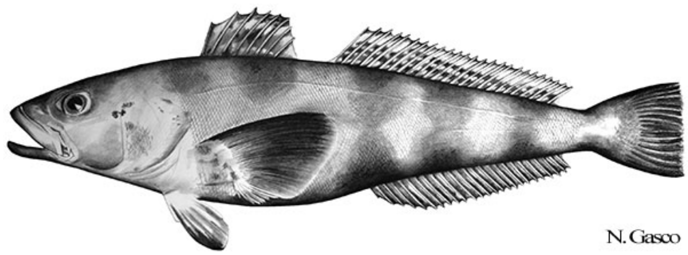
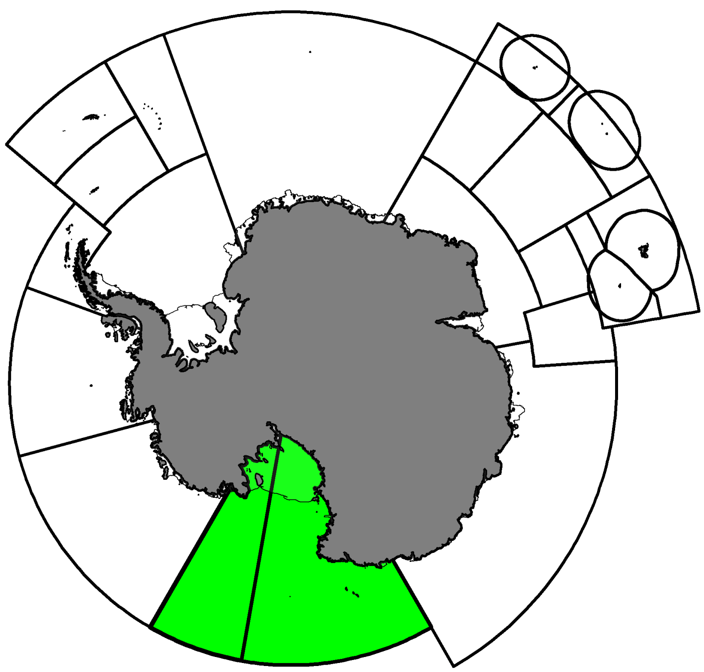
Stock Assessment Report 2024: *Dissostichus mawsoni* in Subarea 88.1

CCAMLR Secretariat

20 December 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, “2024” refers to the 2023/24 CCAMLR fishing season (from 1 December 2023 to 30 November 2024). Coastlines and ice shelves: UK Polar Data Centre/BAS and Natural Earth. Projection: EPSG 6932.

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Assessment models for Antarctic toothfish (Dissostichus mawsoni) in the Ross Sea region to 2023/24

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EN

Assessment models for Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea region to 2023/24

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ABSTRACT

We update 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 2024 season.

The previous assessment model was updated with catch data for 1998–2024, tag-release data for 2004–2023 and tag-recapture observations for 2005–2024, fishery catch-at-age composition data for 1998–2023, and abundance and age composition data from the Ross Sea Shelf Survey (RSSS) for 2012–2023. The model structure was the same as that used for 2023 using Casal2, except that the non-informative selectivity priors used Student's-t distributions and the RSSS catchability coefficient was modified to be a free parameter.

The 2024 base case model Markov chain Monte Carlo posterior estimated B_0 as 77 920 t (95% CIs 72 060–84 690 t) and the current stock status (B_{2024}) as 65.2% B_0 (95% CIs 62.3–68.1 B_0). While there had been no discernible trend or drop in recent recruitment, the precautionary yield was calculated using the CCAMLR 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. This resulted in a catch limit of 3278 t from the 2024 base case model assuming that future recruitment was similar to that from the most recent estimated 10 years (2009–2018). Yields assuming recruitment that was similar to all estimated years (2005–2018) would have resulted in a catch limit of 3460 t. A preliminary exploration of spatial Chapman's was undertaken. This suggested an expected level of reduction of toothfish abundance over time in the western side of the south of 70° S management area, while the other areas displayed some interannual variability but little overall trend.

The application of a *U*-based harvest rate resulted in a higher potential catch limit, as the current stock status was estimated to be above the target of 50% B_0. The revised CCAMLR toothfish decision rules, proposed by WG-SAM-2024 to use the lower value of the constant catch projection and the *U*-based calculation, would not result in a different recommendation of precautionary yield.

Sensitivity models using logistic selectivities for the N70 fishery, and either up- or downweighting the different groups of observations (fishery catch-at-age compositions, tag recapture observations, or the RSSS abundance) did not lead to significantly different results, other than down weighting the RSSS abundance resulted in a slightly higher initial biomass (B_0) and slightly lower current stock status.

An evaluation of potential Harvest Control Rules found that either a constant U-based or the tested ramp rules could be used to maintain the stock status at the target levels, with different rules having different trade-offs between catch, stability and risk or stock depletion. These rules provide an alternative method for managing toothfish fish stocks and we recommend that further work on developing harvest control rules within Management Strategy Evaluations be considered.

Based on these results, we recommend that the 2024 base case model with recent (10-year) recruitment be used for the provision of management advice, leading to a proposed catch limit of 3278 t for RSR Antarctic toothfish for the 2024/25 and 2025/26 seasons.

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1. 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 1997[1]. Since 2004, the catch in the Antarctic toothfish fishery in the RSR has been between 2178 t and 3469 t in each fishing season, increasing to 3499 t for the 2023 season (Devine 2024). Catch limits for the RSR have been determined using the precautionary yield calculations from an integrated stock assessment model using CASAL (Bull et al. 2012) and recently, Casal2 (Casal2 Development Team 2024a). The models integrate the historical catch and observations that include the commercial catch-at-age compositions, Ross Sea Shelf Survey (RSSS) abundance and age compositions, and tag-recaptures from releases of tagged fish.

This report updates 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 2024 season. This updated the 2023 stock assessment model and used catch data for 1998–2024, tag-release data for 2004–2024 and tag-recapture observations for 2005–2023, fishery catch-at-age composition data for 1998–2023, and abundance and age composition data from the Ross Sea Shelf Survey (RSSS) for 2012–2023. The data from the 2024 RSSS was not included as it did not completely survey the core area as the survey voyage was interrupted due to adverse ice conditions (Devine et al. 2024). Release and recapture data for tagged fish and length composition data from vessel trips that had been quarantined or that were from other research programs were excluded. The model structure was the same as that used for 2023 using Casal2, except that the non-informative selectivity priors used Student's-t distributions and the RSSS catchability coefficient was modified to be a free parameter.

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 in 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).

The stock assessment model assumed a single homogeneous area with four geographically defined fisheries (see Figure 1), based on the management areas for Subareas 88.1 and Small-Scale Research Units (SSRUs) 88.2A-B, 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). 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.

The catch for each of the fishery areas included 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 (i.e., catches from the South Pacific Regional Fisheries Management Organisation (SPRFMO). The data and the observations for the models are described in detail in Devine (2024).

[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.

Following recommendations from the 2024 WG-SAM, several additional analyses were carried out. Model validations (SC-CAMLR-41 2022, paragraph 2.8) for the 2024 base case stock assessment are also described.

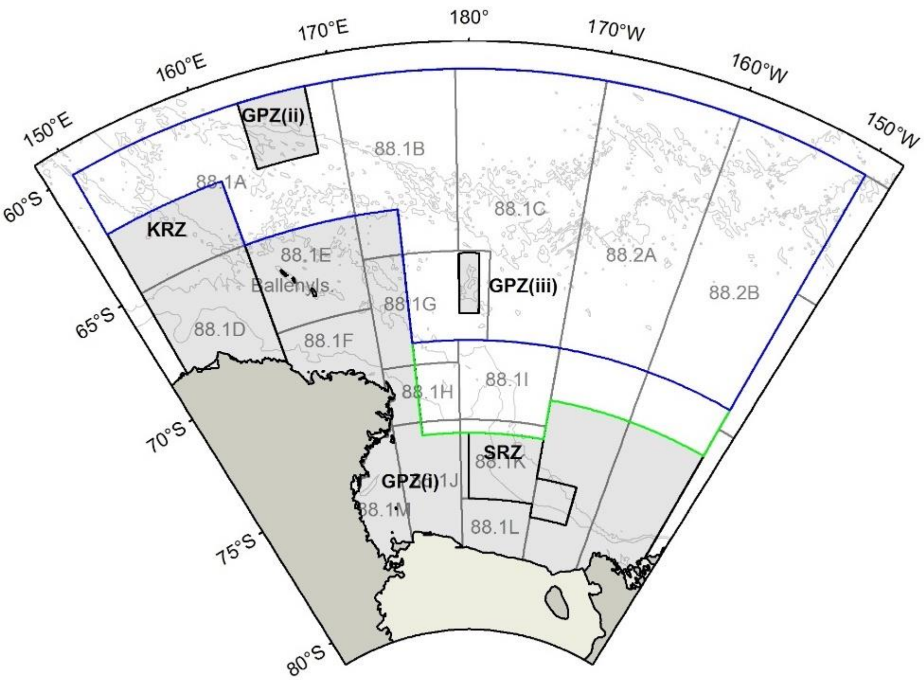

Figure 1: Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Subareas 88.1 and 88.2, Small-Scale Research Units (SSRUs), the Ross Sea region Marine Protected Area (General Protection Zones (GPZ) (i)–(iii), the Krill Research Zone (KRZ), and the Special Research Zone (SRZ); in 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.

2. METHODS

The 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 (Dunn 2019), Grüss et al. (2021), and Mormede et al (2023). The assessment model was implemented using Casal2 (Casal2 Development Team 2024a), with post-processing in R (R Core Team 2022) using the R-libraries *Casal2* (Casal2 Development Team 2024b) and *r4Casal2* (Marsh & Dunn 2024). Detailed descriptions of the stock area, stock assessment methods, and the stock assessment parameters are given in the Stock Annex for the assessment (Dunn & Devine 2024a). Supplementary tables of model outputs are detailed in Appendix A of this paper, and complete sets of model diagnostics are provided by Dunn & Devine (2024b). A summary of significant changes to the assessment methodology since 2005 is given in Appendix B. The Casal2 input and output data files associated with the assessment model are available from the CCAMLR Secretariat upon request.

The model was structured as a sex (male and female) and age-structured model with ages from 1 to 50, whereby the number of male and female fish of each age from 1 to 50 was tracked through time, and the last age group was a plus group (i.e., an aggregate of all fish aged 50 and older). The population was initialised assuming an unfished equilibrium age structure at an initial biomass (i.e., with constant recruitment), estimated by the model. The model was run from the 1995 to 2024 fishing years, and the annual cycle was broken into four discrete time steps: summer (December–March, time step one), tag-loss (to account for potential loss of tags from tagged fish), winter (April-November), and then an age incrementation step. Biomass calculations were made at any point in the model by multiplying the number of fish in each year class by the size-at-age relationship and the length-weight relationship for each sex separately. The annual cycle of the model is detailed in Table 1.

Initially, in time step one, fish were recruited to the model (at age 1). Recruitment was assumed to occur at the beginning of the first (summer) time step, to be 50:50 male to female, and to be the mean (unfished) recruitment (R_0) multiplied by the Beverton-Holt spawning stock-recruitment relationship (Beverton & Holt 1957). Recruitment was assumed constant and equal to R_0 times the stock-recruitment relationship for years where adequate age composition data were not available (see later). Future (projected) recruitment was assumed to be distributed with a mean and the variability observed in the estimated historical recruitment for each Markov chain Monte Carlo (MCMC) iteration, either from resampling a recent period (e.g., the most recent 10-years or most recent 12-years) or from the entire estimated historical recruitment period (see below for more detail).

The catch for the fisheries was assumed to occur in summer as this is the period when the fishery occurs. Total mortality for each fishery was applied by removing half of the natural mortality for the time step, then mortality from the fishery, and then the remaining half of the natural mortality for the time step. The fishing selectivity parameters were assumed double-normal by sex and their parameters were estimated in the model through the fitting of the fisheries age composition data. The RSSS occurs at the end of the summer time step; the survey selectivities were assumed double-normal by sex and were estimated by the model by fitting the survey age composition data. Maturation was specified as the time-invariant proportion of male and female fish-at-age that were mature and calculated as at the middle of the winter time step. Age-incrementation occurred at the end of the year.

Model parameters were estimated by minimising the total objective function, which was the sum of the negative log-likelihoods from the data, the negative-log priors, Jacobians from any transformations where the prior was applied in natural space and included Simplex transformations for year class strengths (YCS) and inverse-transformations for right-hand limb selectivity parameters. Penalty functions were used to apply model constraints such as the catch constraint and the tag-availability constraint. Penalties would have been applied if the biomass from the model was too small to allow the catch to be taken or tagging to occur, but these did not enter the model in any of the scenarios modelled.

Initial fits were evaluated at the mode of the posterior distribution (MPD). The model fits were evaluated by evaluating MPD fits and residual patterns, and by qualitative assessment of the MPD profile distributions (i.e., by evaluating the minimum objective function while fixing one parameter and allowing all other parameters to vary). Residual patterns in the age compositions were investigated using both Pearson and one-step-ahead (OSA) residuals (Trijoulet et al. 2019). OSA residuals were evaluated because, unlike Pearson residuals, these may be more appropriate for non-normal multivariate distributions that have inherent correlations (Trijoulet et al. 2023).

The initial spawning stock biomass (B_0) was estimated in the model, as were YCS and selectivity ogives. The parameters estimated, prior distributions, prior parameters, and bounds are summarised in Table 2.

Most priors were intended to be relatively non-informative and were specified with wide bounds. Student's-t distributions with 4 degrees of freedom with a weak mode and wide standard deviations were used as non-informative priors for the selectivity parameters. Right-hand limb parameters were transformed using the inverse transformation. Either uniform or uniform-log priors were used for the RSSS process error and catchability coefficient q, and B_0. B_0 was estimated using a log transformation. Lognormal priors were used for the estimates of YCS and were estimated using the Simplex transformation.

Bayesian inference was used to obtain samples from the posterior distribution of model parameters using the Metropolis-Hastings algorithm (Gelman et al. 1995, Gilks et al. 1998). Markov chain Monte Carlo (MCMC) estimates were initialised using a random starting point near the MPD (generated from a multivariate Students-t distribution, centred on the MPD with covariance equal to the inverse Hessian matrix), with the correlation matrix derived from the inverse Hessian. MCMCs had a burn-in length of 0.5×10^6 iterations, with every 1000th sample taken from the next 1×10^6 iterations (i.e., a final sample of length 1000 was taken after the burn-in to sample from the posterior distribution). Chains were investigated for evidence of non-convergence with qualitative investigation of MCMC traces and multiple-chain comparisons (i.e., three chains of 1000 samples each), and $\hat{r}$ statistics (Gelman et al. 2015, Vehtari et al. 2017a). The $\hat{r}$ values less than 1.01 are considered evidence of convergence (Monnahan 2024).

Table 1: Annual cycle for the Ross Sea region Antarctic toothfish population model showing the time-steps, order of timing for the catch removals, biological processes and observations.

Month	Catch (%)		Biological processes						Observations				Time step
	Actual	Assumed	Ageing	Recruitment	Maturation	Growth (%)	Natural mortality (%)	Spawning	Tag release	Tag recapture	RSSS survey	Age compositions	
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						

Table 2: The assumed priors for key parameters for the Ross Sea region stock assessment. The prior parameters (and transformation) are mean (mu), and either sigma (scale parameter for the Student's-t) or CV (for the lognormal).

Parameter (transformation)	Distribution	Parameters		Bounds	
		Mu	Sigma/CV		
B_0 (log)	Uniform			10	18
Year class strengths (Simplex)	Lognormal (μ, CV)	1.0	1.1	-10	10[1]
RSSS q	Uniform-log			1e-6	10.0
Selectivities (inverse right-hand limb)[2]	Students-t (μ, σ)	0.01–8[2]	30	1	1–500[2]
RSSS CV process error[3]	Uniform			0.0	10.0

[1] Recruitment parameters were estimated using the Simplex transformation with the bounds in Simplex space and priors in natural space.

[2] Different values were used for mu and the bounds depending on the specific selectivity parameter. Right-hand limb selectivity parameters were estimated using an inverse transformation.

[3] Estimated at MPD and fixed for MCMCs.

The following data were updated in the 2024 assessment model from that used in 2023:

- Annual catch for the 2024 fishing season and catch by management area (N70, S70, and SRZ) were added with minor revisions to the previous catch history.
- Age composition observations from the RSSS were added for 2023.
- IUU catches for 2024 was assumed to be 0 t.
- Scaled catch-at-age compositions from the fishery for 2023 were added and historical catch-at-age compositions (1998–2022) were recalculated and updated.
- Tag-release data for 2023 and associated recapture data for 2024 were added. The tag data for 2005–2024 were revised using the updated correction of vessel-specific tagged fish survival and vessel-specific tag detection rates.
- An additional year's recruitment was estimated by estimating the recruitment multipliers for the model at age 1 for the period 2004–2018 (i.e., YCS for 2003–2017). These were assumed to have a mean of one over that period.

A summary of the observations for the assessment is available by year is given in Figure 2.

The 2023 assessment model (Mormede et al. 2023) had been updated following the recommendations of WG-SAM-2023, including using parameter transformations (SC-CAMLR-42 2023, Annex 16, paragraph 6.37), double tagging loss rate function (SC-CAMLR-42 2023, Annex 16, paragraph 6.39), excluding data on tagged fish released before 2005 (SC-CAMLR-42 2023, Annex 16, paragraph 6.40), and updated tag loss rates for double-tagged fish (SC-CAMLR-42 2023, Annex 16, paragraph 6.21). The 2024 model was updated with Student's-t priors and the use of a free parameter for the RSSS catchability coefficient. The resulting model, following the addition of the new data and Francis reweighting (Francis 2011), resulted in the 2024 base case (R2.0).

As in previous assessments, catch per unit effort (CPUE) indices were not included in the model because CPUE was not likely to reflect changes in abundance (Parker & Mormede 2017, Dunn 2019, Devine & Mormede 2023, Devine 2024).

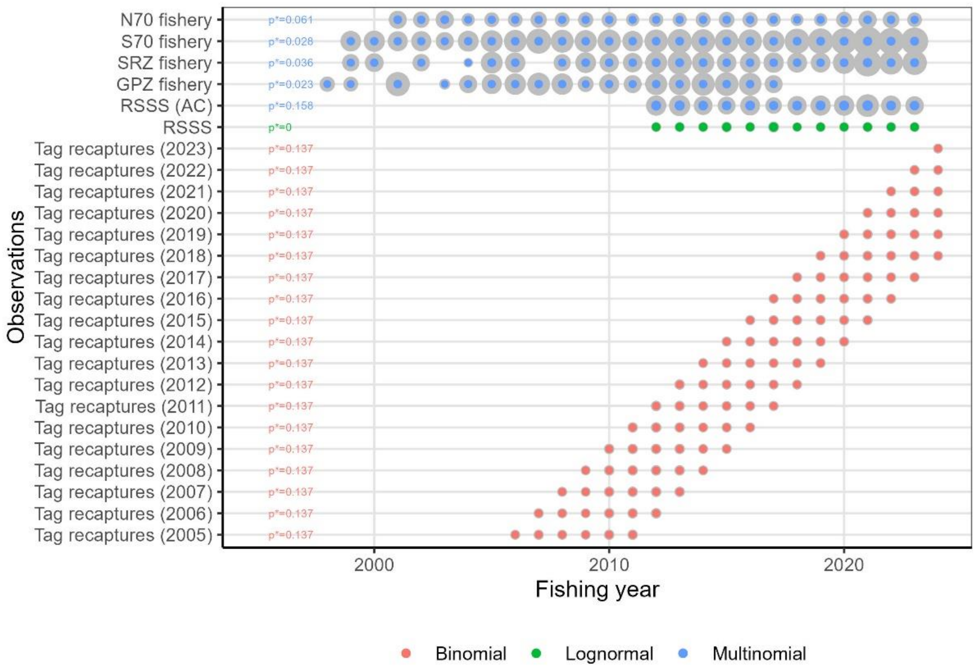

Figure 2: Model observations for the 2024 base case model (R2.0). The coloured points represent the relative effective sample sizes (mean-adjusted for comparability between observation types) for each year and observation type (rows: age-compositions (AC), RSSS abundance, and tag-recapture observations) and likelihood (colour), with the grey outline indicating the initial sample size before reweighting. p* was the multiplier used to adjust the multinomial Ns in each observation from the Francis reweighting (multinomial likelihoods) or the process error CV (lognormal likelihoods).

3. RESULTS

3.1 Audit trail from the 2023 model

Incremental changes from the 2023 base case model (2023-R3) to the 2024 base case model (R2.0) 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, initially without changing the 2023 data weightings. At the end of the audit trail, the data weighting was recalculated using the methods of Francis (2011).

The audit trail is given in Table 3, and suggests that adding new data (R1.0) resulted in essentially the same initial biomass (B_0) but a slightly higher status in 2024. Modifying the uniform selectivity priors (R1.1) did not result in any appreciable change, neither did the change of the parameterisation for the survey catchability coefficient (q) for the RSSS from a nuisance parameter to a free parameter (R1.2) (see Casal2 Development Team 2023). The lower bound for the left-hand limb of the selectivities was modified (R1.3) because initial MCMCs suggested that the previous bound lower of one constrained the lower end of the posterior distribution estimates for those parameters, specifically for the GPZ and RSSS selectivity ogives. They were modified to be 0.01 and allowed the MCMC posterior to explore a greater range, but otherwise did not appreciably affect the resulting biomass or output quantities. The introduction of the catch-at-age compositions for 2023 (R1.4) also had little effect. Overall, the model changes from 2023 to the 2024 base case model after reweighting (R2.0) resulted in only small changes to the output quantities and the SSB trajectory.

Table 3. Audit trail of MPD estimates of the total negative log-likelihood (NLL), number of parameters (n), AIC, B_0 (t), and B_{2023} and B_{2024} (%B_0) for the assessment model, showing the stepwise incremental changes from the 2023 base case model (labelled R3) to the 2024 base case model (labelled R2.0).

Model	Name	NLL	n	AIC	B_0	B_{2023}	B_{2024}
R0.1	R3 (2023) WG-FSA-2023/13	2 976.6	50	6 053.1	78 553	64.4	-
R0.2	R3 (2023) (Casal2 v23.08)	2 976.6	50	6 053.1	78 553	64.4	-
R1.0	2024 initial case (catch & tag data)	3 011.4	51	6 124.7	78 653	66.0	65.2
R1.1	2024 with Student-t priors	3 132.2	51	6 366.4	78 735	66.0	65.3
R1.2	2024 with free *q*'s	3 132.2	52	6 368.4	78 734	66.0	65.3
R1.3	2024 with revised selectivity bounds	3 130.6	52	6 365.2	78 857	66.0	65.2
R1.4	2024 with 2023 CAA data	3 218.4	52	6 540.8	78 964	65.9	65.1
R2.0	2024 base case (reweighted)	3 022.7	52	6 149.5	78 438	65.9	65.3

3.2 Analysis of MPD results

Diagnostic plots for the 2024 base case model (R2.0) are given by Dunn & Devine (2024b). The estimated maximum posterior density (MPD) initial biomass (B_0) was 78 438 t, and the current stock status (B_{2024} %B_0) was estimated to be at 65.9%. The start values and prior assumptions used are given in Table 12, relative data weightings are given in summarised in Table 13, and the total objective function is detailed in

Table 14.

Likelihood profiles were carried out by fixing B_0 over a wide range of plausible values and the remaining parameters (e.g., selectivity parameters) were estimated (Figure 3). The tag-recapture likelihoods of fish released in 2005, 2006, 2016, 2018, 2019, 2022, and 2023 suggested that estimates of initial biomass lower than the MPD estimate were more likely. However, the recaptures of tagged fish released in 2008, 2009, 2012, and 2017, and the catch-at-age compositions from the GPZ, SRZ, and S70 fisheries suggested that estimates of initial biomass higher than the MPD estimate were more likely (Figure 3). Overall, most of the likelihood profiles for individual data sets were not substantially conflicted and they indicated an estimate of B_0 that was near or very near the MPD value.

Plots of the observed proportions-at-age of the catch versus the MPD expected values suggested that while the Pearson residuals for the most common ages were generally adequate, there was evidence of a residual pattern for either changing selectivity through time and/or YCS progression that was not well modelled (Figure 4). Residual patterns in the age compositions were also investigated using one-step-ahead (OSA) residuals (Trijoulet et al. 2019) as, unlike Pearson residuals, these may be more appropriate for non-normal multivariate distributions that have inherent correlations (Trijoulet et al. 2023). Diagnostics for the one-step-ahead residuals are shown in Figure 5 and did not indicate any evidence of departure from the distribution assumptions. Fits to the RSSS local abundance series followed the overall trend (Figure 6).

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 Devine 2024). 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 7).

YCS estimated in the 2024 base case model (R2.0) were consistent with those estimated in the previous stock assessment (Mormede et al. 2023) and the estimated selectivity ogives for the fisheries were also similar (Figure 8)

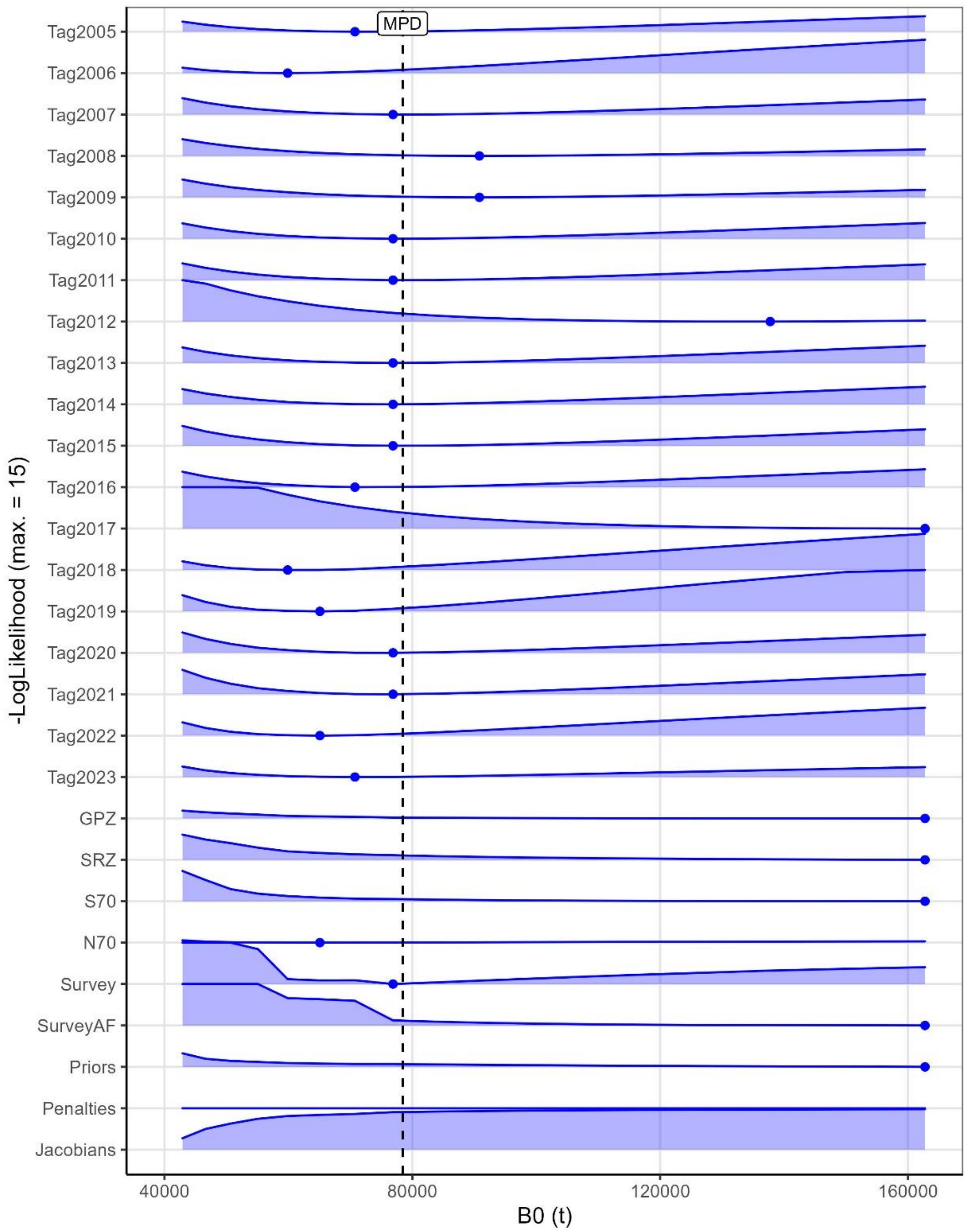

Figure 3: Likelihood profiles for pre-exploitation biomass B_0 for the 2024 base case model of Ross Sea region Antarctic toothfish for each tag release cohort, catch-at-age compositions, RSSS, and penalties and priors. Negative log-likelihood values were rescaled to have a minimum of 0 for each dataset. 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 compositions.

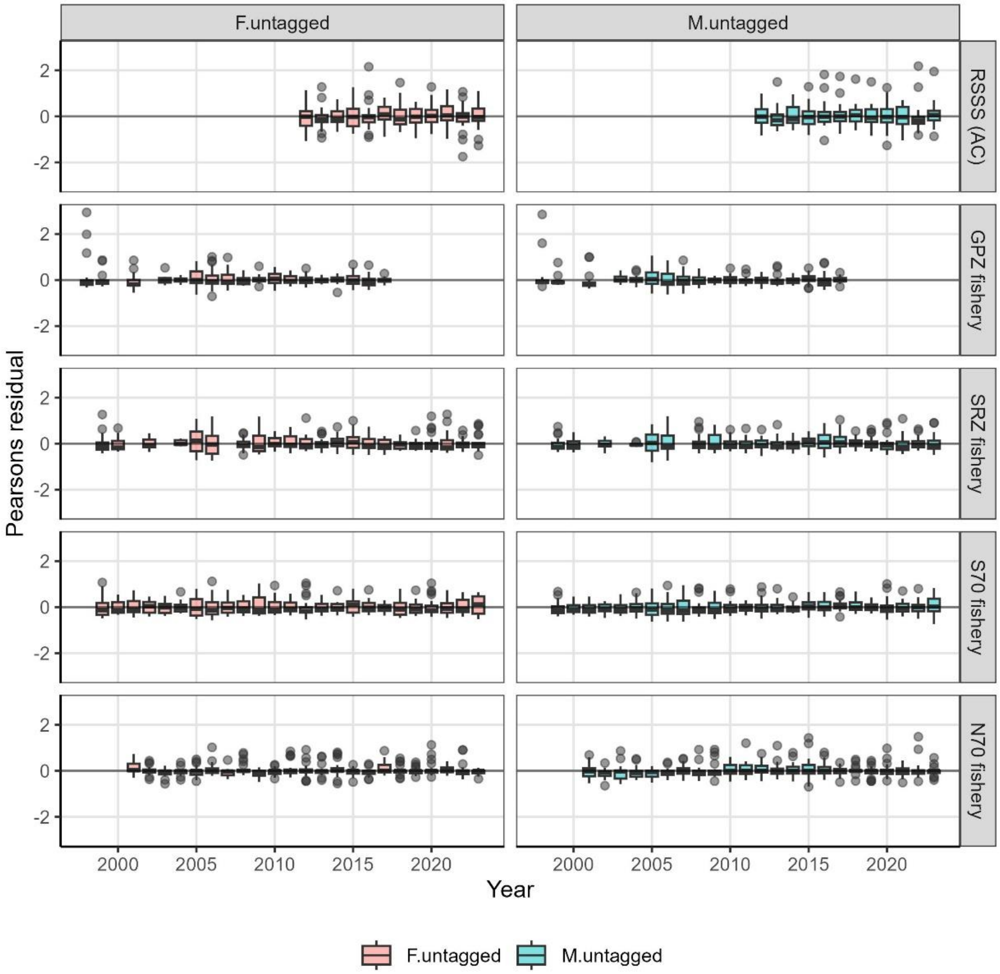

Figure 4: Pearson residuals for female and male composition data for the 2024 base case model (2.0) by management area.

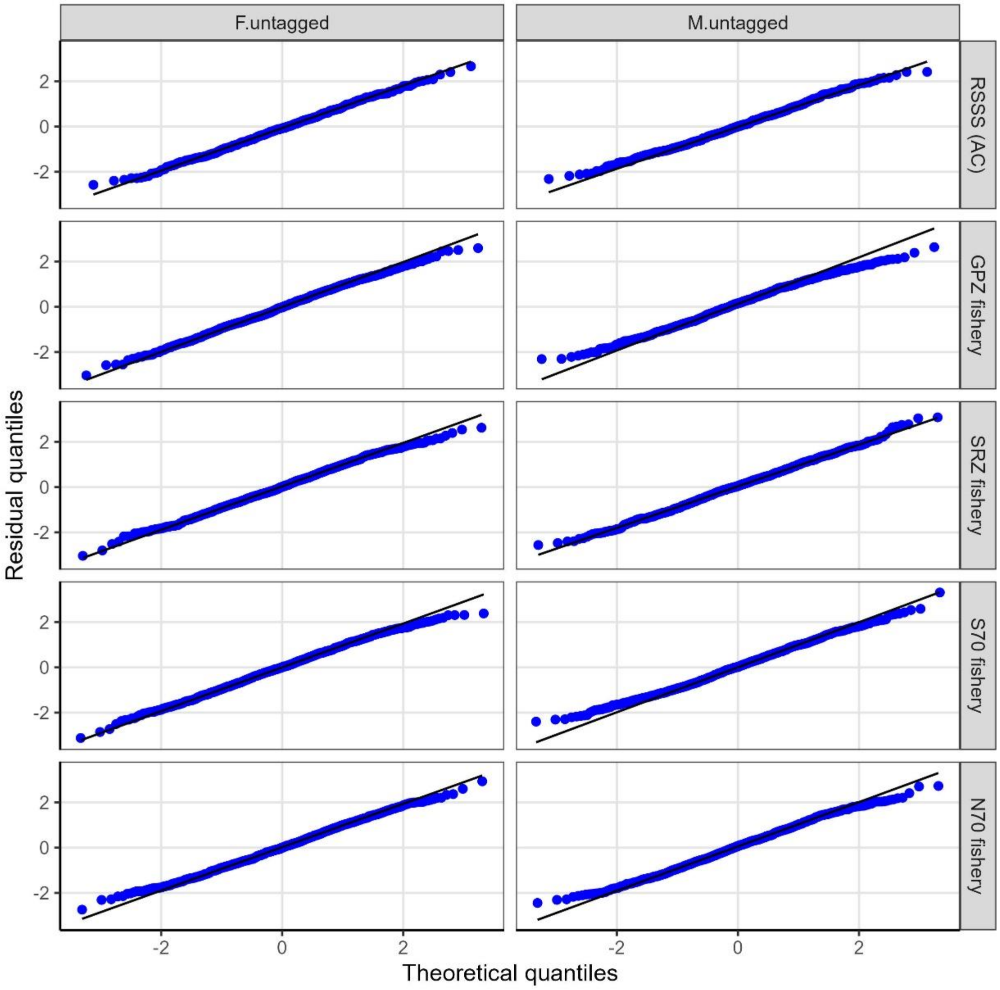

Figure 5: QQ-plots for the one-step-ahead (OSA) residuals for female and male composition data for the 2024 base case model (2.0) by management area.

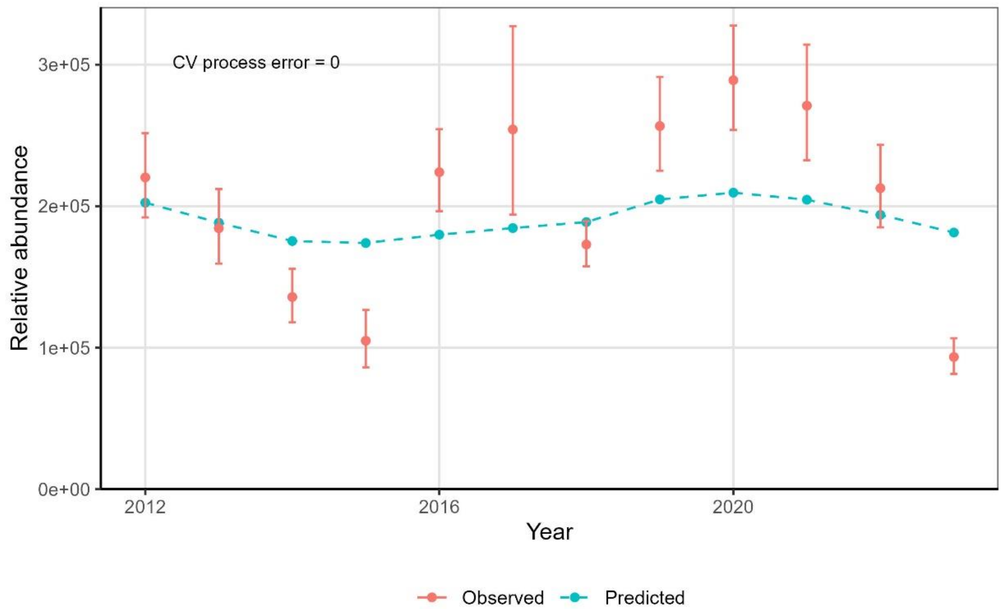

Figure 6: Maximum posterior density (MPD) and Markov chain Monte Carlo (MCMC) fits to the survey (RSSS) local abundance series for the 2024 base case model of the Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*).

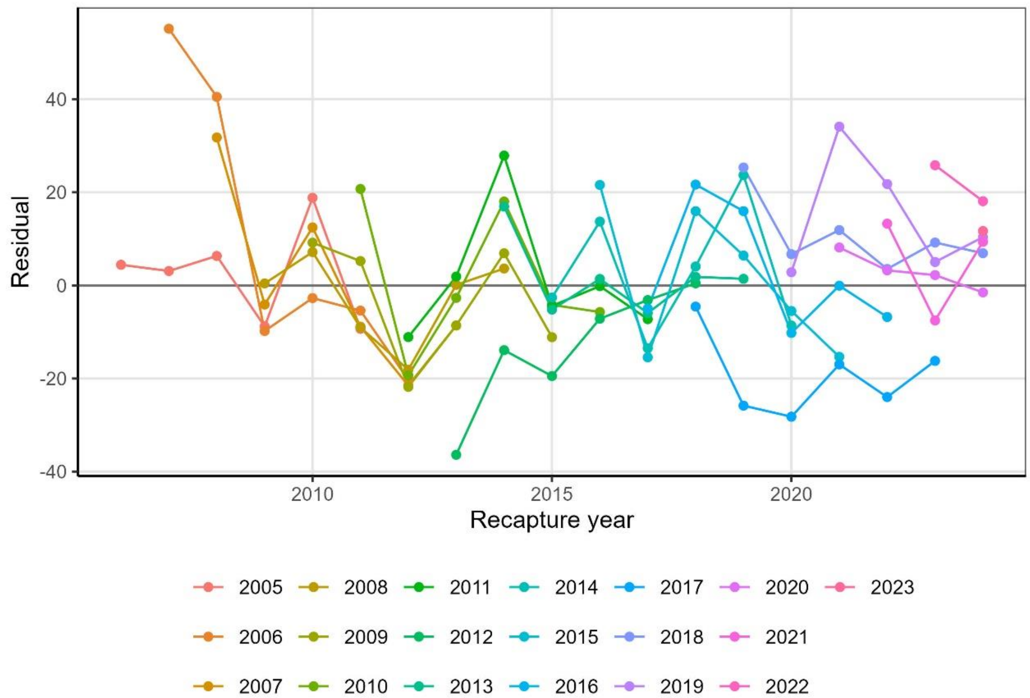

Figure 7: Expected minus the observed number of tagged fish recaptured each year of recapture per year of release for the 2024 base case model of the Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*).

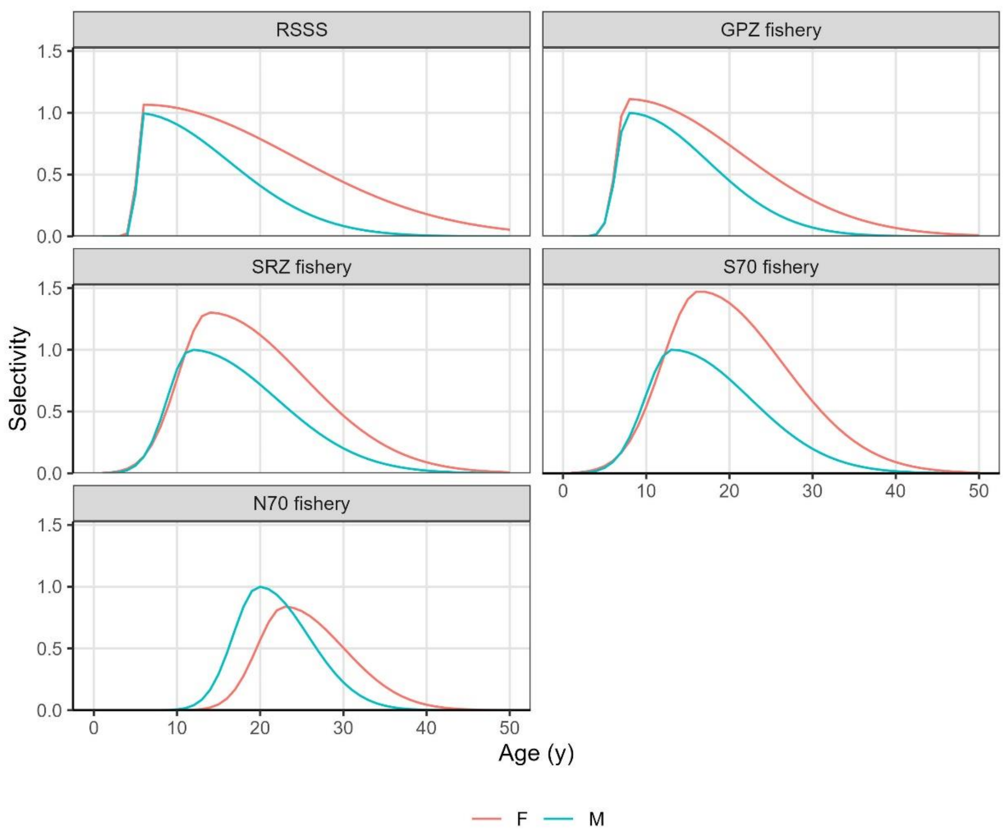

Figure 8: MPD estimated selectivities for male and female toothfish for the RSSS and GPZ, SRZ, S70, and N70 fisheries for the 2024 base case model.

3.3 Sensitivity analyses

3.3.1 Sensitivities of the base case model

Sensitivity runs were carried out that investigated alternative weightings for each of the observation data sets (see Table 4). These sensitivities were run at MPD level only. A sensitivity forcing the N70 fishery to be approximately logistic shaped (by forcing the right-hand-limb of the double-normal selectivity to be large, R4.1) had little effect on the key output values but did result in a substantially worse fit to the N70 age data. Modifying the data weightings for the age composition (R5.1 & R5.2) or tag data (R5.3 & R5.4) did not substantially change the estimates of initial biomass (B_0) or current stock status (Table 4). Adding a process error of CV=0.20 to the RSSS abundance (R5.5) increased the estimate of initial biomass, but also reduced the estimate of the current stock status. While this sensitivity would be unlikely to alter management advice, the change indicated that additional future work on the survey abundance index in the model to help understand this effect would be useful.

Table 4. MPD estimates of the total negative log-likelihood (NLL), number of parameters (n), AIC, B_0 (t), and B_{2024} (%B_0) for Ross Sea region Antarctic toothfish), showing the changes from the 2024 base case model (labelled R2.0) for key sensitivities that alter the relative weights of the tag recapture, age, and RSSS observation likelihoods.

Model	Name	NLL	n	AIC	B_0	B_{2024}
R2.0	2024 base case (reweighted)	3 022.7	52	6 149.5	78 438	65.3
R4.1	2024 base with logistic N70	3 049.4	50	6 198.8	78 330	65.5
R5.1	2024 base with halved tag recapture likelihood	2 858.6	52	5 821.3	78 996	65.4
R5.2	2024 base with doubled tag recapture likelihood	3 347.4	52	6 798.8	77 818	65.3
R5.3	2024 base with halved age composition likelihoods	1 760.2	52	3 624.4	77 140	66.1
R5.4	2024 base with doubled age composition likelihood	5 529.7	52	11 163.5	79 865	64.8
R5.5	2024 base with down-weighted RSSS abundance	2 925.3	52	5 954.5	81 438	62.3

3.3.2 Chapman based estimates of abundance

In addition to the sensitivities above, a preliminary investigation in the use of Chapman estimates as abundance indices, rather than the tag-release and recapture data was undertaken (model R6.0).

Initially, the Ross Sea region was split into smaller regions, defined as the N70 management area, the western and eastern S70 (labelled S70_W and S70_E), north and south SRZ (labelled SRZ_N and SRZ_S). The GPZ was split into a southern area south of 76° S (GPZ_S) and then the rest of the GPZ (GPZ_N). For each region, the catch history was calculated using the same approach as for the 2024 base case model. Similarly, length data were used to determine region specific catch-at-age compositions with the sex-specific age-length keys used that were for the N70 area and then all other areas combined. After applying vessel specific survival rates and detection rates to the tag release and recapture data, the Chapman estimates of abundance (Chapman 1951) for each region were calculated.

The number of recaptured tags available for each region and year is shown in Figure 9. Only four regions had adequate tags recaptured to allow robust time series estimates of abundance, N70, S70_W, S70_E, and SRZ_S. The estimates of abundance for these four regions for tags for one year of liberty are shown in Figure 10. Similar figures for two and three years at liberty are given in Appendix E.

These estimates were used in a modified version of the 2024 base case model (by retaining each region as a fishery with associated age composition data and including the estimates of abundance from the one year at liberty Chapman based estimates as abundance observations; and excluding the tag-release data and tag-recapture observations). In addition, a constraint, in the form of an additional prior, was added to the model to encourage the relative catchability coefficients of the Chapman estimates time series to have a total summed catchability of one, i.e., the estimated catchability of each region was estimated and then the model penalised estimates where the total sum of these catchabilities deviated away from 1. Here, the additional prior was assumed to be normally distributed with μ=1 and CV=0.2.

As this model was preliminary, only a summary of the results is presented here. The resulting estimates of the initial biomass (B_0) and current stock status are given in Table 5. The biomass trajectory is also shown in Appendix E as Figure 29. Fits to the abundance indices were adequate, but future work would need to consider the variance of the estimates and investigate the effect of additional process error (Appendix E, Figure 30). Estimates of the relative catchability for the Chapman estimates were plausible (Appendix E, Figure 31), but also requires additional work to consider the relative abundance from each area in the modelling approach.

Table 5: Median Markov chain Monte Carlo (MCMC) estimates (and 95% CIs) for B_0, B_{2024}, and B_{2024} (%B_0) for the 2024 base case model (R2.0) and the Chapman abundance model (R6.0).

Model	B_0 (t)	B_{2024} (t)	B_{2024} (%B_0)
R2.0 (2024 base)	77 920 (72 060–84 690)	50 860 (45 100–57 310)	65.2 (62.3–68.1)
R6.0 (Chapman)	128 480 (96 370–206 730)	100 940 (69 290–178 590)	78.5 (71.6–86.3)

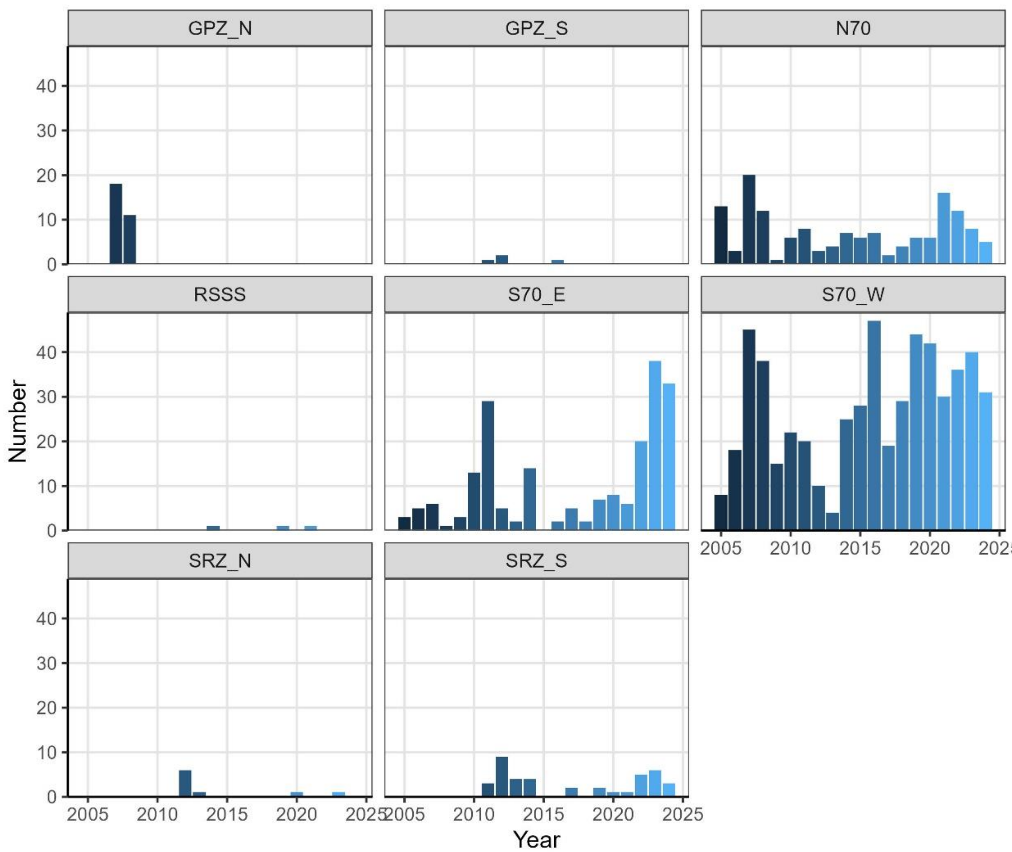

Figure 9: Number of tags recaptured by region and year for the Chapman analyses of abundance by region, 2005-2024.

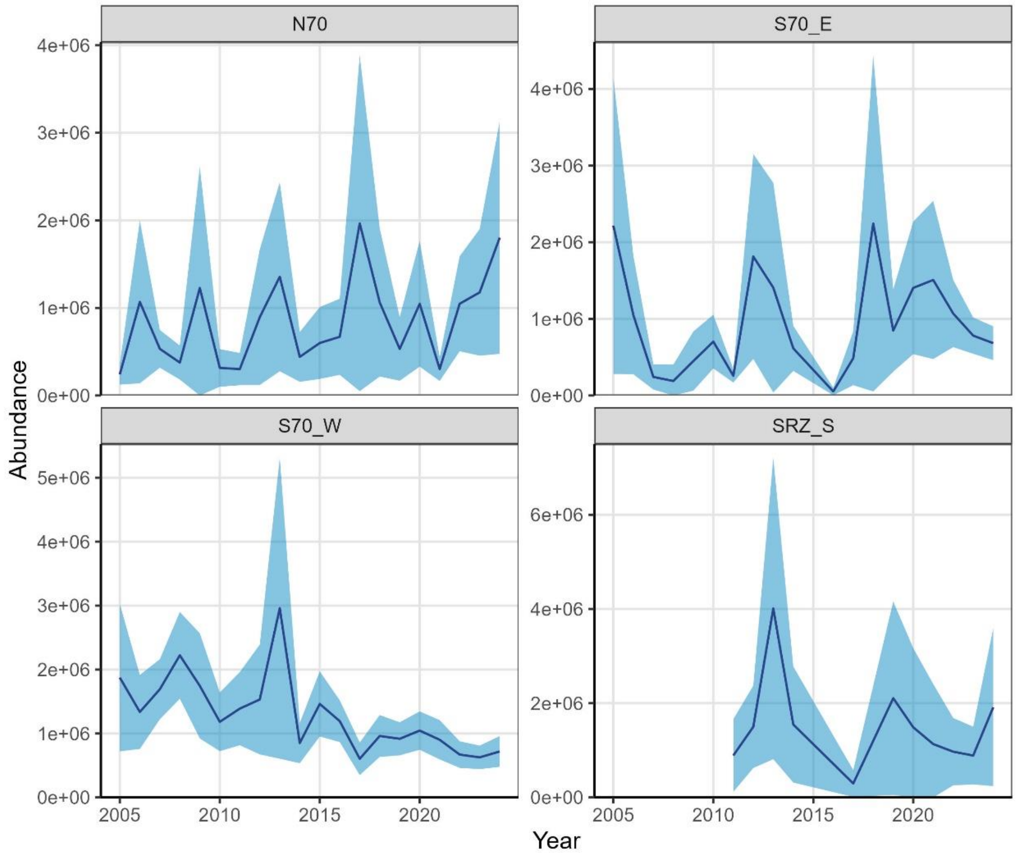

Figure 10: Chapman estimates of selected abundance (N) for the N70, S70_E , S70_W, and SRZ_S regions in the Ross Sea region using one year at liberty. Medians are shown as the dark line, and 95% confidence intervals as the shaded area.

3.4 Markov chain Monte Carlo (MCMC) results

Diagnostic plots for the base case are provided in Dunn & Devine (2024b). Markov chain Monte Carlo (MCMC) trace plots for the estimated parameters showed little evidence of a lack of convergence in the key biomass parameters and the estimated parameters. Multichain diagnostic using approximate $\hat{r}$ statistics (Vehtari et al. 2017b) did not suggest any evidence of non-convergence at the 1.05 threshold and weak evidence of less-than-ideal mixing for the left-hand-limb parameters for the GPZ fishery and the RSSS.

Plots of the estimated parameters (except YCS parameters) from the three MCMC chains are given in Figure 11, along with the MPD and median parameter estimate and the prior value over the range of MCMC estimated values.

Fits to the catch-at-age data suggest no evidence of poor fit when using one-step-ahead residuals for MPD fits, but there were indications of some lack of fit in the MCMC posterior predictions for the age composition data in the earlier years of the fishery. Previous investigations by Mormede et al. (2023) looked at a range of sensitivity analyses, including time-varying selectivity and additional YCS estimation, but found that this lack of fit did not significantly improve. Further consideration of these issues should be investigated in future assessments.

YCS were estimated for the years 2003–2017 for the base case. Stronger than average recruitment in 2006, 2012, and 2014 was estimated (Figure 12) and there appeared to be some indication of an approximately decadal cycle in the pattern; specifically, the progression of cohorts was observed in the age composition observations from the SRZ and S70, where strong cohorts appeared every 8–12 years (Devine 2024). MCMC estimates of YCS found that the recruitment variability over this period was σ_R= 0.50 (95% CIs 0.36–0.67). Over the most recent 10-year period of estimated YCS the mean YCS was μ=0.97 and σ_R=0.52 (95% CIs 0.35–0.71), and over 12 years, μ=0.95 and σ_R=0.51 (95% CIs 0.36–0.68).

Selectivity estimates (see Dunn & Devine 2024b) were similar to those estimated in previous assessments and were consistent with the ontogenetic movement of older fish to deeper waters within the Ross Sea region (Figure 13).

Fits to the survey local abundance series are shown in Dunn & Devine (2024b). 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 compositions, 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.

MCMC estimates of the initial biomass and current biomass are given in Table 6 below. The MPD for the 2024 base case model (R2.0) estimated the initial biomass (B_0) was 78 553 t, and the current biomass (B_{2024}) was estimated to be at 64.4% of B_0. MCMC estimated B_0 as 77 920 t (95% CIs 72 060–84 690 t) and the current stock status (B_{2024}) as 65.2% B_0 (95% CIs 62.3–68.1% B_0). The MCMC posterior estimate of the spawning stock biomass trajectory is shown in Figure 14.

The MCMC biomass trajectory of the base case was compared with that of the previous model runs used for management advice in previous years for 2005–2023 (Figure 15). Although the earlier assessments had wider bounds on the estimates of initial and current spawning stock biomass, there was no evidence of a trend over time with the trajectories.

A retrospective analysis was carried out where, for each year, the latest year's observations (age compositions, RSSS abundance and age compositions, and tag-recapture) were sequentially removed from the base case (Figure 16) to assess the effect of recent data on the outcome of the assessment. For each scenario, the range of years used to standardise YCS to a mean of one was also revised by removing the most recent year. There was no trend with time and hence no patterns in the retrospectives that would indicate poor model behaviour.

A tag-peel retrospective analysis was also carried out, where, for each year, the latest year's tag-recapture observations were sequentially removed from the base case (Figure 17) to assess the effect of recent tag data on the outcome of the assessment. There was no trend with time and hence no patterns in the retrospectives that would indicate poor model behaviour or changing spatial bias from the tag-recapture observations in the assessment.

Table 6: Median Markov chain Monte Carlo (MCMC) estimates (and 95% CIs) for B_0, $B_{current}$, and $B_{current}$ (%B_0) for the 2023 assessment (R3) and the 2024 base case model (R2.0). $B_{current}$ is defined as 2023 for the 2023 model (R3) or 2024 for the 2024 base case model.

Model	B_0 (t)	$B_{current}$ (t)	$B_{current}$ (%B_0)
R3 (2023)	77 855 (71 954–85 115)	49 994 (44 350–57 071)	64.3 (61.4–67.3)
R2.0 (2024 base)	77 920 (72 060–84 690)	50 860 (45 100–57 310)	65.2 (62.3–68.1)

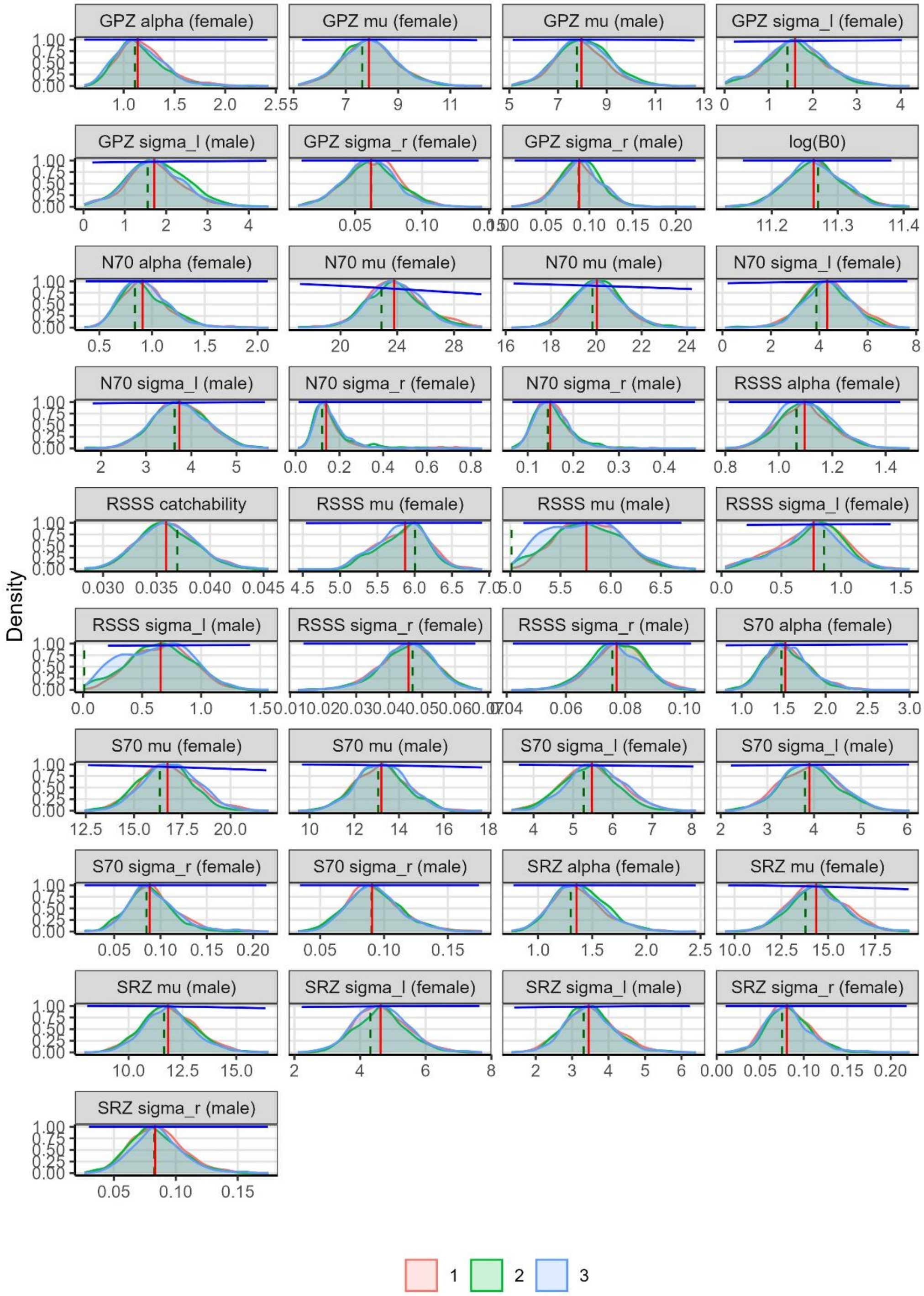

Figure 11: MCMC posterior distributions of all estimated parameters (except YCS) for the three chains (labelled 1–3) from the 2024 base case model (coloured densities), and showing the MPD (green dashed line), median MCMC value (solid red line), and prior (blue line) for each parameter.

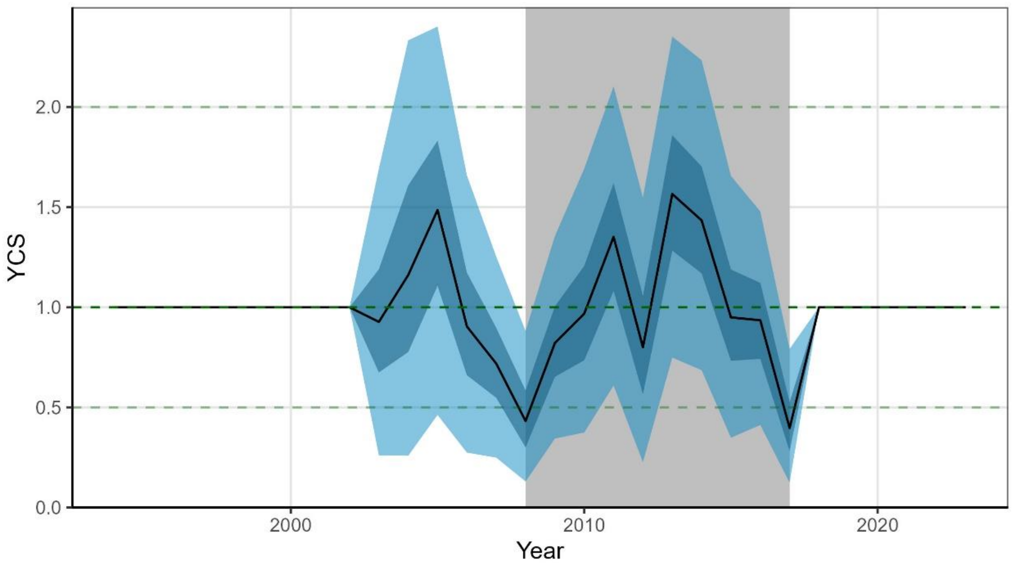

Figure 12: MCMC posterior distribution of year class strengths (YCS) for the 2024 base case (R2.0) of Ross Sea region Antarctic toothfish, with the median (black line), interquartile range (dark blue) and 95% credible intervals (light blue). The most recent 10 years of estimated YCS are shaded in grey.

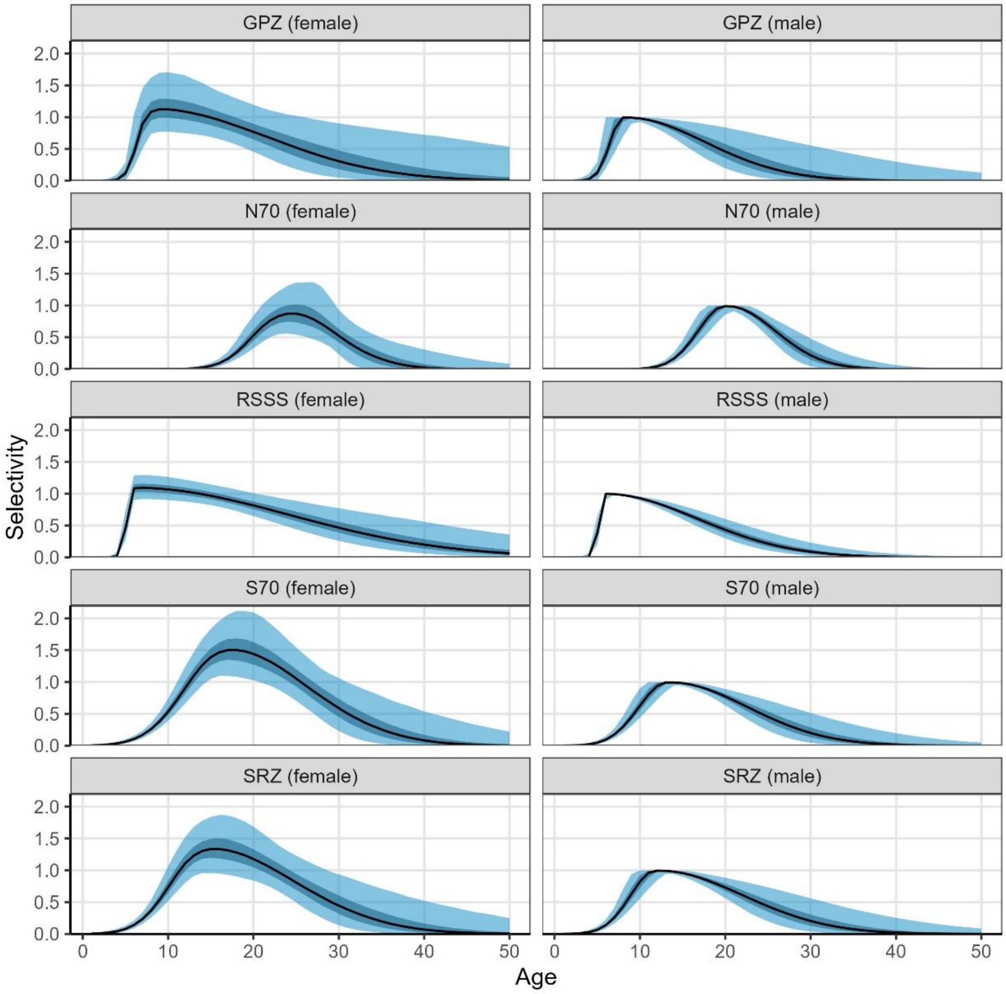

Figure 13:v MCMC posterior distributions of selectivities by sex and management area for the 2024 base case model (R2.0), with the median (black line), interquartile range (dark blue) and 95% credible intervals (light blue).

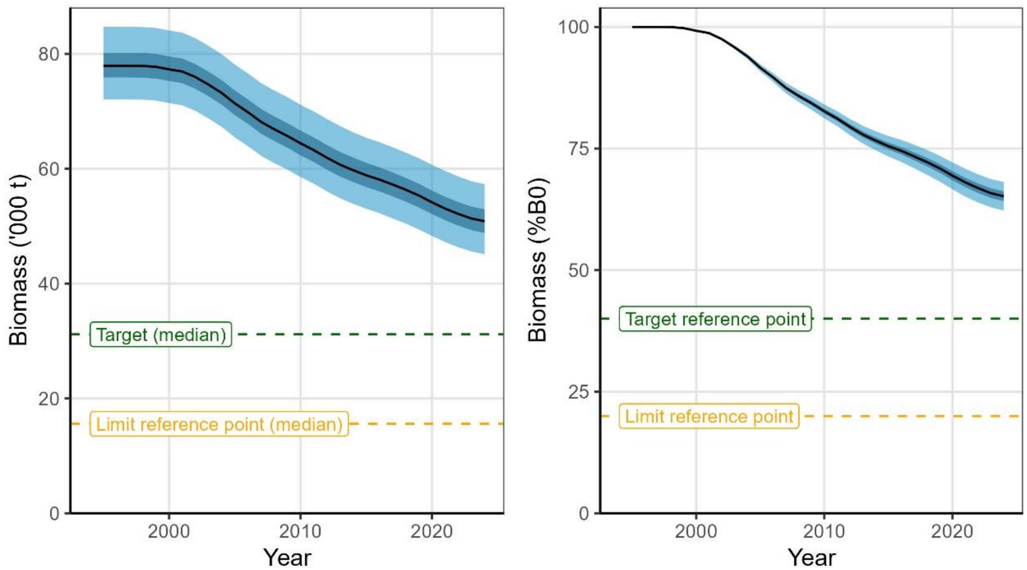

Figure 14: MCMC posterior distributions of SSB trajectories for (left) biomass and (right) biomass as %B_0 for the base case model (R2.0), with the median (black line), interquartile range (dark blue) and 95% credible intervals (light blue).

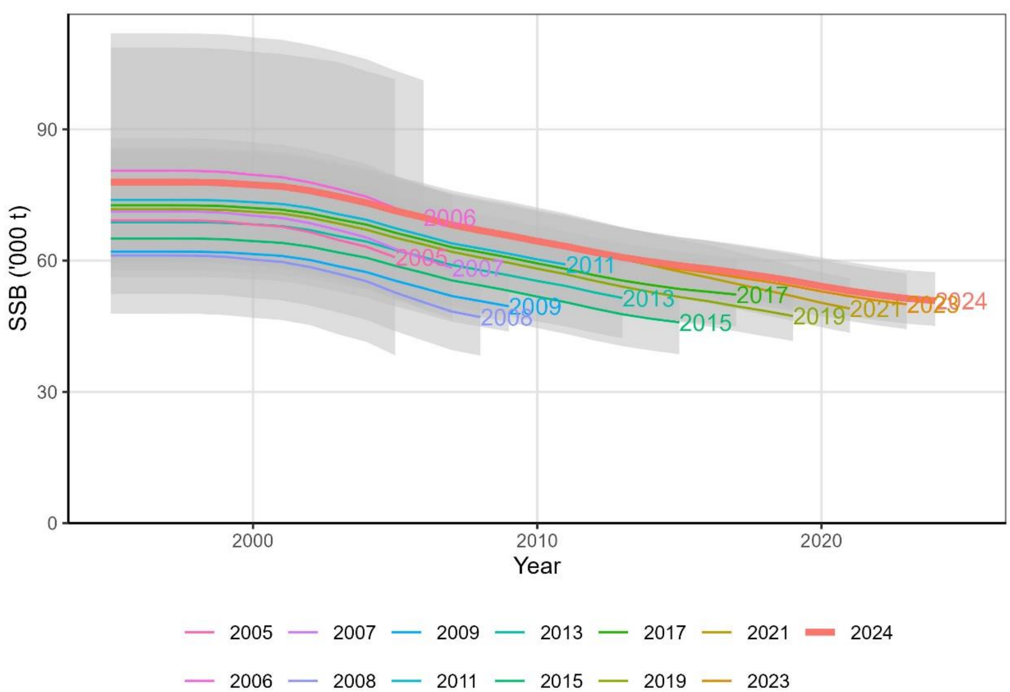

Figure 15: MCMC estimates of the spawning stock biomass trajectory of Antarctic toothfish for the 2024 base case model and previous years' models used for management advice 2005–2023. The 95% credible intervals are shown as grey shading for each model.

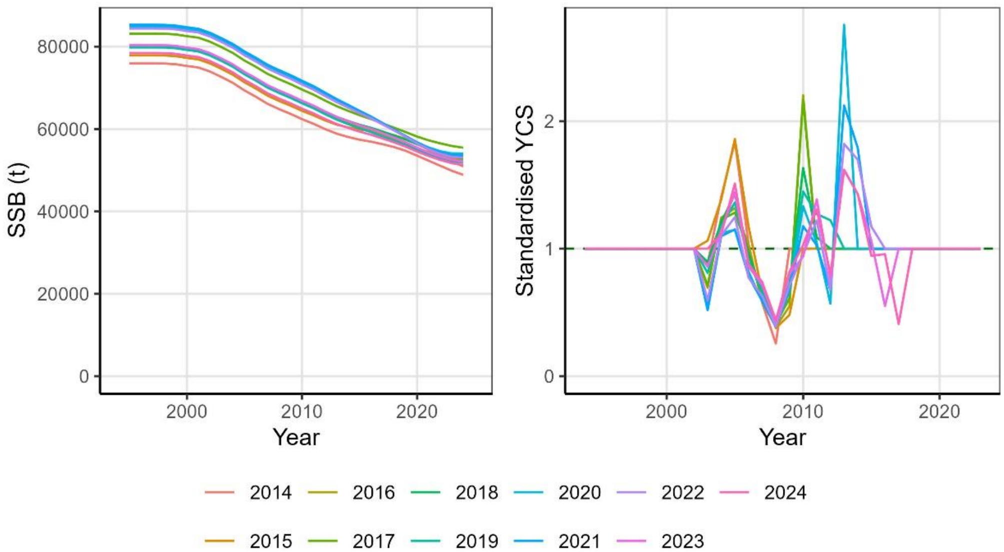

Figure 16: Retrospective analysis of the 2024 base case model for all observation peels (age composition, RSS abundance, and tag-recapture data) for 2014–2024 showing the comparison of the MPD SSB trajectory (t) (left) and estimates of year class strength (right).

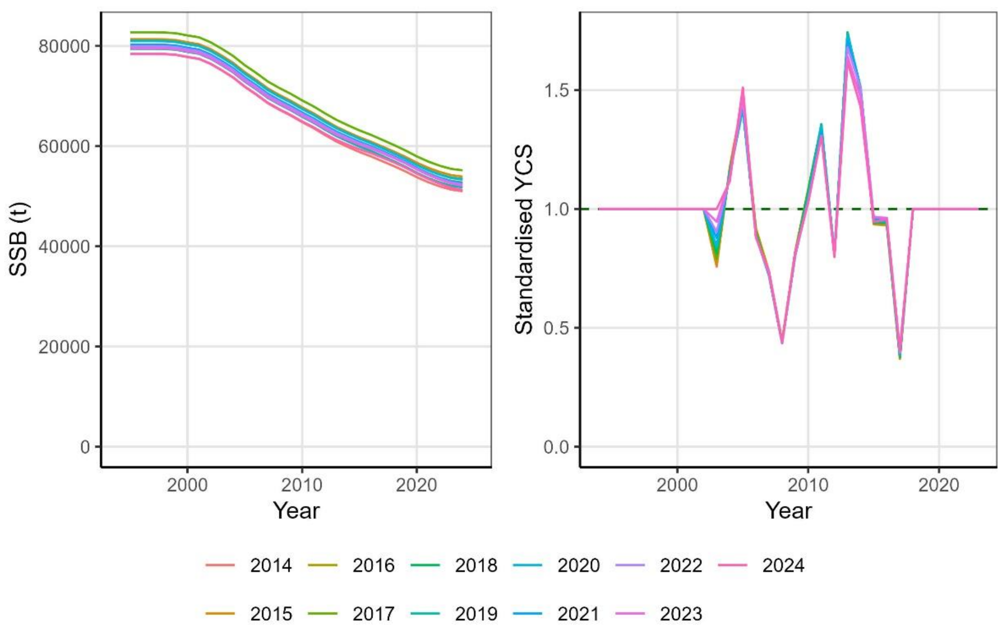

Figure 17: Retrospective analysis of the 2024 base case model with just the tag-recapture peels for 2014–2024 showing the comparison of the MPD SSB trajectory (t) (left) and estimates of year class strength (right).

3.5 Estimates of yield

3.5.1 CCAMLR decision rules

The calculation of precautionary yield used the method noted in SC-CAMLR-XXV (2006, paragraph 4.170(iii)). Projected biomass trajectories are shown in Figure 18. Precautionary yields using the CCAMLR decision rules are given in Table 7 using a future catch split of 19% for N70, 66% for S70 and 15% for the SRZ and either all, recent 10-years or recent 12-years of estimated YCS to predict future recruitment. The precautionary yield calculated using the CCAMLR toothfish decision rules and assuming the recent 10 years of recruitment as future recruitment was 3298 t.

Table 7: Estimated precautionary yields for the 2023 (R3) and 2024 (R2.0) models using the CCAMLR toothfish decision rules with recent 10-year, recent 12-year, and all year class strengths (YCS). The recommended catch limit using recent 10-year YCS is highlighted in grey.

Model	Recruitment assumption	Pr(SSB < 50% B_0)	Pr(SSB < 20% B_0)	Catch limit (t)
R3 (2023)	All YCS	0.50	<0.01	3 499
R2.0	Recent 10-year YCS	0.50	<0.01	3 298
R2.0	Recent 12-year YCS	0.50	<0.01	3 123
R2.0	All YCS	0.50	<0.01	3 460

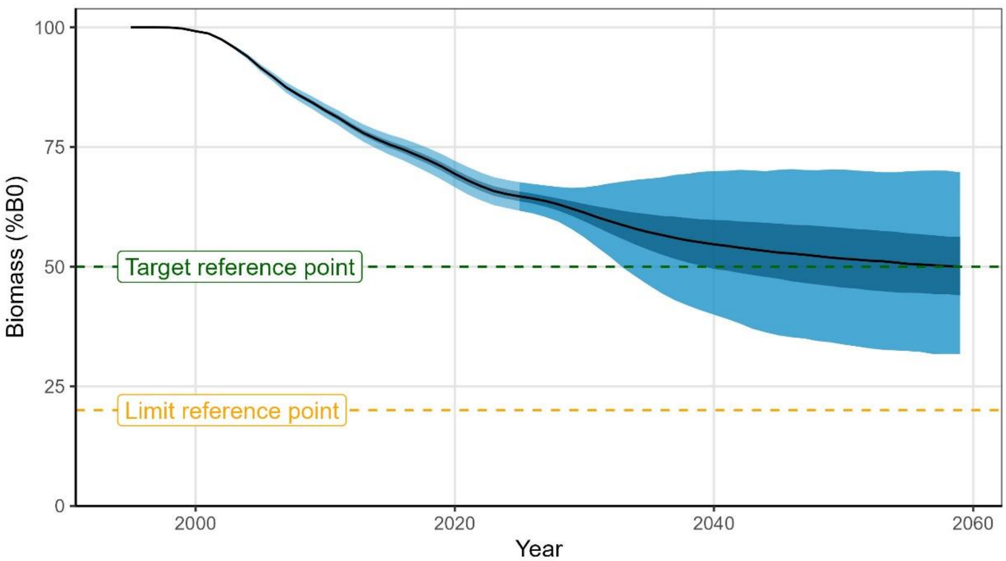

Figure 18: MCMC estimates of SSB in (%B_0) for 1995 to 2024, and then projected out to 2059 for the 2024 base model (R2.0), with the median (black line and points), interquartile range (dark blue) and 95% credible intervals (light blue). Projected values are shown as darker shading.

3.5.2 Estimates of Maximum Sustainable Yield

The target level is well above the value of B_{MSY} and correspondingly the catches are lower than would be achieved by fishing at F_{MSY} (Delegation of the United Kingdom 2019) and without any imposed risk constraint for the stock falling below 20% B_0. Deterministic B_{MSY} for Antarctic toothfish in the Ross Sea region was estimated as a median spawning stock biomass of 24% B_0 and U_{MSY} (i.e., the exploitation rate rather than an instantaneous mortality) was estimated to be about U=0.23.

3.5.3 Estimates of *U*50

Estimates of the constant exploitation rate that would result in the spawning stock averaging at least 50% B_0 (U50) with the constraint that the spawning stock biomass was more than 20% B_0 at least 90% of the time, was determined as the proportion of the total catch divided by the previous year's mid-season spawning stock biomass and applied as a two-year catch limit.

For the 2024 base case model for Antarctic toothfish in the Ross Sea region, U50 was estimated as an exploitation rate of U_{50}=0.085 and when applied to the median estimated spawning stock biomass for 2024, would result in a catch limit of 4324 t for the 2024/25 and 2025/26 seasons assuming average future recruitment (i.e., future YCS with μ=1).

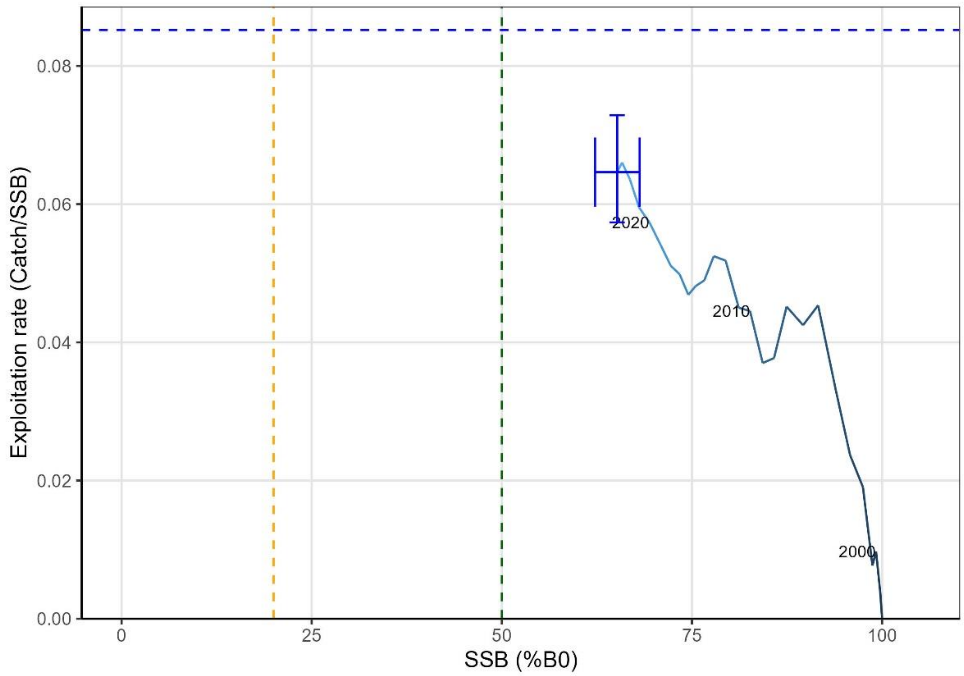

Figure 19: Trajectory over time of exploitation rate (*U*=catch/SSB) and spawning biomass (%B_0), for the base case model, from the start of the assessment period (1995) to the end of the modelled period (2024). The vertical orange line is the limit reference point (20% B_0) and the green line is the target reference point (50% B_0). The exploitation rate relating to the target reference point is represented by the blue horizontal line (*U*50=0.085). Biomass and exploitation rate estimates are medians from MCMC results with a cross indicating the 2024 95% CIs.

3.5.4 Estimates of yield using the proposed revised CCAMLR decision rules

WG-SAM-2024 proposed that the CCAMLR toothfish Decision Rules could be revised to include an exploitation rate calculation (WG-SAM, 2024, paragraph 6.9). The proposed Decision Rules were:

1. Choose a yield γ1, so that the probability of the spawning biomass dropping below 20% of its median pre-exploitation level over a 35-year harvesting period is 10%.
2. Choose a yield γ2, so that the median escapement of the spawning biomass at the end of 35 years is 50% of the median pre-exploitation level.
3. Choose a yield γ3, so that the exploitation rate of the spawning biomass is equal to the long-term exploitation rate that ensures the stock will be at 50% of the median pre-exploitation level under the [X] harvest control rule.
4. Select the lower of γ1, γ2, and γ3 as the yield.

While these revisions to the CCAMLR Decision Rules have yet to be discussed by the Scientific Committee, we applied the constant *U*50 rule to evaluate the outcome that would apply to the Ross Sea region Antarctic toothfish stock from this assessment. Using this method and assuming recent 10 years of recruitment as future recruitment, the catch limit would still be 3298 t.

3.6 Evidence of change related to the effects of environmental variability or climate change

Summary of evidence for changes in stock assessment parameters or processes that could be due to the effects of environmental variability or climate change for the Antarctic toothfish stock assessment for the Ross Sea region, as recommended by SC-CAMLR-42 (2023, paragraph 2.149) and using the template developed by WG-FSA-2023 (SC-CAMLR-42 2023, Annex 15, Table 5).

Analyses from previous work and in this paper indicate that there have not yet been any observable changes in the Ross Sea region Antarctic toothfish stock assessment parameters or processes that could be due to the effects of environmental variability or climate change. The updated table summarising evidence, as requested by the Scientific Committee, is given in Appendix C as Table 16.

4. MODEL VALIDATIONS

The validation steps recommended by SC-CAMLR-41 (2022, Annex 6, paragraph 3.31) from Dunn et al. (2022) for 2023 stock assessment model implemented in Casal2 v23.09 and then run in the latest version, Casal2 v24.08:

- Model R3 was checked against the 2023 model output (Casal2 v 23.09) using the most recent version of Casal2 (v24.08. Results at the MPD level were identical and the MCMC estimates were within random number variance from the two sets of MCMC chains (Table 8).
- The version of Casal2 used (Casal2 v24.08) matches the version reported in the *estimate.log* file.
- Biological parameters in the Casal2 input files are identical to that reported in the Stock Annex (Dunn & Devine 2024a). Catches were checked against previous model runs and reported catches.
- 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 2024 base case that can be used for validating future models matched the updated version (Casal2 v 24.08) and updated *Asserts* for any subsequent models are included within the 2024 base case Casal2 input configuration files.

Table 8. Comparison of MPD and MCMC estimates of B_0 and B_{2023} stock status for the 2023 base case model in Casal2 v23.09 (Mormede et al. 2023) and its equivalent run in Casal2 v24.08.

Platform	Run			MPD		MCMC
		B_0 (t)	B_{2023} (t)	B_{2023} (%B_0)	B_0 (t)	B_{2023} (%B_0)
Casal2 v23.09	R3 (2023 base case)	78 551	50 581	64.4	77 855 (71 954–85 115)	64.3 (61.3–67.3)
Casal2 v24.08	R0.2 (2023 base case)	78 551	50 581	64.4	77 960 (71 930–85 010)	64.3 (61.4–67.3)

5. INVESTIGATION OF HARVEST CONTROL RULES

5.1 Methods

WG-SAM 2024 recommended that the integrated toothfish assessments include an evaluation of Harvest Control Rules (HCRs) for WG-FSA-2024. Three HCRs were evaluated using the base case stock assessment model for Antarctic toothfish in the Ross Sea as the operating model in the HCR evaluation. The methods for the application of the HCRs are described in detail in Ziegler et al. (2024a)

We define the harvest rate $U_{50\%}$ as the harvest rate that, consistent with the CCAMLR Decision Rules for toothfish, in the long run, would ensure the target reference point (TRP) for the stock was 50% B_0 given a specific HCR. Three candidate HCRs (labelled Rules 1, 3, and 6) as recommended by WG-SAM-2024 were evaluated (Figure 20). These were a constant harvest rate (Rule 1) and two ramp rules for harvest rates (Rules 3 and 6) that ramped up from a lower threshold reference point (RP1) of either 20% or 30% B_0 to a constant value above a higher threshold reference point (RP2) of either 50% B_0 or a level slightly below the target based on the estimate of natural mortality M of the respective assessment (i.e. 0.50x(1-0.13)=43.5% B_0).

The simulations assumed an update of catch limits at a frequency of two years for each HCR, corresponding to the typical scheduled frequency for the Ross Sea region assessment. Similar to the management process, the assessment was assumed to occur in the year that the estimate of stock status was made, and changes in the catch limits were implemented in the subsequent year.

Based on the outcomes of the stock assessment, the SSB proxy was simulated with a lognormal distributed value and mean equal to the true SSB. Estimates were made for the distribution and CV using the methods of Cullen & Frey (1999) implemented in the R package *fitdistrplus* (Delignette-Muller & Dutang 2015) and data for 2024 stock status from the base case assessment. This gave a lognormal distribution with CV = 0.07. As these values were possibly overly precise and the true uncertainty in the assessment may be higher, we evaluated the HCRs assuming the proxy SSB index was lognormally distributed with a mean equal to the true SSB and CV=0.20. Although estimates from stock assessments are typically autocorrelated (Wiedenmann et al. 2015), no between-assessment autocorrelation was included in the simulations.

To evaluate the HCRs against the management objectives and management reference points, a set of performance indicators (PIs) was defined (Table 9). The performance indicators included criteria relating to different levels of spawning biomass including those specified by the CCAMLR toothfish Decision Rules (Ziegler et al. 2024b), and to the overall magnitude and stability of annual catches. The results of the 1000 simulations over the entire evaluation period were summarised for each HCR to derive metrics for each performance indicator for the stocks.

Table 9: Performance indicators (PIs) for evaluating candidate HCRs. Each PI relates to results from the simulation over the entire evaluation period.

Code	Performance indicator
P01	Median spawning stock biomass relative to the target level (50% B_0)
P02	Median spawning stock biomass relative to B_0
P03	Proportion of years below 10% B_0
P04	Proportion of years below 20% B_0 (depletion level or limit reference point)
P05	Proportion of years below 30% B_0
P06	Proportion of years below 40% B_0
P07	Proportion of years above the 50% B_0 (target level or target reference point)
P08	Proportion of years above 60% B_0
C01	Median total annual catch (t)
C02	Standard deviation of total annual catch (t)

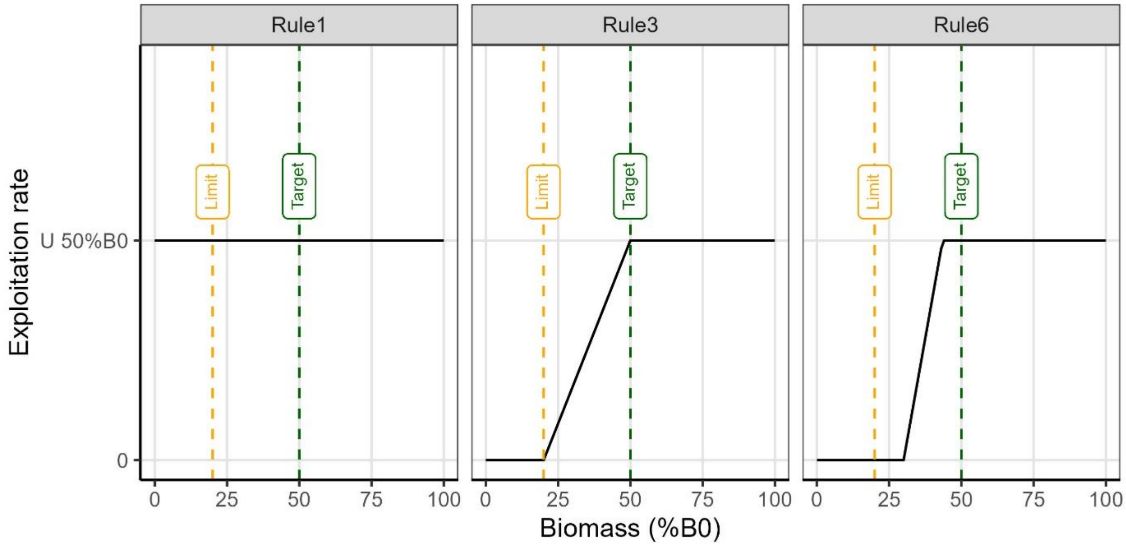

Figure 20: Candidate harvest control rules evaluated for CCAMLR integrated toothfish stock assessments. Black lines indicate the applied harvest rates *U* given spawning stock status (Stock status (%B_0)). For example, in Rule 1, the harvest rate is equal to $U_{50\%B0}$ and is independent of spawning stock status. In Rule 3, the harvest rate is 0 for spawning stock status below the limit reference point (LRP, dashed orange line), increases linearly for spawning stock status between the LRP and target reference point (TRP), and is equal to $U_{50\%B0}$ when spawning stock status is above the TRP. In Rule 6 the harvest rate is 0 for spawning stock status below the 30% B_0 (dashed orange line), increases linearly for spawning stock status up to (1-*M*)x50% B_0, and is equal to $U_{50\%B0}$ when spawning stock status is above the(1-*M*)x50% B_0.

5.2 Management procedure models

The management procedure evaluated the HCRs using the approach outlined in Punt et al. (2016) using proxy estimates of *SSB* in the simulations. The 2024 base case stock assessment, including historical catches, model parameters and estimates, was used to determine the population age structure (numbers-at-age) of the stock in the terminal year of the assessment (2024). For each candidate HCR, a set of 1000 simulations were conducted based on a random set of the MCMC samples from the base case model and an equivalent set of sampled recruitment deviates to determine future recruitments. In each simulation, the population age structure was projected forward initially for a 135-year burn-in phase and then for a 100-year period during which the performance of the HCRs was evaluated.

Annual estimates of stock status were simulated for each simulation by sampling from the "true" stock status with an assumed lognormal distribution and a CV=0.2. Annual fishery catches were then set at two-year intervals based on the specific candidate HCRs which were evaluated assuming no inter-assessment autocorrelation (e.g., ρ=0). For ramp HCRs, catches were decreased according to the ramp rules when the spawning stock status was below the threshold reference point RP_2 (Figure 20).

To search for the target harvest rate ($U_{50\%B0}$ or U_{target}) in Step 1, a range of harvest rates from 0.01 to 0.2 was applied and $U_{50\%B0}$ was determined based on the resulting estimates of stock status during the evaluation phase. In Step 2, each HCR and corresponding $U_{50\%B0}$ was again applied in 1000 simulations over the projection period with a range of future recruitment scenarios. The robustness of each HCR was evaluated using the PIs specified in Table 9.

In the base case, the HCRs were tested with an assumption that future recruitment was average, i.e. μ=1 where they had a mean equal to the period estimated in the assessment models and hence were defined to have a mean of one. Alternatively, future recruitment was assumed to be equal to the most recent 10 estimated years (recent recruitment), or discounted to 75%, 66% or 50% of the historical mean YCS.

The estimated harvest rates $U_{50\%B0}$ and HCR are given in Table 10. The values for $U_{50\%B0}$ showed only relatively small differences between HCRs. Values of $U_{50\%B0}$ were slightly higher and between 0.09–0.11. As reported by Ziegler et al. (2024a), the HCR with constant harvest rate (Rule 1) resulted in the lowest estimates of $U_{50\%B0}$, expected catch and catch variation. Higher values of $U_{50\%B0}$, catch and catch variation were obtained with HCRs that had steeper ramps.

The expected mean and quantiles of spawning stock status (%B_0), and the probability of spawning stock status being below 10% and 20% B_0 for each HCR are given in Table 11. All HCRs had a negligible probability of being below either 10% or 20% B_0.

The range of stock status that could be expected from each HCR is given in Table 11. The three rules evaluated would be expected to have a stock status that would vary between 39–62% B_0. This range could be considered a useful indicator that the HCR operating models may not be adequate to fully capture the performance of the stock. This could be a useful performance indicator for a breakout rule, such that once at or about the target, then the harvest strategy should be reevaluated, and alternative management approaches should be considered if the stock status fell below 39% or was above 62%.

Table 10: Estimated values of the reference harvest rate $U_{50\%B0}$ and the expected long-term mean catch (E(catch)) and standard deviation of the catch (sd(catch)) for each candidate HCR.

Rule	Description	$U_{50\%B0}$	E(catch)	sd(catch)
Rule 1	Constant	0.093	3 620	428
Rule 3	Ramp (0.2, 0.5)	0.106	3 708	645
Rule 6	Ramp (0.2, 0.5-0.5M)	0.104	3 754	564

Table 11: Estimated values of the reference harvest rate $U_{50\%B0}$, the expected mean and 25–75% quantiles of %B_0, and probability of spawning stock status being above 10% and 20% B_0 for each evaluated HCR assuming average future recruitment.

Rule	$U_{50\%B0}$	Mean (%B_0)	5–95% quantiles (%B_0)	Pr(SSB > 10% B_0)	Pr(SSB > 20% B_0)
Rule 1	0.093	0.50	0.39–0.62	1.00	1.00
Rule 3	0.106	0.49	0.41–0.58	1.00	1.00
Rule 6	0.104	0.48	0.40–0.58	1.00	1.00

Using the target harvest rate $U_{50\%B0}$, the performance of the three HCRs under different future recruitment scenarios is shown for performance indicators P02 in Figure 21, P04 in Figure 22, P06 in Figure 23 and C01 in Figure 24.

The performance indicators P02 (distribution of median spawning stock biomass relative to B_0, Figure 21) and P07 (the proportion of years above 50% B_0) confirmed that all HCRs successfully provided a median spawning stock status near 50% if future recruitment was the same as historical recruitment.

Performance indicator P04 for the distribution of the probability of being below the limit reference point (20% B_0) indicated that a constant harvest rate HCR (Rule 1) performed worst but only under very low recruitment conditions, with a significant risk for the spawning stock to drop below the limit reference point (Figure 22). When recruitment was not very low, all the HCRs performed well.

As the base case model had no long-term trend in estimated recruitment, the PI results were similar for 'allYCS' and 'recentYCS' scenarios. When future recruitment was lower than historical recruitment, the scenarios at 75%, 66% or 50% all had a higher probability of being below target and of a risk of being below 20% B_0. In these scenarios, none of the evaluated HCRs gave a stock status at or around 50% B_0 (Figure 23)

Performance indicator C01 indicated that the median annual catch (t) was similar for all HCRs under the 'allYCS' scenario, but that constant harvest rates (Rule 1) tended to yield larger average catches and less catch variability under low recruitment scenarios (Figure 24).

The catch limits that would be obtained from the application of the HCRs, while assuming that the current CCAMLR catch limit would apply when the stock is above the TRP, are given in Figure 25 and tabulated (without the current CCAMLR decision rule constraint) in Table 17.

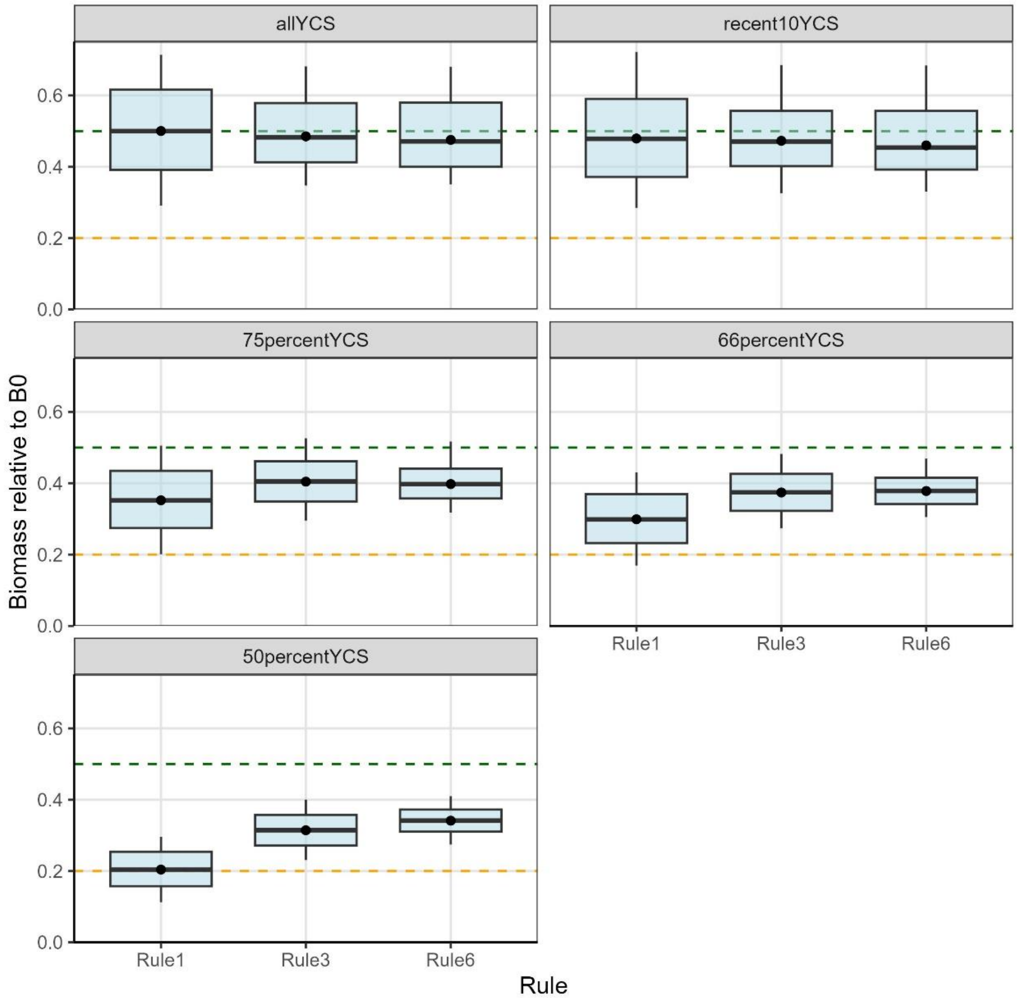

Figure 21: Performance indicator P02 for the distribution of the median spawning stock biomass relative to B0 using the reference $U_{50\%B0}$ for each candidate HCR. Boxes indicate the 80% quantiles and the range (minimum-maximum) by the vertical line. The bold horizontal line indicates the median and the mean is shown by the point. Horizontal dashed lines indicate the target (green, 50% B0) and limit (orange, 20% B0) reference points, respectively.

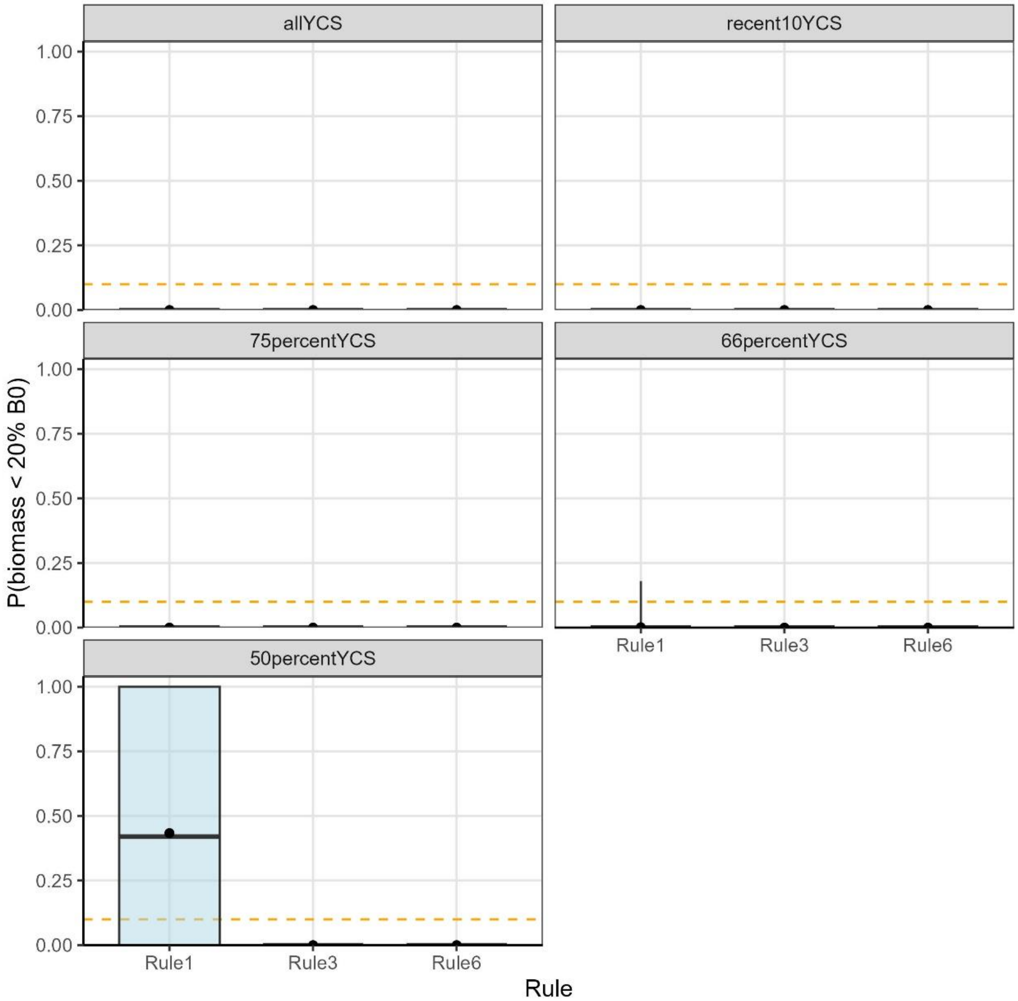

Figure 22: Performance indicator P04 for the distribution of the probability of being below the limit reference point (20% B_0) using the reference $U_{50\%B0}$ for each candidate HCR. Boxes indicate the 80% quantiles and the range (minimum-maximum) by the vertical line. The bold horizontal line indicates the median and the mean is shown by the point. Horizontal dashed line indicates the 10% risk of being below the limit reference point (LRP) of 20% B_0.

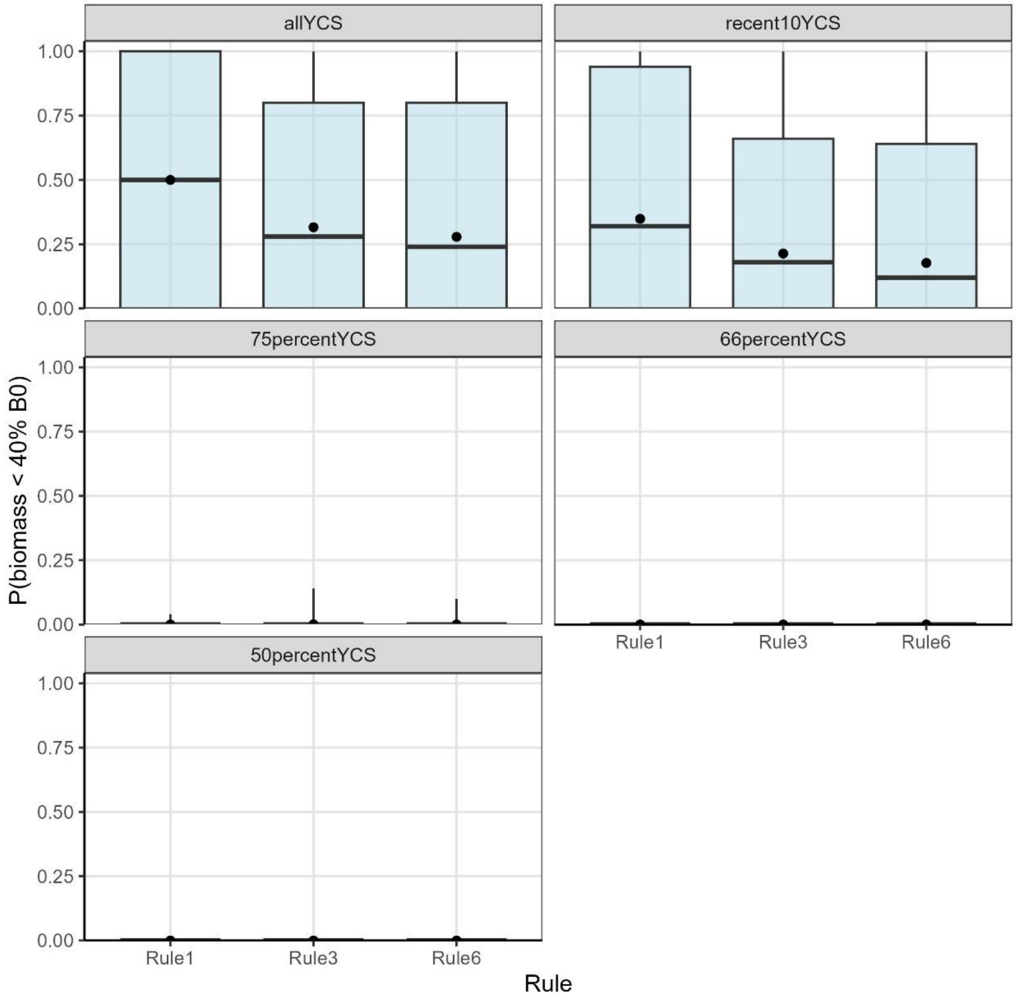

Figure 23: Performance indicator P07 for the distribution of the probability of being above the target reference point (50% B0) using the reference $U_{50\%B0}$ for each candidate HCR. Boxes indicate the 80% quantiles and the range (minimum-maximum) by the vertical line. The bold horizontal line indicates the median and the mean is shown by the point. Horizontal dashed lines indicate the target (green, 50% B_0) and limit (orange, 20% I_0) reference points, respectively.

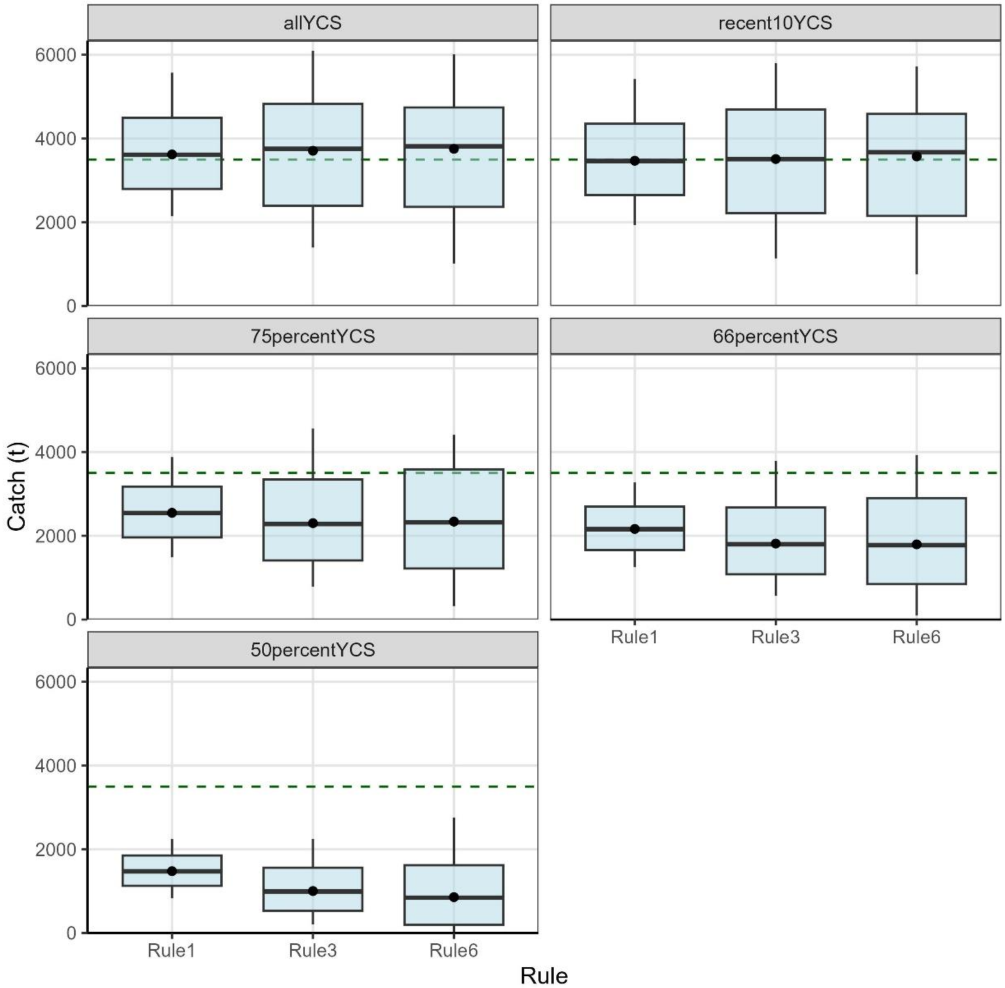

Figure 24: Performance indicator C01 for the distribution of the median annual catch (t) using the reference $U_{50\%B0}$ for each candidate HCR. Boxes indicate the 80% quantiles and the range (minimum-maximum) by the vertical line. The bold horizontal line indicates the median and the mean is shown by the point. Horizontal dashed lines (green) indicate the current (2023/24) catch limit.

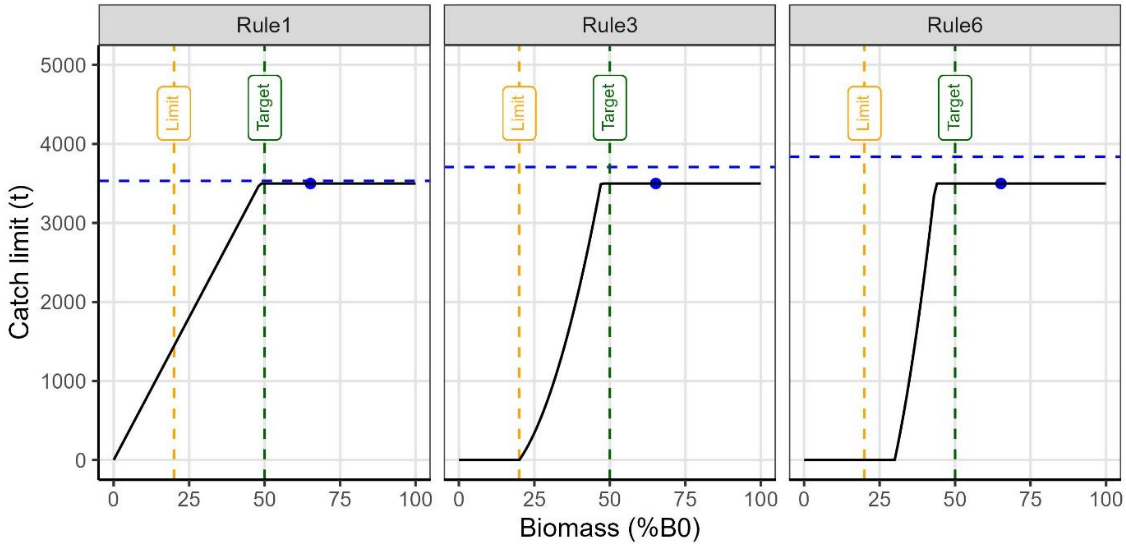

Figure 25: Expected catch limits from the Harvest Control Rules (HCRs). The black line gives the catch limit for the estimated SSB/*B*0 ratio while assuming that the current CCAMLR decision rules will truncate the catch limit when these are lower than the HCR rules. The horizontal blue dashed line gives the average expected long-term average catch under the HCR, and the blue point indicates the current catch limit for the current estimated SSB using the 2024 base case model. Vertical lines indicate the target (green, 40% B_0) and limit (orange, 20% B_0) reference points.

6. DISCUSSION

6.1 Assessment model

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 2024. The base case model was very similar to the 2023 base case model (Mormede et al. 2023). MCMC estimates of the initial biomass and current biomass are given in Table 6 below. The MPD for the 2024 base case model (R2.0) estimated the initial biomass (B_0) was 78 553 t, and the current biomass (B_{2024}) was estimated to be at 64.4% of B_0. The MCMC estimated B_0 as 77 920 t (95% CIs 72 060–84 690 t) and the current stock status (B_{2024}) as 65.2% B_0 (95% CIs 62.3–68.1% B_0).

Fits to the catch-at-age data suggest no evidence of poor fit when using one-step-ahead residuals for MPD fits, but there was some lack of fit in the MCMC posterior predictions for the age composition data in the earlier years of the fishery. Previous investigations by Mormede et al. (2023) looked at a range of sensitivity analyses, including time-varying selectivity and additional YCS estimation, but found that this lack of fit did not significantly improve these fits. Further consideration of these issues should be investigated in future assessments. 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, however, this relationship was not strong. This suggests that the model assumptions of rates of ongoing tag mortality, tag loss rate, tag detection rate and uniform mixing might not be adequate, and while there have been no indications of changing spatial bias in the Ross Sea assessment, this should be monitored in future.

The 2024 model showed that the RSSS abundance and age composition observation informed the estimation of recruitment strength, but there was some limited sensitivity to the influence of the RSSS on estimates of initial and current biomass. 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 an established long time series of standardised abundance surveys to provide fishery-independent information on stock abundance and recruitment. (Anon 2018). Analyses from previous work and in this paper indicate that there have not yet been any observable changes in stock assessment parameters or processes that could be due to the effects of environmental variability or climate change.

Sensitivity runs investigated the effect of alternative data weighting for the sets of observations and did not indicate any key uncertainties that would strongly influence the base case outcomes.

6.2 Management advice

The calculation of precautionary yield used the method noted in SC-CAMLR-XXV (2006, paragraph 4.170(iii)). Precautionary yields using the CCAMLR decision rules are given in Table 7 using a future catch split of 19% for N70, 66% for S70 and 15% for the SRZ and either all, recent 10-years or recent 12-years of estimated YCS to predict future recruitment. The precautionary yield calculated using the CCAMLR toothfish decision rules and assuming recent 10 years of recruitment as future recruitment was 3298 t.

Estimates of the precautionary yield using alternative assumptions of recent recruitment did not significantly impact the yield outcomes, and calculated catch limits ranged from 3123 t using 12 years of recent estimated years of recruitment and 3460 t using all estimated years of recruitment.

6.3 Harvest control rules

The behaviour and robustness of HCRs were explored using the stock assessments for Antarctic toothfish in the Ross Sea region using the 2024 base case. For the three evaluated rules, all achieved a median close to the target level (50% B_0) and avoided the depletion level (20% B_0) when future recruitment was similar to historical recruitment.

The estimation of the target harvest rates $U_{50\%B0}$ that ensures long-term 50% B_0 depended on the current assumed productivity patterns (including natural mortality, growth, maturity, and stock-recruitment) and fisheries selectivity. In contrast to the constant catch HCR which is used as part of the CCAMLR Decision Rules, there is not such a critical requirement to make assumptions about future recruitment patterns. When future recruitment was lower than the historical mean, the evaluated HCRs resulted in long-term spawning stock status below the target level. However, these results are likely to be more negative than what would be expected in reality. In the simulations, the reference biomass value of B_0, LRP and TRP remained unchanged over the simulated projection period. However, in reality the stock assumptions of productivity and recruitment would be re-estimated and adjusted over time with each new stock assessment. Therefore, any reduction in future mean recruitment would be reflected in the values for B_0, LRP and TRP. Under low future recruitment scenarios, the ramp HCRs resulted in higher spawning stock status but provided lower catches and higher interannual variability in catches. This is a function of the shape of the HCR where ramp rules (as opposed to constant harvest rate rules) reduce the catch that can be taken at low levels of stock status. Therefore, ramp rules are more precautionary under low recruitment conditions, but at the cost of lower catches and higher catch variability.

The expected range of stock status values from the HCRs can be used to help inform breakout rules, and for these rules, a performance indicator for breakout could be defined for when the stock status fell below 39% or was above 62%.

7. ACKNOWLEDGMENTS

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8. REFERENCES

Anon (2018). Summary Report of the CCAMLR Independent Stock Assessment Review for Toothfish (Norwich, United Kingdom, 18 to 22 June 2018). SC-CAMLR-XXXVII/02 Rev. 1. CCAMLR, Hobart, Australia.

Beverton, R.J.H.; Holt, S.J. (1957). On the dynamics of exploited fish populations. HMSO, London.

Bull, B.; Dunn, A.; McKenzie, A.; Gilbert, D.J.; Smith, M.H.; Bian, R.; Fu, D. (2012). CASAL (C++ algorithmic stock assessment laboratory) User Manual v2.30-2012/03/21. NIWA Technical Report 135. National Institute of Water and Atmospheric Research, Wellington, 280 p.

Casal2 Development Team (2023). Casal2 user manual for age-based models, v23.09. NIWA Technical Report 139. NIWA. (Using source code from https://github.com/alistairdunn1/CASAL2), Wellington, New Zealand, 291 p.

Casal2 Development Team (2024a). Casal2 user manual for age-based models, v24.07. NIWA Technical Report 139. NIWA. (Using source code from https://github.com/alistairdunn1/CASAL2:Development), Wellington, New Zealand, 311 p.

Casal2 Development Team (2024b). Casal2 extract package. https://github.com/alistairdunn1/Casal2:Development. Version 24.07. NIWA and Ocean Environmental, Wellington, New Zealand.

CCAMLR-XXXV (2016). Report of the thirty-fifth meeting of the Commission. CCAMLR, Hobart, Australia.

Chapman, D.G. (Douglas G. (1951). Some properties of the hypergeometric distribution with applications to zoological sample censuses. University of California publications in statistics 1, 131–159.

Cullen, A.C.; Frey, H.C. (1999). Probabilistic Techniques in Exposure Assessment: A Handbook for Dealing with Variability and Uncertainty in Models and Inputs. Springer Science & Business.

Delegation of the United Kingdom (2019). The CCAMLR Decision Rule, strengths and weaknesses. SC-CAMLR-38/15. CCAMLR, Hobart, Australia, 9 p.

Delignette-Muller, M.L.; Dutang, C. (2015). fitdistrplus: An R Package for Fitting Distributions. Journal of Statistical Software 64, 1–34. https://doi.org/10.18637/jss.v064.i04

Devine, J. (2024). Characterisation of the toothfish fishery in the Ross Sea region (Subarea 88.1 and SSRUs 882A-B) through 2023/24. WG-FSA-2024/xx. CCAMLR, Hobart, Australia, xx p.

Devine, J.; Mormede, S. (2023). Characterisation of the toothfish fishery in the Ross Sea region (Subarea 88.1 and SSRUs 882A-B) through 2022/23. WG-FSA-2023/19. CCAMLR, Hobart, Australia.

Devine, J.A.; Jones, C.M.; Walker, N. (2024). A progress update on the 2024 Ross Sea shelf survey. WG-FSA-2024/21. CCAMLR, Hobart, Australia, 30 p.

Dunn, A. (2019). Assessment models for Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea region to 2018/19. WG-FSA-2019/08. CCAMLR, Hobart, Australia, 30 p.

Dunn, A.; Devine, J.A. (2024a). Stock Annex for the 2024 assessment of Ross Sea region Antarctic toothfish (*Dissostichus mawsoni*). WG-FSA-2024/xx. CCAMLR, Hobart, Australia, xx p.

Dunn, A.; Devine, J.A. (2024b). Diagnostic plots for the 2024 assessment for Ross Sea region Antarctic toothfish (Dissostichus mawsoni). WG-FSA-2024/xx. CCAMLR, Hobart, Australia, xx p.

Dunn, A.; Devine, J.A. (2024c). Assessment models for Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea region to 2023/24. WG-FSA-2024/xx. CCAMLR, Hobart, Australia, xx p.

Dunn, A.; Grüss, A.; Devine, J.A.; Miller, C.; Ziegler, P.; Maschette, D.; Earl, T.; Darby, C.; Massiot-Granier, F. (2022). Integrated toothfish stock assessments using Casal2. WG-SAM-2022/14. CCAMLR, Hobart, Australia, 20 p.

Dunn, A.; Parker, S.J. (2019). Revised biological parameters for Antarctic toothfish in the Ross Sea region (881 & 882AB). WG-FSA-2019/11. CCAMLR, Hobart, Australia, 14 p.

Francis, R.I.C.C. (2011). Data weighting in statistical fisheries stock assessment models. Canadian Journal of Fisheries and Aquatic Sciences 68, 1124–1138.

Gelman, A.; Carlin, J.B.; Stern, H.S.; Dunson, D.B.; Vehtari, A.; Rubin, D.B. (2015). Bayesian Data Analysis, 3rd ed. Chapman and Hall/CRC, New York. https://doi.org/10.1201/b16018

Gelman, A.B.; Carlin, J.S.; Stern, H.S.; Rubin, D.B. (1995). Bayesian data analysis. Chapman and Hall, London.

Gilks, W.R.; Richardson, S.; Spiegelhalter, D.J. (1998). Markov chain Monte Carlo in practice, CRC Interdisciplinary Statistics. Chapman & Hall.

Grüss, A.; Dunn, A.; Parker, S.J. (2021). Assessment model for Antarctic toothfish (Dissostichus mawsoni) in the Ross Sea region to 2020/21. WG-FSA-2021/26. CCAMLR, Hobart, Australia, 21 p.

Hanchet, S.M.; Rickard, G.J.; Fenaughty, J.M.; Dunn, A. (2008). A hypothetical life cycle for Antarctic toothfish (Dissostichus mawsoni) in the Ross Sea region. CCAMLR Science 15, 35–53.

Marsh, C.; Dunn, A. (2024). r4Casal2: R package for post processing Casal2 model output. https://github.com/alistairdunn1/r4Casal2:Development. Version 1.04. NIWA and Ocean Environmental, Wellington, New Zealand.

Monnahan, C.C. (2024). Toward good practices for Bayesian data-rich fisheries stock assessments using a modern statistical workflow. Fisheries Research 275. https://doi.org/10.1016/j.fishres.2024.107024

Mormede, S.; Dunn, A.; Hanchet, S.M. (2014). A Stock Assessment Model of Antarctic Toothfish (Dissostichus Mawsoni) in the Ross Sea Region Incorporating Multi-Year Mark-Recapture Data. CCAMLR Science 21, 39–62.

Mormede, S.; Grüss, A.; Dunn, A.; Devine, J.A. (2023). Assessment model for Antarctic toothfish (*Dissostichus mawsoni*) in the Ross Sea region to 2022/23. WG-FSA-2023/13. CCAMLR, Hobart, Australia, 27 p.

Parker, S.J.; Marriott, P.M. (2012). Indexing maturation of Antarctic toothfish (Dissostichus mawsoni) in the Ross Sea region. WG-FSA-12/40. CCAMLR, Hobart, Australia, 21 p.

Parker, S.J.; Mormede, S. (2017). Mark-recapture inputs to the 2017 Ross Sea region stock assessment (Subarea 88.1 and SSRUs 88.2A-B). WG-FSA-17/36. CCAMLR, Hobart, Australia, 9 p.

Punt, A.E.; Butterworth, D.S.; de Moor, C.L.; De Oliveira, J.A.A.; Haddon, M. (2016). Management strategy evaluation: Best practices. Fish and Fisheries. https://doi.org/10.1111/faf.12104

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

SC-CAMLR-41 (2022). Report of the forty-first meeting of the scientific committee. CCAMLR, Hobart, Australia.

SC-CAMLR-42 (2023). Report of the forty-second meeting of the scientific committee. CCAMLR-42/25. CCAMLR, Hobart, Australia, 177 p.

SC-CAMLR-XXV (2006). Report of the twenty-fifth meeting of the scientific committee. CCAMLR, Hobart, Australia.

SC-CAMLR-XXX (2011). Report of the thirtieth meeting of the scientific committee. CCAMLR, Hobart, Australia.

Trijoulet, V.; Albertsen, C.M.; Kristensen, K.; Legault, C.M.; Miller, T.J.; Nielsen, A. (2023). Model validation for compositional data in stock assessment models: Calculating residuals with correct properties. Fisheries Research 257, 106487. https://doi.org/10.1016/j.fishres.2022.106487

Trijoulet, V.; Fay, G.; Curti, K.L.; Smith, B.; Miller, T.J. (2019). Performance of multispecies assessment models: insights on the influence of diet data. ICES Journal of Marine Science 76, 1464–1476. https://doi.org/10.1093/icesjms/fsz053

Vehtari, A.; Gelman, A.; Gabry, J. (2017a). Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. Statistics and Computing 27, 1413–1432. https://doi.org/10.1007/s11222-016-9696-4

Vehtari, A.; Gelman, A.; Gabry, J. (2017b). Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. Statistics and Computing 27, 1413–1432. https://doi.org/10.1007/s11222-016-9696-4

Wiedenmann, J.; Wilberg, M.J.; Sylvia, A.; Miller, T.J. (2015). Autocorrelated error in stock assessment estimates: Implications for management strategy evaluation. Fisheries Research 172, 325–334. https://doi.org/10.1016/j.fishres.2015.07.037

Ziegler, P.; Dunn, A.; Alewijnse, S.; Devine, J.A.; Le Clech, R.; Earl, T.; Maschette, D.; Masere, C.; Massiot-Granier, F.; Ouzoulias, F.; Peron, C.; Readdy, L.; Walker, N. (2024a). Development of U-based harvest control rules for assessed toothfish fisheries - 2. Exploration of U-based HCRs. WG-SAM-2024/17. CCAMLR, Hobart, Australia, 34 p.

Ziegler, P.; Dunn, A.; Alewijnse, S.; Devine, J.A.; Le Clech, R.; Earl, T.; Maschette, D.; Masere, C.; Massiot-Granier, F.; Ouzoulias, F.; Peron, C.; Readdy, L.; Walker, N. (2024b). Development of U-based harvest control rules for assessed toothfish fisheries - 1. Background. WG-SAM-2024/16. CCAMLR, Hobart, Australia, 13 p.

APPENDIX A: SUPPLEMENTARY INFORMATION FOR THE ASSESSMENT

Table 12: Starting values, priors, number of parameters (*N*), and bounds for the free parameters for the 2024 base case model (R2.0). 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	a_1		8.0	-	Student's-t	-	1.0	50.0
selectivities	s_L		4.0	-	Student's-t	-	0.01	50.0
(male)	s_R	12	10.0	Inverse	Student's-t	No	0.001	1.0
Fishing	a_{max}		1.0	-	Student's-t	-	0.01	10.0
selectivities	a_1		8.0	-	Student's-t	-	1.0	50.0
(female)	s_L		4.0	-	Student's-t	-	0.01	50.0
	s_R	16	10.0	Inverse	Student's-t	No	0.001	1.0
Recruitment		15	1.0	Simplex	Lognormal	No	-10	10
RSSS abundance	CV	1	0.0	-	Uniform	-	0.0	10.0
RSSS selectivity	a_1		8.0	-	Student's-t	-	1.0	50.0
(male)	s_L		4.0	-	Student's-t	-	0.01	50.0
	s_R	3	10.0	Inverse	Student's-t	No	0.001	1.0
RSSS selectivity	a_{max}		1.0	-	Student's-t	-	1.0	10.0
(female)	a_1		8.0	-	Student's-t	-	1.0	50.0
	s_L		4.0	-	Student's-t	-	0.01	50.0
	s_R	4	10.0	Inverse	Student's-t	No	0.001	1.0

Table 13: Francis (2011) weighting factor for catch-at-age compositions for the N70, S70, SRZ, and GPZ areas (w_{N70}, w_{S70}, w_{SRZ}, w_{GPZ}) and the RSSS (w_{RSSS}), RSSS survey abundance (CV), and tag-recapture (ø) observations for the 2023 base case model (R3) and the 2024 base case model (R2.0) for Ross Sea region Antarctic toothfish.

Run	Model	w_{N70}	w_{S70}	w_{SRZ}	w_{GPZ}	w_{RSSS}	CV	ø
R3	2023 base case model	0.058	0.028	0.038	0.022	0.281	0.0	7.10
R2.0	2024 base case model	0.061	0.028	0.036	0.023	0.158	0.0	7.29

Table 14: MPD objective function values (negative log likelihood) and number of estimated parameters for the 2024 base case model (R2.0).

Component	2024 base case (R2.0)
observation-RSSS	71.23
observation-RSSSAgeF	566.49
observation-GPZ	289.93
observation-N70	408.93
observation-S70	693.46
observation-SRZ	554.78
Tag 2005	18.19
Tag 2006	26.78
Tag 2007	21.29
Tag 2008	14.69
Tag 2009	14.31
Tag 2010	18.26
Tag 2011	16.25
Tag 2012	17.13
Tag 2013	14.89
Tag 2014	18.63
Tag 2015	21.32
Tag 2016	18.55
Tag 2017	19.46
Tag 2018	21.26
Tag 2019	21.85
Tag 2020	13.22
Tag 2021	13.28
Tag 2022	12.05
Tag 2023	5.60
Priors	118.98
Penalties	0.00
Jacobians	-8.08
Total	3022.74

APPENDIX B: SIGNIFICANT CHANGES AND DEVELOPMENTS IN THE ROSS SEA REGION ANTARCTIC TOOTHFISH STOCK ASSESSMENT

Table 15: Timeline of significant changes and developments in the Ross Sea region Antarctic toothfish stock assessment.

Year	Model change
2003–2005	Developed biological parameters and tag-based methods for the assessment
2005	First stock assessment for the Ross Sea region Antarctic toothfish, and implemented in CASAL
2006	Revised biological parameters as there were substantially more data available
2008–2013	Used of proxies for tagging survival and detection (relative performance metrics of individual vessels)
2010–2017	Developed Spatial Population Model and used for: - investigation of different spatial management options (RSrMPA) - Evaluation of the potential bias in the assessment resulting from tag mixing assumptions
2012	Revised tag parameters
	Initiated the Ross Sea shelf survey (fishery-independent index of recruitment and age composition data)
2013	Development of tagging survival and tag detection estimation method (relative performance metrics of individual vessels)
2019–2021	Investigation of better tagging survival and tag detection estimation method (relative performance metrics of vessels)
2019	Revised biological parameters as substantially more data were available
2023	Revised tag loss rate parameter as substantially more data were available
2023	Updated the Spatial Population Model with most recent assessment and minor improvements; used to assess the potential impact of the MPA in future years under alternate effort scenarios
	Implemented the base case model using Casal2
	Implemented double tag loss rate parameters for tagged fish
	Implemented parameter transformations to improve model convergence
	Excluded data on tagged fish released before 2005 as these were prior to the standardisation of the tag program
	Updated the tag loss rates and reparametrized the loss rates for double-tagged fish
2024	Non-informative priors revised to be Student's-t priors
	Revised the RSSS catchability coefficient to be estimates as a free parameter rather than a nuisance parameter
	Determination of U-based harvest rates
	Preliminary HCR evaluations

APPENDIX C: SUMMARY OF EVIDENCE FOR CHANGES IN PARAMETERS DUE TO CLIMATE CHANGE

Table 16: Summary of evidence for changes in stock assessment parameters or processes that could be due to the effects of environmental variability or climate change for the Antarctic toothfish stock assessment for the Ross Sea region.

1a	Recruitment	Mean recruitment	Patterns in recruitment from the assessment model showed no evidence of trend over time (Dunn & Devine 2024c).
1b		Recruitment variability (σ_R and autocorrelation)	The time series is currently not long enough to formally evaluate changes in variability, but the depletion rule was not a constraint in the application of the CCAMLR decision rules in the most recent assessment (Dunn & Devine 2024c). Recruitment patterns have indicated an approximate decadal cycle and yield calculations propose using recent 10-years estimated recruitment where this was lower than the historical mean recruitment (Dunn & Devine 2024c).
2	Age at maturity		No analyses have investigated potential changes in age or length at maturity (Parker & Marriott 2012).
3	Stock-recruit relationship		Recent recruitments are consistent with the stock relationship recruitment assumptions, but the time series of recruitment is not long enough to determine if the stock recruitment relationship was affected by climate change (Dunn & Devine 2024c). Long term monitoring of mean recruitment and its relationship to spawning stock biomass may be able to be used to determine if changes in the relationship occur in future years.
4a	Natural mortality	From direct predation	Not known
4b		Not from direct predation	Not known
5	Growth rates		Age-length residual patterns across cohorts suggest that there have been small long-term fluctuations in mean size at age, following a roughly decadal cycle (Dunn & Parker 2019).
6	Length-weight		Patterns of length-weight relationship showed no evidence of trends or variability over time (Dunn & Parker 2019).
7	Sex ratio		No evidence of changes in sex ratio in the catch or the changes RSSS that may be explained by climate change (Devine 2024).
8	Spatial distribution		No evidence of a change in the spatial distribution for distribution Antarctic toothfish in the Ross Sea region from the analysis of fishing effort data (Devine 2024). However, any changes in spatial distribution outside the historical fishing footprint are not known.
9	Stock structure		No new evidence to suggest the stock structure hypothesis for Antarctic toothfish in the Ross Sea has altered from current stock structure hypotheses (Hanchet et al. 2008).
10	Locations of spawning and site fidelity		Not known
11	Depredation		No evidence for any changes in rates or occurrence of mortality depredation from either fisher or observer observations - only rare instances of depredation mortality have been observed in the Ross Sea (Devine 2024).

APPENDIX D: HARVEST CONTROL RULE EVALUATIONS

Table 17: Exploitation rates (*U*) and associated HCR recommended catch limits (t) for values of SSB at 0–100 %B_0 using the HCRs Rule 1, Rule 3, and Rule 4.

	Rule 1		Rule 2		Rule 3	
SSB (%B_0)	*U*	Catch limit	*U*	Catch limit	*U*	Catch limit
0	0.093	0	0.000	0	0.000	0
5	0.093	361	0.000	0	0.000	0
10	0.093	722	0.000	0	0.000	0
15	0.093	1 083	0.000	0	0.000	0
20	0.093	1 444	0.000	0	0.000	0
25	0.093	1 805	0.018	344	0.000	0
30	0.093	2 166	0.035	825	0.000	0
35	0.093	2 528	0.053	1 444	0.038	1 047
40	0.093	2 889	0.071	2 200	0.077	2 393
45	0.093	3 250	0.088	3 094	0.104	3 634
50	0.093	3 611	0.106	4 125	0.104	4 038
55	0.093	3 972	0.106	4 538	0.104	4 442
60	0.093	4 333	0.106	4 950	0.104	4 845
65	0.093	4 694	0.106	5 363	0.104	5 249
70	0.093	5 055	0.106	5 775	0.104	5 653
75	0.093	5 416	0.106	6 188	0.104	6 057
80	0.093	5 777	0.106	6 600	0.104	6 460
85	0.093	6 138	0.106	7 013	0.104	6 864
90	0.093	6 499	0.106	7 425	0.104	7 268
95	0.093	6 860	0.106	7 838	0.104	7 672
100	0.093	7 222	0.106	8 250	0.104	8 076

APPENDIX E: CHAPMAN BASED ESTIMATES AND MODEL SENSITIVITY

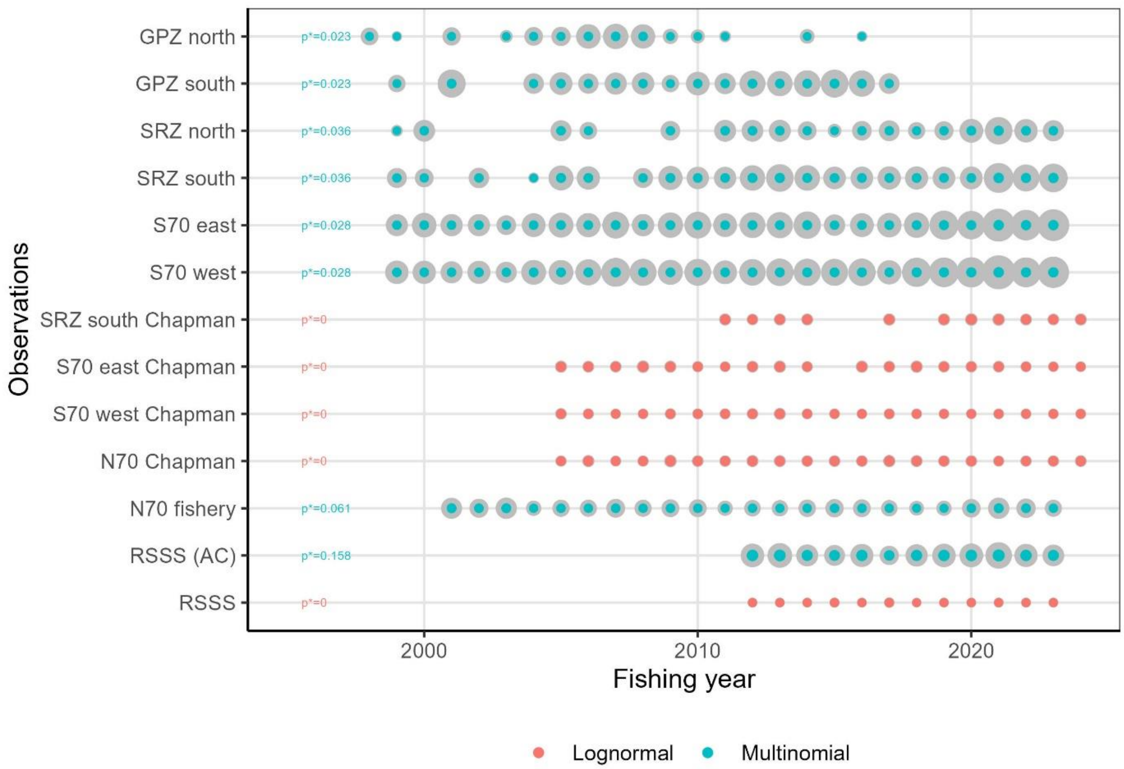

Figure 26: Model observations for the Chapman abundance sensitivity model (R6.0). The coloured points represent the relative effective sample sizes (mean-adjusted for comparability between observation types) for each year and observation type (rows: age-compositions and abundance), and likelihood (colour), with the grey outline indicating the initial sample size before reweighting. p* was the multiplier used to adjust the multinomial Ns in each observation from the Francis reweighting (multinomial likelihoods) or the process error CV (lognormal likelihoods).

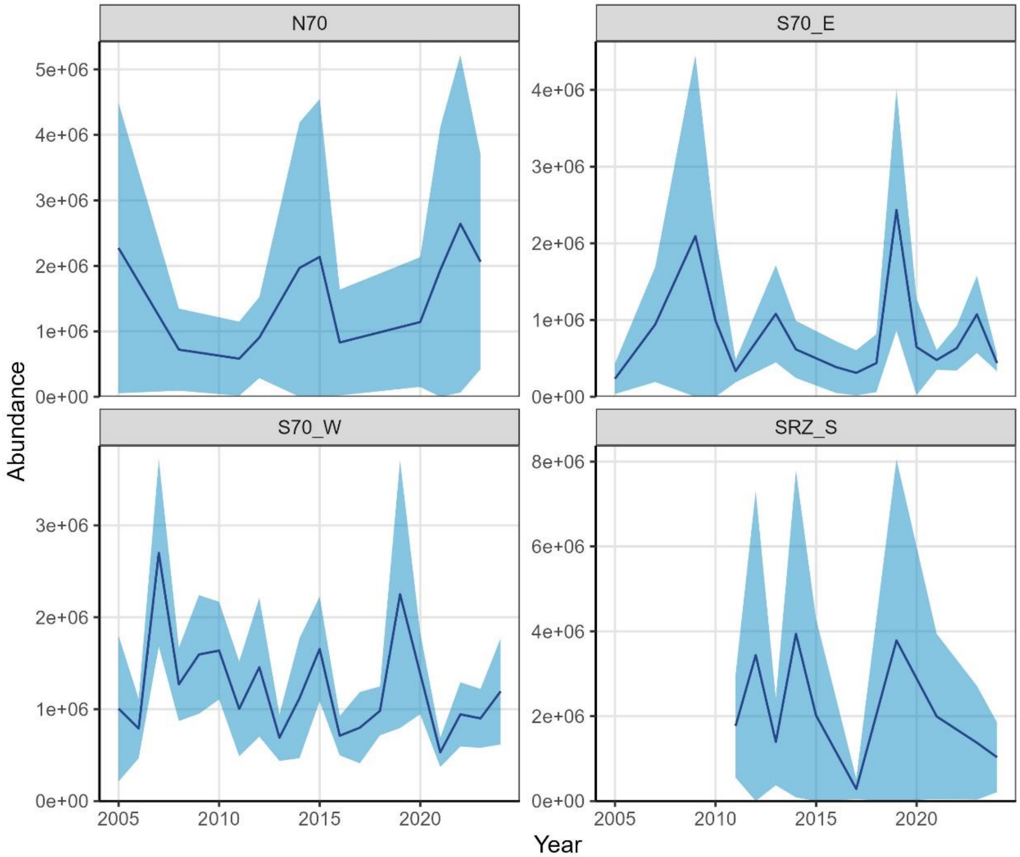

Figure 27: Chapman estimates of abundance (N) for the N70, S70_E , S70_W, and SRZ_S regions in the Ross Sea region using two years at liberty. Medians are shown as the dark line, and 95% confidence intervals as the shaded area.

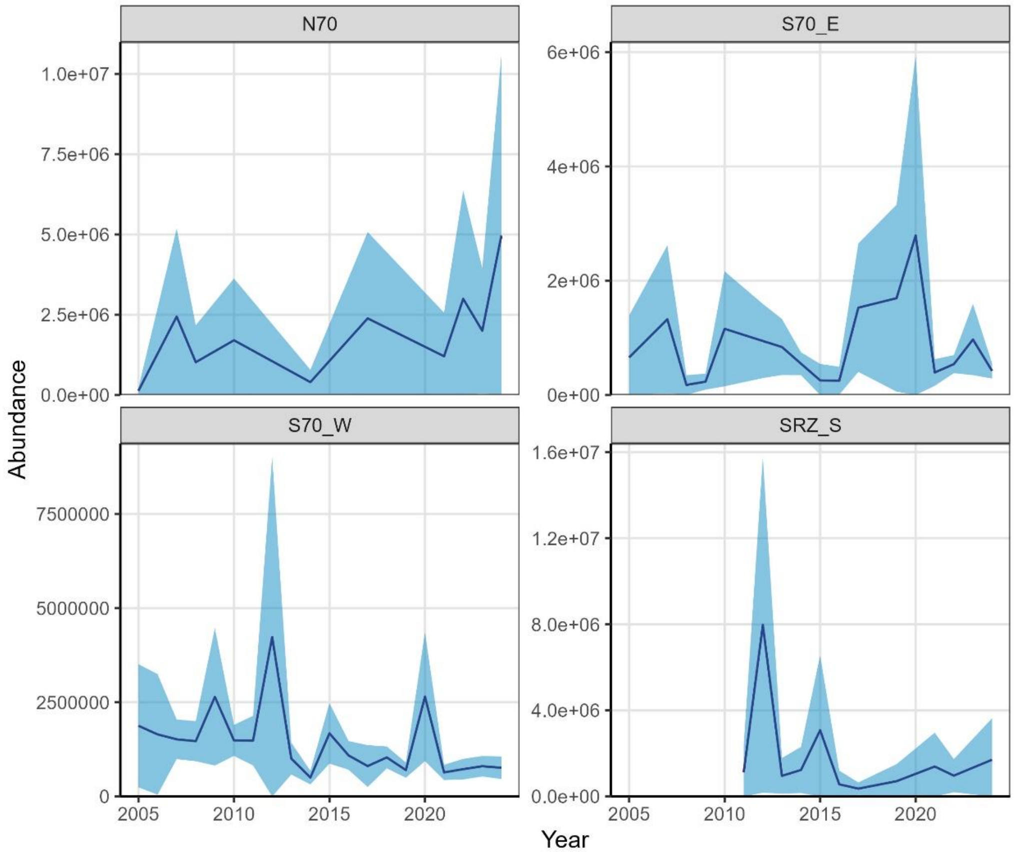

Figure 28: Chapman estimates of abundance (N) for the N70, S70_E , S70_W, and SRZ_S regions in the Ross Sea region using three years at liberty. Medians are shown as the dark line, and 95% confidence intervals as the shaded area.

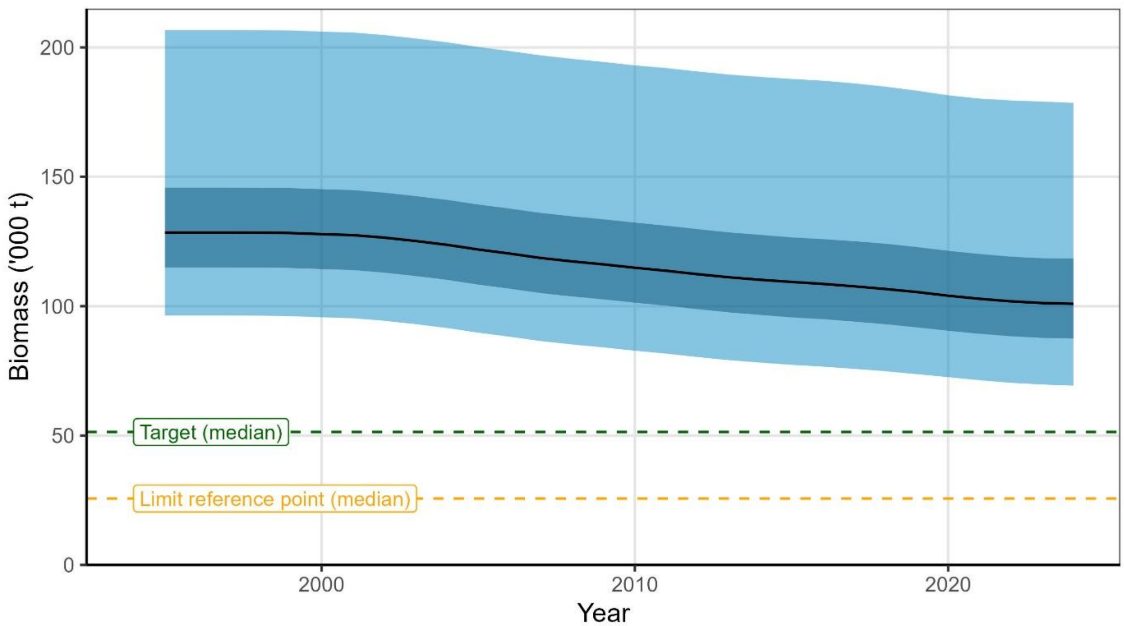

Figure 29: MCMC estimates of SSB trajectory for 1995 to 2024 for the Chapman abundance model (R6.0), with the median (black line and points), interquartile range (dark blue) and 95% credible intervals (light blue).

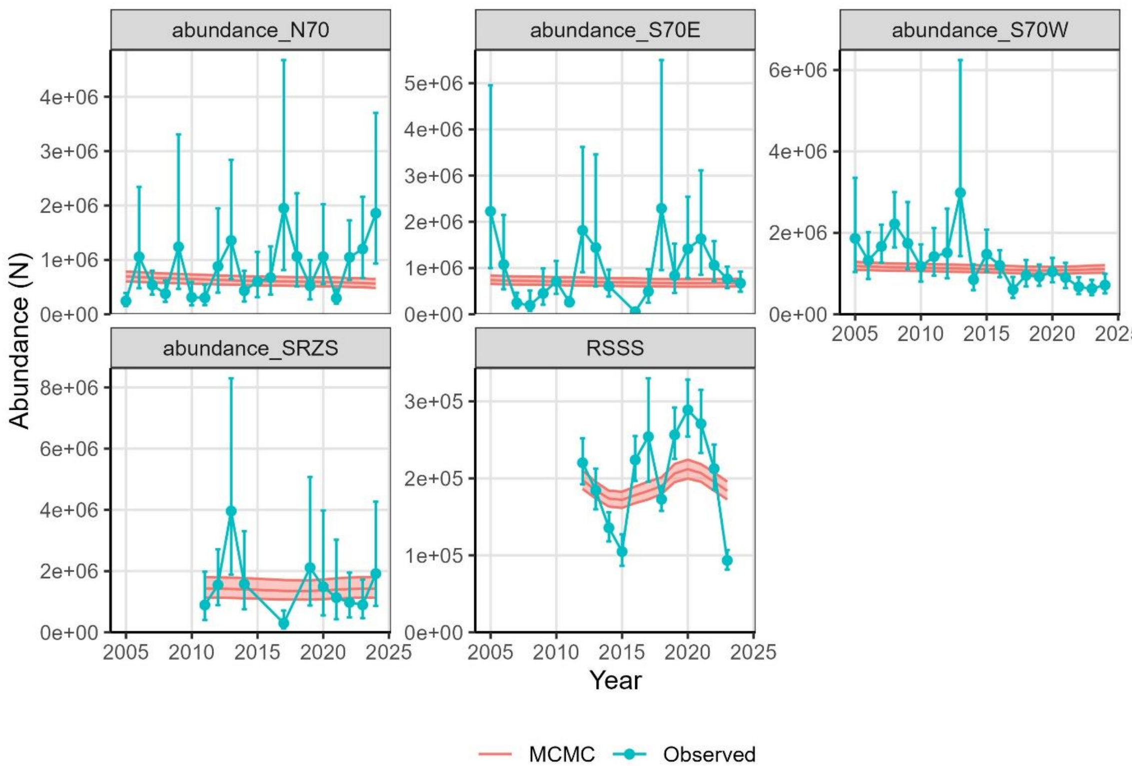

Figure 30: MCMC posterior fits to the N70, S70W, S70E, and SRZS region Chapman estimates and the RSSS, 2005–2024 for the Chapman sensitivity model (R6.0).

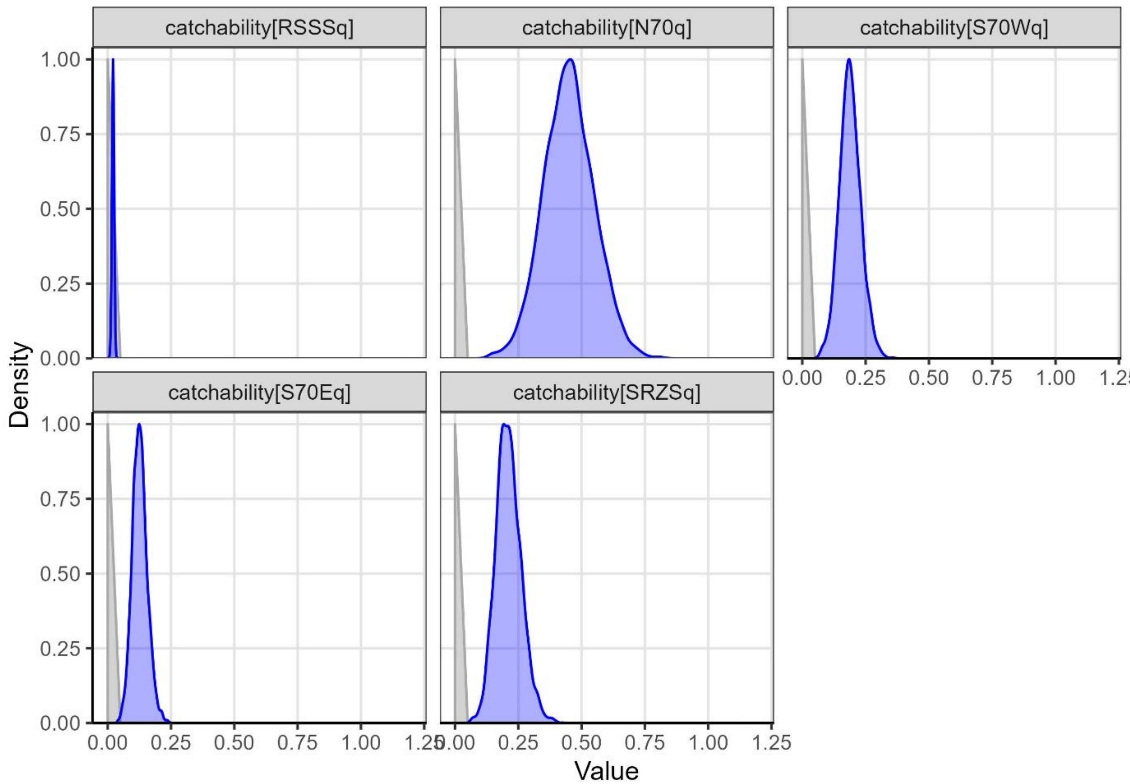

Figure 31: MCMC posterior estimates of catchability for the N70, S70W, S70E, and SRZS region Chapman estimates, 2005–2024 for the Chapman sensitivity model (R6.0). Blue shaded areas represent the MCMC posterior, and the grey shaded areas are the priors.

Additional Resources

- Fishery Summary: pdf, html
- Fishery Report: pdf, html
- Species Description: pdf, html
- Stock Annex: pdf
- Fisheries Documents Browser