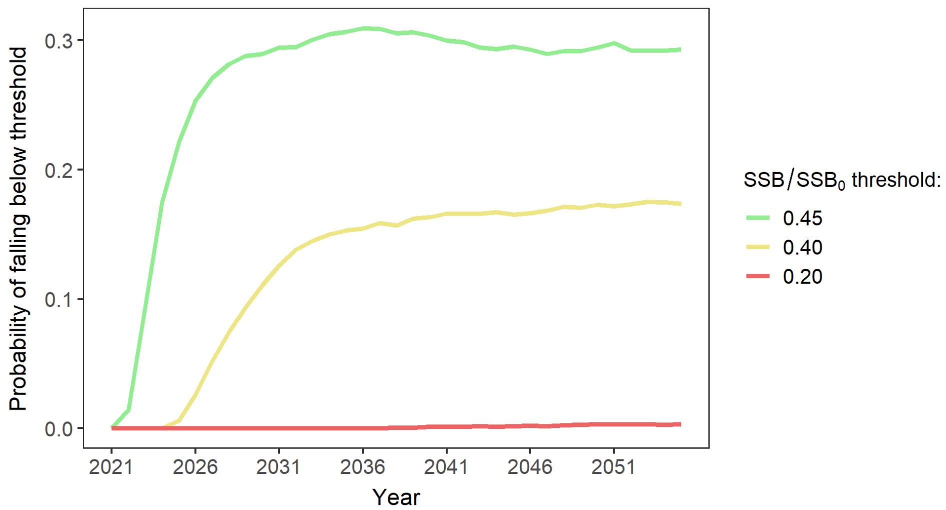

Figure 7. Probability of stock falling below designated SSB/SSB_0 management thresholds; based on 5000 MCMC projections.

4. Discussion

This report presents an updated assessment for Patagonian toothfish (*Dissostichus eleginoides*) in Falkland Islands waters, based on the catch and effort data reported by the fisheries, and toothfish age, length and maturity data collected by observers during commercial trips and research surveys. Compared to the 2019 assessment, this assessment incorporates (a) updated observations and ageing data for 2020, (b) revised longline CPUE time series, (c) CAA observations from two research surveys and (d) revised whale depredation estimates for longline fishery.

The updated assessment for 2020 resulted in lower estimate of SSB_0, but higher estimates of SSB_{2020} and SSB_{2020}/SSB_0 compared to the previous year. Assessing the contribution of different model updates to this change in model estimates is not straightforward due to complex interactions between different datasets (e.g., updating the ALK simultaneously affects CAA data, Von Bertalanffy parameters and selectivity estimates, and each of these in turn can have different effect on the model estimates). However, running multiple models with different combinations of most significant updates indicated that change was mainly driven by the updated CPUE data, and to a lesser extent, whale depredation data. For the umbrella-system fishery, 2020 was the first year since 2017 with recorded increase in CPUE, and this influenced the estimated SSB_{2020}/SSB_0 ratio; excluding the 2020 CPUE datapoint and rerunning the model resulted in lower estimate (0.452), comparable to previous year. Furthermore, Spanish-system CPUE data had the largest overall influence on model outcomes; changing either the treatment of the raw data (outliers, data cleaning) or standardization procedure (using different explanatory variables or modelling techniques) could substantially impact the estimates. In order to make the annual assessments as consistent as possible we tried to keep the changes to the CPUE data minimal, but further review is recommended. Commercial fisheries CPUE data are often the most influential inputs to stock assessment models (Hoyle et al. 2014) and are widely used as an integral part of the stock assessment process (Campbell 2004, Maunder and Punt 2004, Maunder et al. 2006, 2020). However, shortcomings and limitations of this approach are well known and documented (Hilborn and Walters 1992, Harley et al. 2001, Ye and Dennis 2009, Bentley et al. 2011, Thorson et al. 2017). For Falkland Islands toothfish, it might be worth including the tag-recapture data into the model as additional information on the absolute stock abundance. Tag-recapture data are commonly used in Patagonian toothfish and Antarctic toothfish (*Dissostichus mawsoni*) stock assessments (e.g. Hillary et al. 2006, Candy and Constable 2008, Dunn and Hanchet 2010, Mormede et al. 2014, Ziegler and Welsford 2015, Dunn 2019). Although the existing tag-recapture data for Falkland Islands waters are limited (~4400 releases and 175 recaptures since 2016), a 4-year extension of the tagging programme has recently been recommended (Lee and Skeljo 2020). Following this advice, targeted tagging efforts were renewed in 2021 after a two-year hiatus (Skeljo and Pearman 2021). It is recommended that the option of introducing tag-recapture data in the stock assessment be discussed at FIFD and MSCSG and, if needed, external consultation requested on how to incorporate these data into the CASAL software framework.

Introducing CAA data from research surveys had comparatively low effect on the model estimates, as did the exclusion of pre-2008 calamari trawl fishery CAA data. The main reason for including surveys into the model was to provide additional fishery-independent information on toothfish recruitment. Surveys cover the shelf area where juvenile toothfish are found and the use of small mesh size ensures that they are adequately sampled. However, it was found that calamari pre-season survey and commercial calamari fishery provide similar information; excluding each in turn and rerunning the model resulted in almost identical estimates. This is not surprising as both use similar trawl mesh size, cover the same area, and the 100% observer coverage of calamari fishery presumably helps in getting precise estimates of juvenile toothfish bycatch. On the other hand, groundfish survey provides some additional information compared to finfish trawl fishery; even though they cover similar grounds, smaller mesh size used during the survey results in CAA structure dominated by the youngest age class, which is under-represented in commercial fishery due to gear selectivity. Overall, commercial trawl fisheries and two research surveys jointly seem to provide adequate information on the recruitment YCS.

Biological input parameters changed only slightly compared to the previous assessment (due to the new available age readings) and had negligible effect on the model estimates.

The model sensitivity analysis done in 2020 (Skeljo and Winter 2020) suggested a data conflict in the model, i.e. different observations give conflicting information about the stock status. In this assessment we explored this via log likelihood profiles of different observations (Figure A.14), revealing that only the Spanish-system CPUE data strongly constraints SSB_0 values to a lower estimate. The remaining observations are in general indicating that higher SSB_0 is more likely and/or their likelihood profile does not strongly constrain SSB_0 to an upper limit (i.e. higher SSB_0 values are only slightly less likely than the current best estimate). To confirm this, each observation (6 CAA and 2 CPUE datasets) was in turn excluded from the analysis and the model was rerun. Removing one of the trawl fisheries or survey CAA datasets had comparatively little impact on the model estimates, as they provide similar information and can be used interchangeably to an extent. Excluding umbrella-system fishery CAA and CPUE data resulted in lower estimates, i.e. these observations are driving the model estimates up when included in the analysis. Excluding Spanish-system CPUE data resulted in the highest SSB_0 estimates by far, at the upper limit allowed in the model; this is in accordance with the likelihood profile analysis and confirms that the Spanish-system CPUE data are driving the biomass estimates down. We conclude that these data provide the model with vital information on the resource depletion taking place in the early years of fishery, not captured by other observations. In this way, Spanish-system CPUE acts as an anchor that prevents the biomass estimates from gaining exaggerated values. Given its high influence on the model outcomes, further refinement of the Spanish-system dataset is recommended, regarding both the treatment of the raw data (data cleaning) and the standardization process (GLMM).

Finally, it should be noted that further model refinements are anticipated, based on (a) external review recommendations for Falkland Islands toothfish assessment (Bergh 2018), (b) best practices in toothfish stock assessments around the world, and (c) findings of our previous stock assessments and sensitivity analyses. These improvements will be incorporated as they become available.

5. Management advice

Management advice is based on harvest control rules (HCR) established for the Falkland Islands toothfish longline fishery (Farrugia and Winter 2018, 2019) (Appendix 3). The estimated SSB_{2020}/SSB_0 ratio of 0.477 is above *upper target reference point* (0.45), i.e. in the *expansion range*, and the projection suggests it will remain above 0.45 in the future. Since the previous year's ratio was below 0.45, and at least three consecutive years within the expansion range are required before considering TAC alterations, no action is anticipated by HCR at this point.

The recommendation for the toothfish longline fishery is to maintain the annual total allowable catch (TAC) at its current level of 1,040 tonnes.

6. Future assessment requirements

Based on the insights from the current assessment, as well as recommendations from the external review of Falkland Islands toothfish stock assessment (Bergh 2018), several points for future consideration and model refinement were identified:

Model structure

- Explore the option of sex-structuring the model, i.e. treating the CAA and biological data separately for males and females.

Observations

- Explore the option of including the existing toothfish tag-recapture observations into the model, as additional information on stock abundance.

Maturity

- Review the maturity-at-age data; collect new samples and model maturity by fitting the logistic ogive to the revised data.

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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 our stock assessment model. In order to provide unbiased indices of relative stock abundance, these CPUE data had to be standardized to remove the impact of explanatory variables other than abundance (Maunder and Punt, 2004). CPUE standardization has been slightly modified this year by employing a generalized linear mixed modelling approach (GLMM; Pinheiro and Bates 2000), an extension of the generalized linear modelling approach (GLM) used in the previous assessments. GLMMs were fitted using package glmmTMB (Brooks et al. 2017, Magnusson et al. 2017) implemented in R (R Core Team, 2020).

Prior to modelling, data exploration was applied following the protocol described in Zuur et al. (2010). Variables where inspected for outliers and collinearity. Continuous explanatory variables were scaled, i.e. mean was subtracted from the individual values, and the values were divided by its standard deviation. 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 (Maunder and Punt 2004). 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 three broad areas: (a) within the Falklands zone and south of 53.5° S (Burdwood Bank spawning area), (b) within the Falklands zone and north of 53.5° S, and (c) outside the Falklands zone. *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 temporal dependency.

Fitting GLMM to the Spanish-system data included the explanatory variables *Year*, *Month*, *Region*, *Soak-time* and *Vessel*, and the model explained 21.9% 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 13.3% 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.

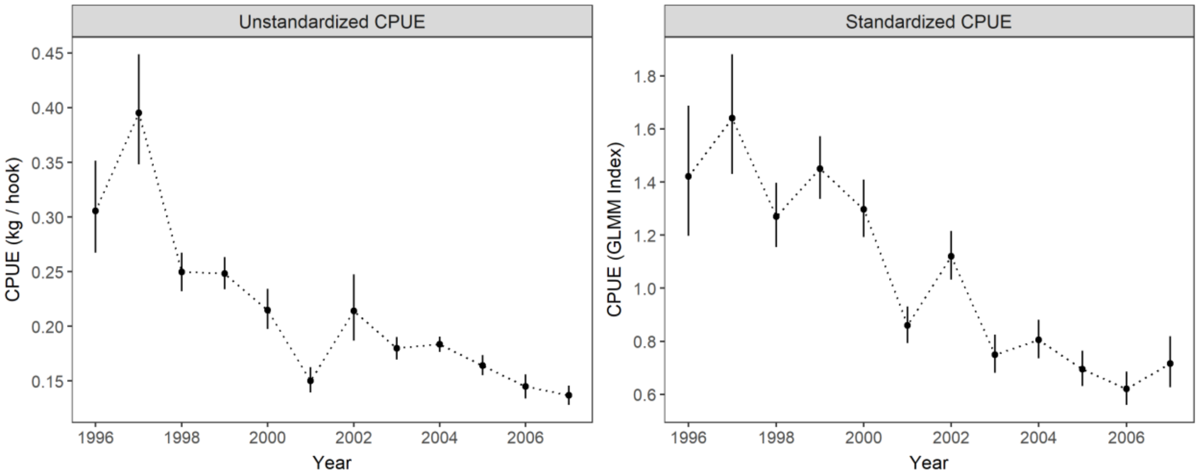

Figure A.1. Spanish-system longline unstandardized and standardized CPUE time series; black vertical lines correspond to 95% confidence intervals.

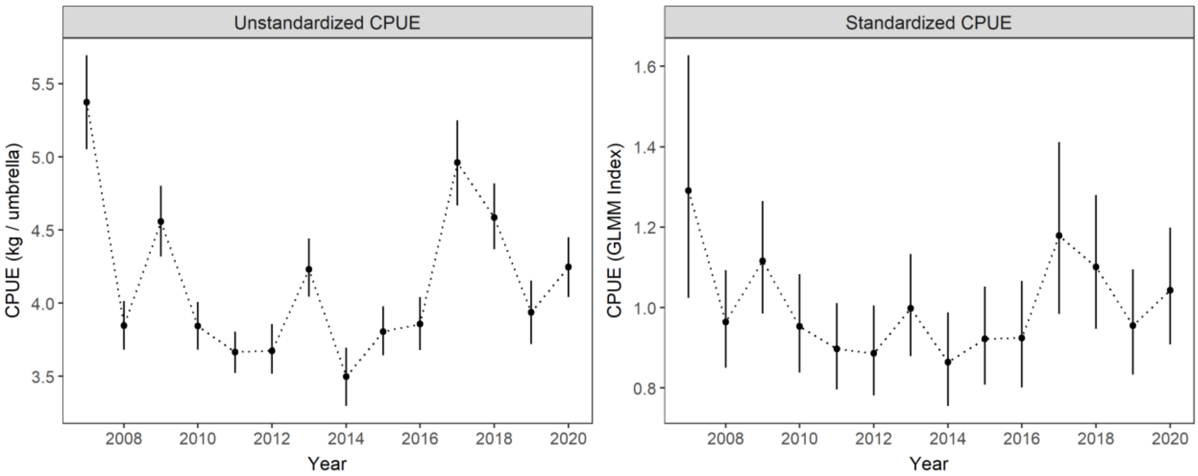

Figure A.2. Umbrella-system longline unstandardized and standardized CPUE time series; black vertical lines correspond to 95% confidence intervals.

Appendix 2. Diagnostics plots

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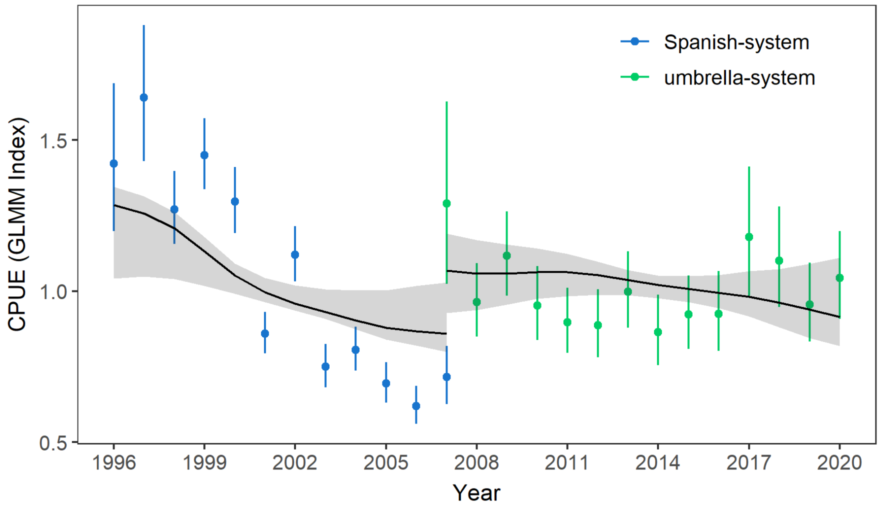

Figure A.3. MPD model fit (black line) to the standardised CPUE indices for Spanish-system (blue dots) and umbrella-system longline (green dots); Vertical blue and green lines denote 95% confidence intervals of the standardised CPUE indices; shaded areas denote MCMC 95% credible intervals of the model fit.

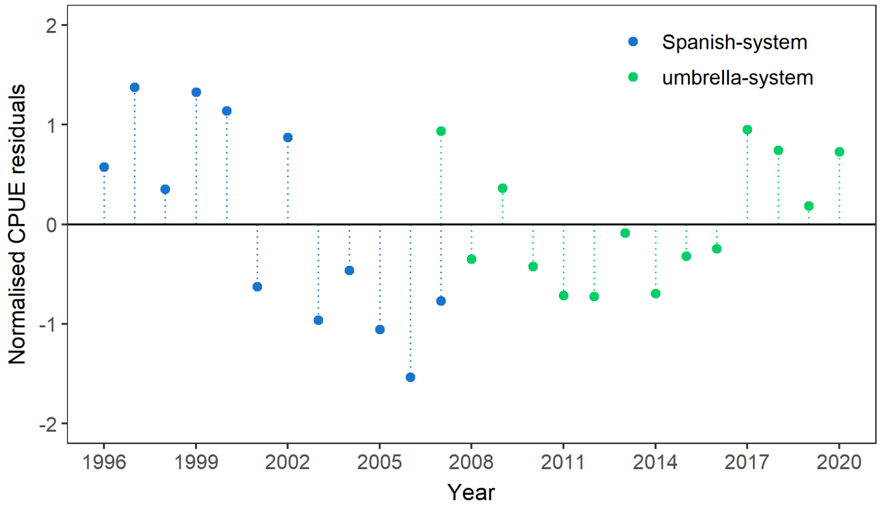

Figure A.4. Normalised residuals from the model fit to the standardized CPUE time series; for Spanish-system (blue) and umbrella-system longline (green).

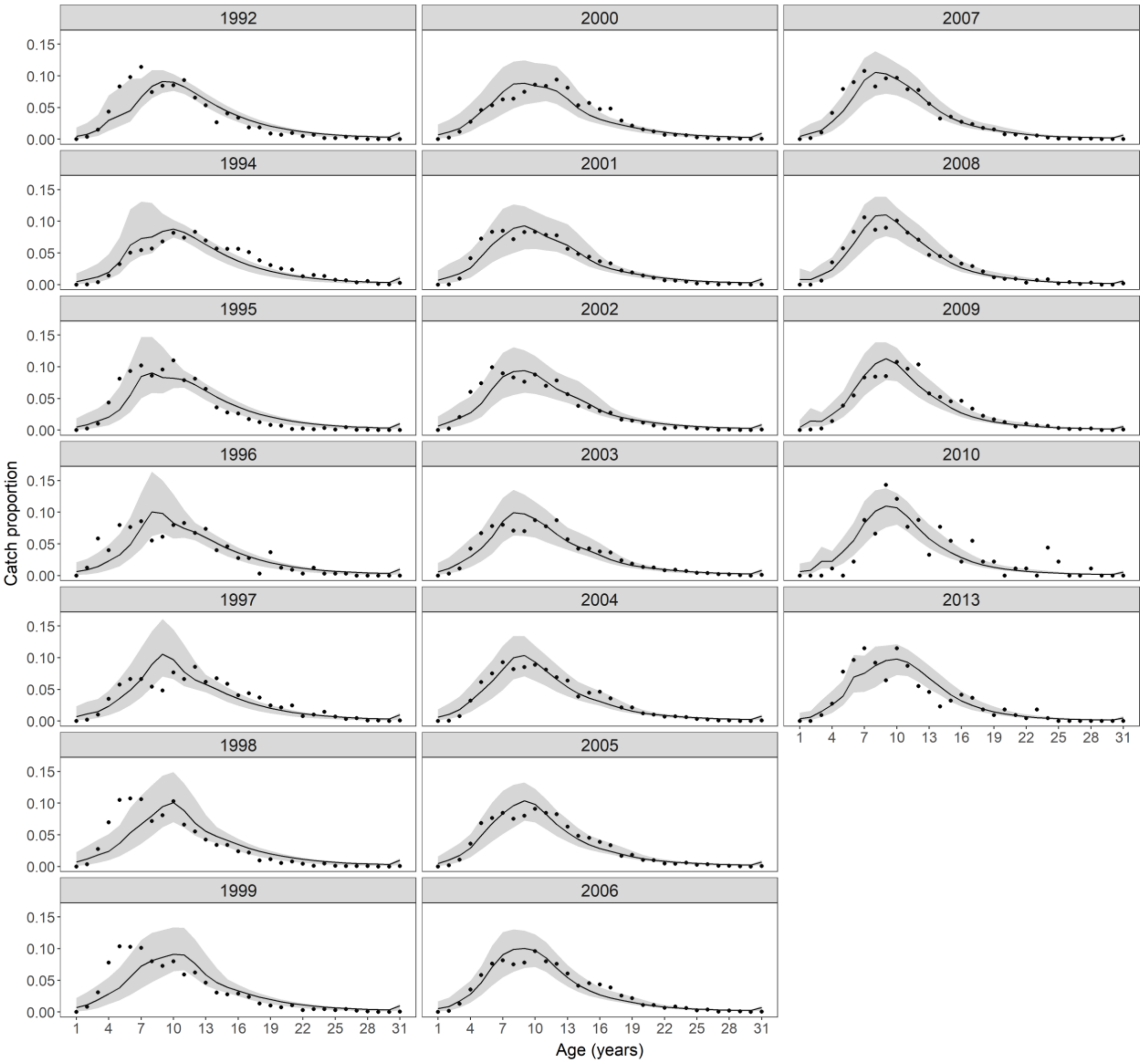

Figure A.5. MPD model fits (solid line) to the observed toothfish catch-proportion-at-age data for the Spanish-system longline fishery (dots); shaded areas denote MCMC 95% credible intervals of the fit.

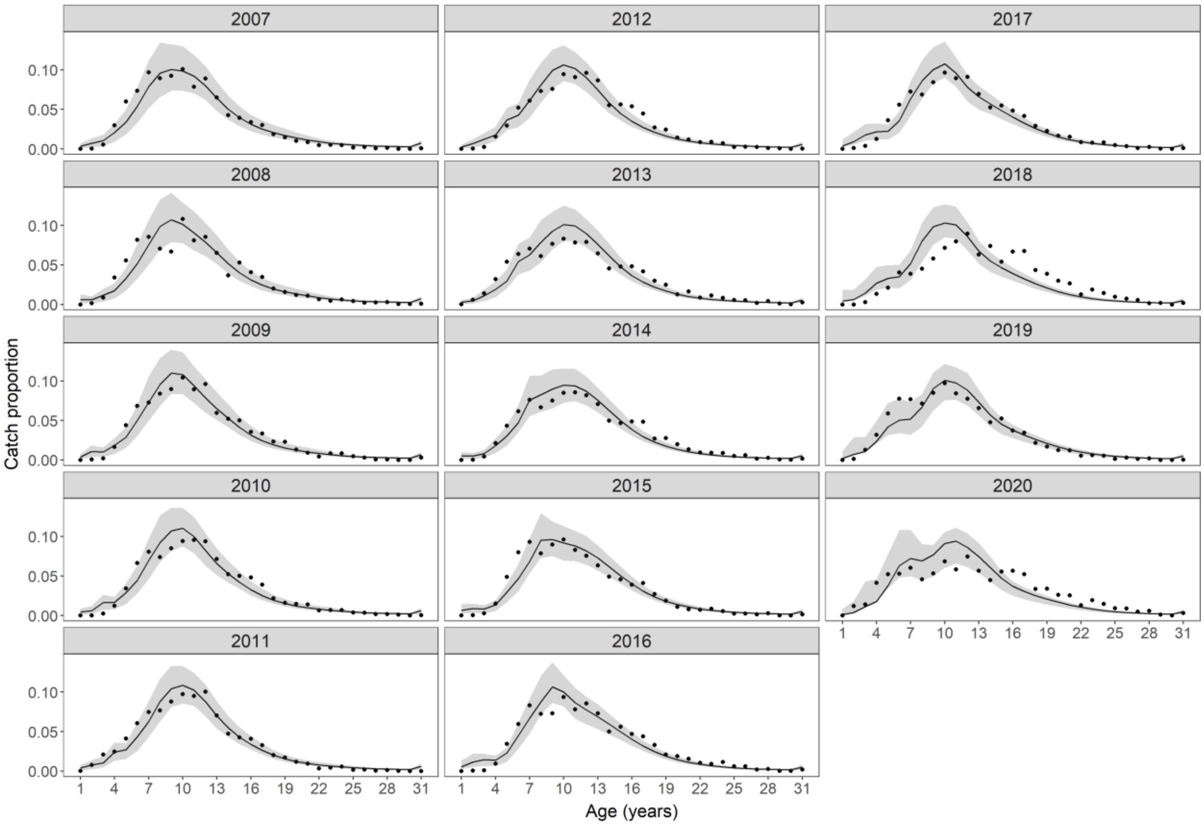

Figure A.6. MPD model fits (solid line) to the observed toothfish catch-proportion-at-age data for the umbrella-system longline fishery (dots); shaded areas denote MCMC 95% credible intervals of the fit.

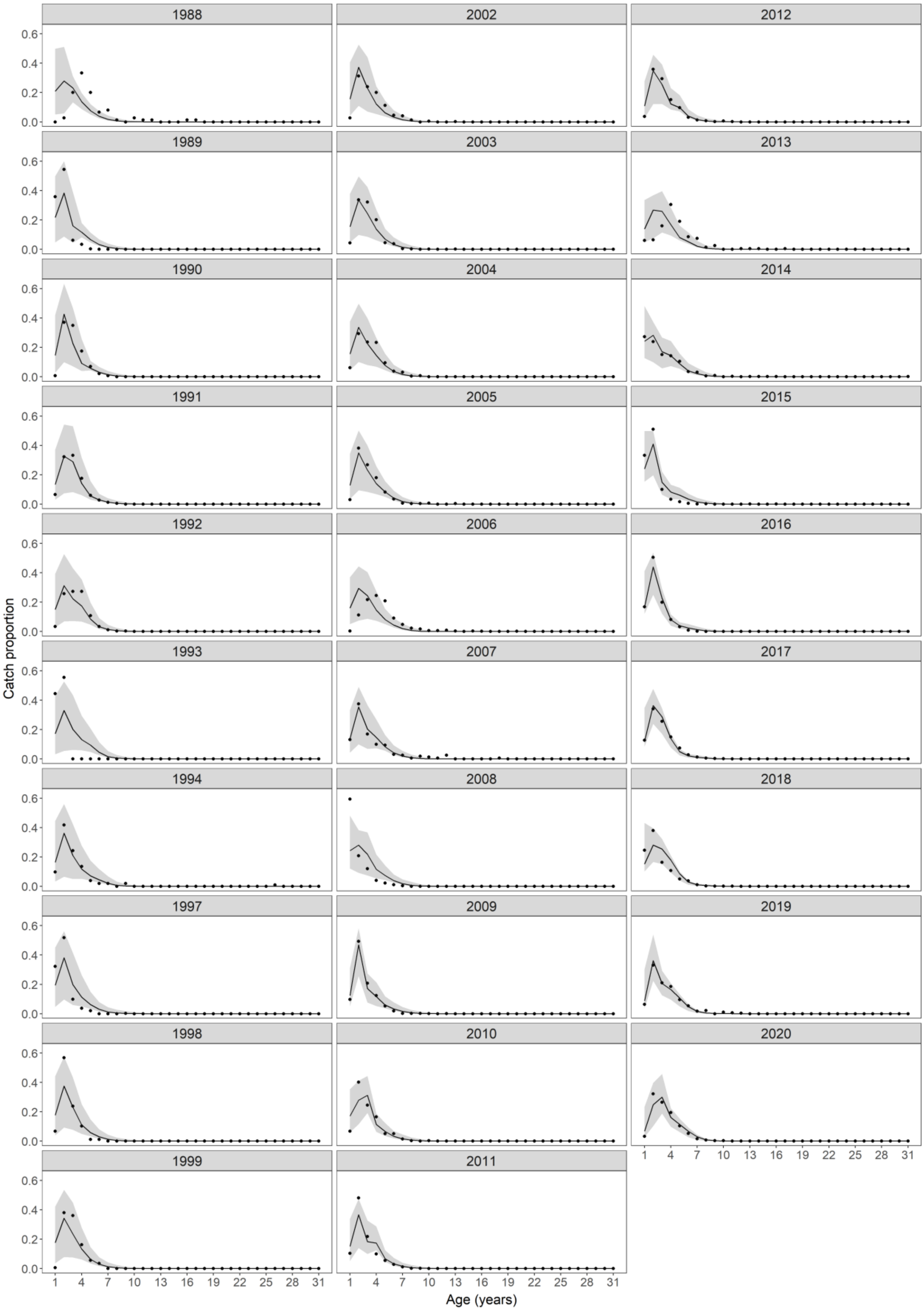

Figure A.7. MPD model fits (solid line) to the observed toothfish catch-proportion-at-age data for the finfish trawl fishery (dots); shaded areas denote MCMC 95% credible intervals of the fit.

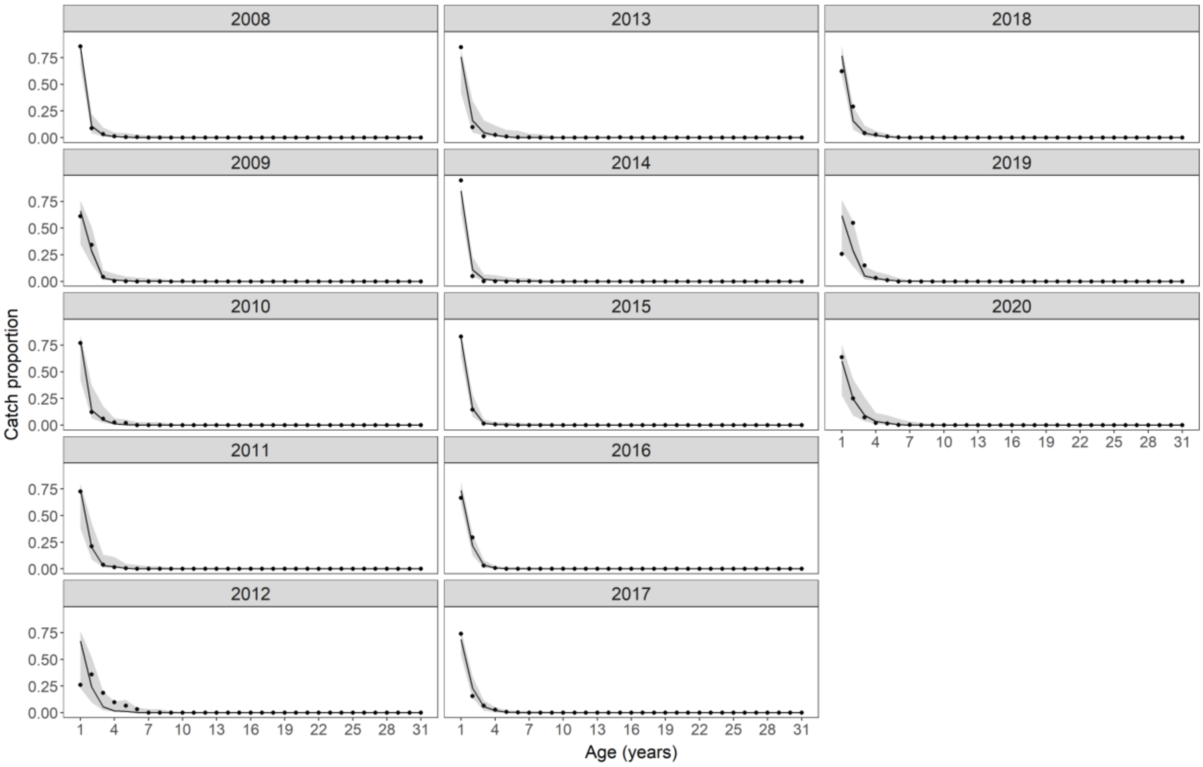

Figure A.8. MPD model fits (solid line) to the observed toothfish catch-proportion-at-age data for the calamari trawl fishery (dots); shaded areas denote MCMC 95% credible intervals of the fit.

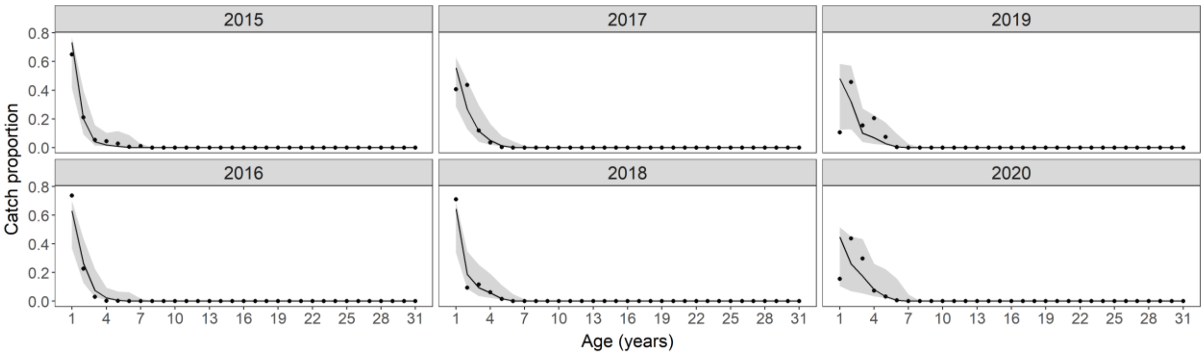

Figure A.9. MPD model fits (solid line) to the observed toothfish catch-proportion-at-age data for the groundfish survey (dots); shaded areas denote MCMC 95% credible intervals of the fit.

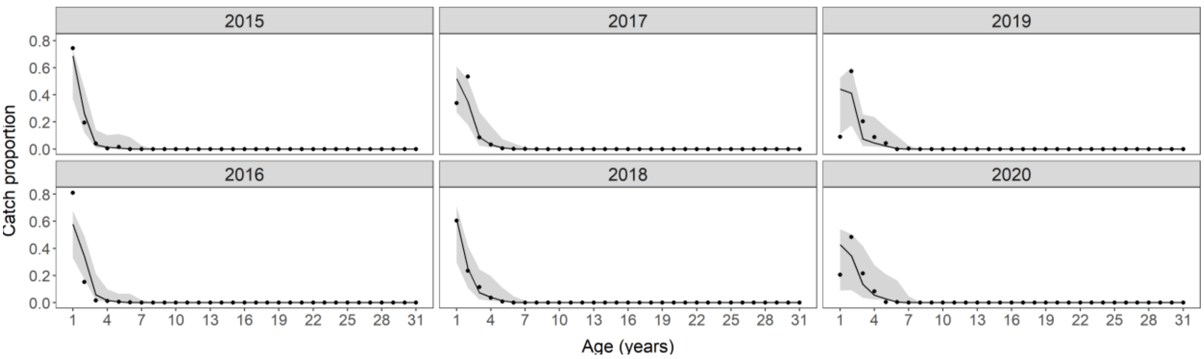

Figure A.10. MPD model fits (solid line) to the observed toothfish catch-proportion-at-age data for the calamari pre-recruitment survey (dots); shaded areas denote MCMC 95% credible intervals of the fit.

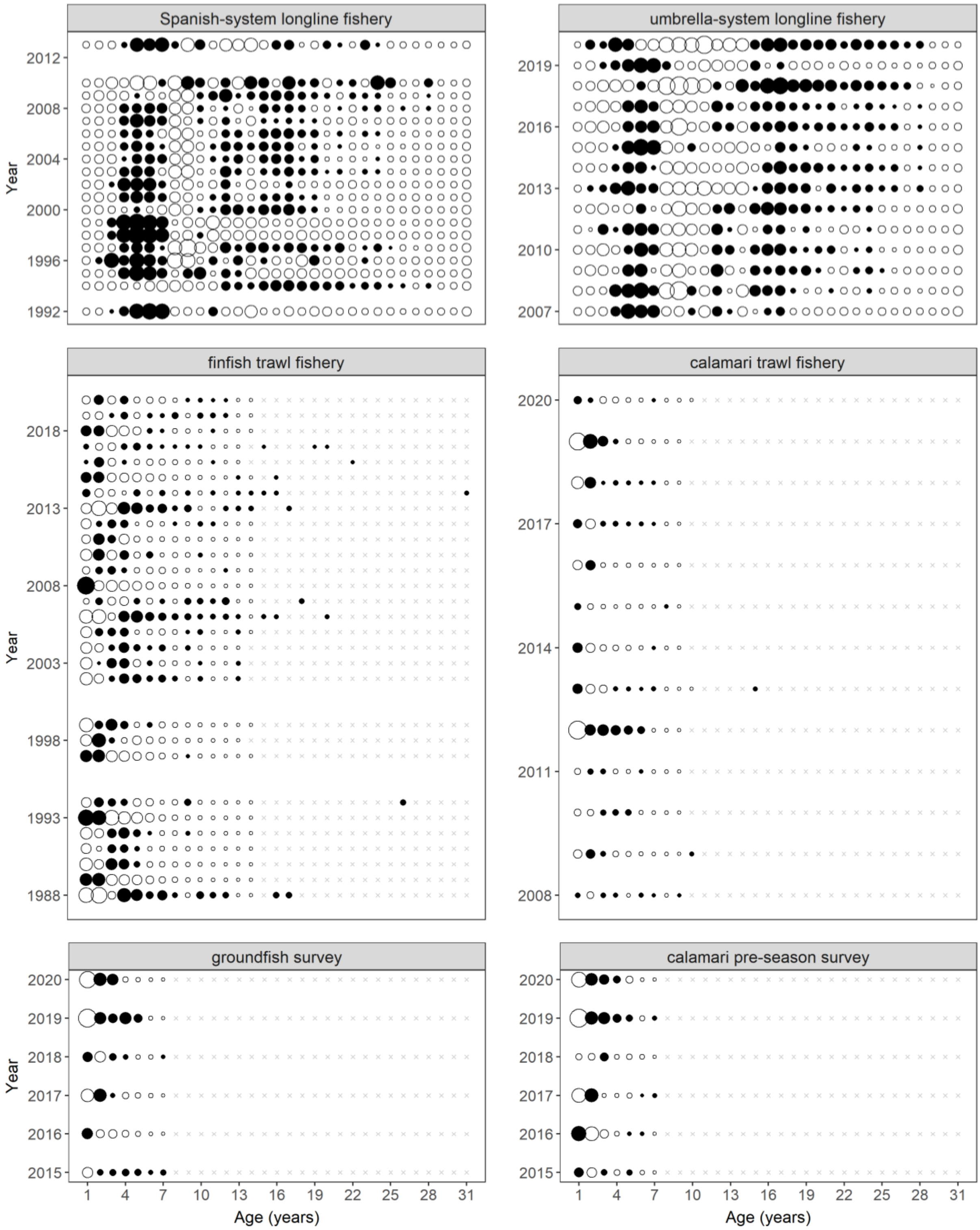

Figure A.11. Residuals from the model fit to observed catch-at-age for four fisheries and two research surveys. Bubble size is relative to the absolute residual value; positive residuals shown as full circles, negative as empty circles.

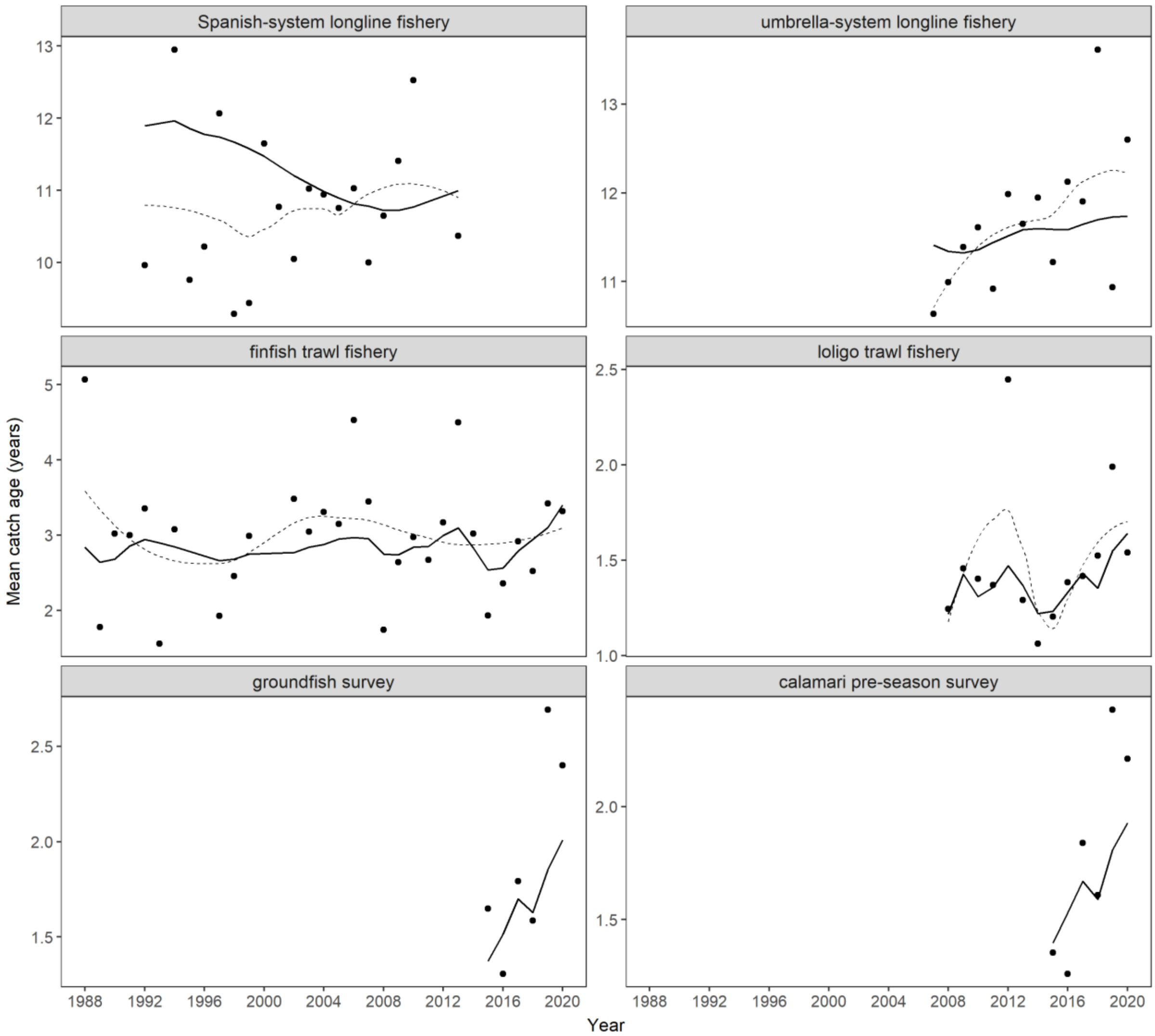

Figure A.12. Model fits (solid lines) to the observed toothfish mean catch-at-age data for four fisheries and two research surveys (black dots); dashed lines denote loess smoothers for the observations (span = 0.75); smoothers were omitted for the survey datasets due to the low number of data points.

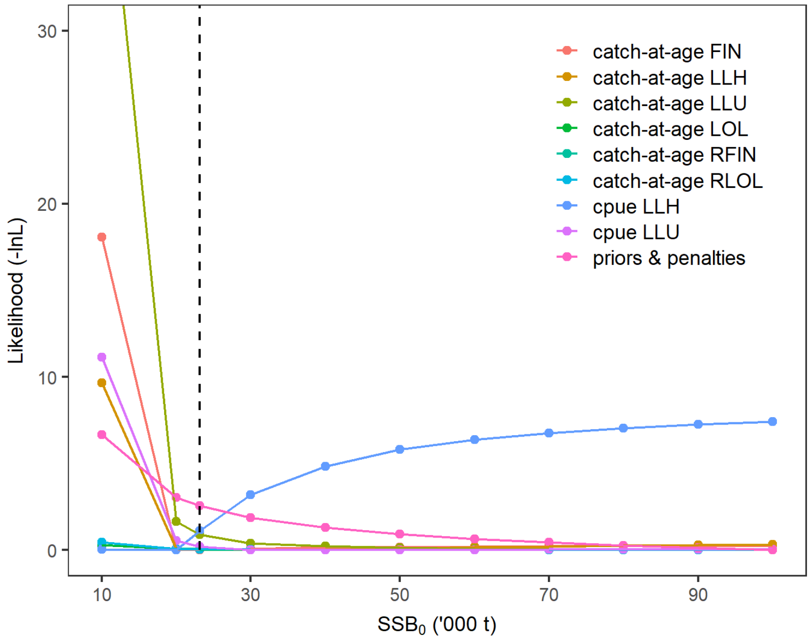

Figure A.13. Likelihood profiles for SSB_0. Negative log likelihood values rescaled to have minimum of zero for each dataset. The dashed vertical line denotes MPD estimate for SSB_0. LLH - Spanish-system longline, LLU - umbrella-system longline, FIN - finfish trawl, LOL - calamari trawl, RFIN - groundfish survey, RLOL - calamari pre-recruitment survey.

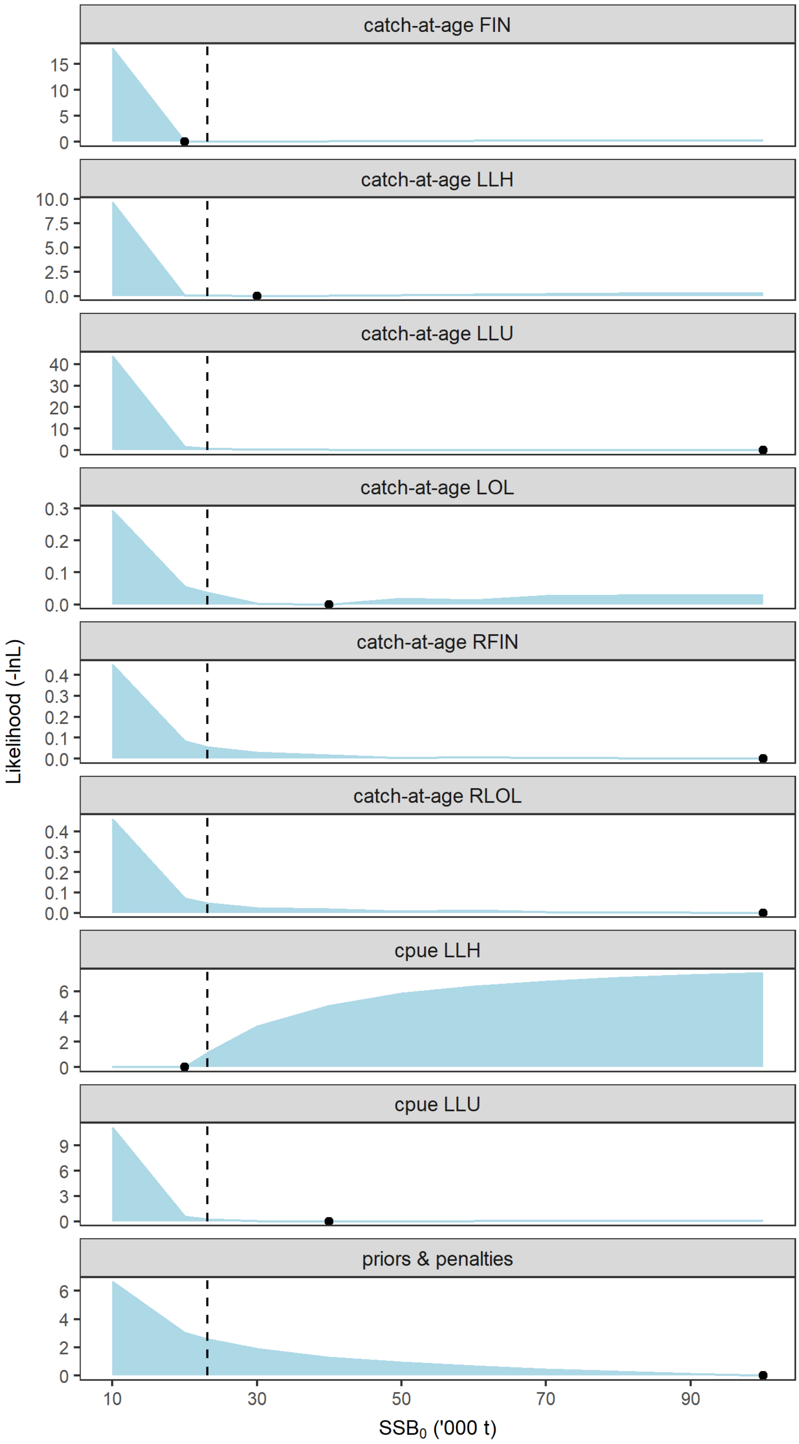

Figure A.14. Likelihood profiles for SSB_0. Negative log likelihood values rescaled to have minimum of zero for each dataset. The dashed vertical lines denote MPD estimate for SSB0; dots denote the SSB0 values with the minimum negative log likelihood value for each dataset. LLH - Spanish-system longline, LLU - umbrella-system longline, FIN - finfish trawl, LOL - calamari trawl, RFIN - groundfish survey, RLOL - calamari pre-recruitment survey.

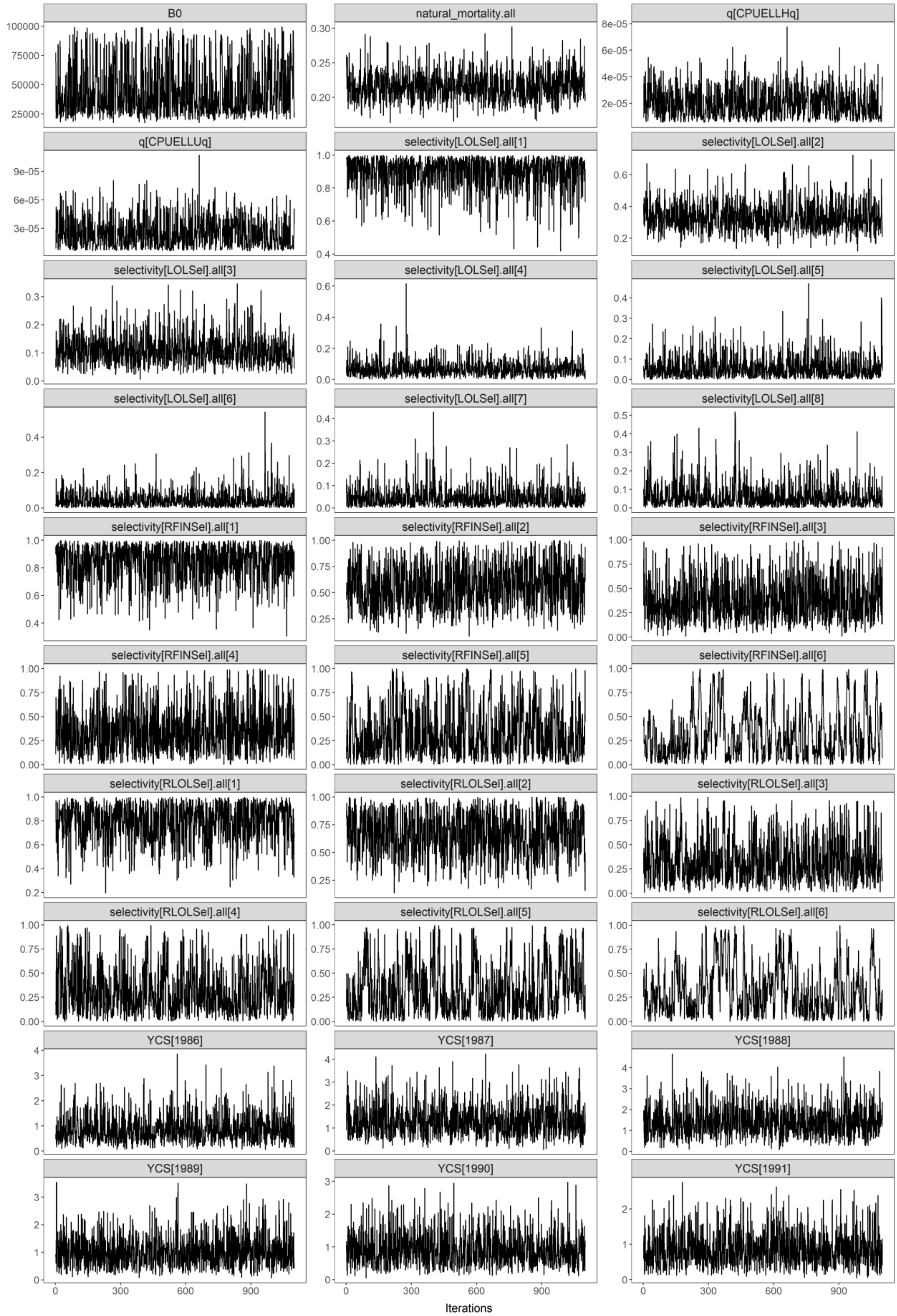

Figure A.15. MCMC posterior trace plots for the estimated parameters; note that the selectivity parameters for LLH, LLU and FIN have been omitted to keep the number of plots manageable (figure 1 of 2).

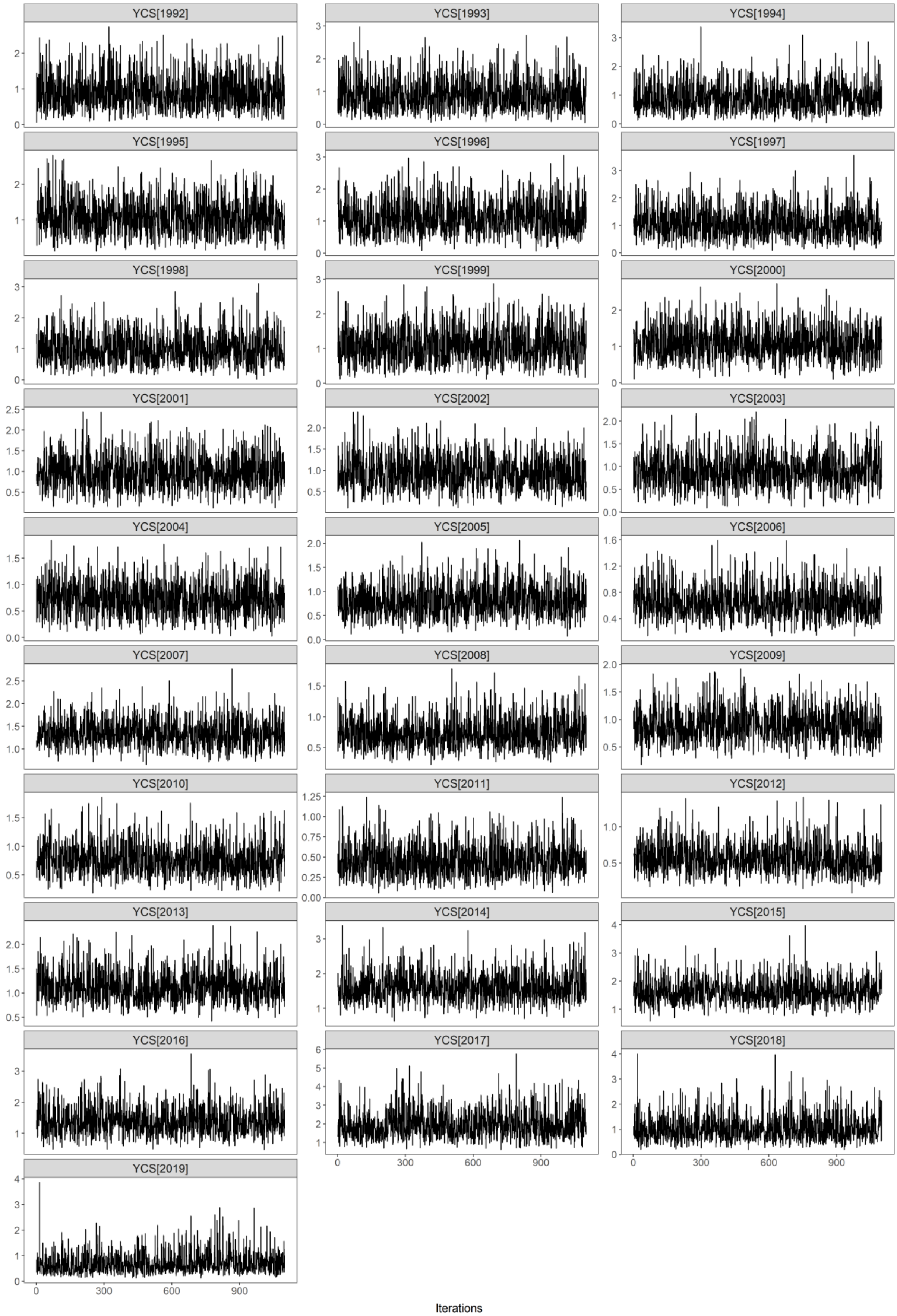

Figure A.15. Continued (figure 2 of 2).

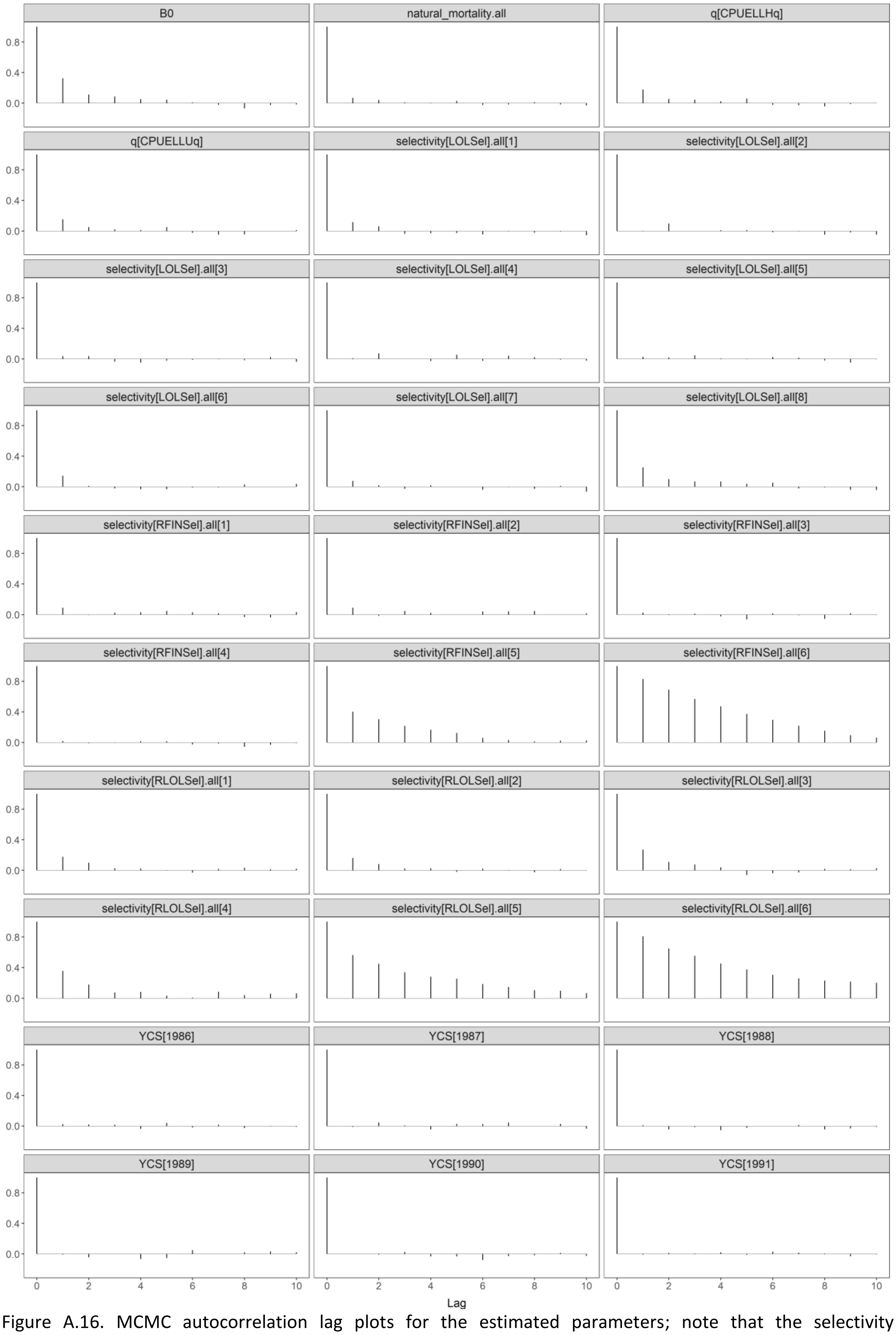

Figure A.16. MCMC autocorrelation lag plots for the estimated parameters; note that the selectivity parameters for LLH, LLU and FIN have been omitted to keep the number of plots manageable (figure 1 of 2).

Figure A.16. Continued (figure 2 of 2).

Appendix 3. Harvest control rules

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Based on the CASAL model output, the following decision matrix of harvest control rules has been established to manage the Falkland Islands toothfish longline fishery (Farrugia and Winter 2018, 2019):

1. *Expansion range:* If the ratio of $SSB_{current}/SSB_0$ has remained above the upper target reference point (45%) for 3 consecutive years and the SSB projection with the current TAC shows no decrease below 45% for at least 10 years (one generation) under precautionary assumptions, the Director may authorize an increase in longline TAC to a level that continues to show no projected $SSB_{current}/SSB_0$ decrease to below 40% (trigger point) for at least 10 years under precautionary assumptions.

2. *Target range:* If the ratio of $SSB_{current}/SSB_0$ is between 40% and 45% (within the target range), current longline TAC is reviewed in relation to stock trends. Current TAC may be maintained if $SSB_{current}/SSB_0$ has increased from the previous assessment, or if the SSB ratio projection shows a level status under precautionary assumptions. TAC may not be increased, but it may be decreased if age-structure distributions anticipate weak recruitment.

3. *Trigger point and range:* If the ratio of $SSB_{current}/SSB_0$ falls to ≤ 40% (trigger point), longline TAC will be decreased to a level that projects an increasing SSB trend under precautionary assumptions. The magnitude of the proposed TAC reduction will be examined using three methods (adapted from ICES, 2017):

    a. Indexed to the reduction of the MSY estimates:
    $$TAC_{year} = TAC_{year-1} * \left(MSY_{year}/MSY_{year-1}\right)$$
    b. Indexed to the reduction of the SSB estimates:
    $$TAC_{year} = TAC_{year-1} * \left(SSB_{year}/SSB_{year-1}\right)$$
    c. Indexed to the reduction in SSB ratios:
    $$TAC_{year} = TAC_{year-1} * \left(SSB\ ratio_{year}/SSB\ ratio_{year-1}\right)$$

    TACs obtained from all three methods will be projected forward in the stock assessment model and the trends in SSB will be compared. The final method will be chosen based on it returning the SSB ratio to above 40% within 10 years (one generation) of the SSB ratio falling below 40%. If more than one method meets this requirement, the chosen method will also depend on discussions between the Fisheries Department and industry.

4. *Limit reference point:* If the ratio of $SSB_{current}/SSB_0$ is ≤ 20%, the longline fishery will be closed pending comprehensive evaluation of conditions required to rebuild the stock. The Director may authorize test fishing to measure biological parameters of the stock, subject to close monitoring by the Fisheries Department.