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Integrated stock assessment for Macquarie Island toothfish using data up to and including 2022

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Contents

1 Summary

This paper presents results from an integrated stock assessment of Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island using data collected up until and including August 2022, but only including conditional age-at-length data until August 2021. 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) harvest control rule.

This assessment uses Template Model Builder (TMB) and fits to data obtained from the tag-recapture program since 1995, to length composition information from 1994–2022, and to age-at-length data obtained from aged otoliths (1997–2021). It is an update of the 2021 assessment [1]. The assessments are based on a length-age structured population dynamics model, with maximum likelihood and Bayesian methods used to fit the available data.

The model designates five fleets: Aurora Trough trawl (ATT); Northern Valley trawl (NVT); Aurora Trough longline (ATL); Northern Macquarie Ridge longline (NMRL); and Southern Macquarie Ridge longline (SMRL). Fits to the length composition data are acceptable and the fits to the age-at-length data are good. The model fits the tag-recapture data well, with good accord between the total number of expected recaptures from both the release or recapture year perspective. There is some spatial divergence in the most recent years (over-predicting returns in the North and under-predicting them in the South) that may be linked to spatial recruitment trends but nothing outside the predictive distribution. The assessment presented here estimates a lower female spawning stock biomass (SSB) stock status of 0.73 (0.66–0.81 95% credible intervals) than the 2021 assessment (median of 0.85 with 0.78–0.92 95% credible intervals). Average recruitment is almost identical to the previous assessment and the most recent recruitment estimates remain above average, albeit highly uncertain.

The two new years of length frequency data include an additional 7,704 fish in 225 hauls for Aurora Trough Longline, 2,405 fish in 92 hauls for Northern Macquarie Ridge Longline and 5,377 fish in 172 hauls for Southern Macquarie Ridge Longline. The remaining length frequency data were amended to ensure that no lengths from tagged fish were included as these may bias length frequency distributions since they were not randomly sampled. New conditional age-at-length data were also available for 2020/21 and 2021/22, with an additional 66 ages in the north and 106 ages in the south in 2020/21 and 40 ages in the north and 150 ages in the south in 2021/22. Age data from 2022/23 were not available for inclusion in this assessment.

New tag recaptures from the 2021/22, and 2022/23 data included 234, 14 and 168 recaptures respectively by the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge Longline fleets. This makes a total of 416 tag recaptures. Fourteen of these involved recaptures of a tag in a different area to its release, with eleven of these fish moving from north to south and four fish moving from south to north. In addition there were 533, 50 and 355 new tag releases in 2021/22 in the Aurora Trough, North Macquarie Ridge and South Macquarie Ridge respectively, and 606, 73 and 247 new tag releases in 2022/23 in those same regions.

The recommended TACs range from 451 to 473 t with an average of 459 t, a 13% decrease from the 2021 average of 644 t. This is driven by a lower stock status estimate compared to that in 2021.

2 Introduction

2.1 Patagonian toothfish

The Patagonian toothfish (*Dissostichus eleginoides*) 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.

Patagonian toothfish have been known to grow to over 2 m in length and may live to more than 50 years of age. They inhabit depths from approximately 300 m to 2,400 m, 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. Patagonian toothfish are believed to reach sexual maturity at around 10 years of age, and possibly older for Macquarie Island fish [3, 4].

Patagonian toothfish lack swim-bladders so often reach the surface in good condition even though they may have been caught from depths of 2,400 m. This has allowed the development of an extensive tagging program 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 [5, 6].

2.2 The fishery

Bottom-set longline and trawl fisheries for the Patagonian toothfish developed in the waters of several of the Southern Ocean's sub-Antarctic islands during the late 1980s and early 1990s. At this time trawl fisheries for toothfish were established within Australian Commonwealth waters around HIMI and Macquarie Island, however longling has become the predominant fishing methods since around 2009.

Macquarie Island lies approximatly 1,500 km to the southeast of Tasmania (Figure 2.1). The fishery off Macquarie Island began in November 1994. Two major trawl fishing grounds have been discovered: Aurora Trough and the Macquarie Ridge Northern Grounds region. A tagging experiment began in 1995/96 within the Aurora Trough and the following season within the Macquarie Ridge region.

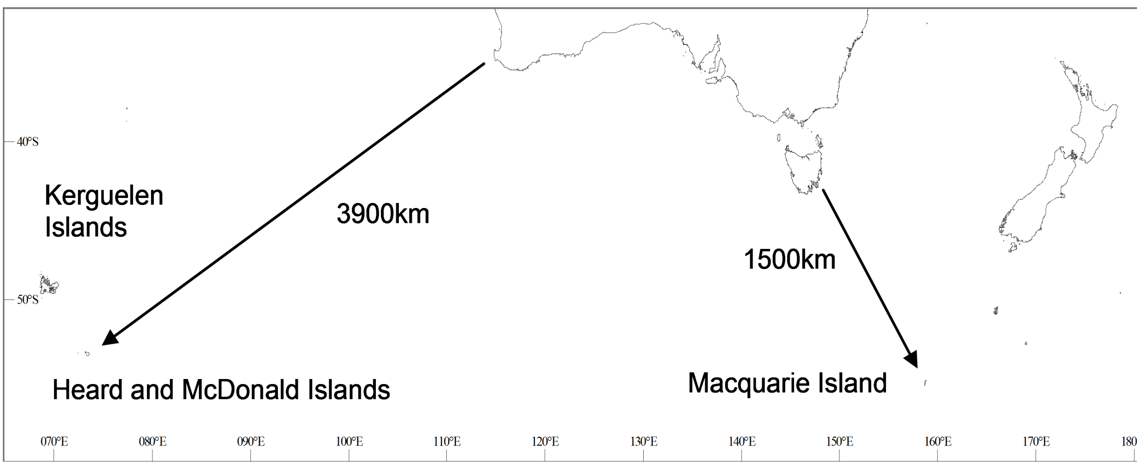

Figure 2.1: *The location of Macquarie Island (54° 30'S, 158° 57'E) and Heard Island and McDonald Islands (53 °06'S, 73 °30'E) relative to New Zealand and Australia.*

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 200 t for the 1996/97 and 1997/98 fishing seasons respectively, and were zero after the 1997/98 fishing season (but with a 40 t research TAC to continue the tagging experiment and monitoring). In 2003/04, following indications of improved stock status from the assessment, Aurora Trough was re-opened to commercial fishing with a 354 t TAC. 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 (Table 2.1).

For the Macquarie Ridge sector, the annual trawl TAC reduced steadily in the years following the 1,500 t TAC of 1998. However, the TACs between 1998/99 and 2006/07 were allowed to increase within the fishing season if the catch rates exceeded 10 t/km^2 over three consecutive fishing days. If this catch rate dropped below the trigger level, then the TAC fell to the lower TAC. If the lower TAC had been reached then fishing ceased.

In July 2007 the AFMA Board agreed to the commencement of longline fishing for Patagonian toothfish in the Macquarie Ridge sector of the MITF for a trial period of three years, with annual reviews, and subject to conditions and specific limits for incidental mortality of seabirds. In 2009, the Aurora Trough quota was also taken by longline. Longline fishing continued for the 2010/11 season, with continued high catch rates in both the Aurora Trough and Macquarie Ridge Sectors. Tagging rates have been high, and there have been longline recaptures of fish tagged in the trawl fishery. Since 2009/10 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 450 t, with a recommendation to catch a little more than half of this total TAC in Aurora Trough (250 t), and 60% of the remainder taken from North Macquarie Ridge (120 t) and the rest from South Macquarie Ridge (80 t). The actual catch in 2017 was around 90 t below the TAC, with around 145 t more than the recommendation of the catch taken from South Macquarie Ridge, but with much less than 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 (Table 3.1). This was the second largest catch by longline in North Macquarie Ridge up until 2018, indicating that considerable effort was made to match the recommended spatial distribution of catches, particularly in the north (Table 3.1). In both 2019/20 and 2020/21, the actual catches were close to the TAC, and the catches in North Macquarie Ridge were even higher than the 2018/19 North Macquarie Ridge catch in both years, ensuring good representation of the catch between northern and southern regions. In the two most recent years catches were below the combined TAC and this divergence increased in 2022/23, where the catch was around 200 t below the TAC. In these two years the proportion of catch taken in North Macquarie Ridge have also fallen substantially (Table 3.1).

2.3 Previous assessments

Prior to 2010, TAC determination for the Macquarie Island Patagonian toothfish stock had been based on stock assessments using the tag-recapture model developed initially by de la Mare and

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]	
20/21	15 Apr 2020 – 14 Apr 2021	555[e]	
21/22	15 Apr 2021 – 14 Apr 2022	555[e]	
22/23	15 Apr 2022 – 14 Apr 2023	635[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

Williams [7], and modifications described in Tuck *et al.* [6]. 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 [8]. In 2004, a new model that expanded upon the traditional tag-based model was introduced [9]. 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 [10, 11]. 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 [12].

The 2010 Aurora Trough assessment base case model estimated the 2010/11 female spawning stock biomass (*SSB*) to be 2,004 t or 54% of unfished spawning biomass [12]. 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 140 t, based on projections under the CCAMLR harvest control rule. The TAC for 2010/11 season for the Macquarie Ridge sector was set at 150 t, 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 [11, 13]. 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 *SSB* was around 64% of unfished conditions, with the spatial models suggesting a slightly less depleted stock, with 2010/11 *SSB* being 67% and 72% of unfished equilibrium respectively. The time series of *SSB* 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 [15, 16]. The Aurora Trough assessment estimated 2011/12 female SSB to be 58% of unfished conditions, while the two area model estimated the 2011/12 *SSB* for the whole of Macquarie Island to be 72% of unfished. The projected catches that met the CCAMLR harvest control rule were 150 t from Aurora Trough and 360 t 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 *SSB* for the whole of Macquarie Island to be 70% of unfished *SSB* [17], the 2013 assessment estimated the 2013/14 female *SSB* for the whole of Macquarie Island to be 69% of unfished [18], with further estimates of 68% for the 2014 assessment [19], 69% for the 2015 assessment [20], 67% for the 2016 assessment [21] and 69% for the 2017 assessment [22].

The 2019 assessment initially estimated the 2019/20 female *SSB* for the whole of Macquarie Island to be 70% of unfished [2] using the same model structure as [22], but with the assessment in TMB rather that Stock Synthesis. However, this estimate for 2019/20 female *SSB* was subsequently revised to 85% using an updated maturity curve [23], prior to setting the TAC. The change from Stock Synthesis to TMB was made to allow for improved incorporating of tag data in the assessment. The 2021 assessment again performed the assessment using TMB and estimated the 2021/22 female *SSB* to be 85%, the same as the 2019 assessment.

2.4 Modifications to the previous assessment

The following data have been added to the current assessment:

1. 2021 and 2022 catches
2. 2021 and 2022 length compositions
3. 2021 and 2022 tag recaptures
4. 2020 and 2021 age-at-length compositions

Ageing data from 2022 were not made available in time for inclusion in this assessment.

3 Data

The four primary data inputs to the model are:

1. **Catch**: in tonnes, per fleet, (1994–2022)
2. **Length frequency**: for each fleet, and using the number of hauls (not fish sampled) as the initial sample size, (1994–2022)
3. **Conditional age-at-length**: for each fleet and sex, we have the number of fish of a given age conditional on the length class samples came from, (1996–2000, 2002, 2003, 2005–2010, 2013–2021)
4. **Tagging data**: release events are now characterised by a length class and area of release, with recapture data being subsequent total recaptures (across all recapture lengths) in each of the spatial regions of the model, from the tag-release-recapture program, begun during the 1995/96 season

3.1 Catch data

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

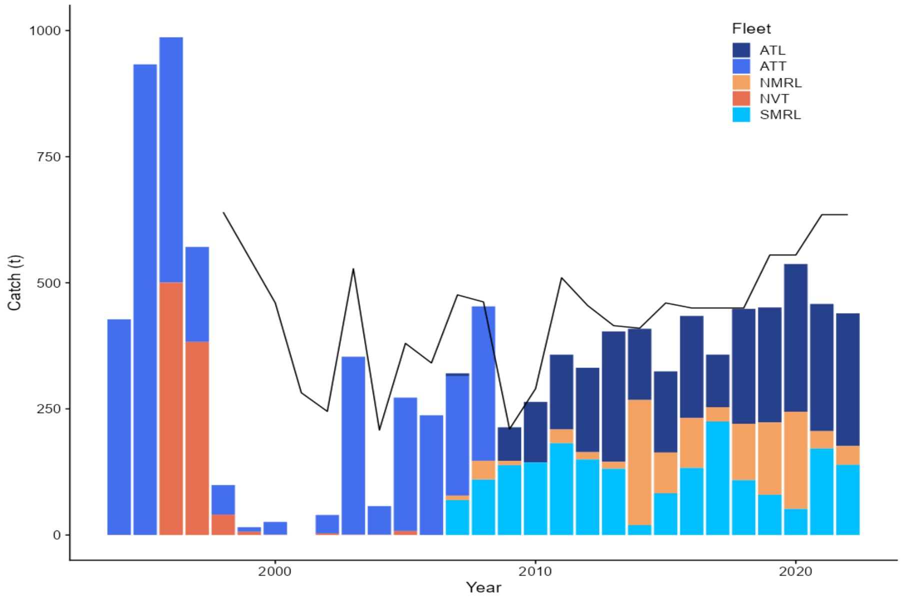

Figure 3.1: *Catch history and total TAC by fishing year, with catches stacked by fleet and the black line representing the combined TAC (with TACs summed for Aurora Trough and Macquarie Ridge from 1996–2011). Fleets in blue colours operate in the southern region and those in oranges operate in the northern region. There were small research quota in the Aurora Trough from 1998-2002 and in 2004.*

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

3.2 Length frequency data

Samples of the length composition of the catch were available for all fishing seasons (1994/95 to 2022/23). Each annual length composition is based on the measurement of several hundreds (or thousands) of fish (Tables 3.2 and 3.3). However, it is unlikely that the number of fish measured in each year is an appropriate metric of the effective sample size, due to expected high correlations among fish lengths within individual hauls/shots. Thus, input assessment sample sizes for the individual length compositions are set at the number of hauls sampled for the trawl data, and the number of shots for the longline data. For all fleets the over-dispersion factor (that scales the initial sample sizes to the correct ones) is estimated within the model.

Disaggregation of the length data by sex is possible, and the model could allow for the inclusion of composition data from both sexed data and data for which the sex is unknown, with the expectation that the latter is a random sample from the catch and is a combination of the individual compositions by sex. The percentage of the seasonal length samples that were sexed has varied considerably over the duration of the fishery. Additionally, inspection of the data suggests that the unsexed fish sampled for length are quite different from the male and female portions of the length composition for some years [14]. Consequently, length data were aggregated by sex for all years. Length bin structure is at 10 cm intervals between 0 and 30 cm, 5 cm intervals between 35–150 cm, and at 10 cm intervals 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 2013–2021 (Table 3.4). New ageing data from 2020/21 and 2021/22 were

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

Fishing season	Trawl		Longline			Total Catch(t)	Combined TAC(t)
	AT	NV	AT	NMR	SMR		
94/95	427.3	0				427	
95/96	932.9	0				933	
96/97	486.3	500.3				987	1750
97/98	188.2	382.8				571	1700
98/99	58.5	40.5				99	640
99/00	9.0	6.6				16	550
00/01	25.4	0.6				26	460
01/02	0.0	0				0	282
02/03	36.4	3.3				40	245
03/04	352.8	0.7				353	528
04/05	56.8	0.6				57	208
05/06	264.5	7.9				272	380
06/07	237.3	0				237	341
07/08	236.8	0	5.4	9.0	69.2	320	476
08/09	306.1	0	0	37.1	109.8	453	462
09/10			66.6	8.7	138.2	214	210
10/11			120.2	0	143.6	264	290
11/12			148.2	27.4	181.9	358	510
12/13			167.3	14.5	149.7	332	455
13/14			258.5	13.8	131.3	404	415
14/15			141.2	248.0	19.6	409	410
15/16			160.8	81.1	82.6	324	460
16/17			202.4	98.9	133.0	434	450
17/18			104.1	28.5	225.0	358	450
18/19			227.8	111.7	108.7	448	450
19/20			227.9	143.5	79.7	451	450
20/21			292.8	192.9	51.6	537	555
21/22			252.1	34.6	171.4	458	555
22/23			262.9	37.2	139.2	439	635

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

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
	19/20	93	3245	35
	20/21	98	3583	37
	21/22	96	3186	33
	22/23	129	4518	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
	16/17	128	3337	26
	17/18	57	1368	24
	18/19	104	3045	29
	19/20	141	4075	29
	20/21	159	4748	30
	21/22	50	1240	25
	22/23	42	1165	28
SMR longline	07/08	28	1589	57
	08/09	44	1750	40
	09/10	50	1886	38
	10/11	34	1546	45
	11/12	96	3388	35
	12/13	126	4080	32
	13/14	94	3107	33
	14/15	18	561	31
	15/16	76	2404	32
	16/17	123	3865	31
	17/18	174	5527	32
	18/19	76	2464	32
	19/20	35	1260	36
	20/21	32	1021	32
	21/22	75	2381	32
	22/23	97	3059	32

added this year, but the 2022/23 conditional age-at-length data were not available.

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	Sex	North	South	Total
97/98	F	13	28	41
	M	23	27	50
98/99	F	71	134	205
	M	83	117	200
99/00	F	87	1	88
	M	117	1	118
00/01	F	3	40	43
	M	7	53	60
03/04	F	0	138	138
	M	2	79	81
05/06	F	26	107	133
	M	37	56	93
06/07	F	0	11	11
	M	0	9	9
07/08	F	33	328	361
	M	13	238	251
08/09	F	33	247	280
	M	4	225	229
09/10	F	35	272	307
	M	25	159	184
10/11	F	0	276	276
	M	0	159	159
13/14	F	25	175	200
	M	14	83	97
14/15	F	95	97	192
	M	23	59	82
15/16	F	76	129	205
	M	19	57	76
16/17	F	72	134	206
	M	31	70	101
17/18	F	20	166	186
	M	12	78	90
18/19	F	55	135	190
	M	26	58	84
19/20	F	89	100	189
	M	9	81	90
20/21	F	50	58	108
	M	16	48	64
21/22	F	19	86	105
	M	21	64	85
Total		1347	4383	5730

3.4 Tag recapture data

Between the 1995/96 and 2022/23 fishing seasons, 21,380 Patagonian toothfish were tagged at Macquarie Island, of which 3,218 have been recaptured (Table 3.5, Table 3.6, Table 3.7). Fish are still being recaptured from releases in the early years of the fishery (Table 3.5, Table 3.6). Of the recaptures in 2021/22, the longest period between tagging and recapture was for a fish tagged in 2005/06. This is two years short of the longest period between initial tagging and recapture, with individual fish tagged 18 years previously also being recaptured in 2015/16, 2016/17, 2017/18 and 2020/21. Of the recaptures in 2022/23, the longest period between tagging and recapture was 11 years, for a fish tagged in 2011/12.

The recapture rates by region in 2021/22 and 2022/23 follow similar patterns to those seen in earlier years. The number of recaptures of fish released in the north is much lower than the number of recaptures of fish released in the south.

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

Release	Release	Num	# recaptures after 180 days at liberty																									
season	fleet	release	96/97	97/98	98/99	99/00	00/01	02/03	03/04	04/05	05/06	06/07	07/08	08/09	09/10	10/11	11/12	12/13	13/14	14/15	15/16	16/17	17/18	18/19	19/20	20/21	21/22	22/23
95/96	ATT	428	57	28	3		1	1	1							1												
95/96	NVT	4																										
96/97	ATT	452		42	7		2		9	1	3		1	1														
96/97	NVT	536		53	5	1			2																			
97/98	ATT	550			18	3	4	5	21	4	15	1		2	3	1	2	2			1							
97/98	NVT	502			9				1					1		1												
98/99	ATT	661				4	5	2	30	2	9	2	2	7		1	1		1									
98/99	NVT	315																				1						
99/00	ATT	697					3	1	35	6	12	1	4	6	2	5	1	5					1					
99/00	NVT	302																1										
00/01	ATT	370						1	23	3	5	1	1	9														
00/01	NVT	134						1			1																	
02/03	ATT	494							60	8	29	6	15	24	2	3	10	1	6	2			1			1		
02/03	NVT	17															1											
03/04	ATT	674								9	23	8	4	13	2	3	2	1	1									
03/04	NVT	60									3																	
04/05	ATT	572									46	7	16	43	4	4	6	3	4	1		1			1			
04/05	NVT	264									2		1	1						1	1							
05/06	ATT	610										25	18	27	2	5	4	4	3	1	1	1	1				1	
05/06	NVT	290																1		2	3	1						
06/07	ATT	467											26	13		1			4		2	1	2					
07/08	ATT	355												31	2		2	1	3	1		2						
07/08	NMRL	26													1		3	2				1						
07/08	SMRL	189												15	4	3	6	6	4		1	4	3	1				
08/09	ATT	727													2	6	12	10	19	6	8	8	1	4		1	1	
08/09	NVT	15																										
08/09	NMRL	82													2		7		1	1								
08/09	SMRL	386													9	9	18	21	11	2	2	2	6	1		1	1	
09/10	ATL	300														27	13	9	13	4	2	3	2			1		
09/10	NMRL	60															5	5			2	1				1	1	
09/10	SMRL	396														26	25	8	20	2	2	4	5	3	2	1		
10/11	ATL	480															11	31	45	6	4	4	1		1		1	

Table 3.6: *Numbers of tagged fish released and recaptured following at least 180 days at liberty, by release fleet and season.*

Release	Release	Num	# recaptures after 180 days at liberty												
season	fleet	release	10/11	11/12	12/13	13/14	14/15	15/16	16/17	17/18	18/19	19/20	20/21	21/22	22/23
10/11	SMRL	509		27	42	34	5	8	10	8	2	1			
11/12	ATL	307			10	37	7	7	12	6	3	3	1	3	
11/12	NMRL	116			1	2	1	3	2	1	1			1	4
11/12	SMRL	504			9	25	4	18	10	9	7	3		1	
12/13	ATL	311				37	12	12	6	6	9	7	1	1	
12/13	NMRL	57									1	1			1
12/13	SMRL	307				20		9	3	5		1		1	
13/14	ATL	532					9	26	23	16	12	11	5	3	
13/14	NMRL	36						3			1				1
13/14	SMRL	256					9	10	1	10	6	7	1	5	1
14/15	ATL	300						9	19	11	13	8	3	2	
14/15	NMRL	499							4		4	6	3	1	
14/15	SMRL	39								2	1	1			
15/16	ATL	361							17	13	27	21	7	6	3
15/16	NMRL	171							2	1	5	3			1
15/16	SMRL	172							12	4	10	4	4	2	2
16/17	ATL	452								12	42	20	14	10	5
16/17	NMRL	186								1	2		2	1	2
16/17	SMRL	270								30	4	16	4	4	2
17/18	ATL	227									20	14	10	8	5
17/18	NMRL	65									1				1
17/18	SMRL	436									38	23	14	20	7
18/19	ATL	510										24	21	27	14
18/19	NMRL	228											2	1	
18/19	SMRL	184										21	14	15	8
19/20	ATL	459											25	22	10
19/20	NMRL	296											9	2	1
19/20	SMRL	172											14	12	10
20/21	ATL	612												46	36
20/21	NMRL	360												3	
20/21	SMRL	109												16	11
21/22	ATL	530													46
21/22	NMRL	50													
21/22	SMRL	342													28

Table 3.7: *Total numbers of tag recaptures by fleet of release (rows) and recapture (columns), for fish at liberty for greater than 180 days. These releases and recaptures are aggregated over all years.*

	Recaptured by:				
Released by:	AT trawl	NV trawl	AT longline	NMR longline	SMR longline
AT trawl	851	1	170	2	39
NV trawl	8	72	1	7	6
AT longline	0	0	910	1	142
NMR longline	0	0	6	78	31
SMR longline	0	0	165	11	717

To allow for mixing of tagged fish with the untagged population, and to prevent the loss of too many tag recapture events in the early data limited assessments for all stock assessment up until 2015, 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 [8]). Given the quantity of tag data now available to the assessment and to ensure full mixing of tagged and untagged fish for all stock assessments after 2016 recaptures were removed from the 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 mixing period, as first applied to the 2016 assessment, was continued in this current assessment. As with the length data, the over-dispersion factor for the tag data is internally estimated within the assessment to deal with spatiotemporal release and recapture correlation.

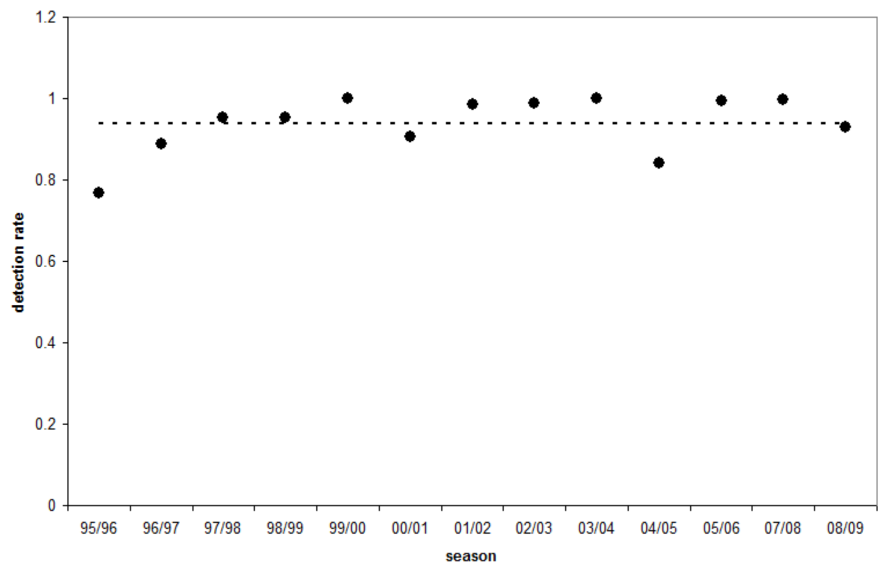

Figure 3.2: *Estimated tag detection rate (points) by fishing season (Tuck and Lamb 2009). Dotted line corresponds to the mean detection rate (0.938) over the time series.*

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 reported.

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. A sensitivity to this assumption is included.

The non-detection of tagged toothfish has been a problem, especially with 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 [8]), 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.

4 Biology

There have been a number of updates to the growth and maturity relationships for this stock over the years. Growth is now estimated externally to the assessment using a conditional age-at-length approach [31]. Updated growth estimates are consistent with those estimated for the previous assessment [32]. In 2019 the maturity-at-length relationships for males and females was also revised [31], resulting in a significant decrease in the length at 50% and 95% maturity for females. These estimates were calculated using updated data for this assessment [32]. The updated estimate of 90.48 cm and 153.04 cm are lower than the 2021 estimates of 98.9 cm and 156.6 cm, respectively.

The length-weight relationship is the same as previously employed:

$$w_l = al^b$$

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

5 Methods

The assessment framework uses the Template Model Builder (TMB) package in R [26]. This is, at present, the most efficient and flexible statistical modelling package available. It allows for highly complex statistical models (including the use of random effects) to be efficiently and robustly estimated. The tmbstan R package is used for the MCMC runs used to generate the key probabilistic summaries of the assessment variables [27]. This links models written in TMB to the currently accepted most efficient MCMC sampler (the No U-turns or NUTS algorithm) and, for the models explored, runs in just over 90 minutes.

5.1 Population dynamics model

The full details of the assessment method can be found in [2].

5.1.1 Length related variables

All the key data series used in the assessment involve size-specific predicted quantities: length distributions in the catch, age-given-length, and length-specific recapture probabilities. As the population dynamics model is primarily age-based we need to translate a number of age-based quantities into length, these include:

- Predicted length frequency (aggregated across sexes) for each fishery.
- Predicted distribution of age-given-length, accounting for ageing error, in each of the fisheries and for both sexes.
- Predicted sex ratio-at-length for each region.
- Predicted spatial recapture probability-at-length, derived from length-based harvest rates and the growth transition matrices for each sex.

For the tagging likelihood we need to calculate a sex-specific growth transition matrix given the length-based nature of this part of the model. This is done following the method outlined in [28] that deals with both the differing size of the length bins, and the stochastic uncertainty in the expected growth increments of the fish, given the growth curve. The transition matrix, $G_{l,l',s}$, is the probability that a fish in length bin l after a given time τ (taken to be one year here) will be in length bin l' (and $\sum_{l'} G_{l,l',s} = 1$).

5.1.2 Candidate selectivity functions

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

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

5.2 Likelihood functions

5.2.1 Length frequency data

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

5.2.2 Conditional age-at-length data

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

5.2.3 Tagging data

For the tag recapture model we derive fits within what would be considered a *multi-state mark-recapture model*. This assumes there are a number of probabilistic states a tagged fish can inhabit over the recapture period of a given release event, including: which length class it is in, what spatial region it is in, what sex it is, and whether it has been recaptured or not. The release covariates are year, length class and region; the recapture covariates are year and region of recapture. Both size at recapture and sex-at-release are integrated over within the tagging model (we do not use the sexed tag recapture information).

The base likelihood for the tagging data is essentially the multinomial distribution, which is known loosely as the Brownie model (size and spatially structured in this case)[29]. This follows the recapture history of a given release event and has been shown to be more informative on both abundance and migration, relative to the previous two-stage likelihood [24]. Tagging data are, however, well known to be often over-dispersed (i.e. more variable than the underlying base distribution would predict). To accommodate this process we again use the Dirichlet multinomial (D-M) distribution to model the likelihood of a given tagging event's recapture history.

5.2.4 Overall likelihood and objective function

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

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

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

5.3 Estimated parameter options

The core set of estimated parameters are:

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

5.4 Model dimensions

This section deals with some high-level summaries of the input data, as well as the relevant dimensions of the model (years, ages, size classes etc.) and settings of the different parameterisations for the various model processes. The model runs from 1985 to 2022 (i.e. 10 years before fishing began) and includes fish aged 1 to 52. Size-classes range from 0 to 190cm: 0 to 30 in 10 cm bins, 30 to 150 cm in 5 cm bins, and from 160 to 190 cm in 10 cm bins. The model is run as a two region model with a Northern and Southern region (with the same latitudinal separator for these regions as used in previous assessments). There are five fleets:

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

6 Results

This section summarises:

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

6.1 Reference assessment model

The reference assessment model has the dimensions outlined in Section 5.4, and uses the data as outlined in Section 3. For the base case, or reference, assessment model, we assume that the reference ages for the Schnute parameterisation of the von Bertalanffy growth function to be $a_1 = 5$ and $a_2 = 20$. This ensures that they are (a) are within the observed data range, and (b) are not too close or too far apart, relative to the data range. For the reference model we keep the growth parameters *fixed*, estimating them using the conditional age-at-length method detailed in [31]. Therefore, these data are used to inform the model on population size and age structure (including recruitment), not growth. The input growth parameters are detailed in Table 6.1.

Table 6.1: *Maximum likelihood estimates (and approximate standard errors in brackets) of the growth parameters used in the reference model. The values used in 2021 are included below the most recent estimates for comparison purposes.*

Variable	k	l_1	l_2	L_∞	t_0	σ_l	ϕ_l
Female	0.055 (0.002)	0.496 (0.003)	1.16 (0.004)	1.67 (0.03)	-1.37 (0.15)	0.15 (0.008)	1.05* (NA)
Male	0.069 (0.002)	0.491 (0.002)	1.02 (0.006)	1.31 (0.03)	-1.83 (0.16)	0.144 (0.012)	1.05* (NA)
Female (2021)	0.055 (0.003)	0.494 (0.003)	1.16 (0.004)	1.68 (0.03)	-1.3 (0.15)	0.15 (0.012)	1.05* (NA)
Male (2021)	0.067 (0.003)	0.488 (0.002)	1.02 (0.007)	1.33 (0.03)	-1.86 (0.18)	0.144 (0.016)	1.05* (NA)

A detailed summary of the estimation of the growth parameters can be found in [32] but Table 6.1 shows the estimate used as model inputs in the reference case. As seen in previous analyses, males grow faster initially, but to a smaller asymptotic length; as a result, size-at-age (and weight) of females is greater than males from about age five onwards. The key parameters (k, l_1, and l_2) are all very accurately estimated (Table 6.1). Variability in mean length-at-age is very well estimated in both cases and is the same for both sexes. The standard errors are informative and suggest that uncertainty in growth is smaller than in all the other parameters used as inputs to the model, or estimated therein (see later). For the female maturity-at-length relationship estimated in [32] the associated lengths at 50% and 95% maturity were 90.48 cm and 153.04 cm, respectively. As with the key growth parameters, the estimated accuracy of these parameters is high enough that considering them effectively fixed inputs to the model is highly unlikely to cause underestimation of the overall level of uncertainty in the key stock status outputs.

6.2 Fitting summary for reference model

The fits to the length frequency data for the two trawl fleets are in Figure 6.1, and for the three longline fleets in Figure 6.2 and Figure 6.3.

Figure 6.4 shows the fits to the female conditional age at length data for the Aurora Troph trawl fleet for males and females and Figure 6.5 shows the same for Northern Valley Trawl fleet. Figure 6 shows the fits to the female conditional age at length data for the Aurora Troph longline fishery, Figure 6.7 shows the same for Northern Macquarie Ridge longline fishery, and Figure 6.8 shows the Southern Macquarie Ridge longline fits.

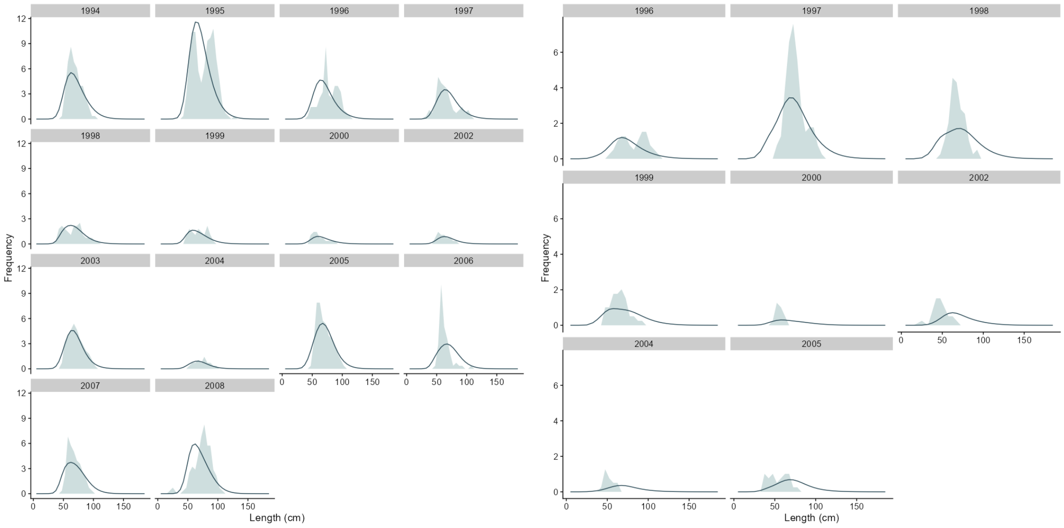

Figure 6.1: *Fits to the ATT (left) and NVT (right) trawl fisheries length data. Shaded area is the observed data, and the lines the predictions.*

The fits to the tagging data (Figure 6.9 – Figure 6.11) are summarised in four key ways:

1. successive recaptures for each year of releases
2. total recaptures for each year of release
3. total recaptures for each year of recapture
4. total recaptures for each year and region of recapture

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

Residuals of the fits to the tagging data are presented in Figure 6.12–Figure 6.13.

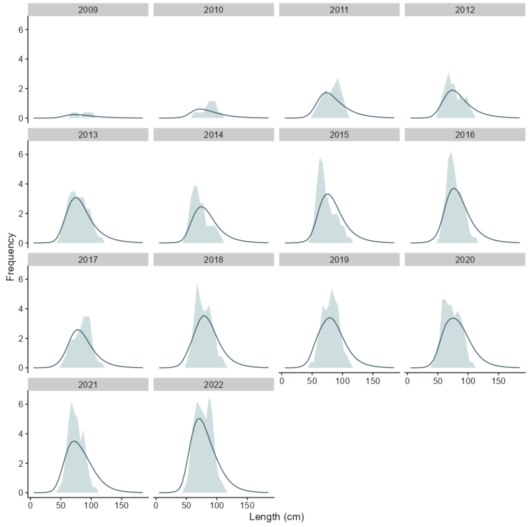

Figure 6.2: *Fits to the ATL longline fisheries length data. Shaded area is the observed data, and the lines are the predictions.*

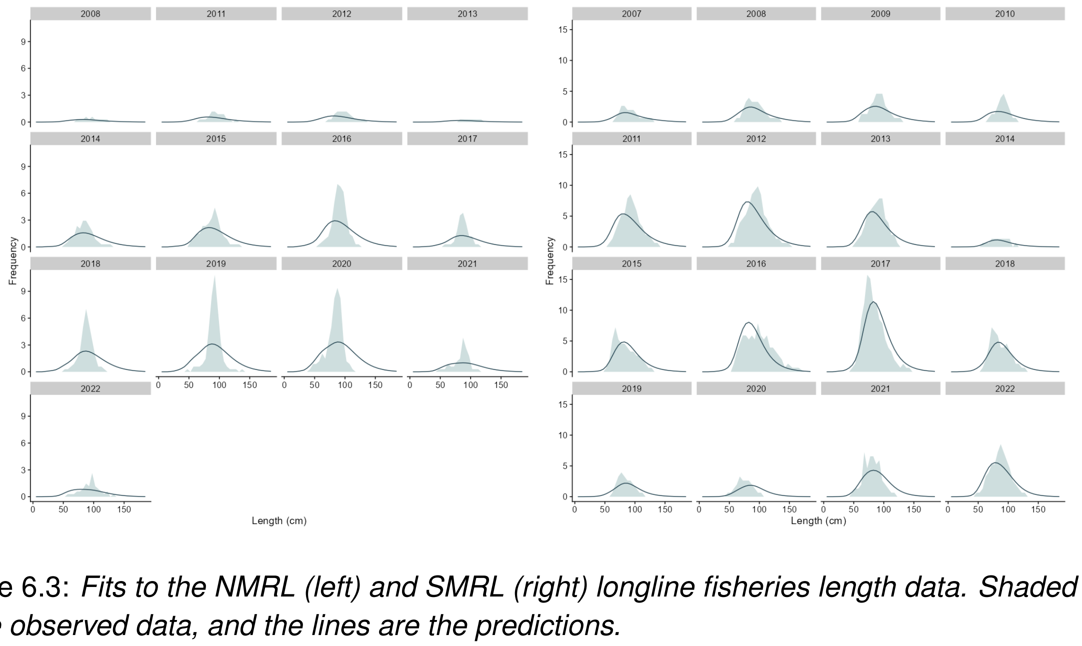

Figure 6.3: *Fits to the NMRL (left) and SMRL (right) longline fisheries length data. Shaded area is the observed data, and the lines are the predictions.*

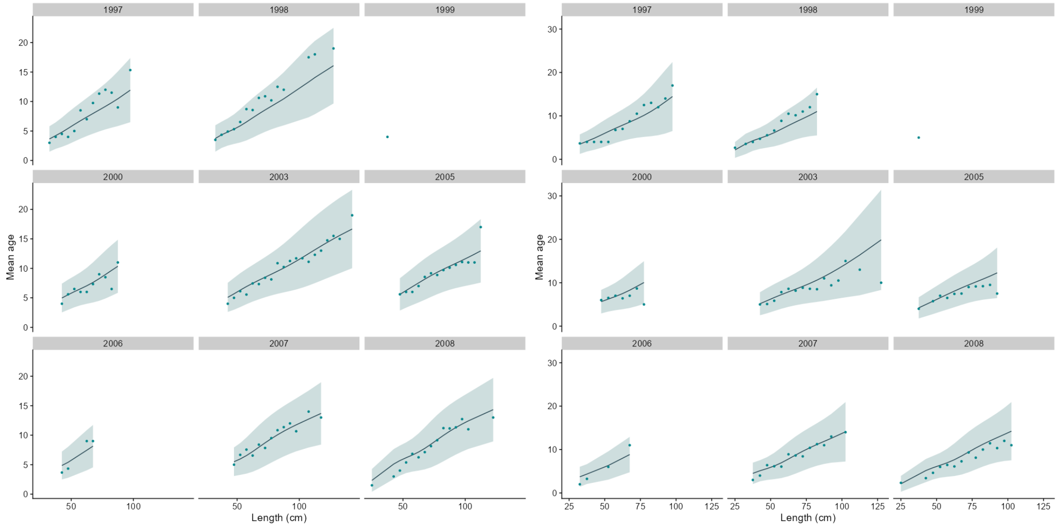

Figure 6.4: *Fits to the ATT trawl fisheries age-given-length data for females (left) and males (right). Points are the observed mean age, and the lines and shaded area are the predicted median and 95th percentile.*

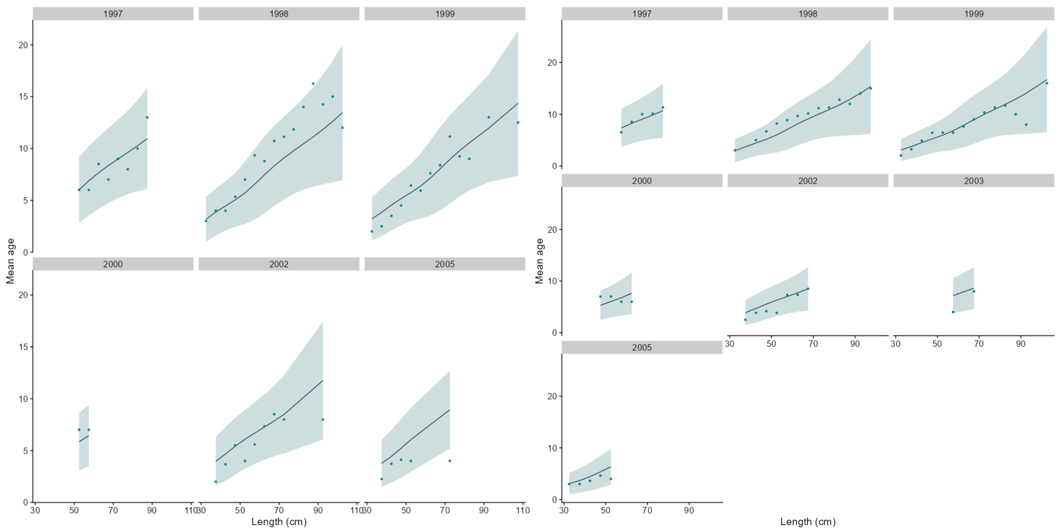

Figure 6.5: *Fits to the NVT trawl fisheries age-given-length data for females (left) and males (right). Points are the observed mean age, and the lines and shaded area are the predicted median and 95th percentile.*

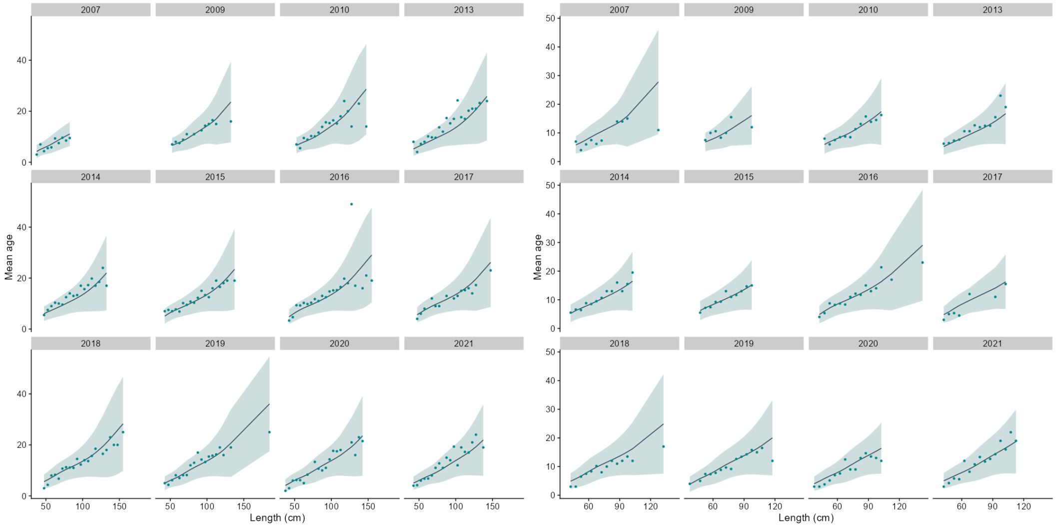

Figure 6: *Fits to the ATL longline fisheries age-given-length data for females (left) and males (right). Points are the observed mean age, and the lines and shaded area are the predicted median and 95th percentile.*

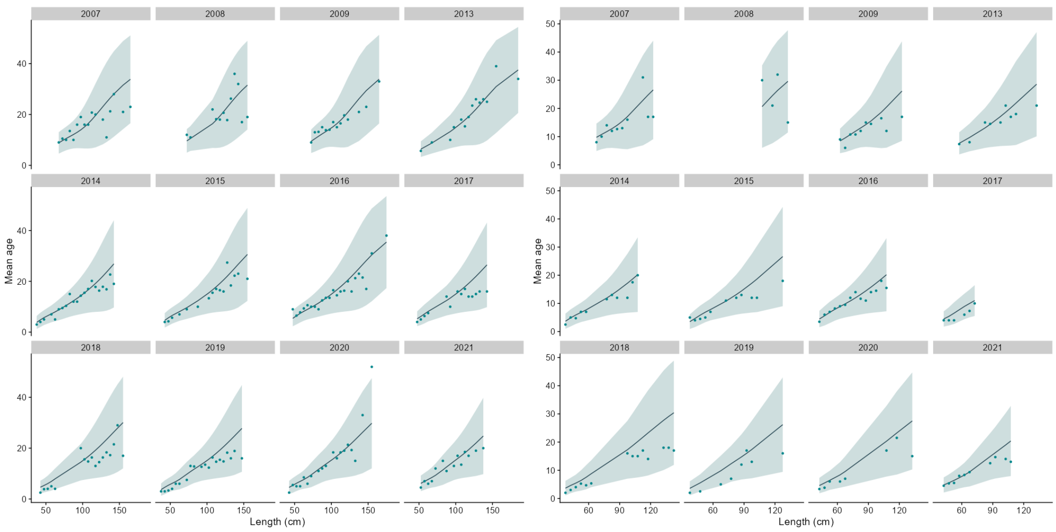

Figure 6.7: *Fits to the NMRL longline fisheries age-given-length data for females (left) and males (right). Points are the observed mean age, and the lines and shaded area are the predicted median and 95th percentile.*

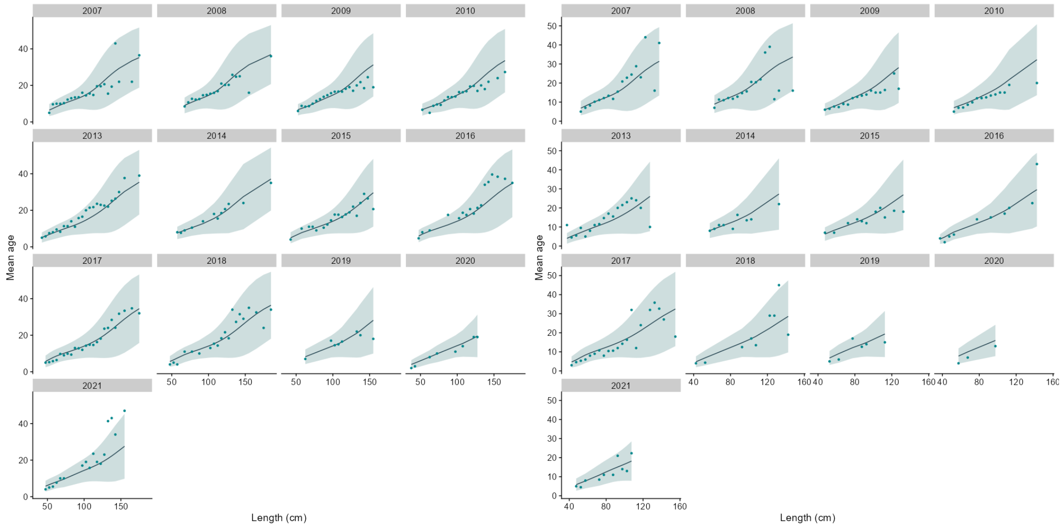

Figure 6.8: *Fits to the SMRL longline fisheries age-given-length data for females (left) and males (right). Points are the observed mean age, and the lines and shaded area are the predicted median and 95th percentile.*

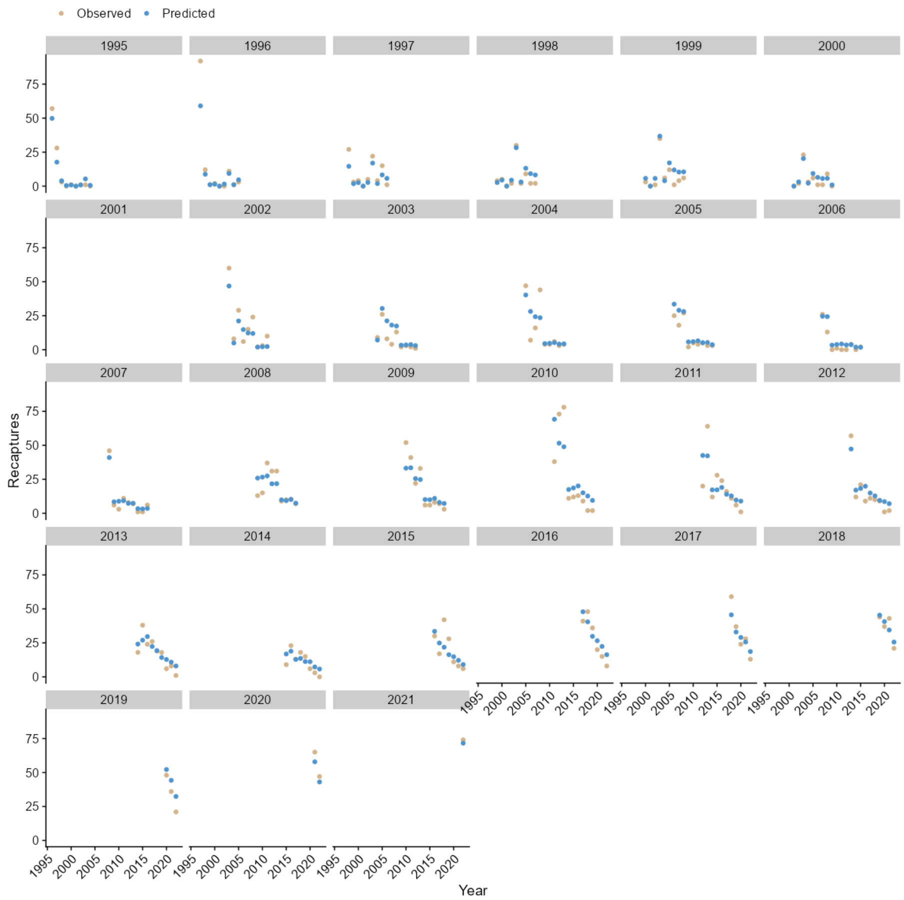

Figure 6.9: *Fits to the tagging data for recaptures following year of release. Observed and predicted recaptures are shown in tan and blue, respectively.*

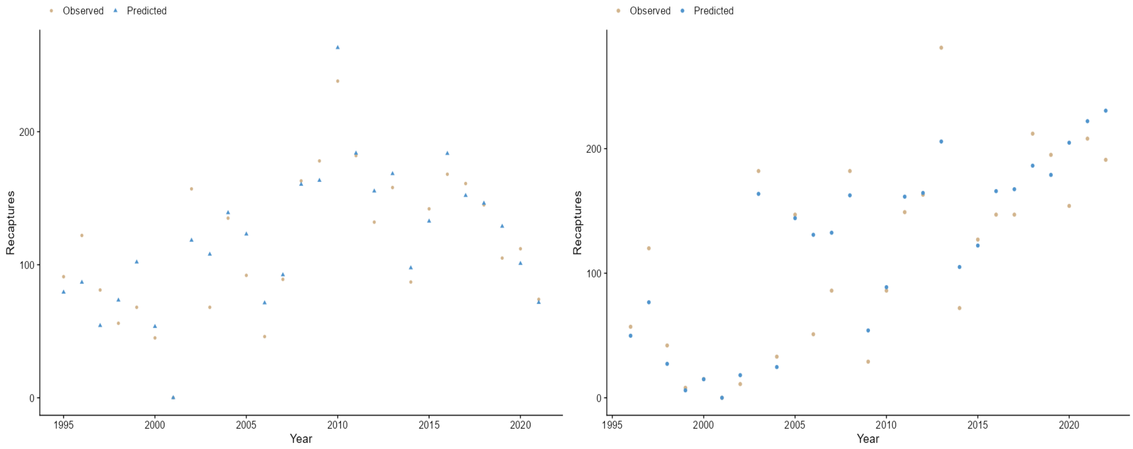

Figure 6.10: *Fits to the total recaptures for each year of release (left) and total recaptures for year of recapture (right).Observed and predicted recaptures are shown in tan and blue, respectively*

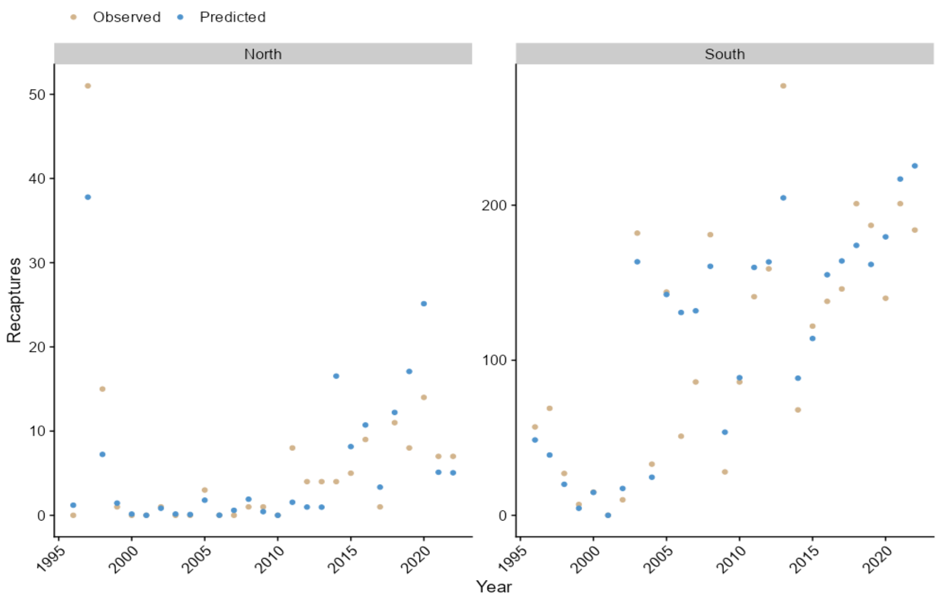

Figure 6.11: *Fits to the recaptures for each year and region of recapture. Observed and predicted recaptures are shown in tan and blue, respectively*

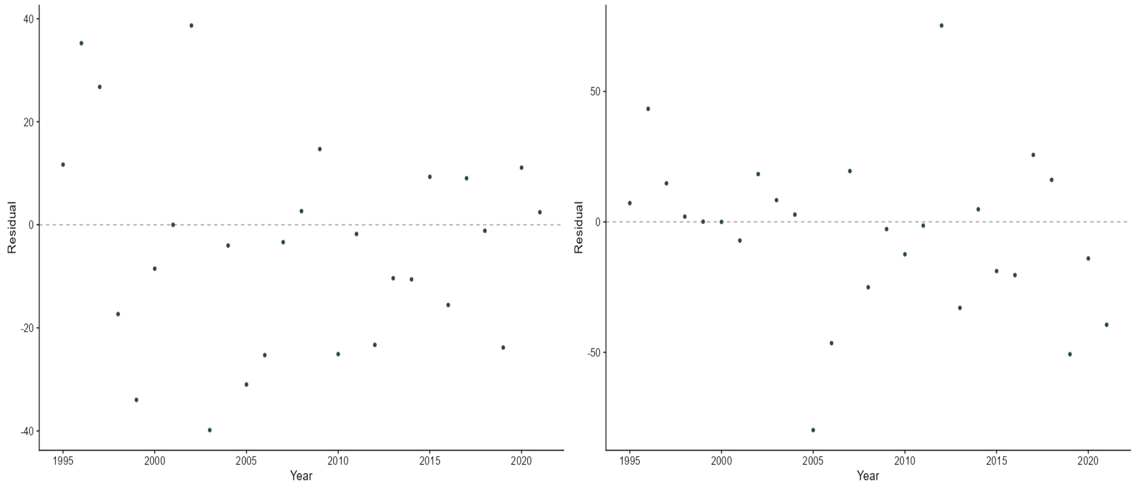

Figure 6.12: *Residuals of fits to the tagging data for recaptures following year of release (top left) and total recaptures for each year of release (top right).*

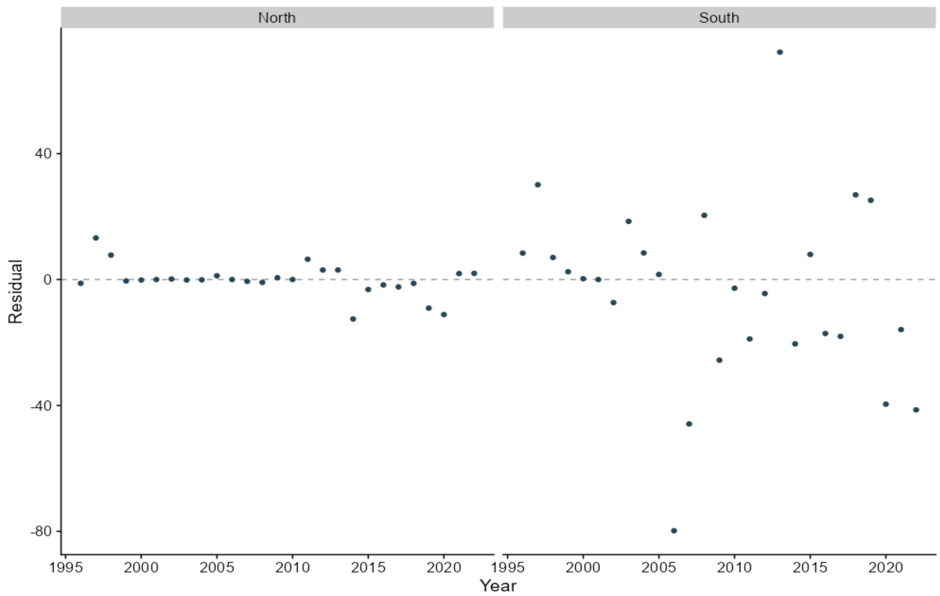

Figure 6.13: *Residuals of fits to the recaptures for each year and region of recapture.*

6.3 Relative data "weighting" estimates

A key feature of the assessment model is that data weighting is achieved via internally estimated parameters, not an ad hoc tuning approach, as is often used in integrated assessments. The results of this model weighting process show that for the ATT and NVT fleets there is clear down-weighting of the haul data - more so for the NVT fleet. For the longline fleets, SMRL is down-weighted very little, but the ATL and NMRL fleet are clearly down-weighted (Table 6.3). For the ATT data this appears to result from random variation whereas the downweighting for the NVT data appears driven by a systemic lack of fit (cf. clear decrease in mean length over time coupled with the assumption of time-invariant selectivity). For the NMRL data by convention we assume logistic selectivity for this and the SMRL fleet to avoid the appearance of cryptic spawner biomass in the population. While logistic selectivity is actually the mode of choice for the ATL, and would be for SMRL if permitted the choice, that the right-hand limb of the length frequency curve is consistently over-estimated in the last five years of data for the NMRL fleet.

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

Variable	φ_{ATT}	φ_{NVT}	φ_{ATL}	φ_{NMRL}	φ_{SMRL}	φ^{tag}
Estimate	2.79	3.95	2.58	3.41	1.52	1.45

For the tagging data the estimate of $\varphi^{\text{tag}} = 1.45$ clearly suggests that the tagging data are over-dispersed, relative to the assumption of a straight multinomial recapture likelihood. For the conditional age-at-length data we assumed a multinomial distribution, given the theory about size-selectivity versus age would suggest that age data from within a given length class would be random (hence, the multinomial would be the right choice). The reality of whether this is true can only be determined once the model has been fitted to the data. Examining the fits to the data for each sex and fishery (Figure 6.4–Figure 6.8) it is apparent that, barring a few isolated examples, the observed mean length-at-age sits within the predicted 95% interval and does not systematically appear above or below the predicted mean. When examining the standardised residuals for over-dispersion (e.g. do they systematically appear greater than 1) there is no evidence that a move to the over-dispersion model (Dirichlet-multinomial) is required. This suggests that:

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

6.4 Population dynamic summaries from MCMC

For the reference assessment base case, we used the `tmbstan` R-based MCMC package [27] to sample from the posterior distribution. The package uses the Hamiltonian MCMC algorithm, designed to solve common problems with traditional MCMC algorithms relating to sampling from complex high-dimensional posterior surfaces. As a result, it is able to obtain a convergent MCMC sample from the posterior (1,000 iterations) in about 90 minutes. The key female *SSB* summaries can be found in Figure 6.14; total recruitment and the key spatial parameters (recruitment fraction

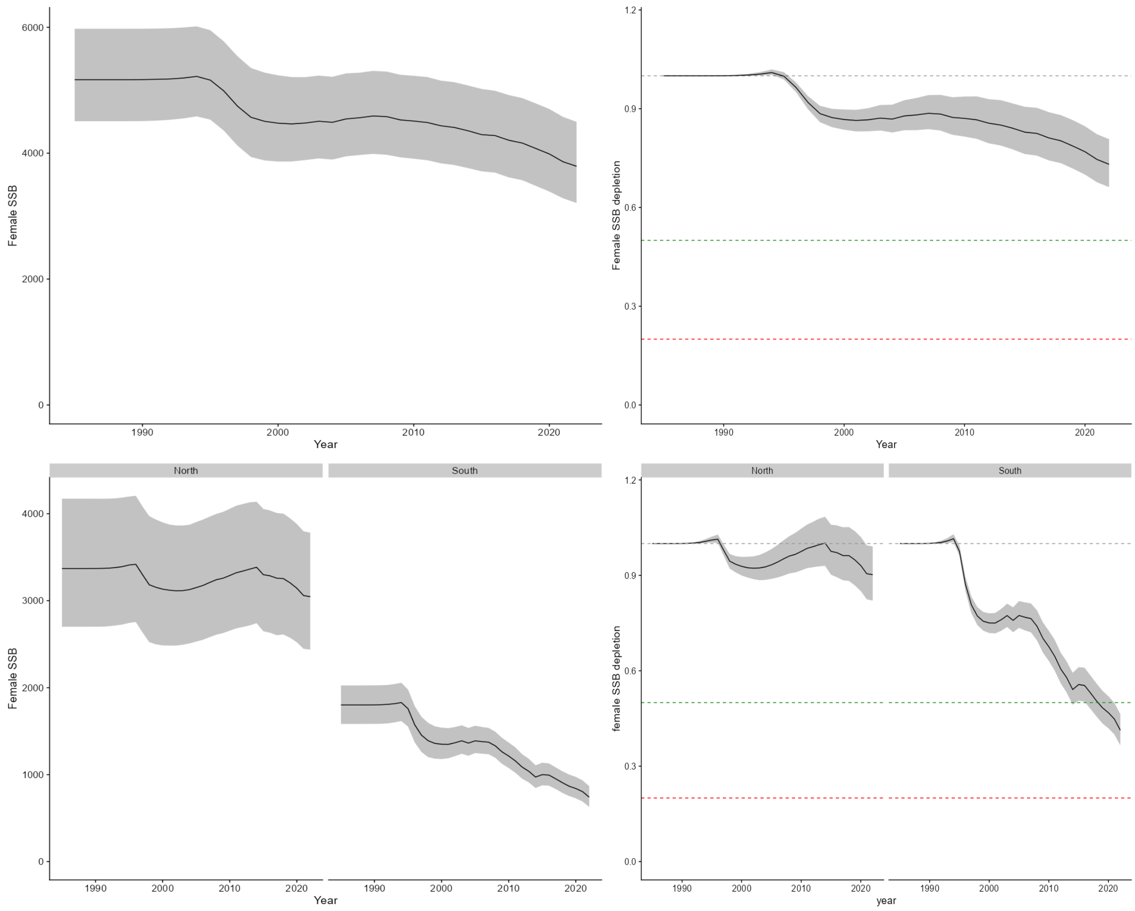

Figure 6.14: *Posterior median and 95% credible intervals for total female SSB (top left), female SSB relative stock status (top right), spatial female SSB (bottom left), and spatial female SSB relative stock status (bottom right).*

to North, η_1, and migration rates between regions) can be found in Figure 6.15 and Figure 6.16.

The current (*ca.* 2022) median estimate (and 95% credible interval) of overall female *SSB* stock status is 0.73 (0.66–0.81). As with previous assessments, the estimated overall level of female *SSB* is consistently higher in the Northern region relative to the Southern region. Spatially, the depletion in the Northern region is 0.90 (0.82–0.99); in the Southern region it is 0.41 (0.37–0.46). Total recruitment has generally varied randomly around the mean level, with short periods of higher or lower recruitment, but not sustained periods of either (showing intermediate levels of positive temporal auto-correlation *ca.* 0.3).

The spatial recruitment fraction to the Northern region has a median (and 95% credible interval) of 0.32 (0.24–0.99) - a little higher than the previous estimate of 0.17 from 2021 [2]. Migration point estimates are similar (around 1% *per annum* from North to South, and 5% from South to North) - a little lower than the 8% from 2021. The reality is that one can obtain the same effective spatial distribution of animals by **either** depositing more or less recruits into a region, **or** having more or less fish move between regions. Additionally, a (comparatively) large change in the spatial recruitment parameter, can be offset by a much smaller proportional shift in a migration parameter. The spatial recruitment dynamic is a “one off” event; migration is the consistent movement of every age-class year upon year. It does not take much change in the latter to offset

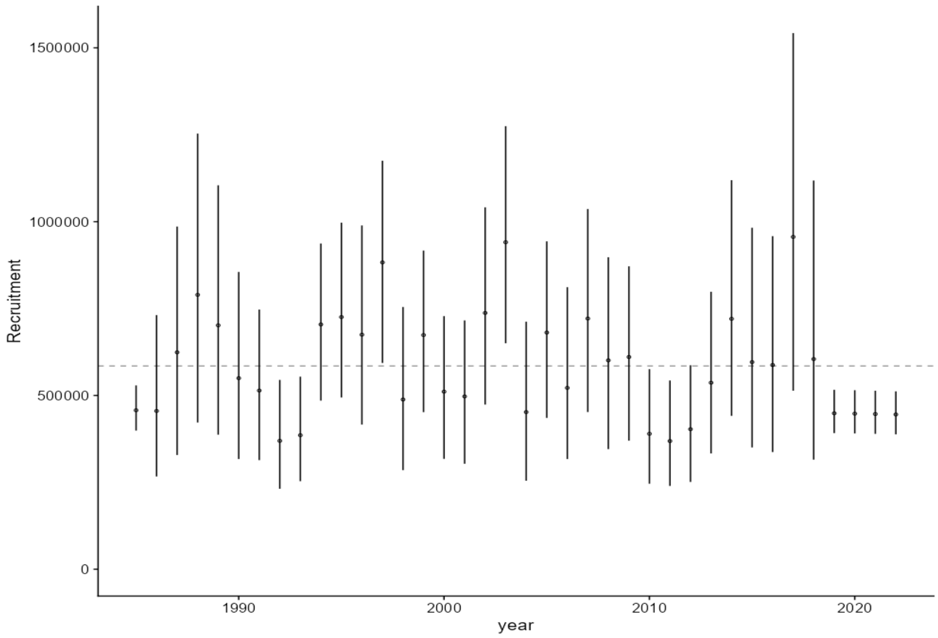

Figure 6.15: *Posterior median and 95% credible intervals for total recruitment.*

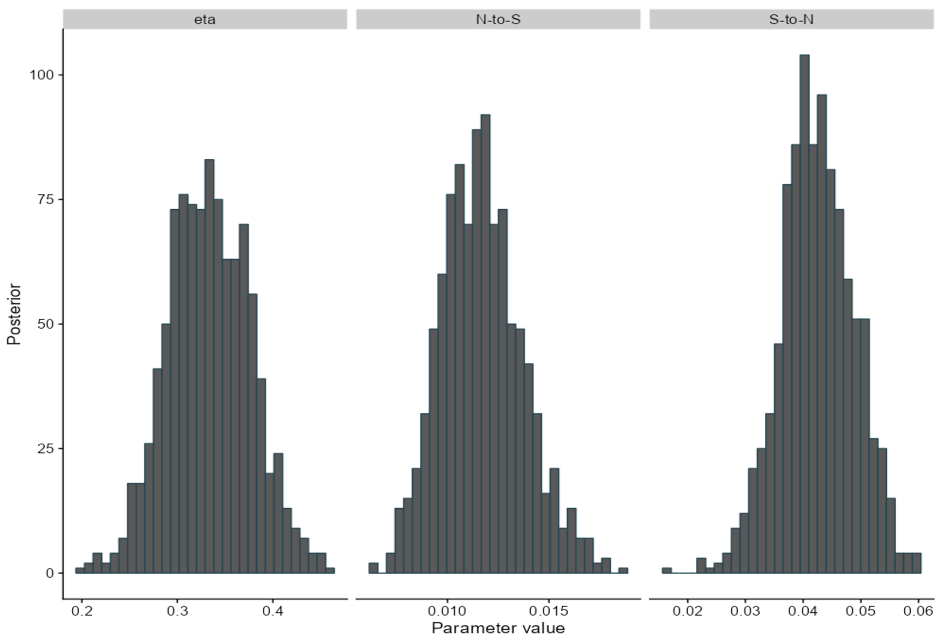

Figure 6.16: *Posterior median and 95% credible intervals for the marginal posteriors for the three spatial parameters:* η_1, $\Phi_{1,2}$, *and* $\Phi_{2,1}$.

a change in the former (as is the case here).

Differences between the relative sizes of the Northern and Southern regions largely depend on the metric chosen. In terms of current female *SSB*, clearly the model estimates more biomass in the North than in the South. This difference between the regions is smaller than observed in the 2021 assessment where a near fourfold difference was estimated. When comparing the difference between exploitable abundance currently accessible by the longline fleets, then the estimated difference between the regions is narrower. The spatial abundance in the North is by far the most uncertain given the much lower level of tag recaptures there relative to the South. Coupled with the low movement rates between regions this results in the abundance in the North - estimated to be the largest region - being a considerable source of variation in estimates of absolute abundance over time. Whereas, there is little change in the absolute abundance in the South relative to the 2021 assessment, as there are over a thousand recent tag recaptures with consistent rates of recaptures per unit of catch. As there is increasing number of recaptures in the North (as seen in the last 4–5 years) the abundance will become more accurately estimated, but also prone to changes in the estimated mean as the accuracy increases, relative to the South. The overall change in abundance and mature biomass relative to the 2021 assessment (around 25–30%) is driven mostly by the decrease in the estimated abundance in the North, though the small decrease in the size at maturity also plays a role.

6.5 Key sensitivity runs

We focus on four key sensitivity tests:

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

For the tag shedding sensitivity test, we assumed what is effectively the worst-case scenario: where the tag shedding is defined as in [33] and this defines π_t^{tag}; as a result, we are at the expected lower-bound of tag retention (for the purposes of detection post-capture). For the alternative natural mortality scenario (HIMI value of $M = 0.155$) we see the most difference in parameter and biomass estimates across the tested scenarios (Table 6.5). Unsurprisingly, the estimate of R_0 increases to accommodate the higher rate of attrition of recruits given the higher M value (Table 6.5). The stock status is lower than for the reference case, around 0.59, with the change driven by differences in spatial recruitment fraction and migration estimates (Table 6.5). Overall, the fit is better for the higher M value as it has been in previous assessments but, given we impose asymptotic selectivity on all the long-line fleets, this is also highly likely due to the model using additional freedom in the parameter to better fit to the age-given-length and tag data via dome-shaped selectivity (Table 6.5). The alternative steepness scenarios change little in terms of stock status or other key parameters - the reference steepness value of 0.75 is the best fit to the data but given how little contrast there is in the recruitment-*SSB* relationship over time this result is unlikely to be significant (Table 6.5). For the tag shedding scenario we see a very slightly lower stock status of 0.72 (Table 6.5). The change in female *SSB* and stock status for each of the scenarios is presented in Table 6.5.

Table 6.3: *Sensitivity test summaries.*

Sensitivity	Depletion	$R_0 \times 10^5$	$\ln \Lambda^{l}$	$\ln \Lambda^{a\|l}$	$\ln \Lambda^{\mathrm{tag}}$	$\ln \Lambda^{\mathrm{tot}}$
Base	0.73	4.57	12,477	13,798	13,329	39,603
$M = 0.155$	0.59	5.57	12,454	13,768	13,318	39,540
$h = 0.6$	0.74	4.60	12,211	13,798	13,328	39,338
$h = 0.9$	0.73	4.54	12,465	13,798	13,328	39,592
Tag shedding	0.72	4.49	12,096	13,799	13,327	39,221

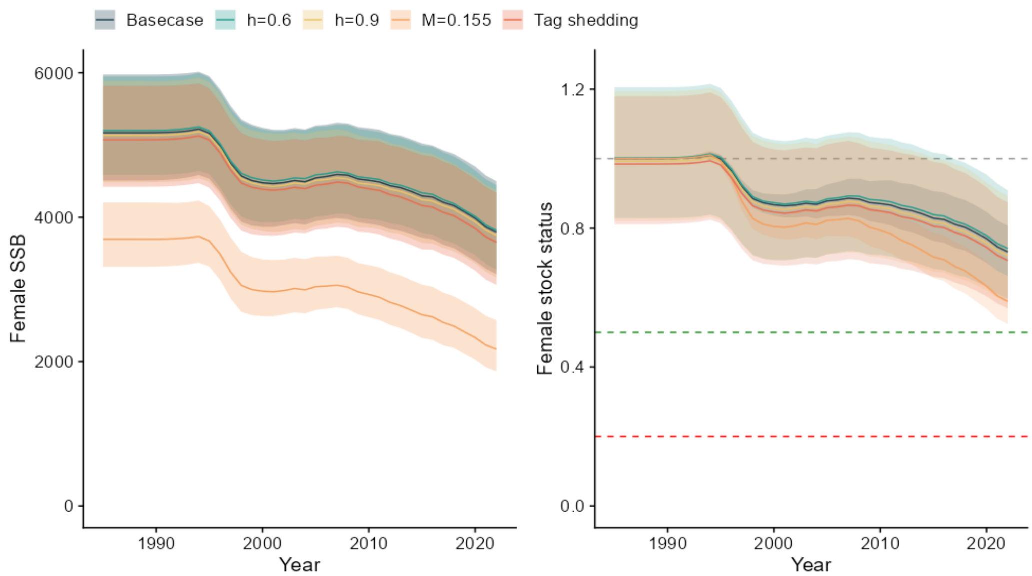

Figure 6.17: *Female spawning stock biomass (SSB) and stock status for each of the sensitivitiy tests.*

7 Recommended TAC scenarios

The CCAMLR decision rule is currently used for Macquarie Island toothfish in relation to calculating recommended TACs. As in previous calculations we explored spatial scenarios where the catch in the Aurora Trough was fixed at a given value, and then the remaining catch was shared between the North and South, given an assumed percentage for each. For the Aurora Trough we explored 200, 250 and 300 tonnes with 50:50, 25:75 percentage splits for the North and South remainder, along with the average split in catch between the North and South regions over the past 3 years (0.42:0.58). Table 7 details the recommended TACs for these spatial catch scenarios.

The recommended TACs range from 451 to 473 tonnes with an average of 459 tonnes, around a 13% decrease from the 2021 average of 644 t. This is driven by the lower stock status estimates in the current assessment compared to that in 2021. The 2021 assessment estimated a increase in R_0 and overall abundance of around 20%, with a similar increase in the TAC. Here we see a similar effect in the opposite direction: estimates of overall abundance decrease by around 25–30%, a slightly larger drop than observed in the recommended TAC. There was a small 9% decrease in both the male and female estimated size-at-maturity [32] which has to be considered also. This effect at the size ranges of relevance (between 90–100 cm) would be to slightly increase female spawning biomass-per-recruit and therefore offset the overall abundance de-

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

Aurora Trough	NMRL	SMRL	NMRL %	SMRL %	TAC
200	137	137	0.5	0.5	473
250	107	107	0.5	0.5	464
300	78	78	0.5	0.5	455
200	65	194	0.25	0.75	458
250	51	153	0.25	0.75	454
300	38	113	0.25	0.75	451
200	113	155	0.42	0.58	468
250	88	122	0.42	0.58	460
300	64	88	0.42	0.58	452
Average					459

crease effect on recommended TACs. However, the overall effect is predominantly driven by the estimated change in overall abundance, which was driven by a decrease in the abundance in the Northern region. This decrease in the Northern region was due to a increase in the number of recaptured tags, and if this trend continues abundance will become more accurately estimated and shifts in spatial parameters are also expected (regional relative recruitment and migration).

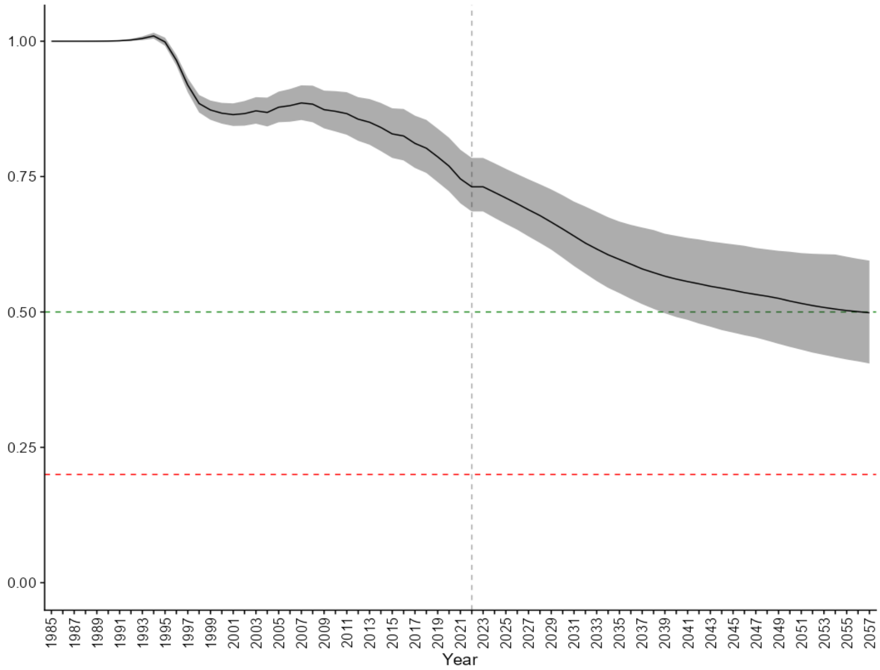

Figure 7.1: *Projection for one of the recommended TAC scenarios. The line is the median and shaded area is the 95% credible intervals for female stock status. The green dashed line is the target reference point and the red dashed line is the limit reference point. The grey dashed line shows the start of projections.*

A final piece of information to be considered when implementing the recommended TACs is detailed in Figure 7.1. The recommended TACs in Table 7 all meet the requisite target in 35 years, however, they reach that target on a downward trajectory, not in an equilibrating sense. This is because the starting stock status of 0.73 required a catch higher than the equilibrium catch when at target, and this level of catch will likely cause the stock to decrease below the target. This outcome assumes that estimates of abundance will not change in future assessments, which we know is not the case. This highlights the sensitivity of management advice to the CCAMLR rule.

8 Discussion

In this paper we detail an update of the adopted assessment model for the Patagonian toothfish fishery around Macquarie Island first detailed in [2]. From the key management variable, female *SSB* based stock status has a median value of 0.73 with a 95% credible intervals of 0.66–0.81, lower than the 0.85 estimate from the 2021 assessment. Fits to the various data sources (size, age given length, tags) are all acceptable and show no obvious model structure problems.

In terms of sensitivities, the steepness alternatives and the tag shedding scenario had negligible impact on model outcomes. Only the higher $M = 0.155$ showed any real difference, with a lower estimate of stock status at 0.59, driven by changes in the spatial recruitment fraction and migration estimates for this scenario. Future development of the model would benefit from exploring a more nuanced spatial recruitment model, where deviations are spatiotemporal in nature, not just estimated for the whole population and then divided between North and South by a time-independent multiplier. Such an approach would estimate not just recruitment variability but also temporal and spatial correlation, and hopefully do a better job at teasing out spatial recruitment patterns if they exist (which they appear to in the tag data).

A range of recommended TACs were calculated (from 451 t–473 t) with an average of 459 t - a 13% decrease from 2021 driven by the lower stock status estimate. The CCAMLR rule will likely continue to cause short-term variability in the TAC as estimates move over time, despite there being no significant changes in overall status from one assessment to the next. MSE work, which will be presented to the SARAG in early 2024 will explore possible alternatives to this rule for setting management advice, and whether they can ameliorate some, if not most, of these issues encountered for both the Macquarie Island and HIMI toothfish fisheries.

9 Acknowledgments

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