Abundance estimation and TAC setting for Patagonian toothfish (*Dissostichus eleginoides)* at Macquarie Island: 2007.

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This paper presents summary results from an assessment of the harvested population of Patagonian toothfish (*Dissostichus eleginoides*) at Macquarie Island to 2007 using data collected up until and including April 2007.

This assessment of Macquarie Island toothfish is based on data from a tag-recapture experiment initiated during the 1995/96 fishing season and continuing to the present day. The tag-recapture assessment uses a population model that includes the dynamics of tagged and un-tagged fish, daily tag releases, tag recaptures, total commercial catches, an estimate of natural mortality, and an estimate of the annual net change in available abundance between seasons for the years 1996 to 2007. The assessment is of the population for the Aurora Trough fishing region of Macquarie Island only. There has been limited fishing in the Macquarie Ridge since the previous assessment. The pre-tagging available abundance (as biomass) is estimated by applying a Petersen tagging model using maximum likelihood methods. The model assumes that the recaptures are effectively rare random events described by the Poisson distribution, and the recapture expectations are conditional on catch numbers and the number of tags still available in the population. The applied assessment model is described in the appendix (see also Tuck et al. 2003). The model accounts for apparent decreasing availability with length by assuming that the likelihood of recapturing a tagged fish is proportional to a given vulnerability function and that availability can change within a season. If the catch rate on any particular day is greater than $10t/km^2$ then a broader vulnerability curve is used (Constable *et al.,* 2001). This model assumes that fluctuations in catch and availability are due to movement patterns within a single reproductively isolated population.

Aurora Trough

Catch rates by season

In season 2006/07, a TAC of 241t was applied for the Aurora Trough ground. There were 15 days of fishing from the 26th of March through to the 9th of April. Average daily catch rates were relatively stable at $25t/km^2$ compared to last season's value of $22t/km^2$. Table 1 shows a summary of relative frequency of average daily nominal catch rates in Aurora Trough by season since 1995/96.

The data extraction methodology has changed between this analysis and the previous (Tuck et al., 2006). The change that occurred for this year's data extraction has been made in order to allow for an inadvertent data loss due to observer data entry error. Normally, the individual weights of fish are used to estimate a mean weight from each shot. The Landing Adjusted Weight is then divided by the mean weight of fish to get the estimate of the number of fish in each shot. Several of the hauls with lost data retained enough tagged fish measurements to enable an estimate of mean weight of fish, but for many of the hauls a mean weight had to be calculated from all the

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fish measured from that area. Thus the estimated number of fish for some shots may be less precise than as used in previous assessments.

The estimated biomass abundance for 2006/07 is surprisingly high (170 to 260% of virgin biomass) and may be consistent with a large recruitment pulse entering the fishery. This interpretation must be treated with a good deal of caution as there may be effects of spatial availability or catchability that can confound the tag-based assessment model.

Tag-recapture data and assessment

The 2006/07 season saw 482 releases and 108 recaptures from Aurora Trough. Fish are still being recaptured that were tagged during the earlier seasons of the fishery (Table 2). Once again the mean weight of sampled fish decreased from the previous season to approximately 2.46kg (Table 3). The decrease in mean weight for 06/07 is driven by a further increase in the proportion of small fish in the catch since last season. Figure 1 shows the raw length frequencies by season for the Aurora Trough. Figure 1b shows catch weighted length frequencies. There is a marked decrease in larger fish of length greater than 70cm compared to 05/06 and a marked increase in fish of length lass than 50cm since the 04/05 season. These observations are consistent with the presence of a strong new cohort entering the fishery however they could also be interpreted as a change in the spatial or temporal availability of younger toothfish. It is to be noted that the fishery operated over a month later than in previous seasons which might have a bearing on toothfish availability.

The detection rate for the 06/07 season is 99.3%. A marked improvement from the values estimated for the 05/06 season which suggests that the detection problems experienced last season have been overcome. The estimated detection rates by season are given in Table 4. For the 06/07 season there were 4 fish that were apparently processed before they entered the electronic detector and if these fish are removed from the detection rate calculation the electronic detection rate improves to 100% - however it is more precautionary to use the lower detection rate for this assessment.

Figures 2a and 2b shows the point estimates and confidence limits for available biomass.

SARAG recommended that, on the basis of new estimates of natural mortality rates for Heard Island toothfish, the base case natural mortality rate should be reduced to midway between the former best and lower bound estimates. Thus a natural mortality rate of M=0.1475 is used for the base case in this assessment.

The assessment model parameters and their confidence limits are shown in Table 6a and 6b. The tag based model estimates that pre-tagging (1 July 1995) available biomass in Aurora Trough was approximately 3,360t and that the estimated available biomass at 30 June 2007 will be 7760t (Figures 1 & Table 7). Estimated available abundance declined over the first three seasons of tagging (to 1997/1998), and then showed an increasing trend to 2002/03. This increase corresponds well with the cessation of targeted commercial fishing and the imposition of a 40t research quota in this region. The estimated available biomass following the 2002/03 season was 3543t. As the estimate of available biomass suggested that the population was at or above pre-tagging abundance levels the fishery was re-opened to commercial fishing with a 354t quota for 2003/04 (10% of the available biomass). Following this season, the estimated available biomass was reduced to 2263t 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 60t (in comparison to 40t 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. In season 2004/05 the estimated percentage of available biomass increased above the reference point and commercial fishery was opened with a TAC of 255t the following season (2005/06) once again had a viable fishery with a TAC of 241t.

Percent remaining calculation

Calculations of the estimated percentage of available biomass remaining are shown in Table 5. This percentage takes the final day of the estimation period (30 June) and divides this number by the first day of the estimation period 1 July 1995 (Model A).

$$PR_A = 100 B_f / B_0 \qquad \text{Model A}$$

where B_f is the final estimate of available biomass and B_0 is the pre-tagging estimate of available biomass.

The percent remaining estimates for Aurora Trough are shown in Table 5. In all cases, the mixing parameter δ was set equal to 10 days. Three values for natural mortality were considered: M=0.13, 0.1475 and 0.165. With natural mortality M=0.1475 the point estimate of percent remaining in Aurora Trough for Model A is 226% assuming a tag detection rate of 0.993. If the tag detection rate of 1.0 is adopted then the point estimate of percent remaining in Aurora Trough increases to 233%.

Decision rules and TAC

The current decision rule pertaining to whether a commercial quota exists in Aurora Trough requires that the estimate of percent remaining available biomass be greater than the reference level of 66.5%.

The current management rules which assume M=0.165, assessment Model A and a commercial TAC of 10% of the estimated available biomass would lead to a 711 t TAC for the 2007/08 season. If as suggested by SARAG a natural mortality rate of M=0.1475 better characterizes the Macquarie Island toothfish population then a TAC of 776 t would be indicated.

Macquarie Ridge

The Maquarie Ridge has not experienced a significant catch since 1997. There are two different hypotheses as to why this could occur:

1) the one stock hypothesis:
all fish are part of a single stock, including those that may be regarded as resident on the Northern Valley trawl grounds and those that may be regarded as transient to the trawl grounds. An increased proportion of the stock periodically becomes available to the trawl fishery; and

2) the two stocks hypothesis:

there is a resident local stock in the Macquarie Ridge and a transient stock that is also occasionally available to the fishery. The resident stock is considerably smaller than the transient stock.

There were no tag releases or recaptures in the Macquarie Ridge in 2006/07. Since the 1998/99 season, only 11 tagged fish have been recaptured from the Macquarie Ridge..

As five fish were recaptured during the 2005/06 season, an update of the stock's abundance may be possible with the tag-recapture model; however due to the low number of recaptures the estimated stock abundance is likely to have a large degree of uncertainty.

Decision rules and TAC

No new information was available for the Macquarie Ridge in 2006/07 and so TAC is to be estimated on the basis of previous assessments, taking into account natural mortality and catches. For 2005/06, the TAC set for Macquarie Ridge was 100t, with a 264t trigger TAC. The TAC of 264t would be triggered if catch rates reach a threshold of an average of $10t/km^2$ over 3 consecutive fishing days. If the catch rates then fall below $10t/km^2$ over 3 consecutive days then the TAC would revert back to 100t, and if more than 100t had been taken the fishery would be closed.

As there were no recaptures and no catch in the 2006/07 season for Macquarie Ridge. A tag based stock assessment was not undertaken. In circumstances where a tag based stock assesmnet is not possible, the decision rule applied to the Macquarie Ridge has been to assume no recruitment to the fishery and then to reduce the previous season's estimate by the catch and one year of natural mortality. This would lead to a recommended TAC for 2007/08 of 85t, with a 224t trigger TAC assuming the previous base case natural mortality of M=0.165. With the current base case natural mortality of M=0.1475 the 07/08 TAC is 86t and trigger limit of 228t.

Concluding points for discussion

This year's analysis has highlighted some issues with the assessment method and management rules. The tag based assessment model and hence management decisions are sensitive to:

- the seasonal number of recaptures. This is particularly important for the first and last seasons,
- the pulse nature of this fishery,
- the assumed natural mortality level,
- the mean weights used in the first and last years. In particular, the 2005/06 season shows a decrease in mean weight. This appears due to the influx of small fish to the available population. The anticipated move to an integrated assessment may resolve this issue, as it has the ability to estimate cohort strength.
- A hard 10% rule for allocating TAC may be inappropriate if a large jump in stock abundance is indicated from one assessment period to the next

The current assessment taken on face value would suggest that a tripling of the TAC to 776t would be appropriate for the 2007/2008 season. However, due consideration should be given to the possibility that this assessment has significantly over-estimated available stock abundance for one or more of several possible reasons.

The tag-based assessment model makes the assumption that availability and catchability of the stock does not vary between seasons. However the catches in a pulse fishery such as at Macquarie Island can be extremely sensitive to spatial or temporal availability changes in the stock. The 2006/2007 season was notable for being almost 2 months later than in previous years. It is conceivable that operating at this later date targets fish that are not available to the fishery earlier in the season.

Another potential source of error arises if vessel targeting practice has altered due to skipper or operational changes as this can impact on the catchability of the stock.

The substantially increased available biomass estimate occurs as a result of a large (almost 50%) increase in the number of fish captured and a concurrent large reduction in the number of tags recovered (about 50%). The large majority of the fish caught this last season were small fish (mean weight 2.46kg) and so the tag based model indicates very large numbers of small fish have become available to the fishers.

If either targeting of small fish classes, or large inter-annual fluctuations in TAC are undesirable, then it may be desirable to identify a more appropriate rule than a simple choice of 10% of available biomass for setting the 2007/08 TAC.

Finally it should be noted that by assuming a base case natural mortality of M=0.1475 the TAC calculations and final available biomass estimates are not directly comparable with previous base case assessments. A retrospective analysis should ideally be done for past seasons using the newly adopted base case mortality.

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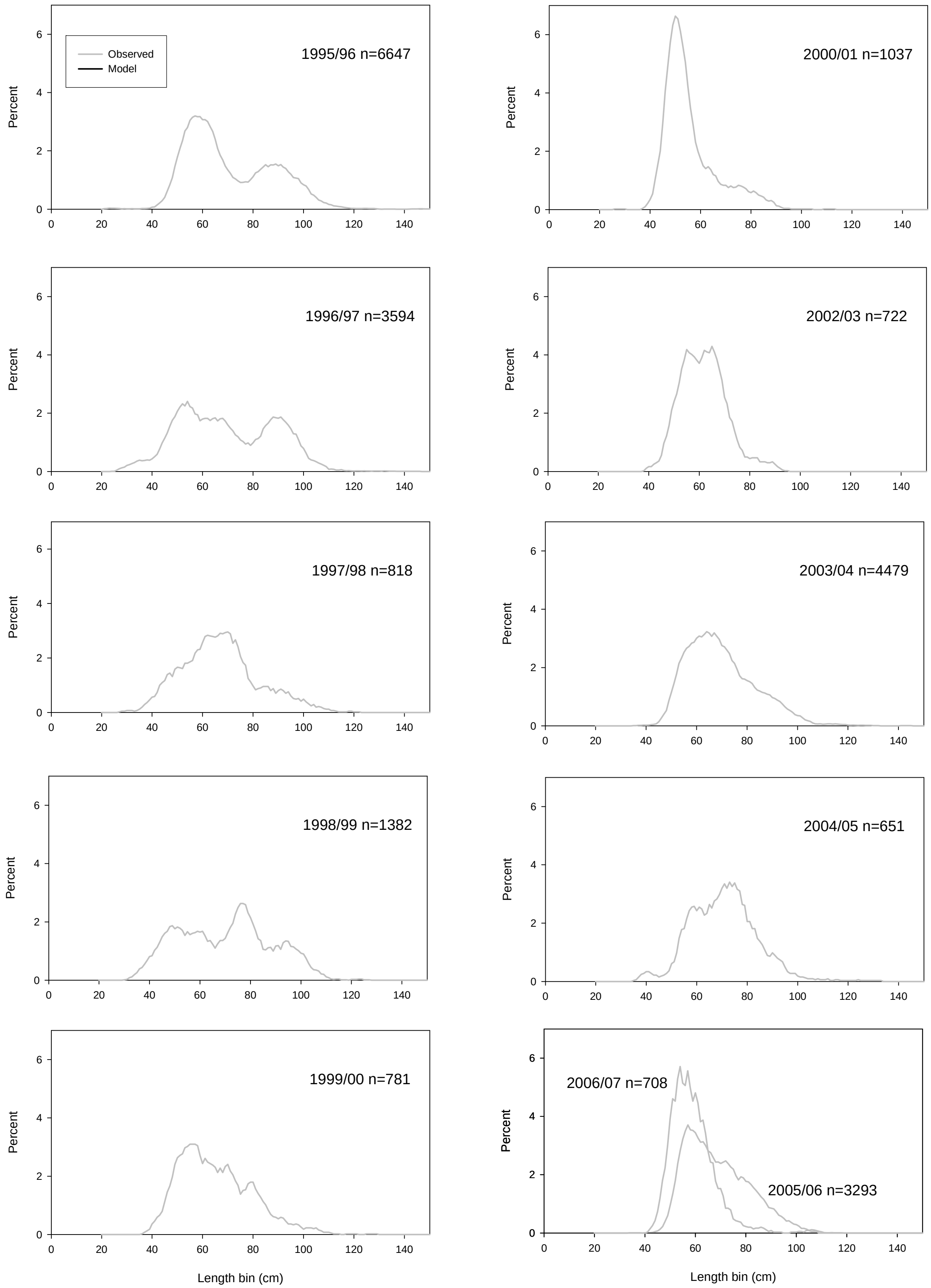

Figure 1. Raw length frequencies for the Aurora Trough, with a running average across five length classes.

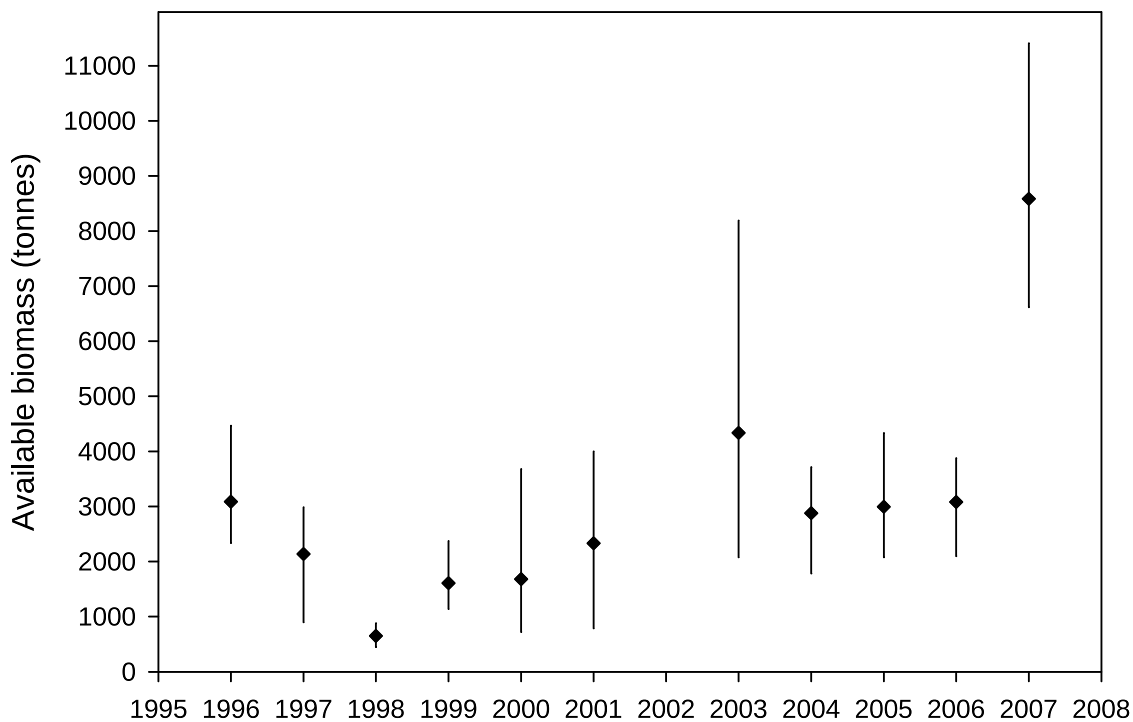

Figure 2a. The 95% confidence limits about the point estimate of available biomass of toothfish at Aurora Trough at 1st January in each year since 1996 (natural mortality M = 0.1475, and tag mixing parameter δ = 10 and detection rate of 0.993 for season 06/07).

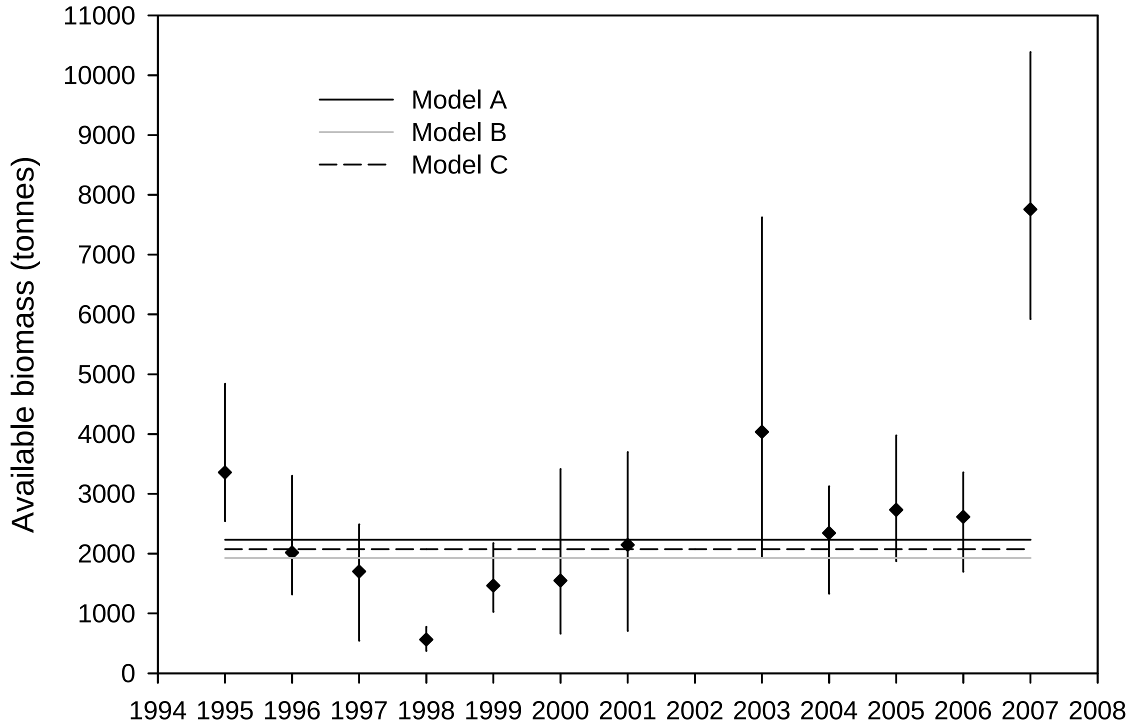

Figure 2b. The 95% confidence limits about the point estimate of available biomass of toothfish at Aurora Trough at 30 June in each year since 1996 with natural mortality M = 0.1475, and tag mixing parameter δ = 10 and detection rate of 0.993 for season 06/07. The 1995 estimate is taken from the initial starting point of the model, 1 July 1995. The horizontal lines indicate the threshold levels for a commercial fishery for each of the percent remaining models (Models A, B and C). If the point estimate is above this line then, according to the current management rule, a commercial fishery exists.

Table 1. Relative frequencies of average daily catch rates (t/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
<1	2	0	3	8	8	1	0	2	0	0	1	0
1-5	31	2	5	6	9	1	0	1	1	0	0	0
5-10	4	6	8	4	1	3	0	1	0	0	3	2
10-20	4	7	6	4	1	5	0	3	5	2	4	6
20-40	3	12	2	4	0	1	0	2	8	1	6	4
40-80	11	6	1	0	0	0	0	1	4	1	2	3
80-120	5	1	0	0	0	0	0	0	2	0	0	0
>120	8	0	0	0	0	0	0	0	0	0	0	0
Total	68	34	25	26	19	11	0	10	20	4	16	15

Table 2. Seasonal catch (numbers), release and recapture figures for the Aurora Trough region. Releases include re-released fish. The table does not include tagged fish released in the Macquarie Ridge and recaptured in Aurora Trough. The numbers in brackets represent the number of tags retained as recaptures after discarding tags recaptured within 10 days.

			95/96	96/97	97/98	98/99	99/00	Win 00	00/01	01/02	02/03	03/04	04/05	05/06	06/07	Total
95/96	180523	486	43(21)	58	28	4	0	0	1	0	1	1	0	0	0	136
96/97	95045	487		37(24)	43	7	0	0	2	0	0	9	1	3	0	102
97/98	58611	641			129(100)	19	3	0	4	0	5	22	4	15	1	202
98/99	14815	605				8(0)	3	1	5	0	3	30	2	9	2	63
99/00	1993	559					0	1	2	0	1	22	4	4	0	34
Winter 00	1495	96						1(0)	1	0	0	13	2	8	1	26
00/01	10837	356							3(0)	0	1	23	3	5	1	36
01/02	0	0								0	0	0	0	0	0	0
02/03	13826	497									6(1)	60	8	29	6	109
03/04	85824	539										70(25)	8	17	8	103
04/05	12084	544											10(0)	46	7	63
05/06	68627	595												87(2)	25	112
06/07	98804	482													57(3)	57
Total	441799	5404	43	95	200	38	6	3	18	0	17	250	42	223	108	1043

Table 3. The mean weight (kg) by season of fish caught in the Aurora Trough region.

Season	95/96	96/97	97/98	98/99	99/00	Win 00	00/01	01/02	02/03	03/04	04/05	05/06	06/07
Mean Weight (kg)	5.17	5.16	3.22	3.89	3.21	2.21	2.44	*2.59*	2.74	4.14	4.88	3.89	2.46

Table 4. The estimated detection rate.

Season	95/96	96/97	97/98	98/99	99/00	Win 00	00/01	02/03	03/04	04/05	05/06	06/07
Detection rate	0.767	0.888	0.954	0.952	1.000	1.000	0.905	0.984	0.987	1.000	0.840	0.993

Table 5. The percent of available biomass remaining in Aurora Trough for **2006/07** using model A (30 June 2006 relative to 1 July 1996), Model B (30 June 2006 relative to 1 July 1995 discounted by one year of natural mortality, *M*), or Model C (30 June 2006 relative to 1 July 1995 discounted by one half of natural mortality).

Model	*M*	% Estimate
A	0.13	256
	0.1475	231
	0.165	209
	0.20	174

Table 6. Point estimates of model parameters with 95% confidence limits for the Aurora Trough showing pre-tagging available numbers N_0 and annual net change in available abundance, ΔN (both as millions of fish) for δ=10 and M = 0.13, 0.1475 and 0.165.

M	0.13	0.165		0.1475	
Parameter	Estimate	Estimate	Lower 95	Estimate	Upper 95
N_0	0.644	0.656	0.492	0.650	0.937
ΔN_{96}	0.09	0.10	-0.16	0.09	0.27
ΔN_{97}	-0.07	-0.06	-0.13	-0.07	0.01
ΔN_{98}	0.28	0.27	0.15	0.28	0.49
ΔN_{99}	0.18	0.20	-0.14	0.19	0.86
ΔN_{00}	0.57	0.53	-0.14	0.55	1.28
ΔN_{02}	1.01	0.91	0.07	0.96	2.48
ΔN_{03}	-0.80	-0.65	-1.01	-0.72	-0.51
ΔN_{04}	0.09	0.10	-0.11	0.10	0.39
ΔN_{05}	0.30	0.29	0.02	0.29	0.52
ΔN_{06}	3.31	2.90	2.23	3.09	4.33

Table 7. Point estimates in tonnes (including 95% Confidence Intervals) of available biomass for Aurora Trough on 1 July 1996 (the first day of the 1996/97 season) and 30 June 2007 (the last day of the 2006/07 season) for δ = 10.

Available Biomass t	*M*=0.13	*M*=0.165		*M*=0.1475	
Date	Point Estimate	Point Estimate	Lower 95% CI	Point Estimate	Upper 95% CI
1-July-1995	3330	3390	2220	3360	4840
30-June-2007	8500	7100	5920	7760	10380

Table 8. The mean weight (kg) by season of fish caught in the Macquarie Ridge region.

Season	96/97	97/98	98/99	99/2000	Win 00	00/01	02/03	03/04	04/05	05/06
Mean Weight (kg)	5.12	4.35	3.12	2.36	3.29	1.53	1.34	2.02	1.89	1.90

Appendix:

Methods

Tag releases and recaptures occur throughout the fishing season at Macquarie Island. We could accumulate each of the catches, releases and recaptures over the fishing season and naively estimate the available abundance by the Petersen method. However, the available abundance could be seriously overestimated as this approach disregards the expectation that a fish tagged early in a fishing season has a higher chance of being recaptured during the season than a fish tagged later in the season. We use a semi-parametric model to account for daily catches, releases and recaptures and assume that there is neither recruitment nor emigration during the fishing season. The net change in magnitude of the available stock occurs between seasons and can be estimated when more than one year of tag returns are available.

The probability of recapturing a tagged fish depends on the size of the catch and the size of the fishable stock. The total expected number of tag returns from a single catch will then depend on the probability of recapture and the number of tagged fish in the water (Petersen's equation[2]). This expectation will vary with time as tagged fish are released and recaptured, and as the size of the population changes with catches, natural mortality and recruitment.

The population models of the assessment include dynamics of tagged and untagged fish, allowing for natural and fishing mortality, net recruitment, growth and daily releases and recaptures. It is assumed that there is neither recruitment nor emigration during the fishing season. The parameters estimated by the model are the pre-tagging available abundance N_0 and the annual net change in available abundance between seasons, ΔN_y. Daily estimates of available biomass can also be tracked.

Between the 1995/96 and 2005/2006 fishing seasons, over 7500 Patagonian toothfish were tagged in the Aurora Trough and Maquarie Ridge fishing grounds, of which around 1098 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 pounds 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. In the 1996/97 season, an electronic tag detector was installed on the vessel. Unfortunately, the electronic detector was initially not fully effective, so less than 100% of the electronic tags were detected.

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.

[2] Provided tagged fish have mixed with the un-tagged population, Petersen's equation states that the proportion of marked fish in the population, m/N, should equal the proportion of recaptured fish in the catch, r/C. Rearranging this equation for recaptures yields, $r = Cm/N$.

The detection of visible tags relies upon the vigilance of the crew and observers but is thought to be relatively high due to multiple handling of captured fish as a routine part of the processing of the catch and the implementation of tag lottery incentives for crew. Non-detection of electronic tags can also be problematic and is thought to be high for years 1996/96 and 2005/06. Tag detection rates can be stimated by comparison of electronically detected tag numbers with visually detected tag numbers. 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]:

$$r_s = n_v n_e / n_{ve}, \qquad \text{(A1)}$$

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.

Model formulation

a) The Length-Independent Selection Model (LIS)

Let N_t be the number of available fish in the population on day t, and C_t the number of fish caught on day t, then:

$$N_t = (N_{t-1} - C_{t-1})S, \qquad \text{(A2)}$$

where $S = exp(-M/365)$ and M is the annual natural mortality rate, which is assumed constant for all time periods. This is the daily version of the catch equation used in cohort analysis (Pope, 1972).

The number of available fish prior to the tagging experiment is given by N_0 and the reference day is taken as 1 July. One year later, ΔN_y fish are added to the population. The term ΔN_y is a measure of the net change in available abundance between seasons. Hence, recruitment of young fish is not explicitly modelled, but is aggregated with availability and movement effects.

Again, using the cohort catch equation, the number of tagged fish in the population on day t is:

$$m_t = (m_{t-1} - r^*_{t-1})S + p_t, \qquad \text{(A3)}$$

where p_t is the number of tagged fish released on day t, and $m_{t_1} = p_{t_1}$ where $t{=}t_1$ is the first day of tagging. The total number of recaptured fish r^*_t on day t is given by:

$$r^*_t = r_t / \omega_t, \qquad \text{(A4)}$$

[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 (A1).

where r_t is the observed number of recaptures and ω_t is the detection rate for day t. The number of observed recaptures on day t is assumed to follow a binomial distribution, $r_t \sim B(\beta_t, C_t)$, with mean μ_t defined by:

$$\mu_t = E[r_t] = \omega_t \frac{m_t}{N_t} C_t = \beta_t C_t , \tag{A5}$$

where $\beta_t = \omega_t m_t / N_t$ for day t. As there are large catches (or samples) and m_t / N_t is small, the Poisson distribution Po approximates the binomial distribution, and thus $r_t \sim Po(\mu_t)$. It is assumed that recaptures are random and not clumped.

Maximum likelihood estimates of pre-tagging available abundance, N_0, and net changes in abundance in year y, ΔN_y, are then found by maximising the log-likelihood function given by:

$$L(r; N_0, \Delta N_y) = \sum_{t:\mu_t \neq 0} (r_t \ln(\mu_t) - \mu_t). \tag{A6}$$

b) The Length-Dependent Selection Model (LDS)

The Patagonian toothfish caught in the trawl fisheries at Heard, McDonald and Macquarie Islands are predominantly between 450 and 1000mm long (Constable *et al.,* 2001). This observed length-frequency is related to both gear selectivity and fish availability. Evidence from deep-set longline toothfish fisheries at other sub-Antarctic Islands where large fish are caught in greater numbers, and the infrequent but evident catch of large fish at Macquarie Island, suggests that toothfish availability decreases with increasing length. This is likely to arise as a result of smaller fish being segregated from adult fish, with the adults tending to be found in deeper water (SC-CAMLR, 1998). The LIS model assumes that all tagged fish remain available to the gear regardless of age or length. As such it is possible that the model assumes there are more tagged fish available than there are in reality, which would lead to an over-estimation of available abundance. This is because Petersen's equation (and the LIS model) assumes that abundance is proportional to the number of tagged fish in the population. Hence, for the same catch and number of recaptures, the population estimate will be biased upward if the number of tagged fish available is, in fact, lower than anticipated.

The LDS model assumes that the likelihood of recapturing a released fish is a function of vulnerability. Initially, every released fish is aged using its recorded release length and the von Bertalanffy growth curve, given by:

$$a = t_0 - \ln(1 - l / L_\infty) / k, \tag{A7}$$

where l is the length, L_∞ is the asymptotic length of a fish, k is a growth parameter and t_0 is the age at which a hypothetical fish is of length 0cm (Quinn and Deriso, 1999). The modelled-tagged fish then grow each day according to the von Bertalanffy growth curve with length a function of age.

Constable *et al.* (2001) estimate the vulnerability at length of Macquarie Island fish with a linearly increasing and decreasing function illustrated in Figure 0.1 (parameters given in Table 0.1). The vulnerability function combines the effects of gear selectivity and fish availability. To account for observed changes in within season availability, Constable *et al.* (2001) estimate two vulnerability functions. The magnitude of the daily catch rate was assumed to be a reasonable indication of the availability of large or small fish. As such, the length composition of catch for which catch rates were less than 10 t/km^2 was used to estimate the vulnerability when only resident smaller fish were available. All length composition data were used to estimate a broader vulnerability curve. Within the assessment model, the observed daily catch rates being above or below 10 t/km^2 determines when the model applies each estimated vulnerability curve.

Table 0.1 Vulnerability parameters as a function of length (cm) for Macquarie Island Patagonian toothfish estimated by Constable et al. (2001). Number pairs are the vertices of a linearly increasing and decreasing vulnerability curve as a function of length. The base-vulnerability curve has been estimated using only length-age data when catch rates are less than 10 t/km2. The broad vulnerability has been estimated using all age-composition data.

	Length (cm)	Vulnerability
Base vulnerability	29.5	0.0
	36.5	0.01
	69.5	1.0
	113.4	0.006
	160	0.0
Broad vulnerability	29.5	0.0
	36.5	0.01
	69.5	1.0
	107.5	1.0
	123.9	0.01
	160	0.0

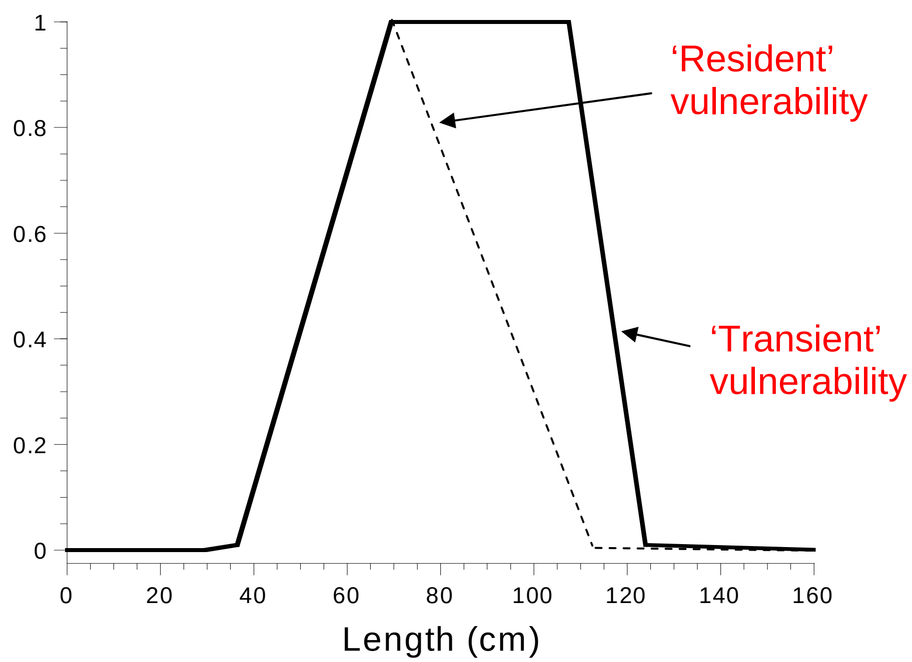

Figure 0.1 The vulnerability functions applied for Macquarie Island Patagonian toothfish. The dashed line represents the base vulnerability. The broader vulnerability curve incorporates the smaller fish of the base vulnerability and additional larger fish that become available if conditions are favourable.

The expected number of surviving available tagged fish on day *t* is,

$$m_t = \sum_j s(l_t^j)\exp(-(t - t_r^j)M / 365)$$
$$- \sum_i \frac{1}{\omega_{t_c^i}} s(l_t^i)\exp(-(t - t_c^i)M / 365), \quad \text{(A8)}$$

where *j* represents all releases (recaptured or not) prior to day *t* and *i* represents recaptured fish alone prior to day *t* (akin to Hearn *et al.* (1987)). Times t_r^j and t_c^i are the day of release and recapture for a tagged fish, where $t_r^j < t$ and $t_c^i < t$. The function $s(l_t^j)$ is the selectivity of tagged fish *j,* which has length l_t^j on day *t*. The first exponent terms give the probability of natural survival of tagged fish *j* from the day of its release to the current day *t*. The expression containing $\omega_{t_c^i}$ accounts for those tagged fish not detected, in a similar manner to equation (A4). Equation (A8) replaces equation (A3) in the description for the LIS Model. If the selectivity function does not vary with length, $s(l_t^j) = 1$ for all lengths, then equation (A3) can be seen as specific case of equation (A8).

Sensitivity to mixing

As the tagged fish are released in a group, they possibly do not mix with the un-tagged population for some days. This can bias estimates of abundance. For example, if tagged fish remain near the vessel and are recaptured shortly after release, then the assessment model is likely to under-estimate abundance. Likewise, if tagged fish (or the vessel) move to another region, tagged fish will be under-represented in the catch and estimates of abundance will be biased upward.

We follow the simple procedure used by Hearn (1986) to allow a period of time for tagged fish to mix with the general population. Note that the equivalent procedure for parametric models is more complex, unless the mixing period is one year (Hoenig *et al.,* 1998). This is an advantage with using a semi-parametric model over the corresponding parametric one.

Let:

δ = the minimum number of days for tagged fish to fully mix with the un-tagged population.

To explore the sensitivity of the model to δ, tagged fish recaptured within δ days are removed from the analysis, i.e. both the release and recapture events are removed from the input data. As released fish cannot contribute to the expectation of recapture within δ days of their release, their inclusion to the formulation for the number of tagged fish in the water (equations (A3) and (A8)) can not occur until δ days after their release. At this point they have experience δ days of natural mortality.

Confidence Limits

The likelihood profile method (as defined by Hilborn and Walters (1995)) is used to calculate a 95% confidence set around a point estimate of a parameter, ρ. The confidence limits defining the boundary of the confidence set are defined as those values of ρ_{sub} that satisfy:

$$L(r; \rho = \rho_{sub}) - L(r; \rho = \rho_{opt}) = \chi^2_{1,1-\alpha} / 2, \quad \text{(A9)}$$

where $L(r;\ \rho = \rho_{opt})$ is the negative log-likelihood corresponding to the maximum likelihood estimate (giving ρ_{opt} as the point estimate), and $L(r;\ \rho = \rho_{sub})$ is the lowest negative log-likelihood when ρ is set to the sub-optimal value ρ_{sub}. The value of the chi-squared distribution with one degree of freedom at confidence level 1-α is given by $\chi^2_{1,1-\alpha}$. For $\alpha = 0.05$, the right-hand side is equal to 1.92.