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Stock assessment and management strategy evaluation for sub-Antarctic fisheries: 2015-2016

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Cover photo: Adult and juvenile Patagonian toothfish.

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1 Non-technical summary

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Objectives

1. To provide the SARAG with updated information on the current status of Patagonian toothfish at Macquarie Island
2. 2. To provide the SARAG with, where deemed necessary, analyses that explore the robustness of the assessment using the MSE approach demonstrated in previous projects
3. To continue monitoring the stock through the tag-recapture program

OUTCOMES ACHIEVED

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 and growth modelling work have been and are being 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 increased both stakeholder's and manager's awareness of exploring the utility of setting and evaluating appropriate management strategies for the fishery, and aided in successfully moving the fishery to a multi-year TAC regime.

In the 2010/2011 season 478 tags were released in the Aurora trough and 507 on the Southern Macquarie ridge. For the Aurora trough releases none were recaptured after at least 10 days-at-liberty in the season of release, with 11 recaptured in the 2011/2012 season and 31 recaptured in the 2012/2013 season. For the Southern Macquarie ridge releases none were recaptured after at least 10 days-at-liberty in the season of release, 27 were recaptured in the 2011/2012 season and 42 recaptured in the 2012/2013 season.

In the 2011/2012 season 303 tags were released in the Aurora trough, and 116 and 497 tags were released on the Northern and Southern Macquarie ridges, respectively. For the Aurora trough releases none were recaptured after 10 days-at-liberty in the season of release, with 10 recaptures in the 2012/2013 season. For the Northern and Southern Macquarie ridge releases none were recaptured after 10 days-at-liberty in the season of release, with 1 recapture of Northern releases in the 2012/2013 season and 9 recaptures of Southern releases in the 2012/2013 season.

In the 2012/2013 season 310 tags were released in the Aurora trough, and 56 and 307 tags were released on the Northern and Southern Macquarie ridges, respectively. In terms of within-season recaptures of fish with over 10 days-at-liberty 1 of the Aurora trough releases and 5 of the Southern Macquarie ridge releases were recaptured.

In the 2013/2014 season 531 tags were released in the Aurora trough, and 36 and 251 tags were released on the Northern and Southern Macquarie ridges, respectively. In terms of within-season recaptures of fish with over 10 days-at-liberty 20 of the Aurora trough releases, 2 of the Northern Macquarie ridge releases, and 2 of the Southern Macquarie ridge releases were recaptured.

In 2015/2016 season 295 fish were released in the Aurora trough, with 499 and 33 tags released on the Northern and Southern Macquarie Ridges, respectively. Only 9 tags, from the Aurora trough releases, were recaptured in the Aurora trough within-season and after 10 days-at-liberty.

The previous project [1] continued the assessment refinement work and MSE work, focussing on appropriate growth models and assumptions made about the tag dynamics in the current assessment. Appendices 1 and 2 detail the assessment documents for 2015 (data up to August 2014) and 2016 (data up to August 2015), respectively. While the spatial structure of the assessments is now fixed, these two assessments also demonstrate the ongoing data-weighting and estimation parameter fine tuning that has occurred in consultation with the SARAG. Overall, the assessments for 2015 and 2016 reveal a consistent story in relation to overall trends and fits to the various data sources. In particular, the best estimates of spawning stock depletion (the key management variable) seem well estimated and have stayed the same: around 0.67-0.69.

One issue that has arisen is estimates of male growth parameters (specifically k and L_∞) increasingly diverging from external estimates. Specifically, k getting smaller and L_∞ getting bigger. Appendix 3 details a paper which explored whether this was driven by the differences in estimation model used for growth outside of and inside of the assessment. This paper obtained consistent estimates of growth using the age-length data regardless of the estimation method, when undertaken outside of the assessment. Subsequent analyses seemed to suggest data other than the age-length data, most likely the tagging data, are driving this effect in the assessment model. While the changing estimates do not affect the assessment results or resultant TAC recommendations, further work will look at how we estimate growth robustly within the assessment in future.

A major change to the fishery that occurred within this project time-frame was the decision to move to multi-year TACs (specifically two-year TACs). Appendix 4 details an information paper submitted to the SARAG about how this might be achieved, using both the stock assessment and Management Procedure frameworks as the two plausible alternatives.

2 Acknowledgements

All authors wish to thank the science, management and industry members of the sub-Antarctic resource assessment group (SARAG) for their contributions to the work presented in this report. Malcolm Haddon (CSIRO) is thanked for his advice and encouragement throughout the project.

2.1 Author listing

The authors listed below contributed to one or more of the papers in the Appendices:

- **Rich Hillary**: CSIRO Oceans and Atmosphere
- **Jemery Day**: CSIRO Oceans and Atmosphere
- **Malcolm Haddon**: CSIRO Oceans and Atmosphere

3 Background

Bottom-set longline and trawl fisheries for the Patagonian toothfish (*Dissostichus eleginoides*) have developed in the waters of several of the Southern Ocean's sub-Antarctic islands. Trawl fisheries for toothfish are now well established within Australian Commonwealth waters around Heard Island and McDonald Island (HIMI) and Macquarie Island. The fishery off Macquarie Island began in November 1994 with one trawl vessel, the Austral Leader, licensed to fish the Macquarie Island toothfish stock. Two major fishing grounds were discovered by trawling: Aurora Trough, and the Macquarie Ridge Northern Trawl ground. The majority of the Macquarie Ridge is untrawlable ground, but potentially accessible by longline gear.

Since 1994 over 11,500 tagged fish have been released in waters surrounding Macquarie Island, with 1,800 recaptured. As a key element in the monitoring of stock status, tagging is critically important to the assessment of Macquarie Island toothfish. All vessels carry AFMA observers who are tasked with collecting comprehensive catch effort and biological data and tagging toothfish, and AAD maintains a database containing all of this data as well as length at age data from otoliths aged between 1996 and 2011. A tag-based assessment and, more recently, an integrated assessment (with a tagging component) have been developed to assess the stock and have been successfully utilised to set TACs in the Aurora Trough for a number of years. In addition, a Management Strategy Evaluation (MSE) has been used to assist the assessment of management strategies for the fishery. With poor capture rates outside of the Aurora Trough region, and thus very few recaptures, the assessment and general management had focussed on the Aurora Trough fishery. However, with industry keen to explore and expand the fishery into untrawlable ground, in 2007 a single longline vessel with strict environmental requirements was allowed to fish. The vessel captured 79 tonnes of toothfish from several areas both to the north and south of the island, including large and spawning fish in new southern grounds. The average mass of fish was 9.5kg, compared to an average of 2.5kg from the trawl fishery earlier in the year. Smaller fish were also captured by longlining, indicating that the Aurora Trough ground is not the sole area supporting juvenile fish. The longline trial continued in 2008 and 2009, each time with on-going success in terms of catches, catch rates and avoiding interactions with birds.

The integrated stock assessment, using the Stock Synthesis software package, has been in place for the past few years, as there is also an MSE framework within which the assessment and other related processes can tested. While several issues relating to aspects of spatial structure have been explored previously, there a still a number of important issues requiring further study:

The ongoing developmental nature of the fishery, as well as potential changes to our understanding of the wider stock structure of the species in the region, will require the spatial structure of the fishery and population models to be assessed and refined going forward. Key model settings relating to data weighting and precision require ongoing exploration given the relatively new status of the integrated assessment. The importance of the key biological parameters (such as certain growth parameters, natural mortality for example) that are not estimated within the assessment, and what can be done to obtain the required data, or what methods of analysis are required, to improve our understanding of these parameters and processes.

The existing integrated assessment structure, as well as the MSE framework, are well placed to answer these key questions and problems as they arise. This project will address these questions by updating the integrated stock assessment, as well as the MSE work both to assess the importance of these future challenges and how we might best deal with them. The project also provides funding for the continued tagging, and related support, of Macquarie Island Patagonian toothfish.

4 Need

The introduction of longlining to the previously trawl-only fishery has provided an ability to set gear in untrawlable ground and led to the discovery of fish outside of the traditional trawl grounds. This has included a diverse size-range of fish and for the first time, spawning fish. The inclusion of this new gear-type, with its greater spatial range and ability to target more mature fish led to the development of improved assessment and management strategy evaluation software under previous projects. There was - and continues to be - a key need for the ongoing assessment of the population through the tag-recapture program, the provision of the latest fishery statistics (eg annual age and length data) and the updating of the stock assessment. Tagging is a vital element of the stock assessment and this proposal includes funding for the purchase and related infrastructure required to deploy approximately 1,000 tags per year. The intention was to maintain the time series of data collected from the fishery and to also maintain the tagging program, as this is the main source of information pertaining to absolute abundance which drives the stock assessment.

This project provided a greater understanding of the status and dynamics of the Patagonian toothfish population surrounding Macquarie Island. The continuing assessment of the status of the population was identified as a priority research area in the sub-Antarctic fisheries strategic research plan. This proposal sought and obtained funding to build upon the existing stock assessment and management strategy framework and continued the stock assessment process for a further two years.

5 Objectives

1. To provide the SARAG with updated information on the current status of Patagonian toothfish at Macquarie Island
2. To provide the SARAG with, where deemed necessary, analyses that explore the robustness of the assessment using the MSE approach demonstrated in previous projects
3. To continue monitoring the stock through the tag-recapture program

6 Benefits/Management Outcomes

The industry fishing for Patagonian toothfish around Macquarie Island, and Heard Island and McDonald Islands will directly benefit from this project, as will those entrusted with the management of these fisheries. Utilisation and conservation benefits will be realised through the development of appropriate harvest strategies that will facilitate the maintenance of harvested populations and marine ecosystems.

Additional benefits of the project could flow to all of the fisheries managed by AFMA as the software developed and many of the conclusions arising from the study are readily transferable to other fisheries. It should be possible to tailor the assessment framework developed as part of this project to other harvested species and regions.

7 Conclusions

Meeting the project objectives:

Objective 1

"To provide the SARAG with updated information on the current status of Patagonian toothfish"

Appendices 1 and 2 detail the stock assessments submitted to the SARAG for the Macquarie Island toothfish fishery in 2015 and 2016, respectively. The stock assessment work forms the primary basis for deciding on the current status of the stock and setting the management advice for this fishery, via the SARAG and South MAC groups. Project scientists attended and contributed to the SARAG meetings all throughout the project lifetime including those meetings focussed more on the Heard and McDonald Island assessment work.

Objective 2

"To provide the SARAG with, where deemed necessary, analyses that explore the robustness of the assessment using the MSE approach demonstrated in previous projects"

Appendix 3 provided the SARAG with a detailed paper exploring the fundamental methodological differences between traditional estimation of growth relationships outside the stock assessment and how it is performed within the stock assessment at present. The paper clearly demonstrated that, when applying the traditional length-at-age versus the more contemporary age-at-length approach used in the assessment *outside* of the assessment, very consistent growth parameters are obtained. The apparent recent divergence of external estimates and those in the assessment are therefore not methodological in nature, but appear to be driven by information from the tagging data rather than the age-length data. The paper provided suggestions for how to maintain a future balance between robust and unbiased growth parameter estimates, and ensuring the associated uncertainty therein is suitably propagated through the assessment model.

Appendix 4 was an information paper submitted to the SARAG detailing plausible options for moving the advice provision process for this fishery to a multi-year TAC framework. Both the currently employed stock assessment approach and the fully-evaluated Management Procedure approach were outlined as candidates. The paper helped stimulate the discussion and decisions that lead to the adoption of a two-year TAC stock assessment driven approach.

Objective 3

"To continue monitoring the stock through the tag-recapture program "

CSIRO project staff and the Australian Antarctic Division (AAD), who oversee the collection and storage of the data from the observers, continue to work together to filter and generate the tagging data for use in the assessments.

References

[1] Hillary, R. M., Day, J., and Haddon, M. (2013) Stock assessment and management strategy evaluation for sub-Antarctic fisheries: 2013–2014. Australian Fisheries Management Authority and CSIRO Oceans & Atmosphere Flagship, Hobart. 148pp.

Appendix 1

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Stock Assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2014

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Prepared for SARAG 51, Hobart, 24 February 2015
Document updated: 3 March 2015

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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 2014. 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 makes use of the Stock Synthesis assessment software v3.11b (Methot & Wetzel, 2013), and fits to data obtained from the tag-recapture program since 1995, to length composition information for the years 1994–2014, and to age-at-length data obtained from aged otoliths (1997–2013). It is an update of the final version of the 2014 assessment (Day *et al.*, 2014). 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, and Northern and Southern Macquarie Ridge longlines). Fits to the length composition data are generally good. The fits to the age-at-length data appear to be reasonable, although larger fish are predicted to be older than they are observed to be (the model is growing older fish too slowly). The model fits the tag-recapture data well, with good accord between the total number of expected recaptures and those observed.

The outcomes from the assessment are very similar to those in the 2014 assessment. The base case current female spawning biomass estimate is 69% of unfished (68% in 2014). The trend in spawning biomass from 1990–2014 is almost identical to that estimated last year, but the estimated magnitude of spawning biomass is about 9% higher in each year, and about 7% higher than the spawning biomass series from the 2013 assessment. The three new recruitment estimates are above average (2004-2006).

The point estimate for the 2014 stock size in the northern area is estimated to be about six times larger than that in the south (female spawning biomass 2,008t and 322t respectively). The northern area is also estimated to be considerably less depleted than the southern area (78% and 40% respectively).

Catch levels that satisfy the CCAMLR control rule have been calculated under ten alternative assumptions regarding how the catches will be allocated to fleet and region. The projected 2015/16 catch from these scenarios ranges from 460t to 530t.

The new 2014 length frequency data include an additional 2216 fish in 62 hauls for Aurora Trough Longline, 2570 fish in 70 hauls for Northern Macquarie Ridge Longline and 528 fish in 17 hauls for Southern Macquarie Ridge Longline. An additional 299 fish from the 2013 catch were aged and these were included as age-at length data for this assessment, with 200 females, 97 males and two unsexed newly aged fish.

Updates to the tag recapture data include 55, five and 16 additional tag recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 76 tag recaptures in 2014, all from fish tagged in previous years. Of these 76 recaptures, none involved recaptures of fish tagged in a different area. In addition there were 295, 499 and 33 new tag releases in 2014, with these releases respectively in the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge.

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 (Constable *et al.*, 2001; Goldsworthy *et al.*, 2001).

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 (Williams *et al.*, 2002; Tuck *et al.*, 2003).

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 1500km 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.

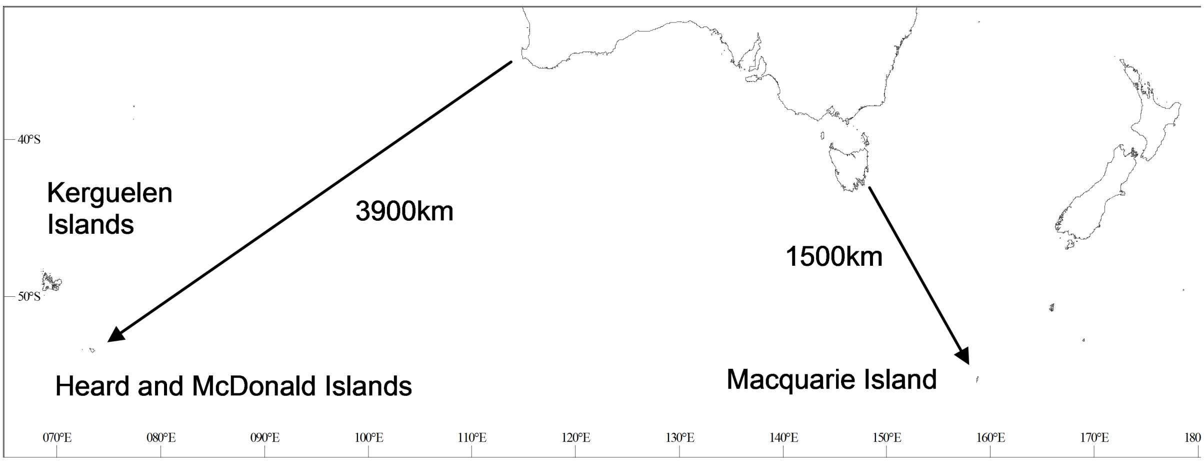

Figure 2.1: The location of Macquarie Island (54° 30'S, 158° 57'E) and Heard Island and McDonald Islands (53 °06'S, 73 °30'E) relative to New Zealand and Australia.

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 354t quota. However, the assessment in the following year suggested that the stock had fallen marginally below the 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 140t in 2010/11 (Table 2.1).

For the Macquarie Ridge sector, the annual trawl TAC has reduced steadily since the 1500t TAC of 1998. However, the TACs since 1999 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.

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

Fishing season	Administrative period	Total Allowable Catch	
	(longline season: 1 May–31 Aug)	Aurora Trough	Macquarie Ridge[a]
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[b]	600 (1000)
99/00	1 Jan 2000 – 31 Dec 2000	40[b]	510 (1000)
00/01	1 Jan 2001 – 31 Dec 2001	40[b]	420 (1000)
01/02	1 Jan 2002 – 31 Dec 2002	40[b]	242 (782)
02/03	1 Jan 2003 – 30 Jun 2003	40[b]	205 (665)
03/04	1 July 2003 – 30 Jun 2004	354	174 (441)
04/05	1 July 2004 – 30 Jun 2005	60[b]	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[c]
08/09	1 July 2008 – 30 Jun 2009	312	150[c]
09/10	1 July 2009 – 14 Apr 2010	60[c]	150[c]
10/11	15 Apr 2010 – 14 Apr 2011	140	150[c]
11/12	15 Apr 2011 – 14 Apr 2012	150	360
12/13	15 Apr 2012 – 30 Apr 2013	455[d]	
13/14	1 May 2013 – 30 Apr 2014	415[d]	
14/15	1 May 2014 – 30 Apr 2015	410[d]	

[a] tonnage shown in brackets would have been triggered if trawl catch rates reached 10 t/km^2 over 3 consecutive fishing days
[b] research TAC to enable tag-based stock assessments
[c] TACs for longline trial
[d] TAC set for entire Macquarie Island region

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 recaptures of fish tagged in the trawl fishery. Since 2009 the catch has been taken entirely by longline.

From 2012/13, a single TAC has been set for the whole of the Macquarie Island region. The 2014/15 TAC was set at 410t, which was a figure arrived at from five of the catch scenarios from the 2014 assessment. This was very close the the actual catch in 2014 (Table 3.1). The distribution of the catch in 2014 was very different to previous years, with a reduction of over 100t in the catch from South Macquarie Ridge and a longline catch from North Macquarie Ridge which is 200t higher than any previous longline catch in this region.

2.3 Previous assessments

Prior to 2010, TAC determination for the Macquarie Island Patagonian toothfish stock had been based on stock assessment using the tag-recapture model developed by de la Mare and Williams (1997), and modifications described in Tuck *et al.* (2003). 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 (Tuck & Lamb, 2009). In 2004, a new model that expanded upon the traditional tag-based model was introduced (Tuck *et al.*, 2006). 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 (Tuck & Methot, 2008; Fay *et al.*, 2009b). 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 (Fay *et al.*, 2010).

The 2010 Aurora Trough assessment base case model estimated current 2010/11 female spawning biomass to be 2,004t or 54% of unfished spawning biomass (Fay *et al.*, 2010). 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 (Fay *et al.*, 2009b; Fay *et al.*, 2009a). 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 (Fay, 2011; Fay *et al.*, 2011). 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 (Wayte & Fay, 2012). The 2013 assessment estimated the 2013/14 female spawning biomass for the whole of Macquarie Island to be 69% of unfished (Wayte & Fay, 2013) and the 2014 assessment estimated the 2014/15 female spawning biomass for the whole of Macquarie Island to be 68% of unfished (Day *et al.*, 2014).

2.4 Modifications to the previous assessment

The following data have been added to the assessment:

1. 2014 catches
2. 2014 length compositions
3. 2014 tag recaptures
4. 2013 age-at-length compositions

3 Data

The data available for model-fitting purposes include length composition data from the fishery (1994/95–2014/15), conditional age-at-length data (1996–2000, 2002, 2003, 2005–2010, 2013), and the results of the tag-release-recapture program, begun during the 1995/96 season.

3.1 Catch data

Stock Synthesis 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).

Longline operations in 2014 caught 143t in the Aurora Trough and 270t in the northern and southern Macquarie Ridge areas.

3.2 Length frequency data

Samples of the length composition of the catch were available for all fishing seasons (1994/95 through 2013/14). Each annual length composition is based on the measurement of several hundreds (thousands) of fish (Table 3.2). 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 input sample sizes for the individual length compositions were set at the number of shots sampled for the trawl data, and 10% of the number of fish sampled for the longline data.

Disaggregation of the length data by sex is possible, and Stock Synthesis allows for the inclusion of composition data from both sexed data and data for which the sex is unknown, with the expectation that

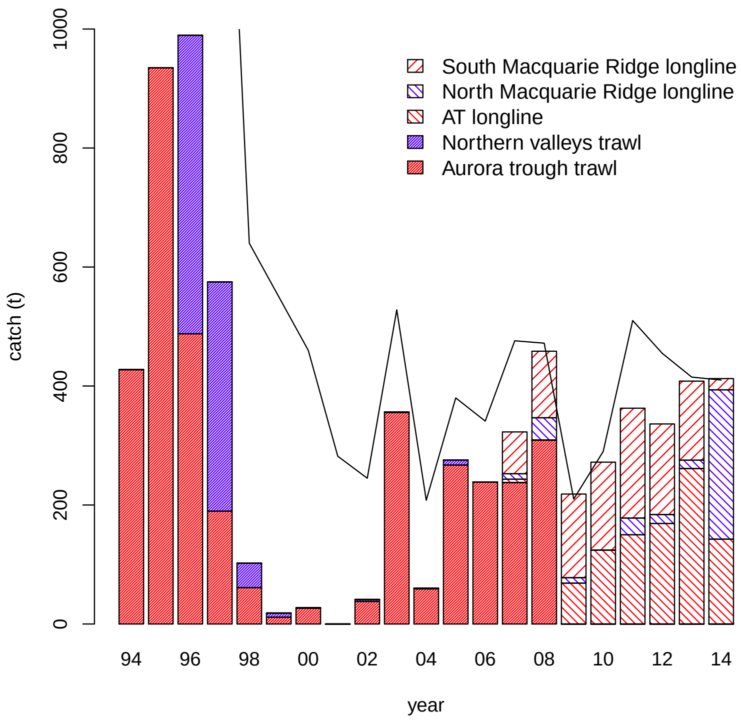

Figure 3.1: Catch history and total TAC by fishing year, with catches stacked by fleet and the grey line representing the combined TAC (with TACs summed for Aurora Trough and Macquarie Ridge from 1996–2011).

Table 3.1: Time series of Patagonian toothfish catches (t) by fishing year and fleet, including total catch over all fleets and 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	934.7	0				935	
96/97	487.8	501.8				990	1750
97/98	189.6	385.2				575	1700
98/99	61.1	41.2				102	640
99/00	11.3	7.2				18	550
00/01	26.4	0.7				27	460
01/02	0.0	0.0				0	282
02/03	37.9	3.3				41	245
03/04	355.4	0.8				356	528
04/05	59.0	1.1				60	208
05/06	267.1	8.6				276	380
06/07	238.5	0.0				239	341
07/08	237.8	0.0	5.4	9.2	70.3	323	476
08/09	308.8	0.0	0	37.5	111.9	458	462
09/10			68.7	9.1	140.6	218	210
10/11			124.0	0	148.0	272	290
11/12			149.9	28.2	184.6	363	510
12/13			169.0	15.0	152.2	336	455
13/14			261.3	14.0	132.9	408	415
14/15			142.6	251.0	18.9	413	410

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

Fleet	Season	# shots	# fish	mean # per shot
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	3367	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
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
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
SMR longline	07/08	28	1589	57
	08/09	44	1750	40
	09/10	50	1886	38
	10/11	34	1545	45
	11/12	96	3388	35
	12/13	126	4080	32
	13/14	94	3107	33
	14/15	17	528	31

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 the unsexed fish sampled for length are quite different from the male and female portions of the length composition for some years (Fay, 2010). 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 (Table 3.3). New ageing data from 2013 were added this year. The input sample sizes for the age-at-length data were set at 10% of the number of otoliths measured.

3.3.1 Conditional age-at-length data

The age data are input as the raw age-at-length data, rather than age compositions generated from applying age-length keys to the catch-at-length compositions. The input compositions are therefore the distribution of ages obtained from samples in each length bin, for those years for which data are available (Table 3.3). Age data that came from tag recaptured fish are not included in the assessment analyses. Where an otolith has been read more than once (e.g. for ageing error estimation), the first age reading is used in the assessment.

3.3.2 Ageing error

Multiple reads of otoliths from Macquarie Island Patagonian toothfish with which to quantify the degree of ageing error have recently become available, but the ageing error matrix is yet to be calculated from these data. As a result, as with the 2010 Aurora Trough assessment, the ageing error matrix calculated for Patagonian toothfish at HIMI (Candy & Welsford, 2009) was used to provide estimates of ageing error, in order to calculate the degree to which a fish of true age i is aged to be j. Stock Synthesis enters ageing error, for each true age, by assuming a normal distribution of observed ages around a mean age and standard deviation for the observations. The ageing error matrix (Table 3.4) assumes ageing was unbiased (i.e. mean observed age was the true age). There is evidence however, that for older fish, the observed age is less than the true age (Candy & Welsford, 2009).

3.4 Tag recapture data

Between the 1995/96 and 2014/15 fishing seasons, 14,826 Patagonian toothfish were tagged at Macquarie Island, of which 2,072 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).

Table 3.3: 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
	f			0
	m			0
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	u			0
	f		31	31
	m		32	32
2003	u			0
	f	138		138
	m	79	2	81
2005	u	1		1
	f	107	26	133
	m	56	37	93
2006	u			0
	f	11		11
	m	9		9
2007	u			0
	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
2011	u			0
	f			0
	m			0
2012	u			0
	f			0
	m			0
2013	u	2		2
	f	175	25	200
	m	83	14	97
total		3027	729	3756

Table 3.4: Ageing error matrix. Shown are the mean and standard deviation of observed ages given a true age read. Values were calculated using the ageing error matrix for Heard and MacDonald Island toothfish as given in Candy and Welsford (2009).

true age	mean age	s.d.	true age	mean age	s.d.	true age	mean age	s.d.
1	1.5	0.82	41	41.5	3.11	81	81.5	9.28
2	2.5	0.83	42	42.5	3.22	82	82.5	9.48
3	3.5	0.84	43	43.5	3.33	83	83.5	9.69
4	4.5	0.85	44	44.5	3.44	84	84.5	9.89
5	5.5	0.87	45	45.5	3.55	85	85.5	10.11
6	6.5	0.89	46	46.5	3.67	86	86.5	10.32
7	7.5	0.91	47	47.5	3.79	87	87.5	10.53
8	8.5	0.94	48	48.5	3.91	88	88.5	10.75
9	9.5	0.97	49	49.5	4.03	89	89.5	10.97
10	10.5	1.00	50	50.5	4.16	90	90.5	11.2
11	11.5	1.03	51	51.5	4.29	91	91.5	11.42
12	12.5	1.06	52	52.5	4.42	92	92.5	11.65
13	13.5	1.1	53	53.5	4.55	93	93.5	11.88
14	14.5	1.14	54	54.5	4.69	94	94.5	12.11
15	15.5	1.18	55	55.5	4.83	95	95.5	12.35
16	16.5	1.22	56	56.5	4.97	96	96.5	12.59
17	17.5	1.27	57	57.5	5.11	97	97.5	12.83
18	18.5	1.32	58	58.5	5.26	98	98.5	13.07
19	19.5	1.37	59	59.5	5.41	99	99.5	13.31
20	20.5	1.42	60	60.5	5.56	100	100.5	13.56
21	21.5	1.48	61	61.5	5.71	101	101.5	13.81
22	22.5	1.54	62	62.5	5.87	102	102.5	14.06
23	23.5	1.60	63	63.5	6.02	103	103.5	14.32
24	24.5	1.66	64	64.5	6.18	104	104.5	14.57
25	25.5	1.73	65	65.5	6.35	105	105.5	14.83
26	26.5	1.80	66	66.5	6.51	106	106.5	15.09
27	27.5	1.87	67	67.5	6.68	107	107.5	15.36
28	28.5	1.94	68	68.5	6.85	108	108.5	15.63
29	29.5	2.02	69	69.5	7.02	109	109.5	15.89
30	30.5	2.09	70	70.5	7.19	110	110.5	16.17
31	31.5	2.17	71	71.5	7.37	111	111.5	16.44
32	32.5	2.26	72	72.5	7.55	112	112.5	16.72
33	33.5	2.34	73	73.5	7.73	113	113.5	17
34	34.5	2.43	74	74.5	7.92	114	114.5	17.28
35	35.5	2.52	75	75.5	8.10	115	115.5	17.56
36	36.5	2.61	76	76.5	8.29	116	116.5	17.85
37	37.5	2.71	77	77.5	8.49	117	117.5	18.13
38	38.5	2.80	78	78.5	8.68	118	118.5	18.42
39	39.5	2.90	79	79.5	8.88	119	119.5	18.72
40	40.5	3.01	80	80.5	9.07	120	120.5	19.01

Table 3.5: Numbers of tagged fish released and recaptured following at least 10 days at liberty, by release fleet and season.

Release season	Release fleet	# rel	Mean length	# recaptures after 10 days at liberty 95/96	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
95/96	AT tr	448	69	20	57	28	3		1	1	1							1				
95/96	NV tr	4	57																			
96/97	AT tr	472	59		24	42	7		2		9	1	3		1	1						
96/97	NV tr	537	61		1	53	5	1			2											
97/98	AT tr	583	60			80	18	3	4	5	21	4	15	1		2	3	1	2	2		
97/98	NV tr	537	70			60	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	315	58				7															
99/00	AT tr	693	65					1	3	1	35	6	12	1	3	6	2	5	1	5		
99/00	NV tr	302	58					3												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	492	63							1	60	8	29	6	15	24	2	3	10	1	6	2
02/03	NV tr	17	57																1			
03/04	AT tr	596	69								26	9	23	8	4	13	2	3	2	1	1	
03/04	NV tr	61	53								1		3									
04/05	AT tr	556	69										46	7	16	43	4	4	6	3	4	1
04/05	NV tr	263	56										2		1	1						1
05/06	AT tr	522	71										2	25	18	27	2	5	4	4	3	1
05/06	NV tr	289	60										1							1		2
06/07	AT tr	435	59											3	26	13		1			4	
07/08	AT tr	296	65												23	31	2		2	1	3	1
07/08	NMR LL	26	78														1		3	2		
07/08	SMR LL	189	81													15	4	3	6	6	4	
08/09	AT tr	588	71													31	2	6	12	10	19	6
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
09/10	AT LL	299	85															27	13	9	13	4
09/10	NMR LL	60	85																5	5		
09/10	SMR LL	395	79															26	25	8	20	2
10/11	AT LL	478	87																11	31	45	6
10/11	SMR LL	507	91																27	42	34	5
11/12	AT LL	303	72																1	10	37	7
11/12	NMR LL	116	83																	1	2	1
11/12	SMR LL	497	78																	9	25	4
12/13	AT LL	310	78																	1	37	12
12/13	NMR LL	56	89																			
12/13	SMR LL	307	87																	5	20	
13/14	AT LL	531	75																		2	9
13/14	NMR LL	36	81																			
13/14	SMR LL	251	81																		2	9
14/15	AT LL	295	72																			
14/15	NMR LL	499	79																			
14/15	SMR LL	33	81																			

Table 3.6: Total numbers of tag recaptures by fleet of release (rows) and recapture (columns), for fish at liberty for greater than 10 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	1061	1	139	1	31
NV trawl	10	143	1	3	4
AT longline	0	0	260	0	15
NMR longline	0	0	1	19	11
SMR longline	1	0	50	4	317

Under the Stock Synthesis framework, tag released fish are assigned to tag groups, with all fish within a tag group (which could be all fish released in a season) assumed to consist of a single age class. As the length range of fish chosen for tagging approximates the length range in the catch, assuming all fish are the same age, while computationally convenient, clearly does not represent the way in which fish are tagged. The method used to assign ages to tag releases within the assessment model can therefore be expected to impact the results. Alternative methods of specifying the age at release for the tagged fish were evaluated using simulation testing (Fay, 2010), with the results suggesting that the best option in terms of being able to estimate biomass is to distribute the annual number of releases into a small number of tag groups per year, with assigned ages to these tag groups based on the length composition of the catch. This method was shown to be superior to fixing the age at release for all releases within a year, and also to assigning a unique age to each tag release based on the individual release lengths.

Annual releases were therefore split into five groups. The ages assigned to the tag groups were determined by comparing the median length of the appropriate quantile of the length composition with the mean length at age from the assumed growth curve. As the majority of tagged fish are not sexed, the growth curve obtained from data for both sexes (Constable *et al.*, 2001) was used to convert the release lengths to ages. It is clear that such an approach is an approximation; however the majority of growth curves estimated for Macquarie Island toothfish predict very similar mean length at age for the lengths at which most fish are tagged.

Recaptures of tagged fish are assumed to be clumped in space rather than be purely random (i.e. negative binomial vs. Poisson distributed) conditional on the catch and expected number of tags available to the fishery, with over-dispersion parameters (an index of aggregation) estimated for each release area. The available recapture data consists of the numbers of recaptured fish each year by each release group (Table 3.5; for brevity, recapture data are aggregated by season). To allow for full mixing of the tagged fish with the untagged population, recaptures within the year of release were removed from the assessment release data if the recapture occurred within 10 days of release (c.f. Tuck and Lamb (2009)).

Accounting for clumping in the tag returns requires the inclusion of an over-dispersion parameter. This term relates to the variability of the observed data, which is greater than that expected if the tags were recaptured randomly. Including over-dispersion in the tag recaptures is implemented by assuming that the recaptures are distributed according to a negative binomial instead of Poisson. The degree of over-dispersion relative to the Poisson is handled by an additional parameter for each tag group, which potentially results in an additional 150 parameters to be estimated. Estimating over-dispersion parameters allows for clumping in the tag recapture data, or less of a penalty on the model fit given more (or less) recaptures than predicted from a tag group in a given year. The 2010 Aurora Trough assessment demonstrated that there was not sufficient information to estimate this parameter by tag group, and the value for the over-dispersion parameter was fixed at the median estimate for those tag groups where there appeared sufficient information for estimation (base case value of 1.9, Fay *et al.* (2010)). Expanding further on this approach, with a modification to Stock Synthesis for the subsequent assessments, over-dispersion parameters can be shared among tag groups, and so a single value for the parameter for each release area was estimated when fitting the model, rather than pre-specifying a fixed value.

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. 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 (2009)), 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.

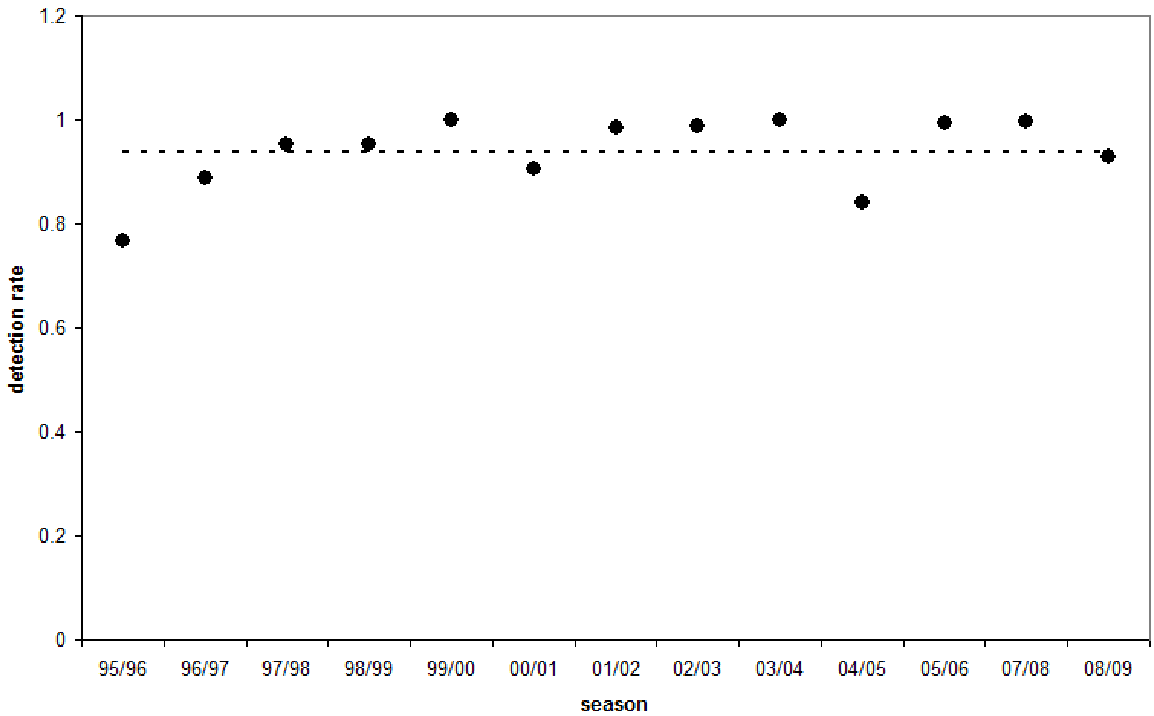

Figure 3.2: Estimated tag detection rate (points) by fishing season (Tuck and Lamb 2009). Dotted line corresponds to the mean detection rate (0.938) over the time series.

3.5 New and updated data summary

Updated data in this assessment include revisions to historical data. For length compositions, the historical revisions include minor adjustments to the numbers of hauls and fish measured in Aurora Trough Trawl, namely one more fish measured in 2003 and one less haul in 2007. The new 2014 length frequency data include an additional 2216 fish in 62 hauls for Aurora Trough Longline, 2570 fish in 70 hauls for Northern Macquarie Ridge Longline and 528 fish in 17 hauls for Southern Macquarie Ridge Longline.

There were minor changes to the historical age-at-length data, with the removal of 18 age-at length records from 1998 to 2009, with all of these records from fish caught in the south. These removals include one female fish in 1998, three female and three male fish in 2003, three female fish in 2005, one male fish in 2007, one female fish in 2008 and one female and five male fish in 2009. An additional 299 fish from the 2013 catch were aged and these were included as age-at length data for this assessment, with 200 females, 97 males and two unsexed newly aged fish.

Updates to the tag recapture information only came from the new 2014 data, with no revisions to historical tag recapture data. This included 55, five and 16 additional tag recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 76 tag recaptures in 2014, all from fish tagged in previous years. Of these 76 recaptures, none involved recaptures of fish tagged in a different area. All southern released fish were recaptured in the south and all northern released fish were recaptured in the north.

In 2014, there were 11 fish tagged by Aurora Trough Trawl that were recaptured, 10 in Aurora Trough and one in Southern Macquarie Ridge. Three fished tagged by Northern Valleys Trawl were recaptured by in the Northern Macquarie Ridge in 2014. There were 38 fish previously tagged by Aurora Trough Longline recaptured in 2014, with 37 of these recaptured in the same area as release, with the remaining one recapture in the Southern Macquarie Ridge. There were an additional two recaptures longline tagged fish from Northern Macquarie Ridge, both recaptured in the same area as release. Twenty two fish previously tagged by longline in Southern Macquarie Ridge were recaptured in 2014 with 8 of these recaptured in Aurora Trough and the remaining 14 recaptured in the Southern Macquarie Ridge.

In addition there were 295, 499 and 33 new tag releases in 2014, with these releases respectively in the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge.

4 Biology

4.1 Growth

Growth of Patagonian toothfish is assumed to follow the von Bertalanffy growth function, with sex-specific parameter values estimated within the model, except for the L_∞ parameter for females which was fixed at 165 cm. The sensitivity of fixing this at 195 cm, as estimated by Constable *et al.* (2001), is examined. Estimating the growth within the assessment model is often preferable if there are sufficient data to do so, as this allows the impacts of length-specific selectivity to be directly accounted for in a consistent fashion with respect to the rest of the assessment. However it needs to be remembered that there is often a strong correlation between the growth and other key fixed (M, steepness) and estimated (SSB_0, selectivity) parameters. The now sizeable amount of ageing data available suggests that this approach should be acceptable. The true number of age samples used in the assessment is complex, and not the same as the number of age samples, but intimately related to the effective sample sizes used in the assessment for the fits to the length and age data.

The values for the parameters of the growth curve used to assign ages to tag releases are given in Table 4.1. These were estimated by Constable *et al.* (2001) from data for both sexes.

Values for the parameters of the weight-at-length relationship are fixed at those in Table 4.2, using param-

Table 4.1: Values for growth parameters.

von Bertalanffy growth parameters	Constable *et al.*(2001)			Base case estimate	
	Both sexes	female	male	female	male
L_∞ (cm)	185.5	195.1	154.2	165 (fixed)	202.2
k (yr^{-1})	0.042	0.038	0.054	0.054	0.036
t_0	-0.781	-1.184	-0.434	-0.32	-1.41
CV of length at age	0.13	0.12	0.14	0.16	0.14

eter values estimated by Constable *et al.* (2001) using data for both sexes.

Table 4.2: Values for biological parameters.

Parameter	Value
Rate of natural mortality, M (yr^{-1})	0.13
Weight at length, wt (kg) $= aL^b$ (cm)	
a	4.4×10^{-6}
b	3.14
length at 50 % maturity (cm)	139.6
length at 95 % maturity (cm)	185.8

4.2 Mortality

Although there is no direct information on natural mortality of Macquarie Island toothfish, the known longevity of the species would indicate that natural mortality is less than M =0.2 yr^{-1} (Constable *et al.*, 2001). The base case analysis uses a fixed value of 0.13 yr^{-1} as in previous assessments, based on an estimate of mortality from Heard Island Patagonian toothfish. M is assumed to be the same for both sexes and constant over age and time. The impacts of using the recent value estimated for the Heard Island Patagonian toothfish (M =0.155 yr^{-1}), and of estimating the value for M are also considered.

4.3 Fecundity and maturity

Base case estimates of length at maturity are fixed at values estimated from data from the longline fishing trial at Macquarie Island (Williams, 2011). Estimated length at 50% maturity for females under this approach was 139.6 cm with a length at 95% maturity of 185.8 cm (Table 4.2).

Without direct information on fecundity or egg production, mature female weight is used as spawning biomass.

5 Assessment methodology

5.1 Population model

The assessment is based on a length-age-structured model of fish population dynamics. It 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 (with the division being the latitude of 54.25 ° south) – are incorporated into the model, with movement of fish between areas, and recruitment to both areas. Differences in the size structure available to the different fleets (e.g. trawl vs. Ridge longlining) within areas are accounted for via the estimated selectivity patterns for each fleet.

A two-sex model is assumed, although the rate of natural mortality is assumed to be the same for both males and females. The population dynamics model, and the statistical approach used in the fitting of the model to the various types of data, are given fully in the technical description of the Stock Synthesis assessment software (Methot, 2010) and are not reproduced here.

5.2 Fleets

The model designates five fishing fleets that exploit the toothfish resource. These are:

1. Aurora Trough trawl,
2. Northern Valleys trawl,
3. Aurora Trough longline,
4. Northern Macquarie Ridge longline and
5. Southern Macquarie Ridge longline

Catches were allocated to the northern and southern Macquarie Ridge fleets with the division being a latitude of 54.25 ° south, which although arbitrary, represents a geographical break in the location of fishing operations, and has been used previously to separate catches (Fay *et al.*, 2009a). Small amounts of catch by trawl outside of the Aurora Trough and Northern Valleys areas during the early years of the fishery were allocated to the appropriate trawl fleet with the same geographical division as for the longline. The Aurora Trough trawl and longline and southern Macquarie Ridge longline fleets are assigned to the southern area in the model, and the Northern Valleys trawl and northern Macquarie Ridge fleets are assigned to the northern area.

5.3 Selectivity

The selectivity pattern for each fleet was assumed to be a function of length, estimated separately within the model, with the selectivity pattern for all fleets assumed to be time-invariant. The function chosen allowed for a dome-shaped selectivity pattern (that is, increasing selectivity with increasing length, and then decreasing selectivity at further increases) given certain values for the four estimated parameters (for each fleet) for the trawl fleets and Aurora Trough longline, but did not impose this pattern on the model. Logistic selectivity was used for the northern and southern Macquarie Ridge longline fleets.

5.4 Stock and recruitment

Recruitment to the toothfish stock is assumed on average to follow a Beverton-Holt stock-recruit relationship (SRR), with the number of fish of age zero a function of the female spawning biomass in the same year. The parameterisation is the average recruitment at unfished equilibrium (R_0), and the steepness parameter h which relates to the ability of the stock to maintain recruitment at low stock size (Mace & Doonan, 1988). R_0 is estimated during the model-fitting process, but h is fixed at 0.75. Annual recruitment deviations from the SRR were estimated for the period 1985–2006, with these deviations taken as being log-normally distributed around the SRR with a standard deviation, σ_R of 0.27. The range of years chosen for recruitment estimation reflects the expectation that cohort effects from these years should be apparent in the data, and whether the asymptotic standard error of the estimate for these parameters is below the variance expected given the value of σ_R. Values for the fixed stock-recruit parameters are the same as those used by Tuck *et al.* (2006) and Fay *et al.* (2010) in previous integrated assessments for Macquarie Island toothfish.

The proportional allocation of new recruits to the two areas is estimated within the model. This proportion is considered fixed through time, therefore both the northern and southern areas experience the same trend and relative changes in recruitment dynamics over time.

5.5 Initial conditions

The population is assumed to be in unfished equilibrium, with an equilibrium age structure, in 1975. Estimated female spawning biomass in 1975 is therefore used as the estimate of unfished spawning biomass, SB_0.

5.6 Movement

Movement of fish among areas is allowed, with the extent of movement (annual movement rates) being estimated during the model fitting process. Movement is modelled as being age-independent.

5.7 Parameters and parameter estimation

Statistical fitting of the population dynamics model to the available data is achieved by minimising an objective function consisting of several likelihood components, reflecting the different types of data input (lengths, age-at-length, and tag recaptures), and also a penalty function constraining the spread of annual recruitment deviations around the stock-recruit relationship.

The base case version of the assessment model utilised the values described above for biological parameters, and those described in Section 3.4 for the tag detection rate, tagging age, and mixing time. Input sample sizes for the individual length compositions for the trawl data were the number of shots sampled, and for the longline data, 10% of the number of fish sampled. The input sample sizes for the age at length data were also set at 10% of the number of otoliths measured.

The estimated parameters of the base case model were: average recruitment before fishing, growth curve parameters for both sexes, annual recruitment deviations from 1985–2006, parameters determining the functional form of the selectivity pattern, the tag-recapture over-dispersion parameter, a parameter for the allocation of recruits to areas, and movement parameters. Additional parameters were estimated in some of the sensitivity analyses.

The results of the estimation procedure provide a prediction of stock status prior to the 2014/2015 fishing season. Key quantities of interest output by the model include time series of female spawning biomass, the current value of this spawning biomass relative to that prior to fishing, and the levels of fishing mortality experienced by the stock. Also calculated are various combinations of predicted catches by fleet for the 2014/15 fishing season that satisfy the CCAMLR control rule (Section 5.9).

5.7.1 Contributions to the likelihood function

The data have four separate contributions to the objective function when fitting the model, from the length compositions, the age-at-length, number of tag recaptures, and allocation of tag recaptures by fleet. The length and age-at-length compositions by year, fleet, and sex (for the age data) are assumed to be samples from multinomial distributions given input sample sizes. For each tag group, the total number of recaptures by year is assumed to be distributed negative binomially. The proportional allocation of these tag recaptures by fleet is then considered to be multinomial.

5.7.2 Penalties

The objective function contains a penalty based on the distribution of recruitment deviations around the stock-recruit relationship, which is assumed to be log-normal with a standard deviation, σ_R which as described above in Section 5.4 is fixed at a value of 0.27.

5.8 Quantification of uncertainty

Variances for the estimates of the model parameters and derived quantities of interest can be determined either by using asymptotic standard errors, or by applying Markov-Chain Monte Carlo (MCMC) methods (Hastings, 1970; Gelman *et al.*, 1995; Gilks *et al.*, 1996). The Metropolis-Hastings algorithm was used to generate a sample of 1,000 parameter vectors from the joint posterior density function for the base case. This sampling process implicitly considers uncertainty in all dimensions of parameter space, and accounts for correlation among model parameters. The samples on which inference is based were generated by running 1,500,000 cycles of the MCMC algorithm, discarding the first 500,000 as a burn-in period and selecting every 1,000th parameter vector thereafter.

5.9 2014/2015 catch determination under the CCAMLR control rule

Values for the 2014/15 catch were calculated under the CCAMLR control rule. The calculated 2014/15 catch was the maximum constant catch applied over a 35 year projection period that satisfied the following criteria:

- the probability that female spawning biomass will fall below 20% of the pre-exploitation level over the 35 year projection period does not exceed 0.1; and
- the median escapement for the fishery of the female spawning biomass shall not be less than 50% over a 35 year projection.

Stochastic projections were conducted using the sample from the posterior distribution. The stochastic projections therefore incorporated both parameter uncertainty and uncertainty in future recruitment events, in the calculation of the 2014/15 catch, given implementation of the CCAMLR control rule.

The catch levels that satisfy the control rule can be expected to change given alternative assumptions regarding how the catches will be allocated to fleet and region. The 2014/15 catch levels were calculated for ten different assumptions of how the catch would be distributed between the longline fleets.

6 Results and discussion

6.1 Bridging analysis

Updated recent data were added sequentially to the 2014 base case model to show the effect on the key model outputs such as female spawning biomass and recruitment. During the 2014 assessment, revisions were made to historical data to remove non-randomly selected length data. This resulted in some changes to the data prior to 2013. In the current assessment, the changes to historical data were so minor and the impact of these changes was so small that these changes are not shown in the list of sequential changes to update the new data. The addition of an extra year of age-at-length data from 2013 and additional length data in 2014, enabled three additional years of recruitment to be estimated in the new assessment. In the 2014 assessment, age-at-length data was only available up until 2010.

The sequential changes to update the base case model were:

1. update historical data,
2. add 2014 catch,
3. add 2014 length compositions,
4. add 2013 age-at-length data,
5. add 2014 tag data,
6. estimate 3 additional years of recruitment, up until 2006,
7. iteratively re-weight the likelihood contributions from the length and age compositions and recruitment variability σ_R.

The addition of 2014 catch, length composition and tag data and 2013 age-at-length data led to an upwards translation of the spawning biomass trajectory (Figure 6.1) and generally higher recruitment estimates (Figure 6.2).

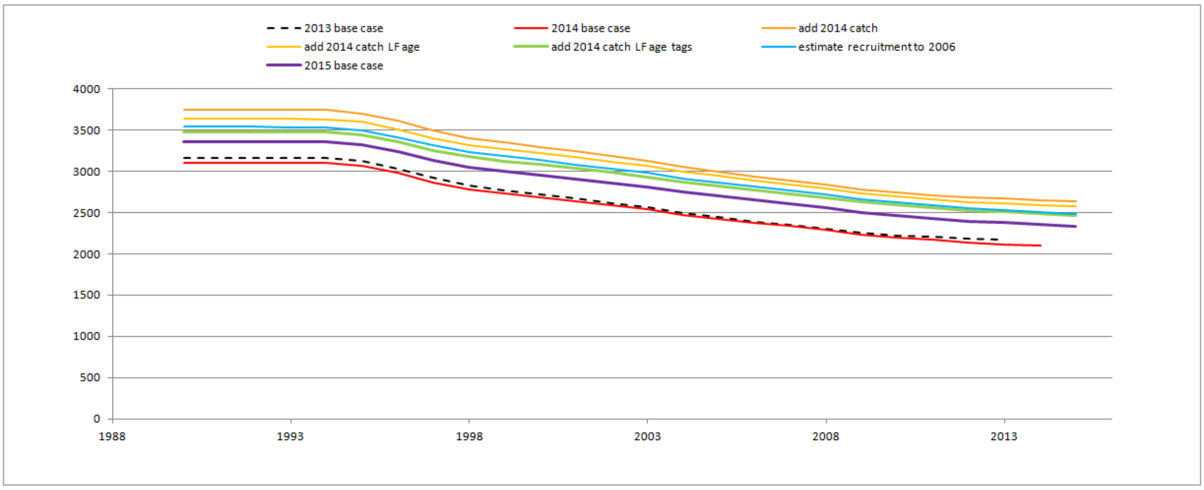

Figure 6.1: Effect on the female spawning biomass trend of sequential updates with the most recent data.

Given the additional age-at-length data available to this assessment, it was possible to estimate three more years of recruitment, through to 2006 and all of these new recruitment estimates for 2004, 2005 and 2006 had positive recruitment deviations, indicating that the estimated recruitment in these years is above average. Addition of the 2014 tag data and estimating recruitment to 2006 resulted in further minor changes to the spawning biomass trajectory (Figure 6.1) and even smaller changes to the estimated recruitment series (Figure 6.2).

The model with the revised historical data and all the new 2014 data added was then iteratively re-weighted by adjusting the input sample sizes for length and age data and by matching the input and output values of σ_R. This iterative procedure is routinely used in a number of stock assessments in other fisheries (Francis, 2011). Iterative re-weighting balances the influence of all data sets according to how statistically informative they are. This iteratively re-weighting procedure was first used in the 2014 assessment and the same procedure was adopted this year. Iteratively re-weighting resulted in a downwards translation of the spawning biomass series, moving this series closer to the spawning biomass series from the 2014 base case.

The 2015 base case model is thus the iteratively re-weighted model with 2014 data added, with recruitment now estimated to 2006, and is indicated by the purple lines in Figure 6.1 and Figure 6.2.

6.2 Diagnostics

6.2.1 Length composition data

The fits to the length composition data are generally good (Figure 6.3 and Figure 6.4), although the residual pattern from the fits to the 2014 length frequencies from Northern Macquarie Ridge is different to the earlier years, possibly related to the much larger then usual catch from Northern Macquarie Ridge. There is a similar pattern for the Aurora Trough longline, with apparently higher proportions of smaller fish in the 2014 sample. For the length composition data, the re-weighted observed sample sizes, relating to either number of shots or number of fish depending on the fleet, plotted against the effective sample size shows that the length composition data is well balanced (Figure 6.5).

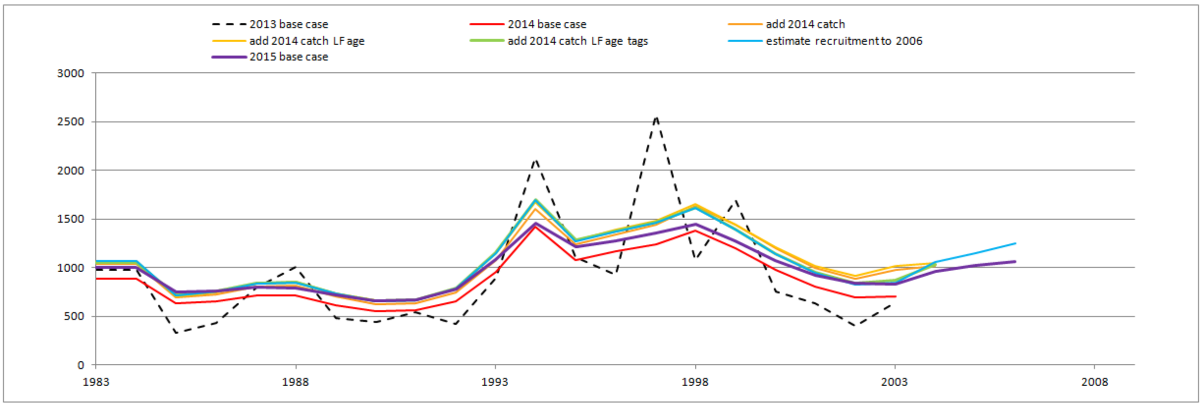

Figure 6.2: Effect on the recruitment estimates of sequential updates with the most recent data.

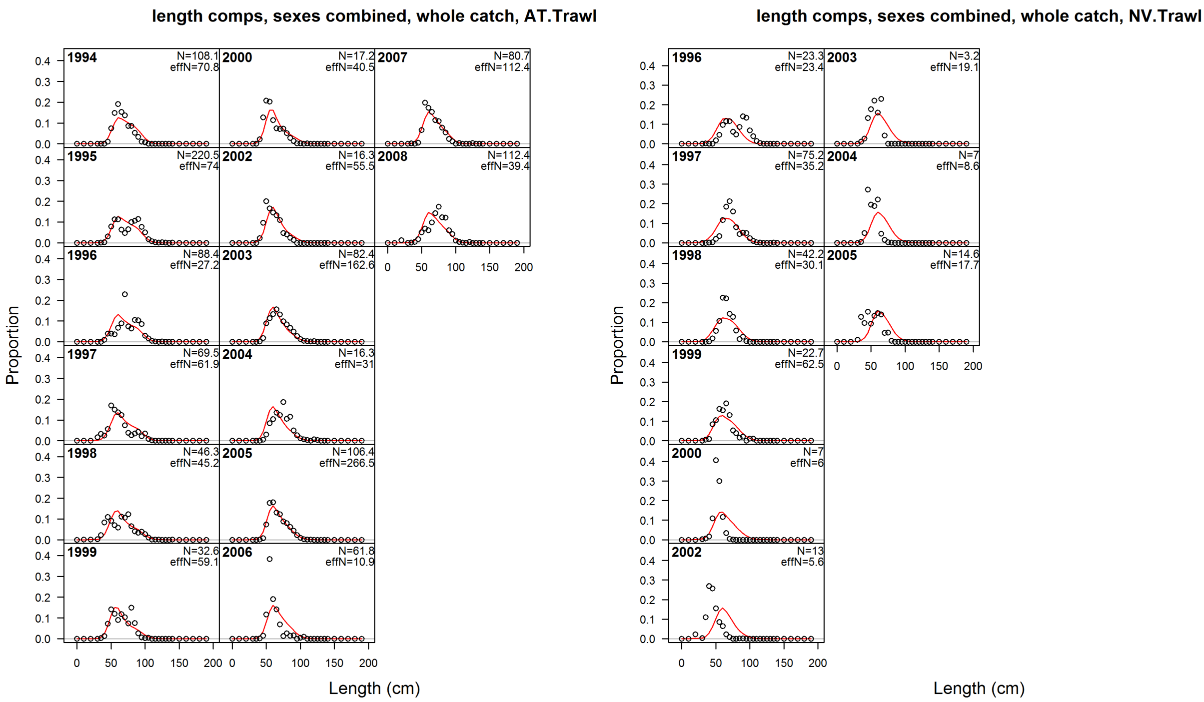

Figure 6.3: Fits to the length composition data for the trawl fleets.

Model fits to the Northern Valley trawl data appear to be unable to capture the variability in the data (Figure 6.3), however the effective sample sizes of much of these data are low (Figure 6.5).

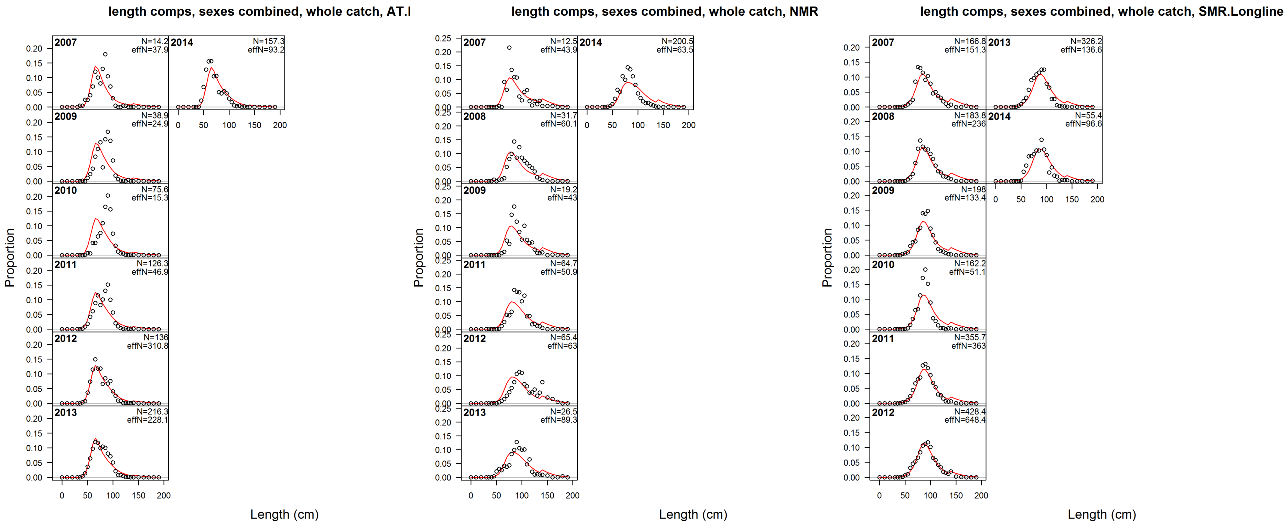

Figure 6.4: Fits to the length composition data for the longline fleets.

Inter-annual variability in the areas and depths fished within fleets likely contribute to some of the variability and inconsistency among data. The lengths of toothfish available to the fishery at Macquarie Island vary considerably by month and depth, and so inconsistencies in the length data from year to year can be expected as a result of spatial and temporal differences in fishing activity by season.

6.2.2 Age-at-length data

The fits to the age-at-length data for the base case are reasonable (Figure 6.6 and 6.7) although larger fish are predicted to be older than they are observed to be (the model is growing older fish too slowly).

6.2.3 Tag recapture data

The base case scenario is able to capture the general pattern of tag recaptures over time very well (Figure 6.8). The numbers of tag recaptures estimated in the last nine years (with the exception of 2008 and 2013), however, were above the number observed, suggesting that the tag data alone may imply a larger population than the integrated model with all the data for these years. However, against this intuition, when the weight given to the tag data likelihood is doubled in a sensitivity test the biomass estimates become lower (Table 6.1), implying that the relationships between these variables requires further attention. This over-estimation of the number of recaptures for these years is also revealed in the residual plots (Figure 6.8), especially for 2011 and 2012. The lack of recaptures for 2006 and 2007 may be related to the length composition for these years, as there were few larger fish caught.

6.3 Base case results

6.3.1 Selectivity

Fitting the assessment model to the length data allows for the selectivity pattern of the fleets to be estimated. The estimated selectivity patterns for the trawl fleets are highly dome-shaped (Figure 6.9). As

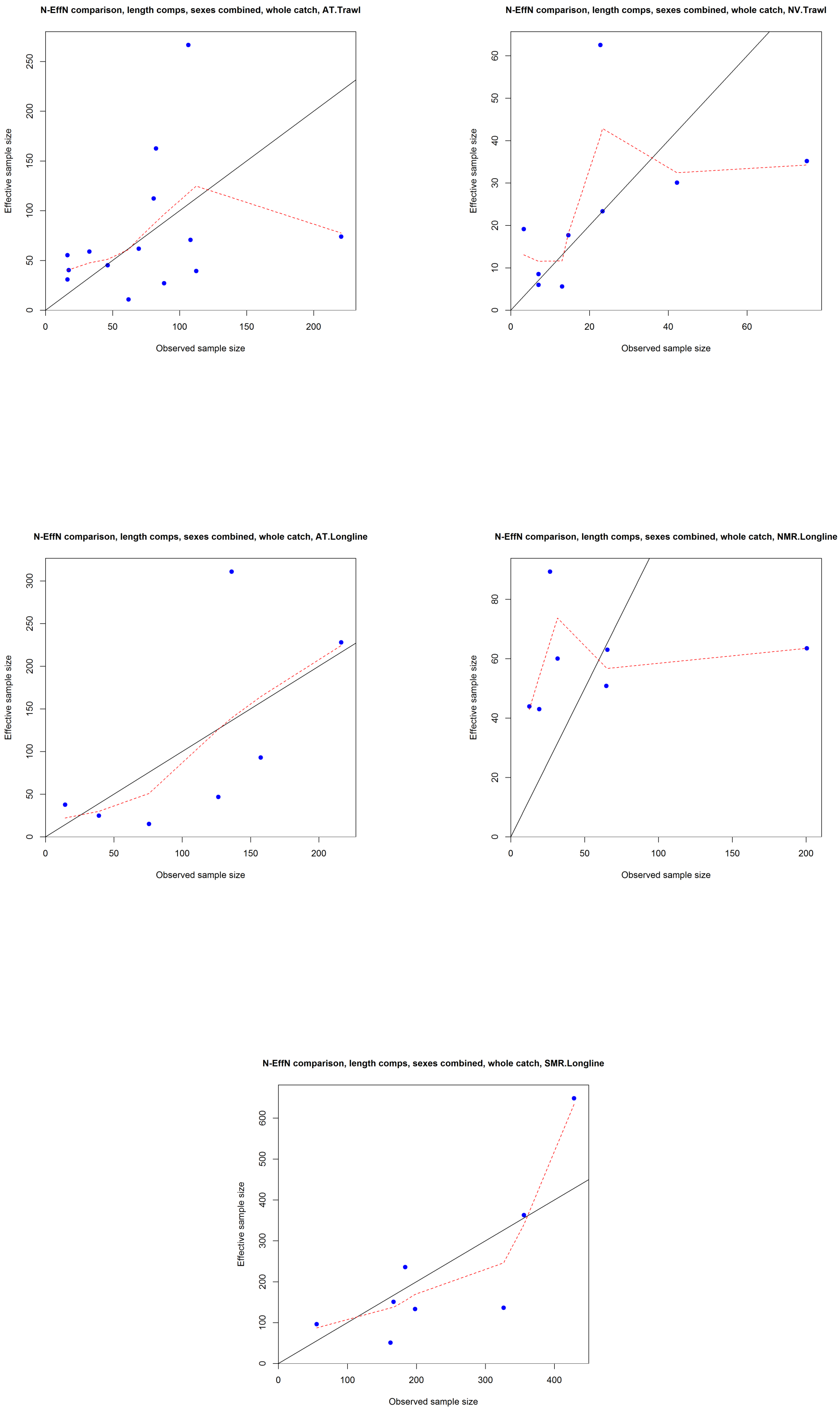

Figure 6.5: Input vs. effective sample size for the length composition data.

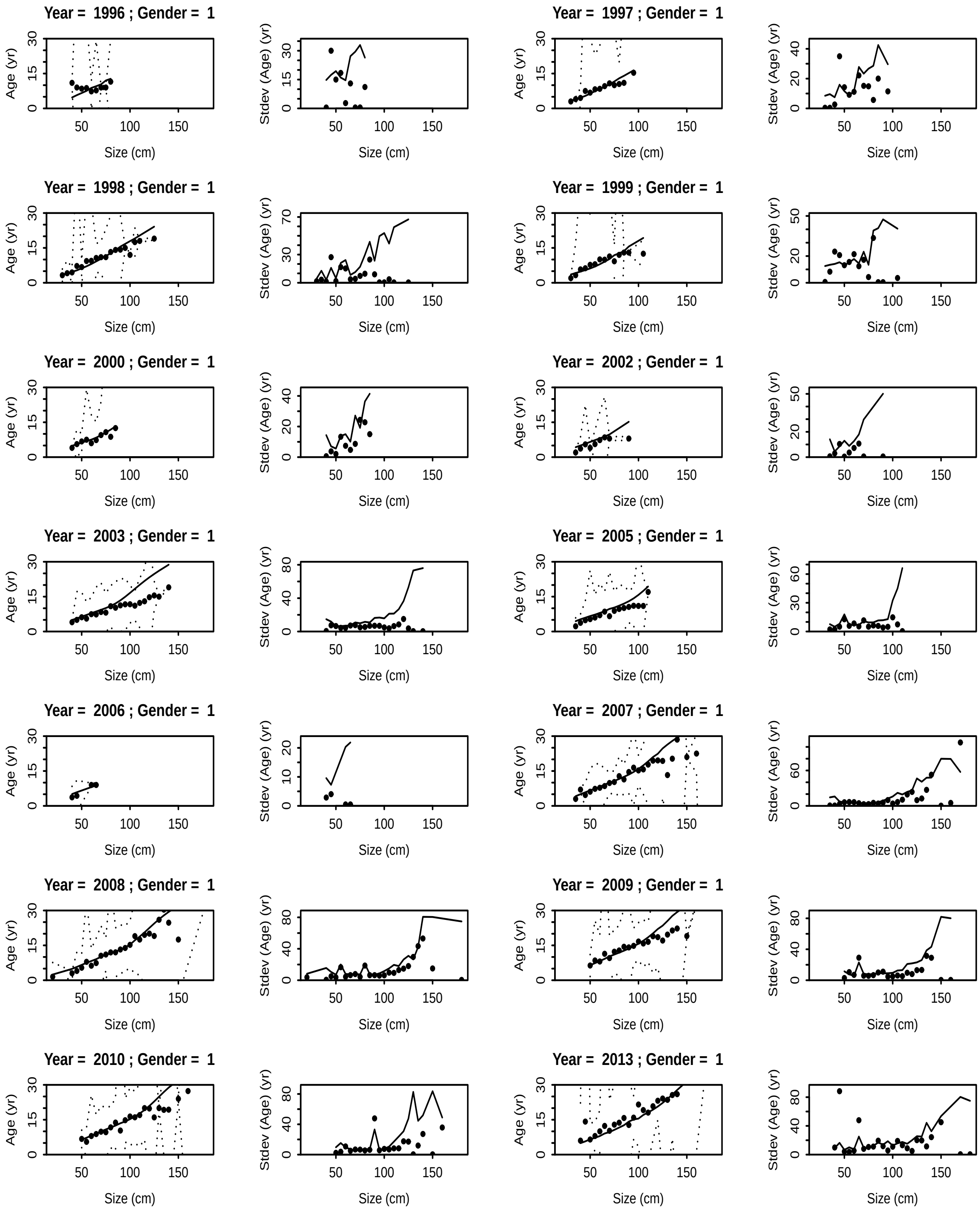

Figure 6.6: Diagnostic plots for the fits to the female (Gender = 1) conditional age-at-length data. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed and predicted) and the 90% CIs based on the chi-square distribution. The dots are the data, the solid lines the expected values, and the dotted lines the 90% CIs.

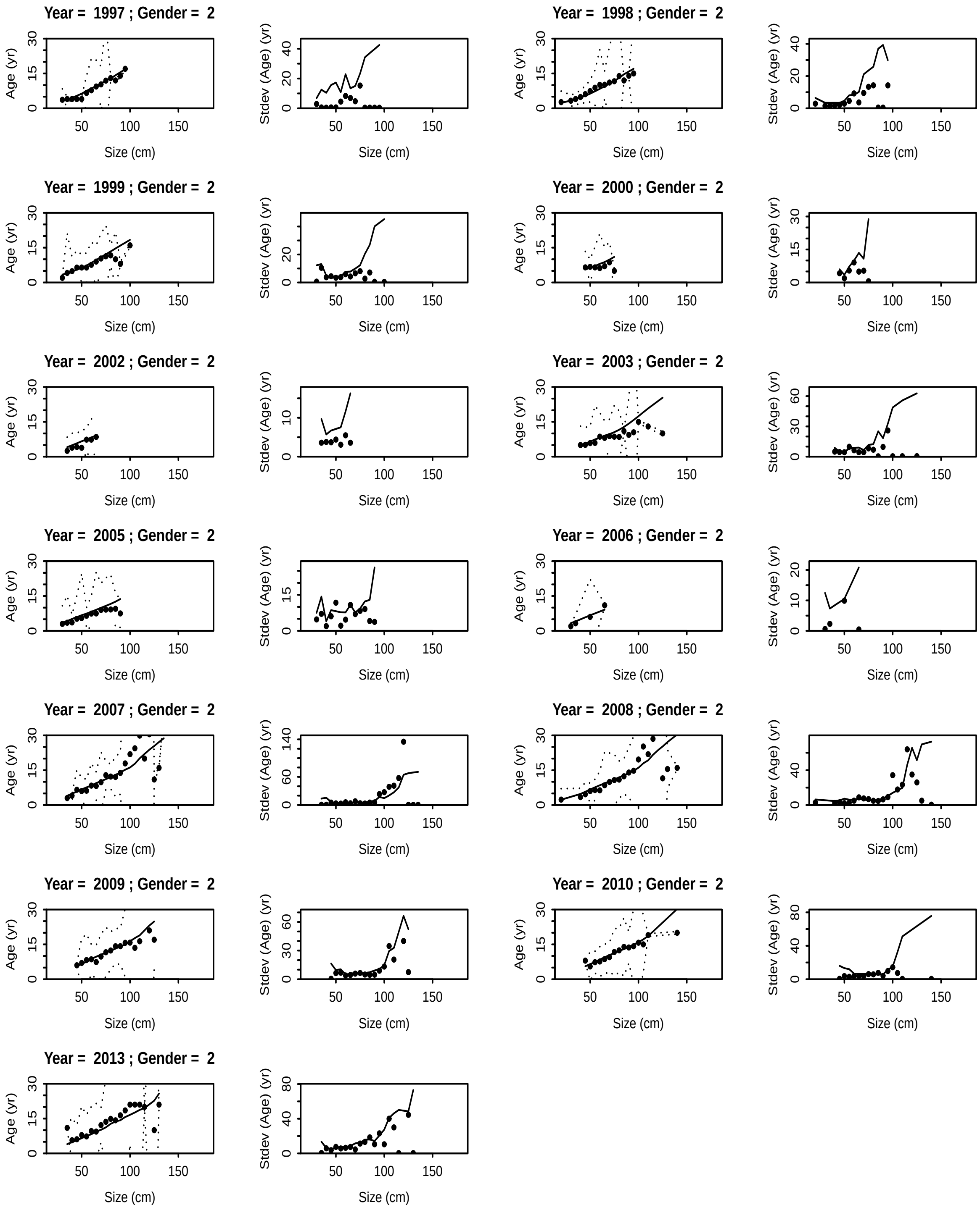

Figure 6.7: Diagnostic plots for the fits to the male (Gender = 2) conditional age-at-length data. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed and predicted) and the 90% CIs based on the chi-square distribution. The dots are the data, the solid lines the expected values, and the dotted lines the 90% CIs.

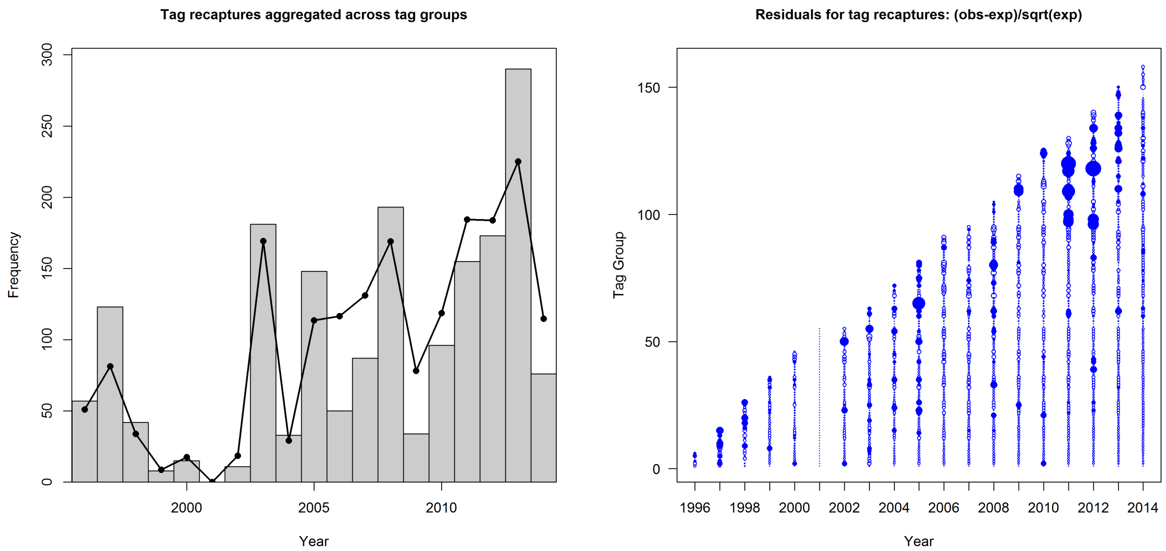

Figure 6.8: Summary of the base case fits to the tag-recapture data. Left-hand panel shows the summed observed (bars) and expected (line) recaptures over years. The right-hand panel shows the residuals by tag group and year (solid blue indicates more recaptures observed than expected).

agreed at RAG meetings in 2011, logistic selectivity has been imposed on the Macquarie Ridge longline fleets, in order to lead to an intrinsically conservative assessment. As with the 2014 assessment the estimated selectivity for the Aurora trough longline fleet is logistic. This is in contrast to the 2013 assessment, where the estimated selectivity for the Aurora trough longline fleet was dome-shaped. Unlike the Macquarie Ridge longline fleets, this ability to catch larger fish is not imposed on the Aurora trough longline fleet selectivity. The estimated selectivity for the longline fleets indicates capture of larger fish than the trawl fishery, as evidenced by the length data, with larger fish still being selected by the longline fleets on the Macquarie Ridge.

6.3.2 Growth

The estimated growth parameters are shown in Table 4.1, and the estimated growth curves in Figure 6.10. The estimated growth curve for males has changed in this assessment, suggesting that males grow larger than females. However, this conclusion should be treated with some caution as there are limited numbers of old fish, so the growth estimates for old fish should be treated with some caution.

6.3.3 Recruitment

The recruitment pattern (Figure 6.11) shows larger year classes estimated in the mid and late 1990s. Variability in length at age, ageing error, and error in the assignment of ages to tagged fish will all contribute to a lack of precision in pinpointing the timing of recruitment events, however the general signal remains. Note that the recruitment pattern is similar to that in the 2014 assessment. Note that the last three estimated recruitment events all have positive recruitment deviations; these three recruitment events are all slightly larger than the expected recruitment if taken directly from the stock-recruitment curve.

The proportion of new recruits allocated to each area is very uncertain, with the 95% confidence interval of the proportion recruiting to the northern area ranging from 25–57% , with a mean of 41% (Figure 6.12). This parameter is estimated as being fixed in time. While the uncertainty in the estimated proportion of recruits to the northern area is similar to the uncertainty estimated in the last two assessments, the estimated proportion recruiting in the north has increased since the 2014 assessment. This estimate may have been affected by the increased catch in the north in 2014.

6.3.4 Movement

The estimation of movement rates is somewhat uncertain. In the base case, the movement rate from south to north is estimated to be between 3% and 7% per annum, with a lower rate of between 0.6% and 1.4% per annum for north-to-south movement (Figure 6.13). More exploration is needed of the interaction of movement parameters with the other components of the model. The model estimates a high movement rate of fish from south to north in order to reconcile the apparently conflicting results of low recaptures of NV trawl-tagged fish and the recapture of southern tagged fish in the north (i.e. if the stock is large enough for the recapture rate of NV trawl-tagged fish to have been low, then there must be movement from south to north in order for any of the southern tagged fish to have been caught at all in the north).

6.3.5 Biomass and fishing mortality estimates

Table 6.1 gives the point estimates for the current and unfished female spawning biomass for the base case model and the models investigated in the sensitivity analyses.

The base case current spawning biomass estimate is 69% of unfished female spawning biomass (Table 6.1), which is the same as the estimate from the 2014 assessment.

The time series of female spawning biomass has declined steadily since the start of the fishery (Figure 6.14), and has stabilised at around 70% of unfished in the last three years. As the biomass levels by area are somewhat mediated by uncertain estimates of recruitment allocation and movement, it is unsurprising that the spawning biomass trend for the spatial model is estimated with large uncertainty.

The point estimate for the 2015 stock size in the northern area is estimated to be about six times larger

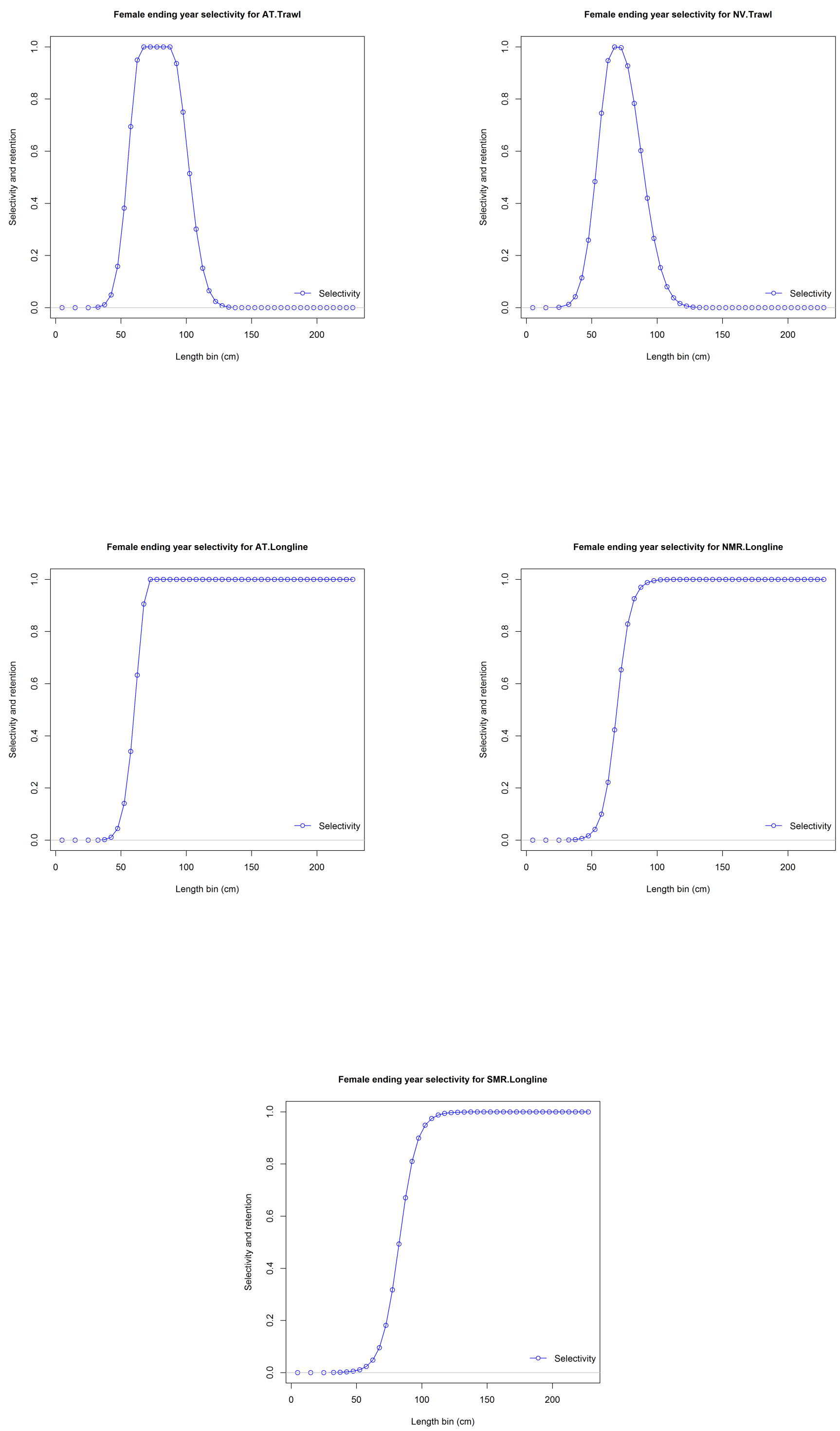

Figure 6.9: Base case estimates of selectivity at length by fleet.

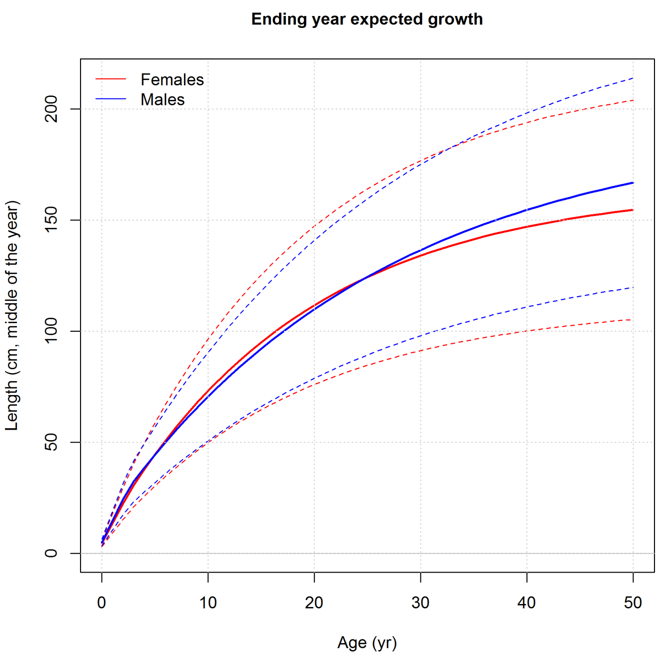

Figure 6.10: The estimated growth curves.

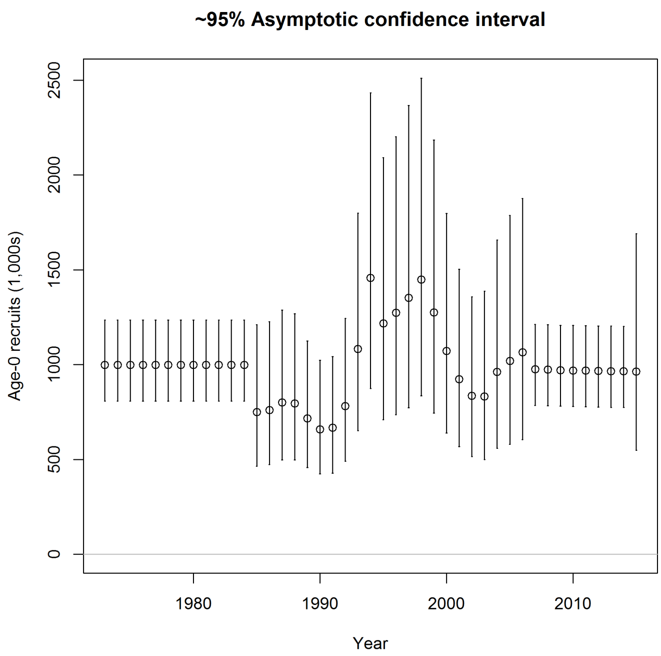

Figure 6.11: Base case estimated recruitment time series (with approximate 95% confidence interval).

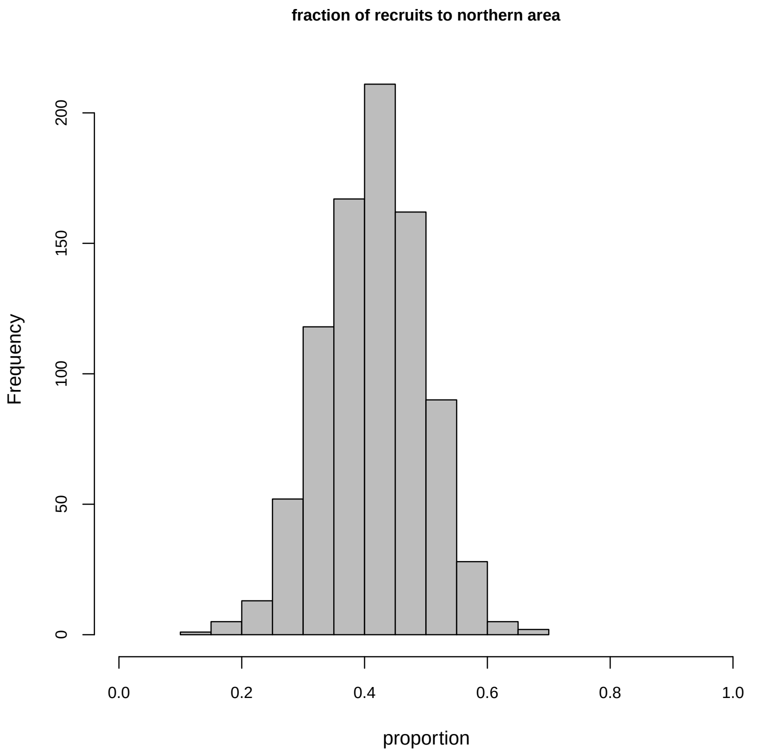

Figure 6.12: Posterior distribution for the proportion of annual recruits allocated to the northern area in the base case model.

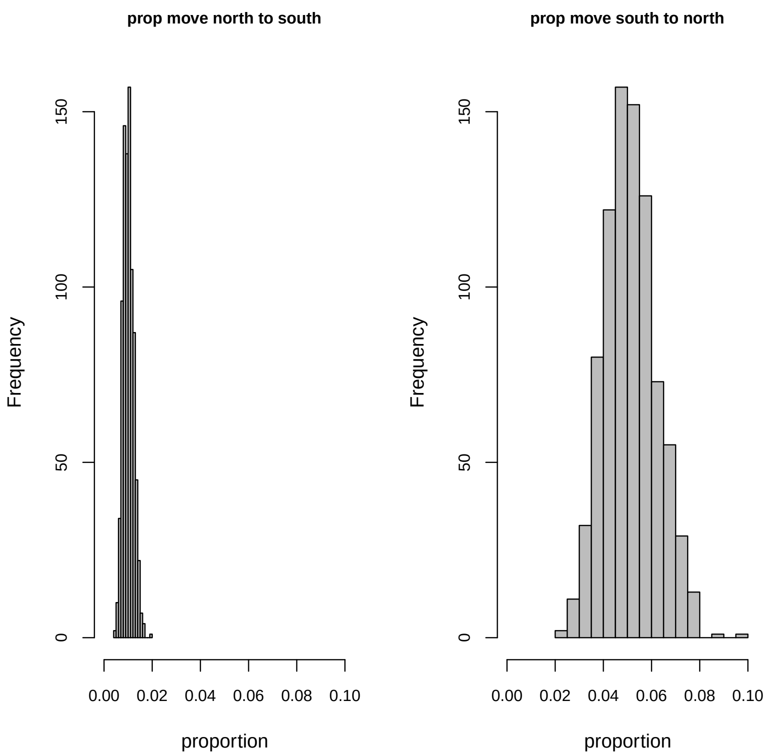

Figure 6.13: Posterior distributions for the values of the movement parameters in the base case model.

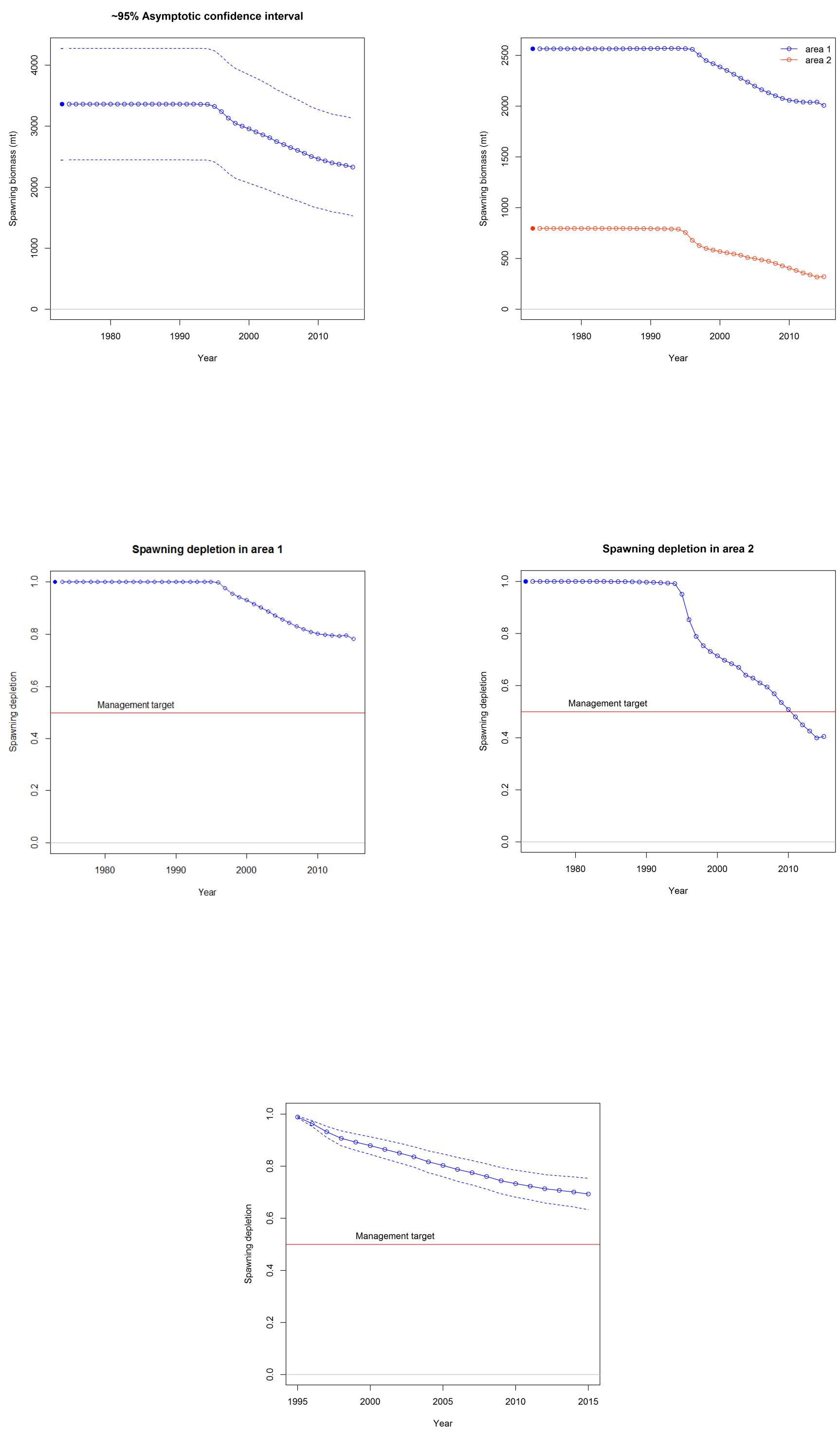

Figure 6.14: Base case estimated time series for female spawning biomass and spawning depletion (spawning biomass relative to unfished), both by area and overall. Area 1 is north, and area 2 is south.

than that in the south (female spawning biomass 2,008t and 322t respectively). The northern area is also estimated to be considerably less depleted than the southern area (78% and 40% respectively).

Table 6.1: Results of the base case and sensitivity analyses, with estimates of female spawning biomass, and the contributions to the negative logarithm of the likelihood function. The base case has the following parameters fixed: female $L_\infty = 165$ cm; $M = 0.13$ yr^{-1}; $h = 0.75$; 50% female maturity at 139.6 cm; $\sigma_R = 0.27$ and logistic selectivity for the north and south Macquarie Ridge longline fleets. The sensitivity analyses listed here explore the impacts of these assumptions. Likelihood values for sensitivities are shown as differences from the base case and are unweighted. A negative value indicates a better fit; a positive value a worse fit. Values in the latter columns in italics indicate values not comparable with those in the base case.

	Female spawning biomass			F_{50} yield	MSY yield	negative log-likelihood					
Model	$SB_{15/16}$	SB_0	$SB_{15/16}/SB_0$			total	length	age	Tag comp	Tag recap	Recruit
Base case	**2330**	**3361**	**0.69**	**448**	**578**	**5735.4**	**578.0**	**3146.6**	**694.0**	**1334.8**	**-18.0**
female L_∞ = 195 cm	3076	4439	0.70	429	560	-29.4	-7.1	-22.9	-0.2	0.8	0.0
$M = 0.155$ yr^{-1}	1125	1838	0.62	362	474	-28.0	-7.0	-8.3	-6.6	-5.4	0.7
M estimated (0.20 yr^{-1})	467	855	0.55	312	423	*-56.8*	*-38.4*	*9.6*	*-6.8*	*-19.8*	*1.4*
$h = 0.5$	2363	3413	0.70	323	357	2.1	2.0	-0.2	0.1	0.1	-0.1
$h = 0.9$	2319	3344	0.70	499	737	-0.8	-0.7	0.1	0.0	0.0	0.0
dome shaped selectivity for NMR & SMR ll	2346	3387	0.70	381	446	*1.1*	*1.0*	*-0.1*	*0.1*	*0.1*	*-0.1*
$\sigma_R = 0.7$	2511	3855	0.66	521	672	63.2	-16.1	67.1	1.2	-4.4	-15.4
leave out 2012 NMR longline	2313	3340	0.70	447	575	*-7.9*	*-8.6*	*1.3*	*-0.1*	*-0.4*	*0.0*
50% female maturity at 130 cm	3033	4315	0.71	469	597	0.0	0.1	0.0	0.0	0.0	0.0
50% female maturity at 120 cm	3822	5349	0.72	491	617	0.0	0.2	0.0	0.0	0.0	0.0
Halve weight on LF data	2138	3149	0.69	473	590	92.8	102.8	4.0	-4.5	-5.3	4.2
Double weight on LF data	2478	3463	0.72	434	573	-37.9	-101.8	45.5	6.0	5.4	-7.1
Halve weight on age data	2089	3060	0.69	461	577	99.0	30.6	76.9	-2.0	-8.0	-1.6
Double weight on age data	2432	3482	0.71	446	580	-39.3	-2.8	-39.5	-0.1	5.2	2.0
Halve weight on tag data	2461	3489	0.72	432	570	-81.6	-77.1	-17.7	4.1	10.3	1.2
Double weight on tag data	2073	3040	0.69	478	593	122.5	68.4	66.4	-3.5	-10.5	-1.6

6.3.6 2014/15 catch levels

Table 6.1 shows the estimated values for the yield at a spawning stock size of 50% unfished, and at the biomass level which results in maximum sustainable yield. Calculation of the 2015/16 TAC under application of the CCAMLR harvest strategy for toothfish (constant catch that gives a median spawning biomass in 35 years no less than 50% of unfished, and a chance of dropping below 20% unfished spawning biomass of less than 10%) requires samples from the posterior distribution in order to calculate the probability-based reference points. The CCAMLR control rule integrates the uncertainty associated with the estimation procedure and future recruitment events. The catch levels that satisfy the control rule can be expected to change given alternative assumptions regarding how the catches will be allocated to fleet and region. Table 6.2 gives the values calculated for the base case for ten catch combination assumptions, with all catch coming from the longline fleets. The projected 2015/16 catch ranges from 460t to 530t.

Table 6.2: Catch combinations for the base case model that satisfy the CCAMLR control rule. These catches are for longline fleets only.

Constraints	Catches (t)			Total catch (t)
AT:NMR:SMR	AT	NMR	SMR	
460t : 0% : 0%	460	0	0	460
250t : 20% : 80%	250	46	184	480
250t : 40% : 60%	250	88	132	470
250t : 60% : 40%	250	126	84	460
200t : 40% : 60%	200	112	168	480
200t : 60% : 40%	200	162	108	470
150t : 0% : 100%	150	0	380	530
150t : 40% : 60%	150	132	198	480
150t : 50% : 50%	150	165	165	480
150t : 100%: 0%	150	310	0	460

Figure 6.15 shows the posterior distribution for female spawning biomass, recruitment, and relative spawning biomass assuming a 250t catch at Aurora Trough, and a split of the remaining catch 20%:80% between the north and the south Macquarie Ridge.

In order for the stochastic projections to work correctly it is not possible to stop the modelling software from estimating the recruitments between the final year in which recruitment is estimated and the end year of data (i.e. 2007–2014 in this case). Instead, to avoid unruly recruitment estimation arising from the model attempting to fit to sparse and noisy data at the end of the time series, it is necessary to downweight the likelihood contribution of these recruitments. Use of this method means that these recruitments are not sampled with the full amount of variability in the stochastic projections. However all recruitments in the projection period are correctly sampled (see the recruitment plot in Figure 6.15).

6.4 Sensitivity Analyses

Sensitivity analyses examine the consequences of alternative assumptions to the base case scenario on the model results. The results of a suite of sensitivity tests are presented in Table 6.1. Where possible, the various contributions to the likelihood function have been presented so the values given are comparable to the base case, even when the values used to calculate the total likelihood were different. This is to facilitate comparisons in the fits to the different data sources among models.

Using the larger estimate of female L_∞ as estimated by Constable *et al.* (2001), results in an improved overall fit, especially to the age data and also to the length data, but makes little difference to the estimate of current spawning stock status.

Fixing the value of the rate of natural mortality, M, at the Heard Island estimate of 0.155 yr^{-1} leads to a better or equivalent fit to all sources of data except for recuitment. Estimating the value for M within the model suggests a value higher than that used in previous assessments for Macquarie Island toothfish, of

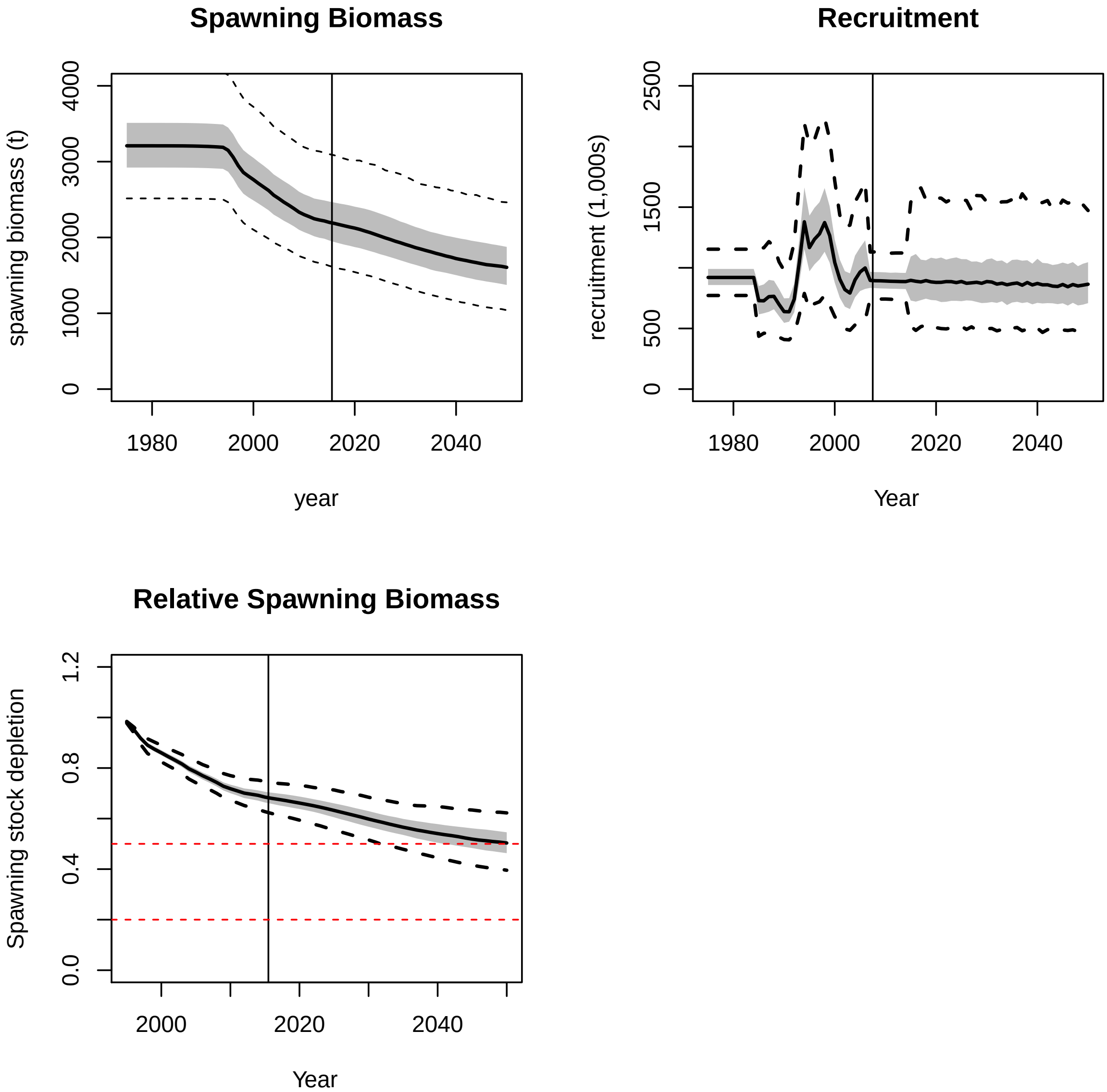

Figure 6.15: Posterior distribution and projection of female spawning biomass, recruitment, and spawning biomass relative to the unfished level, under a constant catch of 480t, split 250t for Aurora Trough, 46t for northern Macquarie Ridge and 184t for southern Macquarie Ridge.

the order of 0.2 yr^{-1}. However, such a high value, which suggests there would be few fish older than 23 years of age, is considered unrealistic for such a relatively long-lived fish. Higher values of M also result in implausibly low estimates of current female spawning biomass. The tendency toward higher estimates for M could mean that the value for this parameter is indeed higher than previously assumed, but could also reflect the effects of tag loss and post-tag mortality, considered here to be negligible.

There appears to be little information in the data regarding the value for the steepness of the stock-recruitment relationship, as the log-likelihood is almost unchanged when alternative fixed values for this parameter are used.

Using dome-shaped selectivity for the Macquarie Ridge longline also has little impact on the fit to the data or the estimate of current spawning stock status. The logistic form has been chosen for the base case model as it is intrinsically more conservative.

Increasing σ_R to 0.7, rather than the tuned value of 0.27, resulted in worse fits overall and in particular to the age data, and resulted in a lower estimate of the current stock status. Excluding the 2012 North Macquarie Ridge longline length data improved the fit to the length data, but had little effect on the current stock status.

Changing the weighting on various data sources changes the estimated biomass trajectory and degrades the overall fit to the data, but has little effect on the estimate of current stock status.

6.5 Discussion points and future work

The analysis presented here raises the following points of discussion and plans for future work:

1. The northern area is estimated to contain larger stock size than in the south. Spawning stock status in the north is well above 50% unfished, whereas in the south it is slightly below 50%.
2. Changes to the spatial distribution of catch in the 2014 season may have provided additional information on the stock status, especially in the north, although there is still considerable uncertainty about movement of fish between these two areas.
3. More exploration is needed of the interaction of movement parameters with the other components of the model.

7 Acknowledgements

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Appendix 2

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Stock Assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2015

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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 2015. 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 makes use of the Stock Synthesis assessment software v3.11b (Methot & Wetzel, 2013), and fits to data obtained from the tag-recapture program since 1995, to length composition information for the years 1994–2015, and to age-at-length data obtained from aged otoliths (1997–2015). It is an update of the final version of the 2015 assessment (Day *et al.*, 2015). 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, and Northern and Southern Macquarie Ridge longlines). Fits to the length composition data are generally good. The fits to the age-at-length data appear to be reasonable, although larger fish are predicted to be older than they are observed to be (the model is growing older fish too slowly). The model fits the tag-recapture data well, with good accord between the total number of expected recaptures and those observed.

The outcomes from the assessment are very similar to those in the 2015 assessment. The base case current female spawning biomass estimate is 67% of unfished at the start of 2016 (69% in 2015). The trend in spawning biomass from 1990–2015 is almost identical to that estimated last year,

Catch levels that satisfy the CCAMLR control rule have been calculated under ten alternative assumptions regarding how the catches will be allocated to fleet and region. The projected 2016/17 and 2017/18 catches from these scenarios ranges from 420t to 500t.

The new 2015 length frequency data include an additional 2950 fish in 84 hauls for Aurora Trough Longline, 2739 fish in 96 hauls for Northern Macquarie Ridge Longline and 1985 fish in 62 hauls for Southern Macquarie Ridge Longline. An additional 276 fish from the 2014 catch and 281 fish from the 2015 catch were aged and these were included as age-at length data for this assessment. This comprised 192 females, 82 males and two unsexed newly aged fish in 2014 and 205 females and 76 males in 2015.

There were considerable revisions to the tag recapture history, with the exclusion of 297 historical recaptures for fish recaptured between 10 and 180 days of release, with 185 of these exclusions from recaptures in the period 1995–1997, with 27 in 2003 and another 54 in the period 2006–2007.

New tag recaptures from the 2015 data included 75, nine and 47 recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 131 tag recaptures in 2015 from fish tagged in previous seasons, with four of these tags recaptured in a different area to their release. One fish tagged in 1997 in the Aurora Trough was recaptured in 2015, which is the longest period between initial tagging and recapture for this fishery. In addition there were 354, 168 and 137 new tag releases in 2015, with these releases respectively in the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge.

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 (Constable *et al.*, 2001; Goldsworthy *et al.*, 2001).

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 (Williams *et al.*, 2002; Tuck *et al.*, 2003).

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 1500km 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.

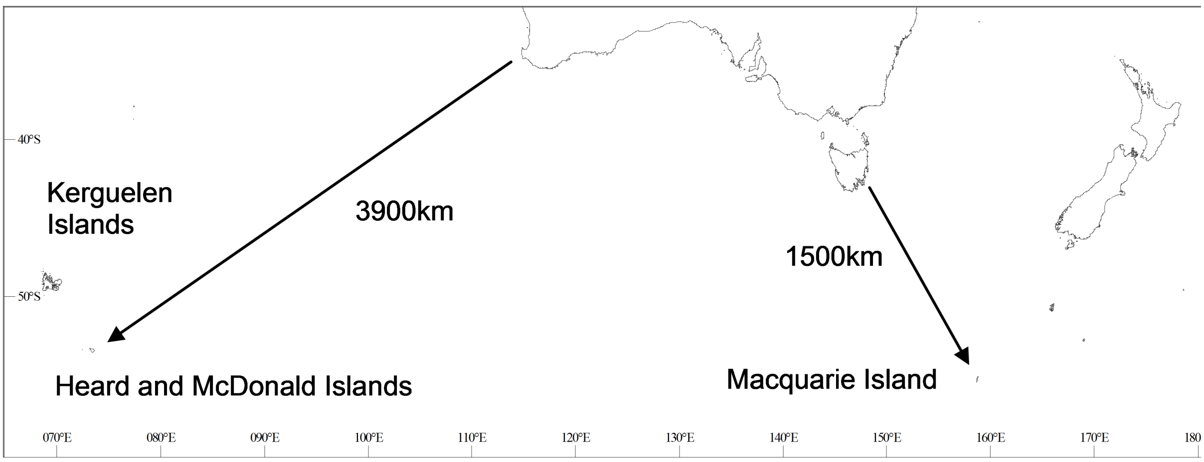

Figure 2.1: The location of Macquarie Island (54° 30'S, 158° 57'E) and Heard Island and McDonald Islands (53 °06'S, 73 °30'E) relative to New Zealand and Australia.

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 354t quota. However, the assessment in the following year suggested that the stock had fallen marginally below the 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 has reduced steadily since the 1500t TAC of 1998. However, the TACs since 1999 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.

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

Fishing season	Administrative period (longline season: 1 May–31 Aug)	Total Allowable Catch: Aurora Trough	Total Allowable Catch: Macquarie Ridge[a]
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[b]	600 (1000)
99/00	1 Jan 2000 – 31 Dec 2000	40[b]	510 (1000)
00/01	1 Jan 2001 – 31 Dec 2001	40[b]	420 (1000)
01/02	1 Jan 2002 – 31 Dec 2002	40[b]	242 (782)
02/03	1 Jan 2003 – 30 Jun 2003	40[b]	205 (665)
03/04	1 July 2003 – 30 Jun 2004	354	174 (441)
04/05	1 July 2004 – 30 Jun 2005	60[b]	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[c]
08/09	1 July 2008 – 30 Jun 2009	312	150[c]
09/10	1 July 2009 – 14 Apr 2010	60[c]	150[c]
10/11	15 Apr 2010 – 14 Apr 2011	140	150[c]
11/12	15 Apr 2011 – 14 Apr 2012	150	360
12/13	15 Apr 2012 – 30 Apr 2013	455[d]	
13/14	1 May 2013 – 30 Apr 2014	415[d]	
14/15	1 May 2014 – 14 Apr 2015	410[d]	
15/16	15 Apr 2015 – 14 Apr 2016	460[d]	

[a] tonnage shown in brackets would have been triggered if trawl catch rates reached 10 t/km^2 over 3 consecutive fishing days
[b] research TAC to enable tag-based stock assessments
[c] TACs for longline trial
[d] TAC set for entire Macquarie Island region

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 recaptures of fish tagged in the trawl fishery. Since 2009 the catch has been taken entirely by longline.

From 2012/13, a single TAC has been set for the whole of the Macquarie Island region. The 2015/16 TAC was set at 460t, 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 (126t) and the rest from South Macquarie Ridge (84t). The actual catch in 2015 was around 150t below the TAC. However the catch followed the recommended percentages by region fairly closely (Table 3.1).

2.3 Previous assessments

Prior to 2010, TAC determination for the Macquarie Island Patagonian toothfish stock had been based on stock assessment using the tag-recapture model developed by de la Mare and Williams (1997), and modifications described in Tuck *et al.* (2003). 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 (Tuck & Lamb, 2009). In 2004, a new model that expanded upon the traditional tag-based model was introduced (Tuck *et al.*, 2006). 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 (Tuck & Methot, 2008; Fay *et al.*, 2009b). 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 (Fay *et al.*, 2010).

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 (Fay *et al.*, 2010). 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 (Fay *et al.*, 2009b; Fay *et al.*, 2009a). 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 (Fay, 2011; Fay *et al.*, 2011). 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 (Wayte & Fay, 2012), the 2013 assessment estimated the 2013/14 female spawning biomass for the whole of Macquarie Island to be 69% of unfished (Wayte & Fay, 2013), with further estimates of 68% for the 2014 assessment (Day *et al.*, 2014) and 69% for the 2015 assessment (Day *et al.*, 2015).

2.4 Modifications to the previous assessment

The following data have been added to the assessment:

1. 2015 catches
2. 2015 length compositions
3. 2015 tag recaptures
4. 2014 and 2015 age-at-length compositions

3 Data

The data available for model-fitting purposes include length composition data from the fishery (1994/95–2015/16), conditional age-at-length data (1996–2000, 2002, 2003, 2005–2010, 2013–2015), and the results of the tag-release-recapture program, begun during the 1995/96 season.

3.1 Catch data

Stock Synthesis 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 previous 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. In the current assessment, the catch data was adjusted to exclude any released fish. This resulted in revisions to the historical catch record, only including those fish that were retained in the catch data.

Longline operations in 2015 caught around 2/3 of the 2015 TAC with 161t caught in the Aurora Trough and 149t caught in the northern and southern Macquarie Ridge areas.

3.2 Length frequency data

Samples of the length composition of the catch were available for all fishing seasons (1994/95 through 2014/15). Each annual length composition is based on the measurement of several hundreds (thousands) of fish (Table 3.2). 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

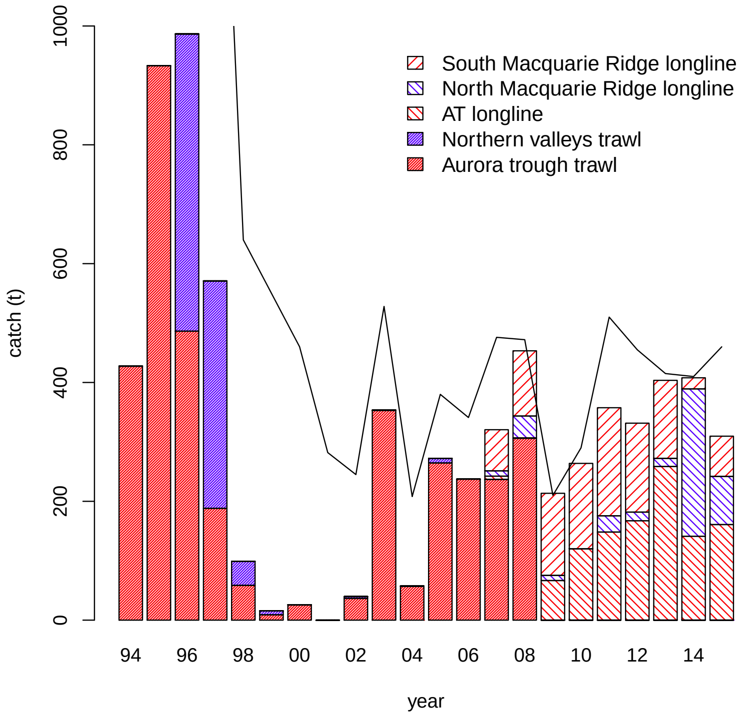

Figure 3.1: Catch history and total TAC by fishing year, with catches stacked by fleet and the grey line representing the combined TAC (with TACs summed for Aurora Trough and Macquarie Ridge from 1996–2011). There were small research quotaa in the Aurora Trough from 1998-2002 and in 2004.

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	18.7	408	410
15/16			160.8	81.1	67.7	309	460

hauls/shots. Thus input sample sizes for the individual length compositions were set at the number of shots sampled for the trawl data, and 10% of the number of fish sampled for the longline data.

Disaggregation of the length data by sex is possible, and Stock Synthesis allows 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 the unsexed fish sampled for length are quite different from the male and female portions of the length composition for some years (Fay, 2010). 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 2013–2015 (Table 3.3). New ageing data from 2014 and 2015 were added this year. The input sample sizes for the age-at-length data were set at 10% of the number of otoliths measured.

3.3.1 Conditional age-at-length data

The age data are input as the raw age-at-length data, rather than age compositions generated from applying age-length keys to the catch-at-length compositions. The input compositions are therefore the distribution of ages obtained from samples in each length bin, for those years for which data are available (Table 3.3). Age data that came from tag recaptured fish are not included in the assessment analyses. Where an otolith has been read more than once (e.g. for ageing error estimation), the first age reading is used in the assessment.

3.3.2 Ageing error

Multiple reads of otoliths from Macquarie Island Patagonian toothfish with which to quantify the degree of ageing error have recently become available, but the ageing error matrix is yet to be calculated from these data. As a result, as with the 2010 Aurora Trough assessment, the ageing error matrix calculated for Patagonian toothfish at HIMI (Candy & Welsford, 2009) was used to provide estimates of ageing error, in order to calculate the degree to which a fish of true age i is aged to be j. Stock Synthesis enters ageing error, for each true age, by assuming a normal distribution of observed ages around a mean age and standard deviation for the observations. The ageing error matrix (Table 3.4) assumes ageing was unbiased (i.e. mean observed age was the true age). There is evidence however, that for older fish, the observed age is less than the true age (Candy & Welsford, 2009).

3.4 Tag recapture data

Between the 1995/96 and 2015/16 fishing seasons, 15,188 Patagonian toothfish were tagged at Macquarie Island, of which 1,909 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), with one fish recaptured in 2015 having been initially tagged in 1997.

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

Fleet	Season	# shots	# fish	mean # per shot
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
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
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
SMR longline	07/08	28	1589	57
	08/09	44	1750	40
	09/10	50	1886	38
	10/11	34	1545	45
	11/12	96	3388	35
	12/13	126	4080	32
	13/14	94	3107	33
	14/15	17	528	31
	15/16	62	1985	32

Table 3.3: 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
	f			0
	m			0
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	u			0
	f		31	31
	m		32	32
2003	u			0
	f	138		138
	m	79	2	81
2005	u	1		1
	f	107	26	133
	m	56	37	93
2006	u			0
	f	11		11
	m	9		9
2007	u			0
	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	3	5
	f	175	25	200
	m	83	14	97
2014	u	2		2
	f	97	95	192
	m	59	23	82
2015	u			0
	f	129	76	205
	m	57	19	76
total		3371	945	4316

Table 3.4: Ageing error matrix. Shown are the mean and standard deviation of observed ages given a true age read. Values were calculated using the ageing error matrix for Heard and MacDonald Island toothfish as given in Candy and Welsford (2009).

true age	mean age	s.d.	true age	mean age	s.d.	true age	mean age	s.d.
1	1.5	0.82	41	41.5	3.11	81	81.5	9.28
2	2.5	0.83	42	42.5	3.22	82	82.5	9.48
3	3.5	0.84	43	43.5	3.33	83	83.5	9.69
4	4.5	0.85	44	44.5	3.44	84	84.5	9.89
5	5.5	0.87	45	45.5	3.55	85	85.5	10.11
6	6.5	0.89	46	46.5	3.67	86	86.5	10.32
7	7.5	0.91	47	47.5	3.79	87	87.5	10.53
8	8.5	0.94	48	48.5	3.91	88	88.5	10.75
9	9.5	0.97	49	49.5	4.03	89	89.5	10.97
10	10.5	1.00	50	50.5	4.16	90	90.5	11.2
11	11.5	1.03	51	51.5	4.29	91	91.5	11.42
12	12.5	1.06	52	52.5	4.42	92	92.5	11.65
13	13.5	1.1	53	53.5	4.55	93	93.5	11.88
14	14.5	1.14	54	54.5	4.69	94	94.5	12.11
15	15.5	1.18	55	55.5	4.83	95	95.5	12.35
16	16.5	1.22	56	56.5	4.97	96	96.5	12.59
17	17.5	1.27	57	57.5	5.11	97	97.5	12.83
18	18.5	1.32	58	58.5	5.26	98	98.5	13.07
19	19.5	1.37	59	59.5	5.41	99	99.5	13.31
20	20.5	1.42	60	60.5	5.56	100	100.5	13.56
21	21.5	1.48	61	61.5	5.71	101	101.5	13.81
22	22.5	1.54	62	62.5	5.87	102	102.5	14.06
23	23.5	1.60	63	63.5	6.02	103	103.5	14.32
24	24.5	1.66	64	64.5	6.18	104	104.5	14.57
25	25.5	1.73	65	65.5	6.35	105	105.5	14.83
26	26.5	1.80	66	66.5	6.51	106	106.5	15.09
27	27.5	1.87	67	67.5	6.68	107	107.5	15.36
28	28.5	1.94	68	68.5	6.85	108	108.5	15.63
29	29.5	2.02	69	69.5	7.02	109	109.5	15.89
30	30.5	2.09	70	70.5	7.19	110	110.5	16.17
31	31.5	2.17	71	71.5	7.37	111	111.5	16.44
32	32.5	2.26	72	72.5	7.55	112	112.5	16.72
33	33.5	2.34	73	73.5	7.73	113	113.5	17
34	34.5	2.43	74	74.5	7.92	114	114.5	17.28
35	35.5	2.52	75	75.5	8.10	115	115.5	17.56
36	36.5	2.61	76	76.5	8.29	116	116.5	17.85
37	37.5	2.71	77	77.5	8.49	117	117.5	18.13
38	38.5	2.80	78	78.5	8.68	118	118.5	18.42
39	39.5	2.90	79	79.5	8.88	119	119.5	18.72
40	40.5	3.01	80	80.5	9.07	120	120.5	19.01

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

Release	Release	# rel	Mean	# recaptures after 180 days at liberty																		
season	fleet		length	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
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																			
99/00	AT tr	692	65					3	1	35	6	12	1	4	6	2	5	1	5			
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	
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	
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
05/06	NV tr	288	60																1		2	3
06/07	AT tr	432	59											26	13		1			4		2
07/08	AT tr	273	65												31	2		2	1	3	1	
07/08	NMR LL	26	78													1		3	2			
07/08	SMR LL	189	81												15	4	3	6	6	4		1
08/09	AT tr	557	71													2	6	12	10	19	6	8
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
09/10	AT LL	299	85														27	13	9	13	4	2
09/10	NMR LL	60	85															5	5			2
09/10	SMR LL	395	79														26	25	8	20	2	2
10/11	AT LL	478	87															11	31	45	6	4
10/11	SMR LL	507	91															27	42	34	5	8
11/12	AT LL	302	72																10	37	7	7
11/12	NMR LL	116	83																1	2	1	3
11/12	SMR LL	497	78																9	25	4	17
12/13	AT LL	309	78																	37	12	12
12/13	NMR LL	56	89																			
12/13	SMR LL	302	87																	20		8
13/14	AT LL	529	75																		9	26
13/14	NMR LL	36	81																			2
13/14	SMR LL	249	81																		9	10
14/15	AT LL	295	72																			9
14/15	NMR LL	499	79																			
14/15	SMR LL	33	81																			
15/16	AT LL	353	76																			
15/16	NMR LL	168	79																			
15/16	SMR LL	136	78																			

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	150	1	32
NV trawl	8	72	1	7	4
AT longline	0	0	315	0	16
NMR longline	0	0	1	23	14
SMR longline	1	0	55	5	352

Under the Stock Synthesis framework, tag released fish are assigned to tag groups, with all fish within a tag group (which could be all fish released in a season) assumed to consist of a single age class. As the length range of fish chosen for tagging approximates the length range in the catch, assuming all fish are the same age, while computationally convenient, clearly does not represent the way in which fish are tagged. The method used to assign ages to tag releases within the assessment model can therefore be expected to impact the results. Alternative methods of specifying the age at release for the tagged fish were evaluated using simulation testing (Fay, 2010), with the results suggesting that the best option in terms of being able to estimate biomass is to distribute the annual number of releases into a small number of tag groups per year, with assigned ages to these tag groups based on the length composition of the catch. This method was shown to be superior to fixing the age at release for all releases within a year, and also to assigning a unique age to each tag release based on the individual release lengths.

Annual releases were therefore split into five groups. The ages assigned to the tag groups were determined by comparing the median length of the appropriate quantile of the length composition with the mean length at age from the assumed growth curve. As the majority of tagged fish are not sexed, the growth curve obtained from data for both sexes (Constable *et al.*, 2001) was used to convert the release lengths to ages. It is clear that such an approach is an approximation; however the majority of growth curves estimated for Macquarie Island toothfish predict very similar mean length at age for the lengths at which most fish are tagged.

Recaptures of tagged fish are assumed to be clumped in space rather than be purely random (i.e. negative binomial vs. Poisson distributed) conditional on the catch and expected number of tags available to the fishery, with over-dispersion parameters (an index of aggregation) estimated for each release area. The available recapture data consists of the numbers of recaptured fish each year by each release group (Table 3.5; for brevity, recapture data are aggregated by season). To allow for full mixing of the tagged fish with the untagged population, recaptures within the year of release were removed from previous assessment release data if the recapture occurred within 10 days of release (c.f. Tuck and Lamb (2009)). Given the quantity of tag data now available to the assessment, recaptures were removed from the 2016 assessment release data if the recapture occurred within 180 days of release. This effectively removes recaptures of any fish tagged within the same fishing season.

Accounting for clumping in the tag returns requires the inclusion of an over-dispersion parameter. This term relates to the variability of the observed data, which is greater than that expected if the tags were recaptured randomly. Including over-dispersion in the tag recaptures is implemented by assuming that the recaptures are distributed according to a negative binomial instead of Poisson. The degree of over-dispersion relative to the Poisson is handled by an additional parameter for each tag group, which potentially results in an additional 150 parameters to be estimated. Estimating over-dispersion parameters allows for clumping in the tag recapture data, or less of a penalty on the model fit given more (or less) recaptures than predicted from a tag group in a given year. The 2010 Aurora Trough assessment demonstrated that there was not sufficient information to estimate this parameter by tag group, and the value for the over-dispersion parameter was fixed at the median estimate for those tag groups where there appeared sufficient information for estimation (base case value of 1.9, Fay *et al.* (2010)). Expanding further on this approach, with a modification to Stock Synthesis for the subsequent assessments, over-dispersion parameters can be shared among tag groups, and so a single value for the parameter for each release area was estimated when fitting the model, rather than pre-specifying a fixed value.

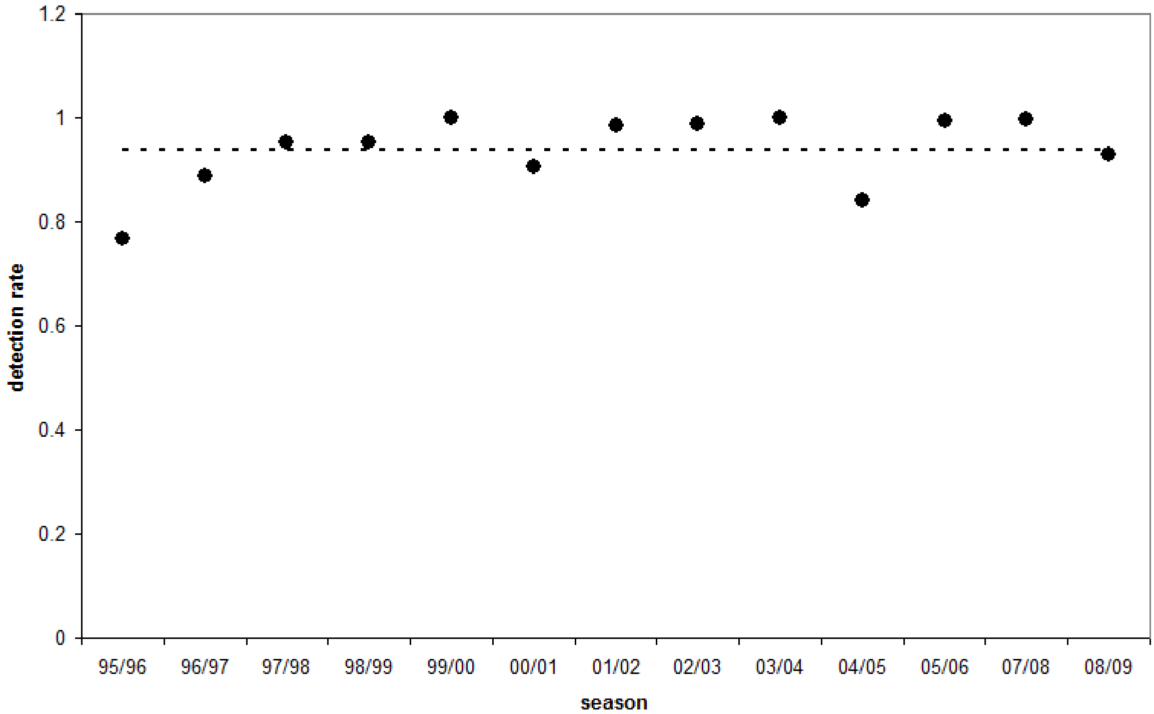

Figure 3.2: Estimated tag detection rate (points) by fishing season (Tuck and Lamb 2009). Dotted line corresponds to the mean detection rate (0.938) over the time series.

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. 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 (2009)), 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 data in this assessment include revisions to historical data. For length compositions, the historical revisions include minor adjustments to the number of fish measured in Aurora Trough Trawl, namely one more fish measured in 2005. The new 2015 length frequency data include an additional 2950 fish in 84 hauls for Aurora Trough Longline, 2739 fish in 96 hauls for Northern Macquarie Ridge Longline and 1985 fish in 62 hauls for Southern Macquarie Ridge Longline.

There were no revisions to the historical age-at-length data up to 2013 used in the 2015 assessment. An additional 276 fish from the 2014 catch and 281 fish from the 2015 catch were aged and these were included as age-at length data for this assessment. This comprised 192 females, 82 males and two unsexed newly aged fish in 2014 and 205 females and 76 males in 2015.

Additions to the historical recapture information include a single additional tag recapture in 2007, from a tag released in the Aurora Trough trawl fleet in 1999. A fish tagged in 1997 in the Aurora Trough was recaptured in 2015, which is the longest period between initial tagging and recapture for this fishery. The tagging mortality is clearly less than 100%.

There were considerable revisions to the tag recapture history, with the exclusion of 297 historical recaptures for fish recaptured between 10 and 180 days of release, with 185 of these exclusions from recaptures in the period 1995–1997, with 27 in 2003 and another 54 in the period 2006–2007.

New tag recaptures from the 2015 data included 75, nine and 47 recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 131 tag recaptures in 2015 from fish tagged in previous seasons. Of these 131 recaptures, 127 were recaptures in the same area (119 in the south, eight in the north), with four recaptures in a different area to the release area, providing additional information on movement of individuals between areas. In 2015, three fish tagged and released by the North Macquarie Ridge Longline fleet were recaptured by the South Macquarie Ridge Longline fleet in 2015 and one fish tagged and released by the South Macquarie Ridge Longline fleet was recaptured by the North Macquarie Ridge Longline fleet.

In 2015, there were 12 fish tagged by Aurora Trough Trawl that were recaptured, 11 in Aurora Trough and one in Southern Macquarie Ridge. Four fished tagged by Northern Valleys Trawl were recaptured by in the Northern Macquarie Ridge in 2015. There were 61 fish previously tagged by Aurora Trough Longline recaptured in 2015, with 60 of these recaptured in the same area as release, with the remaining one recapture in the Southern Macquarie Ridge. There were an additional seven recaptures of longline tagged fish from Northern Macquarie Ridge, with four recaptured in the same area as release and three more recaptured in the Northern Macquarie Ridge. Forty nine fish previously tagged by longline in Southern Macquarie Ridge were recaptured in 2015 with five of these recaptured in Aurora Trough, one in Northern Macquarie Ridge and the remaining 43 recaptured in the Southern Macquarie Ridge.

In addition there were 354, 168 and 137 new tag releases in 2015, with these releases respectively in the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge.

4 Biology

4.1 Growth

Growth of Patagonian toothfish is assumed to follow the von Bertalanffy growth function, with sex-specific parameter values estimated within the model, except for the L_∞ parameter for females which was fixed at 165 cm. The sensitivity of fixing this at 195 cm, as estimated by Constable *et al.* (2001), is examined. Estimating the growth within the assessment model is often preferable if there are sufficient data to do so, as this allows the impacts of length-specific selectivity to be directly accounted for in a consistent fashion with respect to the rest of the assessment. However it needs to be remembered that there is often a strong correlation between the growth and other key fixed (M, steepness) and estimated (SSB_0, selectivity) parameters. The now sizeable amount of ageing data available suggests that this approach should be acceptable. However, the true number of age samples used in the assessment is complex to estimate, and is not the same as the number of age samples, but intimately related to the effective sample sizes used in the assessment for the fits to the length and age data.

The values for the parameters of the growth curve used to assign ages to tag releases are given in Table 4.1. These were estimated by Constable *et al.* (2001) from data for both sexes.

Table 4.1: Values for growth parameters.

	Constable *et al.*(2001)			Base case estimate	
von Bertalanffy growth parameters	Both sexes	female	male	female	male
L_∞ (cm)	185.5	195.1	154.2	165 (fixed)	1851.7
k (yr^{-1})	0.042	0.038	0.054	0.056	0.0028
t_0	-0.781	-1.184	-0.434	-0.085	-2.93
CV of length at age	0.13	0.12	0.14	0.15	0.16

Values for the parameters of the weight-at-length relationship are fixed at those in Table 4.2, using parameter values estimated by Constable *et al.* (2001) using data for both sexes.

Table 4.2: Values for biological parameters.

Parameter	Value
Rate of natural mortality, M (yr^{-1})	0.13
Weight at length, wt (kg) $= aL^b$ (cm)	
a	4.4×10^{-6}
b	3.14
length at 50 % maturity (cm)	139.6
length at 95 % maturity (cm)	185.8

4.2 Mortality

Although there is no direct information on natural mortality of Macquarie Island toothfish, the known longevity of the species would indicate that natural mortality is less than M =0.2 yr^{-1} (Constable *et al.*, 2001). The base case analysis uses a fixed value of 0.13 yr^{-1} as in previous assessments, based on an estimate of mortality from Heard Island Patagonian toothfish. M is assumed to be the same for both sexes and constant over age and time. The impacts of using the recent value estimated for the Heard Island Patagonian toothfish (M =0.155 yr^{-1}), and of estimating the value for M are also considered.

4.3 Fecundity and maturity

Base case estimates of length at maturity are fixed at values estimated from data from the longline fishing trial at Macquarie Island (Williams, 2011). Estimated length at 50% maturity for females under this approach was 139.6 cm with a length at 95% maturity of 185.8 cm (Table 4.2).

Without direct information on fecundity or egg production, mature female weight is used as spawning biomass.

5 Assessment methodology

5.1 Population model

The assessment is based on a length-age-structured model of fish population dynamics. It 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 (with the division being the latitude of 54.25 ° south) – are incorporated into the model, with movement of fish between areas, and recruitment to both areas. Differences in the size structure available to the different fleets (e.g. trawl vs. Ridge longlining) within areas are accounted for via the estimated selectivity patterns for each fleet.

A two-sex model is assumed, although the rate of natural mortality is assumed to be the same for both males and females. The population dynamics model, and the statistical approach used in the fitting of the model to the various types of data, are given fully in the technical description of the Stock Synthesis assessment software (Methot, 2010) and are not reproduced here.

5.2 Fleets

The model designates five fishing fleets that exploit the toothfish resource. These are:

1. Aurora Trough trawl,
2. Northern Valleys trawl,
3. Aurora Trough longline,
4. Northern Macquarie Ridge longline and
5. Southern Macquarie Ridge longline

Catches were allocated to the northern and southern Macquarie Ridge fleets with the division being a latitude of 54.25 ° south, which although arbitrary, represents a geographical break in the location of fishing operations, and has been used previously to separate catches (Fay *et al.*, 2009a). Small amounts of catch by trawl outside of the Aurora Trough and Northern Valleys areas during the early years of the fishery were allocated to the appropriate trawl fleet with the same geographical division as for the longline. The Aurora Trough trawl and longline and southern Macquarie Ridge longline fleets are assigned to the southern area in the model, and the Northern Valleys trawl and northern Macquarie Ridge fleets are assigned to the northern area.

5.3 Selectivity

The selectivity pattern for each fleet was assumed to be a function of length, estimated separately within the model, with the selectivity pattern for all fleets assumed to be time-invariant. The function chosen allowed for a dome-shaped selectivity pattern (that is, increasing selectivity with increasing length, and then decreasing selectivity at further increases) given certain values for the four estimated parameters (for each fleet) for the trawl fleets and Aurora Trough longline, but did not impose this pattern on the model. Logistic selectivity was used for the northern and southern Macquarie Ridge longline fleets.

5.4 Stock and recruitment

Recruitment to the toothfish stock is assumed on average to follow a Beverton-Holt stock-recruit relationship (SRR), with the number of fish of age zero a function of the female spawning biomass in the same year. The parameterisation is the average recruitment at unfished equilibrium (R_0), and the steepness parameter h which relates to the ability of the stock to maintain recruitment at low stock size (Mace & Doonan, 1988). R_0 is estimated during the model-fitting process, but h is fixed at 0.75. Annual recruitment deviations from the SRR were estimated for the period 1985–2006, with these deviations taken as being log-normally distributed around the SRR with a standard deviation, σ_R of 0.27. The range of years chosen for recruitment estimation reflects the expectation that cohort effects from these years should be apparent in the data, and whether the asymptotic standard error of the estimate for these parameters is below the variance expected given the value of σ_R. Values for the fixed stock-recruit parameters are the same as those used by Tuck *et al.* (2006) and Fay *et al.* (2010) in previous integrated assessments for Macquarie Island toothfish.

The proportional allocation of new recruits to the two areas is estimated within the model. This proportion is considered fixed through time, therefore both the northern and southern areas experience the same trend and relative changes in recruitment dynamics over time.

5.5 Initial conditions

The population is assumed to be in unfished equilibrium, with an equilibrium age structure, in 1975. Estimated female spawning biomass in 1975 is therefore used as the estimate of unfished spawning biomass, SB_0.

5.6 Movement

Movement of fish among areas is allowed, with the extent of movement (annual movement rates) being estimated during the model fitting process. Movement is modelled as being age-independent.

5.7 Parameters and parameter estimation

Statistical fitting of the population dynamics model to the available data is achieved by minimising an objective function consisting of several likelihood components, reflecting the different types of data input (lengths, age-at-length, and tag recaptures), and also a penalty function constraining the spread of annual recruitment deviations around the stock-recruit relationship.

The base case version of the assessment model utilised the values described above for biological parameters, and those described in Section 3.4 for the tag detection rate, tagging age, and mixing time. Input sample sizes for the individual length compositions for the trawl data were the number of shots sampled, and for the longline data, 10% of the number of fish sampled. The input sample sizes for the age at length data were also set at 10% of the number of otoliths measured.

The estimated parameters of the base case model were: average recruitment before fishing, growth curve parameters for both sexes, annual recruitment deviations from 1985–2006, parameters determining the functional form of the selectivity pattern, the tag-recapture over-dispersion parameter, a parameter for the allocation of recruits to areas, and movement parameters. Additional parameters were estimated in some of the sensitivity analyses.

The results of the estimation procedure provide a prediction of stock status prior to the 2014/2015 fishing season. Key quantities of interest output by the model include time series of female spawning biomass, the current value of this spawning biomass relative to that prior to fishing, and the levels of fishing mortality experienced by the stock. Also calculated are various combinations of predicted catches by fleet for the 2016/17 fishing season that satisfy the CCAMLR control rule (Section 5.9).

5.7.1 Contributions to the likelihood function

The data have four separate contributions to the objective function when fitting the model, from the length compositions, the age-at-length, number of tag recaptures, and allocation of tag recaptures by fleet. The length and age-at-length compositions by year, fleet, and sex (for the age data) are assumed to be samples from multinomial distributions given input sample sizes. For each tag group, the total number of recaptures by year is assumed to be distributed negative binomially. The proportional allocation of these tag recaptures by fleet is then considered to be multinomial.

5.7.2 Penalties

The objective function contains a penalty based on the distribution of recruitment deviations around the stock-recruit relationship, which is assumed to be log-normal with a standard deviation, σ_R which as described above in Section 5.4 is fixed at a value of 0.27.

5.8 Quantification of uncertainty

Variances for the estimates of the model parameters and derived quantities of interest can be determined either by using asymptotic standard errors, or by applying Markov-Chain Monte Carlo (MCMC) methods (Hastings, 1970; Gelman *et al.*, 1995; Gilks *et al.*, 1996). The Metropolis-Hastings algorithm was used to generate a sample of 1,000 parameter vectors from the joint posterior density function for the base case. This sampling process implicitly considers uncertainty in all dimensions of parameter space, and accounts for correlation among model parameters. The samples on which inference is based were generated by running 1,500,000 cycles of the MCMC algorithm, discarding the first 500,000 as a burn-in period and selecting every 1,000th parameter vector thereafter.

5.9 2016/2017 catch determination under the CCAMLR control rule

Values for the 2016/17 catch were calculated under the CCAMLR control rule. The calculated 2016/17 catch was the maximum constant catch applied over a 35 year projection period that satisfied the following criteria:

- the probability that female spawning biomass will fall below 20% of the pre-exploitation level over the 35 year projection period does not exceed 0.1; and
- the median escapement for the fishery of the female spawning biomass shall not be less than 50% over a 35 year projection.

Stochastic projections were conducted using the sample from the posterior distribution. The stochastic projections therefore incorporated both parameter uncertainty and uncertainty in future recruitment events, in the calculation of the 2015/16 catch, given implementation of the CCAMLR control rule.

The catch levels that satisfy the control rule can be expected to change given alternative assumptions regarding how the catches will be allocated to fleet and region. The 2016/17 catch levels were calculated for nine different assumptions of how the catch would be distributed between the longline fleets.

6 Results and discussion

6.1 Bridging analysis

Updated recent data were added sequentially to the 2015 base case model to show the effect on the key model outputs such as female spawning biomass and recruitment. In the current assessment, the changes to historical data were so minor and the impact of these changes was so small that these sequential historical revisions are only listed as a single step in the list of sequential changes to update the new data. The addition of an extra two years of age-at-length data from 2014 and 2015 and additional length data in 2015, enabled two additional years of recruitment to be estimated in the new assessment. In the 2015 assessment, age-at-length data was only available up until 2013.

The sequential changes to update the base case model were:

1. update historical data,
2. add 2015 catch,
3. add 2015 length compositions,

4. add 2014 and 2015 age-at-length data,
5. add 2015 tag data,
6. estimate two additional years of recruitment, up until 2008,
7. iteratively re-weight the likelihood contributions from the length and age compositions and recruitment variability σ_R.

The combined addition of 2015 catch, length composition and tag data and 2014 and 2015 age-at-length data made little overall difference to the spawning biomass trajectory (Figure 6.1) and recruitment estimates (Figure 6.2). The addition of the age-at-length data saw some changes, especially to the end of the recruitment time series. However, these changes were largely reversed in the next step with the addition of the 2015 tag data, resulting in very similar time series to the 2015 base case. Estimating two more years of recruitment made little difference, as the two additional recruitment event were estimated to be only slightly above average.

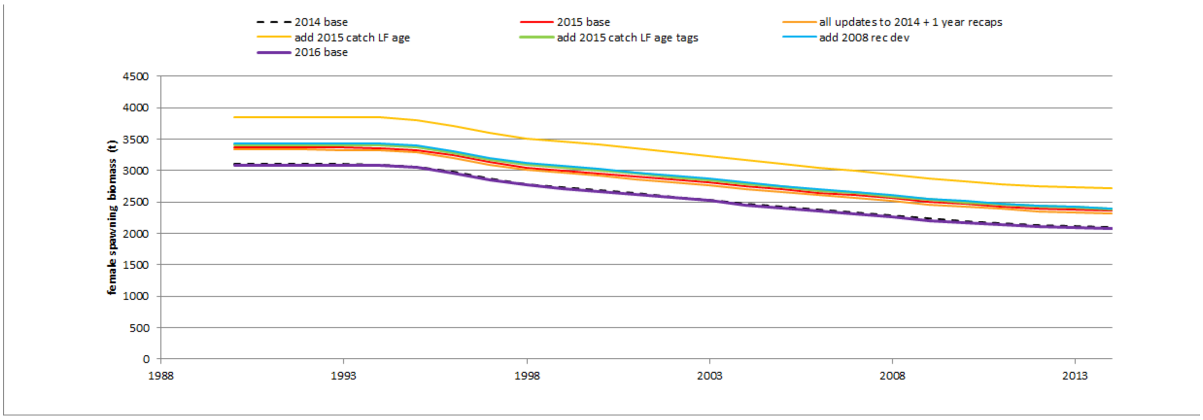

Figure 6.1: Effect on the female spawning biomass trend of sequential updates with the most recent data.

The model with the revised historical data and all the new 2015 data added was then iteratively re-weighted by adjusting the input sample sizes for length and age data and by matching the input and output values of σ_R. This iterative procedure is routinely used in a number of stock assessments in other fisheries (Francis, 2011). Iterative re-weighting balances the influence of all data sets according to how statistically informative they are. This iteratively re-weighting procedure was first used in the 2014 assessment and an updated procedure was adopted this year, following recommendations from the CAPAM data weighting workshop in la Jolla, USA held in October 2015. Iteratively re-weighting resulted in a downwards translation of both the spawning biomass and the recruitment time series, moving this series closer to the spawning biomass series from the 2014 base case.

The 2016 base case model is thus the iteratively re-weighted model with 2015 data added, with recruitment now estimated to 2008, and is indicated by the purple lines in Figure 6.1 and Figure 6.2.

6.2 Diagnostics

6.2.1 Length composition data

The fits to the length composition data are generally good (Figure 6.3 and Figure 6.4), although the residual pattern from the fits to the 2014 and 2015 length frequencies from Northern Macquarie Ridge

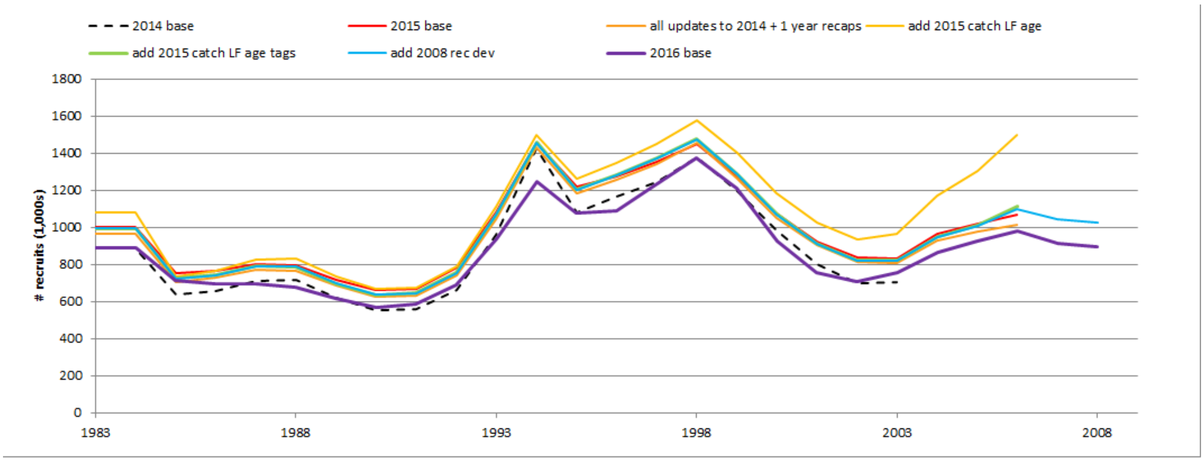

Figure 6.2: Effect on the recruitment estimates of sequential updates with the most recent data.

and 2015 from Southern Macquarie Ridge are different to the earlier years, with fewer large fish and more small fish than expected. However, the fits to the length frequencies from the Aurora Trough longline are excellent since 2012. For the length composition data, the re-weighted observed sample sizes, relating to either number of shots or number of fish depending on the fleet, plotted against the effective sample size shows that the length composition data is reasonably well balanced (Figure 6.5).

Model fits to the Northern Valley trawl data appear to be unable to capture the variability in the data (Figure 6.3), however the effective sample sizes of much of these data are low (Figure 6.5).

Inter-annual variability in the areas and depths fished within fleets likely contribute to some of the variability and inconsistency among data. The lengths of toothfish available to the fishery at Macquarie Island vary considerably by month and depth, and so inconsistencies in the length data from year to year can be expected as a result of spatial and temporal differences in fishing activity by season.

6.2.2 Age-at-length data

The fits to the age-at-length data for the base case are reasonable (Figures 6.6, 6.7, 6.8 and 6.9) although larger female fish are often predicted to be older than they are observed to be (the model is growing older female fish too slowly).

6.2.3 Tag recapture data

The base case scenario is able to capture the general pattern of tag recaptures over time very well (Figure 6.10). While the residuals indicate some unexpected results in 2011 and 2012, there are no consistent patterns overall, and hence no cause for concern. The lack of recaptures for 2006 and 2007 may be related to the length composition for these years, as there were few larger fish caught.

6.3 Base case results

6.3.1 Selectivity

Fitting the assessment model to the length data allows for the selectivity pattern of the fleets to be estimated. The estimated selectivity patterns for the trawl fleets are strongly dome-shaped (Figure 6.11). As agreed at RAG meetings in 2011, logistic selectivity has been imposed on the Macquarie Ridge longline

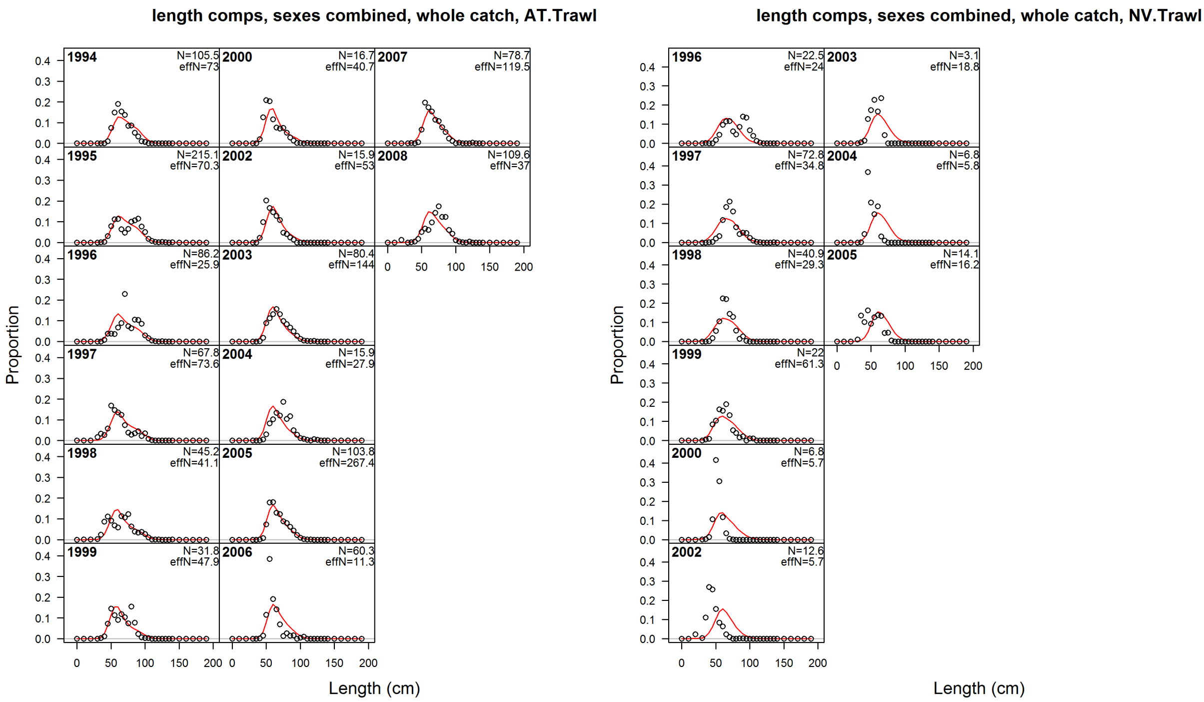

Figure 6.3: Fits to the length composition data for the trawl fleets.

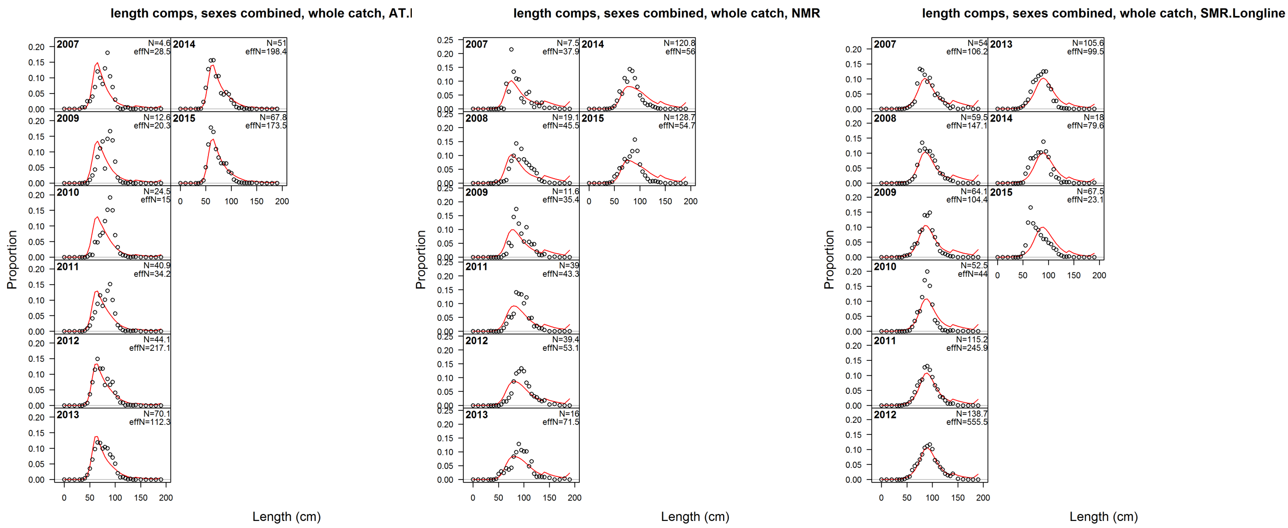

Figure 6.4: Fits to the length composition data for the longline fleets.

fleets, in order to lead to an intrinsically conservative assessment. As with the 2014 and 2015 assessments the estimated selectivity for the Aurora trough longline fleet is logistic. This is in contrast to the 2013 assessment, where the estimated selectivity for the Aurora trough longline fleet was dome-shaped. Unlike the Macquarie Ridge longline fleets, this ability to catch larger fish is not imposed on the Aurora trough longline fleet selectivity. The estimated selectivity for the longline fleets indicates capture of larger fish than the trawl fishery, as evidenced by the length data, with larger fish still being selected by the longline fleets on the Macquarie Ridge.

6.3.2 Growth

The estimated growth parameters are shown in Table 4.1, and the estimated growth curves in Figure 6.12. The estimated growth curve for males has changed in this assessment, suggesting that males potentially grow much larger than females. However, this result for males has been biased as there are limited numbers of old male fish, so the growth estimates for old fish should be treated with some caution.

The growth curve still provides a reasonable fit to the data that is available, despite the order of magnitude increase in L_∞, because the other important growth parameter, K, is negatively correlated with L_∞ and has been reduced by an order of magnitude. The estimated value of the parameter L_∞ for males increased between the 2014 and 2015 assessments, and this estimated has increased rather dramatically in this assessment. Either there is little data available in this assessment to constrain this parameter, or the nature of an integrated assessment allows improved fits to other components of the data to compensate for slightly poorer fits to growth data, or possibly there is a combination of both of these features.

Immediately before beginning the tuning process, L_∞ for males was estimated to be 155. The large increase in the estimate for L_∞ for males, and associated decrease in K, only occurred during the tuning process. Given the tuning made relatively small changes to the spawning biomass and recruitment time series, further changes to the growth estimates were not checked during the tuning process. If this change in parameter value had been detected earlier, it may have been fixed at a more realistic value, resulting

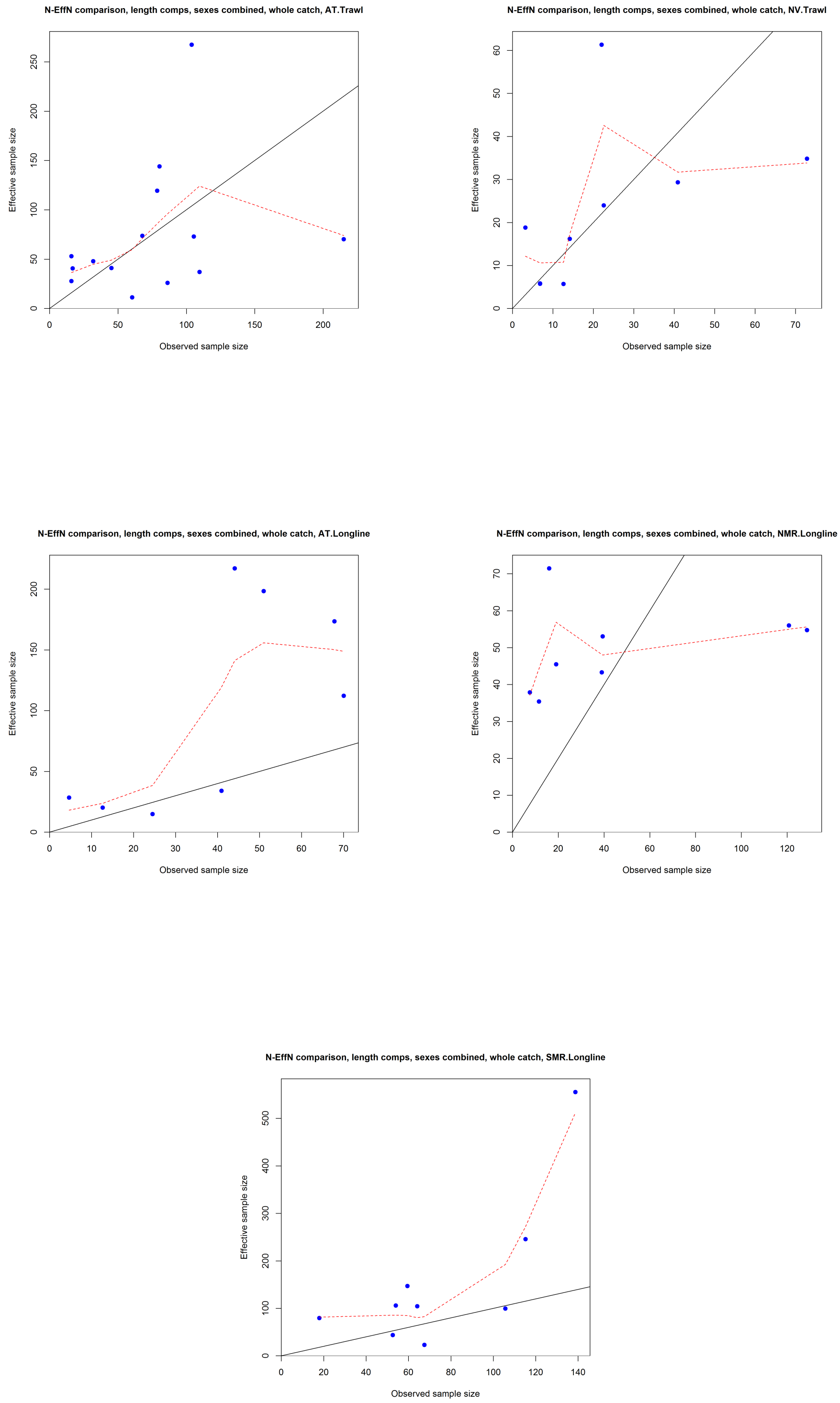

Figure 6.5: Input vs. effective sample size for the length composition data.

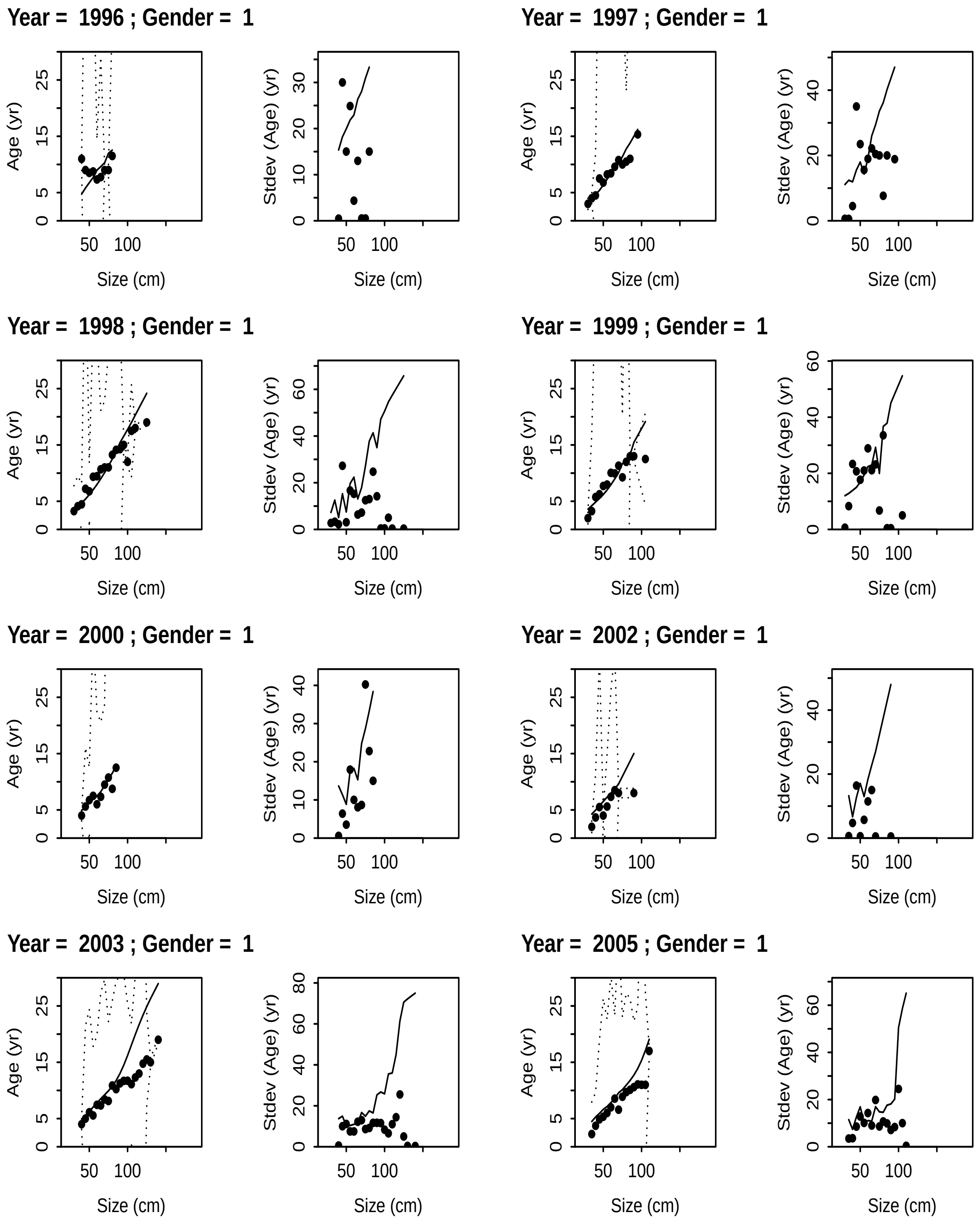

Figure 6.6: Diagnostic plots for the fits to the female (Gender = 1) conditional age-at-length data to 2005. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed and predicted) and the 90% CIs based on the chi-square distribution. The dots are the data, the solid lines the expected values, and the dotted lines the 90% CIs.

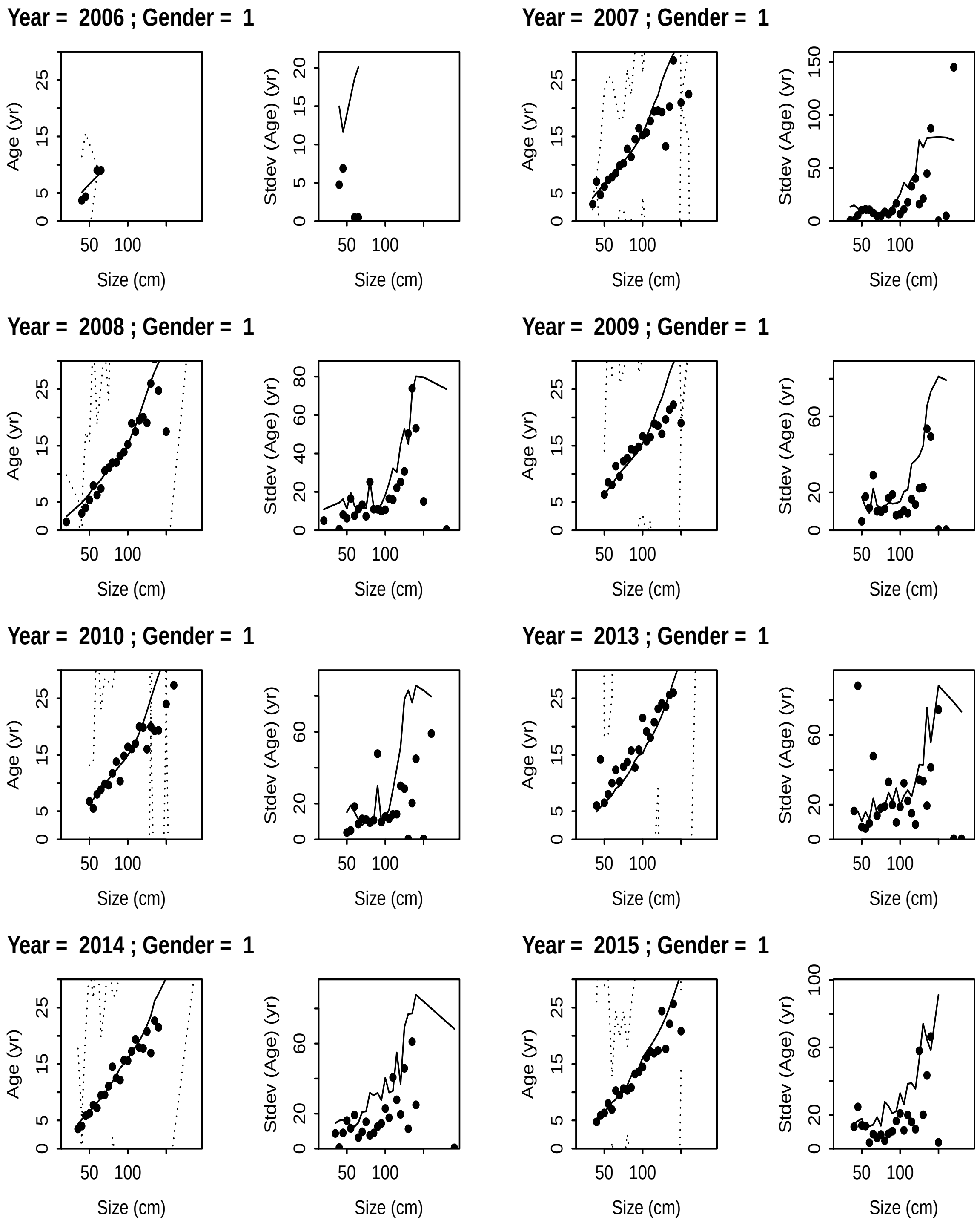

Figure 6.7: Diagnostic plots for the fits to the female (Gender = 1) conditional age-at-length data from 2006. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed and predicted) and the 90% CIs based on the chi-square distribution. The dots are the data, the solid lines the expected values, and the dotted lines the 90% CIs.

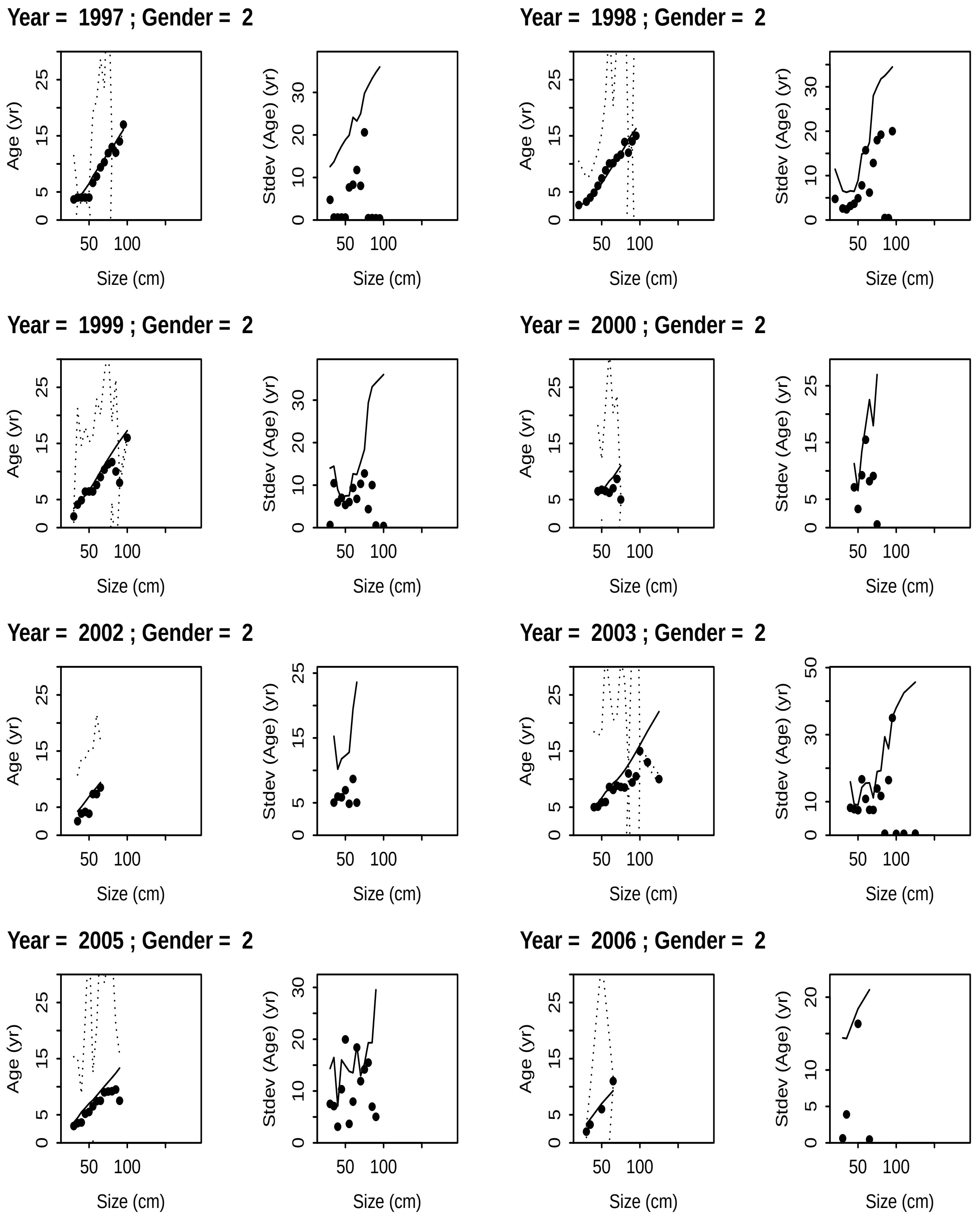

Figure 6.8: Diagnostic plots for the fits to the male (Gender = 2) conditional age-at-length data to 2005. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed and predicted) and the 90% CIs based on the chi-square distribution. The dots are the data, the solid lines the expected values, and the dotted lines the 90% CIs.

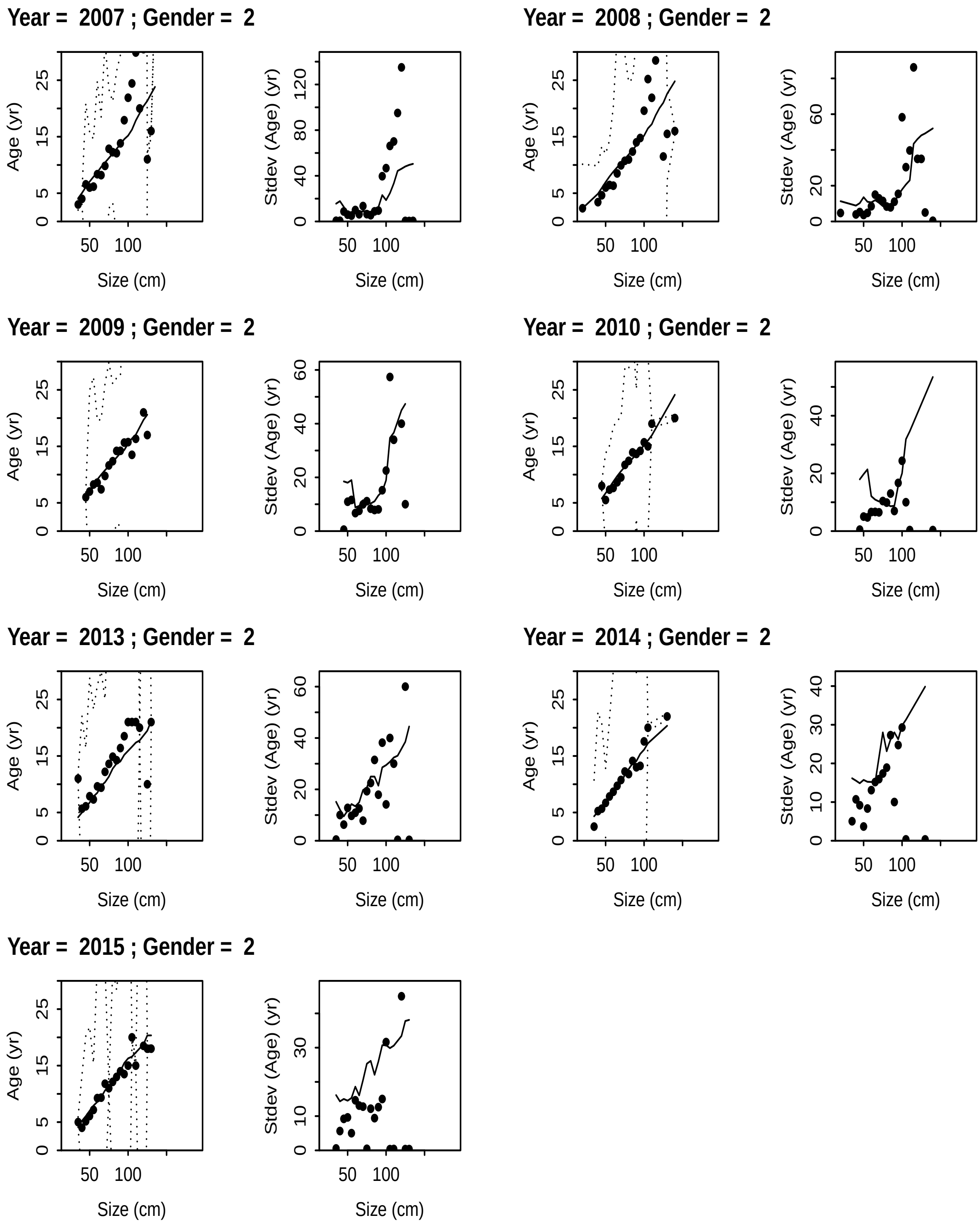

Figure 6.9: Diagnostic plots for the fits to the male (Gender = 2) conditional age-at-length data from 2006. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed and predicted) and the 90% CIs based on the chi-square distribution. The dots are the data, the solid lines the expected values, and the dotted lines the 90% CIs.

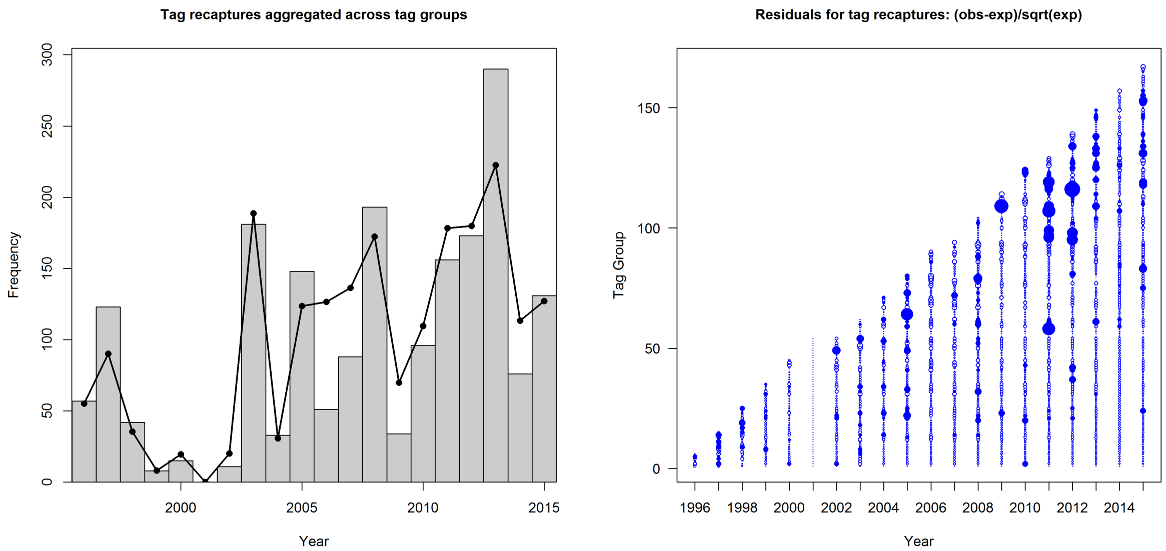

Figure 6.10: Summary of the base case fits to the tag-recapture data. Left-hand panel shows the summed observed (bars) and expected (line) recaptures over years. The right-hand panel shows the residuals by tag group and year (solid blue indicates more recaptures observed than expected).

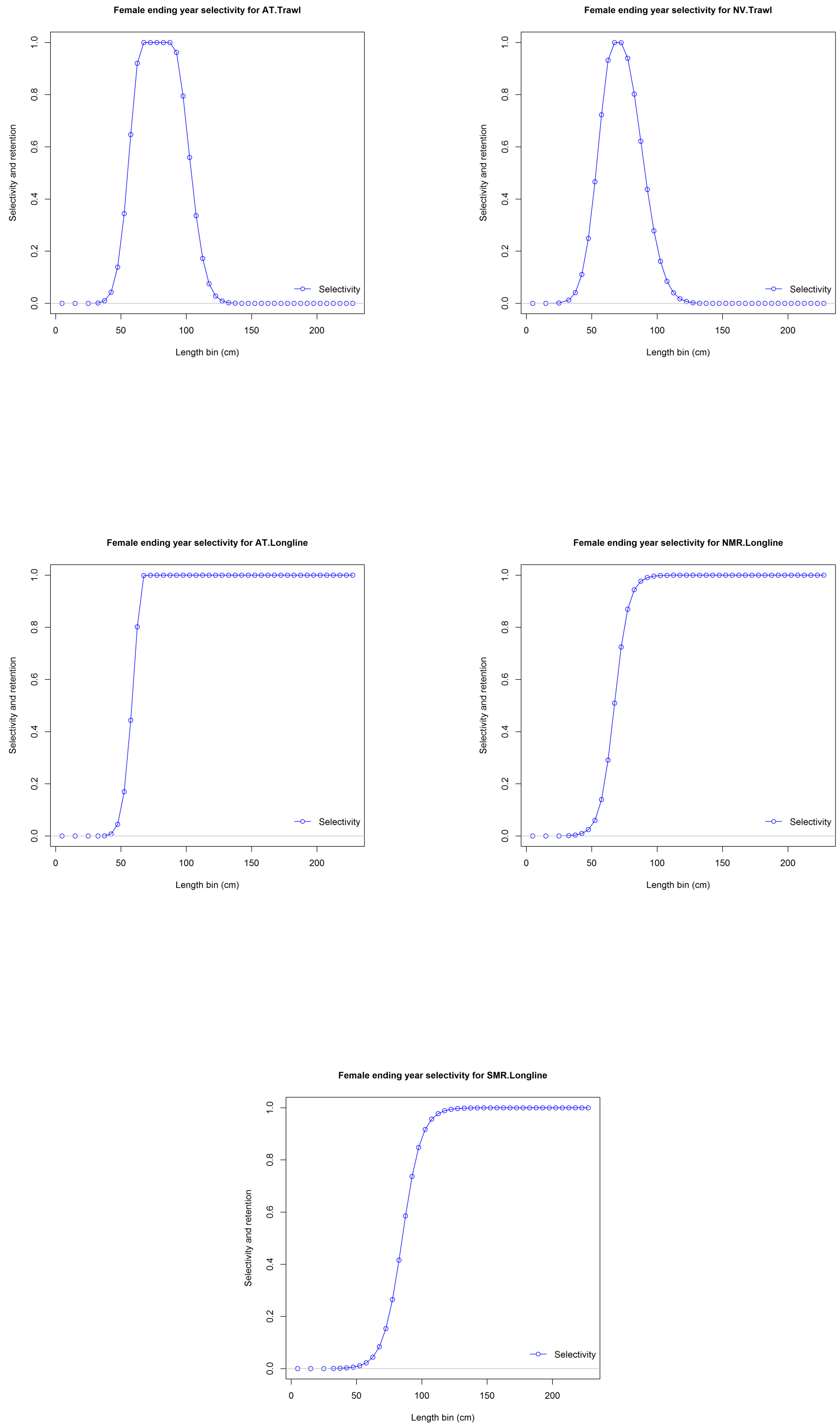

Figure 6.11: Base case estimates of selectivity at length by fleet.

in a slightly different base case. However, given that the fits to male growth are acceptable in the range covering the bulk of the data, and the small changes to the spawning biomass and recruitment series from tuning, a modified base case is unlikely to produce very different results. Consideration should be giving to fixing the value of L_∞ for males in future assessments.

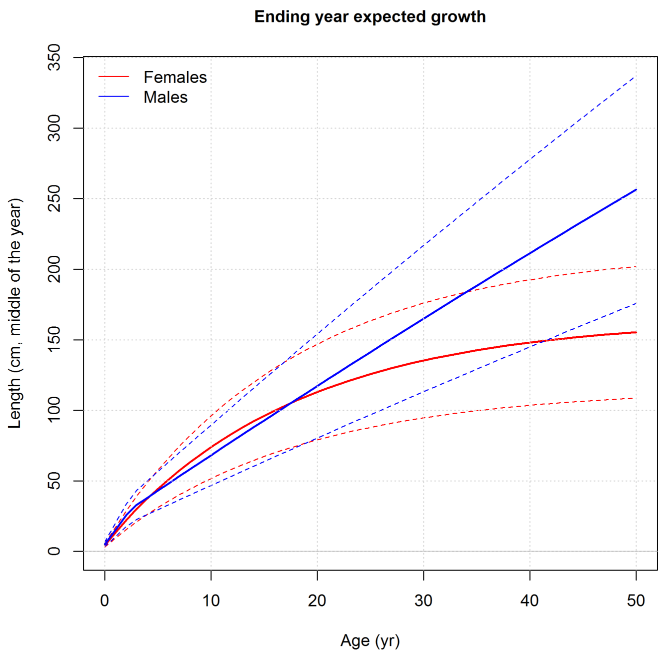

Figure 6.12: The estimated growth curves.

6.3.3 Recruitment

The recruitment pattern (Figure 6.13) shows larger year classes estimated in the mid and late 1990s. Variability in length at age, ageing error, and error in the assignment of ages to tagged fish will all contribute to a lack of precision in pinpointing the timing of recruitment events, however the general signal remains. The recruitment pattern is very similar to that in the 2015 assessment. Note that the last five estimated recruitment events all have positive recruitment deviations; these recruitment events are all slightly larger than the expected recruitment if taken directly from the stock-recruitment curve.

The proportion of new recruits allocated to each area is very uncertain, with the 95% confidence interval of the proportion recruiting to the northern area ranging from 20–52 % , with a mean of 36% (Figure 6.14). This parameter is estimated as being fixed in time. The uncertainty in the estimated proportion of recruits to the northern area is similar to the uncertainty estimated in the last three assessments, and the estimated proportion recruiting in the north is slightly smaller than the proportion estimated in the 2015 assessment.

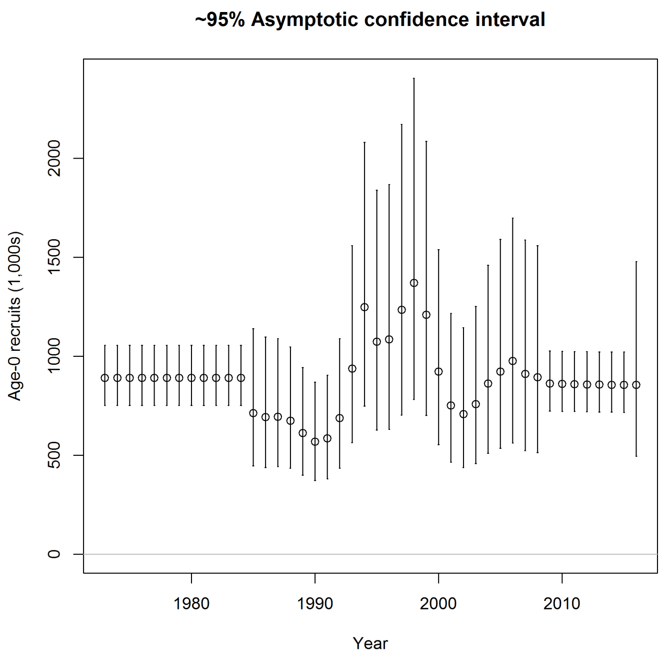

Figure 6.13: Base case estimated recruitment time series (with approximate 95% confidence interval).

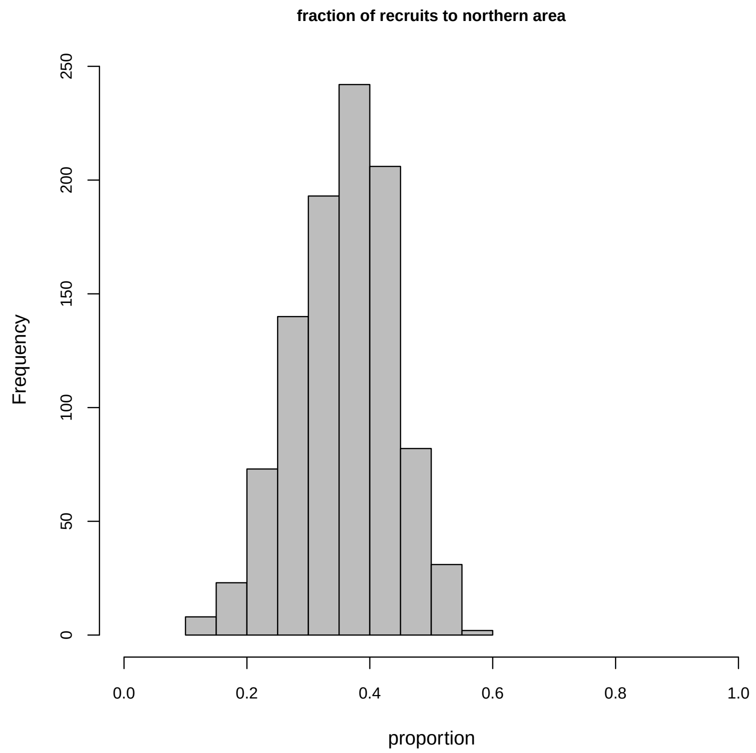

Figure 6.14: Posterior distribution for the proportion of annual recruits allocated to the northern area in the base case model.

6.3.4 Movement

The estimation of movement rates remains somewhat uncertain. In the base case, the movement rate from south to north is estimated to be between 4% and 8% per annum, with a lower rate of between 0.6% and 1.3% per annum for north-to-south movement (Figure 6.15). More exploration is needed of the interaction of movement parameters with the other components of the model. The model estimates a high movement rate of fish from south to north in order to reconcile the apparently conflicting results of low recaptures of NV trawl-tagged fish and the recapture of southern tagged fish in the north (i.e. if the stock is large enough for the recapture rate of NV trawl-tagged fish to have been low, then there must be movement from south to north in order for any of the southern tagged fish to have been caught at all in the north).

6.3.5 Biomass and fishing mortality estimates

Table 6.1 gives the point estimates for the current and unfished female spawning biomass for the base case model and the models investigated in the sensitivity analyses.

The base case current spawning biomass estimate is 67% of unfished female spawning biomass (Table 6.1), compared to an estimate of 69% from the 2014 assessment.

The time series of female spawning biomass has declined steadily since the start of the fishery (Figure 6.16), and has stabilised at just under 70% of unfished in the last three years. As the biomass levels by area are somewhat mediated by uncertain estimates of recruitment allocation and movement, it is unsurprising that the spawning biomass trend for the spatial model is estimated with large uncertainty.

The point estimate for the 2016 stock size in the northern area is estimated to be about seven times larger than that in the south (female spawning biomass 1,799t and 256t respectively). The northern area is also

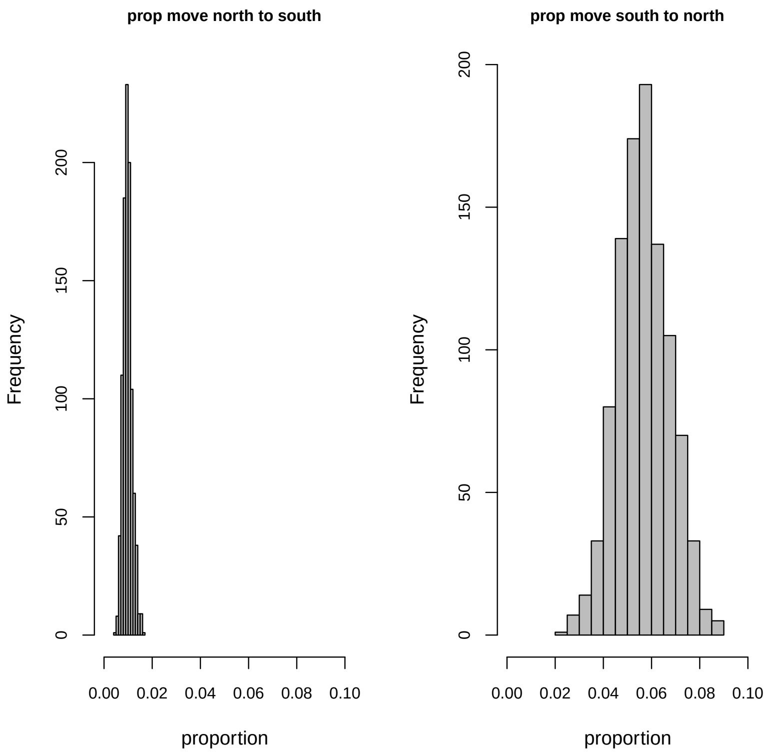

Figure 6.15: Posterior distributions for the values of the movement parameters in the base case model.

estimated to be considerably less depleted than the southern area (75% and 37% respectively).

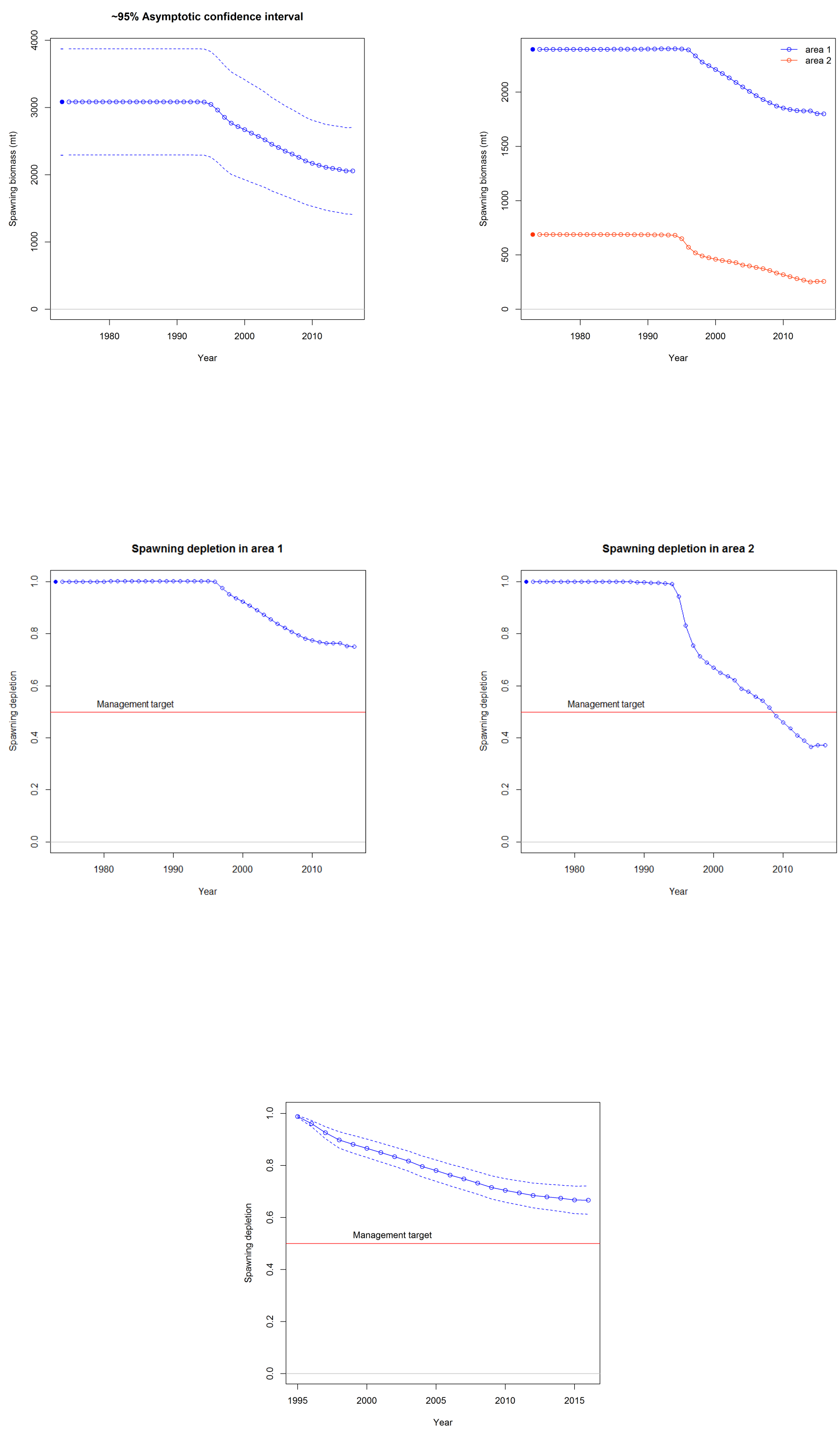

Figure 6.16: Base case estimated time series for female spawning biomass and spawning depletion (spawning biomass relative to unfished), both by area and overall. Area 1 is north, and area 2 is south.

Table 6.1: Results of the base case and sensitivity analyses, with estimates of female spawning biomass, and the contributions to the negative logarithm of the likelihood function. The base case has the following parameters fixed: female $L_\infty = 165$ cm; $M = 0.13$ yr^{-1}; $h = 0.75$; 50% female maturity at 139.6 cm; $\sigma_R = 0.27$ and logistic selectivity for the north and south Macquarie Ridge longline fleets. The sensitivity analyses listed here explore the impacts of these assumptions. Likelihood values for sensitivities are shown as differences from the base case. To enable meaningful comparisons to the base case, when the weighting of components is doubled or halved, re-weighted likelihoods are listed in the table, halving or doubling the likelihood on the component that has been changed. A negative value indicates a better fit; a positive value a worse fit. Values in the latter columns in italics indicate values not comparable with those in the base case.

	Female spawning biomass			F_{50} yield	MSY yield	negative log-likelihood					
Model	$SB_{15/16}$	SB_0	$SB_{15/16}/SB_0$			total	length	age	Tag comp	Tag recap	Recruit
Base case	**2055**	**3083**	**0.67**	**456**	**563**	**2628.5**	**229.5**	**180.5**	**786.4**	**1451.7**	**-19.6**
fix male L_∞ = 130	2678	3826	0.70	441	577	*7.1*	*-7.6*	*-0.7*	*5.1*	*10.0*	*0.2*
fix male L_∞ = 165	2456	3567	0.69	443	572	*3.8*	*-5.4*	*-1.3*	*3.3*	*7.1*	*0.1*
fix male L_∞ = 200	2333	3420	0.68	445	568	*2.4*	*-4.0*	*-1.4*	*2.3*	*5.3*	*0.1*
female L_∞ = 195	2702	4072	0.66	437	547	-1.1	0.7	-1.9	-0.2	0.3	-0.1
$M = 0.155$	1045	1757	0.59	362	460	-14.4	-2.5	-1.7	-6.7	-2.8	-0.7
M estimated (0.20)	430	806	0.53	306	408	*-29.0*	*-1.5*	*-2.1*	*-6.0*	*-18.2*	*-1.2*
$h = 0.5$	2080	3130	0.66	332	361	0.5	0.1	0.0	0.2	0.0	0.2
$h = 0.9$	2047	3067	0.67	505	696	-0.2	-0.1	0.0	-0.1	0.0	-0.1
dome shaped selectivity for NMR & SMR ll	2529	3593	0.70	439	564	*-5.5*	*-5.5*	*0.0*	*1.1*	*-1.3*	*0.2*
50% female maturity at 130 cm	2686	3967	0.68	475	578	0.0	0.0	0.0	0.0	0.0	0.0
Halve weight on LF data	2073	3118	0.66	466	574	2.4	8.7	-1.4	-0.5	-0.2	-4.1
Double weight on LF data	2409	3455	0.70	433	560	7.9	-14.4	1.8	5.6	7.7	7.2
Halve weight on age data	2019	3021	0.67	456	563	1.1	-1.7	3.5	0.3	-1.8	0.9
Double weight on age data	2144	3205	0.67	448	559	1.1	1.1	-2.5	-0.2	4.2	-1.5
Halve weight on tag data	2317	3410	0.68	429	552	4.9	-6.3	-2.7	3.3	11.9	-1.2
Double weight on tag data	2037	3038	0.67	470	579	1.7	1.2	2.2	0.6	-4.7	2.4

6.3.6 2015/16 catch levels

Table 6.1 shows the estimated values for the yield at a spawning stock size of 50% unfished, and at the biomass level which results in maximum sustainable yield. Calculation of the 2016/17 TAC under application of the CCAMLR harvest strategy for toothfish (constant catch that gives a median spawning biomass in 35 years no less than 50% of unfished, and a chance of dropping below 20% unfished spawning biomass of less than 10%) requires samples from the posterior distribution in order to calculate the probability-based reference points. The CCAMLR control rule integrates the uncertainty associated with the estimation procedure and future recruitment events. The catch levels that satisfy the control rule can be expected to change given alternative assumptions regarding how the catches will be allocated to fleet and region. Table 6.2 gives the values calculated for the base case for nine catch combination assumptions, with all catch coming from the longline fleets. Catches were calculated for both 2016/17 and 2017/18, to allow a two year RBC to be set while still complying with the CCCAMLR rule. The projected 2016/17 and 2017/18 catches range from 420t to 500t.

Table 6.2: Catch combinations for the base case model that satisfy the CCAMLR control rule. These catches are for longline fleets only.

Constraints	Catches (t)			Total catch (t)
AT:NMR:SMR	AT	NMR	SMR	
420t : 0% : 0%	420	0	0	420
250t : 20% : 80%	250	42	168	460
250t : 40% : 60%	250	80	120	450
250t : 60% : 40%	250	120	80	450
200t : 40% : 60%	200	104	156	460
200t : 60% : 40%	200	156	104	460
150t : 0% : 100%	150	0	350	500
150t : 50% : 50%	150	160	160	470
150t : 100%: 0%	150	310	0	460

Figure 6.17 shows the posterior distribution for female spawning biomass, recruitment, and relative spawning biomass assuming a 250t catch at Aurora Trough, and a split of the remaining catch 60%:40% between the north and the south Macquarie Ridge.

In order for the stochastic projections to work correctly it is not possible to stop the modelling software from estimating the recruitments between the final year in which recruitment is estimated and the end year of data (i.e. 2007–2015 in this case). Instead, to avoid unruly recruitment estimation arising from the model attempting to fit to sparse and noisy data at the end of the time series, it is necessary to downweight the likelihood contribution of these recruitments. Use of this method means that these recruitments are not sampled with the full amount of variability the stochastic projections. However all recruitments in the projection period are correctly sampled (see the recruitment plot in Figure 6.17).

6.4 Sensitivity Analyses

Sensitivity analyses examine the consequences of alternative assumptions to the base case scenario on the model results. The results of a suite of sensitivity tests are presented in Table 6.1. The various contributions to the likelihood function have been presented so the values given are comparable to the base case. When particular components weighting are doubled or halved (last six rows of Table 6.1), this requires corresponding individual likelihood components to be halved or doubled when reported, and when included in the total likelihood reported in this table. This enables meaningful comparisons of the changes to the overall likelihood and individual likelihoods, so changes to both the overall fits and the fits to the various different data sources can be assessed. Likelihood values for the sensitivities are shown as differences from the base case.

Exploring a range of values for male L_∞, fixed between 130 and 200, all show poorer overall fits, with male L_∞ of 130 giving the poorest fits. The length fits are improved by fixing male L_∞, with better fits for

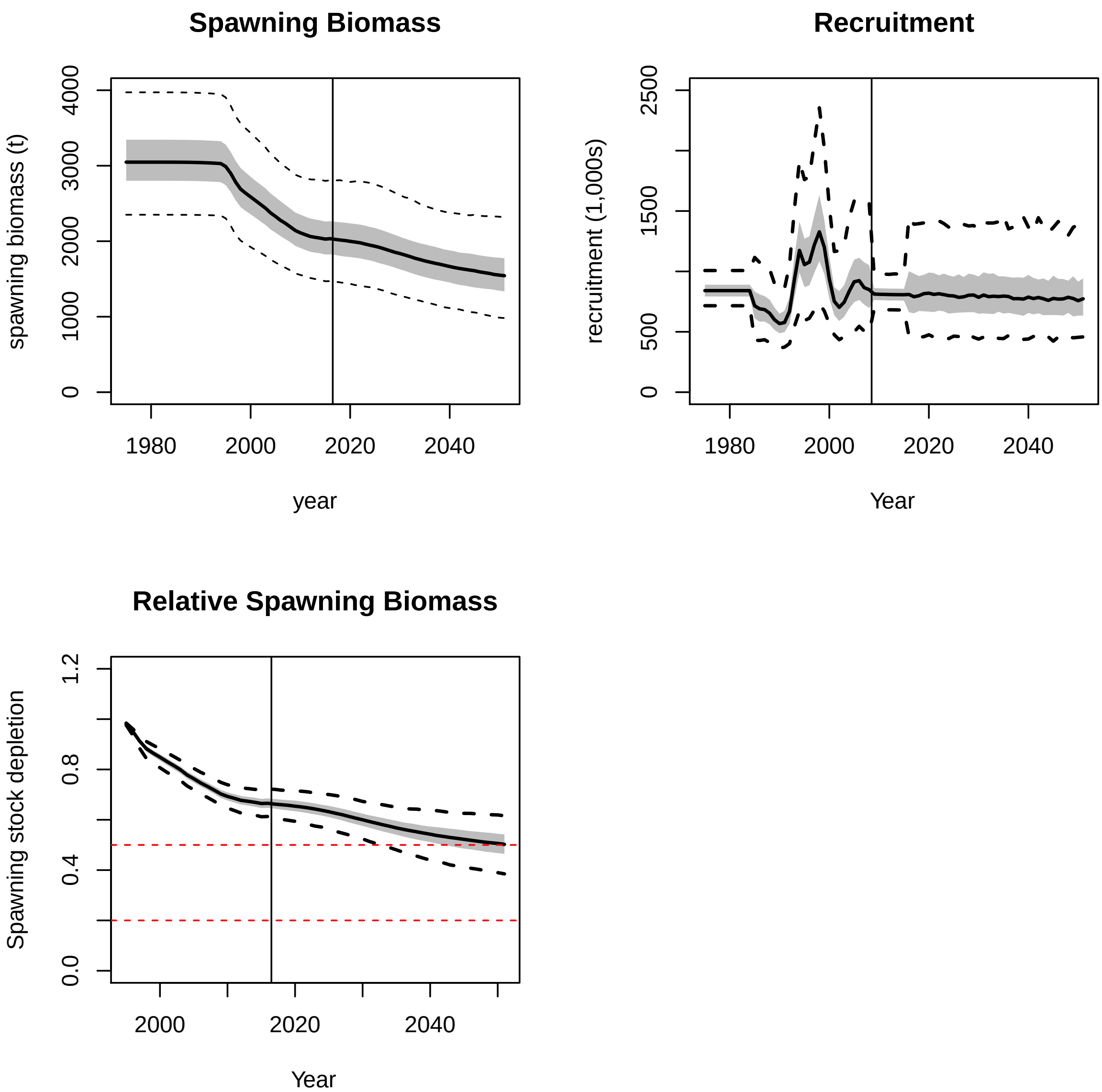

Figure 6.17: Posterior distribution and projection of female spawning biomass, recruitment, and spawning biomass relative to the unfished level, under a constant catch of 450t, split 250t for Aurora Trough, 120t for northern Macquarie Ridge and 80t for southern Macquarie Ridge.

smaller values. The age data fits are largely unchanged, but the fits to the tag data are poorer with a fixed male L_∞ and deteriorate as the value of male L_∞ gets smaller. Current spawning biomass is slightly less depleted when male L_∞ is fixed.

In contrast, using the larger estimate of female L_∞, as estimated by Constable *et al.* (2001), has little impact on any of the fits.

Fixing the value of the rate of natural mortality, M, at the Heard Island estimate of 0.155 yr^{-1} leads to a better overall fit, which largely arises from improvements to fits to the tag data, with similar results when M is estimated within the model. Estimating the value for M within the model suggests a value higher than that used in previous assessments for Macquarie Island toothfish, of the order of 0.2 yr^{-1}. However, such a high value, which suggests there would be few fish older than 23 years of age, is considered unrealistic for such a relatively long-lived fish. Higher values of M also result in implausibly low estimates of current female spawning biomass. The tendency toward higher estimates for M could mean that the value for this parameter is indeed higher than previously assumed, but could also reflect the effects of tag loss and post-tag mortality, considered here to be negligible.

There appears to be little information in the data regarding the value for the steepness of the stock-recruitment relationship, as the log-likelihood is almost unchanged when alternative fixed values for this parameter are used. Similarly, there is little impact from changing the length for 50% female maturity.

Using dome-shaped selectivity for the Macquarie Ridge longline results in better overall fits, mostly through better length fits. The logistic form has been chosen for the base case model as it is intrinsically more conservative.

Changing the weighting on various data sources degrades the overall fit to the data in all cases, but has little effect on the estimate of current stock status. If additional weight is placed on the length data, this supports a less depleted stock, but with poorer overall fits to the data, mostly through poorer fits to the tag data.

All impacts of doubling and halving the weighting on age are minor. Halving the weighting on tag data gives better fits to length and age, but poorer overall fits.

This suggests some conflict in the signal coming from the the tag data and the length data, and to a lesser extent a conflict between the tag data and the age data.

6.5 Discussion points and future work

The analysis presented here raises the following points of discussion and plans for future work:

1. The northern area is estimated to contain larger stock size than in the south. Spawning stock status in the north is well above 50% unfished, whereas in the south it is slightly below 50%.
2. The male L_∞ should probably be fixed in future assessments as there appears to be little information in the data to enable this parameter to be estimated at a biologically realistic value.
3. Changes to the spatial distribution of catch in the 2014 and 2015 seasons may have provided additional information on the stock status, especially in the north, although there is still considerable uncertainty about movement of fish between these two areas.
4. More exploration is needed of the interaction of movement parameters with the other components of the model.

7 Acknowledgements

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Appendix 3

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Age-at-length or length-at-age for modelling the growth of Macquarie Island toothfish?

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Prepared for the SARAG held in Hobart, Australia 9th of February 2015

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Abstract

Traditionally, methods for modelling growth have focussed on length-at-age measurements (e.g. via otoliths or other hard parts), which assume length is sampled randomly for each age-class (and age is known without without error). More recently, the focus has shifted to modelling age-at-length, not length-at-age. This assumes age is sampled randomly within each element of the given length partition. Most often this is done within an integrated stock assessment model, where age frequency conditional on length and length frequency distributions are the primary information sources, not individual length-at-age measurements. A novel method for performing the age-at-length approach outside of the assessment framework is outlined. We contrast the estimates from these two methods with the age-at-length estimates coming from the integrated stock assessment model to see if and - crucially - why the estimates may differ.

1 Introduction

Growth is a central driver of the individual (and population-level) dynamics of a fish (and the stock it belongs to) as well as those of the fishery itself. As befits this centrality, modelling growth has been a mainstay of fisheries science and stock assessment from the beginning. Many sources of data hold information on growth:

- Direct length-at-age: where age is determined from a hard part such as an otolith or, for elasmobranchs, the vertebrae.
- Mark-recapture data: the growth increment between release and recapture is the information source, but there is no information on actual age.
- Length frequency data: in a closed population (specifically within one recruitment cycle) the progression of modes in a length frequency holds information on the growth rate of the population. As with mark-recapture data there is no direct information on age, save the number of age classes present if they are clear enough to be estimated well.

For Macquarie Island toothfish, there is an extensive amount of length-at-age measurements from otoliths and a reasonable amount of tagging data, so there is ample information available for exploring appropriate growth models.

Initial approaches explored the length-at-age modelling framework, which assumes length is sampled randomly for that age, age is known without error, and each measurement of length-at-age is conditionally independent of all the others. The advantages of this approach are that it is conceptually simple to understand, and computationally fairly simple (at least for basic approaches) to implement. The disadvantages are that, in almost all fishery applications, length will not sampled randomly by age, nor will age be known without error, so two out of three of the main assumptions are highly likely to be invalid.

More recently, alternate approaches have explored the age-at-length framework [9, 10]. In this approach the primary data source is the relative frequency of age *conditional* on length, not length-at-age. This assumes that age is sampled randomly *within* a given length bin. Note this does **not** assume length is sampled randomly relative to the population. There will be, almost surely, some length stratification in the samples (via selectivity), but this can be dealt with as we shall see. In the integrated stock assessment framework [8] the effect of this length stratification in the sampling, attributed to length-specific selectivity, is dealt with directly as the selectivity is estimated along with the growth parameters via the inclusion of the length frequency data. Additionally, the ageing error can also be dealt with in this framework. The disadvantages of this approach are that it can be harder to visualise the data, relative to the length-at-age framework, and it is computationally a bit more demanding. An additional disadvantage to implementing this approach in the integrated assessment framework is parameter aliasing and correlation with other (potentially mis-specified) life-history parameters, as well as potentially spurious information from other data sources like abundance indices.

In this paper we explore both approaches to modelling growth, compare and contrast the estimates using previous growth modelling work for this stock and a novel age-at-length approach that can be undertaken outside of the assessment framework. These external estimates are then compared to those from the stock assessment. The point of the external age-at-length model is to serve as a bridge to the full assessment estimates. Length-at-age estimates have often differed from the age-at-length estimates in the assessment model - particularly last year for the males [3]. By having the external age-at-length model we can determine the cause of those differences: is it the alternative modelling approach, or the interaction with other data and life-history parameters in the assessment?

2 Materials and methods

2.1 Data

The length-at-age data, for which we have sex identification, are quite extensive: 1,921 males and 2,756 females, caught between 1996 and 2015. For some fish there are repeated measurements, and in such cases the age used is the mean age of the repeated readings. Ages taken from recaptured tagged fish are also excluded in certain runs given potential concerns around post-tag growth retardation leading to biased lengths for those fish. Figure 2.1 summarises the length-at-age data used in these analyses.

Exactly the same underlying data are used in the age-at-length analyses, but they require a reasonable amount of transformation first. We need to define a length partition so as to be able to bin the data and we chose the following: 0.2m defines the lower bound of the partition (for both sexes) and the partition is split into equal sized bins of width 0.1m up to 1.5m and the final length bin stretches from 1.5m to the maximum observed length of that particular sex. The two key data sets are:

1. The length frequency distribution, $p_{y,l}$, of the aged animals in year y
2. The age frequency distribution, $p_{y,a,l}$, *conditional* on the given length partition element l, in year y

2.2 Length-at-age

As mentioned, the base model is von Bertalanffy with a normal-log likelihood function. This is effectively the same as a normal likelihood with errors proportional to length which, at least for the process error bit, is one of the ways to come at individual variation in L_∞ from a non-hierarchical perspective. So $\widehat{l} = L_\infty \left(1 - e^{-k(a-t_0)}\right)$ and $\log l \sim N(\log \widehat{l}, \sigma_o^2 + \sigma_p^2)$, $\sigma_o^2 = \log(1 + cv_o^2)$ is the observation error (for the given CV of 0.05 for this case), and σ_p^2 is an estimated process error term. The estimated parameters are $\ell_\infty = \log L_\infty$, $\kappa = \log k$, t_0 and σ_p^2 with the following priors:

$$\begin{aligned}
\ell_\infty &\sim N(\mu_{\ell_\infty}, \sigma^2_{\ell_\infty}),\\
\kappa &\sim N(\mu_\kappa, \sigma^2_\kappa),\\
t_0 &\sim N(\mu_{t_0}, \sigma^2_{t_0}),\\
\sigma_p &\sim \sigma_p^{-1},
\end{aligned}$$

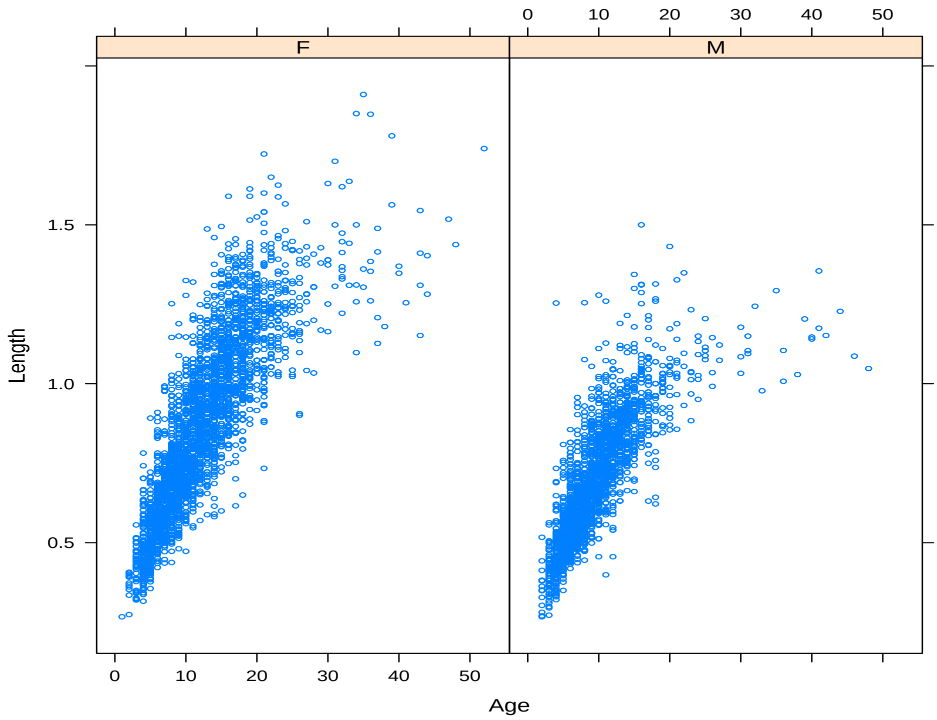

Figure 2.1: *Female (left; N=1,921) and male (right; N=2,756) length-at-age measurements for Macquarie Island toothfish from 1996 to 2015.*

with $\mu_\bullet = 0$ and $\sigma^2_\bullet = 100$ in all cases. With the assumption of a normal likelihood on the log-scale length data the conditional posterior for ℓ_∞ is known:

$$\pi(\ell_\infty \mid \cdots) = N\left(\tilde{\mu}, \tilde{\sigma}^2\right) \tag{2.1}$$

where

$$\tilde{\mu} = \left(\frac{\mu_{\ell_\infty}}{\sigma^2_{\ell_\infty}} + \frac{\sum_{i=1}^{\aleph} \varepsilon_i}{\sigma^2_o + \sigma^2_p} \right) \left(\frac{1}{\sigma^2_{\ell_\infty}} + \frac{\aleph}{\sigma^2_o + \sigma^2_p} \right)^{-1},$$

$$\tilde{\sigma}^2 = \left(\frac{1}{\sigma^2_{\ell_\infty}} + \frac{\aleph}{\sigma^2_o + \sigma^2_p} \right)^{-1},$$

and $\aleph$ is the number of data points and $\varepsilon_i = \log l_i - \log\left(1 - \exp(-k(a_i - t_0))\right)$. This makes it a bit more efficient in terms of MCMC sampler performance, as ℓ_∞ is sampled directly from the conditional posterior in (2.1) and κ, t_0 and σ_p are updated using a Metropolis-within-Gibbs routine written up in C++. A 1,000 iteration burn-in is used, with a further 1,000,000 samples drawn and every 1000$^{\text{th}}$ retained (thinning factor of 1000) to yield 1,000 samples from the posterior (non-convergence checked using standard methods [1]). The reason for the high level of thinning is the strong levels of Markov chain autocorrelation you get with such large and informative data sets, and very correlated parameters like k and L_∞.

2.2.1 Individual asymptotic length

The hierarchical model is a little different in form than the previous example. The first difference is that we remove the process error form from the likelihood, so $\widehat{l_i} = L_{\infty,i}\left(1 - e^{-k(a_i - t_0)}\right)$ and $\log l_i \sim N(\log \widehat{l_i}, \sigma_o^2)$ and the index i relates to each animal that is aged and measured: each animal has its own L_∞. In this formulation, we assume that $\mu_{\ell_\infty} \sim N(\mu_\xi, \sigma_\xi^2)$ and $\sigma^2_{\ell_\infty} \sim IG(\gamma_\xi, \psi_\xi)$ (inverse gamma distribution) and these are our hyper-parameters with the following hyper-priors: $\mu_\xi = 0$, $\sigma_\xi^2 = 100$, $\gamma_\xi = \psi_\xi = 0.001$. This model has *considerably* more parameters than the previous one (for the females/males 1,926/2,761 versus 4) and trying to do this in `ADMB-RE` as a random effect model would be problematic or take far too long in `WinBUGS`. Fortunately, the likelihood and prior structure means that the conditional posteriors for $l_{\infty,i}$, μ_{ℓ_∞} and $\sigma^2_{\ell_\infty}$ are all of a known form:

For $l_{\infty,i}$, we have the following:

$$\pi(l_{\infty,i} \mid \cdots) = N\left(\left(\frac{\mu_{\ell_\infty}}{\sigma^2_{\ell_\infty}} + \frac{\varepsilon_i}{\sigma_o^2}\right)\left(\frac{1}{\sigma^2_{\ell_\infty}} + \frac{1}{\sigma_o^2}\right)^{-1}, \left(\frac{1}{\sigma^2_{\ell_\infty}} + \frac{1}{\sigma_o^2}\right)^{-1}\right), \tag{2.2}$$

and for μ_{ℓ_∞}:

$$\pi(\mu_{\ell_\infty} \mid \cdots) = N\left(\left(\frac{\mu_\xi}{\sigma_\xi^2} + \frac{\sum_{i=1}^{\aleph} l_{\infty,i}}{\sigma^2_{\ell_\infty}}\right)\left(\frac{1}{\sigma_\xi^2} + \frac{\aleph}{\sigma^2_{\ell_\infty}}\right)^{-1}, \left(\frac{1}{\sigma_\xi^2} + \frac{\aleph}{\sigma^2_{\ell_\infty}}\right)^{-1}\right), \tag{2.3}$$

and finally for $\sigma^2_{\ell_\infty}$:

$$\pi(\sigma^2_{\ell_\infty} \mid \cdots) = IG\left(\gamma_\xi + \frac{\aleph}{2}, \left(1 + \frac{\psi_\xi \sum_{i=1}^{\aleph} (l_{\infty_i} - \mu_{\ell_\infty})^2}{2}\right)\psi_\xi^{-1}\right) \tag{2.4}$$

2.3 Age-at-length

This approach makes fundamental use of the same assumed distribution for length-at-age as in the more traditional growth framework. For a given age, a, there is an associated probability of each length bin in the partition, l:

$$\pi_{l|a} = CDF\left(\mu_{\lceil l\rceil,a}, \sigma_{\lceil l\rceil,a}\right) - CDF\left(\mu_{\lfloor l\rfloor,a}, \sigma_{\lfloor l\rfloor,a}\right), \tag{2.5}$$

where $CDF()$ is the Gaussian cumulative distribution function; $\mu_\bullet$ and $\sigma_\bullet$ are the log-scale mean length and associated SD, respectively; and $\lfloor l\rfloor$ and $\lceil l\rceil$ are the infimum and extremum of the partition element l, respectively.

To get the (annual) probability distribution of age-at-length, $\pi_{y,a|l}$, we must apply Bayes' rule:

$$\pi_{y,a|l} = \frac{\pi_{l|a}\pi_{y,a}}{\pi_{y,l}}, \tag{2.6}$$

where

$$\pi_{y,l} = \sum_a \pi_{l|a}\pi_{y,a}. \tag{2.7}$$

It is at this stage that we need to define additional parameters - specifically the prior age-distribution, $p_{y,a}$. In a simple equilibrium population with constant, age-independent M and F and no recruitment variation the age distribution in the population is proportional to $\exp(-Za)$. Indeed, this forms the basis of the approximation used in [10] to avoid having to explicitly model the prior age distribution. In the stock assessment context, with a simple time-invariant selectivity ogive, s_a, then this prior is proportional to $s_a N_{y,a}$, where $N_{y,a}$ is the numbers-at-age matrix. We, however, take a more direct parametric route and model each year-specific prior age distribution as a log-normal distribution, with estimated mean $\mu_{y,a}$ and SD $\sigma_{y,a}$.

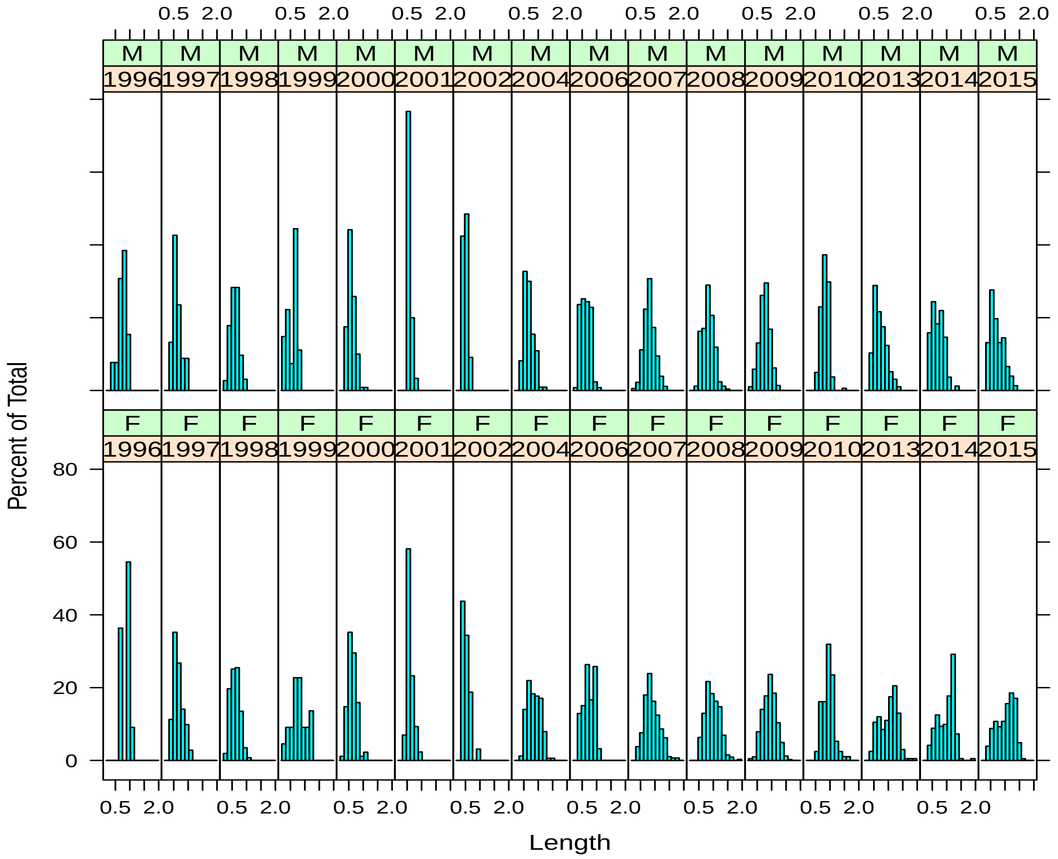

Figure 2.2: *Length frequency of age samples (by sex).*

The conditional age-at-length data alone are insufficient to estimate both the growth and the prior age distribution parameters, but with the inclusion of the length frequency data *can* make joint estimation feasible. We say can make it feasible because that depends on the amount of information on the likely age distribution in the sample contained within the length data. If all the length data are too close to where growth begins to asymptote the amount of information on age dramatically reduces. Additionally, there is often an increase in the precision of the growth estimates that accompanies the inclusion of the length frequency data [9]. As we see in Figure 2.2 the length frequencies of the aged samples are (mostly) unimodal and slightly right-skewed (hence, the choice of a log-normal age prior) and not clustered at the highest observed lengths and so are likely to be informative enough as to the prior age distribution.

The basic (multinomial) log-likelihood for the conditional age-at-length data is as follows:

$$\Lambda_{a|l} \propto \sum_y \sum_l \sum_a n_y p_{y,a,l} \log\left(\pi_{y,a|l}\right), \tag{2.8}$$

and for the length data (also multinomial)

$$\Lambda_l \propto \sum_y \sum_l n_y p_{y,l} \log\left(\pi_{y,l}\right), \tag{2.9}$$

and n_y is the number of samples of length-measured and aged fish taken in that year. The total log-likelihood, Λ, is just the sum of the two terms in Eqns. (2.8) & (2.9).

2.4 Ageing error

Ageing error is a major factor in general for estimating age from hard parts. Fortunately, for Macquarie Island toothfish there are repeat readings taken across otolith readers. This has enabled the construction of an ageing error matrix, $A_{a,a'}$, the $\{a, a'\}^{\text{th}}$ element of which is the probability that the observed age a is actually the "true" age a', and $\sum_a A_{a,a'} = 1$. Essentially, each of column of the matrix defines $\Pr(a \,|\, a')$, and the model-prediction for the observed proportion of age a in the sample, is given by

$$\pi_{y,a|l} = \sum_{a'} \Pr(a \,|\, a')\pi_{y,a'|l}, \tag{2.10}$$

where $\pi_{y,a'|l}$ is the model-predicted proportion of actual age a' fish in the sample.

The current ageing error matrix is based on the HIMI toothfish ageing data, and can be visualised in Figure 2.3. Dealing with ageing error in the length-at-age paradigm is technically quite difficult, requiring a very high dimensional state-space augmentation as it becomes an errors-in-variables problem. In the age-at-length framework, it can be fully accounted for in the likelihood as defined in Eq. (2.8).

2.5 Process error

The underlying assumptions in the age-at-length and the length data are:

1. The number of length-measured and aged samples, n_y, are the true number of independent samples - the *effective* sample size
2. The true level of variability in the length-at-age relationship and prior age distribution is captured in the probability mode defined

Assumption 1 can often be invalid as a lot of sampling is - to some degree - not randomly done; Assumption 2 can be broken by a mis-specified model in the variation in length-at-age (e.g. "fatter" tails than the Gaussian assumed). Given the underlying multinomial likelihood the natural way to do this is via the compound Dirichlet-multinomial distribution. This model assumes a Dirichlet distribution for underlying model-predicted probability $\pi_\bullet$ (be it age-at-length or just length). The key parameter that controls this distribution is ω.

In a very general setting with data, Y, model-predicted sampling probability, π, and underlying sampling probability ξ - where $\xi \sim p(\xi \,|\, \pi, \omega)$ the joint likelihood is defined as:

$$\ell(Y \,|\, \xi, \pi, \omega) \propto \ell(Y \,|\, \xi)p(\xi \,|\, \pi, \omega). \tag{2.11}$$

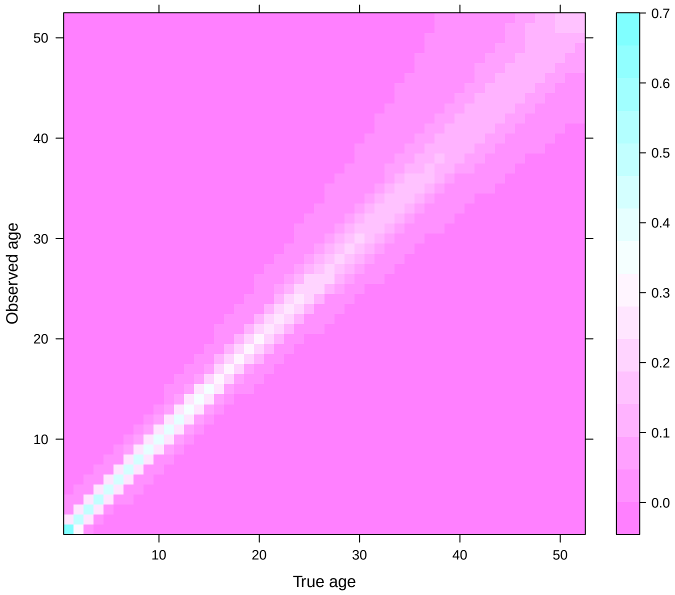

Figure 2.3: *Ageing error matrix used for Macquarie Island toothfish. The x-axis denotes the true age, and the y-axis the observed age*

What we need to do is integrate over ξ to leave the marginal likelihood of the data given the model predicted sampling probability:

$$\ell(Y \mid \pi, \omega) \propto \int \ell(Y \mid \xi) p(\xi \mid \pi, \omega) \mathrm{d}\xi. \tag{2.12}$$

This integral is of a known form, and the marginal log-likelihood for the length data can be expressed in terms of the log-scale gamma function $\gamma = \ln \Gamma()$:

$$\Lambda_l(n_y, p_{y,l} \mid \pi_\bullet, \omega_\bullet) \propto \sum_y \left(\gamma(n_y + \omega_y) - \gamma(\omega_y) + \sum_l \gamma\left(\omega_y \pi_{y,l}\right) - \gamma\left(n_y p_{y,l} + \omega_y \pi_{y,l}\right) \right). \tag{2.13}$$

For the conditional age-at-length data it is a bit more involved, given the more complex nature of the data:

$$\Lambda_{a|l}(n_y, p_{y,l,a} \mid \pi_\bullet, \omega_\bullet) \propto \sum_y \sum_l \left(\gamma(n_y p_{y,l} + \omega_{y,l}) - \gamma(\omega_{y,l}) + \sum_a \left[\gamma\left(\omega_{y,l} \pi_{y,a|l}\right) - \gamma\left(n_y p_{y,l,a} + \omega_{y,l} \pi_{y,a|l}\right) \right] \right). \tag{2.14}$$

In the multinomial-Dirichlet formulation, the key additional variance parameter, ω, is better understood (and defined) via the concept of an over-dispersion coefficient, φ. With sampling probability π and sample size n the mean and variance of the multinomial are $n\pi$ and $n\pi(1-\pi)$, respectively. When assuming the compound multinomial-Dirichlet model then mean is unchanged, but the variance is now $\varphi n\pi(1-\pi)$ where

$$\varphi = \frac{n+\omega}{\omega+1}, \tag{2.15}$$

which, if one is controlling the additional variance via φ or are estimating this parameter directly, leads to the following simple equation for ω:

$$\omega = \frac{n-\varphi}{\varphi-1}. \tag{2.16}$$

One thing to be careful with using this formulation is $\varphi \to 1$. In the limiting case, the true sampling distribution ξ approaches a point distribution (i.e. zero variance). While theoretically valid, numerically it can cause chaos so, if estimating φ, make sure it is penalised to stay away from 1.

In this paper, we manually "tune" each annual value of φ for both the length (annual) and conditional age-at-length data (annually and for each length bin in the partition). The approach is basically the one defined in [6] for a mark-recapture data application to Indian Ocean skipjack tuna. After an initial run, the variance in the standardised residuals is calculated for each year and data set in the full likelihood. This variance is set equal to φ and the model is re-run. If the resulting value of φ is close to 1 we stop the process. The nice part of this formulation is that one never *up-weights* the data, which can happen in assessment contexts when the underlying initial sample size, n, is either unknown or not really believed.

2.6 Model performance criteria

In the length-at-age framework, given the simpler nature of the model there are a number of powerful MCMC tools we can use to analyse how well the model is performing in terms of predicting the observed data. When comparing the two candidate length-at-age models - simple vs. hierarchical - posterior predictive analysis [4, 7] is both relatively simple to implement and very informative. This is done as follows:

1. For a given posterior sample, length-at-age $\tilde{l}$ data are simulated from the likelihood
2. The simulated residual $\tilde{l} - \hat{l}$ is calculated
3. The observed residual $l - \hat{l}$ is also calculated
4. The absolute median deviation in each of these 1,000 residuals, $\tilde{\Delta}$ and Δ, is calculated
5. The statistic $p(\tilde{\Delta} > \Delta)$, known as a Bayesian p-value, is calculated and the plot of the predicted versus observed discrepancy statistics is also useful

The main idea is that if $p(\tilde{\Delta} > \Delta) > 0.5$ the predictions are generally more variable than the observations; *vice versa* for $p(\tilde{\Delta} > \Delta) < 0.5$. Finally, p-values outside the range of 0.05-0.95 are generally indicative of *some* kind of issue with the model and/or likelihood [4].

For the age-at-length data, the whole concept of model performance and predictive interpretation is more complicated than the length-at-age data. For a start, we have two predicted quantities not one: length distribution of the aged samples *and* their associated conditional age-at-length distributions. In the case of the predicted length frequency this is, in effect,a matrix by both year and length partition element; for the age-at-length data it is a three-dimensional array of year/length/age. Unlike the underlying residual between predicted and observed length-at-age, there is no immediately obvious discrepancy statistic with which to perform a posterior predictive analysis.

For the length data, we have the expected proportion of each length-class by year, $\pi_{y,l}$. For each MCMC iteration and we can simulate a prediction, from the compound multinomial-Dirichlet likelihood, of the observed length composition $\tilde{p}_{y,l}$. We also obviously have the actual observed length composition, $p_{y,l}$. To construct a suitable - and univariate - discrepancy statistic we calculate the following two (residual) matrices:

$$\tilde{X} = \tilde{p}_{y,l} - \pi_{y,l}, \tag{2.17}$$
$$X = p_{y,l} - \pi_{y,l}. \tag{2.18}$$

Clearly, we need to some reduce the dimensionality of the matrices $\tilde{X}$ and X and we do this using the Frobenius matrix norm, $\|\|_F$:

$$\| M \|_F = \sqrt{\sum_i \sum_j m_{ij}^2} = \sqrt{\text{trace}\,(M^\dagger M)}, \tag{2.19}$$

where $\dagger$ denotes the matrix transpose. We now define the discrepancy statistics as $\tilde{\Delta} = \| \tilde{X} \|_F$ and $\Delta = \| X \|_F$, and our Bayesian p-value is the same as for the length-at-age data: $p(\tilde{\Delta} > \Delta)$.

For the conditional age-at-length data, we decided to focus on the age-at-length matrix in each year when constructing the discrepancy matrix:

$$\tilde{X}_y = \tilde{p}_{y,l,a} - \pi_{y,a|l}, \tag{2.20}$$
$$X_y = p_{y,l,a} - \pi_{y,a|l}. \tag{2.21}$$

The calculation is essentially the same as for the length data discrepancy, but now we have one for each year. The philosophical reasoning behind this is as follows:

- For the length data, we are interested in capturing the general form of the distribution over the years, so eschew a year-specific discrepancy statistic
- For the age-at-length data there are more processes at work that could lead to both year and length-specific process errors (hence the more detailed process error model for these data). It is for this reason that - for each year - we focus on the predictive performance of the probability model w.r.t. the observed age-at-length distribution.

3 Results

Initially, we address the results of the two different approaches separately, then try to compare and contrast them later on.

3.1 Length-at-age data

In terms of the visual fit to the data, Figure 3.1 summarises the posterior median and 95% predictive credible interval for the length-at-age of both sexes. Overall, there is no substantial difference between

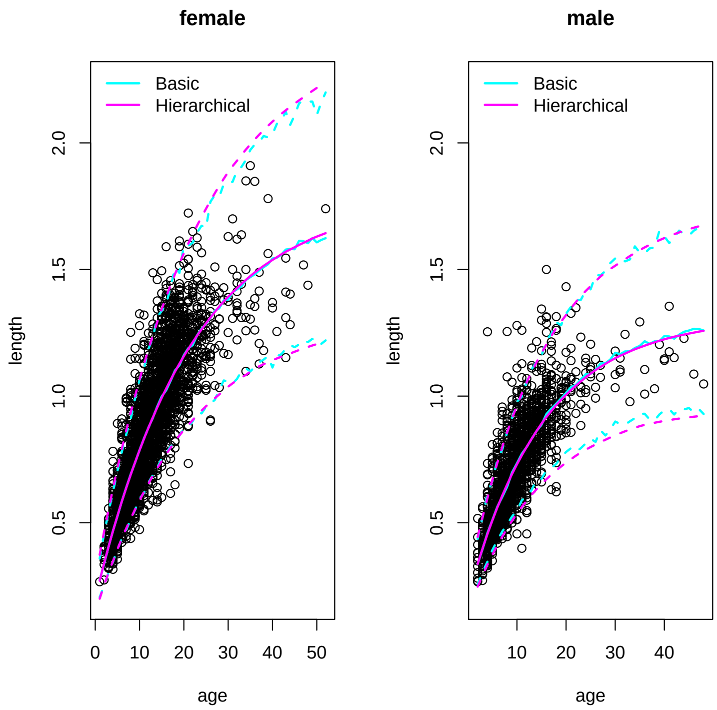

Figure 3.1: *Posterior predictive median (full line) and 95% credible interval (dashed lines) for the basic and hierarchical length-at-age model as applied to the female (left) and male (right) data (circles).*

the basic and hierarchical visual data fits. For the females the hierarchical model predicts a very slightly wider predictive interval with very similar medians; for the males the hierarchical model predicts slightly lower length-at-age in general. Both seem to over the spread of data reasonably well.

Figure 3.2 summarises the predictive performance of both the basic and hierarchical models for the female and male length-at-age data. In terms of Bayesian p-values, for the basic model the values were 0.69 and 0.97 for the female and male data, respectively; for the hierarchical model, they were 0.54 and 0.55. For both sexes, the basic model predicts higher variability in the discrepancy statistic than in the actual observations - particularly for the male data. Additionally the predicted discrepancy statistics show a much broader range than for the observed data. With the hierarchical model the p-values are very close to 0.5 (the "ideal" level) with a very symmetric spread so very consistent with the observations, and with actual values almost three times smaller than the basic model. From the posterior predictive angle, the hierarchical model outperforms the basic one on every level: p-value, symmetry in the discrepancy statistic and a universally better fit to the data.

In one sense, it should be better given it has vastly more parameters. Exactly how many free parameters a hierarchical model has is a complicated concept, given the estimated priors for L_∞ constrain the individual values. This, along with other factors, makes information criterion-based model selection approaches very complicated in the Bayesian hierarchical framework [2]. One interpretation of the Deviance Information Criterion (DIC) [4] we calculated clearly favours the hierarchical model, and this statistic accounts for the additional parameters. However, we do not go further into this analysis as there are other interpretations [2] and it does not contradict the posterior predictive findings: the

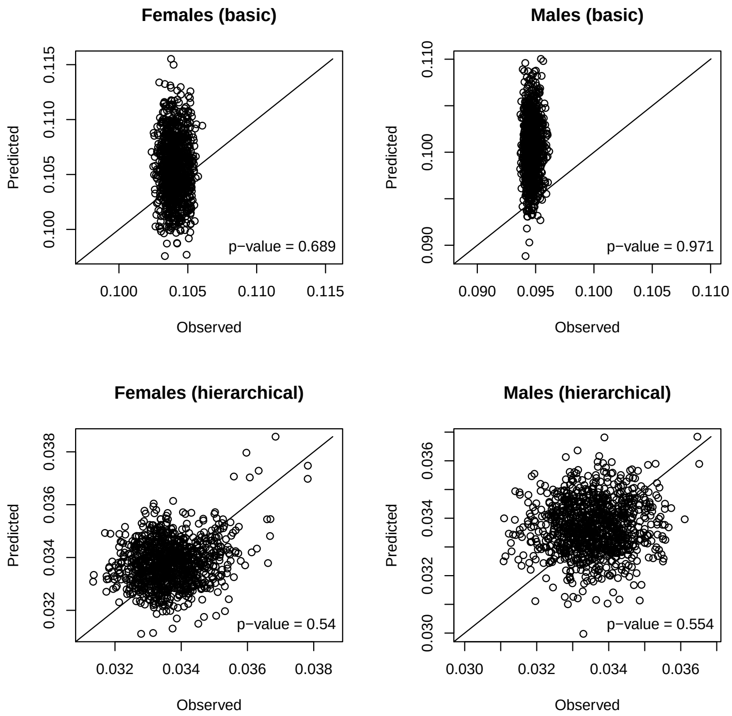

Figure 3.2: *Posterior predictive analysis for the basic (top) and hierarchical (bottom) length-at-age model as applied to the female (left) and male (right) data.*

hierarchical model is the better choice for the length-at-age data for both sexes.

3.2 Age-at-length data

Figures 3.3 and 3.4 visually summarise the fits to the female and male length and age-at-length data, respectively, at the posterior median. The length data are, in general, reasonably well fitted to. The only notable issue is that model fails to capture the apparent bimodality in the female length frequencies in 2014 and 2015. This is not surprising, given we assume a unimodal lognormal distribution for the year-specific prior age distribution in the catch. The underlying (expected) age-at-length relationship is monotonically increasing, so no aspect of the model could capture the apparent bimodality.

For the fits to the conditional age-at-length data, we use the posterior median and 95% credible interval to predict the mean age in each length bin. For the females, the distribution of mean age-at-length appears well captured, with none of the data appearing outside the predicted credible intervals. For the males, this also seems to be the case apart fro 2013, where the mean age at the lowest length bin is significantly higher than model would predict, and much lower for the 1.5–1.6m length bin. In terms of potential year-to-year variation in growth the years 1998 and 2004 seem to exhibit small but systematic differences in mean age-at-length for both sexes, with 2009 being a candidate for the males but not the females.

For these data we undertook predictive analyses for the length and age-at-length data - for the former there was one p-value, and for the latter there was one for each year. For the length data, the Bayesian

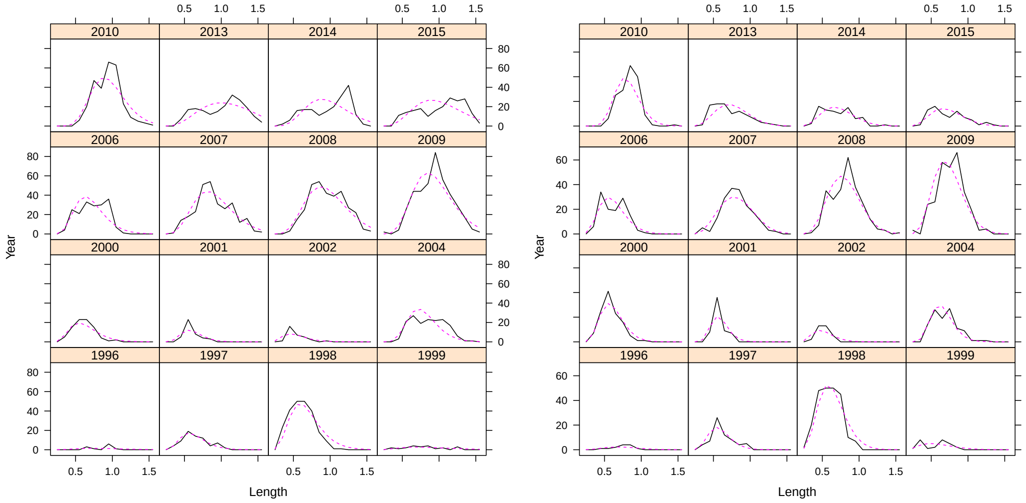

Figure 3.3: *Observed (black line) and estimated (dotted magenta line) length data for females (left) and males (right) at the posterior median parameter estimates.*

p-values for the females and males were 0.38 and 0.44, respectively. Both suggest that we are slightly under-estimating the true variability in the data, and more so for the females than the males (driven largely by the 2013 and 2014 discrepancies). For the conditional age-at-length data the year-specific values range from 0.33–0.58 and a median of 0.47 for the females, and from 0.37–0.56 with a median of 0.45 for the males. So, in general, we are *slightly* under-estimating the variability in the age-at-length data, but otherwise predicting these data well.

To emphasise the need for the detailed process error model we employed, when performing these analyses without any process-error re-weighting (i.e. assuming the straight multinomial is correct) the predictive analyses all show often serious under-estimation of variability in both data sets. We estimated p-values to be mostly very low (less than 0.1) and often well below 0.05 - the point at which the general advice is something in your model is wrong. To sufficiently explain the data and, perhaps more importantly, to increase the likelihood of getting unbiased parameter estimates and not under-estimating parameter variances it may often require more complex probability models than are currently available in major stock assessment packages like Stock Synthesis [8].

3.3 Across all models

Table 3.1 summarises the key growth parameter estimates across all three model structures and for both the sexes. When comparing the two length-at-age approaches (basic and hierarchical) there is little consistent difference between the parameter estimates - in terms of both median and credible intervals. The only difference is for the estimates of female L_∞: for the hierarchical model it is 7% higher than for the basic model. All the other estimates are very close and all sit comfortably within their counterparts' 95% credible interval. One cannot directly compare the variability in L_∞ for the basic and hierarchical models: the basic model estimates one value assuming them to all share this parameter; the hierarchical estimates one for each animal *and* the population mean and variance (summarised in the table via the posterior predictive distribution for L_∞). A rough rule-of-thumb is to compare the CV for the hierarchical model with the square root of the sum of the square of the CV

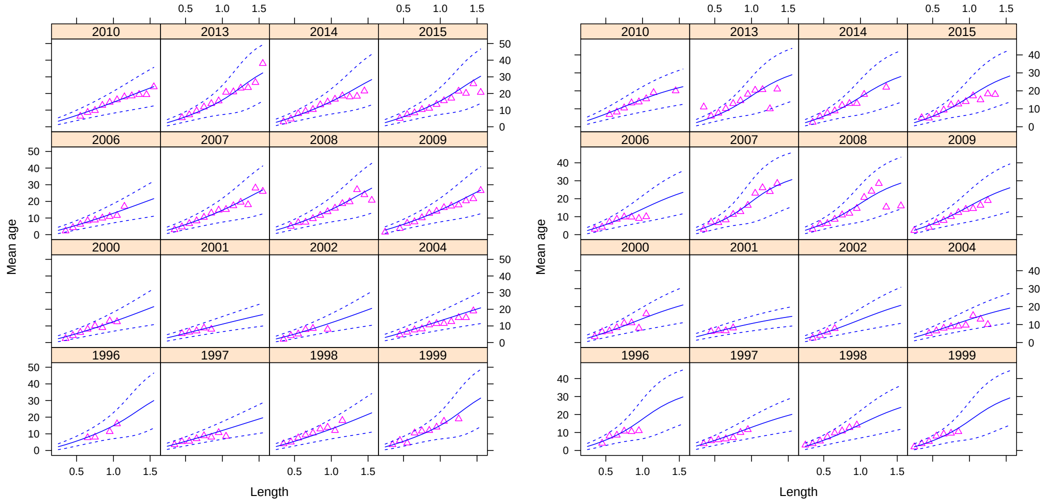

Figure 3.4: *Observed (magenta triangle) and posterior median (blue line) and 95% credible interval (dotted blue line) mean age for each length bin, for females (left) and males (right).*

for L_∞ and $CV_p^2 = \log(1+\sigma_p^2)$, as this parameter is trying to capture the underlying variation in individual L_∞. For both males and females this "effective" CV in population-level L_∞ inferred from the basic model is around 0.15, so very similar to that estimated more formally in the hierarchical model.

Parameter	L_∞	k	t_0	σ_p
		Basic length-at-age		
Males	1.27 (0.03)	0.07 (0.07)	-2.28 (0.1)	0.14 (0.02)
Females	1.69 (0.04)	0.05 (0.08)	-2.52 (0.09)	0.15 (0.02)
		Hierarchical length-at-age		
Males	1.31 (0.15)	0.066 (0.07)	-2.53 (0.09)	N/A
Females	1.81 (0.16)	0.046 (0.07)	-2.55 (0.08)	N/A
		Conditional age-at-length		
Males	1.21 (0.06)	0.08 (0.1)	-1.23 (0.18)	0.15 (0.04)
Females	1.7 (0.07)	0.05 (0.09)	-1.5 (0.15)	0.15 (0.04)

Table 3.1: *Posterior mean (and CV in brackets) estimates for the male and female growth curve parameters and for all three model frameworks explored.*

For simplicity, and given the similarity in the length-at-age estimates, we directly compare only the hierarchical length-at-age estimates with the conditional age-at-length estimates. In terms of posterior median estimates: L_∞ was estimated to be lower for the age-at-length approach for both males and females, though not significantly so; estimates of k were very similar for both sexes; t_0 was estimated to be closer to zero for the age-at-length approach, though not significantly so; and the estimates of σ_p were practically identical. In terms of variance the 95% credible intervals were larger when using the age-at-length approach - most notably for L_∞ and t_0.

There are no obvious model selection tests we could use to decide between the hierarchical length-at-age and conditional age-at-length approaches. For one thing, they are fundamentally different data sets, even though one is effectively derived from the other, so no information theoretic tests could be applied. From the posterior predictive analyses, the hierarchical length-at-age model performs very well; the conditional age-at-length model performs well, with a suggestion of under-estimation of variability in the data, though nothing close to pathological.

3.4 Comparison with the full stock assessment growth estimates

In the current integrated assessment [3] the only fixed growth parameter is L_∞ for the females (at 1.65m) - all other growth parameters are estimated. In the last assessment the estimate of L_∞ for the males was noticeably higher for the males (ca. 2m and above) than for any of the external estimates of growth (see Table 1), and given the negative correlation the estimates of k lower. This year we appear to see the same effect though much increased: estimates of L_∞ and k were 18.5m and 0.003, respectively. In the actual stock assessment model the actual growth parameters are k and the length-at-age for pre-specified ages a_1 and a_2 - L_∞ and t_0 are easily derived from these three parameters but not directly estimated.

3.5 Variability from growth alone in management variables

To explore a little how variability in growth propagates into the variables we are interested in for assessment purposes, let us consider the variation in SSB-per-recruit in the unfished state - this is a major contributor to the variation in B_0. For the unfished SSB-per-recruit, $SPR_{F=0}$, we need to define the equilibrium age structure: $\tilde{n}_a$. For $a = 1$, $\tilde{n}_a = 1$, and for $a = 2, ..., A-1$:

$$\tilde{n}_a = \tilde{n}_{a-1} \exp(-M), \tag{3.1}$$

and assuming a plus group at the maximum age A, we have that

$$\tilde{n}_A = \tilde{n}_{A-1} \frac{\exp(-M)}{1-\exp(-M)}. \tag{3.2}$$

Maturity is defined via length, in terms of a logistic relationship with $l_{50} = 1.396$ and $l_{95} = 1.858$, as is length: $w_l = al^b$, where $a = 4.4 \times 10^{-6}$ and $b = 3.14$. To estimate maturity, m_a, and weight-at-age, w_a, for the population model we need to integrate over the distribution in length-at-age, $\Pr(l \,|\, a)$:

$$m_a = \int \Big[m_l * \Pr(l \,|\, a) \Big] \mathrm{d}l, \tag{3.3}$$

$$w_a = \int \Big[w_l * \Pr(l \,|\, a) \Big] \mathrm{d}l. \tag{3.4}$$

Once we have computed these age-based vectors we calculate the SSB-per-unit-recruit as follows:

$$SPR_{F=0} = \sum_a \tilde{n}_a w_a m_a. \tag{3.5}$$

For each MCMC sample from the (female) conditional age-at-length growth model we calculated the quantity in Eqn.(3.5). Posterior median (and 95% credible intervals) were 3.84 (3.26–4.46) (in units of tonnes $\times 10^{-6}$); the posterior mean is the same as the median with a CV of 0.08. This is not a huge amount of variability, but it does propagate through the assessment over the years, and into the SSB from the very start, so it's not totally ignorable - especially when uncertainty interacts with the Harvest Control Rule as it does with the CCAMLR rule.

4 Discussion & Conclusions

The growth model is of fundamental importance to any length and age structured stock assessment. A number of approaches have been explored over the years, given the extensive set of age and length data for this stock. The default method at the moment is to estimate growth inside the assessment model, using the conditional age-at-length, not the more traditional length-at-age, approach. In this paper we have: (i) updated the existing length-at-age models for the new data (2013–2015); (ii) constructed a novel age-at-length model that estimates growth *outside* the assessment, but in the same general statistical framework; and (iii) compared the growth estimates between themselves and with those from the stock assessment.

As seen in previous work [5], the more complicated hierarchical length-at-age model (with an L_∞ for each animal) outperformed the basic one in terms of explaining the data, but the estimates were very similar. The conditional age-at-length model is, in many ways, more complicated and uses the length frequency and age-at-length frequency data together. We developed a detailed process error model for these data using an empirical Bayes type approach to "tuning" the over-dispersion coefficients. While complex, the approach appeared to be validated when comparing the posterior predictive performance of the models with and without process error (over-dispersion). The model without process error consistently under-estimated the variability in both the length and age-at-length data. When comparing with the hierarchical length-at-age model, estimates of growth rate k were very similar; estimates of L_∞ were slightly lower for the age-at-length approach; estimates of t_0 were closer to zero for the age-at-length approach; and estimates of the stochastic variability in length-at-age (σ_p) were very similar as well. The variance in the parameter estimates were always greater for the age-at-length approach - particularly for both L_∞ and t_0. This is not necessarily a surprise given that ageing error is accounted for in the age-at-length approach, and will have a particular effect on the parameters related to where the data are most sparse: at the upper and lower ends of the age and length range.

In the assessment the fits to the actual length and conditional age-at-length data are acceptable. In one sense this is what really matters: how well are you fitting the ages and lengths in the actual data, not at the extremes. Additionally, given the very strong negative correlation between L_∞ and k the outcomes of the assessment and, crucially, the management advice are unlikely to be altered for fixed growth parameters. However, the estimates are clearly nonsensical in the life-history of the fish, and clearly at odds with both the externally obtained length-at-age and conditional age-at-length estimates. It is not the way the data are used that appears to be the problem, given the consistency of the external estimates, so that leaves only the interaction with other fixed parameters and additional data sets (and their weightings) in the assessment. As mentioned before, the age-at-length approach needs some expression for the prior age distribution in the catch for that year to work. In the external estimates we estimate this directly, but in the assessment it is proportional to $s_a N_{y,a}$, where s_a is the selectivity and $N_{y,a}$ the numbers-at-age matrix. It is the length frequency data that are informative for this process, and a mismatch with assumptions about selectivity and/or M and the information in the length frequency data *will* have implications for the length-at-age parameters, via the Bayesian formulation for the age-at-length equation.

We explored if a mismatch could cause inflation of the L_∞ estimates via the approximation for the age distribution in the catch used in [10]. This assumes a value of total mortality, Z, where the age-prior is proportional to $\exp(-Za)$, and the conditional age-at-length data (but not the length frequency data) are used to estimate the growth parameters. We assumed $F = 0.07$ and $M = 0.13$ based on previous assessments, so $Z = 0.21$. The estimates of L_∞ and k from this method were 2.7m and 0.021, respectively. While not as high as this years estimates, they do compare closely with last years high/low estimates of L_∞/k. The approximation implies a prior age distribution comprised of much more young fish than the actual length frequency data do, which would push the parameters in the direction we see. This *could* be happening in the assessment, and the place to focus on would be the fits to (and weightings for) the trawl length frequency data in the earlier years of the fishery. This, however, is speculative and will require detailed further work including likelihood profiles and residual analyses but does seem a sensible place to explore.

Overall, the length-at-age and conditional age-at-length approaches appear to give generally consistent and precise estimates of the growth parameters of interest. This is obviously comforting but it also gives us a crucial linkage between estimates of length-at-age from the "classical" approach and those obtained via the conditional length-at-age approach in the assessment. Prior to this work, differences could arise from the difference in approach in the assessment, from assumptions made about key life-history parameters or processes (selectivity) within the assessment itself, or from other data sources within the assessment model. We have seen in this work that it if differences do arise, they do not appear to be driven by the statistical differences between the length-at-age and conditional age-at-length approaches. This leaves either model and parameter assumptions made within the assessment or the other data sources as the remaining drivers of different estimates. This has always been the major potential weakness of estimating the growth from within the assessment in the integrated framework. The counter argument is that growth uncertainty *does* matter - especially when maturity is a function of length, as maturity-at-age can then be a source of "stealth" uncertainty. Even with accurate growth estimates such as these, the underlying CV in SSB-per-unit-recruit *just* from the uncertainty in weights and maturity-at-age (i.e. fixed M) is around 8%. So, while not huge, we would ideally want to account for growth uncertainty within the assessment. Here, we seem to be hitting the ever-present bias/variance trade-off by trying to do so.

5 Acknowledgements

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Appendix 4

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Ideas for incorporating multi-year TACs and formally evaluated harvest strategies into the Macquarie Island toothfish fishery

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Prepared for the SARAG held in Hobart, Australia 24$^{\text{th}}$ of February 2015.

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Contents

Abstract

This information paper attempts to outline some potential options, as well as general recommended process guidelines, for moving from annual assessments to multi-year TACs for the Macquarie Island toothfish fishery. This approach, at least in terms of multi-year TACs, has been adopted within CCAMLR for the toothfish fisheries that have a well-established assessment process and are clearly no longer new and exploratory. The use of multi-year TACs may also require MSE testing to identify the risk factors involved in such a move. Given the apparent stabilisation of the Macquarie Island assessment, in terms of both estimates and structure, there is a clear case for exploring how multi-year TACs might work. In this document both the stock assessment approach, as well as the potential for developing fully evaluated harvest strategies, are discussed in relation to multi-year TACs. Finally, given experience in other fisheries, we also discuss some general guidelines that should also be developed if this approach is to be actively explored: explicit management objectives, meta-rule processes, review timelines, and the process to be followed in non-assessment/TAC decision years.

1 Introduction

Currently, the Macquarie Island toothfish fishery runs on an annual assessment and management advice timeline: the agreed assessment model is updated to include the most recent data, the results of which are then used to define a TAC for the following year. The annual nature of this process has made sense in the past given the evolving nature of both the fishery and the assessment model structure over recent years. However, both the fishery (now totally long-line and with one boat) and the assessment model (spatially structured driven by the mark-recapture and ageing/length composition data) have shown a marked degree of stability over the last few years.

For some of its toothfish fisheries, CCAMLR has already been implementing multi-year TACs. Currently, the Ross Sea and South Georgia fisheries are managed via two-year TACs and it is expected that the HIMI fishery will return to biannual TACs once this phase of assessment restructuring and robustness testing has been finalised. While there are no codified set of criteria for moving to multi-year assessments within CCAMLR the general principle seems to be that a stable (in terms of both retrospective estimation and structure) assessment can be moved to multi-year if the Working Group, Scientific Committee and Commission agree.

Stock assessments are expensive and time-consuming, and in a time of decreasing overall funding levels it is right that we explore the most cost-effective ways of managing the fishery whilst maintaining appropriate levels of precaution and meeting the legislative requirements as per the Commonwealth Harvest Strategy Policy. In this paper we endeavour to outline some sensible options for moving away from annual stock assessment and TAC management for the Macquarie Island toothfish fishery.

2 Moving to multi-year TACs

In this section we explore two candidate approaches for managing the fishery via multi-year TACs, as well as some general guidelines and issues that need to be addressed when moving in this direction and away from the annual assessment cycle.

2.1 Multi-year assessments

Multi-year assessments are quite common in the RFMO space:

- Tropical tuna: almost all assessed tropical tuna stocks are subject to multi-year assessments (often every 2 or 3 years depending on the species)
- CCAMLR: currently both the Ross Sea and South Georgia toothfish fisheries are assessed biannually, and it is expected that the HIMI fishery will return to biannual assessments very soon

- CCSBT: although managed via an evaluated harvest strategy, full reconditioning of the OM (*de facto* assessment) is done every 3 years

The arguments for multi-year assessments for toothfish, and for Macquarie Island toothfish in this case, are actually fairly strong because:

1. They are long-lived, so something out of the ordinary is unlikely to happen in say a 2 or 3 year assessment framework that wouldn't happen in the current annual cycle
2. They are managed in a precautionary manner via the CCAMLR decision rule that is adaptive over time and takes a "long view" in terms of the calculation of the TAC
3. The tagging data have shown they provide informative and generally consistent estimates of exploitable abundance, which drives the assessment model

2.2 Harvest strategy approach

The evaluated harvest strategy (HS) - or management procedure (MP) - approach is another viable alternative to annual assessments for this fishery. Within the Commonwealth fisheries, there are a number of evaluated (and some unevaluated) HSs in current operation (SESSF Tiers, ETBF billfish, SBT). The process can be generalised accordingly:

- An Operating Model (OM) is specified (often the stock assessment model with additional simulation code) from which we can simulate the stock, management decisions and the data collection process
- A suite of candidate HSs are defined that use the suite of observations (e.g. tags, catch composition and overall numbers) to estimate things like abundance, fishing mortality and year-class strength. The HS has a specific Harvest Control Rule (HCR) that uses these estimates to set the TAC (or effort for example)
- A well specified set of objectives are agreed for which we wish any HS to be able to meet for our best understanding of the status of the stock
- A set of robustness tests (alternative plausible realities) are defined and for which the candidate HSs are tested against
- A suite of performance criteria (biological and fishery related) are defined to assessment the performance of the candidate HSs
- A "best" candidate HS is chosen based on the performance evaluation

The key advantages of this approach are that (i) the HS is almost always simpler than the assessment model and therefore cheaper, quicker and easier to run and more accessible to a wider set of stakeholders, and (ii) by being fully evaluated via MSE we can have some faith that it can meet our objectives. Previous MSE work with the various incarnations of the Macquarie Island stock assessment model have demonstrated that, for a limited range of scenarios, the current approach is likely to be able to get the stock to the targets implied by the CCAMLR decision rule. With a simpler approach (via a HS) we can look at a wider range of future "what ifs" and look to develop more concrete management objectives and what level of risk we are willing to accept to meet them.

2.3 General guidelines and requirements

Whatever the approach, be it multi-annual assessments or HSs, some MSE work will be required before implementation. In CCAMLR, the implementation of biannual TACs was done so only on the basis of simulation analyses that demonstrated that this approach was highly unlikely to increase the risk to the stock that one would expect when operating on an annual assessment cycle.

The number of years in the assessment cycle is also a key issue to be discussed and analysed in the MSE work. CCAMLR has chosen biannual but for CCSBT, for example, TACs are set for every three years as

MSE work showed little performance difference relative to 2 year TACs. It is probably wise to discuss the relative merits of different intervals initially on a purely operational basis and then see what, if any, are the implications of those choices when simulating the system into the future. Also, some flexibility is required in terms of how much of the TAC may be taken in any one year - a balance between operational flexibility given current conditions (both physical and economic) and mitigating against over-exploitation in any one year must be found.

Whatever the methodology, a clear set of agreed objectives is highly advisable. The CCAMLR decision rule has implicit targets, but by its very definition does not specify when they are to be obtained and focusses solely on the biological risk to the stock. Similarly, one can infer targets from the Commonwealth HSP but not specific times or indeed what additional risk criteria we may be interested in meeting. Even with the assessment/CCAMLR decision rule approach once we move to multi-year TACs there is no guarantee it will meet the inferred targets so some planning in terms of formalising the objectives and as to what to do about that within the HCR in terms of meeting them makes sense.

If a TAC decision is not to be made every year, the process of what is to be done in a non-TAC year must be clearly defined. The first part of this is what analyses (if any) are to be done with the data (catches, tags) even if a full assessment or HS run is not to be undertaken. Obviously, it seems somewhat odd to simply ignore an additional year of data as a lot of information can be easily extracted from the observations even if an assessment is not to be done. This also leads into another every important part of the process: what to do if something “out of the ordinary” happens:

This has been described as the meta-rule process, whereby there needs to be a codified set of instructions about what to do when one (or more) of the following occurs:

1. One (or all) of the observation data sets does not exist, cannot be used or appears outside the bounds tested in the MSE work
2. Another set of data appears that, while not formally included in the assessment or HS process, clearly shows that estimates of key parameters are incorrect (e.g. M was in fact much higher or lower)
3. Structural changes in the fishing process fundamentally shift outside of the bounds tested in the MSE process (e.g. a new long-line method or the return of trawling or pots)

This process has been invaluable in the CCSBT context to ensure that, when something strange does happen (which at some point it will and has for SBT), there is a clear and agreed process for doing something about it and ensuring that the process of management advice is maintained.

A final issue, though not essential, are periodic reviews of the whole process. This makes more sense when one has defined specific objectives that we wish to reach, though it arguably makes sense outside of this scenario too. For some multiple of the mutli-year TAC cycle (e.g. once every 6 years for a biannaul decision cycle) a thorough review of the progress of the approach (be it an assessment or an HS) in terms of progressing towards to objectives is undertaken. Issues addressed: are we where we thought we might be at the start of the process; do the parameters of the HCR need changing to achieve the objectives (called retuning); have any additional data sources appeared that warrant inclusion.

3 Discussion

This paper has outlined some potential approaches to moving the Macquarie Island toothfish fishery away from the annual assessment and management advice cycle it is currently on. Two general approaches explored were multi-year stock assessment and TACs (using the current assessment model) and a fully evaluated harvest strategy/management procedure approach to setting multi-year TACs.

Both approaches have the ability to reduce the overall costs of managing this fishery, though it should be clearly noted that these savings are unlikely to be simply proportional to the number of years a TAC is set for. Any approach will require additional MSE work to ensure the move is robust, relative to the current approach, and in non-TAC decision years one cannot expect that no exploratory data analysis work at all will be done given the new data from the previous fishing season.

Whatever the approach, some general guidelines based on previous experiences within CCAMLR and elsewhere were outlined. The need for clear and agreed management objectives so everyone is clear what the management approach is supposed to be achieve. The need for a clear discussion and study about what flexibilities are required in the system (TAC apportion across years) and what to do when something “out of the ordinary” happens - the meta-rule process.

The Macquarie Island assessment has appeared to obtain a level of stability (in terms of both estimates and structure) that makes it a sensible time to discuss the future management approach in the multi-year context. We hope this paper assists in starting the discussion about how that could happen, what approaches might be worth pursuing, and how this might fit within a longer-term strategic research plan for the fishery.

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