Preliminary assessment of the western and south-western Cape Carpenter resource using an age-structured production model

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April 2011

Abstract

An age-structured production model (ASPM) is used to assess the Carpenter resource off the south western coast of South Africa. The model is fitted to standardized CPUE and length frequency linefish data. Problems encountered when attempting to fit the model to these data are explored. Reasons may include conflicting data, or complexities in the resource dynamics that are not incorporated in the simple density-dependent ASPM dynamics. Plausible parameter estimates are only achieved when fixing or imposing penalty functions for key parameters. However, this leads to deterioration in the fit to the data with systematic trends in the residuals which render results suspect and management advice based on such assessments dubious. Indeed, a management procedure approach may be better suited to circumstances when a "best assessment" is problematic, as seems to be the case here.

1 Introduction

An age-structured production model (ASPM – see Appendix 1) is used here to assess the Carpenter (silverfish) stock off the south western coast (including the Agulhas Bank) of South Africa. No comprehensive assessment has been conducted for this resource since 1999 (Linefish Scientific Working Group Report, 2011). That Report notes that the resource is estimated to be "collapsed" with an approximate 88% decrease since the fishery commenced in the late 1800s (Griffiths 2000). It has thus become a pressing priority to undertake a thorough assessment of this resource, with the eventual aim of developing a management procedure for the Carpenter fishery to ensure future recovery and sustainable long-term use. This assessment intends to be first step in this direction.

2 Data

Total annual Carpenter catches (in tons) for the western South African zone as well as standardised CPUE data and associated CVs for the commercial linefish fleet are given in Table 1 of the Appendix 2. The catch-at-length data can be found in Table 2 of Appendix 2. All data were kindly provided by H. Winkler.

3 Methods

An age-structured production model (ASPM) is used for this assessment. The technical specifications can be found in Appendix 1 of this document. The Pope approximation for the catch equation was employed to facilitate comparison with results of Booth *et al*. (2011). CPUE data are incorporated in the likelihood function using the "additional variance" approach of Geromont and Butterworth (2001). The catch-at-length data were fitted using a proportionally weighted method set out in Brandao and Butterworth (2009) where model predicted catches-at-age are converted to catches-at-length using an age-length transformation matrix.

Parameters estimated include K (carrying capacity), h (steepness of the stock-recruitment curve), the raio of the initial spawning biomass in the first year of the assessment to its pre-exploitation level, B_1 / K, the selectivity-at-age vector S_a, natural mortality rate, M_a, which is assumed to be age-independent, and the stock-recruit residuals. Prior distributions adopted for these parameters are given in Section 1.3 of Appendix 1.

4 Results

Both standardized linefish CPUE and length data are incorporated in the likelihood for the model fit for all runs. Results are grouped into three categories according to values input for the initial spawning biomass compared to the pre-exploitation level (B_1 / K), ranging from 10% to 50% of pristine (Tables 1, 2 and 3). This was necessary as preliminary runs showed that this parameter was not well-estimated (it approached an upper bound of 1, implying that the 1985 biomass was at its pre-exploitation level), so that a prior/penalty needed to be included for this parameter, or else B_1/K had to be fixed. For the base case runs M_a was fixed to a value of $0.2yr^{-1}$ for all ages a, the central value of the prior distribution proposed by Kerwath and Winkler (pers. commn). There are four options shown for each case: estimate the steepness (h) of the stock-recruitment curve, or fix h to 0.6; and estimate the recruitment residuals, or set them all to zero.

- $B_1 / K = 0.3$: Results are shown in Table 1 and Figures 1a, b, c, d and e.
- $B_1 / K = 0.1$: Results are shown in Table 2 and Figures 2a, b, c and d.
- $B_1 / K = 0.5$: Results are shown in Table 3 and Figures 3a, b, c and d.

Table 4 shows results when estimating an age-independent M_a rather than fixing it to $0.2yr^{-1}$ while forcing the selectivity-at-age to be flat at older ages, as well as the introduction of informative (tighter) priors for B_1 / K , M_a and h.

5 Discussion

Initial runs demonstrated that the model has difficulty fitting the data within the permissible parameter space. Key model parameters, such as h, M_a and B_1/K were estimated at the boundaries of their allowed ranges, rendering these fits dubious. It was therefore decided that best practice would be to fix these parameters at plausible values and examine the resultant fits to the data in order to understand why the model is unable to reconcile the data with the prior distributions of parameters.

The goodness of fit for each of the assessments is indicated by the total negative log-likelihood value ($-\ln L_{TOTAL}$). In addition, the Akaike Information Criterion (AIC) statistic is given to aid model selection, where $AIC = -2\ln L_{TOTAL} + 2p$ where p is the number of estimable parameters. The first term is a measure of how well the model fits the data, while the second term is a penalty for the addition of further estimable parameters (Burnham and Anderson, 1998). Both these statistics are shown at the bottom of the Tables. Note that although this assessment is set up in a Bayesian framework, results are given only as posterior modes, corresponding to penalised MLEs in a frequent context; thus strictly AIC can be used to select amongst models only in instances when the penalty functions are unchanged.

Table 1 shows fits to the data when fixing the initial spawning biomass in 1985 to 30% of the pre-exploitation level while at the same time fixing M_a to $0.2yr^{-1}$. The model has difficulty estimating the steepness parameter, *h*, both with and without recruitment fluctuations (columns 1 and 3), and prefers an unrealistically low value of *h*=0.21 (the lower bound for specified for this prior) corresponding to a resource with effectively no productivity. However, when fixing *h* to a more realistic value of 0.6, the fit to the CPUE data deteriorates markedly: the AIC increasing from -44.78 to -3.34 for one estimable parameter less for the case when not allowing for recruitment fluctuations; and an increase in AIC from -42.84 to 9.53 when allowing for recruitment fluctuations. According to the Akaike criterion the preferred model is clearly SC1a (column1) with an AIC score of -44.8. The addition of the 21 additional stock-recruitment residual parameters are therefore not justified in terms of the extent of improvement of fit to the data, though this is not a completely reliable comparison for the reasons given above, essentially here as these residuals are not completely free parameters but instead constrained by their prior.

Figure 1a shows the model estimated and observed CPUE corresponding to the runs in Table 1. To illustrate the effect of an increase in the stock-recruit steepness parameter, *h*, twenty year projections for a zero future catch are plotted. For the *h*=0.6 scenarios, the model estimated CPUE values clearly do not fit the observed CPUE data. For the two scenarios when *h* is estimated, the fit to the CPUE data is much improved, with an historic decrease in CPUE that mimics the trend in the data. However, due to the low estimate of *h*=0.21 (prior lower bound), there is very little recovery of the resource even for a zero future catch. The corresponding spawning biomass plots are given in Figure 1b. The estimated stock recruitment residuals are plotted in Figure 1c for fixed and estimated *h*. Systematic effects amongst the residuals are evident for SC1c (estimate *h*): positive for the 1980s and then negative thereafter. This is the only way the model is able to fit the length data at low *h*. For *h*=0.6, allowing for fluctuations about the stock-recruitment curve had no effect whatsoever on the complete lack of fit to the CPUE and length data (purple plots). The estimated selectivity vectors are shown in Figure 1d. As in the previous graphs, the two plots when *h* are estimated lie on top of the other, both with a negative slope at older ages. However for *h*=0.6, both selectivity vectors have zero slope (i.e. standard logistic curve). Lastly, Figure 1e gives the log residuals of the fit to the catch-at-length data for SC1a. The bubble plot shows that the model systematically over-estimates the proportion of older/larger fish while under-estimating the proportion of fish caught in length groups 250mm to 350mm, which constitute the highest proportion of the catch (see Appendix 2, Figures A-3 and A-4 for length frequency plots).

According to preliminary baseline estimates by Griffiths (2000), the resource in 1985 could well have been far more depleted than the 30% assumed in Table 1. A lower initial spawning biomass depletion of B_1/K=0.1 is assumed for the runs depicted in Table 2. In the case of a severely depleted resource, the steepness, *h*, is estimated at 0.32 and 0.26 (columns 1 and 3 respectively), with associated AICs of -25 and -38 corresponding to the deterministic and stochastic stock-recruitment relationships. However, when fixing *h* at a more realistic value of 0.6, there is a complete lack of fit to both the CPUE and length data, with a substantial increase in additional variance to $\sigma_{ADD} = 0.89$. This is illustrated in Figure 2a, where both *h*=0.6 scenarios (the one lying on top of the other) show an increase in estimated CPUE in contrast to the observed downward CPUE trend. Scenario 2a mimics the decline in historic CPUE, as well as a subsequent recovery when no catch is taken, although perhaps not quite as fast as expected under zero catch. The estimated biomass plots are given in Figures 2b, with the estimated recruitment residuals shown in Figure 2c. As before, due to the inability to fit the data at higher *h*, the recruitment residuals cannot be estimated (purple plot). The residuals when estimating *h* show the same systematic patterns as for scenario 1c. Of these runs, the preferred model in terms of the AIC is scenario 2c which allows for recruitment fluctuations (despite the restrictions the prior places on these fluctuations). Not surprisingly, the low 10% initial depletion necessitates a high estimate of *K* (here estimated at its upper prior bound of 60 000 tons).

When assuming that the 1985 spawning biomass was at 50% of the pre-exploitation level, the same problem persists: the best model fit is achieved when estimating *h* (AIC=-44.74), however this is only achieved for an unrealistically low *h* (no productivity) - see Figure 3a for the fit to the CPUE data. Fixing *h* to 0.6 leads to severe deterioration in fit to the CPUE data when not allowing for recruitment fluctuation (column 2). This is less apparent when estimating the stock recruitment residuals (last two columns of Table 3), with the AIC increasing from -42.80 to -30.34 with increasing *h*. The log recruitment residuals plots in Figure 3c show the same systematic trends as before, the patterns being even more pronounced for the *h*=0.6 case.

The assessments thus far have all assumed an age-independent natural mortality, M_a, of 0.2 yr^{-1} while estimating the fishing selectivity-at-age vector, which decreases with age at older ages. However, the decline in the proportion of older fish caught may equally be due to the lesser numbers of these fish because of higher natural mortality. Table 4 column 1 shows results for estimating the natural mortality rate while fixing the fishing selectivity to that provided by H. Winkler (see Appendix 1). This has the effect of pushing the estimate for age-independent natural mortality up to 0.36yr^{-1}. However, the fit to the length data deteriorates markedly. Estimating a logistic selectivity vector (fully selected at older ages) improves the fit to both the length and CPUE data, with an associated estimate for natural mortality rate, M_a, of 0.21 yr^{-1}. Figure 4a shows the input and estimated selectivity vectors and associated mortality rates. In both cases the steepness is estimated at an unrealistically low 0.21. Columns 3 and 4 of Table 4 show results when imposing penalty functions for the steepness, *h*, initial biomass ratio, B_1/K, as well as age-independent natural mortality rate, M_a (see Appendix 1, Section 1.3 for penalty functions). The model has difficulty to fit the trend in CPUE data when not allowing for recruitment fluctuations for an *h* estimated at 0.44. Allowing for fluctuations about the stock recruitment relationship improves the fit to both CPUE and length data, however this is achieved by a series of positive residuals from 1985 to 1991 followed by a series of negative residuals (Figure 4c). Model estimated and observed CPUE are shown in Figure 4b for these runs.

The exploitable biomass trajectories for all the assessments that fit the data reasonable well are plotted in Figure 5 for comparison. There are clearly many different interpretations, which renders management advice based on these assessments impossible, with current depletion ranging from 6% to over 80%. In terms of model fit to both CPUE and length data, SC1c, SC2c and SC3c fair best, i.e. those assessments for which recruitment fluctuations are allowed. However, for these runs *h* is estimated at 0.21 (the lower bound of the prior), which is unrealistic, or slightly above at 0.26 for SC3c (column 3, Table 3, which corresponds to an initial depletion of 50%). When *h* is fixed at a higher more believable level of 0.6, the only model that fits the data reasonably well is SC3d (column 4, Table 3).

A reasonable fit to the data is also obtained when incorporating a tighter (more informative) prior for *h* (SC4d), with a corresponding estimate of $h = 0.46$. For this case tighter priors were also imposed for B_1/K and M_a, subsequently estimated at 0.43 and 0.17 respectively, with current spawning biomass estimated to be 38% of *K*. However, these assessments cannot be used to base management decisions on as the recruitment residuals are anything but randomly distributed, which renders these results suspect.

6 Conclusions

At this stage the only conclusions that one can draw from these analyses is that this assessment is inconclusive and possibly flawed. There is no way to determine the key model parameters with any confidence and the resultant estimates of statistics pertinent to management decisions are therefore dubious at best. There are two possible reasons for this outcome: either that the data are inconsistent (note that the recent decreasing trend CPUE data is not synchronous with the recent decrease in annual catches), and/or there are complex effects in the resource dynamics that are not incorporated in a standard ASPM assessment with its underlying simple density dependent population regulation mechanism.

7 Further development

An obvious extension of the assessment process is the management procedure (MP) approach. This is particularly useful when there is substantial uncertainty and a “best” assessment cannot be selected due to conflicting or noisy data, or other complexities. The MP approach does not rely on any one assessment, but integrates over a range of possibilities, called operating models (OMs), testing management rules on each such OM to determine which harvesting control rule is the “best” (in the sense of the most robust) across all plausible scenarios.

The present ASPM analysis is particularly useful to highlight some of the shortcomings of a “best assessment” approach when there is little or conflicting information in the data: any number of interpretations are possible depending on what is included in/excluded from the likelihood function and what parameter ranges/prior distributions are allowed. This uncertainty will need to be taken into account in a quantitatively defensible and consistent manner in order to give scientifically rigorous management advice.

Acknowledgements

Financial support of the South African National Research Foundation is gratefully acknowledged. Sven Kerwath and Henning Winkler are thanked for providing the data. We would also like to thank Colin Attwood for his valuable comments regarding the South African line fisheries in general, and the Carpenter resource in particular.

Fit to CPUE and length data: *M*=0.2, B_1/K=0.3, est S_a (project 20 years under zero catch)				
			Est SR residuals 1985-2005	
	SC1a: Est *h*	SC1b: Fix *h*=0.6	SC1c: Est: *h*	SC1d: Fix: *h*=0.6
Parameters:	5	4	26	25
K^{sp}	46194	59460	41263	59485
h	0.21 !	**0.6**	0.21 !	**0.6**
M_α	**0.2**	**0.2**	**0.2**	**0.2**
r^{sp}	**0.3**	**0.3**	**0.3**	**0.3**
agec	4.08	4.53	4.06	4.52
δ	0.76	0.85	0.74	0.85
slope	-0.03	0.0	-0.03	0.0
Stats:				
B_n^{sp} / K^{sp}	0.20	0.88	0.19	0.88
B_{final}^{sp} / K^{sp}	0.22	0.99	0.21	0.99
Max likelihood:				
σ_{ADD}	0.20	0.52	0.18	0.52
σ_{len}	0.09	0.09	0.08	0.09
$-\ln L_{CPUE}$	-21.51	-2.45	-24.42	-2.46
$-\ln L_{len}$	-5.86	-3.21	-11.29	-3.22
$-\ln L_{SR}$			-11.90	-14.55
$-\ln L_{TOTAL}$	-27.38	-5.67	-47.42	-20.24
$AIC = 2p - 2\ln L$	-44.78	-3.34	-42.84	9.53

Table 1: Model estimates (posterior modes) shown for pertinent parameters and management quantities, along with the associated negative (penalized) log likelihood values when fitting to CPUE and length data. Age-independent natural mortality rate is fixed to $0.2yr^{-1}$, while the initial (1985) spawning biomass ration B_1/K, is set to 0.3 for these runs. ***Note: parameters that are estimated to be at the edge of their prior distribution are marked with an exclamation as these values are suspect.***

Fit to CPUE and length data: *M*=0.2, B_1/K=0.1, est S_a (project 20 years under zero catch)				
			Est SR residuals 1985-2005	
	SC2a: Est *h*	SC2b: Fix *h*=0.6	SC2c: Est: *h*	SC2d: Fix: *h*=0.6
Parameters:	5	4	26	25
K^{sp}	37797	48031	60000!	48031
h	0.32	**0.6**	0.26	**0.6**
M_{α}	**0.2**	**0.2**	**0.2**	**0.2**
r^{sp}	**0.1**	**0.1**	**0.1**	**0.1**
agec	4.74	5.10	4.39	5.10
δ	0.16	0.73	0.83	0.73
slope	-0.06	-0.05	0.0	-0.05
Stats:				
B_n^{sp} / K^{sp}	0.06	0.74	0.07	0.74
B_{final}^{sp} / K^{sp}	0.20	0.97	0.11	0.97
Max likelihood:				
σ_{ADD}	0.26	0.89	0.18	0.89
σ_{len}	0.10	0.15	0.08	0.15
$-\ln L_{CPUE}$	-16.41	8.09	-23.46	8.42
$-\ln L_{len}$	-1.19	32.11	-10.73	32.30
$-\ln L_{SR}$			-11.29	-14.56
$-\ln L_{TOTAL}$	-17.61	40.20	-45.48	17.17
$AIC = 2p - 2\ln L$	-25.22	88.4	-38.96	84.34

Table 2: Same as Table 1, but here assuming that the initial spawning biomass is 10% of the pre-exploitable level. ***Note: parameters that are estimated to be at the edge of their prior distribution are marked with an exclamation as these values are suspect.***

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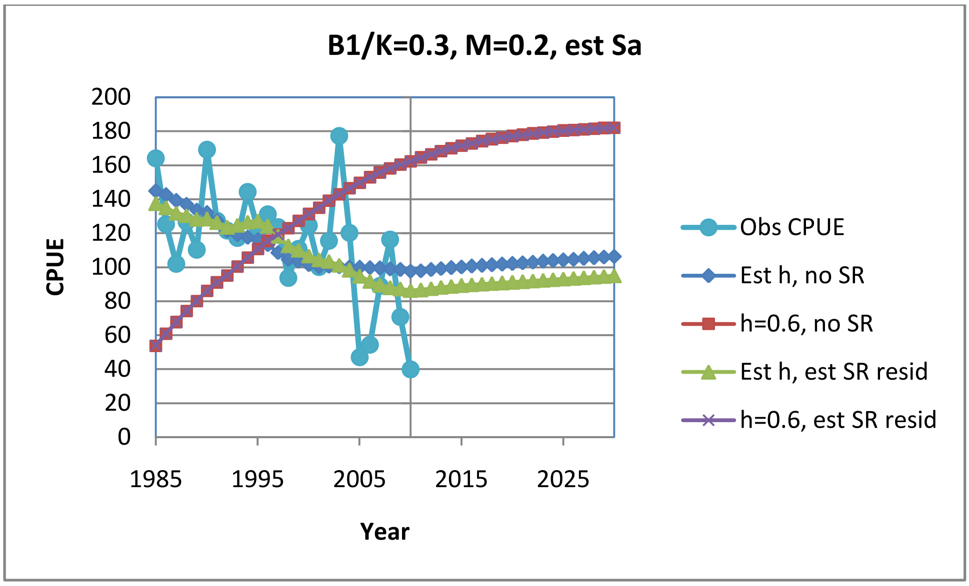
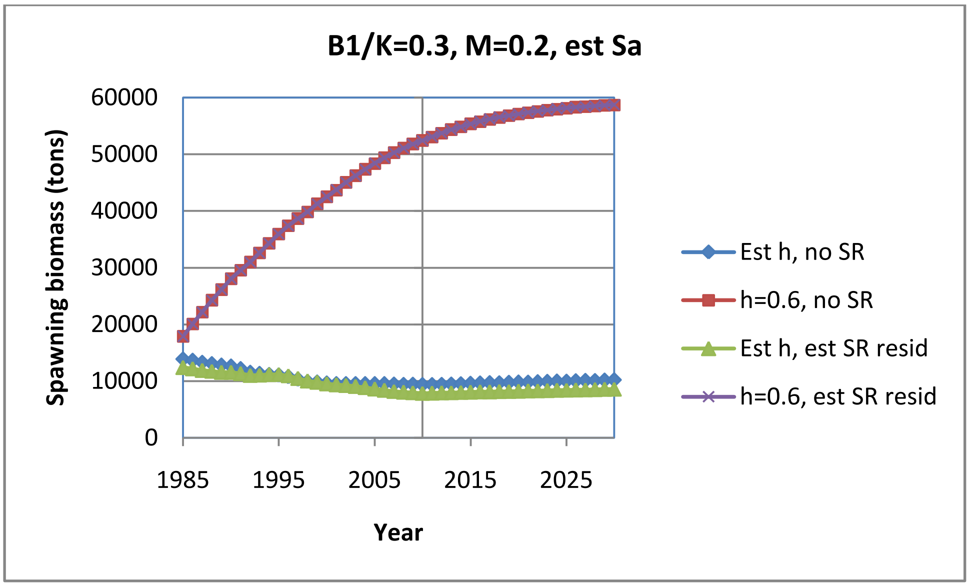
Fit to CPUE and length data: M=0.2, B_1/K=0.5, est S_a (project 20 years under zero catch)				
			Est SR residuals 1985-2005	
	SC3a: Est h	SC3b: Fix h=0.6	SC3c: Est: h	SC3d: Fix: h=0.6
Parameters:	5	4	26	25
K^{sp}	29008	16790	25735	11632
h	0.21!	**0.6**	0.21!	**0.6**
M_{α}	**0.2**	**0.2**	**0.2**	**0.2**
r^{sp}	**0.1**	**0.1**	**0.1**	**0.1**
agec	4.07	4.54	4.06	4.49
δ	0.76	0.88	0.74	0.85
slope	-0.03	0.0	-0.03	0.0
Stats:				
B_n^{sp} / K^{sp}	0.36	0.81	0.32	0.51
B_{final}^{sp} / K^{sp}	0.31	0.98	0.34	0.92
Max likelihood:				
σ_{ADD}	0.20	0.34	0.18	0.20
σ_{len}	0.09	0.09	0.08	0.08
$-\ln L_{CPUE}$	-21.56	-10.44	-24.25	-20.89
$-\ln L_{len}$	-5.80	-5.92	-11.24	-10.08
$-\ln L_{SR}$			-11.90	-9.20
$-\ln L_{TOTAL}$	-27.37	-16.26	-47.40	-40.17
$AIC = 2p - 2\ln L$	-44.74	-24.52	-42.80	-30.34

Table 3: Same as Table 1, but here assuming that the initial spawning biomass is 50% of the pre-exploitable level. ***Note: parameters that are estimated to be at the edge of their prior distribution are marked with an exclamation as these values are suspect.***

Fit to CPUE and length data: est M_a (project 20 years under zero catch)				
	Uninformative priors		Tighter priors: B_1/K, h, M_a	
	SC4a: Est h Input S_a Fix: B_1/K=0.3	SC4b: Est h Est $S_{a\ (slope=0)}$ Fix: B_1/K=0.3	SC4c: Est h, Est $S_{a\ (slope=0)}$ Est: B_1/K	SC4d: Est h, Est $S_{a\ (slope=0)}$ Est: B_1/K Est: SR resid
Parameters:	3	5	6	25
K^{sp}	49067	45353	13030	12310
h	0.21 !	0.21 !	0.44	0.46
M_{α}	0.355	0.211	0.171	0.173
r^{sp}	**0.3**	**0.3**	0.43	0.43
agec		4.13	4.40	4.21
δ		0.77	0.90	0.79
slope		**0**	**0**	**0**
Stats:				
B_n^{sp} / K^{sp}	0.26	0.21	0.48	0.38
B_{final}^{sp} / K^{sp}	0.29	0.23	0.82	0.78
Max likelihood:				
σ_{ADD}	0.22	0.20	0.26	0.19
σ_{len}	0.13	0.09	0.09	0.08
$-\ln L_{CPUE}$	-19.44	-21.41	-14.87	-21.64
$-\ln L_{len}$	14.82	-5.82	-5.63	-11.84
$-\ln L_{SR}$				-10.05
$-\ln L_{TOTAL}$	-4.62	-27.23	-19.04	-42.82
$AIC = 2p - 2\ln L$	-3.24	-44.46	-26.08	-35.66

Table 4: Parameter estimates (posterior modes) shown for pertinent parameters when estimating natural mortality and keeping the selectivity-at-age vector flat at older ages. ***Note: parameters that are estimated to be at the edge of their prior distribution are marked with an exclamation as these values are suspect.***





Figures 1a and b: Past and future model estimated CPUE and spawning biomass for each of the scenarios in Table 1. The current year (2010) is marked by the vertical line. A 20 year projection period with a zero future catch was chosen to illustrate possible resource recovery, or lack thereof.

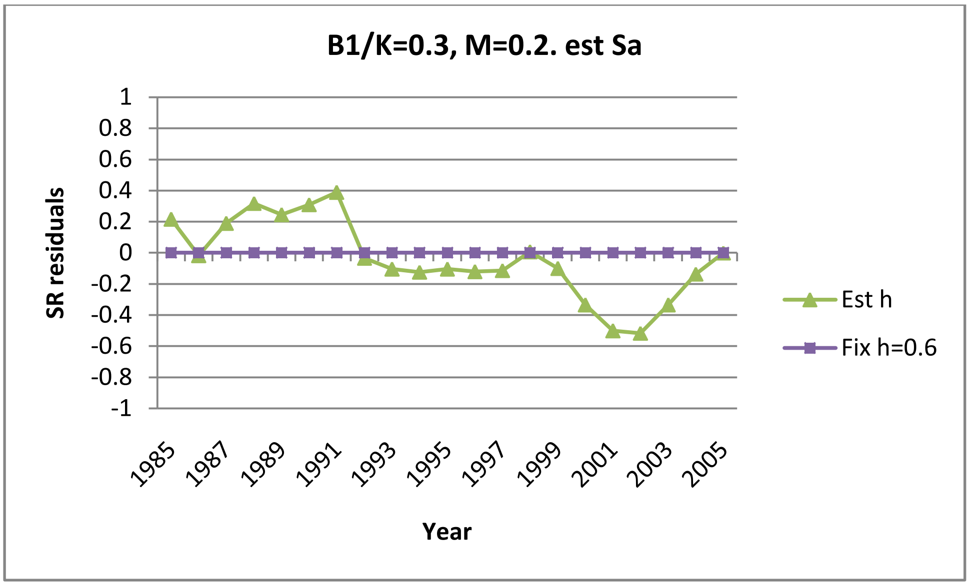


Figure 1c: Model estimated stock recruitment residuals when for fixed *h*-0.6 and estimable *h*.

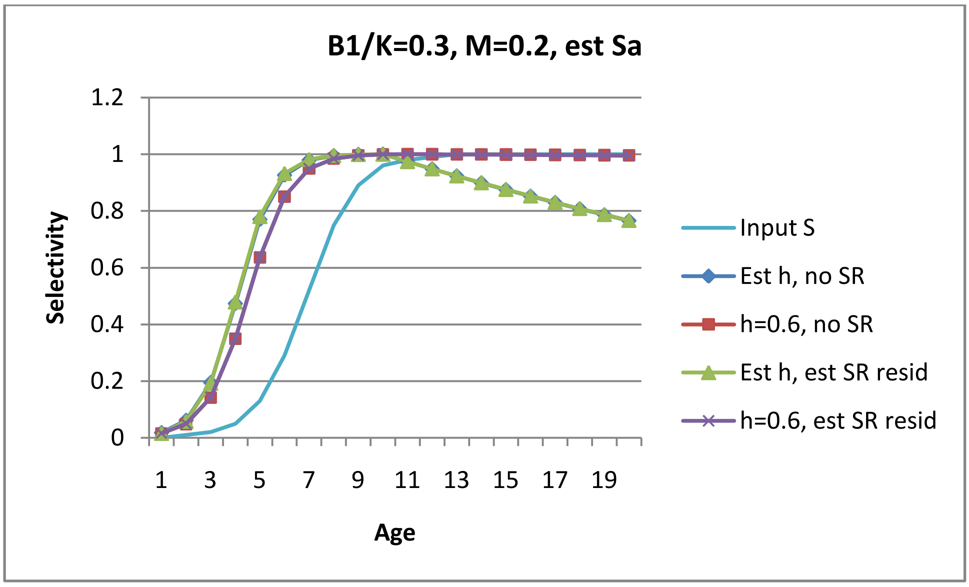
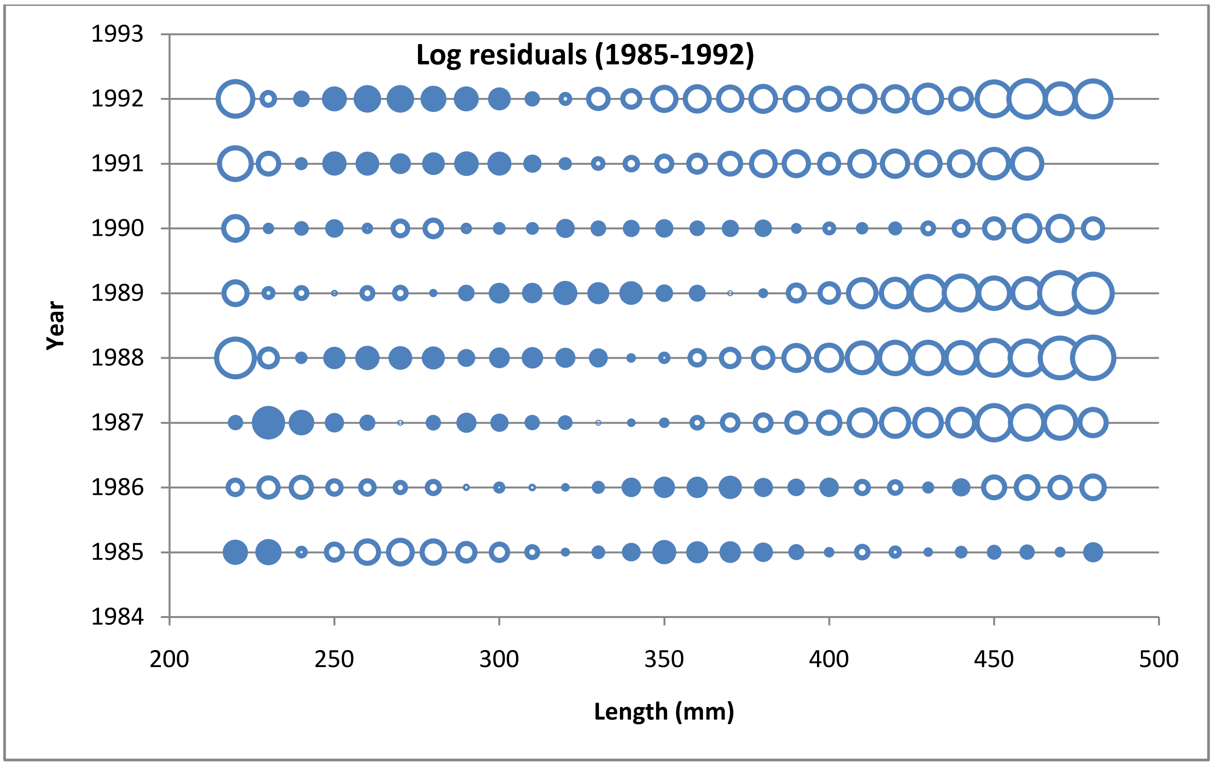
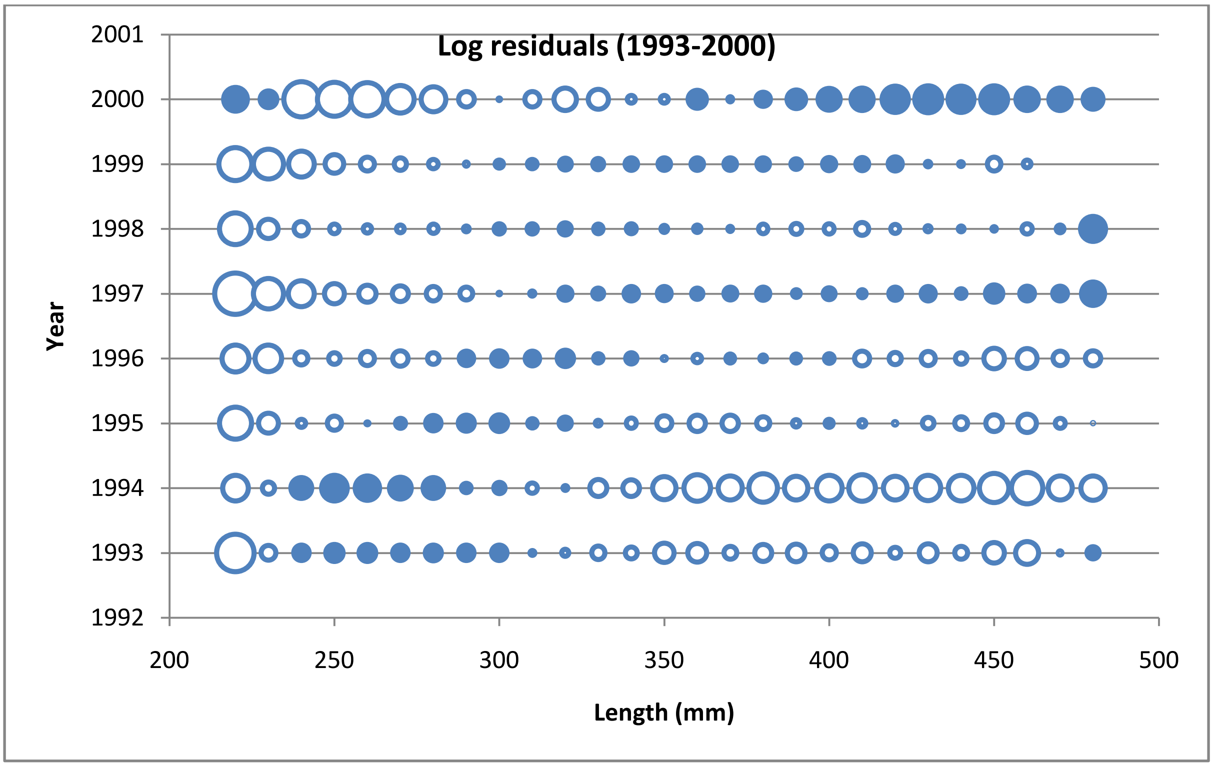


Figure 1d: Original input and model estimated selectivity-at-age for the four scenarios.


Log residuals (1985-1992)
Year
1993
1992
1991
1990
1989
1988
1987
1986
1985
1984
200
250
300
350
400
450
500
Length (mm)


Log residuals (1993-2000)
Year
2001
2000
1999
1998
1997
1996
1995
1994
1993
1992
200
250
300
350
400
450
500
Length (mm)

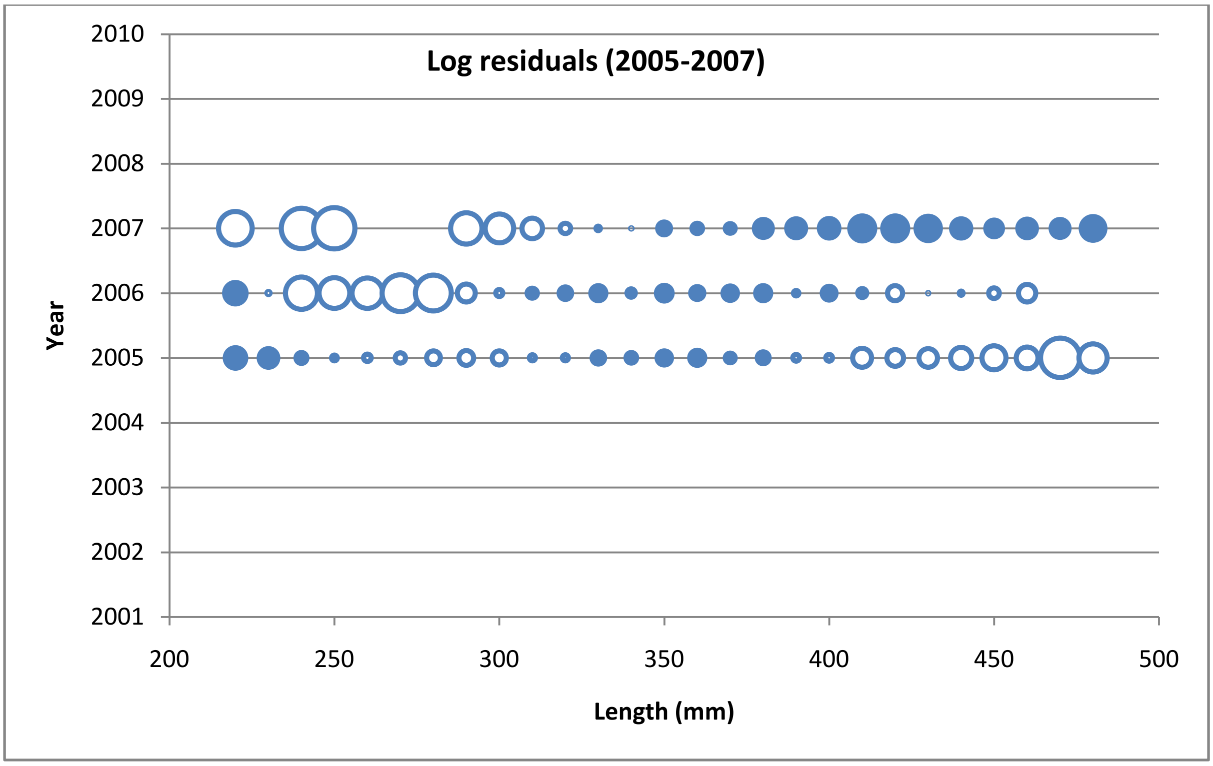
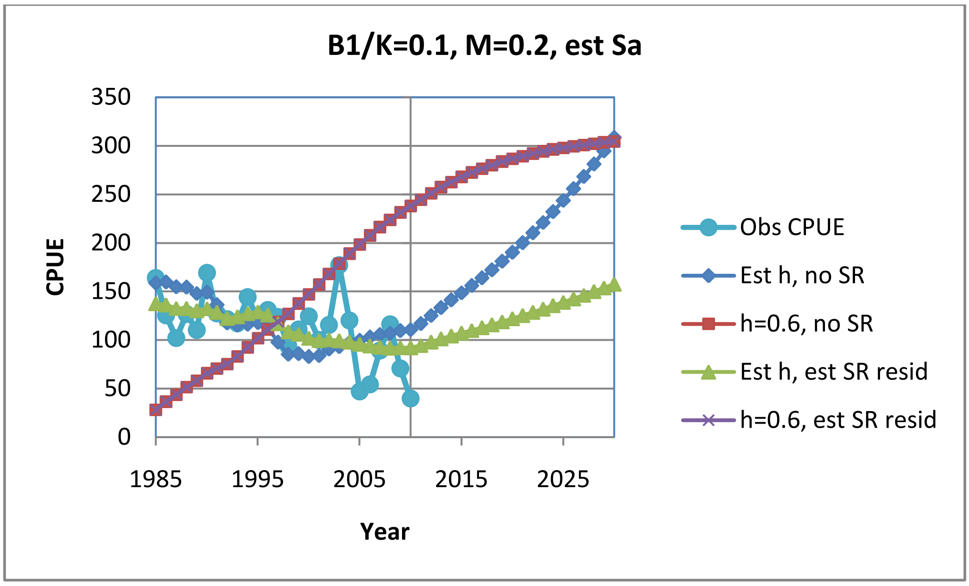
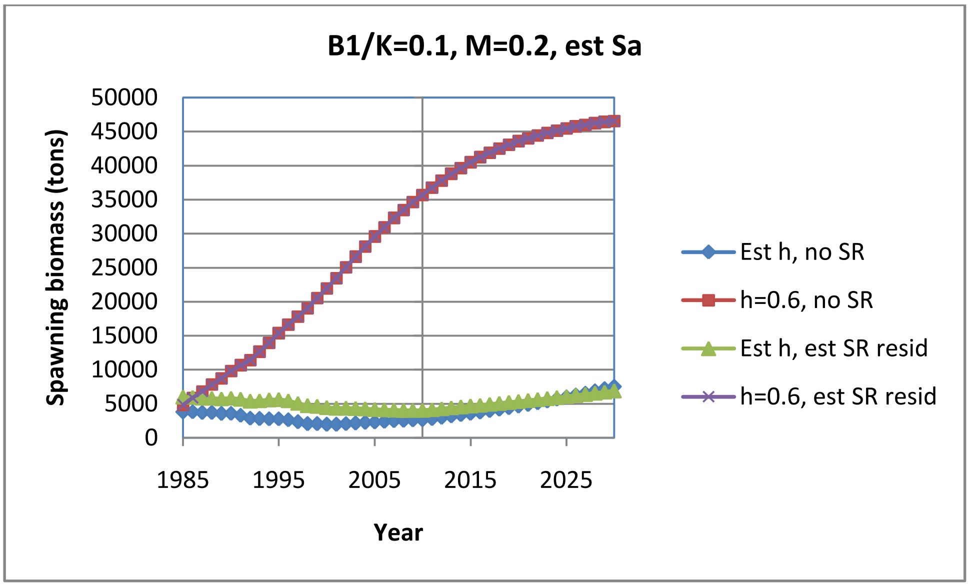


Figure 1e: Model estimated residuals of the fit to the length data for estimated *h* (SC1a) for the years 1985 to 2007. The size of the bubbles are proportional to the log residuals: solid circles for positive residuals and empty circles for negative residuals.





Figures 2a and b: Top: Same as Figures 1a, b and c, but here for an initial biomass ratio of 0.1.

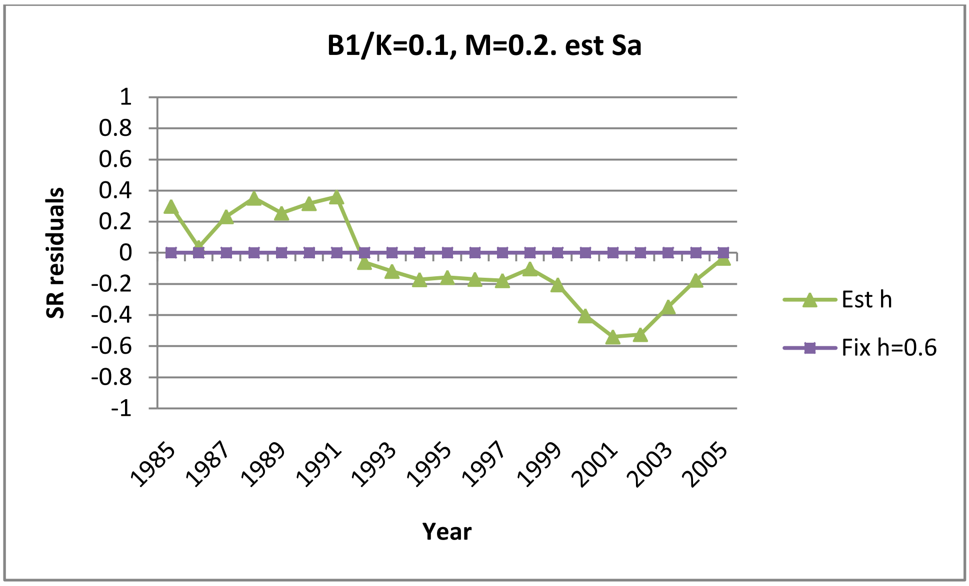


Figure 2c: Model estimated stock recruitment residuals when for fixed *h*-0.6 and estimable *h*.

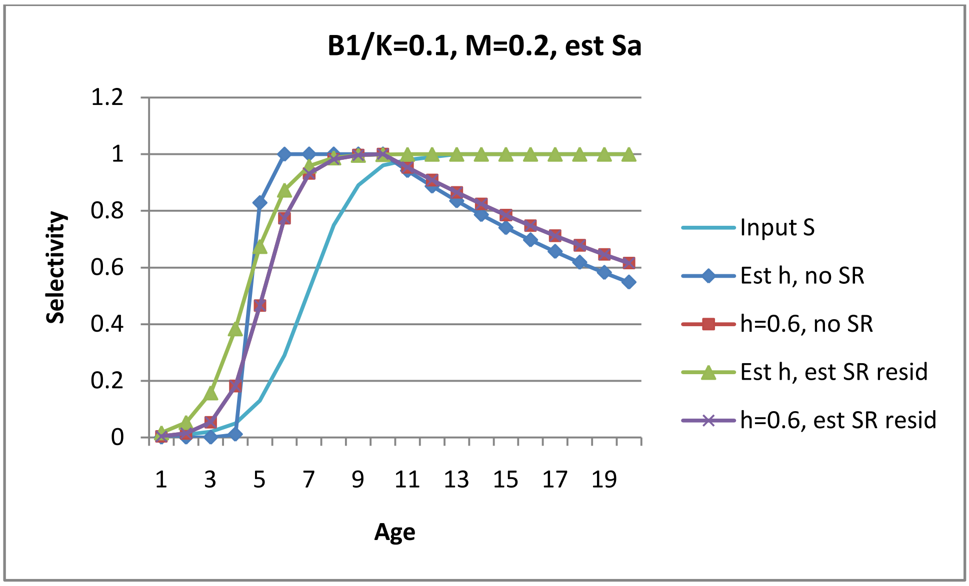
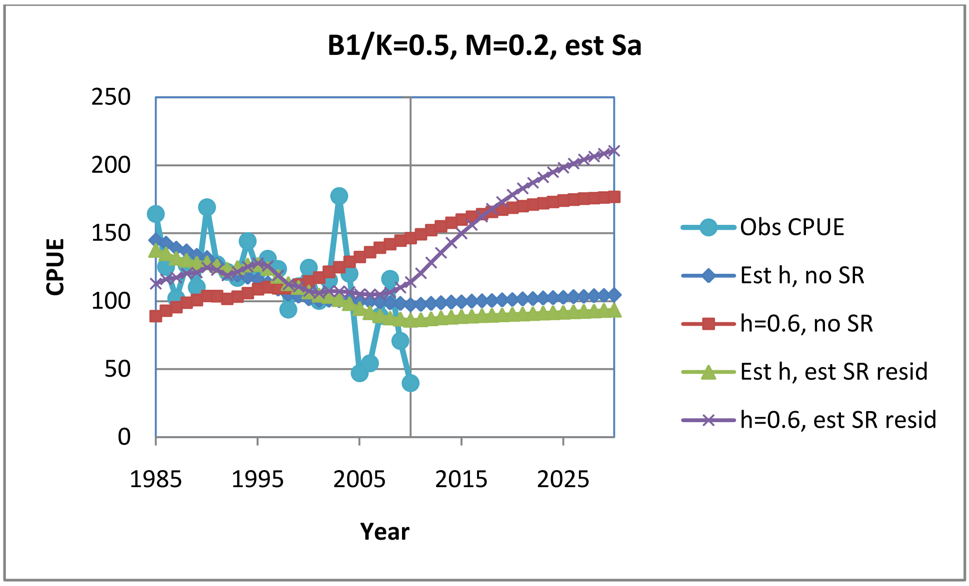
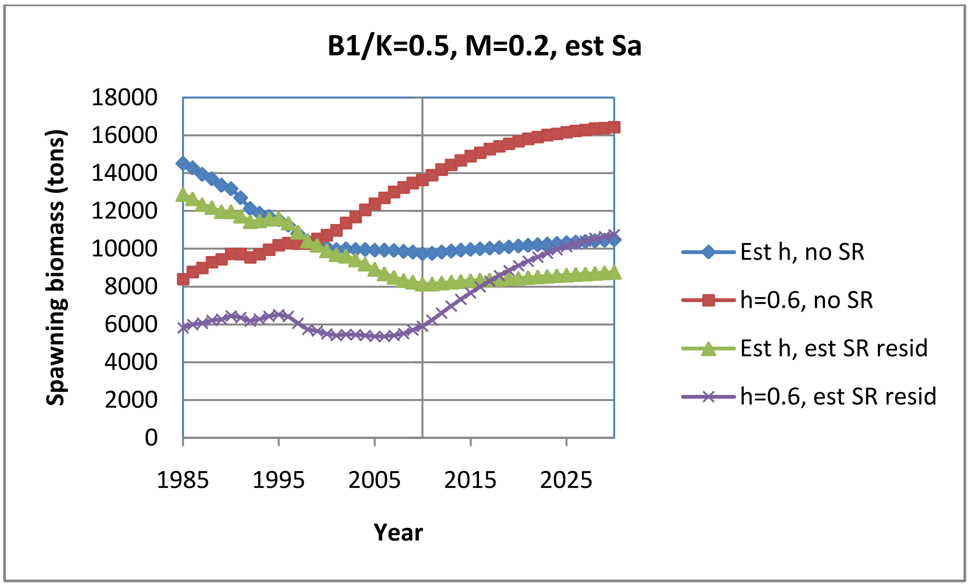


Figure 2d: Original input and model estimated selectivity-at-age vectors when the initial biomass is taken to be 10% of the pristine level.





Figures 3a and b: Same as Figures 1a and b, but here for an initial biomass ratio of 0.5.

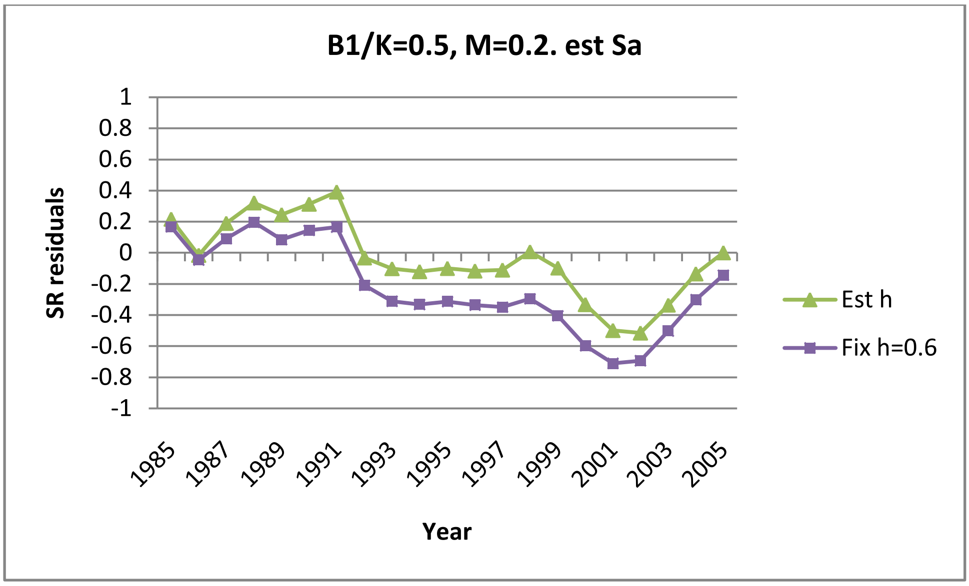


Figure 3c: Model estimated stock recruitment residuals when for fixed *h*-0.6 and estimable *h*.

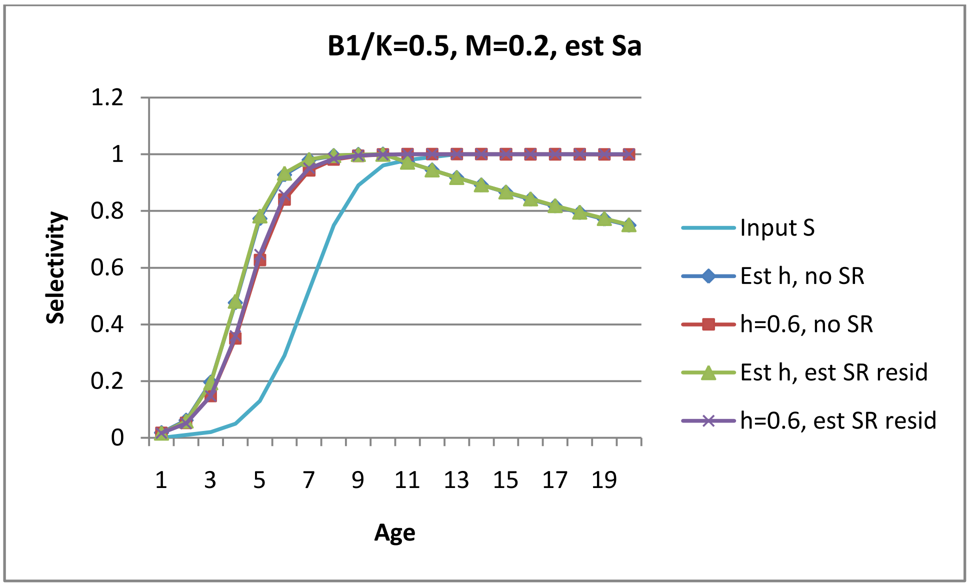


Figure 3d: Original input and model estimated selectivity-at-age for an initial biomass ratio of 50%.

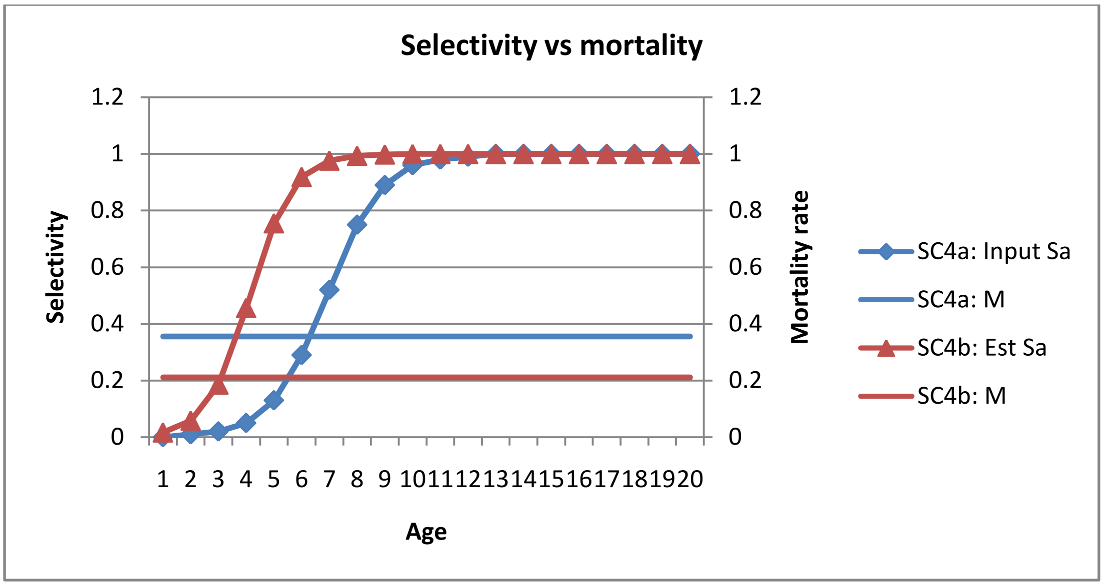


Figure 4a: Model estimated mortality rate and selectivities-at-age for SC4a and b for scenarios where this selectivity is constrained to be flat at large ages.

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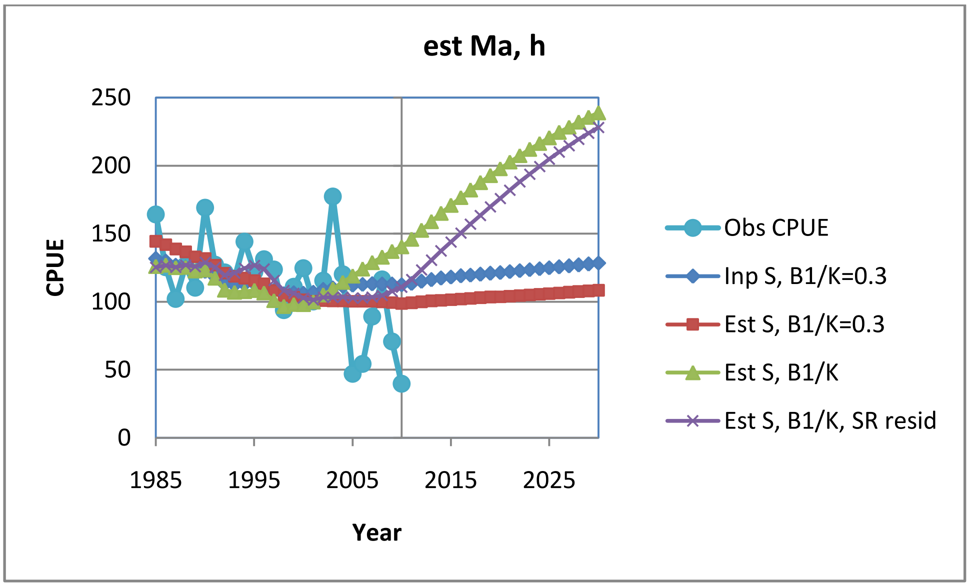

Figure 4b: Model estimated and observed CPUE for SC4a, b, c and d.

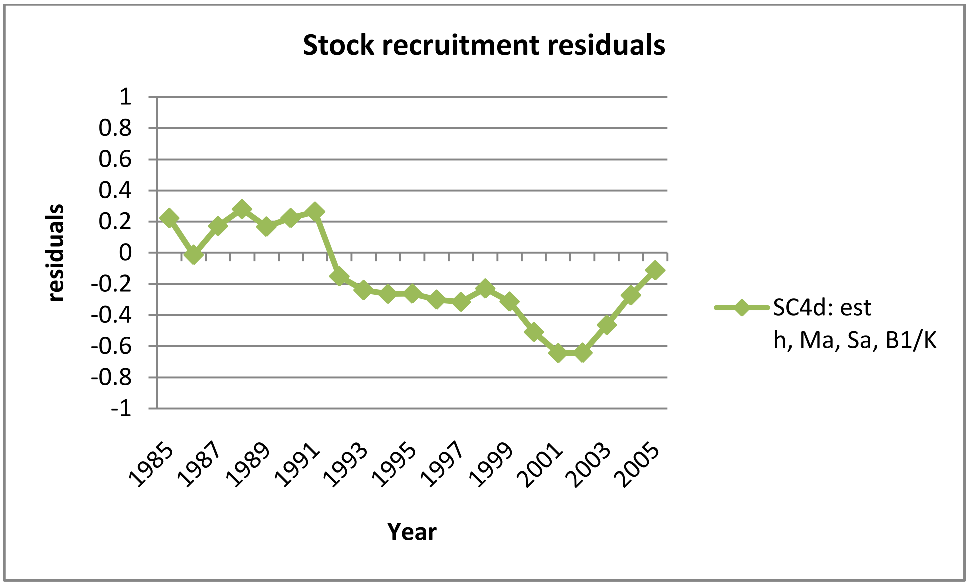

Figure 4c: Recruitment residuals when imposing alternative tighter priors for *h*, M_a and B_1/K for SC4d.

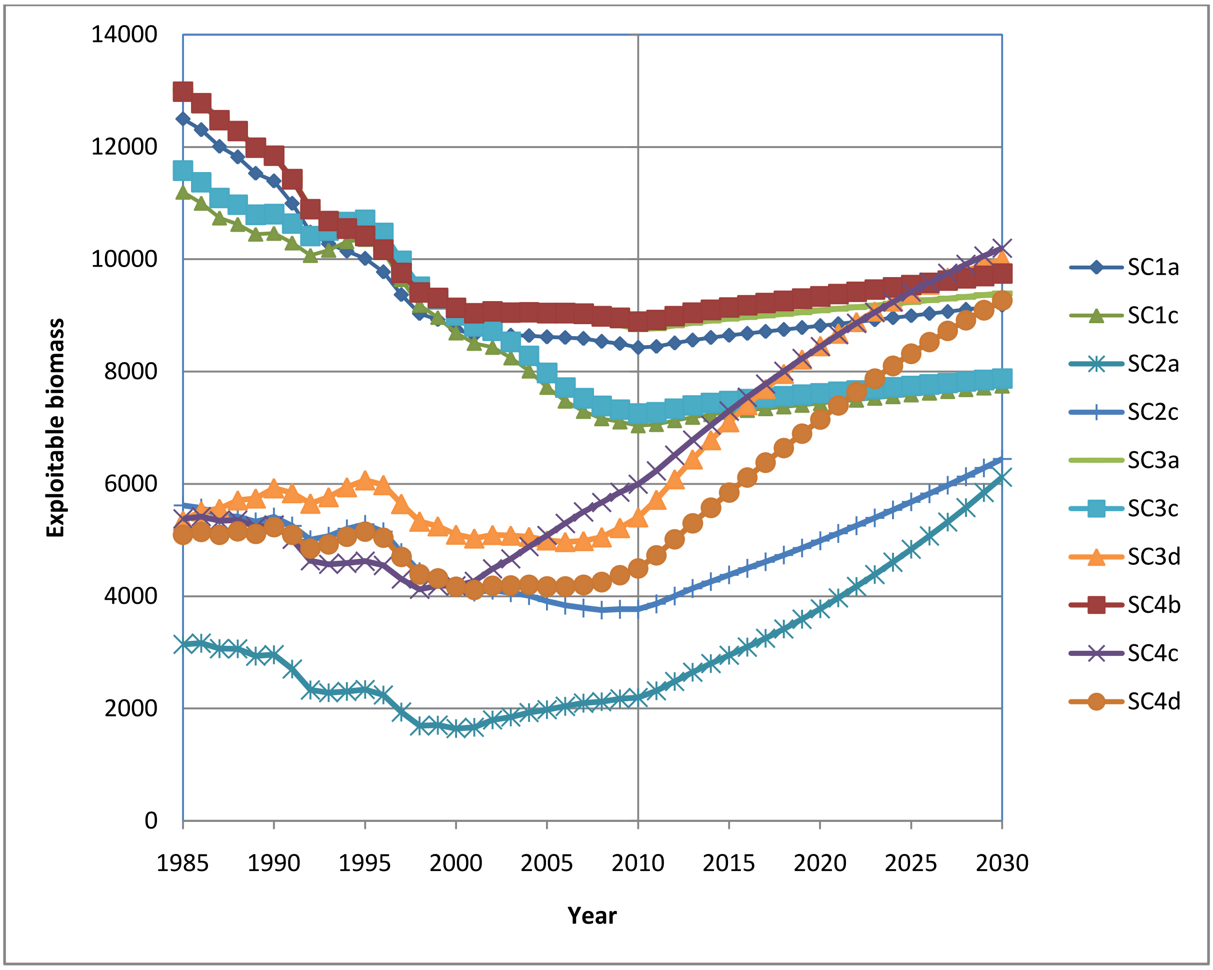

Figure 5: Plots of estimated exploitable biomass series for those scenarios that fit the data reasonably well. Twenty year projections shown for a zero future catch.

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Appendix 1:
The age-structured production model (ASPM)

The resource dynamics are modeled by the following equations, depending whether a continuous or pulse fishery is assumed. For the Baranov approximation (continuous fishing throughout year), the resource dynamics are modeled by the equations:

$$N_{y+1,a\min} = R_{y+1} \tag{1.1}$$

$$N_{y+1,a+1} = N_{y,a} e^{-(M_a + S_{y,a} F_y)} = N_{y,a} e^{-Z_{y,a}} \quad \text{for } a_{\min} \le a < m-2 \tag{1.2}$$

$$N_{y+1,m} = N_{y,m-1} e^{-(M_{m-1} + S_{y,m-1} F_y)} + N_{y,m} e^{-(M_m + S_{y,m} F_y)} \tag{1.3}$$

When employing Pope's approximation (assuming a mid-year pulse fishery), the resource dynamics are modeled by the equations:

$$N_{y+1,a+1} = N_{y,a} \exp^{-M_a} - C_{y,a} e^{-M_a/2} \qquad \text{for } a_{\min} \le a < m-2 \tag{1.4}$$

$$N_{y+1,m} = N_{y,m-1} e^{-M_{m-1}} - C_{y,m-1} e^{-M_{m-1}/2} + N_{y,m} e^{-M_m} - C_{y,m} e^{-M_m/2} \tag{1.5}$$

where

$N_{y,a}$ is the number of fish of age *a* at the start of year *y*,
M_a denotes the natural mortality rate on fish of age *a*,
$S_{y,a}$ is the age-specific selectivity for year *y*,
F_y is the fishing mortality for year *y*,
m is the maximum age considered (taken to be a plus-group), and
$a_{\min}$ is the minimum age considered (0 in this case).

The number of recruits at the start of year *y* (for *y>1*) is related to the spawning stock size by a stock-recruitment relationship:

$$R_y = \frac{\alpha\, B^{sp}_{y-a\min}}{\beta + (B^{sp}_{y-a\min})^{\gamma}} e^{\varsigma_y} \tag{1.6}$$

where

α, β and γ are spawning biomass-recruitment parameters ($\gamma = 1$ for a Beverton-Holt and $\gamma > 1$ for a Ricker-like relationship, and can either be input or treated as an estimable parameter),
ς_y reflects fluctuation about the expected recruitment for year *y*, and

$B^{sp}_{y-a\min}$ is the spawning biomass at the start of year $y-a_{\min}$, given that:

$$B^{sp}_y = \sum_{a=0}^{m} f_a w_a N_{y,a} \tag{1.7}$$

where w_a is the begin-year mass of fish of age a and f_a is the proportion of fish of age a that are mature.

In order to work with estimable parameters that are more meaningful biologically, the stock-recruitment relationship is re-parameterised in terms of the pre-exploitation equilibrium spawning biomass, K^{sp}, and the "steepness" of the stock-recruitment relationship (recruitment at $B^{sp} = 0.2K^{sp}$ as a fraction of recruitment at $B^{sp} = K^{sp}$):

$$\alpha = \frac{(5-0.2^{\gamma-1})\, h\, R_1 (K^{sp})^{\gamma-1}}{5h-1} \tag{1.8}$$

and

$$\beta = \frac{(K^{sp})^{\gamma}(1-h\,0.2^{\gamma-1})}{5h-1} \tag{1.9}$$

where

$$R_1 = K^{sp} / [\ f_0 w_0 + \sum_{a=a\min+1}^{m-1} f_a w_a e^{-(\sum_{a'=a\min}^{a-1} M_{a'})} + f_m w_m \frac{e^{-(\sum_{a'=a\min}^{m-1} M_{a'})}}{1-e^{-M_m}}\ ] \tag{1.10}$$

Note: A Beverton-Holt stock-recruitment relationship is assumed for these analyses, i.e. $\gamma = 1$.

For the Baranov approximation, the total number of fish caught of age a in year *y* is given by

$$C_{y,a} = N_{y,a} \frac{S_{y,a} F_y}{Z_{y,a}} (1-e^{-Z_{y,a}}) \tag{1.11}$$

where the fishing mortality F_y cannot be calculated directly, but is computed using the bisection method.

When assuming Pope's approximation, the number of fish caught of age a in year *y* is given by

$$C_{y,a} = N_{y,a}\ S_{y,a} F_y e^{-M_a/2} \tag{1.12}$$

where the estimate fishing mortality is simply $F_y = C_y / B^{\exp}_y$ (1.13)

The corresponding catch by mass for each year is given by

$$C_y = \sum_{a=a_{\min}}^{m} w_{a+1/2}\, C_{y,a} \qquad (1.14)$$

where $w_{a+1/2}$ denotes the mid-year mass of fish of age.

The model estimate of the exploitable ("available") component of biomass is given by:

$$B_y^{\exp} = \sum_{a=a\min}^{m} w_a S_{y,a} N_{y,a} \qquad \text{for begin-year biomass, and} \qquad (1.15)$$

for the mid-year biomass:

$$B_y^{\exp} = \sum_{a=a\min}^{m} w_{a+1/2} S_{y,a} N_{y,a} e^{-Z_{y,a}/2} \quad \text{for the Baranov approximation, or} \qquad (1.16)$$

$$B_y^{\exp} = \sum_{a=a\min}^{m} w_{a+1/2} S_{y,a} N_{y,a} e^{-M_a/2} \quad \text{for Pope's approximation.} \qquad (1.17)$$

It is usually assumed that the resource is at the deterministic equilibrium that corresponds to an absence of harvesting at the start of the initial year ($B_1^{sp} = K^{sp}$). However, if the initial year does not correspond to the start of the fishery then the initial spawning biomass ratio to the pristine level can be estimated such that $B_1^{sp} = r^{sp} K^{sp}$ where $r^{sp} \neq 1$. In this case the age-structure of B_1^{sp} cannot be assumed to be that corresponding to the equilibrium with zero fishing mortality. An initial fishing mortality, F_0, corresponding to the initial year needs to be computed such that $B_1^{sp} = r^{sp} K$, where the number of recruits in the first year, adjusted to account for previous catches, is given by

$$R_1^* = \frac{\alpha r^{sp} K}{(\beta + (r^{sp} K)^{\gamma})} \qquad (1.18)$$

where α and β are given by equations (1.8) and (1.9) , while the associated initial spawning biomass is given by

$$B_1^{sp} = R_1^* [\sum_{a=a\min+1}^{m-1} f_a w_a e^{-(\sum_{a'=a\min}^{a-1} M_{a'} + S_{a'} F0)} + f_m w_m \frac{e^{-(\sum_{a'=a\min}^{m-1} M_{a'} + S_a F0)}}{1 - e^{-(M_m + S_m F0)}}] \qquad (1.19)$$

In order to generate the initial population numbers using F_0 defined above, we assume that the catches prior to the first year considered in the model are of the same magnitude. A more defensible approach would be to include estimates of historic catches in the model data, even if these are not well recorded, to get improved estimates of R_1^* and F_0 .

Note: Pope's approximation, which assumes a pulse fishery, was adopted for these analyses to facilitate comparison with analyses done by Booth et al. (2011).

1.1 The likelihood function

The model is fitted to generated abundance and length data, as well as catch-at-age data to estimate model parameters. Contributions by each of these to the negative of the log-likelihood (-ln *L*) are as follows.

1.1.1 Abundance data:

The likelihood is calculated assuming that the observed abundance index is log-normally distributed about its expected value:

$$I_y^i = \hat{I}_y^i \exp(\varepsilon_y^i) \qquad \text{or} \qquad \varepsilon_y^i = \ln(I_y^i) - \ln(\hat{I}_y^i) \tag{1.20}$$

where

I_y^i is the abundance index for year *y* and series i,

$\hat{I}_y^i = \hat{q}^i \hat{B}_y$ is the corresponding model estimate, where B_y is the model estimate of exploitable resource biomass, given by equations (1.16) and (1.17),

$\hat{q}^i$ is the constant of proportionality for abundance series *i* (effectively the multiplicative bias if the series reflects abundance in absolute terms), and

ε_y^i from $N(0,(\sigma_y^i)^2)$.

Note therefore that in any year, the selectivity ($S_{y,a}$) is taken to be the same for all abundance indices *i*. The only factor that distinguishes such indices is potentially differing values of the catchability coefficients $\hat{q}^i$.

The contribution of the abundance data to the negative of the log-likelihood function (after removal of constants) is given by:

$$-\ln L = \sum_f \sum_i \left[\sum_y \ln \sigma_y^i + (\varepsilon_y^i)^2 / 2(\sigma_y^i)^2 \right] \tag{1.21}$$

Estimate variance:

In this case, homoscedasticity of residuals is assumed, so that $\sigma_y^i = \sigma^i$, the standard deviation of the residuals for the logarithms of abundance index *i* is estimated in the fitting procedure by its maximum likelihood value:

$$\sigma^i = \sqrt{1/n^i \sum_y (\ln I_y^i - \ln \hat{I}_y^i)^2} \tag{1.22}$$

where n^i is the number of data points for abundance series *i*.

The catchability coefficient q^i for abundance index i is estimated by its maximum likelihood value:

$$\ln \hat{q}^i = 1/n^i \sum_y (\ln I_y^i - \ln \hat{B}_y) \qquad (1.23)$$

Input variance:

In this case, σ_y^i is taken to be the estimate of the coefficient of variation (CV) of the resource abundance estimate for year *y*, which is input.

The constant of proportionality for this abundance index is estimated by its maximum likelihood value which, for the case of a log-normal error distribution, is given by:

$$\ln \hat{q}^i = \frac{\sum_y 1/(\sigma_y^i)^2 \ (\ln I_y^i - \ln \hat{B}_y)}{\sum_y 1/(\sigma_y^i)^2} \qquad (1.24)$$

Additional variance:

For this approach, index variances $((\sigma_y^i)^2)$ corresponding to abundance index i in year *y* are incorporated in the model fitting procedure in the same manner as for the "input variance" scenario described above. Furthermore, the additional variance for each index $((\sigma_A^i)^2)$ is then estimated using an extension of the maximum likelihood approach as proposed in Geromont and Butterworth (2001). In this extension, the catchability coefficient for each index is estimated in the fitting procedure by its maximum likelihood value using equation (1.28) given below, where the total variance for each data point incorporates both input variance $((\sigma_y^i)^2)$ and (estimated) additional variance $((\sigma_A^i)^2)$.

The objective function minimised is thus given by the negative of the log-likelihood, ignoring constants:

$$-\ln L = \sum_i \sum_y [(\varepsilon_y^i)^2 / 2((\sigma_y^i)^2 + (\sigma_A^i)^2) + \ln \sqrt{(\sigma_y^i)^2 + (\sigma_A^i)^2}\,] \qquad (1.25)$$

where

σ_y^i is the (minimum) standard error of the value for abundance series *i* in year *y*, which is input, and

σ_A^i is the square root of the additional variance for abundance series *i*, estimated by its maximum likelihood value from the following relationship which follows from differentiating equation 17:

$$\sum_y \frac{1}{(\sigma_y^i)^2 + (\sigma_A^i)^2} = \sum_y \frac{(\varepsilon_y^i)^2}{((\sigma_y^i)^2 + (\sigma_A^i)^2)^2} \qquad (1.26)$$

where

$$\varepsilon_y^i = \ln(I_y^i) - \ln(q^i \ \hat{B}_y^i) \qquad (1.27)$$

for log-normally distributed errors, where

I_y^i is the abundance index for year *y* and series *i* from fleet *f*,

$\hat{B}_y^i$ is the corresponding resource population model estimate, and

q^i is the catchability coefficient for abundance series *i*, estimated by its maximum likelihood value:

$$\ln \hat{q}^i = \frac{\sum_y [1/(\sigma_y^i + \sigma_A^i)^2] (\ln I_y^i - \ln \hat{B}_y)}{\sum_y 1/(\sigma_y^i + \sigma_A^i)^2} \qquad (1.28)$$

for log-normally distributed errors.

Note that for the special case where $\sigma_y^i = \sigma^i$ (a constant), equation (1.26) above can be simplified so that the "additional variance" is estimated as follows (similar to equation (1.22)):

$$\sigma_A^i = \sqrt{[1/n^i \sum_y (\varepsilon_y^i)^2] - (\sigma^i)^2} \qquad (1.29)$$

This procedure was carried out enforcing the constraint that $(\sigma_A^i)^2 \geq 0$, i.e. the overall variance cannot be less that its externally input component. Thus this method avoids one of the potential problems of the "maximum likelihood" approach described above using equation (1.22): that in certain circumstances unrealistically high precision (and so high weight) can be ascribed to certain indices.

Note: This option is used for the reference case assessment model. This approach is useful when fitting to the Carpenter linefish estimates of abundance thus allowing the input (fixed) variance associated with these indices to be interpreted as the minimum overall variance and letting the model estimate any possible additional variance.

1.1.2 Catches-at-length:

The contribution of the catch-at-length data to the negative of the log-likelihood function when assuming a log-normal error distribution is given by:

$$-\ln L = w\sum_y \sum_l [\ln \sigma_{len} + (\ln p_{y,l} - \ln \hat{p}_{y,l})^2 / 2(\sigma_{len})^2] \qquad (1.30)$$

or, when making an adjustment to effectively weight in proportion to sample size:

$$-\ln L = w\sum_y \sum_l [\ln (\sigma_{len} / \sqrt{p_{y,l}}) + p_{y,a}(\ln p_{y,l} - \ln \hat{p}_{y,l})^2 / 2(\sigma_{len})^2] \qquad (1.31)$$

where

w =0.1 to down-weight the contribution of the length data to the likelihood function to allow for their non-independence,

$p_{y,l} = C_{y,l} / \sum_{l'} C_{y,l'}$ is the observed proportion of fish caught in year y that are of length l,

$\hat{p}_{y,l} = \hat{C}_{y,l} / \sum_{l'} \hat{C}_{y,l'}$ is the estimated proportion of fish caught in year y that are of length l, which is derived from the corresponding model-predicted catches-at-age using the transformation suggested in Brandao and Butterworth (2009) such that :

$$\hat{C}_{y,l} = \sum_a \hat{C}_{y,a} T_{a,l} \qquad (1.32)$$

where

$$\hat{C}_{y,a} = N_{y,a} \frac{S_{y,a} F_y}{Z_{y,a}} (1 - \exp(-Z_{y,a})) \qquad (1.33)$$

and $T_{a,l}$ is the transformation matrix which contains the proportion of fish of age a that fall into length group l. The expected proportion of fish in any length group is sampled from a normal distribution with mean given by the von Bertalanffy equation (1.39), such that:

$$l_a \sim N[l_\infty (1 - e^{-\kappa(t-t_0)}), (\sigma_a^T)^2] \qquad (1.34)$$

with the associated standard deviation, σ_a^T , which is assumed to be proportional to the expected length for age a, such that

$$\sigma_a^T = \sigma^T (l_\infty (1 - e^{-\kappa(t-t_0)})) \qquad (1.35)$$

where σ^T is an estimable parameter.

The standard deviation associated with the catch-at-length data, σ_{len}, is estimated in the fitting procedure by:

$$\sigma_{len} = \sqrt{\sum_y \sum_l (\ln p_{y,l} - \ln \hat{p}_{y,l})^2 / \sum_y \sum_l 1}$$

if equation (1.30) applies, or:

$$\sigma_{len} = \sqrt{\sum_y \sum_l \hat{p}_{y,l} (\ln p_{y,l} - \ln \hat{p}_{y,l})^2 / \sum_y \sum_l 1}$$

if equation (1.31) has been used.

The log-normal error distribution underlying equation (1.30) is chosen on the grounds that (assuming no aging error) variability is likely dominated by a combination of inter-annual variation in the distribution of fishing effort, and fluctuations (partly as a consequence of such variations) in selectivity-at-age, which suggests that the assumption of a constant coefficient of variation is appropriate. However, for ages poorly represented in the sample, sampling variability considerations must at some stage start to dominate the variance. To take this into account weighting by the expected proportions (equation (1.31)) is effected so that undue importance is not attached to data based upon a few samples only.

Note: For the present application, the minimum and maximum length were chosen as 220 and 480 mm respectively with a length interval of 10mm.These minus and plus groups were chosen after inspection of the data and to avoid undue systematic trends in the residuals corresponding to the shorter and longer length ranges were the proportion of fish caught is relatively low.

1.1.3 Stock-recruitment function residuals:

These residuals are assumed to be log-normally distributed and serially correlated. Thus, the contribution of the recruitment residuals to the negative of the log-likelihood function is given by:

$$-\ln L = \sum_{y=y1+1}^{y2} [\ln \sigma_R + [\frac{\varsigma_y - \rho\varsigma_{y-1}}{\sqrt{1-\rho^2}}]^2 / 2\sigma_R^2] \qquad (1.36)$$

where

$\varsigma_y = \rho\varsigma_{y-1} + \sqrt{1-\rho^2}\varepsilon_y$ is the recruitment residual for year *y*, which is estimated for years *y1* to *y2* ,

$\varepsilon_y \sim N(0, \sigma_R^2)$,

$\sigma_R = 0.5$ is the standard deviation of the log-residuals, which is input, and

ρ is the serial correlation coefficient, which is input (0 for these analyses).

In the interest of simplicity, equation (1.36) omits a term in ς_{y1} for the case when serial correlation is assumed ($\rho \neq 0$), which is generally of little quantitative consequence to values estimated.

1.2 Model parameters:

Natural mortality: An age-independent mortality rate, $M_a = 0.2yr^{-1}$ is assumed for the base case runs.

Fishing selectivity: Commercial linefish fishing selectivity can either be input or estimated. In the former case a time-invariant age-dependent fishing selectivity of

S_a=[0.00 0.01 0.02 0.05 0.13 0.29 0.52 0.75 0.89 0.96 0.98 0.99 1.00 1.00 1.00 1.00 1.00 1.00 1.00]

is assumed (provided by H. Winkler).

Alternatively, the selectivities-at-age can be approximated in terms of the following logistic curve:

$$S_a = \frac{1}{1+\exp(-(a-a_c)/\delta\ )} \tag{1.37}$$

and, for *a*>10:

$$S_a = S_a \exp(s\ (a-10))$$

where

a_c yrs is the age-at-50% selectivity,
δ yr^{-1} defines the steepness of the ascending limb of the selectivity curve, and
s measures the rate of decrease (“slope”) in selectivity with age for older fish (*a*>10).

Note: A value of 10 was assumed for these analyses after inspection of Figure A-1 and Figures A-4 and A-5: The largest proportion of catches fall in the 250mm (minimum allowed length) and 350mm age group (ages 4 to 10 years).

Initial spawning biomass ratio: r^{sp} is estimated for these analyses.

Minimum and maximum age: $a_{\min}$ is taken to be 1; *m* is taken as a plus-group and set to 20 (Henning Winkler pers. commn).

Age-at-maturity: The proportion of fish of age *a* that are mature is input. For the reference case this is approximated by a logistic form with $a_{50} = 4yr$ (Brouwer and Griffiths (2005b)):

f_a=[0.05 0.12 0.27 0.50 0.73 0.88 0.95 0.98 0.99 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0]

Mass-at-age: The mass (w) of a fish at age a is given by:

$$w_a = \alpha\,(l_a)^{\beta} \tag{1.38}$$

where l_a is the length of a fish at age a, assumed to be given by the von Bertalanffy growth equation:

$$l_a = l_\infty(1 - \exp(-\kappa(a - t_0))) \tag{1.39}$$

The following values, taken from Brouwer and Griffiths (2005a), are assumed here:

$\alpha = 0.0002$ g,

$\beta = 2.924$,

$l_\infty = 619$ mm,

$\kappa = 0.06$ yr^{-1}, and

$t_0 = -4.5$ yr.

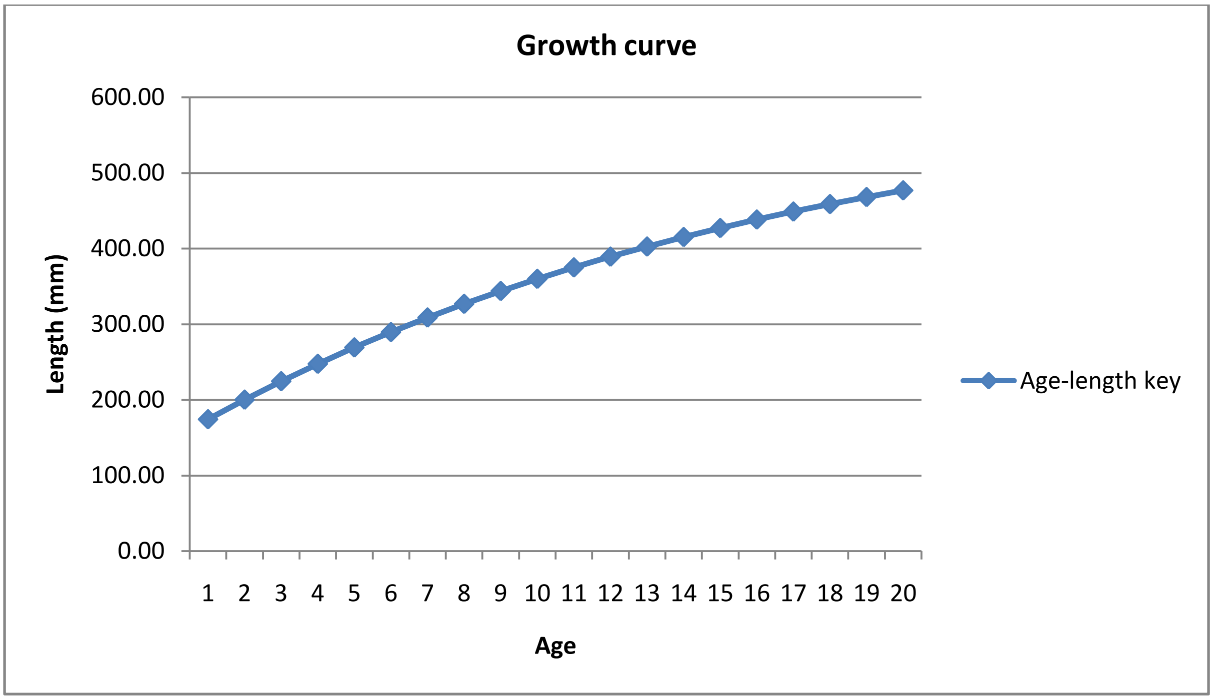

Figure A-1: The von Bertalanffy growth curve assumed for these analyses (Brouwer and Griffiths (2005a)).

1.3 Bayesian approach:

A Bayesian approach is followed where prior distributions are specified for key model parameters such as initial spawning biomass depletion $r^{sp} = B_1^{sp} / K^{sp}$ (when assuming that the resource is not at its pre-exploitation equilibrium spawning biomass, K^{sp}, in the first year), "steepness" of the stock-recruit relationship, h, natural mortality rate, M_a, as well as stock-recruit. These prior distributions reflect some qualitative information available about the resource. When quantitative data are available for the fishery, such as indices of abundance (CPUE) and length frequency data, the prior distributions are updated with respect to the respective likelihoods of the associated population model fits to these data, to provide posterior distributions of model parameters and other management quantities.

Most of the analyses presented assume uniform prior distributions for some key model parameters with the intention of being relatively uninformative:

- Initial biomass ration $r^{sp} \sim U[0.1, 1.0]$
- Steepness: $h \sim U[0.21, 0.95]$
- Mortality: $M_\alpha \sim U[0.17, 0.23]$
- Stock-recruit residuals: $\varepsilon_y \sim N(0, 0.5^2)$

Alternative tighter prior distributions imposed for selected runs are:

- Initial biomass ration $r^{sp} \sim N^6(0.3, 0.15^6)$
- Mortality: $M_\alpha \sim N^6[0.2, 0.03^6]$
- Steepness: $h \sim N^6[0.6, 0.15^6]$

where N^6 refers to a "flattened" normal distribution of the form

$$-\ln L = -\ln L + (x-\mu)^6 / 2(\sigma)^6 \qquad (1.40)$$

where *x* is the estimated parameter and μ is the mean with an associated measure of spread of σ. A "flattened" normal was chosen instead of a uniform distribution to ensure continuity of the respective contributions to the negative log-likelihood function.

No priors distributions were assumed for the von Bertalanffy growth parameters. The total annual catches, C_y, were taken to be exact for the base case runs.

Appendix 2:

Input data

Total annual catches, CPUE and length frequency data were provided by Henning Winkler and Sven Kerwath (pers. commn).

Year	Catch (tons)	CPUE	CV
1985	313.105	164.00474	0.08249524
1986	443.748	125.25751	0.07490713
1987	348.301	101.9071	0.07451718
1988	488.808	126.78956	0.06701664
1989	331.956	110.12566	0.06864165
1990	650.638	169.11762	0.06615197
1991	796.713	127.23586	0.07035701
1992	461.191	121.48753	0.07231863
1993	376.016	117.06365	0.08219
1994	361.268	144.16709	0.08246802
1995	471.676	122.02317	0.0826848
1996	646.383	131.02412	0.08700869
1997	582.861	123.62224	0.09073707
1998	315.828	93.70692	0.07991473
1999	391.69	110.80606	0.08758011
2000	293.019	124.46037	0.08287509
2001	127.216	99.99206	0.09843403
2002	160.201	115.39171	0.10527154
2003	107.332	177.14267	0.11454538
2004	115.359	120.0586	0.10489975
2005	86.953	46.88033	0.17632287
2006	92.043	54.24737	0.21597996
2007	128.4	89.00879	0.15706431
2008	111.198	116.22998	0.22298034
2009	152.986	70.73533	0.25386441
2010	50.572	39.76746	0.52617524

Table A-1. Annual catches in tons and standardized CPUE used for input for these analyses.

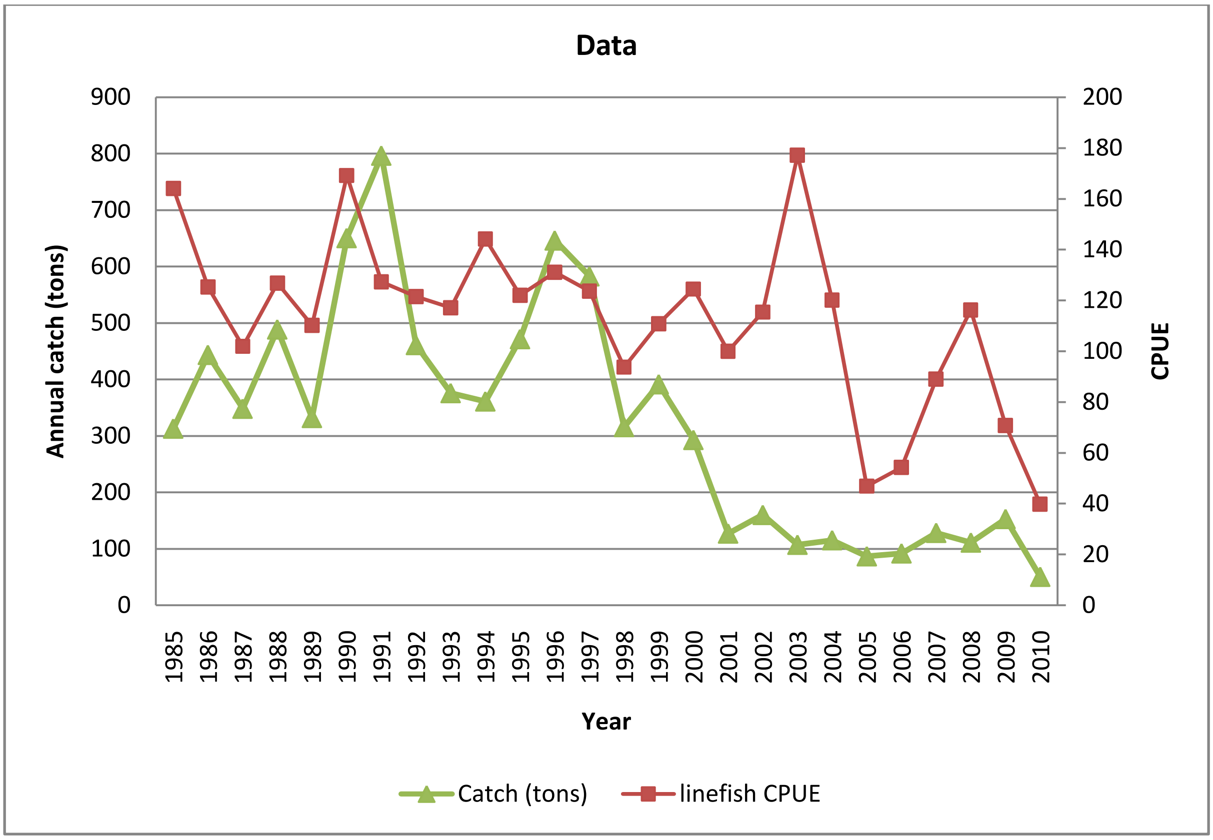

Figure A-2: Annual catch and standardised linefish CPUE data

Length (FL) mm	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
100	0	0	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0	0	0
120	1	0	0	0	0	0	0	0	0	0
130	0	0	0	0	0	0	0	0	0	0
140	0	0	0	0	0	0	0	0	0	0
150	1	0	0	0	0	0	0	0	0	0
160	6	0	2	0	0	0	0	0	0	0
170	7	0	4	1	2	0	2	1	0	2
180	11	0	2	1	5	1	4	1	1	4
190	25	1	10	1	7	14	8	4	1	11
200	32	15	16	4	10	6	29	6	10	12
210	49	28	40	11	14	12	40	25	14	29
220	93	30	100	37	41	34	85	103	25	42
230	140	36	253	138	84	88	212	317	146	118
240	115	53	239	339	124	146	606	703	404	388
250	110	87	223	568	178	200	1102	1219	535	650
260	104	112	260	806	197	198	1399	1821	690	767
270	120	154	276	953	240	198	1545	2213	805	831
280	140	155	337	990	306	196	1770	2187	873	834
290	175	182	381	791	346	255	1885	2005	835	524
300	197	183	377	932	426	306	1933	1927	879	585
310	222	181	323	886	386	285	1419	1368	585	401
320	242	170	292	768	417	305	1127	991	513	404
330	259	181	258	731	367	272	902	661	427	284
340	278	202	244	544	369	260	771	689	411	263
350	307	193	203	434	255	237	610	430	264	164
360	244	167	160	312	216	188	490	351	234	113
370	227	173	129	262	171	186	379	342	276	125
380	183	128	113	209	146	164	280	272	204	79
390	150	111	88	141	99	118	247	286	179	99
400	117	103	68	120	77	97	286	261	178	75
410	86	60	47	79	42	104	191	184	137	63
420	81	53	38	62	36	93	157	172	153	65
430	74	57	34	53	19	62	151	122	102	50
440	73	60	30	51	17	51	133	163	111	44
450	72	26	16	33	21	38	92	62	75	32
460	64	22	15	32	21	24	77	45	59	24
470	46	20	15	16	6	22	80	66	97	35
480	33	13	15	7	6	19	46	33	69	32
490	40	13	9	10	6	12	40	23	51	16
500	25	6	8	7	3	11	29	13	30	10

510	18	2	4	3	2	10	13	9	28	3
520	21	3	9	4		8	12	12	27	8
530	6	2	2	3	3	4	10	3	17	3
540	7	4	4	0	0	3	4	2	19	8
550	6	1	1	0	0	2	3	1	10	2
560	2	1	3	0	1	2	1	4	5	3
570	3	0	0	0	0	1	1	1	12	0
580	1	0	0	0	0	1	1	0	16	2
590	0	0	0	0	0	0	0	2	7	0
600	0	0	0	0	0	1	0	0	10	0
610	0	0	1	0	0	0	0	0	1	0
620	0	0	0	0	0	0	0	0	3	0
630	0	0	0	0	0	0	0	0	0	0
640	0	0	0	0	0	0	0	0	0	0
650	0	0	0	0	0	0	0	0	1	0
660	0	0	0	0	0	0	0	0	0	0
670	0	0	0	0	0	0	0	0	1	0
680	0	0	0	0	0	0	0	0	0	0

Table 3a: Length frequency data for the years 1985 to 1994.

Length (FL) mm	1995	1996	1997	1998	1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**
100	0	1	0	0	0	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0	0	0	0	0	0
120	0	1	0	0	0	0	0	0	0	0	0	0	0
130	0	0	0	0	0	0	0	0	0	0	1	0	0
140	0	0	0	0	0	0	0	0	0	0	2	0	0
150	0	1	0	0	3	1	0	0	0	0	1	0	0
160	0	2	0	0	1	4	0	0	0	0	8	0	0
170	0	11	0	3	10	3	0	0	0	0	15	2	0
180		17	0	4	28	2	0	0	0	0	16	2	0
190	2	14	0	5	14	5	0	0	0	0	15	13	0
200	2	21	2	6	12	11	0	0	0	0	47	22	0
210	19	26	17	43	14	10	0	0	0	0	25	33	0
220	43	30	29	67	33	18	0	0	0	0	78	33	3
230	92	77	80	175	89	23	0	0	0	0	104	23	0
240	218	236	169	337	188	5	0	0	0	0	99	4	1
250	230	309	296	481	351	7	0	0	0	0	102	6	1
260	394	369	443	642	555	10	0	0	0	0	110	8	0
270	556	447	580	803	725	19	0	0	0	0	123	4	0
280	708	545	661	826	837	25	0	0	0	0	111	5	0
290	712	836	682	859	895	39	0	0	0	0	103	38	8

300	775	927	911	1087	1054	57	0	0	0	0	116	73	12
310	565	833	817	1023	1006	39	0	0	0	0	153	95	26
320	556	817	971	986	976	25	0	0	0	0	142	98	47
330	434	638	888	910	947	28	0	0	0	0	213	116	57
340	365	618	918	853	918	40	0	0	0	0	183	77	56
350	273	447	791	696	812	35	0	0	0	0	197	100	70
360	220	358	621	605	703	50	0	0	0	0	182	74	55
370	204	405	608	512	656	30	0	0	0	0	130	78	51
380	201	335	534	407	566	35	0	0	0	0	124	70	73
390	209	314	414	353	482	38	0	0	0	0	76	37	72
400	208	273	392	309	446	39	0	0	0	0	65	51	66
410	160	162	315	252	396	35	0	0	0	0	30	36	100
420	144	152	308	240	351	39	0	0	0	0	30	16	86
430	105	120	272	214	237	34	0	0	0	0	22	22	67
440	90	116	208	190	207	28	0	0	0	0	16	20	37
450	73	75	253	179	146	28	0	0	0	0	11	14	28
460	60	68	201	141	150	18	0	0	0	0	12	8	28
470	70	75	172	149	126	15	0	0	0	0	1	7	22
480	46	34	178	89	96	13	0	0	0	0	4	12	17
490	46	41	125	93	61	4	0	0	0	0	4	8	14
500	26	26	109	129	35	5	0	0	0	0	3	14	10
510	27	21	73	85	36	5	0	0	0	0	1	1	8
520	21	19	63	89	36	1	0	0	0	0	0	5	20
530	21	16	45	73	26	4	0	0	0	0	0	3	6
540	5	6	27	66	19	0	0	0	0	0	0	5	2
550	6	2	15	43	15	0	0	0	0	0	0	5	4
560	2	7	12	32	10	1	0	0	0	0	0	1	4
570	2	8	9	28	6	0	0	0	0	0	0	2	3
580	1	1	2	21	4	0	0	0	0	0	0	1	0
590	0	2	0	10	3	0	0	0	0	0	0	1	1
600	0	3	2	10	5	0	0	0	0	0	0	0	0
610	0	0	1	2	1	0	0	0	0	0	0	0	0
620	0	0	0	5	0	0	0	0	0	0	0	0	0
630	0	0	1	6	0	0	0	0	0	0	0	0	0
640	0	0	0	4	0	0	0	0	0	0	0	0	0
650	0	0	0	1	1	0	0	0	0	0	0	0	0
660	0	0	0	2	0	0	0	0	0	0	0	0	0
670	0	0	0	1	1	0	0	0	0	0	0	0	0
680	0	0	0	1	0	0	0	0	0	0	0	0	0

Table 3b: Length frequency data for the years 1995 to 2007.

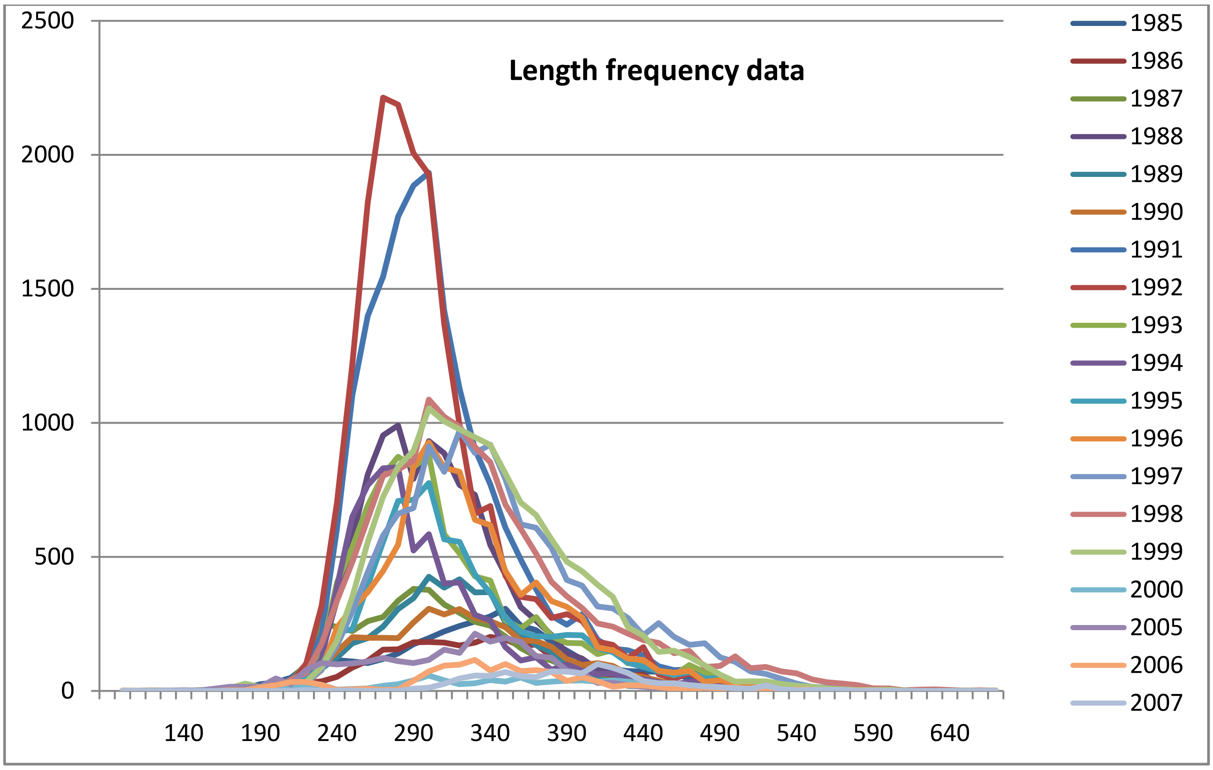

Figure A-3: Length frequencies from line fish catches for years 1985 to 2000 and 2005 to 2007. No data are available from 2001 to 2005.

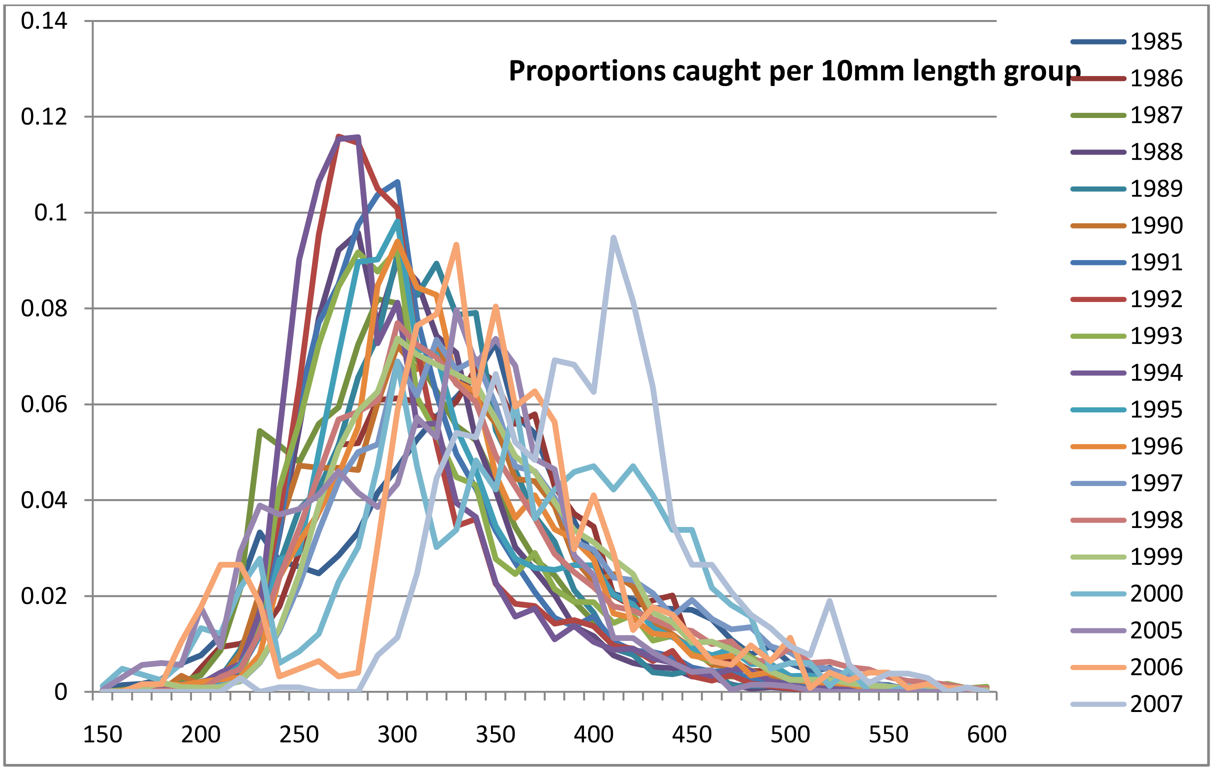

Figure A-4: Proportions caught per length group (mm) for years 1985 to 2000 and 2005 to 2007.