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Preliminary stock assessment of the Macquarie Island fishery for Patagonian toothfish (*Dissostichus eleginoides*) using data up to and including August 2018 using Stock Synthesis

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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 2018, but only including conditional age-at-length data until August 2018. 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 1994–2018, and to age-at-length data obtained from aged otoliths (1997–2017). It is an update of the final version of the 2017 assessment (Day & Hillary, 2017). 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 2017 assessment. The base case current female spawning biomass estimate is 70% of unfished at the start of 2019 (69% in 2017). The trend in spawning biomass from 1990–2016 is almost identical to that estimated in 2017, but the estimated magnitude of spawning biomass is about 8% higher in each year, and about 30% higher than the spawning biomass series from the 2016 assessment. The new recruitment estimates from 2010 and 2011 are just below average.

The point estimate for the 2017 stock size in the northern area is estimated to be about twelve times larger than that in the south (female spawning biomass 2,461t and 197t respectively). The northern area is also estimated to be considerably less depleted than the southern area (77% and 32% respectively).

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. The new 2018 length frequency data include an additional 3335 fish in 93 hauls for Aurora Trough Longline, 3045 fish in 104 hauls for Northern Macquarie Ridge Longline and 2464 fish in 76 hauls for Southern Macquarie Ridge Longline. An additional 276 fish from the 2017 catch were aged and these were included as conditional age-at-length data for this assessment. This comprised 186 females and 90 males in 2016.

Additions to the historical recapture information include only one additional tag recapture in 2016 from a fish tagged by the northern valleys trawl fleet in 1998.

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, with only one of these tags recaptured in a different area (south) to its release (north). In addition there were 225, 65 and 431 new tag releases in 2017, with these releases respectively in the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge.

New tag recaptures from the 2018 data included 146, 11 and 61 recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 218

tag recaptures in 2018 from fish tagged in previous seasons with four recaptures in a different area to the release area (all moving from the north to the south). In addition there were 226, 65 and 432 new tag releases in 2017, 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.

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

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

[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

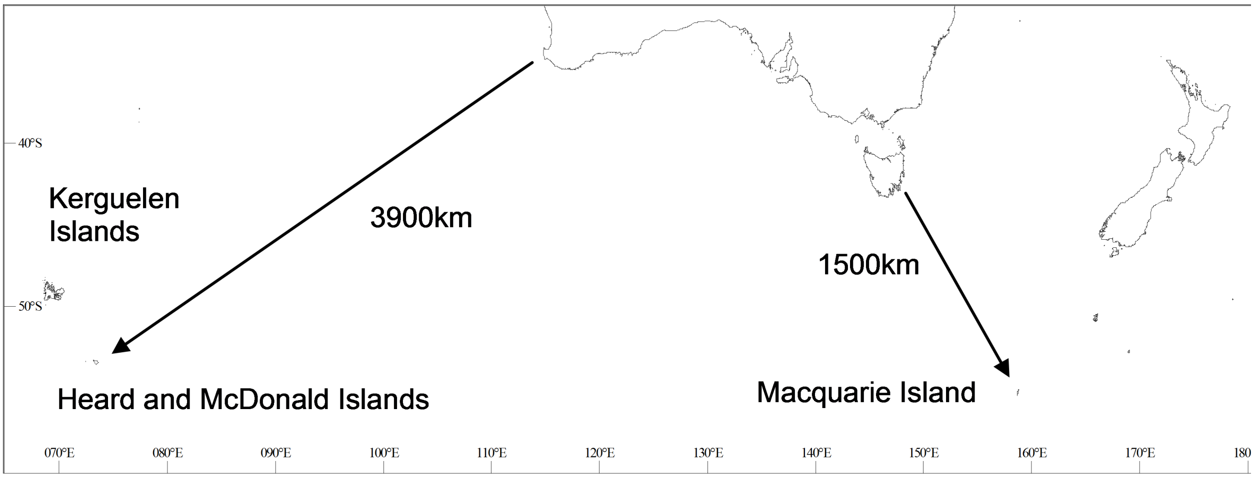

Figure 2.1: The location of Macquarie Island (54° 30'S, 158° 57'E) and Heard Island and McDonald Islands (53 ° 06'S, 73 ° 30'E) relative to New Zealand and Australia.

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

Since 2012/13, a single TAC has been set for the whole of the Macquarie Island region. The 2018/19 and 2019/20 TAC was set at 450t, with a recommendation to catch a little more than half of this total TAC in Aurora Trough (250t), and 60% of the remainder taken from North Macquarie Ridge (120t) and the rest from South Macquarie Ridge (80t). The actual catch in 2017 was around 90t below the TAC, with around 145t more then the recommendation of the catch taken from South Macquarie Ridge, but with much less then the recommended catch taken in the other two regions (Table 3.1). In 2018, the actual catch was within two tonnes of the TAC, with the regional spread of catches close to that recommended in the 2017 assessment 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), 67% for the 2016 assessment (Day *et al.*, 2016) and 69% for the 2017 assessment (Day & Hillary, 2017).

2.4 Modifications to the previous assessment

The following data have been added to the assessment:

1. 2017 and 2018 catches
2. 2017 and 2018 length compositions
3. 2017 and 2018 tag recaptures
4. 2017 age-at-length compositions

Ageing data from 2018 were not made available for this assessment.

3 Data

The data available for model-fitting purposes include length composition data from the fishery (1994–2018), conditional age-at-length data (1996–2000, 2002, 2003, 2005–2010, 2013–2017), 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 earlier assessments comprised the total catch, which included a small proportion of fish that were caught and released (including fish released with tags) as well as fish that were retained. Since the 2017 assessment, the catch data were adjusted to exclude any released fish.

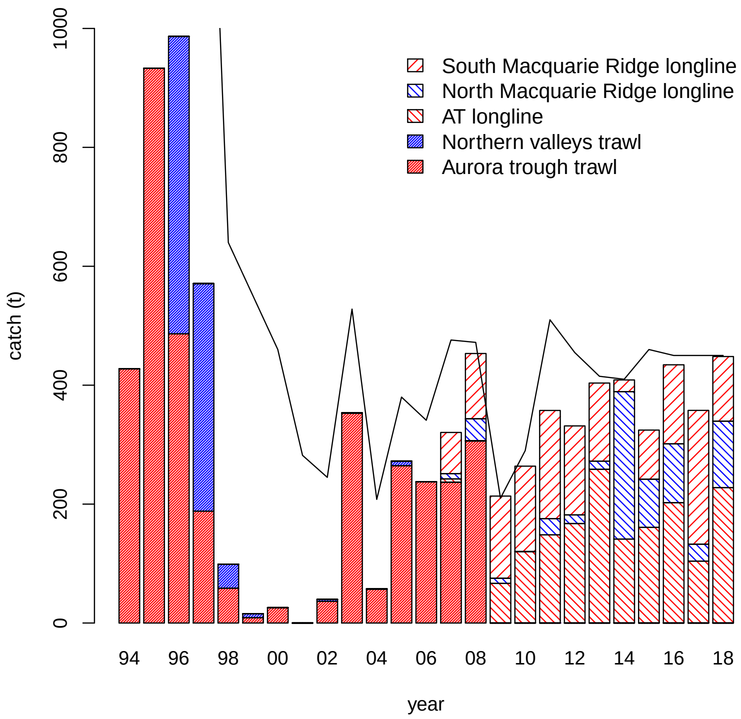

Figure 3.1: Catch history and total TAC by fishing year, with catches stacked by fleet and the grey line representing the combined TAC (with TACs summed for Aurora Trough and Macquarie Ridge from 1996–2011). There were small research quota in the Aurora Trough from 1998-2002 and in 2004. Red coloured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

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

Longline operations in 2017 caught 104t in the Aurora Trough and 254t in the northern and southern Macquarie Ridge areas and in 2018 caught 228t in the Aurora Trough and 220t in the northern and southern Macquarie Ridge areas (Figure 3.1).

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

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

3.2 Length frequency data

Samples of the length composition of the catch were available for all fishing seasons (1994/95 through 2018/19). Each annual length composition is based on the measurement of several hundreds (thousands) of fish (Tables 3.2 and 3.3). However, it is unlikely that the number of fish measured in each year is an appropriate metric of the effective sample size, due to expected high correlations among fish lengths within individual hauls/shots. Thus, when an assessment is done, input sample sizes for the individual length compositions are set at the number of 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
	17/18	66	2254	34
	18/19	93	3335	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
	17/18	57	1368	24
	18/19	104	3045	29
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
	18/19	76	2464	32

3.3 Age data

Age-at-length samples are available from aged fish that were captured in 1996–2000, 2002, 2003, 2005–2010 and 2013–2017 (Table 3.4). New ageing data from 2017 were added this year, but the 2018 conditional age-at-length data was not available in time for this assessment. The input sample sizes for the conditional age-at-length data were set at 10% of the number of otoliths measured.

3.4 Tag recapture data

Between the 1995/96 and 2018/19 fishing seasons, 17,565 Patagonian toothfish were tagged at Macquarie Island, of which 2,443 have been recaptured (Table 3.5, Table 3.6). Fish are still being recaptured from releases in the early years of the fishery (Table 3.5). Of the recaptures in 2017, 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. Of the recaptures in 2018, the longest period between tagging and recapture was for a fish tagged in 2007.

The recapture rates by region in 2017 and 2018 follow similar patterns to those seen in earlier years. 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 and 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. In 2018, 15 fish released in the north were recaptured, with only four of these recaptured in the south. The remaining 203 recaptures from 2018 were of fish which were both released and recaptured in the south.

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
2017	u			0
	f	166	20	186
	m	78	12	90
total		3819	1080	4899

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	16/17	17/18	18/19
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	1
08/09	AT tr	557	71													2	6	12	10	19	6	8	8	1	4
08/09	NV tr	14	51																						
08/09	NMR LL	82	79													2		7		1	1				
08/09	SMR LL	385	79												1	9	9	18	21	11	2	2	2	6	1
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	3
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	2
11/12	AT LL	302	72																10	37	7	7	12	6	3
11/12	NMR LL	116	83																1	2	1	3	2	1	1
11/12	SMR LL	497	78																9	25	4	18	10	9	7
12/13	AT LL	309	78																	37	12	12	6	6	9
12/13	NMR LL	56	89																						1
12/13	SMR LL	302	87																	20		9	3	5	
13/14	AT LL	529	75																		9	26	23	16	12
13/14	NMR LL	36	81																			3			1
13/14	SMR LL	249	81																		9	10	1	10	6
14/15	AT LL	295	72																			9	19	11	13
14/15	NMR LL	499	79																				4		4
14/15	SMR LL	36	80																					2	1
15/16	AT LL	353	76																				17	13	27
15/16	NMR LL	168	79																				2	1	5
15/16	SMR LL	165	80																				12	4	10
16/17	AT LL	445	77																					12	42
16/17	NMR LL	184	84																					1	2
16/17	SMR LL	270	92																					30	4
17/18	AT LL	226	74																						20
17/18	NMR LL	65	79																						1
17/18	SMR LL	432	81																						38
18/19	AT LL	509	74																						
18/19	NMR LL	228	83																						
18/19	SMR LL	184	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	166	1	39
NV trawl	8	72	1	7	6
AT longline	0	0	548	0	60
NMR longline	0	0	2	46	19
SMR longline	1	0	93	5	517

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. The same 180 day period, as first applied to the 2016 assessment, was continued in this current assessment.

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.

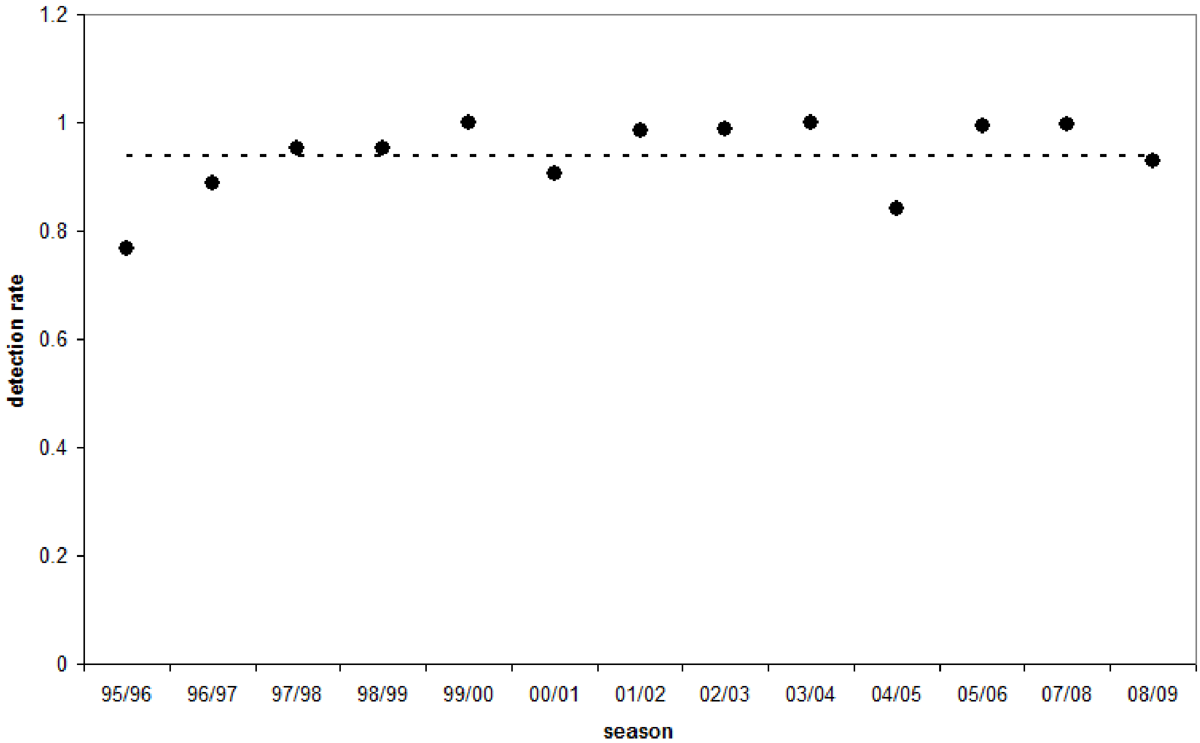

Figure 3.2: Estimated tag detection rate (points) by fishing season (Tuck and Lamb 2009). Dotted line corresponds to the mean detection rate (0.938) over the time series.

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 length data in this assessment include no revisions to historical data prior to 2016. The number of hauls and raw numbers of fish did not change for the 2016 length data, but their were minor updates to the actual length frequency distributions in this year. 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. The new 2018 length frequency data include an additional 3335 fish in 93 hauls for Aurora Trough Longline, 3045 fish in 104 hauls for Northern Macquarie Ridge Longline and 2464 fish in 76 hauls for Southern Macquarie Ridge Longline.

There were no revisions to the historical age-at-length data up to 2016 used in the current assessment. An additional 276 fish from the 2017 catch were aged and these were included as age-at-length data for this assessment. This comprised 186 females and 90 males in 2016.

Additions to the historical recapture information include one additional tag recapture in 2016 from a fish tagged by the northern valleys trawl fleet in 1998. A fish tagged in 1999 in the Aurora Trough was recaptured in 2017. Three individual fish have now been recaptured 18 years after their initial tagging. 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. Of these 158 recaptures, 157 were recaptures in the same area (155 in the south, two in the north), with one recapture in a different area to the release area, providing additional information on movement of individuals between areas. In 2017, the only recapture of fish tagged in one region and recaptured in the other was of a single fish released in the north, tagged by the North Macquarie Ridge Longline fleet, and subsequently recaptured in the south, by the South Macquarie Ridge Longline fleet.

New tag recaptures from the 2018 data included 146, 11 and 61 recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 218 tag recaptures in 2018 from fish tagged in previous seasons. Of these 218 recaptures, 214 were recaptures in the same area (203 in the south, 11 in the north), with four recaptures in a different area to the release area, providing additional information on movement of individuals between areas. In 2018, all four of these recaptures were of fish released in the north, tagged by the North Macquarie Ridge Longline fleet, and recaptured in the south. One fish was recaptured by the Aurora Trough Longline fleet, with the other three 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 2018, there were four fish tagged by Aurora Trough Trawl that were recaptured, three in Aurora Trough and one in Southern Macquarie Ridge. No fish tagged by Northern Valleys Trawl were recaptured in 2018. There were 126 fish previously tagged by Aurora Trough Longline recaptured in 2018, with 118 of these recaptured in the same area as release, with the remaining eight recaptured in the Southern Macquarie Ridge. There were an additional 15 recaptures of longline tagged fish from Northern Macquarie Ridge, with 11 recaptured in the same area as release, one recaptured in Aurora Trough and the remaining three fish recaptured in the Southern Macquarie Ridge. Seventy three fish previously tagged by longline in Southern Macquarie Ridge were recaptured in 2018 with 24 of these recaptured in Aurora Trough and the remaining 49 recaptured in the Southern Macquarie Ridge.

There were 225, 65 and 431 new tag releases in 2017, with these releases respectively in the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge. In 2018, there were an additional 226, 65 and 432 new tag releases, 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	0.21	-0.38
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.

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 a recent value estimated for the Heard Island Patagonian toothfish (M =0.155 yr^{-1}), and of estimating the value for M are also considered.

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

4.3 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

Longline catches listed in the logbooks with the field “Area Name” recorded as “Aurora Trough” are allocated to the Aurora Trough longline fleet. All other longline catches are 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 are allocated to the appropriate trawl fleet with the same geographical division as for the longline, with the southern catches added to the Aurora Trough trawl fleet and the northern catches added to the Northern Valleys trawl fleet.

The Aurora Trough trawl and longline and southern Macquarie Ridge longline fleets are assigned to the southern area in the model (red colours in Figure 3.1), and the Northern Valleys trawl and northern Macquarie Ridge fleets are assigned to the northern area (blue colours in Figure 3.1).

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 1985–2011, 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 1985–2011, 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 2020/2021 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 2020/21 and 2021/2022 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.

Up until the 2016 assessment (Day *et al.*, 2016) the samples on which inference is based were initially generated by running 1,500,000 cycles of the MCMC algorithm, discarding the first 500,00 as a burn-in period and selecting every 1,000th parameter vector thereafter. In the 2016 assessment there were some convergence issues with the MCMC analysis, which required running 2,500,000 cycles of the MCMC algorithm and increasing the thinning to every 2,000th parameter vector after the burn in. This year, the MCMC analysis did not converge, even after 2,500,000 cycles of the MCMC algorithm, so a longer chain was initiated with 4,500,000 cycles, but there was insufficient time for this process to run to completion before this paper was required, due to the long computational requirements.

5.9 2020/2021 catch determination under the CCAMLR control rule

Values for the 2020/21 and 2021/22 catch levels should be calculated under the CCAMLR control rule. The calculated 2020/21 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 are usually conducted using the sample from the posterior distribution, but require the MCMC analysis to converge first. The stochastic projections would incorporate both parameter uncertainty and uncertainty in future recruitment events, in the calculation of the 2020/21 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 2020/21 and 2021/22 catch levels can potentially be calculated for nine different assumptions of how the catch would be distributed between the longline fleet, if the MCMC analysis converges.

6 Results and discussion

6.1 Bridging analysis

Updated recent data were added sequentially to the 2017 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 (2017) and additional length data in 2017 and 2018, enabled two additional years of recruitment to be estimated in the new assessment, with recruitment now estimated up until 2011.

The sequential changes to update the base case model were:

1. update historical data,
2. add 2017 and 2018 catch,
3. add 2017 and 2018 length compositions,
4. add 2017 age-at-length data,
5. add 2017 and 2018 tag data,
6. estimate two additional years of recruitment, up until 2011,
7. iteratively re-weight the likelihood contributions from the length and age compositions and recruitment variability σ_R.

The combined addition of 2017 and 2018 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 changes to both the spawning biomass time series and to the recruitment time series after 2003. However, these changes were largely reversed in the next step with the addition of the 2017 and 2018 tag data, resulting in very similar time series to the 2017 base case. Estimating two more years of recruitment made little difference, as the additional recruitment events were estimated to be only slightly below average.

The model with the revised historical data and all the new 2017 and 2018 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 in 2017, following recommendations from the CAPAM data weighting workshops. Unlike the 2017 assessment, there was little change to either the assessment results or the weighting in the iterative reweighting step.

The 2019 base case model is thus the iteratively re-weighted model with 2017 and 2018 data added, with recruitment now estimated to 2011, 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 fits from 2016 – 2018 are not particularly good.

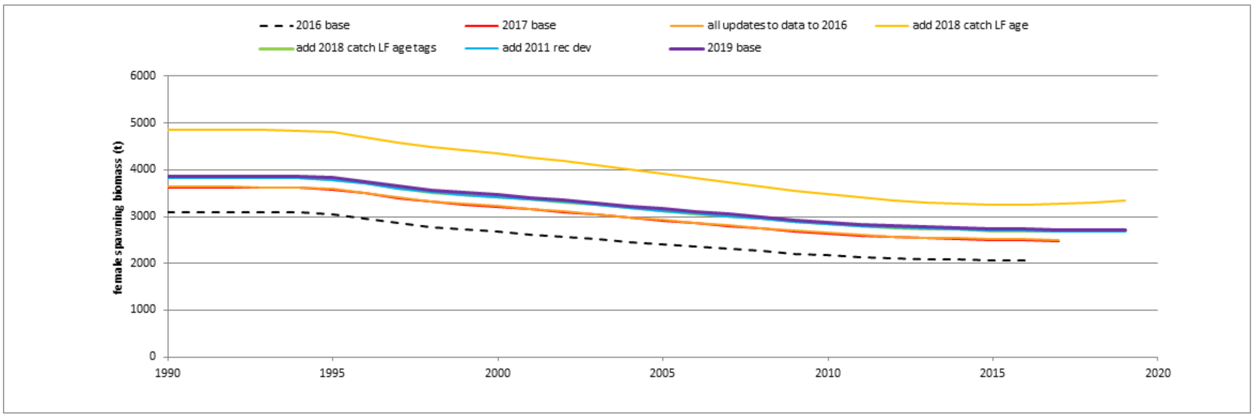

Figure 6.1: Effect on the female spawning biomass trend of sequential updates with the most recent data.

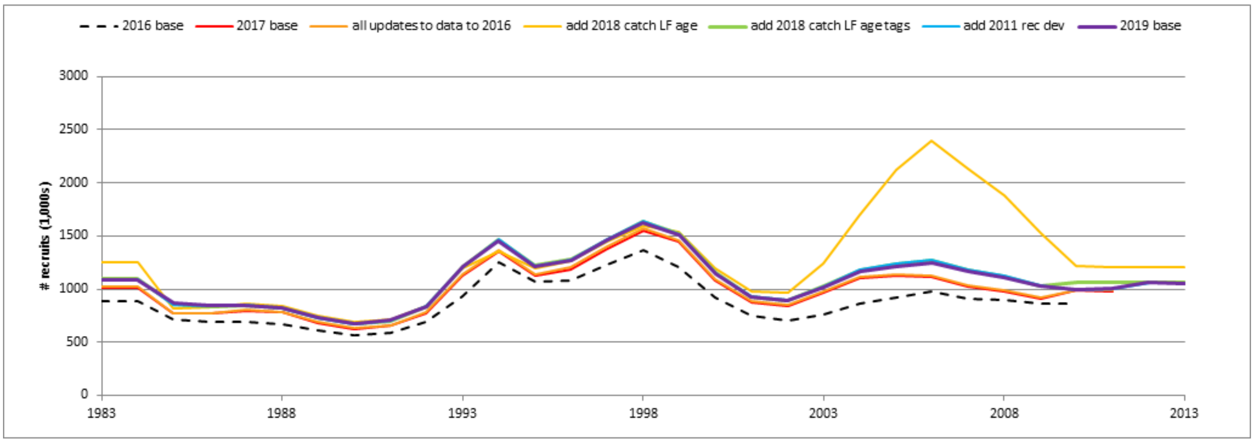

Figure 6.2: Effect on the recruitment estimates of sequential updates with the most recent data.

However, apart from 2017, the fits to the length frequencies from the Aurora Trough longline are excellent since 2012 and the fit to 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).

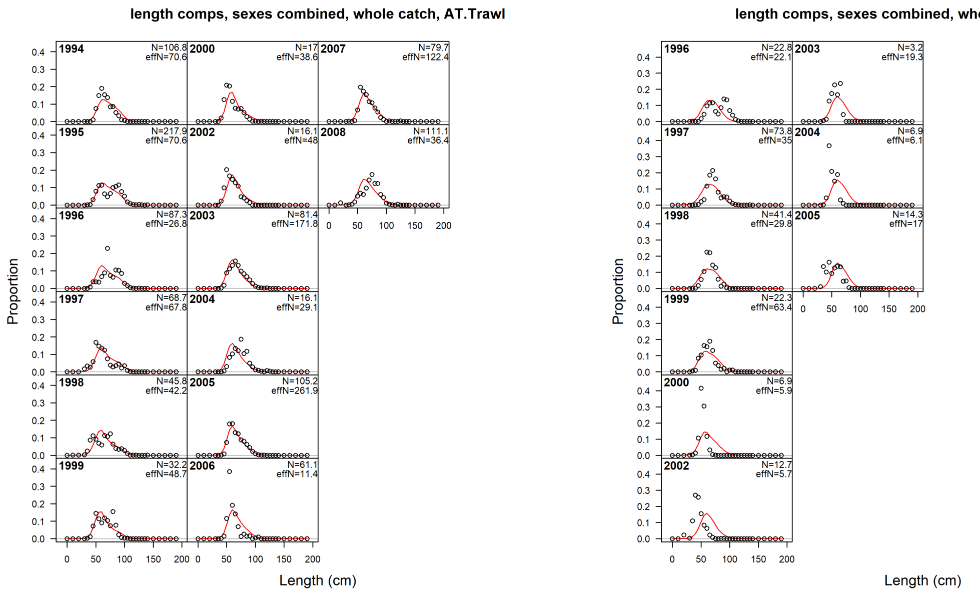

Figure 6.3: Fits to the length composition data for the trawl fleets.

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

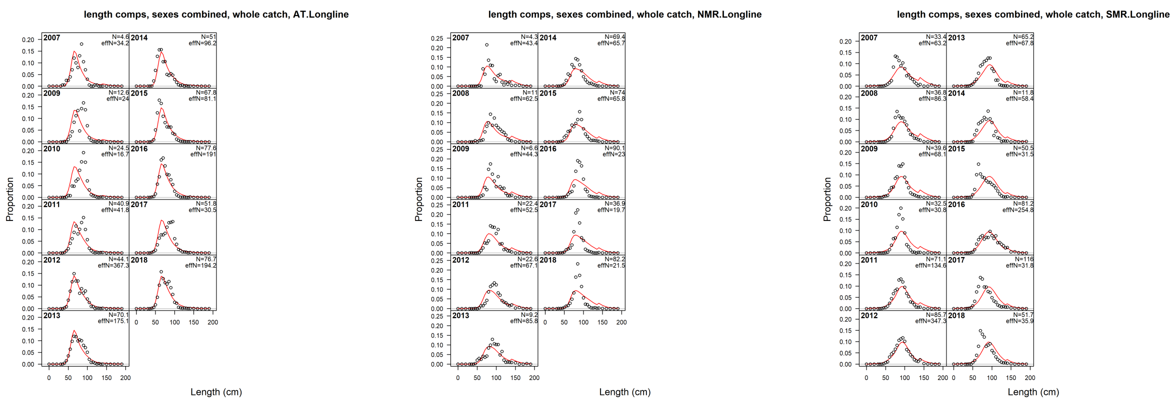

Figure 6.4: Fits to the length composition data for the longline fleets.

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

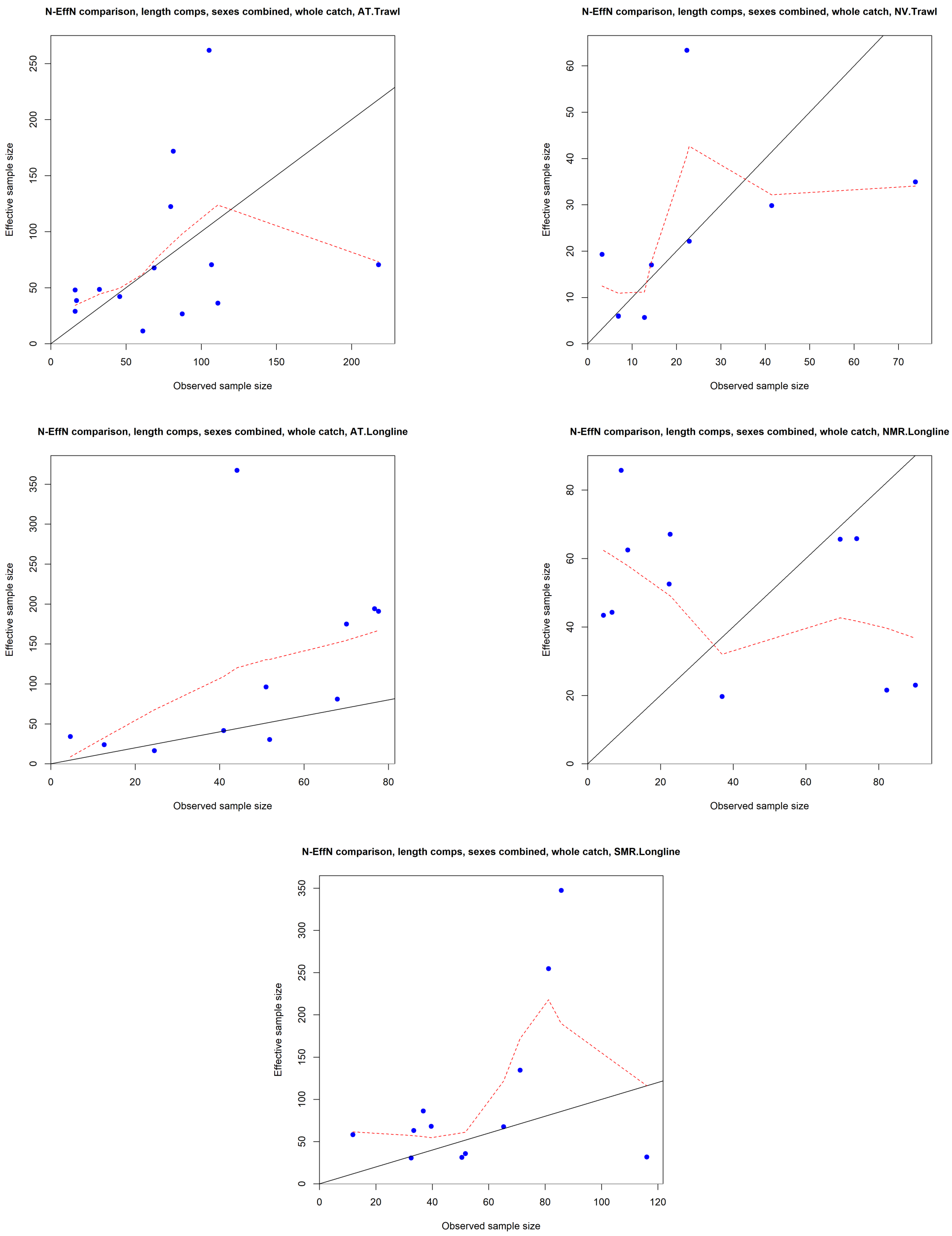

Figure 6.5: Input vs. effective sample size for the length composition data.

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, 6.10 and 6.11) 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 6.12). 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 6.13). 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.

6.3.2 Growth

The estimated growth parameters are shown in Table 4.1, and the estimated growth curves in Figure 6.14. The estimated growth curve for males changed from the 2017 assessment onwards, 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 to inform the estimate of L_∞ for older male fish.

6.3.3 Recruitment

The recruitment pattern (Figure 6.15) 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 2017 assessment. Note that after a run of above average recruitment events in the mid to late 1990s, recruitment was estimated to drop below average in the early 2000s, then returned to slightly above average from 2004 to 2008 and was estimated to be below average in 2009, 2010 and 2011.

The proportion of new recruits allocated to each area is usually very uncertain, with the 95% confidence interval of the proportion recruiting to the northern area ranging from 27–57 % , with a mean of 42% in the 2017 assessment (Day & Hillary, 2017). This calculation requires the MCMC analysis to converge in for the 2019 assessment so is not shown here.

6.3.4 Movement

The estimation of movement rates remains somewhat uncertain. In the 2017 assessment (Day & Hillary, 2017), the movement rate from south to north was estimated to be between 2% and 8% per annum, with

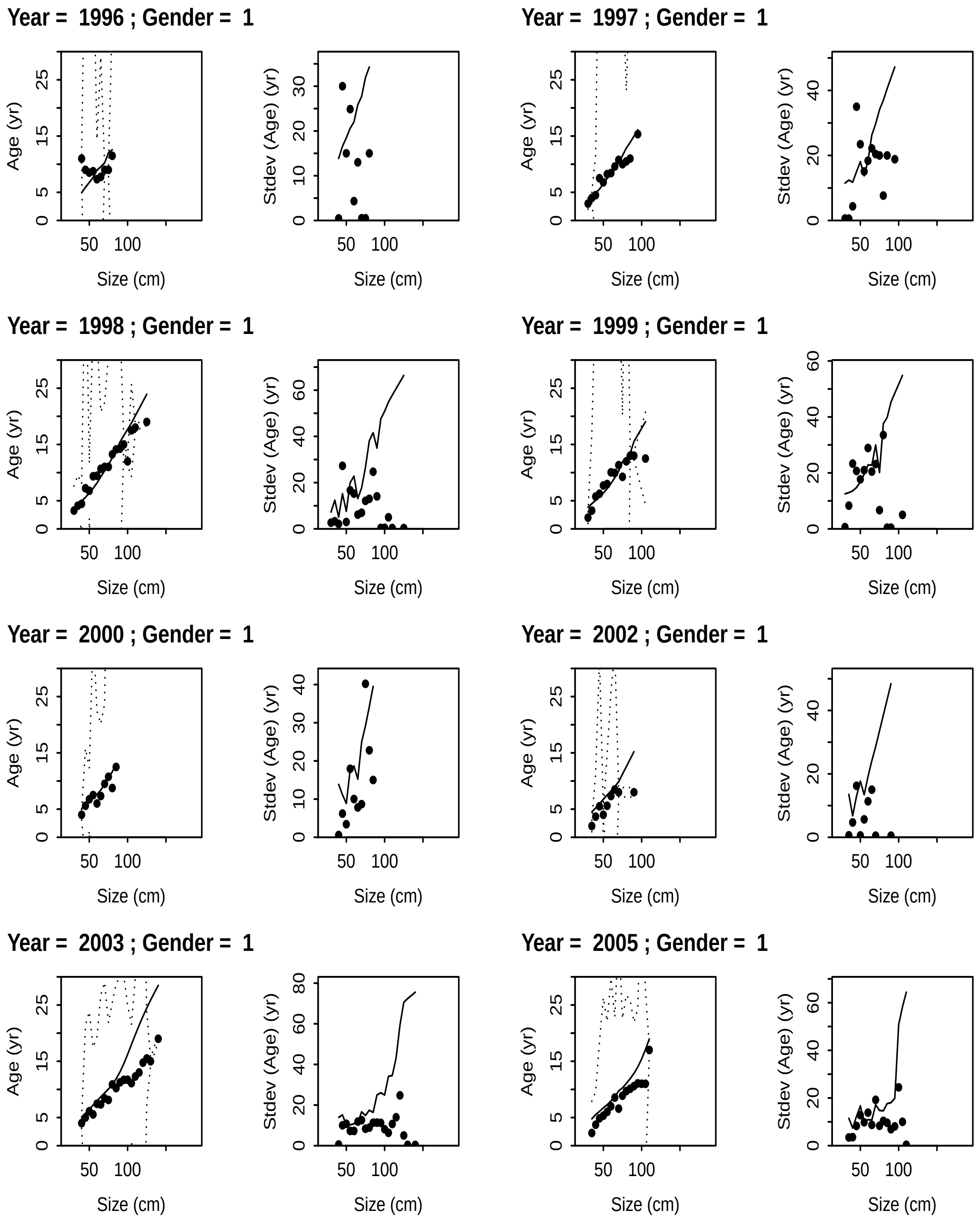

Figure 6.6: Diagnostic plots for the fits to the female (Gender = 1) conditional age-at-length data from 1996 to 2005. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length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

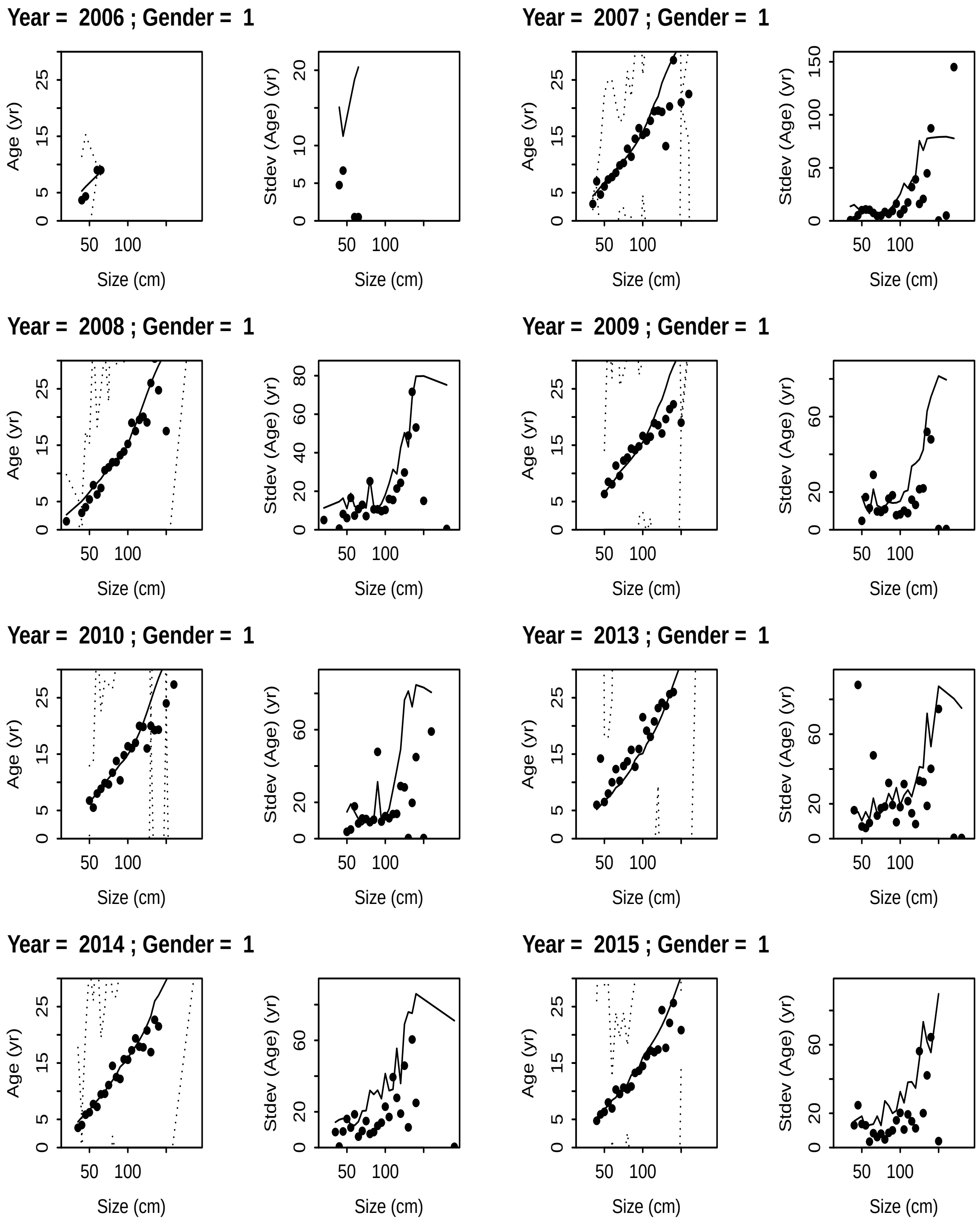

Figure 6.7: Diagnostic plots for the fits to the female (Gender = 1) conditional age-at-length data from 2006 to 2015. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length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

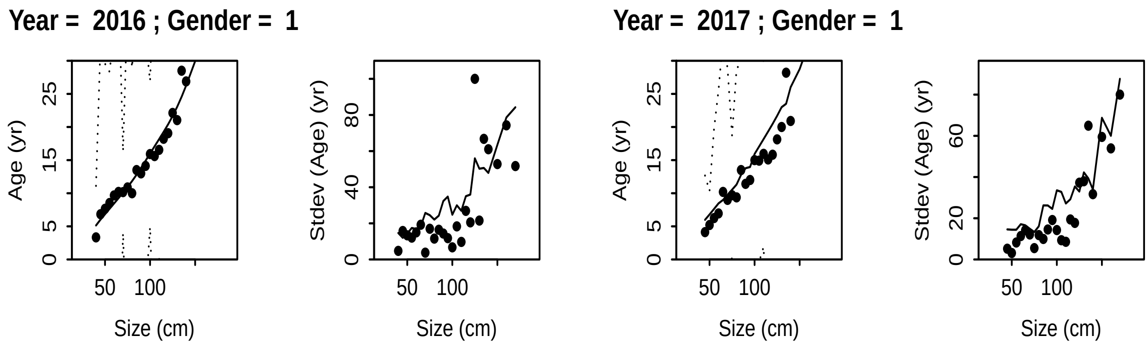

Figure 6.8: Diagnostic plots for the fits to the female (Gender = 1) conditional age-at-length data from 2016 to 2017. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (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.

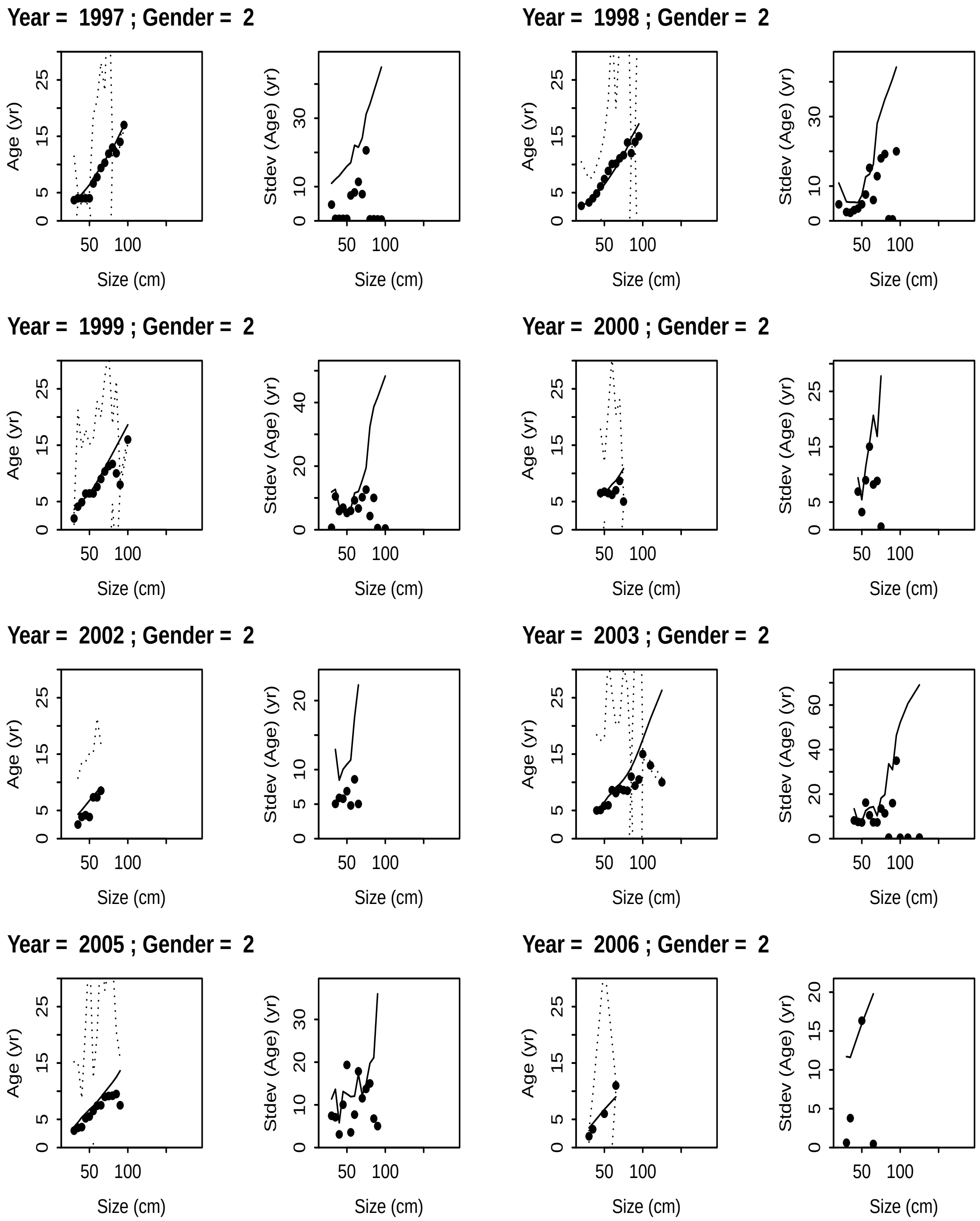

Figure 6.9: Diagnostic plots for the fits to the male (Gender = 2) conditional age-at-length data from 1997 to 2006. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length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

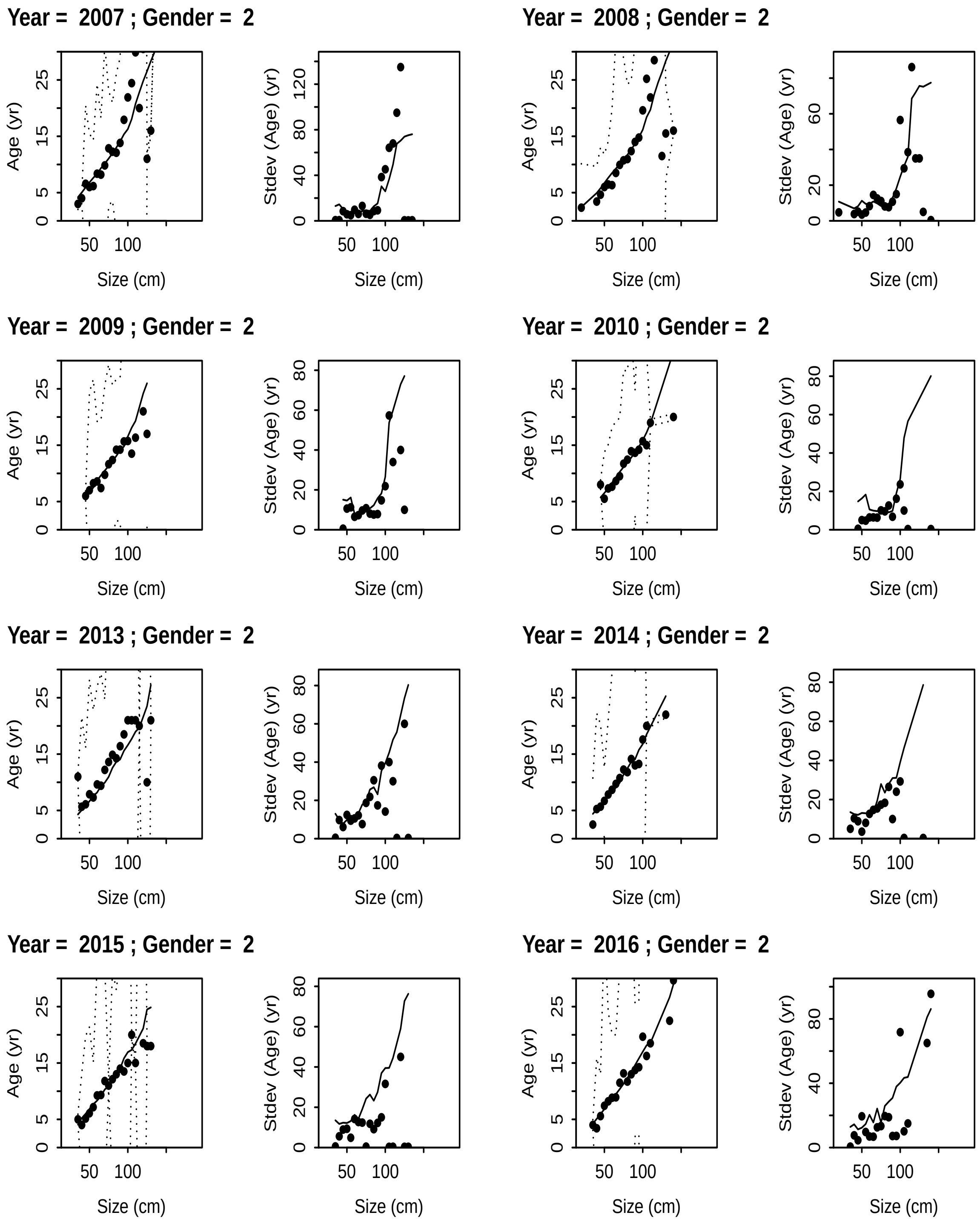

Figure 6.10: Diagnostic plots for the fits to the male (Gender = 2) conditional age-at-length data from 2007 to 2016. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length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

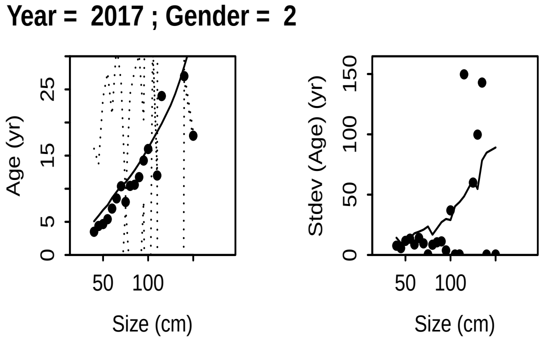

Figure 6.11: Diagnostic plots for the fits to the male (Gender = 2) conditional age-at-length data from 2017. For each year, the two panels are: 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed 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.

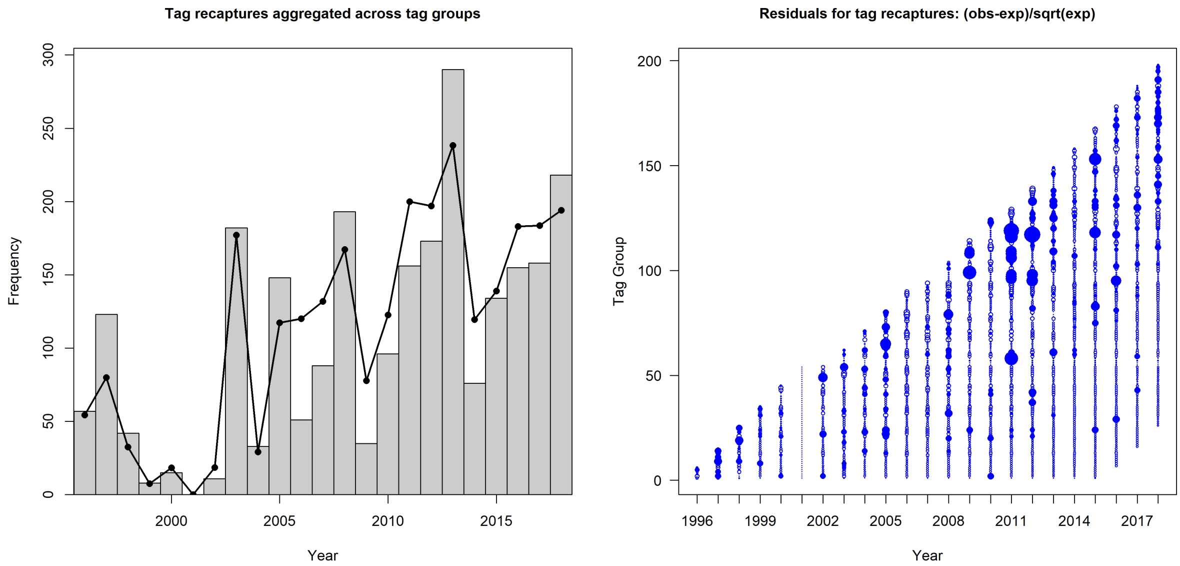

Figure 6.12: Summary of the base case fits to the tag-recapture data. Left-hand panel shows the summed observed (bars) and expected (line) recaptures over years. The right-hand panel shows the residuals by tag group and year (solid blue indicates more recaptures observed than expected).

a lower rate of between 0.7% and 1.4% per annum for north-to-south movement. The updating of these figures for the 2019 assessment cannot be done before the MCMC analysis converges. In any case, more exploration is needed of the interaction of movement parameters with the other components of the model. The 2017 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 lists the models which are usually investigated in the sensitivity analyses.

The base case current spawning biomass estimate is 70% of unfished female spawning biomass (Table 6.1), compared to an estimate of 69% from the 2017 assessment.

The time series of female spawning biomass has declined steadily since the start of the fishery (Figure 6.16), and has stabilised at around 70% of unfished in the last five years or so. 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 2021 stock size in the northern area is estimated to be nearly twelve times larger than that in the south (female spawning biomass 2,461t and 197t respectively). The northern area is also estimated to be considerably less depleted than the southern area (77% and 32% respectively).

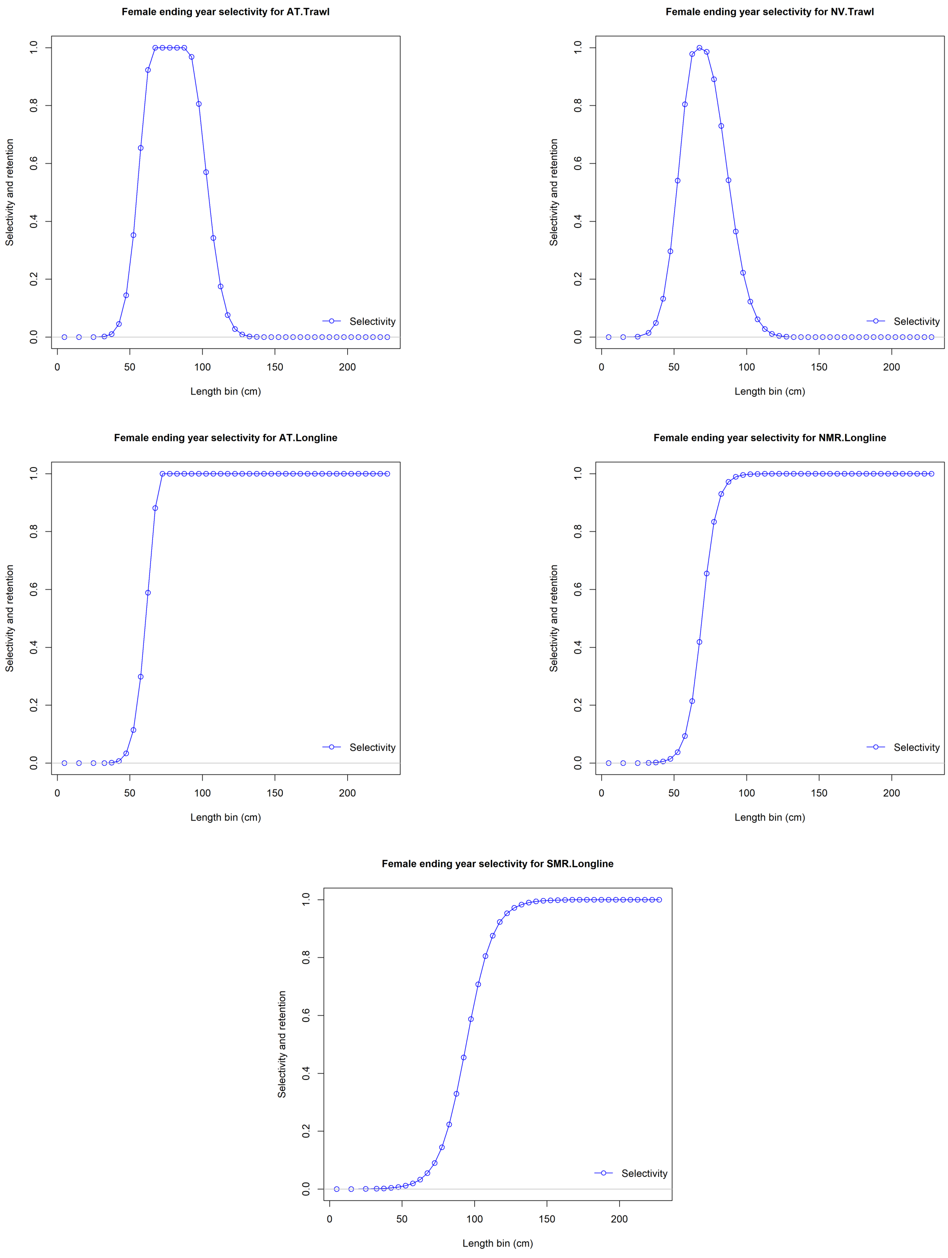

Figure 6.13: Base case estimates of selectivity at length by fleet.

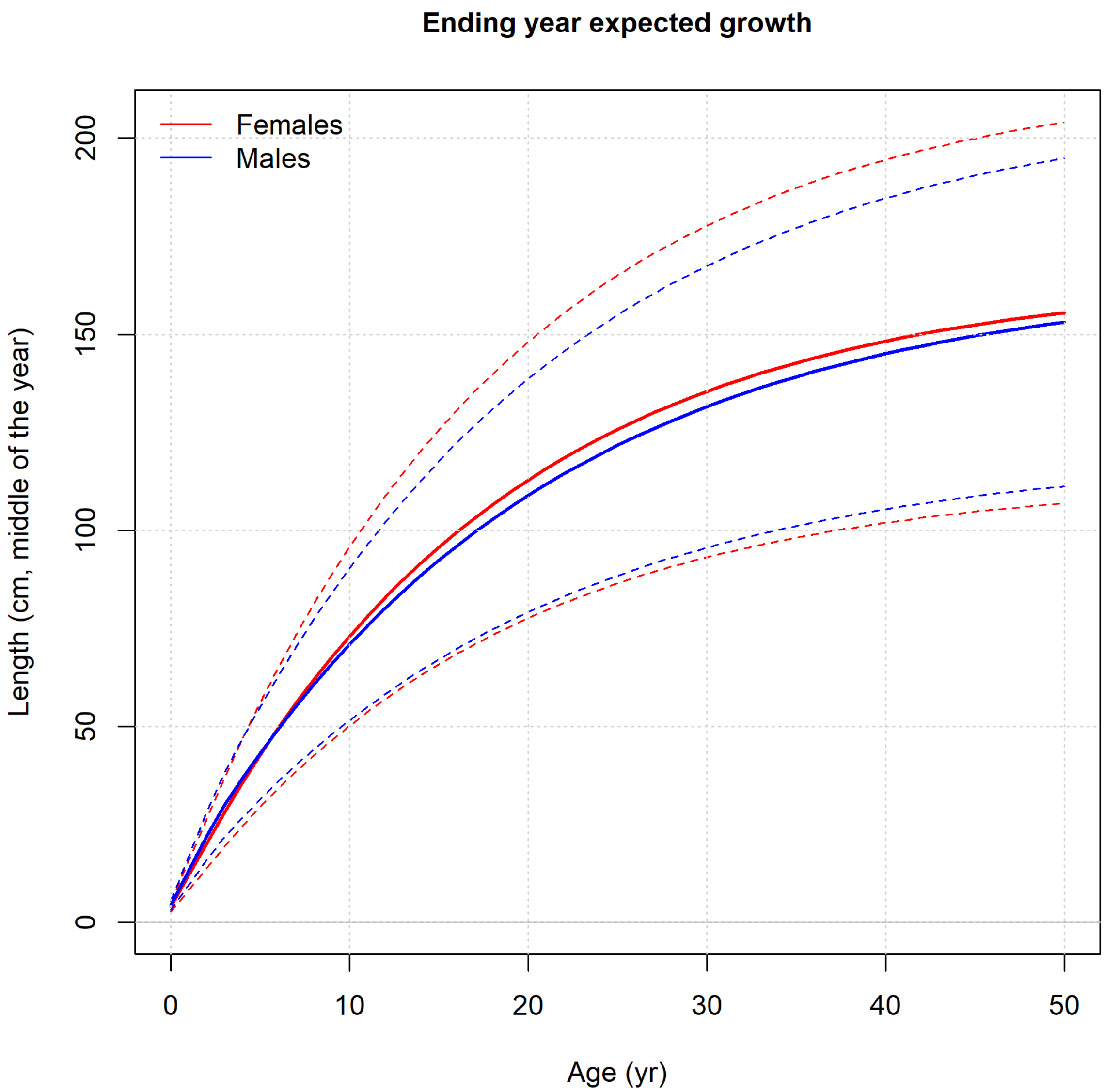

Figure 6.14: The estimated growth curves.

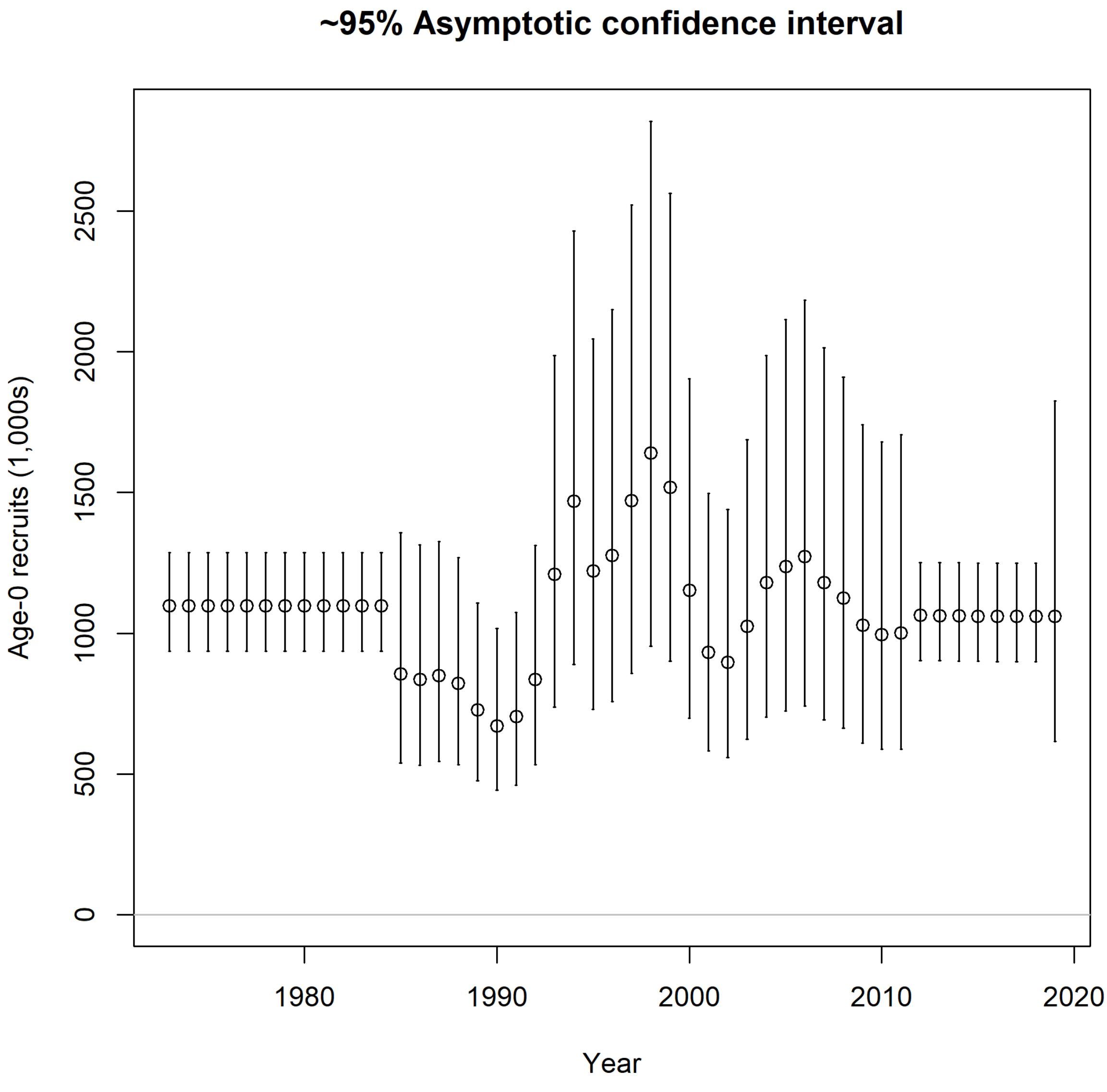

Figure 6.15: Base case estimated recruitment time series (with approximate 95% confidence interval).

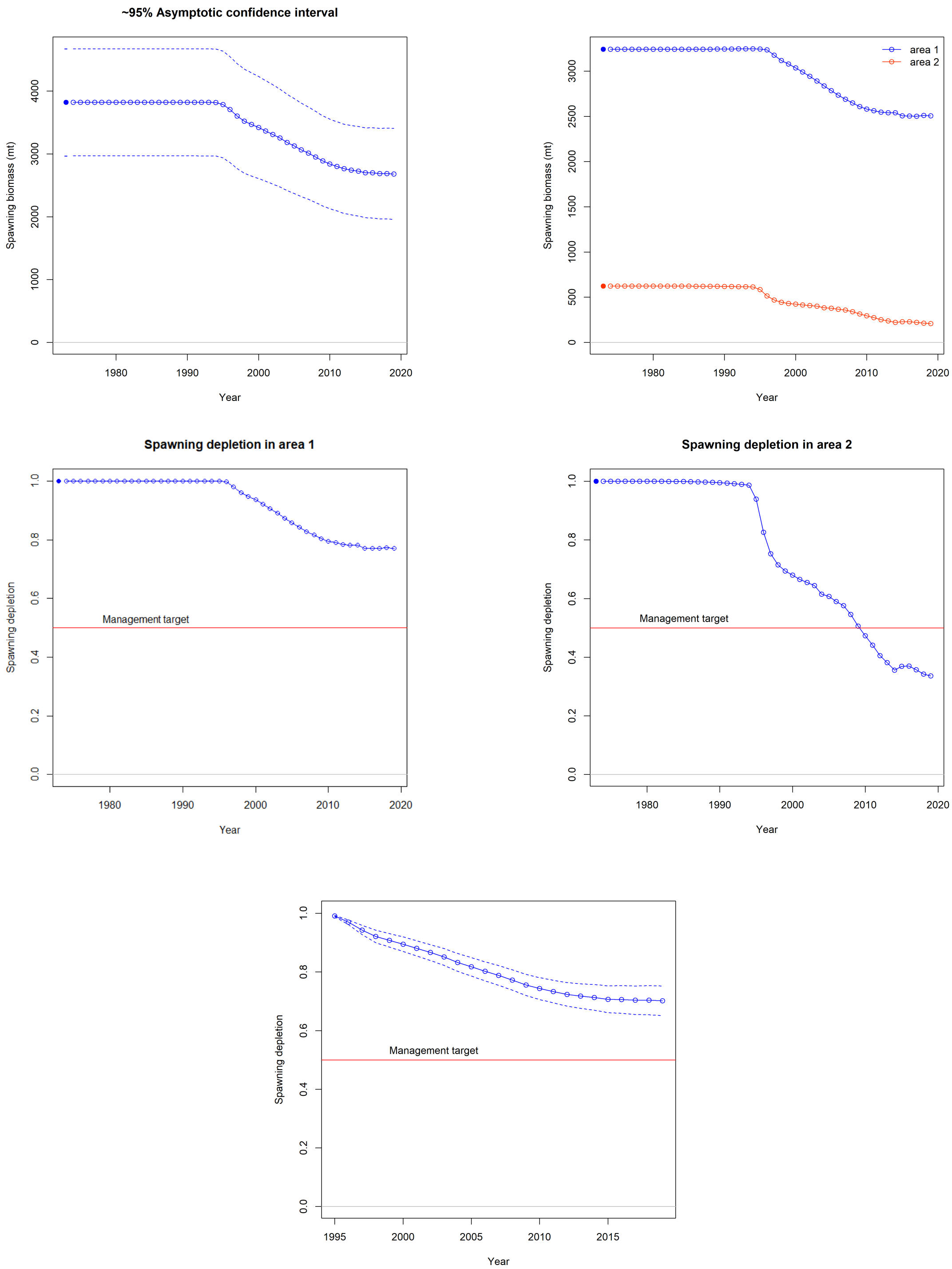

Figure 6.16: Base case estimated time series for female spawning biomass and spawning depletion (spawning biomass relative to unfished), both by area and overall. Area 1 is north, and area 2 is south.

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; 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	$SB_{20/21}$	SB_0	$SB_{20/21}/SB_0$			total	length	age	Tag comp	Tag recap	Recruit
Base case	**2658**	**3821**	**0.70**	**485**	**623**	**3408.1**	**245.2**	**218.9**	**1105.7**	**1861.3**	**-23.1**
fix male L_∞ = 130											
fix male L_∞ = 195											
fix female L_∞ = 195											
fix female & male L_∞ = 195											
$M = 0.155$											
M estimated (0.21)											
$h = 0.5$											
$h = 0.9$											
dome shaped selectivity for NMR & SMR ll											
50% female maturity at 130 cm											
Halve weight on LF data											
Double weight on LF data											
Halve weight on age data											
Double weight on age data											
Halve weight on tag data											
Double weight on tag data											

6.3.6 2020/21 and 2021/22 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 2020/21 and 2021/22 TAC under application of the CCAMLR harvest strategy for toothfish (constant catch that gives a median spawning biomass in 35 years of no less than 50% of unfished spawning biomass, 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. Catches can be calculated for both 2020/21 and 2021/22, to allow a two year RBC to be set while still complying with the CCCAMLR rule.

The usual table of catch levels satisfying the CCAMLR harvest control rule has not been presented in full here, in part due to computational run time and convergence issues with the MCMC runs with the current model. Given there is an alternative model under consideration (Hillary & Day, 2019), these calculations will be completed if required once a decision is made as to which model will be carried forward. The standard list of sensitivities appear in this table indicating the standard

6.4 Sensitivity Analyses

Sensitivity analyses examine the consequences of alternative assumptions to the base case scenario on the model results. The results for the base case are presented in Table 6.1, with a list of the sensitivity tests which are usually reported. The various contributions to the likelihood function are 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.

These sensitivity analyses have not yet been completed, but again given that an alternative model is being considered (Hillary & Day, 2019), it may be better to wait until a decision is made as to which model will be used for management before completing this work. Results of the sensitivities are likely to be very similar to those presented in previous assessments (Day & Hillary, 2017).

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 below 50%.
2. Changes to the spatial distribution of catch in the 2014–2018 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.
4. An alternative model dealing with tagging in a more appropriate manner is worth considering as an alternative to this model (Hillary & Day, 2019).

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References

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

Day, J., & Hillary, R. 2017. *Stock assessment of the Macquarie Island fishery for Patagonian toothfish (Dissostichus eleginoides) using data up to and including August 2016*. Tech. rept. CSIRO technical report and SARAG paper.

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

Day, J., Haddon, M., & Hillary, R. 2015. *Stock assessment of the Macquarie Island fishery for Patagonian toothfish (Dissostichus eleginoides) using data up to and including August 2014*. Tech. rept. CSIRO technical report and SARAG paper.

Day, J., Haddon, M., & Hillary, R. 2016. *Stock assessment of the Macquarie Island fishery for Patagonian toothfish (Dissostichus eleginoides) using data up to and including August 2015*. Tech. rept. CSIRO technical report and SARAG paper.

de la Mare, W.K., & Williams, R. 1997. *Abundance of Patagonian toothfish at Macquarie Island estimated from tagging studies*. Tech. rept. SAFAG paper 97/6.

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.

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

Fay, G., Tuck, G.N., & Lamb, T. 2009a. *Integrated stock assessment for Macquarie Island toothfish using data up to and including July 2009*. Tech. rept. SARAG report.

Fay, G., Tuck, G.N., & Lamb, T. 2009b. Integrated stock assessment for the Aurora Trough Macquarie Island toothfish fishery, using data up to and including 2008/09. *Page 112 of:* Tuck, G.N. (ed), *Stock assessment and management strategy evaluation for sub-Antarctic fisheries: 2007 – 2009*, vol. 63. Hobart: Australian Fisheries Management Authority and CSIRO Marine and Atmospheric Research.

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

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

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

Gelman, A., Carlin, J.B., Stern, H.S., & Rubin, D.B. 1995. *Bayesian data analysis*. London: Chapman and Hall.

Gilks, W.R., Richardson, S., & Spiegelhalter, D.J. 1996. *Markov chain monte carlo in practice*. London:

Chapman and Hall.

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

Hastings, W.K. 1970. Monte Carlo sampling methods using Markov chains and their applications. *Biometrika*, **57**, 97–109.

Hillary, R., & Day, J. 2019. *Proposed new assessment structure for Macquarie Island toothfish using data up to and including 2018*. Tech. rept. CSIRO technical report and SARAG paper.

Mace, P.M., & Doonan, I.J. 1988. *A generalised bioeconomic simulation model for fish population dynamics*. Tech. rept. New Zealand Fisheries Assessment Research Document 88/4, MAFFish Fisheries Research Centre, Wellington.

Methot, R.D. 2010. *User manual for Stock Synthesis 2 (SS2). Model version 3.11a. 159 pp.* Tech. rept.

Methot, R.D., & Wetzel, C. 2013. Stock synthesis: providing a biological and statistical framework for fishery management forecasts across a data-poor to data-rich continuum. *Fisheries Research*, **142**, 86–09.

Tuck, G.N., & Lamb, T. 2009. Abundance estimation and TAC setting for Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island. *Page 112 of:* Tuck, G.N. (ed), *Stock assessment and management strategy evaluation for sub-Antarctic fisheries: 2007 – 2009*, vol. 63. Hobart: Australian Fisheries Management Authority and CSIRO Marine and Atmospheric Research.

Tuck, G.N., & Methot, R.D. 2008. *Progress on the transition of the Macquarie Island Patagonian toothfish assessment to SS3*. Tech. rept. SARAG report.

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

Tuck, G.N., Pribac, F., & Lamb, T. 2006. *An integrated assessment of Patagonian toothfish (Dissostichus eleginoides) in the Aurora Trough region of Macquarie Island: 2006 update*. Tech. rept. SARAG report, AFMA, Canberra.

Wayte, S., & Fay, G. 2013. *Stock assessment of the Macquarie Island fishery for Patagonian toothfish (Dissostichus eleginoides) using data up to and including August 2012*. Tech. rept. CSIRO technical report and SARAG paper.

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

Williams, R. 2011. *Update of the review of data derived from the experimental longline fishery for Dissostichus eleginoides at Macquarie Island 2007-2010*. Tech. rept. AFMA report.

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

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