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

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1 Summary

This paper presents results from an integrated stock assessment of Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island using data collected up until and including August 2015. The assessment uses a spatial model that fits to data from the entire Macquarie Island toothfish fishery, and assumes a single reproductive stock, but takes into account spatial structuring of the population within the region. Two areas – northern and southern – are incorporated into the model, with movement of fish between areas, and recruitment to both areas. A single Total Allowable Catch (TAC) for the entire Macquarie Island region is calculated using the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) control rule.

This assessment makes use of the Stock Synthesis assessment software v3.11b (Methot & Wetzel, 2013), and fits to data obtained from the tag-recapture program since 1995, to length composition information for the years 1994–2015, and to age-at-length data obtained from aged otoliths (1997–2015). It is an update of the final version of the 2015 assessment (Day *et al.*, 2015). The assessments are based on a length-age structured model of fish population dynamics, with maximum likelihood and Bayesian methods used to fit to the available data.

The model designates five different fleets (Aurora Trough trawl, Northern Valley Trawl, Aurora Trough longline, and Northern and Southern Macquarie Ridge longlines). Fits to the length composition data are generally good. The fits to the age-at-length data appear to be reasonable, although larger fish are predicted to be older than they are observed to be (the model is growing older fish too slowly). The model fits the tag-recapture data well, with good accord between the total number of expected recaptures and those observed.

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

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

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

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

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

2 Introduction

2.1 Patagonian toothfish

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

Toothfish have been known to grow to over 2m in length and may live to more than 50 years of age. They inhabit depths from approximately 300m to 2400m, with juveniles generally found in shallower water. They feed on small fish and squid in the mid-water and various fish and crustaceans on the bottom. Toothfish are believed to reach sexual maturity at around 10 years of age, and possibly older for Macquarie Island fish (Constable *et al.*, 2001; Goldsworthy *et al.*, 2001).

Toothfish lack swim-bladders and so often reach the surface in good condition even though they may have been caught from depths down to 2400m. This has allowed an extensive tagging program to develop at both Macquarie Island and the Heard Island and McDonald Islands (HIMI). Tagging studies have increased knowledge of the species movement, growth and available abundance (Williams *et al.*, 2002; Tuck *et al.*, 2003).

2.2 The fishery

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

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

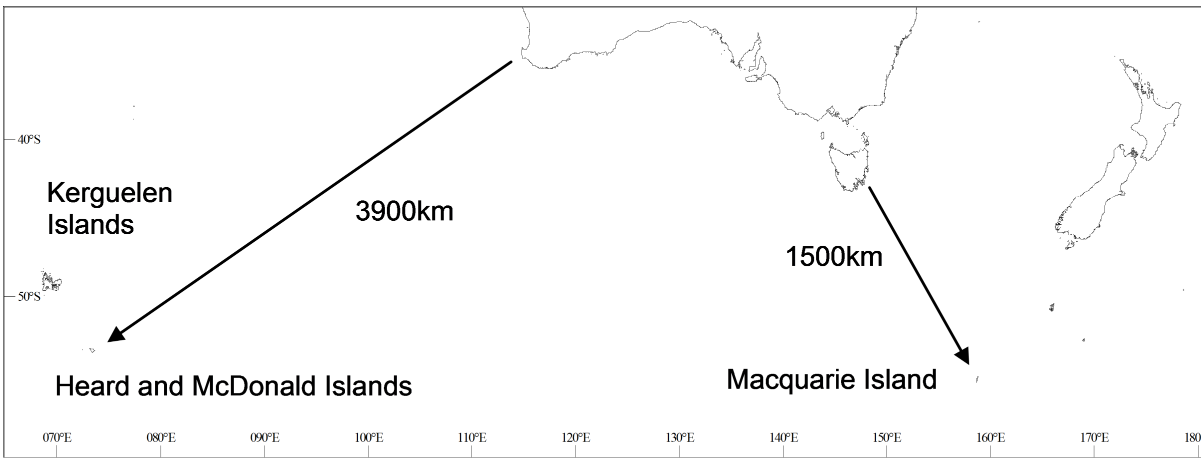

Figure 2.1: The location of Macquarie Island (54° 30'S, 158° 57'E) and Heard Island and McDonald Islands (53 °06'S, 73 °30'E) relative to New Zealand and Australia.

A Total Allowable Catch (TAC) for the fishery was first introduced in the 1996/97 fishing season (Table 2.1, Figure 3.1). The TAC for the 1996/97 fishing season was based on the catches of the first two fishing seasons and the tagging experiment in the 1995/96 fishing season. The setting of TACs after the 1996/97 fishing season was then based on results from a tagging-based stock assessment model. For the Aurora Trough region, commercial TACs for the trawl fishery were 750 and 200t for the 1996/97 and 1997/98 fishing seasons respectively, and were zero after the 1997/98 fishing season (but with a 40t research TAC for continuing the tagging experiment and monitoring). In 2003/04, following indications of improved stock status from the assessment, Aurora Trough was re-opened to commercial fishing with a 354t quota. However, the assessment in the following year suggested that the stock had fallen marginally below the threshold for a commercial fishery so once again, the commercial fishery closed and a research quota was instigated. Since then a commercial fishery has existed in every season except for 2009/10, and the commercial Aurora Trough quota was 150t in 2011/12 (Table 2.1).

For the Macquarie Ridge sector, the annual trawl TAC has reduced steadily since the 1500t TAC of 1998. However, the TACs since 1999 were allowed to increase within the fishing season if the catch rates exceeded 10t/km^2 over three consecutive fishing days. If this catch rate dropped below the trigger level, then the TAC fell to the lower TAC. If the lower TAC had been reached then fishing ceased.

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

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

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

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

From 2012/13, a single TAC has been set for the whole of the Macquarie Island region. The 2015/16 TAC was set at 460t, with a recommendation to catch a little more than half of this total TAC in Aurora Trough (250t), and 60% of the remainder taken from North Macquarie Ridge (126t) and the rest from South Macquarie Ridge (84t). The actual catch in 2015 was around 150t below the TAC. However the catch followed the recommended percentages by region fairly closely (Table 3.1).

2.3 Previous assessments

Prior to 2010, TAC determination for the Macquarie Island Patagonian toothfish stock had been based on stock assessment using the tag-recapture model developed by de la Mare and Williams (1997), and modifications described in Tuck *et al.* (2003). This tag-recapture model estimated pre-tagging available abundance and annual net changes in available abundance between fishing seasons for the major fishing grounds of Macquarie Island (Tuck & Lamb, 2009). In 2004, a new model that expanded upon the traditional tag-based model was introduced (Tuck *et al.*, 2006). This "integrated" assessment included information on length-frequency and tagging data in an age-structured model that allowed estimation of annual spawning biomass and cohort strength. In 2008/09 work commenced on using the integrated assessment platform of Stock Synthesis for the assessment of Aurora Trough Patagonian toothfish (Tuck & Methot, 2008; Fay *et al.*, 2009b). This model development continued and the Stock Synthesis assessment was used to set the TAC for the Aurora Trough component of the fishery for the 2010/11 fishing season (Fay *et al.*, 2010).

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

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

Valleys Macquarie Ridge trawl grounds.

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

From 2012/13 a single TAC was set for the whole of Macquarie Island, and the two area model used as the base case. The 2012 assessment estimated the 2012/13 female spawning biomass for the whole of Macquarie Island to be 70% of unfished (Wayte & Fay, 2012), the 2013 assessment estimated the 2013/14 female spawning biomass for the whole of Macquarie Island to be 69% of unfished (Wayte & Fay, 2013), with further estimates of 68% for the 2014 assessment (Day *et al.*, 2014) and 69% for the 2015 assessment (Day *et al.*, 2015).

2.4 Modifications to the previous assessment

The following data have been added to the assessment:

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

3 Data

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

3.1 Catch data

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

Annual catch data used in previous assessments comprised the total catch, which included a small proportion of fish that were caught and released (including fish released with tags) as well as fish that were retained. In the current assessment, the catch data was adjusted to exclude any released fish. This resulted in revisions to the historical catch record, only including those fish that were retained in the catch data.

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

3.2 Length frequency data

Samples of the length composition of the catch were available for all fishing seasons (1994/95 through 2014/15). Each annual length composition is based on the measurement of several hundreds (thousands) of fish (Table 3.2). However, it is unlikely that the number of fish measured in each year is an appropriate metric of the effective sample size, due to expected high correlations among fish lengths within individual

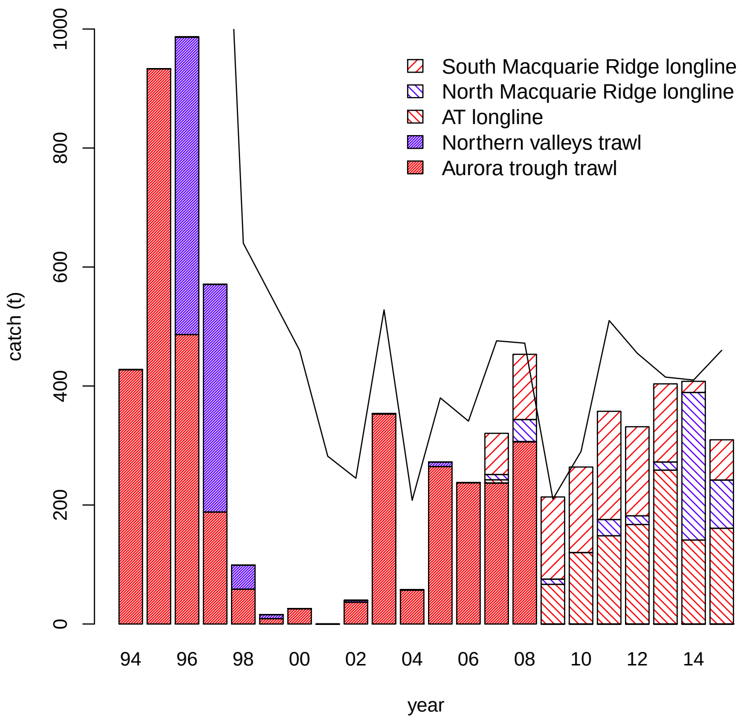

Figure 3.1: Catch history and total TAC by fishing year, with catches stacked by fleet and the grey line representing the combined TAC (with TACs summed for Aurora Trough and Macquarie Ridge from 1996–2011). There were small research quotaa in the Aurora Trough from 1998-2002 and in 2004.

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

Fishing season	Trawl		Longline			Total Catch(t)	Combined TAC(t)
	AT	NV	AT	NMR	SMR		
94/95	427.3	0				427	
95/96	932.9	0				933	
96/97	486.3	500.3				987	1750
97/98	188.2	382.8				571	1700
98/99	58.5	40.5				99	640
99/00	9.0	6.6				16	550
00/01	25.4	0.6				26	460
01/02	0.0	0				0	282
02/03	36.4	3.3				40	245
03/04	352.8	0.7				353	528
04/05	56.8	0.6				57	208
05/06	264.5	7.9				272	380
06/07	237.3	0				237	341
07/08	236.8	0	5.4	9.0	69.2	320	476
08/09	306.1	0	0	37.1	109.8	453	462
09/10			66.6	8.7	138.2	214	210
10/11			120.2	0	143.6	264	290
11/12			148.2	27.4	181.9	358	510
12/13			167.3	14.5	149.7	332	455
13/14			258.5	13.8	131.3	404	415
14/15			141.2	248.0	18.7	408	410
15/16			160.8	81.1	67.7	309	460

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

Disaggregation of the length data by sex is possible, and Stock Synthesis allows for the inclusion of composition data from both sexed data and data for which the sex is unknown, with the expectation that the latter is a random sample from the catch and is a combination of the individual compositions by sex. The percentage of the seasonal length samples that were sexed has varied considerably over the duration of the fishery. Additionally, inspection of the data suggests that the unsexed fish sampled for length are quite different from the male and female portions of the length composition for some years (Fay, 2010). Consequently, length data were aggregated by sex for all years.

Length bin structure is at 5 cm intervals between 30 – 140 cm, and at 10 cm intervals below and above this range up to 190 cm.

3.3 Age data

Age-at-length samples are available from aged fish that were captured in 1996–2000, 2002, 2003, 2005–2010 and 2013–2015 (Table 3.3). New ageing data from 2014 and 2015 were added this year. The input sample sizes for the age-at-length data were set at 10% of the number of otoliths measured.

3.3.1 Conditional age-at-length data

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

3.3.2 Ageing error

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

3.4 Tag recapture data

Between the 1995/96 and 2015/16 fishing seasons, 15,188 Patagonian toothfish were tagged at Macquarie Island, of which 1,909 have been recaptured (Table 3.5, Table 3.6). Fish are still being recaptured from releases in the early years of the fishery (Table 3.5), with one fish recaptured in 2015 having been initially tagged in 1997.

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

Fleet	Season	# shots	# fish	mean # per shot
AT trawl	94/95	126	3414	27
	95/96	257	6721	26
	96/97	103	2725	26
	97/98	81	1409	17
	98/99	54	3354	62
	99/00	38	831	22
	00/01	20	1415	71
	01/02	2	1	1
	02/03	19	733	39
	03/04	96	4580	48
	04/05	19	702	37
	05/06	124	3368	27
	06/07	72	765	11
	07/08	94	1461	15
	08/09	131	2199	17
NV trawl	94/95	3	18	6
	95/96	43	2250	52
	96/97	139	2393	17
	97/98	78	2031	26
	98/99	42	638	15
	99/00	13	350	27
	00/01	2	1	1
	01/02	24	390	16
	02/03	6	83	14
	03/04	13	274	21
	04/05	27	548	20
	07/08	3	14	5
AT longline	07/08	2	200	100
	09/10	9	548	61
	10/11	18	1066	59
	11/12	45	1779	40
	12/13	52	1916	37
	13/14	79	3046	39
	14/15	62	2216	36
	15/16	84	2950	35
NMR longline	07/08	5	160	32
	08/09	13	406	31
	09/10	7	246	35
	11/12	26	829	32
	12/13	31	838	27
	13/14	11	340	31
	14/15	70	2570	37
	15/16	96	2739	29
SMR longline	07/08	28	1589	57
	08/09	44	1750	40
	09/10	50	1886	38
	10/11	34	1545	45
	11/12	96	3388	35
	12/13	126	4080	32
	13/14	94	3107	33
	14/15	17	528	31
	15/16	62	1985	32

Table 3.3: Sample sizes of aged fish from the southern and northern areas of the fishery by year and gender. Tag recaptured fish not included.

Year	gender	south	north	total
1996	u	9	10	19
	f			0
	m			0
1997	u	19	5	24
	f	28	13	41
	m	27	23	50
1998	u	4		4
	f	134	71	205
	m	117	83	200
1999	u	16		16
	f	1	87	88
	m	1	117	118
2000	u	8		8
	f	40	3	43
	m	53	7	60
2002	u			0
	f		31	31
	m		32	32
2003	u			0
	f	138		138
	m	79	2	81
2005	u	1		1
	f	107	26	133
	m	56	37	93
2006	u			0
	f	11		11
	m	9		9
2007	u			0
	f	328	33	361
	m	238	13	251
2008	u	3		3
	f	247	33	280
	m	225	4	229
2009	u	1		1
	f	272	35	307
	m	159	25	184
2010	u	1		1
	f	276		276
	m	159		159
2013	u	2	3	5
	f	175	25	200
	m	83	14	97
2014	u	2		2
	f	97	95	192
	m	59	23	82
2015	u			0
	f	129	76	205
	m	57	19	76
total		3371	945	4316

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

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

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

Release	Release	# rel	Mean	# recaptures after 180 days at liberty																		
season	fleet		length	96/97	97/98	98/99	99/00	00/01	02/03	03/04	04/05	05/06	06/07	07/08	08/09	09/10	10/11	11/12	12/13	13/14	14/15	15/16
95/96	AT tr	428	69	57	28	3		1	1	1							1					
95/96	NV tr	4	57																			
96/97	AT tr	448	58		42	7		2		9	1	3		1	1							
96/97	NV tr	536	61		53	5	1			2												
97/98	AT tr	503	60			18	3	4	5	21	4	15	1		2	3	1	2	2			1
97/98	NV tr	477	69			9				1					1		1					
98/99	AT tr	652	68				4	5	2	30	2	9	2	2	7		1	1		1		
98/99	NV tr	308	57																			
99/00	AT tr	692	65					3	1	35	6	12	1	4	6	2	5	1	5			
99/00	NV tr	299	58																1			
00/01	AT tr	364	59						1	23	3	5	1	1	9							
00/01	NV tr	135	46						1			1										
02/03	AT tr	491	63							60	8	29	6	15	24	2	3	10	1	6	2	
02/03	NV tr	17	57															1				
03/04	AT tr	570	69								9	23	8	4	13	2	3	2	1	1		
03/04	NV tr	60	53									3										
04/05	AT tr	556	69									46	7	16	43	4	4	6	3	4	1	
04/05	NV tr	263	56									2		1	1						1	1
05/06	AT tr	520	71										25	18	27	2	5	4	4	3	1	1
05/06	NV tr	288	60																1		2	3
06/07	AT tr	432	59											26	13		1			4		2
07/08	AT tr	273	65												31	2		2	1	3	1	
07/08	NMR LL	26	78													1		3	2			
07/08	SMR LL	189	81												15	4	3	6	6	4		1
08/09	AT tr	557	71													2	6	12	10	19	6	8
08/09	NV tr	14	51																			
08/09	NMR LL	82	79													2		7		1	1	
08/09	SMR LL	385	79												1	9	9	18	21	11	2	2
09/10	AT LL	299	85														27	13	9	13	4	2
09/10	NMR LL	60	85															5	5			2
09/10	SMR LL	395	79														26	25	8	20	2	2
10/11	AT LL	478	87															11	31	45	6	4
10/11	SMR LL	507	91															27	42	34	5	8
11/12	AT LL	302	72																10	37	7	7
11/12	NMR LL	116	83																1	2	1	3
11/12	SMR LL	497	78																9	25	4	17
12/13	AT LL	309	78																	37	12	12
12/13	NMR LL	56	89																			
12/13	SMR LL	302	87																	20		8
13/14	AT LL	529	75																		9	26
13/14	NMR LL	36	81																			2
13/14	SMR LL	249	81																		9	10
14/15	AT LL	295	72																			9
14/15	NMR LL	499	79																			
14/15	SMR LL	33	81																			
15/16	AT LL	353	76																			
15/16	NMR LL	168	79																			
15/16	SMR LL	136	78																			

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

	Recaptured by:				
Released by:	AT trawl	NV trawl	AT longline	NMR longline	SMR longline
AT trawl	851	1	150	1	32
NV trawl	8	72	1	7	4
AT longline	0	0	315	0	16
NMR longline	0	0	1	23	14
SMR longline	1	0	55	5	352

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

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

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

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

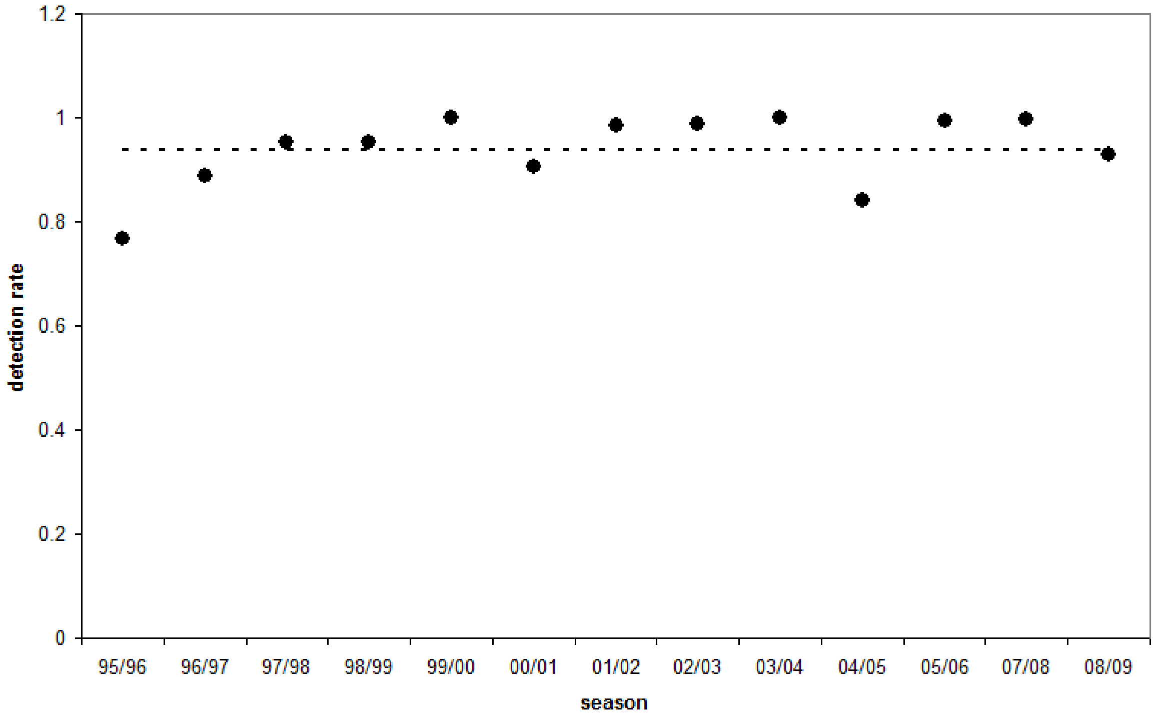

Figure 3.2: Estimated tag detection rate (points) by fishing season (Tuck and Lamb 2009). Dotted line corresponds to the mean detection rate (0.938) over the time series.

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

The non-detection of tagged toothfish has been a problem, especially with the electronic tags. The detection of visible tags also relies upon the vigilance of the crew and observers. Estimates of the tag detection rate by season are available for the trawl fishery (Figure 3.2, data from Tuck and Lamb (2009)), and were input to the model in order to implement a time-varying detection rate. In the absence of additional information, the tag detection rate for the longline fleet was assumed to be 0.94 (the average of the calculated annual values from the trawl fishery) for all years.

3.5 New and updated data summary

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

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

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

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

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

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

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

4 Biology

4.1 Growth

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

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

Table 4.1: Values for growth parameters.

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

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

Table 4.2: Values for biological parameters.

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

4.2 Mortality

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

4.3 Fecundity and maturity

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

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

5 Assessment methodology

5.1 Population model

The assessment is based on a length-age-structured model of fish population dynamics. It uses a spatial model that fits to data from the entire Macquarie Island toothfish fishery, and assumes a single reproductive stock, but takes into account spatial structuring of the population within the region. Two areas – northern and southern (with the division being the latitude of 54.25 ° south) – are incorporated into the model, with movement of fish between areas, and recruitment to both areas. Differences in the size structure available to the different fleets (e.g. trawl vs. Ridge longlining) within areas are accounted for via the estimated selectivity patterns for each fleet.

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

5.2 Fleets

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

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

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

5.3 Selectivity

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

5.4 Stock and recruitment

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

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

5.5 Initial conditions

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

5.6 Movement

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

5.7 Parameters and parameter estimation

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

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

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

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

5.7.1 Contributions to the likelihood function

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

5.7.2 Penalties

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

5.8 Quantification of uncertainty

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

5.9 2016/2017 catch determination under the CCAMLR control rule

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

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

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

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

6 Results and discussion

6.1 Bridging analysis

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

The sequential changes to update the base case model were:

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

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

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

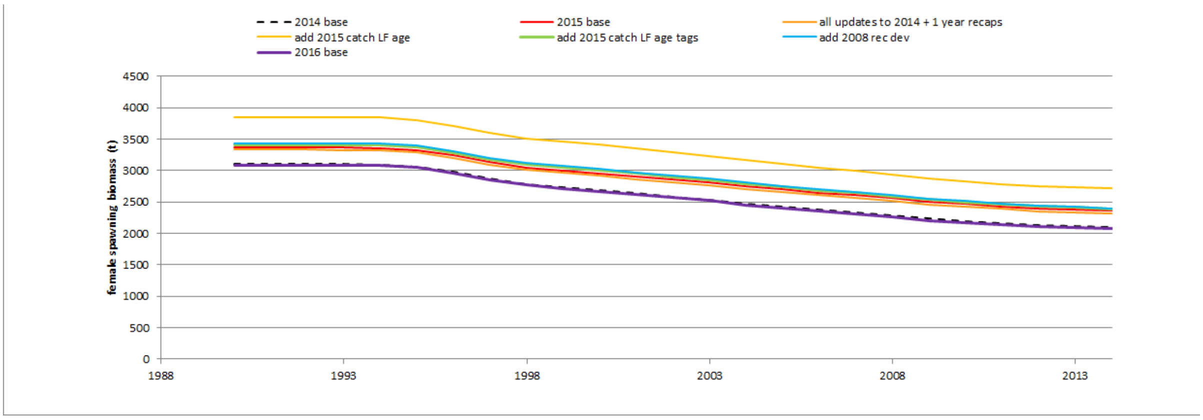

Figure 6.1: Effect on the female spawning biomass trend of sequential updates with the most recent data.

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

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

6.2 Diagnostics

6.2.1 Length composition data

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

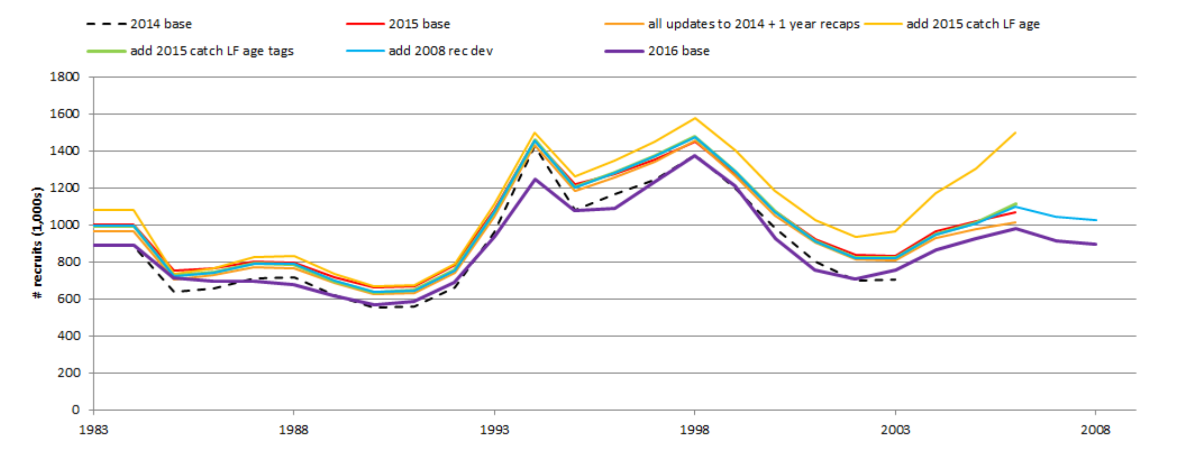

Figure 6.2: Effect on the recruitment estimates of sequential updates with the most recent data.

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

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

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

6.2.2 Age-at-length data

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

6.2.3 Tag recapture data

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

6.3 Base case results

6.3.1 Selectivity

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

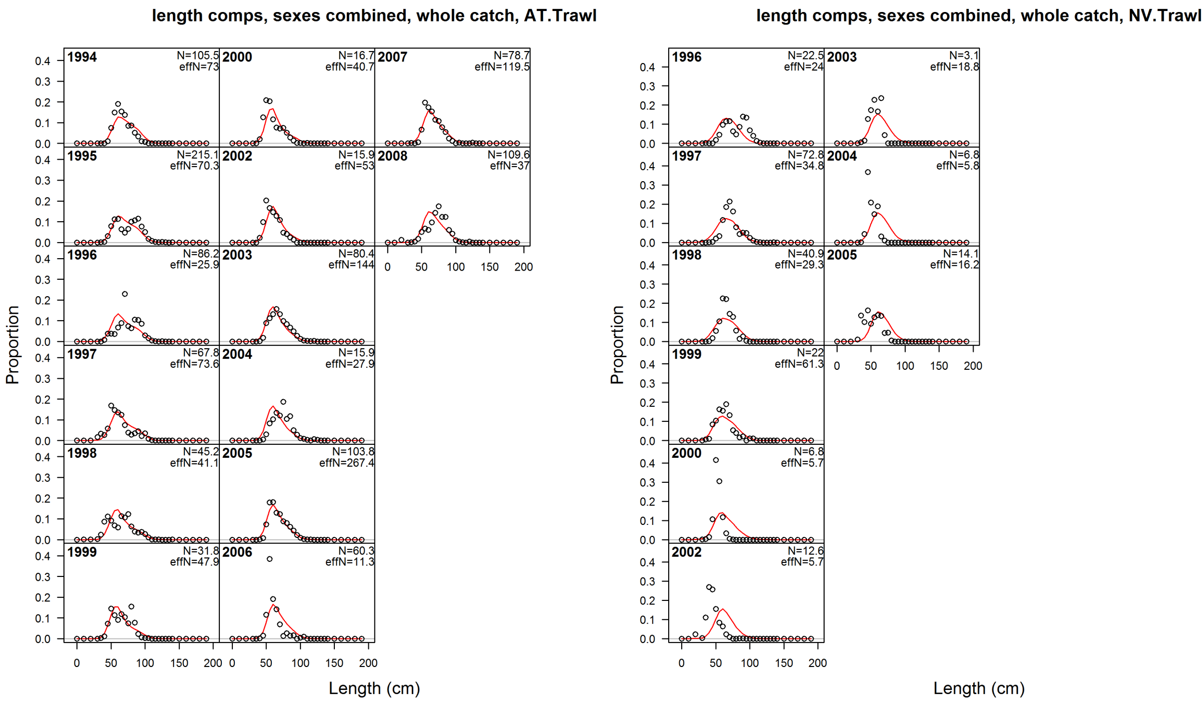

Figure 6.3: Fits to the length composition data for the trawl fleets.

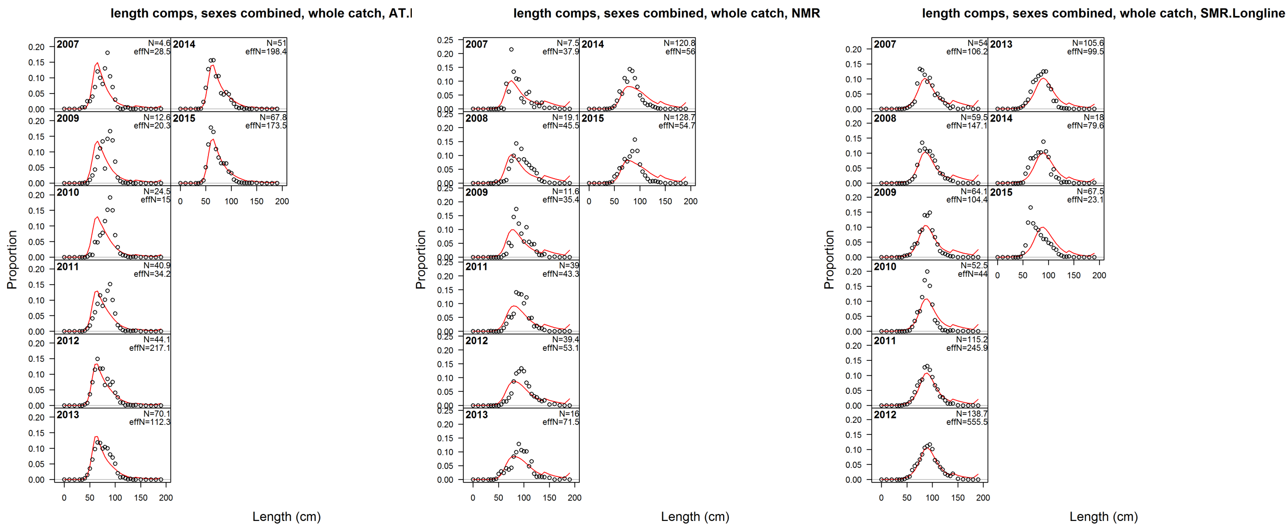

Figure 6.4: Fits to the length composition data for the longline fleets.

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

6.3.2 Growth

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

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

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

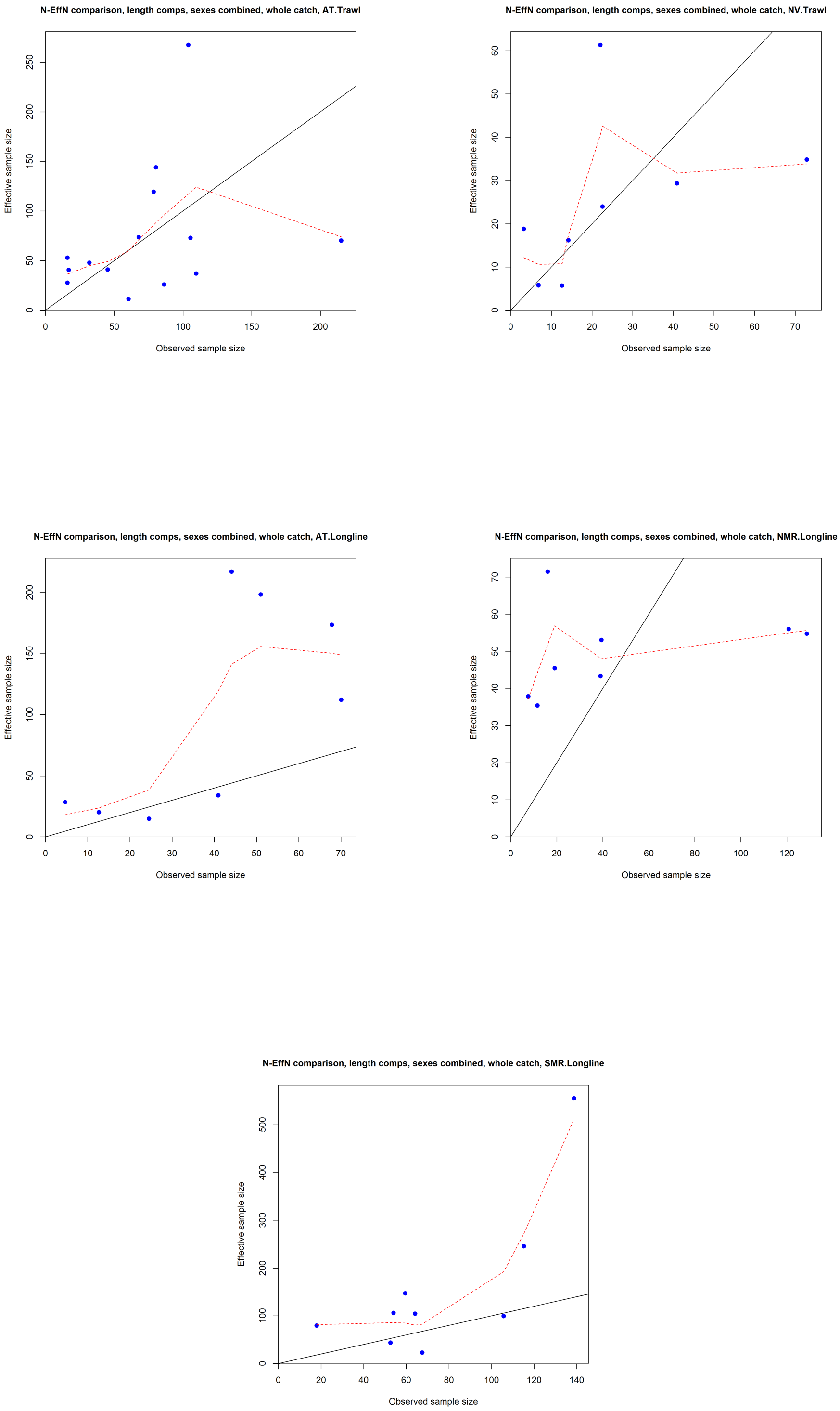

Figure 6.5: Input vs. effective sample size for the length composition data.

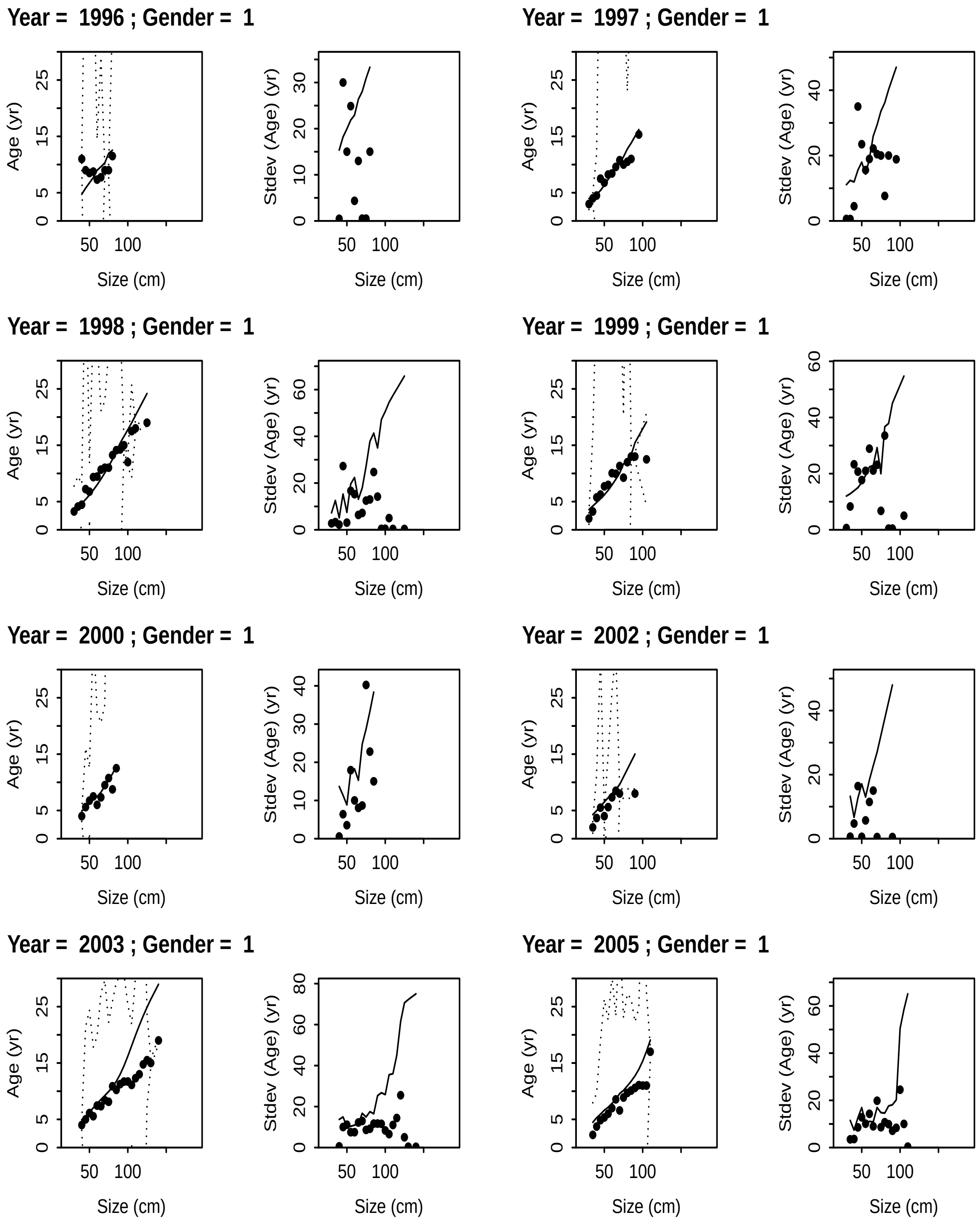

Figure 6.6: Diagnostic plots for the fits to the female (Gender = 1) conditional age-at-length data to 2005. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed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

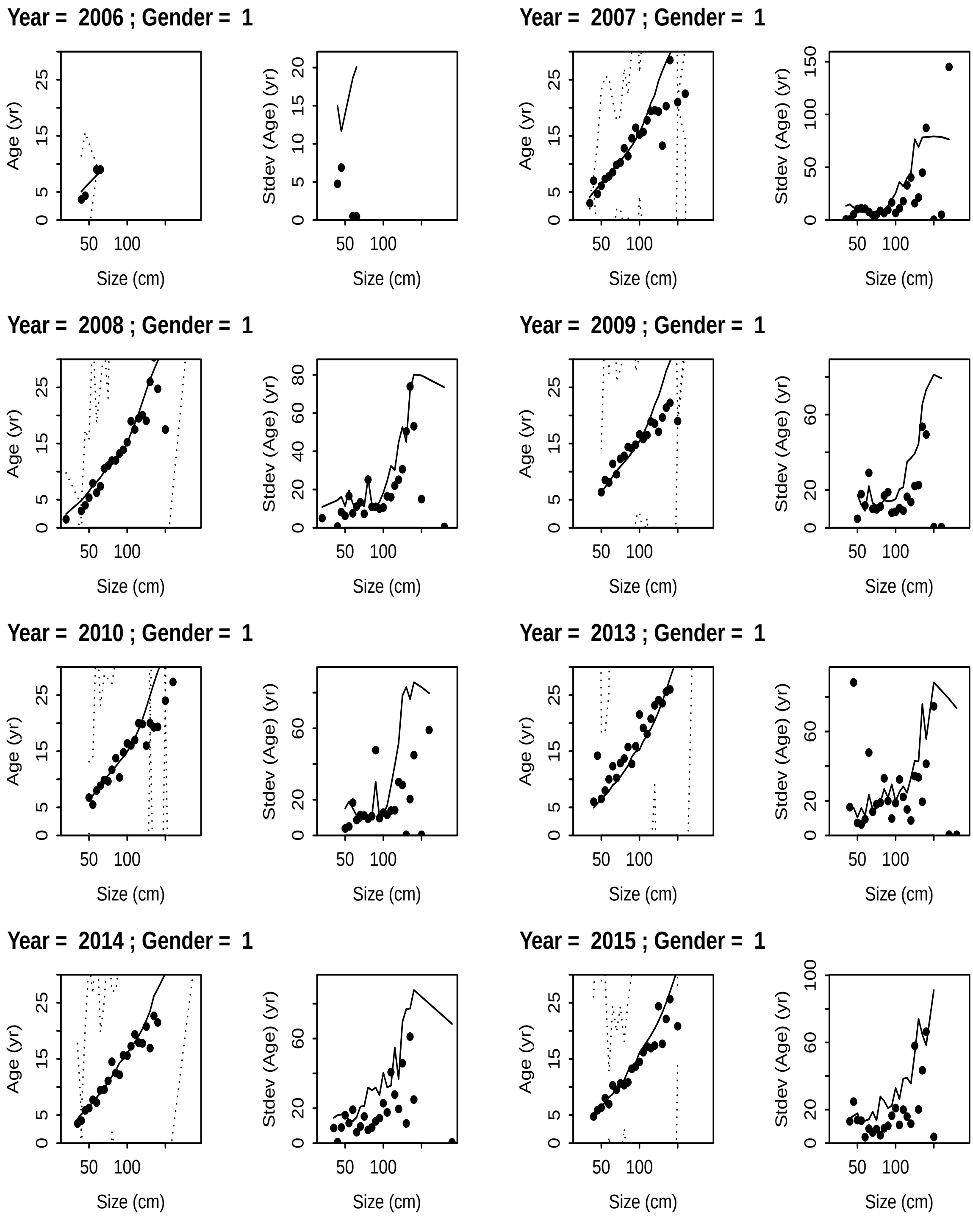

Figure 6.7: Diagnostic plots for the fits to the female (Gender = 1) conditional age-at-length data from 2006. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed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

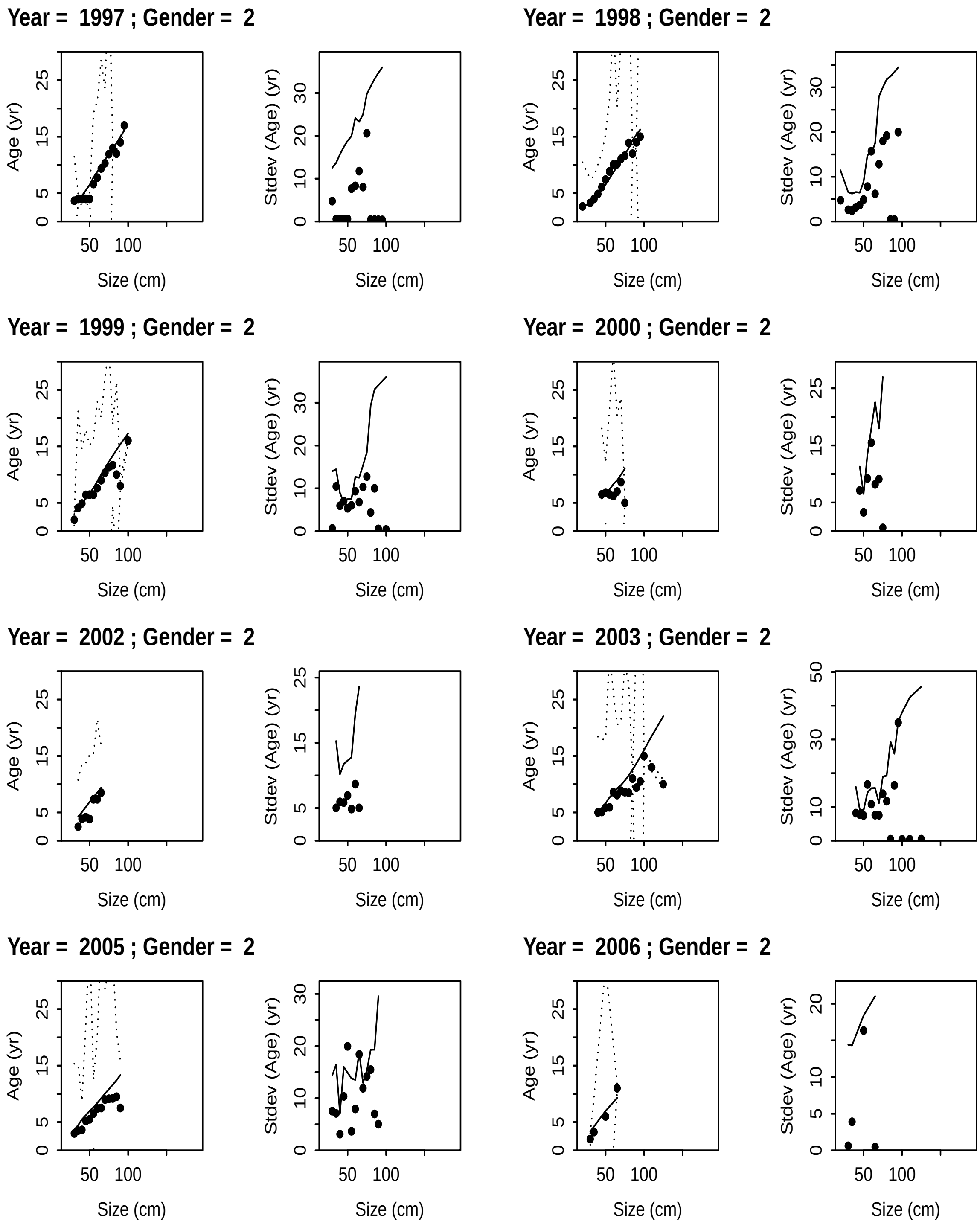

Figure 6.8: Diagnostic plots for the fits to the male (Gender = 2) conditional age-at-length data to 2005. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed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

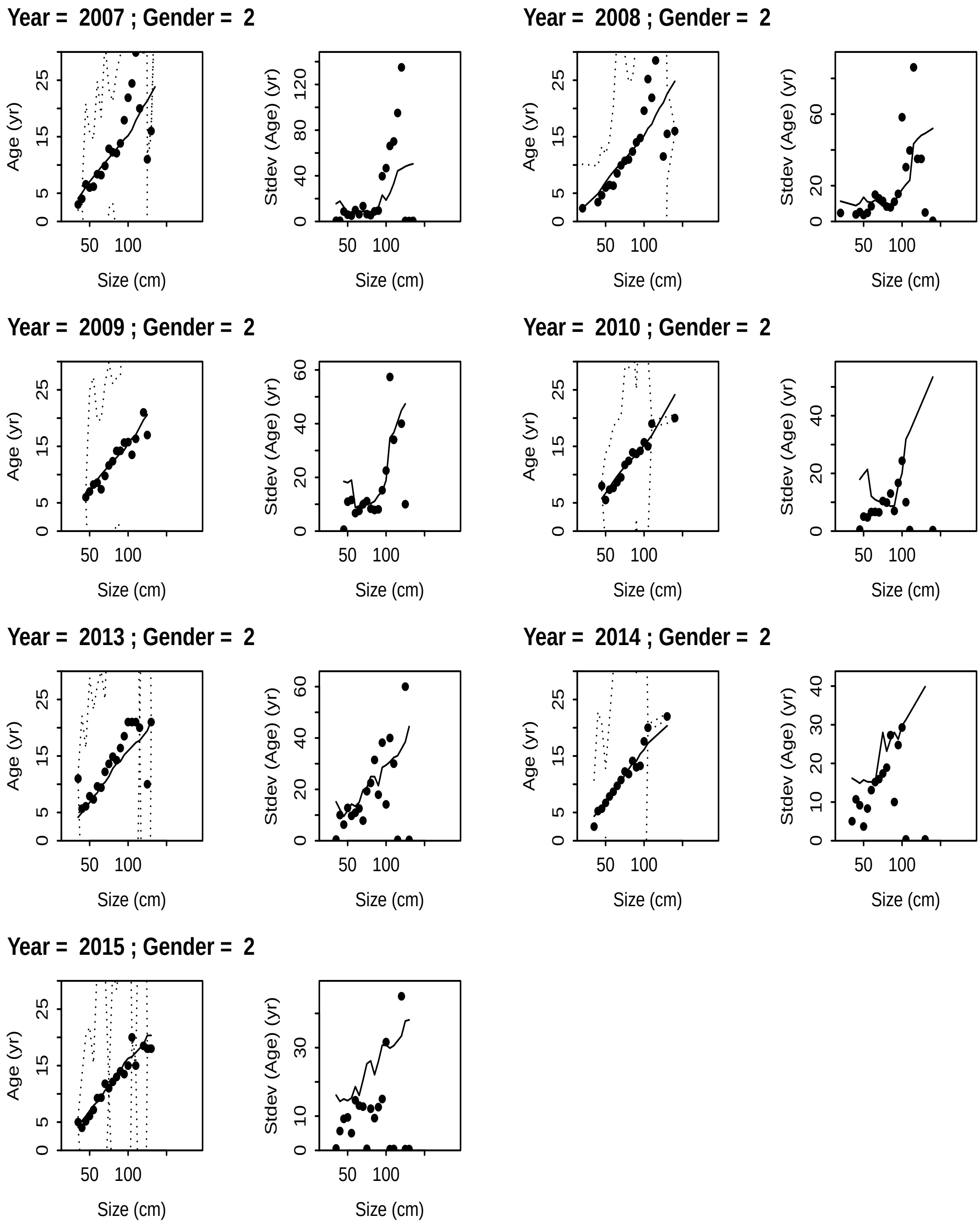

Figure 6.9: Diagnostic plots for the fits to the male (Gender = 2) conditional age-at-length data from 2006. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed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

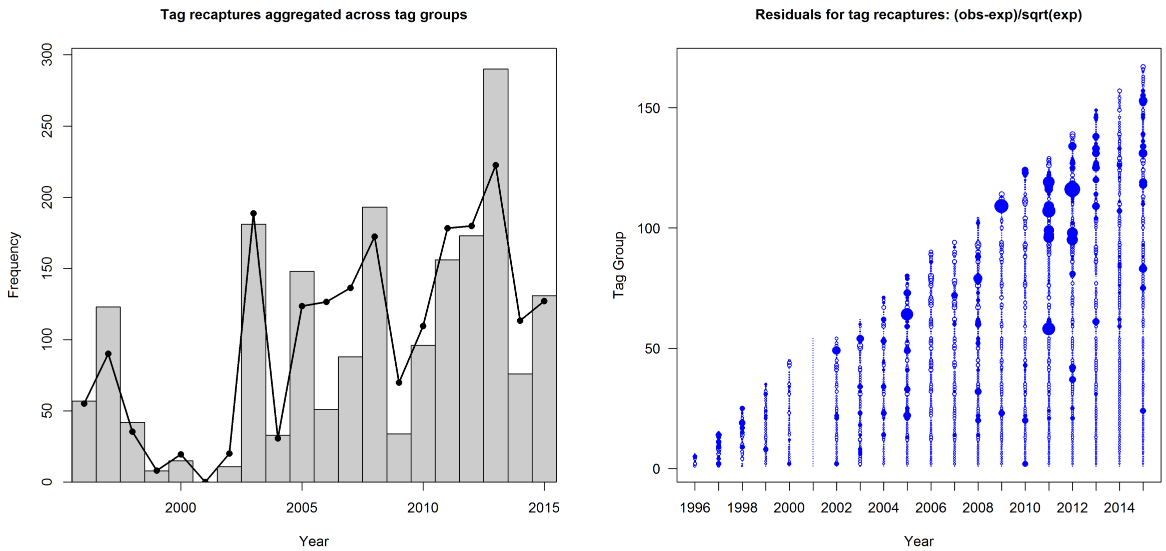

Figure 6.10: Summary of the base case fits to the tag-recapture data. Left-hand panel shows the summed observed (bars) and expected (line) recaptures over years. The right-hand panel shows the residuals by tag group and year (solid blue indicates more recaptures observed than expected).

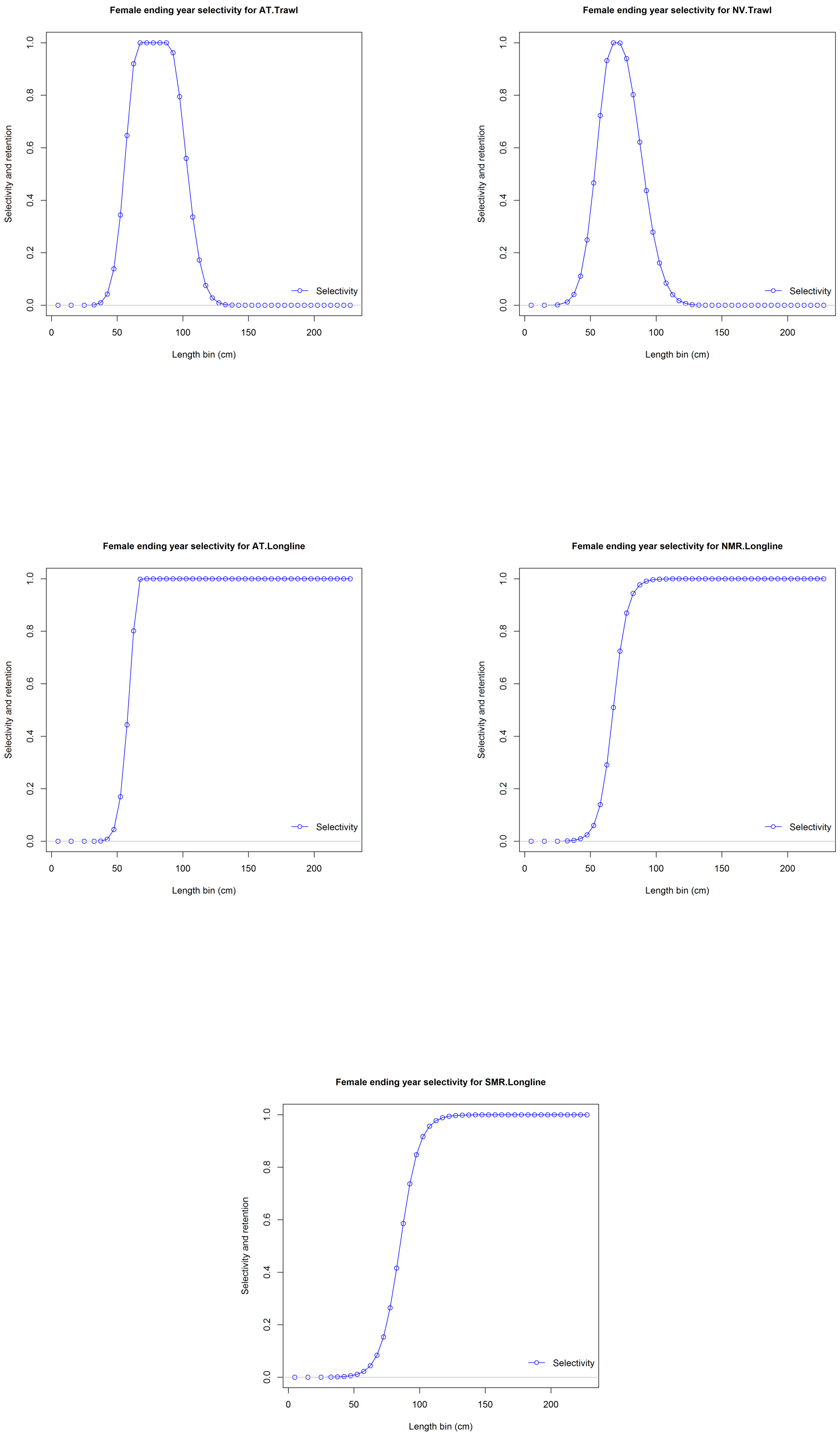

Figure 6.11: Base case estimates of selectivity at length by fleet.

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

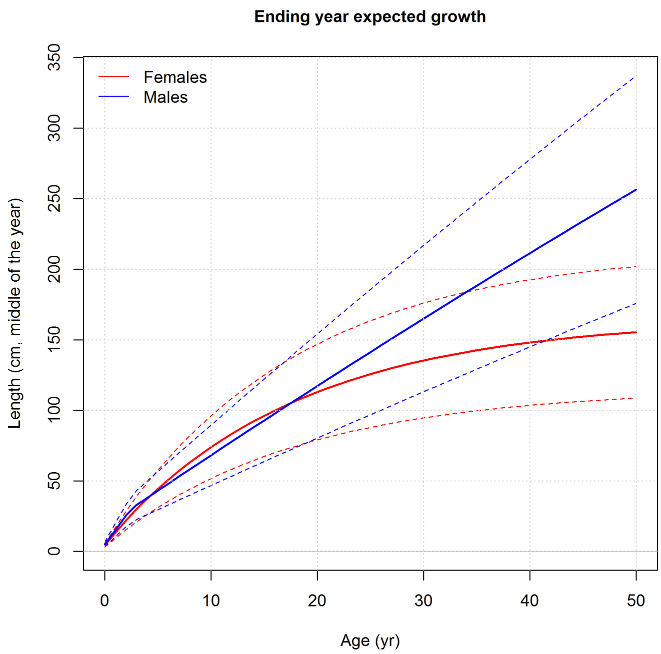

Figure 6.12: The estimated growth curves.

6.3.3 Recruitment

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

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

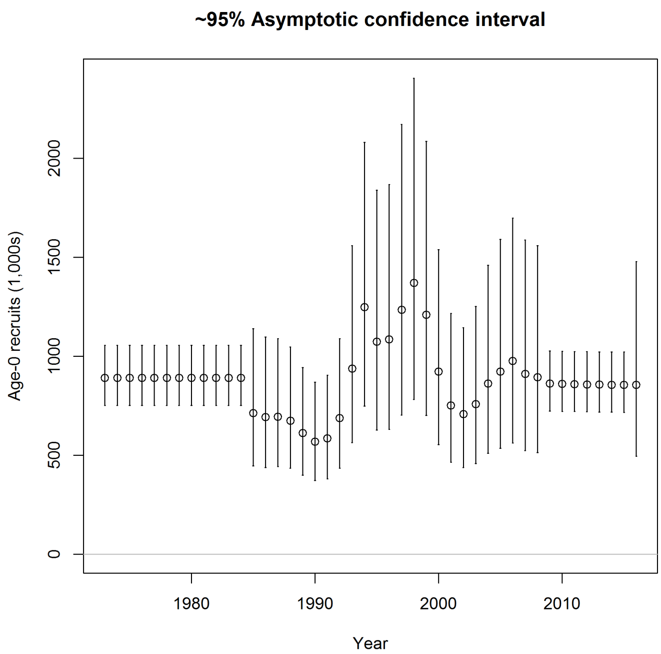

Figure 6.13: Base case estimated recruitment time series (with approximate 95% confidence interval).

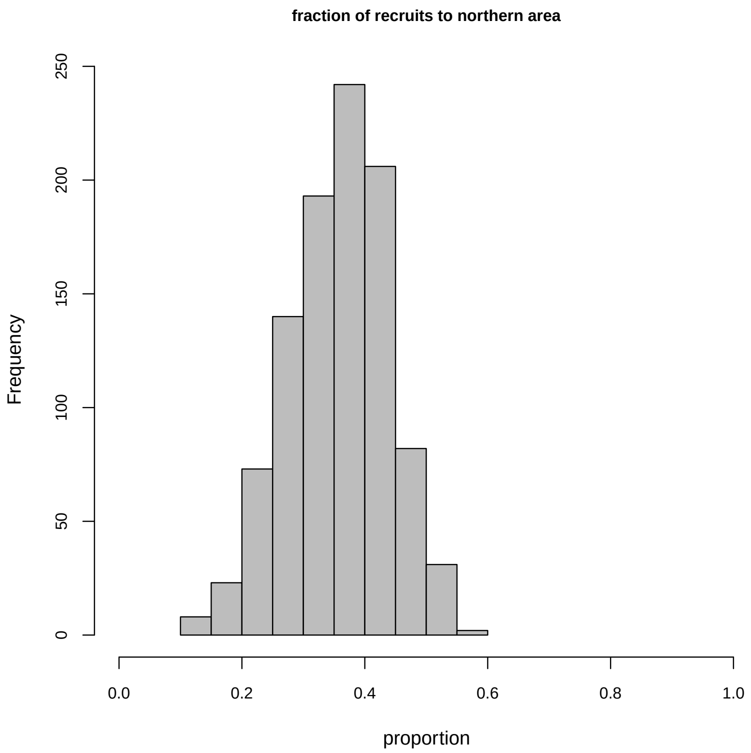

Figure 6.14: Posterior distribution for the proportion of annual recruits allocated to the northern area in the base case model.

6.3.4 Movement

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

6.3.5 Biomass and fishing mortality estimates

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

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

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

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

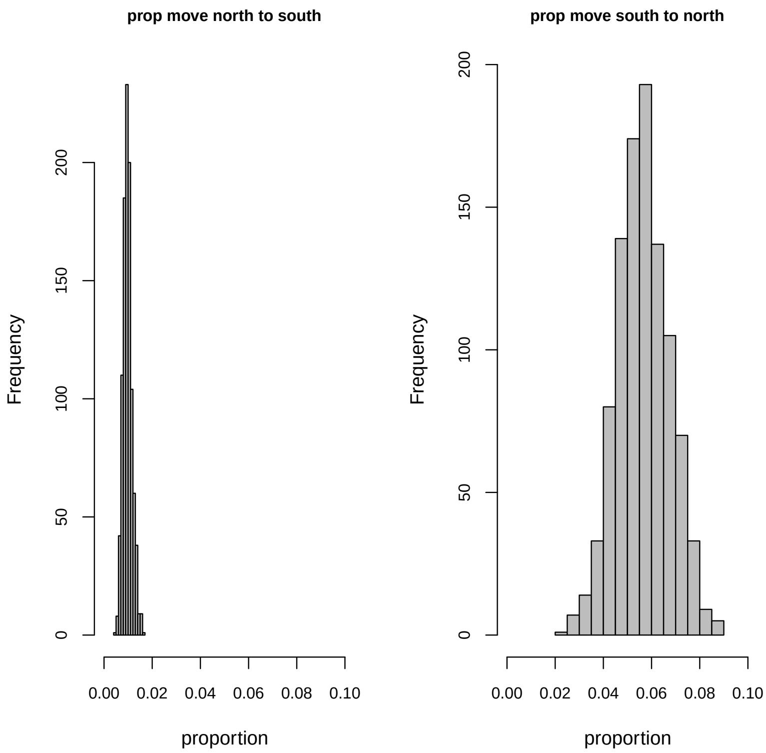

Figure 6.15: Posterior distributions for the values of the movement parameters in the base case model.

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

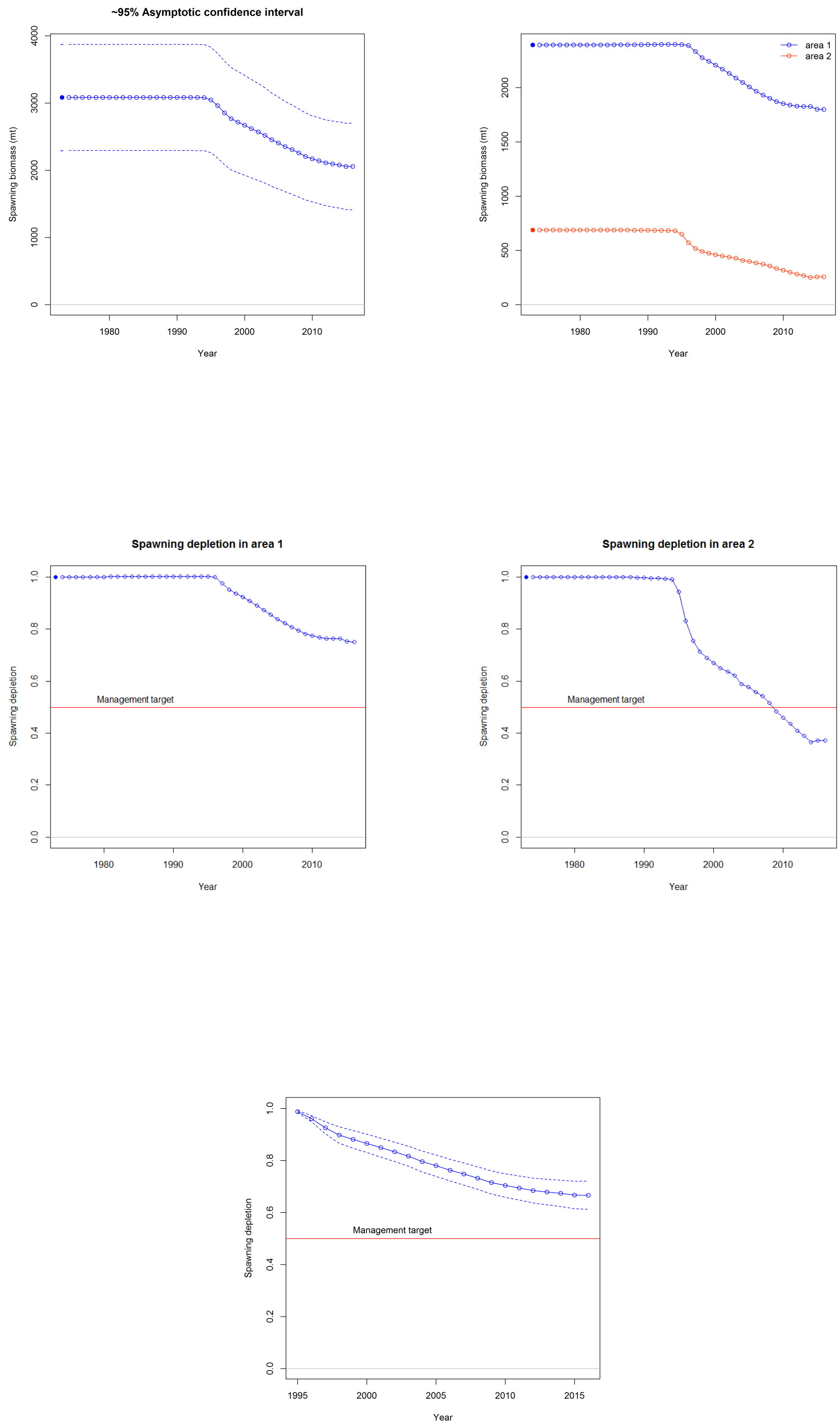

Figure 6.16: Base case estimated time series for female spawning biomass and spawning depletion (spawning biomass relative to unfished), both by area and overall. Area 1 is north, and area 2 is south.

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

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

6.3.6 2015/16 catch levels

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

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

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

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

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

6.4 Sensitivity Analyses

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

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

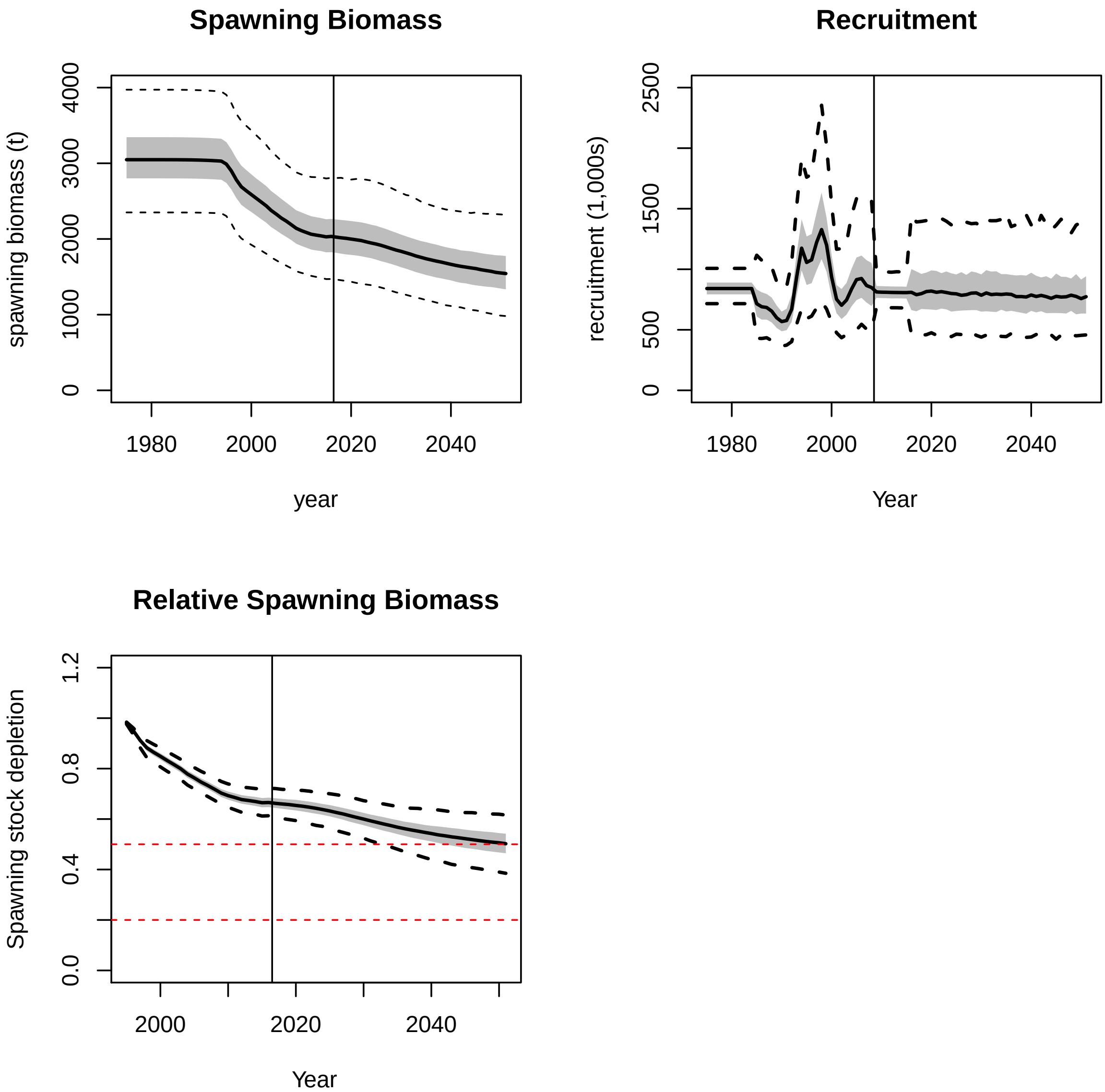

Figure 6.17: Posterior distribution and projection of female spawning biomass, recruitment, and spawning biomass relative to the unfished level, under a constant catch of 450t, split 250t for Aurora Trough, 120t for northern Macquarie Ridge and 80t for southern Macquarie Ridge.

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

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

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

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

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

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

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

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

6.5 Discussion points and future work

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

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

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