Australian Government
Australian Fisheries Management Authority

Macquarie Island toothfish stock assessment 2020-2021

R 2019/0845 2022

Australian Government
Australian Fisheries Management Authority

Box 7051, Canberra Business Centre, ACT 2610 / Ph (02) 6225 5555 / Fax (02) 6225 5500 / AFMA Direct 1300 723 621 afma.gov.au

Contents

1 Non-technical summary

The project has maintained the tagging program that is vital to the ongoing assessment of the toothfish population at Macquarie Island. The assessment and other related outputs are critical to the advice and management process for this particular fishery. The results from the assessment analyses have been used by the SARAG, industry and management authorities to help manage the fishery according to the agreed sustainability criteria and objectives. The results of this project have cemented the revised long-term assessment framework to provide management advice and explore future harvest strategies for this stock.

2 Acknowledgements

The members of the SARAG for their advice, patience and suggestions on the work contained herein.

2.1 Author listing

- **Rich Hillary**: CSIRO Oceans & Atmosphere
- **Jemery Day**: CSIRO Oceans & Atmosphere

3 Background

The previous project developed a new custom built stock assessment model for this fishery and associated routines to calculate recommended TAC options. The model fixed two clear issues with the previous Stock Synthesis framework being used: (i) the version of Synthesis was an unsupported modification and was essentially not recoverable if it failed; the current model is not tied to a specific package but open source statistical estimation software (Template Model Builder) and clear specifications on what it does; (ii) we now model the tagging data in a way commensurate with how these data are released and recaptured, thereby fixing the issue we had before. Everything else is the same as the previous assessment and was shown to give very comparable answers last year when run with the same data and general assumptions.

The main goal of this project is essentially to consolidate this new assessment method, accepted and implemented in the previous project, and use it to calculate a new TAC recommendation in 2021 as well as for any additional work that may arise in other future projects (e.g. any future review and redevelopment of the harvest strategies currently used for this stock). The secondary long-term goal is, as always, to maintain the highly successful and informative tagging program with the data processing done in collaboration with our partners at the AAD.

4 Need

Given the revised stock assessment model was accepted and implemented we envisage using said model in the next scheduled assessment year with the additional two years of data collected over the time-period of the implemented TAC. We will also, in the non-assessment year, undertake a simple data summary and report to the SARAG.

5 Objectives

1. For the non-assessment year (2020) deliver a brief data summary to the SARAG
2. In the next scheduled assessment year (2021) to deliver a revised stock assessment to the SARAG
3. Maintain the current mark-recapture program as the key stock monitoring data set

6 Benefits & management outcomes

The results of the updated stock assessment due in 2021 will be presented both orally and in terms of written reports to the SARAG and others involved in the management of the fishery. The SARAG membership includes representatives from a wide spectrum of research fields (including stock assessment, fish biology and ecological interactions), and from several organisations with expertise related to the fishery (including the Australian Antarctic Division, ABARES, CSIRO Oceans and Atmosphere, Tasmanian Department of Primary Industries Water and Environment, AFMA and industry). The results will also form the basis of subsequent publications in the scientific literature.

The updated stock assessment will provide the most up-to-date information, conditional on the agreed one-year data lag, in terms of data and methods, to facilitate the management of Australia’s sub-Antarctic fisheries, and provide stakeholders greater confidence when making key commercial and sustainability decisions. Information from the stock assessments will feed directly into the TAC setting process for Macquarie Island Patagonian toothfish. As harvest strategies are being developed for this and other Australian fished species (a process required by the Commonwealth harvest strategy policy), improvements in the assessments developed under this project will have direct and immediate impacts on quota levels and other fishery management measures.

7 Conclusions

For **Objective 1** a verbal update was given to the SARAG meeting. For **Objective 2** Appendix 1 details the main results of the revised assessment as presented to the SARAG in May 2022. Appendix 2 details the updated key biological relationships - growth and maturity - required to run the stock assessment. For **Objective 3** Our continued collaboration with our AAD colleagues ensures that high quality mark-recapture data at the required tagging rates are available.

Appendix 1

Oceans & Atmosphere
www.csiro.au

Updated biological relationships for 2021 stock assessment of Macquarie Island toothfish

R. Hillary

16th April 2021

CSIRO Oceans & Atmosphere
Battery Point, Hobart 7000, Tasmania, Australia.

Contents

1 Background

In this paper we detail updates to two key biological relationships that are essential for the Macquarie Island toothfish stock assessment: growth and maturity. For growth we have ageing data up to and including 2019; for maturity we have data up to and including 2020.

2 Growth relationships

We now have ageing data from 1996 up to and including 2019 and so we are in a position to update the male and female growth relationships required for the stock assessment. There are 3,627 female and 2,331 male length-age measurements. That is an additional 403 female and 191 male measurements, relative to the previous growth update in 2019.

2.1 Data & methods

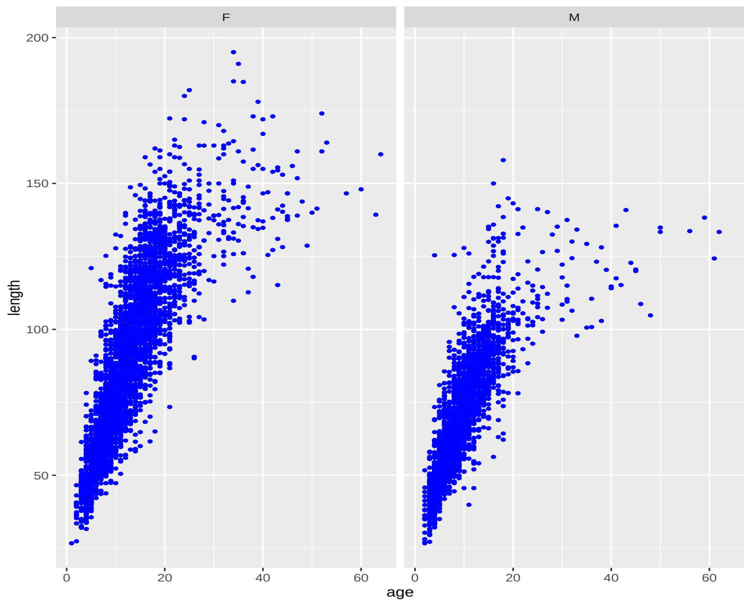

Figure 2.1: *Length-at-age summary for the female (left) and male (right) aged animals.*

The distribution of length-at-age is simply defined from the growth relationship. The mean length-at-age is defined via the Schnute parameterisation of the von Bertalanffy growth curve:

$$\mathbb{E}\left(l(a)\right) = l_1(a_1) + \left(l_2(a_2) - l_1(a_1)\right)\frac{1 - \exp\left(-k\left(a - a_1\right)\right)}{1 - \exp\left(-k\left(a_2 - a_1\right)\right)},$$

where $l_1(a_1)$ and $l_2(a_2)$ are the lengths at reference ages a_1 and a_2 ($a_2 > a_l$), and k is the growth rate.

To generate the distribution of length-at-age we assume a lognormal distribution (with a given standard deviation σ_l) around this mean length-at-age. This gives us a sex-specific distribution of length-at-age, $\pi_{l\,|\,a,s}$.

To get to the "true" distribution of age-given-length we use Bayes' rule:

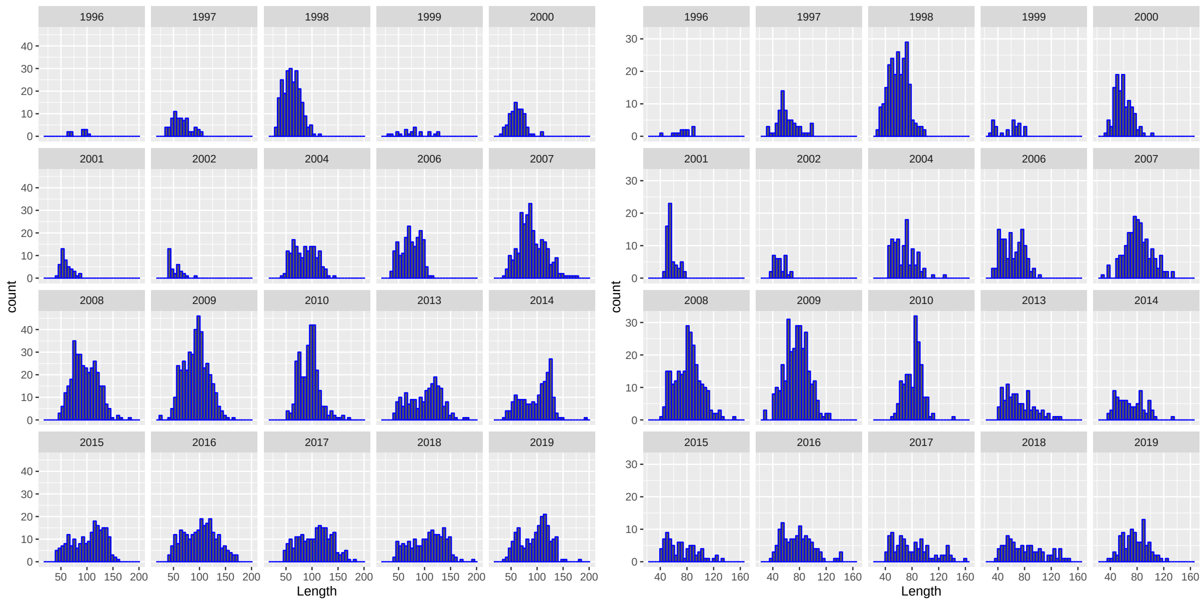

Figure 2.2: *Length frequency summary for the female (left) and male (right) aged animals.*

$$\tilde{\pi}_{a\,|\,y,l,s} = \frac{\pi_{l\,|\,a,s}\pi_{a\,|\,y,s}}{\pi_{l\,|\,y,s}},$$

where $\pi_{y\,|\,a,s}$ is the prior age distribution, and $\pi_{l\,|\,y,s}$ is the length distribution in the fishery:

$$\pi_{l\,|\,y,s} = \sum_a \pi_{l\,|\,a,s}\pi_{a\,|\,y,s},$$

and the prior age distribution is defined as follows:

$$\pi_{a\,|\,y,s} \propto \mathrm{LogN}\left(\mu_{y,s}, \sigma^2_{y,s}\right)$$

For a given ageing error matrix, $A_{a,a'}$, where $\sum_a A_{a,a'} = 1$ and a' is the "true" age in this sense, the adjusted distribution of age-given-length (that we use to compare to the observations) is defined as

$$\pi_{a\,|\,y,l,s} = \sum_{a'} \tilde{\pi}_{a'\,|\,y,l,s} A_{a,a'}.$$

For the length frequency data of the aged fish (again to be understood as being different to the length frequency data per fishery used in the assessment) we assume a Dirichlet-multinomial distribution:

$$\Lambda^l_{y,s} = \frac{(n_{y,s}!)\Gamma(\omega_{y,s})}{\Gamma(n_{y,s}+\omega_{y,s})} \prod_l \frac{\Gamma(n_{y,l,s}+\omega_{y,s}\pi_{l\,|\,y,s})}{n_{y,l,s}!\Gamma(\omega_{y,s}\pi_{l\,|\,y,s})}$$

where $n_{y,s} = \sum_l n_{y,l,s}$, $\Gamma()$ is the gamma function, and the over-dispersion parameter, $\omega_{y,s}$, is defined as follows:

$$\omega_{y,s} = \frac{n_{y,s} - \varphi_{l,s}}{\varphi_{l,s} - 1},$$

and $\varphi_{l,s} > 1$ is the over-dispersion *factor*: the degree to which the multinomial variance is inflated due to correlation between the length classes. The point of going to the trouble of using the D-M formulation is that $\varphi_{l,s}$ is an estimable parameter (as opposed to tuning to get the right value of $n_{y,s}$).

We assume a multinomial distribution for this likelihood as the default, primarily because we assume size dictates selectivity, so we would then expect that the distribution of age *within a given length class* would be random (i.e. multinomial in this case). So, the likelihood of the age-given-length data is as follows:

$$\Lambda^{a|l}_{y,l,s} = \prod_a \left(\pi_{a\,|\,y,l,s}\right)^{n_{y,a,l,s}}$$

For the Schnute model reference ages we assume $a_1 = 5$ and $a_2 = 20$ as assumed in the revised assessment model. Length bins are in 10cm blocks from 20cm at the minimum to a maximum that ensures the largest length bin includes the largest animal observed in the data (for each sex). The parameters estimated in the full model (using both length and age-given-length data) are:

- Mean length-at-age parameters: l_1, l_2, and k
- Standard deviation in mean length-at-age: σ_l
- Prior mean μ_y and standard deviation σ_y of the prior age distribution
- Over-dispersion factor in the length data φ_l

The overall (sex-specific) joint log-likelihood is defined as follows:

$$\ln \Lambda^{\text{tot}}_s = \sum_y \left(\ln \Lambda^l_{y,s} + \sum_l \ln \Lambda^{a\,|\,l}_{y,l,s} \right).$$

We use the TMB package [1] to find the parameters which maximise the joint likelihood of the length and age-given-length data, as well as give us approximate standard errors for each of the parameters and process variables.

2.2 Results

Fits to the female and male size data can be see in Figure 2.3, and the summary of the mean age-given-length can be found in Figure 2.4. Table 2.1 summarises the key parameter estimates. As seen in previous analyses, males seem to grow faster initially, but to a smaller asymptotic length; as a result, size-at-age (and weight) of females is greater than males from about age 5 onwards. The key mean length parameters (k, l_1, and l_2) are all very accurately estimated. Variability in mean length-at-age is very well estimated in both cases and the same for both sexes.

When summarising the fits the length data, for both sexes the fits are generally fairly good, with no apparent systematic issues over time. For both sexes, the estimates of the over-dispersion factor were at the lower bound of 1.05 (we cannot have $\varphi_l = 1$ so 1.05 is a sensible lower bound), strongly indicating an apparent lack of over-dispersion in the size data *of aged animals* and, hence, the logical corollary that a multinomial distribution would in fact be as appropriate. Looking at the fits to the mean age-given-length data, we see good fits for both sexes and across years. Importantly, practically all the estimates sit within the approximate 95% CI. Also, analyses of the standardised residuals for these data show that the variance clusters around about

Variable	k	l_1	l_2	L_∞	t_0	σ_l	φ_l
Female	0.055 (0.003)	0.494 (0.003)	1.16 (0.004)	1.68 (0.03)	-1.3 (0.15)	0.15 (0.012)	1.05* (NA)
Male	0.067 (0.003)	0.488 (0.002)	1.02 (0.007)	1.33 (0.03)	-1.86 (0.18)	0.144 (0.016)	1.05* (NA)
Female (2019)	0.055 (0.003)	0.49 (0.004)	1.15 (0.005)	1.67 (0.04)	-1.29 (0.18)	0.15 (0.015)	1.32 (0.07)
Male (2019)	0.071 (0.004)	0.48 (0.003)	1.01 (0.008)	1.29 (0.04)	-1.63 (0.21)	0.15 (0.02)	1.29 (0.08)

Table 2.1: *Maximum likelihood estimates (and approximate standard errors in brackets) of key estimated parameters and process variables for each sex. The * for each of the over-dispersion coefficients indicate that the estimates hit the lower bound and, as such, we cannot produce sensible standard errors. The 2019 estimates are included for comparison*

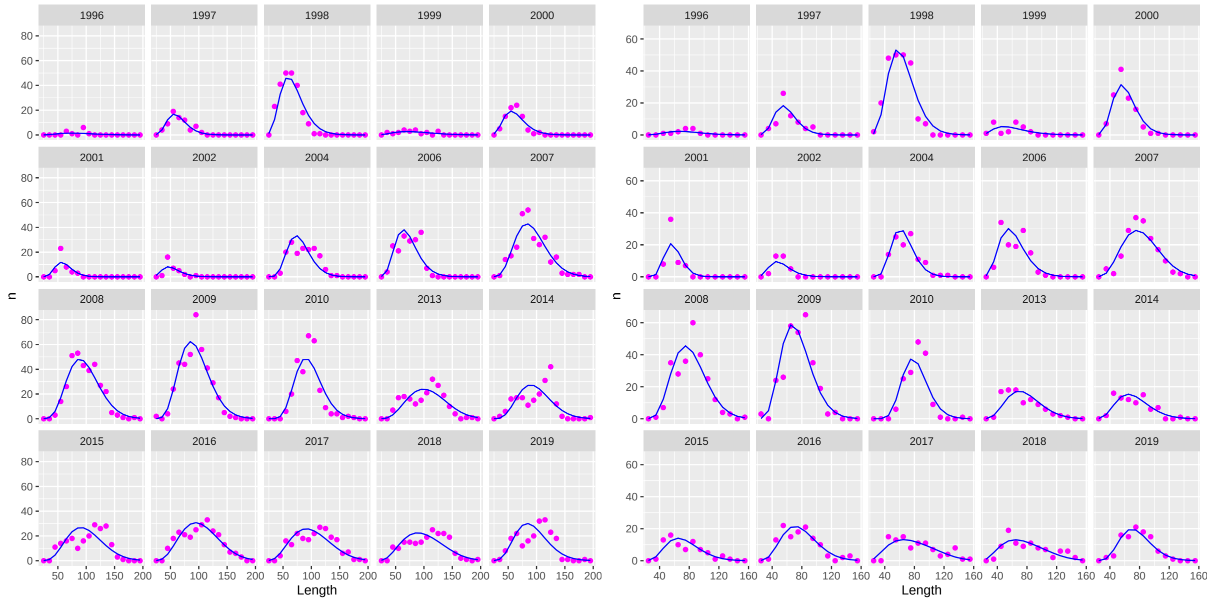

Figure 2.3: *Observed (magenta circles) and predicted (blue lines) length frequency summary for the female (left) and male (right) aged animals.*

0.9 for both sexes - specifically they do not appear consistently over 1 and so the multinomial assumption also seems fine in this case.

3 Maturity relationships

Maturity is a key life-history characteristic used as input to age and size structured integrated assessment models. For the Macquarie Island toothfish stock assessment maturity-at-length is the key relationship [2], translated through the distribution of length-at-age to get an expected maturity-at-age relationship then used to define the female spawning population abundance and age structure. The method used to estimate these key parameters was updated in 2019 [3] to better account for established maturity definitions [4], and agreed by the SARAG to be used in an update to the stock assessment to calculate the recommended TACs later that year.

3.1 Data & Methods

Figure 3.1 summarises the current data (by sex and length) for MI toothfish. The MI assessment uses maturity-at-length as the fundamental input, so we need to do a little work to account for

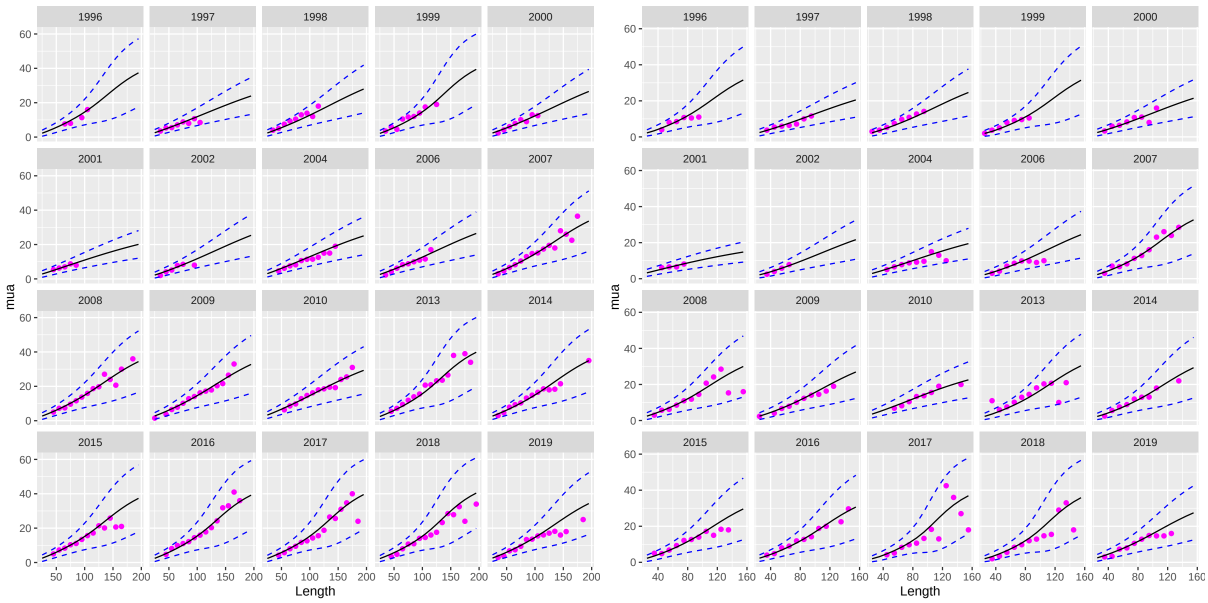

Figure 2.4: *Observed (magenta circles) and predicted median (full blue line) and 95% CI (dotted blue line) mean age-given-length summary for the female (left) and male (right) aged animals.*

the differential treatment of animals that are stage 2 and those that are 3 and above. This is done as follows: within a given length-class, a given proportion of the animals will have maturity stage 2; whatever the expected length class those animals would be in *2 years hence* would be the reference length at which the relative maturity of those animals applies. For the animals of maturity stage 3 and above their length-at-sampling is the reference length. The overall reference length for a given length class is simply the sum of the reference lengths for 2 and 3 and above animals weighted by the relative number of animals in those two maturity stage classifications.

The data are organised in terms of specific and not necessarily equal size length classes, l. For each nominal length class l, the data are n_l (number of animals measured for maturity state, and k_l the number of animals found to be at maturity stage 2–6). Within a given length-class this can be modelled as a binomial process, with associated probability π_l:

$$\pi_l = \frac{g(l)^\nu}{\mu^\nu + g(l)^\nu}, \tag{3.1}$$

where:

- $g(l)$ is the *reference* length-class given an animal is within length class l when measured, accounting for the relative number of maturity stage 2 and 3–6 animals in the sample (see below for details)
- μ is the length at 50% maturity
- ν is a shape parameter

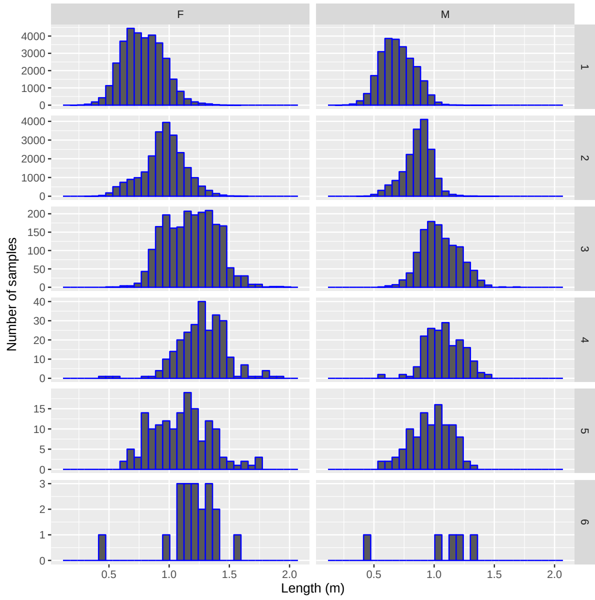

Figure 3.1: *Measured maturity stage (1–6) data (vertical panels) given length (x-axis) in metres and for both sexes.*

The reference length is a given length class is calculated as follows:

$$
\begin{aligned}
w_{l,m} &= \frac{k_{l,m}}{\sum\limits_{j\in\{2,3+\}} k_{l,j}}, \\
g(l) &= \sum_{j\in\{2,3+\}} \gamma(l,j) w_{l,j}, \\
\gamma(l,2) &= l + (L_\infty - l) \times \left(1 - e^{-k\tau}\right), \\
\gamma(l,3+) &\equiv l,
\end{aligned}
$$

where $\tau = 2$ (to represent the length of the animal 2 years hence) and $k_{l,m}$ is the number of animals of maturity stage m in length class l. The likelihood of having maturity stage 2–6, given the parameters μ and ν, is assumed to be binomial:

$$
\ell\left(\mathbf{k} \,|\, \mu, \nu\right) \propto \prod_{l\in\mathcal{L}} \pi_l^{k_l} \left(1 - \pi_l\right)^{n_l - k_l} \tag{3.2}
$$

which is maximised to obtain the MLE estimates of μ and ν. In Eq. (3.2) $\mathbf{k}$ is the vector containing the number of animals in a given length-class at maturity stage 2–6 and $\mathcal{L}$ the length partition.

3.2 Results

For females there were 59,948 measurements with both maturity state *and* length, for males there were 42,504. For females $\mu = 98.9$ and $\nu = 6.41$; for males $\mu = 87.3$ and $\nu = 9.61$. In 2019 for females we estimated that $\mu = 97$ and $\nu = 6.42$; for males $\mu = 0.88$ and $\nu = 9.32$ [3]. In both cases, given the quality of the fits to the data (see Figure 3.2), and the number of data points, the CVs are around 1% or less. The maturity-at-length relationship for both females and males is shown in Figure 3.3.

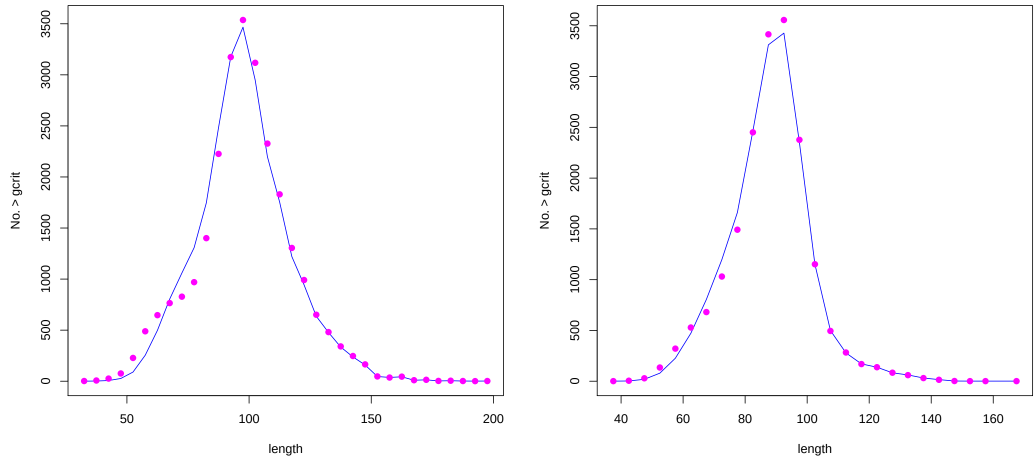

Figure 3.2: *Fits to female (left) and male (right) maturity data, when grouped into the numbers (per length bin) with maturity state of 2 or greater.*

4 Discussion

Using a conditional age-at-length statistical framework first outlined in [5] we estimated the key growth parameters and distributions for both sexes. Data from 1996 and up to and including 2019 are included. The growth parameters are very accurately estimated for both sexes with females generally being longer-at-age than males from age 5 onwards. They are also very consistent with previous estimates [6]. Variability in length-at-age is estimated to be the same for both sexes, as is the over-dispersion factor for the length frequency data. Fits to both the length data and the mean age-at-length data are good, and the multinomial distribution seems appropriate for the age-given-length data. Given the accuracy of the estimates, it seems appropriate to continue to use these estimates as fixed inputs to the revised stock assessment model.

Using the agreed updated method for estimating maturity-at-length [3] we estimated a revised maturity relationship for both males and females. For females the size at 50% maturity was 98.9cm and for males it was 87.3cm (given the growth dimporphism this difference is actually far less pronounced when translating to maturity-at-age). These estimates are, as with the growth parameters, very consistent with those estimated in 2019 [3] and, again as with the growth parameters, estimated with standard errors small enough to make us comfortable with assuming them to be effectively fixed inputs to the stock assessment model.

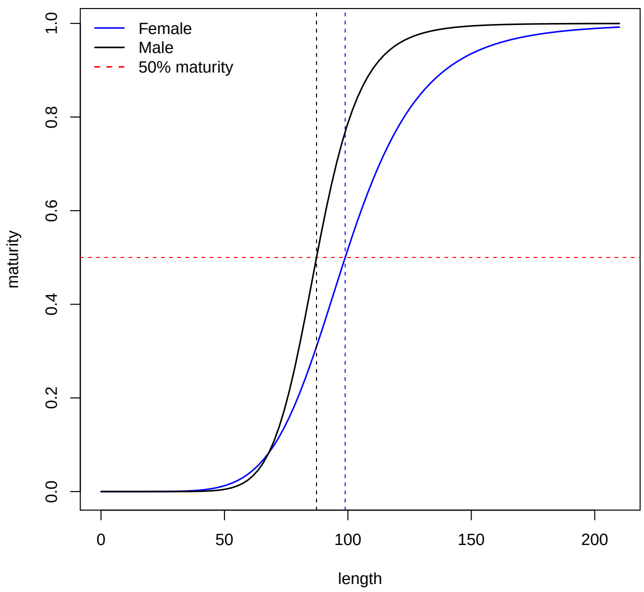

Figure 3.3: *Estimated maturity-at-length relationships for both males and females.*

References

[1] Kristensen, K. *et al.* (2016) TMB: Automatic Differentiation and Laplace Approximation. *J. Stat. Soft.* **70**(5): 1–21.

[2] Proposed new assessment structure for Macquarie Island toothfish using data upto and including August 2018. *SARAG 59*.

[3] Hillary, R. M. (2019) Revised estimates of maturity-at-length for Macquarie Island Patagonian toothfish . *SARAG* March 2019.

[4] Kock K.-H. and A. Kellermann (1991) Review: Reproduction in Antarctic notothenioid fish. *Antarctic Science*, **3**:125–150

[5] Hillary, R. M., Day, J. and Haddon, M. (2015) Age-at-length or length-at-age for modelling the growth of Macquarie Island toothfish? *SARAG, Feb 2015*.

[6] Hillary, R. M. (2019) Estimates of growth parameters for input to the revised stock assessment model. *SARAG* March 2019.

CONTACT US

t 1300 363 400
+61 3 9545 2176
e csiroenquiries@csiro.au
w www.csiro.au

WE DO THE EXTRAORDINARY EVERY DAY

We innovate for tomorrow and help improve today for our customers, all Australians and the world.

Our innovations contribute billions of dollars to the Australian economy every year. As the largest patent holder in the nation, our vast wealth of intellectual property has led to more than 150 spin-off companies.

With more than 5,000 experts and a burning desire to get things done, we are Australias catalyst for innovation.

WE IMAGINE. WE COLLABORATE. WE INNOVATE.

Appendix 2

Oceans & Atmosphere
www.csiro.au

Integrated stock assessment for Macquarie Island toothfish using data upto and including 2020

R. Hillary & J.Day

26th April 2021

CSIRO Oceans & Atmosphere
Battery Point, Hobart 7000, Tasmania, Australia.

Contents

1 Summary

This paper presents results from an integrated stock assessment of Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island using data collected up until and including August 2020, but only including conditional age-at-length data until August 2019. The assessment uses a spatial model that fits to data from the entire Macquarie Island toothfish fishery, and assumes a single reproductive stock, but takes into account spatial structuring of the population within the region. Two areas – northern and southern – are incorporated into the model, with movement of fish between areas, and recruitment to both areas. A single Total Allowable Catch (TAC) for the entire Macquarie Island region is calculated using the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) control rule.

This assessment uses Template Model Builder and fits to data obtained from the tag-recapture program since 1995, to length composition information for the years 1994–2020, and to age-at-length data obtained from aged otoliths (1997–2019). It is an update of the final version of the 2019 assessment [1, 22]. The assessments are based on a length-age structured model of fish population dynamics, with maximum likelihood and Bayesian methods used to fit to the available data.

The model designates five different fleets: Aurora Trough trawl; Northern Valley Trawl; Aurora Trough longline; Northern Macquarie Ridge longline; and Southern Macquarie Ridge longline. Fits to the length composition data are generally good, and the fits to the age-at-length data appear to be also generally good. The model fits the tag-recapture data well, with good accord between the total number of expected recaptures and those observed when viewed from the release or recapture year perspective. There is some spatial divergence in the most recent years (over-predicting returns in the North and under-predicting them in the South) that may be linked to spatial recruitment trends but nothing outside the predictive distribution. The outcomes from the assessment are very similar to those in the 2019 assessment. The reference case 95% credible interval for female spawning biomass depletion is 0.85 (0.78–0.92). Average recruitment is slightly higher (*ca.* 15%) and the most recent recruitment estimates are above average, albeit highly uncertain.

The new 2019 length frequency data include an additional 3245 fish in 93 hauls for Aurora Trough Longline, 4075 fish in 141 hauls for Northern Macquarie Ridge Longline and 1260 fish in 35 hauls for Southern Macquarie Ridge Longline. The new 2020 length frequency data include an additional 3583 fish in 98 hauls for Aurora Trough Longline, 4748 fish in 159 hauls for Northern Macquarie Ridge Longline and 1021 fish in 32 hauls for Southern Macquarie Ridge Longline. There was one additional fish length from Southern Macquarie Ridge from 2017. An additional 274 fish (190 female and 84 male) from the 2019 catch and 281 fish (189 female, 90 male and two unsexed) from the 2020 catch were aged and these were included as conditional age-at-length data for this assessment.

There were no additions or revisions to the historical recapture information. New tag recaptures from the 2018 and 2019 data included 208, 25 and 126 recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 359 tag recaptures in 2018 and 2019 from fish tagged in previous seasons. Eight of these involved recaptures of a tag in a different area to its release, with five of these fish moving from north to south and three fish moving from south to north. In addition there were 459, 297 and 173 new tag releases in 2019 and 611, 360 and 108 new tag releases in 2020 with these releases respectively in the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge. Only

three of the tag recaptures were from fish tagged by the Aurora Trough trawl fleet, with one fish each tagged in 2002 and 2004 and the remaining recapture from a fish tagged in 2008, the last year of trawling in this fishery.

2 Introduction

2.1 Patagonian toothfish

The Patagonian toothfish is a large, long-lived, bottom-dwelling species inhabiting the continental shelf waters of sub-Antarctic islands, oceanic ridges and the southern South American continent. Patagonian toothfish is a highly prized table fish with significant imports to Japanese, North American and European Union markets.

Toothfish have been known to grow to over 2m in length and may live to more than 50 years of age. They inhabit depths from approximately 300m to 2400m, with juveniles generally found in shallower water. They feed on small fish and squid in the mid-water and various fish and crustaceans on the bottom. Toothfish are believed to reach sexual maturity at around 10 years of age, and possibly older for Macquarie Island fish [2, 3].

Toothfish lack swim-bladders and so often reach the surface in good condition even though they may have been caught from depths down to 2400m. This has allowed an extensive tagging program to develop at both Macquarie Island and the Heard Island and McDonald Islands (HIMI). Tagging studies have increased knowledge of the species movement, growth and available abundance [4, 5].

2.2 The fishery

Bottom-set longline and trawl fisheries for the Patagonian toothfish (*Dissostichus eleginoides*) developed in the waters of several of the Southern Ocean's sub-Antarctic islands during the late 1980s and early 1990s. More recently, trawl fisheries for toothfish were established within Australian Commonwealth waters around Heard Island and McDonald Islands (HIMI) and Macquarie Island.

Macquarie Island lies some 1500 km to the southeast of Tasmania (Figure 2.1). The fishery off Macquarie Island began in November 1994. Two major trawl fishing grounds have been discovered: Aurora Trough and the Macquarie Ridge Northern Grounds region. A tagging experiment began in 1995/96 within Aurora Trough and the following season within the Macquarie Ridge region.

A Total Allowable Catch (TAC) for the fishery was first introduced in the 1996/97 fishing season (Table 2.1, Figure 3.1). The TAC for the 1996/97 fishing season was based on the catches of the first two fishing seasons and the tagging experiment in the 1995/96 fishing season. The setting of TACs after the 1996/97 fishing season was then based on results from a tagging-based stock assessment model. For the Aurora Trough region, commercial TACs for the trawl fishery were 750 and 200t for the 1996/97 and 1997/98 fishing seasons respectively, and were zero after the 1997/98 fishing season (but with a 40t research TAC for continuing the tagging experiment and monitoring). In 2003/04, following indications of improved stock status from the assessment, Aurora Trough was re-opened to commercial fishing with a 354 t quota. However, the assessment in the following year suggested that the stock had fallen marginally below the

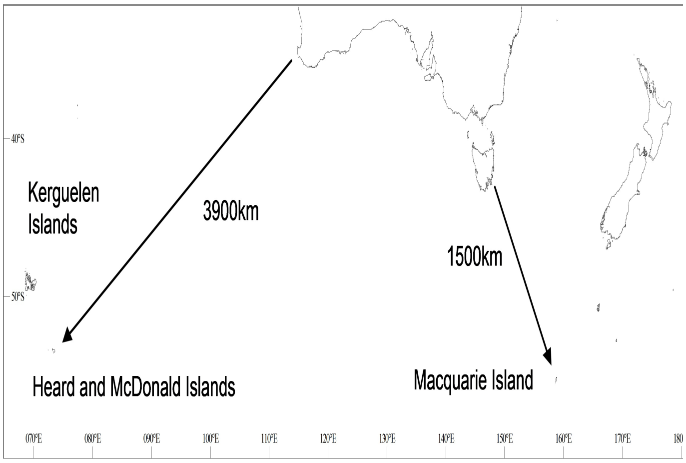

Figure 2.1: The location of Macquarie Island (54° 30'S, 158° 57'E) and Heard Island and McDonald Islands (53 °06'S, 73 °30'E) relative to New Zealand and Australia.

threshold for a commercial fishery so once again, the commercial fishery closed and a research quota was instigated. Since then a commercial fishery has existed in every season except for 2009/10, and the commercial Aurora Trough quota was 150t in 2011/12 (Table 2.1).

For the Macquarie Ridge sector, the annual trawl TAC reduced steadily in the years following the 1500t TAC of 1998. However, the TACs between 1998 and 2006 were allowed to increase within the fishing season if the catch rates exceeded 10t/km^2 over three consecutive fishing days. If this catch rate dropped below the trigger level, then the TAC fell to the lower TAC. If the lower TAC had been reached then fishing ceased.

In July 2007 the AFMA Board agreed to the commencement of longline fishing for Patagonian toothfish in the Macquarie Ridge sector of the MITF for a trial period of three years, with annual reviews, and subject to conditions and specific limits for incidental mortality of seabirds. In 2009, the Aurora Trough quota was also taken by longline. Longline fishing continued for the 2010/11 season, with continued high catch rates in both the Aurora Trough and Macquarie Ridge Sectors. Tagging rates have been high, and there have been longline recaptures of fish tagged in the trawl fishery. Since 2009 the catch has been taken entirely by longline.

Since 2012/13, a single TAC has been set for the whole of the Macquarie Island region. The 2018/19 and 2019/20 TAC was set at 450t, with a recommendation to catch a little more than half of this total TAC in Aurora Trough (250t), and 60% of the remainder taken from North Macquarie Ridge (120t) and the rest from South Macquarie Ridge (80t). The 2020/21 and 2021/22 TAC was increased to 555 t on recommendations from the 2019 stock assessment, again with a recommendation to catch at least 25% of the total catch from North Macquarie RidgeThe actual catch in 2017 was around 90t below the TAC, with around 145t more then the recommendation of the catch taken from South Macquarie Ridge, but with much less then the recommended catch taken in the other two regions (Table 3.1). In 2018, the actual catch was within two tonnes of the TAC, with the regional spread of catches close to that recommended in the 2017 assessment. This was the second largest catch by longline in North Macquarie Ridge up until 2018, indicating that considerable effort was made to match the recommended spatial distribution of catches, particularly in the north. In both 2019 and 2020, the actual catches were close to the TAC, and the catches in North Macquarie Ridge were even higher than the 2018 North Macquarie Ridge catch in both years, ensuring good representation of the catch between northern and southern

Table 2.1: Time series of Patagonian toothfish TAC (t) by fishing year.

Fishing season	Administrative period (longline season: 1 May–31 Aug)[a]	Total Allowable Catch: Aurora Trough	Total Allowable Catch: Macquarie Ridge[b]
94/95	none	-	-
95/96	none	-	-
96/97	1 Sep 1996 – 31 Aug 1997	750	1000
97/98	1 Sep 1997 – 31 Dec 1998	200	1500
98/99	1 Jan 1999 – 31 Dec 1999	40[c]	600 (1000)
99/00	1 Jan 2000 – 31 Dec 2000	40[c]	510 (1000)
00/01	1 Jan 2001 – 31 Dec 2001	40[c]	420 (1000)
01/02	1 Jan 2002 – 31 Dec 2002	40[c]	242 (782)
02/03	1 Jan 2003 – 30 Jun 2003	40[c]	205 (665)
03/04	1 July 2003 – 30 Jun 2004	354	174 (441)
04/05	1 July 2004 – 30 Jun 2005	60[c]	148 (376)
05/06	1 July 2005 – 30 Jun 2006	255	125 (319)
06/07	1 July 2006 – 30 Jun 2007	241	100 (264)
07/08	1 July 2007 – 30 Jun 2008	390	86[d]
08/09	1 July 2008 – 30 Jun 2009	312	150[d]
09/10	1 July 2009 – 14 Apr 2010	60[d]	150[d]
10/11	15 Apr 2010 – 14 Apr 2011	140	150[d]
11/12	15 Apr 2011 – 14 Apr 2012	150	360
12/13	15 Apr 2012 – 30 Apr 2013	455[e]	
13/14	1 May 2013 – 30 Apr 2014	415[e]	
14/15	1 May 2014 – 14 Apr 2015	410[e]	
15/16	15 Apr 2015 – 14 Apr 2016	460[e]	
16/17	15 Apr 2016 – 14 Apr 2017	450[e]	
17/18	15 Apr 2017 – 14 Apr 2018	450[e]	
18/19	15 Apr 2018 – 14 Apr 2019	450[e]	
19/20	15 Apr 2019 – 14 Apr 2020	450[e]	
20/21	15 Apr 2020 – 14 Apr 2021	555[e]	
21/22	15 Apr 2021 – 14 Apr 2022	555[e]	

[a] longline season began on 1 May up until 2014, and started on 15 Apr from 2015 onwards

[b] tonnage shown in brackets would have been triggered if trawl catch rates reached 10 t/km^2 over 3 consecutive fishing days

[c] research TAC to enable tag-based stock assessments

[d] TACs for longline trial

[e] TAC set for entire Macquarie Island region

regions.

2.3 Previous assessments

Prior to 2010, TAC determination for the Macquarie Island Patagonian toothfish stock had been based on stock assessments using the tag-recapture model developed initially by de la Mare and Williams [6], and modifications described in Tuck *et al.* [5]. This tag-recapture model estimated pre-tagging available abundance and annual net changes in available abundance between fishing seasons for the major fishing grounds of Macquarie Island [7]. In 2004, a new model that expanded upon the traditional tag-based model was introduced [8]. This “integrated” assessment included information on length-frequency and tagging data in an age-structured model that allowed estimation of annual spawning biomass and cohort strength. In 2008/09 work commenced on using the integrated assessment platform of Stock Synthesis for the assessment of Aurora Trough Patagonian toothfish [9, 10]. This model development continued and the Stock Synthesis assessment was used to set the TAC for the Aurora Trough component of the fishery for the 2010/11 fishing season [11].

The 2010 Aurora Trough assessment base case model estimated the 2010/11 female spawning biomass to be 2,004t or 54% of unfished spawning biomass [11]. Trawl available biomass was estimated to be well above 66.5% pre-tagging (1995) levels, which had previously been used as the limit reference point for the Aurora Trough toothfish fishery. The 2010/11 TAC for Aurora Trough was set to 140t, based on projections under the CCAMLR control rule. The TAC for 2010/11 season for the Macquarie Ridge sector was set at 150t, as for the previous season, given the absence of an assessment.

The development of stock assessment models that fitted to data from both the Aurora Trough and Macquarie Ridge was presented to SARAG in November 2009 [10, 12]. Several versions of the models were developed which primarily differed in the model structure in terms of accounting for the spatial nature of the fishery. These analyses included: a single area model which designated different fleets to capture the spatial and gear-dependent differences in availability but assumed a homogeneous resource, and two- and three-area models which accounted for heterogeneity in toothfish availability between the northern, southern, and ridge areas of operation of the fishery, with movement among areas. All models were able to fit the length data and age-at-length data equally well, however the models differed in their ability to mimic the patterns of tag recaptures by fleet. The single area models indicated that current spawning biomass was around 64% of unfished conditions, with the spatial models suggesting a slightly less depleted stock, with 2010/11 spawning biomass being 67% and 72% of unfished equilibrium respectively. The time series of spawning biomass showed a steady decline over the duration of the fishery for all models. Models which used multiple areas in addition to multiple fleets estimated larger stock sizes, and larger current stock size relative to those in unfished conditions. Uncertainty in the estimation of movement rates in the spatial models reflected the low numbers of tag recaptures outside the area of release, and also the generally low numbers of recaptures of fish released in the Northern Valleys Macquarie Ridge trawl grounds.

The 2011 assessment used the same models as in 2010, but the base case assessment assumed alternative model parameters [14, 15]. The Aurora Trough assessment estimated 2011/12 female spawning biomass to be 58% of unfished conditions, while the 2 area model estimated the 2011/12 spawning biomass for the whole of Macquarie Island to be 72% of unfished. The projected catches that met the CCAMLR control rules were 150t from Aurora Trough and 360t from Macquarie Ridge (assuming a 70:30 split between the southern and northern Macquarie Ridge).

From 2012/13 a single TAC was set for the whole of Macquarie Island, and the two area model used as the base case. The 2012 assessment estimated the 2012/13 female spawning biomass for the whole of Macquarie Island to be 70% of unfished [16], the 2013 assessment estimated the 2013/14 female spawning biomass for the whole of Macquarie Island to be 69% of unfished [17], with further estimates of 68% for the 2014 assessment [18], 69% for the 2015 assessment [19], 67% for the 2016 assessment [20] and 69% for the 2017 assessment [21]. The 2019 assessment initially estimated the 2019/20 female spawning biomass for the whole of Macquarie Island to be 70% of unfished [1] using the same model structure as [21], but with the assessment in TMB rather that Stock Synthesis. However, this estimate for 2019/20 female spawning biomass was subsequently revised to 85% using an updated maturity curve [22], prior to setting the TAC.

2.4 Modifications to the previous assessment

The following data have been added to the assessment:

1. 2019 and 2020 catches
2. 2019 and 2020 length compositions
3. 2019 and 2020 tag recaptures
4. 2018 and 2019 age-at-length compositions

Ageing data from 2020 were not made available for this assessment.

3 Data

The four primary data inputs to the model are:

1. **Catch biomass**: in tonnes, per fishery, (1994–2020)
2. **Length frequency**: for each fishery, and using the number of hauls (not fish sampled) as the initial sample size, (1994–2020)
3. **Conditional age-at-length**: for each fishery and sex, we have the number of fish of a given age conditional on the length class samples came from, (1996–2000, 2002, 2003, 2005–2010, 2013–2019)
4. **Tagging data**: release events are now characterised by a length class and area of release, with recapture data being subsequent total recaptures (across all recapture lengths) in each of the spatial regions of the model, from the tag-release-recapture program, begun during the 1995/96 season

3.1 Catch data

This stock assessment treats the annual catches as known and exact. These data are therefore directly input into the model and are not fitted. The catch history by fishing year is distributed across two methods, trawl and longline, within the five fleets considered by the stock assessment models: Aurora Trough trawl, Northern Valley trawl, Aurora Trough longline, northern Macquarie Ridge longline, and southern Macquarie Ridge longline (Table 3.1, Figure 3.1).

Annual catch data used in earlier assessments comprised the total catch, which included a small proportion of fish that were caught and released (including fish released with tags) as well as fish that were retained. Since the 2017 assessment, the catch data were adjusted to exclude any released fish.

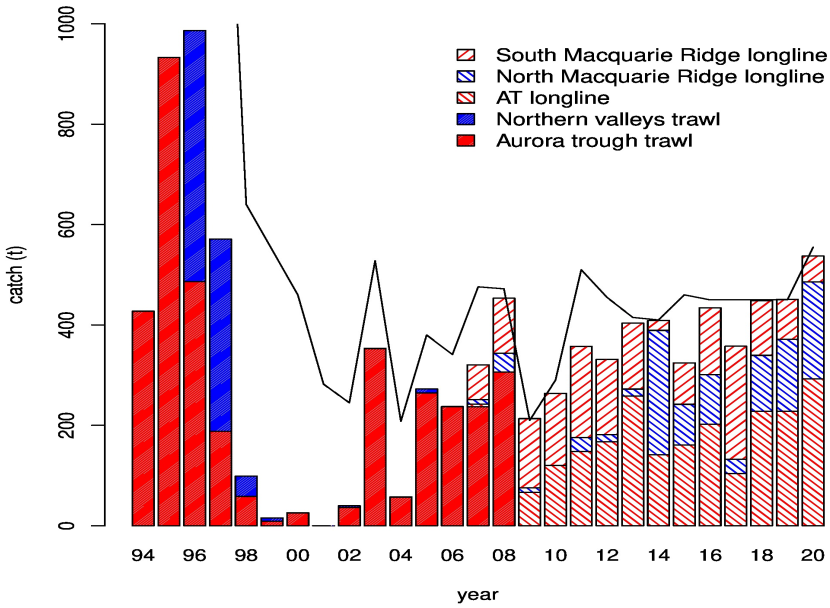

Figure 3.1: Catch history and total TAC by fishing year, with catches stacked by fleet and the grey line representing the combined TAC (with TACs summed for Aurora Trough and Macquarie Ridge from 1996–2011). There were small research quota in the Aurora Trough from 1998-2002 and in 2004. Red coloured bars indicate catches from the south and blue coloured bars indicate catches in the north.

TAC history is listed in Table 2.1 with catches by fleet and area are shown in Table 3.1.

3.2 Length frequency data

Samples of the length composition of the catch were available for all fishing seasons (1994/95 through 2020/21). Each annual length composition is based on the measurement of several hundreds (thousands) of fish (Tables 3.2 and 3.3). However, it is unlikely that the number of fish measured in each year is an appropriate metric of the effective sample size, due to expected high correlations among fish lengths within individual hauls/shots. Thus, when an assessment is done, input sample sizes for the individual length compositions are set at the number of hauls sampled for the trawl data, and the number of shots for the longline data. For all fleets the over-dispersion factor (that scales the initial sample sizes to the correct ones) is estimated within the model.

Disaggregation of the length data by sex is possible, and the model could allow for the inclusion of composition data from both sexed data and data for which the sex is unknown, with the expectation that the latter is a random sample from the catch and is a combination of the individual compositions by sex. The percentage of the seasonal length samples that were sexed has varied considerably over the duration of the fishery. Additionally, inspection of the data suggests that

Table 3.1: Time series of Patagonian toothfish catches (t) by fishing year and fleet, including total catch (removals only) over all fleets and combined TAC (combined over both regions up to 2011/12).

Fishing season	Trawl		Longline			Total Catch(t)	Combined TAC(t)
	AT	NV	AT	NMR	SMR		
94/95	427.3	0				427	
95/96	932.9	0				933	
96/97	486.3	500.3				987	1750
97/98	188.2	382.8				571	1700
98/99	58.5	40.5				99	640
99/00	9.0	6.6				16	550
00/01	25.4	0.6				26	460
01/02	0.0	0				0	282
02/03	36.4	3.3				40	245
03/04	352.8	0.7				353	528
04/05	56.8	0.6				57	208
05/06	264.5	7.9				272	380
06/07	237.3	0				237	341
07/08	236.8	0	5.4	9.0	69.2	320	476
08/09	306.1	0	0	37.1	109.8	453	462
09/10			66.6	8.7	138.2	214	210
10/11			120.2	0	143.6	264	290
11/12			148.2	27.4	181.9	358	510
12/13			167.3	14.5	149.7	332	455
13/14			258.5	13.8	131.3	404	415
14/15			141.2	248.0	19.6	409	410
15/16			160.8	81.1	82.6	324	460
16/17			202.4	98.9	133.0	434	450
17/18			104.1	28.5	225.0	358	450
18/19			227.8	111.7	108.7	448	450
19/20			227.9	143.5	79.7	451	450
20/21			292.8	192.9	51.6	537	555

Table 3.2: Number of length samples by fleet and season for the trawl fleets, both in terms of number of hauls from which samples were taken, and the total number of fish measured.

Fleet	Season	# hauls	# fish	mean # per haul
AT trawl	94/95	126	3414	27
	95/96	257	6721	26
	96/97	103	2725	26
	97/98	81	1409	17
	98/99	54	3354	62
	99/00	38	831	22
	00/01	20	1415	71
	01/02	2	1	1
	02/03	19	733	39
	03/04	96	4580	48
	04/05	19	702	37
	05/06	124	3368	27
	06/07	72	765	11
	07/08	94	1461	15
	08/09	131	2199	17
NV trawl	94/95	3	18	6
	95/96	43	2250	52
	96/97	139	2393	17
	97/98	78	2031	26
	98/99	42	638	15
	99/00	13	350	27
	00/01	2	1	1
	01/02	24	390	16
	02/03	6	83	14
	03/04	13	274	21
	04/05	27	548	20
	07/08	3	14	5

Table 3.3: Number of length samples by fleet and season for the longline fleets, both in terms of number of hauls from which samples were taken, and the total number of fish measured.

Fleet	Season	# hauls	# fish	mean # per haul
AT longline	07/08	2	200	100
	09/10	9	548	61
	10/11	18	1066	59
	11/12	45	1779	40
	12/13	52	1916	37
	13/14	79	3046	39
	14/15	62	2216	36
	15/16	84	2950	35
	16/17	94	3376	36
	17/18	66	2254	34
	18/19	93	3335	36
	19/20	93	3245	35
	20/21	98	3583	37
NMR longline	07/08	5	160	32
	08/09	13	406	31
	09/10	7	246	35
	11/12	26	829	32
	12/13	31	838	27
	13/14	11	340	31
	14/15	70	2570	37
	15/16	96	2739	29
	16/17	128	3337	26
	17/18	57	1368	24
	18/19	104	3045	29
	19/20	141	4075	29
	20/21	159	4748	30
SMR longline	07/08	28	1589	57
	08/09	44	1750	40
	09/10	50	1886	38
	10/11	34	1546	45
	11/12	96	3388	35
	12/13	126	4080	32
	13/14	94	3107	33
	14/15	18	561	31
	15/16	76	2404	32
	16/17	123	3865	31
	17/18	174	5527	32
	18/19	76	2464	32
	19/20	35	1260	36
	20/21	32	1021	32

the unsexed fish sampled for length are quite different from the male and female portions of the length composition for some years [13]. Consequently, length data were aggregated by sex for all years. Length bin structure is at 5 cm intervals between 30 – 140 cm, and at 10 cm intervals below and above this range up to 190 cm.

3.3 Age data

Age-at-length samples are available from aged fish that were captured in 1996–2000, 2002, 2003, 2005–2010 and 2013–2019 (Table 3.4). New ageing data from 2018 and 2019 were added this year, but the 2020 conditional age-at-length data was not available.

3.4 Tag recapture data

Between the 1995/96 and 2020/21 fishing seasons, 19,771 Patagonian toothfish were tagged at Macquarie Island, of which 2,802 have been recaptured (Table 3.5, Table 3.6). Fish are still being recaptured from releases in the early years of the fishery (Table 3.5). Of the recaptures in 2020, the longest period between tagging and recapture was for a fish tagged in 2002. This equals the longest period between initial tagging and recapture, with individual fish tagged 18 years previously also being recaptured in 2015, 2016 and 2017. Of the recaptures in 2019, the longest period between tagging and recapture was for a fish tagged in 2004.

The recapture rate by region in 2019 and 2020 follow similar patterns to those seen in earlier years. In 2017, only three recorded recaptures were of fish released in the north, with only one of these fish recaptured in the south. All 155 remaining recaptures from 2017 were of fish both released and recaptured in the south. In 2018, 15 fish released in the north were recaptured, with only four of these recaptured in the south. In 2019 and 2020, the number of recaptures of fish released in the north is again much lower than the number of recaptures of fish released in the south, with only 27 fish released in the north recaptured in 2019 and 2020 and only five of these three fish recaptured in the south. The remaining 332 recaptures from 2019 and 2020 comprised 329 fish which were both released and recaptured in the south and, those rarest of movements of tagged fish recorded, three fish that were released in the south and recaptured in the north. Over all years, the total number of fish recorded moving from the north to the south is 41, with only 10 fish moving from the south to the north.

Table 3.4: Sample sizes of aged fish from the southern and northern areas of the fishery by year and gender. Tag recaptured fish not included.

Year	gender	south	north	total
1996	u	9	10	19
1997	u	19	5	24
	f	28	13	41
	m	27	23	50
1998	u	4		4
	f	134	71	205
	m	117	83	200
1999	u	16		16
	f	1	87	88
	m	1	117	118
2000	u	8		8
	f	40	3	43
	m	53	7	60
2002	f		31	31
	m		32	32
2003	f	138		138
	m	79	2	81
2005	u	1		1
	f	107	26	133
	m	56	37	93
2006	f	11		11
	m	9		9
2007	f	328	33	361
	m	238	13	251
2008	u	3		3
	f	247	33	280
	m	225	4	229
2009	u	1		1
	f	272	35	307
	m	159	25	184
2010	u	1		1
	f	276		276
	m	159		159
2013	u	2		2
	f	175	25	200
	m	83	14	97
2014	u	2	3	5
	f	97	95	192
	m	59	23	82
2015	f	129	76	205
	m	57	19	76
2016	f	134	72	206
	m	70	31	101
2017	f	166	20	186
	m	78	12	90
2018	f	135	55	190
	m	58	26	84
2019	u	2		2
	f	100	89	189
	m	81	9	90
total		4195	1259	5454

Table 3.5: Numbers of tagged fish released and recaptured following at least 180 days at liberty, by release fleet and season.

Release season	Release fleet	# rel	Mean length	# recaptures after 180 days at liberty 96/97	97/98	98/99	99/00	00/01	02/03	03/04	04/05	05/06	06/07	07/08	08/09	09/10	10/11	11/12	12/13	13/14	14/15	15/16	16/17	17/18	18/19	19/20	20/21
95/96	AT tr	428	69	57	28	3		1	1	1							1										
95/96	NV tr	4	57																								
96/97	AT tr	448	58		42	7		2		9	1	3		1	1												
96/97	NV tr	536	61		53	5	1			2																	
97/98	AT tr	503	60			18	3	4	5	21	4	15	1		2	3	1	2	2			1					
97/98	NV tr	477	69			9				1					1		1										
98/99	AT tr	652	68				4	5	2	30	2	9	2	2	7		1	1		1							
98/99	NV tr	308	57																				1				
99/00	AT tr	692	65					3	1	35	6	12	1	4	6	2	5	1	5					1			
99/00	NV tr	299	58																1								
00/01	AT tr	364	59						1	23	3	5	1	1	9												
00/01	NV tr	135	46						1			1															
02/03	AT tr	491	63							60	8	29	6	15	24	2	3	10	1	6	2			1			1
02/03	NV tr	17	57															1									
03/04	AT tr	570	69								9	23	8	4	13	2	3	2	1	1							
03/04	NV tr	60	53									3															
04/05	AT tr	556	69									46	7	16	43	4	4	6	3	4	1		1			1	
04/05	NV tr	263	56									2		1	1						1	1					
05/06	AT tr	520	71										25	18	27	2	5	4	4	3	1	1	1	1			
05/06	NV tr	288	60																1		2	3	1				
06/07	AT tr	432	59											26	13		1			4		2	1	2			
07/08	AT tr	273	65												31	2		2	1	3	1		2				
07/08	NMR LL	26	78													1		3	2				1				
07/08	SMR LL	189	81												15	4	3	6	6	4		1	4	3	1		
08/09	AT tr	557	71													2	6	12	10	19	6	8	8	1	4		1
08/09	NV tr	14	51																								
08/09	NMR LL	82	79													2		7		1	1						
08/09	SMR LL	385	79												1	9	9	18	21	11	2	2	2	6	1		1
09/10	AT LL	299	85														27	13	9	13	4	2	3	2			1
09/10	NMR LL	60	85															5	5			2	1				1
09/10	SMR LL	395	79														26	25	8	20	2	2	4	5	3	2	1
10/11	AT LL	478	87															11	31	45	6	4	4	1		1	
10/11	SMR LL	507	91															27	42	34	5	8	10	8	2	1	
11/12	AT LL	302	72																10	37	7	7	12	6	3	3	1
11/12	NMR LL	116	83																1	2	1	3	2	1	1		
11/12	SMR LL	497	78																9	25	4	18	10	9	7	3	
12/13	AT LL	309	78																	37	12	12	6	6	9	7	1
12/13	NMR LL	56	89																						1	1	
12/13	SMR LL	302	87																	20		9	3	5		1	
13/14	AT LL	529	75																		9	26	23	16	12	11	5
13/14	NMR LL	36	81																			3			1		
13/14	SMR LL	249	81																		9	10	1	10	6	7	1
14/15	AT LL	295	72																			9	19	11	13	8	3
14/15	NMR LL	499	79																				4		4	6	3
14/15	SMR LL	36	80																					2	1	1	
15/16	AT LL	353	76																				17	13	27	21	7
15/16	NMR LL	168	79																				2	1	5	3	
15/16	SMR LL	165	80																				12	4	10	4	4
16/17	AT LL	445	77																					12	42	20	14
16/17	NMR LL	184	84																					1	2		2
16/17	SMR LL	270	92																					30	4	16	4
17/18	AT LL	226	74																						20	14	10
17/18	NMR LL	65	79																						1		
17/18	SMR LL	432	81																						38	23	14
18/19	AT LL	509	74																							24	21
18/19	NMR LL	228	83																								2
18/19	SMR LL	184	78																							21	14
19/20	AT LL	459	77																								25
19/20	NMR LL	297	82																								9
19/20	SMR LL	173	80																								14
20/21	AT LL	611	73																								
20/21	NMR LL	360	82																								
20/21	SMR LL	108	72																								
Total		19771		57	123	42	8	15	11	182	33	148	51	88	194	35	96	156	173	290	76	134	155	158	218	199	160

Table 3.6: Total numbers of tag recaptures by fleet of release (rows) and recapture (columns), for fish at liberty for greater than 180 days. These releases and recaptures are aggregated over all years.

	Recaptured by:				
Released by:	AT trawl	NV trawl	AT longline	NMR longline	SMR longline
AT trawl	851	1	168	3	39
NV trawl	8	72	1	7	6
AT longline	0	0	712	0	93
NMR longline	0	0	5	68	21
SMR longline	1	0	132	7	608

To allow for mixing of tagged fish with the untagged population, and without losing too many tag recapture events in the early data limited assessments, recaptures within the year of release were removed from previous assessment release data if the recapture occurred within 10 days of release (c.f. [7]) for all stock assessments up until 2015. Given the quantity of tag data now available to the assessment and to ensure full mixing of tagged and untagged fish, recaptures were removed from the release data if the recapture occurred within 180 days of release, for all stock assessments after 2016. This effectively removes recaptures of any fish tagged within the same fishing season. The same 180 day mixing period, as first applied to the 2016 assessment, was continued in this current assessment. As with the length data, the over-dispersion factor for the tag data is internally estimated at run time to deal with spatiotemporal release and recapture correlation.

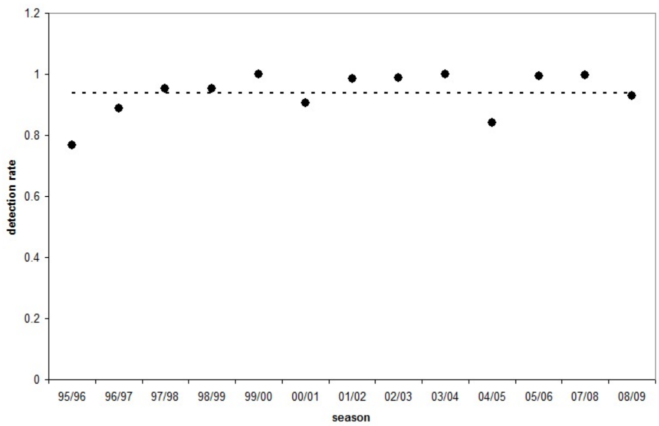

Figure 3.2: Estimated tag detection rate (points) by fishing season [7]. Dotted line corresponds to the mean detection rate (0.938) over the time series.

Tag-recapture experiments rely on the tags being discovered and reported when the fish are captured. This may not occur if tags are lost from the fish, or if tagged fish are not detected. From the recapture of multiple tagged fish in this fishery, estimates of tag loss rates indicate that the probability of losing both tags is negligible. Likewise, many individual fish have been recaptured several times. The rates of tag loss and tagging mortality were assumed to be zero for the base case. This is consistent with previous assessments of toothfish at Aurora Trough and Macquarie Island.

The non-detection of tagged toothfish has been a problem, especially with the electronic tags. The detection of visible tags also relies upon the vigilance of the crew and observers. Estimates of the tag detection rate by season are available for the trawl fishery (Figure 3.2, data from Tuck and Lamb [7]), and were input to the model in order to implement a time-varying detection rate. In the absence of additional information, the tag detection rate for the longline fleet was assumed to be 0.94 (the average of the calculated annual values from the trawl fishery) for all years.

3.5 New and updated data summary

Updated length data in this assessment include one minor revision to historical data prior to 2018, with one additional length record obtained from 2017. The new 2019 length frequency data include an additional 3245 fish in 93 hauls for Aurora Trough Longline, 4075 fish in 141 hauls for Northern Macquarie Ridge Longline and 1260 fish in 35 hauls for Southern Macquarie Ridge Longline. The new 2020 length frequency data include an additional 3583 fish in 98 hauls for Aurora Trough Longline, 4748 fish in 159 hauls for Northern Macquarie Ridge Longline and 1021 fish in 32 hauls for Southern Macquarie Ridge Longline.

There were no revisions to the historical age-at-length data up to 2017 used in the current assessment. An additional 274 fish from the 2018 catch and 281 fish from the 2019 catch were aged and these were included as age-at-length data for this assessment. This comprised 190 females and 84 males in 2018, and 189 females, 90 males and 2 unsexed fish from the 2019 catch.

A fish tagged in 2002 in the Aurora Trough was recaptured in 2020. Four individual fish have now been recaptured 18 years after their initial tagging. New tag recaptures from the 2019 data included 110, 10 and 79 recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 199 tag recaptures in 2019 from fish tagged in previous seasons.

New tag recaptures from the 2020 data included 90, 17 and 53 recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 160 tag recaptures in 2020 from fish tagged in previous seasons.

Of these 359 recaptures, 351 were recaptures in the same area (329 in the south, 22 in the north), with eight recaptures in a different area to the release area (five tagged in the north and recaptured the south and three tagged the south and recaptured in the north), providing additional information on movement of individuals between areas.

In 2019 and 2020, there were three fish tagged by Aurora Trough Trawl that were recaptured, two in Aurora Trough and one in the Northern Macquarie Ridge. No fish tagged by Northern Valleys Trawl were recaptured in 2019 and 2020. There were 197 fish previously tagged by Aurora Trough Longline recaptured in 2019 and 2020, with 164 of these tagged fish recaptured in the same area as release, with the remaining 33 recaptured in the Southern Macquarie Ridge. There were an additional 27 recaptures of longline tagged fish from Northern Macquarie Ridge, with 22 recaptured in the same area as release, three recaptured in Aurora Trough and two more recaptured from Southern Macquarie Ridge. There were 132 fish previously tagged by longline in Southern Macquarie Ridge recaptured in 2019 and 2020 with 39 of these recaptured in Aurora Trough, 91 recaptured in the Southern Macquarie Ridge and the remaining two recaptured from the Northern Macquarie Ridge.

There were 459, 297 and 173 new tag releases in 2019, with these releases respectively in the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge. In 2020, there were an additional 611, 360 and 108 new tag releases, with these releases respectively in the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge.

4 Biology

There have been a number of updates to the growth and maturity relationships for this stock over the years. Growth is now estimated externally to the assessment using a conditional age-at-length approach [30]. In 2019 the maturity-at-length relationships for males and females was also revised [30], resulting in a significant decrease in the length at 50% and 95% maturity for females - the values used in the stock assessment. Currently, the values used are 98.9cm and 156.6cm, respectively. The length-weight relationship is the same as previously employed:

$$w_l = al^b$$

where $a = 4.4 \times 10^{-6}$ and $b = 3.14$ and weight is measured in tonnes, with length measured in centimetres. The age-independent value of natural mortality is $M = 0.13$, and the $M = 0.155$ HIMI natural mortality value is explored as a sensitivity. For the steepness parameter of the stock-recruitment relationship (they key resilience parameter with respect to recruitment overfishing) the default value assumed is $h = 0.75$ with values of $h = \{0.6, 0.9\}$ explored as sensitivity scenarios.

5 Methods

The revised assessment framework uses the Template Model Builder (TMB) package in R [25]. This is, at present, the most efficient and flexible statistical modelling package available. It allows for highly complex statistical models (including the use of random effects) to be efficiently and robustly estimated. For the MCMC runs used to calculate the key probabilistic summaries of the assessment variables we use the tmbstan R package [26]. This links models written in TMB to the currently accepted most efficient MCMC sampler (the No U-turns or NUTS algorithm) and, for the models explored, runs in just over 90 minutes.

5.1 Population and fishery models

The full details of the new assessment method can be found in [1].

5.1.1 Length related variables

All the key data series used in the assessment involve size-specific predicted quantities: length distributions in the catch, conditional age-at-length, and length-specific recapture probabilities. The currency of the population and fishery model is primarily age-based, so we need to translate a number of age-based quantities into length:

- Predicted length frequency (aggregated across sexes) for each fishery
- Predicted distribution of age-given-length, accounting for ageing error, in each of the fisheries and for both sexes
- Predicted sex ratio-at-length for each region

- Predicted spatial recapture probability-at-length, derived from length-based harvest rates and the growth transition matrices for each sex

For the tagging likelihood we need to calculate a sex-specific growth transition matrix given the length-based nature of this part of the model. This is done following the method outlined in [27] that deals with both the differing size of the length bins, and the stochastic uncertainty in the expected growth increments of the fish, given the growth curve. The transition matrix, $G_{l,l',s}$, is the probability that a fish in length bin l after a given time τ (taken to be one year here) will be in length bin l' (and $\sum_{l'} G_{l,l',s} = 1$).

5.1.2 Candidate selectivity functions

Selectivity is assumed to be inherently length-based and not sexually dimorphic, even though selectivity-at-age is given possibly different growth curves for males and females. We explored three potential selectivity functions:

1. **Double-logistic**: essentially a fully smooth function that encompasses the features of the double-normal and double-normal plateau functions
2. **Generalised gamma**: uses a modified gamma distribution-type kernel that is a reduced parameter dome-shaped distribution to avoid over-parameterisation and convergence issues of the double-logistic function when the plateau-type dynamics are absent
3. **Logistic**: usual logistic function that has no potential for dome-shaped dynamics

5.2 Likelihood functions

We have now defined all the key population and fishery variables so we now move on to the likelihood functions of the three main observations used within the assessment.

5.2.1 Length frequency data

The underlying distribution we assume is a Dirichlet-multinomial for the sex-combined length frequencies, where the over-dispersion factor φ_f by fishery f is estimated with all the other parameters.

5.2.2 Conditional age-at-length data

The underlying distribution we assume here is that the age data are multinomial for a given length bin - i.e. the distribution of age within a given length bin is assumed to be random and, hence, no over-dispersion factors.

5.2.3 Tagging data

Forthe tag recapture model we derive fits within what would be considered a *multi-state mark-recapture model*. By this we mean there are a number of probabilistic states a tagged fish can inhabit over the recapture period of a given release event: which length class it is within, what spatial region it is in, what sex it is, and whether it has been recaptured or not. The release covariates are year, length class and region; the recapture covariates are year and region of recapture. So we will integrate across size at recapture and sex-at-release (we don't use the sexed tag recapture information) within the tagging model.

The base likelihood for the tagging data in this format is essentially the multinomial distribution, which is known loosely as the Brownie (size and spatially structured in this case) model [28]. This follows the recapture history of a given release event and has been shown to be more informative on both abundance and migration, relative to the previous two-stage likelihood [23]. Tagging data are, however, well known to be often over-dispersed (i.e. more variable than the underlying base distribution would predict). To accommodate this process we again use the Dirichlet multinomial (D-M) distribution to model the likelihood of a given tagging event's recapture history.

5.2.4 Overall likelihood and objective function

The overall log-likelihood of the data is simply the sum of all three log-likelihoods of the data sources:

$$\ln \Lambda^{\mathrm{tot}} = \ln \Lambda^{l} + \ln \Lambda^{a|l} + \ln \Lambda^{\mathrm{tag}}$$

The full objective function to be maximised includes the recruitment prior and some additional penalties to stop harvest rates and tag recapture probabilities exceeding pre-specified maximum levels.

5.3 Estimated parameter options

The core set of estimated parameters are:

- Unfished total recruitment, R_0
- Selectivity parameters for each fishery
- Recruiment deviations for a pre-specified subset of years
- Spatial recruitment parameters, η_r
- Overall recruitment deviation SD, σ_r
- Parameters of the migration matrix, $\mathbf{\Phi}$
- Over-dispersion parameters φ_f and φ^{tag}

5.4 Model dimensions

This section deals with some high-level summaries of the input data, as well as the relevant dimensions of the model (years, ages, size classes etc.) and what specific choices are made about the different parameterisations for the various model processes. The model runs from 1985 to 2020 (i.e. 10 years before fishing began), ages are from 1 to 52. Size-classes range from 0 to 190cm: 0 to 30 in 10cm bins, 30 to 140cm in 5cm bins, and from 140 to 190cm in 10cm bins. The model is run, as is the current assessment, as a two region model with a Northern and Southern region (with the same latitudinal separator for these regions as used in the current assessment). There are five fisheries:

1. Aurora trough trawl (ATT): assumed in region 2 (Southern region) and with an assumed time-invariant double-logistic selectivity
2. Northern valleys trawl (NVT): assumed in region 1 (Northern region) and with an assumed time-invariant generalised gamma selectivity
3. Aurora trough long-line (ATL): assumed in region 2 (Southern region) and with two possible selectivity options: generalised gamma or logistic
4. North Macquarie ridge longline (NMRL): assumed in region 1 (Northern region) and with two possible selectivity options: generalised gamma or logistic

5. South Macquarie ridge longline (SMRL): assumed in region 2 (Southern region) and with two possible selectivity options: generalised gamma or logistic

6 Results

This section summarises:

- Reference model configuration and fits to the various data sets
- Population dynamic summaries from the MCMC runs for the reference model
- Impact of the outlined sensitivity runs

6.1 Reference assessment model

The reference assessment model has the dimensions outlined in Section 5.4, and uses the data as outlined in Section 3. For the reference assessment model, we assume that the reference ages for the Schnute parameterisation of the von Bertalanffy growth function to be $a_1 = 5$ and $a_2 = 20$. This ensures that they are (a) are within the observed data range, and (b) are not too close or too far apart, relative to the data range. For the reference model we keep the growth parameters *fixed*, estimating them using the conditional age-at-length method detailed in [30]. So, we are using these data to inform the model on population size and age structure (including recruitment), not growth.

Variable	k	l_1	l_2	L_∞	t_0	σ_l	ϕ_l
Female	0.055 (0.003)	0.494 (0.003)	1.16 (0.004)	1.68 (0.03)	-1.3 (0.15)	0.15 (0.012)	1.05* (NA)
Male	0.067 (0.003)	0.488 (0.002)	1.02 (0.007)	1.33 (0.03)	-1.86 (0.18)	0.144 (0.016)	1.05* (NA)
Female (2019)	0.055 (0.003)	0.49 (0.004)	1.15 (0.005)	1.67 (0.04)	-1.29 (0.18)	0.15 (0.015)	1.32 (0.07)
Male (2019)	0.071 (0.004)	0.48 (0.003)	1.01 (0.008)	1.29 (0.04)	-1.63 (0.21)	0.15 (0.02)	1.29 (0.08)

Table 6.1: *Maximum likelihood estimates (and approximate standard errors in brackets) of the growth parameters used in the reference model. The values used in 2019 are included below the most recent estimates for comparison purposes.*

A detailed summary of the estimation of the growth parameters can be found in [30] but Table 6.1 shows the estimate used as model inputs in the reference case. As seen in previous analyses, males seem to grow faster initially, but to a smaller asymptotic length; as a result, size-at-age (and weight) of females is greater than males from about age 5 onwards. The key mean length parameters (k, l_1, and l_2) are all very accurately estimated. Variability in mean length-at-age is very well estimated in both cases and the same for both sexes. The standard errors are informative in that it makes it fairly clear that uncertainty in growth is arguably the least of all the parameters used as inputs to the model, or estimated therein (see later). For the female maturity-at-length relationship estimated in [30] the associated lengths at 50% and 95% maturity were 98.9cm and 156.5cm, respectively. As with the key growth parameters, the estimated accuracy of these parameters is low enough that considering them effectively fixed inputs to the model is highly unlikely to cause underestimation of the overall level of uncertainty in the key stock status inputs.

6.2 Fitting summary for reference model

The fits to the length frequency data for the two trawl fleets are in Figure 6.1, and for the three longline fleets in Figure 6.2.

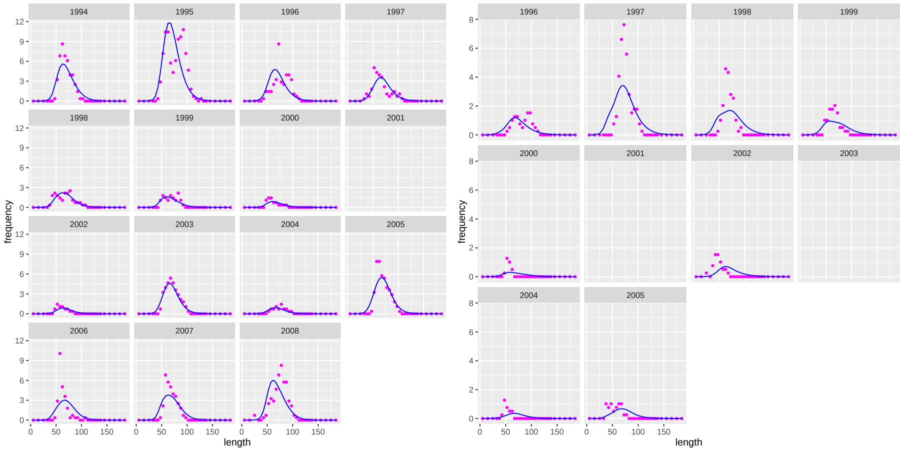

Figure 6.1: *Fits to the ATT (left) and NVT (right) trawl fisheries length data. Magenta circles are the observed data, and the blue lines the predictions.*

Figure 6.3 shows the fits to the female length-conditional age data for the two trawl fleets. and Figure 6.4 shows the same for the males. Figure 6.5 shows the fits to the female length-conditional age data for the three longline fisheries, and Figure 6.6 shows the same for the males.

The fits to the tagging data (Figure 6.7) are summarised in four key ways:

1. Successive recaptures for each year of releases
2. Total recaptures for each year of release
3. Total recaptures for each year of recapture
4. Total recaptures for each year and region of recapture

All of these summaries aggregate across the size spectrum of releases and recaptures for visual brevity, and also because size-at-recapture is not an explicit part of the tagging likelihood.

6.3 Relative data "weighting" estimates

A key feature of the revised assessment model is that data weighting is achieved via internally estimated parameters, not an *ad hoc* tuning approach as is often the case. Focussing on the trawl length data first: for the ATT and NVT fleets there is clear down-weighting of the haul data - more so for the NVT fleet. For the longline fleets, ATL and SMRL are down-weighted very little, but the NMRL fleet is clearly down-weighted. For the ATT data this looks like genuinely random variation; for the NVT data more some kind of systemic lack of fit given the clear decrease in mean length over time (and the assumption of time-invariant selectivity). For the NMRL data by convention we assume logistic selectivity for this and the SMRL fleet to avoid the appearance of cryptic spawner biomass in the population. While logistic selectivity is actually the mode of choice for the ATL, and would be for SMRL if permitted the choice, it seems that we consistently over-estimate the right-hand limb of the length frequency curve in the last five years of data for

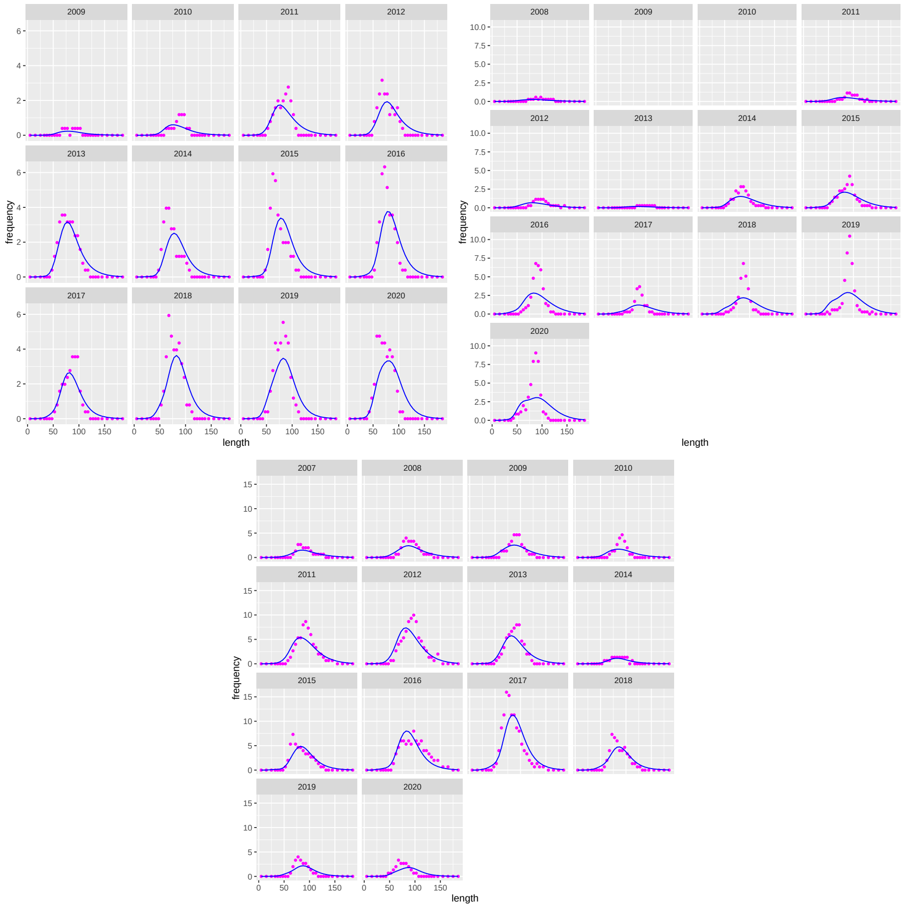

Figure 6.2: *Fits to the ATL (top left), NMRL (top right), and SMRL (bottom) longline fisheries length data. Magenta circles are the observed data, and the blue lines the predictions.*

the NMRL fleet.

Variable	φ_{ATT}	φ_{NVT}	φ_{ATL}	φ_{NMRL}	φ_{SMRL}	φ^{tag}
Estimate	2.77	3.92	2.53	3.54	1.5	1.46

Table 6.2: *Estimates of the over-dispersion factors for the size data for each fleet, φ_f, and the tagging data, φ^{tag}.*

For the tagging data we see that the estimate of $\varphi^{\text{tag}} = 1.46$ clearly suggests that the tagging data are over-dispersed, relative to the assumption of a straight multinomial recapture likelihood. For the conditional age-at-length data we assumed a multinomial distribution, given the theory about size-selectivity versus age would suggest that age data from within a given length class would be random (hence, the multinomial would be the right choice). The reality of whether this is true can only be gleaned once the model has been fitted to the data. When looking at all the fits to the data for each sex and fishery (Figs. 6.3–6.6) we see that, barring a few isolated examples, the observed mean length-at-age sits within the predicted 95% interval and doesn't systematically appear above or below the predicted mean. When one analyses the standardised residuals for over-dispersion (do they systematically appear greater than 1) there is no evidence that a move to the over-dispersion model (Dirichlet-multinomial) is required. This seems to suggest that:

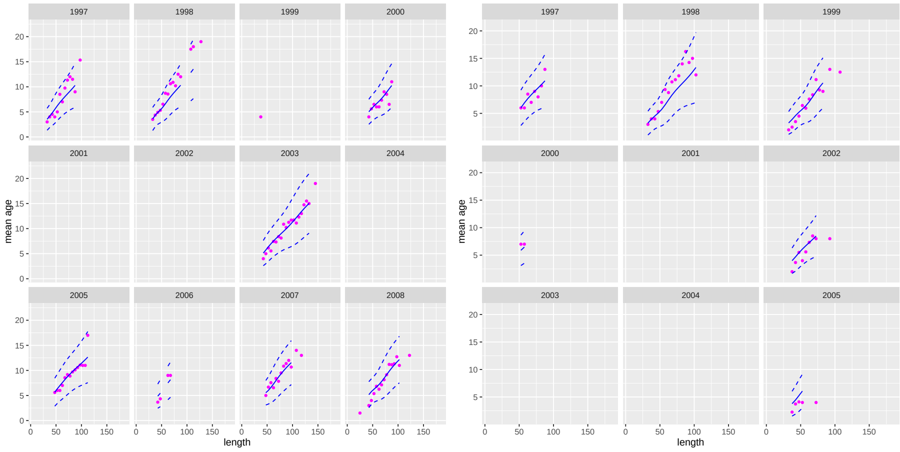

Figure 6.3: *Fits to the ATT (left) and NVT (right) trawl fisheries female age-given-length data. Magenta circles are the observed mean age, and the blue lines the predicted median and 95%ile.*

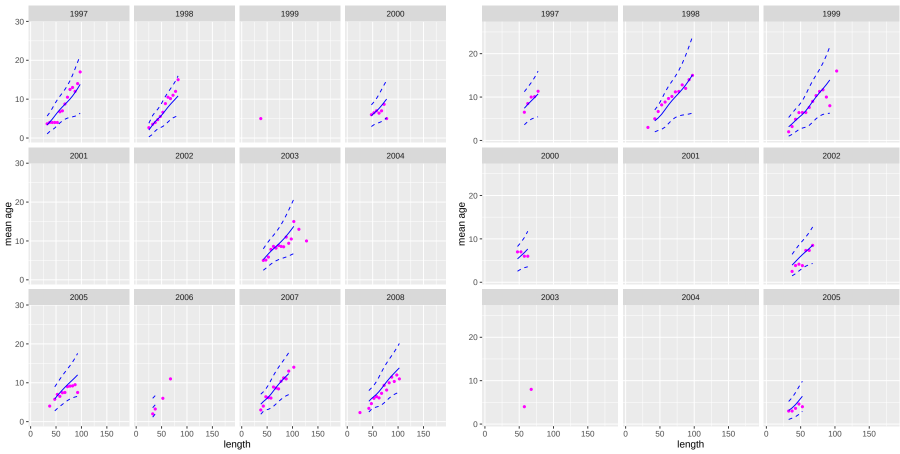

Figure 6.4: *Fits to the ATT (left) and NVT (right) trawl fisheries male age-given-length data. Magenta circles are the observed mean age, and the blue lines the predicted median and 95%ile.*

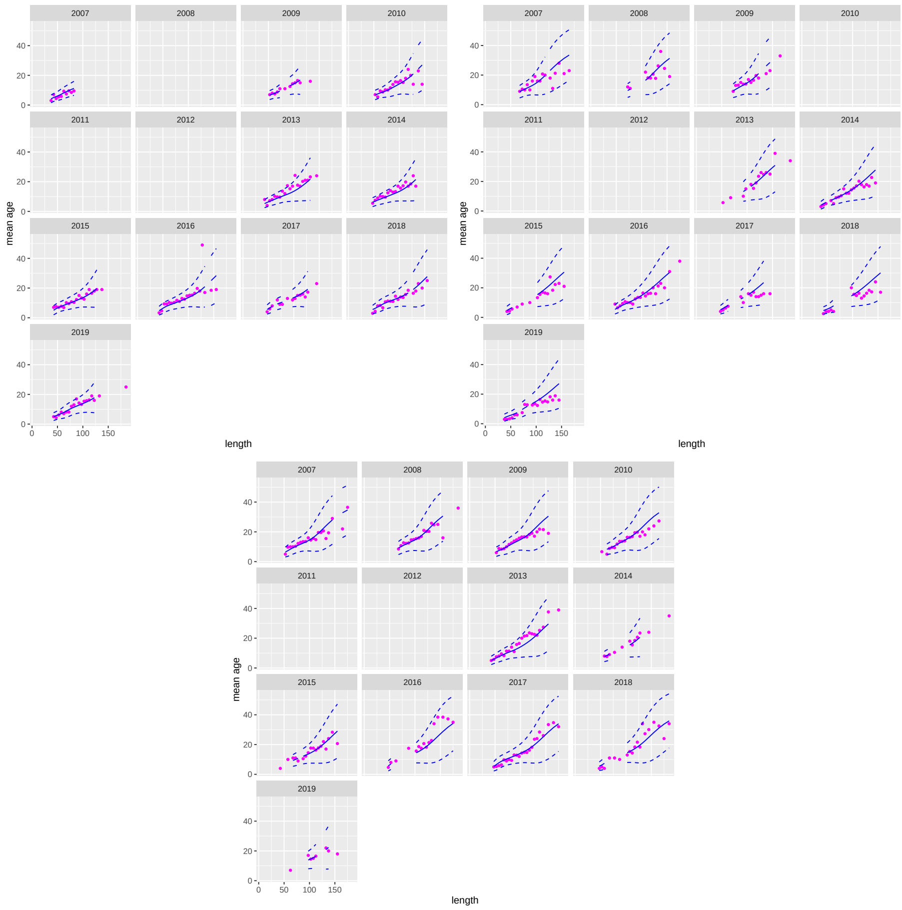

Figure 6.5: *Fits to the ATL (top left), NMRL (top right), and SMRL (bottom) longline fisheries female age-given-length data. Magenta circles are the observed mean age, and the blue lines the predicted median and 95%ile.*

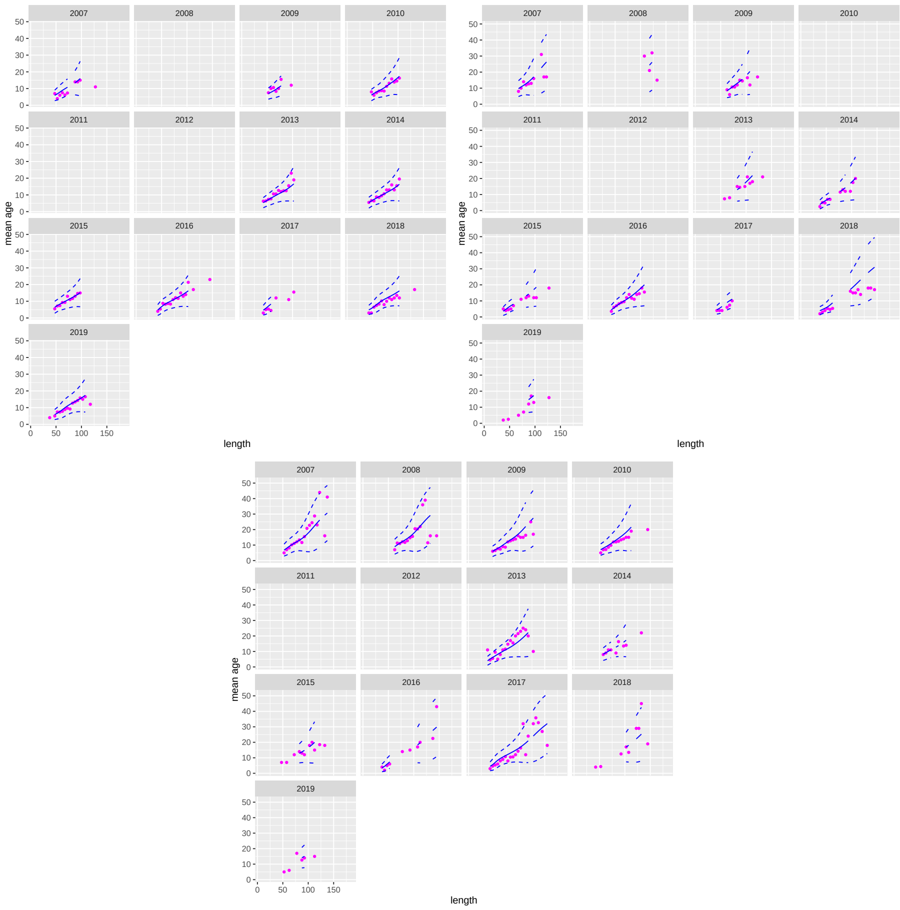

Figure 6.6: *Fits to the ATL (top left), NMRL (top right), and SMRL (bottom) longline fisheries male age-given-length data. Magenta circles are the observed mean age, and the blue lines the predicted median and 95%ile.*

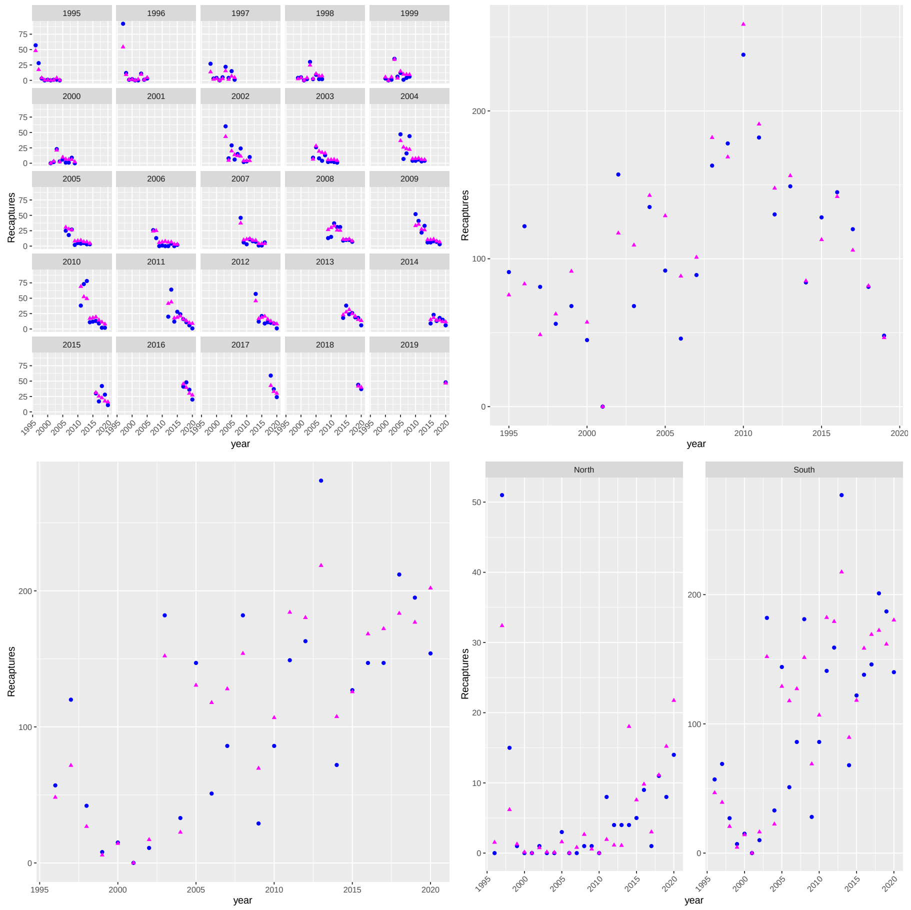

Figure 6.7: *Fits to the tagging data (blue circles, observed; magenta triangles, predicted) for recaptures following year of release (top left), total recaptures for each year of release (top right), total recaptures for year of recapture (bottom left), and recaptures for each year and region of recapture (bottom right).*

- The multinomial distribution assumed for these data appears valid
- The model's predictions of age-given-length are clearly statistically consistent with the data and the assumed growth model
- At least for these data, the model has enough freedom to adequately explain the observations
- It would seem to validate the underlying assumption that size (not age) is the right underlying variable with which to parameterise selectivity

6.4 Population dynamic summaries from MCMC runs

For the reference assessment case, we used the `tmbstan` R-based MCMC package [26] to sample from the posterior distribution. The package uses the Hamiltonian MCMC algorithm, designed to solve a lot of the problems with the more traditional MCMC algorithms, when it comes to sampling from complex high-dimensional posterior surfaces. As a result, it is able to obtain a convergent MCMC sample from the posterior (1,000 iterations) in about 90 minutes. The key female SSB summaries can be found in Figure 6.8; total recruitment and the key spatial parameters (recruitment fraction to North, η_1, and migration rates between regions) can be found in Figure 6.9.

The current (*ca.* 2020) median estimate (and 95% credible interval) of overall female SSB depletion is 0.85 (0.78–0.92). As with previous assessments, the estimated overall level of female SSB (and depletion thereof) is consistently higher in the North, relative to the Southern region. Spatially, the depletion in the Northern region is 0.94 (0.86–1.02); in the Southern region it is 0.51 (0.47–0.57). Total recruitment has generally varied randomly around the mean level, with short periods of higher or lower recruitment, but not sustained periods of either (showing intermediate levels of positive temporal auto-correlation *ca.* 0.3).

The spatial recruitment fraction to the Northern region has a median (and 95% credible interval) of 0.17 (0.05–0.29) - a little higher than the previous estimate of 0.15 from 2019 [1]. Migration point estimates are similar (around 1% *per annum* from North to South, and 8% from South to North) - a little higher than the 6% from 2019. The reality is that one can obtain the same effective spatial distribution of animals by **either** depositing more or less recruits into a region, **or** having more or less fish move between regions. Additionally, a (comparatively) large change in the spatial recruitment parameter, can be offset by a much smaller proportional shift in a migration parameter. The spatial recruitment dynamic is a “one off” event; migration is the consistent movement of every age-class year upon year. It does not take much change in the latter to offset a change in the former (as is the case here).

Differences between the relative sizes of the Northern and Southern regions largely depend on the metric chosen. In terms of current female spawning biomass, clearly the model estimates more (almost six times more) in the North than in the South. If it is total numbers, there are in fact 50% *more* animals estimated to be in the Southern region - more recruits go here initially and these younger age-classes dominate the numbers. If our metric is, say, exploitable abundance currently accessible by the longline fleets then the estimated abundance in the North is around twice that in the South. If that metric is exploitable **biomass** there is around 3–4 times as much in the North, relative to the South.

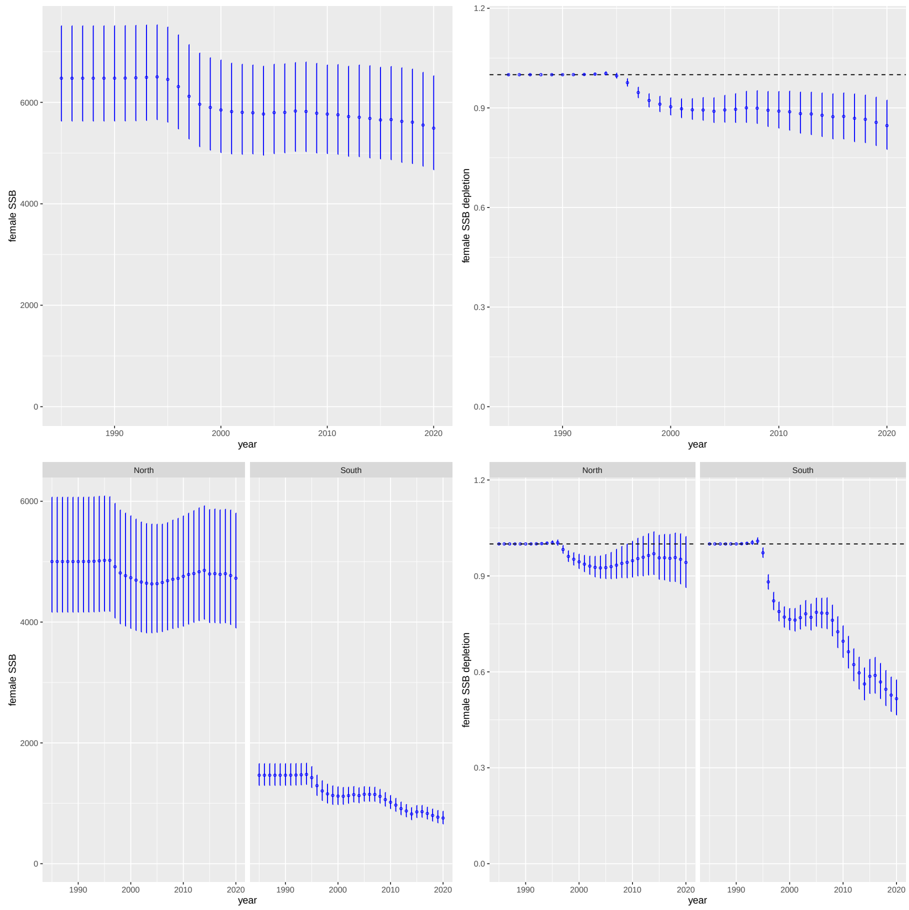

Figure 6.8: *Posterior median and 95% credible intervals for total female SSB (top left), female SSB relative depletion (top right), spatial female SSB (bottom left), and spatial female SSB relative depletion (bottom right).*

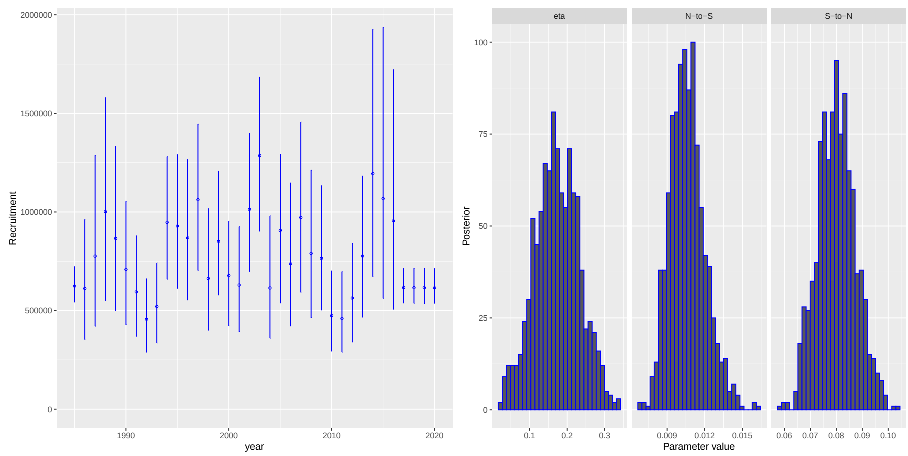

Figure 6.9: *Posterior median and 95% credible intervals for total recruitment (left), and the marginal posteriors for the three spatial parameters:* η_1, $\Phi_{1,2}$, *and* $\Phi_{2,1}$ *(right).*

6.5 Key sensitivity runs

We focus on four key sensitivity tests:

1. Using the estimates of tag shedding rates instead of the previous assumption of effectively zero tag loss over time
2. Assume a lower steepness of $h = 0.6$
3. Assume a higher steepness of $h = 0.9$
4. Assume the HIMI natural mortality of $M = 0.155$

For the tag shedding sensitivity test, we assumed what is effectively the worst-case scenario: where the tag shedding is defined as in Hillary (2019) [31] and this defines π_t^{tag}; as a result, we are basically then at the expected lower-bound of tag retention (for the purposes of detection post-capture). For the alternative natural mortality scenario (HIMI value of $M = 0.155$) we see the most difference across the sensitivity scenarios. Unsurprisingly, we see the R_0 value increases, to accommodate the higher rate of attrition of recruits given the higher M value. The depletion is lower than for the reference case - around 0.74 - driven by differences in spatial recruitment fraction and migration estimates. Overall, the fit is better for the higher M value as it has been in previous assessments but, given we impose asymptotic selectivity on all the long-line fleets, this is also highly likely to afford the model additional freedom to better fit the age-given-length and tag data via increased mortality at older ages as a proxy for dome-shaped selectivity. The alternative steepness scenarios change little in terms of status or other key parameters - the reference steepness value of 0.75 is the best fit to the data but, given how little contrast there is in the recruitment-SSB relationship over time, it is really not worth attaching much significance to this result. For the tag shedding, we see a very slightly lower level of depletion, 0.83, but little else of real significance.

Sensitivity	Depletion	$R_0 \times 10^6$	$-\ln \Lambda^l$	$-\ln \Lambda^{a\|l}$	$-\ln \Lambda^{\text{tag}}$	$-\ln \Lambda^{\text{tot}}$
Base	0.84	6.44	10,933	12,919	11,660	35,513
$M = 0.155$	0.74	7.52	10,953	12,892	11,650	35,496
$h = 0.6$	0.84	6.54	10,967	12,919	11,660	35,548
$h = 0.9$	0.84	6.52	10,993	12,920	11,660	35,573
Tag shedding	0.83	6.29	10,967	12,920	11,658	35,545

Table 6.3: *Sensitivity test summaries: female SSB depletion, overall estimate of R_0, the negative log-likelihood values for all three data sources as well as the overall negative log-likelihood*

7 Recommended TAC scenarios

The CCAMLR decision rule is currently used for Macquarie Island toothfish in relation to calculating recommended TACs. As in previous such calculations, we explored spatial scenarios where the catch in the Aurora trough was fixed at a given value, and then the remainder was shared between the North and South, given an assumed percentage for each. For the Aurora trough we explored 100, 200 and 300 tonnes with 50:50, 75:25, and 25:75 splits for the North and South remainder. Table 7.1 details the recommended TACs for these spatial catch scenarios.

The recommended TACs range from 620 to 665 tonnes with an average of 644 tonnes, around an 11% increase on the 571 average from 2019. Given the overall level of depletion is basically

Aurora trough	NMRL	SMRL	NMRL %age	SMRL %age	TAC
100	270	270	0.5	0.5	640
200	215	215	0.5	0.5	630
300	160	160	0.5	0.5	620
100	136	409	0.25	0.75	645
200	114	341	0.25	0.75	655
300	91	274	0.25	0.75	665
100	420	140	0.75	0.25	660
200	338	112	0.75	0.25	650
300	251	84	0.75	0.25	635
Average					**644**

Table 7.1: *Recommended TAC scenarios for the various spatial catch distribution scenarios explored.*

the same in 2021 as in 2019 what is causing the increase in TAC? There are two inter-related drivers:

1. The estimate of R_0 in 2021 is around 15% higher than in 2019
2. The most recent estimates of recruitment are above the average value

Given the CCAMLR rule and how it functions, any relative change in overall population abundance will tend to result in a relative change of a very similar magnitude in the associated TAC we calculate - all other factors being essentially the same. Given an estimated CV of around 9%, if the true value of R_0 was in between the 2019 and 2021 estimates, then both are within one standard error of this value and, hence, not really different in a statistical sense. This is a feature of - not a bug in - the CCAMLR rule really.

As for recent recruitment being higher, for this we need to consider the following: (i) since 2010 the TAC has been on average increasing; (ii) given the consistent tagging rates per tonne caught the number of tagged fish available to be recaptured has also increased; (iii) overall recaptures have varied around the 150 level and between 100–200 for the past decade. If recruitment and exploitable abundance had been steady over the past decade then we possibly should be seeing an increase in the number of recaptures over that period. We haven't really seen that yet - albeit with high historical variability in overall recaptures - and the only way the model can answer this is by estimating an increasing recruitment trend from 2010–2014 and higher than average values in 2015 and 2016 (these cohorts are observed in the 2020 data at least twice in an absolute sense in the tags). It is too early to be strongly convinced of the strength of these incoming cohorts and if we see them in the future ageing data this will be a more convincing secondary line of evidence.

Figure 7.1 shows the actual projection for one of the TAC scenarios in Table 7.1. The recommended TACs in Table 7.1 all hit the requisite target in 35 years - they do, however, reach that target still going down, not in an equilibrating sense. This is because of the starting depletion of 0.85 means it takes a high enough catch to get to the target in 35 years but that constant catch will then cause the stock to likely decrease below the target. At the 200 year projection target the TAC meeting the rule is closer to 550 tonnes. This is, again, a specific feature of the CCAMLR rule.

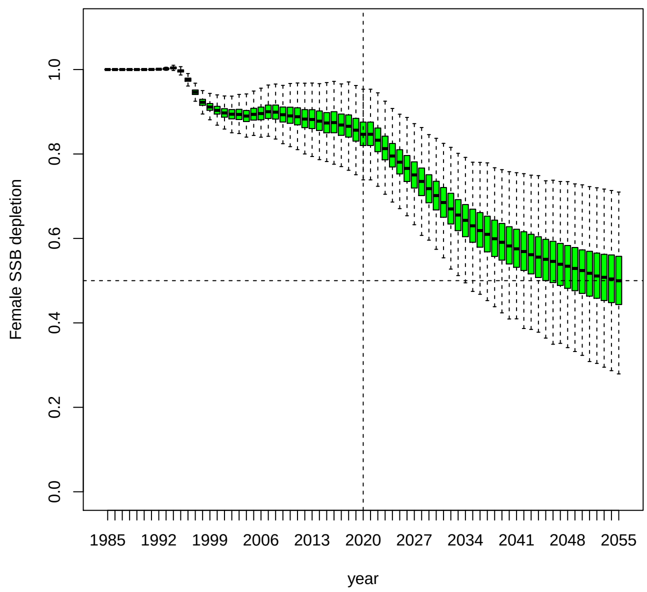

Figure 7.1: *Projection for one of the recommended TAC scenarios in Table 7.1.*

8 Discussion

In this paper we detail an update of the adopted new assessment model for the Patagonian toothfish fishery around Macquarie Island first detailed in [1]. In terms of the key management variable, female total SSB depletion has a median value of 0.85 with a 95% credible interval of 0.78–0.92, which is almost identical to the estimate from 2019, when the updated maturity curve was used. The fits to the various data sources (size, age given length, tags) are all acceptable and show no obvious model structure problems.

In terms of sensitivities the steepness alternatives and the tag shedding scenario made little meaningful difference. Only the higher $M = 0.155$ showed any real difference, with a lower estimate of depletion at 0.74 driven by changes in the spatial recruitment fraction and migration estimates for this scenario. Future development of the model would benefit from exploring a more nuanced spatial recruitment model, where deviations are spatiotemporal in nature not just estimated for the whole population and then divided between North and South by a time-independent multiplier. Such an approach would estimate not just recruitment variability but also temporal and spatial correlation, and hopefully do a better job at teasing out spatial recruitment patterns if they are there (which they appear to be at least in the tag data).

A range of recommended TACs were calculated (from 620t–665t) with an average of 644t - an 11% increase on the 2019 TAC driven by slightly higher average recruitment especially in the most recent years. The CCAMLR rule will likely continue to cause short-term variability in the TAC as the estimates move around over time, despite there being no meaningful changes in overall status from one assessment to the next. We feel it is time to begin considering alternative harvest control rules and undertaking a full management strategy evaluation (MSE) of the alternatives to try and construct a management procedure (MP) that can meet the relevant sustainability objectives with features we would rather see (e.g. lower TAC variability) relative to the current approach.

9 Acknowledgements

Many thanks to AFMA, CSIRO and industry for funding and assistance, and to Tim Lamb for all his help in getting the data together.

References

[1] Hillary, R. M. and Day, J. (2019) Proposed new assessment structure for Macquarie Island toothfish using data upto and including 2018. *SARAG 59*.

[2] Constable, A.J., Williams, R., Tuck, G.N., Lamb, T. and Morrison, S. (2001) Biology and growth of toothfish. *Pages 85–102 of* He, X. and Furlani, D.M. (eds), Ecologically sustainable development of the fishery for Patagonian toothfish (*Dissostichus eleginoides*) around Macquarie Island: population parameters, population assessment and ecological interactions. Fisheries Research and Development Council. Project 97/122.

[3] Goldsworthy, S. D., He, X., Furlani D., Moore, T., Rintoul, S., Koslow, T., Kloser, R., Williams, D., Lewis, M. and Lamb, T. (2001) Physical and biological oceanography. *Pages 28–58 of* He, X. and Furlani, D.M. (eds), Ecologically sustainable development of the fishery for Patagonian toothfish (*Dissostichus eleginoides*) around Macquarie Island: population parameters, population assessment and ecological interactions. Fisheries Research and Development Council. Project 97/122.

[4] Williams, R., Tuck, G.N., Constable, A.J., Lamb, T. (2002) Movement, growth and available abundance to the fishery of *Dissostichus eleginoides*. *CCAMLR Science* **9**: 33–48.

[5] Tuck, G.N., de la Mare, W.K., Hearn, W.S., Williams, R., Smith, A.D.M., He, X. and Constable, A. (2003) An exact time of release and recapture stock assessment model with an application to Macquarie Island Patagonian toothfish (*Dissostichus eleginoides*). *Fisheries Research* **63**: 179–191.

[6] de la Mare, W.K. and Williams, R. (1997) Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies. *SAFAG 97/6*.

[7] Tuck, G.N. and Lamb, T. (2009) Abundance estimation and TAC setting for Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island. *of* Tuck, G.N. (ed), Stock assessment and management strategy evaluation for sub-Antarctic fisheries: 2007 – 2009. Australian Fisheries Management Authority and CSIRO Marine and Atmospheric Research. 112 p.

[8] Tuck, G.N., Pribac, F. and Lamb, T. (2006) An integrated assessment of Patagonian toothfish (*Dissostichus eleginoides*) in the Aurora Trough region of Macquarie Island: 2006 update. *SARAG report*.

[9] Tuck, G.N. and Methot, R.D. (2006) Progress on the transition of the Macquarie Island Patagonian toothfish assessment to SS3. *SARAG report*.

[10] Fay, G., Tuck, G.N. and Lamb, T. (2009) Integrated stock assessment for the Aurora Trough Macquarie Island toothfish fishery, using data up to and including 2008/09. *of* Tuck, G.N. (ed), Stock assessment and management strategy evaluation for sub-Antarctic fisheries: 2007 – 2009. Australian Fisheries Management Authority and CSIRO Marine and Atmospheric Research. 112 p.

[11] Fay, G., Haddon, M. and Tuck, G.N. (2010) Revised base-case results for 2010 stock sssessment of Aurora Trough Macquarie Island toothfish, using data up to and including July 2009. *SARAG report*.

[12] Fay, G., Tuck, G.N. and Lamb, T. (2009) Integrated stock assessment for Macquarie Island toothfish using data up to and including July 2009. *SARAG report*.

[13] Fay, G. (2010) Evaluating a tag-recapture based integrated stock assessment model for Macquarie Island Patagonian toothfish 1: Testing tagging assumptions using Aurora Trough. *SARAG report*.

[14] Fay, G. (2011) Stock assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including June 2010. *SARAG report*.

[15] Fay, G., Tuck, G.N. and Haddon, M. (2011) Stock assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including June 2010 – addendum. *SARAG report*.

[16] Wayte, S.E. and Fay, G. (2012) Stock assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2011. *SARAG report*.

[17] Wayte, S.E. and Fay, G. (2012) Stock assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2012. *SARAG report*.

[18] Day, J., Wayte, S., Haddon, M. and Hillary, R. M. (2014) Stock assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2013. *SARAG report*.

[19] Day, J., Haddon, M. and Hillary, R. M. (2015) Stock assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2014. *SARAG report*.

[20] Day, J., Haddon, M. and Hillary, R. M. (2016) Stock assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2015. *SARAG report*.

[21] Day, J., Haddon, M. and Hillary, R. M. (2017) Stock assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2016. *SARAG report*.

[22] Hillary, R. M. and Day, J. (2019) TAC options given the revised stock assessment and maturity-at-length reelationship. *SARAG 60*.

[23] Hillary, R. M. and Day, J. (2017) Impact of spatial tagging rates for key estimates coming from the Macquarie Island toothfish assessment. *SARAG 56*.

[24] Day, J. and Hillary, R. M. (2019) Stock Assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2018. *SARAG 59*.

[25] Kristensen, K. *et al.* (2016) TMB: Automatic Differentiation and Laplace Approximation. *J. Stat. Soft.* **70**(5): 1–21.

[26] Monnahan, C. C. and Kristensen, K. (2018) No-U-turn sampling for fast Bayesian inference in ADMB and TMB: Introducing the adnuts and tmbstan R packages. *PLoS ONE*. **13**(5): e0197964.

[27] Hillary, R. M. (2011) A new method for estimating growth transition matrices. *Biometrics*. **67**: 76–85.

[28] Hillary, R. M. and Eveson, J. P. (2015) Length-based Brownie mark-recapture models:

Derivation and application to Indian Ocean skipjack tuna. *Fish. Res.* **163**: 141–151.

[29] Hillary, R. M., Day, J. and Haddon, M. (2015) Age-at-length or length-at-age for modelling the growth of Macquarie Island toothfish? *SARAG, Feb 2015*.

[30] Hillary, R. M. (2021) Updated biological relationships for 2021 stock assessment of Macquarie Island toothfish. *SARAG 63*.

[31] Hillary, R. M. (2019) Estimates of tag shedding in the Macquarie Island toothfish tagging program. *SARAG 59*.

CONTACT US

t 1300 363 400
+61 3 9545 2176

e csiroenquiries@csiro.au

w www.csiro.au