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

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1. SUMMARY

The 2006 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 2005 calendar year. In addition, new biological parameters relating to the proportion spawning and the length at maturity have been used. Due to the large differences in magnitude of the estimates of spawning biomass from the acoustic surveys, two models of biological status were explored. These models apply

1) the higher estimates of spawning biomass from the acoustic surveys (Macauley, 2004) and double the egg survey estimates. This model is referred to as the High model.

2) the lower estimates of spawning biomass from the acoustic surveys (Cordue, 2000) and the base-case egg survey estimates of female spawning biomass. This model is referred to as the Low model.

Results conclude that the female spawning biomass in 2005 is around 40% of the reference biomass. However, not surprisingly, the magnitude of the biomass differs substantially between the two models. This is reflected in the application of the harvest control rules, where the Recommended Biological Catches (RBCs) for 2007 are between 11,000 t and 18,000 t for the High model and between 2,000 t and 3,300 t for the Low model. The long-term RBCs also differ markedly; with RBCs of 20,000 t for the High model and 5,500 t for the Low model.

An exploration of the consequences of each of the models and their estimated RBC catch series was undertaken. Each RBC catch series was applied to the Low and High models and the subsequent depletions over 20 years recorded. The results illustrated that, while the 2007 depletion is not greatly affected, over a fairly short period of time (5 years) the impact on the stock can be substantial (collapse) if the high RBC catch series is applied when the Low model is the better representation of the state of the stock. In contrast, the stock gradually increases in biomass if the lower catch series are used and the High model is the actual biological state of the stock.

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 2005 calendar year data and additional information from acoustic surveys of spawning biomass. The same assessment model that has been used in previous years (e.g. Punt et al. 2001, Tuck and Punt, 2005) was used again this year.

This document is supplementary to Tuck (2006; 24-25 July 2006), where a number of stock assessment sensitivities were considered. These sensitivities included (a) various acoustic estimates of 2003-2005 spawning biomass that depended upon assumptions of target strength (b) egg survey estimates for 1994-1995 (c) the use of an age-reading error matrix, and (d) updated biological parameters relating to the proportion spawning and the length at maturity. Following instruction from the Slope Resource Assessment Group (Slope RAG, 24-25 July 2006), this document presents (a) diagnostic plots from two resource models, (b) corresponding recommended biological catches (RBCs) and (c) a management decision table. These are described in more detail below.

The two alternative base-case models considered here both include age-reading error, the 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 acoustic estimates is assumed to pertain to total (male and female) spawning biomass. In previous models (including previous base-case models) a 1:1 sex ratio has been assumed, with the acoustic estimates then being halved in order to fit to female spawning biomass. The two models differ according to the applied 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.

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. 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 2005 was 5000 tonnes (with a voluntary industry reduction to 4200t), down from 7000 t in 2004, 9000 t in 2003 and 10000 t which it had been since 1994. 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 2005 catch- and discard-at-age from the spawning and non-spawning fisheries; updated cpue series (Haddon, 2006), the total mass landed and discarded, mean length- and weight-at-age; updated acoustic estimates of spawning biomass (T. Ryan, pers. comm.) 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). 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 to account for reporting of headed and gutted catches, and scaled up to the SEF2 data (see text).

Year	Landings		Discards	
	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	1840		
1987	1019	2214		
1988	415	2279		
1989	47	2816		
1990	743	2604		
1991	1158	4193		
1992	931	2669		
1993	990	2359		
1994	1194	1916		
1995	1196	1558		80
1996	1464	1504		975
1997	2952	1581		3716
1998	3267	2469		1329
1999	6087	3214		123
2000	6056	2592		69
2001	7613	1496		10
2002	7428	1731		2
2003	7572	900		4
2004	5065	1399		21
2005	2973	1283		431

4.2 Catch rates

Haddon (2006) provides the updated catch rate series for blue grenadier (Table 4.2, Figure 4.1). Models 7 and 6 of Haddon (2006) were used for the non-spawning and spawning fisheries respectively in the assessment models. The series show recent increases in cpue for both sub-fisheries.

Table 4.2. Standardised CPUE (Haddon, 2006) for the spawning and non-spawning sub-fisheries by calendar year.

Year	Spawning		Non-spawning	
	CPUE	Records	CPUE	Records
1986	1.00	65	1.00	1825
1987	1.08	196	1.47	2296
1988	2.35	92	1.57	2606
1989	0.63	31	1.45	3022
1990	0.87	141	1.51	2455
1991	3.26	129	1.11	3541
1992	1.14	168	1.00	3172
1993	2.87	148	0.73	3724
1994	1.65	318	0.64	4015
1995	0.80	476	0.44	4541
1996	1.06	493	0.38	4554
1997	0.83	421	0.38	4758
1998	0.95	578	0.66	4952
1999	0.79	857	0.74	6437
2000	0.89	950	0.66	6078
2001	1.48	1112	0.31	6277
2002	1.02	1047	0.31	5893
2003	0.77	1014	0.23	5341
2004	0.61	735	0.42	5658
2005	0.76	267	0.48	4844

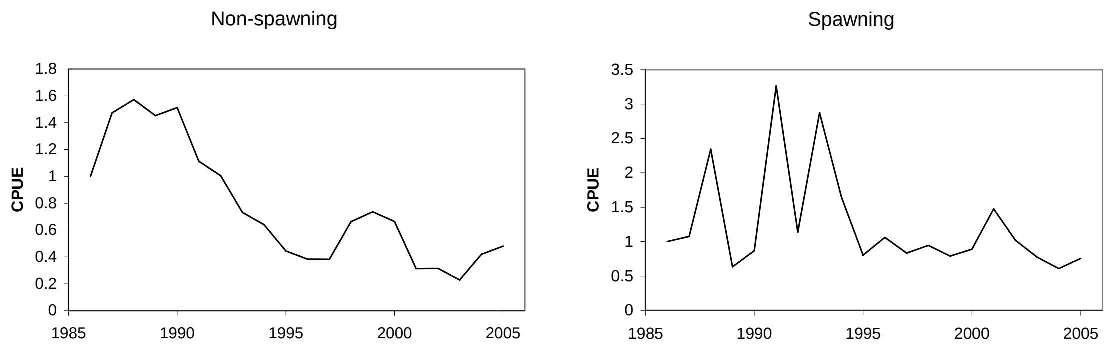

Figure 4.1 The calendar year catch-rate indices for the non-spawning and spawning blue grenadier fisheries (Haddon, 2006).

4.3 Catch-at-age

Although length frequency information is collected at several ports around Australia, traditionally only the data collected in Portland and Beachport (for 2002 to 2004) have been used when constructing a length-frequency distribution for the non-spawning fishery. This was done because BGAG had agreed to only use Portland data - earlier investigations by BGAG members indicated that the data from all ports showed the same trend. However, 2005 length frequencies show large differences in length frequency among ports, with Eden showing a marked increase in small fish compared to the other ports. As such, a catch-weighted length frequency was used to produce the 2005 length frequency, utilizing data from Beachport, Portland and Eden (Figure 4.2). Following instruction from Slope RAG (24-25 July 2006), the age-compositions were recalculated using a single age-length key (not by sub-fishery) based on all the port data for the non-spawning fishery (for years 2002-2005). The age-compositions over all years are shown in Figure 9.5 to Figure 9.10.

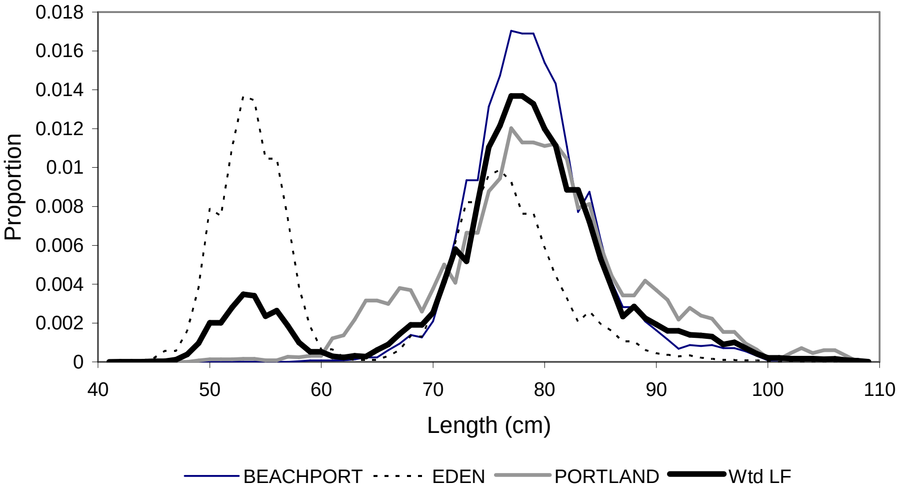

Figure 4.2. The port-based blue grenadier length frequencies for 2005. The Wtd LF line is the catch-weighted length frequency used for the non-spawning sub-fishery.

Spawning sub-fishery length frequencies 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 4.3).

The catch-at-age for 2005 for each of the two sub-fisheries is shown in Figure 4.4. As expected, the non-spawning age composition shows the presence of a recent year-class progressing into the available biomass. This year-class has not yet entered the spawning fishery.

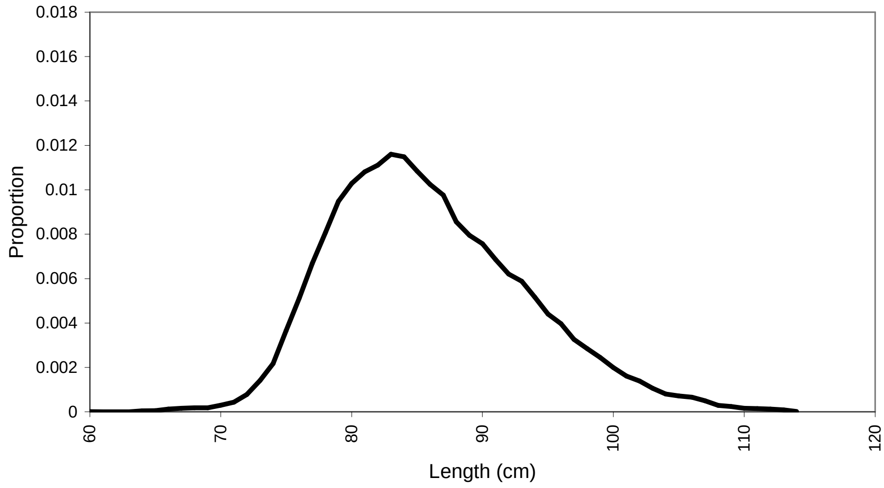

Figure 4.3. The catch-weighted length frequency for blue grenadier of the spawning sub-fishery in 2005.

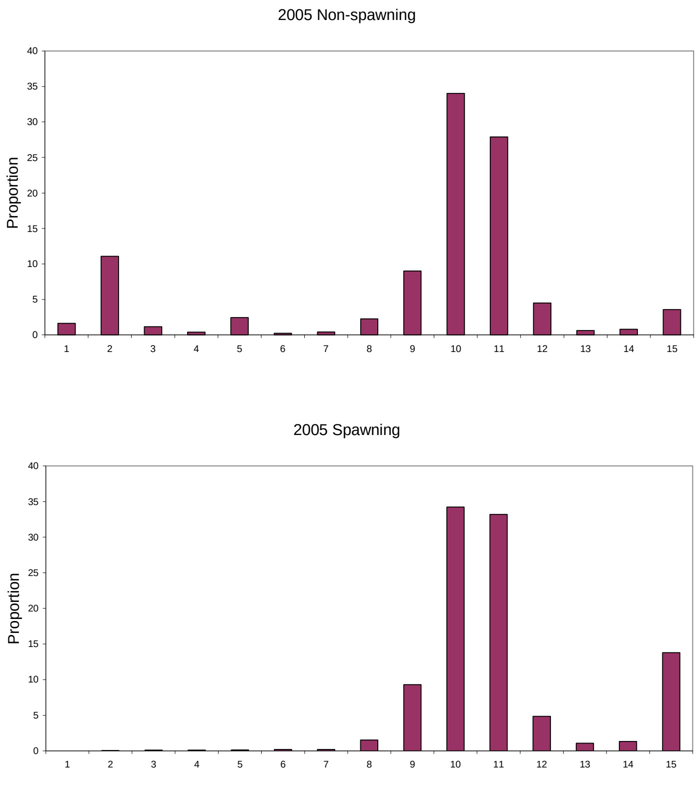

Figure 4.4. The observed proportion caught–at-age data for the non-spawning (top) and spawning (bottom) sub-fisheries in 2005.

4.4 Age-reading error

Standard deviations for aging error have been estimated, producing the age-reading error matrix of Table 4.4.

4.5 Acoustic survey estimates

Following instruction from SlopeRAG (May 2006), several scenarios were considered relating to the acoustic and egg survey biomass estimates in the paper of Tuck (2006; Slope RAG 24-25 July 2006). For the acoustic estimates, five models of biomass were provided by Tim Ryan (pers. comm.). These models differed according to the target strength used. Based on expert judgement, two of these models were used in the assessments of Tuck (2006), namely Macauley (2004) and Cordue (2000). Table 4.3 shows the biomass estimates for each of these models. The model of Macauley (2004) produces markedly higher estimates of biomass (with a lower estimate of target strength) than that of Cordue (2000) (with a correspondingly higher estimate of target strength).

Model	Name	2003	2004	2005
Macauley (2004)	High	131,991	87,852	116,390
Cordue (2000)	Low	23,798	13,544	16,670
c.v. used in assessment model		0.3	0.46	0.3

Table 4.3. The estimated biomass of blue grenadier on the spawning grounds in years 2003 to 2005 according to the models of Macauley (2004) and Cordue (2000) (T. Ryan, pers. comm.).

This paper considers two resource models that differ in terms of the assumptions regarding target strength. These models have been named ‘High’ and ‘Low’ with the name reflecting the relative magnitude of the biomass estimate (and not the target strength value).

4.6 Egg survey estimates

Egg survey estimates of female spawning biomass are available for years 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 ‘High’ resource model, the egg estimates were doubled. For the ‘Low’ resource model, 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	94.7	11.1	0.1	0	0	0	0	0	0	0	0	0	0	0	0
2	5.3	77.7	14.8	0.2	0	0	0	0	0	0	0	0	0	0	0
3	0	11.1	70.2	16.6	0.3	0	0	0	0	0	0	0	0	0	0
4	0	0	14.8	66.4	17.8	0.4	0	0	0	0	0	0	0	0	0
5	0	0	0.1	16.6	63.7	18.2	0.4	0	0	0	0	0	0	0	0
6	0	0	0	0.2	17.8	62.8	18.2	0.4	0	0	0	0	0	0	0
7	0	0	0	0	0.3	18.2	62.8	18.2	0.4	0	0	0	0	0	0
8	0	0	0	0	0	0.4	18.2	62.8	18.2	0.4	0	0	0	0	0
9	0	0	0	0	0	0	0.4	18.2	62.8	18.2	0.5	0	0	0	0
10	0	0	0	0	0	0	0	0.4	18.2	62.8	18.9	0.7	0	0	0
11	0	0	0	0	0	0	0	0	0.4	18.2	61.1	19.9	1.2	0	0
12	0	0	0	0	0	0	0	0	0	0.4	18.9	58.8	21.5	2.2	0.2
13	0	0	0	0	0	0	0	0	0	0	0.5	19.9	54.4	23.0	4.0
14	0	0	0	0	0	0	0	0	0	0	0	0.7	21.5	49.5	24.0
15	0	0	0	0	0	0	0	0	0	0	0	0	1.3	25.2	71.7

4.7 Parameters of breeding biology

Previous models, 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 are 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, the updated parameters have been used and not the traditional values.

5. ANALYTIC APPROACH

5.1 The population dynamics model

The population and likelihood models applied in 2006 are the same as those used in the 2005 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 Koopman, 2005). The 2006 model is updated and extended by including the following data:

- the total mass landed and discarded during 2005; the catch- and discard-at-age during 2005 and the estimated mean length and weight of each age-class present during 2005,
- revised standardised CPUE series,
- an updated age-reading error matrix,
- updated biological parameters for the proportion spawning and the length at maturity, and
- an acoustic estimate from the 2005 spawning biomass off western Tasmania.

Two alternative base-case models are considered in this document. Both include age-reading error, the updated biological parameters for the proportion spawning and the length at maturity (for males and females) and an assumption of 2-times turnover on the spawning ground. The acoustic estimates are assumed to relate to the total (male and female) spawning biomass. In previous models (including previous base-case models) a 1:1 sex ratio has been assumed, with the acoustic estimates then being halved in order to fit to female spawning biomass. The two models differ according to the applied 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 for this model are higher than those for the ‘Low’ model which uses the Cordue (2000) target strength and the base-case egg survey estimates of spawning biomass.

Two sub-fisheries are included in the model – the spawning sub-fishery that operates during winter (June – August inclusive) off western Tasmania, 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 112 estimated parameters: 2 catchability coefficients; 1 female natural mortality, 1 B_0, 27 annual fishing mortality rates for each of the two sub-fisheries; recruitment residuals for 26 years and 19 age classes in the first year; 2 selectivity parameters for the spawning sub-fishery and 3 for the non-spawning; and 4 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.

[1] Copyright 1991, 1992 Otter Software Ltd.

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

6. RESULTS AND DISCUSSION

6.1 Stock assessment – ‘Low’ and ‘High’ models

Figure 9.1 and Figure 9.2 show the observed and predicted fits to the landings and discards from each sub-fishery for each model. The model is forced to fit the recorded landings very well because of the very low c.v. that is assumed for these data (σ_c = 0.05, Table 5.1). The fits to the landings data from the High model are not shown as they do not differ appreciably from those for the Low model. 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.

For the Low model the estimated natural mortality figure for females is approximately 0.18 and consequently that for males is 0.21 (as male natural mortality is assumed to be 1.2 times that of females). For the High model, female natural mortality was estimated to be 0.21, with that of males then being 0.25.

Figure 9.3 shows that the model is not able to fit the early fluctuations in the CPUE for the winter spawning sub-fishery but it is able to achieve a reasonably good fit to the CPUE for recent years. The fit to the CPUE for the non-spawning sub-fishery is reasonably good, although the increase in the CPUE after 1998 is not as well estimated; the drop in CPUE for 2000 is not predicted by the model, which actually predicts an increase, consistent with the growth of a large cohort of grenadier spawned in 1994. Attempts to provide better fits to the non-spawning fishery cpue have not been fruitful (such as forcing fits to the cpue 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. The model is also not able to mimic the increase in standardized CPUE for 2005.

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 9.4. The probability that a fish will be discarded once it has been caught is also shown. Clearly, there is very little difference between the functions estimated by the Low and High models.

The fits to the catch-at-age and the discard-at-age data for both sub-fisheries and both Low and High model are reasonably good (Figure 9.5 to Figure 9.10). Figure 9.11 and Figure 9.12, which show the estimated annual recruitment multipliers, illustrates a long period of poor recruitment following the strong recruitments of 1994 and 1995. While an increase in recruitment is estimated by the model for years 2003 and 2004, these will not have been well estimated (as these fish have mostly not moved into the available population to any noticeable extent) and the real strength of these cohorts will need to be determined over the next few years. The pattern of recruitment multipliers seen in these figures differs somewhat from that of previous models due to the inclusion of age-reading error. Note that the High model produces a substantial recruitment in 1970 which has not been observed in previous models. However, it is clear from the confidence intervals in Figure 9.12 that the model's ability to estimate these early recruitments is poor. Generally, from years after 1977, the confidence intervals on the recruitment multipliers are relatively tight.

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 2005 ($\tilde{B}_{2005}$) and its size in 1986, 1993, and 2004 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 2005 (=*curr*); the estimated recruitment residual for the strong 1994 cohort, and the 2003 cohort, and the negative log likelihood (-ln L) value from the model. Also shown are the base-case results for the previous three year's assessments. Note that the final year of biomass estimation (*curr*) is one year less than the year the assessment is produced.

The Low base-case model concludes that the reference female biomass is approximately 49,300 t and that current female spawner biomass (in the middle of 2005) is approximately 37% of the reference biomass. In contrast, the High base-case model concludes that the reference female biomass is nearly 150,000 t and that current female spawner biomass (in the middle of 2005) is approximately 42% of the reference biomass. These models illustrate that while the estimated magnitude of the biomasses differs greatly, the depletion levels do not differ by nearly as much. Figure 9.13 shows the spawning biomass trajectory for the Low and High models 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 9.14 shows the female spawning biomass trajectory relative to the reference biomass for each model.

The 1994 year-class is estimated to be a larger fraction of its expected value in the Low and High models, compared to past assessments and the July 2006 base-case model. This change in results is a consequence of the change to the age-reading error matrix.

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 2005 assessment. 'Curr' refers to the current or final year of the estimation. The base case (July 2006) model includes the base case estimates from the egg survey, the lower acoustic survey estimates and 2 times turnover. The High Model uses the higher acoustic survey estimates of total spawning biomass with the egg survey estimates of female spawning biomass doubled. The Low model uses the lower acoustic estimates of total spawning biomass with the base-case egg survey estimates.

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										
Base-case (July 2006)	27557	40972	39177	15618	38.12%	0.099	0.054	7.8	1.1	418.69
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

6.2 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 2006.
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 2007.
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 2007 by the exploitation rates calculated at step 4.

Three 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 be 20% of B_{ref}):

a) 20-48-48; a target stock size of 48% of B_{ref}, with the exploitation rate dropping off once the stock drops below the target level.
b) 20-40-48; a target stock size of 48% of B_{ref}, with the exploitation rate dropping off once the stock drops below 0.4 B_{ref}.
c) 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 2007 must be calculated to apply the Tier 1 harvest control rule. The 2007 depletion for the two models is shown inFrom Table 6.3 and Table 6.4, the long-term RBCs under the Low model are approximately 5,300 t for a target depletion of 48% of the reference biomass and 6,000 t for 40%. For the High model, the long-term RBCs are substantially larger. For a target depletion of 48%, the RBCs are approximately 19,600 t, and for 40% the RBC is 22,150.

Table 6.2 and is calculated by assuming a 2006 catch of 3,730 t. The ensuing landed and Total recommended Biological Catches (RBC) for 2007 are given in From Table 6.3 and Table 6.4, the long-term RBCs under the Low model are approximately 5,300 t for a target depletion of 48% of the reference biomass and 6,000 t for 40%. For the High model, the long-term RBCs are substantially larger. For a target depletion of 48%, the RBCs are approximately 19,600 t, and for 40% the RBC is 22,150.

Table 6.2. The different scales of these RBCs reflect the large estimated differences in magnitude of the biomass of the two acoustic models.

The 2006 TAC is 3,730 t. Applying the rule that the TAC should not be increased or decreased by more than 50% of the previous year's TAC, reduces the RBCS from the 'High' model to 5,595 t (1.5 times the 2006 TAC). The RBCs under the 'Low' model are all greater than 50% of the 2006 TAC.

The time series of landed RBCs under each Tier 1 rule and each alternative model (Low and High) is given in Table 6.3 and Table 6.4. Note that the final depletions are not exactly 40% and 48% of B_{ref} even when the catches are those for the model concerned (i.e. RBCs determined from the Low Acoustic model projected forward when reality is assumed to be the Low Acoustic model). 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}.

From Table 6.3 and Table 6.4, the long-term RBCs under the Low model are approximately 5,300 t for a target depletion of 48% of the reference biomass and 6,000 t for 40%. For the High model, the long-term RBCs are substantially larger. For a target depletion of 48%, the RBCs are approximately 19,600 t, and for 40% the RBC is 22,150.

Table 6.2. The estimated 2007 mid-year depletion and RBCs (landed and total; tonnes) for two resource models and three Tier 1 harvest control rules with target biomass depletions of either 48% or 40%.

Model	High acoustic, double egg (High)			low acoustic, base-case egg (Low)		
Tier rule	2007 Depletion	Landed RBC	Total RBC	2007 Depletion	Landed RBC	Total RBC
20:40:40	0.41	18,231	19,492	0.36	3,350	3,560
20:48:48	0.41	11,110	11,866	0.36	1,936	2,056
20:40:48	0.41	14,097	15,062	0.36	2,636	2,801

Table 6.3. The time series of landed RBCs (referred to as Low-RBC) and corresponding depletions relative to B_{ref} for each Tier 1 rule for the Low model.

Low acoustic model						
	Landed RBC			Depletion		
	20:40:40	20:48:48	20:40:48	20:40:40	20:48:48	20:40:48
2006	3730	3730	3730	0.36	0.36	0.36
2007	3350	1936	2636	0.36	0.36	0.36
2008	3828	2439	3165	0.37	0.39	0.38
2009	4481	3094	3852	0.38	0.41	0.40
2010	5116	3780	4263	0.39	0.44	0.41
2011	5530	4322	4522	0.40	0.45	0.43
2012	5664	4718	4706	0.41	0.47	0.44
2013	5756	5001	4845	0.41	0.48	0.46
2014	5823	5126	4954	0.42	0.48	0.47
2015	5874	5178	5039	0.42	0.49	0.47
2016	5914	5219	5108	0.42	0.49	0.48
2017	5947	5251	5164	0.42	0.50	0.49
2018	5972	5278	5209	0.43	0.50	0.49

2019	5993	5300	5245	0.43	0.50	0.50
2020	6009	5318	5274	0.43	0.51	0.50
2021	6022	5332	5297	0.43	0.51	0.50
2022	6032	5344	5316	0.43	0.51	0.51
2023	6040	5353	5331	0.43	0.51	0.51
2024	6047	5360	5342	0.43	0.51	0.51
2025	6051	5365	5351	0.43	0.51	0.51

Table 6.4. The time series of landed RBCs and corresponding depletions relative to B_{ref} for each Tier 1 rule for the High model.

High acoustic model						
	Landed RBC			Depletion		
	20:40:40	20:48:48	20:40:48	20:40:40	20:48:48	20:40:48
2006	3729	3729	3729	0.42	0.42	0.42
2007	18231	11110	14097	0.41	0.42	0.41
2008	18181	12765	14418	0.41	0.44	0.43
2009	19103	14678	15484	0.41	0.46	0.44
2010	20217	16631	16713	0.42	0.47	0.46
2011	20920	18017	17583	0.42	0.48	0.47
2012	21274	18488	18110	0.42	0.49	0.48
2013	21510	18782	18489	0.43	0.49	0.48
2014	21682	18996	18774	0.43	0.50	0.49
2015	21806	19155	18988	0.43	0.50	0.50
2016	21897	19275	19149	0.43	0.51	0.50
2017	21966	19368	19274	0.43	0.51	0.50
2018	22018	19440	19369	0.43	0.51	0.51
2019	22057	19495	19441	0.43	0.51	0.51
2020	22086	19537	19497	0.44	0.51	0.51
2021	22107	19569	19539	0.44	0.51	0.51
2022	22123	19594	19571	0.44	0.51	0.51
2023	22135	19612	19595	0.44	0.52	0.51
2024	22144	19626	19613	0.44	0.52	0.52
2025	22150	19636	19626	0.44	0.52	0.52

6.3 Decision analysis

The Tier 1 RBCs calculated in the previous section lead to six possible landed catch series; one for each of the three Tier 1 rules (20:40:48, 20:40:40, and 20:48:48) and for each of the alternative base-case models (Low, High). As there remains considerable uncertainty regarding the correct target strength model to apply to estimate spawning biomass from the results of the acoustic surveys,, and as the choice of target strength has dramatic implications for the status of the stock, a method of looking at the consequences of each catch series was developed. The general idea of the method is to explore the impact of using each catch series on each of the two possible models of stock status. This way, the consequence of mis-matches between the resource model and the applied RBC catch series, derived from a different resource model, can be explored (e.g. applying the RBCs from the High model, to the Low stock status model).

For each catch series, including a constant catch set at the current TAC of 3,730 t, deterministic projections were conducted over a 20-year time horizon using parameter sets from either the Low or High models. The parameter sets used were (i) those corresponding to the maximum likelihood estimates and (ii) derived to account for the uncertainty in the strength of the 2003 recruitment. As there is uncertainty regarding the strength of the 2003 recruitment – the most recent improved recruitment following several years of poor recruitment – a simple exploration of the impact of the various catch series across this uncertainty was conducted. The 2000 parameter sets from the Bayesian analysis were sorted according to the magnitude of the 2003 recruitment multiplier. Parameter sets representing low, median and high 2003 recruitments were chosen as the 12.5 percentile (250th parameter set), the 50 percentile (median; 1000th set) and the 87.5 percentile (1750th set) respectively. Figure 9.15 shows the 2003 recruitment multipliers sorted by magnitude for the Low and High models.

The additional rule for setting the TAC selected by SlopeRAG requires that the TAC not increase or decrease by more than 50% of the current year's TAC. All of the RBCs from the Low model show changes within this bound (Table 6.3). However the High model RBCs increase immediately to well above 50% of the 2006 TAC (Table 6.4). To account for this, the annual landed RBCs for the High Model were multiplied by 1.5 each year until the adjusted RBC was greater than the estimated RBC. Table 6.5 provides the time-series of adjusted landed RBCs for the High model used in the projections.

The results, using the depletion relative to B_{ref} as the performance measure, are illustrated in

Table 6.6 (for all Tier 1 rules, and for years 2007 and 2012) and Figure 9.16 (for the 20:40:48 Tier 1 rule only). Table 6.6 and Figure 9.16 show that applying the RBCs derived from the High model when the Low model is the actual biological model will very quickly collapse the spawning stock. Not surprisingly, if the lower catch series is applied to a stock that is much larger in magnitude (the High models), then the depletion levels reduce markedly. The trajectories of spawning biomass depletion remain fairly stable, at or about the target level (except for the lower recruitment parameter set, for which depletion in 2012 is below the target level) if the catch series and state of nature match (i.e. Low-RBC with Low model, High-RBC with High model). In general, and as expected, the depletion levels are higher for the parameter sets that use the higher recruitment values for 2003. If the annual catch is fixed at the current TAC of 3,730 t (Figure 9.17) then, under the Low resource model, the depletion gradually rises to about 60% of the reference biomass in 10 years. For the High model, by 2016 the depletion is at or above 70% of the reference biomass.

Table 6.6 illustrates that the impact of each of the 2007 RBCs is not great. However, over a fairly short period of time (5 years), the consequences of the RBCs on the stock can be substantial.

Table 6.5. The time-series of landed RBCs for the High model (referred to as High-RBC) adjusted so that the change in the TAC from one year to the next is not greater than 50% of the current TAC. The shaded cells have been adjusted to some extent.

	High acoustic model		
	Adjusted Landed RBC		
	20:40:40	20:48:48	20:40:48
2006	3730	3730	3730
2007	5595	5595	5595
2008	8393	8393	8393
2009	12589	12589	12589
2010	18883	16631	16713
2011	20920	18017	17583
2012	21274	18488	18110
2013	21510	18782	18489
2014	21682	18996	18774
2015	21806	19155	18988
2016	21897	19275	19149
2017	21966	19368	19274
2018	22018	19440	19369
2019	22057	19495	19441
2020	22086	19537	19497
2021	22107	19569	19539
2022	22123	19594	19571
2023	22135	19612	19595
2024	22144	19626	19613
2025	22150	19636	19626

Table 6.6. The 2007 and 2012 depletion relative to the reference biomass for the two acoustic models (Low, High), four parameters sets (MLE, R125, R500, R875) for an application of a catch time series relating to the three Tier 1 rules under either the Low or High (Low-RBC, High-RBC) models or the current TAC.

2007 Depletion		Low acoustic model				High acoustic model			
Rule	Catch	MLE	R125	R500	R875	MLE	R125	R500	R875
	Ccurr	0.35	0.23	0.40	0.49	0.43	0.37	0.42	0.56
20:40:48	High-RBC	0.34	0.22	0.39	0.48	0.43	0.36	0.42	0.55
20:40:48	Low-RBC	0.36	0.23	0.41	0.49	0.43	0.37	0.42	0.56
20:40:40	High-RBC	0.34	0.22	0.39	0.48	0.43	0.36	0.42	0.55
20:40:40	Low-RBC	0.36	0.23	0.41	0.49	0.43	0.37	0.42	0.56
20:48:48	High-RBC	0.34	0.22	0.39	0.48	0.43	0.36	0.42	0.55
20:48:48	Low-RBC	0.36	0.23	0.41	0.50	0.43	0.37	0.42	0.56

2012 Depletion		Low acoustic model				High acoustic model			
Rule	Catch	MLE	R125	R500	R875	MLE	R125	R500	R875
	Ccurr	0.45	0.27	0.53	0.60	0.66	0.52	0.62	0.75
20:40:48	High-RBC	0.01	0	0.03	0.07	0.52	0.38	0.51	0.63
20:40:48	Low-RBC	0.44	0.26	0.52	0.60	0.65	0.52	0.61	0.74
20:40:40	High-RBC	0	0	0	0	0.50	0.35	0.49	0.61
20:40:40	Low-RBC	0.41	0.24	0.48	0.55	0.64	0.50	0.61	0.73
20:48:48	High-RBC	0.01	0	0.02	0.06	0.52	0.37	0.51	0.62
20:48:48	Low-RBC	0.47	0.28	0.54	0.62	0.66	0.52	0.62	0.75

7. ACKNOWLEDGEMENTS

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9. FIGURES

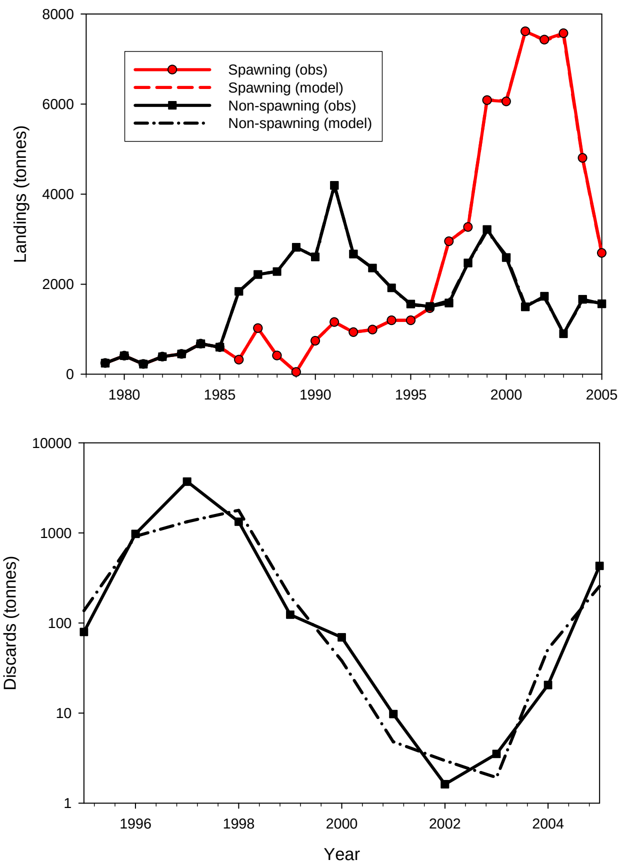


Figure 9.1. Top plot: Annual estimated landings of blue grenadier (obs; scaled to account for headed and gutted fish and to sef2) and estimated by the Low base case model (model). Bottom plot: Discards estimated from the ISMP (solid line) and Low model estimated values (dashed line). The spawning and non-spawning sub-fisheries are shown.

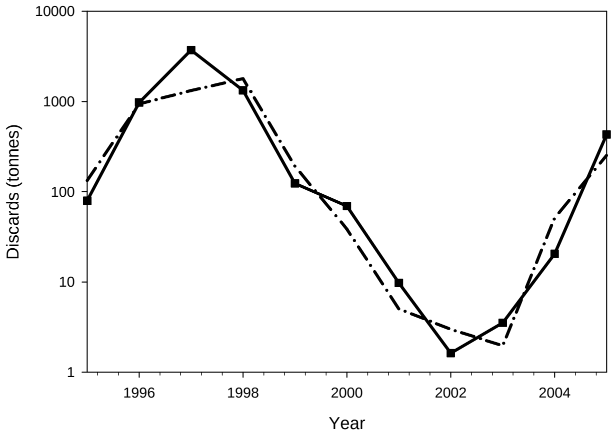
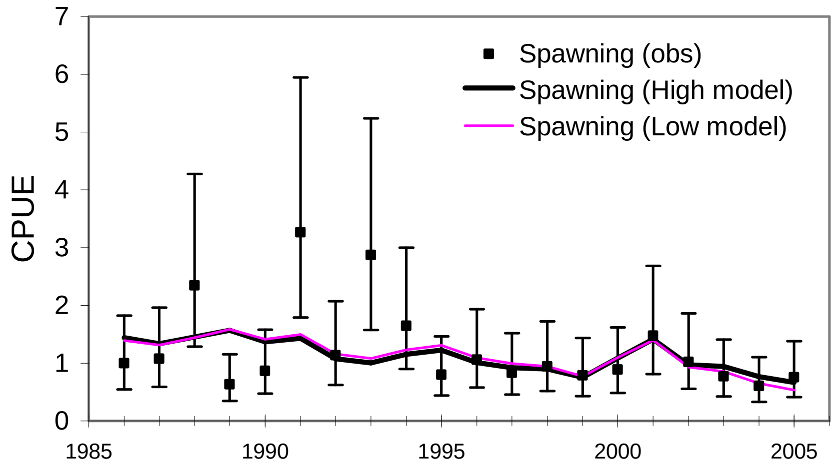


Figure 9.2. Discards estimated from the ISMP (solid line) and High model estimated values (dashed line).



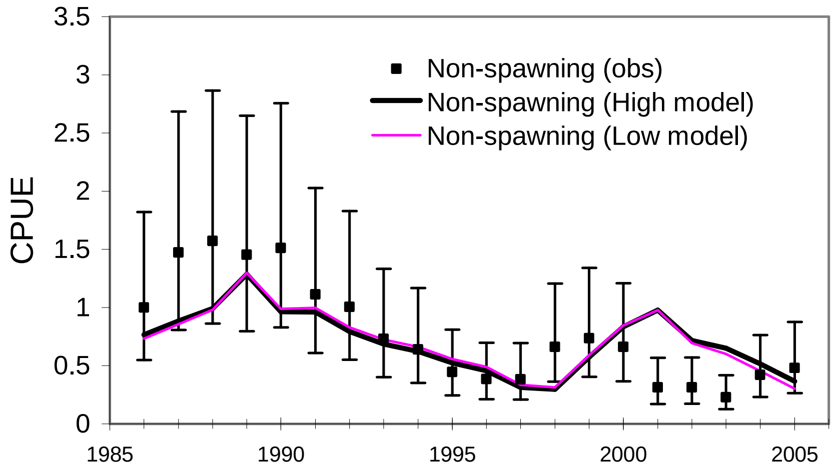


Figure 9.3. Catch-per-unit-effort (CPUE) calculated using a GLM to standardise CPUE from log-books (obs) and the High and Low model estimated CPUE for the spawning fishery (top) and the non-spawning fishery (bottom).

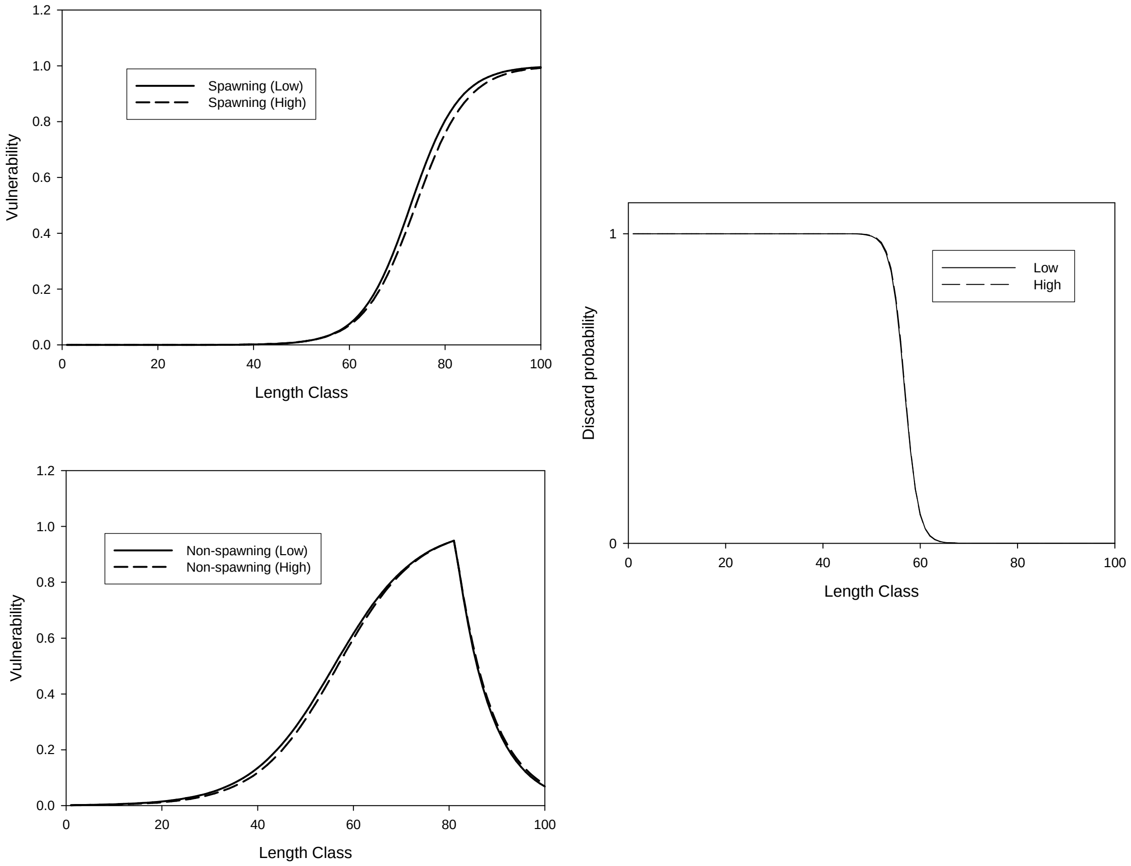


Figure 9.4. Vulnerability of blue grenadier to being caught (but not necessarily landed) by the two sub-fisheries (left) and the probability of being discarded if caught (right) as a function of length class for the Low and High models.

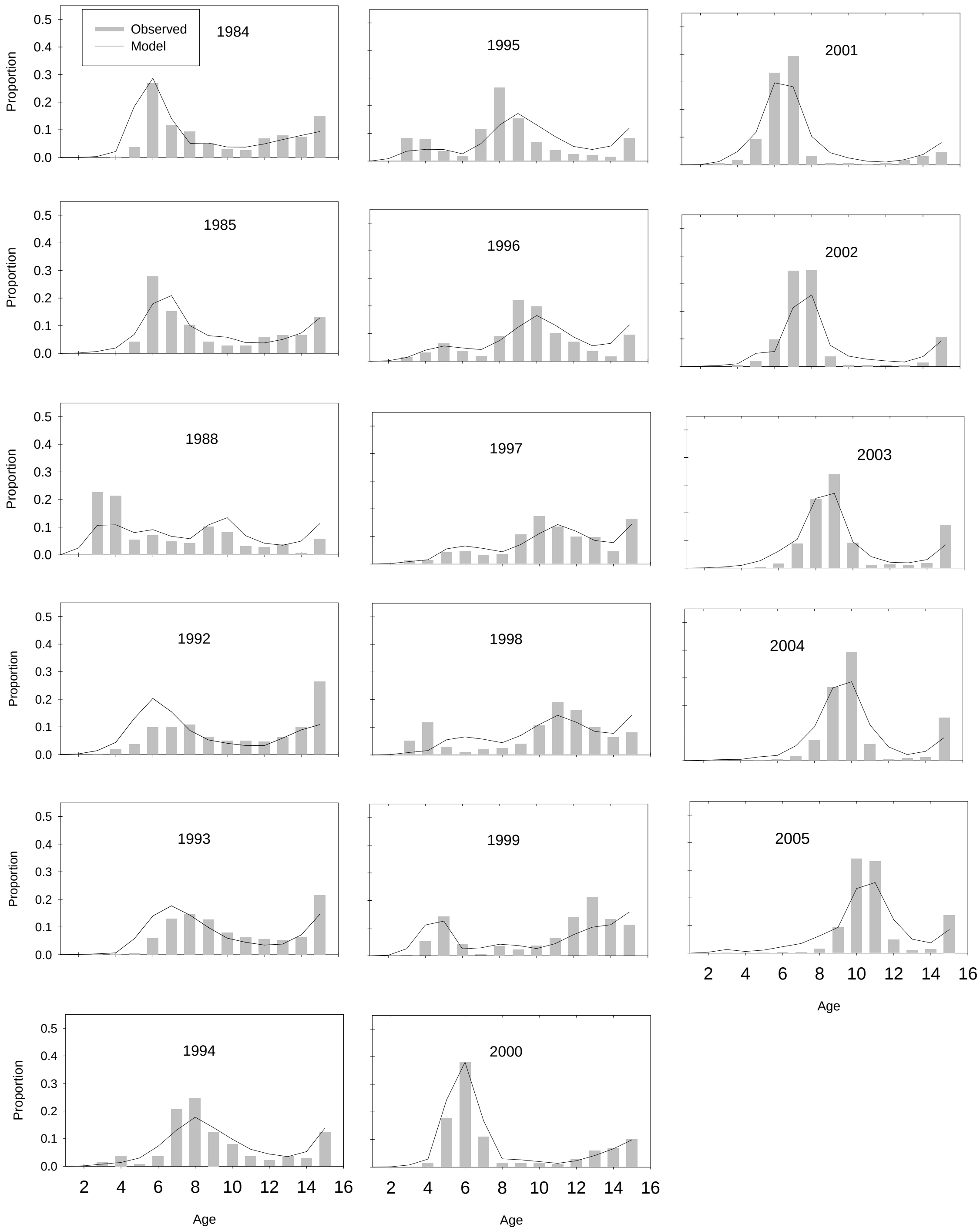


Figure 9.5. Observed (bars) and model estimated (lines) proportion caught at age for the spawning sub-fishery and Low model.

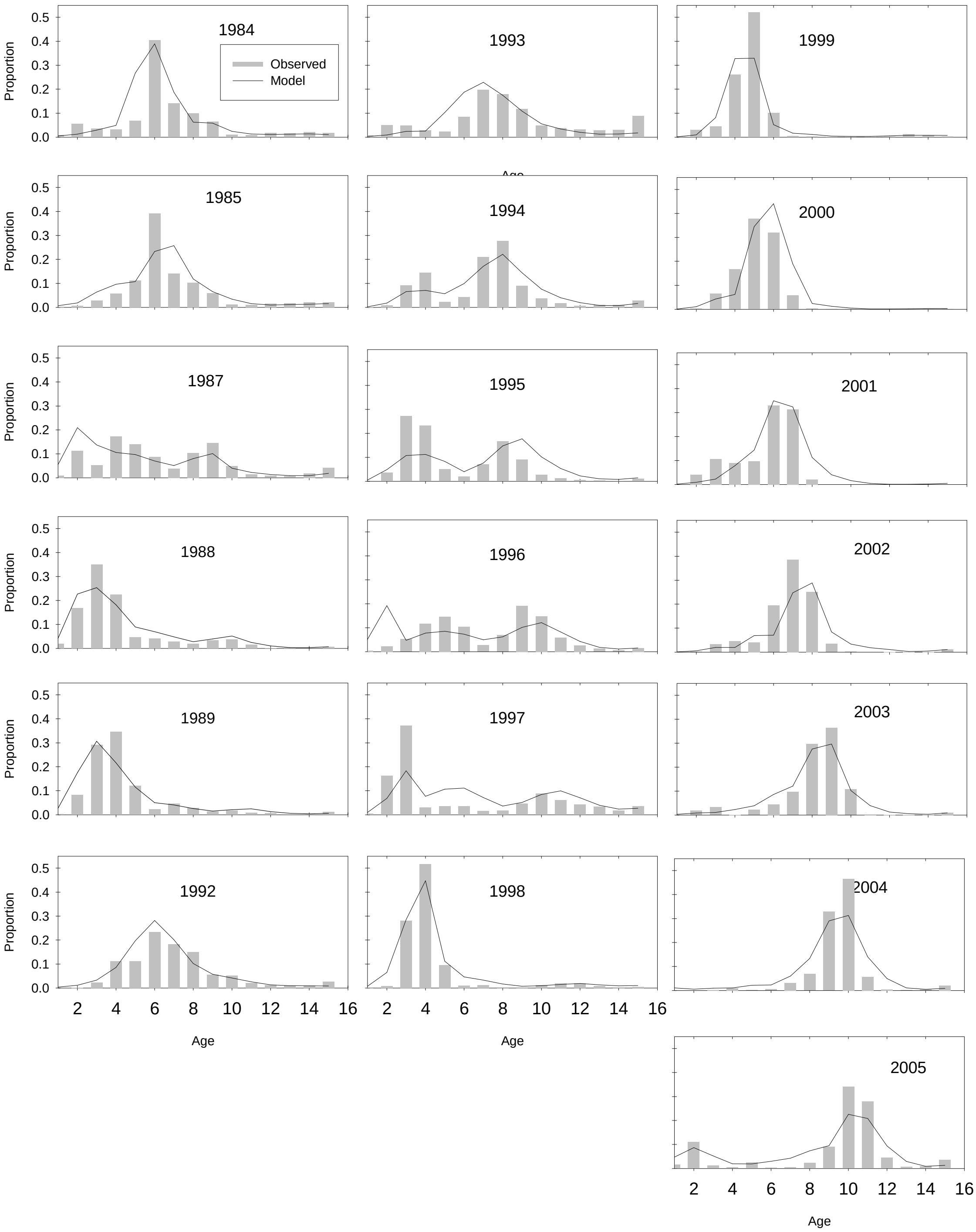


Figure 9.6. Observed (bars) and model estimated (lines) proportion caught at age for the non-spawning sub-fishery and Low model.

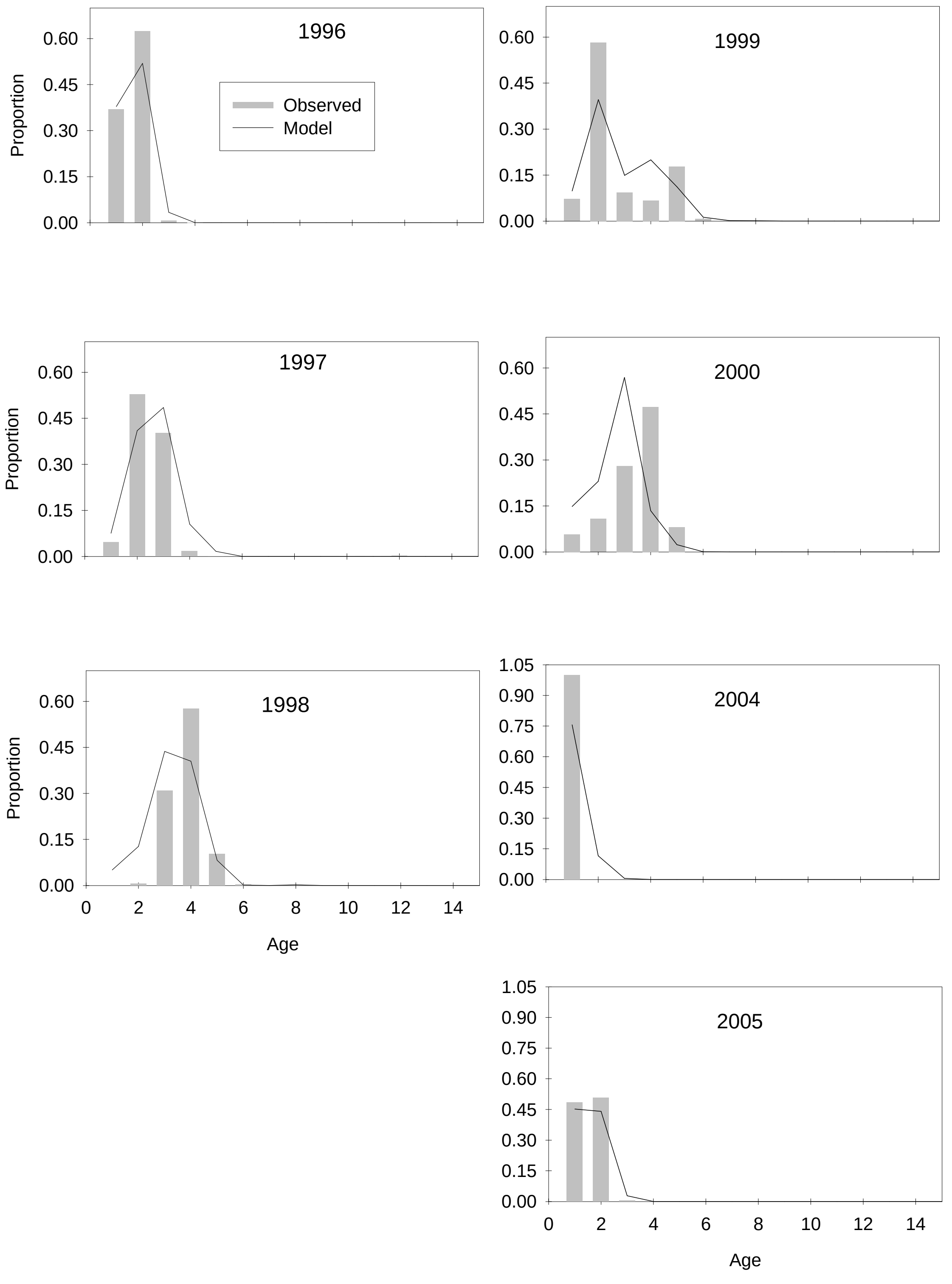


Figure 9.7. Observed (bars) and model estimated (lines) proportion discarded-at-age for the non-spawning sub-fishery and Low model.

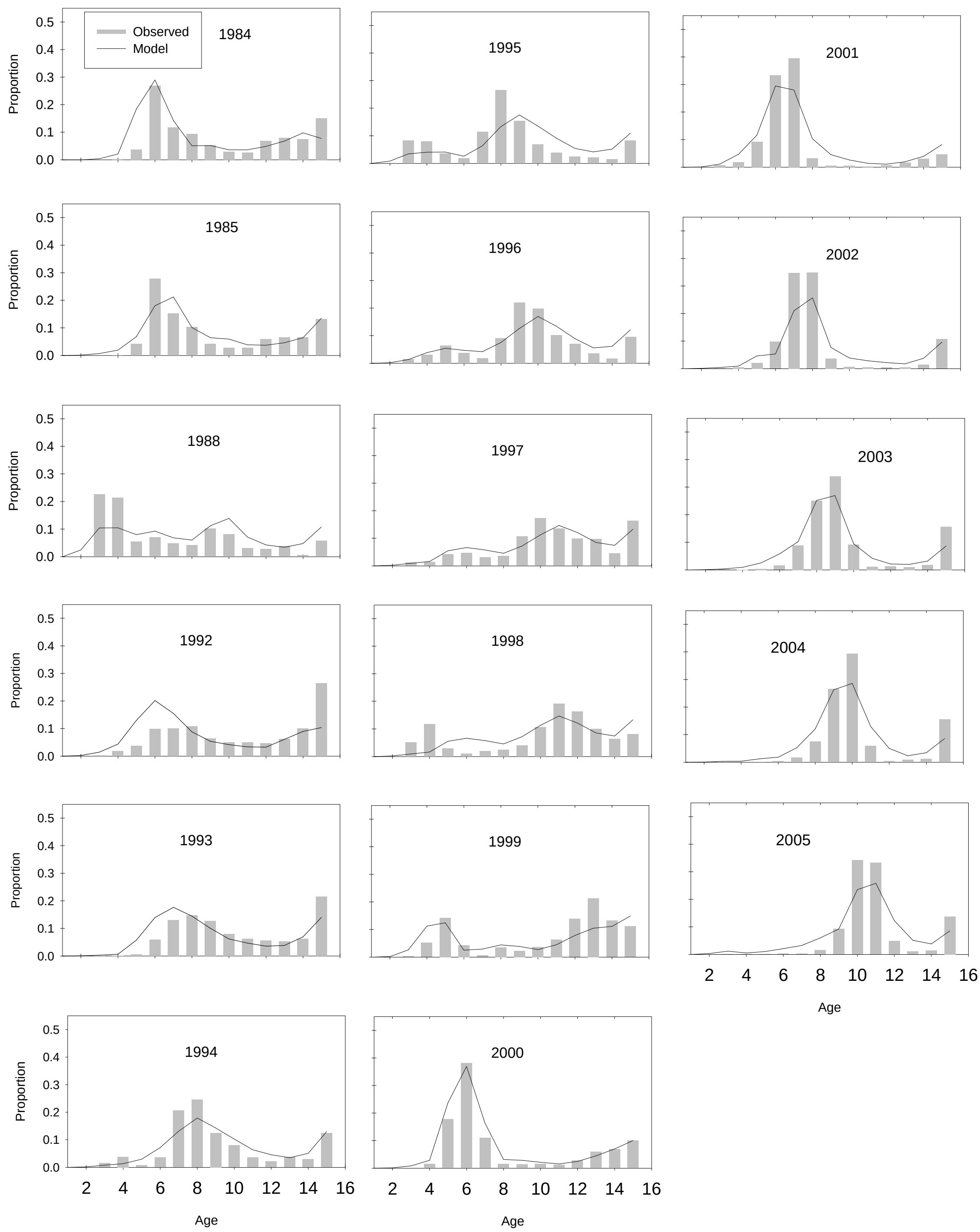


Figure 9.8. Observed (bars) and model estimated (lines) proportion caught at age for the spawning sub-fishery and High model.

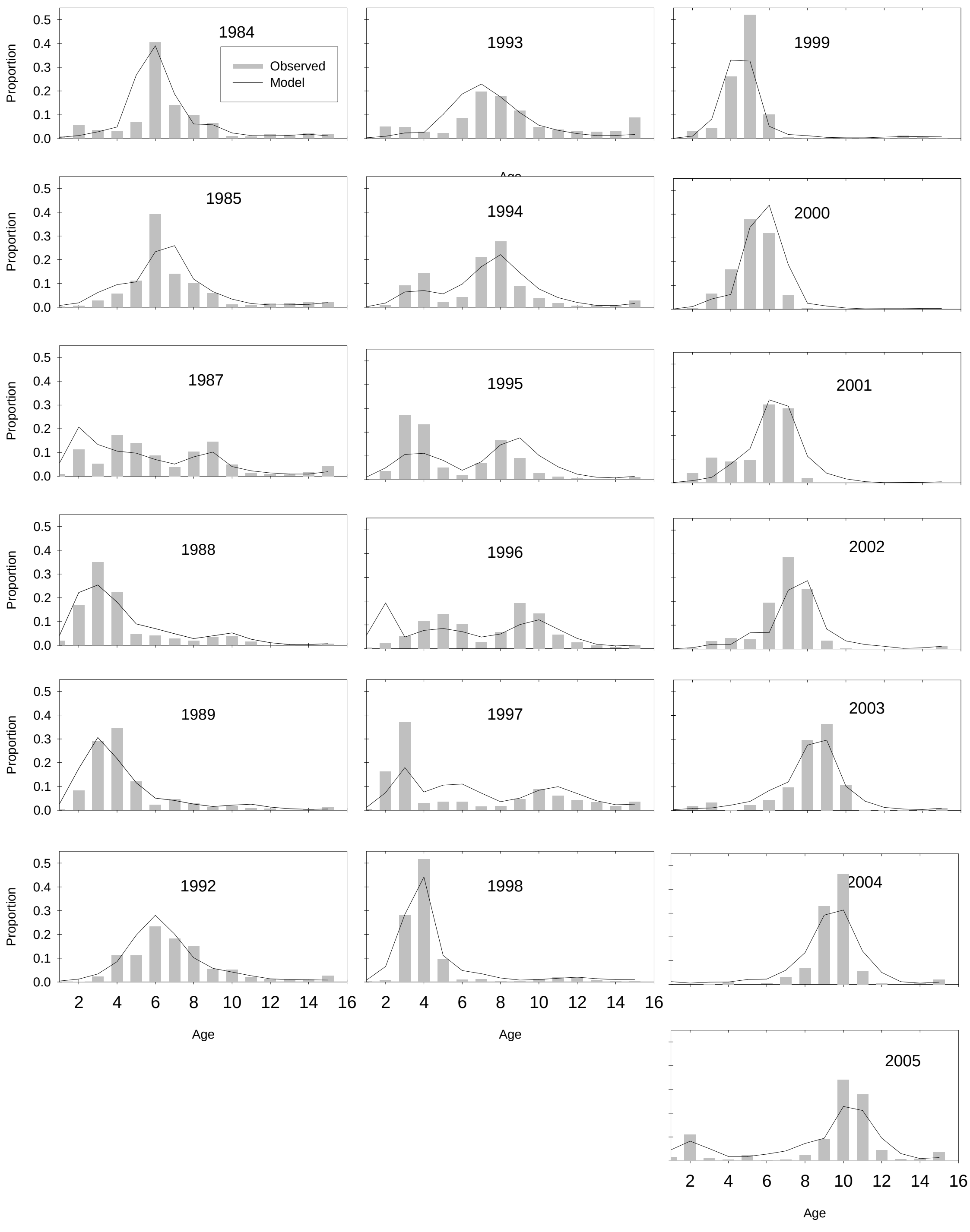


Figure 9.9. Observed (bars) and model estimated (lines) proportion caught at age for the non-spawning sub-fishery and High model.

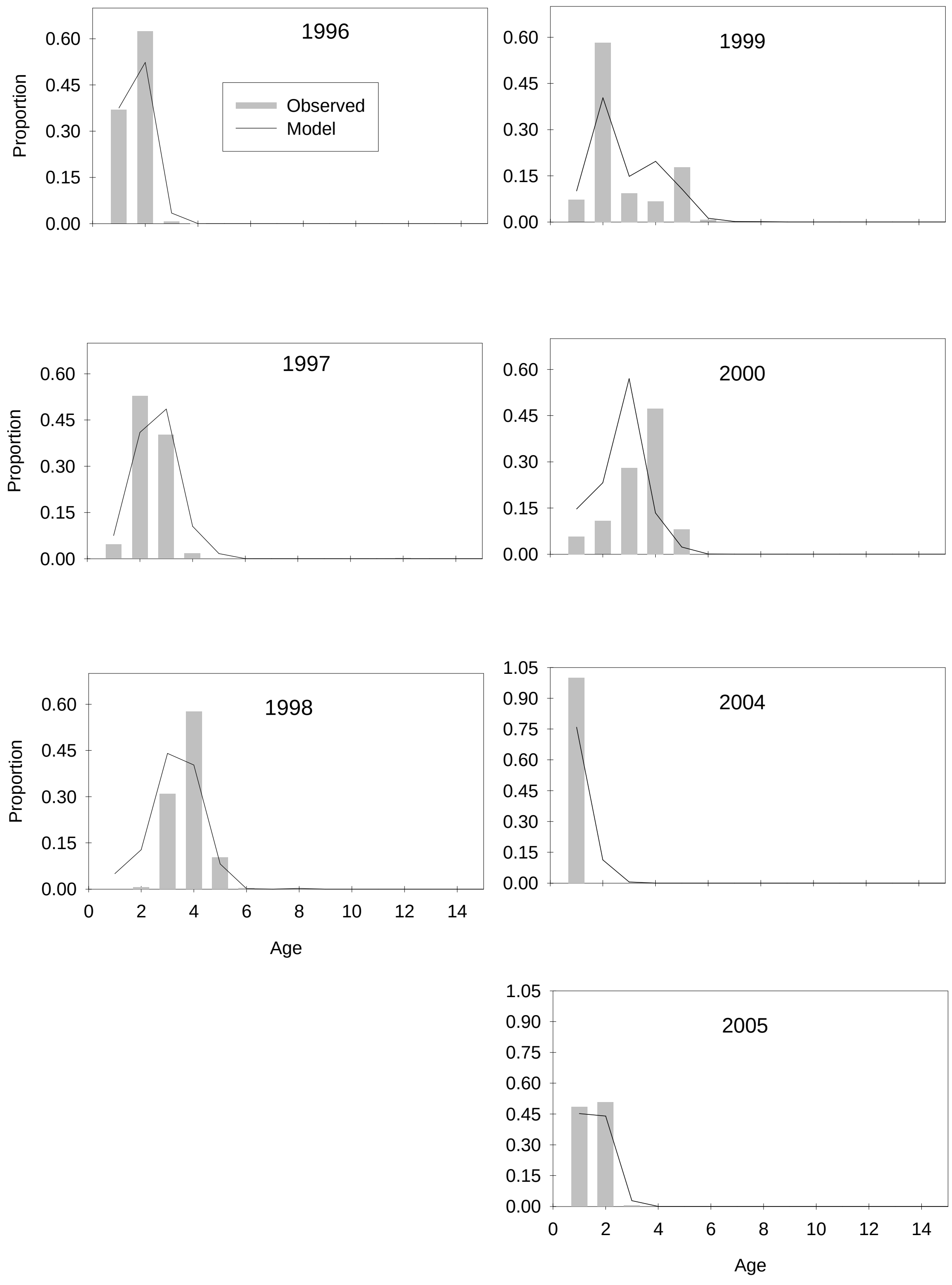
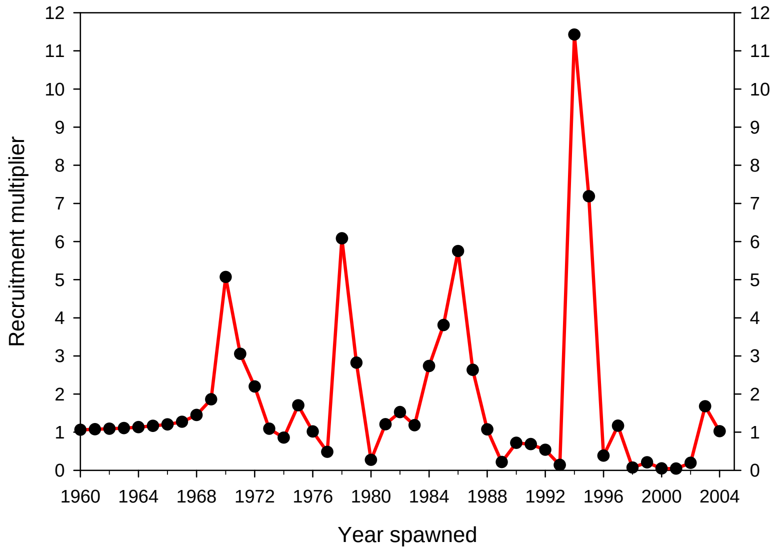


Figure 9.10. Observed (bars) and model estimated (lines) proportion discarded-at-age for the non-spawning sub-fishery and High model.



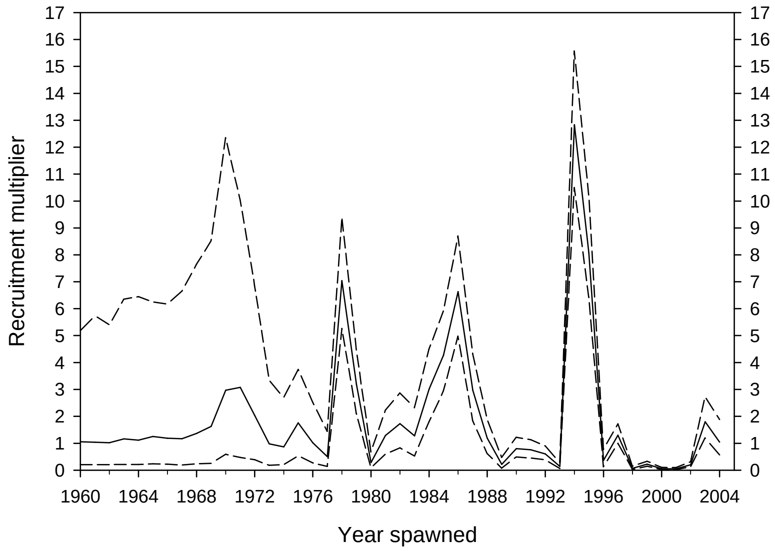
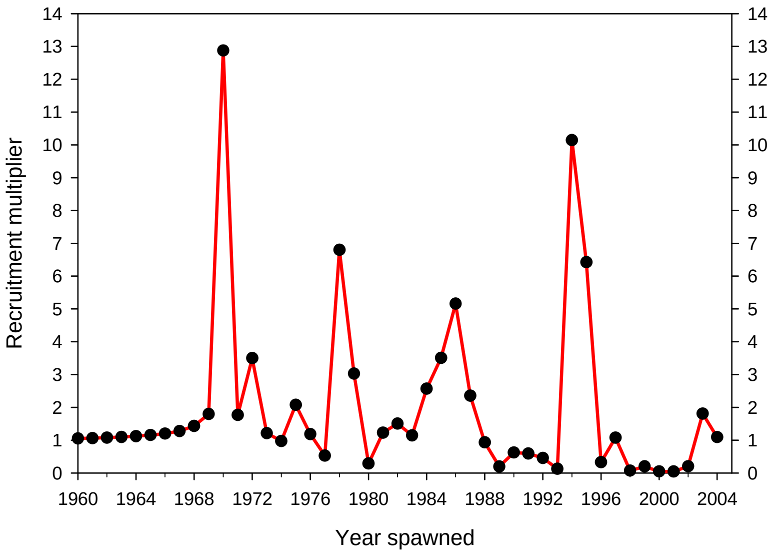


Figure 9.11. Top: Estimated recruitment multipliers (the amount by which the recruitment deviated from that predicted by the stock-recruit relationship) versus year of spawning from Low model. Bottom: The median (solid line), upper and lower 95% bounds (dashed lines) on the recruitment multipliers for the Low model.



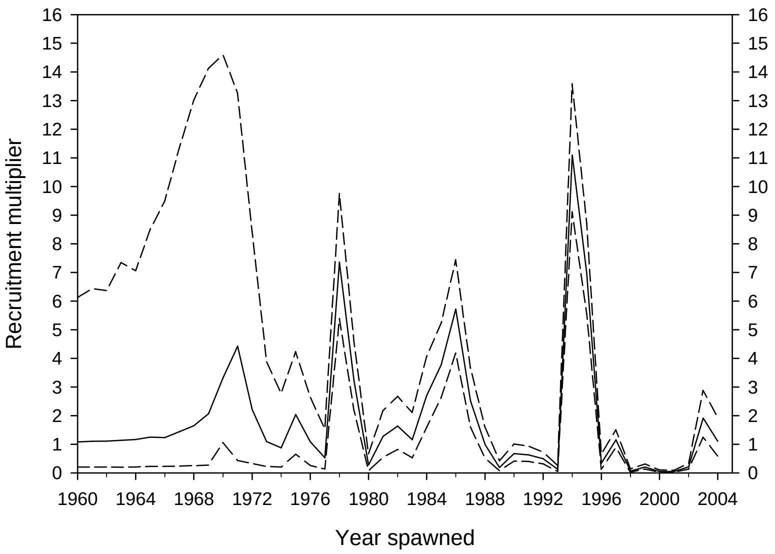


Figure 9.12. Top: Estimated recruitment multipliers (the amount by which the recruitment deviated from that predicted by the stock-recruit relationship) versus year of spawning from High model. Bottom: The median (solid line), upper and lower 95% bounds (dashed lines) on the recruitment multipliers for the High model.

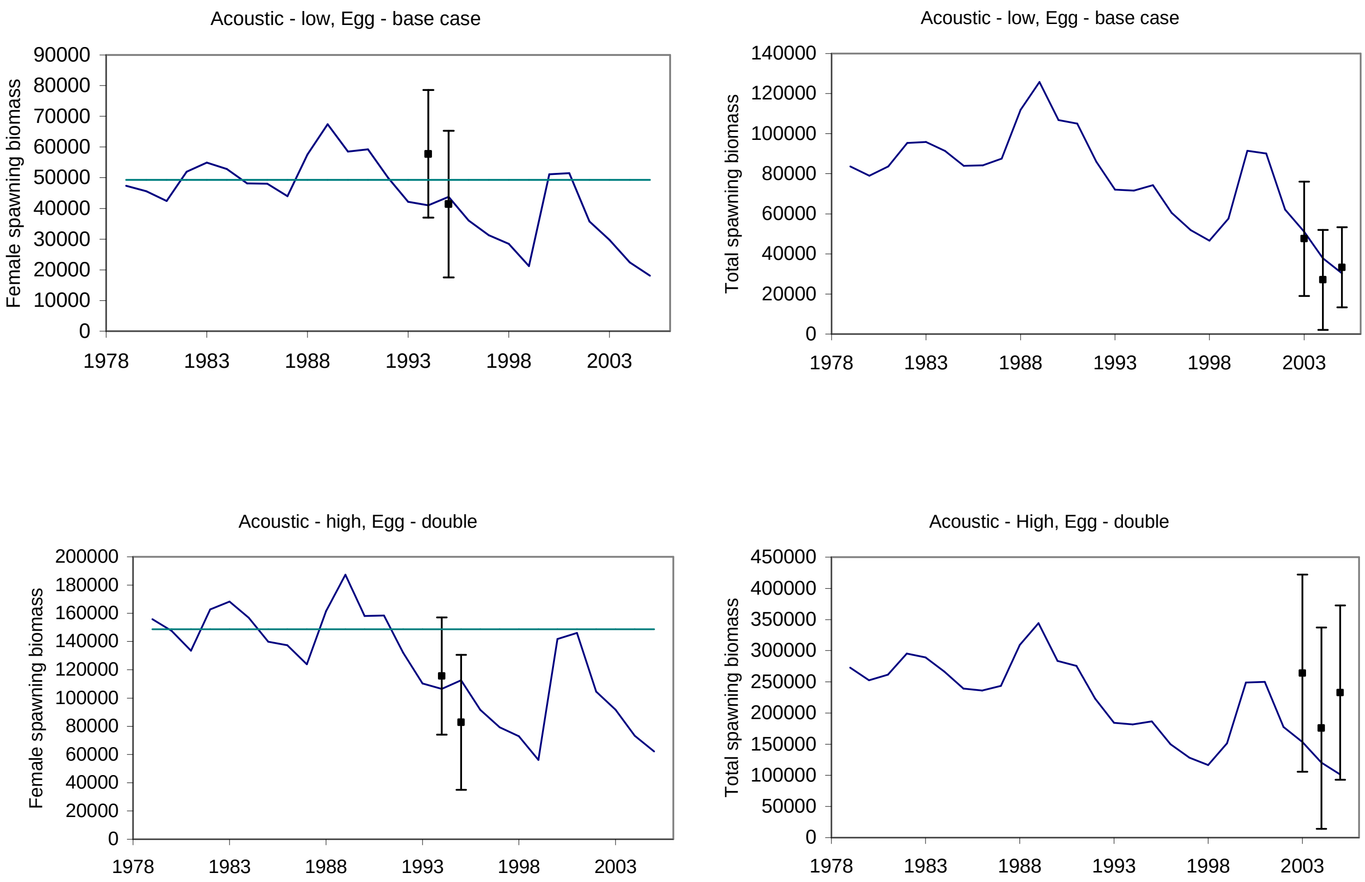


Figure 9.13. The time-trajectory of female spawning biomass (left) and total spawning biomass (right) for the Low model (top) and High model (bottom). The vertical lines show the estimates of spawning biomass derived from surveys of egg abundance in 1994 and 1995 and acoustic surveys from 2003 to 2005. The horizontal line shows B_{ref}, which is defined as the average female spawning biomass over 1979–1988.

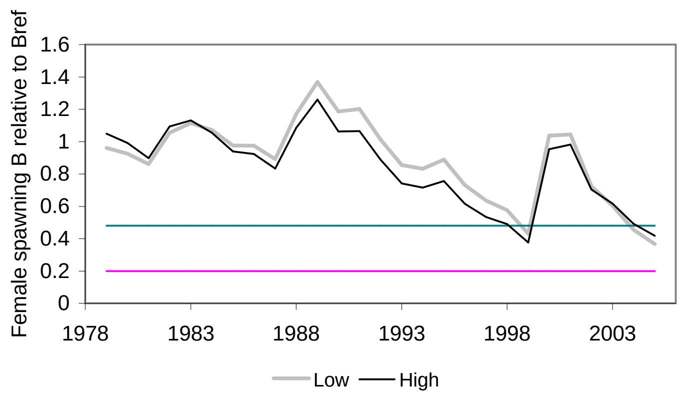


Figure 9.14. The trajectory of female spawning biomass relative to the reference biomass, B_{ref} for the Low and High models. The horizontal lines show the 0.48 and 0.20 levels.

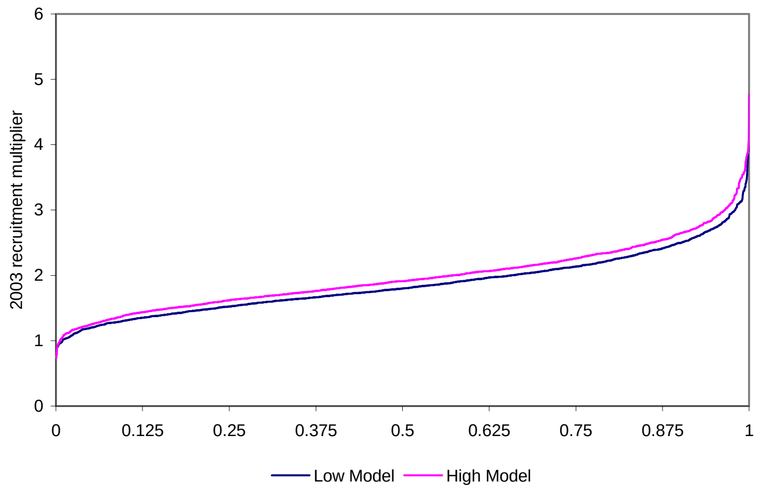


Figure 9.15. The 2003 recruitment multipliers from a Bayesian analysis sorted by increasing magnitude for the Low and High models. The parameter sets chosen for the decision analysis correspond to 0.125 (referred to as R125), 0.5 (R500) and 0.875 (R875).

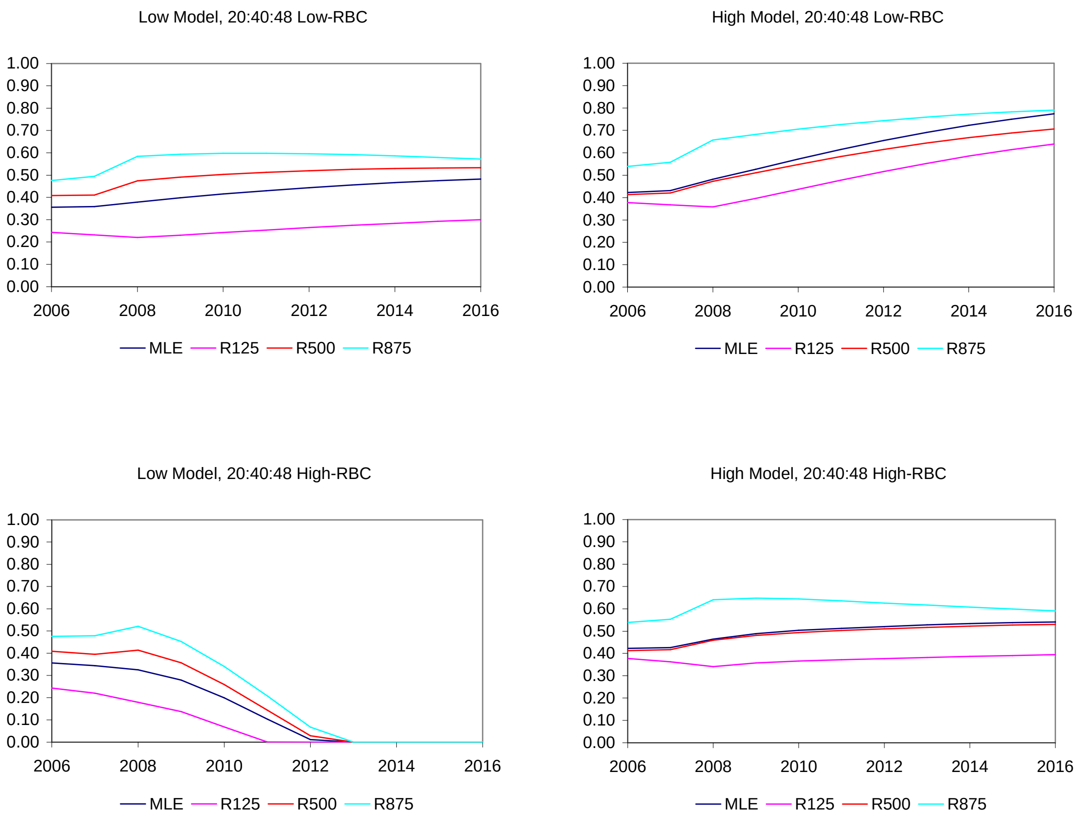


Figure 9.16. Projections over a 10-year period for the two catch series based on the 20:40:48 Tier 1 rule (Low-RBC, High-RBC) when the true state of nature is either of the two alternative models (High, Low Model) ,i.e. leading to four possible crosses of model and catch series. Results are shown for four different parameters sets (MLE, R125, R500, and R875) for each model.

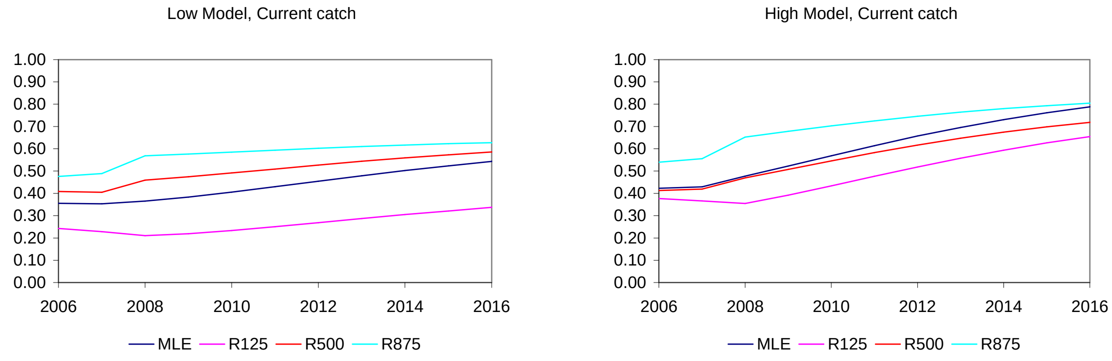


Figure 9.17. Projections over a 10-year period for fixed annual catch equal to the current TAC (3,730 t) when the true state of nature is either of the two alternative models (High, Low Model). Results are shown for four different parameters sets (MLE, R125, R500, and R875) for each model.

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:

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

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:

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

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:

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

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

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

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:

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

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

L^f_{95} 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*, $\hat{C}^f_{y,a}$, and the number of fish of age *a* discarded by sub-fishery *f*, during year *y*, $\hat{D}^f_{y,a}$, are given by the equations:

$$\hat{C}^f_{y,a} = \sum_s \frac{(1-P_{y,a})S^f_{y,a}F^f_y}{Z^s_{y,a}} N^s_{y,a}(1-e^{-Z^s_{y,a}}) \quad \text{(A.7a)}$$

$$\tilde{D}^f_{y,a} = \sum_s \frac{P_{y,a}S^f_{y,a}F^f_y}{Z^s_{y,a}} N^s_{y,a}(1-e^{-Z^s_{y,a}}) \quad \text{(A.7b)}$$

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

$$P_{y,a} = \frac{\gamma(\sum_s N^s_{y,1})^\phi / \max_{y'}(\sum_{s'} N^{s'}_{y',1})^\phi}{1+e^{-(L_a-L^D_{50})/\delta}} \quad \text{(A.8)}$$

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

L^D_{50} 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 :

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

where $C_y^{f,\mathrm{obs}}$ 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:

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

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*:

$$\hat{\rho}_{y,a}^{f} = \sum_{a"} \chi_{a,a"}\, \hat{C}_{y,a"}^{f} / \sum_{a'=1}^{x} \hat{C}_{y,a'}^{f} \tag{A.14}$$

$\chi_{a,a'}$ 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 $\rho_{y,a}^{f,\text{obs}}$ 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:

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

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*:

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

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:

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

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}.