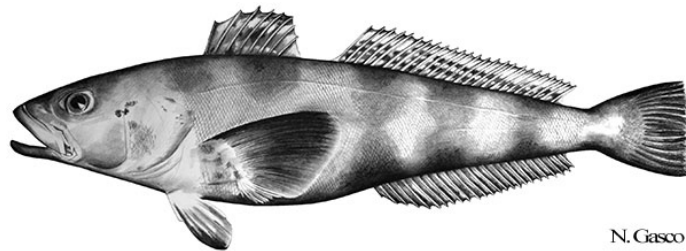


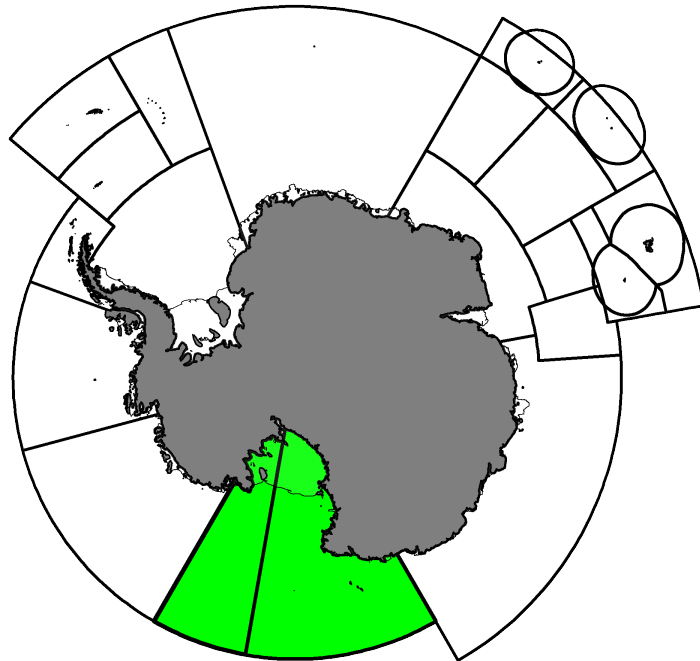
Stock Assessment Report 2023: *Dissostichus mawsoni* in Subarea 88.1

CCAMLR Secretariat

04 March 2024



Antarctic toothfish *Dissostichus mawsoni* Norman, 1937.



Map of the management areas within the CAMLR Convention Area. Subarea 88.1, SSRUs 882A and 882B, the regions discussed in this report are shaded in green. Throughout this report, “2023” refers to the 2022/23 CCAMLR fishing season (from 1 December 2022 to 30 November 2023). Coastlines and ice shelves: UK Polar Data Centre/BAS and Natural Earth. Projection: EPSG 6932.



CCAMLR

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Commission pour la conservation de la faune et la flore marines de l'Antarctique
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Assessment model for Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea region to 2022/23

Mormede, S., A. Grüss, A. Dunn and J. Devine



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Assessment model for Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea region to 2022/23

Mormede, S.¹; Grüss, A.²; Dunn, A.³; and Devine, J.⁴

¹ soFish Consulting, Ltd., Wellington, New Zealand

² National Institute of Water and Atmospheric Research, Wellington, New Zealand

³ Ocean Environmental Ltd., Wellington, New Zealand

⁴ National Institute of Water and Atmospheric Research, Nelson, New Zealand

ABSTRACT

This paper reports on the update of the Bayesian sex- and age-structured integrated stock assessment model for Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea region (RSR; Subareas 88.1 and Small-Scale Research Units (SSRUs) 88.2A-B) using the most recent available data for the RSR Antarctic toothfish fishery. The assessment model used catch data for 1998–2023, tag-release data for 2004–2022 and associated tag-recapture observations for 2005–2023, fishery catch-at-age data for 1998–2022, abundance observations from the Ross Sea Shelf Survey (RSSS) for 2012–2023, and age observations from the RSSS for 2012–2022. Data (releases and recaptures of tagged fish, and length data) from vessel trips that had been quarantined since the 2019 assessment were excluded. The model structure was the same as that used in 2021, updated to the software Casal2 and including the recommendations of the 2023 Working Group on Statistics, Assessments and Modelling.

The 2023 base case model Markov chain Monte Carlo estimated MCMC estimated B_0 as 77 855 t (95% CIs 71 954–85 115 t) and the current stock status (B_{2023}) as 64.3% B_0 (95% CIs 61.3–67.3% B_0). The MPD estimated status in 2021 from the 2023 assessment (66.8%) was almost the same as that estimated by the 2021 assessment (66.0%). The maximum posterior density estimate of spawning stock biomass trajectory was almost identical in the equivalent model run in CASAL.

Multiple sensitivity runs were carried out, following recommendations from the 2023 Working Group on Statistics, Assessments and Modelling. Models fitting to all recaptured tagged fish rather than only those at liberty for six years or less resulted in a higher initial biomass, potentially due to the potential bias of tag mixing assumptions and tagging loss rate estimate. Models with time-varying selectivities resulted in much more complex models with little improvement in the catch-at-age residuals and had similar biomass outcomes to the base case. Models estimating year class strength further back in time provided no improvement in the performance of the models and unexpected estimates of early year class strengths. When combined with time-varying selectivities, the age composition residuals looked more promising although not markedly so. Models fitting to tagging data by age rather than by length resulted in higher initial biomass yet similar estimates of other parameters and fits and require further investigation.

The precautionary yield calculated using the Commission for the Conservation of Antarctic Marine Living Resources toothfish decision rules and applying a catch split of 19% for the area north of 70° S, 66% for south of 70° S, and 15% in the Special Research Zone was 3499 t with the base case model. We recommend a catch limit of 3499 t for RSR Antarctic toothfish in the 2023/24 and 2024/25 fishing seasons. We also recommend further work on model selectivity assumptions and the use of age-based release and recapture data of tagged fish in particular.

INTRODUCTION

The exploratory Antarctic toothfish (*Dissostichus mawsoni*) fishery in the Ross Sea region (RSR; defined as Subareas 88.1 and Small-Scale Research Units (SSRUs) 88.2A-B; see Figure 1) began in 1997¹. Since 2004, the catch in the Antarctic toothfish fishery in the RSR has been between 2178 t and 3210 t in each fishing season, increasing to 3495 t for the 2021 and 2022 seasons (Devine & Mormede 2023). Detailed description of the stock area, stock assessment methods, and the stock assessment parameters are given in the Stock Annex for the 2023 assessment of RSR Antarctic toothfish (Mormede et al. 2023a). Additional tables of model outputs are detailed in the Appendix of this paper, and complete sets of model diagnostics are provided by Mormede (2023b). The Casal2 input and output data files associated with the assessment model are available from the CCAMLR Secretariat upon request.

Catch limits for the RSR have been determined in the past using yield calculations from an integrated stock assessment model using the software CASAL with catch from the onset of the Antarctic toothfish fishery, catch-at-age data, data from the Ross Sea Shelf Survey (RSSS), and the tag-release and recapture data from the tagging programme initiated in 2001. In 2023, Casal2 was used for the RSR stock assessment and yield calculations, following the recommendation by CCAMLR (CCAMLR-41 2022, para 2.6-2.8).

In 2016, the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) adopted the Ross Sea region Marine Protected Area (RSrMPA) (CCAMLR-XXXV 2016), which was implemented on 1st December 2017 for the 2017/18 season. The fishery is now managed within four management areas. Within the Special Research Zone (SRZ) of the RSrMPA, the catch limit is fixed at 15% of the total available catch limit (CM 91-05 paragraph 8). Otherwise, the remaining catch limit is spread between north of 70° S (19%) and south of 70° S (66%) in areas outside the RSrMPA (CM 41-09 paragraph 2).

In this report, we use the general stock assessment package Casal2 (Casal2 Development Team 2023) for the 2023 version of the RSR stock assessment model and provide a comparison for the base case using the stock assessment package CASAL, which has been used in assessments up to 2021 (Bull et al. 2012). The RSR stock assessment model assumes a single homogeneous area with four geographically defined fisheries, based on the management areas for Subareas 88.1 and Small-Scale Research Units (SSRUs) 88.2A-B (see Devine & Mormede 2023 Figure 41.1), i.e., (1) north of 70° S and outside the RSrMPA (N70), (2) south of 70° S and outside the RSrMPA (S70), (3) the Special Research Zone (SRZ), and (4) remaining areas in the RSR including historical catches taken inside the general protected zones (GPZ, Figure 1). With the implementation of the RSrMPA under CM 91-05, exploratory fishing has been excluded from the Ross Sea shelf (GPZ) since 2018 and exploratory fishing catches and observations are historical. The Ross Sea shelf survey (RSSS), although within what is now the GPZ, is treated as a different fishery in the model.

Data included in the 2023 Antarctic toothfish assessment are those used in the 2021 assessment (Grüss et al. 2021) with the addition of the most recent available data. These are: (1) the catch for each of the fishery areas, including catches from quarantined vessel trips, estimates of illegal, unreported, and unregulated (IUU) catch, Antarctic toothfish taken in research surveys undertaken under CM 24-01, and Antarctic toothfish taken from outside the Convention area that are likely a part of the RSR biological stock (South Pacific Regional Fisheries Management Organisation (SPRFMO)); (2) catch-at-age frequencies for the four fishery areas up to 2022; (3) tag-release data from 2005 up to 2022 and associated tag-recapture data up to 2023; and (4) the RSSS abundance time series up to 2023 and associated age frequencies up to 2022 (Devine & Mormede 2023).

¹ Note that this report uses the CCAMLR split year that is defined from 1st December to 30th November. Hence, the term “year” refers to the fishing season in which most fishing occurs, e.g., the season from 1st December 1996 to 30th November 1997 (1996/97) is labelled as 1997.

In the following, we describe the 2023 assessment for RSR Antarctic toothfish and the main assessment model diagnostics. Following recommendations from the 2023 Working Group on Statistics, Assessments and Modelling (CCAMLR 2023), multiple sensitivities were carried out. Model validations (SC-CCAMLR-41, para 2.8) for the base case assessment are also described.

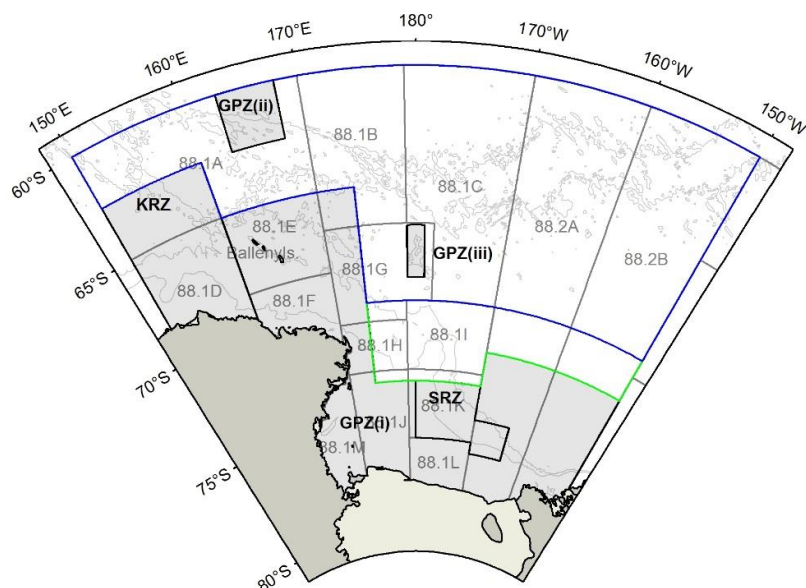


Figure 1: Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Subareas 88.1 and 88.2, Small-Scale Research Units (SSRUs), the Ross Sea region Marine Protected Area (General Protection Zones (GPZ) (i)–(iii), the Krill Research Zone (KRZ), and the Special Research Zone (SRZ); in dark grey shade), and the Ross Sea region (bounded region). The blue polygon delineates the N70 management area, while the green polygon delineates the S70 management area. Depth contours (light grey) are plotted at 1000 and 3000 m.

METHODS

The 2023 assessment model of RSR Antarctic toothfish is a Bayesian sex- and age- structured population model, following the structure detailed by Mormede et al. (2014), (Mormede & Parker 2017), Dunn (2019) and Grüss et al. (2021). The 2023 assessment model was implemented using the general stock assessment package Casal2 (Casal2 Development Team 2023) v23.09 2023-09-01. A detailed description of the stock area, stock assessment methods, and the stock assessment model parameters are given in the Stock Annex (Mormede et al. 2023a). The annual cycle of the model is detailed in Table 1.

Table 1: Annual cycle for the Ross Sea Region Antarctic toothfish population model. AFs = catch-at-age frequencies, CPUE = catch per unit effort (not used in these models). Actual catch was calculated based on the catches from the 2018–2023 period, including SPRFMO catches (in October).

Month	Catch (%)		Biological processes					Observations			Time step		
	Actual	Assumed	Ageing	Recruitment	Maturation	Growth (%)	Natural mortality (%)	Spawning	Tag release	Tag recapture		RSSS survey	AFs
Nov	0.0												
Dec	66.0												
Jan	33.5	100		X			50		X	X	X	X	Summer
Feb	0.2												
Mar	0.0												
Apr	0.0												
May													Tag Loss
Jun	0.0												
Jul	0.0												
Aug	0.0	0					50	X					Winter
Sept	0.0												
Oct	0.4												
Year end	0.0	0	X			100							Age Increment
Total	100.0	100				100	100						

The following data were updated in the 2023 assessment model from that used in the 2021 assessment model (Devine & Mormede 2023):

- Annual catch for the 2022 and 2023 fishing seasons and catch by management area (N70, S70, SRZ, and GPZ) were added with minor revisions to the previous catch history.
- Catch from the RSSS was updated and added for 2022 and 2023. Reported catches outside the CCAMLR Convention area (SPRFMO) were updated and added for 2022 (Fenaughty 2022) and 2023 (Nyegaard & Fenaughty 2023). IUU catch for 2022 and 2023 were assumed to be 0 t.
- Scaled catch-at-age frequencies from the fishery for 2021 and 2022 were added, and historical catch-at-age frequencies (1998–2020) were updated.
- Tag-release data for 2021 and 2022 and associated recapture data for 2022 and 2023 were added, and the tag-recapture time series data for 2001–2023 were revised, including correction of vessel specific tagged fish survival and vessel specific tag detection rates.
- RSSS standardised abundance series were updated to 2023, and RSSS catch-at-age frequencies for 2022 were added.
- Multipliers for recruitment to the model at age 1 were estimated for the period 2004–2017 (i.e., year class strengths for 2003–2016) and were assumed to have an average of one over that period.

This initial 2023 model was then updated following the recommendations of WG-SAM-2023 (CCAMLR 2023), including using parameter transformations (para 6.37), double tagging loss rate function (para 6.39), excluding data of tagged fish released from before 2005 (para 6.40), and updated tag loss rates for double tagged fish (para. 6.21). The resulting model was the base case (R3). Sensitivity runs were also recommended and are discussed later.

As in previous assessments, catch per unit effort (CPUE) indices were not included in the 2023 assessment model because CPUE was not likely to reflect changes in abundance (Parker & Mormede 2017; Dunn 2019; Devine & Mormede 2023).

RESULTS

1.1 Audit trail from the 2021 assessment model

Incremental changes from the 2021 base case assessment model (R0) to the 2023 base case assessment model (R3) were made and are given below as an audit trail describing the effect of each step change. Revised and additional observations and data were added incrementally, without changing the 2021 data weightings. The data weightings were estimated using the methods of Francis (2011a, 2011b) to obtain the 2023 initial and base models. Details of each of the steps are given in Table 2.

The audit trail suggests that adding new data resulted in a small reduction in initial biomass but slightly higher status in 2021. The model improvements from the initial model to the base case model resulted in little change to the initial biomass or its trajectory.

Table 2. Audit trail of maximum posterior density (MPD) estimates of B_0 (t), B_{2021} (t), and B_{2021} as a percent of B_0 for Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*), describing the stepwise incremental changes from the 2021 base case assessment model (2021-R1.1) to the 2023 base case assessment model (R3).

Run	Description	B_0 (t)	B_{2021} (t)	B_{2021} (% B_0)
2021-R1.1	2021 base	79 079	49 589	62.7
R0	update data	76 803	50 737	66.1
R1	initial	76 986	50 921	66.1
R2.1	transforms	76 382	50 207	65.7
R2.2	double tag loss	77 531	51 342	66.2
R2.3	add initial loss rate	77 315	51 130	66.1
R3	tagging data from 2005 (base case)	78 553	52 461	66.8

1.2 Analysis of MPD results

Diagnostic plots for the 2023 base case assessment model (R3) are given by Mormede et al. (2023b). The estimated maximum posterior density (MPD) initial biomass (B_0) for the 2023 assessment model was 78 553 t, and the current biomass (B_{2023}) was estimated to be at 64.4% of B_0 . The start values and prior assumptions used are given in Table A.1, relative data weightings are summarised in Table A.2, and the total objective function is detailed in Table A.3.

Likelihood profiles were carried out by fixing B_0 over a range of plausible values, and the remaining parameters (e.g., selectivity parameters) were estimated (Figure 2). The tag-recaptures of fish released in 2008, 2009, 2012, 2017, and the catch-at-age frequencies from the survey, GPZ, SRZ and S70 management areas suggested that estimates of initial biomass lower than the MPD estimate were less likely, whereas the recaptures of tagged fish released in 2005–2007, 2010, 2011, 2013–2016, 2018–2022, the survey abundance index and the catch-at-age frequencies from the N70 fisheries suggested that estimates of initial biomass higher than the MPD estimate were less likely (Figure 2).

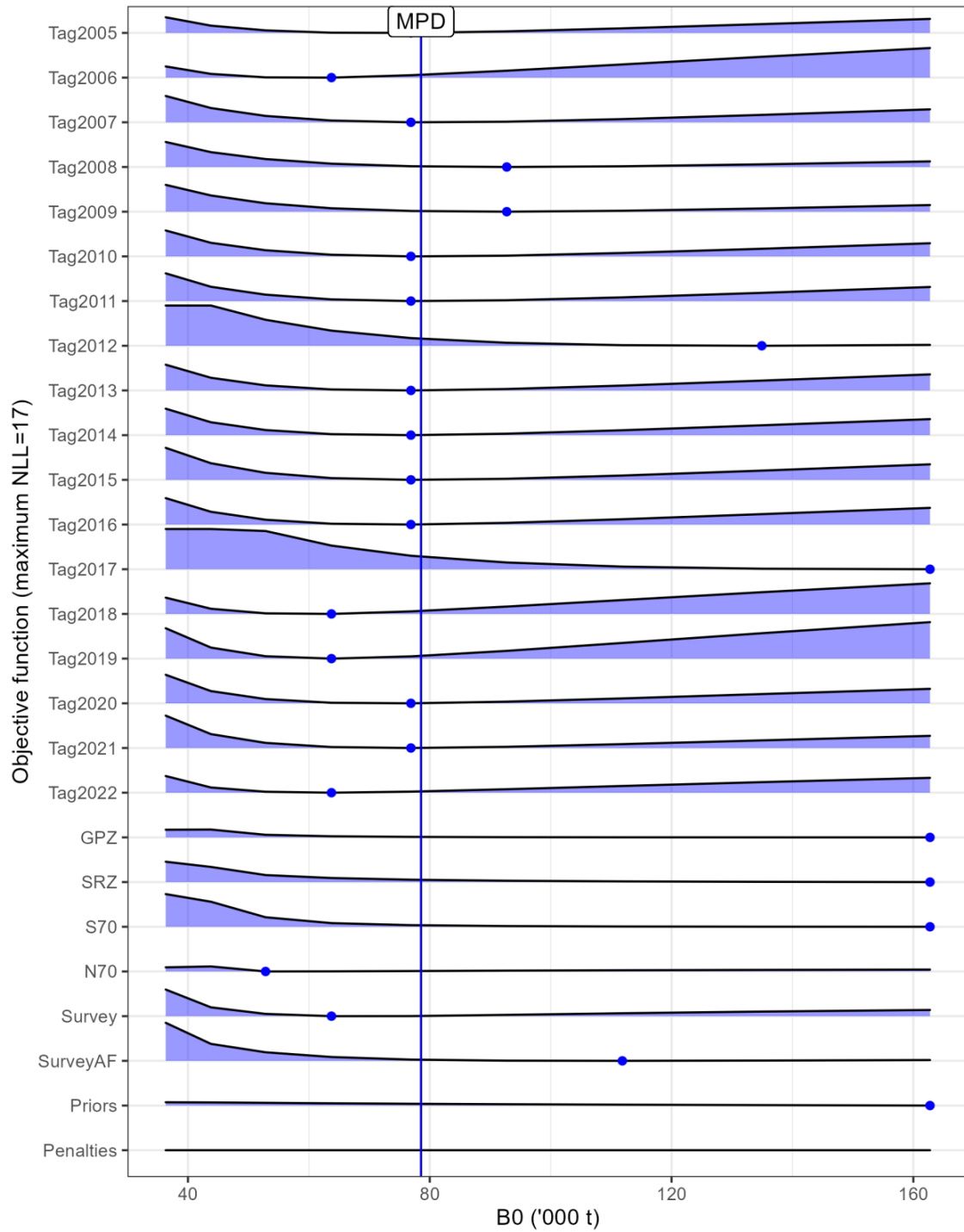


Figure 2: Likelihood profiles for pre-exploitation biomass B_0 for the 2023 base case assessment model of Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*) for each tag release cohort, catch-at-age frequencies, RSSS, and penalties and priors. Negative log likelihood values were rescaled to have a minimum of 0 for each dataset. The points indicate the minimum for each set of data and the vertical line indicates the maximum posterior density (MPD) value for B_0 . AF = catch-at-age frequencies.

Plots of the observed proportions-at-age of the catch versus the MPD expected values suggested that while the residuals for the most common ages were generally adequate, there was a residual pattern suggesting evidence for either changing selectivity through time and/or YCS progression that was not

well accounted for (Figure 3). Fits to the RSSS local abundance series followed the overall trend (Figure 4).

Plots of the observed number of tagged fish recaptured versus MPD expected values suggested adequate fits in most of the tag-release data, and there was no evidence of systematic bias in the expected tag detection rate (see the diagnostic plots in Mormede et al. 2023b). The residuals for the number of tagged fish recaptured from each tag-release cohort suggest positive or negative bias correlated with the year of recapture, rather than the year of release up until the 2016 release year, but seemed to be correlated with the year of release from the 2017 release year (Figure 5).

Year classes estimated in the 2023 base case assessment model (R3) were consistent with those estimated in the previous stock assessment (Grüss et al. 2021).

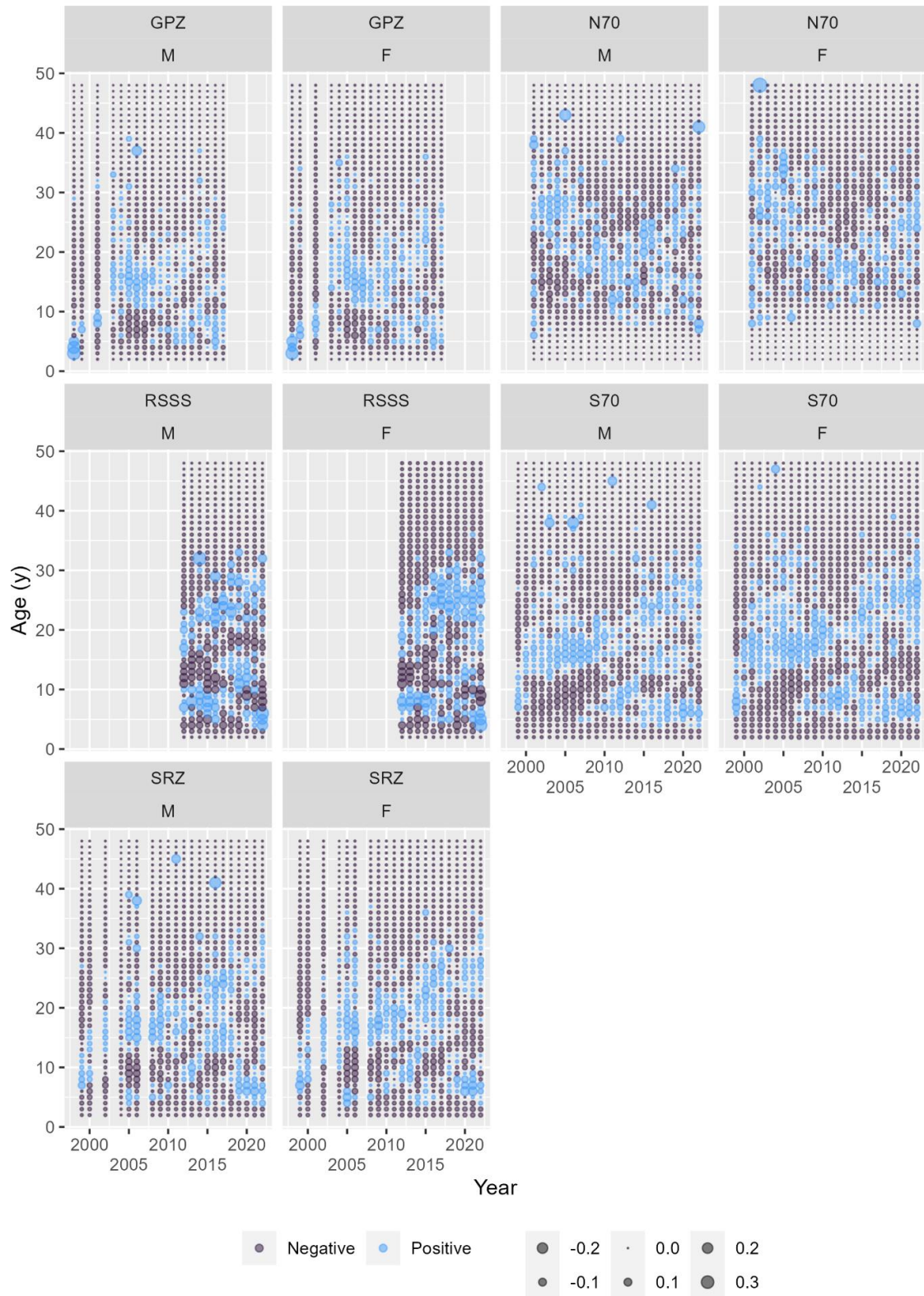


Figure 3: Pearson residuals of the catch-at-age data for males and females of the Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*) by management area, for the 2023 base case assessment model.

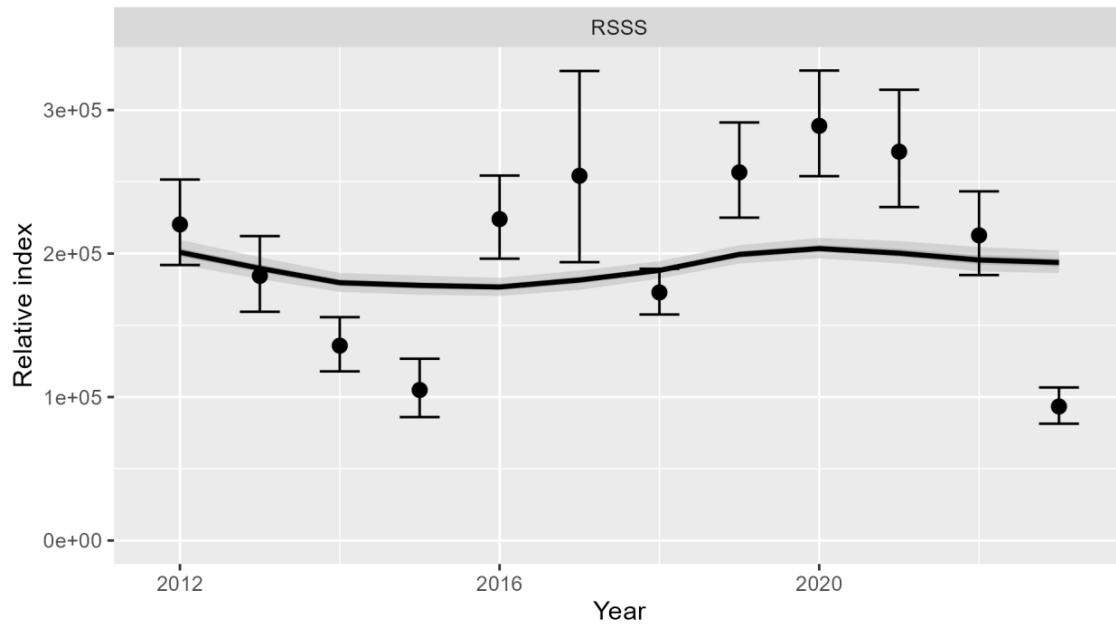


Figure 4:Maximum posterior density (MPD) and Markov chain Monte Carlo (MCMC) fits to the survey (RSSS) local abundance series for the 2023 base case assessment model of the Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*).

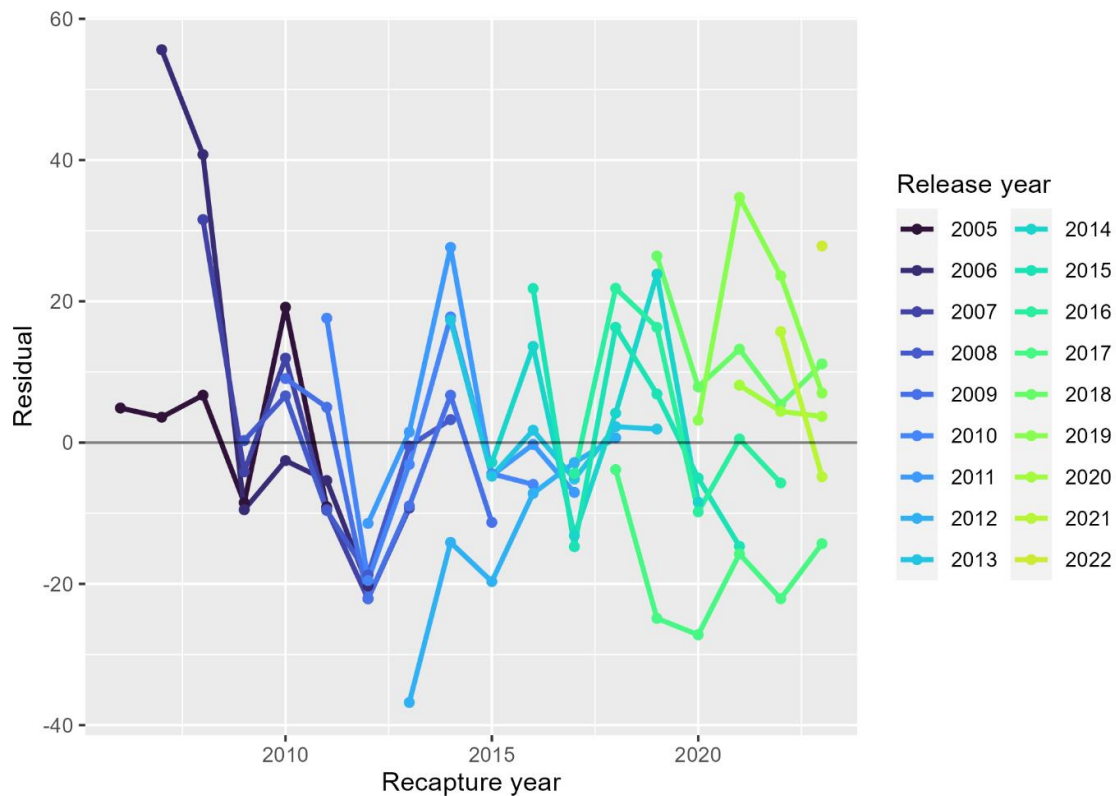


Figure 5: Expected minus observed number of tagged fish recaptured each year of recapture per year of release for the 2023 base case assessment model of the Ross Sea Region Antarctic toothfish (*Dissostichus mawsoni*).

1.3 Sensitivity analyses

Multiple sensitivity runs were carried out, including following recommendations from the 2021 Working Group on Fisheries Stock Assessments (CCAMLR 2021, para 3.68) and the 2023 Working Group on Statistics, Assessments and Modelling (CCAMLR 2023, para 6.22 and 6.27). These sensitivities were run at MPD level only unless stated otherwise.

1.3.1 Fitting to all recaptures of tagged fish

Models fitting to all recaptures of tagged fish rather than only those at liberty for six years or less resulted in a higher initial biomass, likely due to the potential bias of tag mixing assumptions and tagging loss rate estimate; the biomass trajectory was similar (Figure 6). All other estimates and fits were very similar (not shown). The MPD profile with tagging data summarised by time at liberty showed that the longer the time at liberty, the higher the expected initial spawning stock biomass (Figure 7). This is consistent with the MPD profile of the initial spawning stock biomass when plotted in terms of years at liberty of tagging data for the base case model, which also showed that higher time at liberty usually correlated with a higher initial spawning stock biomass (Dunn & Grüss 2023; Mormede et al. 2023a).

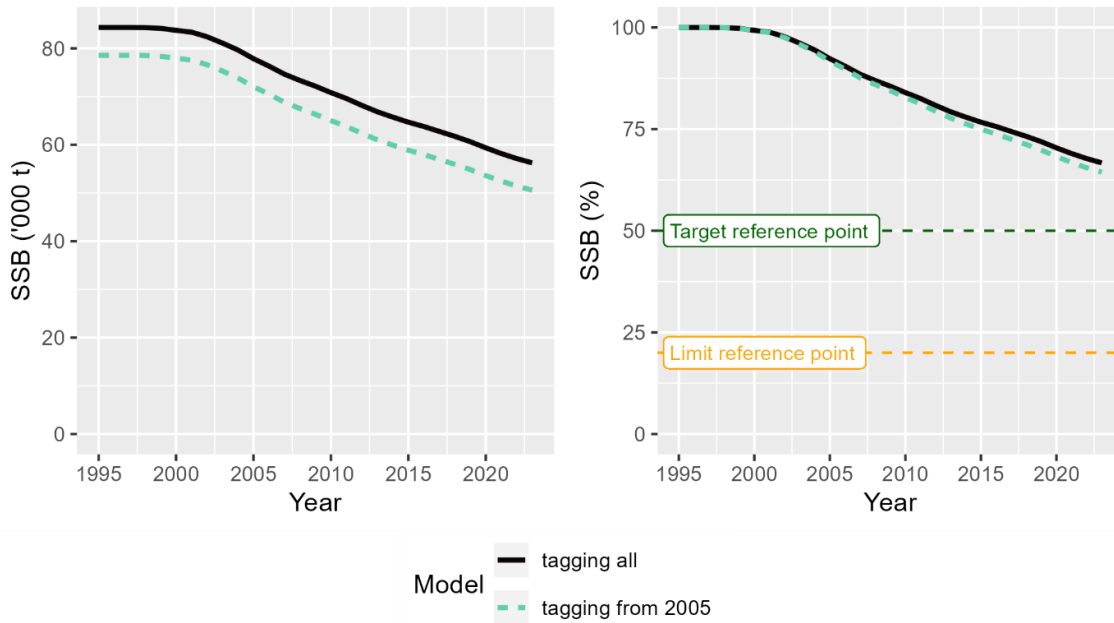


Figure 6: Comparison of the spawning biomass trajectory between the base case model (tagging from 2005) and the equivalent model fitted to the recaptures of all tagged fish (tagging all) at MPD level, in thousands of tonnes (left) or percentage of initial spawning biomass (right).

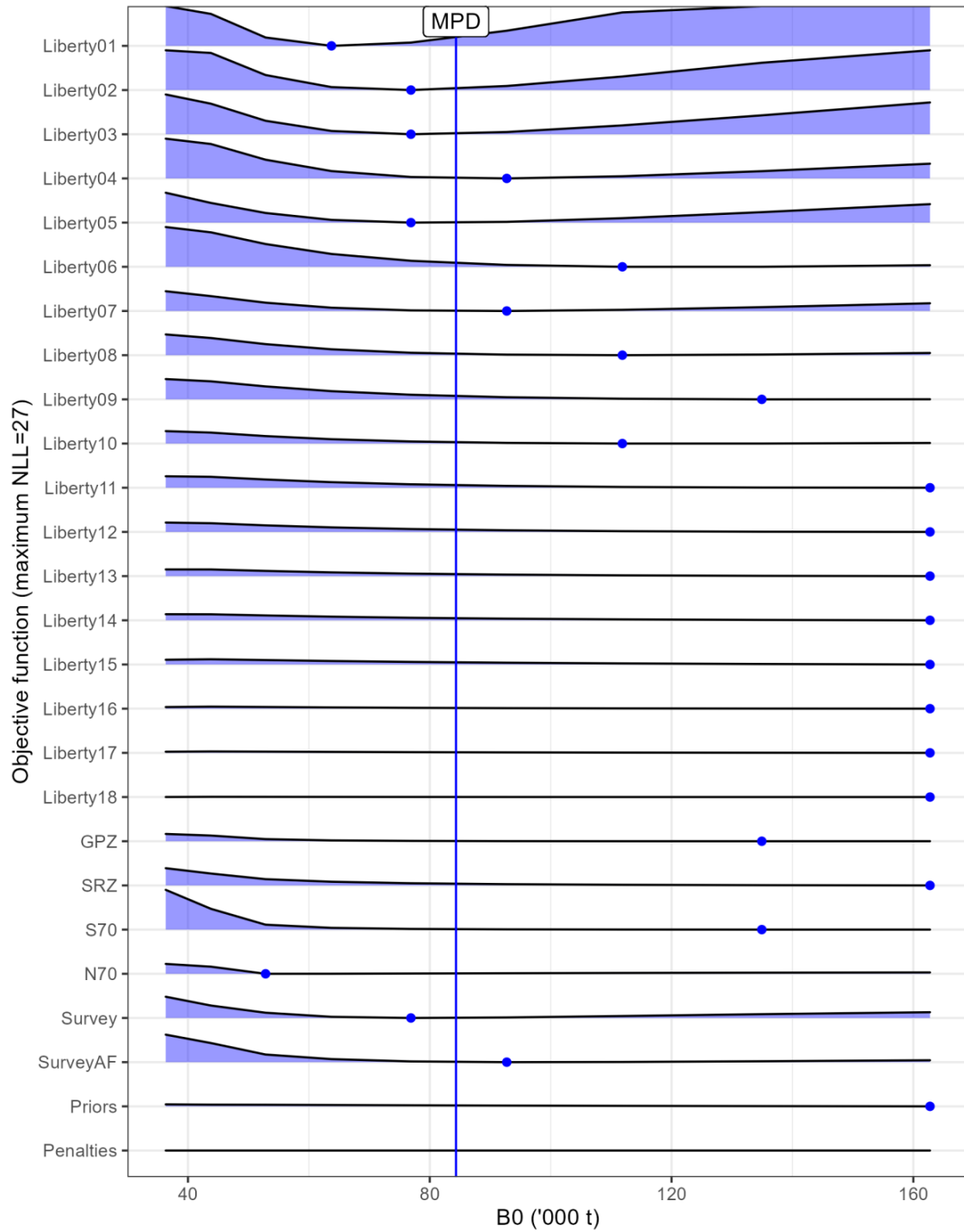


Figure 7: Likelihood profiles for pre-exploitation biomass B_0 for the assessment model of Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*) with all recaptures of tagged fish, with tagging data summarised as a function of time at liberty (Liberty02 corresponds to tagged fish recaptured after two years at liberty). Negative log likelihood values were rescaled to have minimum of 0 for each dataset. The points indicate the minimum for each set of data and the vertical line indicates the maximum posterior density (MPD) value for B_0 . AF = catch-at-age frequencies.

1.3.2 Alternative selectivities

The base case model had residual trends in the catch-at-age frequencies (see Mormede et al. 2023b for detailed plots), similar to the patterns in previous models (e.g., see Grüss et al. 2021). Various options were investigated to improve the fits to the catch-at-age frequency data, starting with selectivities.

As there were almost no observations of age 2 and 3 individuals in the catch-at-age frequency data, these ages were excluded. This resulted in identical initial spawning stock biomass and trajectory and only minor changes to the MPD estimates of selectivity, all well within the MCMC range. Assuming a logistic selectivity for the N70 fishery resulted in identical estimates and fits but a worsening of the fits by 52 negative log likelihood points. We recommend alternative shapes for domed selectivity be developed and evaluated.

Because of the temporal pattern in the catch-at-age frequency residuals, time-varying selectivities were considered. Three options were investigated: time blocks of selectivities, annually varying selectivity parameter μ or annually varying selectivity parameter α , all applied to all the fisheries. The selectivity of the Ross Sea shelf survey was not allowed to vary as the survey is standardised. The time blocks were selected based on the tree regression analysis of mean age (Devine & Mormede 2023) and confirmed visually as corresponding to the patterns observed in the catch-at-age frequency residuals. The blocks were 1998–2002, 2003–2007, 2008–2014, 2015–2020 and 2021–2023, resulting in an additional 105 parameters estimated. Only the model with blocks of selectivity resulted in an improved model, with an AIC improvement of 174 negative log likelihood points. The other models resulted in poorer fits, which could be expected given the selectivities estimated by the model with selectivity blocks (Figure 8). Many of the estimated selectivities were estimated at the right-hand limb bound which might indicate issues in minimisation. This run was attempted at MCMC but reached computational resource limitations and should be investigated further.

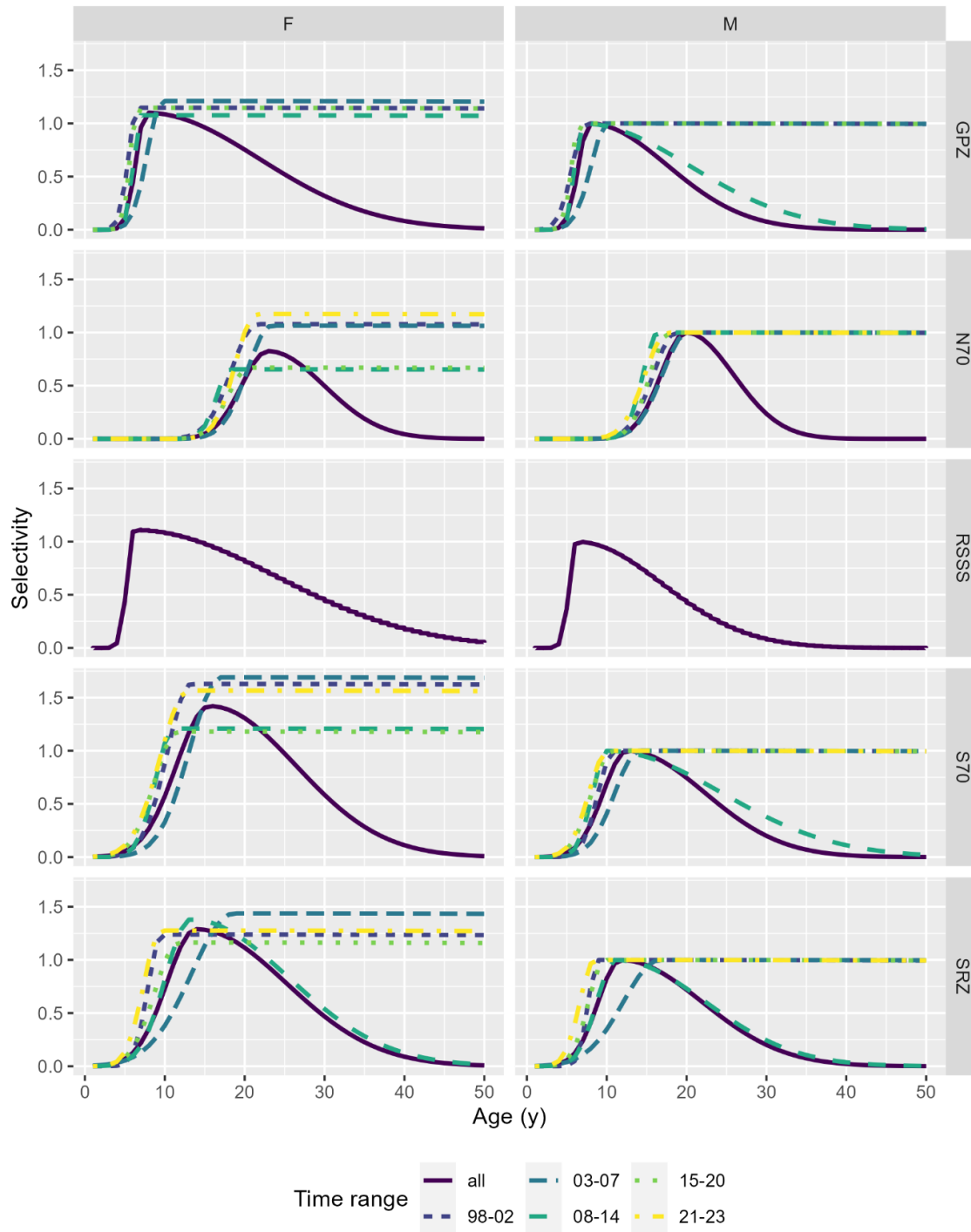


Figure 8: Estimated time-block selectivities for the different fisheries. Note the RSSS selectivity was not time-varied.

1.3.3 Estimating additional recruitment multipliers

The base case model estimated year class strengths for 2003–2016, parameterised as multipliers on recruitment at age 1 in the model for the years 2004 to 2017. A fish recruited in 2004 would have been

15 in 2019, and therefore observed three times in the model from the 2022 catch-at-age frequency observations of the RSSS. Fish older than 15 were not well represented in the RSSS.

However, the residual trends in the catch-at-age frequencies could also be partly driven by early year class strengths that are currently fixed in the base case model and estimating the recruitment multipliers for earlier years might help improve the residuals in the catch-at-age frequencies.

Models with recruitment multipliers based on different periods were investigated. Recruitment multipliers estimated from 1999 based on RSSS fish aged 20, 1981 based on S70 fish aged 20, and 1976 based on N70 fish aged 25 were run and included estimating selectivities by time-blocks. Although the catch-at-age frequency residuals marginally improved, these models did not perform better than the base case model based on total objective function. They all had similar initial spawning stock biomasses, apart from the model with YCS estimated from 1975 (Figure 9). In the models with the earlier recruitment multipliers estimated, strong recruitment multipliers were estimated in 1990 and 1993 as well as an early period of lower recruitment (Figure 10).

Models with no survey information included (abundance series or catch-at-age observations) resulted in different estimates of recruitment multipliers, highlighting the importance of that time series. Furthermore, when estimating YCS from 1998 without blocks of selectivity, the initial biomass and biomass trajectory were different, highlighting the interplay between selectivity blocks and year class strengths.

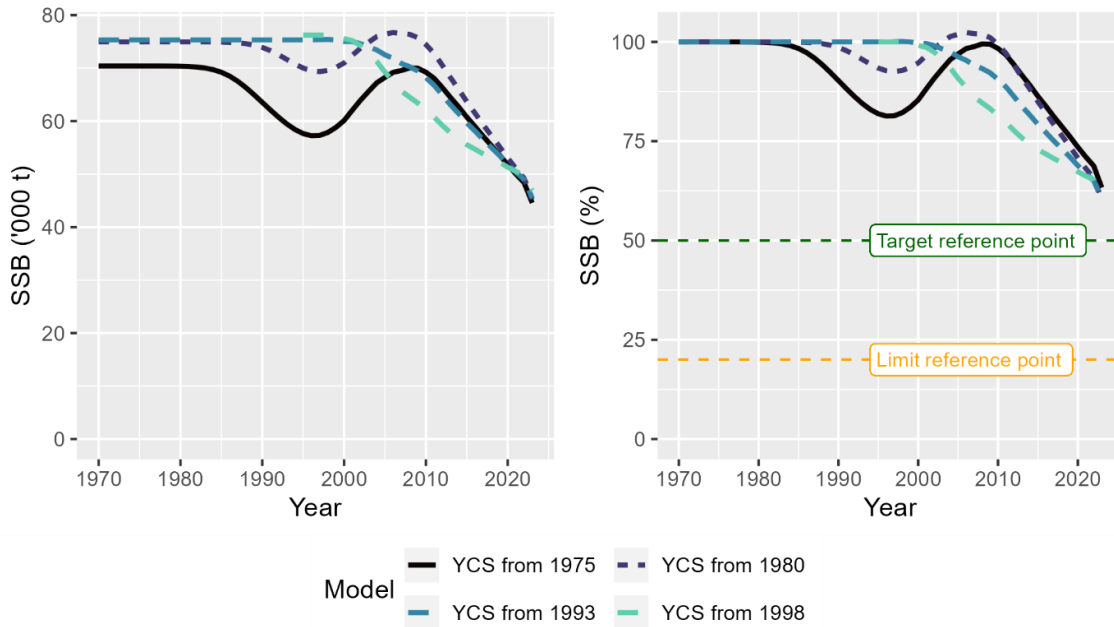


Figure 9: Estimates of spawning stock biomass in thousands of tonnes (left) and proportion of initial spawning stock biomass (right) for models with various start years for the estimation of recruitment multipliers.

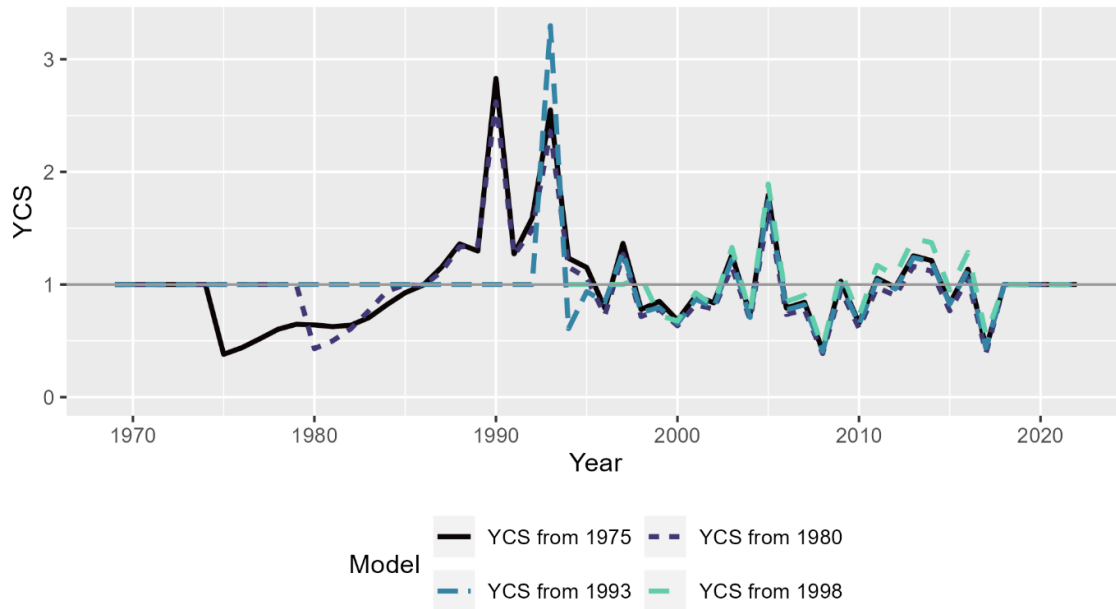


Figure 10: Estimates of year class strengths (YCS) for models with various start years for the estimation of recruitment.

1.3.4 Using tag data by age

Following the recommendation from WG-SAM-2023 (CCAMLR 2023, para 6.28), the base case model was updated to incorporate releases and recapture observations of tagged fish by age rather than by length, following the method of Grüss et al. (2023). The model resulted in a much higher initial biomass (Figure 11) and, other than the estimate of B_0 , the parameter estimates and the resulting model fits were almost identical apart from the estimate of a few year class strengths (Figure 12) and fits to the 2020 and 2022 releases of tagged fish. Those parameter estimates were similar at both MPD and MCMC level (not shown). We recommend that models that use age-based release and recapture observations of tagged fish should be investigated further before they can be used for management advice, to understand their behaviour. Therefore, despite this further work, the recommendation from WG-SAM-2023 still stands (CCAMLR 2023, para 6.28).

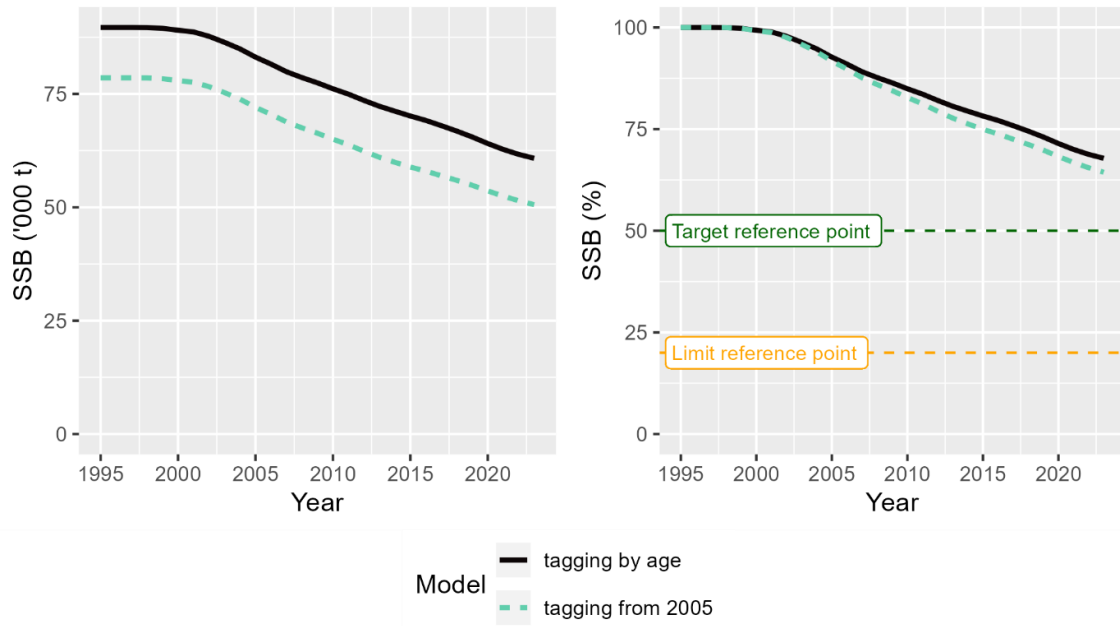


Figure 11: Estimates of spawning stock biomass in thousands of tonnes (left) and proportion of initial spawning stock biomass (right) for the base model (tagging from 2005) and the model with tag data by age (tagging by age).

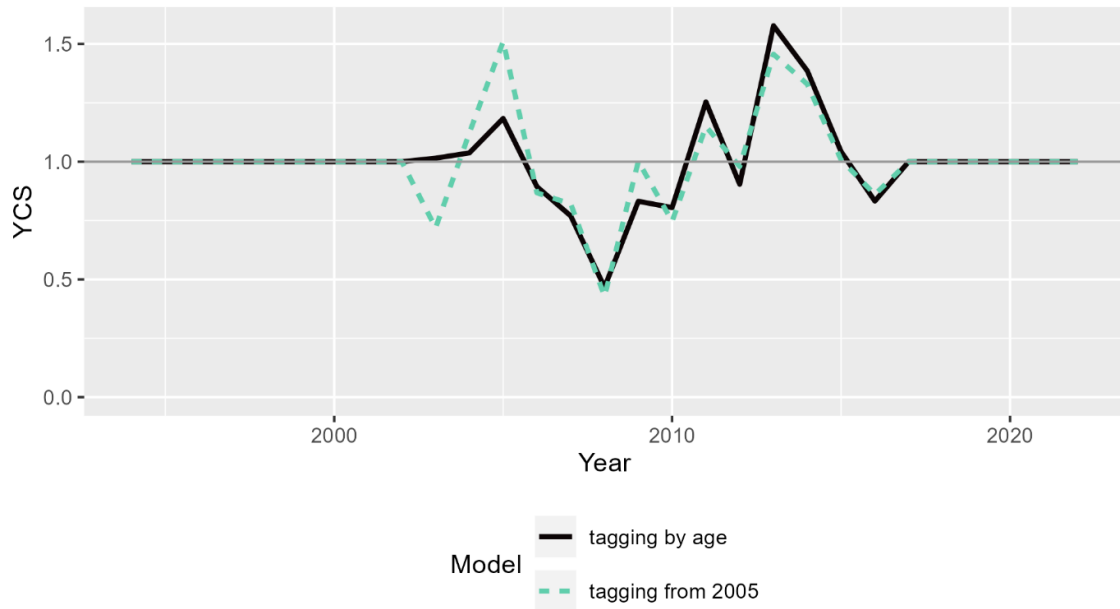


Figure 12: Estimates of year class strengths (YCS) for the base model (tagging from 2005) and the model with tag data by age (tagging by age).

1.4 Markov chain Monte Carlo (MCMC) results

Diagnostic plots for the base case are provided in Mormede et al. (2023b). Markov chain Monte Carlo (MCMC) trace plots showed no evidence of lack of convergence in the key biomass parameters and most of the estimated parameters, but there was weak evidence of two modes for the right-hand declining limb of both the male and female selectivities for the N70, S70, and SRZ fisheries. Multichain diagnostic

using approximate $\hat{r}$ statistics (Vehtari et al. 2017) did not suggest any evidence of non-convergence. Between-sample autocorrelations were low and the median jump size as a proportion of the range of each parameter suggested no evidence of non-convergence.

Fits to the catch-at-age data suggest some evidence of poor fit, especially in the earlier years of the fishery. However, the sensitivity analyses detailed above did not improve those fits much. Further consideration of these issues should keep being investigated in future assessments.

Recruitment multipliers were estimated for the years 2004–2017 for the base case. Stronger than average recruitment in 2006, 2014, 2017 and 2018 was estimated (Figure 13). MCMC estimates of YCS suggested that recruitment variability over this period was about $\sigma_R = 0.42$ (95% CIs 0.30–0.58) and that the 95% credible interval of autocorrelation was between -0.59 and 0.22.

Fits to the survey local abundance series are shown in Figure 4. Fluctuations in the survey abundance trend were likely representative of variability in local abundance, with the overall pattern consistent with the assessment model. The patterns of estimated YCS were consistent with the patterns in the RSSS catch-at-age frequencies, suggesting that the RSSS was monitoring the relative recruitment of the population. The RSSS was noted by the 2018 independent review of the integrated modelling methods used to assess toothfish (Anon 2018) as an important index for the assessment, and as a means to employ a fishery independent method to monitor recruitment.

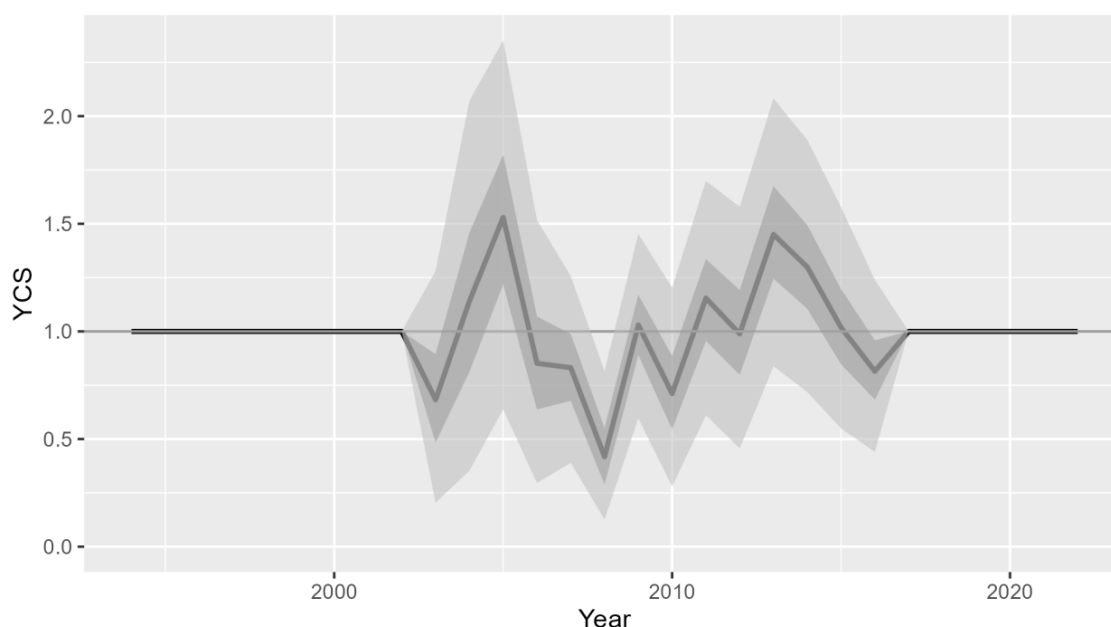


Figure 13: Markov chain Monte Carlo (MCMC) predicted distribution of year class strengths (YCS) for the 2023 base case assessment of Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*), with the median (black line and points), interquartile range (dark grey) and 95% credible intervals (light grey).

1.5 Estimates of biomass and yield

MCMC estimates of the initial biomass and current biomass are given in Table 3 below and variability of the initial biomass estimated in showed in Figure 14. The MPD for the base case model (R3) estimated the initial biomass (B_0) for the 2023 assessment model was 78 553 t, and the current biomass (B_{2023}) was estimated to be at 64.4% of B_0 . MCMC estimated B_0 as 77 855 t (95% CIs 71 954–85 115 t) and the current stock status (B_{2023}) as 64.3% B_0 (95% CIs 61.3–67.3% B_0).

The calculation of precautionary yield used the method noted in SC-CAMLR-XXV (2006, para 4.70 (iii)) and described in the report of WG-FSA-SAM (2005, para 2.36). Projected biomass trajectories are shown in Figure 15. Precautionary yields using the CCAMLR decision rules are given in Table 4 and in Figure 16 using a future catch split of 19% for N70, 66% for S70 and 15% for the SRZ. The precautionary yield calculated using the CCAMLR toothfish decision rules was 3499 t.

The MCMC biomass trajectory of the 2023 base case was compared with that of the previous model runs used for management advice in previous years (Figure 17). Although the various assessments resulted in variable initial biomasses, there was no trend with time in those. A peeled retrospective analysis was carried out, whereby more and more data were removed from the base case (Figure 18). There is also no trend with time in this analysis.

Table 3: Median Markov chain Monte Carlo (MCMC) estimates (and 95% credible intervals) of B_0 , B_{2023} , and B_{2023} as % B_0 for the 2021 base case assessment model (2021-R1.1) and the 2023 base case assessment model (R3).

Model	B_0 (t)	B_{2023} (t)	B_{2023} (% B_0)
2021-R1.1	78 373 (71 999–85 663)		
R3	77 855 (71 954–85 115)	49 994 (44 350–57 071)	64.3 (61.4–67.3)

Table 4: Estimated risks of the 2021 catch limit (3495 t) using the CCAMLR toothfish decision rules for the 2021 base case assessment model (2021-R1.1) and the estimated precautionary yield for the 2023 base case assessment model (R3).

Model	Pr(SSB < 50% B_0)	Pr(SSB < 20% B_0)	Catch limit (t)
2021-R1.1 estimated precautionary yield	0.50	<0.01	3495
R3 estimated precautionary yield	0.50	<0.01	3499

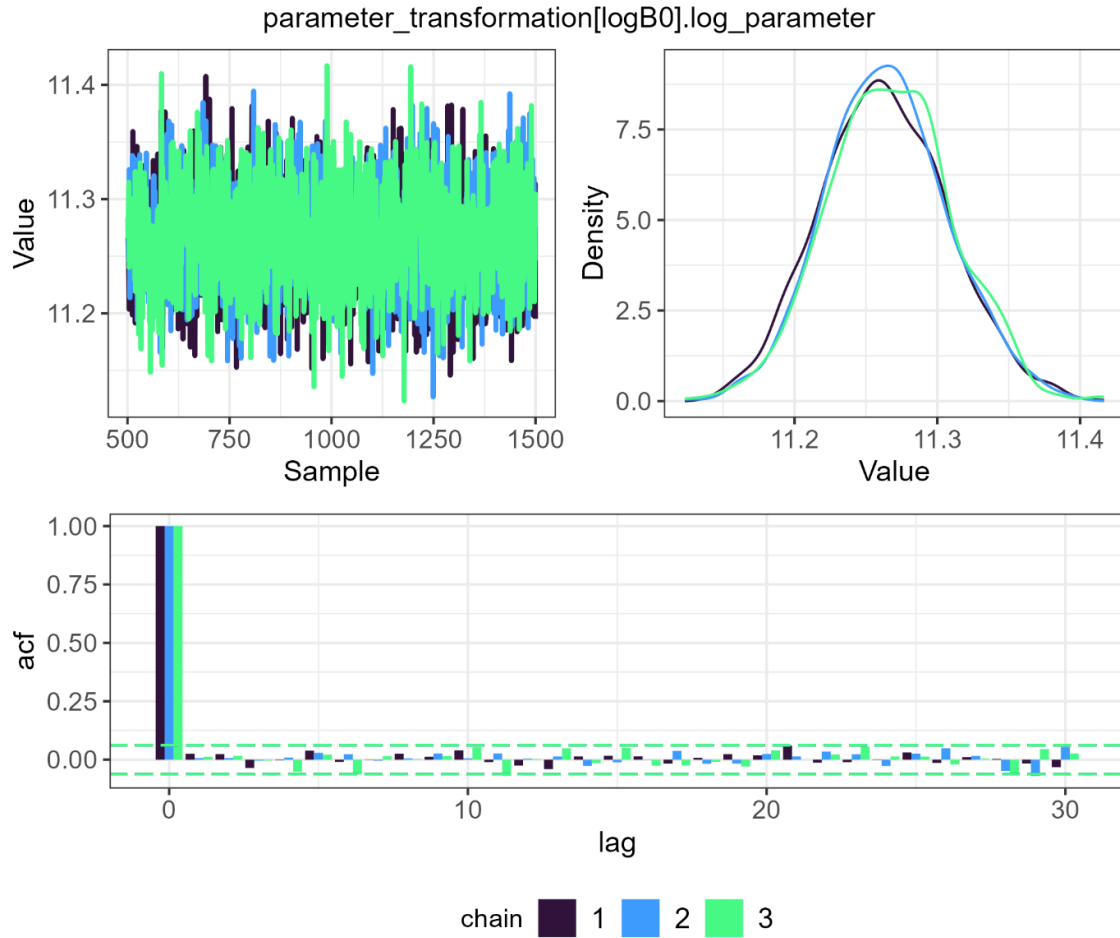


Figure 14: Markov chain Monte Carlo (MCMC) posterior distributions of parameter $\log(B_0)$ for the three chains used for the base case assessment model.

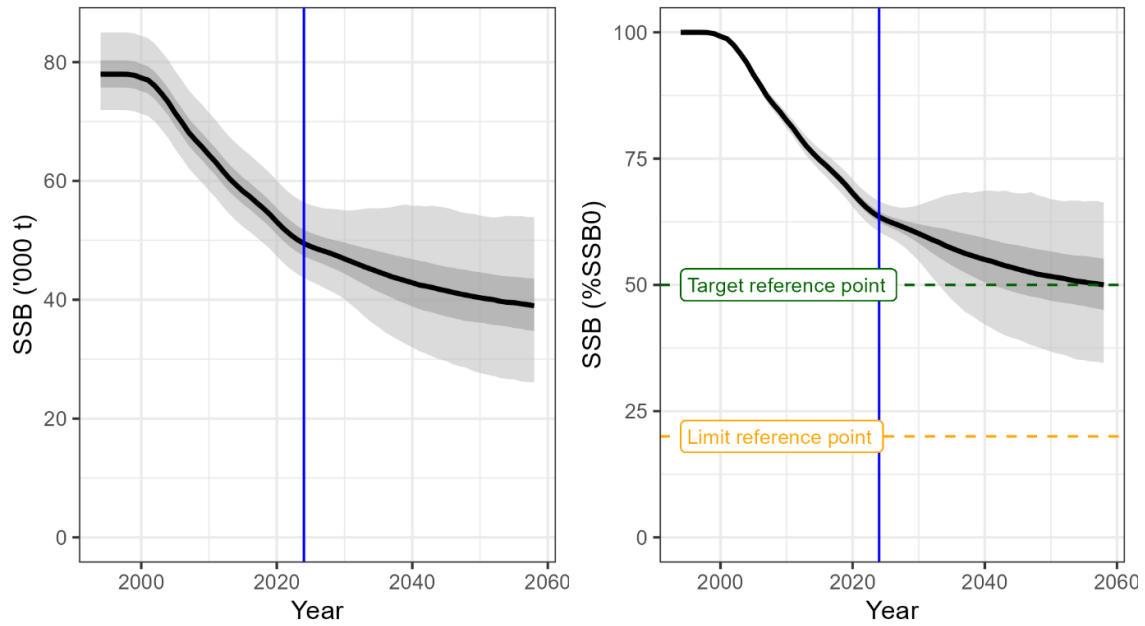


Figure 15: Markov chain Monte Carlo (MCMC) estimate of spawning stock biomass in thousands of tonnes (left) and proportion of initial spawning stock biomass (right) projected out to 2058 for the base model (R3), with the median (black line and points), interquartile range (dark grey) and 95% credible intervals (light grey).

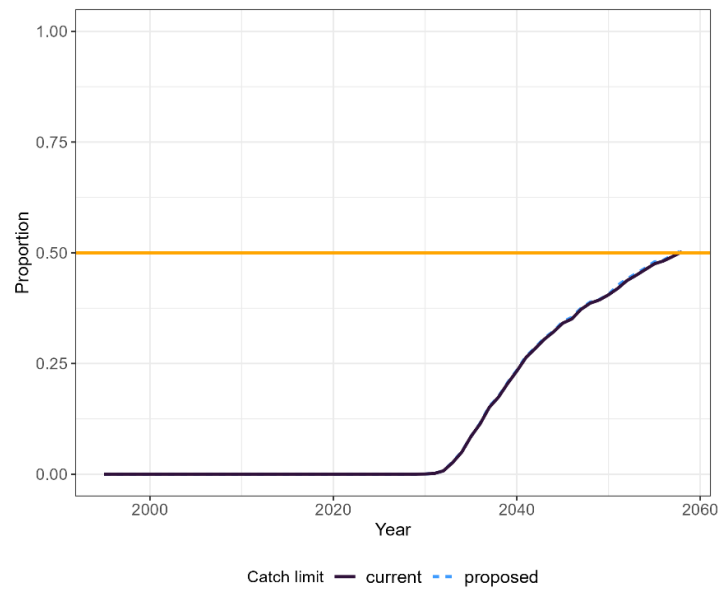


Figure 16: Estimated risk for the base case assessment model (R3) under the CCAMLR toothfish decision rules with the $\Pr(\text{SSB} < 0.5B_0) \geq 0.5$ with the current catch limit (3495 t) (dashed lines) and maximum catch that meets the decision rule criteria for each model (3499 t, solid line).

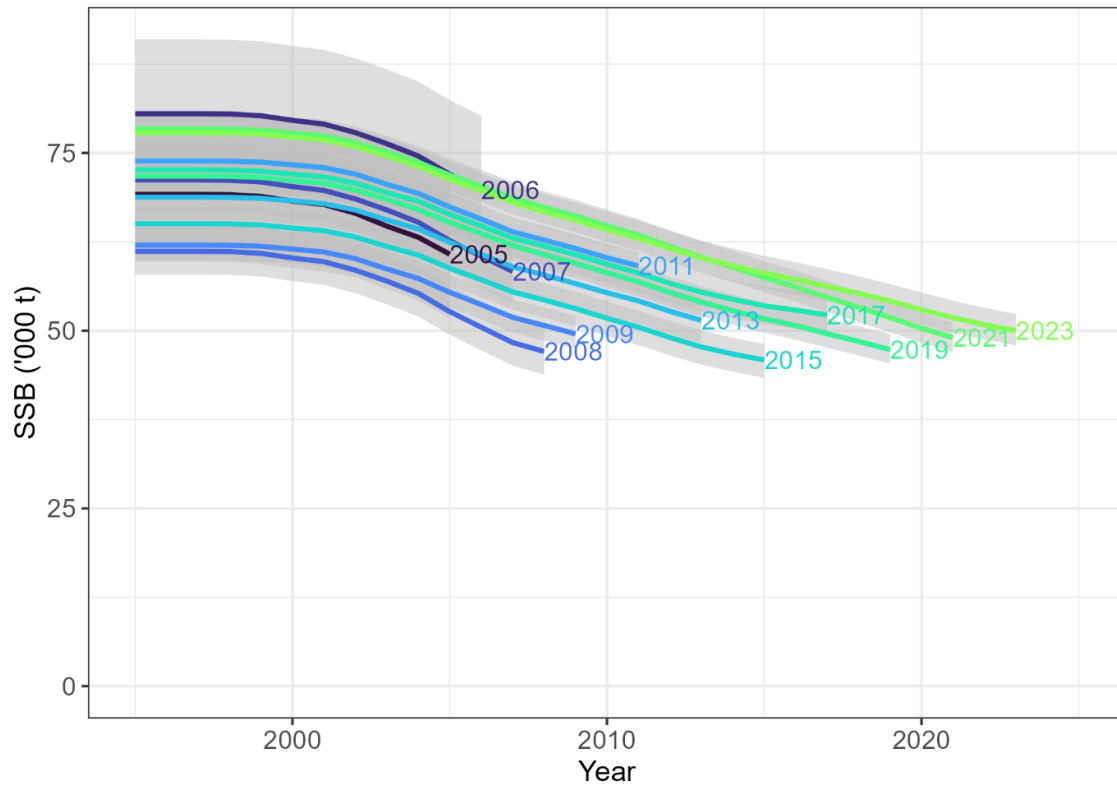


Figure 17: Markov chain Monte Carlo (MCMC) estimates of the trajectory of Antarctic toothfish (*Dissostichus mawsoni*) spawning stock biomass for the base case assessment model (R3) and previous models used for management advice (years of management in the figure). The 95% credible intervals are shown as grey shading for each model.

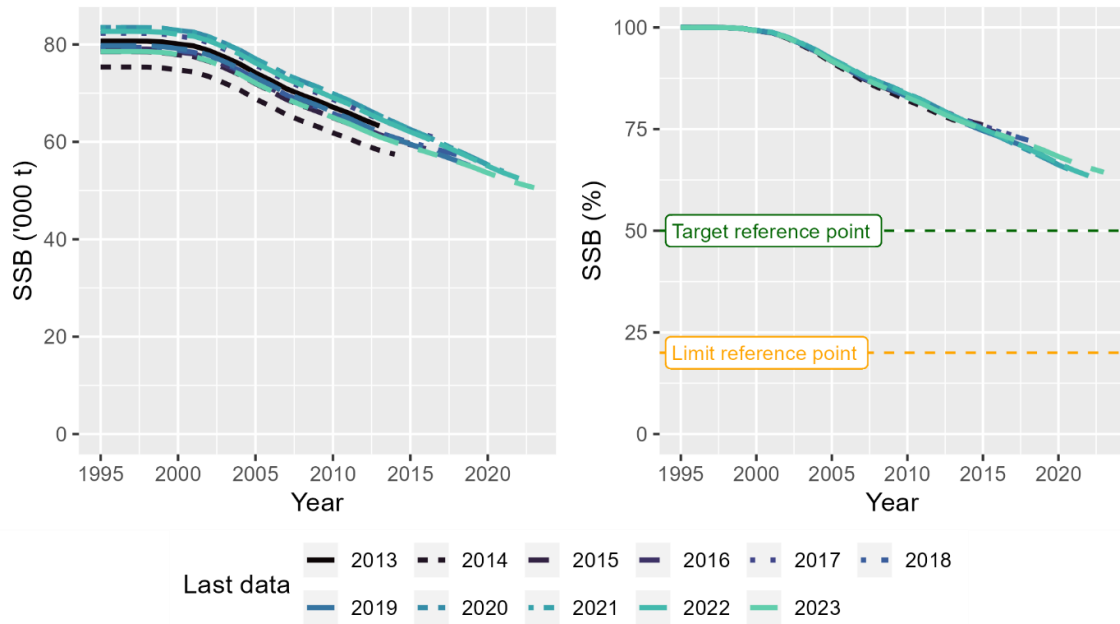


Figure 18: Peeled retrospective analysis of the base case model for 2013–2023. Comparison of the spawning biomass trajectory between the runs at MPD level, in thousands of tonnes (left) and percentage of initial spawning biomass (right).

1.6 Model validations

The validation steps recommended by SC-CAMLR (2022, para 3.31), and detailed in Dunn et al. (2022) for Casal2 stock assessment models were carried out as follows for model R3:

- Model R3 was checked against an equivalent CASAL model using the approved CASAL version v2.30-2012-03-21 rev 4648 (CCAMLR-38 2019, Annex 5). Namely, model R3 was rerun in CASAL compatibility mode and with a single tag loss rate of 0.0084; an equivalent CASAL model was run. Results at MPD level show that the values of the estimate of B_0 for the base case comparison between CASAL and Casal2 were very close, and within the level of tolerance expected between the two packages (Table 5).
- The version of Casal2 used (Casal2 v23.09 2023-09-01) matches the version reported on the estimate.log file.
- Biological parameters in the Casal2 input files are identical to that reported in the Stock Annex (Mormede et al. 2023a). Catches were checked against previous model runs and reported catches (Mormede et al. 2023b).
- Reported output quantities in the files are the same as described in this paper.
- Key model population structure, observation, estimation and other assumptions are the same as described in this paper.
- Asserts for the 2023 base case that can be used for validating future models are included within the Casal2 input configuration files.
- Parameter transformations were investigated and included in the final model.

Table 5. Comparison of the base case model run in Casal2 or its equivalent run in CASAL at MPD level.

Platform	Run	Description	B_0 (t)	B_{2023} (t)	B_{2023} (% B_0)
Casal2	R3	base	78 551	50 581	64.4
Casal2	R3csl	R3 CASAL compatibility	77 374	49 439	63.6
CASAL	R3csl2	R3 in CASAL	77 853	49 777	63.9

DISCUSSION

This paper updates the assessment model for Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea Region (Subareas 88.1 and SSRUs 88.2A-B), including available data up to and including 2023.

The base case model was very similar to the 2021 base case model (Grüss et al. 2021). Fits to the tag data and catch-at-age data were adequate and had a similar pattern to previous assessments. There was a correlation in the tag-recapture residuals based on year of recapture, likely a reflection of spatial changes and variability in fishing effort when tags are detected, through time. A correlation in the tag-recapture residuals based on the year of release might be present since the 2017 releases and should be monitored. There seems to be a relationship between initial biomass and time at liberty, whereby the longer the time at liberty the higher the estimated initial biomass — suggesting that the model assumptions of rates of ongoing tag mortality, tag loss rate, tag detection rate and uniform mixing might not be adequate. These should be tested alongside the suggestions of WG-SAM-2023, such as higher than expected natural mortality, ontogenetic changes in residence time, or age-based changes in movement patterns, could be explored as well as incorporating hypotheses concerning fishing behaviours or localised changes to fishing grounds, which may explain the residual pattern in tag-recapture data. (CCAMLR 2023, para 6.42)

The 2023 model showed that the information from the RSSS informed the estimation of recruitment strength. Over the period covered by the RSSS, four strong recruitment years were recorded (2006, 2014, 2017 and 2018), as well as weak recruitment years (2003, 2007–2009 and 2011). The RSSS abundance trends for the survey were fitted reasonably, albeit with interannual variability. Although local abundance trends may fluctuate due to local abundance variation, the overall pattern of a decrease and increase is consistent with the assessment model. The regular monitoring of recruitment also acts as an important safeguard to detect any unusual recruitment patterns that may occur in the future (SC-CAMLR-XXX 2011). For example, if there was a series of poor recruitments detected in the survey then the projected catch limits would be revised accordingly. This highlights the importance of established long time series of standardised abundance surveys to provide fishery-independent information on stock abundance and on recruitment (Anon 2018).

Multiple sensitivity runs were carried out following recommendations from CCAMLR. Models fitting to all tagged fish recaptured rather than only those at liberty for six years or less resulted in a higher initial biomass, likely due to the potential bias of tag mixing assumptions and tagging loss rate estimate. This result was borne out when examining the profiles on initial biomass based on time at liberty. Sensitivities were also run incorporating the tagging data by age rather than by length. Although the fits were very similar, the management outcome would be quite different and warrants further investigation.

Alternative selectivities and range of estimates of recruitment were investigated. These two issues were found to be interrelated. The use of time blocks of selectivities was the most promising and should be investigated further. Alternative shapes of selectivity should also be investigated. We note that the residuals in catch-at-age frequencies still presented patterns that could not be fully resolved at this stage.

The model estimate of biomass and yield was within four tonnes of that of the 2023 assessment. The CCAMLR precautionary yield for the Ross Sea region (i.e., $\Pr(\text{SSB} > 50\% B_0) > 50\%$ and $\Pr(\text{SSB} < 20\% B_0) < 10\%$) was calculated as 3499 t. We recommend that the catch limit be set at a total 3499 t for RSR Antarctic toothfish in the 2023/24 and 2024/25 fishing seasons. We also recommend further work on model selectivity assumptions and the use of age-based release and recapture data of tagged fish in particular.

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APPENDIX – SUPPLEMENTARY INFORMATION

Table A.1: Starting values, priors, number of parameters (N), and bounds for the free parameters for the 2023 base case assessment model (R3) for Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*). B_0 = pre-exploitation spawning stock biomass; RSSS = Ross Sea Shelf Survey.

Parameter		N	Start value	Transform	Prior	Prior applied to transform	Bounds	
							Lower	Upper
B_0 (t)		1	70 000	log	Uniform	yes	10	18
Fishing selectivities (male)	a_I		8.0	-	Uniform	-	1.0	50.0
	S_L		4.0	-	Uniform	-	1.0	50.0
	S_R	12	10.0	inverse	Uniform	no	0.002	1
Fishing selectivities (female)	a_{max}		1.0	-	Uniform	-	0.01	10.0
	a_I		8.0	-	Uniform	-	1.0	50.0
	S_L		4.0	-	Uniform	-	1.0	50.0
	S_R	16	10.0	inverse	Uniform	no	0.002	1
Recruitment		15	1.0	simplex	Lognormal	no	-10	10
RSSS abundance	CV	1	0.0	-	Uniform	-	0	10.0
RSSS selectivities (male)	a_I		8.0	-	Uniform	-	1.0	50.0
	S_L		4.0	-	Uniform	-	1.0	50.0
	S_R	3	10.0	inverse	Uniform	no	0.002	1
RSSS selectivities (female)	a_{max}		1.0	-	Uniform	-	0.01	10.0
	a_I		8.0	-	Uniform	-	1.0	50.0
	S_L		4.0	-	Uniform	-	1.0	50.0
	S_R	4	10.0	inverse	Uniform	no	0.002	1

Table A.2: Francis (2011) weighting factor for catch-at-age weight for the N70, S70, SRZ, and GPZ areas (w_{N70} , w_{S70} , w_{SRZ} , w_{GPZ}) and the RSSS (w_A), survey abundance c.v., and tag-recapture ($\emptyset$) observations for the 2021 base case assessment model (2021-R1.1) and the 2023 base case model (R3) for Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*).

Run	Model	w_{N70}	w_{S70}	w_{SRZ}	w_{GPZ}	w_A	c.v.	$\emptyset$
2021-R1.1	2021 base case assessment model	0.06	0.03	0.04	0.02	0.23	0.0	6.22
R3.0	2023 base case assessment model	0.06	0.03	0.04	0.02	0.28	0.0	7.10

Table A.3: Maximum posterior density (MPD) objective function values and number of estimated parameters for the 2023 base case assessment model (R3) for Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*). RSSS = Ross Sea Shelf Survey.

Component	Base case (R3)
RSSS abundance series	89.2
RSSS Age Frequencies	734.3
GPZ Age Frequencies	283.3
S70 Age Frequencies	657.0
SRZ Age Frequencies	535.7
N70 Age Frequencies	384.0
Tag 2005	18.6
Tag 2006	27.6
Tag 2007	21.8
Tag 2008	15.0
Tag 2009	14.6
Tag 2010	18.3
Tag 2011	16.6
Tag 2012	17.7
Tag 2013	15.2
Tag 2014	19.2
Tag 2015	21.9
Tag 2016	18.9
Tag 2017	19.3
Tag 2018	19.3
Tag 2019	18.3
Tag 2020	11.0
Tag 2021	8.4
Tag 2022	5.4
Jacobian-logB0	0.0
Jacobian-SimplexYCS	37.6
Jacobian-invRSSSM	-5.1
Jacobian-invRSSSF	-6.1
Jacobian-invGPZM	-4.9
Jacobian-invGPZF	-5.6
Jacobian-invS70M	-4.8
Jacobian-invS70F	-5.0
Jacobian-invSRZM	-5.0
Jacobian-invSRZF	-5.2
Jacobian-invN70M	-3.9
Jacobian-invN70F	-4.2
penalties	-
priors	-3.3
total score	2 976.6

Additional Resources

- Fishery Summary: [pdf](#), [html](#)
- Fishery Report: [pdf](#), [html](#)
- Species Description: [pdf](#), [html](#)
- Stock Annex: [pdf](#)
- [Fisheries Documents Browser](#)