Updated stock assessment of blue grenadier *Macruronus novaezelandiae* based on data up to 2007

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17/18 November 2008
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Important Notice

Use of this Report

CONTENTS

1. SUMMARY 1

2. INTRODUCTION 1

3. THE FISHERY 2

4. DATA 2

4.1 Catch 2

4.2 Catch rates 3

4.3 Length Frequencies and Catch-at-age 5

4.4 Age-reading error 8

4.5 Acoustic survey estimates 9

4.6 Egg survey estimates 9

4.7 Parameters of breeding biology 11

5. ANALYTIC APPROACH 11

5.1 The population dynamics model 11

5.2 The objective function 11

5.3 Parameter estimation 12

6. RESULTS AND DISCUSSION 13

6.1 Stock assessment 13

6.2 Retrospective analysis 17

6.3 Transition from the 2007 to the 2008 assessment 17

6.4 Harvest control rule application 17

7. ACKNOWLEDGEMENTS 20

8. REFERENCES 20

9. FIGURES 22

10. APPENDIX: THE POPULATION DYNAMICS MODEL AND LIKELIHOOD MODEL 36

10.1 Basic dynamics 36

10.2 Vulnerability 38

10.3 Catches 38

10.4 The likelihood function 39

LIST OF FIGURES

Figure 4.1 The calendar year catch-rate indices for the non-spawning (top) and spawning (bottom) blue grenadier fisheries (Haddon, 2008) in comparison to the series for 2006 and 2007 (Haddon, 2007). 5

Figure 4.2 The onboard lengths for years 2007, 2006 and all years combined. Green represents retained fish, brown are discarded fish and grey (in 2007) are proportions of fish where it was not possible to distinguish between discarded and retained fish. 6

Figure 4.3 The proportion discarded-at-age from the non-spawning fishery for 2007..... 6

Figure 4.4. The port-based catch-weighted length frequencies for the non-spawning blue grenadier fishery over years 2002-2007. 7

Figure 4.5. The catch-weighted length frequency for blue grenadier of the spawning sub-fishery in years 2004-2007. 8

Figure 4.6. The observed proportion caught–at-age data for the non-spawning (left) and spawning (right) sub-fisheries in 2007. 8

Figure 9.1. Top plot: Annual landings of blue grenadier (obs) and estimated by the base case model (model). Bottom plot: Discards estimated from the ISMP (solid line) and base-case model estimated values (dashed line). Note that the lines for the modelled spawning and non-spawning (model) landings overlay those of the observed (obs) lines for each sub-fishery. 22

Figure 9.2. Catch-per-unit-effort (CPUE) calculated using a GLM to standardise CPUE from log-books (obs; Haddon, 2008) and the base-case model estimated CPUE for the spawning fishery (top) and the non-spawning fishery (bottom). 23

Figure 9.3. Vulnerability of blue grenadier to being caught (but not necessarily landed) by the two sub-fisheries (top) and the probability of being discarded if caught (bottom) as a function of length class for the base case model. 24

Figure 9.4. Observed (bars) and model estimated (lines) proportion caught at age for the spawning sub-fishery and base case model. 25

Figure 9.5. Observed (bars) and model estimated (lines) proportion caught at age for the non-spawning sub-fishery and base case model. 26

Figure 9.6. Observed (bars) and model estimated (lines) proportion discarded-at-age for the non-spawning sub-fishery and base case model. 27

Figure 9.7. Estimated recruitment multipliers (the amount by which the recruitment deviated from that predicted by the stock-recruit relationship) versus year of spawning for the base case model. Bottom: The median (solid line), upper and lower 95% bounds (dashed lines) on the recruitment multipliers for the base case model. 28

Figure 9.8. The time-trajectory of female spawning biomass (left) and total spawning biomass (right) for the base case model. The vertical lines show the estimates of spawning biomass derived from surveys of egg abundance in 1994 and 1995 and acoustic surveys from 2003 to 2007. The horizontal line shows B_{ref}, which is defined as the average female spawning biomass over 1979–1988. 29

Figure 9.9. The trajectory of female spawning biomass relative to the reference biomass, Bref for the base case model. The horizontal lines show the 0.48 and 0.20 levels. 29

Figure 9.10. The female spawning biomass (top) in relation to the egg survey estimates of biomass and the total spawning biomass (bottom) in relation to the acoustic estimates for each of the base case (‘Low’) assessments from 2004 to 2008. 30

Figure 9.11 The estimated annual recruitment multipliers for each of the base case assessments of blue grenadier from 2003 to 2008. 31

Figure 9.12. The female spawning biomass as a function of the data sources provided to the assessment. 2007 is the series from the 2007 assessment (Tuck and Punt, 2007), C = catch data series from 2008 included, CAA = updated age data are included, CPUE = updated catch rates series from 2008 is included (Haddon, 2008). 2008 is equivalent to C + CPUE + CAA + D + AC, where AC is the inclusion of the 2007 acoustic biomass estimate 32

Figure 9.13 The female spawning biomass relative to the reference biomass as a function of the data sources provided to the assessment. 2007 is the series from the 2007 assessment (Tuck and Punt, 2007), C = catch data series from 2008 included, CAA = updated age data are included, CPUE = updated catch rates series from 2008 is included (Haddon, 2008). 2008 is equivalent to C + CPUE + CAA + D + AC, where AC is the inclusion of the 2007 acoustic biomass estimate. 33
Figure 9.14. The trajectories of the landed RBC (top) and the corresponding depletion level (bottom) according to the 2 potential harvest control rules applied in the SESSF. The depletion figure also shows the depletion if a constant catch equal to the current catch of 4,368t is applied over all projected years. 34
Figure 9.15 The trajectory of female spawning biomass relative to the reference biomass following the historic period and future projections under the two harvest control rules (20:40:40 and (20:35:48). 35

LIST OF TABLES

Table 4.1. Landed and discarded catches for the winter spawning and non-spawning sub-fisheries by calendar year. These estimates have been adjusted scaled up to the SEF2 data (see text). The annual TAC is also shown. *Note that a voluntary industry reduction to 4,200 t was implemented in 2005. 3
Table 4.2. Standardised CPUE (Haddon, 2007) for the spawning and non-spawning sub-fisheries by calendar year. 4
Table 4.3. The estimated biomass (tonnes) of blue grenadier on the spawning grounds in years 2003 to 2007 (Ryan and Kloser, 2008). 9
Table 4.4. The age-reading error matrix, shown as the percentage of times an animal with true age given by the column header is aged to be of the age given by the rows. Source: A.E. Punt and Central Aging Facility (CAF, PIRVic, Queenscliff, Victoria). 10
Table 5.1. Parameter values assumed for some of the non-estimated parameters of the base-case model. 12
Table 6.1. Estimated values for several parameters of interest. The base case model is shown as well as sensitivity tests. Results are shown for base-case runs in the previous 3 years for comparison with the 2008 assessment. ‘Curr’ refers to the current or final year of the estimation. The High Models use the higher acoustic survey estimates of total spawning biomass with the egg survey estimates of female spawning biomass doubled. The Low models use the lower acoustic estimates of total spawning biomass with the base-case egg survey estimates. Both of these models assume 2 times turnover. The 2008 base case model uses the Low model assumptions, assumes all fish less than 50cm were discarded in 2007 and assumes a cpue cv of 0.3. 15
Table 6.2. The estimated 2009 mid-year depletion and RBCs (landed and total; tonnes) for the base-case model for two Tier 1 harvest control rules with target biomass depletions of either 48% or 40%. 19
Table 6.3. The time series of landed RBCs and corresponding depletions relative to B_{ref} for each Tier 1 rule. Also shown is the annual depletion if the current landed catch of 4,368 t is maintained over all projected years. 19

1. SUMMARY

The 2008 assessment of blue grenadier *Macruronus novaezelandiae* uses the age-structured integrated assessment method developed by Punt et al. (2001). The assessment has been updated by the inclusion of data from the 2007 calendar year. In addition, age reading error and new biological parameters relating to the proportion spawning and the length at maturity, first introduced in August 2006, have been used. Estimates of spawning biomass from acoustic surveys from 2003-2007 (with 2 times turnover) and egg survey estimates of female spawning biomass from 1994-1995 (base-case estimates) are included. This corresponds to the 'Low' model of Tuck and Punt (2006; 2007) and is referred to as the base-case model here.

Results conclude that the female spawning biomass in 2007 is around 71% of the reference biomass and the depletion in 2009, used for the harvest control rules, will be approximately 50%. This compares with 47% for the 2006 depletion and 44% for the 2008 depletion in the 2007 assessment. The increases relative to the reference biomass between the 2007 and 2008 assessments are in part due to recent estimated biomasses being shifted upward through the increased level of the 2006 and 2007 acoustic estimate and the increased cpue in both sub-fisheries since 2005. The age data also suggests an increase in biomass. The marked decline in predicted biomass relative to the reference level over years 2007 and 2009 (from 0.71 to 0.50) is worth noting. This is likely to be due to the declining availability of the large cohort of the mid-1990s (as they senesce) and the majority of the catch being caught from the relatively smaller cohort of 2003/04

The Recommended Biological Catch (RBC) (landed catch and discards) for 2009 for the base-case model is 6,459 t (20:40:40) or 5,036 (20:35:48). The long-term RBCs are between 5,000 and 5,600 t. In comparison, the RBCs for 2008 from the 2007 assessment were between 3,300 t and 4,700 t, with long-term RBCs of around 5,500 t.

The 2008 assessment shows a further recruitment in 2006. The magnitude of this recruitment is uncertain and will become clearer as these fish move into the available biomass. The recruitments of 2003/04 and 2006 are estimated to be about twice that expected from the stock-recruitment relationship. While a positive sign for the stock and fishery following several years of poor recruitment, these recruitments are not estimated to be as large as the recruitments of the mid-1990s.

2. INTRODUCTION

An integrated analysis model has been applied to the blue grenadier stock of the Southern and Eastern Scalefish and Shark Fishery (SESSF), with data updated by inclusion of the 2007 calendar year data (catch and discard at age; updated catch rate series; landings and discard catch weight) and additional information from acoustic surveys of spawning biomass (series from 2003-2007). The same assessment model that has been used in previous years (e.g. Punt et al., 2001; Tuck and Punt, 2006; 2007) was used this year. This document presents (a) diagnostic plots and (b) recommended biological catches (RBCs) from an application of the Tier 1 harvest control rules.

The model considered here includes age-reading error (Punt, pers. comm.), updated biological parameters for the proportion spawning and length at maturity (for males and females) and an assumption of 2-times turnover on the spawning ground. The base-case egg survey estimates of female (only) spawning biomass for 1994 and 1995 are included. The acoustic estimates are assumed to pertain to total (male and female) spawning biomass. In Tuck and Punt (2006; 2007) two models were considered, differing according to the target strength used to produce the absolute estimates of spawning biomass from the acoustic surveys and assumptions about the egg survey estimates. The 'High' model assumes the target strength of Macauley (2004) and doubles the egg survey estimates. The survey estimates of absolute abundance used when fitting this model are higher than those used when fitting the 'Low' model which uses the Cordue (2000) target strength and the base-case egg survey estimates of spawning biomass. Following the recommendations of Ryan et al. (2007), here we only consider the 'Low' model (referred to as the base case model here), with the spawning biomass estimates resulting from the target strength estimates of Ryan and Kloser (2008).

3. THE FISHERY

Blue grenadier are found from New South Wales around southern Australia to Western Australia, including the coast of Tasmania. Data support the hypothesis of a single breeding population in Australian waters, however spawning fish have recently been caught off the east coast of Australia. Blue grenadier is a moderately long-lived species with a maximum age of about 25 years and an age at maturity of 4-5 years. Spawning occurs off western Tasmania between late May and early September. Adults migrate to the spawning area from throughout southeastern Australia, with large fish arriving earlier in the spawning season.

Blue grenadier are caught by demersal trawling. The global agreed TAC in 2007 was 3,530 tonnes (with an additional 583 t for 1 January to 30 April 2008) and in 2006 it was 3,730 tonnes. The annual TACs are show in Table 4.1. There are two defined sub-fisheries: the spawning and non-spawning fisheries. The non-spawning fishery catches have been relatively poor over the last few years, whereas the spawning fishery catches have shown a marked increase since the mid-1990s.

4. DATA

The model has been updated by the inclusion of the 2007 catch- and discard-at-age from the spawning and non-spawning fisheries; updated cpue series (Haddon, 2008), the total mass landed and discarded, mean length- and weight-at-age; updated acoustic estimates of spawning biomass (Ryan and Kloser, 2008) and estimates of the female spawning biomass in 1994 and 1995 from egg surveys (Bulman et al., 1999). Data were formulated by calendar year (i.e. 1 Jan to 31 Dec).

4.1 Catch

The landings from the SEF1 logbook data were used to apportion catches to the spawning and non-spawning fisheries. The SEF1 landings have been adjusted upwards to take account of differences between logbook and landings data (multiple of 1.4 for the non-spawning fishery since 1986; 1.2 for the spawning fishery from 1986 up to and including 1996; D. Smith, pers. comm.). These figures were then scaled up to the SEF2 data. As SEF2 data were only available from 1993, for years prior to this the average scaling factor from 1993 to 1998 was used to scale the data. The landings data are provided in Table 4.1.

Table 4.1. Landed and discarded catches for the winter spawning and non-spawning sub-fisheries by calendar year. These estimates have been adjusted scaled up to the SEF2 data (see text). The annual TAC is also shown. *Note that a voluntary industry reduction to 4,200 t was implemented in 2005.

Year	Landings		Discards		TAC
	Spawning	Non-spawning	Spawning	Non-spawning	
1979	245	245			
1980	410	410			
1981	225	225			
1982	390	390			
1983	450	450			
1984	675	675			
1985	600	600			
1986	321	1832			
1987	1020	2211			
1988	416	2254			
1989	47	2780			
1990	743	2543			
1991	830	3816			
1992	663	2384			
1993	990	2359			
1994	1196	1915			10000
1995	1196	1558		80	10000
1996	1465	1505		975	10000
1997	2957	1576		3716	10000
1998	3283	2451		1329	10000
1999	6106	3218		123	10000
2000	6037	2618		69	10000
2001	7670	1502		10	10000
2002	7417	1744		2	10000
2003	7504	986		4	9000
2004	4866	1785		37	7000
2005	2973	1732		513	5000*
2006	2058	1798		142	3730
2007	1815	1641		13	3530

4.2 Catch rates

Haddon (2008) provides the updated catch rate series for blue grenadier (Table 4.2, Figure 4.1). Models 5 and 4 of Haddon (2008) were recommended for use in the assessment models for the non-spawning and spawning fisheries respectively. Both series have declined in 2007 relative to 2006 but are still high compared to 2004 as a result of the large increases in 2005 and 2006.

Table 4.2. Standardised CPUE (Haddon, 2007) for the spawning and non-spawning sub-fisheries by calendar year.

Year	Spawning		Non-spawning	
	CPUE	Records	CPUE	Records
1986	1.00	77	1.00	2838
1987	1.40	156	1.25	3357
1988	2.99	91	1.33	3914
1989	0.76	31	1.48	4274
1990	0.75	147	1.44	3490
1991	2.91	132	1.00	4543
1992	1.31	189	0.87	3579
1993	2.32	154	0.67	4192
1994	1.25	318	0.58	4485
1995	0.51	477	0.41	5065
1996	0.76	489	0.36	5351
1997	0.58	436	0.38	6097
1998	0.91	575	0.61	6596
1999	0.68	1044	0.64	8072
2000	0.71	931	0.46	7622
2001	1.15	1085	0.26	7177
2002	0.83	1024	0.27	6304
2003	0.80	1018	0.22	5650
2004	0.66	803	0.36	6390
2005	1.40	410	0.43	5323
2006	2.44	466	0.57	4330
2007	1.40	304	0.50	3652

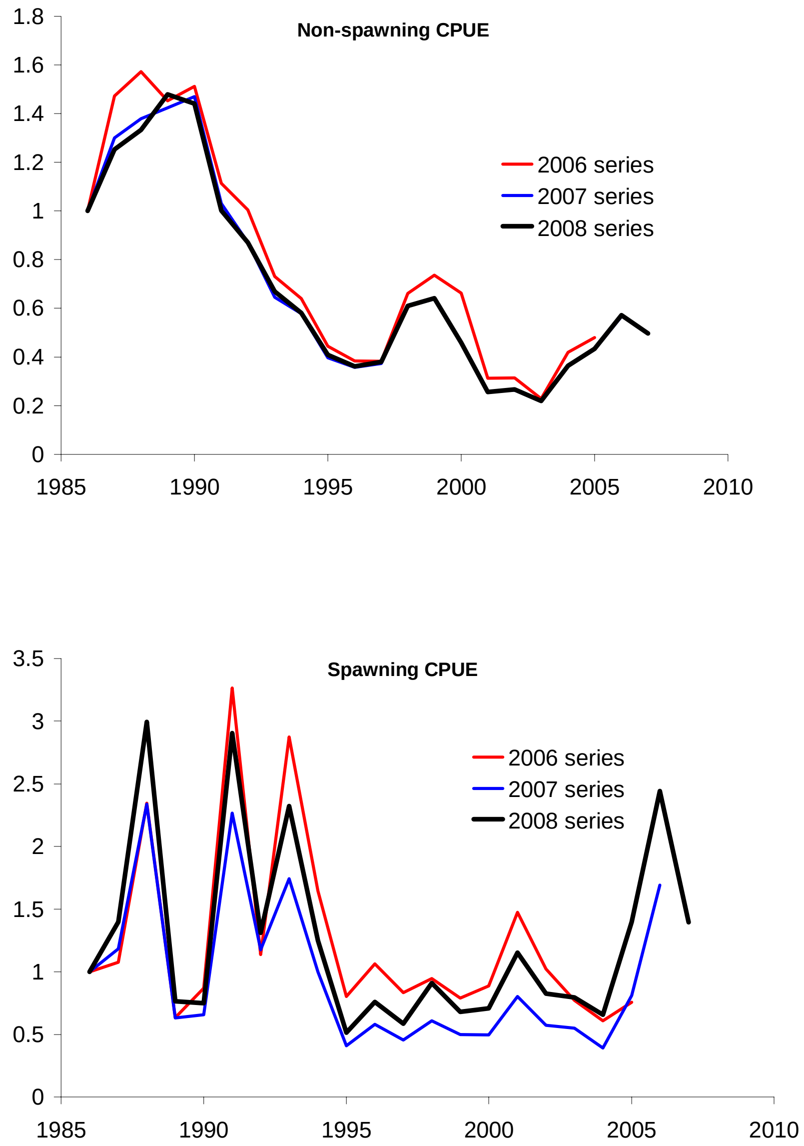


Figure 4.1 The calendar year catch-rate indices for the non-spawning (top) and spawning (bottom) blue grenadier fisheries (Haddon, 2008) in comparison to the series for 2006 and 2007 (Haddon, 2007).

4.3 Length Frequencies and Catch-at-age

The onboard length data for 2007, 2006 and all other years combined are shown in Figure 4.2. As it was not possible to distinguish between discard and retained lengths in 2007, it was assumed for the base-case model that all fish of length smaller than 50cm were discarded. The discards-at-age for 2007 are shown in Figure 4.3. A model sensitivity was considered where fish less than 70cm were assumed to have been discarded.

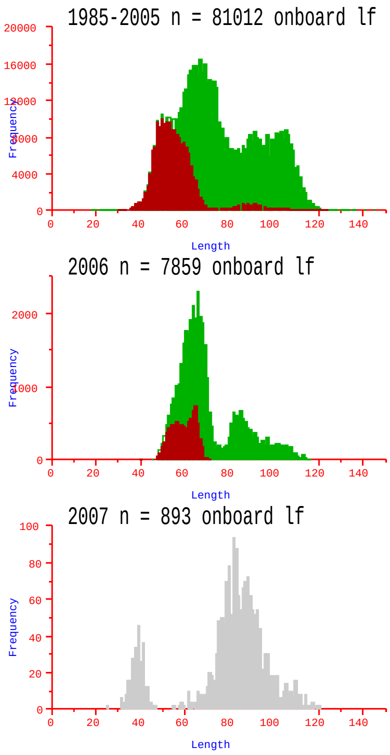


Figure 4.2 The onboard lengths for years 2007, 2006 and all years combined. Green represents retained fish, brown are discarded fish and grey (in 2007) are proportions of fish where it was not possible to distinguish between discarded and retained fish.

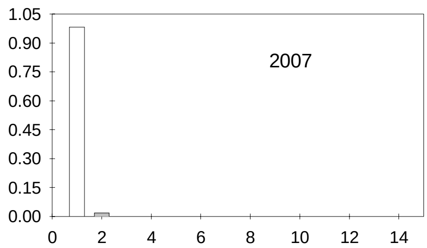


Figure 4.3 The proportion discarded-at-age from the non-spawning fishery for 2007.

Catch-weighted length frequencies across ports were used to produce the non-spawning length frequencies used in this assessment (N. Klaer, pers. comm.; D. Smith, pers. comm.). Figure 4.4 shows recent year non-spawning length frequencies. The age-compositions over all years are shown in Figure 9.4 to Figure 9.6.

Spawning sub-fishery length frequencies for 2007 were obtained from AFMA on-board observations. To obtain the overall length-frequency, length records were catch-weighted by the weight of catch from the haul and the sample weight of the fish (Figure 4.5).

The catch-at-age for 2007 for each of the two sub-fisheries is shown in Figure 4.6. As expected, the non-spawning age composition shows the presence of a recent year-class progressing into the available biomass. This year-class has now entered the spawning fishery also.

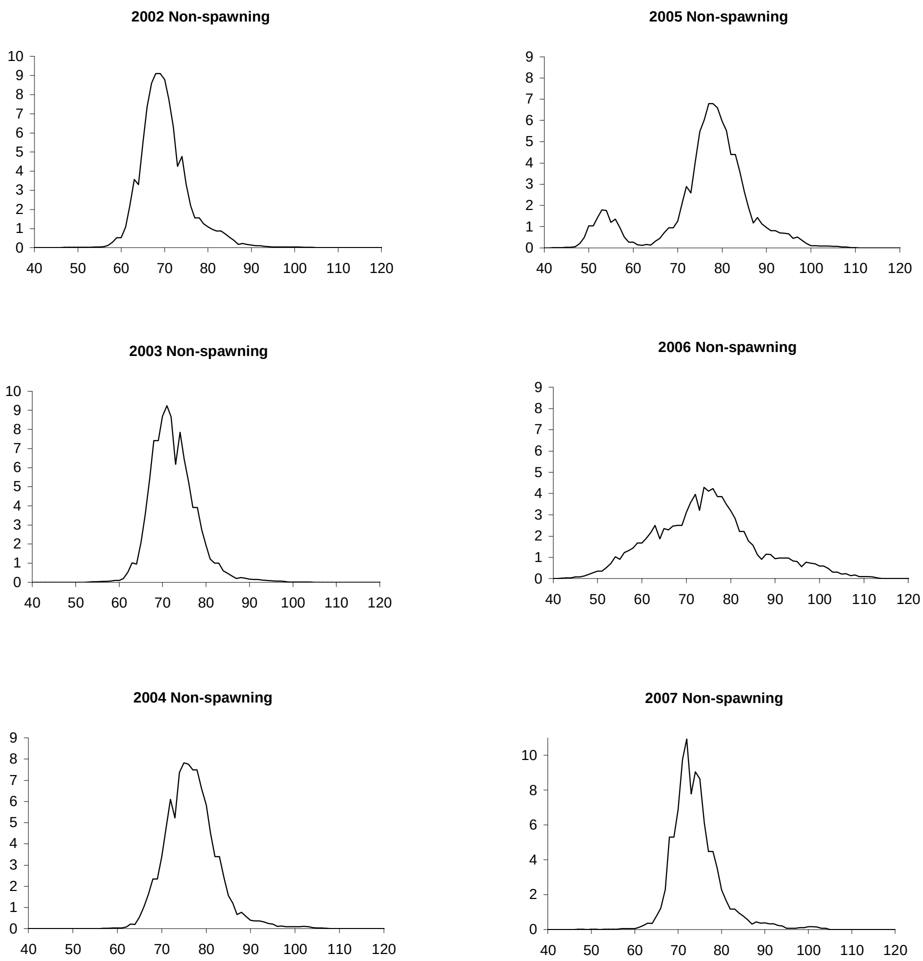


Figure 4.4. The port-based catch-weighted length frequencies for the non-spawning blue grenadier fishery over years 2002-2007.

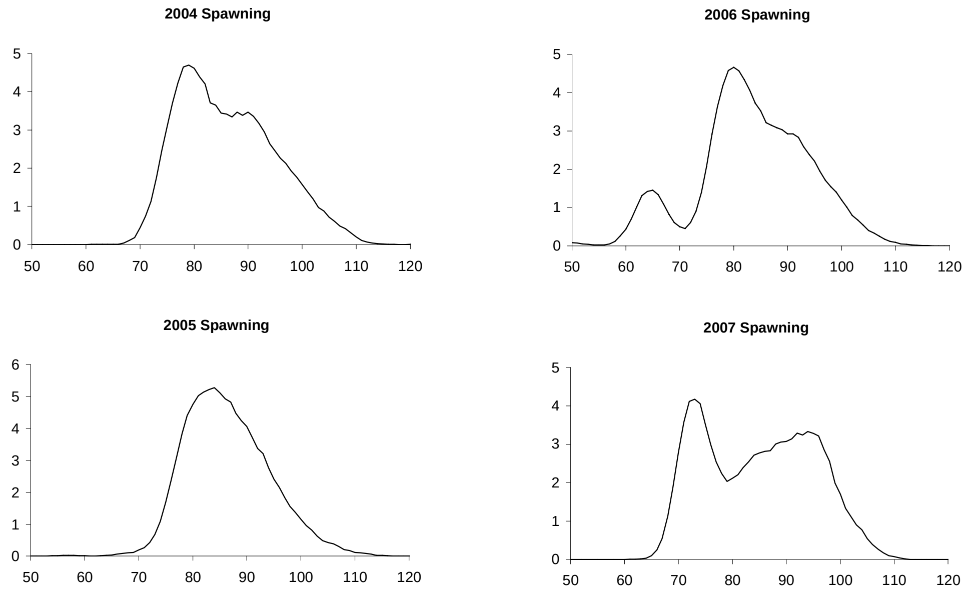


Figure 4.5. The catch-weighted length frequency for blue grenadier of the spawning sub-fishery in years 2004-2007.

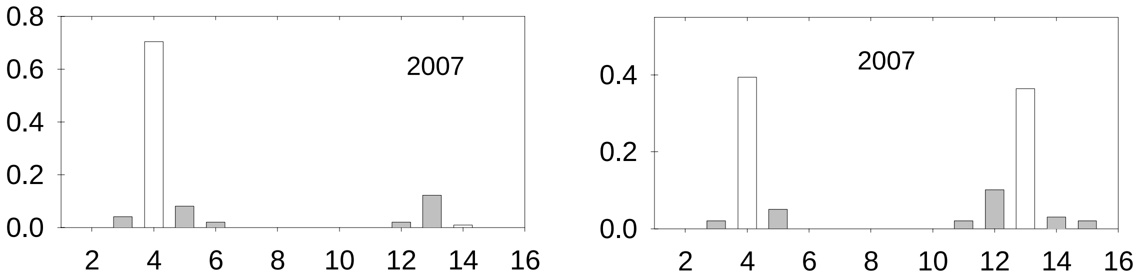


Figure 4.6. The observed proportion caught–at-age data for the non-spawning (left) and spawning (right) sub-fisheries in 2007.

4.4 Age-reading error

Standard deviations for aging error have been estimated, producing the age-reading error matrix of Table 4.4 (Punt, pers. comm.).

4.5 Acoustic survey estimates

Estimates of spawning biomass for years 2003-2007 are provided in Ryan and Kloser (2008). Two models of target strength were used in the assessments of Tuck and Punt (2006; 2007), namely Macauley (2004) and Cordue (2000). However, following the recommendations of Ryan and Kloser (2008), only estimates based on their results are presented here.

Blue grenadier in-situ target strength (TS) measurements are being used to convert the peak industry acoustic survey results to biomass in Australian waters (Kloser et al. 2007). These measurements were supported by acoustic modelling of the blue grenadier swim bladder and a range of assumed school fish tilt angles. New Zealand target strength measurements of hoki (same species as blue grenadier) were reviewed and these were a factor of 5-7 lower than Australian in-situ results due to the assumptions of fish tilt orientation and species identification (Kloser at al. 2007). No evidence to support the hoki assumed tilt distribution or species identification was found in the blue grenadier experiments, but these lacked visual verification of targets. To resolve this, new measurements of blue grenadier were obtained in the winter of 2008 with an Acoustic-Optical system attached to the headline of a trawl net off the west coast of Tasmania (Ryan et al. 2008). In-situ TS values were made that had corresponding video and digital photos, removing any uncertainty regarding species identification. A preliminary assessment of these TS measures support earlier blue grenadier target strength results. Uncertainty regarding tilt orientation is being reviewed and investigated as part of the research project. Based on the evidence to date, our biomass results are based on blue grenadier in situ target strength measurements for ongoing blue grenadier peak biomass surveys.

Table 4.3 shows the spawning biomass estimates with their corresponding c.v. It is assumed that the spawning ground experiences a turnover rate equal to 2 (i.e. for the model applied here, the spawning biomass estimates are doubled).

Table 4.3. The estimated biomass (tonnes) of blue grenadier on the spawning grounds in years 2003 to 2007 (Ryan and Kloser, 2008).

	2003	2004	2005	2006	2007
Spawning biomass (t)	24,690	16,295	18,852	42,882	56,630
c.v. used in assessment model	0.3	0.46	0.3	0.3	0.52

4.6 Egg survey estimates

Egg survey estimates of female spawning biomass are available for 1994 and 1995 (Bulman et al., 1999). The egg-estimates (cv) for 1994 and 1995 respectively are: 57,772 (0.18) and 41,409 (0.29). For the analysis considered here, the base-case egg estimates were used.

Table 4.4. The age-reading error matrix, shown as the percentage of times an animal with true age given by the column header is aged to be of the age given by the rows. Source: A.E. Punt and Central Aging Facility (CAF, PIRVic, Queenscliff, Victoria).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	88.6	12.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	11.4	75.5	13.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	12.2	73.8	13.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	13.1	72.0	14.9	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	13.9	70.0	15.9	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.1	14.9	68.0	16.8	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.1	15.9	65.9	17.8	0.5	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.1	16.8	63.7	18.8	0.7	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.2	17.8	61.5	19.8	0.9	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	18.8	59.1	20.7	1.3	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	19.8	56.8	21.5	1.7	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	20.7	54.4	22.3	2.2	0.1
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	21.5	52.0	23.0	2.9
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	22.3	49.6	23.5
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	25.2	73.6

4.7 Parameters of breeding biology

The assessment models prior to 2006, including base-case models, have assumed that the proportion of females that spawn is 0.77 and that the length at maturity is 70cm (Punt et al., 2001). These values were taken from research on hoki in New Zealand (Livingston et al., 1997). Recent studies have provided more up-to-date values for these parameters that are specific to the Australian stock of blue grenadier (S. Russell and D. Smith, pers. comm.), namely 0.84 for the proportion of females that is on the spawning grounds, and lengths at 50% maturity of 63.7cm for females and 56.8cm for males. As no information was available on the proportion of non-spawning male blue grenadier, it was assumed that this proportion was the same as that for females. In the results that follow (as was the case in Tuck and Punt (2006; 2007)), the updated parameters have been used.

5. ANALYTIC APPROACH

5.1 The population dynamics model

The population and likelihood models applied in 2008 are the same as those used in the 2007 assessment and are based upon the integrated analysis model developed for blue grenadier in the South East Fishery by Punt et al. (2001; Appendix; see also Tuck and Punt, 2007). The 2008 model is updated and extended by including the following data:

- the total mass landed and discarded during 2007; the catch- and discard-at-age during 2007 and the estimated mean length and weight of each age-class present during 2007,
- revised standardised CPUE series,
- an updated age-reading error matrix,
- an acoustic estimate of the 2007 spawning biomass off western Tasmania.

Two sub-fisheries are included in the model – the spawning sub-fishery that operates during winter (June – August inclusive) off western Tasmania (zone 40), and the non-spawning sub-fishery that operates during other times of the year and in other areas throughout the year. The model is sex dis-aggregated. However, male and female fish are assumed to grow at the same rate.

Parameter uncertainty is examined through the use of sensitivity tests and by applying the Markov Chain Monte Carlo (MCMC) algorithm (Hastings, 1970; Gelman et al., 1995).

5.2 The objective function

The negative of the logarithm of the likelihood function includes five components. These relate to minimizing the sizes of the recruitment residuals, fitting the observed catches and discards by fleet, fitting the observed age-compositions by fleet, fitting the catch rate information, and fitting the estimates of spawner biomass from the egg and acoustic surveys. The Appendix has details of the likelihood formulations (see also Punt et al. (2001)).

5.3 Parameter estimation

The values assumed for some of the (non-estimated) parameters of the base case models are shown in Table 5.1. The model has 118 estimated parameters: 2 catchability coefficients; 1 female natural mortality, 1 B_0, 31 annual fishing mortality rates for each of the two sub-fisheries; recruitment residuals for 28 years and 19 age classes in the first year; 2 selectivity parameters for the spawning sub-fishery and 3 for the non-spawning; and 2 parameters for the probability of discarding-at-length function.

The values for the parameters that maximize the objective function are determined using the AD Model Builder package[1]. This assessment quantifies the uncertainty of the estimates of the model parameters and of the other quantities of interest using Bayesian methods. The Markov Chain Monte Carlo (MCMC) algorithm (Hastings, 1970; Gelman et al., 1995) was used to sample 2000 equally likely parameter vectors from the joint posterior density function. The samples on which inference is based were generated by running 2,000,000 cycles of the MCMC algorithm, discarding the first 1,000,000 as a burn-in period and retaining every 500th parameter vector thereafter.

Table 5.1. Parameter values assumed for some of the non-estimated parameters of the base-case model.

Parameter	Description	Value
N	Weight for the catch- and discard-at-age data	50
σ_r	c.v. for the recruitment residuals	1.0
σ_c	c.v. for the landings data	0.05
σ_d	c.v. for the discard data	0.3
σ_q	c.v. for the CPUE data	0.3
h	“steepness” of the Beverton-Holt stock-recruit curve	0.9
x	age of plus group	15 years
μ	fraction of mature population that spawn each year	0.84
l_∞	von Bertalanffy parameter (maximum length)	102.76 cm
κ	von Bertalanffy parameter (growth rate)	0.16 y^{-1}
t_0	von Bertalanffy parameter	-2.209 y
aa	allometric length-weight equations	0.00375 g^{-1}.cm
bb	allometric length-weight equations	3.013
l_m	length at maturity (knife-edged) (M, F)	63.7, 56.8cm

[1] Copyright 1991, 1992 Otter Software Ltd.

6. RESULTS AND DISCUSSION

6.1 Stock assessment

Figure 9.1 shows the observed and predicted fits to the landings and discards from each sub-fishery. The model is forced to fit the recorded landings because of the low c.v. that is assumed for these data (σ_c = 0.05, Table 5.1). The model is able to fit the recent drop in the mass of discards and the recent increase; however the large discard measured in 1997 is not well estimated despite the ability of the model to allow for density-dependant discarding.

The estimated natural mortality figure for females is approximately 0.171 and consequently that for males is 0.21 (as male natural mortality is assumed to be 1.2 times that of females). This compares with 0.165 and 0.2 in Tuck and Punt (2007).

For the winter spawning sub-fishery, Figure 9.2 shows that the model is not able to fit the early large fluctuations in the CPUE, nor the large increases in CPUE in years 2005, 2006 and 2007 Note that the 2007 catch rate has declined substantially from the 2006 value, but is still higher than catch rates from the mid-1990s to 2004. Previously, the model has been able to achieve a reasonable fit to the CPUE in those intermediate years, but it is now balancing its desire to fit to the lower catch rate years and the higher catch rates of the last 3 years.

The fit to the CPUE for the non-spawning sub-fishery consistently shows an inability to fit to the increased catch rates observed in the late 1990s. The model shows an increase (and decline) in catch rate after the observed catch rate increase (and decline). However, the modelled CPUE has begun increasing in line with the observed increases in 2005 and 2006. In general though, it appears the modelled non-spawning catch rate is 1 to 2 years out of phase with that observed. Attempts to provide better fits to the non-spawning fishery catch rates have not been fruitful (such as forcing fits to the catch rate by lowering the cv). This issue will be explored further as a high priority. Changes to the form of the selectivity function may prove successful and conversion of the model to SS2 may assist this exploration.

The estimated vulnerability of fish of a given length class to being caught (but not necessarily landed) by either sub-fishery is shown in Figure 9.3. The probability that a fish will be discarded once it has been caught is also shown.

The fits to the catch-at-age and the discard-at-age data for both sub-fisheries are reasonably good across all years (Figure 9.4 and Figure 9.6). The catch ate age data for 2007 however shows a lack of fit; underestimating 4 and 13 year olds and over-estimating 3 year olds. A comparison of the age-length keys (ALKs) in 2006 and 2007 shows that there were many fish aged as 2 year olds in 2006. These fish do not appear in as high a proportion as 3 year olds in the 2007 ALK. This is because the birth date for blue grenadier is 1 June. In 2007, blue grenadier were not collected for ageing until after 1 June 2007. As such, all of the fish of ages 2 and 3 in 2006 (from the same cohort) are aged as 4 year olds in 2007 (K. Krusic-Golub, pers. comm.). Further exploration of assessment models with a biological year should be considered in order to overcome this issue.

Figure 9.7 shows the estimated annual recruitment multipliers, and illustrates a long period of poor recruitment following the strong recruitments of 1994 and 1995. An increase in recruitment has been estimated for years 2003, 2004 and 2006. These recent recruitment events are approximately 2 to 3 times that predicted by the stock recruitment relationship. The recruitments do not appear to be as strong as those of the mid-1990s. Given the smaller number of onboard samples taken in 2007, the magnitude and potential of the most recent estimated recruitment (2006) will become clearer over the next few years as it enters the commercial fishery.

Table 6.1 shows the results against various quantities of interest for the base case models. The quantities of interest shown are the estimated pristine female spawning biomass (B_0); the reference biomass (B_{ref}) which is the average female spawning biomass over 1979–1988; the spawning biomass in 1979 ($\tilde{B}_{79}$) and in 2007 ($\tilde{B}_{2007}$) and its size in 2007 relative to the reference level (depletion, $\tilde{B}_y / B_{ref}$); the estimated fishing mortality rate for the spawning (F^1_{curr}) and non-spawning (F^2_{curr}) sub-fisheries for 2007 (=*curr*); the estimated recruitment residual for the strong 1994 cohort, and the more recent 2004 cohort, and the negative log likelihood (-ln L) value from the model. Also shown are the base-case results for previous years' assessments. Note that the final year of biomass estimation (*curr*) is one year less than the year the assessment is produced.

The assessment of 2008 concludes that the reference female biomass is approximately 45,500 t and that current female spawner biomass (in the middle of 2007) is approximately 71% of the reference biomass. Figure 9.8 shows the spawning biomass trajectory with the egg survey estimates (left; female spawning biomass only) and the acoustic estimates (right; total spawning biomass). Intervals on survey estimates are 2 standard deviations. Figure 9.9 shows the female spawning biomass trajectory relative to the reference biomass for each model. The trend in relative spawning biomass is similar to those seen in previous assessments; however, there is an increase in the most recent 2 years that was not predicted in the 2007 assessment (see below).

Table 6.1. Estimated values for several parameters of interest. The base case model is shown as well as sensitivity tests. Results are shown for base-case runs in the previous 3 years for comparison with the 2008 assessment. 'Curr' refers to the current or final year of the estimation. The High Models use the higher acoustic survey estimates of total spawning biomass with the egg survey estimates of female spawning biomass doubled. The Low models use the lower acoustic estimates of total spawning biomass with the base-case egg survey estimates. Both of these models assume 2 times turnover. The 2008 base case model uses the Low model assumptions, assumes all fish less than 50cm were discarded in 2007 and assumes a cpue cv of 0.3.

Specification	B_0	B_{ref}	$\tilde{B}_{79}$	$\tilde{B}_{curr}$	$\tilde{B}_{curr} / B_{ref}$	F^1_{curr}	F^2_{curr}	R_{94}	R_{03}	-ln L
Previous assessment results										
Base-case, *curr*=2002	33026	52605	51685	31241	59.39%	0.175	0.027	6.0	-	352.42
Base-case, *curr*=2003	26877	42082	41441	18066	42.93%	0.278	0.026	6.2	-	362.06
Base-case, *curr*=2004	30241	48612	47311	21283	43.78%	0.139	0.036	6.9	0.71	396.00
2006 assessment, *curr*=2005										
Low Model	27467	49293	47396	18065	36.65%	0.085	0.067	11.4	1.7	372.67
High Model	63917	148749	155947	62203	41.82%	0.027	0.020	10.1	1.8	378.56
2007 assessment, *curr*=2006										
Low Model	30340	50644	44701	23867	47.13%	0.050	0.055	11.6	2.1	466.49
High Model	69677	140254	130565	75166	53.59%	0.016	0.019	10.2	2.0	466.40
2008 assessment, *curr*=2007										
Base case model	29023	45493	39963	32423	71.3%	0.039	0.037	13.1	2.8	524.76
Discard all < 70cm	26954	43953	38323	32847	74.7%	0.038	0.038	13.9	3.5	546.82
Cpue cv=0.15	35249	64690	56705	42478	65.6%	0.030	0.026	11.0	2.8	727.10
Half age Weight	31334	47460	40790	35092	73.9%	0.037	0.032	11.8	2.5	337.84

6.2 Retrospective analysis

Figure 9.10 and Figure 9.11 show the female spawning biomass, total spawning biomass and recruitment multipliers for each of the assessments from 2004 to 2008. This shows how the 2008 spawning biomass trajectories have increased in recent years compared to previous assessments. This is due to the increase in observed catch rate, the age data and the large 2006 acoustic estimate (Tuck and Punt, 2007).

6.3 Transition from the 2007 to the 2008 assessment

To explore the changes observed in Figure 9.10 and Figure 9.11 following the inclusion of the 2007 calendar year data, a sequential analysis was conducted to determine the influence of each of the input data sources. Figure 9.12 show the SSB time series as each data source (listed and labelled below) is added and an assessment conducted. Note that the age data below refers to the catch-at-age, discard-at-age, mean length-at-age and age-reading error data. The various transitional assessments and their data-source changes are:

1. The 2007 assessment result (**2007**)
2. The 2007 assessment data with the addition of the updated catches, including 2007 (**2007 C**)
3. Option 2 with the updated catch rate series of 2008 (**C + Cpue**)
4. Option 2 with the addition of the age data (**C + Age Data**)
5. Option 4 with the addition of the cpue data (**C + Cpue + Age Data**)
6. Option 5 with the addition of the updated discard masses (**C + Cpue + AgeData + D**)
7. The 2008 assessment result (**2008**)

Note that the 2008 assessment result is equivalent to (**C + Cpue + AgeData + D + AC**), where AC is the acoustic estimates of spawning biomass.

Figure 9.12 and Figure 9.13 show that, as each data source is added, the most recent year female spawning biomass changes from the 2007 assessment values through to the 2008 assessment values. The inclusion of the ageing data and cpue produces a substantial upward shift in the trajectory. The updated acoustic data do not greatly influence the time series due to the large error bounds on the 2007 biomass estimate.

6.4 Harvest control rule application

The steps involved in computing the Recommended Biological Catch for 2007 using the Tier 1 rules are:

1. Determine the relationship between exploitation rate and spawning biomass, where the relative exploitation rates among the fleets are based on the exploitation rates estimated for 2008.
2. Find the exploitation rates so that spawning biomass is a pre-specified fraction of that in an unfished state.
3. Determine the depletion of the spawning biomass in the middle of 2009.
4. Determine the correction factor (if needed), and multiply the exploitation rates calculated at step 2 by this correction factor.
5. Multiply the numbers-at-age in the middle of 2009 by the exploitation rates calculated at step 4.

Two variants of the Tier 1 rules are applied depending on specifications for the target spawning biomass and the depletion at which the exploitation rate begins to be reduced to zero (all variants set the exploitation rate to zero if the stock is assessed to be depleted to below 20% of B_{ref}):

a) 20-35-48; a target stock size of 48% of B_{ref}, with the exploitation rate dropping off once the stock drops below 0.35 B_{ref}.
b) 20-40-40; a target stock size of 40% of B_{ref}, with the exploitation rate dropping off once the stock drops below the target level.

The mid-year depletion in 2009 must be calculated to apply the Tier 1 harvest control rule. The 2009 depletion is shown in Table 6.2 and is calculated by assuming a 2008 catch of 4,368 t. The resulting landed and total Recommended Biological Catches (RBC) for 2009 are given in Table 6.2.

The time series of landed RBCs and depletions under each Tier 1 rule is given in Table 6.3, Figure 9.14 and Figure 9.15. Note that the final depletions are not exactly 40% and 48% of B_{ref} . This occurs presumably because density-dependence in the stock recruitment model is a function of depletion relative to B_0 and not relative to B_{ref}. As a result the depletion in terms of B_0 is higher than in terms of B_{ref}. The annual depletion levels under the 2008 catch of 4,368t are also shown in this table. From Figure 9.15 it is worth noting the marked decline in biomass relative to the reference level over years 2007 and 2009 (from 0.71 to 0.50). This is likely to be due to the declining availability of the large cohort of the 1990s (as they senesce; Figure 9.4) and the majority of the catch being caught from the relatively smaller cohort of 2003/04.

From Table 6.3, the long-term RBCs are approximately 4,700t for a target depletion of 48% of the reference biomass and 5,270t for 40% (note these values are approximate as they have not stabilised over the 20 year projection horizon considered in Table 6.3).

Table 6.2. The estimated 2009 mid-year depletion and RBCs (landed and total; tonnes) for the base-case model for two Tier 1 harvest control rules with target biomass depletions of either 48% or 40%.

Tier rule	2009 Depletion	Landed RBC	Total RBC (landed+discard)
20:40:40	0.50	6,089	6,459
20:35:48	0.51	4,750	5,036

Table 6.3. The time series of landed RBCs and corresponding depletions relative to B_{ref} for each Tier 1 rule. Also shown is the annual depletion if the current landed catch of 4,368 t is maintained over all projected years.

	Landed RBC		Depletion		
	20:40:40	20:35:48	20:40:40	20:35:48	Ccurr=4,368
2008	4367	4367	0.60	0.60	0.60
2009	6089	4750	0.50	0.51	0.51
2010	6027	4812	0.53	0.55	0.56
2011	5882	4795	0.51	0.54	0.55
2012	5823	4833	0.50	0.54	0.56
2013	5757	4855	0.48	0.53	0.56
2014	5646	4821	0.47	0.53	0.56
2015	5558	4794	0.46	0.52	0.56
2016	5491	4772	0.46	0.52	0.57
2017	5439	4756	0.45	0.52	0.57
2018	5399	4743	0.45	0.52	0.57
2019	5368	4734	0.44	0.52	0.57
2020	5344	4727	0.44	0.51	0.58
2021	5325	4721	0.44	0.51	0.58
2022	5311	4716	0.44	0.51	0.58
2023	5299	4713	0.44	0.51	0.58
2024	5290	4710	0.44	0.51	0.58
2025	5283	4707	0.44	0.51	0.58
2026	5277	4705	0.43	0.51	0.58
2027	5272	4704	0.43	0.51	0.58

7. ACKNOWLEDGEMENTS

Many thanks are due to Sandy Morison, Andre Punt and all of the SS2-WG for their assistance with model discussions and development. Malcolm Haddon is thanked for providing catch rate indices, Mike Fuller and Neil Klaer for their advice on data matters. Kyne Krusic-Golub (Central Aging Facility) and the AFMA observer section are thanked for providing the aging data and spawning length frequency data respectively.

8. REFERENCES

Bulman, C. M., Koslow, J. A., and Haskard, K. A. 1999. Estimation of the spawning stock biomass of blue grenadier (*Macruronus novaezelandiae*) off western Tasmania based upon the annual egg production method. Marine and Freshwater Research. 50:197-207.

Francis, R.I.C.C. 1992. Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplosethus atlanticus*) on the Chatham Rise, New Zealand. Canadian Journal of Fisheries and Aquatic Sciences 49: 922-930.

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

Haddon, M. 2007. Standardized Commercial Catch-Effort data for selected Shelf and Slope Assessment Group Species for 1986 - 2006. Technical paper presented to the Slope Resource Assessment Group. July 23-24, 2007, Queenscliff, Victoria.

Haddon, M. 2008. Catch Rate Standardizations 2008 (for data 1986 – 2007). Technical paper presented to Slope Resource Assessment Group. 17-18 November 2008. Hobart, Tasmania.

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

Kloser R.J., Ryan T.E. and Geen, G. 2007. Development of a sustainable industry-based acoustic observation system for blue grenadier at the primary spawning sites. Report to Australian Fisheries Management Authority (AFMA).

Livingston, M.E., Vignaux, M. and Schofield, K.A. 1997. Estimating the annual proportion of non-spawning adults in New Zealand hoki, *Macruronus novaezelandiae.* Fishery Bulletin (US) 95:99-113.

McAllister, M.K., Pikitch, E.K., Punt, A.E., and Hilborn, R. 1994. A Bayesian approach to stock assessment and harvest decisions using catch-age data and the sampling/importance resampling algorithm. Canadian Journal of Fisheries and Aquatic Sciences 51: 2673-2687.

Punt, A.E., Smith, D.C., Thomson, R.B., Haddon, M., He. X and Lyle, J.M. 2001. Stock assessment of the blue grenadier *Macruronus novaezelandiae* resource off south eastern Australia. Marine and Freshwater Resources. 52:701-717.

Ryan, T.E. and Kloser, R.J. 2008. Industry based acoustic surveys of Tasmanian West Coast blue grenadier during the 2007 spawning season. Australian Fisheries Management Authority. August 2008. Project 2006/832.

Ryan, T.E., Kloser, R.J and Geen, G. 2007. Industry based acoustic surveys of Tasmanian West Coast blue grenadier during the 2006 spawning season. Final report to AFMA. Project 2006/808.

Ryan, T.E., Kloser, R.J., and Macaulay, G.J. 2008. Visually verified in situ target strength measurements of fish using an acoustic-optical system attached to a trawl net. ICES Symposium on the Ecosystem Approach with Fisheries Acoustics and Comlementary Technologies, Bergen, Norway June 2008

Tuck, G.N. 2006. Updated stock assessment for blue grenadier in the Southern and Eastern Scalefish and Shark Fishery: July 2006. Report to the Slope Resource Assessment Group. 24-25 July 2006.

Tuck, G.N., Koopman, M. 2005. Updated stock assessment for blue grenadier in the South East Fishery, August 2005. Report to the Slope Resource Assessment Group. 25-26 August 2005.

Tuck, G.N., Punt, A.E. 2006. Updated stock assessment of blue grenadier *Macruronus novaezelandiae* based on data up to 2005: application of new base-case models, harvest control rules and decision analysis. Report to the Slope Resource Assessment Group. 25 August 2006.

Tuck, G.N., Punt, A.E. 2007. Updated stock assessment of blue grenadier *Macruronus novaezelandiae* based on data up to 2006: July 2007. Report to the Slope Resource Assessment Group. 25 August 2006.

Tuck, G.N., Smith, D.C and Talman, S. 2004. Updated stock assessment for blue grenadier in the South East Fishery, August 2004. Report to the Slope Resource Assessment Group. August 2004.

9. FIGURES

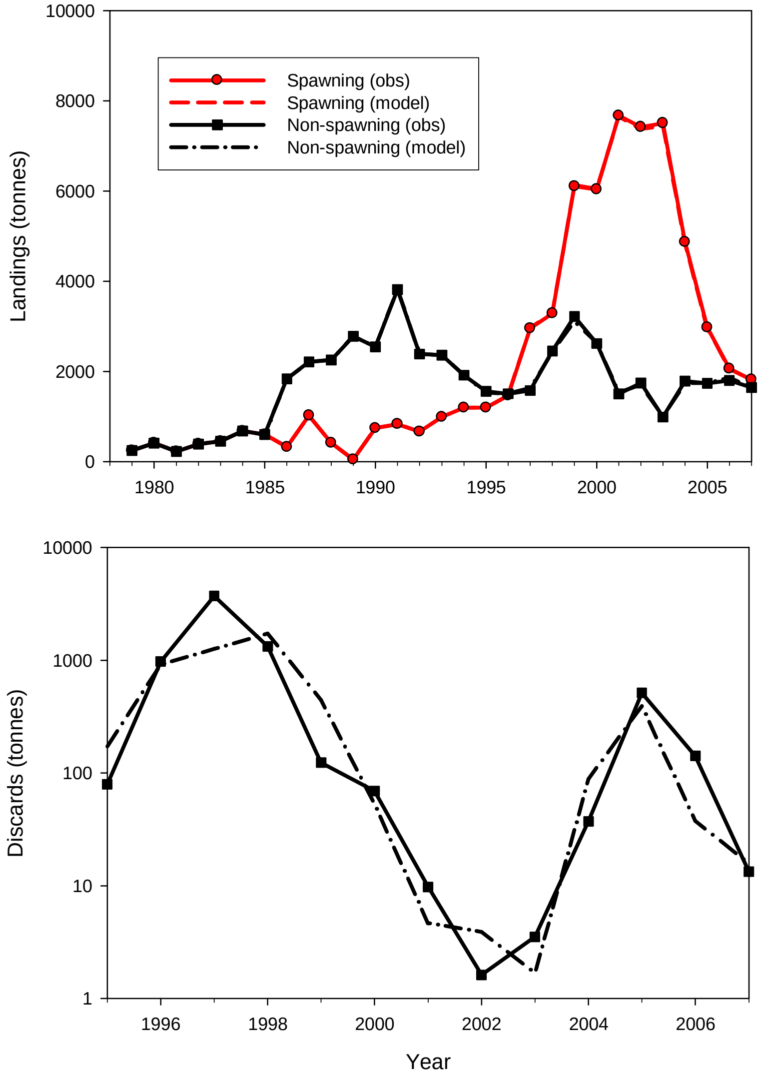
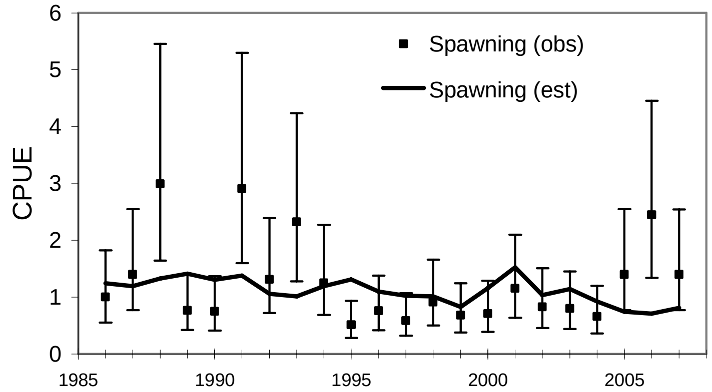


Figure 9.1. Top plot: Annual landings of blue grenadier (obs) and estimated by the base case model (model). Bottom plot: Discards estimated from the ISMP (solid line) and base-case model estimated values (dashed line). Note that the lines for the modelled spawning and non-spawning (model) landings overlay those of the observed (obs) lines for each sub-fishery.



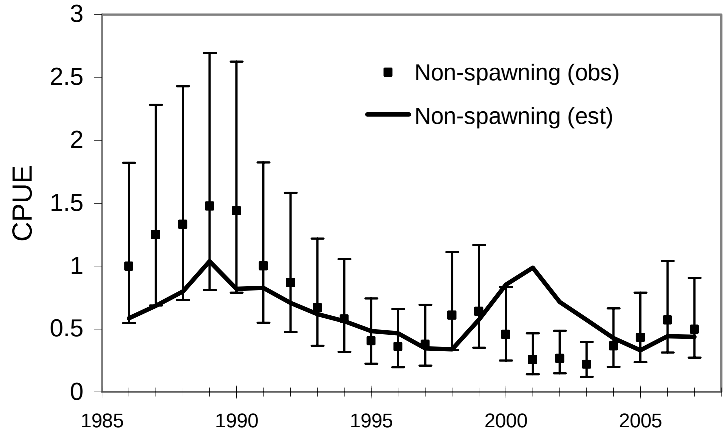


Figure 9.2. Catch-per-unit-effort (CPUE) calculated using a GLM to standardise CPUE from log-books (obs; Haddon, 2008) and the base-case model estimated CPUE for the spawning fishery (top) and the non-spawning fishery (bottom).

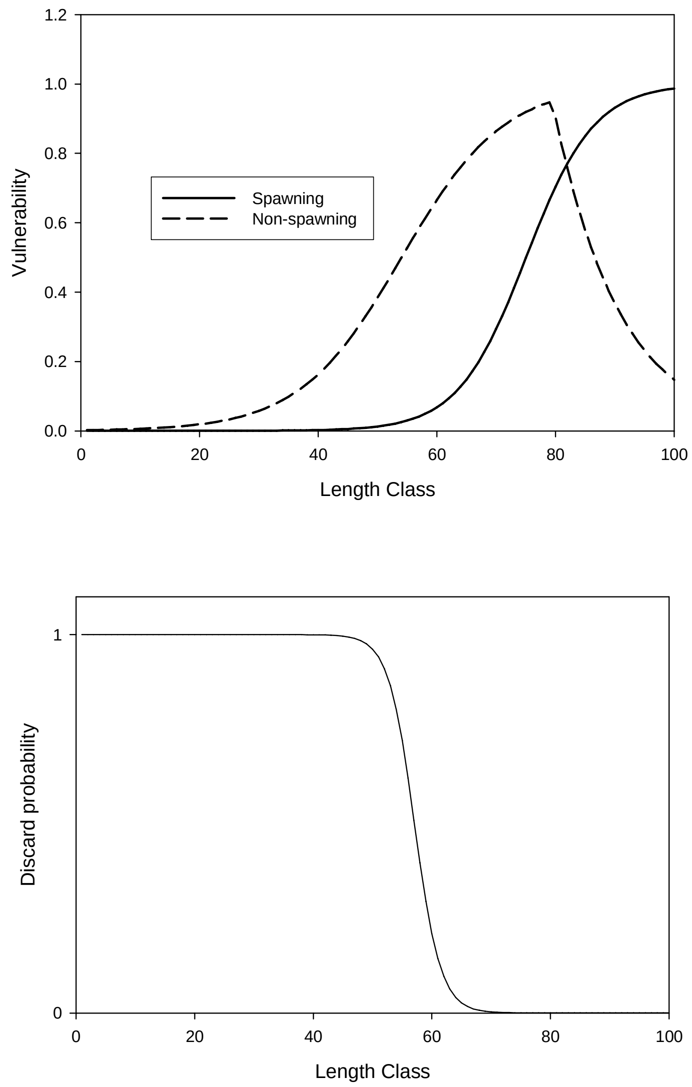


Figure 9.3. Vulnerability of blue grenadier to being caught (but not necessarily landed) by the two sub-fisheries (top) and the probability of being discarded if caught (bottom) as a function of length class for the base case model.

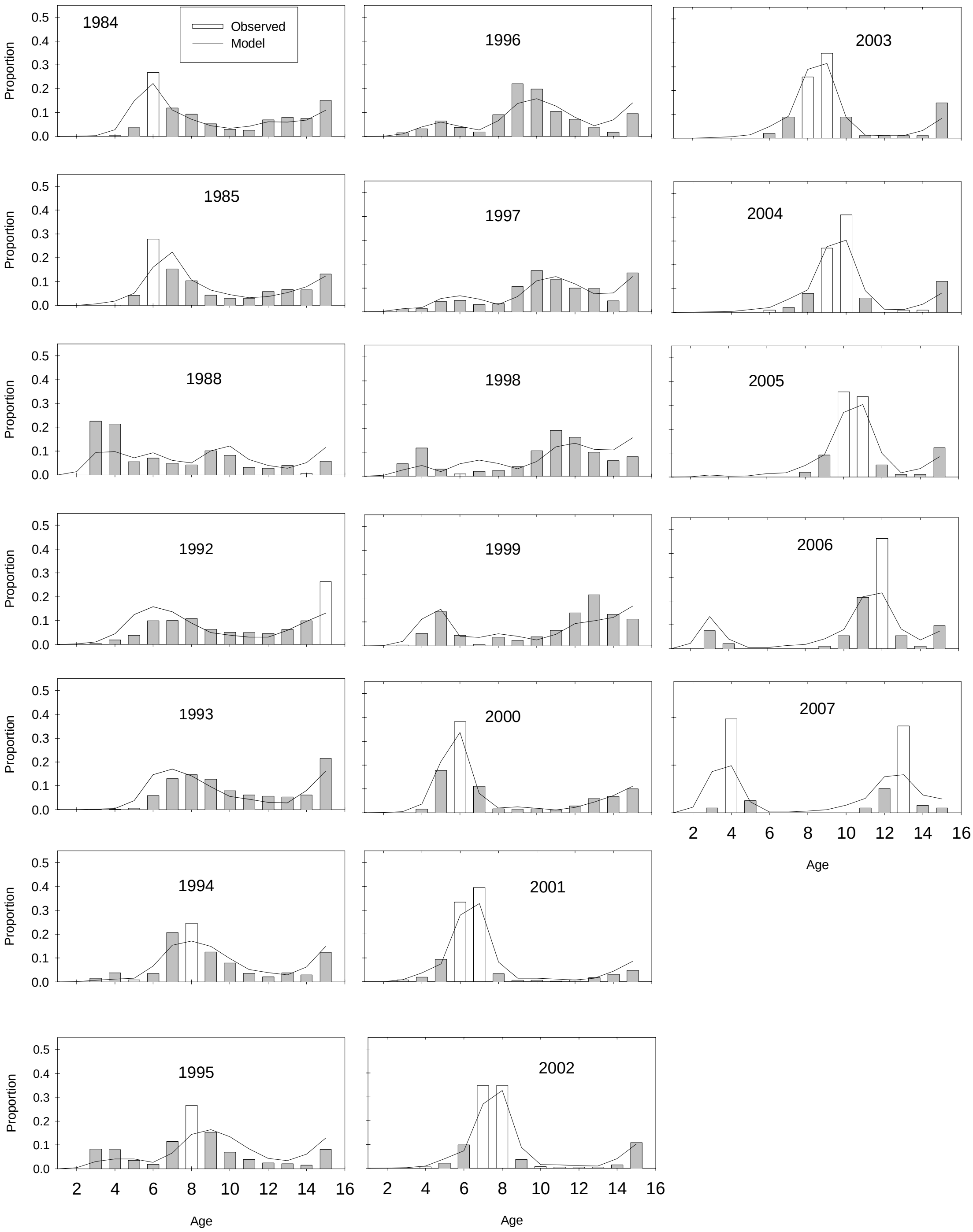


Figure 9.4. Observed (bars) and model estimated (lines) proportion caught at age for the spawning sub-fishery and base case model.

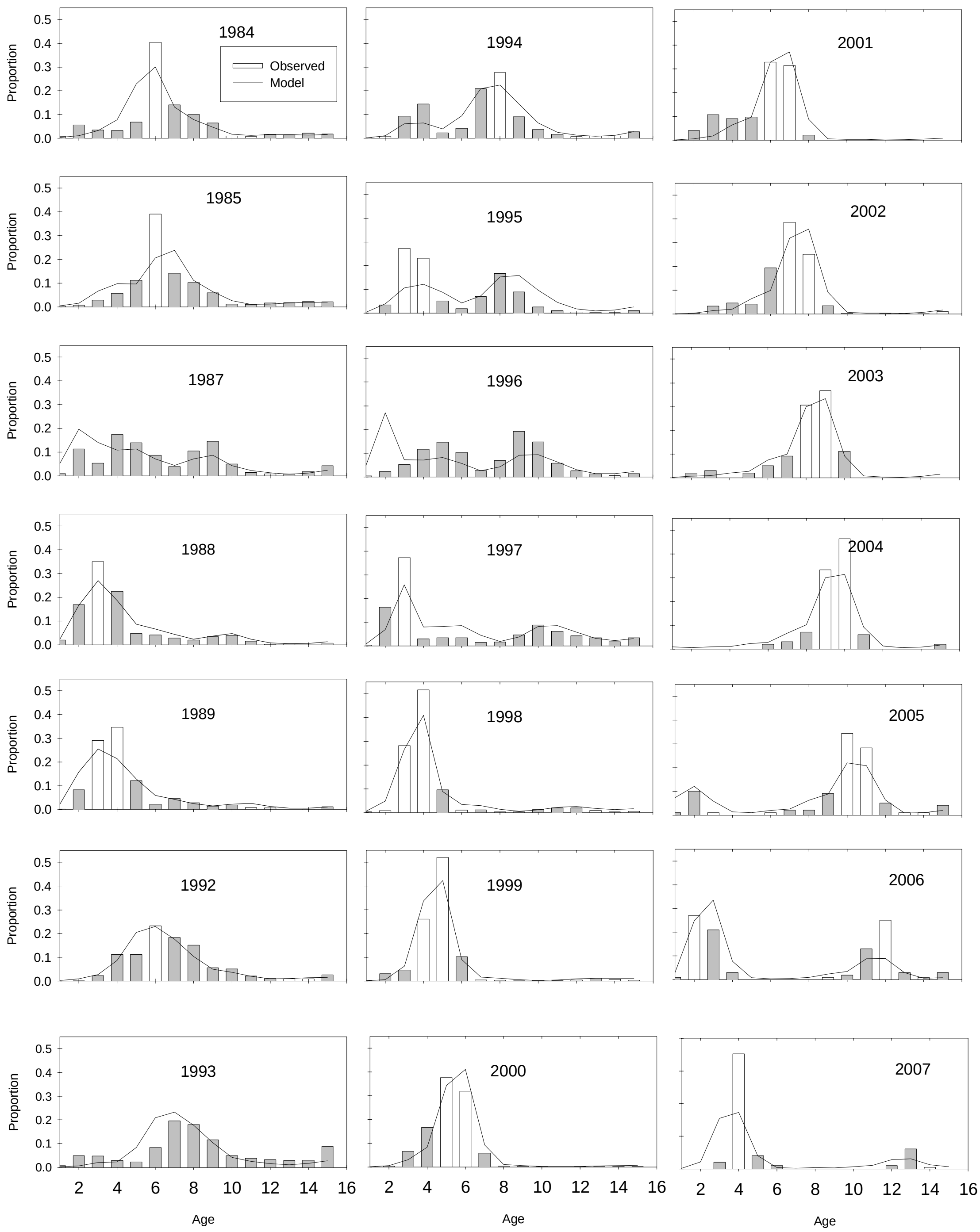


Figure 9.5. Observed (bars) and model estimated (lines) proportion caught at age for the non-spawning sub-fishery and base case model.

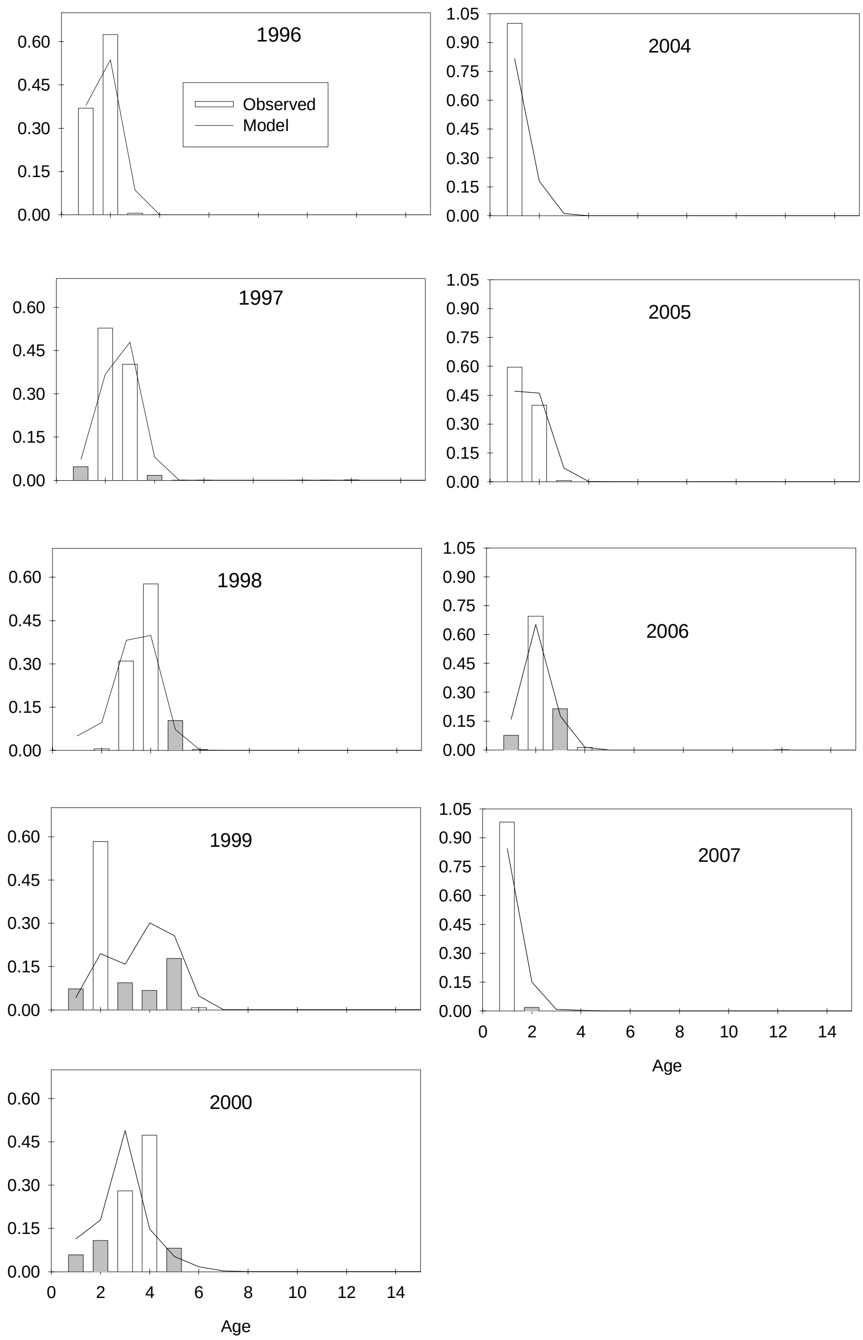
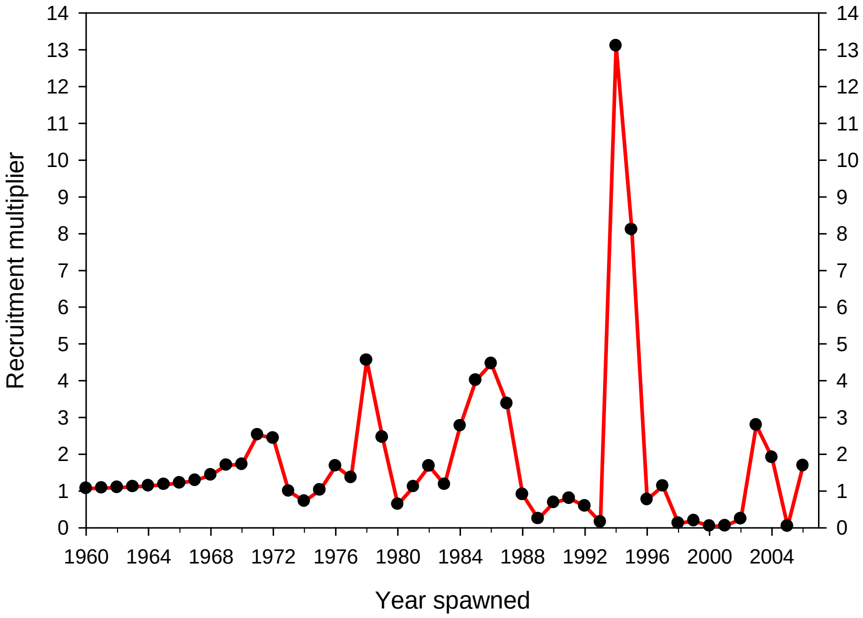


Figure 9.6. Observed (bars) and model estimated (lines) proportion discarded-at-age for the non-spawning sub-fishery and base case model.



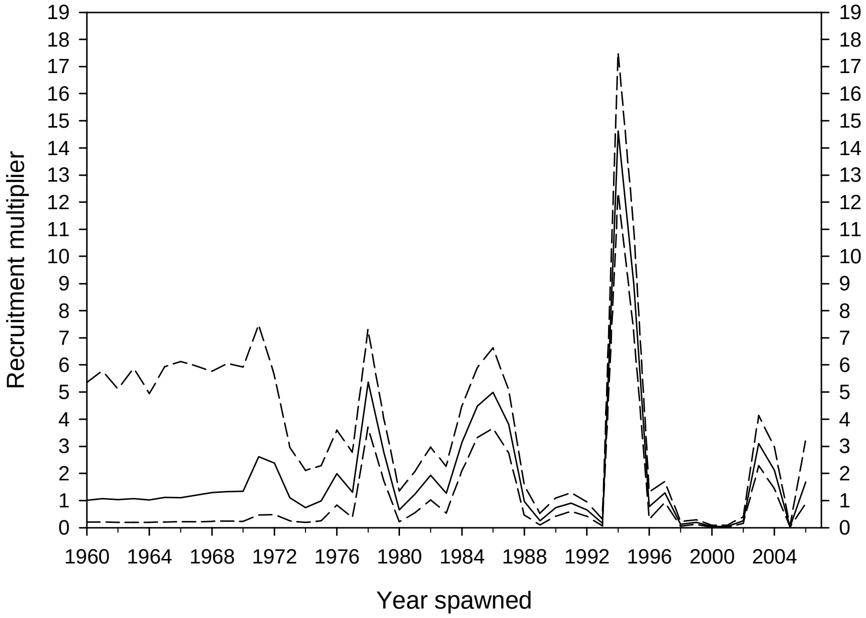


Figure 9.7. Estimated recruitment multipliers (the amount by which the recruitment deviated from that predicted by the stock-recruit relationship) versus year of spawning for the base case model. Bottom: The median (solid line), upper and lower 95% bounds (dashed lines) on the recruitment multipliers for the base case model.

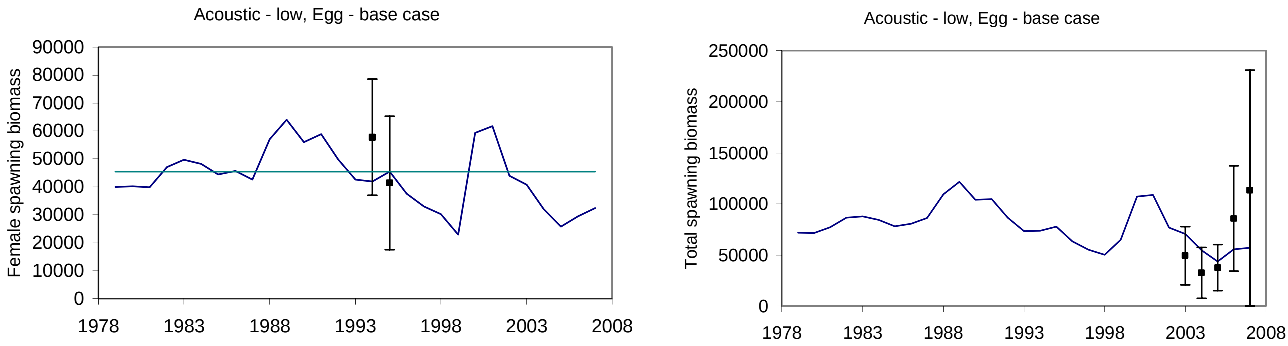


Figure 9.8. The time-trajectory of female spawning biomass (left) and total spawning biomass (right) for the base case model. The vertical lines show the estimates of spawning biomass derived from surveys of egg abundance in 1994 and 1995 and acoustic surveys from 2003 to 2007. The horizontal line shows B_{ref}, which is defined as the average female spawning biomass over 1979–1988.

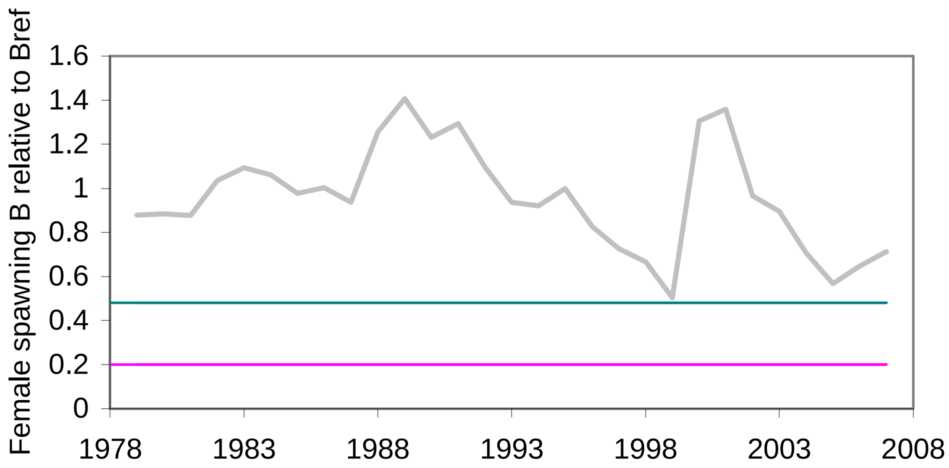
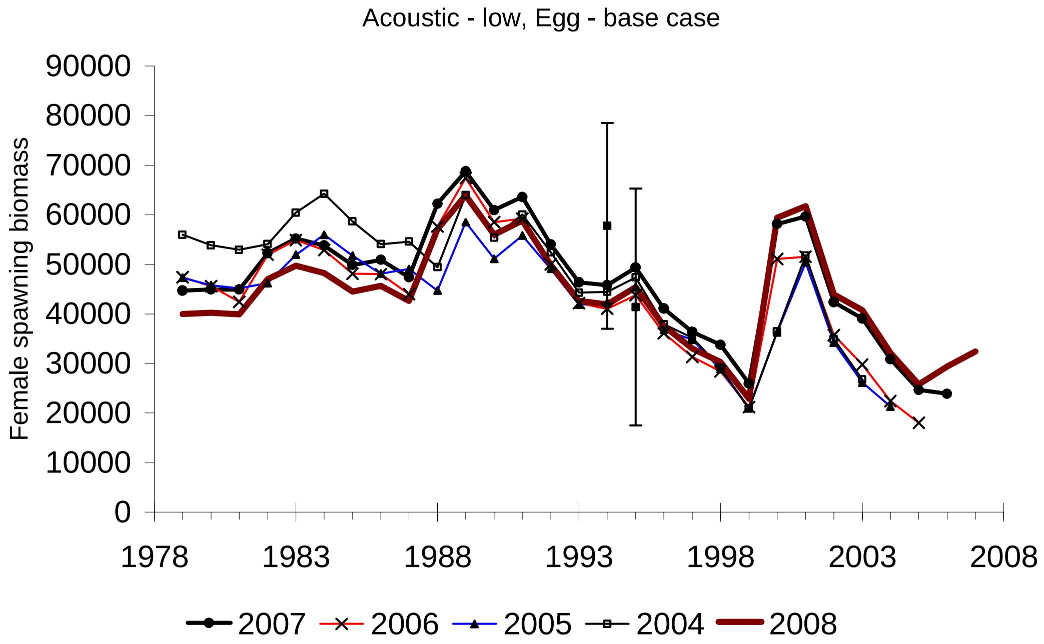


Figure 9.9. The trajectory of female spawning biomass relative to the reference biomass, Bref for the base case model. The horizontal lines show the 0.48 and 0.20 levels.



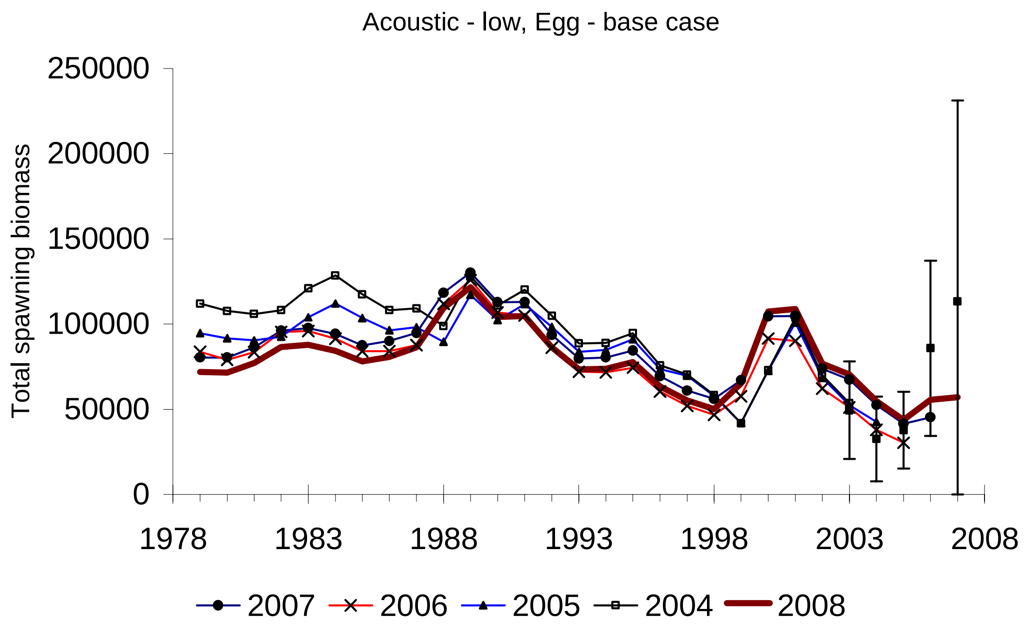


Figure 9.10. The female spawning biomass (top) in relation to the egg survey estimates of biomass and the total spawning biomass (bottom) in relation to the acoustic estimates for each of the base case (‘Low’) assessments from 2004 to 2008.

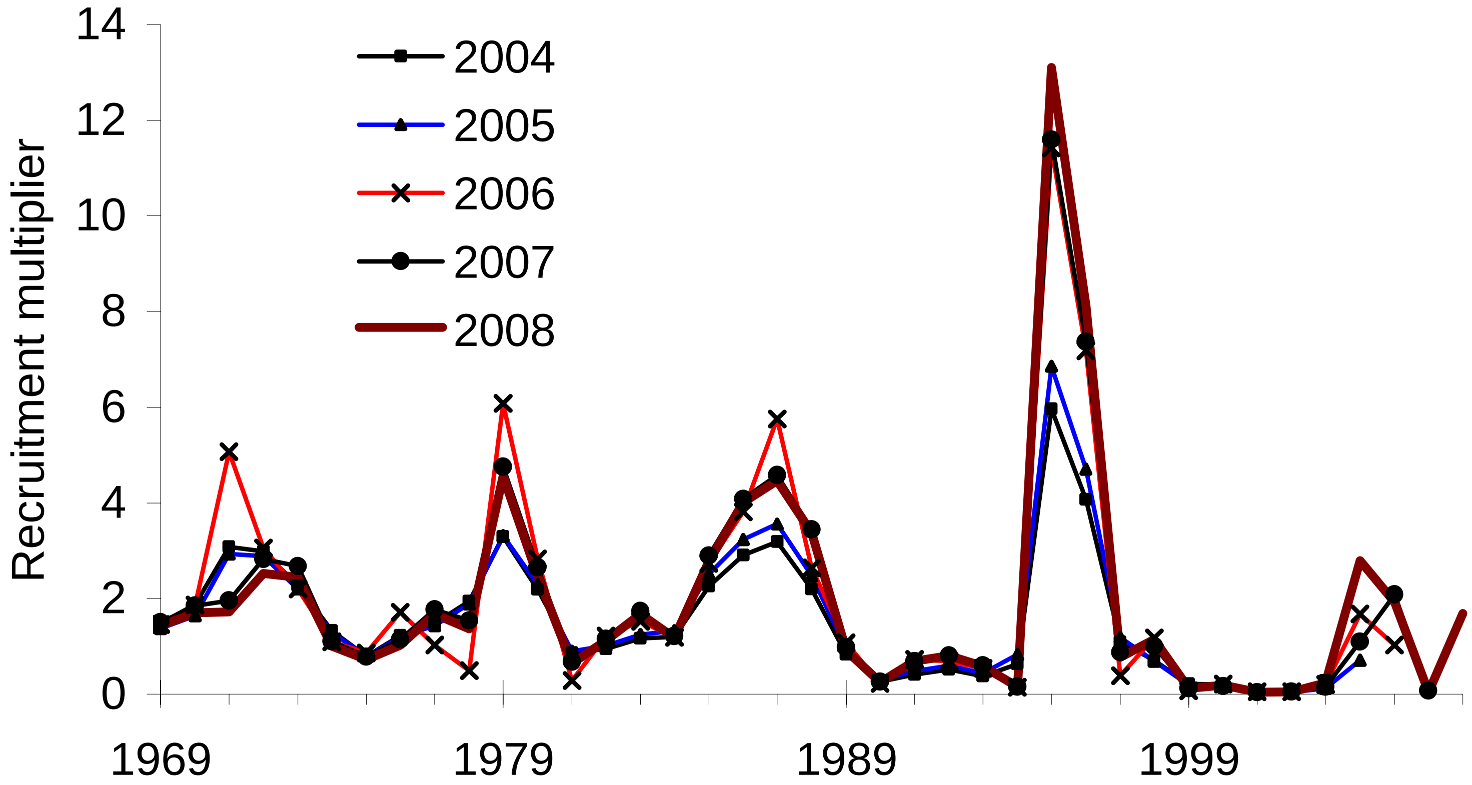


Figure 9.11 The estimated annual recruitment multipliers for each of the base case assessments of blue grenadier from 2003 to 2008.

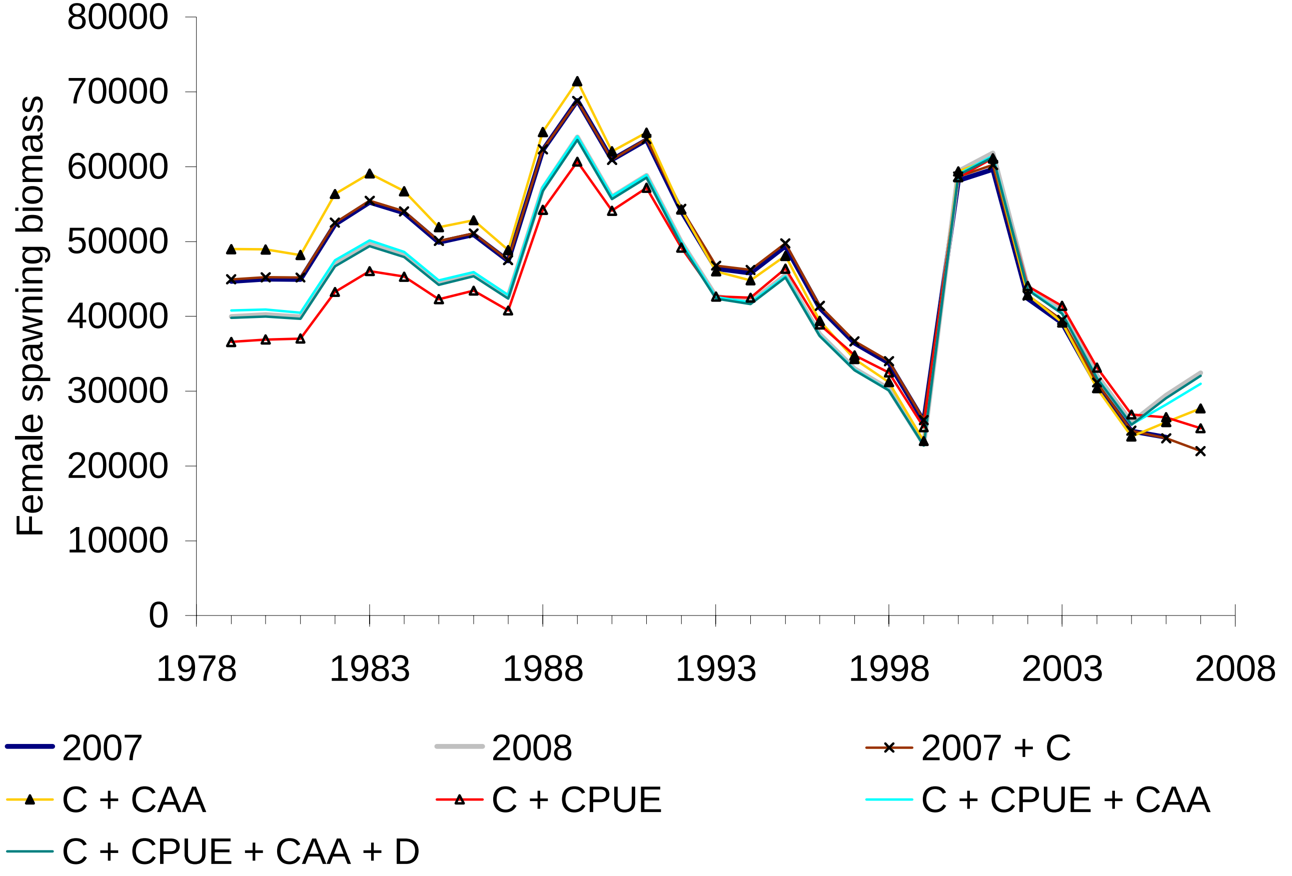


Figure 9.12. The female spawning biomass as a function of the data sources provided to the assessment. 2007 is the series from the 2007 assessment (Tuck and Punt, 2007), C = catch data series from 2008 included, CAA = updated age data are included, CPUE = updated catch rates series from 2008 is included (Haddon, 2008). 2008 is equivalent to C + CPUE + CAA + D + AC, where AC is the inclusion of the 2007 acoustic biomass estimate

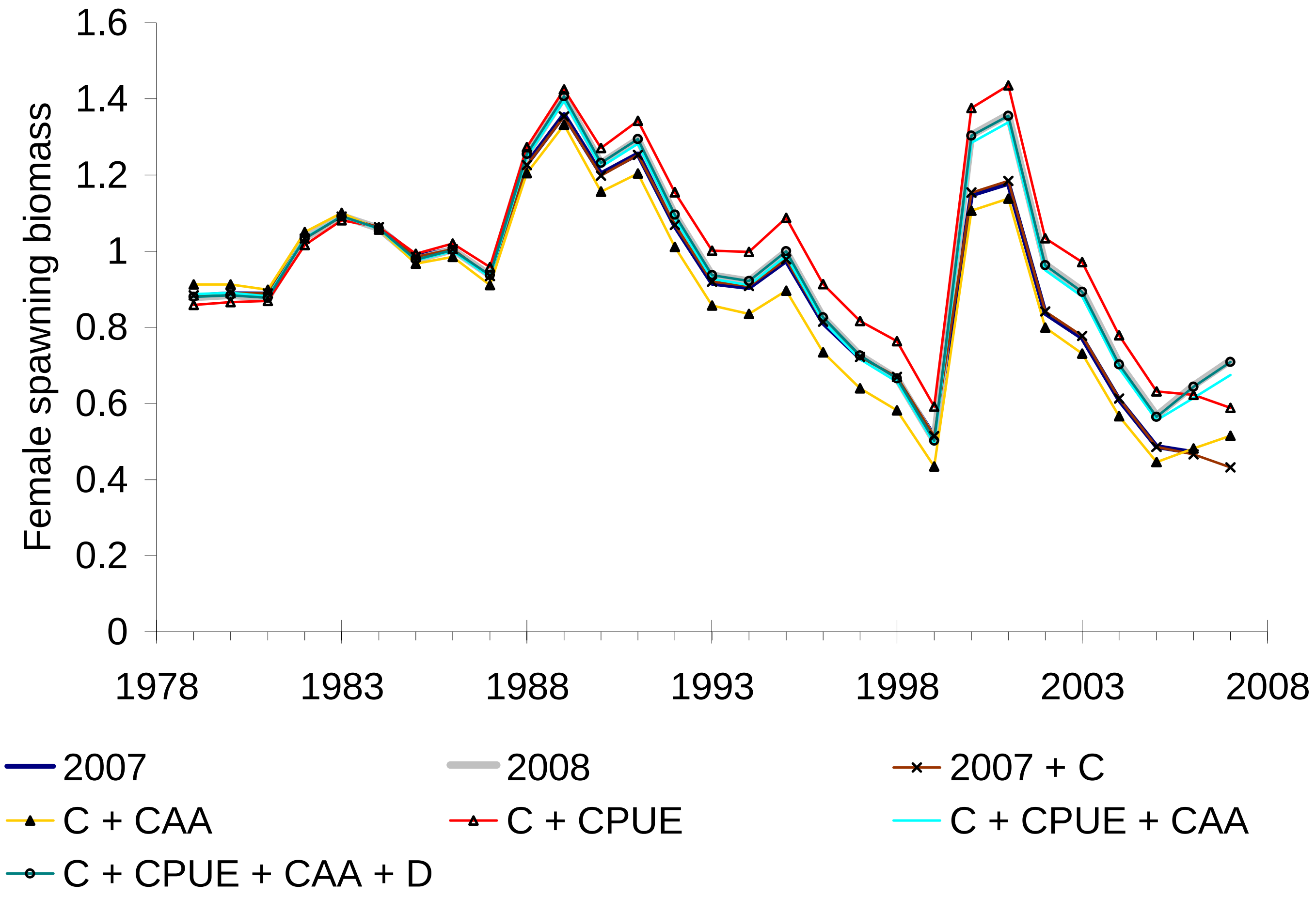


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Figure 9.13 The female spawning biomass relative to the reference biomass as a function of the data sources provided to the assessment. 2007 is the series from the 2007 assessment (Tuck and Punt, 2007), C = catch data series from 2008 included, CAA = updated age data are included, CPUE = updated catch rates series from 2008 is included (Haddon, 2008). 2008 is equivalent to C + CPUE + CAA + D + AC, where AC is the inclusion of the 2007 acoustic biomass estimate.

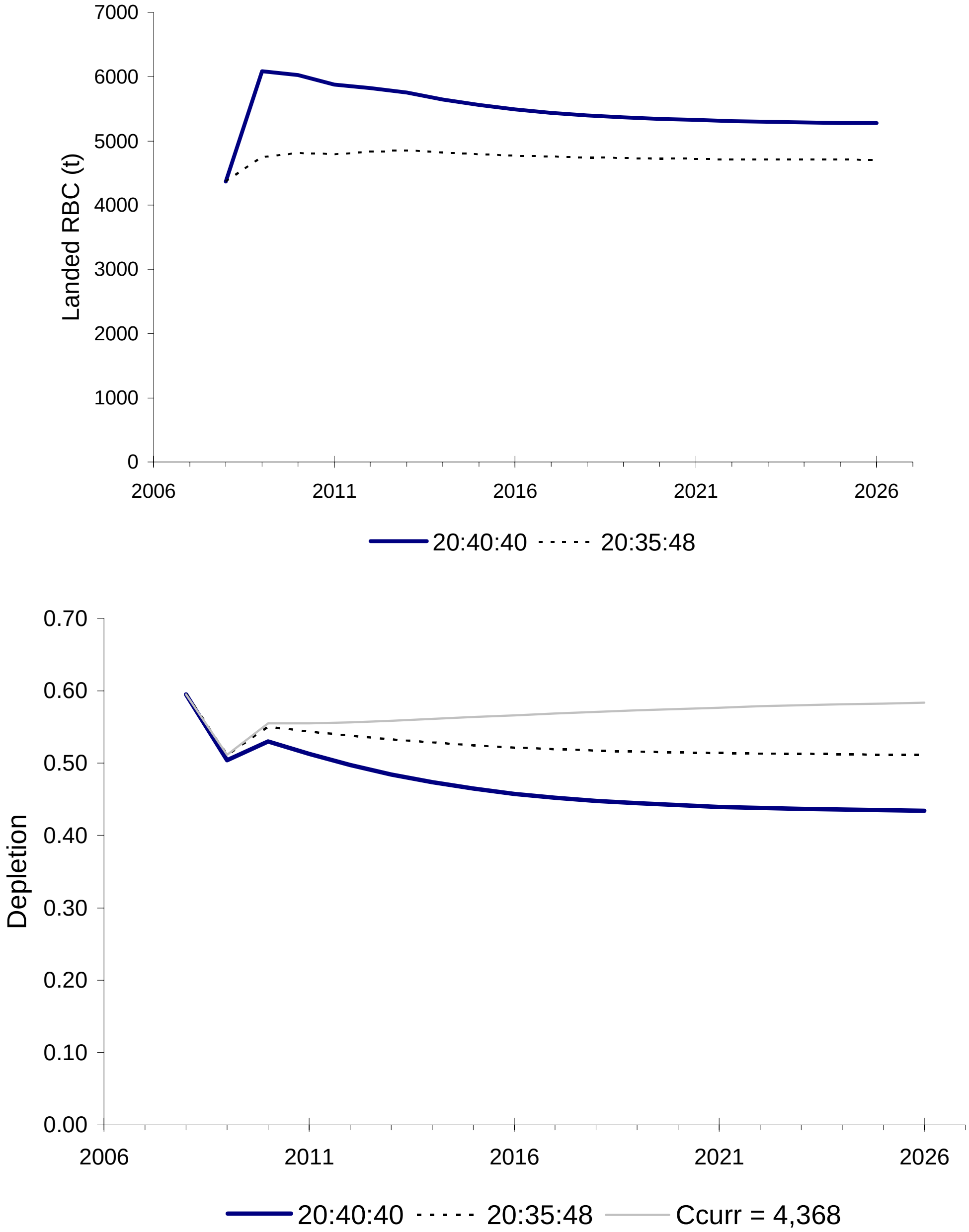

Figure 9.14. The trajectories of the landed RBC (top) and the corresponding depletion level (bottom) according to the 2 potential harvest control rules applied in the SESSF. The depletion figure also shows the depletion if a constant catch equal to the current catch of 4,368t is applied over all projected years.

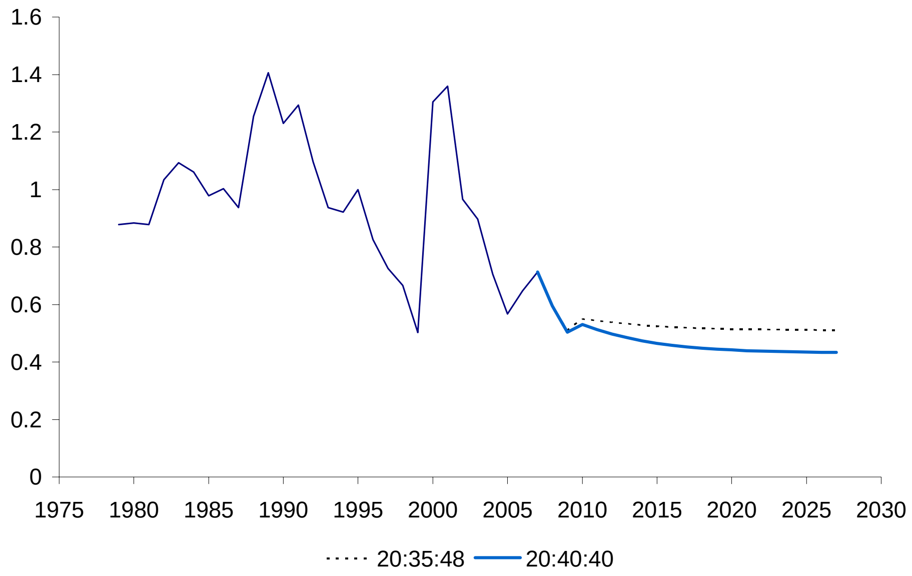

Figure 9.15 The trajectory of female spawning biomass relative to the reference biomass following the historic period and future projections under the two harvest control rules (20:40:40 and (20:35:48).

10. APPENDIX: THE POPULATION DYNAMICS MODEL AND LIKELIHOOD MODEL

The equations presented in this appendix have been adapted from those in Punt *et al.* (2001).

10.1 Basic dynamics

The dynamics of animals of sex s aged 1 and above are governed by the equation:

$$N^s_{y+1,a} = \begin{cases} N^s_{y+1,1} & \text{if } a=1 \\ N^s_{y,a-1}e^{-Z^s_{y,a-1}} & \text{if } 1<a<x \\ N^s_{y,x}\,e^{-Z^s_{y,x}} + N^s_{y,x-1}\,e^{-Z^s_{y,x-1}} & \text{if } a=x \end{cases} \quad \text{(A.1)}$$

where $N^s_{y,a}$ is the number of fish of sex s and age a at the start of year y (where y runs from 1 to t),

$Z^s_{y,a}$ is the total mortality on fish of sex s and age a during year y:

$$Z^s_{y,a} = M^s + S^1_a\,F^1_y + S^2_a\,F^2_y \quad \text{(A.2)}$$

M^s is the (age-independent) rate of natural mortality for animals of sex s,

$S^f_{y,a}$ is the vulnerability by sub-fishery f (f=1 for the 'spawning' sub-fishery, and f=2 for the 'non-spawning' sub-fishery) on fish of age a during year y,

F^f_y is the fully-selected fishing mortality by sub-fishery f during year y, and

x is the maximum age-class (taken to be a plus-group).

The number of 1-year-olds of sex s at the start of year y+1 is related to the spawner biomass of females in the middle of the preceding year according to the equation:

$$N^s_{y+1,1} = \left[0.5\,\tilde{B}_y\,/(\alpha+\beta\,\tilde{B}_y)\right]e^{\varepsilon_y} \quad \text{(A.3)}$$

where $\tilde{B}_y$ is the spawner biomass of females in the middle of year y:

$$\tilde{B}_y = \mu\sum_{a=1}^{x} f_{y,a}\,w_{y,a}\,N^{\mathrm{f}}_{y,a}\,e^{-Z^{\mathrm{f}}_{y,a}/2} \quad \text{(A.4)}$$

is the proportion of mature females that spawn each year,

$f_{y,a}$ is the proportion of females of age *a* that are mature during year *y*:

$$f_{y,a} = \begin{cases} 1 & \text{if } L_{y,a} \geq 70\,\text{cm} \\ 0 & \text{otherwise} \end{cases}$$

$w_{y,a}$ is the mass of a fish of age *a* in the middle of the year *y*,

$L_{y,a}$ is the mean length of a fish of age *a* during year *y* (given either by the empirical mean length-at-age each year, or from the fit of a von Bertalanffy growth curve),

α, β are the parameters of the stock-recruitment relationship, and

ε_y is the recruitment residual for year *y* (for ease of presentation, $\exp(\varepsilon_y)$ will be referred to as the recruitment anomaly for year *y*).

The values for α and β are determined from the steepness of the stock-recruitment relationship (*h*) and the virgin biomass (B_0) using the equations of Francis (1992). The assumption that maturity is knife-edged at 70 cm is very crude and a research project has been proposed to provide a more realistic picture of maturity as a function of length. In principle, the probability of being mature-at-length could have been assumed to be the same as vulnerability to the 'spawning' sub-fishery. This assumption has been made for assessments of blue grenadier in New Zealand (e.g. McAllister *et al*., 1994). However, it may be substantially in error for blue grenadier in Australia because it is known that fish of different sizes arrive on the spawning grounds at different times, and that some immature fish are caught during the 'spawning' sub-fishery.

The specifications for the numbers-at-age at the start of 1979 are based on the assumption that the stock would have been close to its unexploited equilibrium size at that time:

$$N^s_{1979,a} = 0.5 \begin{cases} R_0\, e^{-(a-1)M^s}\, e^{\varepsilon_a} & \text{if } a < x \\ R_0\, e^{-(x-1)M^s} / (1 - e^{-M^s}) & \text{if } a = x \end{cases} \qquad \text{(A.5)}$$

where R_0 is the expected number of 1-year-olds at unexploited equilibrium (the sex ratio at age 1 is taken to be 1:1), and

ε_a is the recruitment residual for age a.

The equation for the plus-group does not include a contribution by a recruitment residual because this group comprises several age-classes, which will largely damp out the impact of inter-annual variation in year-class strength.

10.2 Vulnerability

The vulnerability of the gear is governed by a logistic curve that permits the probability of capture to drop off with length:

$$S_{y,a}^{f} = \begin{cases} (1+e^{-\ell n19(L_{y,a}-L_{50}^{f})/(L_{95}^{f}-L_{50}^{f})})^{-1} & \text{if } L_{y,a} \le L_{95}^{f} \\ (1+e^{-\ell n19(L_{y,a}-L_{50}^{f})/(L_{95}^{f}-L_{50}^{f})})^{-1} e^{-\lambda^{f}(L_{y,a}-L_{95}^{f})} & \text{otherwise} \end{cases} \qquad \text{(A.6)}$$

where L_{50}^{f} is the length-at-50%-vulnerability for sub-fishery *f*,

L_{95}^{f} is the length-at-95%-vulnerability for sub-fishery *f*, and

λ^{f} is the "vulnerability slope" for sub-fishery *f*.

The vulnerability pattern for the 'spawning' sub-fishery is assumed to be asymptotic (i.e. $\lambda = 0$ for the 'spawning' sub-fishery).

10.3 Catches

The catch (in number) of fish of age *a* by sub-fishery *f* during year *y*, $\hat{C}_{y,a}^{f}$, and the number of fish of age *a* discarded by sub-fishery *f*, during year *y*, $\hat{D}_{y,a}^{f}$, are given by the equations:

$$\hat{C}_{y,a}^{f} = \sum_{s} \frac{(1-P_{y,a}) S_{y,a}^{f} F_{y}^{f}}{Z_{y,a}^{s}} N_{y,a}^{s} (1-e^{-Z_{y,a}^{s}}) \qquad \text{(A.7a)}$$

$$\tilde{D}_{y,a}^{f} = \sum_{s} \frac{P_{y,a} S_{y,a}^{f} F_{y}^{f}}{Z_{y,a}^{s}} N_{y,a}^{s} (1-e^{-Z_{y,a}^{s}}) \qquad \text{(A.7b)}$$

where $P_{y,a}$ is the probability of discarding a fish of age *a* during year *y*:

$$P_{y,a} = \frac{\gamma(\sum_{s} N_{y,1}^{s})^{\phi} / \max_{y'}(\sum_{s'} N_{y',1}^{s'})^{\phi}}{1+e^{-(L_a - L_{50}^{D})/\delta}} \qquad \text{(A.8)}$$

γ is the maximum possible discard rate for the largest year-class,

L_{50}^{D} is the length at which discarding is half the maximum possible rate,

δ is the parameter that determines the width of the relationship between length and the discard probability, and

ϕ is the parameter that controls the extent of density-dependent discarding.

The rate of discarding is therefore assumed to be related only to the size of the year-class at birth; the impact of density-dependence on the rate of discarding is assumed to be constant during the whole of an animal's life. The first assumption will be violated to some extent because *inter alia* the rate of discarding will depend on the abundance of other year-classes in the population (through high-grading). Violation of the second assumption is probably inconsequential because for older ages the form of the denominator of Equation (A.8) will mean that $P_{y,a} \approx 0$.

The model estimates of the catch (in mass) by sub-fishery *f* during year *y*, $\hat{C}_y^f$, and of the mass of fish discarded by sub-fishery *f* during year *y*, $\hat{D}_y^f$, are given by the equations:

$$\hat{C}_y^f = \sum_{a=1}^{x} w_{y,a} \hat{C}_{y,a}^f \qquad \text{(A.9a)}$$

$$\hat{D}_y^f = \sum_{a=1}^{x} w_{y,a} \hat{D}_{y,a}^f \qquad \text{(A.9b)}$$

Equations (A.9a) and (A.9b) imply that the (expected) mass of a fish of age *a* that is discarded is the same as the (expected) mass of a fish of age *a* that is retained.

10.4 The likelihood function

The negative of the logarithm of the likelihood function includes five contributions. These relate to minimising the sizes of recruitment residuals, fitting the observed catches / discards by fleet, fitting the observed catch / discard age-compositions, fitting the catch rate information, and fitting the estimates of spawner biomass from the egg-production method.

$$L = \sum_{i=1}^{5} L_i \qquad \text{(A.10)}$$

The contribution of the recruitment residuals to the negative of the logarithm of the likelihood function is based on the assumption that the inter-annual fluctuations in year-class strength are independent and log-normally distributed with a CV of σ_r[2]:

$$L_1 = \tfrac{1}{2\sigma_r^2}\left(\sum_{a=1}^{x-1}\varepsilon_a^2 + \sum_{y=1}^{t-1}\varepsilon_y^2\right) \qquad \text{(A.11)}$$

The contribution of the observed catch (in mass) information to the negative of the logarithm of the likelihood function is based on the assumption that the errors in measuring the catch in mass are log-normally distributed with a CV of σ_c:

$$L_2 = \tfrac{1}{2\sigma_c^2}\sum_f \sum_{y=1}^{t} (\ell n C_y^{f,\text{obs}} - \ell n \hat{C}_y^f)^2 \qquad \text{(A.12)}$$

where $C_y^{f,\text{obs}}$ is the observed catch (in mass) by sub-fishery *f* during year *y*.

The contribution of the observed mass of discards to the negative of the logarithm of the likelihood function follows Equation (A.12) except that $\hat{C}_y^f$ is replaced by $\hat{D}_y^f$, $C_y^{f,obs}$ is

[2] The summation in Equation (A.11) runs to *x*-1 and *t*-1 because the plus-group (age *x*) is not impacted by variability in year-class strength, and because the model is not used to predict the number of 1-year-olds for year *t*+1.

replaced by the observed mass of discards by sub-fishery *f* during year *y*, and the summations over year are restricted to those years for which estimates of discards are available.

The contribution of the age composition information to the negative of the logarithm of the likelihood function is based on the assumption that the age-structure information is determined from a random sample of *N* animals from the catch:

$$L_3 = -\sum_f \sum_y \sum_{a=1}^{15+} N\, \rho_{y,a}^{f,\text{obs}}\, \ell n(\hat{\rho}_{y,a}^f) \qquad \text{(A.13)}$$

where $\rho_{y,a}^{f,\text{obs}}$ is the observed proportion which fish of age *a* made up of the catch during year *y* by sub-fishery *f*,

$\hat{\rho}_{y,a}^f$ is the model-estimate of the proportion which fish of age *a* made up of the catch during year *y* by sub-fishery *f*:

$$\hat{\rho}_{y,a}^f = \sum_{a''} \chi_{a,a''}\, \hat{C}_{y,a''}^f \Big/ \sum_{a'=1}^{x} \hat{C}_{y,a'}^f \qquad \text{(A.14)}$$

$\chi_{a,a'}$ is the probability that an animal of age *a*' will be found to be age *a* (the age-reading error matrix).

Note that all animals aged 15 and older are treated as a single "age-class" when fitting to the catch proportion-at-age information. This prevents data for older fish (for which there is relatively little data) having a disproportionate influence on the results. The summations over year include only those years for which age-composition data are available. The contribution of the age-composition of the discards follows Equations (A.13) and (A.14), except that $\rho_{y,a}^f$ is replaced by the model-estimate of the proportion which fish of age a made up of the discards during year y by sub-fishery f, and $\rho_{y,a}^{f,obs}$ is replaced by the observed proportion which fish of age a made up of the discards during year y by sub-fishery f.

The contribution of the catch rate data to the negative of the logarithm of the likelihood function is based on the assumption that fluctuations in catchability are log-normally distributed with a CV of σ_q :

$$L_4 = \frac{1}{2\sigma_q^2} \sum_f \sum_y (\ell \text{n} I_y^f - \ell \text{n}(q^f B_y^f))^2 \qquad \text{(A.15)}$$

where q^f is the catchability coefficient for sub-fishery *f*, and

I_y^f is the catch-rate index for sub-fishery *f* and year *y*, and

B_y^f is the mid-season (available) biomass for sub-fishery *f* and year *y*:

$$B_y^f = \sum_s \sum_a w_{y,a}\, (1 - P_{y,a})\, S_a^f\, N_{y,a}^s\, e^{-Z_{y,a}^s/2} \qquad \text{(A.16)}$$

The summation over year includes only those years for which catch rate data are available.

The contribution of the egg-production or acoustic estimates to the negative of the logarithm of the likelihood function is given by:

$$L_5 = \sum_{y=1994/5} (\tilde{B}_y - B_y^{obs})^2 / (2\sigma_y^2) \qquad \text{(A.17)}$$

where B_y^{obs} is the estimate of female spawner biomass for year *y* based on egg-production or acoustic methods, and

σ_y is the standard error of B_y^{obs}.