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Stock assessment and management strategy evaluation for the Macquarie Island toothfish fishery 2017-2018

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27 June 2018

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1 Non-technical summary

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Objectives

1. In the assesment year, to provide the SARAG with updated assessments of the status of the stock of Patagonian toothfish at Macquarie Island
2. In the non-assessment year, to provide the SARAG with the requisite analyses of the data to decide as to whether the current TAC is to be maintained or otherwise
3. In the non-assessment year, to provide the SARAG with options relating to potentially moving the assessment from the current Stock Synthesis platform to a longer term, and more suitable, alternative
4. To continue monitoring the stock through the mark-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, spatial tagging analyses, and non-assessment data analyses 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 stakeholders and managers 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, and the development of a ’future-proofed’ stock assessment for the following years.

The tagging program in the Macquarie Island fishery continues to provide us with consistent and informative data on stock abundance, mortality and migration. Rates of recovery per tonne caught are within historical bounds, and analyses of alternative methods for using these data in the stock assessment have shown how best to make the most of these data in the future assessment framework.

Previous projects have undertaken stock assessment and management strategy evaluation work to strive to provide the best available science for managing this fishery. As of 2018, the assessment shows a level of stability (in both status and TAC recommendations) and consistency between data sets that has been achieved largely by the previous project outcomes and recommendations.

In this project we have updated the stock assessment in 2017, in the non-assessment year provided analyses of the data to see whether anything strange was apparent and if the TAC advice may have required revisiting. We have outlined a path to constructing a new bespoke stock assessment framework that will - as much as can be - future-proof both the assessment and MSE frameworks that have underpinned the work done in previous projects.

2 Acknowledgements

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

2.1 Author listing

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

- **Rich Hillary**: CSIRO Oceans & Atmosphere
- **Jemery Day**: CSIRO Oceans & 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 Oceans sub-Antarctic islands. Both trawl and later longline fisheries for toothfish are now well established within Australian Commonwealth waters around Heard 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 16,800 tagged fish have been released in waters surrounding Macquarie Island, with 2,225 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 2015. 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.

For the past few years the fishery has been a one boat fishery, and long-line only. The TAC has varied between 410t and 510t between the 11/12 and 17/18 fishing seasons. This reflects the apparent stability in the stock assessment results during this period.

4 Need

Given the move to a two-year TAC cycle, with a one-year data lag, an assessment was required in 2017, and interim analyses of the data were required in the non-assesment year 2018. As discussed at the previous SARAG meeting, the current Stock Synthesis assessment platform has both limitations with respect to modelling tagging data and has a limited lifespan given it is a custom version put together by a previous CSIRO scientist who has now left the country. The non-assessment provided a good opportunity at explore longer-term more stable platforms for the assessment in the future.

This project continued the work of previous projects in terms of our 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 built upon the existing stock assessment and management strategy framework, continued the stock assessment and monitoring process for a further two years, and laid out an blueprint for the future long-term assessment of this fishery.

5 Objectives

1. In the assesment year, to provide the SARAG with updated assessments of the status of the stock of Patagonian toothfish at Macquarie Island
2. In the non-assessment year, to provide the SARAG with the requisite analyses of the data to decide as to whether the current TAC is to be maintained or otherwise
3. In the non-assessment year, to provide the SARAG with options relating to potentially moving the assessment from the current Stock Synthesis platform to a longer term, and more suitable, alternative
4. To continue monitoring the stock through the mark-recapture program

6 Benefits/Management Outcomes

Progress reports and results will be presented initially in the form of both reports and oral presentations to the Sub-Antarctic Resource Assessment Group (SARAG) and others involved in the management of the fishery. The SARAG membership includes representatives from a wide spectrum of research fields (including stock assessment, fish biology and ecological interactions), and from several organisations with expertise related to the fishery (including the Australian Antarctic Division, ABARES, CSIRO Oceans and Atmosphere, Tasmanian Department of Primary Industries Water and Environment, AFMA and industry).

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

7 Conclusions

Meeting the project objectives:

Objective 1

"In the assesment year, to provide the SARAG with updated assessments of the status of the stock of Patagonian toothfish at Macquarie Island "

Appendix 1 details the full stock assessment (with data up to and including August 2016) submitted to, and subsequently endorsed by, the SARAG in September 2017.

Objective 2

"In the non-assessment year, to provide the SARAG with the requisite analyses of the data to decide as to whether the current TAC is to be maintained or otherwise"

Appendix 2 contains the ideas for what fishery variables to explore in the non-assessment year, in relation to whether anything has substantially changed or is different to previous years and whether the TAC advice requires revisiting. Appendix 3 contains the actual data analyses done, given the concepts outlined in Appendix 2.

Objective 3

"In the non-assessment year, to provide the SARAG with options relating to potentially moving the assessment from the current Stock Synthesis platform to a longer term, and more suitable, alternative"

A number of arguments for and against: (i) *status quo* (stick with Stock Synthesis), (ii) move to another package like `CASAL`, or (iii) develop a bespoke stock assessment were verbally presented to the SARAG in February 2018 and in the proposal submitted to the AFMA ARC for the next phase of this project sequence. The suggestion made by CSIRO, and endorsed by the SARAG, was to develop a bespoke model to be able to deal with the spatial structure in the assessment, future MSE needs, and (as detailed in Appendix 4) making the most of the mark-recapture data when estimating both abundance and migration.

Objective 4

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

Our continued collaboration with our AAD colleagues ensures that high quality mark-recapture data at the required tagging rates are available. Appendix 4 also explored in detail whether changes to the current tagging rate, and spatial requirements thereof, were necessary. The conclusion was that 2 tags per tonne was still sufficient and that no additional suggestions on spatial tagging rates was required, given historical spatial catch proportions between areas are likely to be reflective of future likely scenarios.

References

[1] R. M. Hillary, J. Day, and M. Haddon (2016) Macquarie Island toothfish stock assessment and management strategy evaluation: 2015–2016, *Final Report*.

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 2016

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Prepared for SARAG 56, Hobart, 6 September 2017
Pre-meeting draft: 5 September, 2017.

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Citation

Day J and Hillary R (2017) Stock Assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2016. Report to SARAG 56, 6 September 2017. CSIRO, Australia.

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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 2016. 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 1994–2016, and to age-at-length data obtained from aged otoliths (1997–2016). It is an update of the final version of the 2016 assessment (Day *et al.*, 2016). 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 2016 assessment. The base case current female spawning biomass estimate is 69% of unfished at the start of 2017 (67% in 2016). The trend in spawning biomass from 1990–2016 is almost identical to that estimated last year, but the estimated magnitude of spawning biomass is about 20% higher in each year, and about 8% higher than the spawning biomass series from the 2015 assessment. The new recruitment estimate from 2009 is below average.

The point estimate for the 2017 stock size in the northern area is estimated to be about eight times larger than that in the south (female spawning biomass 2,203t and 280t respectively). The northern area is also estimated to be considerably less depleted than the southern area (77% and 37% respectively).

Catch levels that satisfy the CCAMLR control rule have been calculated under nine alternative assumptions regarding how the catches will be allocated to fleet and region. The projected 2018/19 and 2019/20 catches from these scenarios range from 430t to 520t.

The new 2016 length frequency data include an additional 3376 fish in 94 hauls for Aurora Trough Longline, 3337 fish in 128 hauls for Northern Macquarie Ridge Longline and 3865 fish in 123 hauls for Southern Macquarie Ridge Longline. An additional 307 fish from the 2016 catch were aged and these were included as age-at-length data for this assessment. This comprised 206 females and 10 males in 2016.

There were minor revisions to the tag recapture history. Additions to the historical recapture information include three additional tag recaptures in 2015, two of these from tags released by the Southern Macquarie Ridge Longline fleet in 2011 and 2012 and the remaining tag released in 2013 by the Northern Macquarie Ridge Longline fleet in 2007.

New tag recaptures from the 2015 data included 102, 10 and 46 recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 158 tag recaptures in 2015 from fish tagged in previous seasons, with three of these tags recaptured in a different area to their release. In addition there were 446, 184 and 271 new tag releases in 2016, 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.

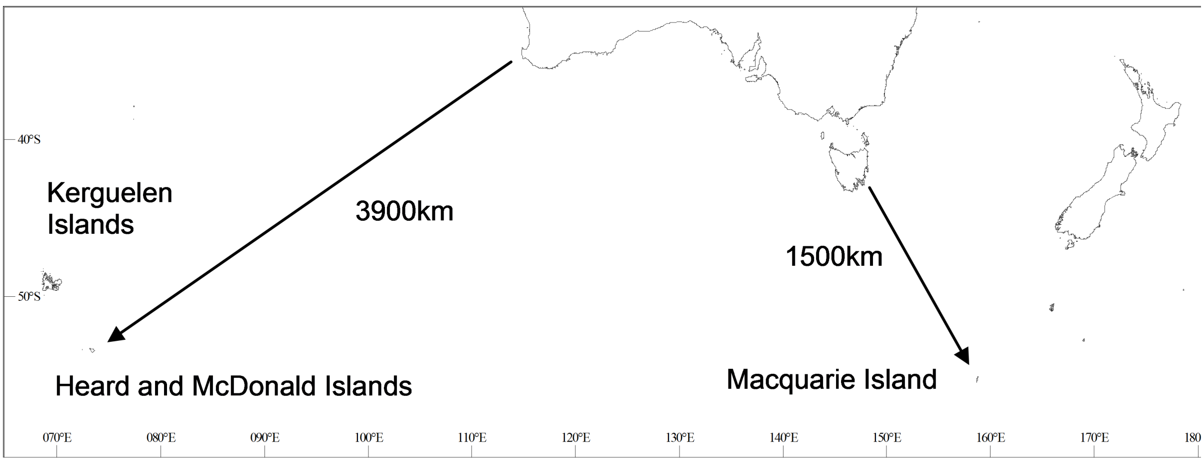

Figure 2.1: The location of Macquarie Island (54° 30'S, 158° 57'E) and Heard Island and McDonald Islands (53 ° 06'S, 73 ° 30'E) relative to New Zealand and Australia.

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).

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

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

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

[a] longline season began on 1 May up until 2014, and started on 15 Apr from 2015 onwards.
[b] tonnage shown in brackets would have been triggered if trawl catch rates reached 10 t/km^2 over 3 consecutive fishing days
[c] research TAC to enable tag-based stock assessments
[d] TACs for longline trial
[e] TAC set for entire Macquarie Island region

exceeded 10t/km^2 over three consecutive fishing days. If this catch rate dropped below the trigger level, then the TAC fell to the lower TAC. If the lower TAC had been reached then fishing ceased.

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

Since 2012/13, a single TAC has been set for the whole of the Macquarie Island region. The 2016/17 TAC was set at 450t, with a recommendation to catch a little more than half of this total TAC in Aurora Trough (250t), and 60% of the remainder taken from North Macquarie Ridge (120t) and the rest from South Macquarie Ridge (80t). The actual catch in 2016 was around 15t below the TAC, with around 50t more then the recommendation of the catch taken from South Macquarie Ridge, but with less then the recommended catch taken in the other two regions (Table 3.1). Note that this is the second largest catch by longline in North Macquarie Ridge, indicating that considerable effort was made to match the recommended spatial distribution of catches.

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), 69% for the 2015 assessment (Day *et al.*, 2015) and 67% for the 2016 assessment (Day *et al.*, 2016).

2.4 Modifications to the previous assessment

The following data have been added to the assessment:

1. 2016 catches
2. 2016 length compositions
3. 2016 tag recaptures
4. 2016 age-at-length compositions

3 Data

The data available for model-fitting purposes include length composition data from the fishery (1994–2016), conditional age-at-length data (1996–2000, 2002, 2003, 2005–2010, 2013–2016), 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 2016 caught 202t in the Aurora Trough and 232t in the northern and southern Macquarie Ridge areas. Catch figures in 2014 and 2015 were updated from those used in the last assessment, with additional catches in southern Macquarie Ridge of 1t and 15t respectively.

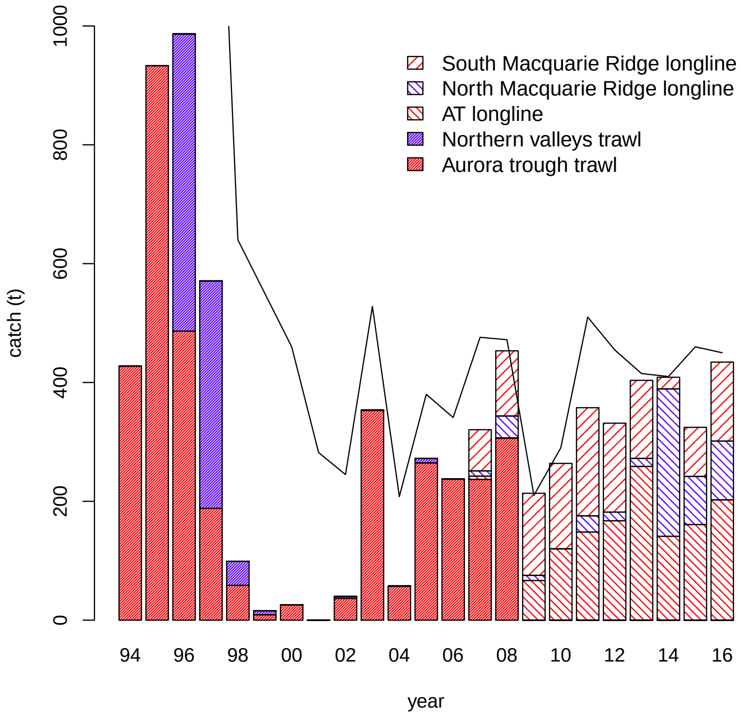

Figure 3.1: Catch history and total TAC by fishing year, with catches stacked by fleet and the grey line representing the combined TAC (with TACs summed for Aurora Trough and Macquarie Ridge from 1996–2011). There were small research quota in the Aurora Trough from 1998-2002 and in 2004.

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

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

3.2 Length frequency data

Samples of the length composition of the catch were available for all fishing seasons (1994/95 through 2016/17). Each annual length composition is based on the measurement of several hundreds (thousands) of fish (Tables 3.2 and 3.3). However, it is unlikely that the number of fish measured in each year is an appropriate metric of the effective sample size, due to expected high correlations among fish lengths within individual hauls/shots. Thus 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.

Table 3.2: Number of length samples by fleet and season for the trawl fleets, 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

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.

Table 3.3: Number of length samples by fleet and season for the longline fleets, 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 longline	07/08	2	200	100
	09/10	9	548	61
	10/11	18	1066	59
	11/12	45	1779	40
	12/13	52	1916	37
	13/14	79	3046	39
	14/15	62	2216	36
	15/16	84	2950	35
	16/17	94	3376	36
NMR longline	07/08	5	160	32
	08/09	13	406	31
	09/10	7	246	35
	11/12	26	829	32
	12/13	31	838	27
	13/14	11	340	31
	14/15	70	2570	37
	15/16	96	2739	29
	16/17	128	3337	26
SMR longline	07/08	28	1589	57
	08/09	44	1750	40
	09/10	50	1886	38
	10/11	34	1546	45
	11/12	96	3388	35
	12/13	126	4080	32
	13/14	94	3107	33
	14/15	18	561	31
	15/16	76	2404	32
	16/17	123	3865	31

3.3 Age data

Age-at-length samples are available from aged fish that were captured in 1996–2000, 2002, 2003, 2005–2010 and 2013–2016 (Table 3.4). New ageing data from 2016 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 3.4). 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 3.5) 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, 16,121 Patagonian toothfish were tagged at Macquarie Island, of which 2,067 have been recaptured (Table 3.6, Table 3.7). Fish are still being recaptured from releases in the early years of the fishery (Table 3.6), with one fish recaptured in 2015 having been initially tagged in 1997. Of the recaptures in 2016, the longest period between tagging and recapture was for a fish tagged in 2004.

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

Year	gender	south	north	total
1996	u	9	10	19
	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		2
	f	175	25	200
	m	83	14	97
2014	u	2	3	5
	f	97	95	192
	m	59	23	82
2015	u			0
	f	129	76	205
	m	57	19	76
2016	u			0
	f	134	72	206
	m	70	31	101
total		3575	1048	4623

Table 3.5: 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 3.6: 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	16/17
95/96	AT tr	428	69	57	28	3		1	1	1							1						
95/96	NV tr	4	57																				
96/97	AT tr	448	58		42	7		2		9	1	3		1	1								
96/97	NV tr	536	61		53	5	1			2													
97/98	AT tr	503	60			18	3	4	5	21	4	15	1		2	3	1	2	2			1	
97/98	NV tr	477	69			9				1					1		1						
98/99	AT tr	652	68				4	5	2	30	2	9	2	2	7		1	1		1			
98/99	NV tr	308	57																				1
99/00	AT tr	692	65					3	1	35	6	12	1	4	6	2	5	1	5				
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		1
04/05	NV tr	263	56									2		1	1						1	1	
05/06	AT tr	520	71										25	18	27	2	5	4	4	3	1	1	1
05/06	NV tr	288	60																1		2	3	1
06/07	AT tr	432	59											26	13		1			4		2	1
07/08	AT tr	273	65												31	2		2	1	3	1		2
07/08	NMR LL	26	78													1		3	2				1
07/08	SMR LL	189	81												15	4	3	6	6	4		1	4
08/09	AT tr	557	71													2	6	12	10	19	6	8	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	2
09/10	AT LL	299	85														27	13	9	13	4	2	3
09/10	NMR LL	60	85															5	5			2	1
09/10	SMR LL	395	79														26	25	8	20	2	2	4
10/11	AT LL	478	87															11	31	45	6	4	4
10/11	SMR LL	507	91															27	42	34	5	8	10
11/12	AT LL	302	72																10	37	7	7	12
11/12	NMR LL	116	83																1	2	1	3	2
11/12	SMR LL	497	78																9	25	4	18	10
12/13	AT LL	309	78																	37	12	12	6
12/13	NMR LL	56	89																				
12/13	SMR LL	302	87																	20		9	3
13/14	AT LL	529	75																		9	26	23
13/14	NMR LL	36	81																			3	
13/14	SMR LL	249	81																		9	10	1
14/15	AT LL	295	72																			9	19
14/15	NMR LL	499	79																				4
14/15	SMR LL	36	80																				
15/16	AT LL	353	76																				17
15/16	NMR LL	168	79																				2
15/16	SMR LL	165	80																				12
16/17	AT LL	446	77																				
16/17	NMR LL	184	84																				
16/17	SMR LL	271	92																				

Table 3.7: 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	161	1	34
NV trawl	8	72	1	7	6
AT longline	0	0	396	0	19
NMR longline	0	0	1	33	15
SMR longline	1	0	65	5	390

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 3.6; 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.

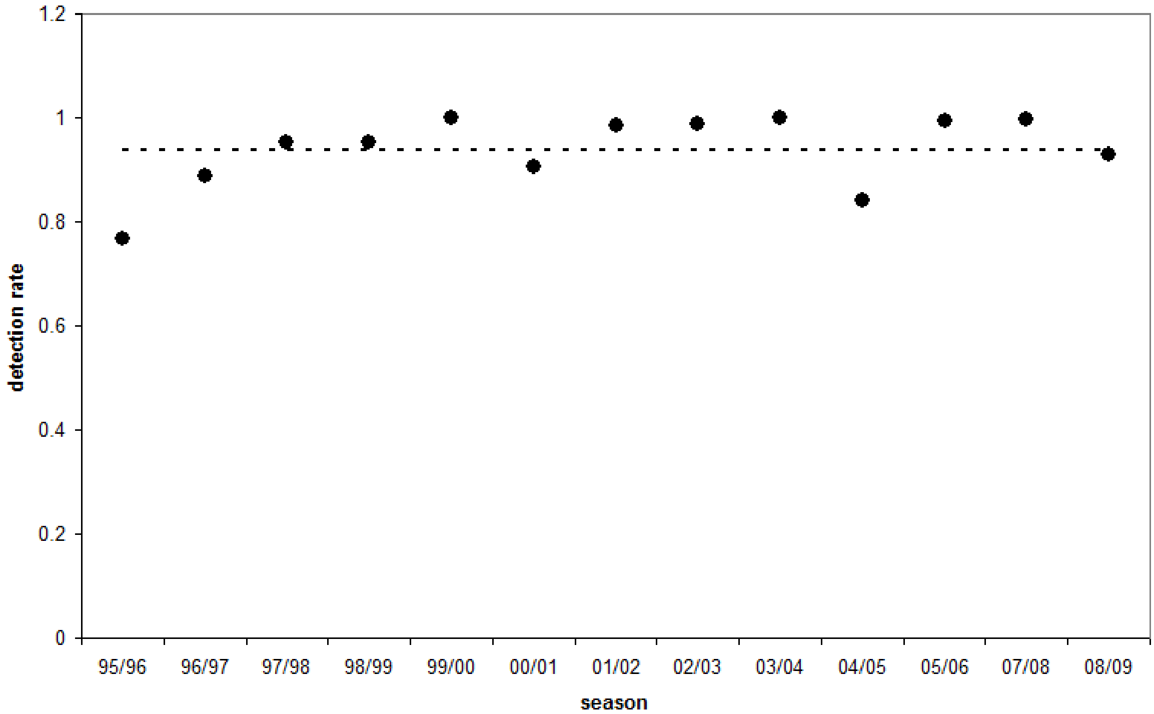

Figure 3.2: Estimated tag detection rate (points) by fishing season (Tuck and Lamb 2009). Dotted line corresponds to the mean detection rate (0.938) over the time series.

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 hauls and fish measured in Southern Macquarie Ridge Longline, namely one more fish measured in 2010, one more haul and 33 more fish measured in 2014 and 14 more hauls and 419 more fish measured in 2015. The new 2016 length frequency data include an additional 3376 fish in 94 hauls for Aurora Trough Longline, 3337 fish in 128 hauls for Northern Macquarie Ridge Longline and 3865 fish in 123 hauls for Southern Macquarie Ridge Longline.

There were no revisions to the historical age-at-length data up to 2015 used in the 2016 assessment. An additional 307 fish from the 2016 catch were aged and these were included as age-at-length data for this assessment. This comprised 206 females and 10 males in 2016.

Additions to the historical recapture information include three additional tag recaptures in 2015, two of these from tags released by the Southern Macquarie Ridge Longline fleet in 2011 and 2012 and the remaining tag released in 2013 by the Northern Macquarie Ridge Longline fleet in 2007. 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%.

New tag recaptures from the 2015 data included 102, 10 and 46 recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 158 tag recaptures in 2015 from fish tagged in previous seasons. Of these 158 recaptures, 155 were recaptures in the same area (145 in the south, 10 in the north), with three recaptures in a different area to the release area, providing additional information on movement of individuals between areas. In 2016, all three of these recaptures were of fish released in the north and recaptured in the south. One fish tagged and released by the North Macquarie Ridge Longline fleet was recaptured by the South Macquarie Ridge Longline fleet, and two fish tagged and released by the Aurora Trough trawl fleet was recaptured by the South Macquarie Ridge Longline fleet.

In 2016, there were 13 fish tagged by Aurora Trough Trawl that were recaptured, 11 in Aurora Trough and two in Southern Macquarie Ridge. Two fish tagged by Northern Valleys Trawl were recaptured in the Southern Macquarie Ridge in 2016. There were 84 fish previously tagged by Aurora Trough Longline recaptured in 2015, with 81 of these recaptured in the same area as release, with the remaining three recaptured in the Southern Macquarie Ridge. There were an additional 11 recaptures of longline tagged fish from Northern Macquarie Ridge, with 10 recaptured in the same area as release and one more recaptured in the Southern Macquarie Ridge. Forty eight fish previously tagged by longline in Southern Macquarie Ridge were recaptured in 2015 with 10 of these recaptured in Aurora Trough and the remaining 38 recaptured in the Southern Macquarie Ridge.

In addition there were 446, 184 and 271 new tag releases in 2016, 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 and males 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)	165 (fixed)
k (yr^{-1})	0.042	0.038	0.054	0.057	0.052
t_0	-0.781	-1.184	-0.434	0.19	-0.34
CV of length at age	0.13	0.12	0.14	0.16	0.14

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 1985–2009, 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 2018/2019 fishing season. Key quantities of interest output by the model include time series of female spawning biomass, the current vaue 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 2018/19 and 2019/20 fishing seasons 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 2017/2018 catch determination under the CCAMLR control rule

Values for the 2018/19 catch were calculated under the CCAMLR control rule. The calculated 2018/19 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 2018/19 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 2018/19 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 2016 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 year of age-at-length and additional length data in 2016, enabled one additional year of recruitment to be estimated in the new assessment, with recruitment now estimated up until 2009.

The sequential changes to update the base case model were:

1. update historical data,
2. add 2016 catch,
3. add 2016 length compositions,
4. add 2016 age-at-length data,

5. add 2016 tag data,
6. estimate one additional year of recruitment, up until 2009,
7. iteratively re-weight the likelihood contributions from the length and age compositions and recruitment variability σ_R.

The combined addition of 2016 catch, length composition, age-at-length data and tag 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 2016 tag data, resulting in very similar time series to the 2016 base case. Estimating one more year of recruitment made little difference, as the additional recruitment event was estimated to be only slightly below average.

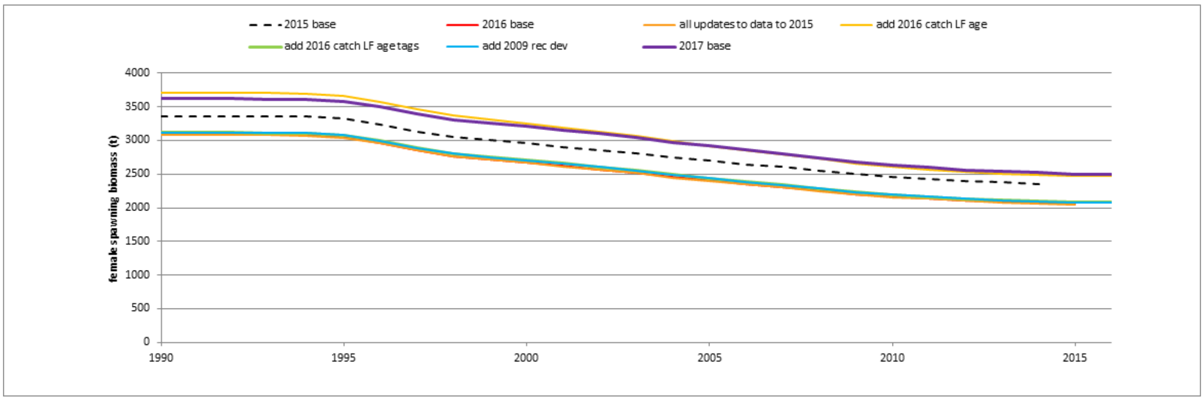

Figure 6.1: Effect on the female spawning biomass trend of sequential updates with the most recent data.

The model with the revised historical data and all the new 2016 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 workshops. Iteratively re-weighting resulted in a upwards translation of both the spawning biomass and the recruitment time series, moving this series closer to the spawning biomass series from the 2015 base case, but with a very similar relative trend to that seen in both the 2015 and 2016 assessments. The recruitment series looks closer to the recruitment series from the 2015 assessment than the 2016 assessment, but again the overall trends for all three assessments are similar.

The 2017 base case model is thus the iteratively re-weighted model with 2016 data added, with recruitment now estimated to 2009, 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 length frequencies from Northern Macquarie Ridge since 2014 suggest fewer large fish are being caught in this area and the fit in 2016 is not particularly good. However, the fits

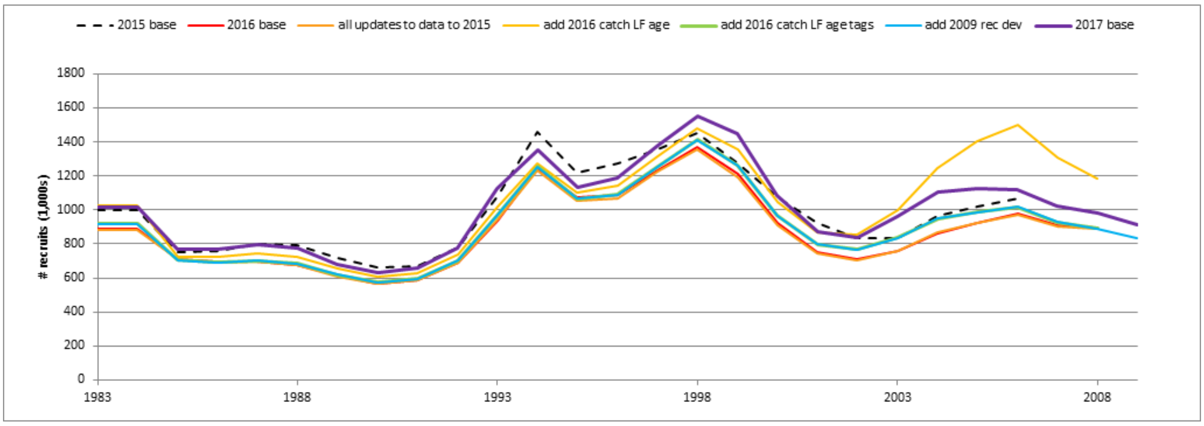

Figure 6.2: Effect on the recruitment estimates of sequential updates with the most recent data.

to the the length frequencies from the Aurora Trough longline are excellent since 2012 and the fit to the the length frequencies from Southern Macquarie Ridge in 2016 are excellent. Length frequencies from different regions are being fit simultaneously, so it is not that surprising that fits are better for some regions than others.

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 an improvement over the un-reweighted sample sizes although it remains difficult to balance all samples equally effectively (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, 6.9 and 6.10) 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 6.11). 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.

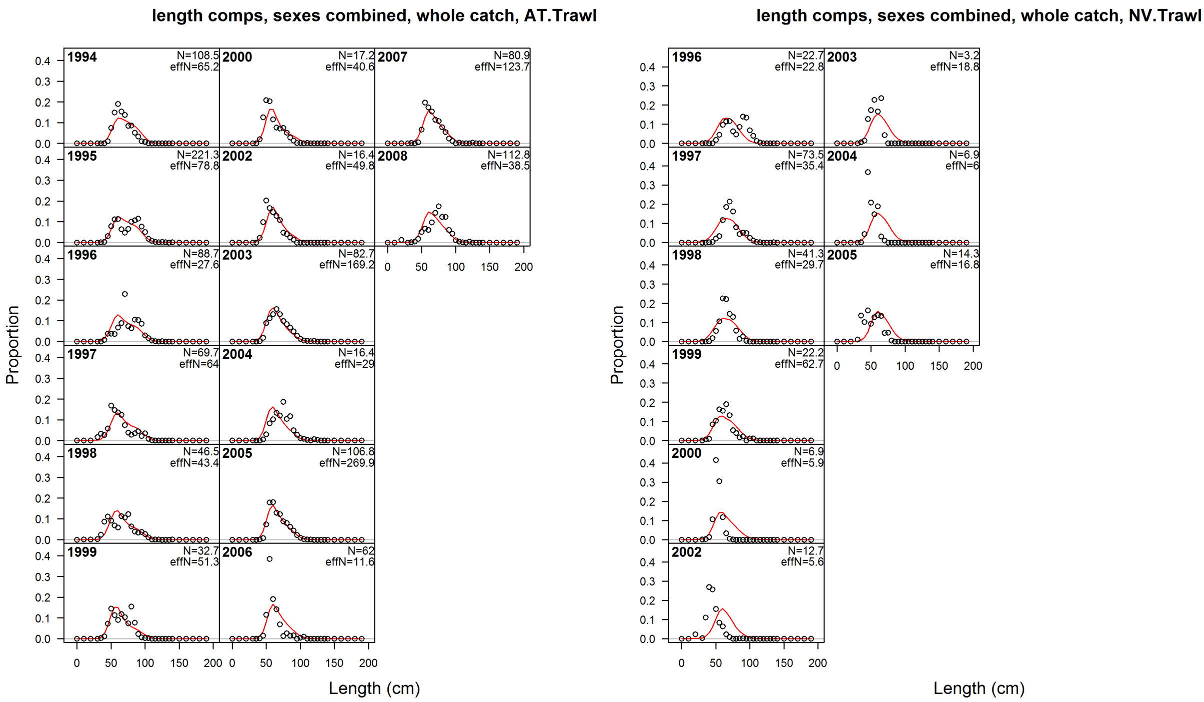

Figure 6.3: Fits to the length composition data for the trawl fleets.

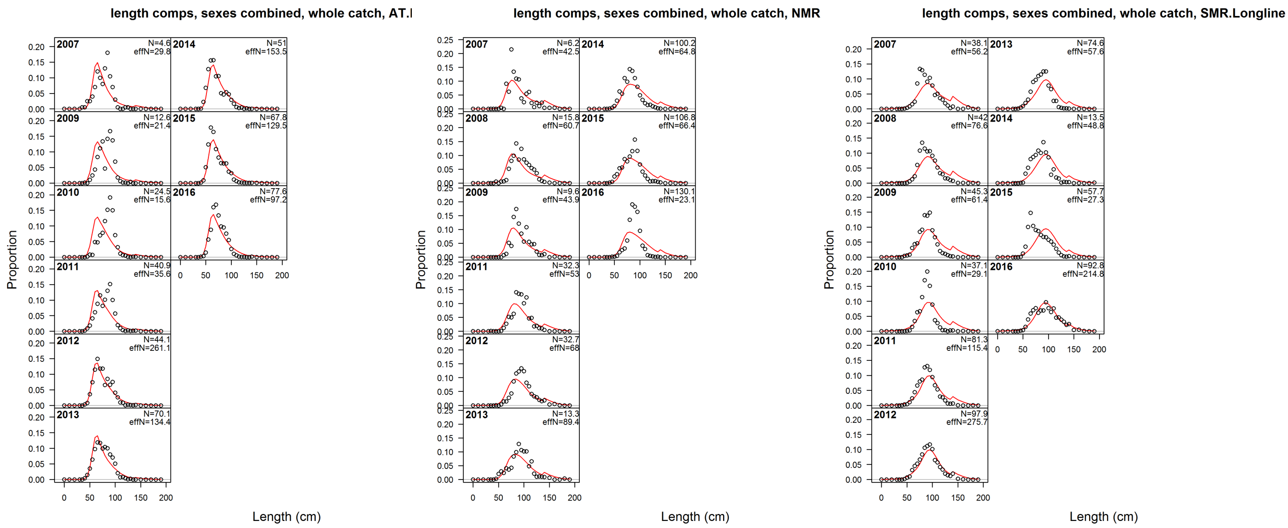

Figure 6.4: Fits to the length composition data for the longline fleets.

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 6.12). Fits to the length data for the Northern Valley trawl fleet deteriorate from 2000, with generally smaller fish caught than expected. However, the sample sizes for these length frequencies are small and the total catch from this fleet is very small in this time period, often less than 1t and always less than 10t per year. This compares to catches of around 500t and 400t in the Northern valley trawl fleet in 1996 and 1997 and 40t in 1998. While this selectivity could be time blocked to improve the fits, the relative size of the catch by this fleet from 2000 onwards suggests that this would have minimal impact on the model.

As 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, 2015 and 2016 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. The selectivity for the Macquarie Ridge longline fleets moved to slightly larger fish, compared to the 2016 assessment.

6.3.2 Growth

The estimated growth parameters are shown in Table 4.1, and the estimated growth curves in Figure 6.13. The estimated growth curve for males has changed in this assessment, with L_∞ fixed at 165cm, the same value used for females. In earlier assessments, L_∞ was estimated for males, but the estimates were unreasonably large, from a biological perspective, in the 2016 assessment, with little data available

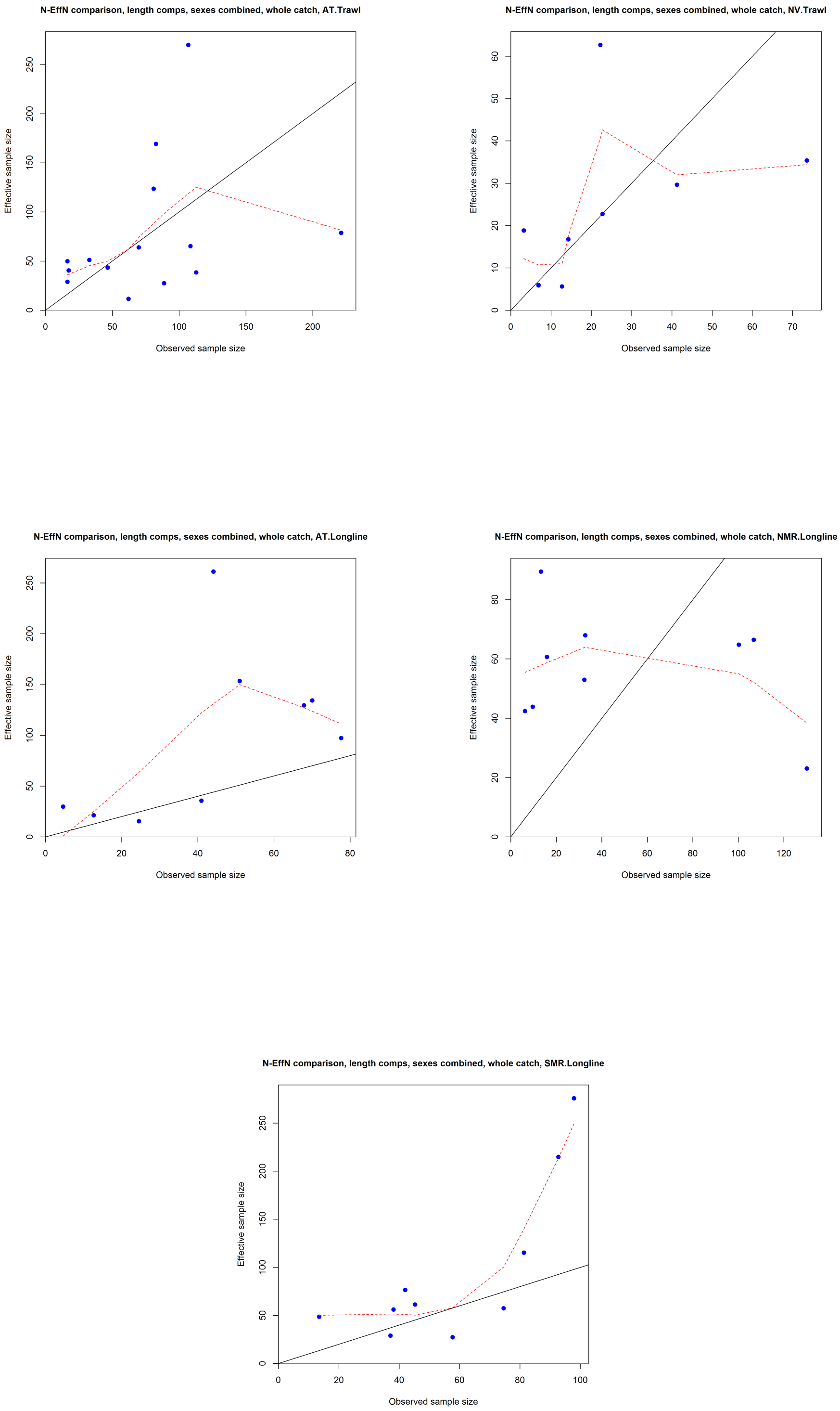

Figure 6.5: Input vs. effective sample size for the length composition data.

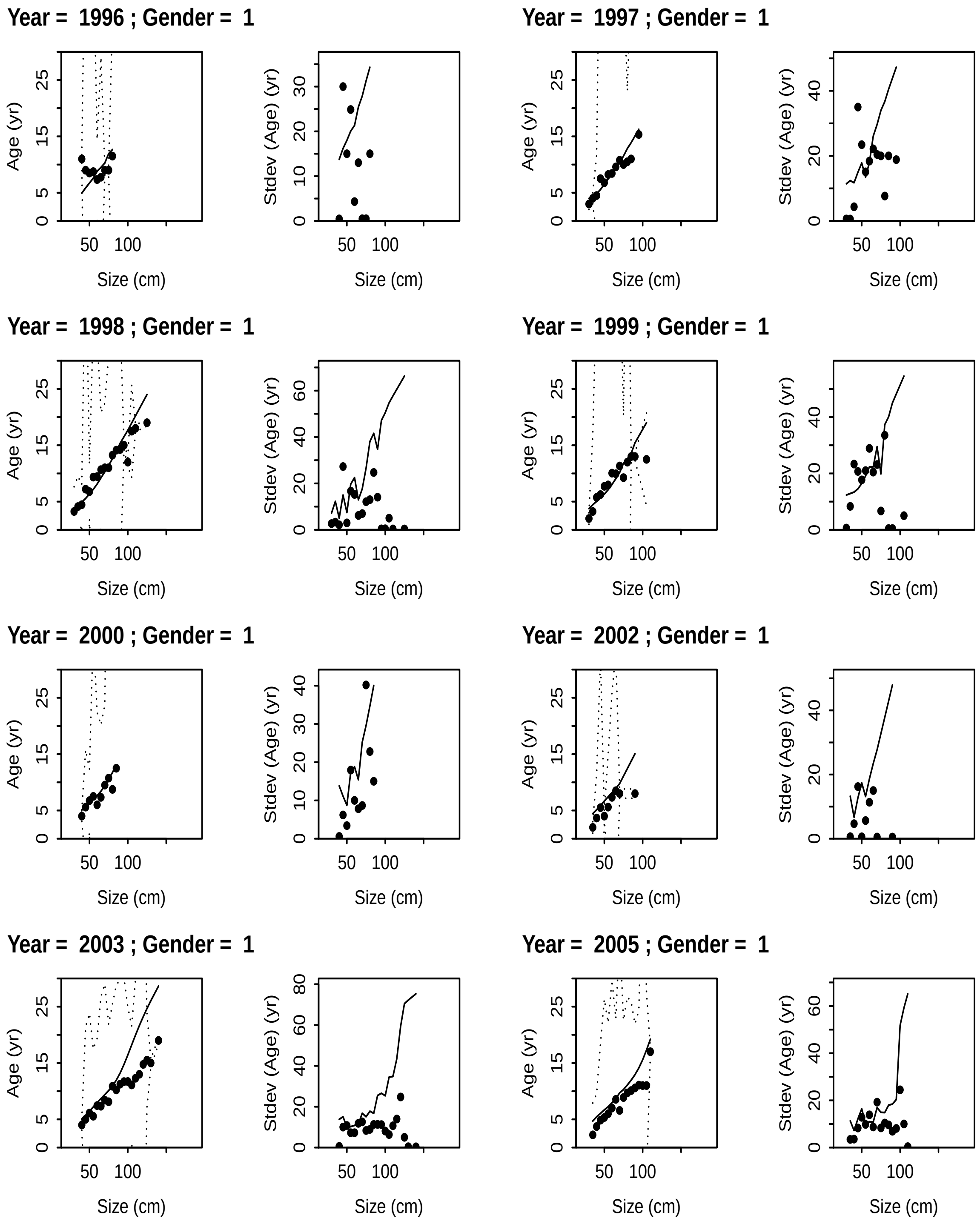

Figure 6.6: Diagnostic plots for the fits to the female (Gender = 1) conditional age-at-length data from 1996 to 2005. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (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.

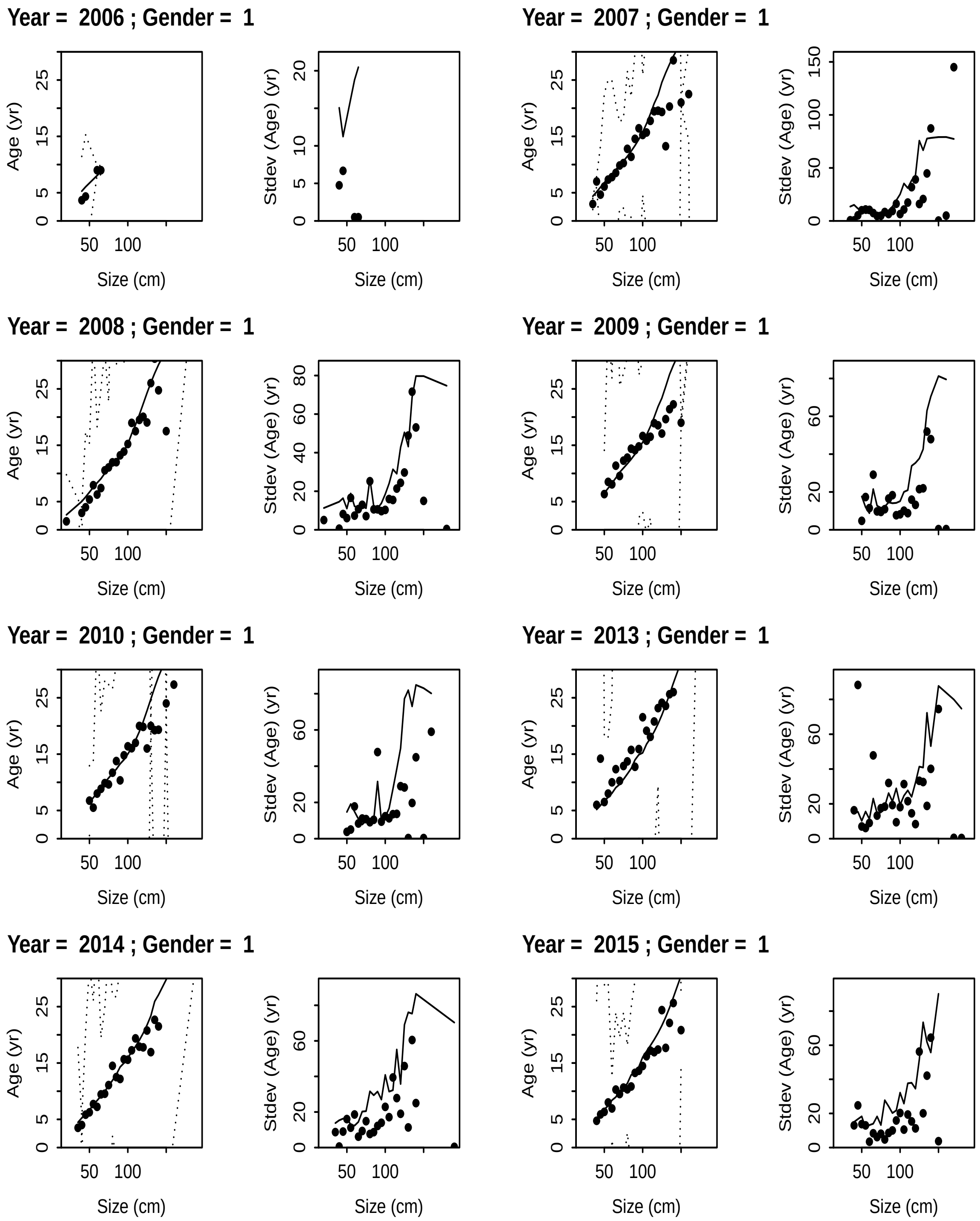

Figure 6.7: Diagnostic plots for the fits to the female (Gender = 1) conditional age-at-length data from 2006 to 2015. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (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.

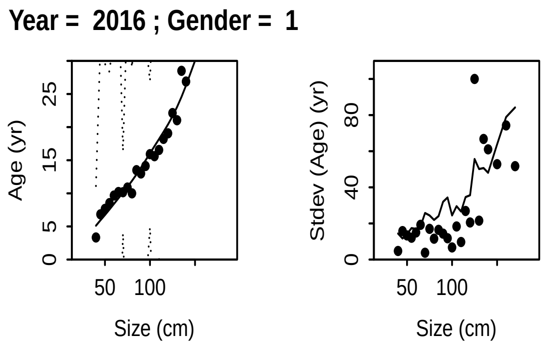

Figure 6.8: Diagnostic plots for the fits to the female (Gender = 1) conditional age-at-length data from 2016. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed 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.

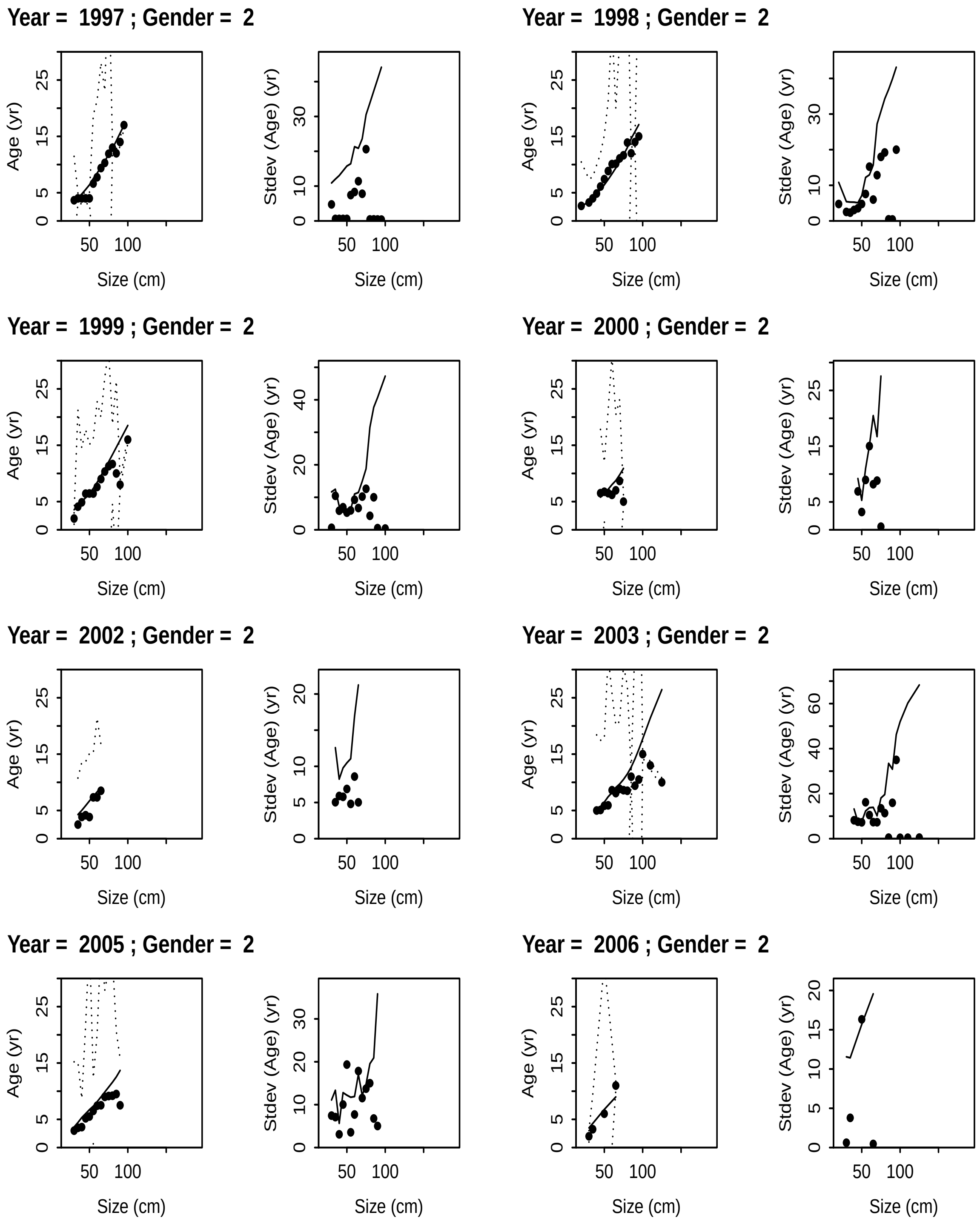

Figure 6.9: Diagnostic plots for the fits to the male (Gender = 2) conditional age-at-length data from 1997 to 2006. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (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.

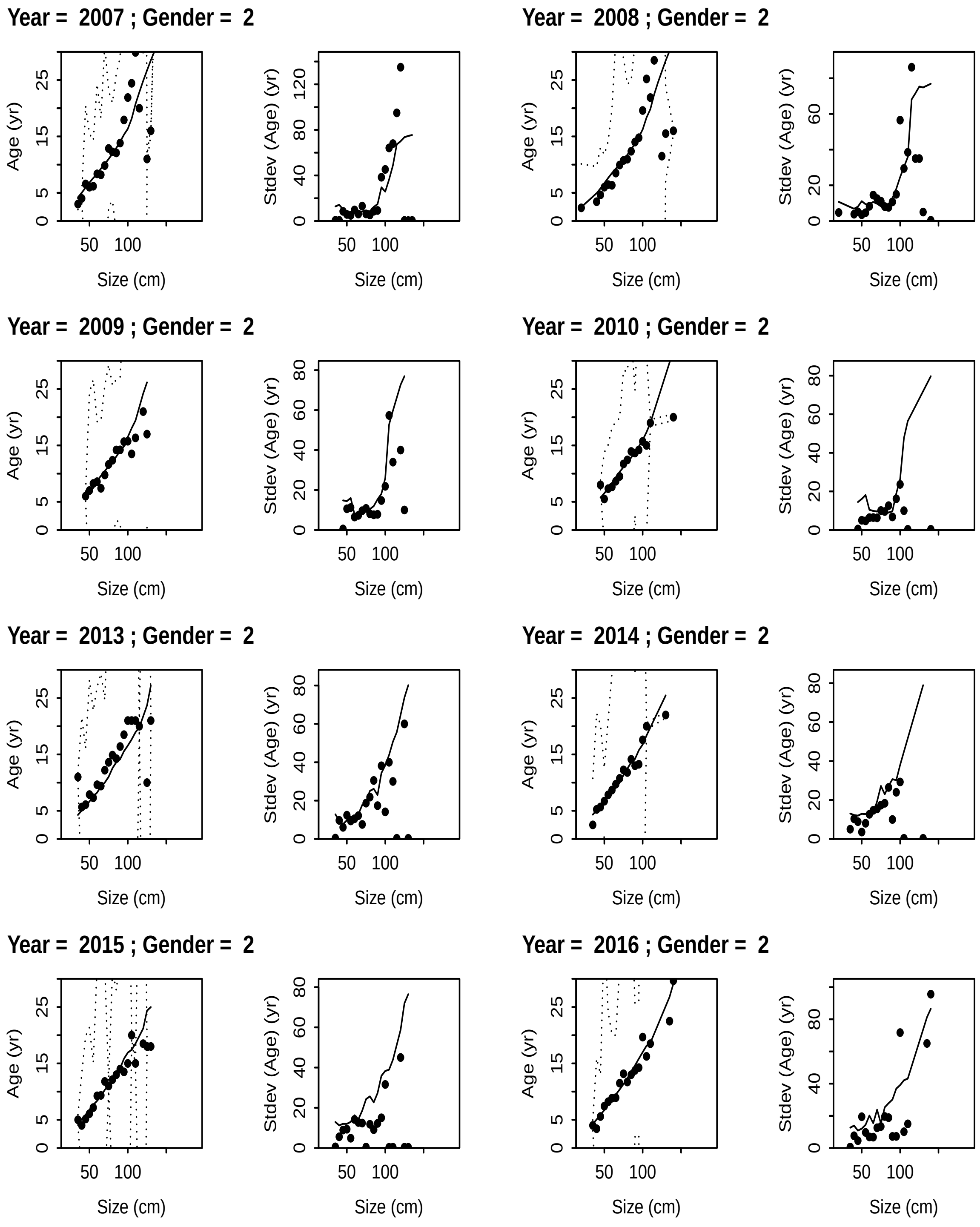

Figure 6.10: Diagnostic plots for the fits to the male (Gender = 2) conditional age-at-length data from 2007 to 2016. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (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.

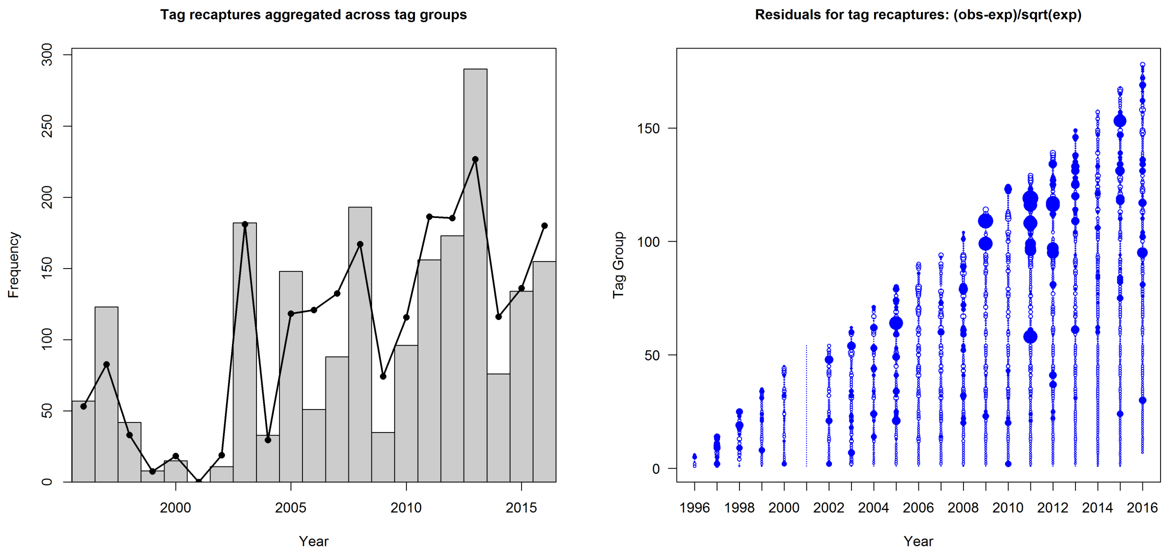

Figure 6.11: Summary of the base case fits to the tag-recapture data. Left-hand panel shows the summed observed (bars) and expected (line) recaptures over years. The right-hand panel shows the residuals by tag group and year (solid blue indicates more recaptures observed than expected).

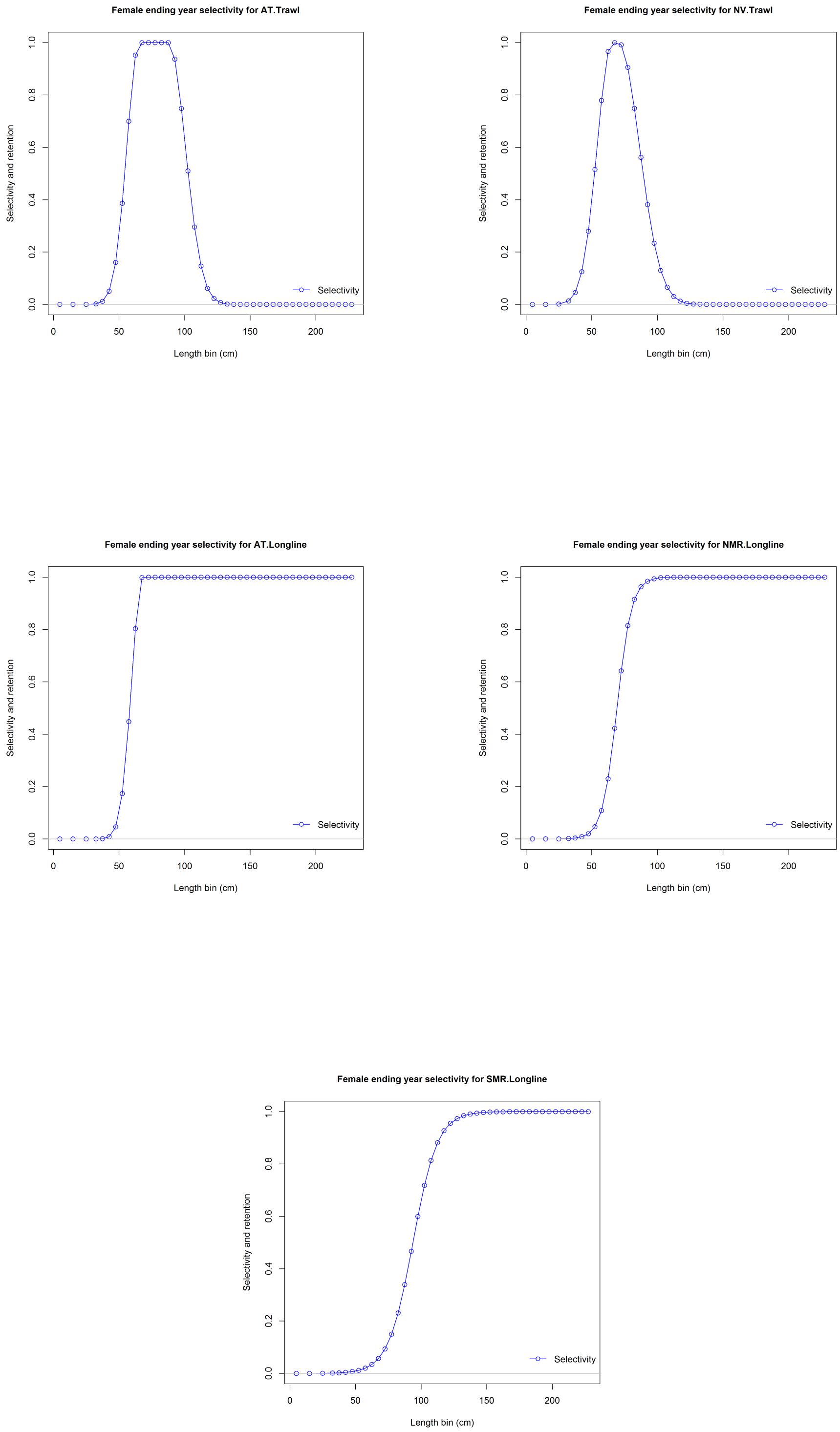

Figure 6.12: Base case estimates of selectivity at length by fleet.

to inform the estimate of L_∞ for older male fish.

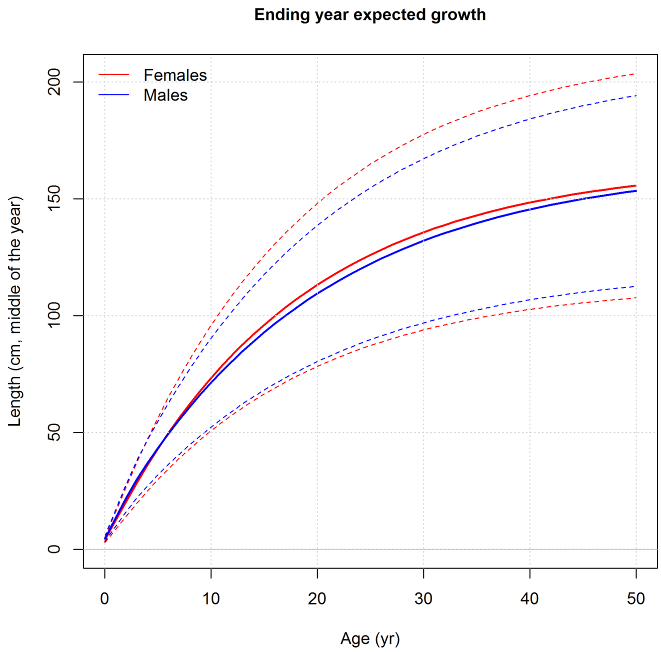

Figure 6.13: The estimated growth curves.

6.3.3 Recruitment

The recruitment pattern (Figure 6.14) 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 2016 assessment, with slight increases in the estimates of recruitment in 2004 and 2005 and slight decreases in 2007 and 2008. Note that after a run of above average recruitment events in the mid to late 1990s, recruitment dropped in the early 2000s, then returned to slightly above average from 2004 to 2006 and was estimated to be below average in 2009.

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 27–57 % , with a mean of 42% (Figure 6.15). 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.

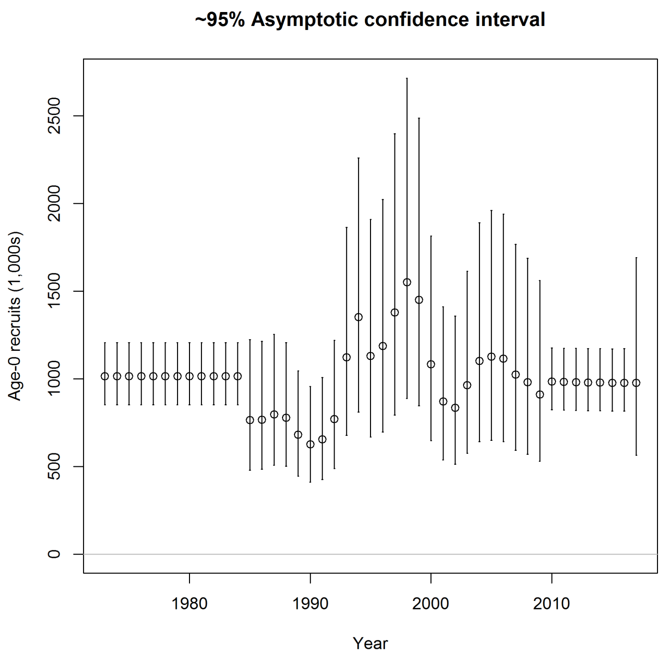

Figure 6.14: Base case estimated recruitment time series (with approximate 95% confidence interval).

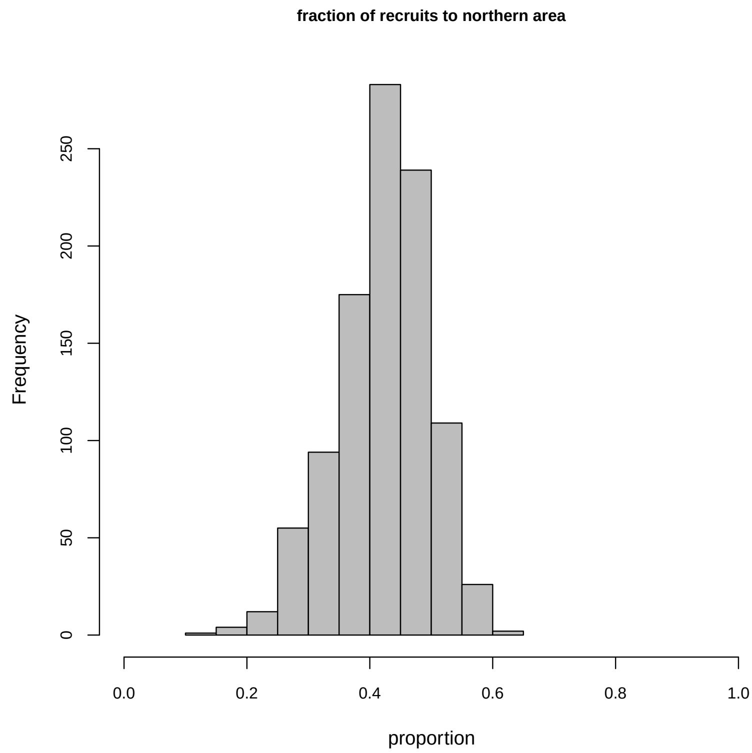

Figure 6.15: Posterior distribution for the proportion of annual recruits allocated to the northern area in the base case model.

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 2% and 8% per annum, with a lower rate of between 0.7% and 1.4% per annum for north-to-south movement (Figure 6.16). 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), compared to an estimate of 67% from the 2016 assessment.

The time series of female spawning biomass has declined steadily since the start of the fishery (Figure 6.17), and has stabilised at just under 70% of unfished in the last four 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 2017 stock size in the northern area is estimated to be nearly eight times larger than that in the south (female spawning biomass 2,203t and 280t respectively). The northern area is also

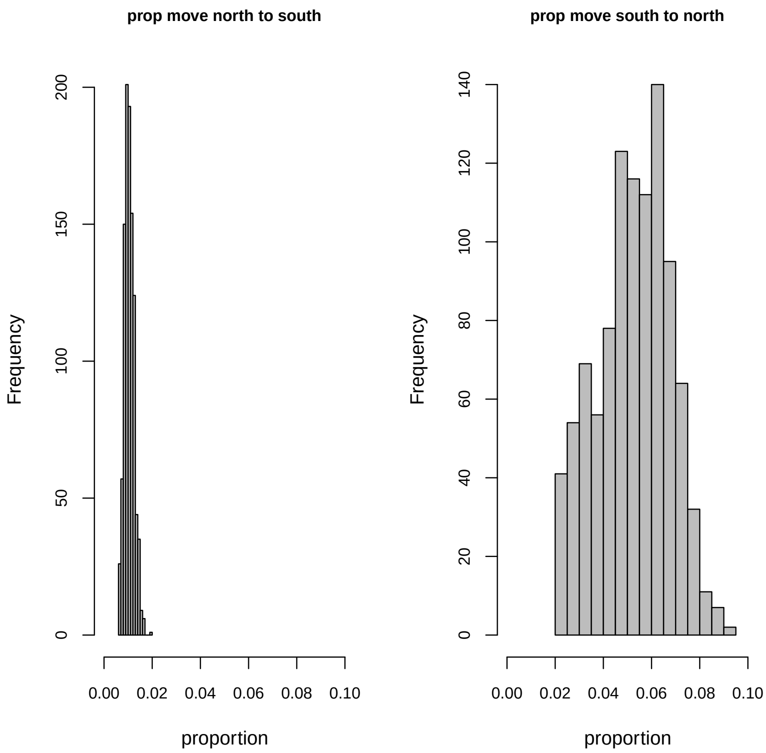

Figure 6.16: Posterior distributions for the values of the movement parameters in the base case model.

estimated to be considerably less depleted than the southern area (77% and 37% respectively).

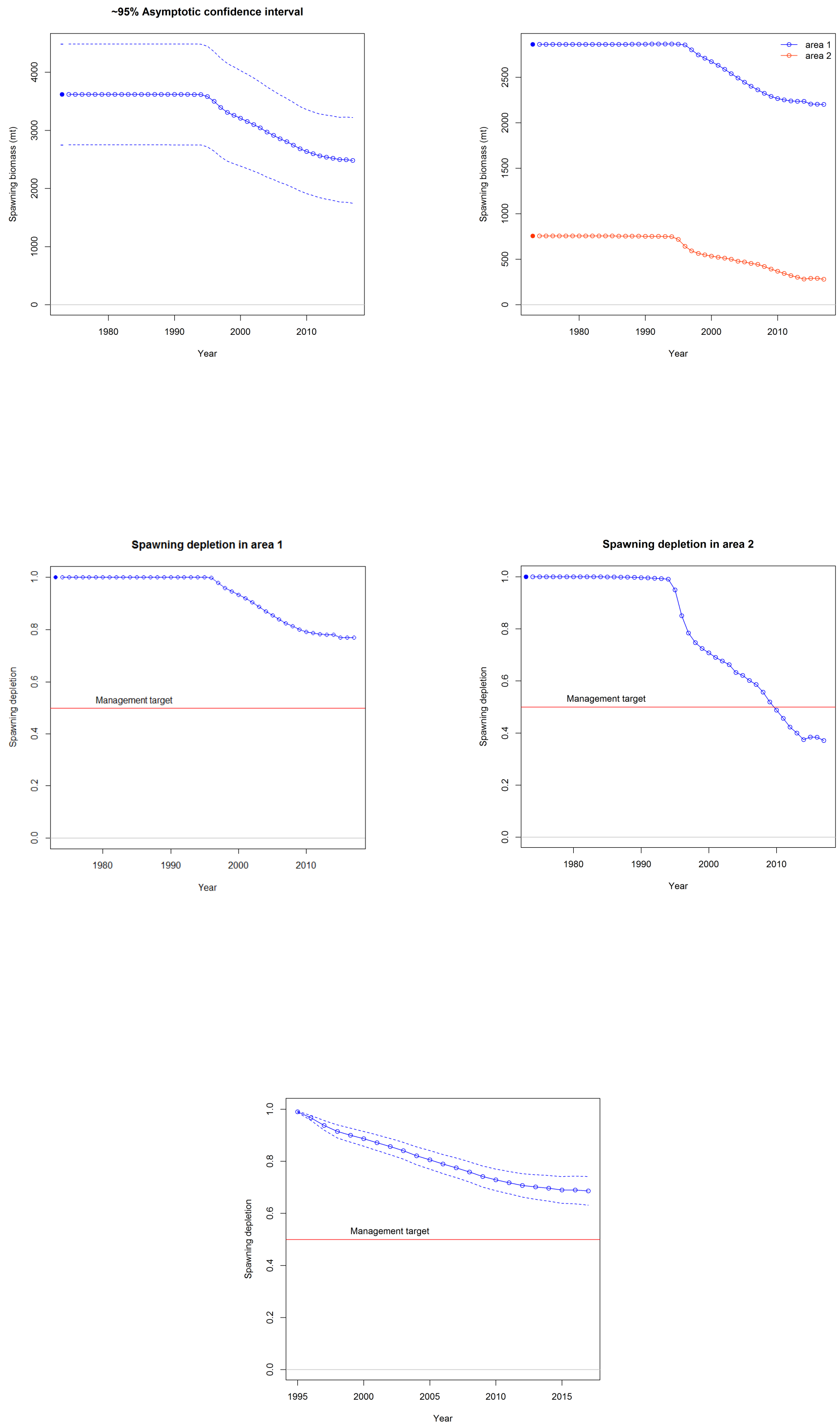

Figure 6.17: Base case estimated time series for female spawning biomass and spawning depletion (spawning biomass relative to unfished), both by area and overall. Area 1 is north, and area 2 is south.

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; male $L_\infty = 165$ 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	$SB_{17/18}$	SB_0	$SB_{17/18}/SB_0$			total	length	age	Tag comp	Tag recap	Recruit
Base case	**2484**	**3618**	**0.69**	**455**	**588**	**2889.5**	**232.6**	**201.7**	**878.8**	**1597.1**	**-20.6**
fix male L_∞ = 130	2694	3864	0.70	451	592	3.2	-2.4	0.8	1.4	3.1	0.3
fix male L_∞ = 195	2360	3471	0.68	456	583	-1.4	1.5	-0.1	-0.8	-1.9	-0.1
fix female L_∞ = 195	2997	4477	0.67	438	563	-3.9	2.7	-1.4	-1.7	-3.1	-0.3
fix female & male L_∞ = 195	2889	4343	0.67	440	561	-4.3	4.0	-1.3	-2.2	-4.4	-0.4
$M = 0.155$	1195	1995	0.60	354	468	-16.4	-2.7	-2.0	-9.9	-0.9	-0.8
M estimated (0.21)	466	862	0.54	296	415	*-35.9*	*-1.4*	*-2.4*	*-9.7*	*-21.2*	*-1.2*
$h = 0.5$	2515	3678	0.68	328	363	0.6	0.2	0.1	0.2	0.0	0.2
$h = 0.9$	2473	3598	0.69	506	748	-0.2	-0.1	0.0	-0.1	0.0	-0.1
dome shaped selectivity for NMR & SMR ll	2953	4101	0.72	481	625	*-7.2*	*-5.9*	*0.1*	*0.9*	*-2.2*	*-0.1*
50% female maturity at 130 cm	3235	4629	0.70	476	607	0.0	0.0	0.0	0.0	0.0	0.0
Halve weight on LF data	2558	3739	0.68	464	599	2.8	9.8	-1.7	-1.3	0.1	-4.1
Double weight on LF data	2402	3471	0.69	443	573	3.8	-8.8	3.1	2.0	0.4	7.0
Halve weight on age data	2519	3653	0.69	458	591	1.7	-2.4	5.3	0.4	-2.5	0.9
Double weight on age data	2457	3593	0.68	451	583	0.9	2.6	-2.3	-0.9	2.9	-1.4
Halve weight on tag data	2359	3484	0.68	439	568	1.8	-1.6	-1.5	0.6	5.7	-1.5
Double weight on tag data	2611	3761	0.69	468	602	2.1	1.7	2.7	0.0	-4.9	2.6

6.3.6 2016/17 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 2018/19 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 2018/19 and 2019/20, to allow a two year RBC to be set while still complying with the CCCAMLR rule. The projected 2018/19 and 2019/20 catches range from 430t to 520t.

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	
430t : 0% : 0%	430	0	0	430
250t : 20% : 80%	250	44	176	470
250t : 40% : 60%	250	84	126	460
250t : 60% : 40%	250	120	80	450
200t : 40% : 60%	200	108	162	470
200t : 60% : 40%	200	150	100	450
150t : 0% : 100%	150	0	370	520
150t : 50% : 50%	150	160	160	470
150t : 100%: 0%	150	300	0	450

Figure 6.18 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. 2007–2016 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 6.18).

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 195 and female L_∞, fixed between 165 and 195, show improved overall fits for larger values of L_∞, with some conflicts between length and tag

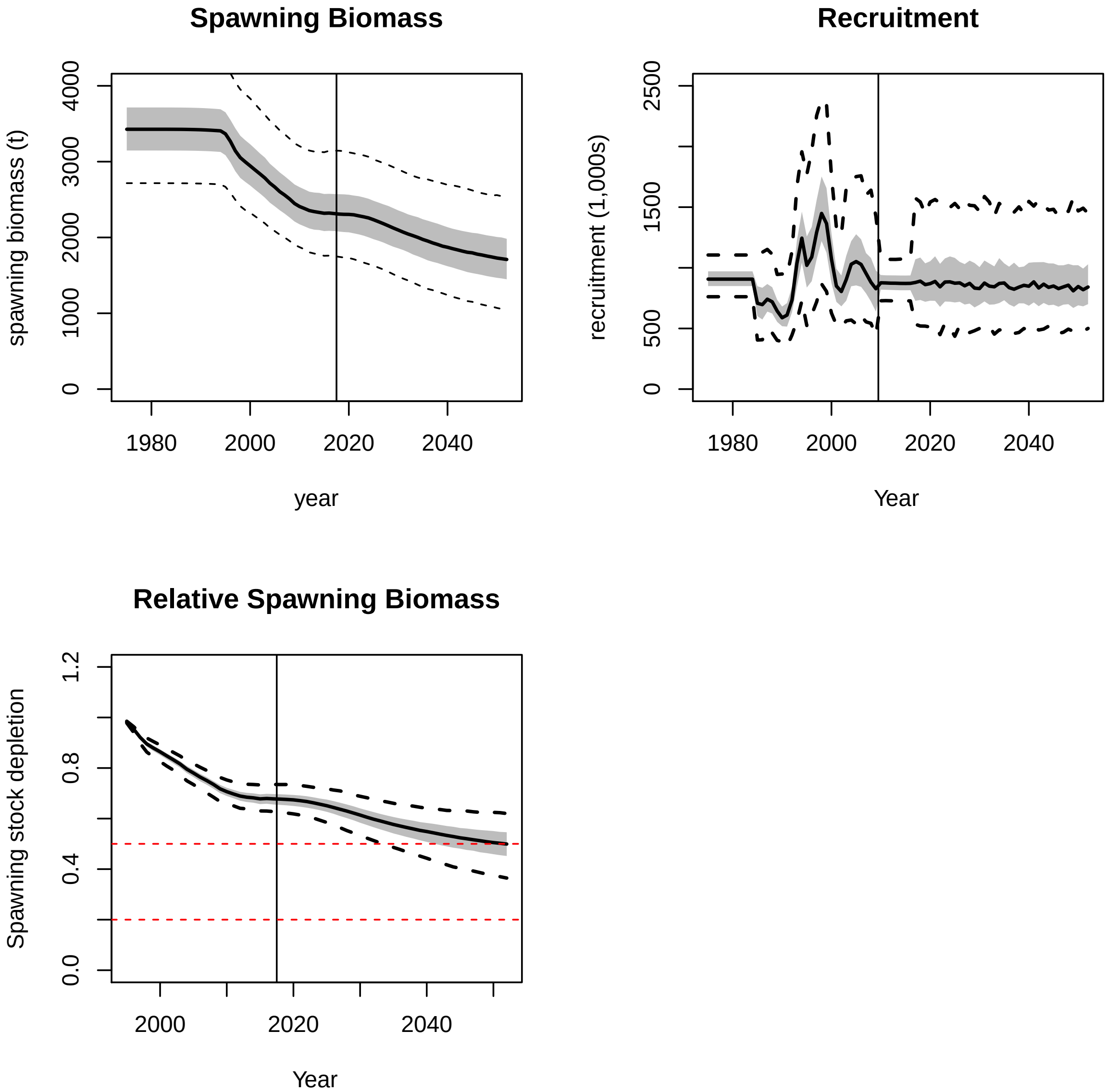

Figure 6.18: Posterior distribution and projection of female spawning biomass, recruitment, and spawning biomass relative to the unfished level, under a constant catch of 450t, split 250t for Aurora Trough, 120t for northern Macquarie Ridge and 80t for southern Macquarie Ridge.

components of the likelihood. However, larger values of L_∞ do not make sense biologically.

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, the likelihood from the recruitment deteriorates, with poorer overall fits to the data, also through poorer fits to the age data. All impacts of doubling and halving the weighting on age and tagging data are minor.

This suggests some conflict between recruitment estimates and the signal coming from 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. Changes to the spatial distribution of catch in the 2014, 2015 and 2016 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.
3. More exploration is needed of the interaction of movement parameters with the other components of the model.

7 Acknowledgements

This work was funded by AFMA and CSIRO's Oceans & Atmosphere National Research Flagship. The authors thank the AFMA scientific observers for conducting the tagging program and the owners, officers and crew of the *Southern Champion, Avro Chieftain* and *Janas* for their excellent cooperation throughout. This assessment is based on that developed by Gavin Fay in 2011. We thank him for the use of his software. Tim Lamb at the Australian Antarctic Division is thanked for provision and preparation of the stock assessment data. Malcolm Haddon is thanked for his advice and comments during the development of this work. All members of SARAG are thanked for their insightful and helpful discussion of the stock assessment results.

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Appendix 2

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Tag rates and monitoring data to potentially inform breakout rules for non-assessment years for the Macquarie Island toothfish fishery

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Prepared for the SARAG held in Hobart, Australia 16th–17th of May 2017

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Abstract

This paper addresses the likely effect of changes in the tagging rate per tonne of fish caught, with respect to the precision of abundance estimates in the assessment model. It also proposes some possible monitoring series that can be generated and discussed in the RAG in non-assessment years, and could be used to develop breakout rules if the RAG choses such a route. Moderate changes in the tagging rate would have commensurately moderate effects on the expected precision of abundance estimates in the model - with precision increasing/decreasing with increasing/decreasing tagging rates. There would also be expected to be a similarly moderate average increase/decrease in the predicted TAC given the current harvest control rule explicitly acts on uncertainty in current and future projected abundance. In terms of easily generated and interpretable monitoring series, we suggested options relating to total catch by area, mean length and/or age in the catch by area, sex ratio in the catch, nominal CPUE, catch-to-TAC ratio and some more specific metrics for the tagging data. These simple series all measure aspects of importance in the stock assessment, and as such would be useful for a simple set of monitoring data for non-assessment years. As to potential breakout rules, given the non-probabilistic nature of the various monitoring series (i.e. we cannot sensibly specify lower/upper percentiles) we do not attach any specific levels that may suggest a meta-rule process needs to be invoked. If such breakout rules are to be codified, this will have to be a RAG level discussion and agreement given it will likely be both qualitative and somewhat subjective.

1 Effect of varying tagging rate

The mark-recapture program is the major information source on absolute abundance - both magnitude and precision thereof - in the Macquarie Island toothfish fishery stock assessment [1]. Precision in mark-recapture estimates is dominated by the number of recaptures (R), which are themselves a function of tag releases (T), tag resampling levels (basically catch in numbers C times reporting rate p_{rep}), and the total abundance of the population N. The simplest way this all comes together is via the Petersen estimator of abundance, $\widehat{N}$:

$$\begin{aligned} R &= \frac{Cp_{\text{rep}}}{N} \times T, \\ \mathbb{E}(\widehat{N}) &= \frac{Cp_{\text{rep}}}{R} \times T, \\ CV(\widehat{N}) &\approx R^{-1}. \end{aligned}$$

To see what effect the tag rate (per unit catch whatever it is) has on the precision of the estimates is fairly simple in the Petersen paradigm. For overall levels of catch, C, and abundance, N, that don't change - neither we assume does reporting rate here - then the number of tags in the water is just $T = \tau C$, where τ is the tagging rate per unit catch. We focus then on the number of recaptures now:

$$R = \tau \frac{C^2 p_{\text{rep}}}{N},$$

so - all other things being equal - the number of recaptures is linearly determined by the tagging rate. The follow on from that is that the CV of the abundance estimate (our precision metric) is related to the inverse square root of the tagging rate τ: $CV(\widehat{N}) \propto \tau^{-1/2}$. This makes it simple to explore the effect - in terms of the precision of the abundance estimate - of changing the tagging rate τ. With a nominal tagging rate of 2 tags per tonne we seem to be managing to obtain an abundance CV (in terms of SSB which is what we really care about) of around 15% [1]. This fits very well with the average number of recaptures per year (around 100) and the levels of over-dispersion estimated in the assessment [1]. So, if we increased the tagging rate to 3 tags per tonne, we would expect the precision of the abundance estimates to be better - around 12% - but not by much given the square root effect. You get diminishing levels of returns in terms of precision improvements for increasing tagging rates. If we decrease the tagging rate to 1.5 tags per tonne we would expect a CV of around 17%, so a small deterioration in abundance precision. A reduction to 1 tag per tonne would yield a likely CV of 21%.

There is a potential downside to decreasing the tagging rate, given the interaction between TAC from the harvest control rule (HCR) and assessment precision (as precision gets better, so does the TAC). It will probably be modest, but we would expect there to be some noticeable percentage difference between the TAC calculated from an assessment where 3 tags per tonne is the norm, versus one where the tagging rate was 1 tag per tonne. However, the level of difference between the expected TAC from assessments driven by tagging programs of 2 vs. 1.5 tags per tonne would almost certianly be less than the inter-annual variation in TAC given the inherent variability in the assessment itself over time.

2 Monitoring series for non-assessment years

Macquarie Island toothfish are now on a two-year TAC cycle, with assessments scheduled to be done every other year. In non-assessment years the general consensus is that the relevant body (RAG in this case) should look at certain aspects of the updated data, relative to the historical set, to glean what they can from the new data without doing a full assessment. As to what is to be done based on these exploratory data analyses is still an open question. Actions can be formalised into a process often called meta-rules, where specific levels of the monitoring data are defined such that values deemed to be outside these levels result in a course of action being taken. Additionally this course of action is variable also - if the signals are negative or very out of the ordinary a full assessment might be requested. The specific codification of “exceptional circumstances” and “breakout rules” (which make up most of the meta-rules process) is not something we specifically cover here, given it will have a large degree of both qualitative and somewhat subjective elements that would have to be discussed and agreed by the RAG and MAC. What we can expore are the types of monitoring (or sentinel) series we can generate and discuss within the RAG context to assist in this wider process.

2.1 Spatial catch and composition

The Macquarie Island toothfish fishery has a relatively clear spatial structure, in terms of fishing locations: Aurora trough (AT), and the Northern (NMR) and Southern (SMR) Macquarie ridges. As of the present, the only type of gear used is long-line and is also, at the moment, one vessel. Catch-per-unit-effort data (CPUE) is not used in the assessment and, given only one vessel, is unlikely to be informative at this stage with respect to relative abundance. However, given the recent HIMI fishery experience with a year of very low catch rates, in the absence of apparent abundance declines, we do suggest that nominal CPUE be included in an annual and spatially aggregated form in the monitoring series. We suggest the following as an initial list of catch-specific monitoring data:

1. Proportion of catch biomass taken by fishery region (AT, NMR, SMR)
2. Mean length and/or age (if available) in each fishery region
3. Sex ratio in the catch by fishery region

4. Ratio of actual catch taken to the TAC

Looking at these series relative to historical levels (at least for long-line specific data not the trawl data) should - in theory - give us some indication that either we are seeing things we have already seen, or something that we haven't in terms of catch characteristics.

2.2 Spatial tagging data

It is the tagging data that are the strongest information on absolute abundance and, as such, the strongest influence on depletion levels and resultant TAC levels. The probability model structure for the tagging data in the assessment is fairly detailed, separating out age, reporting rate and catch composition influences on the number of recaptures. While necessary to do in terms of obtaining unbiased abundance information, we can perhaps use something simpler to again develop monitoring series that are informative as to whether we are getting data well outside the range already seen - which are, by implication, comfortable with.

We propose to use the simple Petersen idea, outlined in the tagging rate section, as the basis for the monitoring series. There will be both a time and spatial element to these data, so we define the following useful variables:

1. $T_{y,r}$: tag releases in year y in region r
2. $R_{y,r,y',r'}$: tag recaptures in year y' in region r' of releases in year y and region r
3. $C_{y,r}$: total catch (in numbers) in year y and region r

Given we do not look at within-season recaptures from an abundance perspective, then some kind of Petersen-like ratio of use would be:

$$\frac{T_{y-\eta}C_y}{R_y},$$

where $\eta \geq 1$ is a lag coefficient. There are number of lag and spatial combinations, as well as release events, over which we can nuance this sum, but is has all the general features of what drive the abundance information in the tagging data. The spatial index would be something like

$$\tilde{n}_{y,r} = \frac{1}{\eta}\sum_{i=1}^{\eta}\left(\frac{\sum_s T_{y-i,s}C_{y,r}}{\sum\limits_s R_{y,r,y-i,s}}\right),$$

which is a way of getting an average (of sorts) abundance signal across release events (the η parameter) and regions (the sum over s) *for a given region r in year y*. In theory, if something **very odd** is happening in the tag recapture data - e.g. the tag return rate per unit catch doubles or halves - this would likely detect it.

It would not be expected to detect something strange happening in say the movement dynamics of the fish, simply because we are summing over both release and recapture spatial effects (the summation over s). To get at a metric that might highlight odd trends in the relative recapture rate, consider the following:

$$\psi_{y,r,s} = \frac{1}{\eta}\sum_{i=1}^{\eta}\left(\frac{R_{y-i,r,y,s}\hat{p}_{y,s}}{\sum_s R_{y-i,r,y,s}\hat{p}_{y,s}}\right),$$

where $r \neq s$ and $\hat{p}_{y,s}$ is the relative catch numbers by area (so sums to one over s) and accounts for differential sampling intensity for tags across the spatial region, which can obviously bias relative return rates by region. We don't really need to correct for differences in tag releases per area, simply because that gets automatically normalised out in the underlying ratio of recaptures and because the metric is both release region and event specific. Although release events are averaged out via the sum over i.

3 Discussion

In terms of tagging rates, dropping the tagging rate from a nominal level of 2 tags per tonne to say 1.5 tags per tonne is unlikely to decrease either the precision of the assessment, or the TAC calculated from the HCR driven by the assessment. Dropping to 1 tag per tonne would likely result in noticeable lower precision and some kind of perceptible decrease in average TACs over time.

We proposed a set of readily calculable monitoring series, for both the catch and tagging data, that could assist in detecting potentially anomalous trends in years when an assessment is not being undertaken. We do not suggest explicit levels of deviation that would constitute "exceptional circumstances", nor do we suggest what kind of "breakout rules" should be used in the event that exceptional circumstances are agreed to have been triggered. Experience in a number of fisheries has shown that this will be a qualitative and somewhat subjective process, with consensus a key factor, so we simply report the possible monitoring series for further discussion by the RAG.

4 Acknowledgements

This work was funded by AFMA and CSIRO Oceans & Atmosphere.

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

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Appendix 3

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Interim data inspection in lieu of assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2017

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Prepared for SARAG 58, Hobart, August 2018
Document updated: 11 June, 2018.

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Citation

Day J and Hillary R (2018) Interim data inspection in lieu of assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2017. Report to SARAG 58, August 2018. CSIRO, Australia.

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Contents

1 Summary

This report investigates data diagnostics in lieu of a full stock assessment for Patagonian Toothfish (*Dissostichus eleginoides*) at Macquarie Island using data collected up until and including August 2017. The focus is to look at diagnostics exploring length frequency distributions by area or fishery and the catches and number of recaptures of tagged fish from each area, to see if there are any indications of some change to the fishery which may warrant further investigation or an earlier assessment.

Standard tables and figures used in the most recent assessment report (Day & Hillary, 2017) with updates to data to August 2017 are included.

2 Updated Catches to August 2017

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

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

TAC history is listed in Table 2.1 with catches by fleet and area are shown in Table 2.2.

[a] longline season began on 1 May up until 2014, and started on 15 Apr from 2015 onwards.
[b] tonnage shown in brackets would have been triggered if trawl catch rates reached 10 t/km^2 over 3 consecutive fishing days
[c] research TAC to enable tag-based stock assessments
[d] TACs for longline trial
[e] TAC set for entire Macquarie Island region

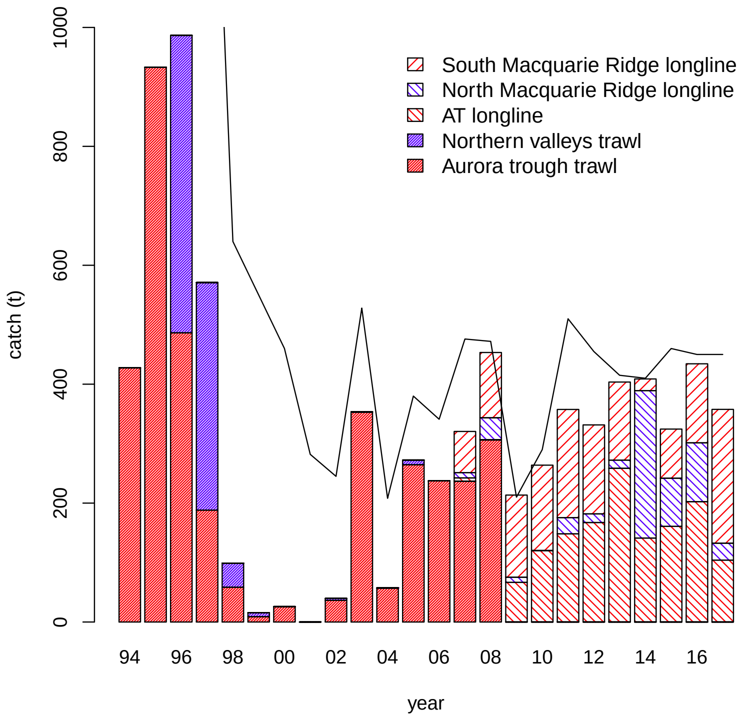

Figure 2.1: Catch history and total TAC by fishing year, with catches stacked by fleet and the grey line representing the combined TAC (with TACs summed for Aurora Trough and Macquarie Ridge from 1996–2011). There were small research quota in the Aurora Trough from 1998-2002 and in 2004. Red coloured bars indicate catches from the south and blue coloured bars indicate catches in the north.

Table 2.2: Time series of Patagonian toothfish catches (t) by fishing year and fleet, including total catch (removals only) over all fleets and combined TAC (combined over both regions up to 2011/12).

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

Longline operations in 2017 caught 104t in the Aurora Trough and 254t in the northern and southern Macquarie Ridge areas (Figure 2.1).

2.1 Length frequency data

Samples of the length composition of the catch were available for all fishing seasons (1994/95 through 2017/18). Each annual length composition is based on the measurement of several hundreds (thousands) of fish (Tables 2.3 and 2.4). However, it is unlikely that the number of fish measured in each year is an appropriate metric of the effective sample size, due to expected high correlations among fish lengths within individual hauls/shots. Thus, when an assessment is done, input sample sizes for the individual length compositions are set at the number of shots sampled for the trawl data, and 10% of the number of fish sampled for the longline data.

Table 2.3: Number of length samples by fleet and season for the trawl fleets, 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

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

Table 2.4: Number of length samples by fleet and season for the longline fleets, 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 longline	07/08	2	200	100
	09/10	9	548	61
	10/11	18	1066	59
	11/12	45	1779	40
	12/13	52	1916	37
	13/14	79	3046	39
	14/15	62	2216	36
	15/16	84	2950	35
	16/17	94	3376	36
	17/18	66	2254	34
NMR longline	07/08	5	160	32
	08/09	13	406	31
	09/10	7	246	35
	11/12	26	829	32
	12/13	31	838	27
	13/14	11	340	31
	14/15	70	2570	37
	15/16	96	2739	29
	16/17	128	3337	26
	17/18	57	1368	24
SMR longline	07/08	28	1589	57
	08/09	44	1750	40
	09/10	50	1886	38
	10/11	34	1546	45
	11/12	96	3388	35
	12/13	126	4080	32
	13/14	94	3107	33
	14/15	18	561	31
	15/16	76	2404	32
	16/17	123	3865	31
	17/18	174	5526	32

this range up to 190 cm.

2.2 Tag recapture data

Between the 1995/96 and 2016/18 fishing seasons, 16,842 Patagonian toothfish were tagged at Macquarie Island, of which 2,225 have been recaptured (Table 2.5, Table 2.6). Fish are still being recaptured from releases in the early years of the fishery (Table 2.5). Of the recaptures in 2016, the longest period between tagging and recapture was for a fish tagged in 1999. This equals the longest period between initial tagging and recapture, with individual fish tagged 18 years previously also being recaptured in 2015 and 2016.

Table 2.5: 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	16/17	17/18
95/96	AT tr	428	69	57	28	3		1	1	1							1							
95/96	NV tr	4	57																					
96/97	AT tr	448	58		42	7		2		9	1	3		1	1									
96/97	NV tr	536	61		53	5	1			2														
97/98	AT tr	503	60			18	3	4	5	21	4	15	1		2	3	1	2	2			1		
97/98	NV tr	477	69			9				1					1		1							
98/99	AT tr	652	68				4	5	2	30	2	9	2	2	7		1	1		1				
98/99	NV tr	308	57																				1	
99/00	AT tr	692	65					3	1	35	6	12	1	4	6	2	5	1	5					1
99/00	NV tr	299	58																1					
00/01	AT tr	364	59						1	23	3	5	1	1	9									
00/01	NV tr	135	46						1			1												
02/03	AT tr	491	63							60	8	29	6	15	24	2	3	10	1	6	2			1
02/03	NV tr	17	57															1						
03/04	AT tr	570	69								9	23	8	4	13	2	3	2	1	1				
03/04	NV tr	60	53									3												
04/05	AT tr	556	69									46	7	16	43	4	4	6	3	4	1		1	
04/05	NV tr	263	56									2		1	1						1	1		
05/06	AT tr	520	71										25	18	27	2	5	4	4	3	1	1	1	1
05/06	NV tr	288	60																1		2	3	1	
06/07	AT tr	432	59											26	13		1			4		2	1	2
07/08	AT tr	273	65												31	2		2	1	3	1		2	
07/08	NMR LL	26	78													1		3	2				1	
07/08	SMR LL	189	81												15	4	3	6	6	4		1	4	3
08/09	AT tr	557	71													2	6	12	10	19	6	8	8	1
08/09	NV tr	14	51																					
08/09	NMR LL	82	79													2		7		1	1			
08/09	SMR LL	385	79												1	9	9	18	21	11	2	2	2	6
09/10	AT LL	299	85														27	13	9	13	4	2	3	2
09/10	NMR LL	60	85															5	5			2	1	
09/10	SMR LL	395	79														26	25	8	20	2	2	4	5
10/11	AT LL	478	87															11	31	45	6	4	4	1
10/11	SMR LL	507	91															27	42	34	5	8	10	8
11/12	AT LL	302	72																10	37	7	7	12	6
11/12	NMR LL	116	83																1	2	1	3	2	1
11/12	SMR LL	497	78																9	25	4	18	10	9
12/13	AT LL	309	78																	37	12	12	6	6
12/13	NMR LL	56	89																					
12/13	SMR LL	302	87																	20		9	3	5
13/14	AT LL	529	75																		9	26	23	16
13/14	NMR LL	36	81																			3		
13/14	SMR LL	249	81																		9	10	1	10
14/15	AT LL	295	72																			9	19	11
14/15	NMR LL	499	79																				4	
14/15	SMR LL	36	80																					2
15/16	AT LL	353	76																				17	13
15/16	NMR LL	168	79																				2	1
15/16	SMR LL	165	80																				12	4
16/17	AT LL	445	77																					12
16/17	NMR LL	184	84																					1
16/17	SMR LL	270	92																					30
17/18	AT LL	226	74																					
17/18	NMR LL	65	79																					
17/18	SMR LL	432	81																					

Table 2.6: 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	163	1	38
NV trawl	8	72	1	7	6
AT longline	0	0	430	0	52
NMR longline	0	0	1	35	16
SMR longline	1	0	69	5	468

There do not appear to be any remarkable differences in recapture rates by region in 2017. As usual, the number of recaptures of fish released in the north is much lower than the number of recaptures of fish released in the south, with only three fish released in the north recaptured in 2017, with only one of these three fish recaptured in the south. All 155 remaining recaptures from 2017 were of fish both released and recaptured in the south.

2.3 New and updated data summary

Updated data in this review include no revisions to historical data. The new 2017 length frequency data include an additional 2254 fish in 66 hauls for Aurora Trough Longline, 1368 fish in 57 hauls for Northern Macquarie Ridge Longline and 5526 fish in 174 hauls for Southern Macquarie Ridge Longline.

Additions to the historical recapture information include three additional tag recaptures in 2015, two of these from tags released by the Southern Macquarie Ridge Longline fleet in 2011 and 2012 and the remaining tag released in 2013 by the Northern Macquarie Ridge Longline fleet in 2007. A fish tagged in 1999 in the Aurora Trough was recaptured in 2017, which is the equal longest period between initial tagging and recapture for this fishery. The tagging mortality is clearly less than 100%.

New tag recaptures from the 2017 data included 40, two and 116 recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 158 tag recaptures in 2017 from fish tagged in previous seasons, which is exactly the same number of recaptures as in 2016. Of these 158 recaptures, 157 were recaptures in the same area (155 in the south, two in the north), with only one recaptures in a different area to the release area, providing additional information on movement of individuals between areas. In 2017, this recapture in a different region was a single fish released in the north and recaptured in the south. This fish was tagged and released by the North Macquarie Ridge Longline fleet and was recaptured by the South Macquarie Ridge Longline fleet.

In 2017, there were six fish tagged by Aurora Trough Trawl that were recaptured, two in Aurora Trough and four in Southern Macquarie Ridge. No fish tagged by Northern Valleys Trawl were recaptured in 2017. There were 67 fish previously tagged by Aurora Trough Longline recaptured in 2017, with 34 of these recaptured in the same area as release, with the remaining 33 recaptured in the Southern Macquarie Ridge. There were an additional three recaptures of longline tagged fish from Northern Macquarie Ridge, with two recaptured in the same area as release and one more recaptured in the Southern Macquarie Ridge. Eighty two fish previously tagged by longline in Southern Macquarie Ridge were recaptured in 2017 with four of these recaptured in Aurora Trough and the remaining 78 recaptured in the Southern Macquarie Ridge.

In addition there were 225, 65 and 431 new tag releases in 2016, with these releases respectively in the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge.

2.3.1 Length composition data

Length frequency data suggest that in 2017 slightly smaller than normal fish were caught on Southern Macquarie Ridge and slightly larger than normal fish were caught in Aurora Trough. In Northern Macquarie Ridge there appear to very little change to the length frequency distribution. Note that the catch in Southern Macquarie Ridge was higher both in absolute numbers in recent years and as a proportion of the total catch compared to the distribution of catches by area in recent years.

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.

3 Acknowledgements

This work was funded by AFMA and CSIRO's Oceans & Atmosphere National Research Flagship. The authors thank the AFMA scientific observers for conducting the tagging program and the owners, officers and crew of the *Southern Champion, Avro Chieftain* and *Janas* for their excellent cooperation throughout. This assessment is based on that developed by Gavin Fay in 2011. We thank him for the use of his software. Tim Lamb at the Australian Antarctic Division is thanked for provision and preparation of the stock assessment data.

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

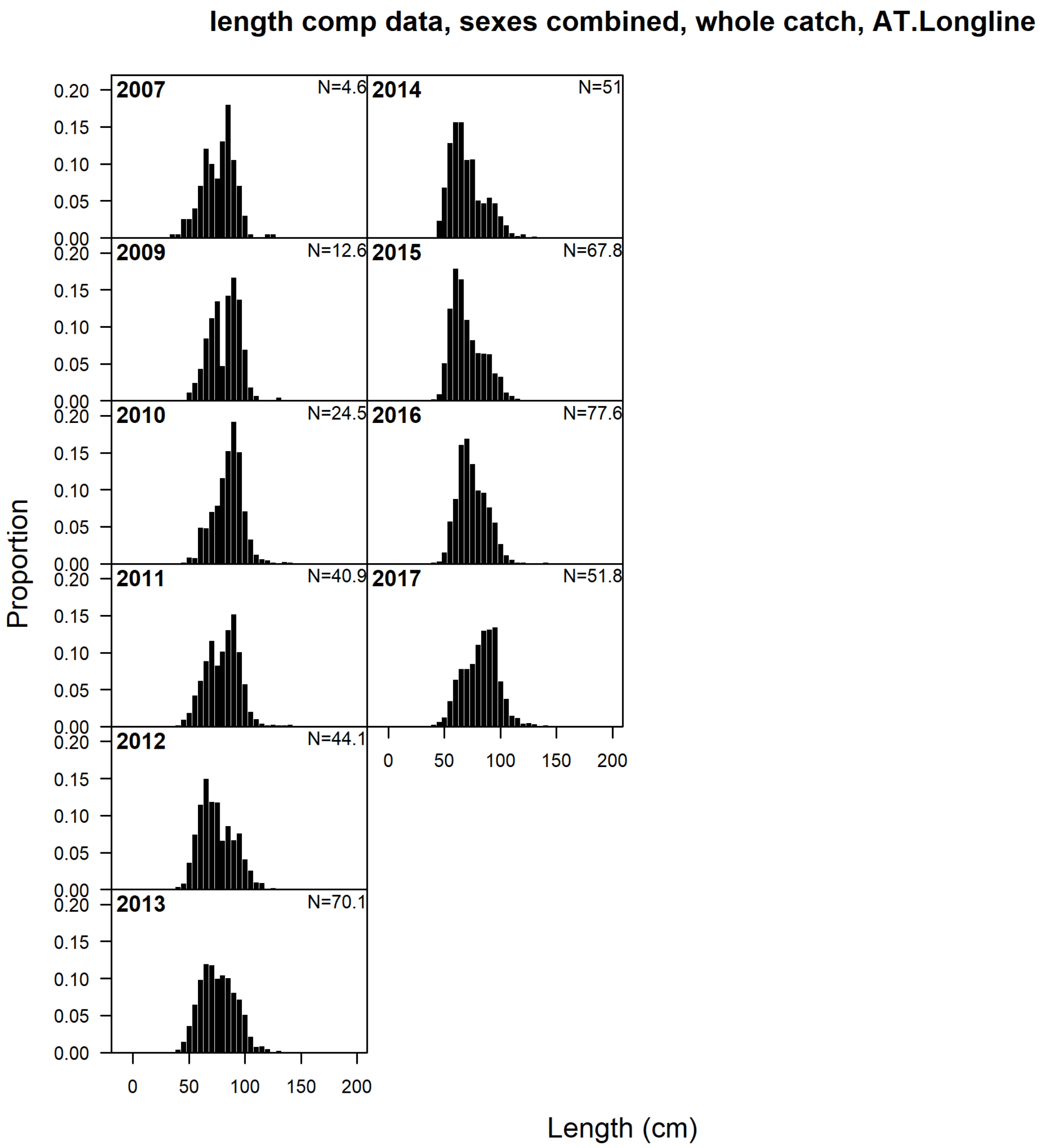

Figure 2.2: Length composition data for the Aurora Trough longline fleet.

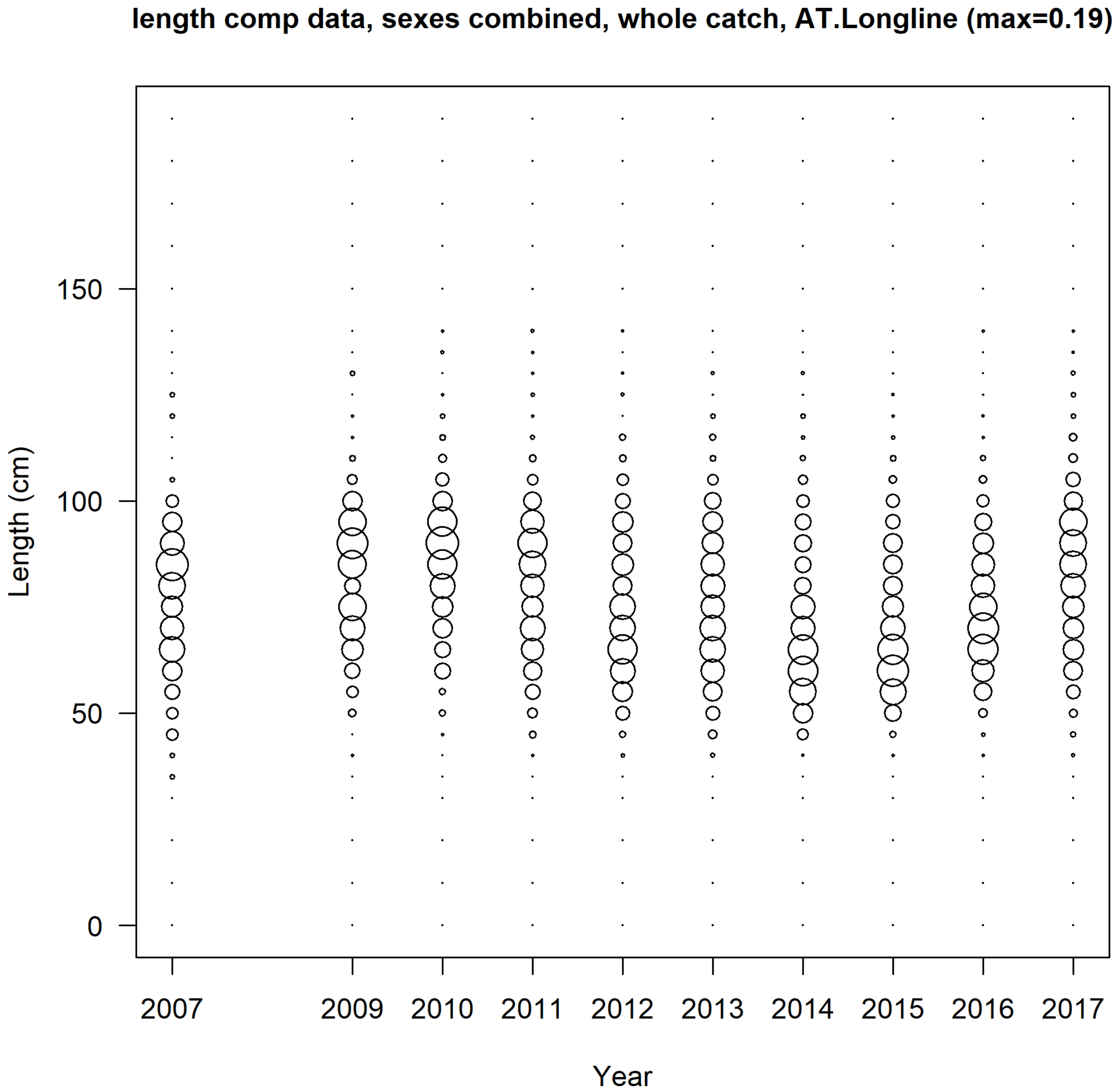

Figure 2.3: Length composition data (bubble plot) for the Aurora Trough longline fleet.

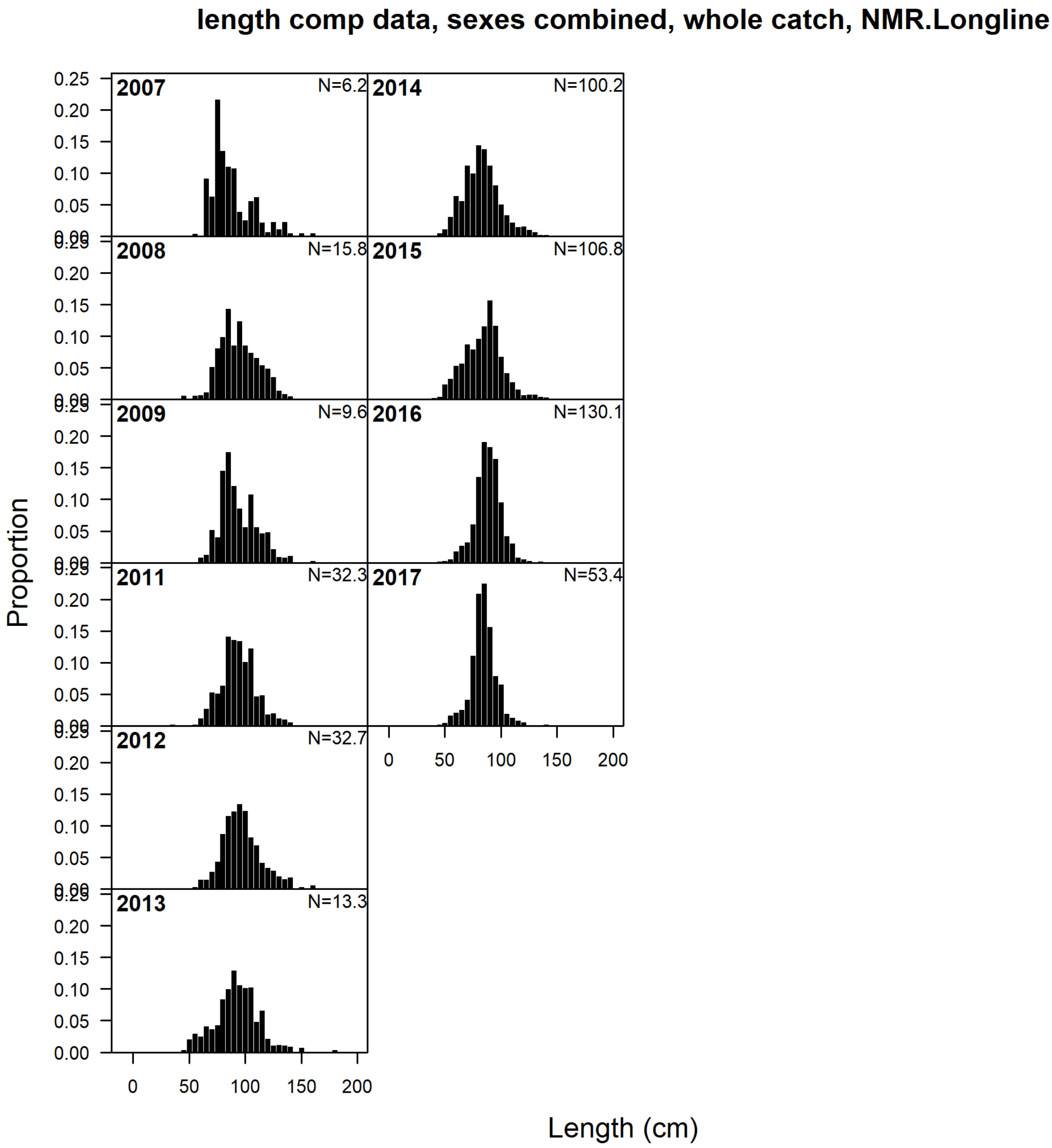

Figure 2.4: Length composition data for the Northern Macquarie Ridge longline fleet.

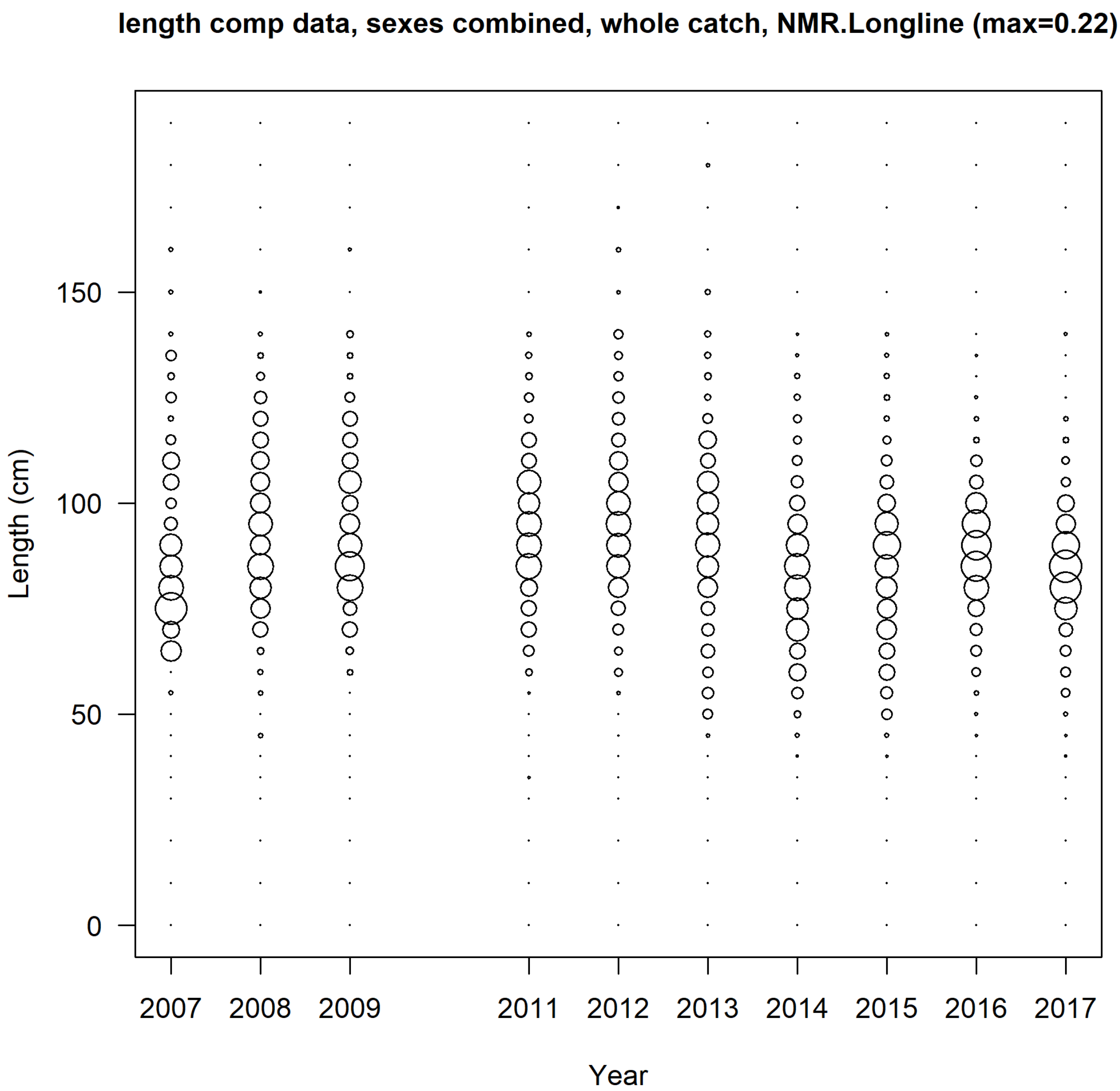

Figure 2.5: Length composition data (bubble plot) for the Northern Macquarie Ridge longline fleet.

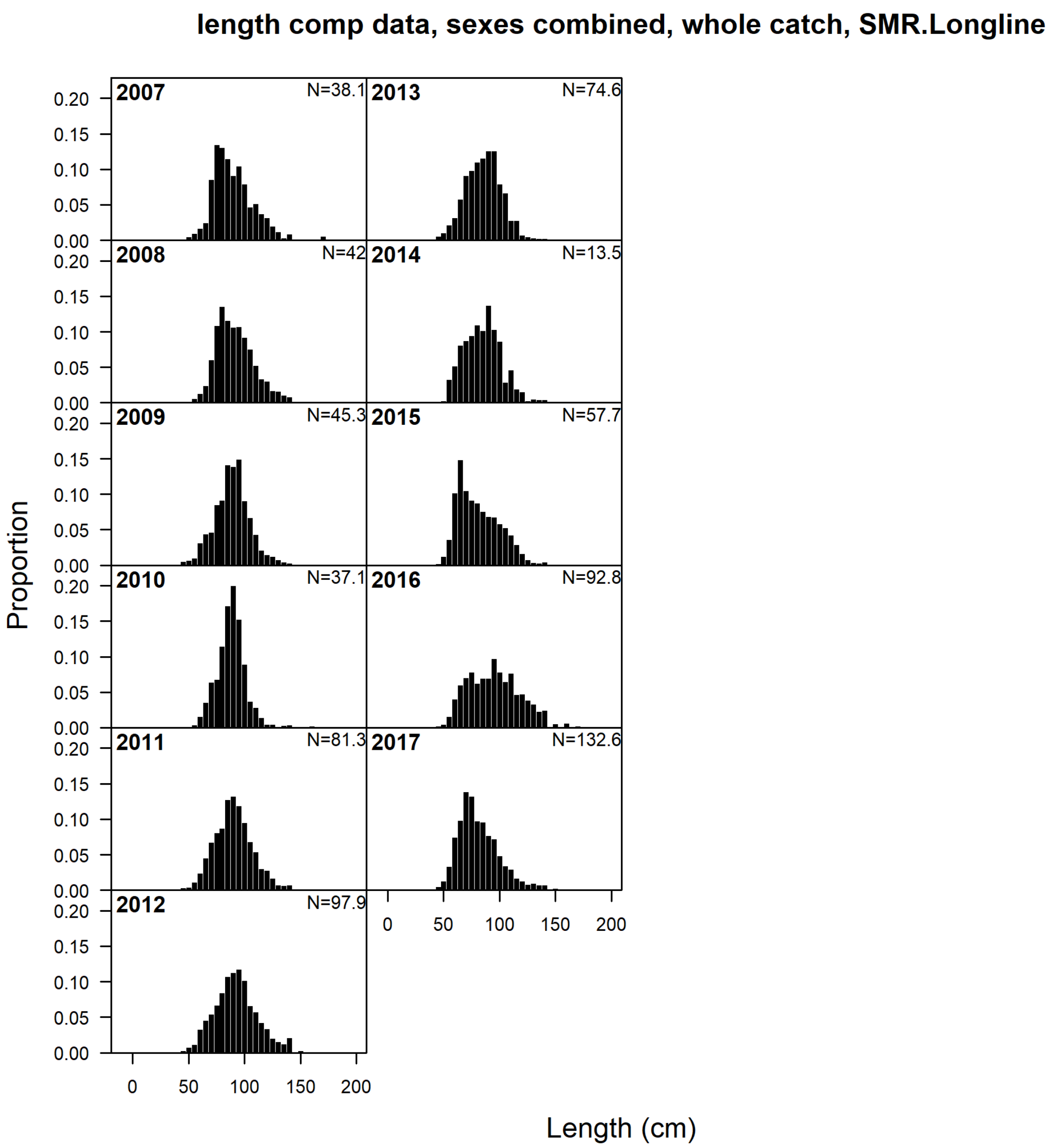

Figure 2.6: Length composition data for the Southern Macquarie Ridge longline fleet.

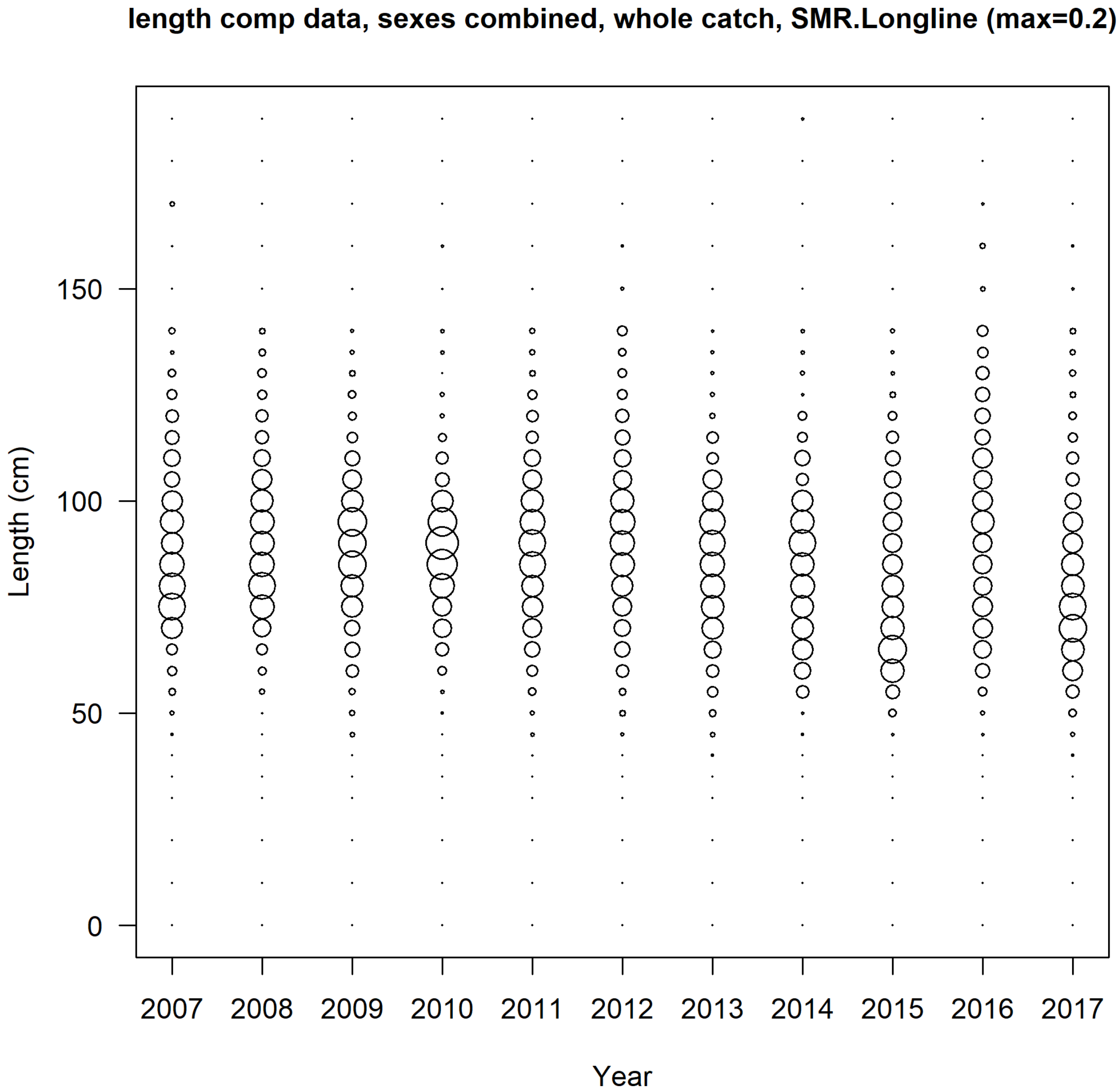

Figure 2.7: Length composition data (bubble plot) for the Southern Macquarie Ridge longline fleet.

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Appendix 4

Impact of spatial tagging rates for key estimates coming from the Macquarie Island toothfish assessment

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Abstract

The mark-recapture program underpins the estimation of absolute abundance and migration rates in the Macquarie Island toothfish stock assessment. The current spatial configuration of the assessment is with two regions - northern and southern - with movement between them and variable fishing pressure over time. We explored how a range of area-specific tagging rates (per tonne caught), conditional on the overall rate being fixed at 2 tags per tonne, interacted with a range of plausible true spatial mean recruitment and migration rates, in terms of the uncertainty in resultant estimates of spawning abundance and the key spatial parameters. An information theoretic approach is employed which permits us to avoid the need for either simulation or estimation in producing the uncertainty estimates, using previous work around bias levels for these types of estimators to deal with the bias/variance question.

Introduction

We explore how factors we can potentially control (spatial tagging rates per tonne and overall spatial catch splits, effective length sample sizes) interact with things we cannot control (spatial recruitment and migration rates) when we estimate abundance, migration and selectivity in the Macquarie Island stock assessment model.

Methods

The modelling ideas behind the work can be broadly split into two main sections: one dealing with the conditioning of the operating model used as the basis for the population dynamics; the other dealing with the statistical principles used to construct the uncertainty estimates, given the underlying "true" population dynamics and the specifics of the sampling regimes for the fishery (in terms of both tagging rates and length sampling).

Spatial population dynamics

The spatial Operating Model (OM) is both age and spatially structured. An equilibrium structure is assumed with an average total recruitment level, $\bar{R}$, which is distributed across regions $r = 1, \cdots, R$: $N_{1,r} = \eta_r \bar{R}$, where $\sum \eta_r = 1$. The stock-recruit relationship (assumed to be Beverton-Holt) is factored in at estimation time and we detail that process later on when discussing the conditioning of the OM. For ages $a = 1, \cdots, A-1$ we have the following:

$$N_{a+1,r} = \sum_{s=1}^{R} \pi_{s,r} N_{a,s} e^{-M} \left(1 - h_s s_{a,s}\right), \tag{1}$$

$$C_{a,r} = N_{a,r} h_r s_{a,r}, \tag{2}$$

where $N_{a,r}$ are the numbers-at-age; $C_{a,r}$ is the catch numbers-at-age; M is the rate of natural mortality; h_r and $s_{a,r}$ the spatial harvest rate and selectivity-at-age, respectively; and $\pi_{s,r}$ the probability that an animal currently in area s will move into area r in the following year (and $\sum_s \pi_{s,r} = 1$). No movement is assumed in the plus group, A, and it is dealt with in the usual way given the equilibrium assumption. Spawning stock biomass and total catch biomass (both region-specific and in total) are intuitively defined:

$$S_r = \sum_a N_{a,r} w_a m_a, \tag{3}$$

$$C_r = \sum_a C_{a,r} w_a, \tag{4}$$

$$S = \sum_s S_s, \tag{5}$$

$$C = \sum_s C_s, \tag{6}$$

where w_a and m_a are the weight and maturity-at-age vectors, respectively. The dynamics of the tagged population are basically the same as those for the actual population with two minor tweaks:

1. There is an additional tag-shedding rate, ν, (if required) and this is "added" to the natural mortality term: $\exp\left(-M - \nu^2\right)$ (squared because we double tag)

2. There is an initial tag survival probability, π^{tag}, that applies only in the year of tagging, and is just used to instantly adjust the total number of tags released into the population.

The spatial split in total catch biomass will be a useful variable - both for conditioning the OM to a given scenario and in defined spatial tag releases - and is obviously defined: $\delta_r = C_r/C$. A total tag release rate-per-tonne, ψ, is assumed to be fixed with some freedom in the spatial tagging rates-per-tonne, ψ_r, where $\psi = \sum_r \delta_r \psi_r$. The tag release numbers-by-region are then simply given by $T_r = \psi_r C_r$.

Another key factor in the conditioning of the OM is spawner biomass depletion, γ (both spatially and in total). The stock assessment assumed that at a spatially aggregated spawning biomass produces the mean recruitment numbers, and we take the same approach. An efficient short-cut is used to calculate γ, given the key parameters $\boldsymbol{\theta} = \{\bar{R}, \eta_r, \pi_{s,r}\}$. This is done first via the total spawner biomass-per-recruit: ρ. For given population parameters, harvest rates and selectivity functions ρ is calculated; it is then calculated for zero harvest rates (no fishing). The ratio of the fished-to-unfished spawner biomass-per-recruit, $\tilde{\gamma}$, is then calculated. The *actual* depletion level (now accounting for the stock-recruit relationship) is calculated as follows:

$$\gamma = \frac{4h\tilde{\gamma} + h - 1}{5h - 1}, \tag{7}$$

where h is the steepness of the stock-recruit relationship (a steepness of 1 implies $\gamma \equiv \tilde{\gamma}$). Spatial SSB depletion levels are then simple to define:

$$\gamma_r = \tilde{\gamma}_r \left(\frac{\gamma}{\tilde{\gamma}}\right). \tag{8}$$

The key release covariates are age and region of release; for recaptures, it is age and region of capture. We first intend to mimic the tag recapture likelihood as it is currently implemented in SS3 Methot and Wetzel (2013), which is used for the current assessment. It takes a two-step account of the tag recapture process as follows:

- For a given release region and age, subsequent recaptures are aggregated across all regions and the assumed likelihood is negative binomial (with associated over-dispersion parameter). For our purposes we assume the base likelihood to be an over-dispersed binomial (for reasons made clear later on). This likelihood will be the dominant source of information on absolute abundance.
- Spatial recaptures are treated as multinomial, with the proportions of recaptures across the various regions the multinomial probability, and the sample size is the total number of recaptures across the regions. This likelihood will be the dominant source of information on migration rates and spatial relative recruitment.

The final aspect we consider is the estimation of selectivity (primarily via the length frequency information of the catches by region). We would be under-estimating the uncertainty in both abundance and migration if we simply assumed we knew selectivity without error, so including it makes sense. We first outline the length-based selectivity model, then how this is translated to age, then how the predicted length frequencies are calculated. Region-specific selectivity is assumed to be logistic in nature:

$$s_{l,r} = \left(1 + 19^{-(l-\lambda_{r,50})/(\lambda_{r,95}-\lambda_{r,50})}\right)^{-1} \tag{9}$$

where $\lambda_{r,50}$ and $\lambda_{r,95}$ parameters are the lengths at 50% and 95% selection, respectively. The selectivity-at-age is derived from the selectivity-at-length via the distribution of length-at-age, $\pi_{l|a}$:

$$s_{a,r} = \int s_{l,r}\pi_{l|a}\mathrm{d}l. \tag{10}$$

Tag recapture likelihood models

For the tag likelihood utilised in the current stock assessment, the probability of recapturing a tag released in area r and at age a across **all** the spatial regions τ years after release (with $\tau \geq 1$ given the current non-mixing period of 1 season) is given by the following:

$$p^{\mathrm{rec}}_{a+\tau,|\,r,a} = \xi^{\mathrm{rep}} \sum_{s=1}^{R} \omega_{s,a+\tau\,|\,r,a} h_s s_{a+\tau,s}, \tag{11}$$

where ξ^{rep} is the reporting rate, and $\omega_{s,a+\tau\,|\,r,a}$ is the proportion of tagged fish in area s at age $a+\tau$, given their release in area r at age a. The total number of recaptures is then a binomial variable, with underlying probability as defined in (11) and sample size $T_{a+\tau\,|\,r,a}$, which is the total number of tags still both alive and possessing at least one tag at age $a+\tau$, given their release in area r at age a. The expected number of recaptures is as follows:

$$R_{a+\tau\,|\,r,a} = T_{a+\tau\,|\,r,a}\, p^{\text{rec}}_{a+\tau,|\,r,a}. \tag{12}$$

The spatial aspect of the mark-recapture likelihood relates to the proportions of recaptures of a given release event across all regions, via a multinomial distribution. The spatial proportions of recaptures, conditional on a given release age a and region r, are given by the following:

$$\zeta_{s,a+\tau\,|\,r,a} = \frac{p^{\text{rec}}_{a+\tau,s|\,r,a}}{\sum\limits_{k=1}^{R} p^{\text{rec}}_{a+\tau,k|\,r,a}}, \tag{13}$$

where the associated sample size for this multinomial distribution is the total number of recaptures across all spatial regions given in (12). These two likelihood functions, relating first to total recaptures and then to the spatial distribution thereof, fully describe how these data are treated in the current stock assessment model.

To incorporate the uncertainty in the estimated selectivity parameters, via the length frequency data, we assume a multinomial distribution for these data (as is currently done in the assessment). The predicted spatial catch-at-age (2) is converted to a predicted distribution of catch-at-length as follows:

$$C_{r,l} = \sum_{a} C_{r,a}\pi_{l|a}, \tag{14}$$

$$p_{r,l} = \frac{C_{r,l}}{\sum_k C_{r,k}}. \tag{15}$$

The term $p_{r,l}$ define the length frequency in region r, and for the likelihood model we assume a given effective sample size n^{eff}

Construction of the uncertainty estimates

Traditionally, analyses of this kind first simulate the data, then back-estimate the key parameters for the given models used to simulate them. If workable, this can yield both the potential bias and parameter uncertainty properties for the pre-agreed data collection regime. This can be both difficult to do in practice (getting models to both converge and obtain uncertainty estimates for all simulated data sets) and not always necessary if previous work has explored the bias properties associated with these types of models. In this case, the predominant issue is obtaining uncertainty estimates, if either the bias properties are known (and can be accommodated), or the models are essentially unbiased for the kinds of sampling regimes under consideration.

An idea originally proposed for exploring the uncertainty of adult abundance and mortality information via close-kin mark-recapture (CKMR) was outlined in Bravington *et al.* (2016). These models generally have a Bernoulli/binomial likelihood function as they relate to pairwise comparisons of animals and whether they are related in a specific way or not - e.g. parent-offspring. The general idea is to construct the Hessian matrix for the key estimable parameters (which defines the approximate parameter covariance matrix) via an approximation to the Fisher information (FI) at the base information level for each data source. For the total tag recaptures these are region and age at release/recapture; for the spatial tag recaptures these are both region and age at release *and* recapture; for the length frequency data this is the region and length at capture.

The Fisher information is defined in two ways. The first is in terms of the expected value of the square of the score (gradient of log-likelihood) at the maximum likelihood estimate:

$$\mathcal{I}(\boldsymbol{\theta}) = \int \left(\frac{\partial}{\partial \boldsymbol{\theta}} \ln \ell(X \,|\, \boldsymbol{\theta}) \right)^2 \ell(X \,|\, \boldsymbol{\theta}) \mathrm{d}X = \mathbb{E}^X \left[\left(\frac{\partial}{\partial \boldsymbol{\theta}} \ln \ell(X \,|\, \boldsymbol{\theta}) \right)^2 \right], \tag{16}$$

where $\ell(X \,|\, \widehat{\boldsymbol{\theta}})$ is the likelihood function. The Fisher information (see Appendix) can also be written in terms of the second derivative of the log-likelihood (the Hessian):

$$\mathcal{I}(\boldsymbol{\theta}) = -\mathbb{E}^X \left[\frac{\partial^2}{\partial \boldsymbol{\theta}^2} \ln \ell(X \,|\, \boldsymbol{\theta}) \right] \tag{17}$$

For a Bernoulli process with probability p, the FI is given by $1/(p(1-p))$ (Appendix); for a binomial process with sample size n this becomes $n/(p(1-p))$. For the Bernoulli process a conservative approximation to the FI is simply $1/p$ - for things such as tag recapture data when the probability of recapture is small this basically is a minor under-estimation (and associated minor over-estimate of uncertainty) in the FI. For multinomial data this approximation is actually exact (as long as we remember to sum across all the possibilities in the process).

In our case, the probability of occurrence is actually a function of the parameters we are really interested in, $p(\boldsymbol{\theta})$. The Fisher information of the parameter vector (see Appendix) is defined as follows:

$$\mathcal{I}(\boldsymbol{\theta}) = \mathcal{I}(p) \left(\frac{dp}{d\boldsymbol{\theta}} \right)^2 = \frac{1}{p} \left(\frac{dp}{d\boldsymbol{\theta}} \right)^2, \tag{18}$$

which, to improve numerical stability given small probabilities, can be shown (see Appendix) to be equivalent to the following:

$$\mathcal{I}(\boldsymbol{\theta}) = 4 \left(\frac{d\sqrt{p}}{d\boldsymbol{\theta}}\right)^{\dagger} \left(\frac{d\sqrt{p}}{d\boldsymbol{\theta}}\right) \tag{19}$$

This gives us the (approximate) Hessian matrix for the data at their base level covariates, $\mathbf{z}$. A very useful result is that the overall Hessian matrix, H, can be defined in terms of the sum over all the unique covariate groups of the individual Hessian matrices $H(\mathbf{z})$ as defined in (19):

$$H = \sum_{\mathbf{z} \in \mathcal{Z}} n^{\mathbf{z}} H(\mathbf{z}), \tag{20}$$

where $\mathcal{Z}$ is the set of possible covariates, and $n^{\mathbf{z}}$ is the number of observations of that covariate type in the data set. The assumed independence between the different data sets (total recaptures, spatial recapture distribution, and length frequency) means the overall Hessian matrix, from which we can form the approximate covariance of the parameter vector as a whole, is the sum of the data set specific Hessian matrices as defined in (21). The parameter covariance matrix, $\Sigma_{\boldsymbol{\theta}}$, is the inverse of this overall Hessian matrix. Approximate estimates of the variance of parameters *derived* from $\boldsymbol{\theta}$ (such as spawning stock biomass, mean recruitment level and so on) via some differentiable function $g(\boldsymbol{\theta})$ can be derived via the delta method:

$$\mathbb{V}(g(\boldsymbol{\theta})) \approx \left(\frac{dg}{d\boldsymbol{\theta}}\right)^{\dagger} \Sigma_{\boldsymbol{\theta}} \left(\frac{dg}{d\boldsymbol{\theta}}\right). \tag{21}$$

If there is evidence of over-dispersion in any of the key processes (such as for the total tag recapture model (Day *et al.*, 2015)) this is simple to account for in the construction of the overall Hessian matrix for the parameters. With a given estimate of the variance inflation factor, φ, then we simply divide the Hessian matrices by this variance inflation factor, which will inflate the overall variance appropriately.

To make sure all these calculations are accurately done, we use automatic differentiation (AD) - specifically the `CppAD` package - so that all gradients and derived quantities are calculated to machine precision. This is a fairly complex derivation and perhaps a little opaque given it leans quite heavily on statistical theory, but once done it makes it *very* quick and simple (relative to both simulating data and back-estimating parameter) to obtain the uncertainty estimates of interest, given the data collection settings.

Results

Conditioning the OMs and scenarios explored

The key control parameters are mean recruitment, the spatial recruitment proportion and the migration rates between regions. In a two region model (such as that considered in the Macquarie Island toothfish assessment), this is 4 parameters. We are working in an equilibrium paradigm and so we need to decide what are the key control factors we will impose on the model to parameterise it, and what parameters we estimate to condition the OM.

The four major factors we impose to condition the OM are:

1. Total SSB depletion to be 0.5 (the current target)
2. Total catch to be 440t (the long-term TAC likely to meet the target)
3. The catch split by region (25:75 and 50:50 North and South)

To meet those criteria, once imposed, we allow the following three factors to vary:

1. $\bar{R}$ the mean total recruitment
2. h_1 and h_2 the region-specific harvest rates

The assessment parameters we keep fixed are:

1. $\eta_1 \in \{0.2, 0.4, 0.6\}$ the spatial recruitment proportion
2. $\pi_{1,2} \in \{0.01, 0.05\}$ the movement from N to S
3. $\pi_{2,1} \in \{0.05, 0.025\}$ the movement from S to N

The scenarios around spatial recruitment fraction, regional catch split, and the movement parameters result in 24 distinct scenarios. The naming convention around the scenarios is in terms of $ijkl$ where: i is one of the three η_1 options; j is one of the two N to S movement scenarios; k is one of the two S to N movement scenarios; and l is one of the two spatial catch split scenarios. So *1111* would be $\{\eta_1, \pi_{12}, \pi_{21}, \delta_1\} = \{0.4, 0.01, 0.05, 0.25\}$. Given recent estimates of selectivity given the spatial length data we assumed that : $\lambda_{1,50} = 65$, $\lambda_{1,95} = 80$, $\lambda_{2,50} = 75$, $\lambda_{2,95} = 100$.

The conditioning code actually works by solving the system of non-linear equations that hit the target SSB depletion, total catch and relative catch split by region, by changing $\bar{R}$, h_1 and h_2. All the 24 scenarios were solved so that the targets were attained exactly.

In terms of total and spatial tagging rates per tonne we assumed that total tagging rate per tonne, ψ, was kept at 2 in all cases. Given this overall rate, we explored $\psi_1 = \{1.5, 2, 3\}$ for the Northern area, which obviously interacts with ψ and the spatial catch split to implicitly define the tagging rate for area 2 the Southern area.

Uncertainty estimates of key assessment variables

The key uncertainty estimates we focus on are for equilibrium spawning stock biomass (SSB), and the movement parameters $\pi_{1,2}$ and $\pi_{2,1}$ to see how well the different tagging strategies compare when estimating overall spawning stock size and the movement between areas. To deal with with recruitment variability, and it's contribution to overall uncertainty in equilibrium SSB we used the following two relationships for the unfished SSB:

$$B_0 = R_0 \sum_a e^{-M(a-1)} w_a m_a,$$

$$\mathbb{V}(B_0) = R_0^2 \left(e^{\sigma_r^2} - 1\right) \sum_a \left(e^{-M(a-1)} w_a m_a\right)^2.$$

There is another similar, albeit somewhat more complicated formula to calculate the variance in equilibrium SSB in the exploited state, but we omit that here. The current level of $\sigma_r \approx 0.3$ is assumed in these runs, and the resultant CV in equilibrium SSB ranges between a CV of 0.05 to 0.06. We assume (probably safely) that stochastic recruitment variation will alter the variation in overall abundance, but not migration, and is independent of the other factors. We can then simply used the additive nature of independent variance components to calculate the overall variation in SSB given both the tagging based estimates and recruitment variation.

Figure 1 shows the predicted coefficient of variation (CV) in the overall SSB for each of the three spatial tagging rate scenarios $\psi_1 \in \{1.5, 2, 3\}$ contingent on an overall tagging rate of 2 tags per tonne. The range of CVs for the $\psi_1 = 1.5$ (less tagging in the North) is between 0.12–0.5 but the key features causing estimates of the CV to be above 0.3 are (i) 25% of the catch coming from the Northern area; (ii) higher levels of relative recruitment to the Northern area; and (iii) lower levels of migration from the Southern to the Northern area. There is a clear general trend that - overall - as we gradually increase the number of tags released in the Northern area $\psi_1 \to 1.5 \to 2 \to 3$ the estimates of the CV in overall SSB decrease, particularly the largest CV scenarios.

Figure 2 summarises the median and approximate 95% CI for the North to South movement rate, $\pi_{1,2}$. For lower levels of releases in the northern region ($\psi_1 = 1.5$) if the true rate of migration between the Northern and Southern regions is low (0.01) the estimates gradually get worse as the catch share moves from being 25/75 to 50/50 (i.e. more catch in the Northern area), and as the rate of movement between the Southern and Northern area decreases (from 0.05 to 0.025). This trend also follows for the 2 and 3 tag per tonne release rates in the North. Similarly to the SSB CV estimates, the movement estimates get more accurate as the number of releases in the Northern region increases.

Figure 3 the same result for the South to North movement rate,$\pi_{2,1}$. The trends for these

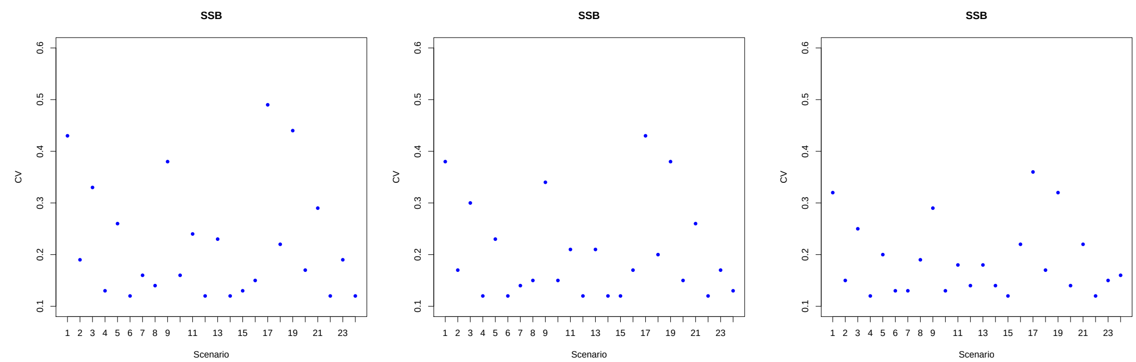

Figure 1: *The predicted CV in overall SSB across all 24 scenarios for a tagging rate of 1.5 (left), 2 (middle), and 3 (right) tags-per-tonne in the Northern area.*

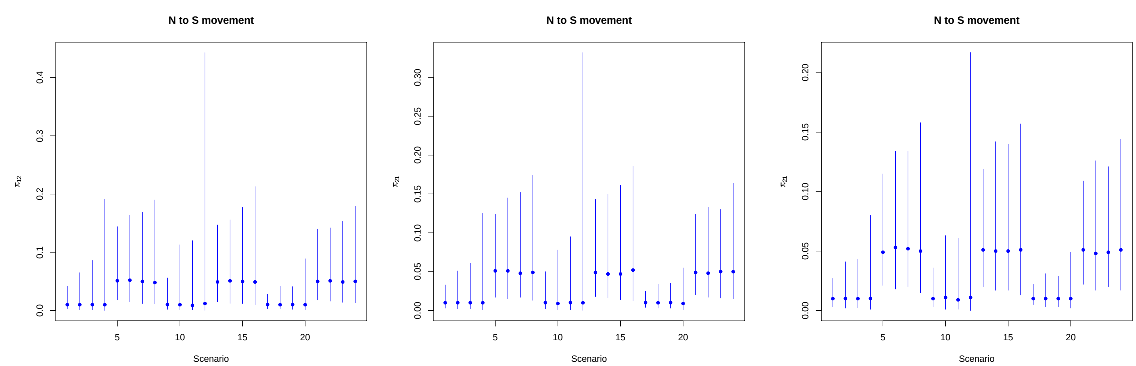

Figure 2: *The median (blue circle) and approximate 95% CI (blue line) for the North to South movement rate, $\pi_{1,2}$, across all 24 scenarios for a tagging rate of 1.5 (left), 2 (middle), and 3 (right) tags-per-tonne in the Northern area.*

estimates - across all spatial release scenarios - is less clear. More accurate estimates seem to be associated with scenarios where the spatial catch share is 50/50, movement between the South and the North is lower not higher, or where the only change from the base case is that the proportion of recruitment to the Southern area is at its lowest level ($\eta_1 = 0.6$). In contrast to the North to South movement parameter, across the board as the spatial tagging rate becomes focussed more on the North, the South to North movement estimates generally get more uncertain.

Estimates of selectivity for the Northern area for the length at 50% selection have a range of CVs from 0.2 to 0.3, and for the length at 95% selection the CVs range between 0.4 and 0.6. Both are better when the TAC split is 50/50 across the regions (i.e. where samples are

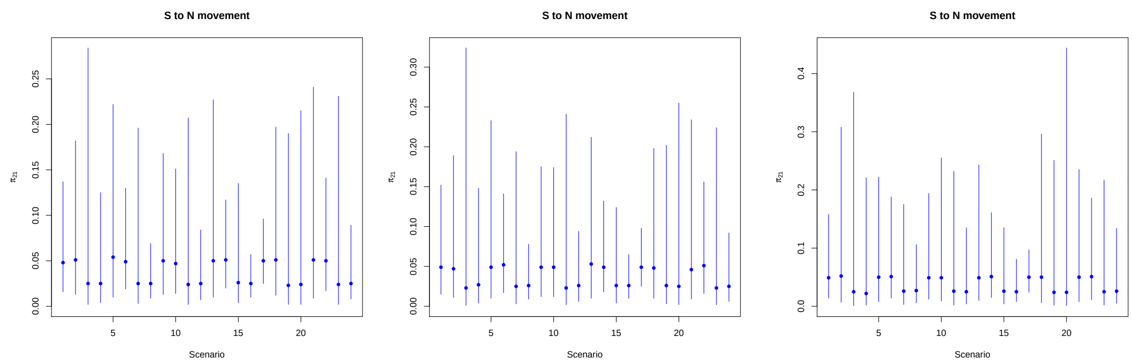

Figure 3: *The median (blue circle) and approximate 95% CI (blue line) for the South to North movement rate, $\pi_{2,1}$, across all 24 scenarios for a tagging rate of 1.5 (left), 2 (middle), and 3 (right) tags-per-tonne in the Northern area.*

actually taken in the Northern area). Estimates of selectivity for the Southern area for the length at 50% selection have a range of CVs from 0.08 to 0.16, and for the length at 95% selection the CVs range between 0.16 to 0.31. The estimates are also better for when there is more catch taken in the South ($\delta_2 = 0.75$) but not by much, relative to how much the Northern estimates improve when the catch split is more like 50/50.

Discussion

What constitutes the "best" spatial tagging design has been a question of interest for a number of years for this fishery and the stock assessment used to drive its management advice. In this paper we have tried to systematically approach how the spatial catch distribution, the underlying population dynamic parameter (both scale and spatial), and spatial tagging regimes interact in relation to the uncertainty estimates in the key assessment parameters driven by the tagging data (SSB and migration).

An information theoretic approach, originally suggested in (Bravington *et al.*, 2016) in relation to close-kin mark-recapture models and extended to the conventional mark-recapture and length frequency data we collect routinely, was used. This avoids the need for both simulation and back-estimation of the key parameters. We refer interested readers to Eveson *et al.* (2012) for factors that are known to bias these kinds of estimators. Given that, while spatial tagging rates varied, there was a balanced strategy with releases and recaptures in all spatial areas - and with this and the overall number of recaptures in general - estimation variance will be a much more influential factor than bias.

For estimates of overall SSB, the overarching result was that - across all other factors - having higher rates of tag release in the Northern regions, relative to the South, resulted in more accurate estimates of SSB. More specifically, all the CVs were between 0.1 and 0.35 and this regime avoided the appearance of high estimates (above 0.4 and approaching 0.5). At a more detailed level, lower levels of catch taken in the Northern area, higher levels of relative recruitment to the Northern area, and lower levels of migration from the South to the North result in consistently high CVs for SSB.

When estimating movement between the regions, at the highest level there is a clear trade-off between the accuracy of North to South/South to North movement as we shift the spatial tagging rates. Perhaps unsurprisingly, the more tags-per-tonne we release in the Northern region, the more precise the movement estimates from the North to the South, and the less precise the movement rates from the South to the North. As we move the releases more to the Southern region this trend generally reverses. For the North to South estimates, the 50/50 catch split and lower South to North movement rates seemed to result in less accurate estimates. The contrast with the South to North estimates they generally seemed to associate with more the 50/50 spatial catch split, and with less proportional recruitment to the Southern region ($\eta_1 = 0.6$).

Estimates of selectivity are generally good - more so for the Southern area relative to the North, especially at the older ages. The accuracy of Northern parameters was clearly associated with a 50/50 catch ratio; this effect was less clear for the Southern region, but still associated with higher catch levels in the South.

There are a number of clear influencing factors such as spatial catch split, spatial tagging rate per tonne, south to north migration rates and spatial recruitment factors. Some of these we can control - like spatial catch split and tagging rates - but the others we simply have to live with. Additionally, not all levers that we can pull are going to be beneficial across the board. For example, increasing the tagging rate in the Northern area seems to improve the estimates of SSB and the North to South movement parameters, but the South to North movement estimates become more uncertain. A 50/50 spatial catch ratio (i.e. not 25/75 North/South) improves the estimates of SSB, South to North movement and Southern selectivity, but did the opposite to North to South movement.

It is not, perhaps, surprising that there is no unequivocally optimal spatial tagging strategy and/or spatial catch distribution. There are clear trade-offs between key assessment outputs. If the primary focus is SSB then higher release rates in the North *and* enforcing a 50/50 spatial catch split quite clearly results in more accurate estimates, and avoids overly large CVs. The 50/50 catch ratio does seem to have negative effects on some of the movement parameters (North to South). Without a full MSE analysis it is hard to know how these trade-offs would play out in terms of fishery performance and management outcomes. What we can perhaps say is that having higher rates of tagging in the Northern area appear to have generally positive outcomes - in particular for the key management variable of SSB. Also, these are implicitly long term rates for all key data collection and management levers - these ignore the potential for additional information that can be gained from time-varying levels of spatial catch and tagging rates.

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Appendix

Calculating the Fisher information via the second derivative option requires far more calculation than does the option via the square of the score (i.e. needing only first derivatives). The two methods defined in the main text are equivalent, and we show now why is this the case. Consider first the second derivative of the log-likeilihood:

$$\frac{\partial^2}{\partial \boldsymbol{\theta}^2} \ln \ell(X \mid \boldsymbol{\theta}) = \frac{\frac{\partial^2}{\partial \boldsymbol{\theta}^2} \ell(X \mid \boldsymbol{\theta})}{\ell(X \mid \boldsymbol{\theta})} - \left(\frac{\frac{\partial}{\partial \boldsymbol{\theta}} \ell(X \mid \boldsymbol{\theta})}{\ell(X \mid \boldsymbol{\theta})} \right)^2 = \frac{\frac{\partial^2}{\partial \boldsymbol{\theta}^2} \ell(X \mid \boldsymbol{\theta})}{\ell(X \mid \boldsymbol{\theta})} - \left(\frac{\partial}{\partial \boldsymbol{\theta}} \ln \ell(X \mid \boldsymbol{\theta}) \right)^2$$

Taking the first part of the above equation and calculating its expectation over the data:

$$\mathbb{E}^X \left[\frac{\frac{\partial^2}{\partial \boldsymbol{\theta}^2} \ell(X \mid \boldsymbol{\theta})}{\ell(X \mid \boldsymbol{\theta})} \right] = \int \frac{\partial^2}{\partial \boldsymbol{\theta}^2} \ell(X \mid \boldsymbol{\theta}) \mathrm{d}X = \frac{\partial^2}{\partial \boldsymbol{\theta}^2} \int \ell(X \mid \boldsymbol{\theta}) \mathrm{d}X = 0.$$

The additive nature of the expectation, and the result in the previous equation, give rise the the equivalent definitions of the Fisher information:

$$\mathcal{I}(\boldsymbol{\theta}) = \mathbb{E}^X\left[\left(\frac{\partial}{\partial \boldsymbol{\theta}}\ln \ell(X\,|\,\boldsymbol{\theta})\right)^2\right] = -\mathbb{E}^X\left[\frac{\partial^2}{\partial \boldsymbol{\theta}^2}\ln \ell(X\,|\,\boldsymbol{\theta})\right].$$

For the Bernoulli process, with probability p, the likelihood (and log-likelihood) of a binary outcome $X = \{0, 1\}$ is

$$\begin{aligned} \ell(X\,|\,p) &= p^X(1-p)^{X-1}, \\ \ln \ell(X\,|\,p) &= X\ln p + (1-X)\ln(1-p), \end{aligned}$$

and the second derivative of the log-likelihood is given by

$$\frac{\partial^2}{\partial \boldsymbol{\theta}^2}\ln \ell(X\,|\,p) = \frac{X}{p^2} + \frac{1-X}{(1-p)^2}.$$

For the Bernoulli distribution we have that $\mathbb{E}(X) = p$, so the expected value of the second derivative of the log-likelihood (i.e. FI) is:

$$\mathcal{I}(p) = \frac{p}{p^2} + \frac{1-p}{(1-p)^2} = \frac{1}{p} + \frac{1}{1-p} = \frac{1}{p(1-p)} > \frac{1}{p},$$

which would make p^{-1} a conservative approximation to the Fisher information for Bernoulli processes (such as the total tag recapture model).

Here we detail exactly how we calculate the Fisher information matrix for the estimated parameters, given the original Fisher information is defined in terms of the underlying probability (which is a function of the estimated parameters). Assuming $p(\boldsymbol{\theta})$ is at least two-times differentiable in terms of $\boldsymbol{\theta}$ then, via the chain rule, we have that

$$\mathcal{I}(\boldsymbol{\theta}) = -\mathbb{E}^X\left[\frac{\partial^2}{\partial p^2}\ln \ell(X\,|\,p)\left(\frac{\partial p}{\partial \boldsymbol{\theta}}\right)^2 + \frac{\partial}{\partial p}\ln \ell(X\,|\,p)\frac{\partial^2 p}{\partial \boldsymbol{\theta}^2}\right].$$

Taking the second part of the expression in the above expectation we have that

$$\mathbb{E}^X\left[\frac{\partial}{\partial p}\ln \ell(X\,|\,p)\frac{\partial^2 p}{\partial \boldsymbol{\theta}^2}\right] = \frac{\partial^2 p}{\partial \boldsymbol{\theta}^2}\mathbb{E}^X\left[\ln \ell(X\,|\,p)\right] = \frac{\partial^2 p}{\partial \boldsymbol{\theta}^2}\frac{\partial}{\partial p}\left(\int \ell(X\,|\,p)\mathrm{d}X\right) = \frac{\partial^2 p}{\partial \boldsymbol{\theta}^2}\times\frac{\partial}{\partial p}(1) = 0.$$

So the second part of the term over which we take the expectation to obtain the parameter-focussed Fisher information disappears, leaving only the following:

$$\mathcal{I}(\boldsymbol{\theta}) = -\mathbb{E}^X\left[\frac{\partial^2}{\partial p^2}\ln \ell(X\,|\,p)\left(\frac{\partial p}{\partial \boldsymbol{\theta}}\right)^2\right] = -\left(\frac{\partial p}{\partial \boldsymbol{\theta}}\right)^2\mathbb{E}^X\left[\frac{\partial^2}{\partial p^2}\ln \ell(X\,|\,p)\right] = \mathcal{I}(p)\left(\frac{\partial p}{\partial \boldsymbol{\theta}}\right)^2.$$

The base level Fisher information for the Bernoulli process is

$$\mathcal{I}(\boldsymbol{\theta}) = \left(\frac{\partial p}{\partial \boldsymbol{\theta}}\right)^{\dagger} \frac{1}{p} \left(\frac{\partial p}{\partial \boldsymbol{\theta}}\right),$$

but with small probabilities (such as those in mark-recapture models) this can scale very poorly numerically. Consider $f = \sqrt{p}$, then

$$\frac{df}{d\boldsymbol{\theta}} = \frac{1}{2\sqrt{p}} \frac{dp}{d\boldsymbol{\theta}},$$

and

$$\left(\frac{df}{d\boldsymbol{\theta}}\right)^{\dagger} \left(\frac{df}{d\boldsymbol{\theta}}\right) = \frac{1}{4p} \left(\frac{dp}{d\boldsymbol{\theta}}\right)^{\dagger} \left(\frac{dp}{d\boldsymbol{\theta}}\right).$$

Given this it follows that:

$$\frac{1}{p} \left(\frac{dp}{d\boldsymbol{\theta}}\right)^{\dagger} \left(\frac{dp}{d\boldsymbol{\theta}}\right) = 4 \left(\frac{d\sqrt{p}}{d\boldsymbol{\theta}}\right)^{\dagger} \left(\frac{d\sqrt{p}}{d\boldsymbol{\theta}}\right),$$

which is more numerically stable and easier to deal with.

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