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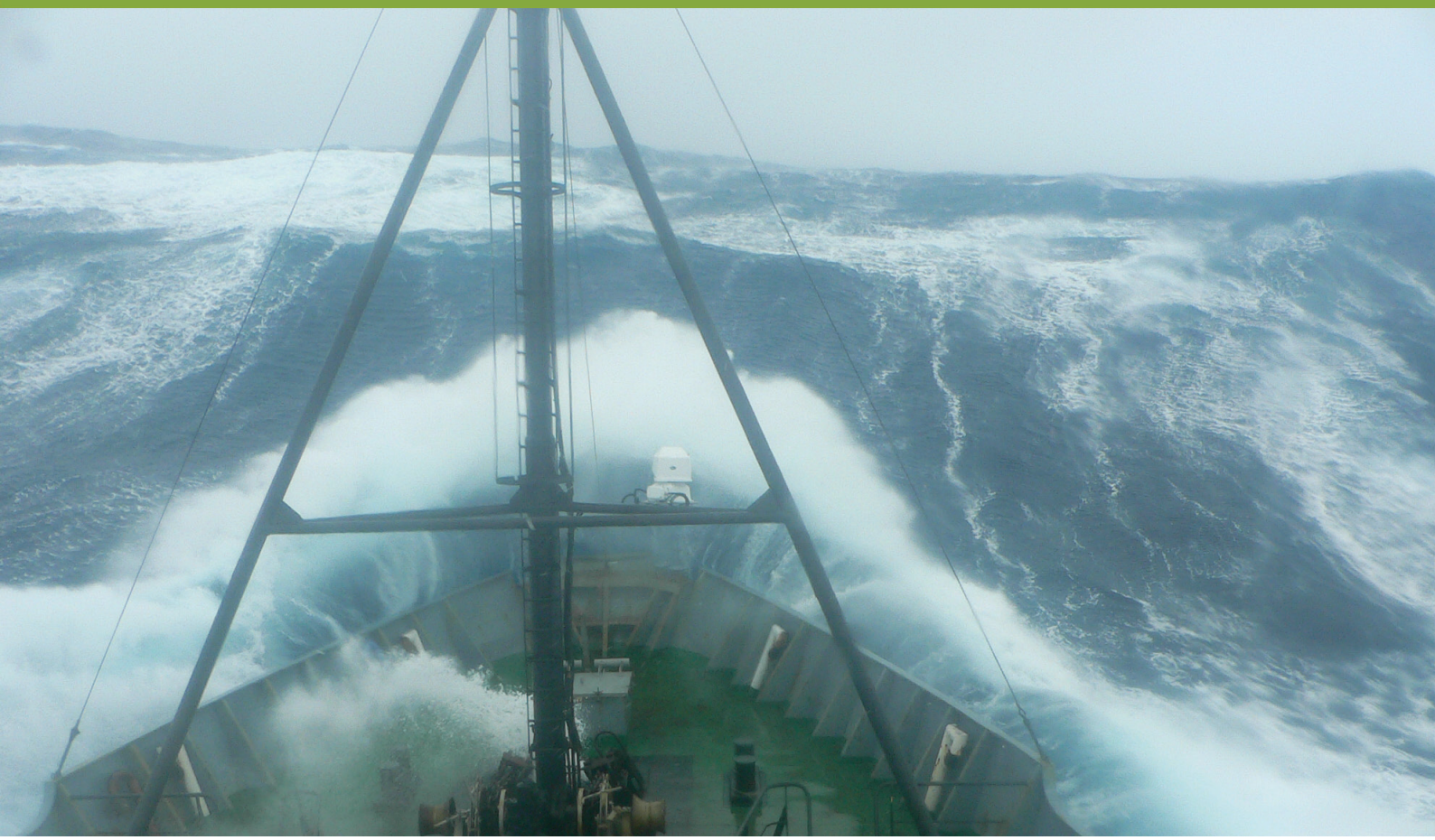
Development of a multi-gear spatially explicit assessment and management strategy evaluation for the Macquarie Island Patagonian toothfish fishery



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Gavin Fay and Geoff Tuck (Eds.)
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1. NON-TECHNICAL SUMMARY

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OBJECTIVES:

1. To provide the SARAG with a revised assessment that provides estimates of the status of Patagonian toothfish around Macquarie Island

2. To develop methods in the assessment that account for (a) the expanding spatial aspects of the fishery and (b) the introduction of longline fishing in the area.

3. To update and further develop the MSE to include the new assessment model and include hypotheses about the spatial aspects of the stock.

4. To continue monitoring the stock through the tag-recapture program

OUTCOMES ACHIEVED

The assessment of stock status of Patagonian toothfish at Macquarie Island is based on the methodologies presented in this report. The assessment outputs are critical to the management and TAC setting process for this fishery. The results from the Management Strategy Evaluation are being used by SARAG, industry and management to help manage the fishery in accordance with agreed sustainability objectives. The results of the project have increased fishers' and managers' awareness of the utility of setting and evaluating appropriate management strategies for this fishery.

The Patagonian toothfish (*Dissostichus eleginoides*) tagging program at Macquarie Island during the experimental longline fishery between 2007 and 2010 is described in Chapter 6. From 2007 to 2010, four voyages were undertaken by longliners to Macquarie Island; in 2007 by the FV *Avro Chieftain* and 2008-2010 by the FV *Janas*. Fishing was successfully spread along the ridge in order to better understand the stock's spatial extent, movement rates ontogenetic changes in distribution and stock size. A high average tagging rate was achieved in all seasons.

A total of 151 tagged fish have been recaptured since 2007 (95 of them in 2010); of these, 120 (79%) have moved less than 10 n miles during up to 12.8 years at liberty. 108 of these fish (72% of the total recaptures) stayed within the same ground in which they were released. A large number of fish have stayed within Aurora Trough, with a generally long time at liberty. This is a consequence of the very large number of fish tagged within Aurora Trough since 1997 during the trawl fishery, as well as an apparent tendency for fish to reside in (or return to) Aurora Trough over many years. Of the remaining recaptures, 31 had moved more than 10 n miles. 13 of these fish originated in Aurora Trough, all but one released during the trawl fishery, and all moved southwards.

Chapter 7 presents the results of applying simple Peterson-based tag-recapture models to the Macquarie Island longline fishery, with the intent of examining the influence of TAC and tagging rate on the precision of the abundance estimate, given different assumptions regarding the current stock size. The change in precision in the estimate of 2009 abundance obtained by increasing the TAC above 150t is examined, as is the precision in the 2010 abundance estimate given different values for both the 2009 and 2010 TAC and the tagging release rate in 2009. The results suggest that there may be little benefit, in terms of the precision of abundance estimates, to increasing the TAC for 2009 or increasing the tagging rate from the prior 3 tags per tonne. The reductions in the CV associated with these changes are small, and in practice are likely to be swamped by the additional uncertainties that will be introduced through both observation error, and errors associated with deviations from the assumptions inherent to the particular calculations and the Lincoln-Petersen estimator as a whole.

Chapter 8 presents preliminary results of fitting an integrated assessment model (Stock Synthesis) to the available data from the trawl and longline fishery for Patagonian toothfish at Macquarie Island. The model fits to data obtained from the tag-recapture program at Macquarie Island since 1995, to length composition data for the years 1994-2009, and to age-at-length data from aged otoliths. A focus is placed on presenting the results of assuming different model structures rather than exhaustive sensitivity analyses. Three structural versions of the assessment model are presented:

1. a single area model which designates five different fleets (Aurora Trough trawl and longline, Northern Valley trawl, and North and South Macquarie Ridge longline) to attempt to capture the spatial and gear-dependent differences in availability but which assumes that the population these fleets exploit is homogeneous,
2. a two-area model which accounts for heterogeneity in toothfish availability between the northern and southern areas of operation of the fishery, with movement among areas, and
3. a three-area model which separates the major historical trawl grounds (Aurora Trough and Northern Valleys) from the Macquarie Ridge, with recruitment occurring only at the trawl grounds, and movement of fish between areas thereafter.

All models are able to fit the length data and age-at-length data equally well. The models all also manage to mimic the total number of annual tag recaptures well.

The models differ in their ability to mimic the patterns of tag recaptures by fleet. The single-area model cannot reconcile the heterogeneity in recaptures among fleets (ie it predicts fewer recaptures for the fleet of release than observed, and predicts more recaptures for the other fleets than observed). This occurs because the model is treating the population as one homogeneous pool and has no means of preventing the tagged fish from being available to the other fleets. Models 2 and 3 (multi-area models) do a better job at capturing the pattern of

recaptures by fleet, although both models over-predict the recaptures in recent years from the longline fishery.

Model 1 indicates that current spawning biomass is around 64% of unfished conditions, whereas models 2 and 3 suggest a slightly less depleted stock, with 2010/11 spawning biomass being 67 and 72% of unfished equilibrium respectively. The time series of spawning biomass show a steady decline over the duration of the fishery for all models. Models which use multiple areas in addition to multiple fleets estimate larger stock sizes, and larger current stock size relative to those in unfished conditions. Model 2 estimates low rates of movement among the two areas (<1% per annum), and estimates the spawning biomass in the Northern area to be slightly larger than the southern one, with the southern area having a lower biomass relative to unfished conditions. This is unsurprising given that the bulk of the fishery has operated in this area. Model 3 estimates the majority of the spawning biomass to be in the Macquarie Ridge area, with high rates of movement into this area from the Aurora Trough once fish mature. Under Model 3, the Northern Valleys area is estimated to have a much larger spawning biomass than the Aurora Trough area, as the estimated movement rate from this area to the Ridge is low. This is due to the low number of recaptures by longline of trawl-tagged Northern Valleys fish.

The previous integrated assessment is refined for application to Aurora Trough only in Chapter 9. The model designates two different fleets (Aurora Trough trawl and longline), and estimates separate selectivity patterns for each fleet. Several modifications were made to the previous assessment model. These included:

1. the use of separate growth curves by sex,
2. consideration of alternative growth curves based on fits to growth increment data from tag returns,
3. updating of the maturity ogive as a result of model fits to maturity data from Macquarie Island obtained during the longline trial conducted in 2007/2009,
4. disaggregating the length composition data by sex for some years,
5. removal of age-at-length data for years other than 1997 and 1998,
6. use of ageing error matrix from the 2009 HIMI assessment,
7. implementation of time-varying tag detection rates,
8. disaggregation of the assumed ages of tag releases into multiple tag groups per season based on the distribution of lengths-at-release.

Fits to the length composition data are adequate, although lengths 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.

The models fit the tag-recapture data well, with good accord between the total number of expected recaptures and those observed. However, the numbers of recaptures predicted by the models was higher than those observed for the 2006/07 and 2007/08 seasons. This is largely due to a lack of 80+cm fish in the length data for these years. The choice of how many groups to disaggregate the tag release data into (in terms of assigning ages of releases) did not impact the assessment results greatly.

The general pattern to the time series of recruitments is estimated consistently, with recruitment pulses estimated to have occurred around 1980, 1987, 1994, and 1998/99. Additional age data will likely improve the ability to estimate both the magnitude of individual recruitments and growth.

In general, the models estimate current spawning biomass to be around 50-60% of unfished spawning biomass, with the base-case estimate of 2010/11 spawning biomass relative to unfished levels being 57%. Revised lengths at maturity (50% mature at 139 cm) lead to smaller absolute values for the spawning biomass, which is largely unavailable to both the trawl and longline fisheries. The 2010/2011 trawl available biomass is estimated to be well above the limit reference point of 66.5% pre-tagging (1995) levels, with the base-case trawl available biomass estimated to be 2,932t. Under the current harvest strategy, this would imply a 2010/11 TAC for the Aurora Trough of 293t. The difference between the estimates of trawl available biomass between the new assessment and the previously applied tag-only model is a result of pre-tagging biomass not being estimated as high, and that the decline in available biomass in 2009 was not as great as that from the 2009 assessment. The projected catch for 2010/11 under the current harvest strategy for Aurora Trough is greater than that calculated under an F50 harvest strategy (constant harvest rate at the level expected to result in an equilibrium level of 50% unfished spawning biomass), 161t, and also the catch level that would be calculated under the CCAMLR control rule, which would be 184t.

Chapter 10 updates the uncertainty estimates reported in the Aurora Trough stock assessment chapter by applying Markov Chain Monte Carlo (MCMC) methods to the base-case scenario. This allows for a more accurate representation of the uncertainty associated with estimation and is superior to the normal approximation used to calculate the 2010/11 catch under the CCAMLR control rule as reported in Chapter 9. The results indicate that the highest 2010/11 catch by trawl in Aurora Trough which satisfies the requirements of the CCAMLR control rule is 138t. This is lower than the 184t reported from the approximation made in the stock assessment report, and is a result of the posterior distributions for average recruitment and the 1994, 1998, and 1999 recruitment deviations not containing as large values as included under the approximation.

Chapter 11 presents an update of the Aurora Trough base-case stock assessment based upon the following agreed assumptions/parameterizations:

1. value for the rate of natural mortality, M, of 0.13 yr^{-1},
2. use of the sex-specific growth curve parameters estimated by Constable *et al*. (2001),
3. length at 50% maturity of 89cm,
4. exclusion of tag recaptures in the year of release from the likelihood,
5. including over-dispersion in the tag-recapture likelihood,
6. a tag detection rate for the longline fleet of 0.94, the average of the annual values estimated for the trawl fleet.

The catch level for 2010/11 is calculated under the CCAMLR control rule, following application of Markov Chain Monte Carlo (MCMC) methods to characterise uncertainty in the parameter estimation. The constant catch satisfying the CCAMLR rule is calculated assuming that future catches are taken solely by trawl, or solely by longline.

The new base-case estimates 2010/11 spawning biomass to be 2,004t or 54% of unfished spawning biomass. The new base-case estimate for 2010/11 trawl available biomass is 2,920t. Trawl available biomass is 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 projected catch for 2010/11 under the CCAMLR control rule using the revised base-case is 140t. The magnitude of this catch is increased to 164t when the projected catches are assumed to be taken solely by longline instead of trawl. The catch levels under the CCAMLR control rule are, not surprisingly, similar to those calculated under an equilibrium F50 strategy (ie fishing at a constant harvest rate at the level expected to result in an equilibrium level of 50%

unfished spawning biomass), which are 145 and 173t if catches are taken purely by trawl or longline respectively.

Chapter 12 tests the ability of an integrated assessment model for Patagonian toothfish within Aurora Trough at Macquarie Island to estimate biomass and management reference points. The work deals primarily with testing how assumptions related to the aggregation of tag release data within the assessment model impact the ability to estimate key quantities of interest.

A simulation modelling framework is used (MSE), with an operating model tuned to represent the dynamics of the toothfish population assuming a single stock in Aurora Trough with exploitation by trawl and longline fisheries. The operating model generates data akin to that available from the Aurora Trough fisheries, namely results of a tag recapture program, length composition data, and age composition data. The value of additional data types and quantities are assessed. The estimation model, a stock assessment in the Synthesis software, is similar to the operating model, and is fitted to the data generated by the operating model, with different levels of aggregation in these data prior to estimation. The performance of the assessment model is evaluated by comparing estimates of quantities such as current spawning biomass, relative spawning biomass, trawl available biomass, and the recruitment time series with their true values in the operating model.

The assessment model is strongly influenced by the available tagging data, which can be included in the assessment in a number of ways. Scenarios examined include fixing the age at release for all tagged fish, or, for each year of tag data, splitting the tag releases into several tag groups and assigning these smaller groups individual ages, based on the length composition of the catch for that year. These scenarios were conducted for cases where the data available was considered to be equivalent to that actually available from the Aurora Trough, a ‘data-rich’ case which reduced the influence of observation error on the results, and for cases where the annual sample sizes of the age data were increased, to reflect the possible effect on the results of ageing additional otoliths that have been collected at Macquarie Island but remain as yet un-aged.

The results indicated that using a fixed age of release for all tagged fish in all years at Aurora Trough is unwise. Also, disaggregation to the greatest extent possible results in low numbers of recaptures for each tag group and hence inaccurate and imprecise estimates given the numbers of tags that have been released in the Aurora Trough. Disaggregating the data into a small number of tag groups per year (*e.g.* 5) currently appears to be the most sensible option for input into the Synthesis-based stock assessment of this resource

Scenarios which varied the quantity of age data available but kept the rest of the data at realistic levels demonstrated that much of the improvement in estimation performance associated with the data-rich scenario can be attributed to the age data. The results demonstrate that there is considerable value in ageing existing otoliths collected at Macquarie Island, particularly given that the realistic case assumed more age information than is available currently.

Chapter 14 uses Management Strategy Evaluation (MSE) to test the performance of a spatially-explicit stock assessment coupled with the CCAMLR harvest control rule and a constant fishing mortality harvest strategy for the Macquarie Island toothfish fishery. The operating model used for the simulations is conditioned on fits to the available data from Macquarie Island, assuming a two area model (northern and southern areas) that includes movement of toothfish between areas, and accounts for the recent development of fishing by longlining methods in the Aurora Trough and on the Macquarie Ridge, in addition to the fishing grounds traditionally fished by trawling. The MSE considers a stock assessment model similar to the

operating model. The stock assessment model is fit to data generated from the operating model, and the TAC for the following year is determined using the chosen harvest strategy. The operating model dynamics are then projected given the new TAC. At the end of a 35 year projection period from the present, a set of summary statistics are calculated to evaluate the performance of the harvest strategy with respect to management objectives. Scenarios considered include the sensitivity of results to (i) the choice of harvest control rule, (ii) the way future catches (and therefore tags) are allocated spatially, and (iii) in the quantities of data obtained for inclusion into the stock assessment procedures.

The results suggest that, when applying the CCAMLR control rule, the stock assessment and harvest strategy are able to satisfy management objectives with respect to spawning biomass levels, both in terms of target biomass and risk of falling below limit biomass reference points. Performance under a constant F strategy appeared more conservative, with final stock size being higher and catches lower than under the CCAMLR control rule. The spatial allocation of future catches when implementing the harvest strategy was an important determinant of harvest strategy performance, with equal allocation of catch to the northern and southern areas resulting in higher catches, lower final relative spawning biomass, and also less biased estimates of relative spawning biomass toward the end of the time series. Changing the future tagging rate also impacted performance by resulting in lower (and more variable) annual average catches when the tag rate was decreased to one tag per tonne. Spawning stock biomass levels were maintained at target levels under this scenario however, indicating that the harvest strategy responded appropriately to the increase in estimation uncertainty associated with fewer data when the tagging rate was reduced.

An inspection of the error in the estimates of final year relative spawning biomass during the time series of the simulation projections revealed a cumulating bias in the stock assessment results. This bias appeared to be related to both the way in which future catches and tag releases are allocated spatially, and also as a result of mis-specification between the way in which the tagged population is modelled between the operating model and the stock assessment model. High exploitation rates in one area under certain spatial allocation of future catches tends to result in poorer estimation of movement and spatial allocation of recruitment in the assessment model, as tags are removed from the population before they can provide information on movement dynamics. Additional analyses that modelled the dynamics of the tagged population in the operating model as discrete resulted in different values for performance measures than the prior assumption of continuous dynamics. Chapter 12 revealed that incorrect assignment of ages to tag releases within the model also produces bias in assessment results. Model mis-specification therefore appears to be an important driver of harvest strategy performance. Future work will explore further the sources of bias given different operating model scenarios and degrees of mis-specification, in order to evaluate whether there exist scenarios that provide sufficiently robust outcomes to such biases.

KEYWORDS: Patagonian toothfish, Stock assessment, Macquarie Island, Heard Island and McDonald Islands, Management strategy

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3. BACKGROUND

3.1 Patagonian toothfish

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.

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 2000m, 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 trawled from depths of 400m and more. This has allowed an extensive tagging program to develop at both Macquarie Island and HIMI. Tagging studies have increased knowledge of the species movement, growth and available abundance (Williams *et al*., 2002; Tuck *et al*., 2003).

3.2 Macquarie Island

Macquarie Island lies some 1500km to the southeast of Tasmania (Figure 3.1). The fishery off Macquarie Island began in November of 1994. Two major 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. Between 1995/96 and 2010/11, 12079 tags have been deployed and 1795 tagged fish have been recaptured. Very few tagged fish have been recaptured having moved between the main fishing grounds during this period (21 from Aurora Trough to Macquarie Ridge and 14 from Macquarie Ridge to Aurora Trough).

A Total Allowable Catch (TAC) for the fishery was first introduced in the 1996/97 fishing season. 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 stock assessment model. For the Aurora Trough region, commercial TACs for the trawl fishery were 750 and 200 tonnes (t) 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 trawl fishery has existed in every season except for 2009/10, and the commercial trawl quota was 140t in 2010/11 (Table 3.1).

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

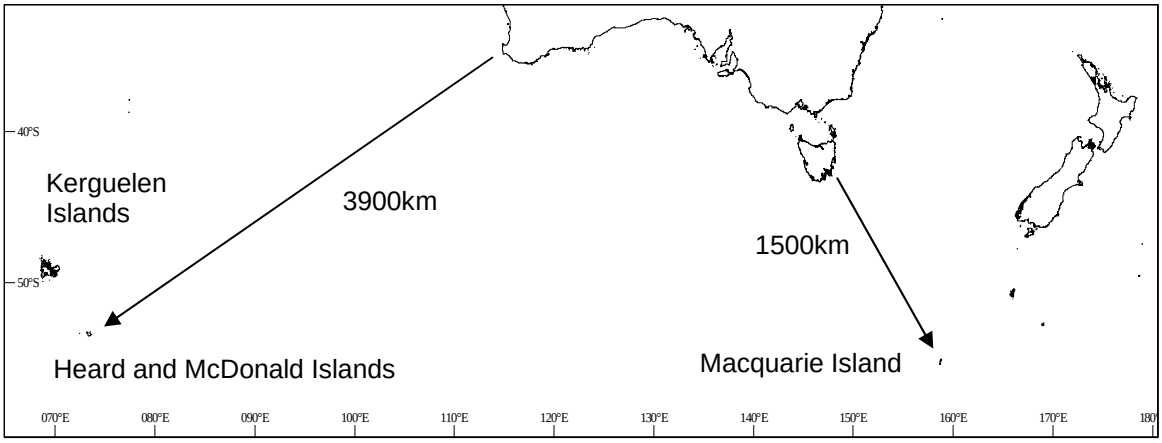

Figure 3.1. The location of Macquarie Island (54°30'S, 158°57'E) and Heard Island and McDonald Islands (53°06'S, 73°30'E) relative to New Zealand and Australia.

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. The trial was initiated in August of 2007 with the vessel *Avro Chieftain*. In 2007 a total of 79t of Patagonian toothfish was caught from 167,000 hooks set, including 5000 hooks set in Aurora Trough. Between 2007 and 2010 a total of 2430 tagged fish were released, with 151 recaptured. Of the recaptures, 120 have moved less than 10nm. Catch rates have varied between 500kg/1000 hooks in 2007 and 1077kg/1000 hooks in 2010. Average catch rates were highest in Aurora Trough (Williams, 2011).

The assessment of the Macquarie Island Patagonian toothfish stock has been based on the tag-recapture model developed by de la Mare and Williams (1997), and modifications described in Tuck *et al.* (2003). The tag-recapture model used population and tag accumulation models to account for tags being released at various times throughout the season and the effects of removals by fishing. The model estimates pre-tagging available abundance and the annual net change in available abundance between fishing seasons for the major fishing grounds of Macquarie Island. In 2004, a new model that expanded upon the traditional tag-based model was introduced. 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. The model was also able to project the stock into the future under various fixed TAC scenarios in order to provide insights into appropriate TACs and the likely short and long-term impact on mature biomass. However, with the introduction of the longline fishery at Macquarie Island, with its potentially greater spatial range and ability to target more mature

fish, the tag-recapture based assessment and MSE needed to be updated in order to appropriately account for the new gear type and spatial aspects of the fishery. This report documents the development of these models and presents results from the new stock assessment and MSE.

Table 3.1. The Total Allowable Catch (TAC) and Catch for the Macquarie Island Patagonian toothfish fishery in Aurora Trough and Macquarie Ridge.

Administrative Period	Aurora Trough		Macquarie Ridge	
	TAC	Catch	TAC	Catch
1994 – 31 Aug 1996	Not set	1351	Not set	0
1 Sept 1996 – 31 Aug 1997	750	489	1000	586
1 Sept 1997 – 31 Dec 1998	200	200	1500	397
1 Jan 1999 – 31 Dec 1999	40 (research)*	36	600 (1000)	26
1 Jan 2000 – 31 Dec 2000	40 (research)*	11	510 (1000)	7
1 Jan 2001 – 31 Dec 2001	40 (research)*	23	420 (1000)	0.1
1 Jan 2002 – 31 Dec 2002	40 (research)*	36	242 (782)	2.5
1 Jan 2003 – 30 June 2003	40 (research)*	0	205 (665)	0.6
1 July 2003 – 30 June 2004	354	352	174 (441)	0.7
1 July 2004 – 30 June 2005	60 (research)*	57	148 (376)	0.6
1 July 2005 – 30 June 2006	255	241	125 (319)	8.5
1 July 2006 – 30 June 2007	241	238	100 (264)	0.7
1 July 2007 – 30 June 2008	390	223	86***	84
1 July 2008 – 30 June 2009	312	307	150***	149.7
1 July 2009 – 14 April 2010	60 (research)***	66	150***	146.1
15 April 2010 – 14 April 2011	140	125	150***	138.9

* a research TAC for Aurora Trough was set to enable the tag based stock assessments to be undertaken. Commercial TACs were not set during these periods.

** for the Macquarie Ridge sector, the tonnage (shown in brackets) would have been triggered if trawl catch rates reached a threshold of 10 tonnes per km^2 over 3 consecutive fishing days. This TAC has not been triggered since operations began.

*** the TACs shown are those set for the longline trial.

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4. NEED

The fishery for Patagonian toothfish at Macquarie Island has expanded from a trawl only fishery (since 1994) to include a single longline vessel. The ability to set gear in untrawlable ground has led to the discovery of fish outside of the traditional trawl grounds. This has included a diverse size-range of fish and for the first time, spawning fish. The inclusion of this new gear-type, with its potentially greater spatial range and ability to target more mature fish, needs to be considered appropriately (in conjunction with the trawl fishery) to ensure the continued sustainability of the fish stock. A tag/recapture based assessment and MSE has been developed for the trawl-only fishery but will need substantial updating to include the new gear type and spatial aspects of the fishery. There is also a key need for the continued monitoring of the population through the tag-recapture programme. Tagging is a vital element of the stock assessment and this project included funding for the purchase and related infrastructure required to deploy approximately 1000 tags per year.

5. OBJECTIVES

1. To provide the SARAG with a revised assessment that provides estimates of the status of Patagonian toothfish around Macquarie Island.

2. To develop methods in the assessment that account for (a) the expanding spatial aspects of the fishery and (b) the introduction of longline fishing in the area.

3. To update and further develop the MSE to include the new assessment model and include hypotheses about the spatial aspects of the stock.

4. To continue monitoring the stock through the tag-recapture program.

6. A REVIEW OF THE *DISSOSTICHUS ELEGINOIDES* TAGGING PROGRAM AT MACQUARIE ISLAND, 2007-2010

Dirk Welsford, Dick Williams, Tim Lamb

6.1 Introduction

The Australian Antarctic Division manages the *Dissostichus eleginoides* tagging program conducted at both Heard Island and the McDonald Islands in the Indian Ocean Sector of the Southern Ocean, and Macquarie Island in the Pacific Sector. This role includes evaluating tagging systems and equipment, instructing Australian Fisheries Management Authority observers in correct tagging procedures, maintaining and distributing tags and tagging equipment to AFMA observers deployed on fishing vessels, providing at sea data capture and storage, quality checking data when it is returned from vessels, storing it in a secure database and disseminating data to researchers for use in assessments.

Here we describe the *Dissostichus eleginoides* tagging program at Macquarie Island during the experimental longline fishery between 2007 and 2010, and summarise data on releases and captures.

6.2 Methods

Due to the exploratory nature of the longline fishery, and the relative lack of data on distribution and abundance of toothfish along the Macquarie ridge in deeper waters that are accessible by longlines, the vessels fishing were requested to spread their fishing along the ridge, and tag as many fish as possible, aiming for 3-4 fish per tonne green weight landed.

From the start of the mark-recapture program at Macquarie Island in 1995-6, all fish tagged have been tagged in a consistent way. Observers haphazardly select toothfish representative of the sizes of fish being caught on a line and without any severe external injuries as they come aboard, and are placed in a holding tank filled with seawater. Fish are observed after ~30 minutes or so, and fish showing no signs of morbidity are measured, weighed and tagged. Two dart tags are placed together generally behind the dorsal fin. In addition for fish larger than 400 mm in total length a TIRIS© (Texas Instruments) passive integrated transponder (PIT) electronic tag was also inserted in the muscle behind the head of each toothfish. Fish are then returned to the holding tank for ~30 minutes, scrutinised again for signs of morbidity, and if judged to be highly likely to survive, are released through the vessel scuppers, with the observer recording the exact time and location of release.

Tag recaptures are generally first reported by crew members as fish are hauled aboard the vessel. The observer records the captures times and location, and measures and weighs the fish and euthanises the fish by severing the spinal column. The observer then removes the dart tags and dissects the PIT tag out of the fish, opens the visceral cavity to inspect the gonad to determine it sex and reproductive developmental stage, and removes the otoliths.

All fishing catch and effort data, as well as biological and tagging data, tags and otoliths are is submitted to AAD at the conclusion of each voyage. All data is entered into a secure SQL

database following a quality control procedure, including linking release details of all recaptured tagged fish.

6.3 Results and Discussion

From 2007 to 2010, four voyages were undertaken by longliners to Macquarie Island; in 2007 by the *FV Avro Chieftain* and 2008-2010 by the *FV Janas*. Fishing was successfully spread along the ridge, and a high average tagging rate was achieved in all seasons. Figure 6.1 shows the locations of the fishing grounds and the standardised ground names used in this report, and Table 6.1 indicates the number of tags released in each ground. Tagging rates exceeded 3 tags per tonne on all voyages.

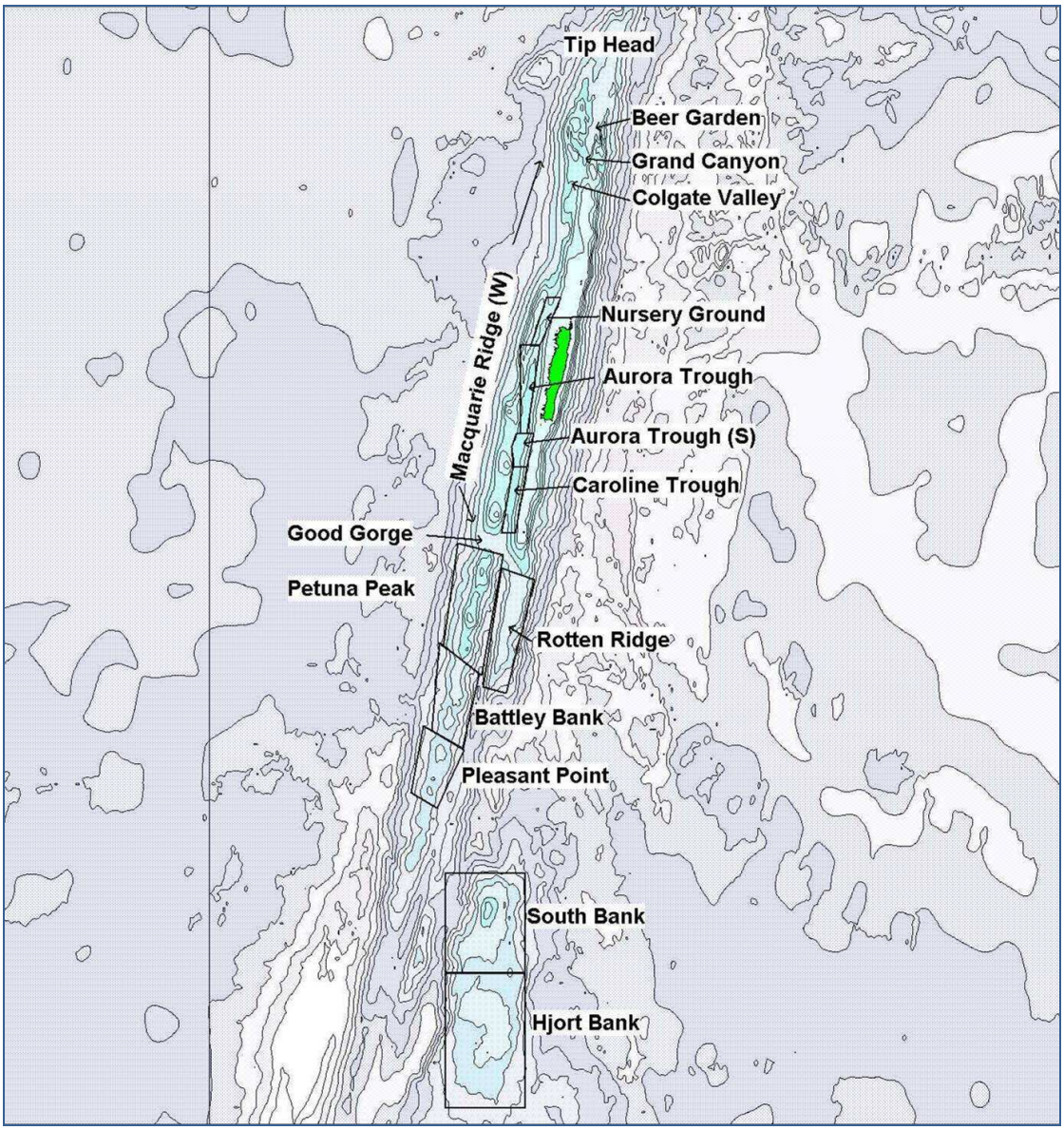

Figure 6.1. Locations of fishing grounds.

Table 6.1. Summary of placement of tagged toothfish by ground. Numbers in brackets are recaptured tagged fish that were re-released.

Ground	2007	2008	2009	2010	Total
Hjort Bank	20				20
South Bank	4				4
Pleasant Point	18	89			107
Caroline Ridge (W)	96	98	120 (+2)	48 (+1)	362 (+3)
Caroline Ridge (E)	38	78 (+2)	100	166	382 (+2)
Macquarie Ridge (W)	31	180 (+1)	124		335 (+1)
Tip Head	9	20			29
Aurora Trough			342 (+1)	484 (+2)	826 (+3)
Aurora Trough (S)			30	45	75
Caroline Trough			40	250 (+2)	290 (+2)
Total	216	465 (+3)	756 (+3)	993 (+5)	2430 (+11)

A total of 151 tagged fish have been recaptured since 2007 (95 of them in 2010); 44 of which were tagged by *Avro Chieftain* in 2007 and 2008, 53 by the trawlers *Austral Leader* and *Southern Champion* since 1997, 52 by *Janas* in 2009, 2 by *Janas* in 2010 and one tagged outside the Macquarie Island AFZ. Of these, 120 (79%) have moved less than 10 n miles during up to 12.8 years at liberty (Table 6.2). 108 of these fish (72% of the total recaptures) stayed within the same ground in which they were released. The remaining 12 short distance movers were recaptured in an adjacent ground. Mean movement rates ranged from less than 0.2 $nm.yr^{-1}$ in Aurora Trough South, to over 10 $nm.yr^{-1}$ for one fish released in Aurora Trough and recaptured in Caroline Trough, and one fish released in Pleasant Point and recaptured at Battley Bank West, both after less than one year at liberty. 22 of the 59 fish that stayed within Aurora Trough were at liberty for more than four years. The large number of fish that have stayed within Aurora Trough, with a generally long time at liberty is a consequence of the very large number of fish tagged within Aurora Trough since 1997 during the trawl fishery, as well as an apparent tendency for fish to reside in (or return to) Aurora Trough over many years.

31 of the remaining recaptures had moved more than 10 n miles (Table 6.3 and Figure 6.2). 13 of these fish originated in Aurora Trough, all but one released during the trawl fishery, and all moved southwards as far as Pleasant Point in 0.8 to 14.2 years, with the majority taking 4-10 years (Figure 6.2a). Three fish were released in the Nursery Ground immediately north of Aurora Trough. One of these moved northwards a short distance to neighbouring Macquarie Ridge and the other two moved 48 to 63 n miles south to Petuna Peak and Battley Bank and were at liberty for 9 to 11.5 years. Of the remaining 15 fish, 3 moved virtually the entire length of the main ridge, two southwards from Grand Canyon (a trawling ground near Tip Head) and the other northwards from Battley Bank to the northern part of Macquarie Ridge, a distance of 75-96 n miles (Figure 6.2b). The other 12 fish moved distances of 12 to 70 n miles between non-adjacent grounds, 7 northwards and 5 southwards in 0.8-10 years.

The final recapture was of a fish with a foreign tag of the type used by New Zealand and CCAMLR in Antarctic waters, which was recaptured at Battley Bank (W). Detailed data on the release of this fish has not been made available, but circumstantial evidence suggests that it may have been tagged in the New Zealand EEZ on the northern extension of the Macquarie Ridge in early 2009[1]. This would mean the fish had travelled south westwards about 200 n miles in four months. This is particularly noteworthy as it is the first recorded capture of a fish originating outside the Macquarie Island AFZ.

Table 6.2. Details of fish movements of less than 10 n miles within grounds or between adjacent grounds.

Release Ground	**Recapture Ground**	**Number of recaptures**	**Mean distance between release and recapture (nm)**	**Mean days at liberty**	**Mean movement rate (nm.yr^{-1})**
Aurora Trough	Aurora Trough	59	3.73	1120	1.22
Aurora Trough	Aurora Trough (S)	2	3.24	286	4.14
Aurora Trough	Caroline Trough	1	8.66	288	10.98
Aurora Trough (S)	Aurora Trough (S)	1	2.18	3761	0.21
Caroline Trough	Caroline Trough	8	3.20	253	4.62
Caroline Trough	Petuna Peak (E)	1	0.55	315	0.64
Macquarie Ridge (W)	Macquarie Ridge (W)	8	4.82	410	4.29
Macquarie Ridge (W)	Petuna Peak (W)	2	1.22	545	0.82
Petuna Peak (W)	Petuna Peak (W)	10	2.51	620	1.48
Petuna Peak (W)	Good Gorge	1	5.27	718	2.68
Petuna Peak (E)	Petuna Peak (E)	11	3.54	416	3.11
Petuna Peak (E)	Battley Bank (E)	1	7.08	339	7.63
Petuna Peak (E)	Caroline Trough	1	6.6	690	3.49
Battley Bank (W)	Battley Bank (W)	5	0.75	353	0.78
Battley Bank (W)	Battley Bank (E)	1	1.96	391	1.83
Battley Bank (W)	Pleasant Point	1	8.00	345	8.47
Battley Bank (E)	Battley Bank (E)	1	5.45	696	2.86
Pleasant Point	Pleasant Point	5	1.38	335	1.50
Pleasant Point	Battley Bank (W)	1	9.61	335	10.48
		120	3.53	793	2.19

[1] Anon (2010). Introduction of Patagonian Toothfish (PTO) into the Quota Management System on 1 October 2010: Final Advice Paper. http://www.fish.govt.nz/NR/rdonlyres/6F5F0AAB-7D56-410F-940E-0BBD938BCAC9/0/toothfish_FAP.pdf

Table 6.3. Details of fish movements of greater than 10 n miles.

	Release ground	Recapture ground	Number of recaptures	Range of distance (n miles)	Range of days at liberty
Northward	Aurora Trough	Caroline Trough	8	11.8-26.0	286-5196
	Aurora Trough	Petuna Peak	3	27.1-43.72	2043-3775
	Aurora Trough	Battley Bank	1	53.65	886
	Aurora Trough	Pleasant Point	1	66.1	2041
	Nursery Ground	Macquarie Ridge	1	19.61	4273
	Nursery Ground	Petuna Peak	1	48.35	3321
	Nursery Ground	Battley Bank	1	63.26	4285
	Grand Canyon	Petuna Peak	1	75.0	4560
	Grand Canyon	Battley Bank	1	96.11	3879
	Macquarie Ridge	Good Gorge	1	70.2	369
	Macquarie Ridge	Petuna Peak	1	12.2	688
	Petuna Peak	Petuna Peak	2	11.7-17.7	313-3779
	Petuna Peak	Battley Bank	1	14.6	702
Southward	Aurora Trough S	Aurora Trough	1	15.3	3781
	Petuna Peak	Aurora Trough	1	29.5	285
	Petuna Peak	Caroline Trough	1	12.8	299
	Petuna Peak	Macquarie Ridge	1	17.33	335
	Battley Bank	Macquarie Ridge	1	95.55	713
	Battley Bank	Petuna Peak	1	32.8	691
	Pleasant Point	Petuna Peak	1	21.94	389

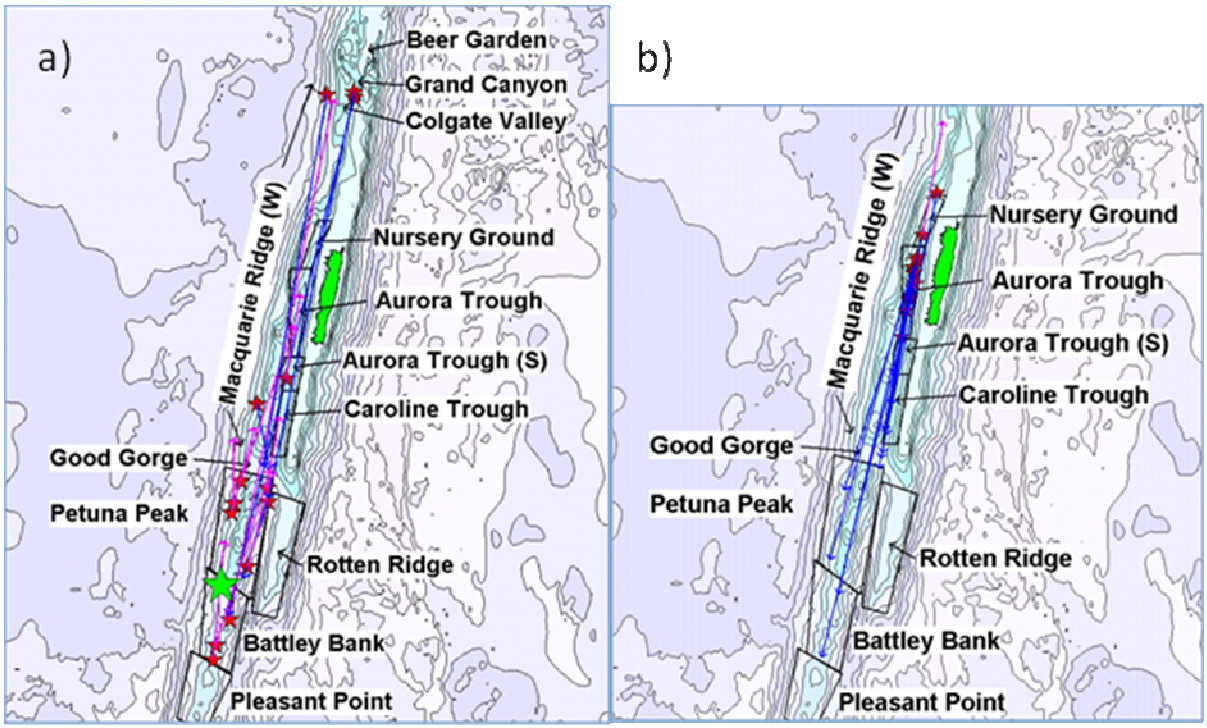

Figure 6.2. a) Movements of recaptured tagged toothfish originating in Aurora Trough and Nursery Ground. Red stars denote release location and arrows point to recapture locations (purple: moving northwards and blue: moving southwards). b) Movements of recaptured tagged toothfish originating outside Aurora Trough and Nursery Ground. The large green star denotes the recapture location of the foreign tagged fish.

7. IMPACT OF ALTERNATIVE TAGGING SCENARIOS ON ABUNDANCE ESTIMATION OF PATAGONIAN TOOTHFISH IN THE MACQUARIE RIDGE LONGLINE FISHERY

Gavin Fay

7.1 Summary

This chapter summarises the results of calculations that apply simple Lincoln-Petersen based tag-recapture models to data from the exploratory longline fishery for Patagonian toothfish at Macquarie Island. The goal was to evaluate the impact on the precision of current and future abundance estimates of alternative tagging scenarios, related to the TAC for the Macquarie Ridge sector. Results suggest that, based on 2007 and 2008 tag releases and assumptions about the exploitation level that catches in 2009 could impose on the population, the expected CVs in abundance for 2009 and 2010 are relatively low, and there is little perceived improvement in abundance estimate precision associated with increases in either or both the TAC and the tagging rate.

7.2 Introduction

The longline trial for Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island has operated in 2007 and 2008, with catches of 85 t and 148 t respectively. Associated with these catches have been tag releases of 684 fish (216 in 2007 and 468 in 2008), and recaptures of 18 tagged fish (2 in both 2007 and 2008 from trawl tagged fish, and 16 in 2008 from longline tagged fish released in 2007). It is of benefit to understand how both the numbers of tags in the water, and the tagging rate contribute to understanding of stock abundance on Macquarie Ridge, as this can inform the allocation of future catches and appropriate tagging rates.

This chapter presents the results of applying some simple Peterson-based tag-recapture models to the Macquarie Island longline fishery, with the intent of examining the influence of TAC and tagging rate on the precision of the abundance estimate, given different assumptions regarding the current stock size. The change in precision in the estimate of 2009 abundance obtained by increasing the TAC above 150t is examined, as is the precision in the 2010 abundance estimate given different values for both the 2009 and 2010 TAC and the tagging release rate in 2009.

7.3 Methods

The impact of alternative tagging scenarios on the ability to estimate abundance was evaluated by calculating the expected precision of the unbiased Lincoln-Petersen abundance estimator (Seber 1992) given different assumptions about the rate of tagging, the current exploitation rate, the future TAC, and the number of tags available in the population to be re-caught. The calculations considered that the Macquarie Ridge longline fishery is exploiting a separate

resource from the trawl fishery in Aurora Trough. The impact of scenarios on the precision of both the 2009 and 2010 abundance estimates were evaluated.
The coefficient of variation (CV) of the abundance estimate can be formulated as a function of the number of tags available to be recaptured and the exploitation rate (*cf.* Hillary 2008):

$$CV(\tilde{N}_t) = \sqrt{\frac{\tilde{T}_t(1-u_t)}{(\tilde{T}_t+1)(u_t\tilde{T}_t+2)}} \tag{1}$$

where $\tilde{N}_t$ is the estimate of abundance at time *t*,

$\tilde{T}_t$ is the number of fish tagged and available to be recaught at time *t*, and

u_t is the exploitation rate at time *t*.

7.3.1 2009 abundance estimate

Exploitation rate - The exploitation rate u_t is the ratio of both the numbers of recaptures to the number of tags available to be recaught, and the catch biomass to the exploitable biomass. As there is currently no abundance estimate for Macquarie Ridge, the exploitation rates that the recent longline catches have imposed on the stock are unknown. Consequently, a range of values for the exploitation rate (0.01-0.2, or 1%-20%) that the proposed 2009 TAC of 150t would impose on the stock were explored.

2009 TAC – To explore the impact of setting a higher TAC than 150t in 2009 on the precision of the abundance estimate, alternative values for the 2009 catch of 175, 200, and 250t were explored.

Available tags - The number of fish available to be tagged in 2009, $\tilde{T}_{2009}$, was calculated by assuming that the only fish available were those released during the 2007 and 2008 longline trial (that is, no fish tagged in trawl fishery at Macquarie Island were available), and that these fish had experienced 2 and 1 year's worth of natural mortality. In addition, the 2008 recaptures from the 2007 released fish were also removed.

$$\tilde{T}_{2009} = \left[\left(216\ e^{-M}\right) - 16 + 468\right]e^{-M} \tag{2}$$

The rate of natural mortality, *M*, was assumed to be 0.13 yr^{-1}, consistent with the value used in the stock assessment for Aurora Trough (Tuck and Lamb 2008).

7.3.2 2010 abundance estimate

The precision of the 2010 abundance estimate is determined not only by that year's exploitation rate, but also by both the exploitation rate and TAC in 2009, and the 2009 tagging rate, as these will determine the value for the number of tags available to be recaught in 2010, ie $\tilde{T}_{2010}$. The calculations of the CV in abundance for 2010, $CV(\tilde{N}_{2010})$, are therefore based on the range of values for the 2009 TAC and u_{2009} considered above and assumptions regarding u_{2010} (same range as for 2009) and the 2009 tagging rate (i.e. number of tags per tonne of TAC). The number of tags available to be caught in 2010 is therefore:

$$\tilde{T}_{2010} = \left[\tilde{T}_{2009}(1-u_{2009}) + \lambda_{09}\mathrm{TAC}_{'09}\right]e^{-M} \tag{3}$$

where λ_{09} is the tagging rate (per tonne) in 2009.

Tagging scenarios – The tagging rate of longline operations at Macquarie Island has been around 3 tags per tonne. Indications are that this could be increased if sufficient benefit from this additional effort were to be demonstrated. A range of possible 2009 tagging rates from 1 to 5 tags per tonne of the 2009 TAC was considered to assess the effect on the CV of the abundance estimate of either decreasing or increasing the tag rate.

7.4 Results

7.4.1 2009 abundance estimate

The CV in the Lincoln-Petersen abundance estimate for 2009 unsurprisingly decreases as exploitation rate increases, with lower rates of improvement in the CV at higher exploitation rates (Figure 7.1). The gain in CV of moving to a higher TAC given a fixed exploitation rate at 150t is greatest as exploitation rate increases, with little to no reduction in CV with increasing the catch when the exploitation rate is low (contour lines in Figure 7.1 are almost vertical at low values for the exploitation rate given catches of 150t).

7.4.2 2010 abundance estimate

The precision of the 2010 abundance estimate improves as the tagging rate increases, irrespective of the total TAC in 2009 and the exploitation rate in 2010 (Figure 7.2 and Figure 7.3). In addition, for a fixed tagging rate, precision also improves (CV decreases) as the TAC 2009 increases. Both these factors essentially do the same thing, that is, both a larger 2009 TAC and a greater tagging rate lead to more tags in the water and therefore a larger value for $\tilde{T}_{2010}$.

There appears to be little sensitivity of the 2010 abundance CV to the exploitation rate in 2009, with the contour lines in Figure 7.2, Figure 7.3, and Figure 7.4 being almost horizontal. This suggests that, with the additional release of tags in 2009, the expected recaptures in 2009 do not impact the ability to estimate future abundance, except at high exploitation rates and low tagging rates (*e.g.* Figure 7.2 and Figure 7.3, 1 tag per tonne).

The expected CVs of the abundance estimates are in general low, and although there is an improvement in precision (reduction in TAC) associated with either a larger 2009 TAC or higher 2009 tagging rate, this improvement is rather minimal. Figure 7.5 demonstrates the expected utility of moving from a 2009 TAC of 150t and a tagging rate of 3 tags per tonne to a 2009 TAC of 200t and a tagging rate of 4 tags per tonne. Even at high levels of exploitation, the percent improvement in the CV with the higher TAC and tag rates is not more than 14% of the values obtained under the 150t TAC scenario (Figure 7.5, right-hand panel). At low exploitation rates, this % improvement in CV is much lower (Figure 7.5).

7.5 Discussion

The results of the calculations suggest that there may be little benefit, in terms of the precision of abundance estimates, to increasing the TAC for 2009 or increasing the tagging rate from the prior 3 tags per tonne. The reductions in the CV associated with these changes are small, and in practice are likely to be swamped by the additional uncertainties that will be introduced through both observation error, and errors associated with deviations from the assumptions inherent to the particular calculations and the Lincoln-Petersen estimator as a whole (closed population, tags are fully mixed and are equally available to the fishery, etc.).

Evaluating the impact of data collection schemes (tag release-recapture program) on the ability to estimate quantities of interest (vulnerable biomass) is an important part of their implementation, as often there are fixed resources that can be allocated to monitoring programmes and it is of interest to allocate these optimally, in order to derive the most benefit. While the calculations presented here are fairly simple in approach, they do provide a means to evaluate potential benefits (or lack thereof) of alternative options. With regard to the tag recapture program in the Macquarie Island longline fishery, there is also a trade-off to be considered in that the performance of the data collection scheme (its ability to estimate abundance precisely) is also tied to a measure of risk, that is given a fixed intensity of tagging effort, the CV of abundance is dependent on the TAC. This implies that the most precise estimates of abundance are associated with exploitation levels that impose a level of risk to the stock. No accounting for risk to the stock is made here when comparing different levels of catch or levels of tagging intensity. However, the current target exploitation rate used in the harvest strategy for the Aurora Trough is 10% of available biomass (*e.g.* Tuck and Lamb 2008), and other target rates of exploitation for Patagonian toothfish stocks that have been designed to minimise risk are within the range of options considered in the calculations here.

7.6 References

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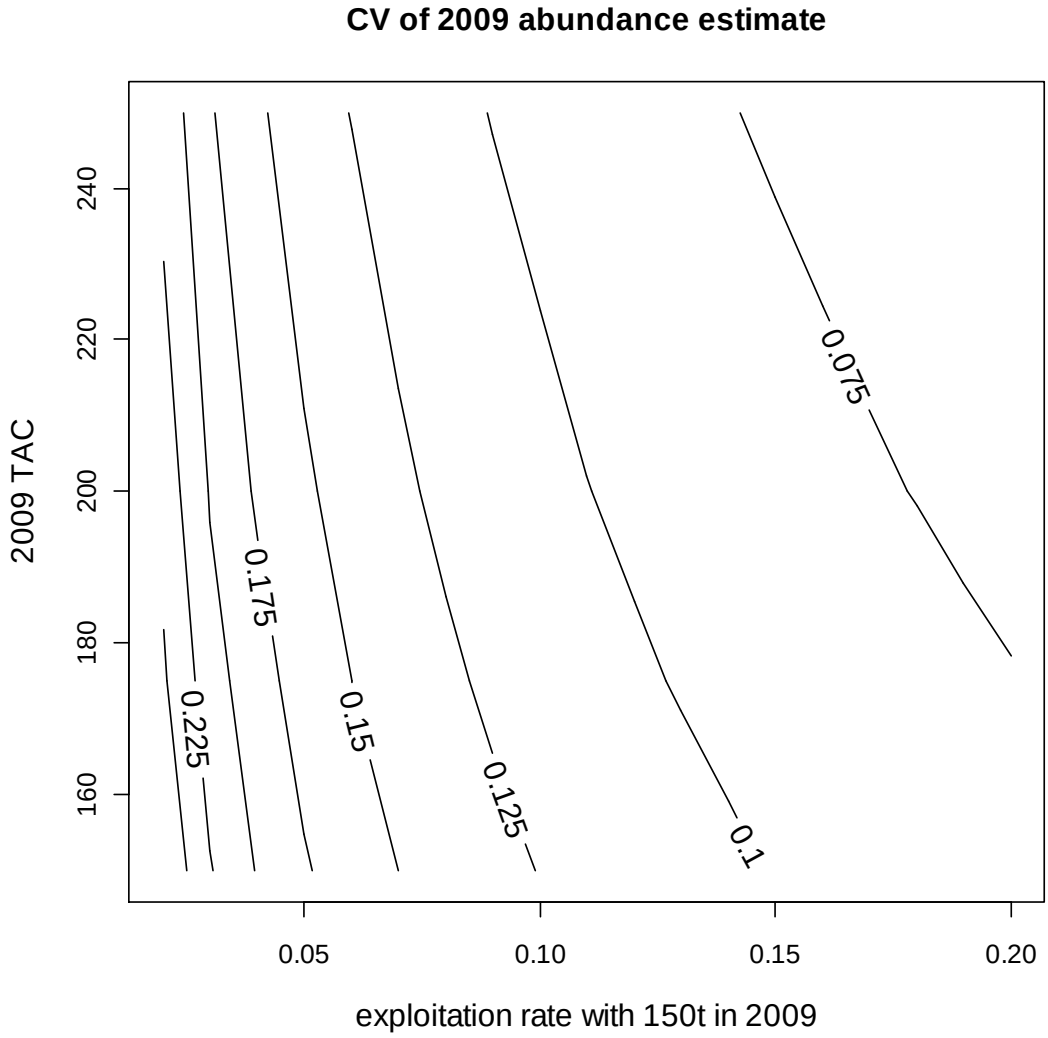

Figure 7.1. Changes in the coefficient of variation (CV) of the 2009 abundance estimate given different assumptions regarding the size of the stock (exploitation rate with 150t, low values imply a large stock, high values imply a smaller stock), and different levels of TAC for 2009.

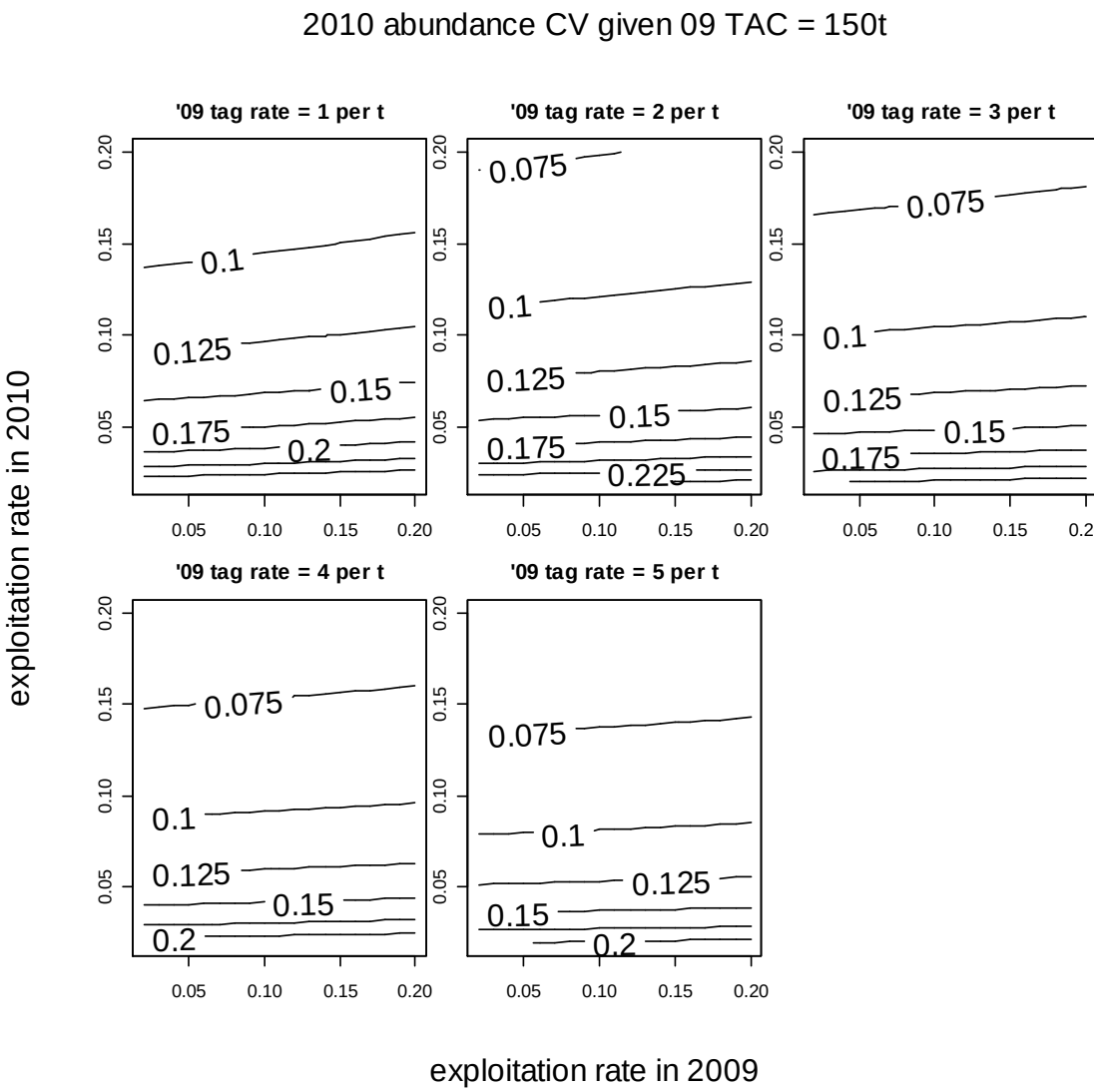

Figure 7.2. Changes in the CV in the 2010 abundance estimate given 150t TAC in 2009 and different exploitation rates in 2009 and 2010, for different intensities of tagging in 2009.

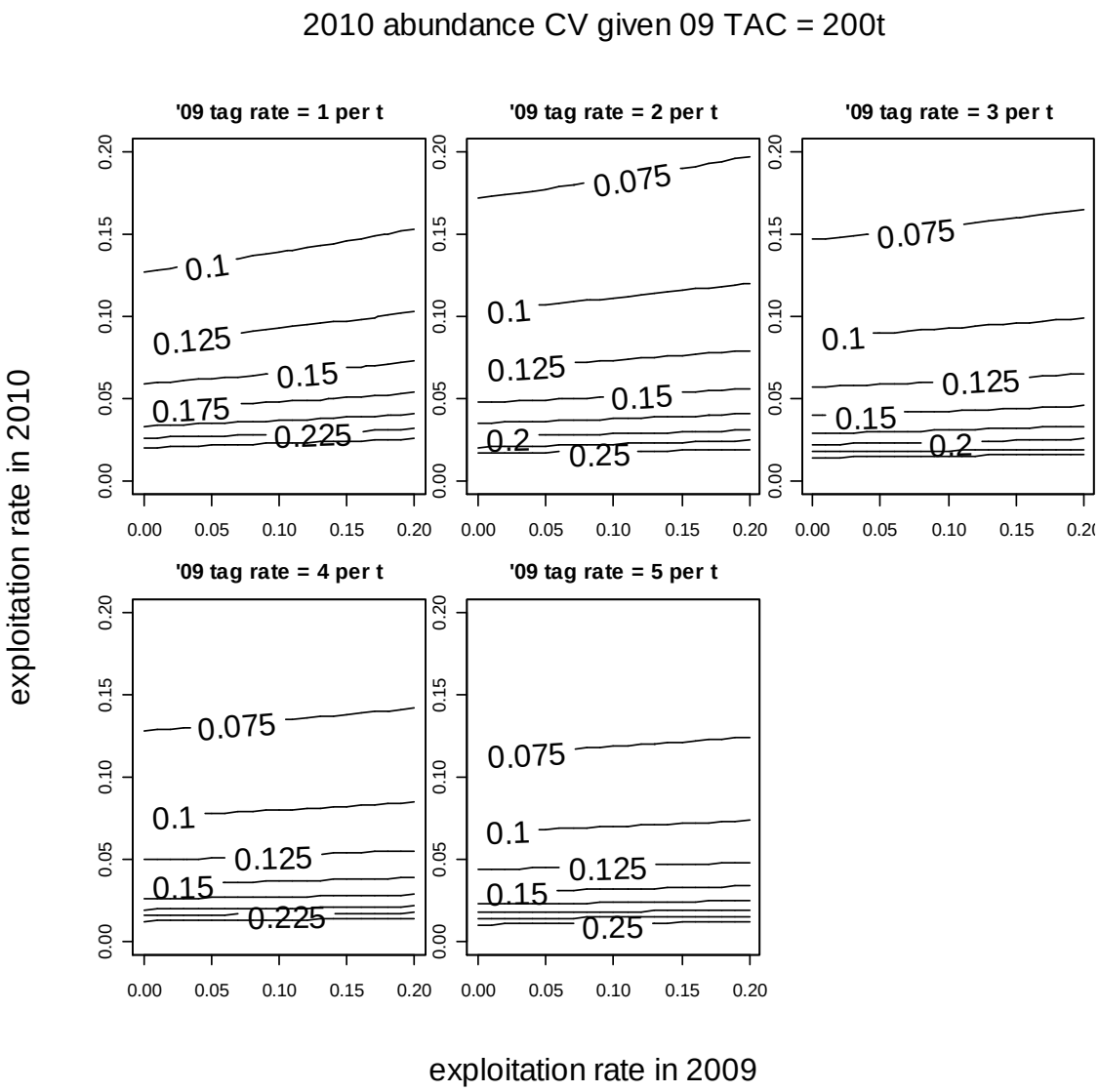

Figure 7.3. Changes in the CV in the 2010 abundance estimate given a 2009 TAC of 200t and different exploitation rates in 2009 and 2010, for different intensities of tagging in 2009.

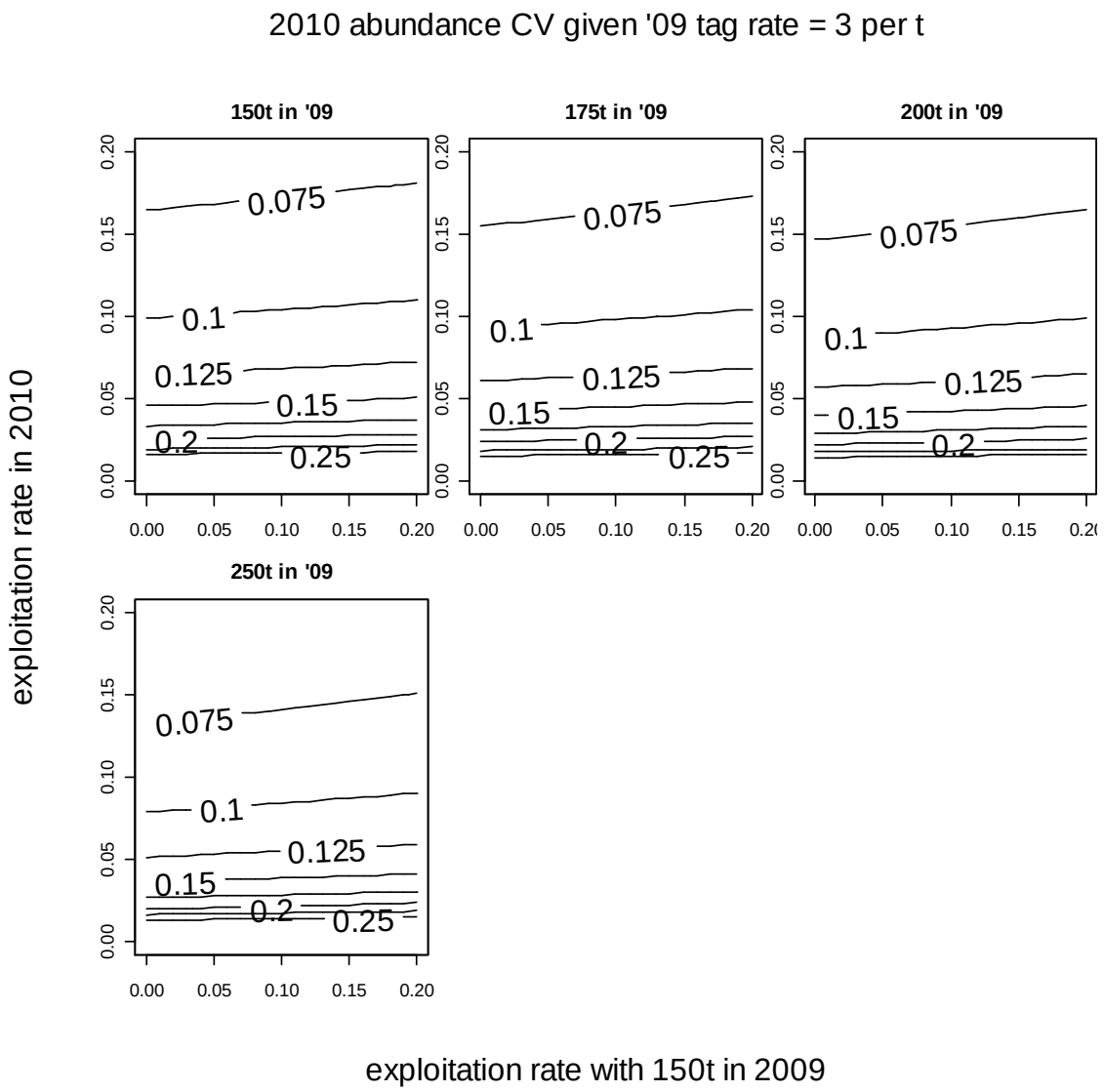

Figure 7.4. Changes in the CV in the 2010 abundance estimate given a 2009 tagging rate of 3 tags per tonne of TAC.

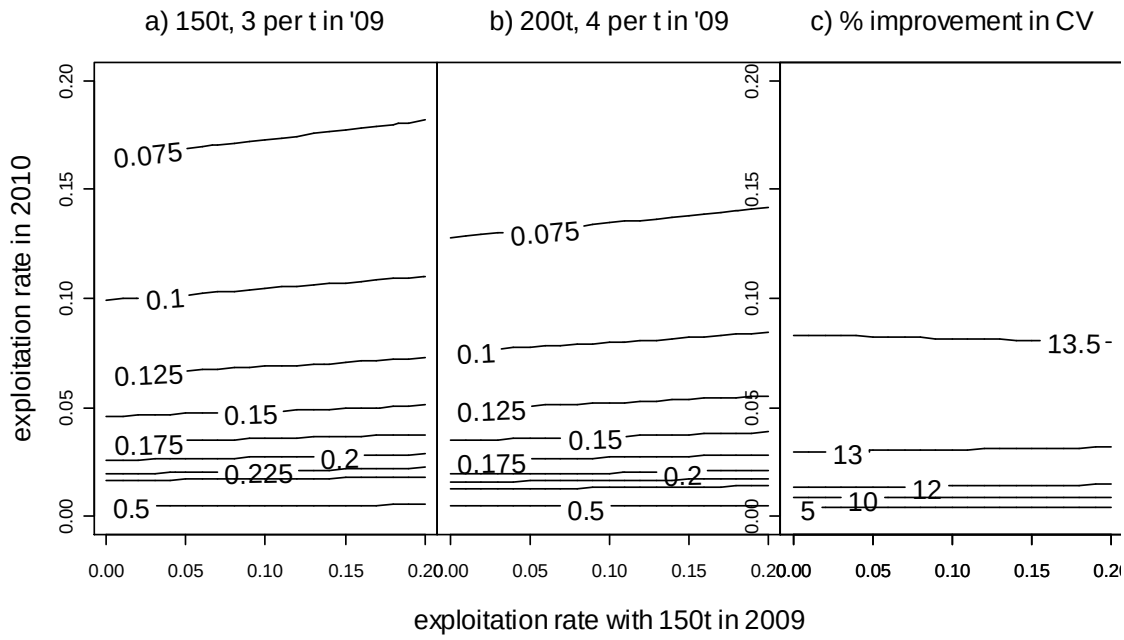

Figure 7.5. CV of 2010 abundance estimate given range of exploitation rates in 2009 and 2010 with a) a catch of 150t in 2009 and a tagging rate of 3 tags per tonne, b) a catch of 200t in 2009 and a tagging rate of 4 tags per tonne. Panel c) shows the percent improvement in the CV of the 2010 abundance estimate as a result of moving from a) to b).

8. DEVELOPMENT OF SPATIALLY-EXPLICIT INTEGRATED STOCK ASSESSMENT MODELS FOR THE MACQUARIE ISLAND TOOTHFISH FISHERY USING DATA UP TO AND INCLUDING JULY 2009[2]

Gavin Fay, Geoff Tuck, Tim Lamb

8.1 Summary

This chapter presents preliminary results of fitting an integrated assessment model (Stock Synthesis) to the available data from the trawl and longline fishery for Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island. The model fits to data obtained from the tag-recapture program at Macquarie Island since 1995, to length composition data for the years 1994-2009, and to age-at-length data from aged otoliths.

A focus is placed on presenting the results of assuming different model structures rather than exhaustive sensitivity analyses. Three structural versions of the assessment model are presented:

1. a single area model which designates five different fleets (Aurora Trough trawl and longline, Northern Valley trawl, and North and South Macquarie Ridge longline) to attempt to capture the spatial and gear-dependent differences in availability but which assumes that the population these fleets exploit is homogeneous,

2. a two-area model which accounts for heterogeneity in toothfish availability between the northern and southern areas of operation of the fishery, with movement among areas, and

3. a three-area model which separates the major historical trawl grounds (Aurora Trough and Northern Valleys) from the Macquarie Ridge, with recruitment occurring only at the trawl grounds, and movement of fish between areas thereafter.

All models are able to fit the length data and age-at-length data equally well. The models all also manage to mimic the total number of annual tag recaptures well.

The models differ in their ability to mimic the patterns of tag recaptures by fleet. The single-area model cannot reconcile the heterogeneity in recaptures among fleets (ie it predicts fewer recaptures for the fleet of release than observed, and predicts more recaptures for the other fleets than observed). This occurs because the model is treating the population as one homogeneous pool and has no means of preventing the tagged fish from being available to the other fleets. Models 2 and 3 (multi-area models) do a better job at capturing the pattern of recaptures by fleet, although both models over-predict the recaptures in recent years from the longline fishery.

[2] Paper presented to SARAG in November, 2009.

Model 1 indicates that current spawning biomass is around 64% of unfished conditions, whereas models 2 and 3 suggest a slightly less depleted stock, with 2010/11 spawning biomass being 67 and 72% of unfished equilibrium respectively. The time series of spawning biomass show a steady decline over the duration of the fishery for all models. Models which use multiple areas in addition to multiple fleets estimate larger stock sizes, and larger current stock size relative to those in unfished conditions. Model 2 estimates low rates of movement among the two areas (<1% per annum), and estimates the spawning biomass in the Northern area to be slightly larger than the southern one, with the southern area having a lower biomass relative to unfished conditions. This is unsurprising given that the bulk of the fishery has operated in this area. Model 3 estimates the majority of the spawning biomass to be in the Macquarie Ridge area, with high rates of movement into this area from the Aurora Trough once fish mature. Under Model 3, the Northern Valleys area is estimated to have a much larger spawning biomass than the Aurora Trough area, as the estimated movement rate from this area to the Ridge is low. This is due to the low number of recaptures by longline of trawl-tagged Northern Valleys fish.

There are a number of issues related to these assessments. Key points include:

4. There are limited data informing the models regarding movement among areas, as the number of tag recaptures from areas other than the area of release is low. Current estimates of movement rates among areas can be expected to be uncertain.

5. Allocation of recruitment in the 3-area model is only to the traditional trawl grounds. As a result, all young fish are assumed to pass through these areas. However, fishing by trawl operations along the ridge in early years did yield small fish similar in size to those in the Aurora Trough.

6. Stock Synthesis assumes a fixed age of release for all fish in a given tag group (often considered as being all tagged fish by one gear in one year). The implications of this are currently unclear. The expected numbers of tag recaptures from a tag group in a given year will clearly depend on the assumed ages at release. Also not clear are any potential for this fixed assumption to impact estimates of individual year class strengths, and movement rates.

7. Estimates of growth of toothfish at Macquarie Island are based on a growth curve calculated in 2001 and should be updated to include more recent available data, including growth increment data from tag recaptures (there is a paucity of ageing data). The parameters of the growth curve are an important determinant of biomass within the model and have implications for the functional form for selectivity of the longline gear. The age-at-length data for Macquarie appear consistent with a maximum size well below the current growth curve estimate. Currently there have been no sampling of fish > 130cm or of age >20 yrs.

8. The assessments described here all fit a single population dynamics model to the data from all the regions/sectors of the fishery. Not explored are alternatives whereby several separate assessments are conducted, i.e. one for the Aurora Trough, one for the Northern Valleys, etc. Conducting multiple assessments is another alternative that might be considered for application of harvest strategies at Macquarie. Such an approach would have an underlying assumption of the different areas holding separate stocks, or at least significantly separate populations.

9. The current framework considers that both the longline and trawl fisheries take place at the same time, i.e. halfway through a season. However, this has not been the case, with the longlining operations occurring in winter whereas the trawl fishery has typically operated during the summer.

10. Consideration by SARAG of spatial and/or multiple gear assessments for Macquarie Island toothfish raises issues related to how catches would be allocated, both by area and by gear, under a harvest strategy. The presence of multiple fleets and multiple areas within the model means that there are multiple numbers for quantities such as available biomass, which has typically been used as the basis for setting TACs for this stock.

The assessment models presented here represent a range of alternative model structures, and encapsulate a number of different hypotheses about the dynamics of toothfish at Macquarie Island and the interactions of this population with the fishery. The performance of these assessments, in particular the robustness of their ability to estimate biomass and fishing mortality levels to assuming different model structures (that likely differ from the true population structure), needs to be tested within the current Management Strategy Evaluation project underway for this fishery.

8.2 Introduction

This paper presents summary results from integrated stock assessments of Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island to 2010/11 using data collected up until and including July 2009.

This assessment makes use of the Stock Synthesis assessment software (v3.04a, *e.g.* Methot 2007), and fits to data obtained from the tag-recapture program since 1995, to length composition information for the years 1994-2009, and to age-at-length data obtained from aged otoliths. The assessment updates preliminary results presented to SARAG in 2008 (Tuck and Methot, 2008), and 2009 (Fay *et al*., 2009). The assessment model is also set up to enable comparisons with the tagging model currently used for providing advice for setting the TAC at Macquarie Island (Tuck and Lamb, 2009; Tuck *et al.*, 2003).

The new assessment is based on a length-age structured model of fish population dynamics and uses a maximum likelihood framework to fit to the available data. As with the integrated assessments previously applied to Macquarie Island toothfish (Tuck *et al*. 2006), use of the Stock Synthesis framework enables estimation of spawning biomass and selectivity curves, in addition to the estimate of trawl available biomass, which is typically the output of the tagging model (*e.g.* Tuck *et al*. 2003).

8.2.1 Patagonian toothfish

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.

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 2,000m, 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 trawled from depths of 400m and more. This has allowed an extensive tagging program to develop at both Macquarie Island and HIMI. Tagging studies have increased knowledge of the species movement, growth and available abundance (Williams *et al*., 2002; Tuck *et al*., 2003).

8.2.2 Background to the fishery

Macquarie Island lies some 1,500 km to the southeast of Tasmania (Figure 8.1). The trawl fishery off Macquarie Island began in November of 1994. Two major fishing grounds have been discovered: Aurora Trough and the Macquarie Ridge Northern Valleys region. A tagging experiment began in 1995/96 within Aurora Trough and the following season within the Macquarie Ridge Northern Valleys region. Between 1995/96 and 2009/10, over 11,000 tags have been deployed and more than 1,700 tagged fish have been recaptured. Very few tagged fish (11) have been recaptured having moved between the two main fishing grounds during this period.

A Total Allowable Catch (TAC) for the fishery was first introduced in the 1996/97 fishing season. 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 stock assessment model. For the Aurora Trough region, commercial TACs were 750 and 200 mt for the 1996/97 and 1997/98 fishing seasons respectively, and were zero after the 1997/98 fishing season (but with a 40 mt 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 354 mt 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. In 2005/06 the fishery was re-opened with a commercial TAC of 255 mt and again in 2006/07 (prior to commencement of this project) the TAC was 241 mt (Table 8.1). In season 2008/09, the TAC for the Aurora Trough ground was 312 mt. There were 22 days of fishing from 29 January 2009 through to 19 February 2009. The total catch from Aurora Trough was 307 mt. Average daily catch rates were around 38 mt/km^2 for the first 10 days of fishing, but declined to average 11 mt/km^2 over the remaining fishing days. Table 8.2 shows a summary of relative frequency of average daily nominal catch rates in Aurora Trough by season since 1995/96. In season 2009/10, the TAC for Aurora Trough was reduced to a research quota of 60 mt on the basis of assessment results which indicated that the available biomass to trawl was below 66.5% of pre-tagging levels.

For the Macquarie Ridge Northern Grounds region, the annual TAC has reduced steadily since the 1500 mt TAC of 1998. In season 2006/07 the TAC was 100 mt. However, since 1999 since

1999 there has been a provision to allow an increase to the TAC within the fishing season if the catch rates exceeded 10 mt/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. The trial was initiated in August of 2007 with the vessel *Avro Chieftain*. In 2008 the vessel operated during July and August. In 2009 the trial continued with the vessel *Janas* operated during July. In 2007 a total of 79 mt of Patagonian toothfish were caught from 167,000 hooks set, including 5000 hooks set in Aurora Trough. This set caught 5.4 mt with a mean weight per fish of 5.9 kg. The average fish size across the Ridge was 9.5 kg. A total of 216 fish were tagged, with 2 fish recaptured. In 2008 nearly 320,000 hooks were set, with a catch of 148 mt across the Ridge. Catch rates were approximately 500 kg/1000 hooks. Mature fish were caught in grounds at the northern and southern ends of the Ridge. In 2008 a total of 465 tagged fish were released and 18 recaptured (16 from 2007). In 2009, a total of 219 mt of toothfish were caught, with 69 mt being from the Aurora Trough under the assigned research quota.

Table 8.1. The Total Allowable Catch (TAC) and Catch for the Macquarie Island Patagonian toothfish fishery in Aurora Trough and Macquarie Ridge. Numbers in parentheses for the Macquarie Ridge TAC are the Trigger TAC. Measures were available to allow an increase in the TAC if the average catch per unit effort exceeded 10t/km^2 over 3 consecutive fishing days.

Administrative Period	Aurora Trough		Macquarie Ridge	
	TAC (mt)	Catch (mt)	TAC (mt)	Catch (mt)
1994 – 31 Aug 1996	Not set	1351	Not set	0
1 Sept 1996 – 31 Aug 1997	750	490	1000	502
1 Sept 1997 – 31 Dec 1998	200	208	1500	400
1 Jan 1999 – 31 Dec 1999	40 (research)	38	600 (1000)	26
1 Jan 2000 – 31 Dec 2000	40 (research)	14	510 (1000)	8
1 Jan 2001 – 31 Dec 2001	40 (research)	24	420 (1000)	0.20
1 Jan 2002 – 31 Dec 2002	40 (research)	38	242 (782)	2.50
1 Jan 2003 – 30 June 2003	40 (research)	0	205 (665)	0.60
1 July 2003 – 30 June 2004	354	355	174 (441)	0.80
1 July 2004 – 30 June 2005	60 (research)	59	148 (376)	1.10
1 July 2005 – 30 June 2006	255	267	125 (319)	8.500
1 July 2006 – 30 June 2007	241	238	100 (264)	0.07
1 July 2007 – 30 June 2008	390	223	86 (228)	0.06
1 July 2008 – 30 June 2009	312	307	75 (200)	0.30
1 July 2009 – 30 June 2010	60		150 (175)	

Table 8.2. Relative frequencies of average daily catch rates (mt/km^2) in Aurora Trough.

CPUE bin	95/96	96/97	97/98	98/99	99/00	00/01	01/02	02/03	03/04	04/05	05/06	06/07	07/08	08/09
<1	2	0	3	8	8	1	0	2	0	0	1	0	0	0
1-5	31	2	5	6	9	1	0	1	1	0	0	0	6	3
5-10	4	6	8	4	1	3	0	1	0	0	3	2	6	5
10-20	4	7	6	4	1	5	0	3	5	2	4	5	5	5
20-40	3	12	2	4	0	1	0	2	8	1	6	5	4	5
40-80	11	6	1	0	0	0	0	1	4	1	2	3	0	3
80-120	5	1	0	0	0	0	0	0	2	0	0	0	0	1
>120	8	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	68	34	25	26	19	11	0	10	20	4	16	15	21	21

8.2.3 Assessment history

Stock assessment of the Macquarie Island Patagonian toothfish stock has been based on the tag-recapture model developed by de la Mare and Williams (1997), and modifications described in Tuck *et al.* (2003). The tag-recapture model uses population and tag accumulation models to account for tags being released at various times throughout the season and the effects of removals by fishing. The model estimates pre-tagging available abundance and the annual net change in available abundance between fishing seasons for the major fishing grounds of Macquarie Island. In 2004, a new model that expands upon the traditional tag-based model was introduced. 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. The model can also project the stock into the future under various fixed TAC scenarios in order to provide insights into appropriate TACs and the likely short and long-term impact on mature biomass. In 2008/09 work commenced on using the integrated assessment platform of Stock Synthesis for the assessment of Aurora Trough Patagonian toothfish (Fay *et al*., 2009), of which the assessment described within this document is the next extension.

Estimated available abundance declined over the first three seasons of tagging (to 1998/1999), and then showed an increasing trend to 2003/04 (Figure 8.2). In 2003, the model estimated available biomass for the 2003/04 season suggested that the population was at or above pre-tagging abundance levels, and so the fishery was re-opened to commercial fishing.

Following the 2003/04 season, the estimated available biomass reduced to 2,263 mt at 30 June 2004 (Tuck *et al*., 2004). As the estimated percentage of available biomass remaining reduced marginally below the reference point (66.5% of unfished available biomass, see below) used to determine whether a commercial quota applies, a precautionary approach was considered appropriate and only a research quota was set for Aurora Trough for season 2004/05. The research quota was increased to 60 mt (in comparison to 40 mt in previous seasons) to increase the likelihood of recapturing tagged fish and thereby improving the precision of estimates for the most recent season's biomass. Note that current estimates of available biomass in this season suggest that a commercial fishery would actually have existed in 2004/05 under the current parameterization of the model. Since then minor data updates and changes to the assumed value of natural mortality have occurred. For season 2005/06, the estimated percentage of available biomass was above the reference point and the commercial fishery was opened with a TAC of 255 mt. The following season (2006/07) once again had a viable fishery with a TAC of 241 mt.

In season 2006/07, the catch and tag size distribution was dominated by fish smaller than had usually been seen (Pribac *et al*., 2007). In particular, there were very few fish of 70cm and above. As a result, recaptures from this size range were absent and the proportionate number of recaptures relative to number caught was small. As a consequence the estimated available biomass increased substantially, to 7,760 mt, implying a trawl TAC of 776 mt for season 2007/08. The tag-based model assumes that availability and catchability does not change from year to year and so can be very sensitive to changes in spatial and temporal distributions seen in a fishery that is pulse-like in nature (eg there were only 15 days of fishing in 2006/07). Given these uncertainties, SARAG agreed with an industry proposal to set a precautionary TAC of 390 mt for season 2007/08. In season 2007/08, the length frequency resembled those of years prior to 2006/07, and a TAC of 312 mt was set for season 2008/09 (Tuck and Lamb, 2008).

The 2008/09 assessment model estimate of the trawl available biomass in Aurora Trough under the base case parameter set was 2,188 mt, or 65.8% of the initial trawl available biomass (Figure 8.2). Under the current TAC setting process for Aurora Trough, this suggested

cessation of the commercial fishery and the implementation of a research TAC. This was implemented for 2009/10, with the research quota for the Aurora Trough being caught by longlining during July 2009. As there was only one trawl shot in the Macquarie Ridge Northern Trawl Ground during the 2008/09 season, with only 14 tag releases and 1 recapture, insufficient data were available to update the assessment of this part of the stock in 2009. Consequently, the decision rule for setting the trawl-based TAC, namely to assume no fishery recruitment and to reduce the previous year's trawl-based TAC by natural mortality and catch, resulted in a TAC of 66 mt with a trigger TAC of 175 mt.

In 2008, Tuck and Methot (2008) presented to SARAG progress on developing a new integrated assessment using the Stock Synthesis assessment platform. The intent of the new integrated assessment was to provide a means of accounting for information from the expansion of the fishery at Macquarie Island with the recent longline trial. The integrated assessment includes information on length-frequency and tagging data in an age-structured model that allows estimation of annual spawning biomass and cohort strength. Results showed that the new assessment could replicate the results of the tag-only assessment and the previous integrated assessment. Following this, the results of fitting Stock Synthesis to the available data from the Aurora Trough trawl fishery for Macquarie Island Patagonian toothfish were presented to SARAG in 2009 (Fay *et al*., 2009). The base-case model estimated that 2009/10 toothfish spawning biomass in Aurora Trough to be 50% of that in the unfished equilibrium state, with 2009/10 trawl available biomass estimated to be 75% of the pre-tagging level. Estimates of current stock status were sensitive to the value assumed for the rate of natural mortality, the initial year in which recruitment deviations were estimated, and the age assumed for tagged fish on release. Estimates of available biomass showed a declining and then recovering trajectory, similar to that observed in the previous tag-only and integrated assessment models. This model then formed the basis for the expansion to include data from longline and the Northern Valleys trawl grounds which are presented here.

8.3 Data

The data available for model-fitting purposes included length composition data from the fishery (1994/95-2009/10), conditional age-at-length data (1997-2000, 2003, 2005, 2008), and the results of the tag-release-recapture program, begun during the 1995/96 season.

8.3.1 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 to. Table 8.3 shows the catch history by fishing year for both trawl and longline, for the Aurora Trough, Northern Valleys, and Macquarie Ridge (North and South of 54.25 degrees South). Small amounts of catch by trawl outside of Aurora Trough and the Northern Valleys areas during the early years of the fishery have been added into the catch series for these fleets dependent on the shot location relative to a latitude of 54.25 degrees South.

Table 8.3. Time series of catches (mt) by fishing year and fleet. Fleet designations are: AT- Aurora Trough, NV – Northern Valleys, NMR – North Macquarie Ridge (north of 54.25 degrees south), SMR – South Macquarie Ridge. Small amounts of catches along the Macquarie Ridge caught by trawl in the early years of the fishery have been included in the time series for the Aurora Trough and Northern Valleys.

	Trawl		Longline			Total
Year	AT	NV	AT	NMR	SMR	Catch
94/95	425.9	0.2				426
95/96	927.9	0.1				928
96/97	487.8	501.8				990
97/98	189.6	385.2				575
98/99	61.1	41.2				102
99/00	11.3	7.2				18
00/01	26.4	0.7				27
02/03	37.8	3.3				41
03/04	355.4	0.8				356
04/05	59.0	1.1				60
05/06	267.1	8.6				276
06/07	238.5	0.1				239
07/08	237.8	0.1	5.4	9.1	70.8	323
08/09	308.8	0.3		37.5	111.9	458
09/10			68.7	9.5	140.6	219

8.3.2 Length frequency data

Samples of the length composition of the catch (Figure 8.3) were available for all fishing seasons (1994/95 through 2009/10). Each annual length composition is based on the measurement of several hundreds (thousands) of fish, 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 lengths within individual hauls/shots. The sample sizes in both numbers of fish and shots sampled are shown in Table 8.4.

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. Inspection of the data suggests that the unsexed fish sampled for length are quite different to the male and female portions of the length composition for that year (Figure 8.4). Fish less than 30cm, most likely immature, only appear in the unsexed component (Figure 8.4 and Figure 8.5). Assuming that these unsexed fish are random samples from the sex-specific compositions is clearly not sensible. Two solutions are proposed:

1. Length data are not disaggregated by gender and individual compositions are structured only by fleet and fishing year,

2. The unsexed fish are randomly allocated to either male or female. This approach relies on an assumption that growth prior to maturity is identical between sexes.

Option 1 has been implemented in the analyses described in this report.

Length bin structure is at 5cm intervals, except for the smaller fish, where the length bins are 10 cm wide.

Since the late 1990s, there appears to be a strong cohort moving through the length classes (Figure 8.3, Figure 8.5), consistently seen until at least 2004/05. The length frequency of 2006/07 follows that of 2005/06 in showing a greater proportion of small fish (~50cm in length) than in the previous years, such as 2004/05, where the mode was around 70 to 75cm. However, the 2006/07 length frequency is notable for having very few fish of length greater than 80cm, unlike 2005/06.

Table 8.4. Number of length samples by fleet and season, both in terms of number of shots from which samples were taken, and the total number of fish measured.

Fleet	Season	# shots	# fish	mean # per shot
AT Trawl	94/95	126	3,405	27
	95/96	248	6,581	27
	96/97	96	2,685	28
	97/98	75	1,331	18
	98/99	52	4,600	88
	99/00	39	879	23
	00/01	20	1,627	81
	02/03	19	743	39
	03/04	96	4,536	47
	04/05	19	724	38
	05/06	125	3,377	27
	06/07	75	768	10
	07/08	99	1,564	16
	08/09	128	2,268	18
NV Trawl	95/96	3	18	6
	96/97	43	2,275	53
	97/98	132	2,346	18
	98/99	72	2,089	29
	99/00	42	657	16
	00/01	13	449	35
	02/03	24	404	17
	03/04	6	84	14
	04/05	13	289	22
	05/06	33	631	19
	06/07	2	8	4
	08/09	3	14	5
AT Longline	07/08	2	200	100
	09/10	9	672	75
NMR Longline	07/08	5	160	32
	08/09	13	478	37
	09/10	8	441	55
SMR Longline	07/08	29	1,699	59
	08/09	44	1,878	43
	09/10	50	3,235	65

8.3.3 Age data

Age at length samples are available from aged fish that were captured in 1996-2000, and 2002-2008.

Conditional age-at-length data

The age data are input as the raw age-at-length data, rather than age compositions generated from applying age-length keys to the catch-at-length compositions. The input compositions are therefore the distribution of ages obtained from samples in each length bin, for those years for which data are available. These data are summarised in Table 8.5. As selectivity is modelled as being a function of length (Section 8.5.3), disaggregation of these data by fleet is only necessary for scenarios that consider multiple areas.

The majority of the otoliths that have been aged since 2000 come from tag-recaptured fish (Table 8.5, column 'tag recaptures'). It is perhaps then not reasonable to assume that these data are representative samples of the age distribution of the catch. As a result, age data that came from tag recaptured fish are not included in the base case analyses. Not including these data appreciably reduces the amount of ageing data and consequently limits the information the model has to estimate growth. Sensitivity of model results to including the tag recaptured age-length data will be considered as the development of the assessment progresses.

Table 8.5. Sample sizes of aged fish by year and gender noting the numbers obtained from tag recaptured fish.

		# of aged otoliths		
Year	gender	random	tag recaptures	Total
1996	unsexed		2	2
	female	19	29	48
	male		26	26
1997	unsexed	24		24
	female	41	55	96
	male	50	55	105
1998	unsexed	5		5
	female	207	5	212
	male	201	7	208
1999	unsexed	16		16
	female			
	male		1	1
2000	unsexed	8		8
	female		2	2
	male			
2002	unsexed			
	female		1	1
	male		2	2
2003	unsexed		1	1
	female		26	26
	male	1	28	29
2004	unsexed			
	female		7	7
	male		4	4
2005	unsexed			
	female	1	53	54
	male		36	36
2006	unsexed		34	34
	female		7	7
	male		8	8
2007	unsexed			
	female		12	12
	male		26	26
2008	unsexed	2	1	3
	female	2	50	52
	male	9	46	55
Totals	all	586	524	1110

Ageing error

There are currently no multiple reads of otoliths from Macquarie Island Patagonian toothfish with which to quantify the degree of ageing error. As a result, the ageing error matrix calculated for Patagonian toothfish at HIMI (Candy and Welsford 2009) was used to provide estimates of ageing error, in order to calculate the degree to which a fish of true age *i* is aged to be *j*. Stock Synthesis enters ageing error by, for each true age, assuming a normal distribution of observed ages around a mean age and standard deviation for the observations. Two sets of

ageing error matrices were therefore calculated from the Candy and Welsford matrix, one that assumed ageing was unbiased (ie mean observed age was the true age), and one that allowed for a bias in the mean observed age (Table 8.6). The latter was calculated because there is evidence that for older fish, the observed age is less than the true age (Table 8.6, compare mean age of matrix #2 with the true age).

Table 8.6. Ageing error matrices. Shown are the mean and standard deviation of observed ages given a true age read. The numbers in matrix # 1 assumes that the ageing is unbiased, where those in matrix #2 use the actual values for the mean read ages given true ages. Values were calculated using the ageing error matrix for Heard & MacDonald Island toothfish as given in Candy and Welsford (2009).

	matrix # 1		matrix # 2	
true age	mean age	s.d.	mean age	s.d.
1	1.5	1.29	1.6	1.08
2	2.5	0.79	2.2	0.77
3	3.5	0.83	3.1	0.91
4	4.5	0.85	3.9	0.99
5	5.5	0.88	4.9	1.01
6	6.5	0.90	5.8	1.03
7	7.5	0.93	6.8	1.05
8	8.5	0.95	7.8	1.07
9	9.5	0.98	8.9	1.10
10	10.5	1.01	9.9	1.14
11	11.5	1.04	10.9	1.17
12	12.5	1.07	12.0	1.22
13	13.5	1.11	13.1	1.25
14	14.5	1.14	14.2	1.26
15	15.5	1.18	15.2	1.31
16	16.5	1.22	16.3	1.32
17	17.5	1.27	17.3	1.35
18	18.5	1.31	18.4	1.38
19	19.5	1.36	19.4	1.39
20	20.5	1.41	20.4	1.46
21	21.5	1.47	21.4	1.51
22	22.5	1.53	22.3	1.59
23	23.5	1.59	23.2	1.68
24	24.5	1.65	24.1	1.74
25	25.5	1.72	25.0	1.82
26	26.5	1.79	26.0	1.88
27	27.5	1.86	27.0	1.94
28	28.5	1.94	28.0	2.01
29	29.5	2.03	29.0	2.11
30	30.5	2.13	30.0	2.20
31	31.5	2.17	30.7	2.40
32	32.5	2.06	31.3	2.50
33	33.5	2.09	32.0	2.65
34	34.5	1.87	32.3	2.09
35+	35.5	3.30	33.0	1.92

8.3.4 Tag recapture data

Between the 1995/96 and 2009/10 fishing seasons, over 11,000 Patagonian toothfish were tagged at Macquarie Island, of which nearly 1,700 have been recaptured. Although toothfish are trawled from more than 400m depth, tagging is straightforward because toothfish lack swim-bladders and reach the surface in good condition. Lively fish are selected from the catch and placed in a holding tank of circulating seawater. A length range of fish is chosen that approximates the length range in the catch. The fish are tagged with electronic tags (TIRIS radio frequency identification transponders) and a visible plastic tag (double tagged since 1997/98). The fish are then replaced in the holding tank for about 30 minutes after tagging to check on vital signs and then released through a scupper in the factory. Table 8.7 and Table 8.8 summarise the numbers of releases and recaptures over the duration of the tagging program. Fish are still being recaptured from releases in the early years of the fishery (Table 8.7).

Under the Synthesis framework, annual releases of tagged fish from an area (i.e. a tag 'group') are all assumed to consist of a single age class. While computationally convenient, this clearly does not represent the way in which fish are tagged, as fish are generally assumed to be done so in proportion to the length frequency of the catch. It is yet unclear what the consequence of assigning a fixed age for all fish in a tag group would be, and this is something that the MSE work currently underway for testing the Synthesis assessment at Macquarie is going to address. In the meantime, the value for age of releases was set at 9 for all trawl-released tags in all years, and 12 for those from longline, with the impact of assuming alternative values to be explored within sensitivity analyses. Other options available to address this issue include say using the distribution of release lengths and growth estimates to calculate a rough mean age of release for each tag group (allowing the age at release to vary in time but not within a tag group), or by creating multiple tag groups for each year of release, each with a unique release age, perhaps with numbers assigned to each of the tag groups depending on the length composition of releases. The former of the two solutions matches the approach used in the currently applied tag only assessment model (*e.g.* Tuck and Lamb 2009). The mean length at release by tag group does suggest the possibility that fish tagged in the Northern Valleys may have been younger than those in the Aurora Trough (Table 8.7).

Recaptures of tagged fish are assumed to be random (Poisson distributed) conditional on the catch and expected number of tags available to the fishery. Departure from the Poisson assumption can be implemented via use of an alternative assumption of a negative binomial distribution of recaptures, which involves estimation of additional over-dispersion parameters that describes the degree of departure from the Poisson distribution. The available recapture data consists of the numbers of recaptured fish each year by each release group (Table 8.7). To allow for full mixing of the tagged fish with the untagged population, recaptures within the year of release were removed from the assessment data if the recapture occurred within 10 days of release (*cf.* Tuck and Lamb 2009). Again, sensitivity analyses will explore alternative values for this mixing time.

There are limited instances of recaptures of tagged fish by fleets other than that of release (Table 8.8). For the spatial models considered, information on the rates of movement among areas will be informed by these recaptures (and the lack thereof). For those fish recaptured not by their fleet of release, the tendency has been for a movement south (10 NV trawl-tagged fish recaptured in AT as opposed to 1 AT fish being caught in the NV trawl), and a progression to becoming available to the longline fishery. Interestingly, there has not yet been any recaptures of Northern Valley trawl-tagged fish by the NMR longline (Table 8.8).

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, as many individual fish have been recaptured several times, tagging mortality was assumed to be zero.

The non-detection of tagged Patagonian 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. If it is assumed that the probability of detecting the two types of tags is independent, the total number of recaptured tagged fish in a season, r_s, can be estimated by the moment estimator[3]:

$$r_s = n_v n_e / n_{ve}, \tag{1}$$

where n_v and n_e are the number of tagged fish detected either visually or electronically, and n_{ve} is the number detected by both methods. Table 8.9 shows the number of tags detected either visually or electronically by season for the Aurora Trough and Macquarie Ridge fishing grounds. As an example of the detection rate calculation, in the 1996/97 season n_v = 33 + 36 = 69, n_e = 11 + 36 = 47 and n_{ve} = 36, giving an estimate of recaptured tagged fish r_s = 90.08. As a total of 80 fish were detected, the estimated detection rate over days t when both visual detection and electronic detection were operational is ω_t^{ve} = 0.89. A detection rate based only on the visual detection of tags, ω_t^{v}, can also be calculated using this method.

The tag detection rate was assumed constant over time in the assessment models, as there is currently no way of implementing a time-varying reporting rate within the Synthesis framework in the fashion that would be desired to reflect the estimates. The value for the rate was held fixed at 0.94 (reflecting an average of the calculated annual values for this parameter). The ability to account for time-varying reporting rates should be incorporated into later versions of Synthesis fairly rapidly. In principle, one could adjust the annual number of recaptures by the detection rate for that year to account for the changes, however this approach is impractical in this instance due to the large number of zeroes in the recapture matrix (Table 8.7).

[3]This equation derives from the probability of detecting tags by both methods being the product of the probabilities of detecting each type of tag independently. Replacing probabilities with their sample frequencies and rearranging for the unknown total recaptures r_s yields equation (1).

Table 8.7. Numbers of tagged fish in each tag group for the two area model, assigned by season and area. Age at release is the assumed age of release for all tag releases in the tag group. Mean length is in cm. Fleet codes are: 1=AT Trawl, 2= NV Trawl, 3=AT Longline, 4= NMR Longline, 5= SMR Longline.

Tag Group	Release Season	Release Fleet	Age at Release	Number	mean length	# recaptures by season after 10 days at liberty														
						95/96	96/97	97/98	98/99	99/00	00/01	01/02	02/03	03/04	04/05	05/06	06/07	07/08	08/09	09/10
1	1995	1	9	460	69	19	58	28	4	0	1	0	1	1	0	0	0	0	0	0
2	1995	2	9	4	57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1996	1	9	474	59		24	43	7	0	2	0	0	9	1	3	0	1	1	0
4	1996	2	9	538	61		1	53	5	1	0	0	0	2	0	0	0	0	0	0
5	1997	1	9	604	60			80	18	3	4	0	5	22	4	15	1	0	2	3
6	1997	2	9	538	70			60	9	0	0	0	0	1	0	0	0	0	1	0
7	1998	1	9	653	68				0	4	5	0	3	30	2	9	2	2	7	0
8	1998	2	9	315	58				7	0	0	0	0	0	0	0	0	0	0	0
9	1999	1	9	693	65					1	3	0	1	35	6	12	1	3	6	2
10	1999	2	9	302	58					3	0	0	0	0	0	0	0	0	0	0
11	2000	1	9	365	59						0	0	1	23	3	5	1	1	9	0
12	2000	2	9	135	46						0	0	1	0	0	1	0	0	0	0
13	2002	1	9	492	63								1	60	8	29	6	15	24	2
14	2002	2	9	17	57								0	0	0	0	0	0	0	0
15	2003	1	9	601	69									27	9	23	8	4	13	2
16	2003	2	9	61	53									1	0	3	0	0	0	0
17	2004	1	9	556	69										0	46	7	16	43	4
18	2004	2	9	263	56										0	2	0	1	1	0
19	2005	1	9	522	71											2	25	18	27	2
20	2005	2	9	289	60											1	0	0	0	0
21	2006	1	9	446	59												3	27	13	0
22	2007	3 and 5	12	190	81													0	16	4
23	2007	4	12	26	78													0	0	1
24	2007	1	9	297	65													23	31	2
25	2008	5	12	386	79														1	9
26	2008	4	12	82	79														0	2
27	2008	1	9	589	71														32	2
28	2008	2	9	14	51															0
29	2009	3 and 5	12	696	82															0
30	2009	4	12	60	85															0

Table 8.8. Total numbers of tag recaptures by fleet of release (columns) and recapture (rows), for fish at liberty for greater than 10 days. Numbers in parentheses correspond to additional numbers of recaptures caught within the first 10 days of release.

	Released by				
Recaptured by	AT Trawl	NV Trawl	AT Longline	NMR Longline	SMR Longline
AT Trawl	1070 (389)	10	0	0	1
NV Trawl	1	143 (23)	0	0	0
AT Longline	14	0	0	0	0
NMR Longline	1	0	0	1	1
SMR Longline	7	1	0	2	28

Table 8.9. Number of tagged fish detected visually and electronically (TIRIS) at Macquarie Island (all grounds) and the detection rate by season. Only tags detected while the electronic detector was functional are included.

Season	Total tags detected	Detected both TIRIS & visually (n_{ve})	Detected TIRIS only	Detected visually only	Estimated no. recaptured (r_s)	Visual Detection rate (ω_i^v)	Detection rate (ω_i^{ve})
1996/97	80	36	11	33	90.08	0.766	0.888
1997/98	297	144	15	138	311.45	0.905	0.954
1998/99	40	13	1	26	42	0.929	0.952
1999/00	9	6	0	3	9	1.000	1.000
2000/01							0.905[a]
2002/03	18	14	2	2	18.29	0.875	0.984
2003/04	257	173	17	64	260.29	0.911	0.987
2004/05	51	40	4	7	51.7	0.909	0.986[b]
2005/06	237	40	10	187	283.75	0.800	0.835[bc]
2006/07	110	89	17	4	110.76	0.845	0.993
2007/08	135	119	7	9	135.53	0.944	0.996
2008/09	281	145	32	103	302.73	0.821	0.928

8.4 Biology

8.4.1 Growth

Growth of Patagonian toothfish is assumed to follow the von Bertalanffy growth function, with sex-specific parameter values estimated from age and length data by Constable *et al*. (2001) as indicated in Table 8.10. The model considers gender-specific growth, with separate sets of growth curve parameter values for both males and females. Females grow larger than males. A single set of growth curve parameters based on an estimate from both sexes is also available.

Stock Synthesis allows for growth to be estimated within the model, often advantageous as the impacts of selectivity on the observed age and length can be directly accounted for. Constable *et al*. (2001) directly included an accounting for selectivity, so biases associated with selectivity are likely to be minimised. The values for k, t_0,and the CV in length at age in Table 8.10 are used as starting values for the estimation rather than estimating the growth parameters. It is noted that the age-at-length data from the 1990s is the data that the growth estimates were obtained from.

An update to the growth estimates is probably appropriate. One option would be to include the recent age-at-length data from the tag recaptures when fitting the population dynamics model, and estimate the growth curve parameters within this framework. Alternatively, these data can be used outside of the model using the methods of Constable *et al*. (2001) to obtain growth curve parameter estimates.

Additional data on growth is available for Macquarie Island toothfish however, from the growth increments of the tag released and recaptured fish. As Synthesis currently does not have the means of including the growth increment data, estimation of growth parameters from these data must be conducted outside of the population dynamics model. Work to estimate growth of toothfish at Macquarie Island using both these data and the traditional age and length observations, while retaining the important correction for selectivity bias, is currently underway and will be incorporated into future assessments.

Values for the parameters of the weight-at-length relationship are fixed at those in Table 8.10.

8.4.2 Mortality

Although there is no direct information on natural mortality of Macquarie Island toothfish, the known longevity of the species would indicate that natural mortality was less than M = 0.2 yr^{-1} (Constable *et al*. 2001). In this report, natural mortality is assumed to be similar to that estimated for Heard Island Patagonian toothfish. In the 2008/09 assessment, following recommendations from SARAG, on the basis of new estimates of natural mortality rates for Heard Island toothfish, the value of natural mortality for the base-case model was reduced from 0.1475 yr^{-1} to 0.13 yr^{-1}. This lower value (0.13) is used in the assessments here, with M being the same for both sexes and constant over age and time.

8.4.3 Fecundity and maturity

Length at maturity was assumed to be 89 cm (Table 8.10). This results an age-specific maturity curve identical to that used by Tuck *et al.* (2006) in previous integrated assessments for Macquarie toothfish, with 50% of females mature at age 14 and 95% of fish mature at 17 yrs. Without direct information on fecundity or egg production, mature female weight is used as spawning biomass.

Table 8.10. Values for biological parameters.

Parameter	both sexes	females	males
rate of natural mortality, M (yr^{-1})	0.13	0.13	0.13
von Bertalanffy growth parameters			
L infinity (cm)	185.5	195.1	154.2
k (yr^{-1})	0.042	0.038	0.054
t_0	-0.781	-1.184	-0.434
CV of length at age	0.13	0.12	0.14
weight at length (wt = a*L^b)			
a	4.40E-09	5.40E-09	5.00E-09
b	3.14	3.11	3.12
length at maturity (cm)		89	

8.5 Assessment methodology

The assessment is based on a length-age-structured model of fish population dynamics, and is applied to the stock inhabiting the Macquarie Island region, which is assumed to be a single stock. A two-sex model is assumed, although the rate of natural mortality is assumed to be the same for both males and females, and versions of the assessment do consider growth to be identical among sexes. 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 2007) and are not reproduced here. As with the integrated assessments previously applied to Macquarie Island toothfish (Tuck *et al*., 2006), use of the Stock Synthesis framework enables estimation of spawning biomass and selectivity curves, in addition to the estimates of available (or vulnerable) biomass, which has been the output of the tagging model used for assessment of toothfish at Macquarie in the past (*e.g.* Tuck and Lamb 2009).

8.5.1 Population model

The models consider a single stock of toothfish in the Macquarie Island region, with different model structures making assumptions about how these fish are distributed spatially. In Synthesis, fish recruit at age 0, even though they do not appear in the data at this age. A maximum age (plus group) of 120 years is used. This large age is due to the slow growth rate of Patagonian toothfish under the base-case growth parameters (Table 8.10), as fish do not attain their maximum length until around this age. While no fish appear in the age data older than 20 years, and the rate of natural mortality does not suggest such longevity, it is necessary to keep track of these older ages in the model in order that biomass is calculated correctly because fish are still growing.

Three different model structures are considered:

1. a single area model which only uses fleets to attempt to capture the spatial and gear-dependent differences in availability, but which otherwise assumes that the population these fleets exploit is homogeneous,

2. a two-area model which accounts for heterogeneity in toothfish availability between the northern and southern areas of operation of the fishery, with movement among areas, and

3. a three-area model which separates the major historical trawl grounds (Aurora Trough and Northern Valleys) from the Macquarie Ridge, with recruitment occurring at the trawl grounds, and movement of fish among areas thereafter.

The single area model is the simplest away of accounting for differences due to space. The two area model assumes that separation among the toothfish population fished areas is a result of north-south structuring, and assumes that differences in selectivity can account for differences in availability to the different gear types. The 3 area model assumes that fish on the Ridge are geographically separated from the trawl ground areas, but that, once fish move off the trawl grounds onto the Ridge, they mix freely.

8.5.2 Selection of fleets

The models designate five fishing fleets that exploit the toothfish resource. These are:

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

Each fleet operates in a single area, with assignment to area dependent on the model structure as outlined above in the previous Section 8.5.1.

8.5.3 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), but did not impose this pattern on the model.

8.5.4 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 spawning biomass in the same year. The parameterization 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 and 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 1982-2003, with these deviations taken as log-normally distributed around the SRR with standard deviation, σ_R of 0.7. The range of years chosen for recruitment estimation reflects both the expectation that cohort effects from these years be seen in the data and whether the asymptotic standard error of 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*. (2009) in other integrated assessments for Macquarie toothfish.

For the spatial models, proportional allocation of the annual numbers of recruits to the different areas is estimated within the model, but this proportional allocation is assumed fixed over time.

8.5.5 Movement

Movement of fish among areas is allowed for the multi-area models, with the extent of movement (annual movement rates) being estimated during the model fitting process. Movement can be modelled as being age-dependent, with the annual fraction of fish that moves for each area-pair having 2 values, 1 value for premature fish and another once mature.

However, for the three area model (Model 3), because the model structure is assuming that fish recruit in trawl grounds and migrate onto the Ridge as they get older, movement between the two trawl ground areas, and movement from the Ridge to the trawl grounds is not modelled as being age-dependent. Age-independent movement is also considered for the 2 area model (Model 2).

8.5.6 Initial conditions

The population is assumed to be in unfished equilibrium, with an equilibrium age structure, in 1975. Spawning biomass in 1975 is therefore used as unfished spawning biomass, SB_0.

8.5.7 Parameters and parameter estimation

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

The base-case versions of the 3 assessment models utilised the fixed values for biological parameters detailed in Table 8.10 (gender-specific growth), and those described in Section 8.3.4 for the tag detection rate, tagging age, and mixing time. Input sample sizes for the individual length compositions were the number of shots sampled for the trawl data, and 0.1 of the number of fish sampled for the longline data. The input sample sizes for the age at length data were the number of aged otoliths in each length bin.

For Model 1, the estimated parameters of the model were: average recruitment before fishing, annual recruitment deviations from 1982-2003, and parameters determining the functional form of the selectivity pattern. This resulted in 43 estimated parameters under the base-case scenario.

Model 2 had an additional 3 estimated parameters to Model 1, for estimation of the recruitment area allocation (1) and movement (2). An additional two movement parameters were estimated when this was assumed to be age-dependent.

Model 3 had 11 additional estimated parameters than Model 1, for estimation of the recruitment area allocation (1) and movement (10)

The results of the estimation procedure provide a prediction of stock status prior to the 2010/2011 fishing season. Key quantities of interest output by the model include time series of spawning biomass and vulnerable biomass, the current values of these quantities relative to those prior to fishing, and the levels of fishing mortality experienced by the stock.

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 with input sample sizes. For each tag group, the total number of recaptures by year is assumed to be Poisson distributed. The proportional allocation of these tag recaptures by fleet is then considered to be multinomial.

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 8.5.4 is fixed at a value of 0.7.

8.5.8 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 based on inverting the hessian matrix, or applying Markov-Chain Monte Carlo (MCMC) methods (*e.g.* Hastings, 1970; Gilks *et al*., 1996; Gelman *et al*., 1995). As the goals of the current exercises are to explore the consequences of model structures, any estimates of uncertainty shown are based on asymptotic standard errors, calculated internally as standard by Stock Synthesis.

8.6 Results

Key results are shown, rather than repeat every single diagnostic for each of the 3 model structures.

8.6.1 Diagnostics

Length composition data

All three model structures fit the length composition data reasonably well. The model is able to capture the apparent presence of a strong cohort within the length structure in the early years of the fishery (Figure 8.7), but appears as a result to over-estimate the presence of larger fish in the Northern Valleys for the later years, although the sample sizes for these years for this fleet are generally fairly small (Figure 8.8). The length data from the Southern Macquarie Ridge longline fleet in 2009 appears somewhat different to that from 2007 and 2008, with a lack of larger fish in the data which the model does not account for (Figure 8.9). Inspection of shot location suggests that a good proportion of shots in 2009 were done at a different location (perhaps also different depths) than in the other years and this may explain the difference.

Using the number of shots sampled as the input sample size for the trawl length data seems more than adequate, with the output effective sample size for these data on average being approximately equivalent to the number of shots (Figure 8.7 and Figure 8.8). The number of shots does not seem to represent the effective sample size well however for the longline data. Dividing the number of length measurements by 10 for these data appears a reasonable first step at balancing the variance associated with these data although these can be improved upon (Figure 8.9).

Age-at-length data

The fits to the age-at-length data for Model 1 when growth is not estimated but separate curves for each sex are used are summarised in Figure 8.10. The fits appear to be fairly reasonable for 1998, the year for which the sample size was largest, although the model does appear to not be growing fish fast enough (larger fish are predicted to be older than they are observed to be). As

the values for the growth curve parameters were fixed, some lack of fit to these data is to be expected, however the fact that the predictions appear to be somewhat in accord with the data suggests that the assumption of the values for the growth curve parameters is not too unreasonable.

Tag recapture data

The different model structures differed quite appreciably in their ability to fit to the tag-recapture data. All models were however able to capture the general pattern of recaptures over time (Figure 8.11, top left panel). There were a large number of large residuals for the recaptures by tag group for each year (Figure 8.11), with notable departures from the Poisson distribution that these data were assumed to follow. A lack of fit to the number of recaptures in the initial year of release is perhaps not surprising, however it is clear that the large residuals are not limited to these instances.

Over-estimation of recaptures in the year of release is perhaps due to the model assuming tags are instantaneously available to that year's entire catch, when in actuality, tagging occurs throughout the fishing season and so not all releases are available to the fishery until after the minimum mixing time. Temporal variability in this over-estimation could also be a result of known changes in the tag detection rate (here assumed to be constant over time).

Although the pattern in the fit to the number of recaptures by tag group and year was fairly consistent among the different model structures, the models differed in their ability mimic the allocations of recaptures by fleet. In particular, the 1 area model (Model 1) could not reconcile the heterogeneity in recaptures among fleets. The model predicted less recaptures for the fleet of release than observed, and predicted more recaptures for the other fleets than observed. This is unsurprising as the model is treating the population as a single homogeneous pool. The multiarea models (Models 2 and 3) do better at capturing the allocation pattern, although the model appears to somewhat over-predict recaptures from the longline fleets.

Recruitment residuals

The asymptotic standard errors of the estimated recruitment deviations do not show any cause for concern regarding their estimation (Figure 8.12). There is a lack of evidence for really well-estimated recruitments (ASE for most is around 0.5), however this is perhaps not surprising given the paucity of age data, and the likelihood that the lumping of tag releases into fixed age groups will introduce some error.

8.6.2 Base-case results

Selectivity

Fitting the assessment model to the length data allows for the selectivity pattern of the trawl fishery with fish length to be estimated. The estimated selectivity patterns are clearly influenced by the assumptions about model structure and movement dynamics, as the patterns obtained for each fleet are different depending on the model (Figure 8.13, Figure 8.14, Figure 8.15). In general, the trawl selectivity patterns are highly dome-shaped and show good accordance with the fixed selectivity patterns used in previous assessments for Aurora Trough toothfish. The estimated selectivity for the AT longline indicates capture of smaller fish than the NMR and SMR fleets, as evidenced by the length data. The SMR longline selectivity for

Model 1 is effectively asymptotic, as there are very few fish in the age structure at the largest lengths. The AT longline selectivity for Model 3 is also estimated to be asymptotic (Figure 8.15). Model 3 estimates a fairly high movement rate out of the Aurora Trough to the other areas and as a result this estimated selectivity pattern does not diminish the fit to the length data for this fleet.

Recruitment

The time series of estimated recruitment is fairly consistent among models (Figure 8.16), with a large year class estimated in 1987, poor recruitments either side of this, and a period of generally above average recruitment after 1993. As with previous integrated assessments (*e.g.* Tuck *et al*., 2006), the estimated time-series of annual recruitment appears to show an episodic pattern, with pulses of larger than average year classes approximately every four or five years. The 1987 year class is estimated to be high presumably to fit the length data from the trawl fishery in 1995-1997. The approximate 95% confidence intervals in Figure 8.16 demonstrate the uncertainty with which the individual recruitment values are estimated, particularly in the later years when fish have not been available to the fishery for very long.

For the multi-area models, the spatial allocation of the annual numbers of recruits was estimated. The 2 area model allocates 40% of the annual numbers of recruits to the southern area and 60% to the northern area, whereas the 3 area model allocates only one-third of the annual numbers of recruits to the Aurora Trough and the remainder to the Northern Valleys.

Movement

The estimation of movement rates appears sensitive to the choices as to whether movement is age-dependent (i.e. different values pre- and post-maturity). Model 2 estimates low annual movement rates between areas with 1% of fish moving both from the southern area to the north, and in the other direction, per year. In contrast, if movement rate is allowed to be age-dependent, the post-mature movement rate from south to north is estimated to be 26% per annum, with no real increase in the rate for north-to-south migration, although the model delivers pretty much identical results in terms of time series of biomass as before. This suggests that a) the simpler approach might be preferable, and b) the values for these parameters (movement) are poorly defined – there is very little data to inform them, and at best they are likely confounded with selectivity. More exploration is needed of the interaction of movement parameters with the other components of the model. As with Model 2, Model 3 estimates a low rate of annual movement (<1%) between the Aurora Trough trawl area and the Northern Valleys. Post-mature movement of fish from the Aurora Trough to the Macquarie Ridge area is estimated to be high (33% per annum), although the model does not do the same with fish in the Northern Valleys, estimating only a low (1% per annum) movement rate of fish from this area to the Ridge. This is likely due to the fact that only 1 Northern Valleys trawl-tagged fish has been recaptured in the longline fishery (Table 8.8), whereas in the last few seasons there have been several instances of fish tagged in the Aurora Trough being recaptured by longline in the SMR.

Biomass and fishing mortality estimates

The model estimates of current (2010/11) and unfished spawning biomass are given in Table 8.11. Model 1 indicates that current spawning biomass is around 64% of unfished conditions, whereas Models 2 and 3 suggest a less depleted stock, with 2010/11 spawning biomass being 67 and 72% of unfished equilibrium respectively. The time series show a steady decline over

the duration of the fishery (Figure 8.17). Unsurprisingly, the absolute values for estimated spawning biomass increase with increasing spatial complexity. (estimates of unfished spawning biomass ranging from around 8,500 mt for Model 1 and around 17,500 mt for Model 3). Model 2 estimates the spawning biomass in the northern area to be slightly larger than the southern one (Figure 8.17), and the southern area also has a lower biomass relative to unfished conditions. This is unsurprising given that the bulk of the fishery has operated in this area. Model 3 estimates the majority of the spawning biomass to be in the Macquarie Ridge area (Figure 8.17, bottom right-hand panel), a function of the movement of animals to this area once they mature, particularly from the Aurora Trough. The Northern Valleys area is estimated to have a much larger spawning biomass than the Aurora Trough area under Model 3, unlike the results obtained from Model 2. This is due to the lack of movement estimated to occur out of the Northern Valleys region, as discussed in the previous paragraph.

The equilibrium spawning potential ratio (SPR) is a well-used, convenient index that gives a direct measure of fishing intensity on the spawning potential of the stock. While SPR does not directly demonstrate the fraction of the stock that is caught each year, it is useful because a single metric of annual fishing mortality is hard to define in a model that admits multiple areas, multiple fleets, and dome-shaped selectivity. Low levels of SPR are associated with high fishing intensity. Indeed, an adjusted form of SPR enables direct comparison with values commonly used as reference points for fisheries management, such as the *F* that results in a spawning biomass 50% of the unfished state (in this case an SPR of 0.5). Table 8.11 shows that the current values of SPR are well above 0.5 and so the current impact of the fishery in this regard is relatively low. Figure 8.18 shows the time series of SPR for the 3 models, and reveals that the impact of the fishery is estimated to have been largest when assuming Model 1. This is not surprising, given that this model estimates the smallest stock size. All 3 models indicate that the level of fishing pressure in 1996 was greater than that required to reduce the population to below 50% unfished spawning biomass (Figure 8.18, points below red dashed horizontal line).

The estimates of current spawning biomass presented here are considerably higher (and suggest a less-depleted stock) than those from previous assessments for Macquarie Island. This is unsurprising, as this is the first instance in which catches and tag returns from multiple areas and multiple gears have been included in the single assessment model. Admitting multiple areas, and allowing dome-shaped selectivity for the longline fleets creates the potential for unavailable biomass within the fishery, thus increasing the stock size.

Table 8.11. Estimates of unfished spawning biomass, current (2010/11) spawning biomass, the level of current spawning biomass relative to the unfished state, and the current value for the spawning potential ratio (SPR) for the different model structures.

	Spawning biomass			$SPR_{09/10}$
Scenario	SB_0 (t)	$SB_{10/11}$ (t)	$SB_{10/11}/SB_0$	
Model 1 (1 area)	8,536	5,435	0.64	0.75
Model 2 (2 area)	13,484	9,089	0.67	0.83
Model 3 (3 area)	17,536	12,560	0.72	0.87
sensitivity analyses				
estimating growth curve (single sex)				
1 area	5,776	3,384	0.59	
2 area	7,745	5,045	0.65	
3 area	7,448	5,029	0.68	

8.7 Concluding points

Key points resulting from the analyses in this paper are:

1. The models presented here are the first instance of an attempt to integrate the data for Macquarie Island toothfish from multiple gear types and areas into a single assessment framework.

2. The models represent a range of alternative model structures, that encapsulate a number of different hypotheses about the dynamics of Patagonian toothfish at Macquarie Island and the interactions of this population with the fishery, although there potentially remain others to be explored.

3. The performance of these assessments, in particular the robustness of their ability to estimate biomass and fishing mortality levels to assuming different model structures (that likely differ from the true population structure), needs to be tested within the current Management Strategy Evaluation (MSE) project underway for this fishery.

4. Models which use multiple areas in addition to multiple fleets estimate larger stock sizes, and larger current stock size relative to that in unfished conditions.

5. All base models presented suggest that spawning biomass is currently above 50% of unfished conditions.

6. All models appear able to fit the length data and age-at-length data equally well.

7. The overall pattern of observed tag recaptures is mimicked well by the different models.

8. The models differ in their ability to mimic the patterns of tag recaptures by fleet. The one-area model cannot reconcile the heterogeneity in recaptures among fleets. The multi-area models do better but in general appear to over-predict the number of recaptures from the longline fleets.

9. There are limited data informing the models regarding movement among areas, as the number of tag recaptures from areas other than the area of release is low. Estimates of movement rates among areas can be expected to be uncertain. Simpler assumptions regarding movement appear more sensible.

10. Estimated rates of movement between the northern and southern areas are on the order of 1% per annum. Although low, this appears to be sufficient to mimic the observed data.

11. The 3 area model estimates the bulk of the biomass to be in the Macquarie Ridge, which follows the assumptions behind the model scenario. The model estimates a high movement rate out of the Aurora Trough to the Ridge, but does not do the same for the Northern Valleys, instead retaining biomass in this area. This appears to be due to a lack of tag returns from Northern Valley tagged fish in the longline operations.

12. Allocation of recruitment in the 3-area model is only to the traditional trawl grounds. As a result, all young fish are assumed to pass through these areas. However, fishing by trawl operations along the ridge in early years did yield small fish.

13. The implications of assuming a fixed age of release for each gear that is both time and space invariant are unclear. The expected numbers of tag recaptures from a tag group in a given year will clearly depend on the assumed ages at release. Also not clear are ways in which this fixed assumption will impact estimates of individual year class strengths, and movement rates. This has been flagged as an important point to address in the MSE work.

14. Estimates of growth of Patagonian toothfish at Macquarie Island should be updated to include growth increment data from tag recaptures, as these should be based on as much available data as possible. The parameters of the growth curve are an important determinant of biomass within the model and have implications for the functional form for selectivity of the longline gear. Versions of the models that estimated growth resulted in estimates of maximum size well below those of the 2001 growth curve. As a result, much smaller biomass estimates resulted. Currently there have been no sampling of fish > 130cm or of age >20 yrs at Macquarie, hence the low growth estimates.

15. This document describes instances whereby a single population dynamics model is fit to all the data from all the regions of the fishery. Not explored are alternatives where several separate assessments are conducted, i.e. one for the Aurora Trough, one for the Northern Valleys, etc.

16. The current framework considers that both the longline and trawl fisheries take place at the same time, i.e. halfway through a season. However, this has not been the case, with the longlining operations occurring in winter whereas the trawl fishery has typically operated during the summer. Sensitivity analyses should explore the impact of moving the timing of the different fleets within the seasons, as it is important that cohorts are able to be tracked successfully.

17. Consideration by SARAG of spatial and/or multiple gear assessments for Patagonian toothfish at Macquarie Island raises issues related to how future catches should be allocated, both by area and by gear. Such considerations would need to be dealt with when applying the harvest strategy. The presence of multiple fleets and multiple areas within the model means that there are more than one single number for quantities such as available biomass, which has typically been used as the basis for setting TACs for this stock.

8.8 Acknowledgments

The authors thank the AFMA scientific observers for conducting the tagging program and the owners, officers and crew of the *Southern Champion*, *Avro Chieftain*, and *Janas* for their excellent cooperation throughout. M. Haddon and SARAG members are thanked for valuable comments on earlier drafts of this document.

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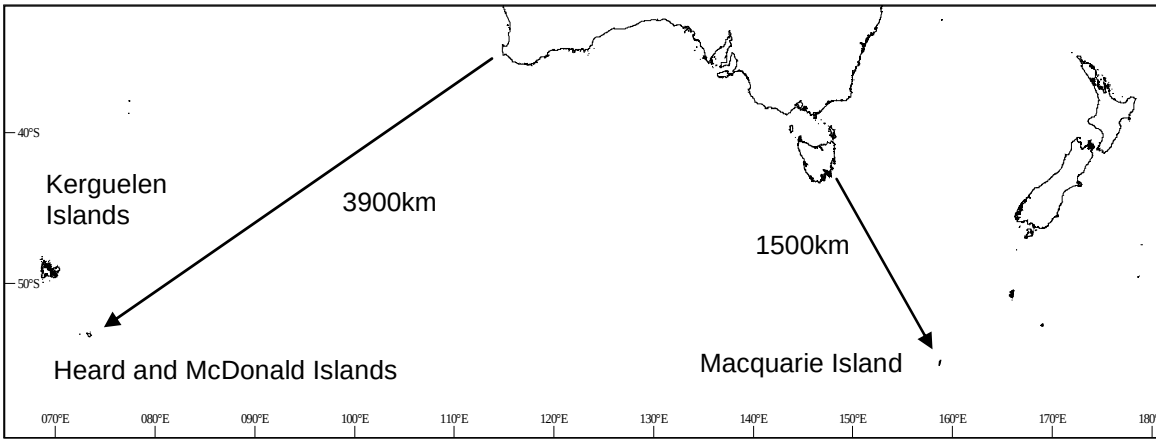

Figure 8.1.The location of Macquarie Island (54°30’S, 158°57’E) and Heard Island and McDonald Islands (53°06’S, 73°30’E) relative to New Zealand and Australia.

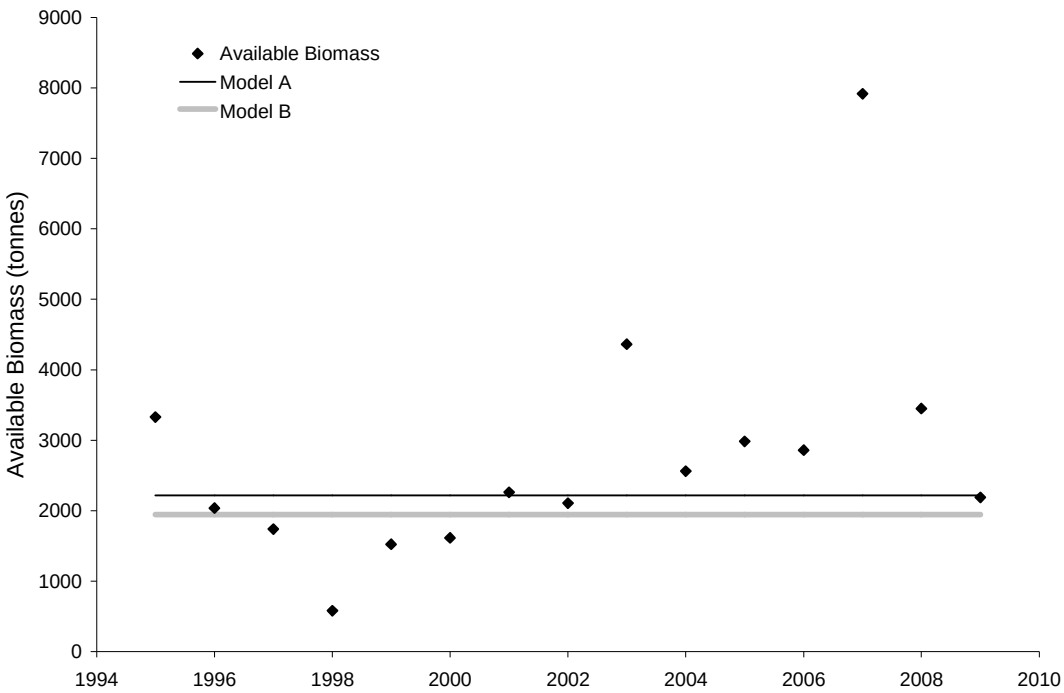

Figure 8.2. Results of 2009 stock assessment (Tuck and Lamb 2009). Point estimates of trawl available biomass of toothfish at Aurora Trough at 30 June in each year since 1996 with natural mortality M = 0.13, and tag mixing parameter δ = 10. The 1995 estimate is taken from the initial starting point of the model, 1 July 1995. The horizontal line indicates the threshold levels for a commercial fishery for the percent remaining models, Model A and Model B. If the point estimate is above this line then, according to the current management rule, a commercial fishery exists.

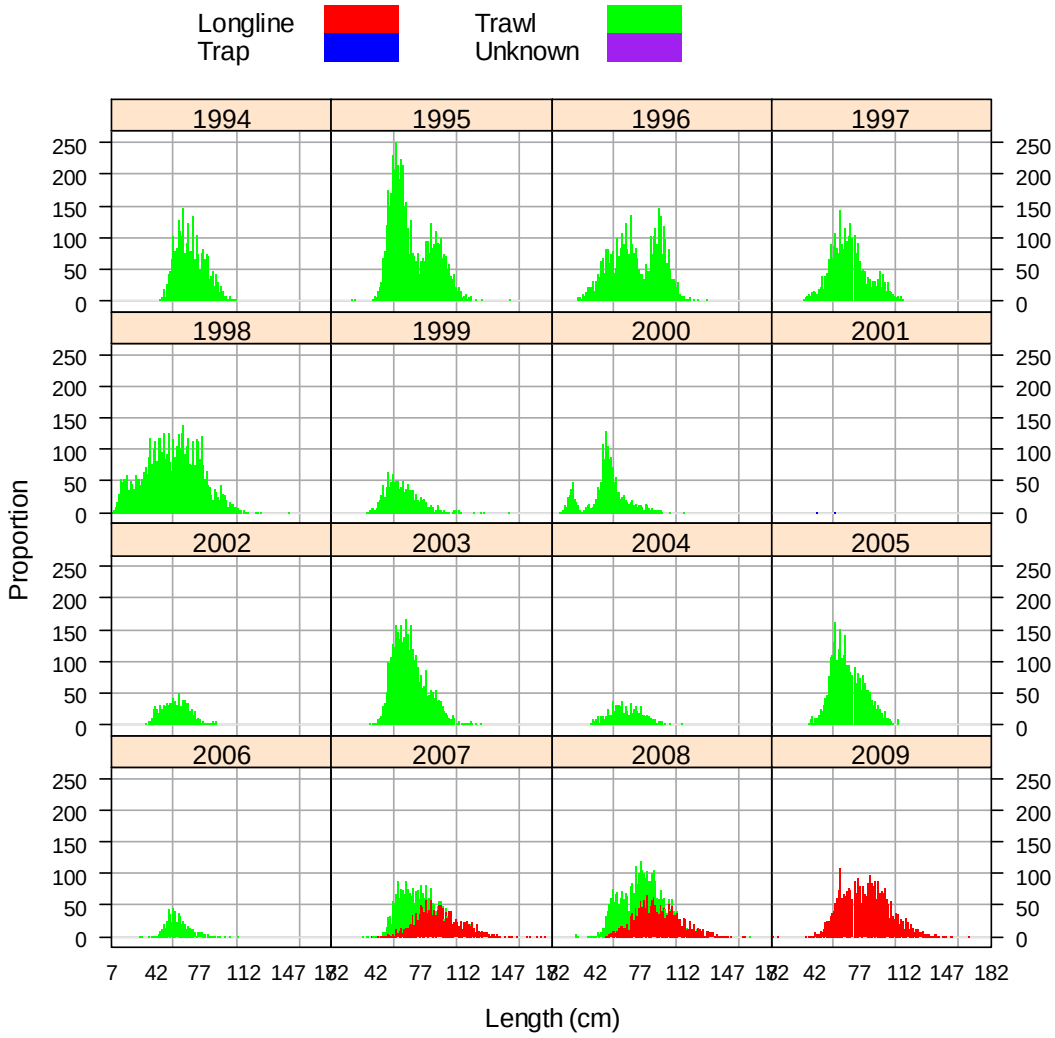

Figure 8.3. Seasonal length composition data by gear type.

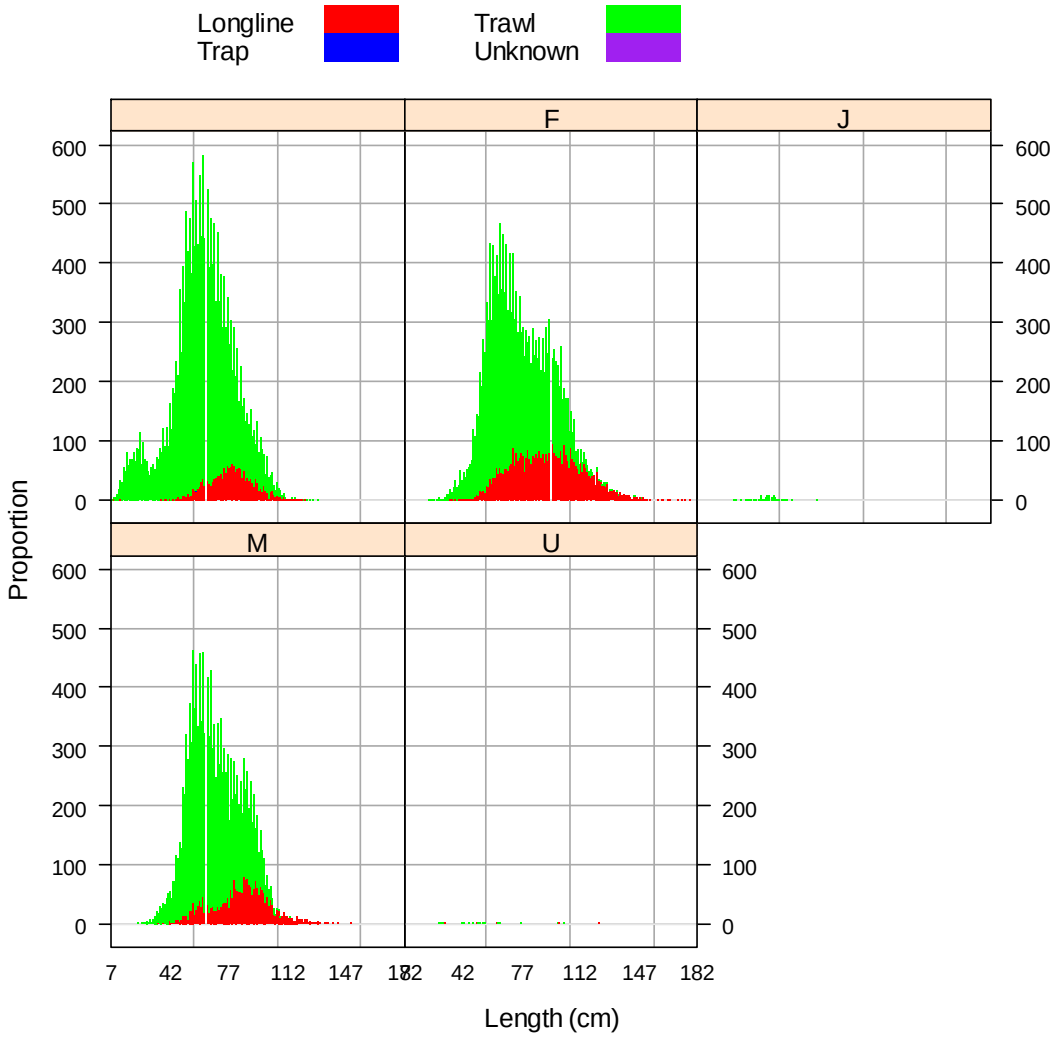

Figure 8.4. Length distributions by gear for each sex code (pooled over all years). Note presence of fish of length <30 cm in the unheaded category.

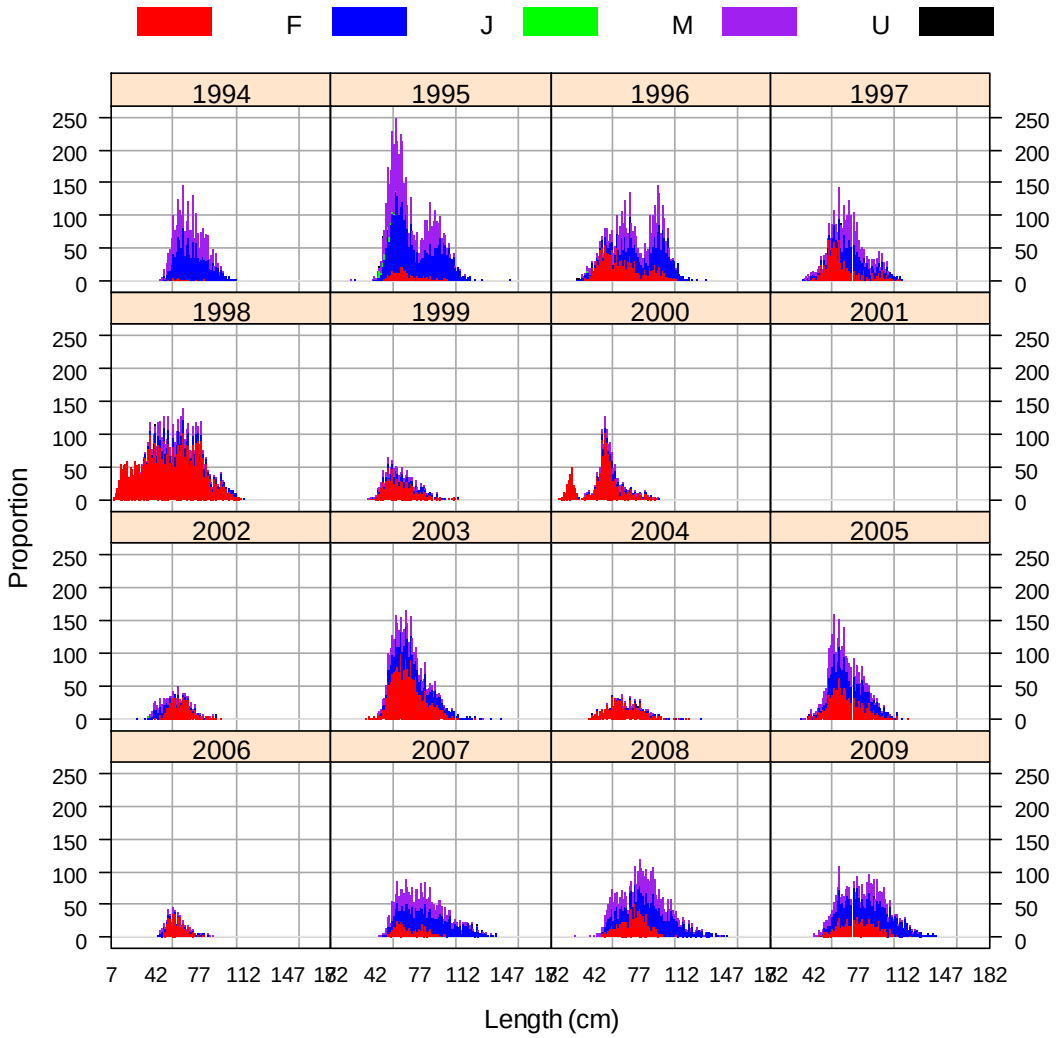

Figure 8.5. Seasonal length compositions (all gears) by sex.

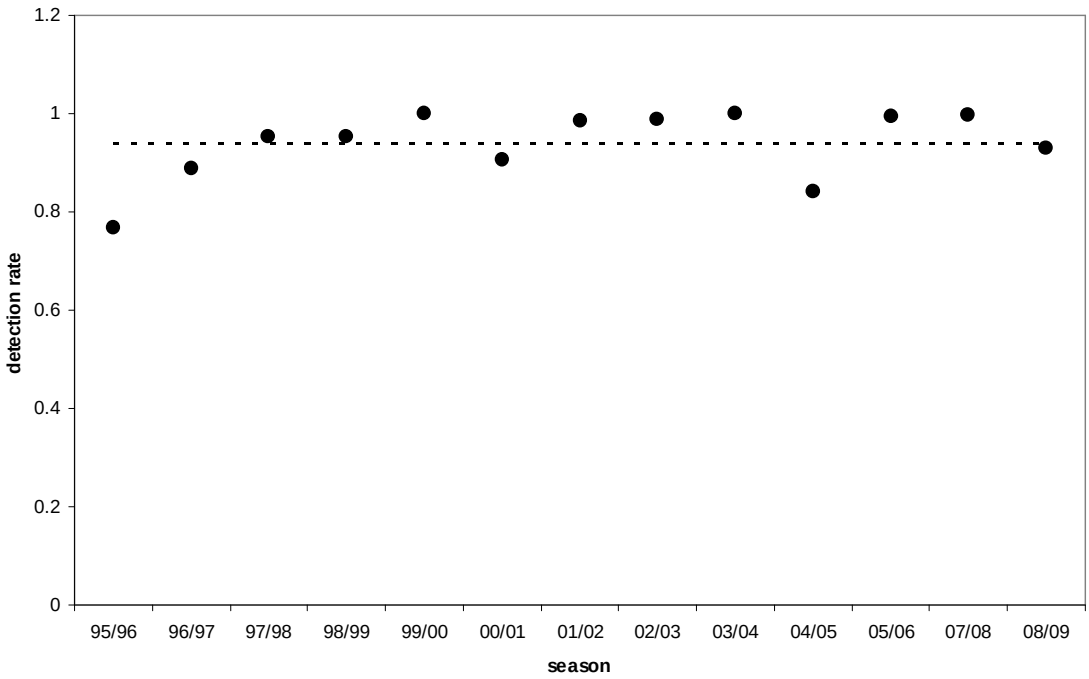

Figure 8.6. Estimated tag detection rate (points) by fishing season. Dotted line corresponds to the mean detection rate (0.938) used in the assessment model.

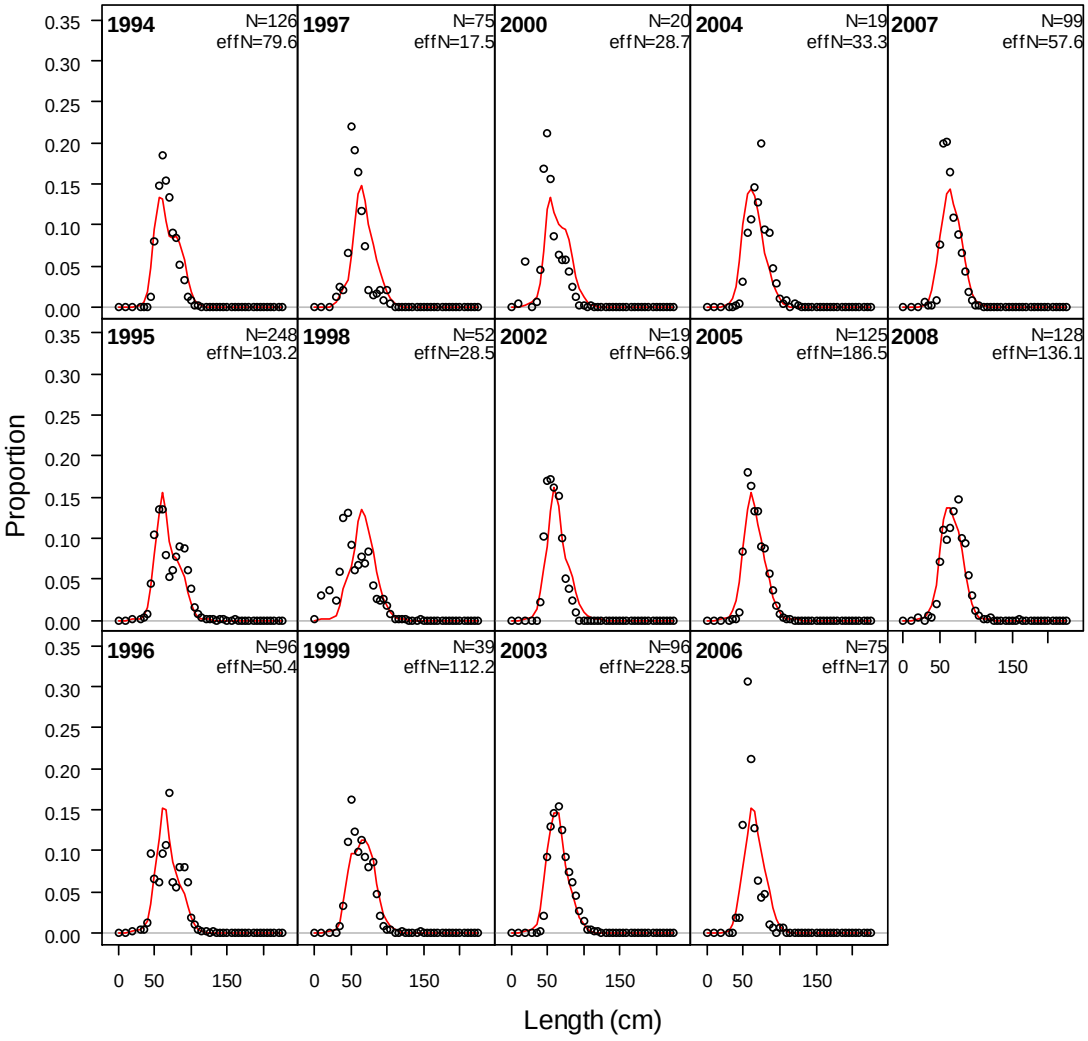

Figure 8.7. Fits to the Aurora Trough trawl length composition data for Model 1.

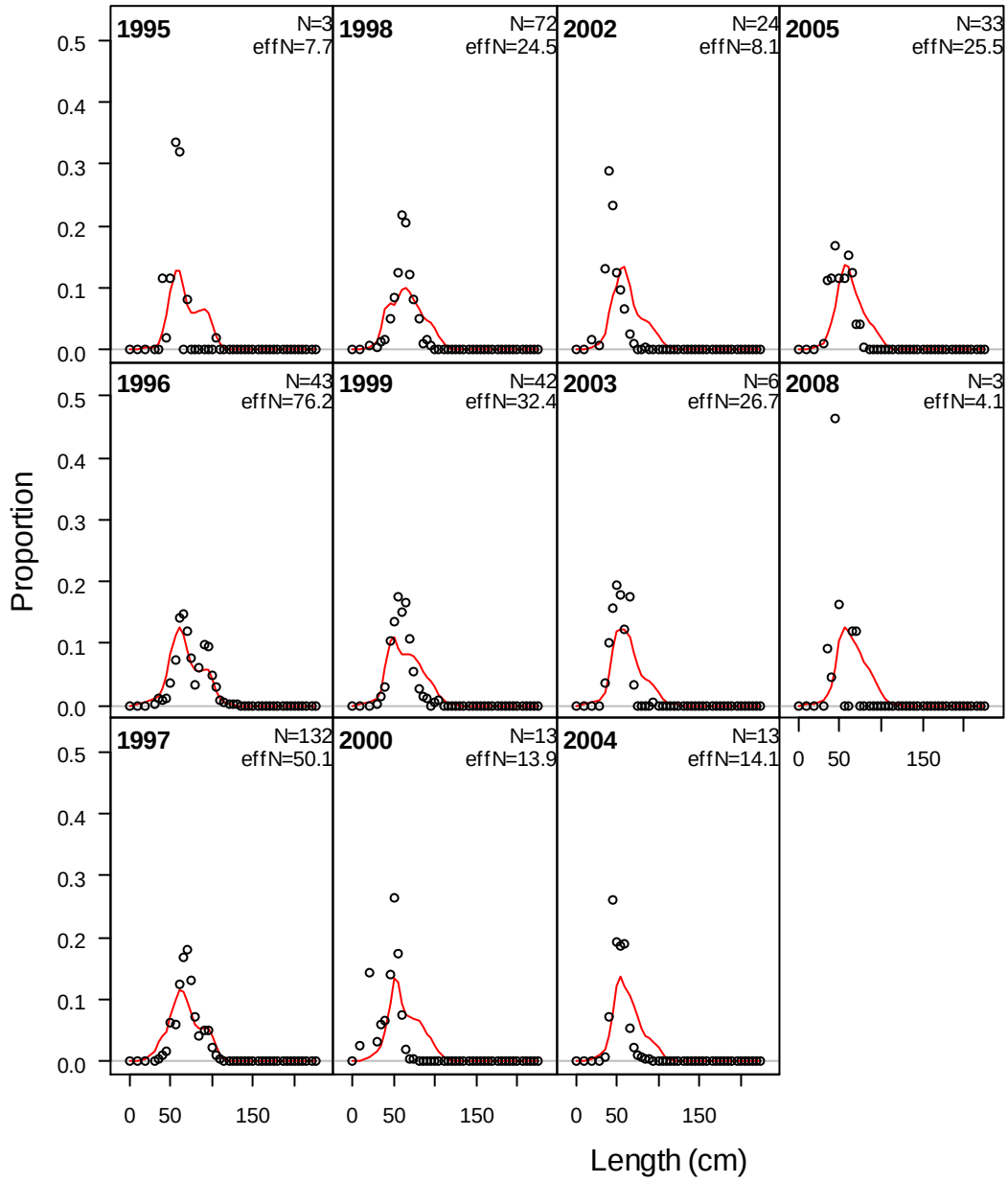

Figure 8.8. Fits to the Northern Valleys length composition data for Model 1.

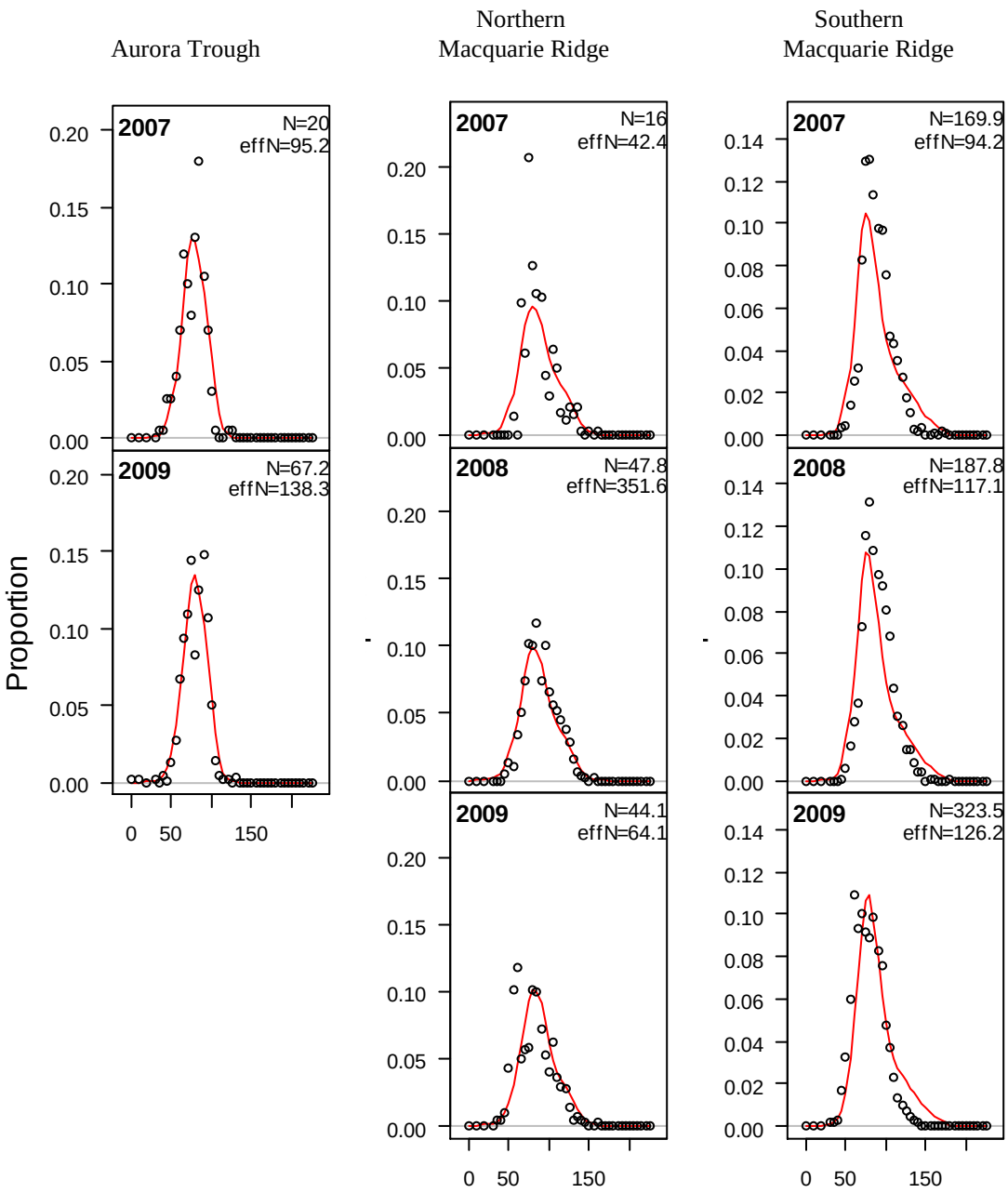

Figure 8.9. Fits to the longline length composition data for Model 1. Columns correspond to the different fleets.

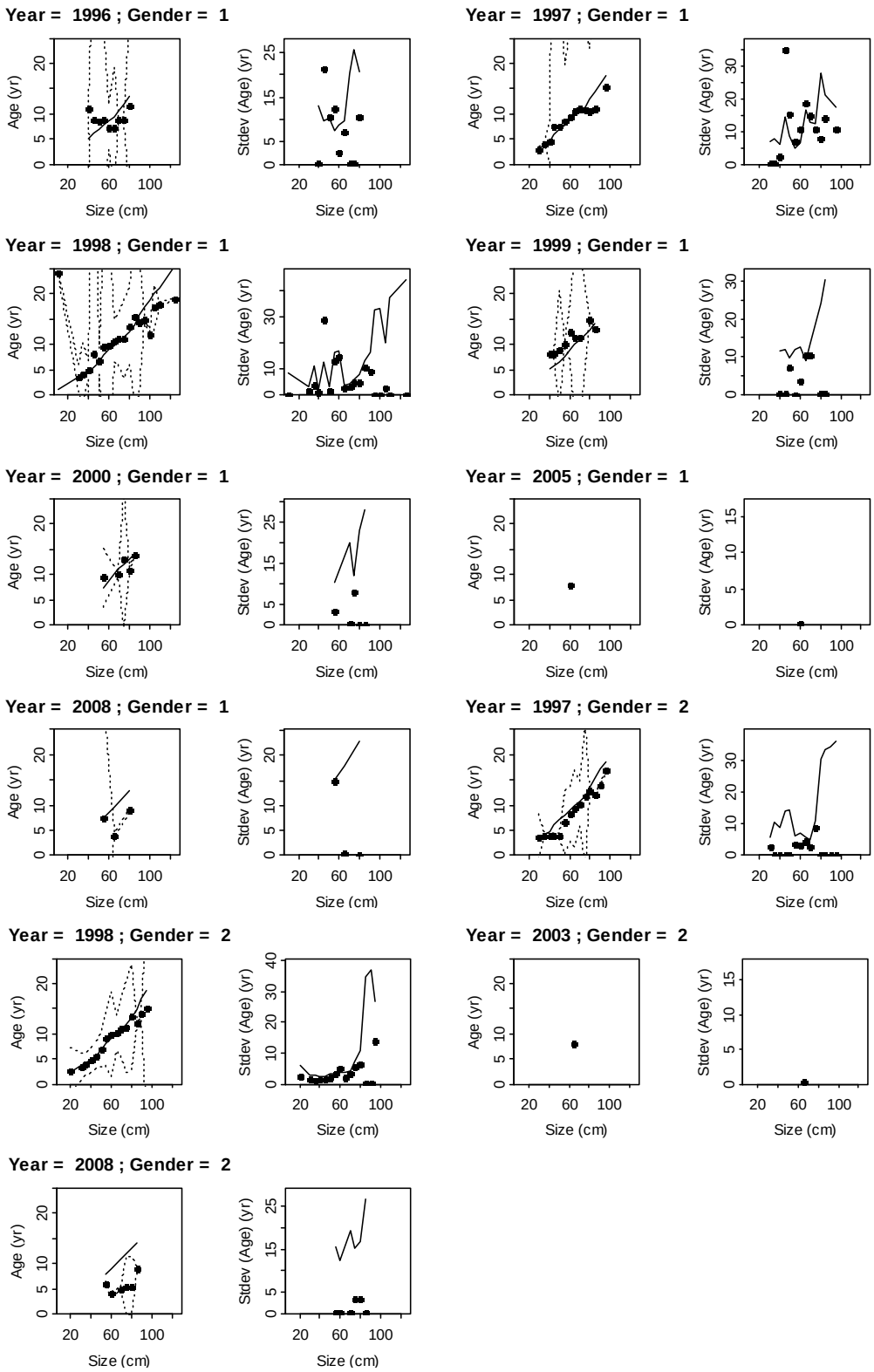

Figure 8.10. Diagnostic plots for the fit to the conditional age at length data for Model 1. For each year and gender (1=female, 2=male), the two panels are 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed and predicted) and the 90% CIs based on the chi-square distribution. The dots are the data, the dotted lines the 90% CIs and the lines the expected values.

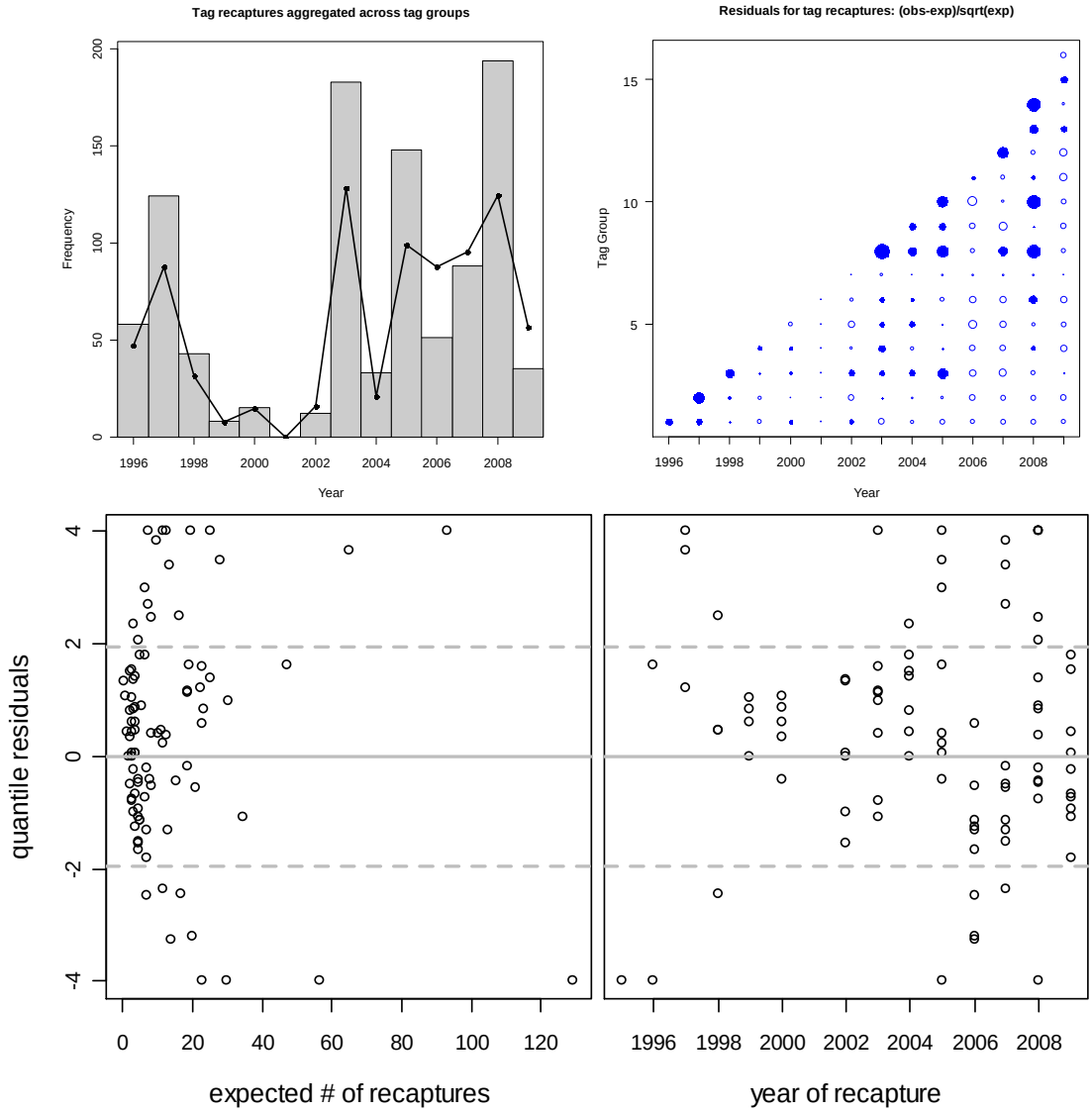

Figure 8.11. Summary of the fits to the tag recapture data for Model 1. Top left panel shows the summed observed (bars) and expected(line) recaptures over years, the top-right panel shows the residuals by tag group and year (blue indicates positive residual), and the bottom panels display the quantile residuals, with the dashed lines indicating the interval within which 95% of the residuals would be expected to occur.

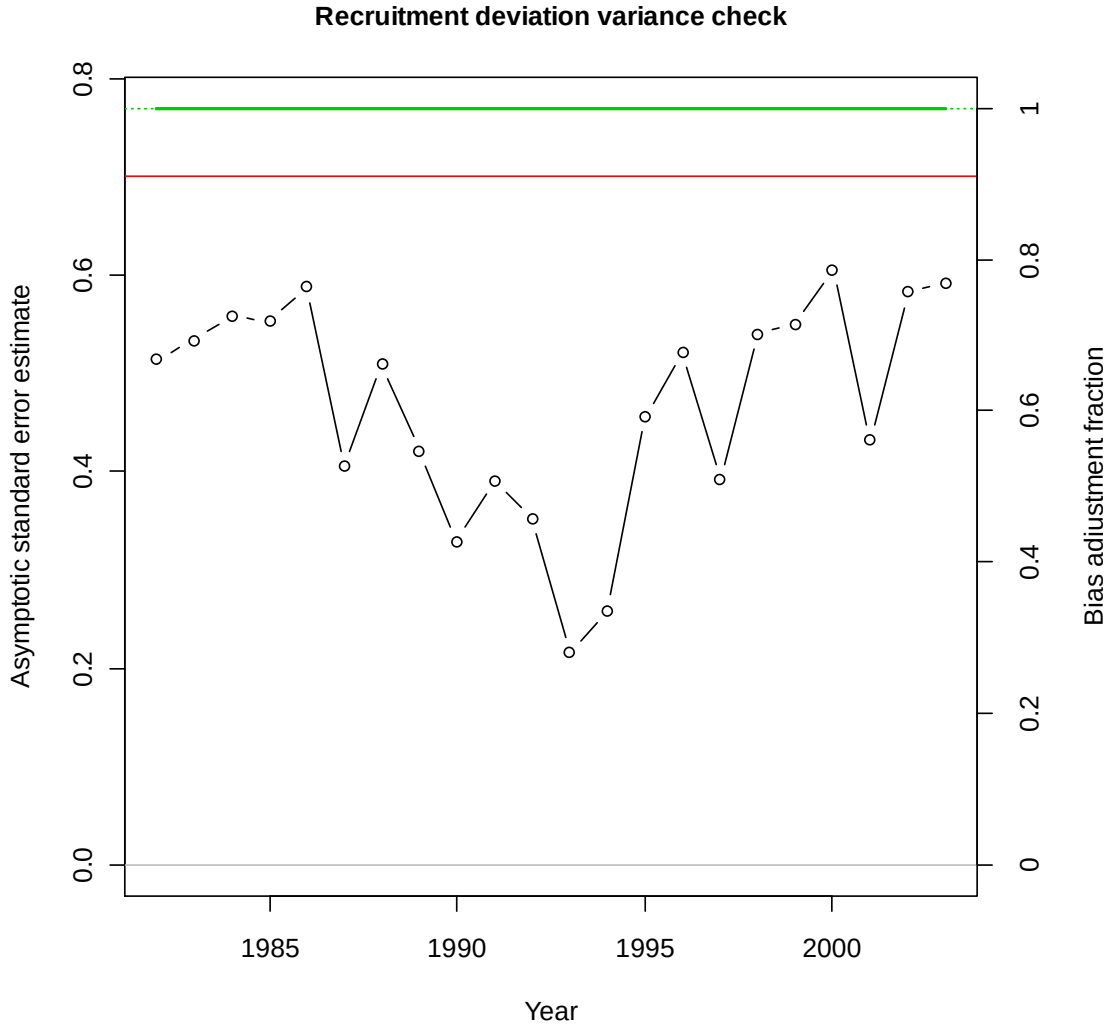

Figure 8.12. Asymptotic standard error of estimate for the recruitment deviations for Model 1.

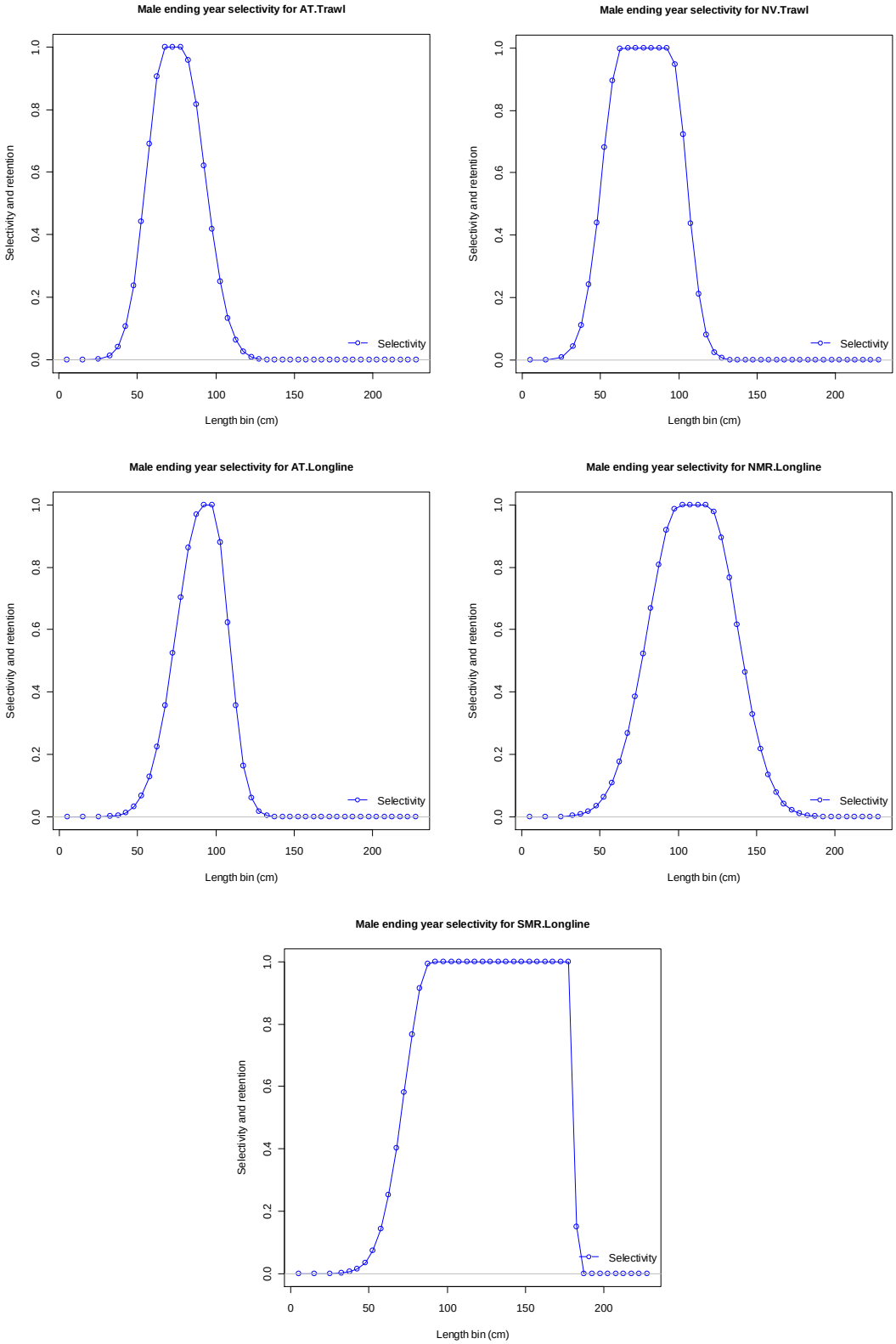

Figure 8.13. Estimated selectivity patterns for the five fleets under Model 1.

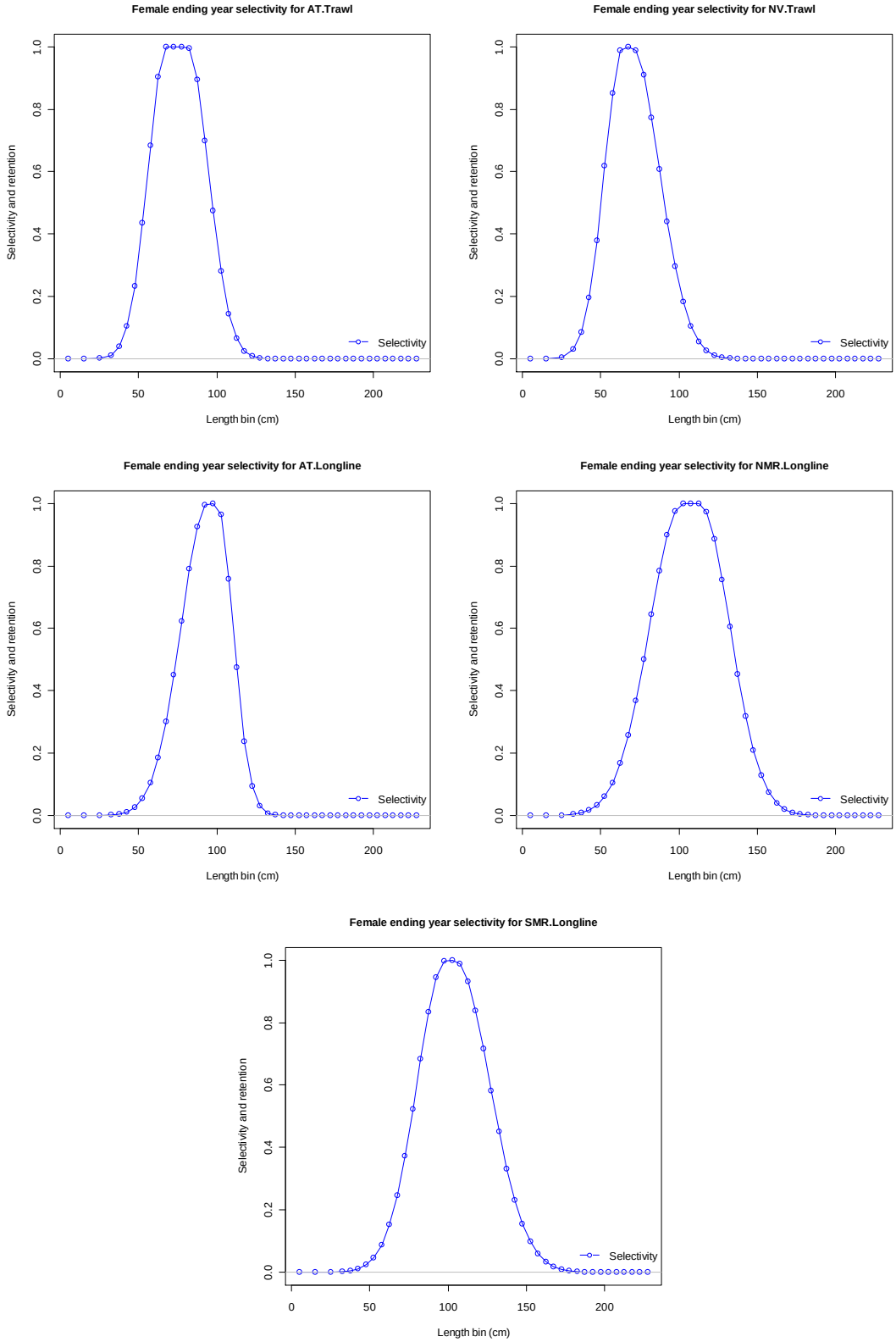

Figure 8.14. Estimated selectivity patterns by fleet for Model 2.

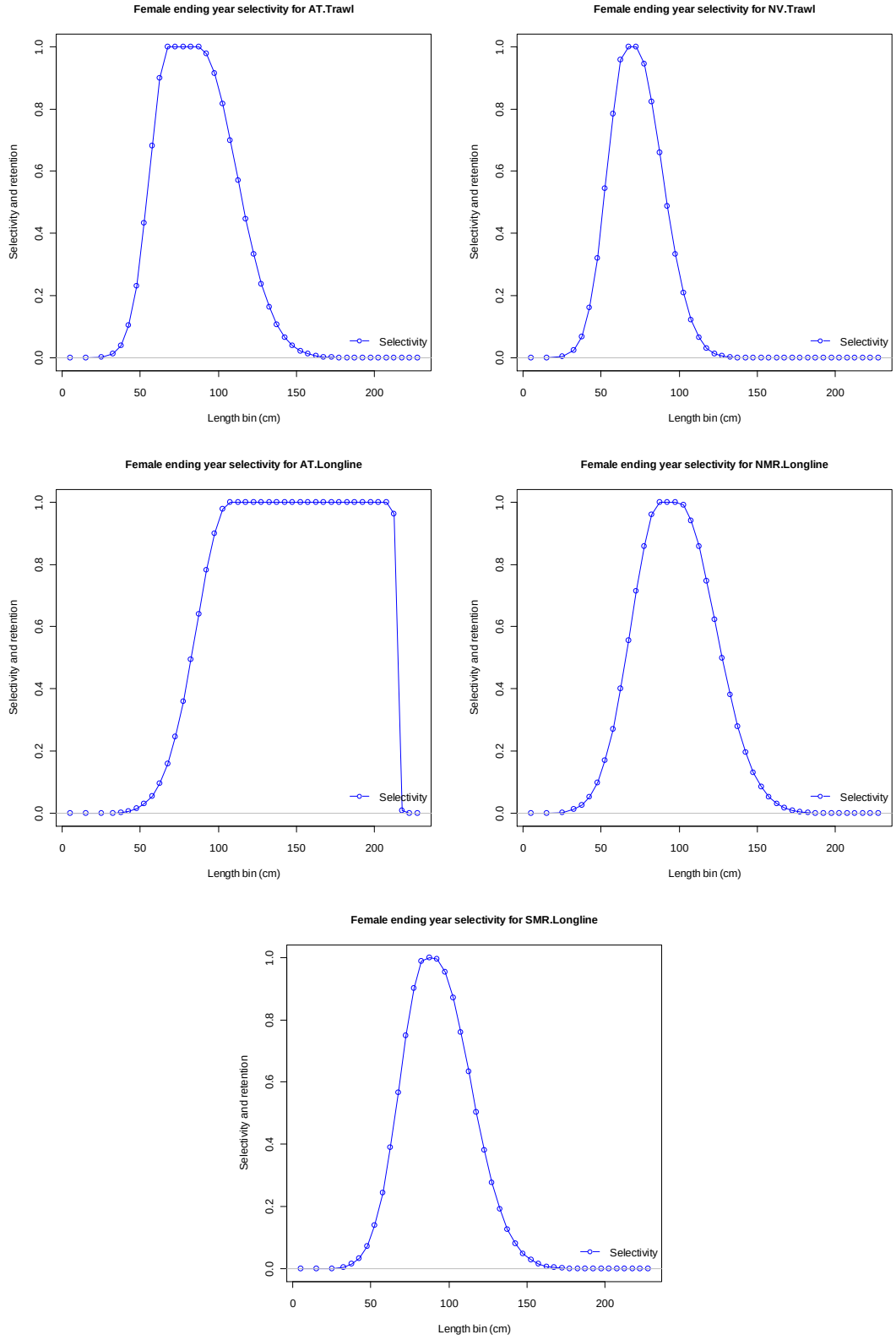

Figure 8.15. Estimated selectivity patterns by fleet for Model 3.

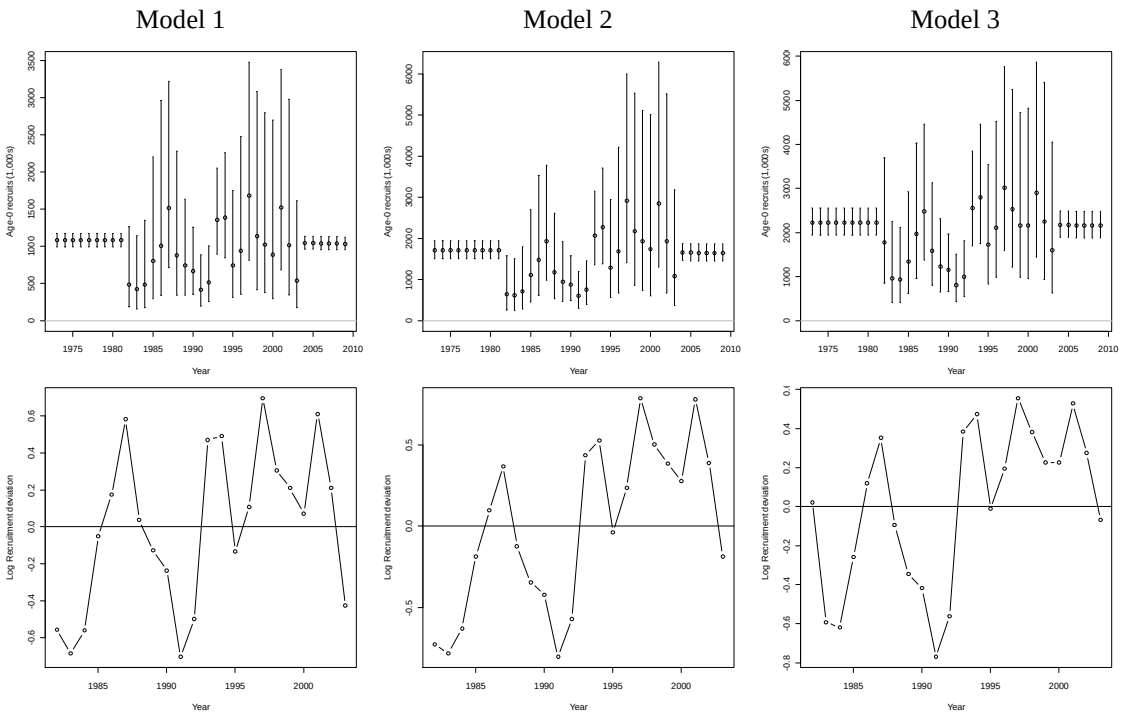

Figure 8.16. Time series of estimated recruitments and recruitment residuals for the 3 models.

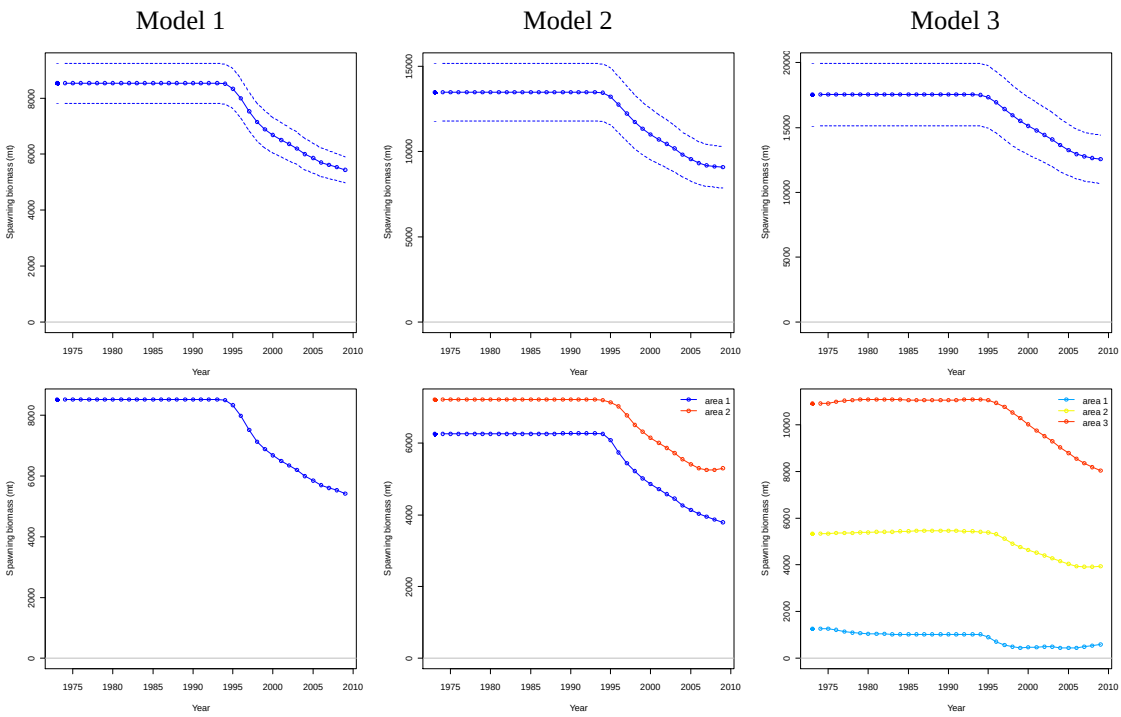

Figure 8.17. Time series (with approximate 95% confidence intervals) of spawning biomass for the 3 models. The bottom row of panels demonstrates how the spawning biomass is apportioned by area. For Model 2, area 1 is the southern area and area 2 is the northern area. For Model 3, area 1 is the Aurora Trough, area 2 the Northern Valleys, and area 3 is the Macquarie Ridge.

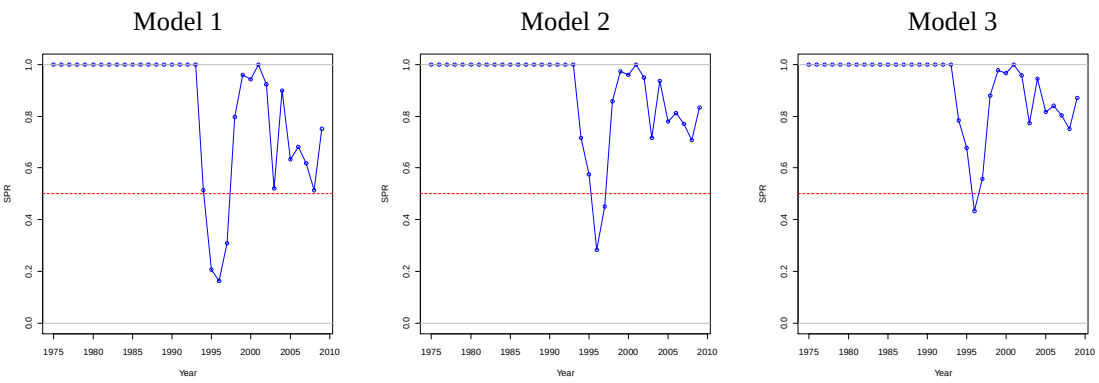

Figure 8.18. Time series of spawning potential ratio (SPR) for the 3 models. The red horizontal dashed line indicates an SPR value of 0.5. If the value for SPR is below this line this indicates that the rate of fishing mortality in that year was likely greater than that which on average results in a spawning biomass of 50% unfished levels.

9. INTEGRATED STOCK ASSESSMENT FOR THE AURORA TROUGH MACQUARIE ISLAND TOOTHFISH USING DATA UP TO AND INCLUDING JULY 2009[4]

Gavin Fay

9.1 Summary

This chapter presents results of fitting an integrated assessment model (Stock Synthesis) to the available data from the trawl and longline fishery for Patagonian toothfish (*Dissostichus eleginoides*) within Aurora Trough at Macquarie Island. The model fits to data obtained from the tag-recapture program at Macquarie Island since 1995, to length composition data for the years 1994-2009, and to age-at-length data from aged otoliths taken in 1997 and 1998.

The model designates two different fleets (Aurora Trough trawl and longline), and estimates separate selectivity patterns for each fleet.

Several modifications have been made to the assessment model since the material presented to the SARAG in September 2009. Reasons for and details of these changes are discussed in the document. These changes include:

1. the use of separate growth curves by sex,
2. consideration of alternative growth curves based on fits to growth increment data from tag returns,
3. updating of the maturity ogive as a result of model fits to maturity data from Macquarie Island obtained during the longline trial conducted in 2007/2009,
4. disaggregating the length composition data by sex for some years,
5. removal of age-at-length data for years other than 1997 and 1998,
6. use of ageing error matrix from the 2009 HIMI assessment,
7. implementation of time-varying tag detection rates,
8. disaggregation of the assumed ages of tag releases into multiple tag groups per season based on the distribution of lengths-at-release.

A large number of alternative models were fit to the available data, to determine the impact of key uncertainties.

Fits to the length composition data are adequate, although the model is unable to reconcile some of the variability in the data with the dynamics of the population model. Versions of the model that estimate the growth parameters tend to reduce the variability in length-at-age (to levels not consistent with the age-at-length data), and also emphasise differences in the growth rates of males and females, which improves the fit to the length data. The lengths of toothfish available to the fishery at Macquarie Island varies 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.

[4] Paper presented to SARAG on 16 March, 2010

Not surprisingly, the models fit the age-at-length data well using the original growth curve, with the fit to these data declining when the CV of length at age is reduced, or the data are not included in the likelihood function. Placing additional emphasis on the fit to the length data when estimating growth curve parameters also degrades the fit to the age data, however the fit to the age data was not generally affected by the majority of other uncertainties explored across models.

The models fit the tag-recapture data well, with good accord between the total number of expected recaptures and those observed. That said, the numbers of recaptures predicted by the models was higher than those observed for the 2006/07 and 2007/08 seasons. This is largely due to a lack of 80+cm fish in the length data for these years. The fits to the tag-return data are improved with higher values for the rate of natural mortality, *M*. This could indicate that *M* is higher for Macquarie Island toothfish than previous assessments have assumed, or could also reflect movement of fish away from Aurora Trough, and possibly the effects of tag loss. The choice of how many groups to disaggregate the tag release data into (in terms of assigning ages of releases) did not impact the assessment results greatly.

The choice of growth curves impacted greatly on the estimates of spawning biomass, as the alternative growth curve estimated from the growth increment data have lower maximum sizes. However, the impact of the choice of growth curve on the estimates of trawl available biomass was lower, mainly because the growth curves are fairly similar at the lengths vulnerable to the trawl fishery.

The general pattern to the time series of recruitments is estimated consistently, with recruitment pulses estimated to have occurred around 1980, 1987, 1994, and 1998/99. In order to fit the apparent presence of a strong year class in the 1996/97 length data, the model estimates the few years of pre-1980 recruitment to be below average. The estimates for recent recruitments (mid to late 1990s and early 2000s) are uncertain, which likely reflects the paucity of age data and the lack of resolution in the length data due to variability in length at age. Additional age data will likely improve the ability to estimate both the magnitude of individual recruitments and growth.

In general, the models estimate current spawning biomass to be around 50-60% of unfished spawning biomass, with the base-case estimate of 2010/11 spawning biomass relative to unfished levels being 57%. Revised lengths at maturity (50% mature at 139 cm) lead to smaller absolute values for the spawning biomass, which is largely unavailable to both the trawl and longline fisheries. The spawning biomass shows low responsiveness to changes in the magnitude of catches within the fishery.

The current (2010/2011) trawl available biomass is estimated to be well above the limit reference point of 66.5% pre-tagging (1995) levels, with the base-case trawl available biomass estimated to be 2,932t. Under the current harvest strategy, this would imply a 2010/11 TAC for the Aurora Trough of 293t. The difference between the estimates of trawl available biomass between the new assessment and the previously applied tag-only model is a result of pre-tagging biomass not being estimated as high, and that the decline in available biomass in 2009 was not as great as that from the 2009 assessment. The estimate of current trawl available biomass can in general be expected to be somewhat uncertain given that there is a little information on the new recruitments entering the fishery. Sensitivity analyses conducted largely showed a robustness in the estimates of trawl available biomass to a suite of alternative assumptions regarding the data. Changes in the results from those under the base-case were most notable when different values for natural mortality and growth were used, when tagged

fish recaptured within the year of release were included in the model, and when overdispersion (clumpiness) was allowed in the rate of tag recapture.

The projected catch for 2010/11 under the current harvest strategy for Aurora Trough is greater than that calculated under an F50 harvest strategy (constant harvest rate at the level expected to result in an equilibrium level of 50% unfished spawning biomass), 161t, and also the catch level that would be calculated under the CCAMLR control rule, which would be 184t.

9.2 Introduction

This chapter presents results from integrated stock assessments of Aurora Trough Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island to 2010/11 using data collected up until and including July 2009.

This assessment makes use of the Stock Synthesis assessment software (v3.04b, *e.g.* Methot, 2007), and fits to data obtained from the tag-recapture program since 1995, to length composition information for the years 1994-2009, and to age-at-length data obtained from aged otoliths. The assessment updates results presented to SARAG in 2008 (Tuck and Methot, 2008) and 2009 (Fay *et al*., 2009a). The assessment model is also set up to enable comparisons with the tagging model currently used for providing advice for setting the TAC at Macquarie Island (Tuck and Lamb 2009, Tuck *et al.*, 2003).

The new assessment is based on a length-age structured model of fish population dynamics and uses a maximum likelihood framework to fit to the available data. As with the integrated assessments previously applied to Macquarie Island toothfish (Tuck *et al*., 2006), use of the Stock Synthesis framework enables estimation of spawning biomass and selectivity curves, in addition to the estimate of trawl available biomass, which is typically the output of the tagging model (*e.g.* Tuck *et al*., 2003).

Stock assessment of the Macquarie Island Patagonian toothfish stock has been based on the tag-recapture model developed by de la Mare and Williams (1997), and modifications described in Tuck *et al.* (2003). The tag-recapture model uses population and tag accumulation models to account for tags being released at various times throughout the season and the effects of removals by fishing. The model estimates pre-tagging available abundance and the annual net change in available abundance between fishing seasons for the major fishing grounds of Macquarie Island. In 2004, a new model that expanded upon the traditional tag-based model was introduced. 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 (Fay *et al*., 2009a), of which the assessment described within this document is the next extension.

The 2009 assessment estimates for available abundance at Aurora Trough (*cf*. Tuck and Lamb, 2009) are shown in Figure 9.2. Available abundance was estimated to have declined over the first three seasons of tagging (to 1998/1999), and then increased. The 2009 assessment estimated that available abundance since 2003/04 had been largely above 66.5% pre-tagging levels (Figure 9.2), with the 2009 estimate being slightly below this limit reference point for the implantation of a research quota in Aurora Trough (Figure 9.2, Tuck and Lamb, 2009).

In 2008, Tuck and Methot (2008) presented to SARAG progress on developing a new integrated assessment using the Stock Synthesis assessment platform. The intent of the new integrated assessment was to provide a means of accounting for information from the expansion of the fishery at Macquarie Island with the recent longline trial. The integrated assessment includes information on length-frequency and tagging data in an age-structured model that allows estimation of annual spawning biomass and cohort strength. Results showed that the new assessment could replicate the results of the tag-only assessment and the previous integrated assessment. Following this, the results of fitting Stock Synthesis to the available data from the Aurora Trough trawl fishery for Macquarie Island Patagonian toothfish were presented to SARAG in 2009 (Fay *et al*., 2009a). The base-case model estimated that 2009/10 toothfish spawning biomass in Aurora Trough to be 50% of that in the unfished equilibrium state, with 2009/10 trawl available biomass estimated to be 75% of the pre-tagging level. Estimates of current stock status were sensitive to the value assumed for the rate of natural mortality, the initial year in which recruitment deviations were estimated, and the age assumed for tagged fish on release. Estimates of available biomass showed a declining and then recovering trajectory, similar to that observed in the previous tag-only and integrated assessment models. The analyses that follow expand on this work by updating the data with that obtained from the longline fishery in 2009, and by additional modifications to the assessment model, described below.

9.3 Data

The data available for model-fitting purposes included length composition data from the fishery (1994/95-2009/10), conditional age-at-length data (1997-2000, 2003, 2005, 2008), and the results of the tag-release-recapture program, begun during the 1995/96 season.

9.3.1 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 to. Table 9.1 shows the catch history by fishing year for both trawl and longline at the Aurora Trough.

9.3.2 Length frequency data

Samples of the length composition of the catch were available for all fishing seasons (1994/95 through 2009/10). Each annual length composition is based on the measurement of several hundreds (thousands) of fish, 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. The actual sample sizes in both numbers of fish and shots sampled are shown in Table 9.2.

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 (Table 9.2). Additionally, inspection of the data suggests that the unsexed fish sampled for length are quite different to the male and female portions of the length composition for some years (Figure 9.3). Consequently, length data were aggregated by sex for

the seasons 1998/99, 2000/01, 2002/03, 2004/05, and 2006/07, with disaggregation by sex for all other years.

Length bin structure is at 5cm intervals, except for the smaller fish, where the length bins are 10 cm wide. The length of toothfish available to the fishery at Aurora Trough appears to be seasonally and depth dependent (Figure 9.4). As the distribution of fishing effort by depth and month has changed from season to season Figure 9.4, it can be expected that some variability in the length composition data will be due to differences in when and where samples were taken as opposed to differences associated with population dynamics and the effects of fishing.

9.3.3 Age data

Age at length samples are available from aged fish that were captured in 1996-2000, and 2002-2008.

Conditional age-at-length data

The age data are input as the raw age-at-length data, rather than age compositions generated from applying age-length keys to the catch-at-length compositions. The input compositions are therefore the distribution of ages obtained from samples in each length bin, for those years for which data are available. These data are summarised in Table 9.3.

The majority of the otoliths that have been aged since 2000 come from tag-recaptured fish (Table 9.3, column 'tag recaptures'). As such, it is not reasonable to assume that these data are representative samples of the age-at-length distribution of the entire catch. As a result, age data that came from tag recaptured fish are not included in the base case analyses. Not including these data appreciably reduces the amount of age data. In fact, the sample sizes for years other than 1997 and 1998 are so low that age data from years other than 1997 and 1998 are not included in the base-case models. Sensitivity of model results to including the tag recaptured age-length data is considered.

Ageing error

There are currently no multiple reads of otoliths from Macquarie Island Patagonian toothfish with which to quantify the degree of ageing error. As a result, the ageing error matrix calculated for Patagonian toothfish at HIMI (Candy and Welsford, 2009) was used to provide estimates of ageing error, in order to calculate the degree to which a fish of true age *i* is aged to be *j*. Stock Synthesis enters ageing error by, for each true age, assuming a normal distribution of observed ages around a mean age and standard deviation for the observations. The ageing error matrix (Table 9.4) assumes ageing was unbiased (ie mean observed age was the true age). There is evidence however, that for older fish, the observed age is less than the true age (Candy and Welsford 2009).

9.3.4 Tag recapture data

Between the 1995/96 and 2009/10 fishing seasons, over 11,000 Patagonian toothfish were tagged at Macquarie Island, of which nearly 1,700 have been recaptured. Table 9.5 summarises the numbers of releases and recaptures at Aurora Trough over the duration of the tagging program. Fish are still being recaptured from releases in the early years of the fishery (Table 9.5).

Under the 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. The impact of alternative methods of disaggregating tag released fish into tag groups within the model was addresses in the sensitivity analyses.

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 an 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 are very similar at the lengths at which most fish are tagged.

Recaptures of tagged fish are assumed to be random (Poisson distributed) conditional on the catch and expected number of tags available to the fishery. The available recapture data consists of the numbers of recaptured fish each year by each release group (Table 9.5), for brevity release data are aggregated by season). To allow for full mixing of the tagged fish with the untagged population, recaptures within the year of release were removed from the assessment release data if the recapture occurred within 10 days of release (*cf*. Tuck and Lamb, 2009). Furthermore, for the base-case analyses, the recaptures within the year of release were not included when fitting the model.

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 9.5, data from Tuck and Lamb 2009), and were input to the model in order to implement a time-varying detection rate.

This is a modification to the previous SS3 model for Aurora Trough, which held the tag detection rate constant over time. The tag detection rate for the longline fleet was assumed to be 100%, but sensitivity analyses explored the impact of setting it to 0.94 (the average of the calculated annual values from the trawl fishery).

9.4 Biology

9.4.1 Growth

Growth of Patagonian toothfish is assumed to follow the von Bertalanffy growth function, with sex-specific parameter values estimated from age and length data by Constable *et al*. (2001) as indicated in Table 9.6. The base-case analyses held the values for these parameters fixed. Alternatives explored in the sensitivity analyses included estimating some or all of the growth curve parameters, and holding the values fixed at an alternative set of parameter values, obtained from fits to the growth increment data available from the tag recaptures at Macquarie Island (Table 9.6). It is noted that the age-at-length data from the 1990s is the data that the Constable *et al*. (2001) growth estimates were obtained from. Estimating the growth within the assessment model is preferable if there are sufficient data to do so, as this allows the impacts of length-specific selectivity to be directly accounted for, and in a consistent fashion with respect to the rest of the assessment.

Growth estimates based on the growth increment and ageing data from tag-recaptured fish were estimated using a random effects framework that accounted for ageing error, observation error in the length measurements, and individual variability in the maximum length. The effects of age-specific selectivity were accounted for however the method did not account for unequal probability of observing different lengths given an age. Including the age-at-length data from non tag-recaptures in the growth estimation resulted in slightly different estimates, as seen in Table 9.6. Only data from fish that had been sexed were used in the estimation – inclusion of additional data from unsexed fish had negligible impact on the results, primarily due to most of these fish also not having been aged. The growth estimates obtained from this estimation are typified by a much lower value for the maximum length compared to the estimates obtained by Constable *et al*. (2001). This is most likely a consequence of forcing the age at which fish have zero length to be zero.

The values for the parameters of the growth curve used to assign ages to tag releases are given in Table 9.6. These were estimated by Constable *et al*. (2001) from data for both sexes.

Values for the parameters of the weight-at-length relationship are fixed at those in Table 9.7.

9.4.2 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 was less than $M = 0.2\ \text{yr}^{-1}$ (Constable *et al*., 2001). In this report, natural mortality is assumed to be similar to that estimated for Heard Island Patagonian toothfish. The base-case analyses use the estimate from the 2008/09 Aurora Trough stock assessment, which is $0.13\ \text{yr}^{-1}$. M is assumed to be the same for both sexes and constant over age and time. The impact of assuming alternative values for M either as a result of fixing the value or by estimation, are also considered.

9.4.3 Fecundity and maturity

Binomial GLMs were fit to the available data on female toothfish maturity from Macquarie Island. This consists of paired length and maturity stage observations. Fish with maturity stages 1 and 2 were considered to be immature, whereas those in stages 3+ were considered to be mature. Estimated length at 50% maturity for females under this approach was 139.6 cm with a

length at 95% maturity of 185.8cm (Table 9.7). The estimated maturity ogive is shown in Figure 9.6. It is noted that even with the data from longlining, there have been very few observations of mature fish. Indeed, a cumulative plot of the data with length shows that 95% of the maturity observations were of fish of TL < 115 cm, which is well below the estimated length at 50% maturity (Figure 9.6). There appears to be a gear-related difference in the onset of maturity, with a greater proportion of the fish obtained from trawl being mature before reaching 100 cm in the Aurora Trough than by longline (Figure 9.7), perhaps indicating the mature fish are more vulnerable to trawling. This difference is further complicated by spatial and depth factors. Estimating maturity solely from those observations made at Aurora Trough results in a smaller length at 50% maturity (124.9 cm). The lack of larger fish in the sample from this area suggests it is perhaps more appropriate to use the estimates obtained from the total sample. However, it should be noted that estimates of maturity are likely to be biased by uneven sampling among areas/depths if the movement of fish to areas/depths is maturity-driven.

It is noted that all these estimates of length at maturity are larger than those used in previous integrated assessments for Macquarie toothfish (*e.g.* Tuck *et al*., 2006; Fay *et al*., 2009a), which assumed a length at maturity of 89 cm, resulting in an age-specific maturity curve with 50% of females mature at age 14 and 95% of fish mature at 17 yrs. Consequently, estimates of spawning biomass can be expected to differ appreciably. The previously used values are explored in a sensitivity analysis.

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

9.5 Assessment methodology

The assessment is based on a length-age-structured model of fish population dynamics, and is applied to the population inhabiting the Aurora Trough region, which is assumed to be a single stock. 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, 2007) and are not reproduced here. As with the integrated assessments previously applied to Macquarie Island toothfish (Tuck *et al*., 2006), use of the Stock Synthesis framework enables estimation of spawning biomass and selectivity curves, in addition to the estimates of available (or vulnerable) biomass, which has been the output of the tagging model used for assessment of toothfish at Macquarie in the past (*e.g.* Tuck and Lamb, 2009).

9.5.1 Population model

The models consider a single stock of toothfish in the Aurora Trough region. A single area model is used, with no spatial complexity in the population dynamics. In Synthesis, fish recruit at age 0, even though they do not appear in the data at this age. A maximum age (plus group) of 120 years is used. This large age is due to the slow growth rate of Patagonian toothfish, as fish do not attain their maximum length under the base-case growth parameters until around this age. While the rate of natural mortality does not suggest such longevity, it is necessary to keep track of these older ages in the model in order that biomass (which is derived from numbers at length) is calculated correctly because fish are still growing.

9.5.2 Selection of fleets

The models designates two fishing fleets that exploit the toothfish resource. These are:

1. Aurora Trough trawl, and

2. Aurora Trough longline.

9.5.3 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), but did not impose this pattern on the model. Sensitivity analyses also explored using the fixed selectivity patterns used in the previous tag-only assessment model (*e.g.* Tuck and Lamb 2009).

9.5.4 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 spawning biomass in the same year. The parameterization 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 and 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 1975-2002, with these deviations taken as being log-normally distributed around the SRR with a standard deviation, σ_R of 0.7. The range of years chosen for recruitment estimation reflects the expectation that cohort effects from these years be seen in the data and whether the asymptotic standard error of 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*. (2009a) in other integrated assessments for Macquarie toothfish.

9.5.5 Initial conditions

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

9.5.6 Parameters and parameter estimation

Statistical fitting of the population dynamics model to the available data is achieved by minimizing an objective function consisting of several likelihood components, reflecting the different types of data input (lengths, age-at-length, and tag recaptures), and also the distribution 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 9.3.4 for the tag detection rate, tagging

age, and mixing time. Input sample sizes for the individual length compositions were the number of shots sampled for the trawl data, and 50% of the number of fish sampled for the longline data. The annual input sample sizes for the age at length data was 25.

The estimated parameters of the base-case model were: average recruitment before fishing, annual recruitment deviations from 1975-2002, and parameters determining the functional form of the selectivity pattern. This resulted in 37 estimated parameters under the base-case scenario. 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 2010/2011 fishing season. Key quantities of interest output by the model include time series of trawl available biomass, spawning biomass, and the current values of these quantities relative to those prior to tagging/fishing, and the levels of fishing mortality experienced by the stock. Also calculated are the predicted catches for the 2010/11 fishing season given the current and alternative harvest strategies.

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 Poisson distributed. The proportional allocation of these tag recaptures by fleet is then considered to be multinomial. The latter component is only of interest for 2007, as this is the only overlap between the two gears.

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 9.5.4 is fixed at a value of 0.7.

9.5.7 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 based on inverting the hessian matrix, or applying Markov-Chain Monte Carlo (MCMC) methods (*e.g.* Hastings, 1970; Gilks *et al*., 1996; Gelman *et al*., 1995). The latter can be computed once a base-case model has been approved. Estimates of uncertainty shown are based on asymptotic standard errors, calculated internally as standard by Stock Synthesis.

9.6 Results

Diagnostic plots are given for the base-case scenario, with results for this and sensitivity analyses then presented and discussed.

9.6.1 Diagnostics

Length composition data

The fits to the length composition data are adequate. The use of the number of shots as the effective sample size for the trawl data appears reasonable (Figure 9.8). The model is able to capture the apparent presence of a strong cohort within the length structure in the early years of the fishery fairly well (Figure 9.9), and also fits the sex-specific 2006 and 2007 length data. Consequently, the fits in some years are somewhat degraded, with a general tendency for the model to ignore apparent bimodalities in individual length compositions, as there is a lack of a consistent signal both between and within years. The model mimics the general pattern in the length data from the longline fleet in 2007 and 2009 (Figure 9.10). Again, a bimodality in the combined sexes and male component for 2009 is not apparent in the female data, and so the model smooths through these data. The model is unable to predict the occasional small numbers of very small (less than 40cm) fish seen in some years (*e.g.* 1998 and 2000, Figure 9.9).

Age-at-length data

The fits to the age-at-length data for the base-case are summarised in Figure 9.11. The fits appear to be fairly reasonable, although the model does appear to not be growing fish fast enough (larger fish are predicted to be older than they are observed to be). As the values for the growth curve parameters were fixed, some lack of fit to these data is to be expected. There appears to be some evidence for an over-prediction in the variability in age-at-length, although this may be due in part to the small sample size of the age data.

Tag recapture data

The base-case scenario was able to capture the general pattern of tag recaptures over time very well (Figure 9.12, left panel). The number of tag recaptures estimated in 2006 and 2007 was well above those observed. This over-estimation of the number of recaptures for these years is also revealed in the residual plot (Figure 9.12). Inspection of individual tag group recapture histories reveals this hole in the data for these years (particularly for 2006), with many tag groups having positive numbers of recaptures following this period (not shown). This lack of recaptures for 2006 and 2007 may be related to the length composition for these years, as there were few larger fish caught. Indeed, most of the discrepancy between the model and the data for 2006 is due to fish tagged prior to 2005 (almost half of the tag recaptures in 2006 were from fish that had been tagged in 2005).

Recruitment residuals

The asymptotic standard errors of the estimated recruitment deviations (Figure 9.13), suggest that individual recruitments after 1995 are perhaps not well estimated, however this is perhaps not surprising given the paucity of age data, and the aggregation of the tag releases into a small number of age groups will introduce further error. Nevertheless, there is evidence in the data (see the length compositions) for estimation of these year classes.

9.6.2 Base-case results

Selectivity

Fitting the assessment model to the length data allows for the selectivity pattern of the two fleets to be estimated. The estimated selectivity patterns are highly dome-shaped (Figure 9.14) and the trawl estimates show good accordance with the fixed selectivity patterns used in previous assessments for Aurora Trough toothfish. The estimated selectivity for the longline fleet indicates capture of larger fish than the trawl fishery, as evidenced by the length data. However, this selectivity pattern is still estimated to be dome-shaped because of a lack of larger (>150 cm) fish in the length composition.

Recruitment

As with previous integrated assessments (*e.g.* Tuck *et al*., 2006), the estimated time-series of annual recruitment appears to show an episodic pattern, with pulses of larger than average year classes approximately every four or five years. The time series of estimated recruitment (Figure 9.15), shows pulses of recruitment in 1980, 1987, 1994, and 1998/99. The estimation of the positive 1980 recruitment is associated with negative recruitment residuals both prior to and afterwards, as the model seeks to create the appropriate holes needed in the age structure in order to fit the early length composition data. The model estimates that recruitment after 1993 has generally been above average. The approximate 95% confidence intervals in Figure 9.15 demonstrate the uncertainty with which the individual recruitment values are estimated, particularly in the later years when fish have not been available to the fishery for very long. The large recruitments estimated in the late 1990s are consistent with the 2006 and 2007 length data.

Biomass and fishing mortality estimates

Under the base-case, current (2010/11) trawl available biomass (calculated as mid-season available biomass) is estimated to be above pre-tagging levels (Figure 9.16), with the time series clearly showing the impact of the fishery in the 1990s, and subsequent recovery in biomass following closure. 2010/11 available biomass is estimated to be 2,932t (Table 9.8). The results are somewhat different from the results of the tag only assessment model applied in 2009 (Figure 9.2), which indicated that the 2009 available biomass was below the limit reference point of 66.5% pre-tagging levels. The base-case also estimates a smoother trend in the changes in biomass, unsurprising as changes in biomass are mediated by the restrictions of a population model, which was not the case with the tag-only model. Figure 9.16 demonstrates that the available biomass matches quite well between the tag-only assessment and the new base-case. Pre-tagging (1995) available biomass is not estimated to be as high as in the previous assessment, nor is the 2009 available biomass estimated to be so low. These differences cannot be ameliorated by say, fixing the selectivity patterns at the previously used values and removing the length and age data from the likelihood function.

Model estimates of current (2010/11) and unfished spawning biomass are given in Table 9.8. The base-case indicates that current spawning biomass is at 57% of unfished conditions. The time series (Figure 9.17) shows a steady decline over the duration of the fishery. There is little response in the spawning biomass to changes in the catch levels over time, largely a result of the fact that the large size at maturity means most of the spawning biomass will be made up of year classes that have either never been available to the fishery, or were only available to the fishery for a few years. As such, it is unsurprising that the spawning biomass trend does not mimic that of the trawl available biomass.

The equilibrium spawning potential ratio (SPR) is a well-used, convenient index that gives a direct measure of fishing intensity on the spawning potential of the stock. Low levels of SPR are associated with high fishing intensity. Indeed, an adjusted form of SPR enables direct comparison with values commonly used as reference points for fisheries management, such as the *F* that results in a spawning biomass 50% of the unfished state (in this case an SPR of 0.5). Figure 9.18 shows the time series of SPR for the base-case, and reveals that the fishing pressure from 2005-2008 is estimated to have been greater than that which would on average have been required to reduce the population to below 50% unfished spawning biomass (Figure 9.18, points below red dashed horizontal line).

2010/11 catch levels

Under the current harvest strategy for Aurora Trough, the TAC is 10% of the estimated trawl available biomass if this is above 66.5% of pre-tagging levels. As the base-case estimate of current trawl available biomass is estimated to be above pre-tagging levels, this results in a TAC calculation of 293t (Table 9.8). Table 9.8 also reports what the 2010/11 catch would be under an F50 strategy, that being the catch at the harvest rate associated with achieving a spawning biomass of 50% of unfished conditions. The base-case estimated value is 161t, with the long-term catch at 50% unfished spawning biomass being a little less than this, 134t (a result of both current age structure and the fact that current spawning biomass is estimated to be above 50% unfished). This suggests that the catch implied by the current harvest strategy will on average result in a level of spawning biomass lower than the desired management target of 50% unfished spawning biomass.

Calculation of the 2010/11 TAC under application of the CCAMLR harvest strategy for toothfish (constant catch that gives a median spawning biomass in 35 yrs no less than 50% of unfished, and a chance of dropping below 20% unfished spawning biomass of less than 10%) requires samples from the posterior distribution in order to calculate the probability-based reference points. An approximation to the posterior distribution can be made by assuming that the estimated variance-covariance matrix of the parameters obtained during the estimation is multivariate normal, generating possible values for future recruitments, and projecting the model forward given this parameter uncertainty. While clearly an approximation to the results that would be obtained under a full MCMC run, this option allows for rapid calculation of catch levels using the CCAMLR rule. Implementing this for the base-case results in a 2010/11 catch level of 184t, again less than that suggested by the current rule.

9.6.3 Sensitivity analyses

Sensitivity analyses examine the consequences of alternative assumptions to the base-case scenario on the model results. The results of a large suite of sensitivity tests are presented in Table 9.8, with discussion on the major points outlined in the sections below. Where possible in Table 9.8, the various contributions to the likelihood function have been presented so the values given are comparable to the base-case, even when the values used to calculate the total likelihood were different. This is to facilitate comparisons in the fits to the different data sources among models.

Natural Mortality

Higher estimates of the rate of natural mortality, *M*, are associated with improved fits to the data, in particular the tag-recapture data (Table 9.8). Estimating the value for *M* within the model suggests a value higher than that used in previous assessments for Macquarie Island toothfish, 0.17 yr^{-1}. Scenarios that estimated growth parameters in addition to *M* resulted in

even higher estimates. Higher values for *M* are associated with lower estimates for trawl available biomass, resulting in a lower calculated 2010/11 catch, and lower estimates for spawning biomass, both in absolute terms and relative to unfished conditions. 2010/11 spawning biomass is estimated to be 48% of unfished conditions when *M* is estimated to be 0.17 yr^{-1}, which is below the management target.

The tendency toward higher estimates for *M* could mean that the value for this parameter is indeed higher than previous assumed, but could also reflect loss of fish due to movement of fish away from Aurora Trough, and possibly the effects of tag loss, considered here to be negligible.

Growth

Using either the alternative growth curves, or estimating growth parameters within the assessment model results in an improved fit to the length data (Table 9.8). Use of the new growth curve results in a poorer fit to the 1997 and 1998 age-at-length data. The improvements in fit are due to the new growth curve accentuating the differences in growth between sexes prior to age 20. Estimating growth curve parameters is challenging due to the lack of age data, the model estimates of growth appear largely driven by wanting to pick up some of the spikiness in the length composition data, with the model estimating the variability in length at age to be much lower than that indicated from the fits to the age data.

Despite these changes to parameter values, there is little impact on the estimates for current trawl available biomass (Table 9.8), with this still being on the order of 2,900t.

Maturity

Using the estimates of length-at-maturity from previous assessments rather than the updated values has little impact on both the fit to the data and the results (Table 9.8), other than that the absolute values for the spawning biomass are unsurprisingly estimated to be higher under this scenario.

Stock-recruitment

As with the maturity scenario, alternative assumptions regarding the stock-recruit parameters and recruitment deviations have very minor impacts on the results. This is perhaps unsurprising given the imprecision with which a large number of individual recruitments were estimated in the base-case (Figure 9.15), it is the general trends in recruitment that appears important. Additionally, spawning biomass has not been depleted to levels at which the effects of a stock-recruitment relationship would be expected to be expressed.

Data

Changing the relative weights associated with the different data components also tended to have little impact on the results (Table 9.8), with much lower changes in model fit to the various data sources than when the values for *M* and growth were changed. Including age-at-length data from tag recaptures resulted in slightly higher estimates of current trawl available biomass, although when these data were coupled with growth estimation, current trawl available biomass was estimated to be 2,512t, lower than the base-case, and at the expense of the fit to the tag recapture data (Table 9.8).

Current estimates of trawl available biomass were also largely insensitive to the assumptions related to the tagging data. Interestingly, there was very little difference in the available biomass estimates dependent on the method for assigning ages to tag-released fish. These

assumptions did have an impact on spawning biomass estimates though, with the scenarios assuming a single age at release for all fish tagged in a given year resulting in higher biomass estimates and a less depleted spawning stock. This is consistent with the results of simulation testing these assumptions detailed in Fay (2010).

Including the recaptures made within the year of release did impact the results in that available biomass was estimated to be higher than the base-case, and the estimate of pre-tagging (1995) available biomass was more closely aligned with that from the previously applied tag-only assessment. Current spawning biomass was also estimated to be larger, and closer to unfished conditions under this scenario. While the fits to the tag recapture data are not comparable to the base-case for this scenario, there was almost no change in the fit to both the length and age-at-length data from that obtained in the base-case when these data were included. Clearly, assumptions regarding the time over which fish can be considered to be mixed with the rest of the population has a marked effect on the model output.

Allowing for a departure from the assumption that the recaptures are purely random (ie that recaptures can be 'clumped' via the negative binomial instead of Poisson distributed), by including overdispersion, also impacts the results. There is a marked improvement in fit to the tag-recapture data, and a reduction in the estimate for current trawl available biomass from the base-case, to 2,722t. Allowing for overdispersion in this fashion clearly better reflects the manner in which the data were obtained, although represents a departure from the assumptions used in previous assessments. Current implementation of the overdispersion in Synthesis is by tag group rather than by time.

9.7 Discussion

The analyses presented here raise the following points of discussion.

1. The current (2010/2011) trawl available biomass is estimated to be well above the limit reference point of 66.5% pre-tagging (1995) levels, with the base-case trawl available biomass estimated to be 2,932t. Under the current harvest strategy, this would imply a 2010/11 TAC for the Aurora Trough of 293t. The difference between the estimates of trawl available biomass between the new assessment and the previously applied tag-only model is a result of pre-tagging biomass not estimated as high, and that the decline in available biomass in 2009 was not as great as that from the 2009 assessment. The estimate of current trawl available biomass can in general be expected to be somewhat uncertain given that there is a little information on the new recruitments entering the fishery.

2. In general, the new assessment estimates current spawning biomass to be around 50-60% of unfished spawning biomass, with the base-case estimate of 2010/11 spawning biomass relative to unfished levels being 57%. Revised lengths at maturity (50% mature at 139 cm) lead to smaller absolute values for the spawning biomass, which is largely unavailable to both the trawl and longline fisheries. The spawning biomass shows low responsiveness to changes in the magnitude of catches within the fishery.

3. The general pattern to the time series of recruitments is estimated consistently, with recruitment pulses estimated to have occurred around 1980, 1987, 1994, and 1998/99, with the year in which the latter event having occurred being somewhat uncertain. In order to fit the apparent presence of a strong year class in the 1996/97 length data, the model estimates the few years of pre-1980 recruitment to be below average. The

estimates for the magnitude of individual recruitments since the mid-1990s are uncertain, which likely reflects the paucity of age data and the lack of resolution in the length data due to variability in length at age. With the taking of the 2009/10 catch by longline, it is not possible to estimate the relative strength of the 2003 year class, and so recruitment estimation is lagged by 7 years, rather than the 6 that would be expected given the growth curve and selectivity of the trawl fishery.

4. The projected catch for 2010/11 under the current harvest strategy for Aurora Trough is greater than that calculated under an F50 harvest strategy (constant harvest rate at the level expected to result in an equilibrium level of 50% unfished spawning biomass), 161t, and also the catch level that would be calculated under the CCAMLR control rule, which would be 184t. This is consistent with previous applications of integrated assessment models to Aurora Trough, and suggests that a harvest rate of 10% vulnerable biomass may lead to catches in excess of those which would satisfy the management target.

5. Sensitivity analyses conducted largely showed a robustness in the estimates of trawl available biomass to a suite of alternative assumptions regarding the data. Changes in the results from those under the base-case were most notable when different values for natural mortality and growth were used, when tagged fish recaptured within the year of release were included in the model, and when overdispersion (clumpiness) was allowed in the rate of tag recapture.

6. The fits to the tag-return data were improved with higher values for the rate of natural mortality, *M*, than that used in the 2009 stock assessment. This could indicate that *M* is higher for Macquarie Island toothfish than previous assessments have assumed, or could also reflect movement of fish away from Aurora Trough, and possibly the effects of tag loss. The ongoing development of spatial assessments of the Macquarie Island fishery that include the dynamics of toothfish on the Macquarie Ridge will help to address the issue of apparent mortality of fish from Aurora Trough due to movement dynamics.

7. The choice of growth curves impacted greatly on the estimates of spawning biomass, as the alternative growth curve estimated from the growth increment data has lower maximum sizes. The impact of the choice of growth curve on the estimates of trawl available biomass though was lower, mainly because the growth curves are fairly similar at the lengths and ages vulnerable to the trawl fishery.

8. The model fits to the length composition data are adequate, although the model is unable to reconcile some of the variability in the data with the dynamics of the population model. Versions of the model that estimate the growth parameters tend to reduce the variability in length-at-age (to levels not consistent with the age-at-length data), and also emphasise differences in the growth rates of males and females, to improve the fit to the length data. The lengths of toothfish available to the fishery at Macquarie Island varies 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. The provision of better estimates of growth by the collection of additional age data may help to reconcile whether or not model-estimated growth parameters are simply following these additional sources of variability.

9. There is a lack of age-at-length data for Macquarie Island toothfish, even when age data from tag-recaptured fish are included in the model. Small sample sizes are probably most responsible for apparent inconsistencies in the age data among years. Consequently, growth and recruitment estimation is imprecise. Unsurprisingly, the age-at-length data from 1997 and 1998 are well mimicked by the model under the original growth curve, with the fit to these data declining when the CV of length at age is reduced, or the data are not included in the likelihood function. Including ages from tag recaptures in the age-at-length data is not appropriate as these data do not represent random samples of the age structure of the catch, rather just that of the portion of the catch that is tagged. Attempts were made to incorporate the growth data from the tag returns into the model by the use of the new estimates of growth curve parameters, based purely on external fits to the growth increment and ages from tag-recaptured fish.

10. The models fit the tag-recapture data well, with good accord between the total number of expected recaptures and those observed. The numbers of tag recaptures in 2006/07 was well below that predicted by the model, likely a result of large fish being absent from the catch in this season, as many of the tag groups were again seen in later years, and a majority of the tag returns in 06/07 were from fish tagged the previous season, which are more likely to have been smaller fish. Analysis of the tag recaptures under the model that assigned ages to fish based on their release lengths revealed that most of the 06/07 recaptures of fish tagged in 05/06 were from the younger (smaller) tag groups.

11. The choice of how many groups to disaggregate the tag release data into (in terms of assigning ages of releases) did not impact the assessment results greatly in terms of trawl available biomass, although estimates of this and spawning biomass were higher under models which assumed only 1 age at release per year. These results are consistent with those obtained during simulation testing of this assumption, which led to the conclusion that, for the quantity of data available from the fishery at Aurora Trough, splitting the tag releases into 5 tag groups per year was the better option.

12. Additional assumptions regarding the treatment of tagging data did impact the model results. Decreasing the time assumed in order to allow for mixing of tag releases within the rest of the population resulted in higher estimates of both available and spawning biomass. The base-case assumption to remove the recaptures in the year of release from the likelihood function is probably most appropriate for a model that operates on an annual basis, as this removes the effect of variability in season length on the results. That is, if the annual catch is spread out over a longer period, one might expect more recaptures of fish tagged within that season than a shorter season, which would not be a result of differences in the harvest rate.

13. The models presented here all assume single stock dynamics at Aurora Trough. This may very well be inaccurate given knowledge of the toothfish population elsewhere in the Macquarie Island region. However, the analyses presented here are the best representation of the data at Aurora Trough given this assumption.

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Table 9.1.Time series of Aurora Trough catches (t) by fishing year and fleet.

	Catch (t)		
Season	Trawl	Longline	Total
94/95	417.6		418
95/96	926.0		926
96/97	487.8		488
97/98	188.8		189
98/99	56.9		57
99/00	11.2		11
00/01	26.4		26
02/03	37.8		38
03/04	355.2		355
04/05	59.0		59
05/06	267.0		267
06/07	238.4		238
07/08	237.8	5.4	243
08/09	308.8		309
09/10	0.0	68.7	69

Table 9.2. Number of length samples by fleet and season, both in terms of number of shots from which samples were taken, and the total number of fish measured. The last column indicates the percentage of the total number of fish measured for which a gender of either male or female was assigned.

Fleet	Season	# shots	# fish	mean # per shot	% sexed
AT Trawl	94/95	126	3,405	27	98%
	95/96	245	6,539	27	92%
	96/97	96	2,685	28	64%
	97/98	74	1,329	18	53%
	98/99	38	3,496	92	15%
	99/00	27	827	31	21%
	00/01	17	1,532	90	22%
	02/03	17	740	44	17%
	03/04	94	4,484	48	49%
	04/05	16	691	43	20%
	05/06	122	3,356	28	70%
	06/07	74	731	10	28%
	07/08	99	1,564	16	80%
	08/09	128	2,268	18	71%
AT Longline	07/08	2	200	100	100%
	09/10	9	672	75	55%

Table 9.3. Sample sizes of aged fish from Aurora Trough by year and gender noting the numbers obtained from tag recaptured fish.

		# of aged otoliths		
Year	gender	random	tag recaptures	Total
1996	unsexed	9	2	11
	female		29	29
	male		26	26
1997	unsexed	19		19
	female	28	31	59
	male	27	33	60
1998	unsexed	4		4
	female	73	3	76
	male	42	3	45
1999	unsexed	16		16
	female			
	male		1	1
2000	unsexed	8		8
	female		2	2
	male			
2002	unsexed			
	female		1	1
	male		2	2
2003	unsexed		1	1
	female		26	26
	male	1	28	29
2004	unsexed			
	female		7	7
	male		4	4
2005	unsexed		2	2
	female		51	51
	male		35	35
2006	unsexed		35	35
	female		8	8
	male		9	9
2007	unsexed			
	female		12	12
	male		26	26
2008	unsexed	2	1	3
	female	2	45	47
	male	9	37	46
Totals	all	240	460	700

Table 9.4. Ageing error matrix. Shown are the mean and standard deviation of observed ages given a true age read. Values were calculated using the ageing error matrix for Heard & MacDonald Island toothfish as given in Candy and Welsford (2009).

true age	mean age	s.d.	true age	mean age	s.d.
1	1.5	0.82	61	61.5	5.71
2	2.5	0.83	62	62.5	5.87
3	3.5	0.84	63	63.5	6.02
4	4.5	0.85	64	64.5	6.18
5	5.5	0.87	65	65.5	6.35
6	6.5	0.89	66	66.5	6.51
7	7.5	0.91	67	67.5	6.68
8	8.5	0.94	68	68.5	6.85
9	9.5	0.97	69	69.5	7.02
10	10.5	1.00	70	70.5	7.19
11	11.5	1.03	71	71.5	7.37
12	12.5	1.06	72	72.5	7.55
13	13.5	1.10	73	73.5	7.73
14	14.5	1.14	74	74.5	7.92
15	15.5	1.18	75	75.5	8.10
16	16.5	1.22	76	76.5	8.29
17	17.5	1.27	77	77.5	8.49
18	18.5	1.32	78	78.5	8.68
19	19.5	1.37	79	79.5	8.88
20	20.5	1.42	80	80.5	9.07
21	21.5	1.48	81	81.5	9.28
22	22.5	1.54	82	82.5	9.48
23	23.5	1.60	83	83.5	9.69
24	24.5	1.66	84	84.5	9.89
25	25.5	1.73	85	85.5	10.11
26	26.5	1.80	86	86.5	10.32
27	27.5	1.87	87	87.5	10.53
28	28.5	1.94	88	88.5	10.75
29	29.5	2.02	89	89.5	10.97
30	30.5	2.09	90	90.5	11.20
31	31.5	2.17	91	91.5	11.42
32	32.5	2.26	92	92.5	11.65
33	33.5	2.34	93	93.5	11.88
34	34.5	2.43	94	94.5	12.11
35	35.5	2.52	95	95.5	12.35
36	36.5	2.61	96	96.5	12.59
37	37.5	2.71	97	97.5	12.83
38	38.5	2.80	98	98.5	13.07
39	39.5	2.90	99	99.5	13.31
40	40.5	3.01	100	100.5	13.56
41	41.5	3.11	101	101.5	13.81
42	42.5	3.22	102	102.5	14.06
43	43.5	3.33	103	103.5	14.32
44	44.5	3.44	104	104.5	14.57
45	45.5	3.55	105	105.5	14.83
46	46.5	3.67	106	106.5	15.09
47	47.5	3.79	107	107.5	15.36
48	48.5	3.91	108	108.5	15.63
49	49.5	4.03	109	109.5	15.89
50	50.5	4.16	110	110.5	16.17
51	51.5	4.29	111	111.5	16.44
52	52.5	4.42	112	112.5	16.72
53	53.5	4.55	113	113.5	17.00
54	54.5	4.69	114	114.5	17.28
55	55.5	4.83	115	115.5	17.56
56	56.5	4.97	116	116.5	17.85
57	57.5	5.11	117	117.5	18.13
58	58.5	5.26	118	118.5	18.42
59	59.5	5.41	119	119.5	18.72
60	60.5	5.56	120	120.5	19.01

Table 9.5. Numbers of tagged fish released and recaptured at Aurora Trough by season.

Tag Group	Release Season	Release Fleet	Number	mean length (cm)	# recaptures by season after 10 days at liberty													
					95/96	96/97	97/98	98/99	99/00	00/01	02/03	03/04	04/05	05/06	06/07	07/08	08/09	09/10
1	95/96	Trawl	444	69	18	57	28	3	0	1	1	1	0	0	0	0	0	0
2	96/97	Trawl	472	59		24	42	7	0	2	0	9	1	3	0	1	1	0
3	97/98	Trawl	581	60			80	18	3	4	5	21	4	15	1	0	2	3
4	98/99	Trawl	596	71				0	4	5	2	30	2	9	2	2	6	0
5	99/00	Trawl	654	66					1	3	1	35	6	12	1	3	5	2
6	00/01	Trawl	351	60						0	1	23	3	5	1	1	9	0
7	02/03	Trawl	492	63							1	60	8	29	6	15	24	2
8	03/04	Trawl	572	69								26	9	23	8	4	13	2
9	04/05	Trawl	530	70									0	46	7	16	42	4
10	05/06	Trawl	510	71										2	25	18	27	2
11	06/07	Trawl	435	59											3	26	13	0
12	07/08	Trawl	297	65												23	31	2
13	08/09	Trawl	588	71													31	2
14	09/10	Longline	299	85														0

Table 9.6. Values for growth parameters.

				Growth estimated			
	Constable et al. 2001			just tagging data		tagging and a@l	
von Bertalanffy growth parameters	both sexes	females	males	females	males	females	males
L infinity (cm)	185.5	195.1	154.2	163.2	122.4	156.7	116.6
k (yr^{-1})	0.042	0.038	0.054	0.057	0.081	0.059	0.087
t_0	-0.781	-1.184	-0.434	0	0	0	0
CV of length at age	0.13	0.12	0.14	0.13	0.14	0.11	0.12

Table 9.7. Values for biological parameters. Bolded value for *M* indicates that used in the base-case analyses.

Parameter	Value
rate of natural mortality, *M* (yr^{-1})	**0.13**, 0.1475
weight at length (wt = a*L^b)	
a	4.40E-09
b	3.14
length at 50% maturity (cm)	139.6
length at 95% maturity (cm)	185.8

Table 9.8. Results of the base-case and sensitivity analyses, with estimates of the trawl available biomass, spawning biomass, 2010/11 catch, and the contributions to the negative logarithm of the likelihood function. Values in the latter columns in italics indicate values not comparable with those in the base-case.

	Trawl available biomass (TAB)			Spawning biomass			2010/11 catch			negative log-likelihood					
	2010/11	pre-tagging (1995)	2010/1995	$SB_{2010/11}$	SB_0	$SB_{2010/11}/SB_0$	current strategy	F50	Yield at $0.5SB_0$	Total	Length	Age	Tag comp	Tag Recap	Rec't
Base-case	2,932	2,339	1.25	798	1,387	0.57	293	161	134	1200.89	489.23	66.05	5.04	641.00	-0.43
Natural Mortality															
M = 0.1475 yr^{-1}	2,673	2,345	1.14	500	946	0.53	267	145	129	1196.94	489.21	66.09	5.05	637.50	-0.91
M estimated (0.17 yr^{-1})	2,373	2,347	1.01	295	613	0.48	237	128	124	1195.20	490.24	66.25	5.06	634.85	-1.20
Growth															
estimate k, CV, and L@A3	2,861	2,501	1.14	1,196	1,879	0.64	286	193	155	1153.26	441.57	65.33	4.92	641.51	-0.08
also estimate M (0.181 yr^{-1})	2,167	2,455	0.88	356	681	0.52	217	139	138	1143.30	441.66	65.83	4.91	632.43	-1.53
use new growth parameters	2,937	2,202	1.33	618	1,170	0.53	294	170	130	1192.59	471.76	70.44	5.16	643.84	1.38
estimate all growth with prior on new values	2,877	2,317	1.24	720	1,292	0.56	288	170	132	*1179.06*	453.87	68.27	5.11	647.78	1.83
Maturity															
length at 50% mature 89cm	2,915	2,344	1.24	1,924	3,605	0.53	291	170	141	1200.90	489.15	66.03	5.04	641.06	-0.38
Stock-Recruitment															
recruits estimated 1980-2002	2,866	2,362	1.21	855	1,435	0.60	287	159	138	*1201.90*	490.14	66.27	5.02	641.42	*-0.95*
recruits estimated 1960-2002	2,946	2,335	1.26	790	1,392	0.57	295	161	134	*1200.62*	488.86	66.03	5.04	640.95	*-0.26*
full bias adjustment in 1975	2,978	2,319	1.28	821	1,496	0.55	298	163	144	*1197.32*	490.20	66.16	5.03	640.70	*-4.78*
sigma R = 0.6	2,923	2,348	1.24	793	1,358	0.58	292	160	131	*1199.17*	489.28	66.04	5.04	641.33	*-2.52*
sigma R = 1.0	2,942	2,335	1.26	820	1,495	0.55	294	161	144	*1206.60*	489.28	66.07	5.04	640.62	*5.59*
Length data															
sample size = 10% Nfish	2,844	2,278	1.25	762	1,314	0.58	284	162	128	*1369.65*	*654.64*	62.89	5.01	645.32	1.77
halve weight given to length data	2,974	2,270	1.31	790	1,395	0.57	297	163	134	*955.39*	493.39	65.62	5.02	638.94	-0.89
double weight given to length data	2,855	2,435	1.17	788	1,323	0.60	285	156	127	*1688.05*	485.50	66.23	5.05	643.50	2.28
Age-at-length data															
halve weight given to age data	2,931	2,294	1.28	792	1,385	0.57	293	161	133	*1167.66*	489.13	66.86	5.03	640.50	-0.44
double weight given to age data	2,932	2,422	1.21	805	1,386	0.58	293	160	133	*1266.22*	490.04	64.68	5.04	641.98	-0.20
include age data from tag recaptures	3,104	2,200	1.41	746	1,364	0.55	310	168	132	*1404.74*	492.09	*268.18*	5.04	639.42	0.02
as previous, but with new growth parameters	3,047	2,110	1.44	586	1,159	0.51	305	174	129	*1374.04*	473.08	*251.03*	5.17	642.78	1.98
as previous, also estimate growth parameters	2,512	1,782	1.41	1,799	3,433	0.52	251	202	145	*1339.91*	447.79	*239.78*	5.30	645.81	1.23
Tag-recapture data															
include recaptures in year of release	3,381	2,964	1.14	1,045	1,633	0.64	338	185	156	*1412.36*	488.40	64.42	*5.25*	*855.27*	-0.98
longline tag detection rate = 0.94	2,917	2,338	1.25	796	1,385	0.57	292	160	133	1199.69	489.19	66.04	5.00	639.91	-0.46
overdispersion in tag recaptures	2,722	2,474	1.10	859	1,431	0.60	272	152	137	1130.54	487.87	65.62	5.03	573.26	-1.25
1 tag group per year, fix age of release (9, 12)	2,985	2,510	1.19	907	1,494	0.61	299	168	143	*818.41*	488.32	65.78	*4.96*	*260.10*	-0.75
1 tag group per year, age of release varies	2,995	2,467	1.21	888	1,474	0.60	299	168	141	*825.76*	488.74	65.93	*4.93*	*266.68*	-0.52
lots of tag groups per year (release lengths)	2,910	2,317	1.26	781	1,369	0.57	291	159	132	*1450.84*	489.26	66.10	*5.04*	*890.78*	-0.34
halve weight given to tag recapture data	2,846	2,507	1.14	847	1,428	0.59	285	156	137	*879.53*	487.72	65.45	5.04	644.84	-1.11
double weight given to tag recapture data	3,003	2,173	1.38	749	1,341	0.56	300	164	129	*1839.93*	492.43	66.80	5.02	637.63	0.40

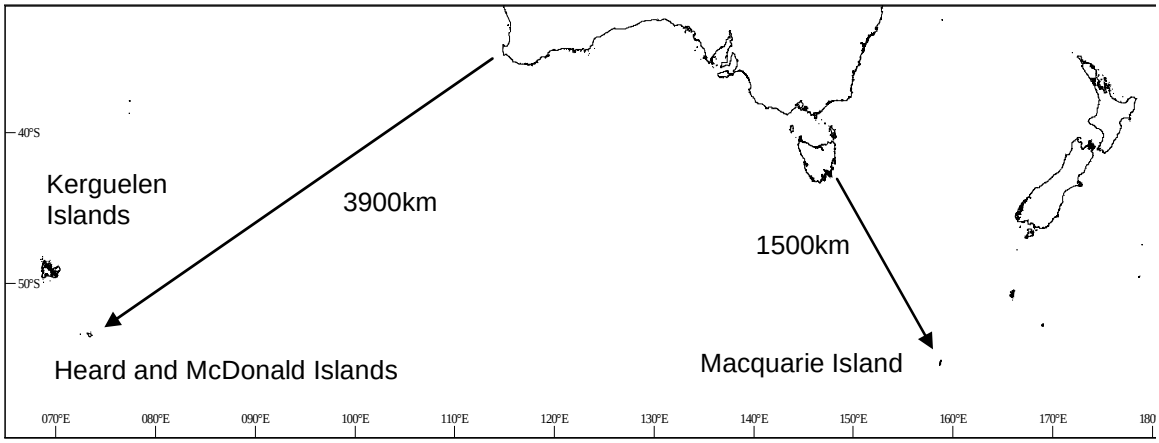

Figure 9.1. The location of Macquarie Island (54°30'S, 158°57'E) and Heard Island and McDonald Islands (53°06'S, 73°30'E) relative to New Zealand and Australia.

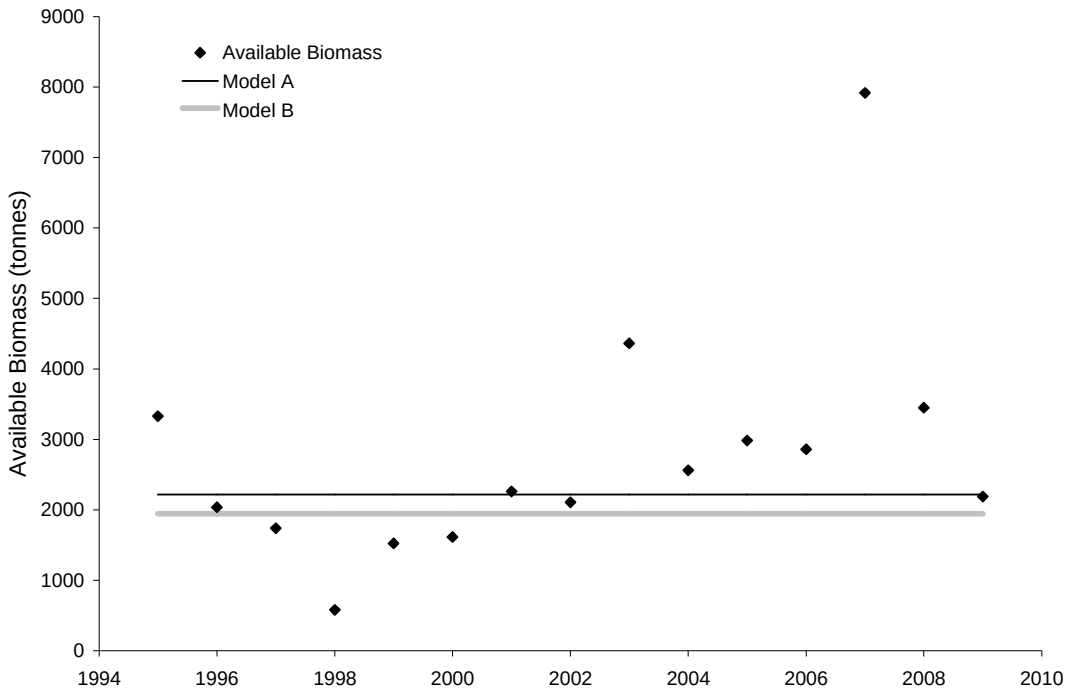

Figure 9.2. Results of 2009 stock assessment (Tuck and Lamb 2009). Point estimates of trawl available biomass of toothfish at Aurora Trough at 30 June in each year since 1996 with natural mortality M = 0.13, and tag mixing parameter δ = 10. The 1995 estimate is taken from the initial starting point of the model, 1 July 1995. The horizontal line indicates the threshold levels for a commercial fishery for the percent remaining models, Model A and Model B. If the point estimate is above this line then, according to the current management rule, a commercial fishery exists

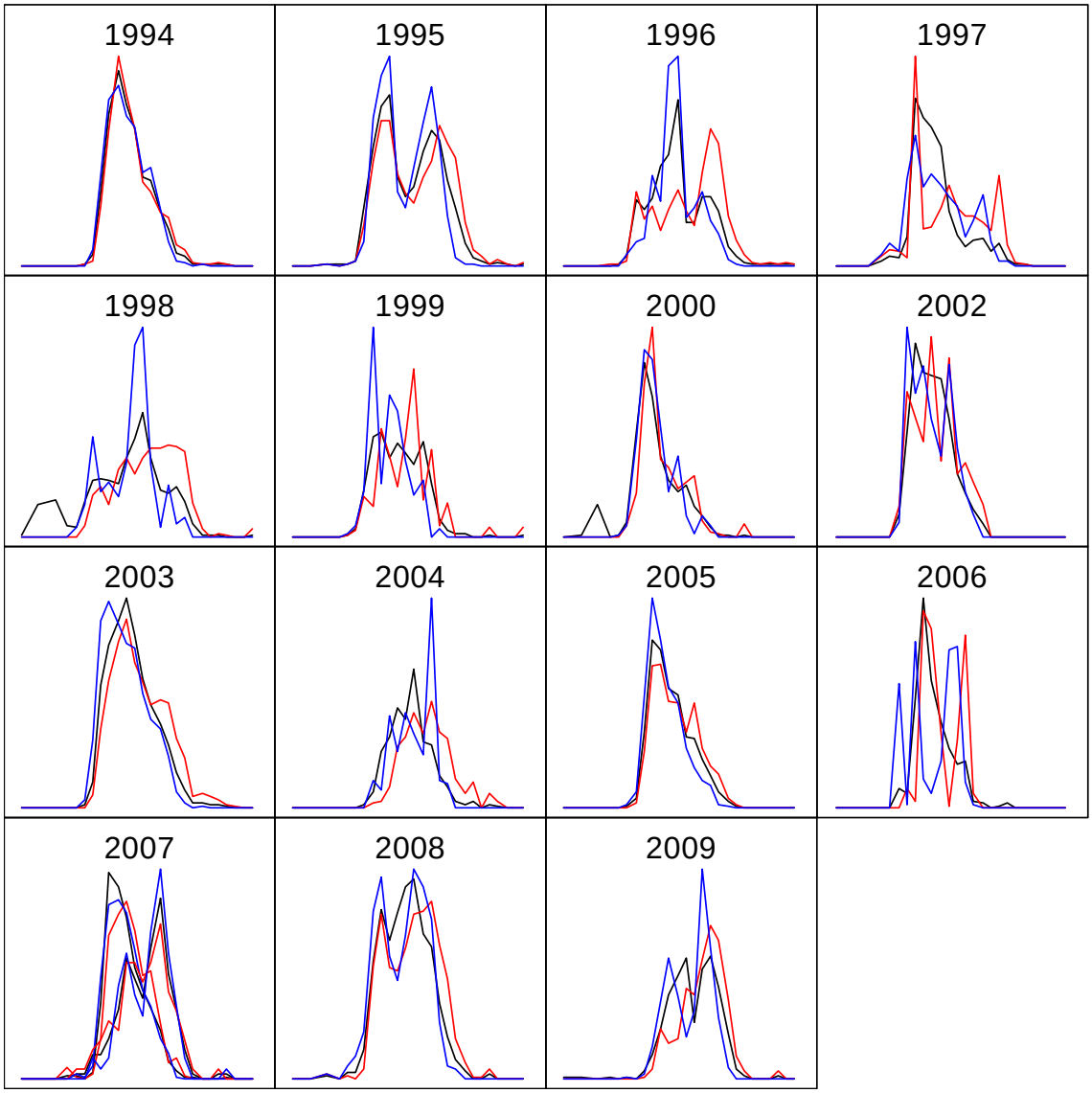

Figure 9.3. Length compositions by sex (red=female, blue=male), and aggregated (black).

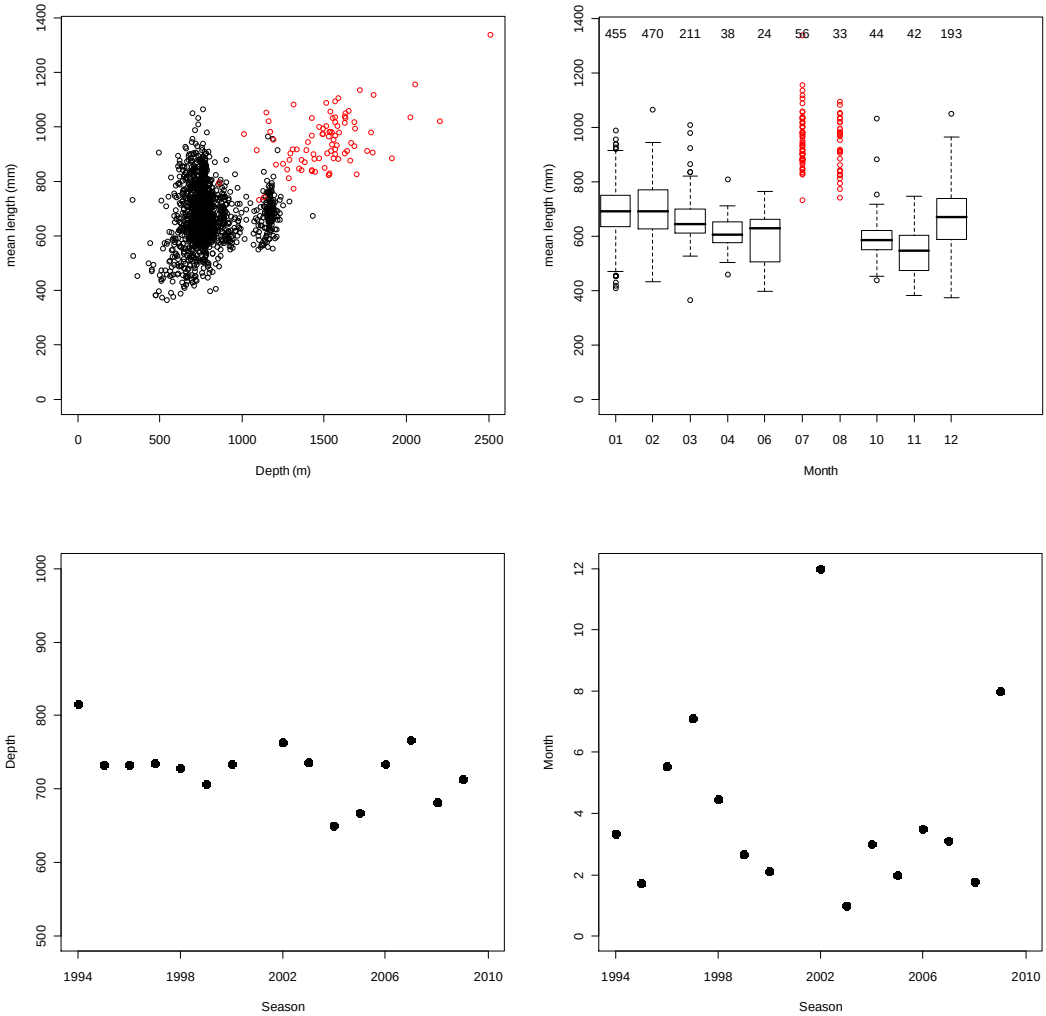

Figure 9.4. Variability in mean length with depth (top-left panel), and month (top-right panel), and seasonal variability in both the mean depth and mean month of the catch (bottom panels).

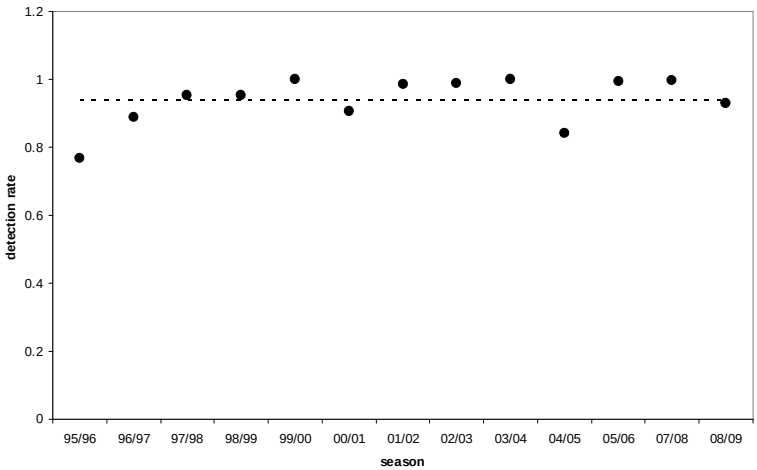

Figure 9.5. Estimated tag detection rate (points) by fishing season (Tuck and Lamb, 2009). Dotted line corresponds to the mean detection rate (0.938) over the time series.

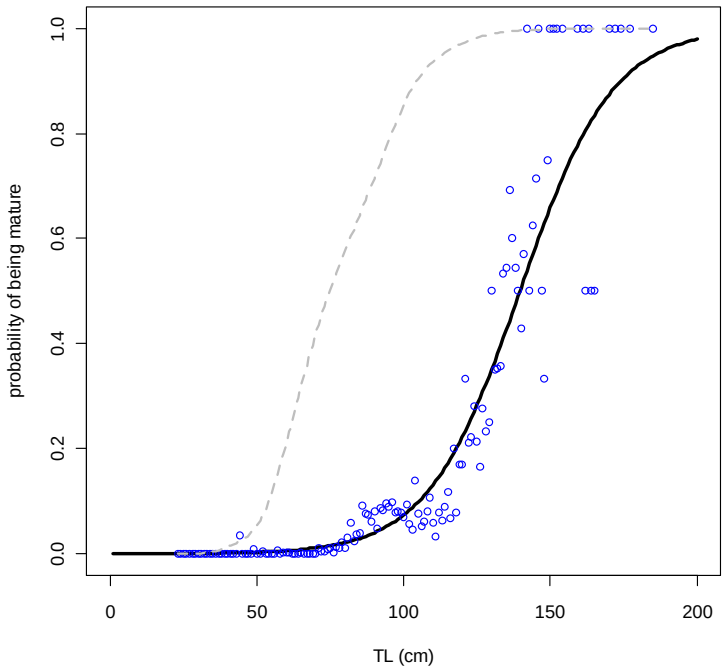

Figure 9.6. Estimated maturity ogive (black solid line) for female toothfish using all available data from Macquarie Island. Blue circles indicate the proportion of mature fish observed at each 1cm length bin. The grey dashed line shows the cumulative proportion of the number of observations with increasing length.

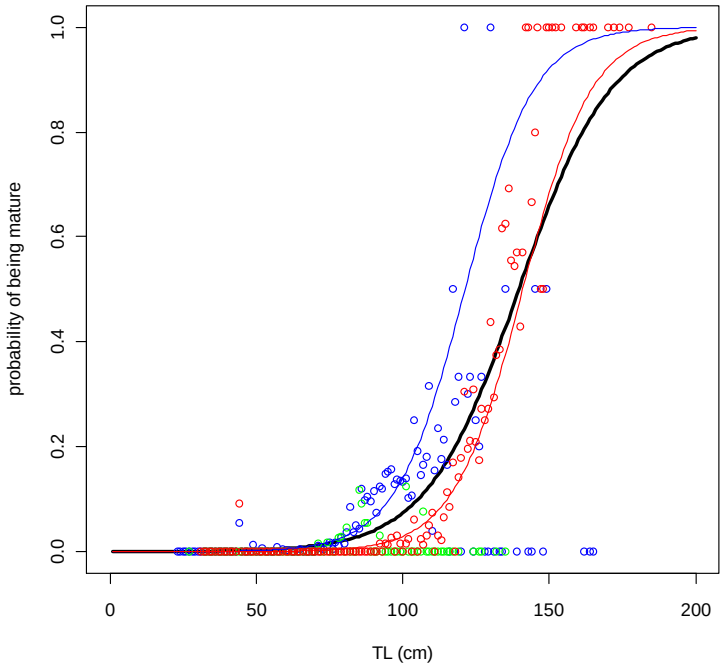

Figure 9.7. As for Figure 9.6, except that the data are plotted by spatial area, with blue circles coming from the Aurora Trough, green from the Northern Valleys, and red from Macquarie Ridge. Blue and red lines show the curves resulting from estimation using only the data from the respective areas.

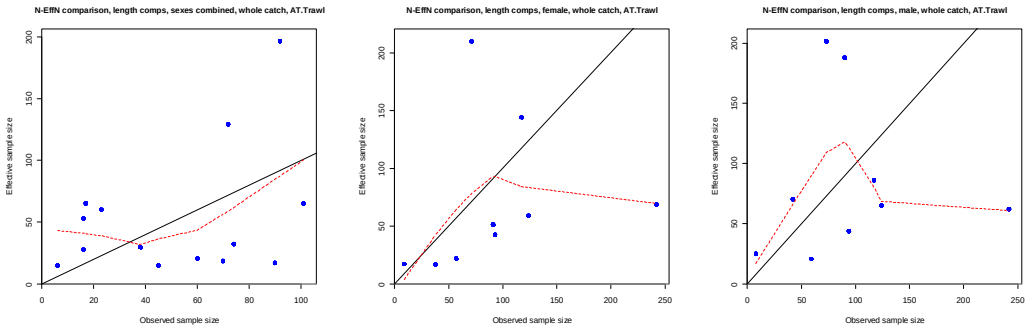

Figure 9.8. Input versus effective sample size for the trawl length composition data.

a) sexes combined

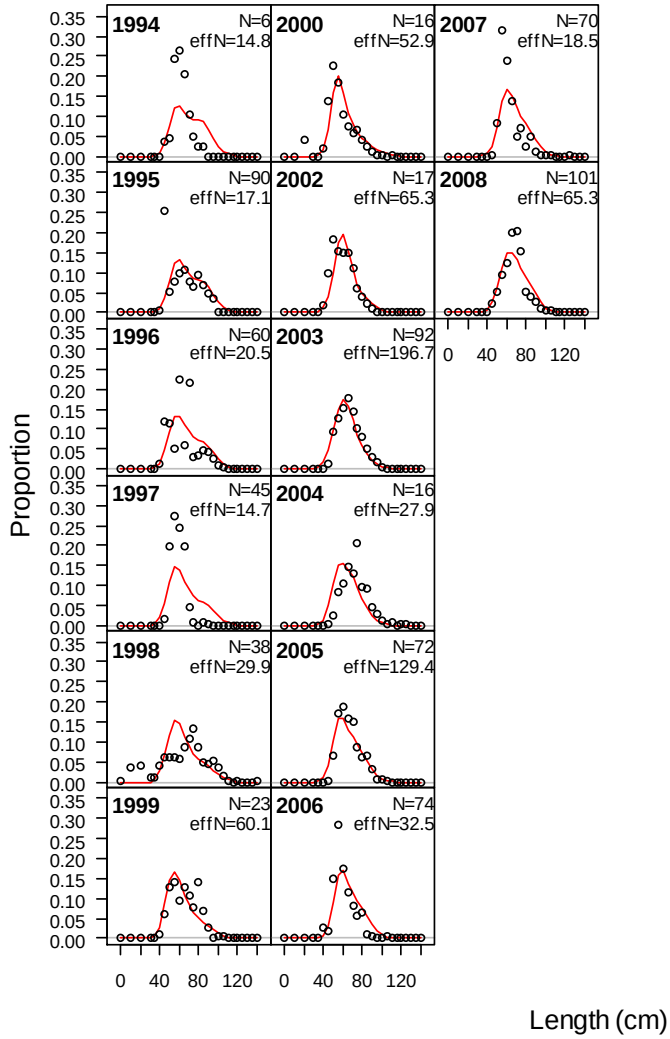

Figure 9.9. Base-case fits to the Aurora Trough trawl length composition data.

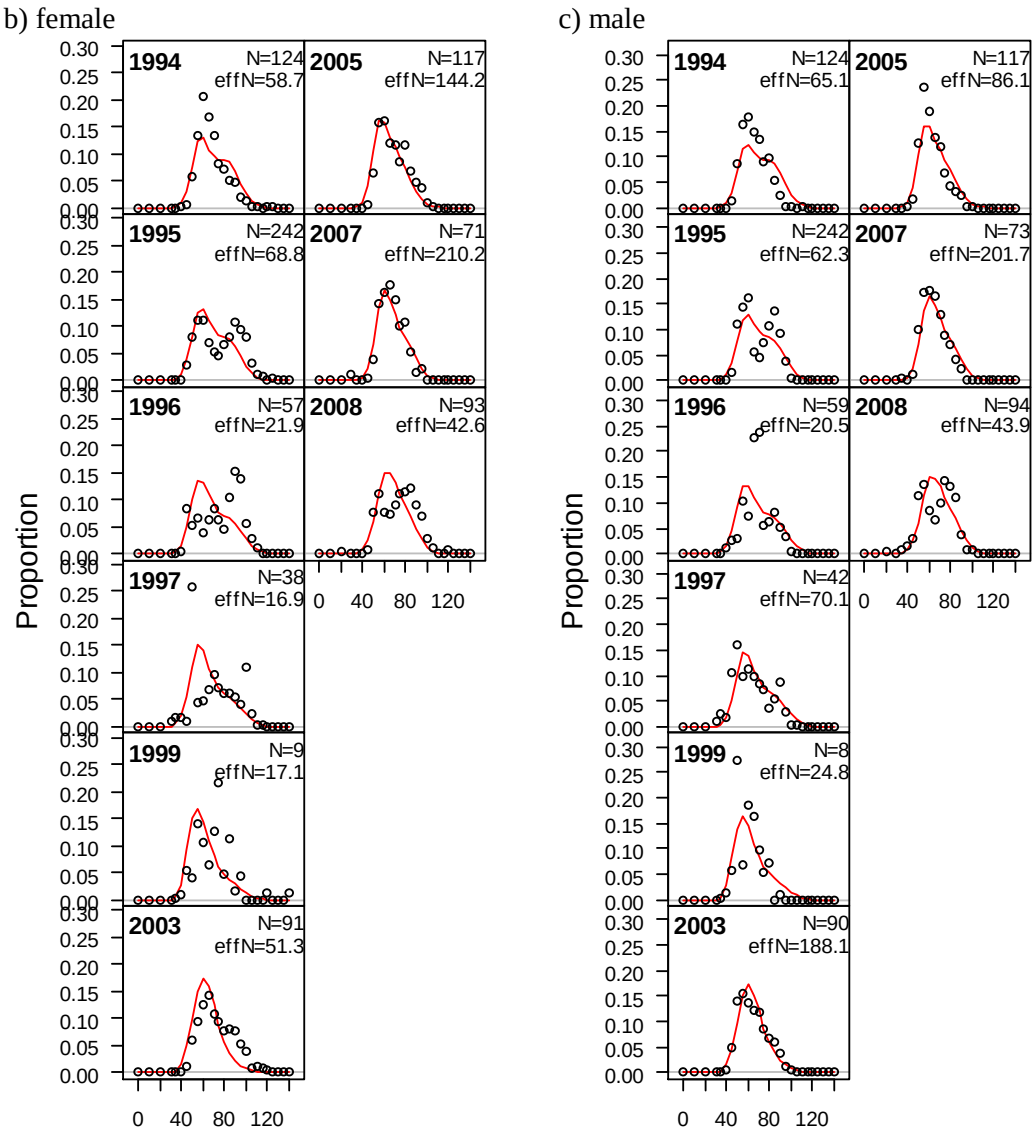

Figure 9.9 continued.

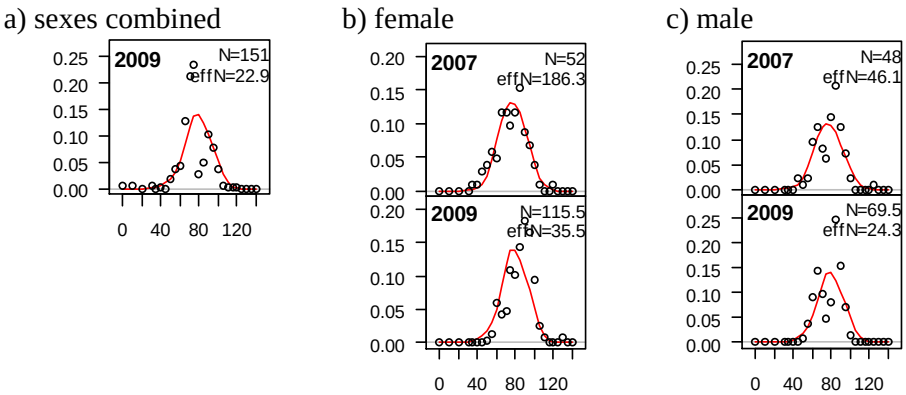

Figure 9.10. Base-case fits to the longline length composition data.

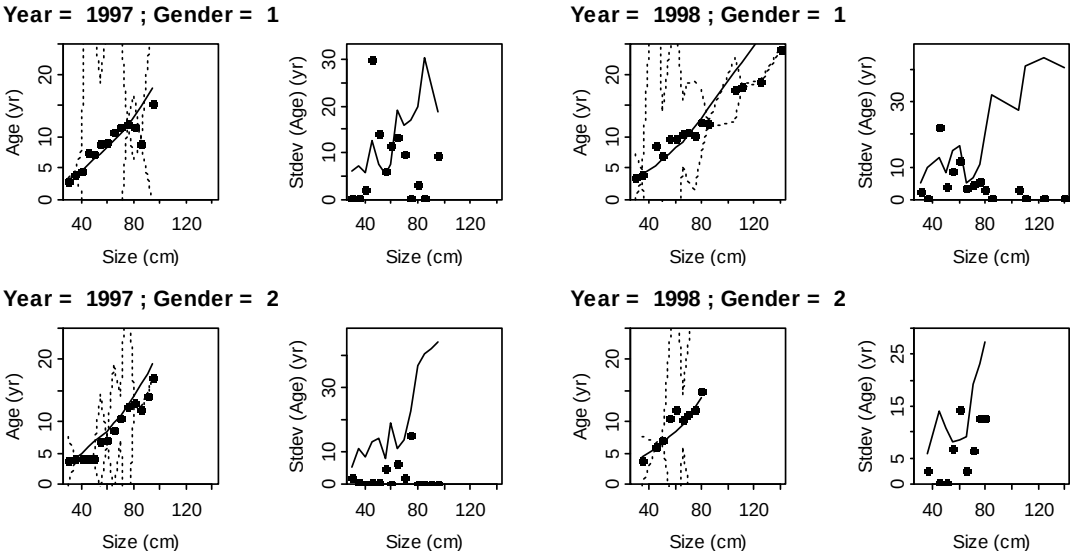

Figure 9.11. Diagnostic plots for the fit to the conditional age at length data. For each year and gender (1=female, 2=male), the two panels are 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed and predicted) and the 90% CIs based on the chi-square distribution. The dots are the data, the dotted lines the 90% CIs and the lines the expected values.

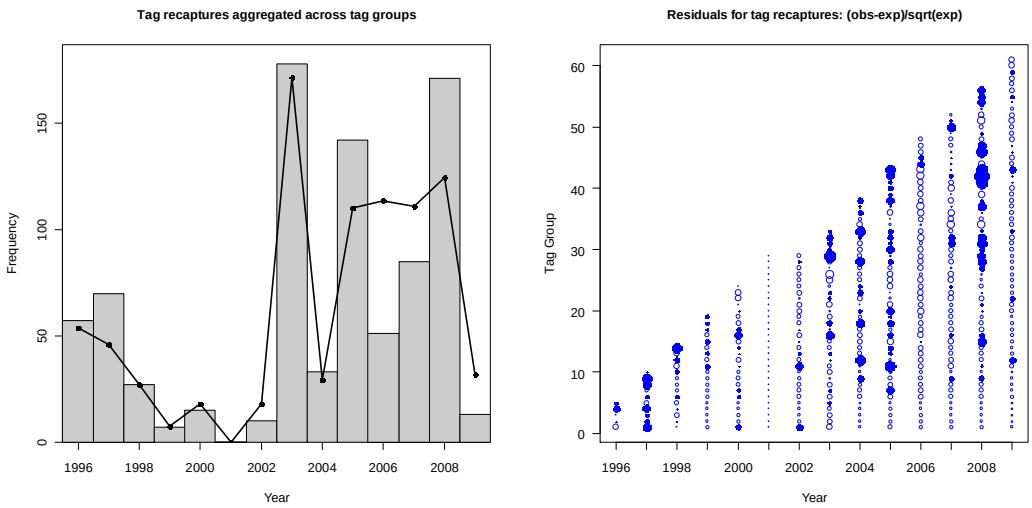

Figure 9.12. Summary of the fits to the tag recapture data for Model 1. Left-hand panel shows the summed observed (bars) and expected(line) recaptures over years, and the right-hand panel shows the residuals by tag group and year (blue indicates more recaptures observed than expected).

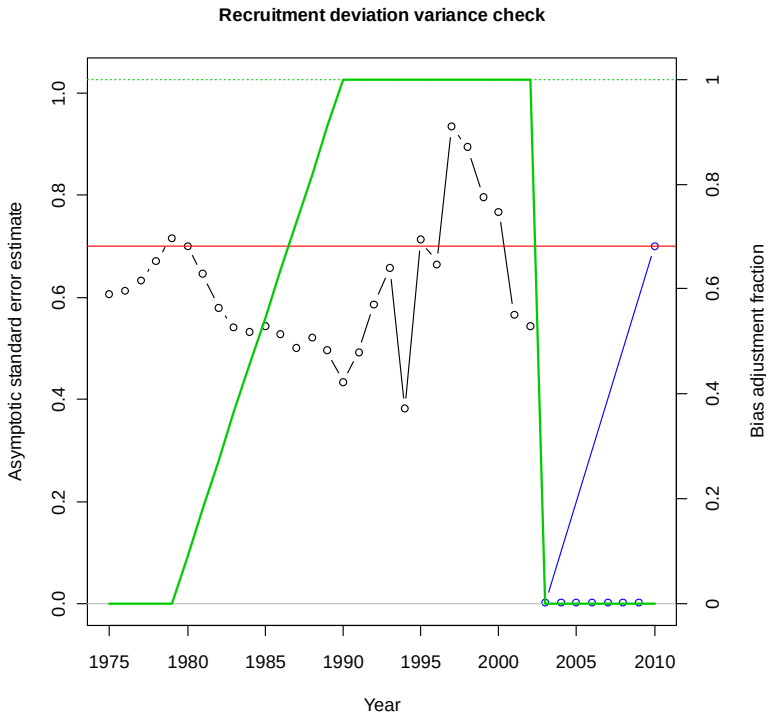

Figure 9.13. Asymptotic standard error of estimate for the recruitment deviations for Model 1.

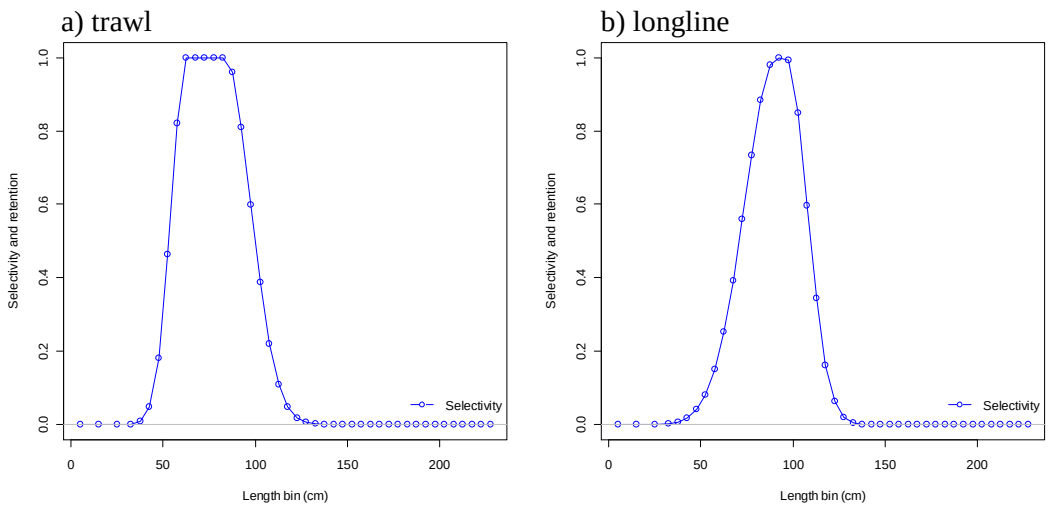

Figure 9.14. Base-case estimates of selectivity at length for trawl and longline.

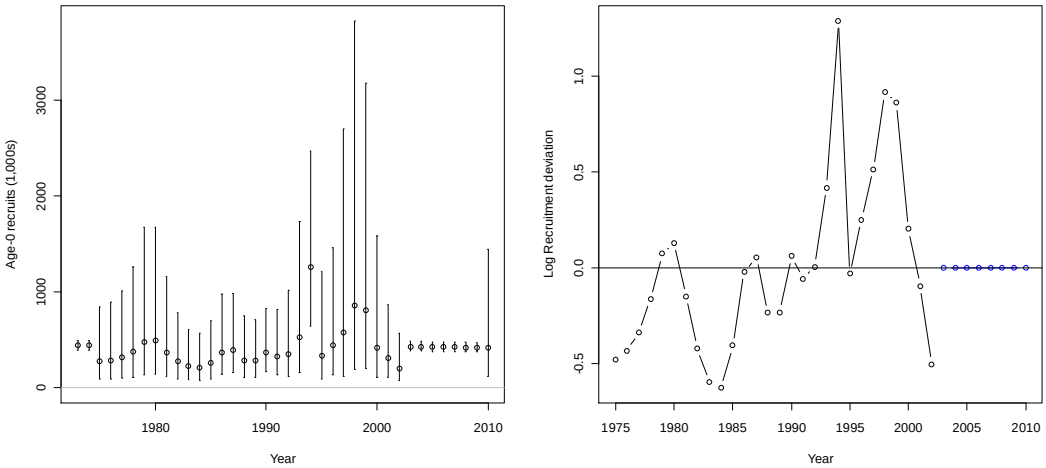

Figure 9.15. Base-case time series of estimated recruitments and recruitment residuals.

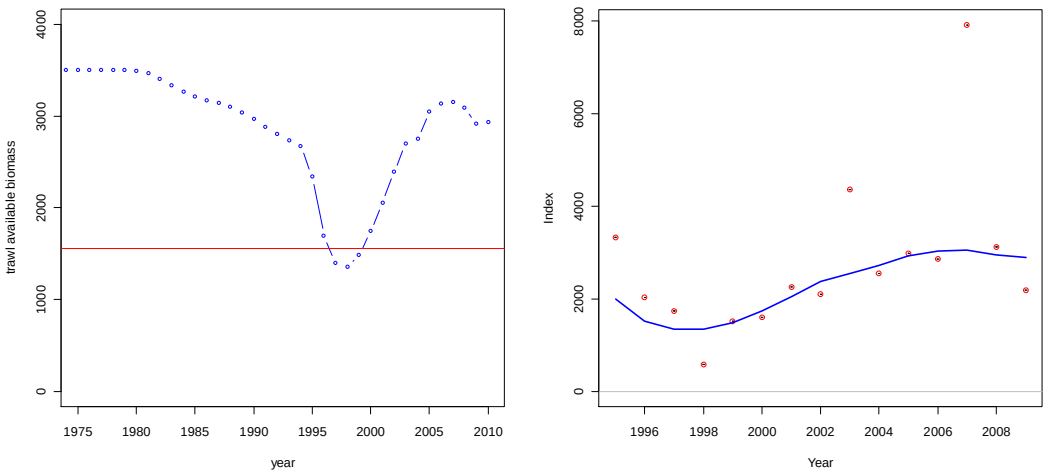

Figure 9.16. Base-case estimated time series of the trawl available biomass (left panel). Horizontal red line indicates 66.5% of pre-tagging (1995) available biomass. Right-hand panel compares the base-case estimate (blue line) with the 2009 tag-only assessment results (red points).

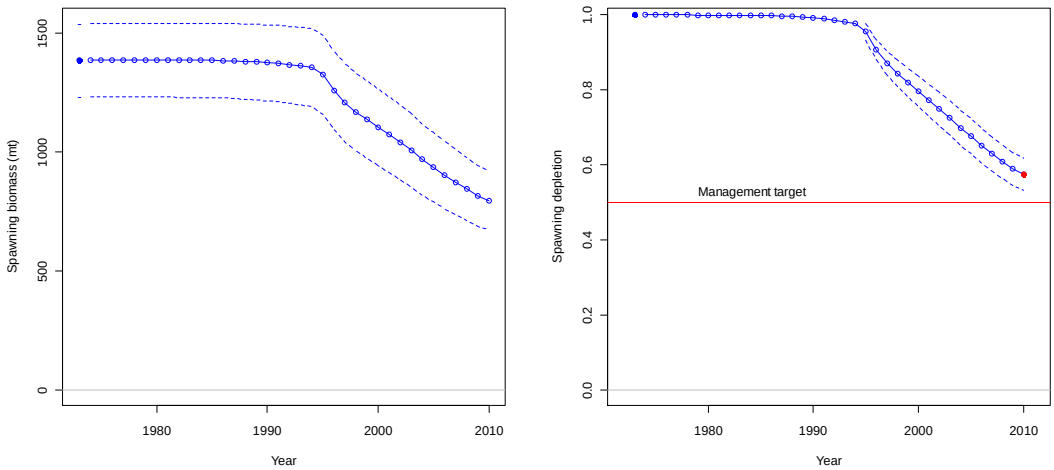

Figure 9.17. Base-case estimates for the time series (with approximate 95% confidence intervals) of spawning biomass (left panel), and spawning biomass relative to unfished (1975) conditions (right panel, denoted spawning depletion).

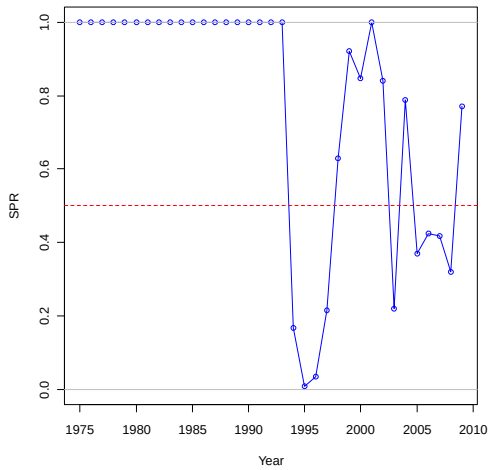

Figure 9.18. Time series of spawning potential ratio (SPR). The red horizontal dashed line indicates an SPR value of 0.5. If the value for SPR is below this line this indicates that the rate of fishing mortality in that year was likely greater than that which on average results in a spawning biomass of 50% unfished levels.

10. APPLICATION OF MCMC METHODS TO THE AURORA TROUGH SS3 ASSESSMENT BASE-CASE SCENARIO[5]

Gavin Fay

10.1 Summary

This chapter updates the uncertainty estimates reported in the Aurora Trough stock assessment chapter by applying Markov Chain Monte Carlo (MCMC) methods to the base-case scenario. This allows for a more accurate representation of the uncertainty associated with estimation and is superior to the normal approximation used to calculate the 2010/11 catch under the CCAMLR control rule as reported in the assessment document.

The results indicate that the highest 2010/11 catch by trawl in Aurora Trough which satisfies the requirements of the CCAMLR control rule is 138t. This is lower than the 184t reported from the approximation made in the stock assessment report, and is a result of the posterior distributions for average recruitment and the 1994, 1998, and 1999 recruitment deviations not containing as large values as included under the approximation.

10.2 Methods

10.2.1 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 based on inverting the hessian matrix (as reported in the 2010 Aurora Trough stock assessment report, Fay 2010), or by applying Markov-Chain Monte Carlo (MCMC) methods (*e.g.* Hastings, 1970; Gilks *et al*., 1996; Gelman *et al*., 1995). The Metropolis-Hastings variant of the MCMC algorithm was used to sample 1,000 equally likely parameter vectors from the joint posterior density function for the base-case. This sampling process implicitly considers uncertainty in all dimensions of parameter space, and accounts for correlation among model parameters. The samples on which inference is based were generated by running 1,500,000 cycles of the MCMC algorithm, discarding the first 500,000 as a burn-in period and selecting every 1,000th parameter vector thereafter. A potential problem with the MCMC algorithm is how to determine whether convergence to the actual posterior distribution has occurred. Diagnostic statistics developed by Geweke (1992), Heidelberger and Welch (1983), and Raftery and Lewis (1992), and the extent of auto-correlation among the samples in the chain were used to determine whether there was a lack of convergence in the chain.

10.2.2 Projection under the CCAMLR control rule

In addition to the deterministic projections from the base-case results, the sample from the posterior distribution for the base-case was used to conduct stochastic projections given both parameter uncertainty and uncertainty in future recruitment events, in order to calculate the

[5] Paper presented to the SARAG on 16 March, 2010

2010/11 catch given implementation of the CCMALR control rule, where next year's catch is the constant catch such that:

- the probability that 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 spawning biomass shall not be less than 50% over a 35 year projection.

The sampled posterior was therefore projected forward 35 years under a range of constant catch scenarios in order to find the maximum catch level that satisfies both criteria.

10.3 Results

10.3.1 Diagnostics

Figure 10.1 summarises the values of five convergence statistics (the ratio of the batch standard deviation to the naive standard deviation, the extent of lag-1 auto-correlation, the *p*-value computed from the Geweke statistic, whether the Heidelberger and Welch test is passed or not, and the value of the single-chain Gelman statistic) for the model parameters. Ideally, the value of the first statistic should be close to 1, the value of the second statistic should be close to zero, the value of the third statistic should be greater than 0.05, and the value of the last statistic should be less than 1.05. There appears to be some evidence for a lack of convergence for a couple of the parameters given the distribution for the lag-1 autocorrelation, most notably the 1994 recruitment deviation. This is not surprising given the expected low mixing rate for this parameter due to the precision of its estimate compared to other recruitments. This perhaps indicates that it might be necessary to run the MCMC algorithm for longer and increase the thinning coefficient.

10.3.2 2010/11 catch levels

The maximum constant catch level by trawl that satisified both the CCAMLR criteria was 138t. Under this catch, median spawning biomass is just above 50% unfished levels after the 35 year projection, with a zero probability of the stock being reduced below 20% unfished spawning biomass during this period. Figure 10.2 summarises the posterior distribution for the time series of spawning stock depletion, spawning biomass relative to unfished. 138t is considerably less than the 184t calculated using the multivariate normal approximation to the posterior reported in the Aurora Trough stock assessment document (Fay 2010). A comparison of the posterior with the distribution from the approximation reveals that this is due to both a smaller average recruitment level with the posterior distribution, and that the distributions for the larger year classes (*e.g.* 1994, 1998, 1999) not including as high values in the posterior than in the approximation (Figure 10.3 and Figure 10.4). A catch of 134t under the CCAMLR control rule is consistent with the long-term catch under a constant F50 harvest rate policy, calculated under the base-case to be 134t (Fay 2010, Table 9.8 in Chapter 9).

10.4 References

Fay, G. 2010. Integrated stock assessment for the Aurora Trough Macquarie Island toothfish using data up to and including July 2009. Document presented to SARAG 38, March 2010.

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

Geweke, J. 1992. Evaluating the accuracy of sampling-based approaches to the calculation of posterior moments. p. 169–193 in J.M. Bernardo, J. Berger, A.P. Dawid and A.F.M. Smith. [Ed.] Bayesian Statistics 4, Oxford University Press, Oxford.

Gilks, W.R., Richardson, S., and D.J. Spiegelhalter. 1996. Markov Chain Monte Carlo in Practice. Chapman and Hall, London.

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

Heidelberger, P. and P.D. Welch. 1983. Simulation run length control in the presence of an initial transient. Operations Research 31: 1109–1144.

Raftery, A.E. and S. Lewis. 1992. How many iterations in the Gibbs sampler? p. 763–773. In: J.M. Bernardo, J. Berger, A.P. Dawid and A.F.M. Smith. [Ed.] Bayesian Statistics 4, Oxford University Press, Oxford.

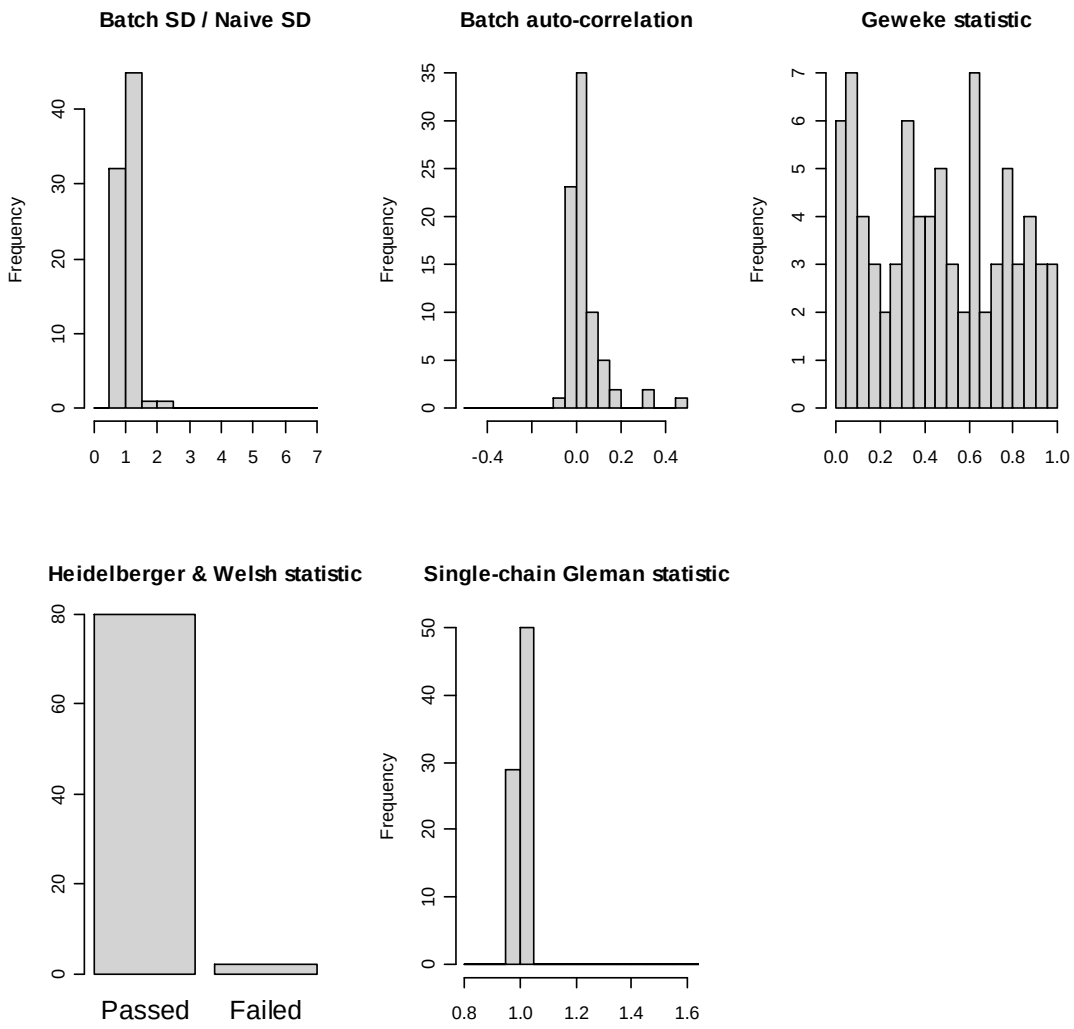

Figure 10.1. MCMC diagnostic statistics for the base-case model parameters.

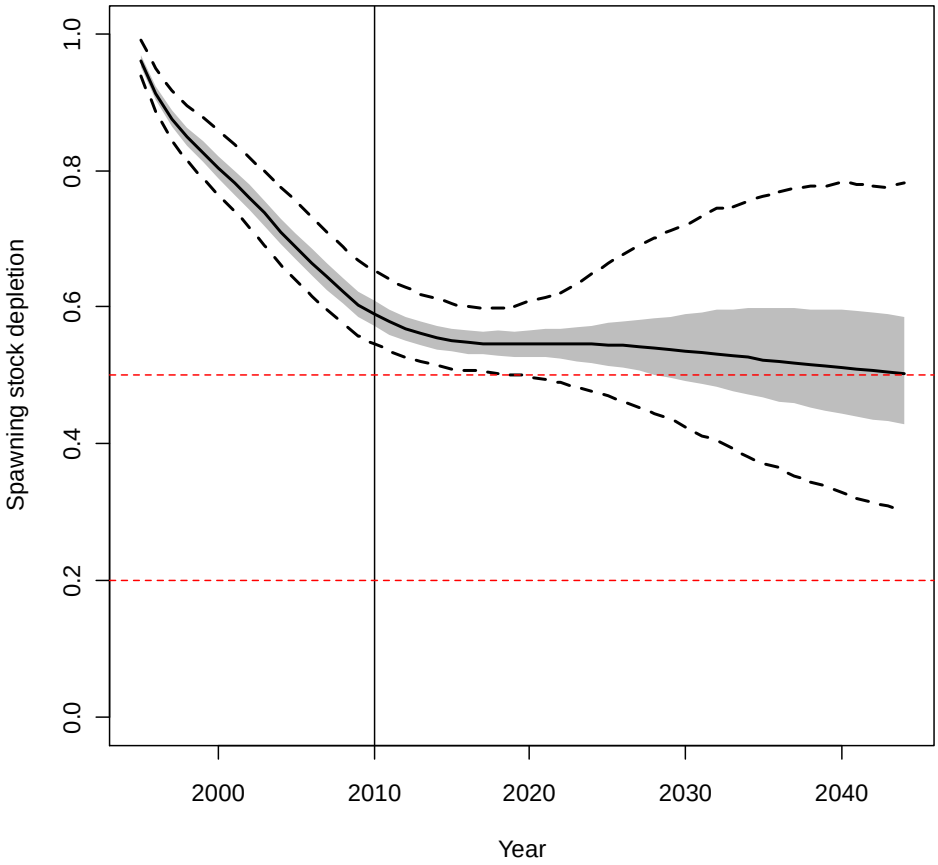

Figure 10.2. Summary of the posterior distribution for the projected spawning stock depletion given a constant annual future catch of 138t by trawl. Plotted are the median (black solid line), central 50% (grey shaded area), and 95% (dashed lines) credibility intervals. Black vertical line indicates the beginning of the projection period, horizontal dotted lines indicate the management target of 50% unfished spawning biomass and the limit reference point of 20% spawning biomass.

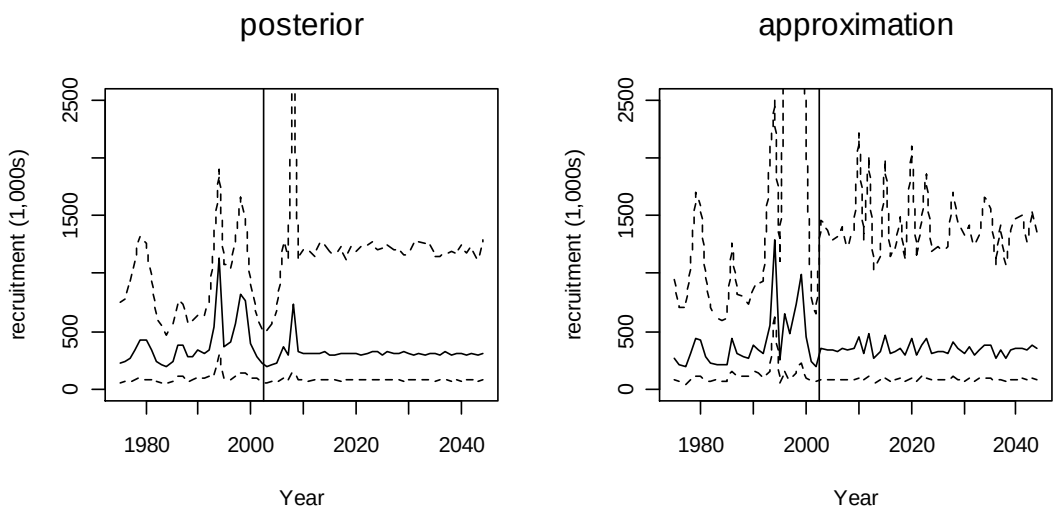

Figure 10.3. Distributions (median and 95% intervals) for recruitment time series obtained from the posterior and the approximation.

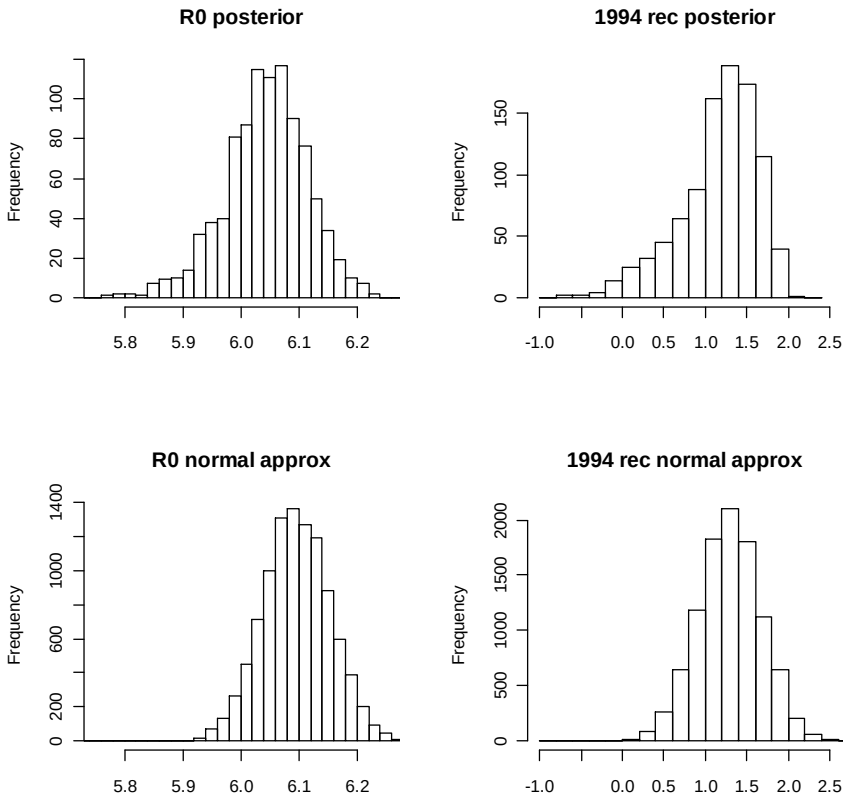

Figure 10.4. Comparison of the distributions for average unfished recruitment (R0) and the 1994 recruitment deviation obtained from the posterior and the normal approximation.

11. REVISED BASE-CASE RESULTS FOR 2010 STOCK ASSESSMENT OF AURORA TROUGH MACQUARIE ISLAND TOOTHFISH, USING DATA UP TO AND INCLUDING JULY 2009[6]

Gavin Fay, Malcolm Haddon, Geoff Tuck

11.1 Summary

This chapter presents the results of a revised base-case analysis of the Aurora Trough stock assessment using Stock Synthesis, following discussions by the Sub-Antarctic Resource Assessment Group (SARAG) on Tuesday March 16th, 2010. The base-case decided by SARAG was to use the following assumptions/parameterizations:

1. value for the rate of natural mortality, *M*, of 0.13 yr^{-1},
2. use of the sex-specific growth curve parameters estimated by Constable *et al.* (2001),
3. length at 50% maturity of 89cm,
4. exclusion of tag recaptures in the year of release from the likelihood,
5. including over-dispersion in the tag-recapture likelihood,
6. a tag detection rate for the longline fleet of 0.94, the average of the annual values estimated for the trawl fleet.

While the sensitivity analyses in the 2010 Aurora Trough stock assessment document (Fay 2010) explored the effect of these assumptions, they were not included together in the same analysis. Updated results of applying this version of the model, and key sensitivity analyses from this revised base-case are therefore presented. The catch level for 2010/11 is calculated under the CCAMLR control rule, following application of Markov Chain Monte Carlo (MCMC) methods to characterise uncertainty in the parameter estimation. The constant catch satisfying the CCAMLR rule is calculated assuming that future catches are taken solely by trawl, or solely by longline.

Inclusion of an over-dispersion term when modelling the tag-recaptures leads to a lower penalty being applied to a lack of recaptures from tagged fish released in the last few years. Consequently, the result of including this over-dispersion is a smaller current stock size than when tag recaptures are assumed to be completely random. Data are insufficient to estimate individual over-dispersion parameters for each tag group and so the over-dispersion parameter is fixed at the median of the estimates for those tag groups for which data are available.

The new base-case estimates current (2010/11) spawning biomass to be 2,004t or 54% of unfished spawning biomass. The new base-case estimate for current (2010/11) trawl available

[6] Paper distributed to SARAG members in March, 2010

biomass is 2,920t. Trawl available biomass is 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 projected catch for 2010/11 under the CCAMLR control rule using the revised base-case is 140t. The magnitude of this catch is increased to 164t when the projected catches are assumed to be taken solely by longline instead of trawl. The catch levels under the CCAMLR control rule are, not surprisingly, similar to those calculated under an equilibrium F50 strategy (ie fishing at a constant harvest rate at the level expected to result in an equilibrium level of 50% unfished spawning biomass), which are 145 and 173t if catches are taken purely by trawl or longline respectively.

11.2 Introduction

This chapter presents results of a revised base-case for the integrated stock assessment of Aurora Trough Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island to 2010/11 using data collected up until and including July 2009. The revisions are based on discussion of the analyses in Fay (2010), discussed at the 38th meeting of the SARAG on Tuesday March 16th, 2010. 2010/11 catch levels, for provision of advice in determining the 2010/11 TAC are calculated based on these revised base-case results.

Aside from the assumptions discussed below, the analyses presented here use the same approach, data, and model parameterizations as discussed in Fay (2010).

11.3 Base-case analysis

11.3.1 Revised assumptions

The assumptions that the revised base-case analysis are based on were explored during sensitivity analyses in Fay (2010), although the consequence of their simultaneous application were not addressed in a single analysis. Model parameters not mentioned below were assumed to be the same as in the previous base-case scenario presented in Fay (2010). Specifications for the new base-case, as determined by SARAG, are as follows:

1. the value for the rate of natural mortality, *M*, to be fixed at 0.13 yr^{-1},

2. use of the sex-specific growth curve parameters estimated by Constable *et al*. (2001),

3. a length at 50% maturity of 89cm, as used in previous integrated stock assessments (*e.g.* Tuck *et al*. 2006) of Aurora Trough toothfish,

4. exclusion of tag recaptures in the year of release from the likelihood,

5. including over-dispersion in the tag-recapture likelihood, allowing for ‘clumping’ in the numbers of tag recaptures,

6. fixing the tag detection rate for the longline fleet at 0.94, which is an average of the annual values estimated for the trawl fleet.

11.3.2 Over-dispersion in tag recaptures

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, potentially resulting in an additional 61 parameters (over the 37 previously) 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.

Allowing the over-dispersion parameters to vary by tag group resulted in an improved fit to the tag recapture data (Table 11.1). However, a lack of information from some of the tag groups means that there is considerable uncertainty regarding the values for these parameters which is not accounted for in the point estimate. The distribution of point estimates for the over-dispersion parameter (Figure 11.1) is different from that obtained when the uncertainty is taken into account through application of MCMC methods (Figure 11.2). The posterior medians of the over-dispersion parameters for some tag groups move toward a larger value, revealing a lack of information in the data regarding the value for these parameters, and the influence of the (flat) prior distribution. The consequence is a lower estimated biomass than predicted by the point estimate. Indeed, when individual over-dispersion parameters are estimated, the MCMC chain fails to converge, and the point estimate for the time series of spawning biomass lies well outside the 95% CI from the posterior distribution (Figure 11.3). This suggests that the point estimates for at least some of the over-dispersion parameters are not appropriate. Perhaps more importantly, the uncertainty in these estimates is poorly represented. This produces problems when running the MCMC chain to characterise the uncertainty around the assessment results.

The tag-recaptures are not returned randomly so it is recognised that over-dispersion in the tag recaptures should be included in the assessment. However, there is clearly insufficient tagging data to enable the valid estimation of individual over-dispersion parameters for each tag group, which would be the ideal when attempting a full characterization of the uncertainty associated with the tag-recapture data. Assuming the aggregation of tag returns is a reflection of the behaviour of the tagged fish, it is reasonable to assume that there should be some similarity to the over-dispersion expressed by different tag groups (*e.g.* all fish tagged in the same year should have the same value, or all fish of a given age, etc.). Indeed, for those tag groups where there appeared to be sufficient information to estimate the value of the over-dispersion parameter, the posterior distributions were very similar. In the absence of sufficient data to estimate individual parameters for each tag group a different solution is required. Using a Poisson distribution is effectively assuming an over-dispersion parameter of 1.0, that is a constant value across all groups. As an alternative, it is proposed that, to generate a viable base-case, all over-dispersion parameters are assumed to take the same value, with this value being pre-specified at the median of the estimates from those tag groups which appeared to have sufficient information to estimate them from the MCMC. Computationally, it is not currently possible in Synthesis to estimate 1 parameter and have the other tag groups take this value. Working with the useable results from the MCMC generates 2 estimates of the over-dispersion parameter, one from the point estimates (1.9) and one from the posterior medians (5.8). The

latter is higher due to the consideration of uncertainty, although the value is likely heavily influenced by the choice of prior. The impact of assuming a single value on the model fit is considered, and a likelihood profile across different values for the parameter constructed.

11.3.3 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 based on inverting the hessian matrix (as reported in the 2010 Aurora Trough stock assessment report, Fay 2010), or by applying Markov-Chain Monte Carlo (MCMC) methods (*e.g.* Hastings, 1970; Gilks *et al*., 1996; Gelman *et al*., 1995). The Metropolis-Hastings variant of the MCMC algorithm was used to sample 1,000 equally likely parameter vectors from the joint posterior density function for the base-case. This sampling process implicitly considers uncertainty in all dimensions of parameter space, and accounts for correlation among model parameters. The samples on which inference is based were generated by running 1,500,000 cycles of the MCMC algorithm, discarding the first 500,000 as a burn-in period and selecting every 1,000th parameter vector thereafter. A potential problem with the MCMC algorithm is how to determine whether convergence to the actual posterior distribution has occurred. Standard diagnostic statistics developed by Geweke (1992), Heidelberger and Welch (1983), and Raftery and Lewis (1992), and the extent of auto-correlation among the samples in the chain were used to determine whether there was a lack of convergence in the chain.

11.3.4 Projection under the CCAMLR control rule

In addition to the deterministic projections from the base-case results, the sample from the posterior distribution for the base-case was used to conduct stochastic projections given both parameter uncertainty and uncertainty in future recruitment events, in order to calculate the 2010/11 catch given implementation of the CCAMLR control rule, where next year's catch is the constant catch such that:

- the probability that 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 spawning biomass shall not be less than 50% over a 35 year projection.

The sampled posterior was therefore projected forward 35 years under a range of constant catch scenarios in order to find the maximum catch level that satisfies both criteria.

11.4 Results

11.4.1 Diagnostics

Diagnostic plots for the various sources of data are shown in Figure 11.13 through Figure 11.18 in the appendix (Section 11.8). These plots are included for completeness, in that they represent the new base-case. Little attention is paid to these plots in discussion as this is covered in the assessment document (Fay 2010).

Tag recapture data

As reported in Fay (2010), estimating over-dispersion parameters results in an improved fit to the tag recapture data. The estimated values for the degree of over-dispersion varied considerably among tag groups, although tag groups for which there has been a long or positive recapture history were generally estimated to have low over-dispersion. The estimation of large values for the degree of over-dispersion for some of the recent tag groups reflects the fact that there have been few (or no) recaptures from these groups as of yet (Figure 11.1).

Assuming a fixed value greater than 1 for the over-dispersion parameters also results in an improved fit to the tag recapture data over that obtained when assuming Poisson (or that the over-dispersion parameters are fixed at 1), with only 25 units of log-likelihood difference between the fit at a value of 1.9 compared with that obtained when estimating the additional 61 parameters Table 11.1 (as a rough guide, each extra parameter should improve the log-likelihood by approximately 1.92 units so 61 parameters giving an improvement of only 25 would normally be rejected as a modelling option). Examining the likelihood profile across different fixed values for the over-dispersion parameter, when all tag groups are assumed to have the same value, the best fit (lowest value for the negative log-likelihood) is obtained with an over-dispersion value of 2.15, however a value of 1.9 is well within the approximate 95% confidence interval (Figure 11.4, portion of the curve below the dotted horizontal line). Figure 11.4 also demonstrates how much an improvement over the assumption that the recaptures are Poisson (over-dispersion = 1) is, as the model fit at this value lies well outside the 95% confidence interval. Similarly, the larger degree of over-dispersion indicated by the poorly converged posterior medians (5.8) is a poor representation of the data, as the fit obtained under this scenario also lies well outside the interval.

MCMC diagnostics

Figure 11.5 summarises the values of five statistics (the ratio of the batch standard deviation to the naive standard deviation, the extent of lag-1 auto-correlation, the *p*-value computed from the Geweke statistic, whether the Heidelberger and Welch test is passed or not, and the value of the single-chain Gelman statistic) used to diagnose non-convergence of the MCMC chain for the model parameters. Ideally, the value of the first statistic should be close to 1, the value of the second statistic should be close to zero, the value of the third statistic should be greater than 0.05, and the value of the last statistic should be less than 1.05. There appears to be some evidence for a lack of convergence for a couple of the parameters given the distribution for the lag-1 autocorrelation (Figure 11.5) most notably the 1994 recruitment deviation. This is not surprising given the expected low mixing rate for this parameter due to the precision of its estimate compared to other recruitments. This perhaps indicates that it might be necessary to run the MCMC algorithm for longer and increase the thinning coefficient, however the likely influence of this on overall model results is negligible.

11.4.2 Base-case results

Selectivity and Recruitment

The estimated selectivity patterns (Figure 11.6) and the estimates for the time-series of recruitment (Figure 11.7) are much the same as reported in the original assessment (Fay 2010).

The recruitment time series shows pulses of recruitment in 1980, 1987, 1994, and 1998/99, although estimation of individual recruitment events is generally uncertain (Figure 11.7).

Biomass and fishing mortality estimates

Under the revised base-case, current (2010/11) trawl available biomass (calculated as mid-season available biomass) is estimated to be above pre-tagging levels (Figure 11.8), with the time series clearly showing the impact of the fishery in the 1990s, and subsequent recovery in biomass following closure. 2010/11 available biomass is estimated to be 2,920t (Table 11.1).

Model estimates of current (2010/11) and unfished spawning biomass are given in Table 11.1. The base-case indicates that current spawning biomass is at 54% of unfished conditions. Uncertainty estimates indicate some probability that the stock may currently be below the management target of 50% unfished spawning biomass (Figure 11.9). Figure 11.10 shows the time series of Spawning Potential Ratio (SPR) for the base-case as a measure of fishing intensity, and reveals that the fishing pressure from 2005-2008 is estimated to have been greater than that which would on average have been required to reduce the population to below 50% unfished spawning biomass (Figure 11.10, points below red dashed horizontal line).

2010/11 catch levels

The maximum constant catch level by trawl that satisfies both the CCAMLR criteria was 140t. Under this catch, median spawning biomass is just above 50% unfished levels after the 35 year projection, with a zero probability of the stock being reduced below 20% unfished spawning biomass during this period given the 1,000 vectors of spawning biomass obtained from the sample of the posterior distribution. Figure 11.11 summarises the posterior distribution for the time series of spawning biomass and spawning stock depletion (spawning biomass relative to unfished). If the catch over the 35 year projection period is assumed to be taken by longline instead of trawl, then the constant catch satisfying the CCAMLR control rule criteria is 164t.

Catches of 140t and 164t under the CCAMLR control rule are consistent with the long-term catches under a constant F50 harvest rate policy, calculated under the base-case to be 145t for catches by trawl only and 173t if catches were by longline (Table 11.1).

11.4.3 Sensitivity analyses

The results of a small number of key sensitivity tests to the new base-case are presented in Table 11.1.

Maturity

Using the larger estimates of length-at-maturity from analysis of new data (Fay 2010, length of 50% maturity of 139cm) has little impact on both the fit to the data and the results, other than that the absolute values for the spawning biomass are unsurprisingly estimated to be lower under this scenario.

Tagging Data

As with the results in Fay (2010), there was very little difference in the available biomass estimates dependent on the method for assigning ages to tag-released fish (Table 11.1). Estimates of current spawning biomass relative to unfished were higher than the base-case when assuming a single age at release for all fish tagged in a given year, and lower when disaggregating the data into lots of ages of release per year.

A larger, less depleted spawning stock is estimated when the tag recaptures obtained within the year of release are included in the model (Table 11.1). However, including these recaptures is probably not appropriate in an annual model as they likely are reflective of season length rather than exploitation rate and so are not comparable from year to year.

Increasing the tag detection rate for the longline fleet to 100% (instead of the base-case 94%) resulted in almost negligible change to the model results (Table 11.1).

The model results are also clearly affected by the value chosen for the degree of over-dispersion in the tag recaptures (whether they are allowed to depart from random and be clumped), with the uncertainty characterised by the likelihood profile Figure 11.4. Increasing levels of over-dispersion are associated with a smaller estimated current spawning stock size, and also lower spawning stock size relative to unfished levels (Table 11.1). The impact of the value for the over-dispersion parameter on the estimate of the F50 catch by trawl is shown in Figure 11.4. The profile suggests very little change in the 2010/11 catch over the range of values for the over-dispersion parameter contained within the approximate 95% confidence interval (1.8-2.6). Fixing the over-dispersion parameters at 5.8 results in a lower catch than the revised base-case with the F50 catch being 118t by trawl and 141t by longline in this case.

11.5 Discussion

The new, revised base-case analysis incorporates the changes suggested by SARAG.

1. Under the new base-case, the current (2010/2011) trawl available biomass is estimated to be well above the limit reference point of 66.5% pre-tagging (1995) levels, with the base-case trawl available biomass estimated to be 2,920t. Spawning biomass is estimated to currently be 54% of unfished spawning biomass, with the base-case estimate of 2010/11 spawning biomass being 2,004t.

2. Under the CCAMLR control rule, the calculated catch for 2010/11 is 140t, assuming that future catches are taken by trawl.

3. The inclusion of over-dispersion in the tag recaptures is problematic in that there is insufficient information to estimate these parameters individually. Consequently, uncertainty in the value for the degree of over-dispersion is not incorporated when conducting the MCMC. Inclusion of over-dispersion is an improvement over assuming that recaptures are purely Poisson (as evidenced by the likelihood profile in Figure 11.4). Fixing the value for all tag groups at a level suggested by the data, as implemented here, is therefore suggested as better than ignoring the effect, even if full characterisation of the uncertainty is not possible. Results of sensitivity analyses

suggest that there will be little change to the calculated 2010/11 catch levels given the range of values for over-dispersion that remain consistent with the data. Planned developments to the Synthesis software include more comprehensive control over the parameters controlling tagging, and it is envisaged that this will allow improvement in the way the over-dispersion is handled without resorting to the over-parameterised case of individual parameters by tag group.

4. The new, revised base-case uses the previously implemented length at 50% maturity of 89cm. Analyses of recently collected data from longline suggest that this size at maturity may be larger – the results of which on the assessment are to estimate a smaller spawning stock size. However, there is little impact on the calculated long-term F50 catch when this is assumed to be taken by trawl.

5. The value assumed for the tag detection rate had almost no impact on the model results. This is because longline fishing in the Aurora Trough has so far been minimal. If the data from Aurora Trough continue to be derived from longline fishing operations, then the value for the detection rate will become more influential to the assessment.

6. Additional assumptions regarding the treatment of tagging data did impact the model results. Decreasing the time assumed to allow for mixing of tag releases within the rest of the population resulted in higher estimates of both available and spawning biomass. The base-case assumption to remove the recaptures in the year of release from the likelihood function is probably most appropriate for a model that operates on an annual basis, as this removes the effect of variability in season length on the results. That is, if the annual catch is spread out over a longer period, one might expect more recaptures of fish tagged within that season than a shorter season, which would not be a result of differences in the harvest rate.

11.6 Acknowledgements

The authors thank the AFMA scientific observers for conducting the tagging program and the owners, officers and crew of the *Southern Champion*, *Avro Chieftain,* and *Janas* for their excellent cooperation throughout. T. Lamb at the Australian Antarctic Division is thanked for provision and preparation of the stock assessment data. The members of SARAG are thanked for their thorough review and comments on the assessment, leading to the analyses presented here.

11.7 References

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Table 11.1. Results of the revised base-case and sensitivity analyses, with estimates of the trawl available biomass, spawning biomass, 2010/11 catch, and the contributions to the negative logarithm of the likelihood function. Values in the latter columns in italics indicate values not comparable with those in the base-case.

	Trawl available biomass (TAB)			Spawning biomass			F50 yield at $0.5SB_0$ (t)		negative log-likelihood					
	2010/11	pre-tagging (1995)	2010/1995	$SB_{2010/11}$	SB_0	$SB_{2010/11}/SB_0$	trawl	longline	Total	Length	Age	Tag comp	Tag Recap	Rec't
Base-case (over-dispersion = 1.9)	2,920	2,465	1.18	2,004	3,709	0.54	145	173	1156.1	488.1	65.6	5.00	598.1	-0.77
Maturity														
length at 50% mature 139cm	2,939	2,459	1.19	840	1,428	0.59	137	157	1156.1	488.2	65.6	5.00	598.1	-0.81
Tag-recapture data														
individual overdispersion parameters	2,685	2,476	1.08	2,001	3,704	0.54	144	172	1130.3	487.8	65.6	4.99	572.9	-1.25
no overdispersion in tag recaptures (Poisson)	2,900	2,343	1.24	1,919	3,598	0.53	141	169	1199.7	489.1	66.0	5.00	640.0	-0.40
overdispersion = 2.15	2,856	2,459	1.16	1,973	3,673	0.54	143	172	1155.3	488.0	65.6	5.00	597.6	-0.87
overdispersion = 5.8	1,915	2,167	0.88	1,401	3,014	0.46	118	141	1191.6	487.8	65.7	5.01	634.7	-1.66
include recaptures in year of release	3,521	3,162	1.11	2,709	4,476	0.61	173	207	*1315.9*	487.9	64.2	5.20	*759.8*	-1.24
longline tag detection rate = 100%	2,937	2,467	1.19	2,011	3,717	0.54	145	174	1156.8	488.1	65.6	5.04	598.7	-0.75
1 tag group per year, fix age of release (9, 12)	3,064	2,664	1.15	2,263	4,000	0.57	155	186	*787.3*	487.6	65.3	4.94	*230.5*	-1.01
1 tag group per year, age of release varies	3,088	2,640	1.17	2,256	3,983	0.57	154	185	*791.4*	487.7	65.4	4.90	*234.3*	-0.86
lots of tag groups per year (release lengths)	2,764	2,355	1.17	1,829	3,505	0.52	137	164	*1426.3*	488.3	65.7	5.00	*867.9*	-0.65

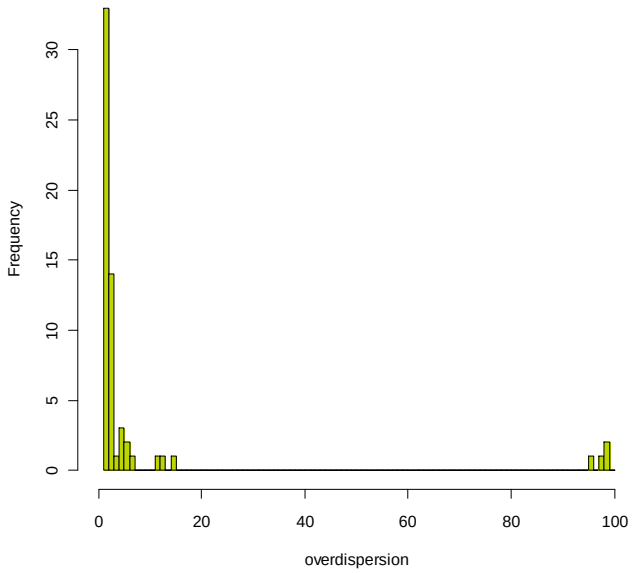

Figure 11.1. Distribution of the estimates for the over-dispersion parameters. A value close to 1 indicates low over-dispersion (recaptures are effectively Poisson distributed), whereas values greater than 1 indicate higher degrees of over-dispersion.

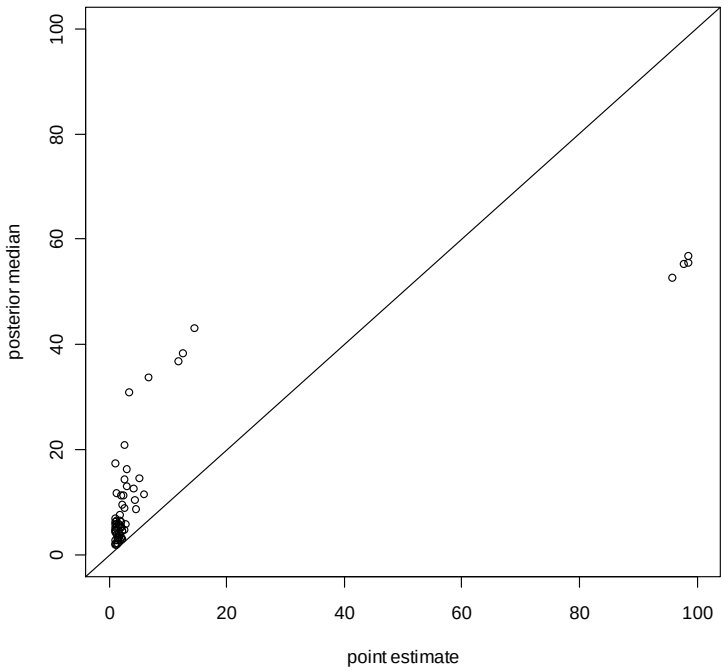

Figure 11.2. Comparison of over-dispersion parameter estimates from the point estimate (x axis) and the value for the posterior median (y axis).

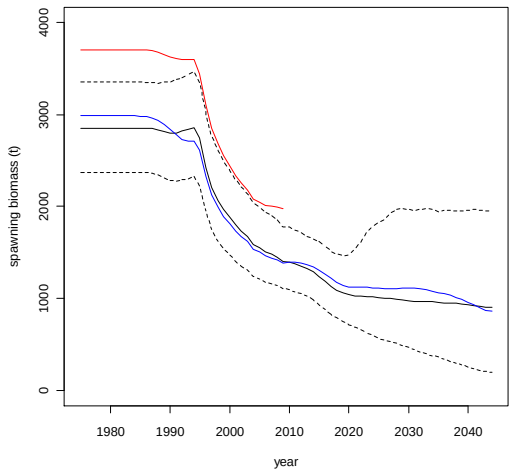

Figure 11.3. Posterior median (black line) and 95% CI for a version of the revised base-case with estimation of individual over-dispersion parameters for each tag group. Red line indicates the point estimate, which is well outside the 95% interval for this (poorly determined) scenario. Blue line is the vector from the posterior sample that gives the best fit to the data.

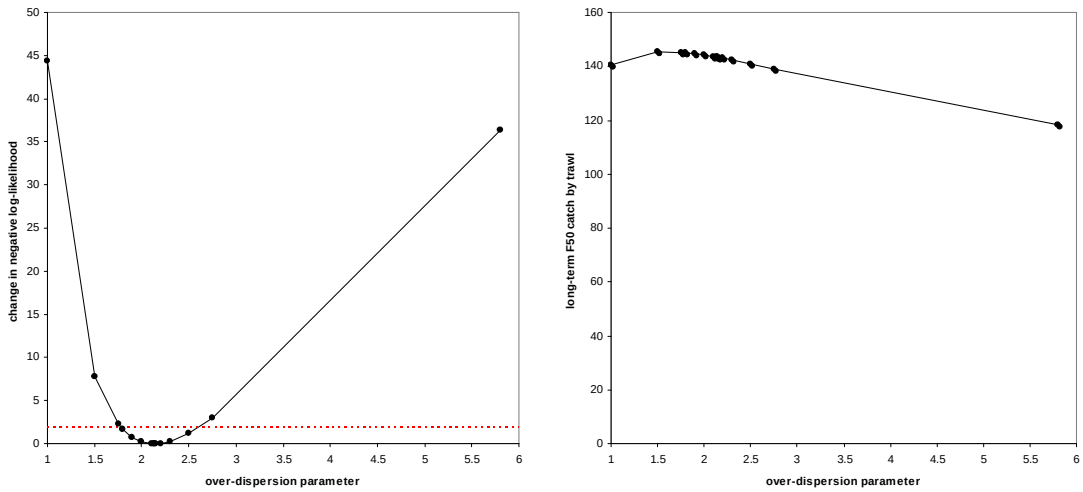

Figure 11.4. Likelihood profile for the value of the over-dispersion parameter when the same value is assumed for all tag groups. Red dotted line indicates the approximate 95% confidence interval – points on the black line below the red line lie within the interval. Right panel shows the impact on the estimate of the long-term trawl catch under an F50 strategy (approximately equal to the catch under the CCAMLR rule) with changing the value for the over-dispersion parameter.

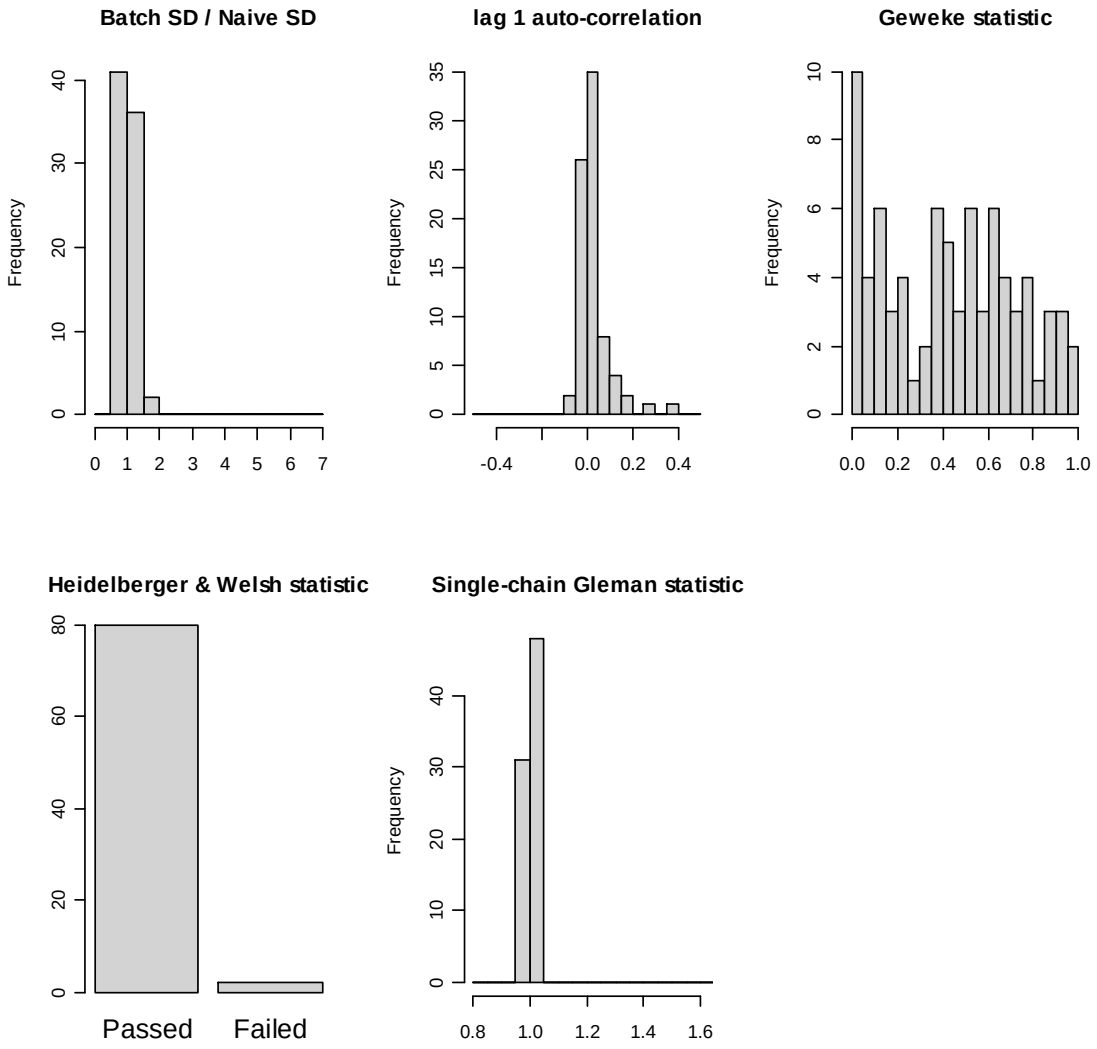

Figure 11.5. MCMC diagnostic statistics for the revised base-case model parameters.

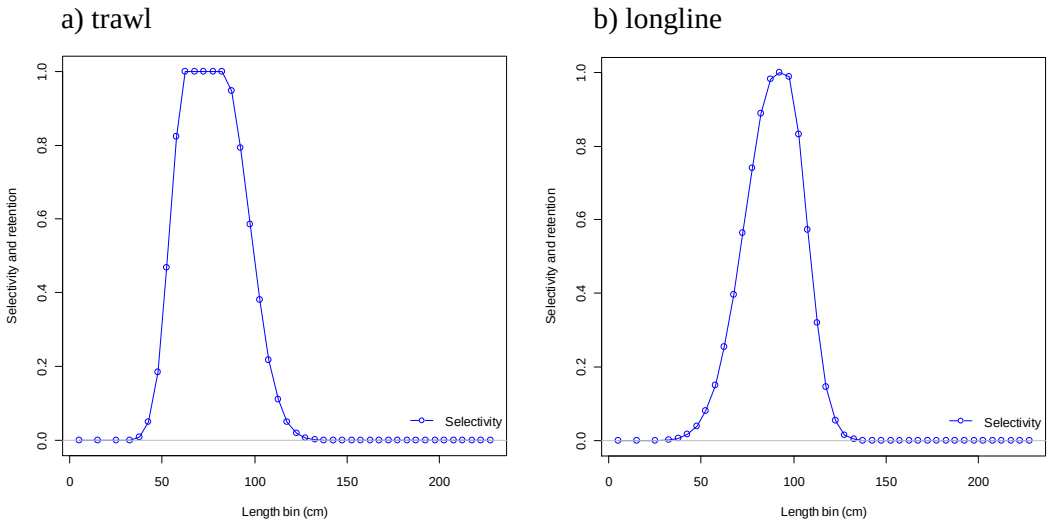

Figure 11.6. Base-case estimates of selectivity at length for trawl and longline.

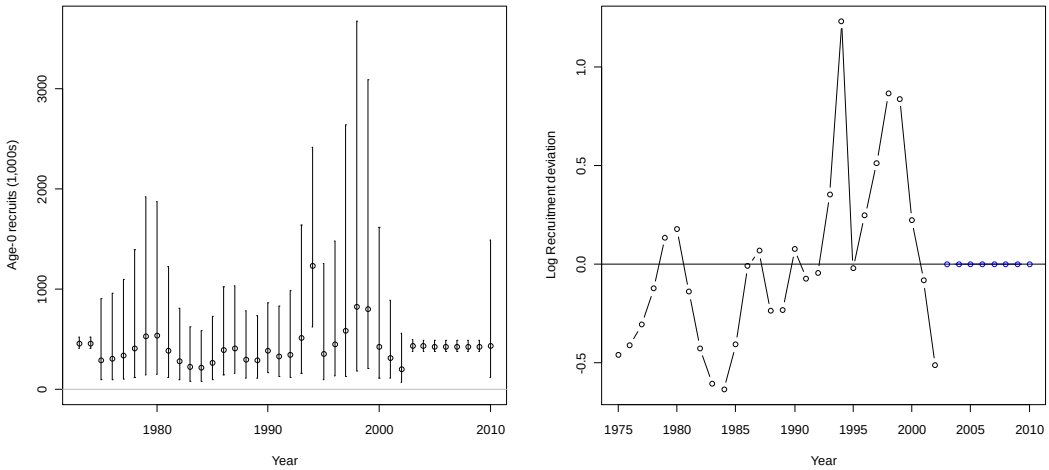

Figure 11.7. Base-case time series of estimated recruitments and recruitment residuals. The bars in the left hand graph depict the 95% percentile confidence intervals computed from the asymptotic standard errors.

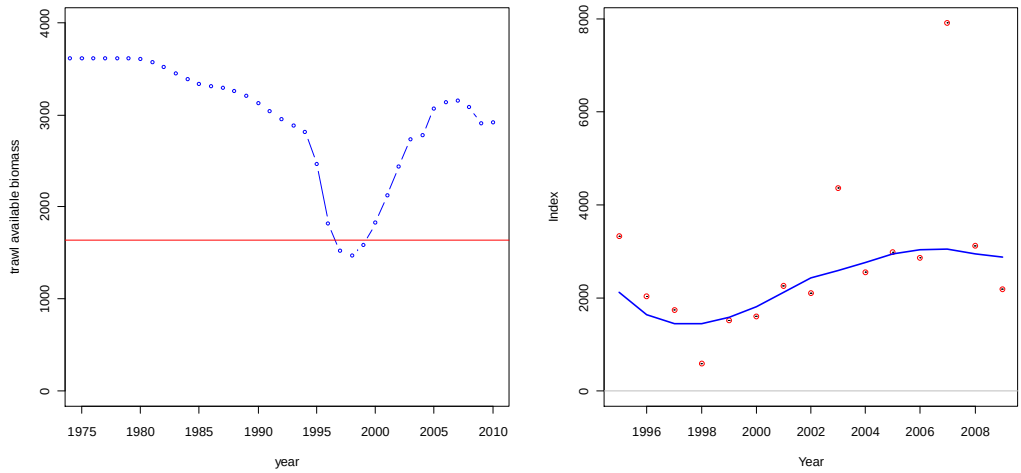

Figure 11.8. Base-case estimated time series of the trawl available biomass (left panel). Horizontal red line indicates 66.5% of pre-tagging (1995) available biomass. Right-hand panel compares the base-case estimate (blue line) with the 2009 tag-only assessment results (red points).

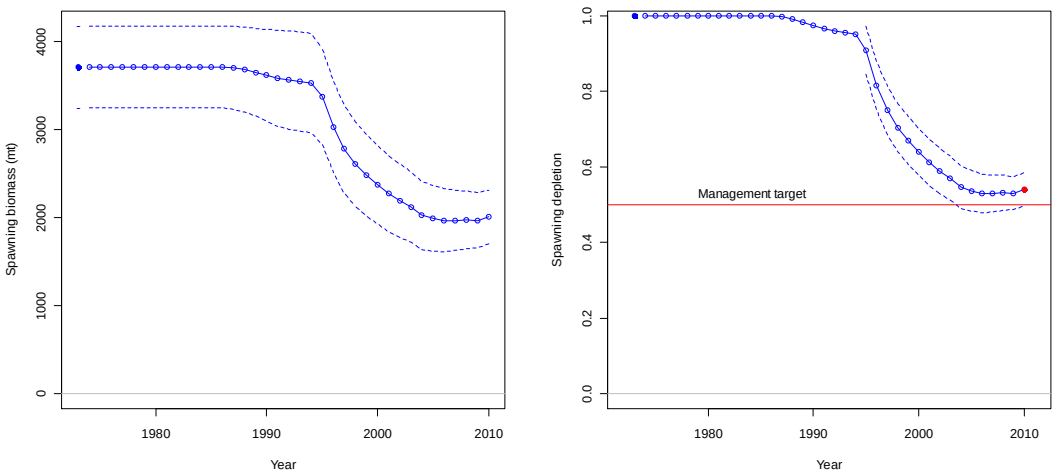

Figure 11.9. Base-case estimates for the time series (with approximate 95% confidence intervals) of spawning biomass (left panel), and spawning biomass relative to unfished (1975) conditions (right panel, denoted spawning depletion).

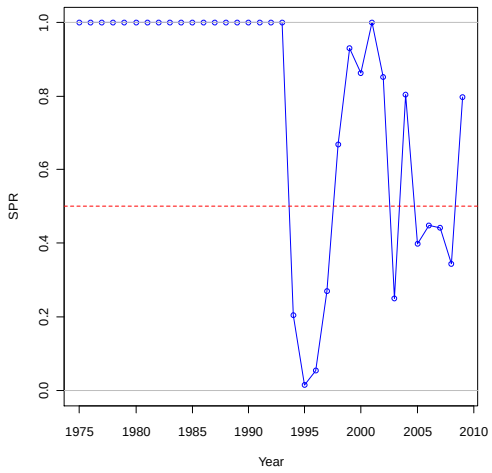

Figure 11.10. Time series of spawning potential ratio (SPR). The red horizontal dashed line indicates an SPR value of 0.5. If the value for SPR is below this line this indicates that the rate of fishing mortality in that year was likely greater than that which on average results in a spawning biomass of 50% unfished levels.

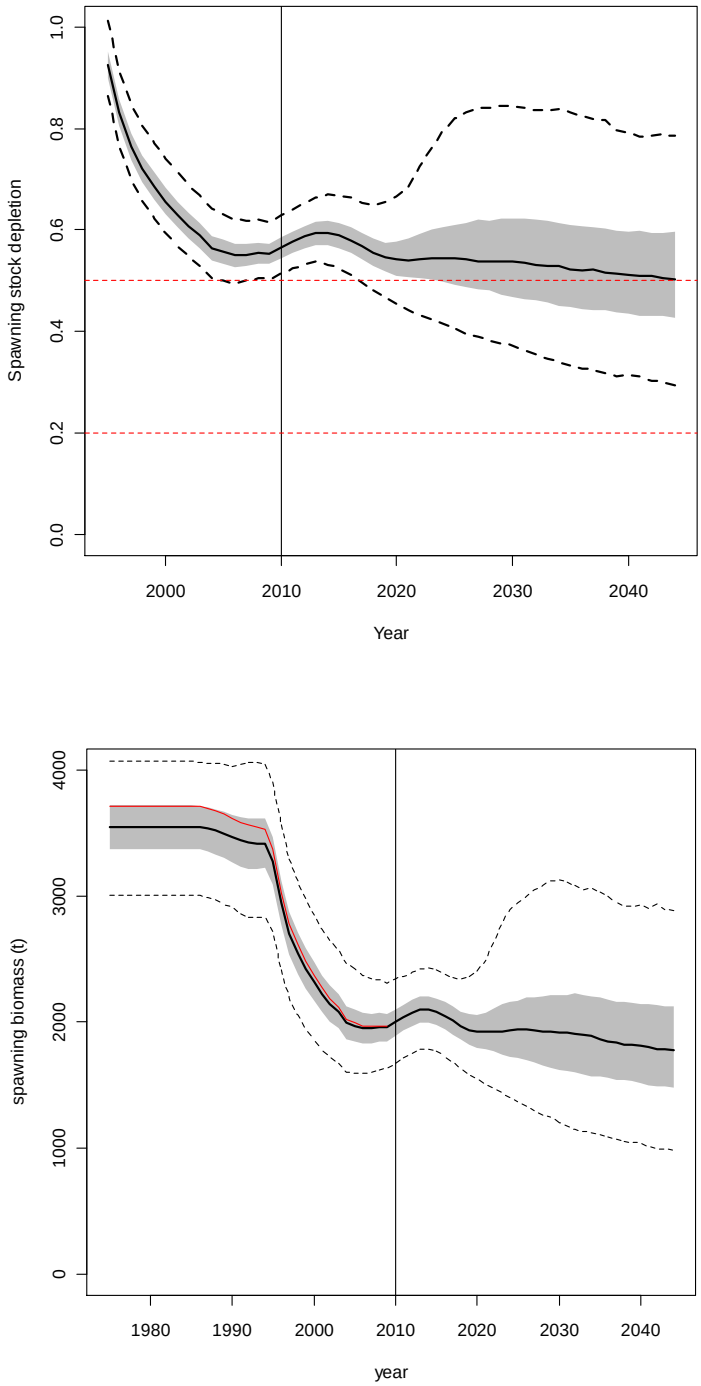

Figure 11.11. Summary of the posterior distribution for the projected spawning stock depletion and spawning biomass given a constant annual future catch of 140t by trawl. Plotted are the median (black solid line), central 50% (grey shaded area), and 95% (dashed lines) credibility intervals. Black vertical line indicates the beginning of the projection period, horizontal dotted lines indicate the management target of 50% unfished spawning biomass and the limit reference point of 20% spawning biomass. Red solid line on spawning biomass panel indicates the time series of spawning biomass obtained from the point estimate.

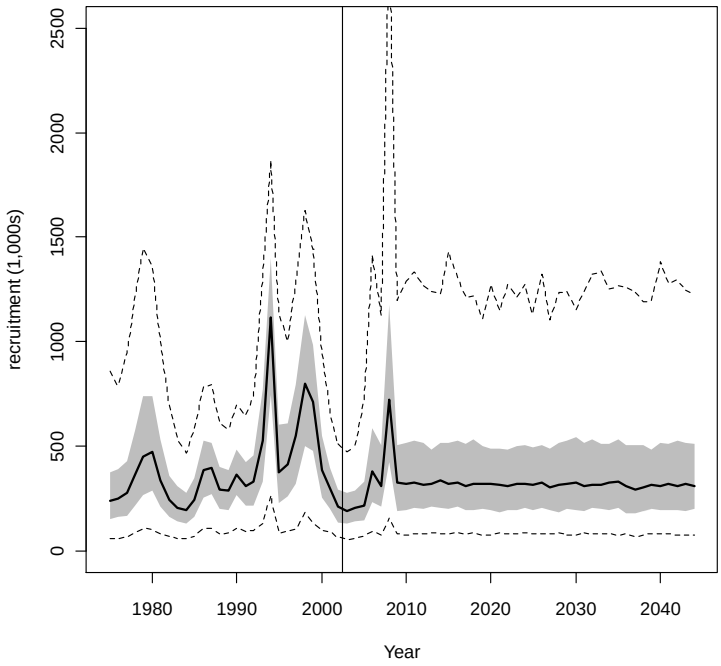

Figure 11.12. Summary of the distribution (shading as per Figure 11.11) for the time series of recruitment obtained from the posterior.

11.8 Appendix

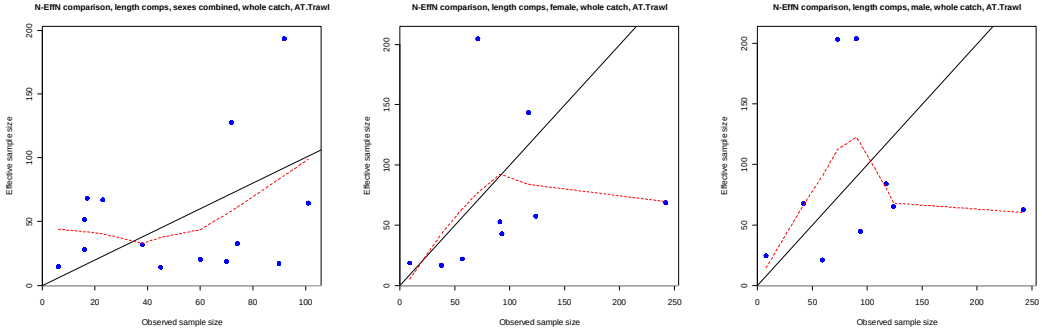

Figure 11.13. Input versus effective sample size for the trawl length composition data.

a) sexes combined

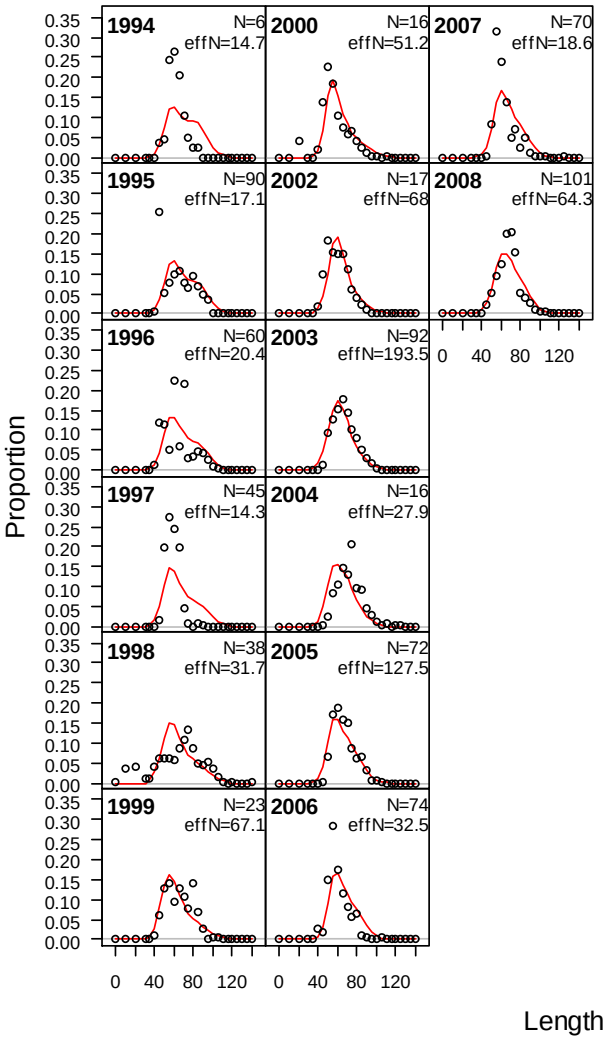

Figure 11.14. Base-case fits to the Aurora Trough trawl length composition data.

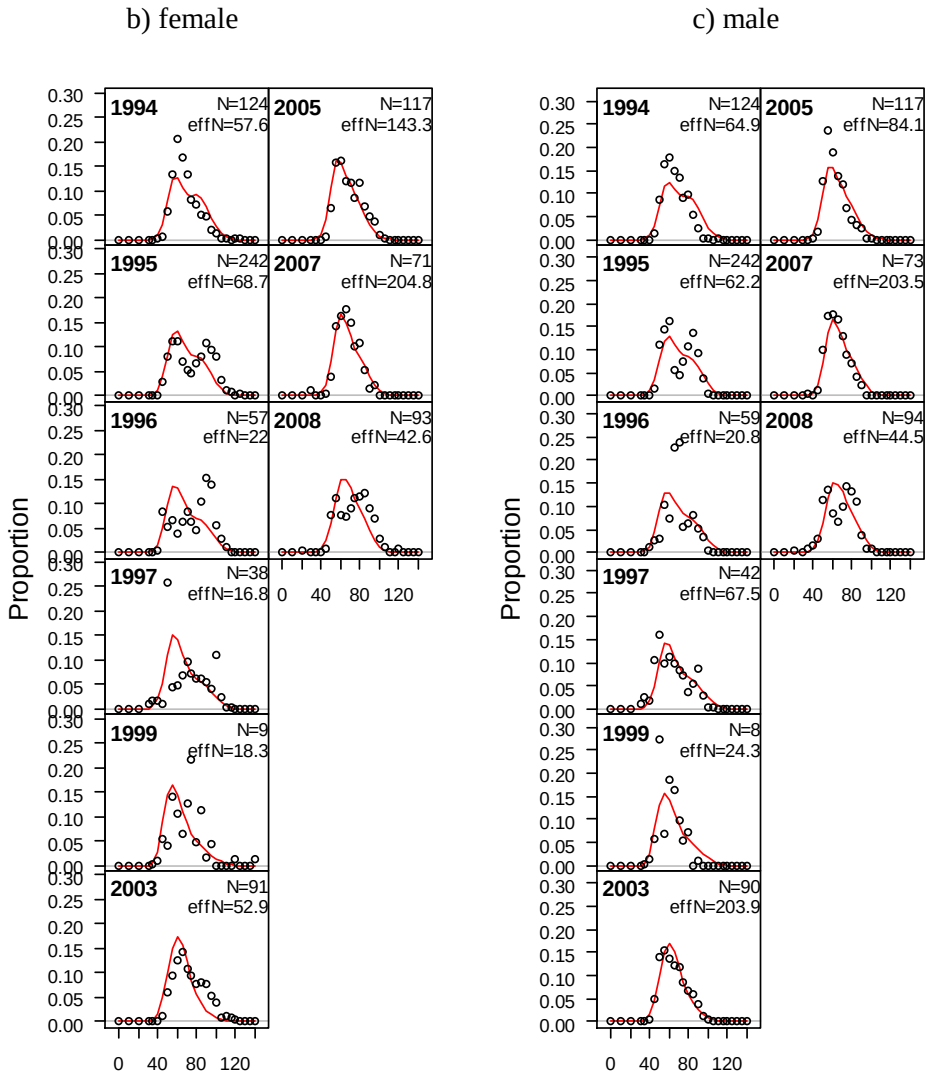

Figure 11.14 continued.

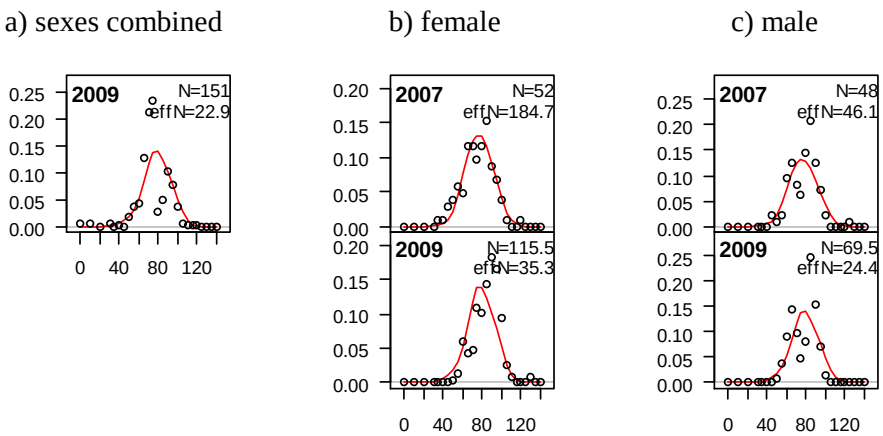

Figure 11.15. Base-case fits to the longline length composition data.

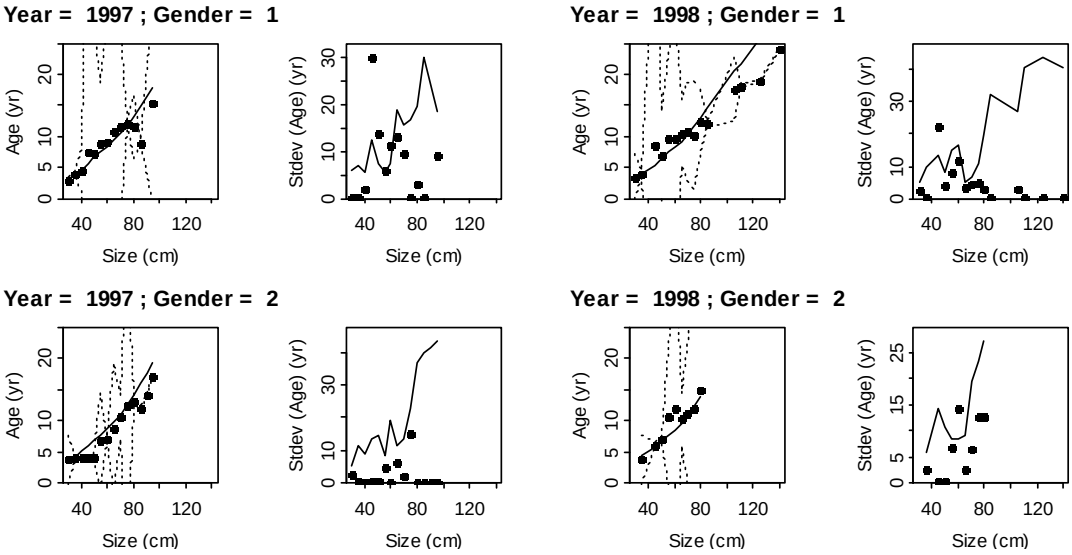

Figure 11.16. Diagnostic plots for the fit to the condiitional age at length data. For each year and gender (1=female, 2=male), the two panels are 1. Mean age-at-length by size-class (observed and predicted) and the 90% CIs based on adding 1.64 SE of mean to the data, and 2. SE of mean age-at-length (observed and predicted) and the 90% CIs based on the chi-square distribution. The dots are the data, the dotted lines the 90% CIs and the lines the expected values.

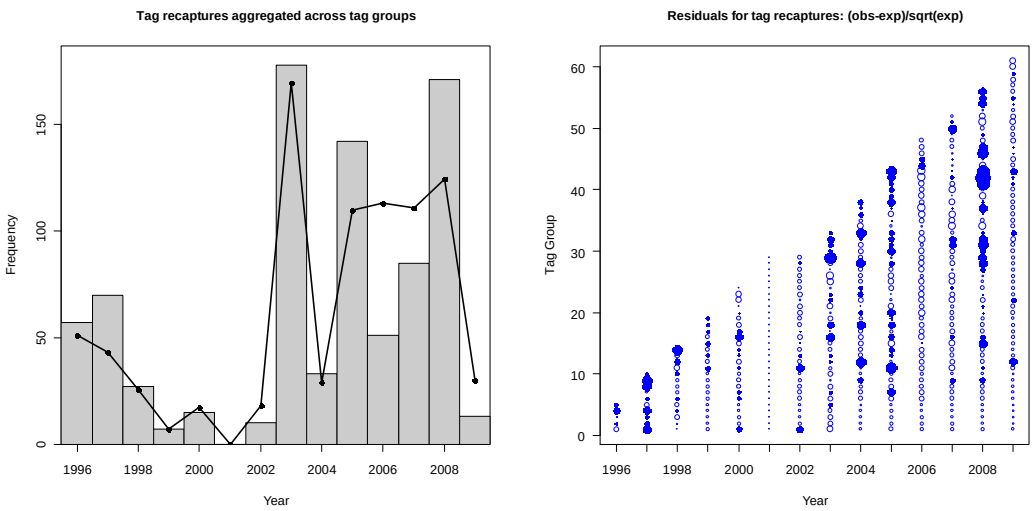

Figure 11.17. Summary of the fits to the tag recapture data for Model 1. Left-hand panel shows the summed observed (bars) and expected(line) recaptures over years, and the right-hand panel shows the residuals by tag group and year (blue indicates more recaptures observed than expected).

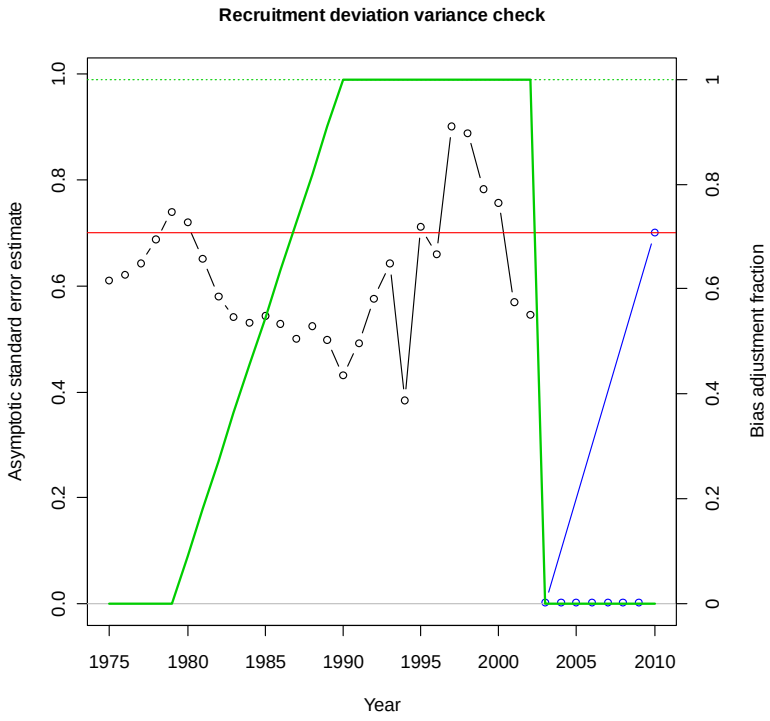

Figure 11.18. Asymptotic standard error of estimate for the recruitment deviations for Model 1.

12. EVALUATING A TAG-RECAPTURE BASED INTEGRATED STOCK ASSESSMENT MODEL FOR MACQUARIE ISLAND PATAGONIAN TOOTHFISH: TESTING TAGGING ASSUMPTIONS USING AURORA TROUGH[7]

Gavin Fay

12.1 Summary

This chapter tests the ability of an integrated assessment model for Patagonian toothfish (*Dissostichus eleginoides*) within Aurora Trough at Macquarie Island to estimate biomass and management reference points. The work deals primarily with testing how assumptions related to the aggregation of tag release data within the assessment model impact the ability to estimate key quantities of interest.

A simulation modelling framework is used, with an operating model tuned to represent the dynamics of the toothfish population assuming a single stock in Aurora Trough with exploitation by trawl and longline fisheries. The operating model generates data akin to that available from the Aurora Trough fisheries, namely results of a tag recapture program, length composition data, and age composition data. The value of additional data types and quantities are assessed. The estimation model, a stock assessment in the Synthesis software, is similar to the operating model, and is fitted to the data generated by the operating model, with different levels of aggregation in these data prior to estimation. The performance of the assessment model is evaluated by comparing estimates of quantities such as current spawning biomass, relative spawning biomass, trawl available biomass, and the recruitment time series with their true values in the operating model.

The assessment model is strongly influenced by the available tagging data, which can be included in the assessment in a number of ways. Scenarios examined include fixing the age at release for all tagged fish, or, for each year of tag data, splitting the tag releases into several tag groups and assigning these smaller groups individual ages, based on the length composition of the catch for that year. These scenarios were conducted for cases where the data available was considered to be equivalent to that actually available from the Aurora Trough, a 'data-rich' case which reduced the influence of observation error on the results, and for cases where the annual sample sizes of the age data were increased, to reflect the possible effect on the results of ageing additional otoliths that have been collected at Macquarie Island but remain as yet un-aged.

The results indicate that when a single release age is assumed for all tagged fish, the stock assessment model performs poorly, with biased estimates of both spawning and available biomass. Performance improves when the tag releases are split into a small number of tag groups (3, 5, or 7), with little difference in performance among these scenarios. Disaggregating the tag releases to the greatest extent possible (1 tag group per length bin, scenario 'lots') is the best reflection of the actual tagged population, however this scenario performed poorly when the amount of data was set to the 'realistic' levels of the data available for Aurora Trough, with

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the 3, 5, and 7, tag group scenarios doing better at estimating historic and current biomass levels.

Not surprisingly, a movement to the data-rich case resulted in improved performance, however the general pattern of performance relative to tagging scenario was consistent with the realistic scenario, although the biggest improvement in performance over the realistic case was for the 'lots' option. Indeed, the 'lots' scenario did seem to be the best option for estimation of current biomass in the data-rich case.

Positive biases in the estimates of current biomass (spawning and available) remained even in the data-rich case for the 3, 5, and 7 tag scenarios. It is unclear what is responsible for this bias, it does not appear due to model mis-specification with respect to recruitment estimation. The bias may be due to a false signal in relative year class strength from the tag recapture history associated with the incorrect assignment of tag releases to ages. This will serve to reduce the quality of the information available to estimate recruitments and result in a shrinkage of their estimation toward the mean. Biased abundance estimates have been shown to result from this.
Scenarios which varied the quantity of age data available but kept the rest of the data at realistic levels demonstrated that much of the improvement in estimation performance associated with the data-rich scenario can be attributed to the age data. While the data-rich sample sizes are unattainable, the results demonstrate that there is considerable value in ageing existing otoliths collected at Macquarie Island, particularly given that the realistic case assumed more age information than is available currently.

The analyses presented here are of limited scope, and additional work should be undertaken to see if the patterns found are consistent given alternative operating model scenarios, which might include representation of additional uncertainties such as the current relative biomass (here assumed to be 50% unfished spawning biomass), and whether growth, mortality, and productivity data are either incorrect or estimated within the stock assessment.

The results do however indicate that using a fixed age of release for all tagged fish in all years at Aurora Trough is unwise. Also, disaggregation to the greatest extent possible results in low numbers of recaptures for each tag group and hence inaccurate and imprecise estimates given the numbers of tags that have been released in the Aurora Trough. Disaggregating the data into a small number of tag groups per year (*e.g.* 5) currently appears to be the most sensible option for input into the Synthesis-based stock assessment of this resource.

12.2 Introduction

This chapter presents results of testing the performance of an integrated stock assessment of Aurora Trough Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island with respect to different assumptions about the use and availability of data to the assessment.

The paper uses a simulation testing framework whereby the stock assessment model is fitted to fisheries data generated from an operating model, which represents the true dynamics of the toothfish resource and fishery. The ability of the assessment model to estimate quantities of interest such as trawl available biomass and current spawning biomass can then be evaluated by comparing the results of the assessment process to the true values in the operating model. It specifically enables a critical evaluation of the likely impact of different assumptions made during the assessment process on the ability of the assessment model to estimate key quantities of interest.

An integrated stock assessment model using the Stock Synthesis assessment software (v3.04b, *e.g.* Methot 2007) is being prepared for provision of scientific advice regarding the exploitation of toothfish at Macquarie Island. Central to the data set for this population are the results of a tag-recapture program, implemented in 1995 and continued to the present day. This new assessment is based on a length-age structured model of fish population dynamics and uses a maximum likelihood framework to fit to the available data, which include tag recapture data, length composition data, and age-at-length data. Use of the Stock Synthesis framework enables estimation of spawning biomass and selectivity curves, in addition to the estimate of trawl available biomass. Trawl available biomass has been the quantity used as the basis for management of toothfish at Macquarie Island and was the primary output from the previously used tagging model (*e.g.* Tuck *et al*., 2003).

The assumptions made within the tagging component of the Stock Synthesis software have so far not been extensively tested. Between the 1995/96 and 2009/10 fishing seasons, over 11,000 Patagonian toothfish were tagged at Macquarie Island, of which nearly 1,700 have been recaptured. In particular, Synthesis assumes that each tag 'group' (which could be all fish tagged and released in a given year) have the same age of release. It is not clear how the level of aggregation of tag data into tag groups impacts the estimation ability of the assessment model. Typically fish are tagged and released in proportion to the distribution of size at capture, and it is therefore unlikely that all fish have the same age. This is especially true if, as for Patagonian toothfish at Macquarie, growth is sex-dependent.

In this paper we test the impact of aggregating the tagging data by considering several different options for the treatment of the tag release data, which consist of numbers and lengths at release, but which do not assume that the sex or age of releases are known. We compare the ability of the stock assessment model to estimate current and historical levels of biomass given these different aggregation levels. Performance of the assessment model is evaluated given the types and quantity of data currently available from the Aurora Trough trawl and longline fisheries, and for different scenarios which vary the types and amount of data available. This was done in order to see how the impact of some of these assumptions may change if different data (more ages, index of abundance, higher tagging rate) were to become available, and also to see how the different types of data interact with the results of the tag-recapture program during the estimation procedure.

12.3 Methods

Performance of the stock assessment model is evaluated using a simulation modelling framework. The general approach on which the operating model is based consists of tuning an age-structured operating model to represent a set of hypotheses about the dynamics of the Aurora Trough toothfish population and fishery. The values for the parameters of the operating model are based on both agreed values and the results of fitting stock assessment models to the available data from the Aurora Trough fishery.

The operating model is projected over a historical period given the known catch history for toothfish at Aurora Trough, and values for the various types of data are generated given the known 'true' population. The tag release and recapture data are then aggregated according to the particular scenario being tested, and the chosen assessment method (Stock Synthesis) is fitted to these data. Summary statistics are then calculated by comparing the results of the assessment procedure to the true values in the operating model from which the data were generated. One hundred simulations were conducted for each scenario, with each simulation

differing due to process error in the population dynamics and observation error when generating the data. The summary statistics for each simulation are further analysed to derive a set of performance measures for the assessment model given the scenario, which are used to compare results among scenarios.

12.3.1 Operating model

The operating model consists of an age-structured population dynamics model that can be parameterised to include spatial regions (with movement of fish among regions), and multiple fleets, to capture key dynamics for toothfish. Full technical specifications for the generalised version of the operating model are detailed in Fay *et al*. (2009a). Analyses detailed in this present paper consider a single structural version of the operating model to represent the dynamics of toothfish in the Aurora Trough. The operating model assumes a single stock occupying a single region (Aurora Trough) which is exploited by two fleets, trawl and longline (with different selectivity patterns for each gear type). The parameters of the operating model are either taken from previous assessments of toothfish at Macquarie island, agreed values for biological parameters, or from the results of fitting the stock assessment model to the available data for Aurora Trough toothfish (*e.g.* Fay *et al*., 2009b). The impact of alternative parameterizations of the operating model is considered for some cases (chiefly, the current value of relative spawning stock biomass) in order to investigate the implications of interactions between key uncertainties and the estimation procedure. The parameterization of the operating model, along with values for biological parameters, are given in Table 12.1 and Figure 12.1.

The catch history used to drive the population dynamics (Figure 12.1) is the actual time series of catches from Aurora Trough.

12.3.2 Assessment model

The stock assessment model is similar to the operating model in that it considers exploitation of a singe stock at Aurora Trough by trawl and longline fisheries. The population is assumed to be in unfished equilibrium, with an equilibrium age structure, in 1975. Spawning biomass in 1975 is therefore used as the estimate of unfished spawning biomass, SB_0. Note that the operating model does not have an equilibrium age structure at this time, as the impact of historical recruitments on age structure are included.

In general, the biological parameters of the assessment model and the parameters of the stock-recruit relationship (apart from the average level of unfished recruitment) were fixed at their ‘correct’ values as used in the operating model. 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, 2007) and are not reproduced here. Statistical fitting of the population dynamics model to the available data is achieved by minimizing an objective function consisting of several likelihood components, reflecting the different types of data input (lengths, age-at-length, and tag recaptures), and also the distribution of annual recruitment deviations around the stock-recruit relationship.

The estimated parameters of the assessment model were: average recruitment before fishing, annual recruitment deviations from 1982-2003, and the parameters determining the functional form of the selectivity pattern for each fleet. This resulted in 31 estimated parameters. 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), but did not impose this pattern on the model. The range of years chosen for recruitment estimation reflects the expectation that cohort effects from these years be seen in the data and result from previous applications of the assessment model to Aurora Trough data (Fay *et al*., 2009b).

12.3.3 Data

The data types generated from the operating model were similar to those available from the Aurora Trough fisheries. These included annual length composition data, the results of a tag-release-recapture program, assumed to have begun 1 year after the start of the fishery, and age composition data.

Two levels of data quantity were evaluated: a) a 'data-rich' case in which both the numbers of tag releases and the annual sample sizes of the length and age data were very large, and b) a 'realistic' case in which the annual numbers of tag releases were the same as those actually released in the Aurora Trough fishery, and the annual sample sizes for the length and age data were at levels comparable to the effective sample sizes for these data predicted from fitting the assessment model to the actual data from the fishery (*e.g.* Fay *et al*., 2009b). Additional modifications to these two major cases were made to evaluate specific assumptions and are described below. The inclusion of the 'data-rich' case, while not representative of possible data collection, allows a baseline as to the very best that can be expected from the assessment models given the other assumptions, thus allowing those assumptions to be tested without the uncertainty associated with observation error.

Table 12.2 shows the numbers of tag releases and annual sample sizes associated with the two cases. Scenarios under the realistic case where the amount of age data is increased are considered – this reflects the fact that currently, a large number of otoliths collected from toothfish at Macquarie Island remain un-aged. This scenario therefore considers the relative value to the stock assessment results of ageing these fish.

Tag release and recapture data

A main aim of the paper is to test the assumptions associated with aggregating the tag release data into tag groups within the model. Under the Synthesis framework, annual releases of tagged fish from an area (ie a tag 'group') are all assumed to consist of a single age class. While computationally convenient, this clearly does not represent the way in which fish are tagged, as fish are generally assumed to be done so in proportion to the length frequency of the catch. For the two data quantity cases we considered the following scenarios which each differed in the way that the tag data were treated for the assessment. No matter the scenario, the operating model always tagged fish in proportion to the true length/age composition of the catch, as this most correctly reflects the way in which toothfish are selected for tagging (Tuck and Lamb 2009). The scenarios considered by the assessment model were:

1. a single tag group by year and fleet, with a fixed age of release over time,

2. as for 1, except that the age of release is assumed to vary over time dependent on the median length of the catch for that year/fleet,

3. 3, 5, or 7 tag groups by year and fleet, with the ages and numbers allocated to each tag group dependent on the length composition.

4. individual tag groups by 5 cm length bin containing catch, with assignment of age and numbers to each tag group as in 3.

In all cases, the releases are aggregated by sex. In scenarios 2-4, assignment of ages for tag groups is based on the length composition by assuming the known values for the von Bertalanffy growth function. Scenario 3 considered fixed numbers of tag groups per year (3, 5, or 7), whereas scenario 4 reflects a case where there are a large number of tag groups per year (1 per 5cm length bin in the assessment model), akin to assigning each individual tag released fish an age based on its release length. The numbers allocated to each tag group were calculated by splitting the relevant length composition into the appropriate number of groups, apportioning the number of fish in each tag group by the proportions by length bin, and then assigning ages to the tag group based on the expected age given the growth curve and the median length of each tag group. Allocation of numbers and ages is by the length composition as the length at release is always recorded.

An additional scenario, whereby the true age distribution of tags is used, could also be implemented. While not achievable in practice, this would again represent a best possible case scenario where the full age structure detail in the tagged population is retained by the assessment.

Disaggregation of the annual tag numbers naturally results in fewer tagged fish in each tag group. As a result, a loss in precision can be expected as the probability of non-recapture in a given year for each tag group will increase.

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. For the purposes of this paper, rates of tag loss and tag mortality were assumed to be zero and 100% of fish were detected (both in the operating model and the assessment model).

12.3.4 Performance measures

Assessment performance was compared among scenarios using the median of the absolute relative errors (MARE) for the following quantities of interest:

1. unfished spawning biomass, B_0,

2. current (2010) spawning biomass (B_{2010}),

3. 2010 relative spawning biomass (B_{2010}/B_0),

4. pre-tagging (1995) trawl available biomass (VB_{1995}),

5. 2009 trawl available biomass (VB_{2009}),

6. 2009 relative trawl available biomass (VB_{2009}/VB_{1995}).

These quantities do not include productivity related quantities such as B_{MSY} or F_{MSY}, largely because the assessment model does not estimate steepness, growth or *M*, although it does estimate selectivity.

The MARE is a single statistic that accounts for both bias and imprecision, with higher values for the MARE indicating poorer estimation performance, and values approaching zero indicating improved performance. Comparison among scenarios was also made using the distributions for the percent relative errors of estimate (%REEs) and the values for the median relative error (MRE) and median absolute deviation from the median (MADM) of the performance measures. Inspection of the values for MRE and MADM allow for an assessment of whether bias or imprecision is contributing to the MARE. The MARE, MRE, and MADM simply represent alternative ways of summarising the distribution of the results across simulations into a single value.

The ability of the assessment models to track individual year class strengths accurately was evaluated by calculating the median mean absolute error (MMAE) of the estimated recruitments:

$$\text{MMAE} = median_i \left(\sum_y \left| (\hat{R}_{y,i} - R_{y,i}) \right| \Big/ N_y \right) \tag{1}$$

where $R_{y,i}$ is the recruitment multiplier in year y for simulation *i* from the operating model, $\hat{R}_{y,i}$ is the estimated recruitment multiplier, N_y is the number of years of estimated recruitments. The metric is only calculated over the final 15 years of the estimation as the initial recruitment deviations can be expected to be incorrect because the assessment model is mis-specified (ie it assumes average recruitment before 1982, not so in the operating model).

The MMAE then gives an indication of how well in general the assessment model does at estimating individual year class strengths. For each simulation, the mean of the time series of absolute errors is calculated (rather than say, the median) as this is more prone to being influenced by low numbers of poorly estimated recruitments.

12.4 Results

In the data-rich case, there appears to be little difference in the MARE for the unfished spawning biomass (Table 12.3) with increasing numbers of tag groups. However, the MARE of current spawning biomass (and as a result current relative spawning biomass) decreases as the number of tag groups increases, suggesting improved performance when age structure in the tag releases is accounted for. Inspection of the values for the MRE however, indicate a positive bias in estimates of spawning biomass (most pronounced for current biomass levels) when there is only 1 tag group per year (irrespective of whether the age is fixed for all years or allowed to vary), and a negative biomass when the number of tag groups is increased to the maximum (‘lots’). There appears to be little difference in the performance when there are 3, 5, or 7 tag groups per year (Table 12.3 and Figure 12.2). A similar pattern is observed for the ability of the assessment models to estimate the trawl available biomass quantities (Figure 12.2), although the estimate of the available biomass prior to the tagging program (VB_{1995}, currently used as the reference point used to set TACs in the fishery) is positively biased (Table 12.3, ‘VB95’ column).

The patterns observed in the data-rich case are repeated for the 'realistic' case, although the magnitudes of the biases in the estimation are greater (Table 12.4 and Figure 12.3). When there is only 1 tag group per year (all released fish assigned the same age), the median relative errors for current spawning and available biomass in the realistic case are on the order of 20%, as is the negative bias in estimation of the current spawning biomass under the 'lots' scenario (Figure 12.3).

Clearly, assuming all released fish are of the same age is a poor choice when comparing performance to those scenarios that increased the number of tag groups. In the data-rich case, the 'lots' option appears to be the best choice for estimating current biomass levels, although the 3, 5, and 7 tag group scenarios seem to be better at estimating the unfished spawning biomass and pre-tagging available biomass (Figure 12.2). When moving to the realistic case however, which represents the data currently available for stock assessment at Aurora Trough, disaggregating the tag releases as much as possible ('lots') generally results in poorer performance than the 3, 5, or 7 tag group options (Figure 12.3). There is little difference in estimation performance among these scenarios.

For the 3, 5, or 7, tag group scenarios, there is a general tendency towards poorer estimation of current biomass levels (either spawning or available) than that for unfished or pre-tagging conditions. Even in the data-rich case, there is a positive bias in the estimates of current biomass (Figure 12.2, B_{2010} and VB_{2009}, and Table 12.3).

Additional age data could potentially be made available from currently un-aged otoliths collected from the Aurora Trough. In order to see how the annual sample size for the age data contributes to the differences in performance between the realistic and data-rich cases. Figure 12.4 and Figure 12.5 show how the relative errors of the estimates for the spawning biomass and available biomass quantities changes for the '5 tag groups' and 'lots' scenarios given annual sample sizes of 0, 20 (realistic case), 50, and 500 for the age data while keeping the numbers of releases and sample size for the lengths at the realistic levels. The results suggest that additional age data is responsible for the majority of the difference in performance between the realistic and data-rich cases.

Estimation of individual year classes appears unaffected by the tagging aggregation assumptions, with little change in the MMARE of recruitment by scenario. Unsurprisingly though, the MMARE is lower for the data-rich case than the realistic data case, indicating improved performance.

12.5 Discussion

The following points arise from the results which merit discussion:

- Assuming that all tag releases in a given year are of the same age ('fix' or '1') is a poor choice. Similarly, given the amount of data currently available from the Macquarie Island toothfish fishery, disaggregating the tag releases to the highest extent possible ('lots') should not be undertaken.

- Splitting the annual tag releases into a small number of groups, with ages based on the relative proportions in the length composition appears to be the best choice.

- Even for the 3, 5, and 7 tag group scenarios, there are positive biases in the estimation of both current spawning biomass and current vulnerable biomass levels. The bias in spawning biomass could be due to model mis-specification, with respect to whether

individual year classes are assumed to be at average levels or not. It should be noted that the bulk of the current spawning biomass will be made up of cohorts that were already outgrowing the available biomass at the onset of the fishery and there is likely low information content on the strength of these recruitments. That said, the bias in current spawning biomass appears to remain even when the years in which the age structure is in equilibrium are matched between the operating model and estimation model. That the results are unbiased in the data-rich case for the 'lots' scenario might indicate that assigning the wrong age to released fish (when the number of tag groups is small) creates a false signal regarding year class strengths in the tag recapture data. Biases in abundance estimates are known to result as a consequence of insufficient information to estimate recruitment strengths in integrated assessment models (Rick Methot and Ian taylor, NOAA Fisheries, Pers. Comm.). Estimates of current vulnerable biomass can be expected to be imprecise, as they will contain several year classes for which there is relatively little information, and also individuals from year classes where recruitment is not estimated at all due to the paucity of their expectation in the data. These latter phenomena should not however, result in the biases observed.

- The quantity of age data appears to be central to the improvement in performance associated with the shift from the 'realistic' to the 'data-rich' case. Currently, the only age data for Aurora Trough are limited to two years with >80 samples and much lower numbers for a handful of additional years. However, there remain a considerable number of otoliths collected from toothfish at Macquarie Island which remain unaged. The results presented here clearly demonstrate the value of ageing more of these samples in terms of obtaining more accurate assessment results.

- The results should be considered preliminary as they only consider the case where current spawning biomass is 50% unfished level (although this is around the level at which the biomass at Aurora Trough is thought to be) and for the most part, the assessment model is correct – i.e. mortality and growth parameters, steepness, etc. are assumed known. It may be of interest to determine whether the changes in performance associated with the disaggregation of tag releases into multiple age classes are also observed given some of these additional uncertainties.

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Table 12.1. Values for the parameters of the operating model not shown in Figure 12.1.

Parameter	Value
Biology	
M, natural mortality	0.13
weight-length ($w = a*L^b$)	
a	4.4E-09
b	3.14
Current stock status	
B_{2010} / B_0	0.5
Stock-Recruitment	
σ_R, std dev of LN(recruitments)	0.7
h, steepness	0.75
Tagging	
tag detection rate	1
tag mortality / loss rate	0
tag-recapture over-dispersion	0

Table 12.2. Annual sample size of length and age data and number of tags released per annum for the 'realistic' and 'perfect information' cases.

Data source	realistic	perfect information
length N_y	50	500
age N_y	20 (0,50,500)	500
tag release #'s		
1995	460	1,000
1996	474	1,000
1997	602	1,000
1998	597	1,000
1999	654	1,000
2000	352	1,000
2001	0	1,000
2002	492	1,000
2003	577	1,000
2004	530	1,000
2005	510	1,000
2006	446	1,000
2007	297	1,000
2008	589	1,000
2009	300	1,000

Table 12.3. MARE, MRE, and MADAM of the performance measures for the data-rich scenarios. Ideally, the values should be close to zero.

Scenario	B_0	B_{2010}/B_0	B_{2010}	VB_{1995}	VB_{2009}	VB_{09}/VB_{95}	Rec
				MARE			MMARE
fixed	0.10	0.16	0.21	0.07	0.28	0.20	0.14
1	0.10	0.16	0.21	0.07	0.28	0.19	0.14
3	0.10	0.13	0.16	0.04	0.12	0.14	0.14
5	0.10	0.12	0.14	0.04	0.11	0.13	0.14
7	0.12	0.13	0.14	0.04	0.11	0.13	0.14
lots	0.12	0.14	0.14	0.05	0.12	0.15	0.15
				MRE (bias)			
fixed	0.05	0.12	0.20	0.07	0.28	0.20	
1	0.04	0.12	0.19	0.06	0.28	0.19	
3	0.00	0.08	0.12	0.00	0.10	0.10	
5	-0.01	0.08	0.10	-0.01	0.08	0.10	
7	-0.01	0.09	0.09	-0.01	0.06	0.07	
lots	-0.08	0.02	-0.04	0.05	-0.03	-0.08	
				MADM (imprecision)			
fixed	0.11	0.14	0.18	0.04	0.15	0.20	
1	0.11	0.14	0.17	0.04	0.16	0.19	
3	0.10	0.13	0.16	0.04	0.12	0.16	
5	0.09	0.12	0.15	0.04	0.13	0.16	
7	0.11	0.13	0.16	0.03	0.11	0.13	
lots	0.10	0.15	0.14	0.02	0.10	0.12	

Table 12.4. MARE, MRE, and MADM of the performance measures for the realistic scenarios. Ideally, the values should be close to zero.

Scenario	B_0	B_{2010}/B_0	B_{2010}	VB_{1995}	VB_{2009}	VB_{09}/VB_{95}	Rec
				MARE			MMARE
fixed	0.09	0.16	0.22	0.16	0.25	0.11	0.24
1	0.10	0.17	0.21	0.15	0.24	0.10	0.24
3	0.11	0.15	0.18	0.06	0.11	0.08	0.26
5	0.10	0.13	0.14	0.04	0.08	0.08	0.23
7	0.10	0.13	0.14	0.04	0.08	0.10	0.25
lots	0.16	0.16	0.24	0.19	0.08	0.17	0.29
				MRE (bias)			
fixed	0.05	0.11	0.20	0.16	0.25	0.08	
1	0.04	0.10	0.18	0.15	0.24	0.07	
3	0.01	0.09	0.12	0.06	0.11	0.04	
5	0.02	0.08	0.11	0.04	0.08	0.03	
7	0.01	0.07	0.09	0.03	0.07	0.07	
lots	-0.15	-0.09	-0.24	0.19	0.05	-0.13	
				MADM (imprecision)			
fixed	0.10	0.12	0.14	0.04	0.14	0.13	
1	0.10	0.14	0.13	0.03	0.11	0.11	
3	0.11	0.12	0.14	0.05	0.09	0.09	
5	0.09	0.12	0.13	0.04	0.08	0.09	
7	0.09	0.11	0.13	0.05	0.09	0.10	
lots	0.09	0.18	0.14	0.05	0.08	0.07	

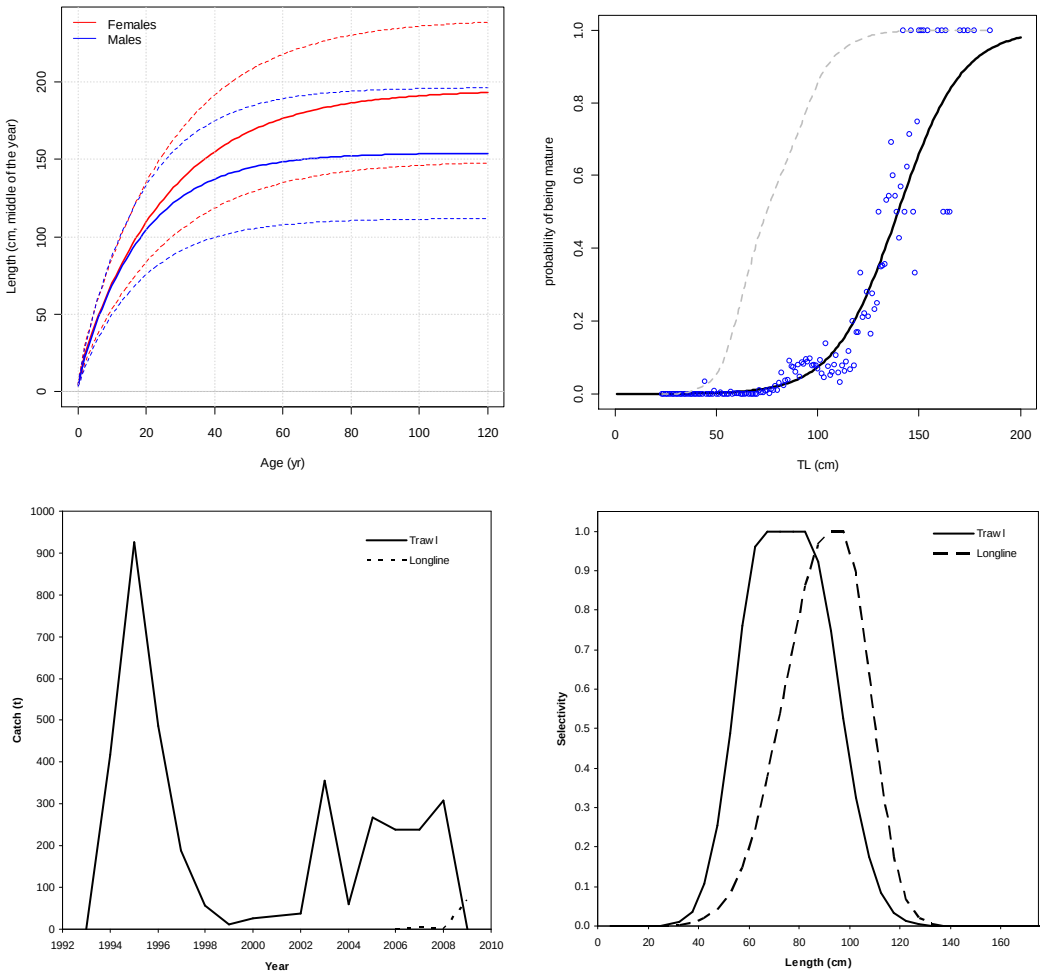

Figure 12.1. Growth curves (top-left), maturity ogive (top-right), catch history (bottom-left), and true selectivity at length patterns (bottom-right) used in the operating model. Values for the growth curve parameters are taken from Constable *et al*. (2001).

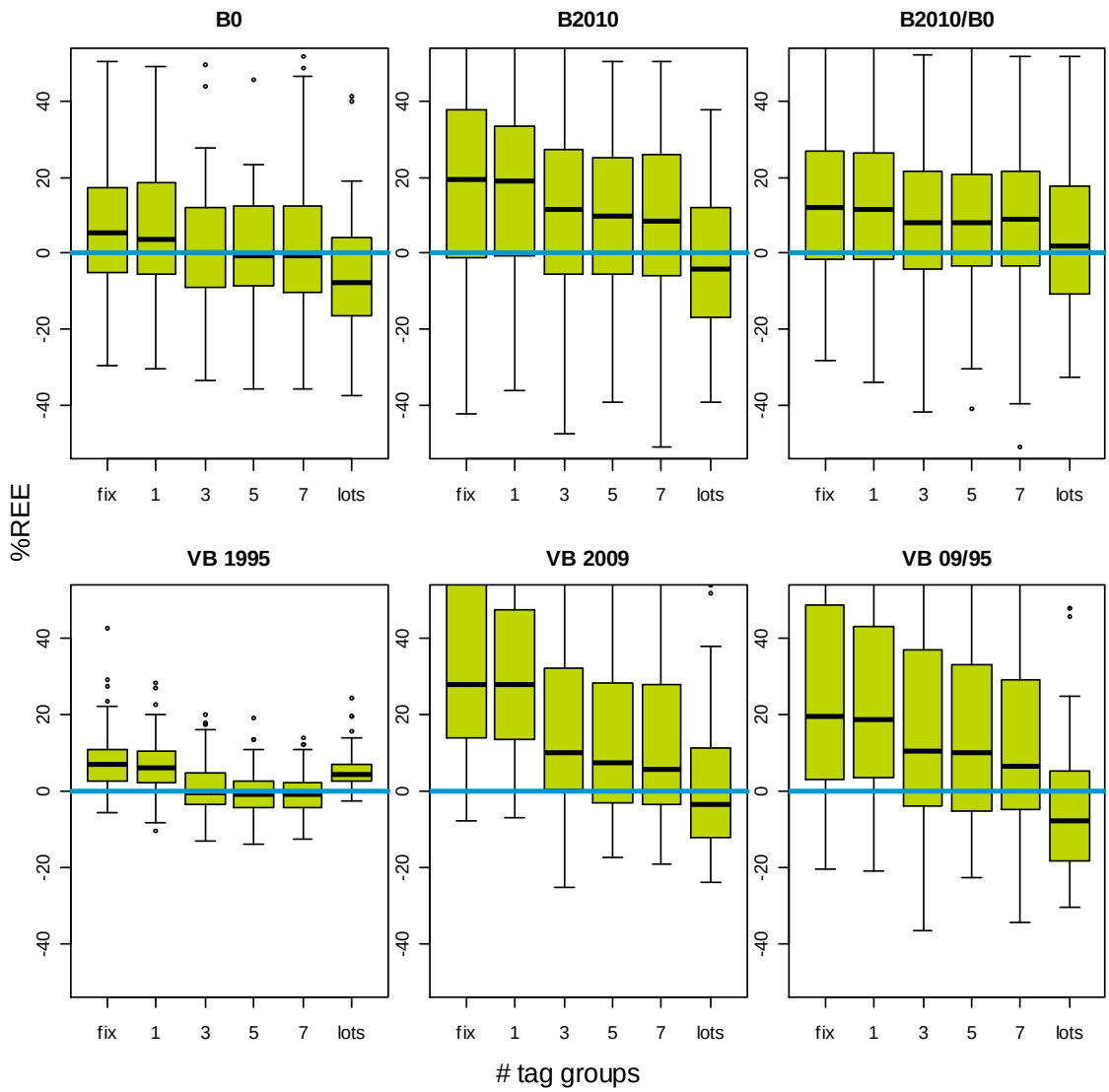

Figure 12.2. Distributions of %REE (the Relative Error of the Estimates) for spawning and trawl available biomass quantities for the data-rich scenarios.

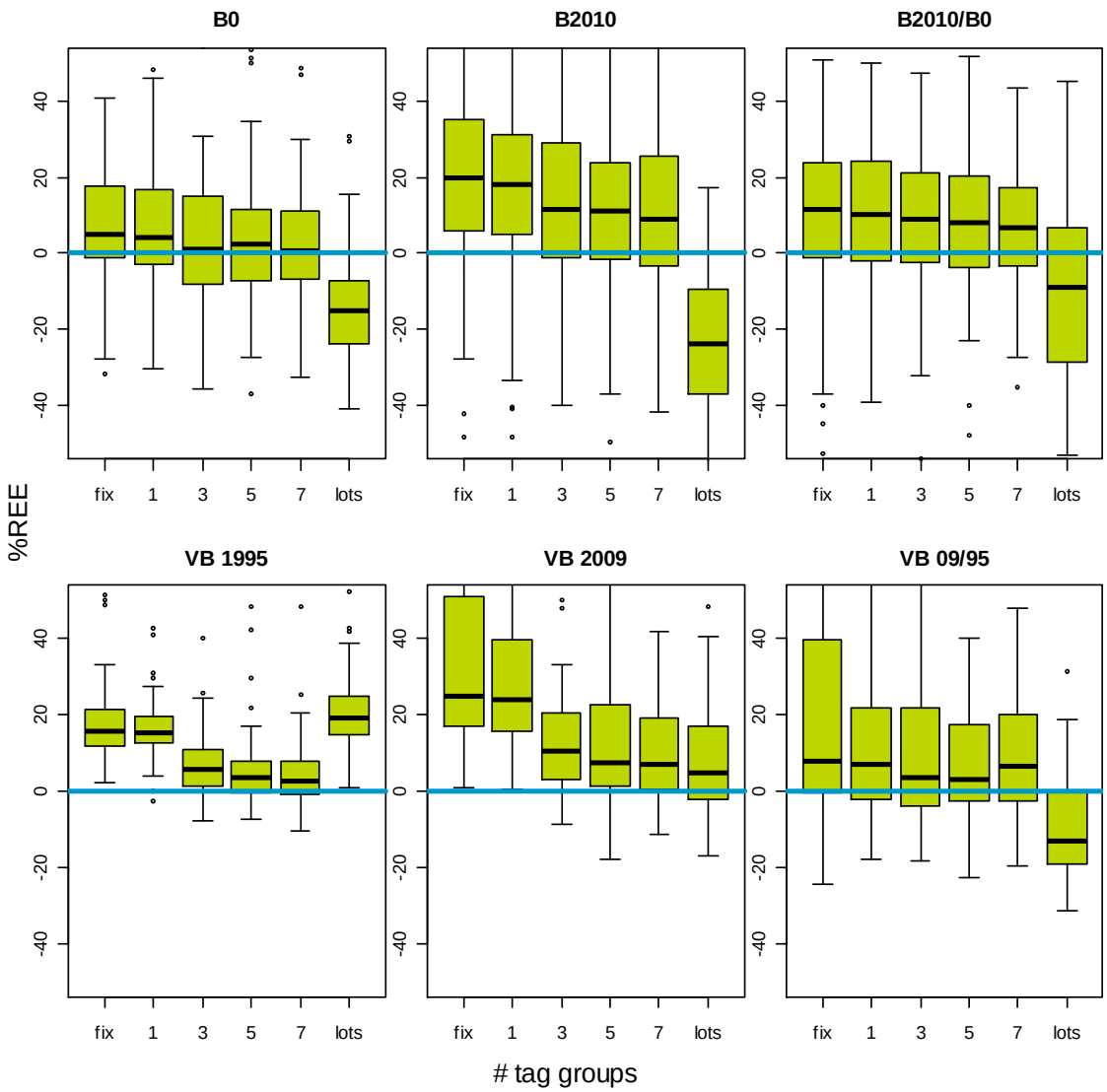

Figure 12.3. Distributions of %REE for spawning and trawl available biomass quantities for the realistic case (with age data).

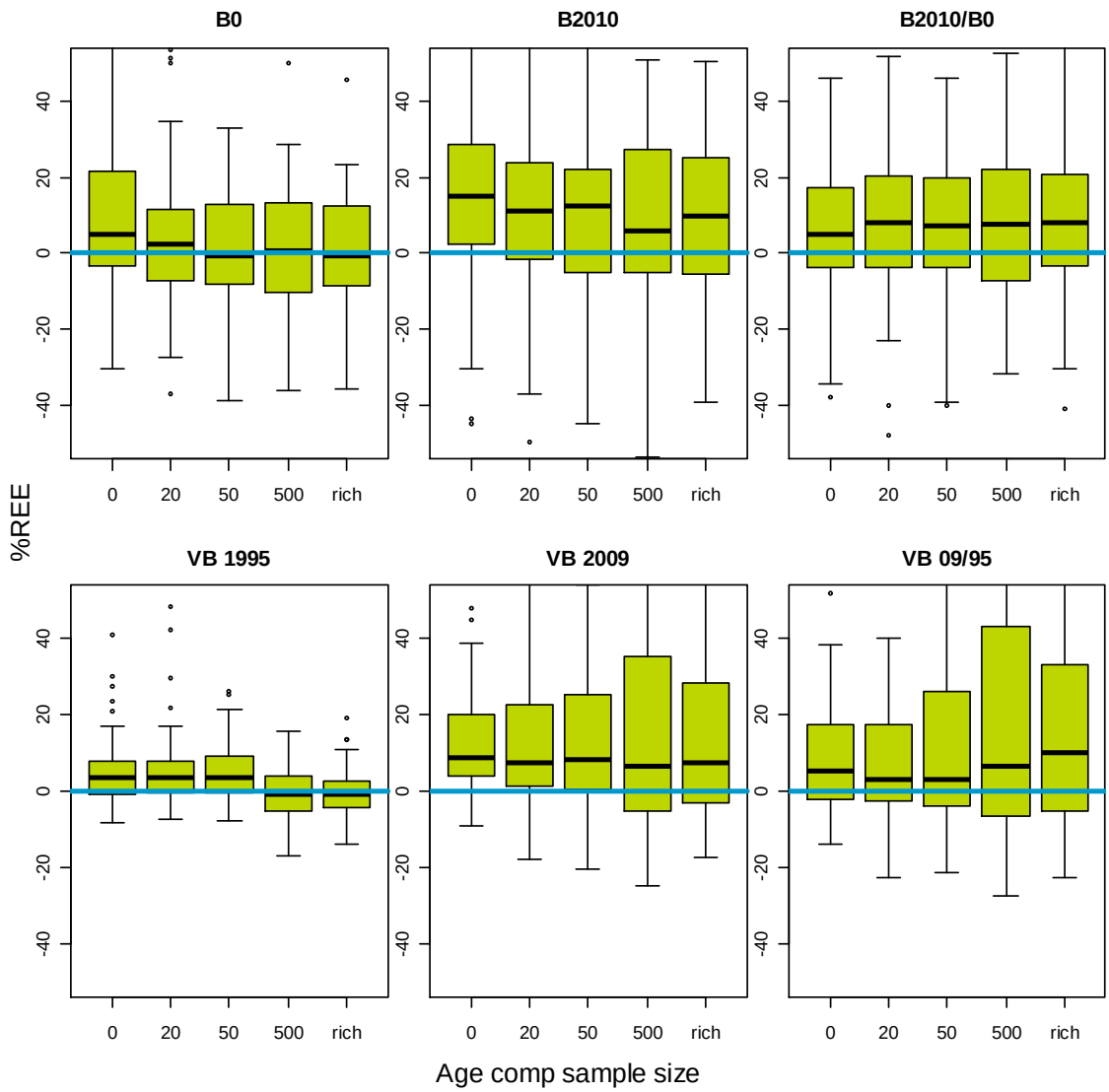

Figure 12.4. Distributions of %REE for spawning and trawl available biomass quantities given a range of annual sample sizes for the age data, for the scenario where there are 5 tag groups, and length comp sample size and tag release numbers are held at 'realistic' levels. 'rich' column shows the performance obtained when all data sources are at the data-rich levels.

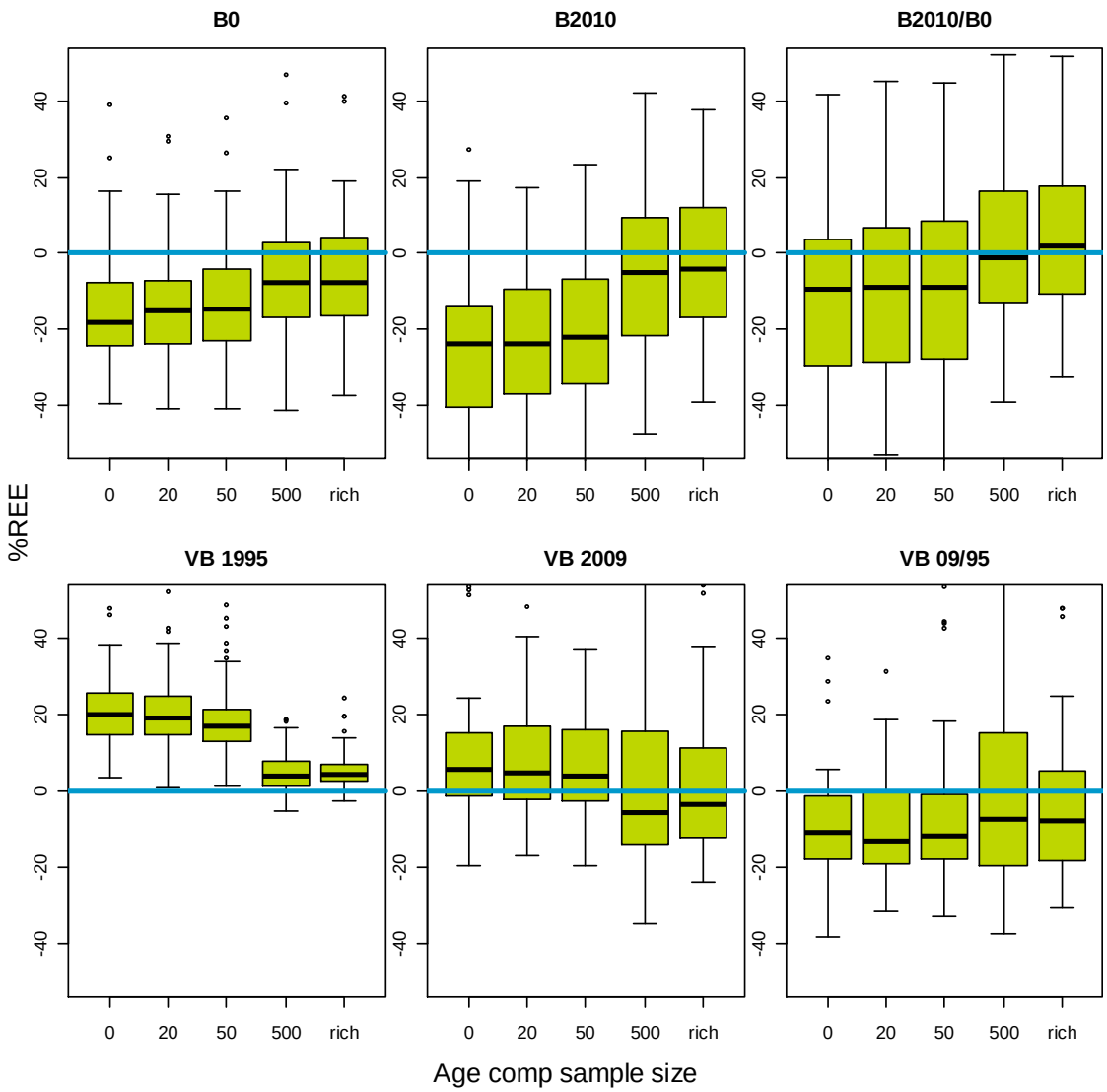

Figure 12.5. Distributions of %REE for spawning and trawl available biomass quantities given a range of annual sample sizes for the age data, for the scenario where there are 'lots' of tag groups, and length comp sample size and tag release numbers are held at 'realistic' levels.

13. UPDATE ON MSE PROGRESS FOR THE MACQUARIE ISLAND TOOTHFISH FISHERY[8]

Gavin Fay

13.1 Introduction

This chapter provides an outline of the modelling framework for the Management Strategy Evaluation (MSE) of the Macquarie Island toothfish fishery, with focus on the scope of scenarios tested and analysed.

Key questions addressed in the MSE work include:

- How does the SS assessment perform given uncertainties in spatial dynamics, movement, biology and mortality rates?
- How does the current harvest strategy perform in terms of meeting management objectives?
- How robust is the harvest strategy to these uncertainties given the available assessment method?
- How does the method of obtaining an abundance estimate and the spatial collection of data impact the harvest strategy?

The MSE approach undertaken consists of conditioning an operating model, which is used to represent truth in the simulations, to the available data from Macquarie Island given different hypotheses regarding population dynamics, and key uncertainties for toothfish biology and the fishery dynamics. This operating model is used to generate data akin to that actually available, which is used by an assessment model (implemented in Stock Synthesis, *e.g.* Methot 2007) to provide input to a harvest control rule used to determine future catch levels, which are fed back to the operating model for forward projection. Following a projection period of 35 years (timeline identified under the CCAMLR harvest strategy), performance measures are calculated from the simulations and used to compare performance of the assessment and harvest strategy with respect to management objectives among scenarios.

•Spatial complexity is being addressed via the different structural forms of the assessment model, by both estimating different selectivity patterns for the different areas fished by different gear types, and by explicit spatial structure within the assessment model. The models reflect those analyses presented to the SARAG in November 2009. A two-area model (northern and southern grounds), with movement between grounds estimated within the assessment model from the tag recapture data, appears sufficiently complex to capture the salient features of the fishery.

•Conditioning of the operating model for the MSE analyses is achieved by fitting Stock Synthesis to the data from the fishery given structural assumptions about spatial dynamics, and key biological parameters. This involves fitting the new stock assessment models and then capturing uncertainty in the values for the model parameters through Bayesian methods using

[8] Paper presented to SARAG on 29 November, 2010

Markov Chain Monte Carlo (MCMC) techniques. The set of plausible operating model scenarios was determined from the results of a workshop held in 2009.

13.2 Operating model

The operating model is based on the technical specifications described in Fay *et al.* (2009), with additional modifications, primarily to accommodate tagging, in order to reflect the dynamics at Macquarie Island. The model includes spatially explicit age structured population dynamics, and handles multiple gear types from fisheries operating in one or more areas. Conditioning of the operating model is achieved by fitting alternative model scenarios (which reflect hypotheses about spatial structure, and biological and fishery parameters) in Stock Synthesis to the available data from the trawl and longline fisheries. This conditioning is based on the model structures developed by Fay *et al*. (2009) and presented to SARAG in December 2009, with updating of the model fits based on additional data from the 2010 longline operations. The remainder of this section outlines the various scenarios considered in defining the specifications for the operating model.

13.2.1 Spatial / Fishery structure

Spatial structure according to the 2 area / 3 area hypotheses explored using SS in 2009 (effectively North/South). A single area model is not considered for the operating model as this scenario was unable to mimic the historical tag-recapture data.

The model assumes separate selectivity patterns for the following fisheries/fleets: Aurora Trough trawl, Northern Valley trawl, Aurora Trough longline, North Macquarie Ridge longline, Southern Macquarie Ridge longline. The selectivity is modelled as a dome-shaped function of length, although the selectivity of longline on the Macquarie ridge is modelled as being asymptotic (no decline in selectivity for the largest sizes).

The models estimate that allocation of recruits to the northern area is lower than that for the southern area (Aurora Trough). However, the distribution of recruits to area is somewhat uncertain, a feature captured by the model output and progressed to the simulations. The annual proportional allocation of recruits to areas is assumed to be constant over time.

13.2.2 Movement

There are limited data informing the models regarding movement among areas, as the number of tag recaptures from areas other than the area of release is low. Current estimates of movement rates among areas can be expected to be uncertain. The multiple area models estimate low rates of movement in both north and south directions in terms of the fraction of fish moving. Point estimates result in a proportion of fish that move from north to south that is estimated to be less than those moving south to north, despite a lack of recaptures in this direction. This is a result of the low intensity of fishing in the northern area compared to the south. As with the spatial allocation of recruits, uncertainty in the value for movement parameters from the estimation is included in the MSE simulations.

13.2.3 Growth

The recent additional age-at-length data from longlining operations at Macquarie has improved the ability to estimate growth within the assessment model, and so the values for the majority of

growth parameters are estimated from the data this way. However, there remains considerable uncertainty regarding the value for the maximum size of toothfish at Macquarie, with a large range of values being consistent with the data. Growth can be considered a key uncertainty for the fishery, as the values for length at age will ultimately determine the fishable biomass in the population, and hence the absolute value for sustainable catches. Operating model scenarios are conducted with several alternative fixed values for the true value for the maximum size parameter – based on the previous estimated growth curve (Constable *et al*., 2001, 195cm for females), and an independent estimate from tag recapture growth increment data (165 cm for females). Assumptions made in the assessment model will address the consequences of mis-specifying growth for the assessment and performance of the harvest strategy.

13.2.4 Natural mortality

The value for the rate of natural mortality is fixed when conditioning the operating model, at either 0.13 yr^{-1} or 0.1475 yr^{-1}, consistent with previous assessments for toothfish at Macquarie Island.

13.2.5 Maturity

Specification of maturity in the operating model is by length, and follows the maturity ogive used for previous assessments (*e.g.* Fay 2010a), and also an alternative based on the recent longline data, as suggested as a sensitivity in the 2010/11 Aurora Trough assessment (Fay 2010a).

13.2.6 Stock-recruitment relationship

The stock-recruit relationship is assumed to be stochastic surrounding a Beverton-Holt type relationship, with the value for future recruitments during the projection period being drawn from this curve with process error. The values for the recent historical recruits, and their uncertainty, are obtained from the fits to the current data set. There is little information in the available data to estimate the steepness parameter and the true value is fixed at alternative values (0.75, 0.5, 0.9) in the operating model, with key scenarios looking at the effect of mis-specifying the value for this parameter.

13.2.7 Tagging parameters

Estimates for the annual reporting rates are used to condition the population dynamics model, and the distribution of these rates is used in the operating model when generating the tagging data.

Overdispersion in the recaptures of tagged fish are assumed to follow the distribution of those obtained from fitting the models to the data from Macquarie, and separate values are obtained for fish released in northern and southern areas. Overdispersion reflects clumpiness in the way in which fish are recaptured and is therefore a departure froim assuming the recaptures are purely random. Such uncertainty can be estimated from the data and is therefore also included in the simulation work.

A key feature of the tagging component of Stock Synthesis is the assignment of ages to tag releases when fitting the model, with model output being sensitive to the method chosen for assigning these ages. Conditioning of the operating model to determine the true dynamics is

based on scenarios where annual tag releases were split into five age classes. This scenario was shown by Fay (2010b) to provide the most robust estimates of biomass. The data collection scenarios described below allow for the exploration of various alternatives

13.3 Assessment model

The assessment models tested are, in principle, much the same as the operating models, although in general are somewhat simpler. Assessment models are implemented in Stock Synthesis, using the data generated from the operating models.

The performance of the assessment models will be tested with respect to mis-specification of:

- Assessment model spatial structure,
- Natural mortality rate, steepness, maturity,
- Ages assigned to tag releases.

For each operating model, the stock assessment models either consider:

- a single assessment using 1 area (i.e. assume a single homogeneous mixed stock),
- a single assessment that includes spatial complexity by defining two areas (north and south), or
- two separate stock assessments by area (north and south).

Conducting multiple assessments is another alternative that might be considered for application of harvest strategies at Macquarie. Such an approach would have an underlying assumption of the different areas holding separate stocks, or at least significantly separate populations.

The impact of alternative data collection schemes on assessment and harvest strategy performance is an important component of the MSE project. This includes both the quantities of data (*e.g.* the sample size for length data, and the tagging rate), and where the information is collected from. The latter is related to how the catch is distributed spatially within the fishery following determination of a TAC under application of the harvest strategy.

The data collection specifications will assume that the historical data is as per that available, sample sizes for future length and age-at-length data as per the recent longline data, and tagging rates at the current rate of tagging.

The subsequent project will address the relative benefits or otherwise of alternative data streams and levels of data quality, including different tagging rates, an index of abundance (*e.g.* from standardised CPUE), and higher sample sizes for the length and age compositions. Previous work already suggests that the ageing data is important in reducing bias in the assessments and such data should continue to be collected.

In all cases, the assessment models will assume that the effective sample sizes (extent of observation error) for the different data sources are known correctly. That is, the value for the

sample size used to generate the data is used in the assessment model (in practice of course, these are not known, and labor-intensive methods are often employed during assessment procedures to obtain these values).

General improvement in assessment performance is considered after 3, 5, 10 years, in terms of examining the short-term benefits to data collection, specifically with respect to the ability of the assessment to estimate biomass, recruitments, growth, and other parameters (or to perhaps provide an indication that a revision to the assumed values for a particular parameter is necessary).

13.4 Harvest strategies

A discussion of the range of harvest strategies to be tested in the MSE was held at SARAG in November 2009. SARAG agreed that the MSE should test performance of strategies with respect to the objectives of the CCAMLR decision rule. Following adoption by the SARAG of the CCAMLR control rule for the purposes of setting the TAC in the Aurora Trough for the 2010/11 season, the harvest strategies tested during the MSE analyses will be limited to an approximation of the CCAMLR control rule, given the different assessment methods and spatial TAC distribution scenarios. The performance of alternative harvest control rules may be addressed in the subsequent project.

The scenarios are guided by industry advice on intent. That is, all future catches will be from longline, and there will be a maximum annual catch of 150t from the Aurora Trough.

The analyses will explore the impact of the spatial distribution of future catches on the performance of the assessment and harvest strategy. The spatial distribution of catch not only determines the length and age composition of the catch, but also affects where tagged fish are released. The scenarios will explore the following methods of distributing the future catches along the Ridge and in the Aurora Trough, given the limits imposed by the harvest strategy, in order to compare how performance measures such as total catch over the projection period, and the relative risk of not meeting management objectives change, in addition to the impact on the precision of future assessments:

- In proportion to available biomass,
- Equal splitting between areas,
- all the catch (minus that from the Aurora Trough) taken in the southern area one year, all in the northern the next, etc.

13.5 Performance measures

Performance of the assessment procedures and application of the harvest strategy is evaluated by calculating a set of performance measures at the end of the 35 year projection period:

1. The median (over simulations) spawning stock status at the end of the projection period (final spawning biomass as a fraction of unfished spawning biomass, B_0).

2. The probability of the spawning biomass being below the limit reference point of 20% unfished levels (B_{20}) at the end of the projection period.

3. The probability of the spawning biomass going below the limit reference point (B_{20}) at some point during the projection period.

4. The total catch over the projection period.

5. The variability of the annual catches during the projection period.

6. The number of years for which the TAC is less than some threshold value which would likely result in non-profitable fishing operations.

Performance measures 1-3 relate to the effect of implementing the harvest strategy on spawning biomass, and relate to the management objectives. Measures 4-6 provide information regarding the catch performance of the strategy.

As mentioned above, the assessment performance is also addressed by looking at how the overall bias and precision in estimates of quantities such as biomass, relative biomass, and recruitment, changes over time following implementation of the harvest strategy and collection of further data from the developing areas of the fishery.

13.6 References

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14. MANAGEMENT STRATEGY EVALUATION FOR THE MACQUARIE ISLAND PATAGONIAN TOOTHFISH FISHERY

Gavin Fay

14.1 Introduction

This chapter describes the application of Management Strategy Evaluation (MSE) to the fishery for Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island. A spatially explicit age- and length- structured population dynamics model is used as an operating model to generate data akin to that available from the Macquarie Island fishery, including data from the tag-recapture program, and length and age composition data. Under the MSE framework, each realisation of these data are utilised by a stock assessment model to obtain estimates of current stock status, a harvest strategy is applied to obtain the value for the following year's catch, and the operating model dynamics are updated given this catch. This data generation / assessment / operating model update cycle is continued for a period of 35 years, with performance measures across simulations calculated at the end of the projection period.

Conditioning of the operating model for the MSE analyses is achieved by fitting Stock Synthesis (Methot, 2007) to the data from the fishery given a structural assumption about spatial dynamics, and values for some key biological parameters. This involves fitting the 2011 base-case stock assessment model and then capturing uncertainty in the values for the model parameters through Bayesian methods using Markov Chain Monte Carlo (MCMC) techniques.

The work presented here considers one structural version of the operating model, consistent with that used as the base-case for the stock assessment model. The performance of alternative harvest strategies are evaluated, where the harvest strategies differ (i) in the choice of harvest control rule applied, (ii) in the way future catches (and therefore tags) are allocated spatially, and (iii) in the quantities of data obtained for inclusion into the stock assessment procedures.

Key questions addressed include:

- How does the stock assessment perform given uncertainties in spatial dynamics, movement, biology and mortality rates?
- How does the current harvest strategy perform in terms of meeting management objectives?
- How robust is the harvest strategy to these uncertainties given the available assessment method?
- How does the spatial collection of data impact the harvest strategy?

14.2 Methods

The simulation framework consists of: (i) selecting a scenario to be tested, (ii) choosing an assessment method and parameters for a harvest strategy control rule (including specifications of how future data will be collected), (iii) obtaining a set of parameters for the operating model, (iv) projection of the dynamics of the operating model over a historical period (1900/01 – 2010/11), (v) generation of data (including tag releases and recaptures), (vi) stock assessment using the chosen method, (vii) application of the selected harvest strategy to obtain the value for the following year's catch, and (viii) an update of the operating model dynamics for the following year given this new catch level. This assessment/update cycle is repeated each year for 35 years, and the 35 year projection period is repeated 100 times for each scenario, with each of the 100 simulations obtaining an individual realisation from the operating model (see below), and then further differing due to observation error and process error (annual recruits) in the projection period. Performance statistics are obtained at the end of the projection period, and these are summarised across simulations to obtain a set of performance measures for each scenario.

14.2.1 Operating model

The operating model is based on the technical specifications described in Fay *et al.* (2011a), with additional modifications, primarily to accommodate tagging, in order to reflect the dynamics of the fishery at Macquarie Island. The model includes spatially-explicit age-structured population dynamics, and handles multiple gear types from fisheries operating in one or more areas. Conditioning of the operating model is achieved by fitting alternative model scenarios (which reflect hypotheses about spatial structure, and biological and fishery parameters) in Stock Synthesis to the available data from the trawl and longline fisheries. This conditioning is based on the base-case model structure and parameter scenario from the 2011 stock assessment (Fay, 2011; Fay *et al.*, 2011b), used to determine the TAC for the 2011/12 season. Table 14.1 provides the details of the specifications for the operating model.

The operating model assumes that there is spatial structure in the population by modelling two areas (northern and southern). A single area model is not considered for the operating model as this scenario was unable to mimic the historical tag-recapture data. The operating model assumes separate selectivity patterns for the following fisheries/fleets:

1. Aurora Trough trawl (ATT)
2. Northern Valley trawl (NVT)
3. Aurora Trough longline (ATLL)
4. North Macquarie Ridge longline (NMR)
5. Southern Macquarie Ridge longline (SMR).

As per the 2011 base-case assessment, selectivity for the ATT, ATLL, and NVT fleets is modelled as a dome-shaped function of length, whereas the selectivity of longline on the

Macquarie ridge (NMR and SMR) is modelled as being asymptotic (no decline in selectivity for large fish).

Allocation of the annual recruits to the two areas is achieved by a fixed proportion over time. Uncertainty in the value for this proportion is captured by the samples from the posterior distribution. Similarly, uncertainty in the values for the magnitude of movement rates between areas, growth curve parameters, selectivity patterns, as well as the magnitude of recruitment events in the period from 1985-2003, are characterised using the posterior sample obtained from the MCMC draws from the 2011 base-case assessment. The values for parameters fixed for all realisations of the operating model are detailed in Table 14.1.

Data are generated from the operating model according to the observation model described in Fay *et al.* (2009) and Fay *et al.* (2011a), and the values for the effective sample sizes are given in Table 14.1. The operating model is conditioned on time-varying tag reporting rate (Fay 2011), however the operating model generates tag recapture data assuming a time-invariant 100% reporting rate. Tag loss is also assumed to be negligible. While these assumptions are fairly simplistic assumptions about the tagging process, they more easily allow for comparison of model performance among scenarios. Similarly, overdispersion in the recaptures of tagged fish are assumed to follow the distribution of those obtained in the 2011 stock assessment, and separate values are used for fish released in northern and southern areas. Overdispersion reflects clumpiness in the way in which fish are recaptured and is therefore a departure from assuming the recaptures are purely random. Uncertainty in the true values for these parameters is again included in the operating model based on the posterior sample.

14.2.2 Assessment model

Assessment models are implemented in Stock Synthesis, using the data generated from the operating models. In the analyses presented in this paper, the general structure of the assessment model is aligned with that of the operating model (i.e. the 2011 stock assessment), with some simplifications. Further work will explore the consequences of model mis-specification when applying the assessment models. Key features of the assessment model include:

- Unfished equilibrium age structure in 1975,
- A fixed assumed natural mortality rate of $0.13yr^{-1}$,
- Assumed length at 50% maturity of 139cm,
- Fixed value for female L_∞ of 165cm,
- Estimation of remaining growth curve parameters,
- Recruitment deviations estimated from 1985 onwards, with the last year class strength estimated being that seven years prior to the last year of data,
- Logistic selectivity for the NMR and SMR fleets, dome-shaped selectivity for remaining fleets,

- Assumption of 100% tag reporting rate,
- Assume no tag loss or tag mortality,
- Assignment of five tag release groups for each year and area, all tagged fish in each tag group are assumed to be of the same age,
- Estimated overdispersion parameters for the tag recaptures by release area,
- Length and age-composition data are assumed to be distributed according to a Multinomial with an assumed effective sample size (annual of 100 for lengths, 50 for ages).

The assessment model therefore differs from the operating model in the year assumed for equilibrium age structure, assumption of average recruitment for the years 1975-1984 and the most recent years of data, and in the ages assumed for the tag releases (the operating model assumes that fish are tagged according to the age structure of the catch in the year of release), in addition to the effects of sampling error on the data.

Several scenarios (Table 14.2) are tested in which the quantities of data available to the assessment models during the projection period are varied. These include:

- Alternative future tagging rates of 2 (base), 1, and 3 tags per tonne of the TAC,
- Either 4 (base) or 10 years of historical age data, reflecting the current situation where there remain otoliths that have been collected from the fishery but that are un-aged.

The data scenarios also include information on where the data were collected. This is related to how future catches are distributed spatially within the fishery following determination of a TAC under application of the harvest strategy, and are discussed below.

14.2.3 Harvest Strategies

Following adoption by the SARAG of the CCAMLR control rule for the purposes of setting the TAC in the Aurora Trough for the 2010/11 season (and also spatially for 2011/12), harvest strategies tested during the MSE analyses are limited to an approximation of the CCAMLR control rule, given alternative data and spatial TAC distribution scenarios. The results of following an F50 strategy (constant fishing mortality rate at that estimated to result on average in a spawning biomass 50% of unfished levels) are briefly discussed. The specifications for the harvest strategy scenarios are given in Table 14.2.

The scenarios are guided by industry advice on the allocation of catch obtained from the Aurora Trough. All future catch levels (post 2010/11) in the simulations assume that there will be a maximum annual catch of 150t from the Aurora Trough, and that, should the total TAC be lower than 150t, the catch will be taken from the Aurora Trough.

The analyses explore the impact of the spatial distribution of future catches on the performance of the assessment and harvest strategy. The spatial distribution of catch not only determines the

length and age composition of the catch, but also affects where tagged fish are released. The scenarios explore the following allocations of future catches along the Ridge and in the Aurora Trough, given the limits imposed by the harvest strategy:

- 70% of the Ridge catches from the Southern area, 30% from the north,
- 50:50 allocation of the TAC (minus that from the Aurora Trough) by area for the Ridge.

Approximation to the CCAMLR control rule is required in the MSE context, as application of the rule requires the calculation of probability-based reference points not achievable from point estimates following maximisation of the likelihood function during estimation. In reality, this would be achieved by obtaining a sample from the posterior distribution using MCMC methods. However, such an approach is time-intensive and therefore prohibitive in a simulation framework whereby 35 assessments need to be conducted per projection. The approximation to the CCAMLR control rule uses the estimated variance-covariance matrix of the model parameters to obtain 100 samples from the posterior assuming a multivariate normal. The parameter values from these samples from the posterior are fed back into the assessment model in order to implement projections under alternative future constant catches (given the spatial allocation methods) in order to find the largest catch which satisfies the following:

- The median spawning biomass after a 35 year projection is at least 50% of the estimated unfished level.
- The probability that the spawning biomass drops below 20% of unfished levels over a 35 year projection period is less than 0.1.

Note that the 35 year projection period referred to here is that estimated from the end of the current year's assessment, and is not the same as the 35 year projection period of the operating model used to calculate performance measures (i.e. the MSE looks at performance over the period 2011-2046, whereas an assessment conducted in 2030 [during the simulations] would use a projection period of 2031-2066 to calculate the TAC for 2031).

Comparison is made with the CCAMLR rule to an F50 control rule that calculates catches for the following year by applying a fixed fishing mortality rate (that estimated to result in 50% unfished spawning biomass at equilibrium) to the current estimated age structure. This control rule requires an assumption of the relative F pattern among fleets for calculation of the reference fishing mortality rate. The analyses shown assume either equal F's among active fleets, or a relative F pattern of 1 (ATLL): 0.1 (NMR) : 2 (SMR). The latter pattern was obtained by projecting the 2011 base case stock assessment under different patterns until the average catches equalled 150t from ATLL, and a 70:30 SMR:NMR split for the remainder. While not perfect, this is more consistent with the way in which future catches are allocated, and is perhaps more in line with that discussed for the CCAMLR control rule above. Further work will be needed to address how the assumed F pattern for calculation of reference points influences results. The F50 control rule is tested because it is more rapidly implemented within the simulation framework as it does not rely on estimates of the uncertainty in stock status and so the variance-covariance matrix of the model parameters does not need to be obtained. As a result, the relative impact of different scenarios can be evaluated more quickly.

14.2.4 Performance measures

Performance of the assessment procedures and application of the harvest strategy is evaluated by calculating a set of performance measures at the end of the 35 year projection period:

1. The median (over simulations) spawning stock status at the end of the projection period (final spawning biomass as a fraction of unfished spawning biomass, B_0),

2. The standard deviation of the final relative spawning stock status,

3. The probability of the spawning biomass going below the limit reference point (B_0) at some point during the projection period,

4. The median (over simulations) of the average of the annual catches over the projection period,

5. The median (over simulations) of the CV for the annual catches during the projection period.

Performance measures 1-3 relate to the effect of implementing the harvest strategy on spawning biomass, and relate to the management objectives. Measures 4 and 5 provide information regarding the catch performance of the strategy.

As mentioned above, the assessment performance is also addressed by looking at how the overall bias and precision in estimates of quantities such as biomass, relative biomass, and recruitment, changes over time following implementation of the harvest strategy and collection of further data from the developing areas of the fishery.

14.3 Results and Discussion

The values for the performance measures obtained from the 35 year projection period for each scenario are presented in Table 14.3. Under the base-case scenario (Scenario #1, CCAMLR control rule, 70:30 SMR:NMR catch allocation, future tag rate of 2 tags per tonne), the harvest strategy satisfies the CCAMLR objectives, with median spawning depletion of 50% B0 and a very low (non-existent) probability of dropping below 20% of unfished spawning biomass over the projection (Table 14.3). Scenario #2 shows the impact that the spatial allocation of catches has on the results, with the stock not being maintained above 50% B0 and higher average annual catch when the allocation of catches in the harvest strategy is 50:50 among the NMR and SMR longline fleets.

Changing the future tagging rate impacts performance by resulting in lower (and more variable) average annual catch when the tag rate is decreased to one tag per tonne (Table 14.3, scenario 3), with slightly higher average annual catches when the tag rate is increased from two to three tags per tonne (Table 14.3, scenario 4). Spawning stock biomass levels are maintained at or just above target levels however, demonstrating that the harvest strategy is responding appropriately to the increase in uncertainty of estimation when the tagging rate is reduced.

The outcomes of the F50 rule appear considerably more conservative than the application of the approximated CCAMLR control rule, with consistently higher values for the final spawning stock status, and lower average annual catches given the same scenario under the CCAMLR rule (Table 14.3). Higher average catches and lower spawning stock size are obtained when the F pattern assumed to calculate the reference fishing mortality rate and the TAC is more in line with the way in which catches are actually allocated (Table 14.3, scenario 11). However, when the CCAMLR is used but more data are available to the estimator, the final stock depletion is higher than under the base-case scenario, with associated lower catches.

An inspection of the median %REE of the estimates of final year relative spawning biomass in years 1, 5, 10, and 35 of the projection (Table 14.3, last 4 columns) reveals a progressive negative bias in the stock assessments as the simulations progress. For example, under the base-case scenario, the assessment is unbiased in estimating final year stock depletion at the start of the projection, but shows a median percent error of -25% in the final year's stock assessment, after many more years of data have become available to the estimator (Table 14.3, scenario #1). The assessment model is therefore estimating the stock to be more depleted than it is, most likely explaining the failure of the F50 rule to achieve a median spawning biomass 50% of unfished. The magnitude in the bias appears reduced for those scenarios where the future Macquarie Ridge catches are allocated equally among areas (Table 14.3, scenarios #2 and #7), as opposed to 70:30 SMR:NMR. This suggests that how the data are collected from the fishery is important in correctly determining the dynamics. Increasing exploitation rate in the southern area under the 70:30 allocation is coincident with increasing bias in the estimation of parameters determining movement rates and fraction of recruits allocated by area, suggesting that tags might be removed from the population at a rate too high to properly observe the spatial dynamics. Additional analyses that considered the population dynamics of the tagged population in the operating model as being discrete (versus continuous, as treated in the base scenarios, and in the assessment models) resulted in very different performance for the F50 control rule (Table 14.4), supporting the results of Fay (2010a) that mis-specifying the age structure of the tag releases can appreciably impact assessment model performance. The increasing bias in assessment with increasing length of the data stream warrants further exploration. Clearly, including the uncertainty in the estimate of stock status when determining the management action (as in the CCAMLR rule), mitigates the bias somewhat, as the CCAMLR rule scenarios generally appear to result in higher catches while still (broadly) satisfying management objectives. However, previous comparisons of the approximation to the CCAMLR rule with the actual values from the true posterior suggested an over-estimation of the CCAMLR catch level as a result of assuming multivariate normally distributed posterior distribution (Fay, 2010b).

The results of the MSE analyses demonstrate that the currently applied control rule in the Macquarie Island toothfish fishery can satisfy management objectives in terms of maintaining spawning biomass at or above target levels, and that the risk of dropping below limit reference levels under such a strategy is low. The future tagging rate has an impact on results, with slightly lower average catches when the tagging rate is reduced from two to one tag per tonne. Additional analyses will evaluate the performance of these harvest strategies when the assessment model is mis-specified, such as whether the assumed values for natural mortality, steepness, and maturity are incorrect. The spatial allocation of the TAC also appears to impact the performance of the harvest strategy, with equal allocation of catch to the northern and

southern areas resulting in higher catches, lower final relative spawning biomass, and also less biased estimates of relative spawning biomass toward the end of the time series.

14.4 Acknowledgements

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Table 14.1. Specifications and parameter values of the operating model.

Specification	**Description**	**Parameter value**
Number of areas	2 (North and South)	
Number of fleets	5	Northern area: Northern Valleys trawl (NV), Northern Macquarie Ridge Longline (NMR) Southern area: Aurora Trough Trawl (ATT), Aurora Trough Longline (ATL), Southern Macquarie Ridge Longline (SMR).
Area-specifc recruitment allocation	Fixed proportion over time	Estimated
Movement between regions	Fixed proportion by age over time. 2 movement parameters: one for north-south movement, one for south-north movement.	Estimated
rate of natural mortality, *M*	Constant over age, time-invariant.	0.13 yr^{-1}
Maturity	Maturity at length governed by logistic pattern, time-invariant. Length at 50% mature Length at 95% mature	 139.5cm 186 cm
Growth	Follows Von Bertalanffy Sex-specific growth curves, time-invariant. CV of length at age constant over age.	Female L_∞ fixed at 165cm. Remaining parameters estimated.
Weight-at-length	$W = aL^b$ a b	 4.4E-06 3.14
Steepness of stock-recruitment relationship, *h*	time-invariant	0.75

Specification	**Description**	**Parameter value**
Standard deviation of log-recruitment residuals, σ_R	Time-invariant	0.7
Recruitment residuals	Log-normally distributed (mean = 0, standard deviation σ_R)	1985-2003 estimated 1900-84, 2004+ stochastic
Selectivity	Length-specific by fleet. NVT, ATT, ATLL: dome-shaped. NMR, SMR: asymptotic	Estimated
Tag reporting rate		100%
Tag loss rates		0
Tag releases	1995-2010 release numbers as per historical. 2011+ tagging rate (per t) Five tag release groups assigned by year and area of release. Ages of tag releases assigned according to length composition for that area and year.	 2, (1), (3) Tag release age according to an assumed growth curve (Constable *et al.*, 2001).
Tag recaptures	Number of tag recaptures by true release negative binomially distributed. Over-dispersion in tag recapture numbers modelled as area-specific (by release). Multinomial allocation of tag recaptures to fleet and area.	Over-dispersion estimated
Length composition data	Available for all years of fishery Annual effective sample size	 100
Age composition data	Number of years data available in 2010/11. Annual effective sample size	4 (10) 50

Table 14.2. Specifications for the harvest strategies and data collection schemes.

Scenario #	Control rule	Maximum AT longline catch	SMR:NMR catch allocation	Future tagging rate (per tonne)	Number of years of historical age data
1	CCAMLR	150	70:30	2	4
2	CCAMLR	150	50:50	2	4
3	CCAMLR	150	70:30	1	4
4	CCAMLR	150	70:30	3	4
5	CCAMLR	150	70:30	2	10
6	F50	150	70:30	2	4
7	F50	150	50:50	2	4
8	F50	150	70:30	1	4
9	F50	150	70:30	3	4
10	F50	150	70:30	2	8
11	F50 (Falloc 1:0.1:2)	150	70:30	2	4

Table 14.3. Values for the performance measures for the scenarios.

#	Control rule	SMR:NMR catch allocation	Tag rate	#yrs age data	# sims	Median final depl.	Std. dev final depl,	P(B/B0)< 0.2	Median average annual catch	Median CV annual catch	Median %REE BFinal/B0 2011	Median %REE BFinal/B0 2016	Median %REE BFinal/B0 2026	Median %REE BFinal/B0 2046
1	CCAMLR	70:30	2	4	86	0.49	0.087	0	541.3	0.17	-0.02	-0.06	-0.11	-0.26
2	CCAMLR	50:50	2	4	100	0.44	0.086	0.01	571.3	0.14	-0.02	-0.05	-0.06	-0.18
3	CCAMLR	70:30	1	4	70	0.53	0.11	0.014	523.8	0.21	-0.04	-0.07	-0.14	-0.31
4	CCAMLR	70:30	3	4	31	0.48	0.087	0	566.2	0.18	-0.07	-0.11	-0.14	-0.28
5	CCAMLR	70:30	2	10	19	0.54	0.11	0	529.9	0.12	0.07	-0.02	-0.05	-0.26
6	F50	70:30	2	4	72	0.64	0.089	0	351.1	0.21	-0.01	-0.04	-0.07	-0.18
7	F50	50:50	2	4	97	0.62	0.089	0	399.2	0.18	0.01	-0.03	-0.04	-0.12
8	F50	70:30	1	4	92	0.67	0.099	0	358.8	0.22	-0.02	-0.05	-0.08	-0.20
9	F50	70:30	3	4	97	0.65	0.096	0	374.4	0.20	-0.01	-0.04	-0.08	-0.16
10	F50	70:30	2	8	83	0.65	0.095	0	367.1	0.20	0.00	-0.04	-0.07	-0.19
11	F50 (Falloc 1:0.1:2)	70:30	2	4	86	0.63	0.083	0	408.8	0.31	-0.01	-0.06	-0.08	-0.20

Table 14.4. Values for the performance measures for the F50 scenarios when the operating model tagging population dynamics are modelled as being discrete.

#	Control rule	SMR:NMR catch allocation	Tag rate	#yrs age data	# sims	Median final depl.	Std. dev final depl,	P(B/B0)< 0.2	Median average annual catch	Median CV annual catch	Median %REE BFinal/B0 2011	Median %REE BFinal/B0 2016	Median %REE BFinal/B0 2026	Median %REE BFinal/B0 2046
1	F50	70:30	2	4	95	0.47	0.061	0	563.6	0.24	0.09	0.12	0.09	0.04
2	F50	50:50	2	4	95	0.5	0.072	0	532.4	0.22	0.09	0.12	0.13	0.03
3	F50	70:30	1	4	94	0.56	0.076	0	496.8	0.27	0.09	0.12	0.10	-0.05
4	F50	70:30	3	4	97	0.36	0.12	0.1	670.4	0.22	0.09	0.12	0.12	0.18
5	F50	70:30	2	10	95	0.5	0.072	0	532.4	0.22	0.09	0.12	0.13	0.03
6	F50 (Falloc 1:0.1:2)	70:30	2	4	98	0.48	0.059	0	545.4	0.24	0.10	0.13	0.09	0.03

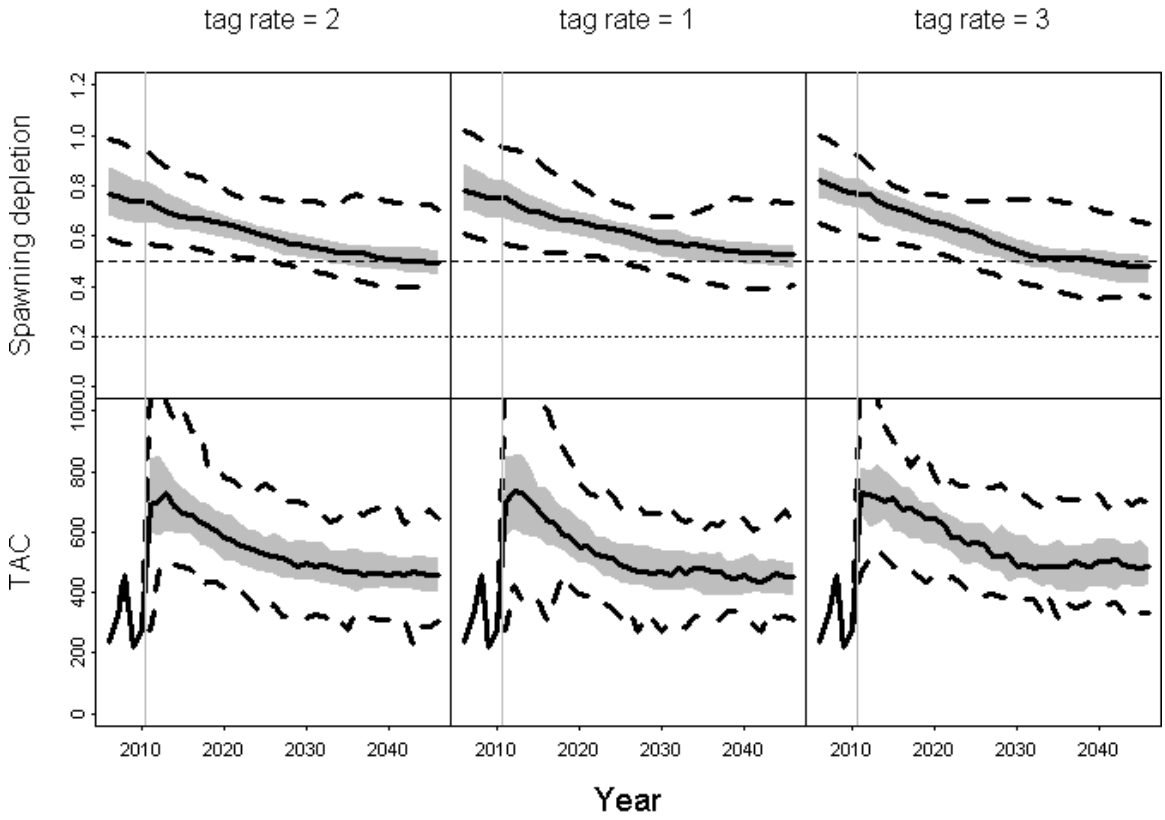

Figure 14.1.True distributions (median, 95% and inter-quartile range) for the time series of relative spawning biomass and catch obtained when applying the approximation to the CCAMLR control rule for future tagging rates of two, one, and three tags per tonne. Vertical line indicates the start of the projection period. Dotted lines in upper panels indicate 50% and 20% of unfished levels.

15. BENEFITS / MANAGEMENT OUTCOMES

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

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

16. CONCLUSION

Objective 1. To provide the SARAG with a revised assessment that provides estimates of the status of Patagonian toothfish around Macquarie Island

Outcome:

The fishery for Patagonian toothfish at Macquarie Island has expanded from a trawl only fishery (since 1994) to include a single longline vessel (since 2007). The ability to set gear in ground previously unavailable to the trawl has led to the discovery of fish of a diverse size-range and for the first time, spawning fish. The inclusion of this new gear-type, with its potentially greater spatial range and ability to target more mature fish, needed to be considered appropriately (in conjunction with the trawl fishery). Through this project, the stock assessment has moved from its tag-only origins to an 'integrated' assessment that includes information from both gears, gender, catch, tag recaptures, age and length, and maturity. The new assessment model can provide direct estimates of spawning biomass and recruitment and consider alternative management strategies (eg the CCAMLR control rule)

The Aurora Trough base-case stock assessment (Chapter 11) was conducted using the Stock Synthesis software and updated based upon the following assumptions/parameterizations:

1. value for the rate of natural mortality, M, of 0.13 yr^{-1},
2. use of the sex-specific growth curve parameters estimated by Constable *et al*. (2001),
3. length at 50% maturity of 89cm,
4. exclusion of tag recaptures in the year of release from the likelihood,
5. including over-dispersion in the tag-recapture likelihood,
6. a tag detection rate for the longline fleet of 0.94, the average of the annual values estimated for the trawl fleet.

The catch level for 2010/11 was calculated under the CCAMLR control rule, following application of Markov Chain Monte Carlo (MCMC) methods to characterise uncertainty in the parameter estimation. The constant catch satisfying the CCAMLR rule was calculated assuming that future catches are taken solely by trawl, or solely by longline.

The new base-case estimated 2010/11 spawning biomass to be 2,004t or 54% of unfished spawning biomass. The new base-case estimate for 2010/11 trawl available biomass was 2,920t. 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 Aurora Trough projected catch for 2010/11 under the CCAMLR control rule using the revised base-case was 140t. The magnitude of this catch increased to 164t when the projected catches were assumed to be taken solely by longline instead of trawl.

Objective 2. To develop methods in the assessment that account for (a) the expanding spatial aspects of the fishery and (b) the introduction of longline fishing in the area.

Outcome:

Chapter 8 presents an analysis of the stock assessment under 3 different spatial hypotheses for the Macquarie Island fishery:

1. a single area model which designates five different fleets (Aurora Trough trawl and longline, Northern Valley trawl, and North and South Macquarie Ridge longline) to attempt to capture the spatial and gear-dependent differences in availability but which assumes that the population these fleets exploit is homogeneous,

2. a two-area model which accounts for heterogeneity in toothfish availability between the northern and southern areas of operation of the fishery, with movement among areas, and

3. a three-area model which separates the major historical trawl grounds (Aurora Trough and Northern Valleys) from the Macquarie Ridge, with recruitment occurring only at the trawl grounds, and movement of fish between areas thereafter.

All models were able to fit the length data, age-at-length data and the total number of annual tag recaptures well.

The models differed in their ability to mimic the patterns of tag recaptures by fleet. The single-area model was not able to reconcile the heterogeneity in recaptures among fleets (ie it predicted fewer recaptures for the fleet of release than observed, and predicted more recaptures for the other fleets than observed). This occurred because the model was treating the population as one homogeneous pool and had no means of preventing the tagged fish from being available to the other fleets. Models 2 and 3 (multi-area models) did a better job at capturing the pattern of recaptures by fleet, although both models over-predicted the recaptures in recent years from the longline fishery.

Model 1 indicated that current spawning biomass is around 64% of unfished conditions, whereas models 2 and 3 suggested a slightly less depleted stock, with 2010/11 spawning biomass being 67 and 72% of unfished equilibrium respectively. The time series of spawning biomass show a steady decline over the duration of the fishery for all models. Models which use multiple areas in addition to multiple fleets estimate larger stock sizes, and larger current stock size relative to those in unfished conditions.

Model 2 estimated low rates of movement among the two areas (<1% per annum), and estimated the spawning biomass in the Northern area to be slightly larger than the southern one, with the southern area having a lower biomass relative to unfished conditions. This is unsurprising given that the bulk of the fishery has operated in this area.

Model 3 estimated the majority of the spawning biomass to be in the Macquarie Ridge area, with high rates of movement into this area from the Aurora Trough once fish

mature. Under Model 3, the Northern Valleys area was estimated to have a much larger spawning biomass than the Aurora Trough area, as the estimated movement rate from this area to the Ridge is low. This is due to the low number of recaptures by longline of trawl-tagged Northern Valleys fish.

The 2 area model appeared able to mimic the available data sufficiently well without being overly complicated or highly sensitive. Following further data from the 2010/11 fishing season, this model structure was developed further as the basis for providing a spatial stock assessment model to the SARAG for consideration as the basis for setting TACs for both sectors of the fishery for the 2011/12 season.

Objective 3. To update and further develop the MSE to include the new assessment model and include hypotheses about the spatial aspects of the stock.

Outcome:

Management Strategy Evaluation (MSE) was used to test the performance of a spatially-explicit stock assessment coupled with the CCAMLR harvest control rule and a constant fishing mortality harvest strategy for the Macquarie Island toothfish fishery. The operating model used for the simulations is conditioned on fits to the available data from Macquarie Island, assuming a two area model (northern and southern areas) that includes movement of toothfish between areas, and accounts for the recent development of fishing by longlining methods in the Aurora Trough and on the Macquarie Ridge, in addition to the fishing grounds traditionally fished by trawling. The MSE considers a stock assessment model similar to the operating model. The stock assessment model is fit to data generated from the operating model, and the TAC for the following year is determined using the chosen harvest strategy. The operating model dynamics are then projected given the new TAC. At the end of a 35 year projection period from the present, a set of summary statistics are calculated to evaluate the performance of the harvest strategy with respect to management objectives. Scenarios considered include the sensitivity of results to (i) the choice of harvest control rule, (ii) the way future catches (and therefore tags) are allocated spatially, and (iii) in the quantities of data obtained for inclusion into the stock assessment procedures.

The results suggest that, when applying the CCAMLR control rule, the stock assessment and harvest strategy are able to satisfy management objectives with respect to spawning biomass levels, both in terms of target biomass and risk of falling below limit biomass reference points. Performance under a constant F strategy appeared more conservative, with final stock size being higher and catches lower than under the CCAMLR control rule. The spatial allocation of future catches when implementing the harvest strategy was an important determinant of harvest strategy performance, with equal allocation of catch to the northern and southern areas resulting in higher catches, lower final relative spawning biomass, and also less biased estimates of relative spawning biomass toward the end of the time series. Changing the future tagging rate also impacted performance by resulting in lower (and more variable) annual average catches when the tag rate was decreased to one tag per tonne. Spawning stock biomass levels were maintained at target levels under this scenario however, indicating that the harvest strategy responded appropriately to the increase in estimation uncertainty associated with fewer data when the tagging rate was reduced.

An inspection of the error in the estimates of final year relative spawning biomass during the time series of the simulation projections revealed a cumulating bias in the stock assessment results. This bias appeared to be related to both the way in which future catches and tag releases are allocated spatially, and also as a result of mis-specification between the way in which the tagged population is modelled between the operating model and the stock assessment model. High exploitation rates in one area under certain spatial allocation of future catches tends to result in poorer estimation of movement and spatial allocation of recruitment in the assessment model, as tags are removed from the population before they can provide information on movement dynamics. Additional analyses that modelled the dynamics of the tagged population in the operating model as discrete resulted in different values for performance measures than the prior assumption of continuous dynamics. Chapter 12 revealed that incorrect assignment of ages to tag releases within the model also produces bias in assessment results. Model mis-specification therefore appears to be an important driver of harvest strategy performance. Future work will explore further the sources of bias given different operating model scenarios and degrees of mis-specification, in order to evaluate whether there exist scenarios that provide sufficiently robust outcomes to such biases.

Objective 4. To continue monitoring the stock through the tag-recapture program

The tag-based monitoring program continued through seasons 2008/09 to 2010/2011. For the 2008/09 season, observers tagged 468 fish from the longline vessel, while 675 were released from the trawl vessel (17 recaptures by longline, 299 tag recaptures total). For the 2009/10 season, observers on the longliner *Janas* tagged and released 756 fish, while 35 tagged fish were recaptured. Of the 756 fish, 300 were tagged and released in Aurora Trough. For the 2010/11 season, observers on the *Janas* tagged and released 993 fish, and recorded 95 recaptures, of which 5 were re-released. The tag-recapture program is a critical component of the ongoing assessment of this population.