The 2005 age-structured production model assessments and constant catch projections for the south coast rock lobster resource

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Summary

The 2005 assessment was routinely extended, taking account of a further year's catch, CPUE and catch-at-age data.

CPUE shows a continuation of the increase that commenced in 1998. However, sustainable yield estimates are generally less than those for the 2004 assessment, although estimates of current biomass levels relative to *K* increase. The Reference Case (RC) scenario suggests that a TAC of about 360 MT or less would be appropriate to prevent biomass decline in the future. Other scenarios suggest either higher or lower values than this. If the catch-at-age data are down-weighted, then this 360 MT level for the TAC is increased to 390 MT. On the other hand, the scenario which assumes the 1996+ recruitment to be equal to the average of the previous 10 years is more pessimistic and suggests an appropriate TAC level of only some 300 MT or less to prevent biomass decline.

A model (Model 2) which allows for time-varying selectivity is presented and shows promising results. Model 2 is better able to reproduce the recent CPUE trend. Preliminary results for a model that fits to catch-at-length rather than catch-at-age data, using a selectivity-at-length rather than selectivity-at-age function, are presented, but these do not as yet reflect satisfactory fits to the data so that they should not be considered reliable in the context of stock status estimates.

These different scenarios reflect very different interpretations of the recent increase in CPUE for the resource. If the catch-at-age data are down-weighted, the model fit essentially ignores them and suggests a recent increase in abundance. However, under either the effort saturation or the time-varying selectivity approaches, spawning biomass is estimated to have decreased further over recent years.

Introduction

The age-structured production model applied previously to South Coast rock lobster population has been used to update the assessment of the resource and to provide a range of projections into the future for a number of harvesting policies. The age-structured production model is unchanged from that initially described by Geromont (2000a) and used for the 2001, 2002, 2003 and 2004 assessments (Johnston and Butterworth 2001;

2002a; 2003a; 2003b, 2004). This age-structured model is described in detail in RLWS/DEC05/ASS/7/2/2.

The Reference Case (RC) "Bayesian" ASPM assessment[1] as considered for 2005 involves the following choices (essentially unchanged from 2003 and 2004).

1. Use of GLM-standardised CPUE for 1977-2003[2].
2. Use of scientific-sample-based catch-at-age data for 1994-2003, with an 8- and 20+ grouping. Note that the MCM rock lobster Working Group agreed that the 1999 scientific catch-at-age data should not be included in the RC assessment due to poor spatio-temporal coverage for that season that may render them unrepresentative.
3. A Beverton-Holt stock recruit relationship.
4. Deterministic recruitment, except for estimation of recruitment residuals from 1974-1995 with zero serial correlation ($\rho = 0$) and a CV (σ_R) of 0.4.

This report provides results of several updates to the current reference case (RC) model used for assessing the south coast rock lobster resource. To summarise, the current RC model:

i) fits a selectivity function dependent on age which is time invariant, and
ii) fits to catch-at-age data which are input into the model.

In this report we initiate exploration of the following refinements:

a) time-varying selectivity, and
b) fitting directly to catch-at-length data.

Time-varying selectivity

We refer to this as Model 2. It is identical to the RC model, except that the selectivity function (which depends on age) is allowed to vary over the time period for which catch-at-age data are available (1994-2003). To effect this, the form of the selectivity function is generalised to:

$$S_{y,a} = \frac{1}{1+e^{-K(a-(a50+\delta_y)}} \quad \text{where } K = \frac{\ln 19}{\Delta} \tag{1}$$

The estimable parameters are thus: $a50$ (the expected age at 50% selectivity), Δ and δ_y for y = 1994-2003 (excluding 1999 as there are no catch-at-age data for 1999). Note that the expected age at 95% selectivity ($a95$) is given by $a50 + \Delta$.

It is also assumed that for y<1994, 1999, and 2004+ the δ_y = 0.

[1] "Bayesian" is in quotes as these assessments have not been conducted in a fully Bayesian mode in the past – only the posterior mode, or equivalently a prior-penalised MLE, has been considered.

[2] In this report the year "2000", for example, refers to the 2000/01 season

An extra term is added to the likelihood function in order to smooth the extent of change in the selectivity, as follows:

$$-\ln L \rightarrow -\ln L + \sum_{y=1994}^{y=2003} \left(\frac{\delta_y}{\sigma_{sel}} \right)^2 \text{ (sum excluded 1999)} \qquad (2)$$

where the σ_{sel} is input (a value of 0.75 was found to provide reasonable performance). It may appear from the form of equation (1) that there is a confounding between $a50$ and δ_y as δ_y is estimated for every year for which there are catch-at-age data input to the model. This is however not the case (otherwise the term added in expression (2) would secure a mean at the estimated δ_y's of zero). The reason is that δ_y is set to zero for other years, to which $a50$ then applies, and this then influences the model estimated CPUE (equation (3) below) for those years, which in turn impacts the overall value of the likelihood.

Another issue is that for equation (1), if δ_y decreases, this means that selectivity is increasing on younger lobsters, while given that the model fitting procedure assumes that

$$C\hat{P}UE_y = q\sum_a w_a S_{y,a} N_{y,a} \qquad (3)$$

this situation seems implausible, in that an enhanced CPUE would result even if there was no any increase in abundance.

Presumably enhanced catches of younger animals are achieved by spatially redistributing effort on a scale finer than captured by the GLM standardisation of the CPUE. A standard method to adjust for this, while maintaining a constant catchability coefficient *q*, is to renormalise the selectivity function in some way:

$$S_{y,a} \rightarrow S^*_{y,a} = S_{y,a} / X_y \qquad (4)$$

where here as a simple initial approach we have chosen:

$$X_y = \sum_{a1}^{a2} \frac{S_{y,a}}{a2 - a1 + 1} \qquad (5)$$

i.e., normalising selectivity by its average over a certain age range, so that now if δ_y decreases, the $S^*_{y,a}$ will decrease for large *a* to compensate for the effort spread to locations where younger animals are found associated with the increase for smaller *a*.

The authors experimented with choices for *a*1 and *a*2. A choice of *a*1=8 and *a*2=12 as a standard gave reasonable performance and are used for the Model 2 results reported at this workshop.

Data

The annual total catch (by mass) (C_y) and relative abundance index ($CPUE_y$) data used are reported in Table 1a. The relative abundance index corresponds to the standardised CPUE time series provided by Glazer (2005). The commercial catches-at-age ($C_{y,a}$) derived from the updated scientific length data (see Groeneveld 2005) are given in Table 2 (Bergh pers. commn). Table 3 summarises somatic growth curve parameter values (Glazer and Groeneveld 1999).

Sensitivity analyses

In addition to the RC, results for the following sensitivity analyses are also reported (in Table 4b).

1) Historic catches = MCM records + over-catches

The MCM catch records where available (from 1995) are used in place of the TAC. The same set of over-catches is added as for the RC. Table 1 reports this catch series.

2) Over-catches 87-97 set = 100 tons per year

The RC historic catch series is modified by setting the over-catches between 1987 and 1997 to 100 tons per year. Table 1 reports the final catch series.

3) Effort Saturation

This scenario examines the possibility that the proportional relationship between CPUE and biomass does not hold true at high levels of effort due to competition between units of effort – i.e. effort saturation occurs. This effort saturation effect is taken into account here by allowing the constant of proportionality between the GLM derived CPUE index and exploitable biomass, q, to become a declining function of fishing effort once effort exceeds a certain level (see RLWS/DEC05/ASS/7/2/2 for details). This analysis also includes fitting to the 1998 Effort Saturation Experiment data (Groeneveld *et al.* 1999). For this application, parameters E' and n^* are fixed at 2500 and 1.0 respectively (see Model 5c of Geromont 2000b). Thus the extent of effort saturation is determined by the parameter E^* alone.

4) Sensitivity to 1995+ recruitment

This assumes that the 1996+ recruitment residuals are equal to the average of the preceding 10-year period (i.e. 1986-1995 average). The rationale for this assumption is that a ten-year average, rather than a longer period (the whole history of the fishery), should be used because recent recruitments have tended to be below expected levels, so that using this recent 10-year average when projecting into the future may be a more realistic approach.

5) Catch-at-age down-weighting
The catch-at-age data are down-weighted by a multiplicative factor of 0.10 in the likelihood function as an *ad hoc* approach to allow for positive correlations in these data.

Projections

The resource is projected ahead from 2005 to 2015 under a number of constant catch (CC) levels: 300 MT, 330 MT, 360 MT, 390 MT, 420 MT and 450 MT.

Results

Table 4a compares results for the reference case (RC), Model 2 and Model 5 (fitting to catch-at-length data directly), whilst Table 4b compares the assessment results for the RC model and the five sensitivity analyses described above.

Figure 1a shows the RC fit to CPUE data where the lack of fit to more recent years is evident. Figure 1b shows the fit for the model where the catch data are down-weighted (cdw) – here we see a much improved fit to CPUE. Figure 1c shows the Model 2 fit where a much improved fit to the observed recent upward CPUE trend is also evident – *without* requiring down-weighting of the catch-at-age data.

Figure 2 shows the estimated selectivity (at age) functions estimated for Model 2. Figure 3 shows a plot of the δ_y values for 1994-2003. Note that the 1999 value is not estimated in the model as there are no 1999 catch-at-length data, so that this is set to zero. Figure 4a illustrates that Model 2 fits reasonably to the catch-at-age data when these are averaged over all years. Figure 4b shows these fits for each of the years individually.

The reason that Model 2 is able to reflect the recent increase in CPUE is evident from Figures 2 and 3: δ_y increases for recent years, reflecting lesser effort on smaller lobster, and hence an enhanced contribution to the expected CPUE (equation 3) from the older animals. The model is not here using the extra flexibility provided by the δ_y parameters solely as a "convenience" to allow reflection of a CPUE increase. There is also some direct suggestion of this selectivity change from the catch-at-age data in isolation. Figure 5 plots a time series of average age of the catch (treating 20+ animals as 20), and shows that this increases over recent years. Note that although the model reflects the increase in CPUE for this reason, the estimated recent trend in spawning biomass does not show an increase (Figure 6).

Figure 8a and 8b show the exploitable and spawning biomass trends for the RC and effort saturation (Sensitivity 3) scenarios.

Figure 9a shows the stock-recruit residuals estimated for the RC, effort saturation and catch-at-age down-weighting scenarios, and Figure 9b shows this trend for Model 2 (time-varying selectivity).

Fitting directly to catch-at-length data

The data that are collected from the fishery each year are recorded as catch-at-length. To date, these data have been converted into catch-at-age data (by the coarse approach of cohort slicing) for use as input to the age-structured-production-model (ASPM) that is used for assessing the resource. Here the authors attempt to fit directly to the catch-at-length data. The conversion of modelled catch-at-age to catch-at-length data is effected by the approach of (Brandão *et al.* 2002), where σ_{length} is the CV of an assumed normal distribution about the length-at-age curve (Brandão *et al.* 2002). The first step was to attempt this with the existing selectivity-at-age functional form (equation 1) (first without and then with variation over time). These we refer to as Models 3 and 4, i.e.:

Model 3 = fit to catch-at-length data; selectivity-at-age time invariant function, and

Model 4 = fit to catch-at-length data, selectivity-at-age time varying.

It transpired that neither of these models produced particularly satisfactory fits to either the CPUE or catch-at-length data. The estimated selectivity functions were all knife-edged. This is somewhat unrealistic, as is suggests that all lower length lobsters in the catch are slower growing animals of ages 11 and above, to the exclusion of faster growing animals of lesser ages.

Selectivity-at-length function

Given this last result, it was decided that, given also fitting now to catch-at-length data, it would be desirable rather to estimate a selectivity function that is dependent on length in contrast to age. Model 5 thus fits to catch-at-length data, while at the same time estimating a selectivity-at-length function. Model 5 assumes this selectivity function to be time invariant. Future work will take Model 5 a step further by allowing this selectivity function to vary over time.

Certain results such as the MSY related estimates are not yet available for Model 5, due to modelling complexity of such outputs and time constraints. The value of natural mortality M is currently fixed at 0.12 for Model 5. Figure 11a reports the Model 5 fits to CPUE data. Figure 11b shows the Model 5 stock-recruit residuals. Figure 11c shows the Model 5 fit to the catch-at-length data (averaged over all years), and Figure 11c compares the Model 5 estimated catch-at-age with the observed catch-at-age data. Model 5 estimates a considerably lower current biomass value than other models of this resource (see Table 1). **However**, it is clear that the fits attained thus far in an initial exercise are **not** satisfactory, and further work needs to be done before results from this approach can come under serious consideration.

Projections

Table 5 presents results of projected spawning biomass trends for the RC and the five sensitivity analyses, as well as for Model 1 for a range of future constant catches. The projected exploitable biomass trends are also illustrated in Figures 10a-d for the RC and the effort saturation, recent low recruitment and catch-at-age down-weight scenarios.

Discussion

The 2004 RC assessment of the south coast rock lobster resource estimated the resource at the start of 2003 to be 29% of carrying capacity for the exploitable portion of the stock, and 32% of capacity for the spawning biomass. The updated 2005 RC assessment estimates these values to now be 32% and 34% respectively (see Table 4b). Whilst these values are comparatively slightly higher than those estimates for the 2004 assessment, both the spawning biomass and exploitable biomass are now estimated to have declined slightly between the years 2003 and 2004. The MSY for the resource is estimated to be 365 MT for the RC model, and between 351 and 447 for the five sensitivity analyses.

The RC MSY estimate (365 MT) is lower than that estimated by the 2004 assessment (383 MT) – see Table 4b. (The RC MSY estimates for the 2002 and 2003 assessments were 350 and 347 MT respectively). The 95% confidence interval for the updated 2005 MSY estimate as calculated using a likelihood profile method (which treats the Bayesian priors as penalty functions) is [112; 428].

The sensitivity test where the MCM catch records are used in place of TAC values (see Table 1a) gives results quite similar to those for the RC. The sensitivity test for which the over-catches for 1987-1997 are replaced by 100 tons per year, results in more optimistic results: for example, the MSY is higher at 391 MT (RC = 365 MT).

The effort saturation scenario results are more positive than those for the RC model. The ES model estimated CPUE is able to reproduce the observed CPUE trends, particularly in more recent years, to a better extent that the RC (Figure 1a).

Down-weighting the catch-at-age data also results in a more optimistic appraisal of the resource. Through this down-weighting, this model is able to better fit the CPUE data (Figure 1b), in particular the recent upturn in CPUE. The fits to the catch-at-age data do however deteriorate substantially (see Figure 7), particularly for more recent years such as the 2002 and 2003 seasons for which there is appreciable overestimation of the proportion of small and underestimation of that of large lobsters.

The projected spawning biomass trends estimated for the different future constant catch harvesting strategies are rather different across the various scenarios (see Table 5 for the RC and five sensitivity scenarios). The RC predicts catches of a little less than 350 MT will result in the spawning biomass remaining at its current (2004) level. Catches much above 360 MT are shown to result in spawning biomass declines for the over-catch 87-97 set equal to 100 tons per year, the effort saturation and the catch-at-age down-weight scenarios. The lower recruitment scenario is the most pessimistic, suggesting that future annual catches set at even 300 MT will result in a spawning biomass decline, and the historic catch equal to the MCM records scenario suggests future catches larger then 330 MT will result in a spawning biomass decline. These results, whilst qualitatively similar to those presented to the Rock Lobster Working Group last year, are more pessimistic.

Plots of exploitable biomass trajectories show that for the RC, a future CC of 360 MT will keep the exploitable biomass level constant, whilst larger TACs will cause the exploitable biomass to decline (Figure 10a). The effort saturation and catch-at-age down-weight scenarios are somewhat more optimistic (Figures 10b and d) and indicate that future CC of 390 MT or less will prevent further decline in the exploitable biomass. The lower recent recruitment scenario (1996+ recruitment assumed to equal the previous 10 year average) produces the least optimistic projection results (Figure 10c). This scenario suggests that a future TAC of 300-330 MT is needed to prevent further decline in the exploitable biomass.

The 2005 assessment results are thus more pessimistic than those produced in 2004 for similar scenarios. This is likely primarily the result of a reduction in the rate of CPUE increase over the last season, though the further year of age-structure data now available are also having an influence.

Model 2

It would appear that Model 2 provides a superior fit to both the CPUE and catch-at-age data to that of the current reference case model. Model 2 is able to fit both these data sources well (Figure 1c and Figures 4b and c). For this reason, Model 2 is selected as the underlying model for initial OMP development for this resource by the authors (see RLWS/DEC05/MAN/8/2/2/2).

An important results from Model 2 it that it is not interpreting the recent CPUE increase as an increase in resource abundance (see Figure 6), but as a reflection of a concentration of effort towards larger lobsters over recent years (see Figures 2 and 3). Table 5 gives results for constant catch projections under Model 2.

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Table 1: Total annual catch scenarios (data from WG/06/04/SCRL1) and GLM standardised CPUE (Glazer 2005) data for the South Coast rock lobster fishery.

	RC	Sensitivity 1: Historic Catches= MCM records+ over-catches	Sensitivity 2: Over-catches 87-97 set=100 tons per year	
Year	**Total Catch (MT tails)**	**Total Catch (MT tails)**	**Total Catch (MT tails)**	**CPUE (kg tails/trap)**
1973	372	372	372	
1974	973	973	973	
1975	551	551	551	
1976	712	712	712	
1977	667	667	667	0.2157
1978	461	461	461	0.2036
1979	122	122	122	0.1586
1980	176	176	176	0.2009
1981	348	348	348	0.1897
1982	407	407	407	0.1636
1983	524	524	524	0.1933
1984	450	450	450	0.1611
1985	450	450	450	0.1586
1986	450	450	450	0.2076
1987	452	452	552	0.1848
1988	452	452	552	0.2221
1989	452	452	552	0.2048
1990	477	477	577	0.1729
1991	524.54	524.54	577	0.1425
1992	529.96	529.96	577	0.1389
1993	524.27	524.27	577	0.1272
1994	507.89	507.89	552	0.1162
1995	504.89	472.99	527	0.1082
1996	442.69	428.39	515	0.0905
1997	416.39	384.09	502	0.0829
1998	516.03	460.73	516.03	0.0792
1999	512.16	514.86	512.16	0.0806
2000	423.4	378	423.4	0.0902
2001	288	288	288	0.1011
2002	340	325	340	0.1108
2003	350	350	350	0.1152
2004	382	382	382	

Table 2: Scientific sampling-based catches at-age (proportions) for the South Coast rock lobster. [Note that the 1999 values are omitted from the assessment because of poor sampling levels that season.]

AGE	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
6	0.0000	0.0000	0.0039	0.0000	0.0056	0.0000	0.0000	0.0000	0.0000	0.0000
7	0.0003	0.0006	0.0140	0.0003	0.0201	0.0009	0.0012	0.0001	0.0011	0.0009
8	0.0029	0.0093	0.0266	0.0066	0.0484	0.0244	0.0069	0.0010	0.0190	0.0092
9	0.0215	0.0554	0.0478	0.0609	0.0834	0.1229	0.0389	0.0105	0.0510	0.0218
10	0.0709	0.1265	0.0819	0.1467	0.1233	0.2021	0.1166	0.0451	0.0767	0.0446
11	0.1441	0.1838	0.1202	0.2080	0.1429	0.1958	0.2099	0.1119	0.0930	0.0816
12	0.1537	0.1369	0.1256	0.1373	0.0939	0.1039	0.1648	0.1548	0.0986	0.1033
13	0.1493	0.1110	0.1184	0.1079	0.0844	0.0800	0.1224	0.1552	0.1143	0.1278
14	0.1343	0.0829	0.1054	0.0775	0.0744	0.0591	0.0782	0.1437	0.1242	0.1453
15	0.0677	0.0440	0.0603	0.0412	0.0462	0.0372	0.0397	0.0762	0.0708	0.0868
16	0.0786	0.0548	0.0782	0.0498	0.0637	0.0507	0.0461	0.0924	0.0927	0.1155
17	0.0386	0.0342	0.0419	0.0262	0.0361	0.0265	0.0252	0.0459	0.0510	0.0564
18	0.0293	0.0319	0.0349	0.0215	0.0315	0.0214	0.0213	0.0354	0.0434	0.0433
19	0.0238	0.0274	0.0296	0.0192	0.0271	0.0171	0.0195	0.0290	0.0368	0.0372
20+	0.0849	0.1013	0.1113	0.0968	0.1192	0.0579	0.1094	0.0990	0.1275	0.1266

Table 3: Somatic growth parameters as detailed in Glazer and Groeneveld (1999).

α (w in gm)	0.0007
β	2.846
l_∞ (mm CL)	111.9
κ (year^{-1})	0.08
t_0 (years)	0.0

Table 4a: Stock assessment results for the current Reference Case and a number of refined analyses. Units of mass-related quantities (e.g. *MSY*) are tons. Note that recruitment residuals from 1974 to 1995 are estimated in all instances. The figures underlined are medians from an MCMC analysis.

	Reference Case	**Model 2 (time varying selectivity at age)**	**Model 5 (fit to catch-at-length data; selectivity-at-length function)**
K^{sp}	8299	8093	4870
h	0.857	0.880	0.857
M	0.107	0.125	0.120 fixed
a_{50}	10.08	10.46	l_{50} = 61.17
a_{95}	12.49	12.55	l_{95} = 69.22
σ	0.184	0.141	0.364
σ_{age}	0.070	0.056	-
σ_{length}	-	-	0.144
-*lnL* CPUE	-32.21	-39.41	-13.75
-*lnL* age	-88.77	-113.96	-
-*lnL* length			-10.90
-*lnL* S-R	3.20	2.15	2.15
-*lnL*(total)	**-118.27**	**-144.25**	**-22.62**
MSY	365	<u>378</u>	- *
$MSYL^{exp}/K$	0.218	0.183	- *
B^{sp}_{05}	2545	<u>2354</u>	511
B^{exp}_{05}	2261	<u>4070</u>	380
B^{exp}_{2004}/K^{exp}	0.298	<u>0.271</u>	0.071
$B^{exp}_{2004}/B^{exp}_{msy}$	1.358	1.625	- *
B^{sp}_{2004}/K^{sp}	0.322	<u>0.304</u>	0.103

* Still to be computed

Table 4b: Stock assessment results for the Reference Case and a number of sensitivity analyses. Units of mass-related quantities (e.g. *MSY*) are tons. Note that recruitment residuals from 1974 to 1995 are estimated in all instances.

	Reference Case	**Sensitivity 1: Historic Catches= MCM records+ over-catches**	**Sensitivity 2: Over-catches 87-97 set=100 tons per year**	**Sensitivity 3: Effort saturation**	**Sensitivity 4: Lower recruitment (1996+ R = previous 10 year average)**	**Sensitivity 5: Catch-at-age log-likelihood down-weighted by 0.10 multiplier**
$\boldsymbol{K^{sp}}$	8299	8139	8748	7597	8289	7029
h	0.857	0.842	0.857	0.888	0.856	0.933
$\boldsymbol{M}$	0.107	0.105	0.107	0.130	0.107	0.140
a_{50}	10.08	10.08	10.09	10.03	10.08	11.10
a_{95}	12.49	12.49	12.50	12.36	12.50	13.47
$n*$	-	-	-	1.0 fixed	-	-
E'	-	-	-	2500 fixed	-	-
$\boldsymbol{E*}$	-	-	-	7161	-	-
$\boldsymbol{\sigma}$	0.184	0.180	0.169	0.094	0.184	0.075
$\boldsymbol{\sigma_{age}}$	0.070	0.070	0.070	0.069	0.070	0.135
-*lnL* CPUE	-32.21	-32.75	-34.54	-50.41	-32.26	-56.57
-*lnL* age	-88.77	-89.09	-89.30	-89.79	-88.91	-11.53
-*lnL* S-R	3.20	3.20	3.35	5.89	3.30	5.30
-*lnL* effort expt	**-**	**-**	**-**	-1.27	**-**	**-**
-*lnL*(total)	**-118.27**	**-119.16**	**-121.05**	**-136.24**	**-118.41**	**-53.08**
MSY	365	351	391	417	369	447
$\boldsymbol{MSYL^{exp}/K}$	0.218	0.224	0.217	0.194	0.218	0.133
$B_{2004}^{\exp}/K^{\exp}$	0.298	0.292	0.311	0.351	0.298	0.351
$B_{2004}^{\exp}/B_{msy}^{\exp}$	1.358	1.301	1.433	1.806	1.369	2.635
B_{2004}^{sp}/K^{sp}	0.322	0.316	0.334	0.374	0.322	0.435
B_{2014}^{sp}/K^{sp} **CC=330 MT**	0.306	0.288	0.338	0.384	0.264	0.462
$B_{2014}^{sp}/B_{04}^{sp}$ **CC=330 MT**	0.950	0.909	1.013	1.025	0.820	1.064

Table 5: Projected spawning biomass estimates for various harvesting strategies and models. Units of mass-related quantities (e.g. *RY*) are tons. [Shaded cells show a biomass reduction relative to 2004.]

Statistic	**Strategy**	**Reference Case**	**Sensitivity 1: Historic Catches= MCM records+ over-catches**	**Sensitivity 2: Over-catches 87-97 set=100 tons per year**	**Sensitivity 3: Effort saturation**	**Sensitivity 4: Lower recruitment (1996+ R = previous 10 year average)**	**Sensitivity 5: Catch-at-age log-likelihood down-weighted by 0.10 multiplier**	**Model 2: Time varying selectivity**
B^{sp}_{2004}/K^{sp}	**ALL**	0.322	0.316	0.334	0.374	0.322	0.434	0.394
B^{sp}_{2014}/K^{sp}								
	CC = 450	0.225	0.206	0.260	0.300	0.188	0.376	0.330
	CC = 420	0.251	0.232	0.286	0.328	0.211	0.405	0.355
	CC = 390	0.278	0.259	0.312	0.356	0.237	0.433	0.380
	CC = 360	0.306	0.288	0.338	0.384	0.264	0.462	0.405
	CC = 330	0.334	0.316	0.365	0.412	0.292	0.491	0.430
	CC = 300	0.362	0.345	0.391	0.440	0.319	0.520	0.455
$B^{sp}_{2014}/B^{sp}_{2004}$								
	CC = 450	0.693	0.645	0.777	0.800	0.574	0.864	0.946
	CC = 420	0.776	0.729	0.855	0.874	0.651	0.930	1.019
	CC = 390	0.863	0.818	0.934	0.950	0.735	0.997	1.091
	CC = 360	0.950	0.909	1.013	1.025	0.820	1.064	1.162
	CC = 330	1.037	1.000	1.092	1.101	0.907	1.130	1.234
	CC = 300	1.123	1.091	1.171	1.176	0.993	1.197	1.305

Figure 1a: Observed and estimated CPUE for the Reference Case (RC) and effort saturation (ES – Sensitivity 3) scenarios.

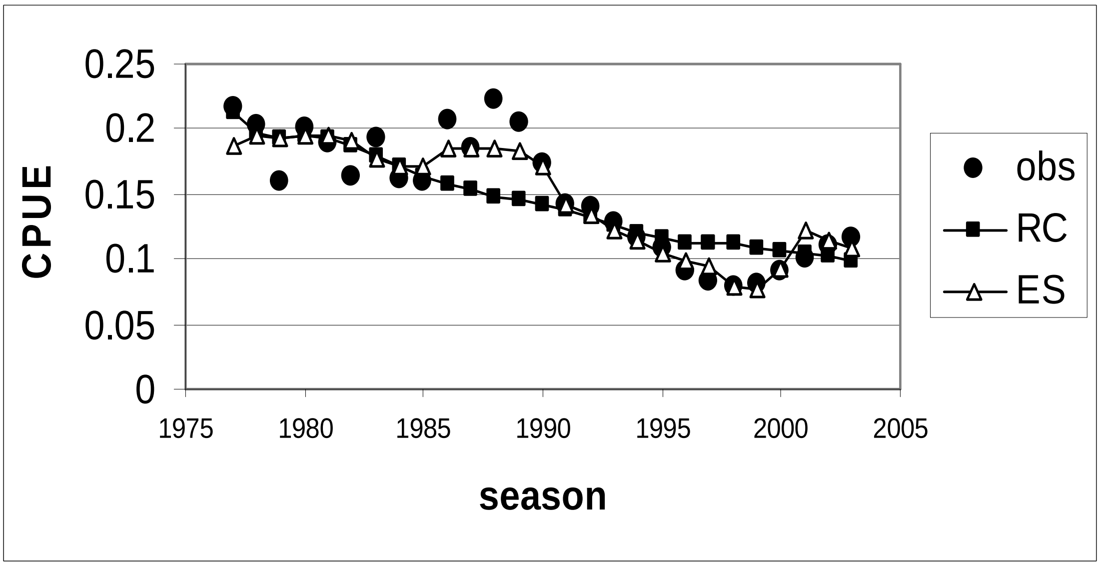


Figure 1b: Observed and estimated CPUE for the lower recruitment (Sensitivity 4: 1996+ R = previous 10 year average) and catch-at-age down-weight (cdw – Sensitivity 5) scenarios.

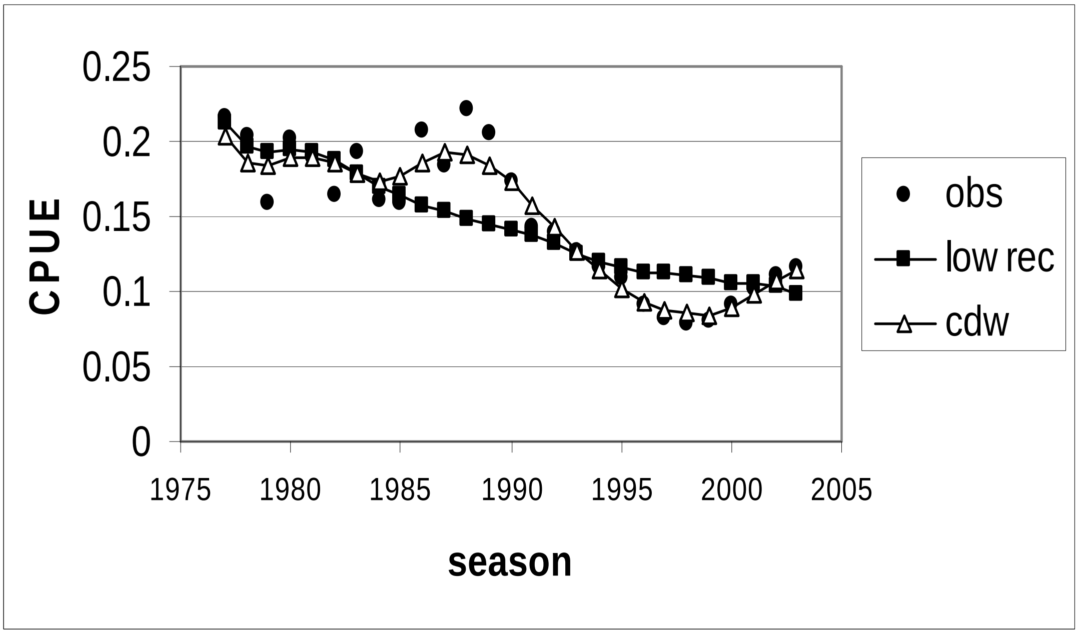


Figure 1c: Observed and estimated CPUE for Model 2 (time-varying selectivity).

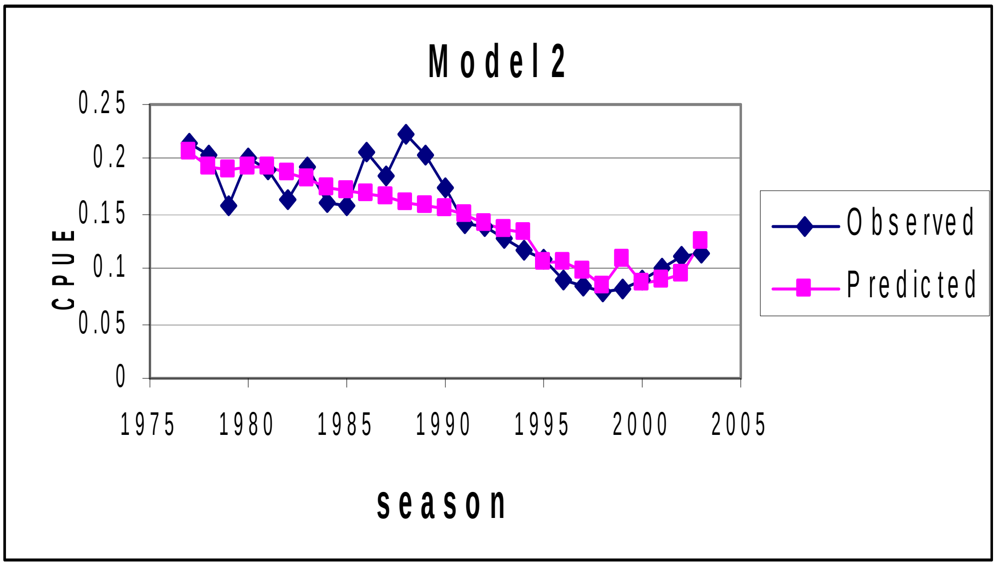
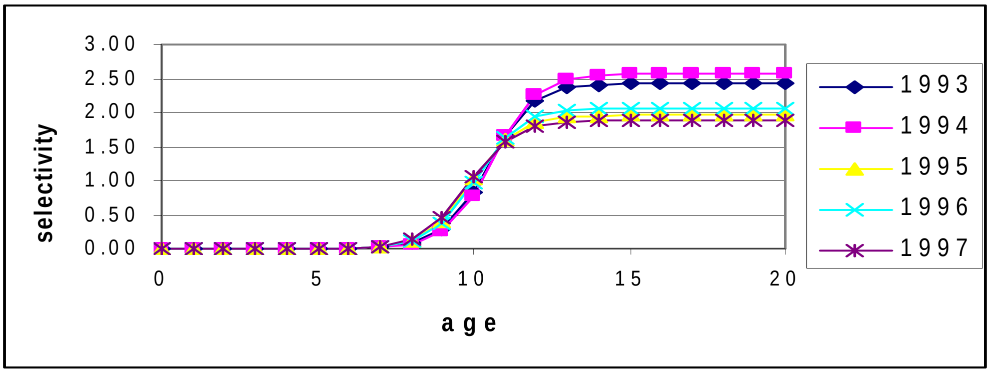


Figure 2: Model 2 selectivity functions estimated for each year. (Note that the renormalized selectivity $S^*_{y,a}$ is shown.)



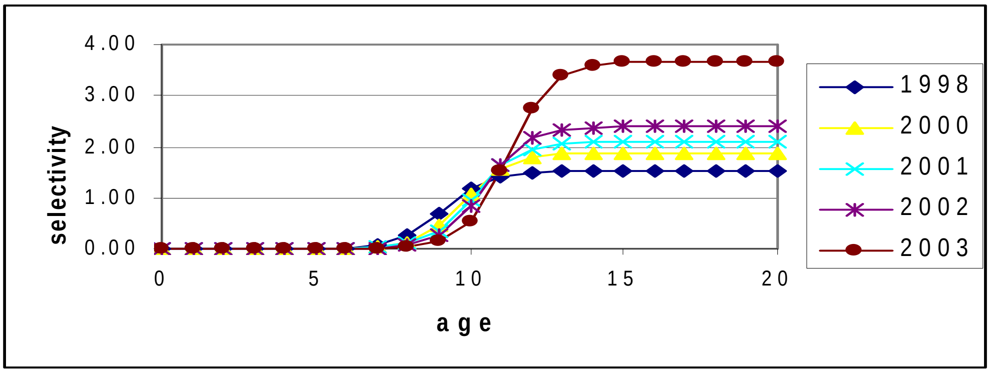


Figure 3: Plot of Model 2 δ_y estimates for 1994-2003 (note that the values for 1999, 2004 and 2005 are set to zero, as are values prior to 1994).

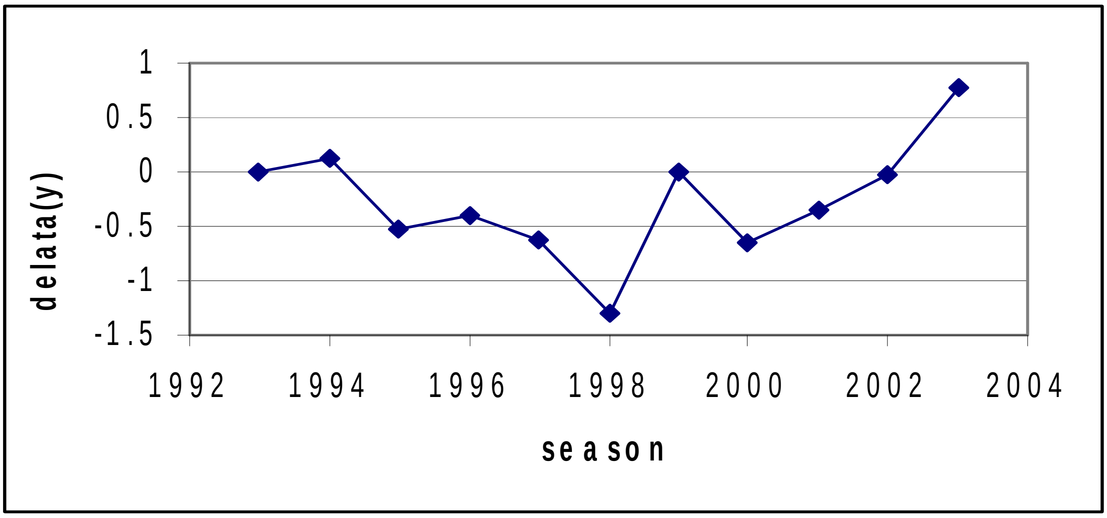


Figure 4a: Model 2 histogram plot of model fits to catch-at-age proportion data (averaged over all years). Note that age-classes 6 and 7 are lumped with age 8 to form an 8-age0class in the likelihood, and that age 20 is a 20+ age group.

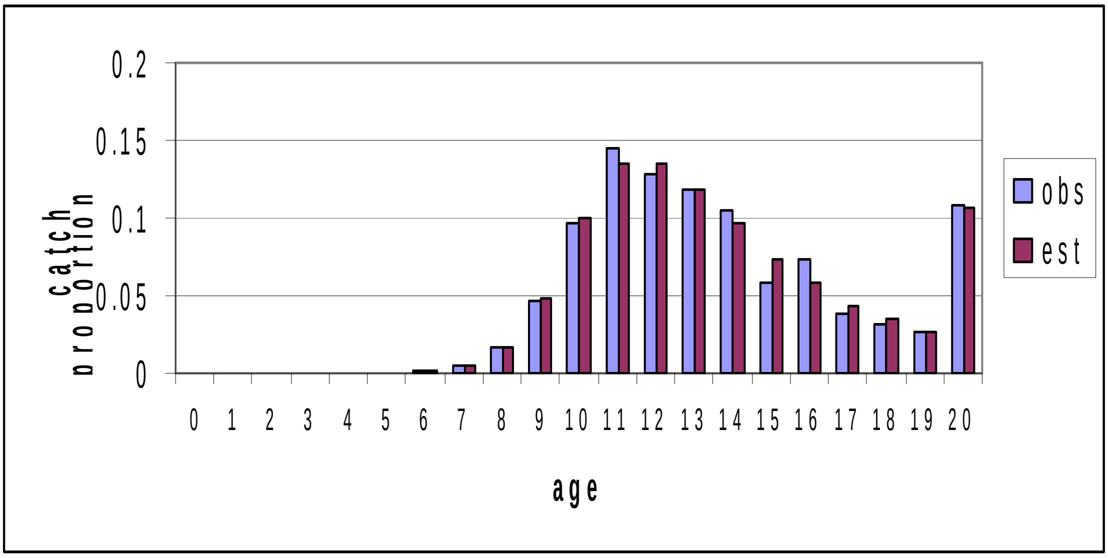
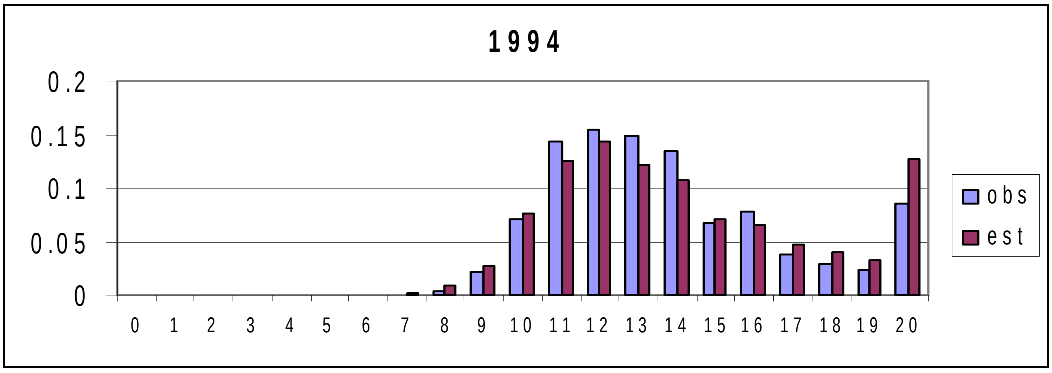
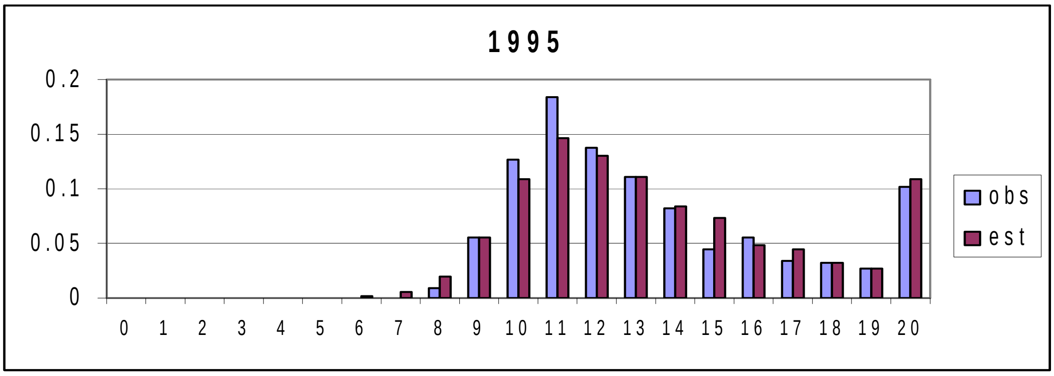
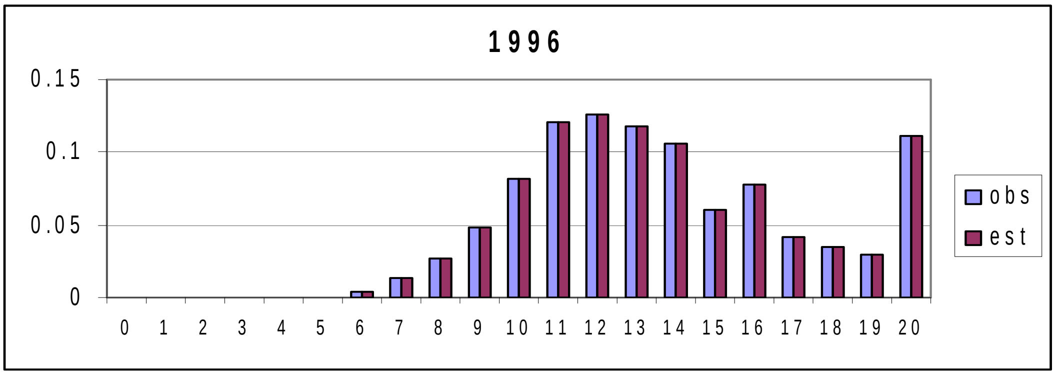
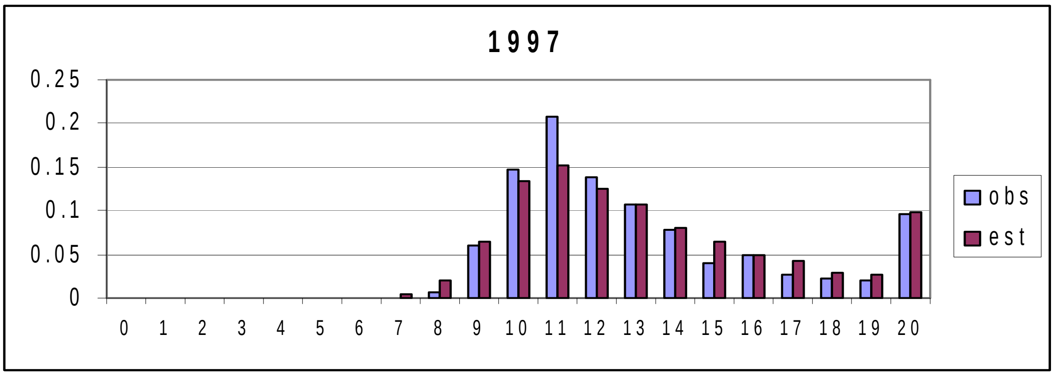


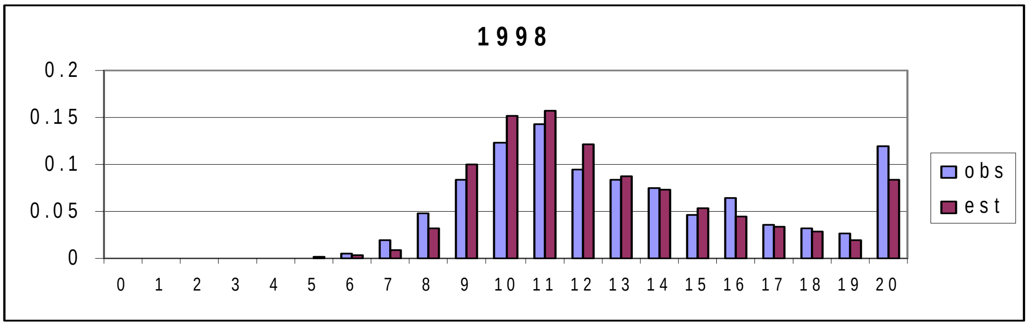
Figure 4b: Model 2 histogram plots of model fits to catch-at-age proportions for each year.

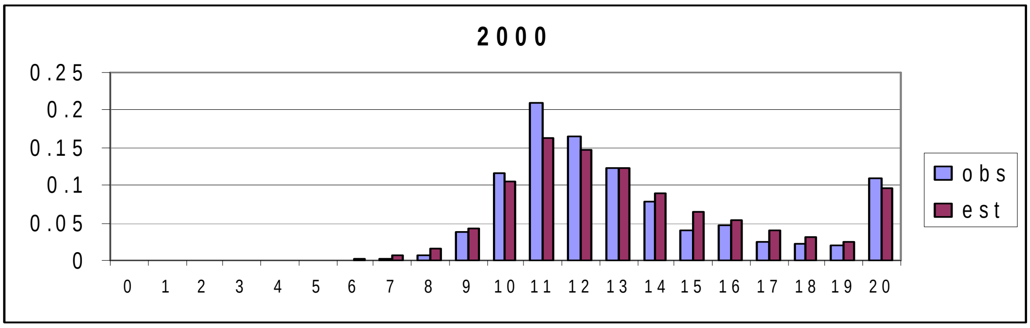


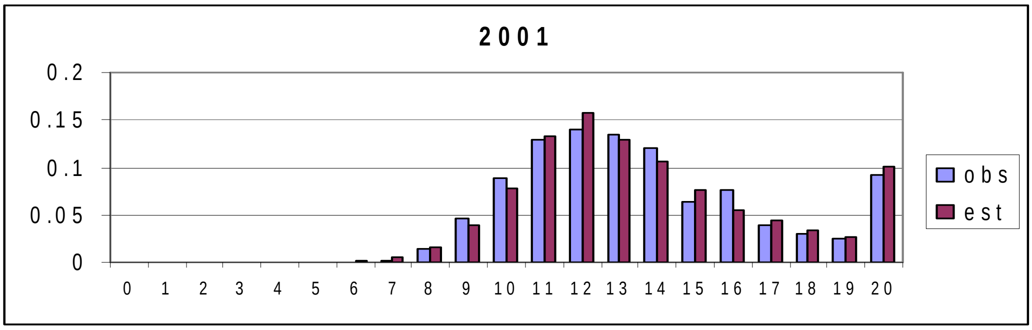







1998
0.2
0.15
0.1
0.05
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
obs
est


2000
0.25
0.2
0.15
0.1
0.05
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
obs
est


2001
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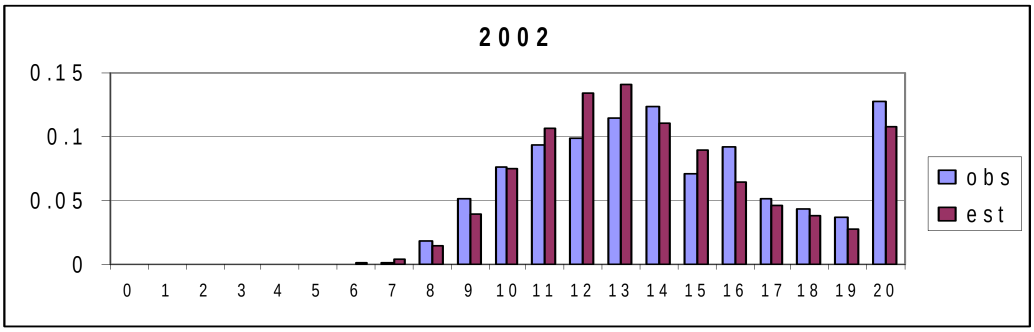
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
obs
est


2002
0.15
0.1
0.05
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
obs
est

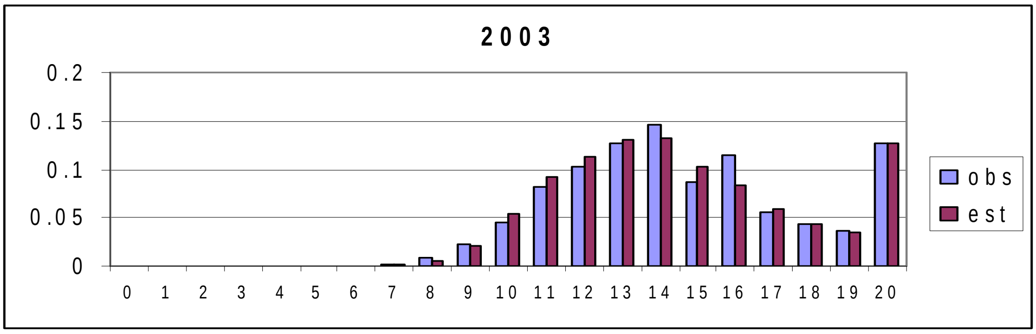

2003
0.2
0.15
0.1
0.05
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
obs
est

Figure 5: Time series of the average age of the catch (treating 20+ animals as 20).

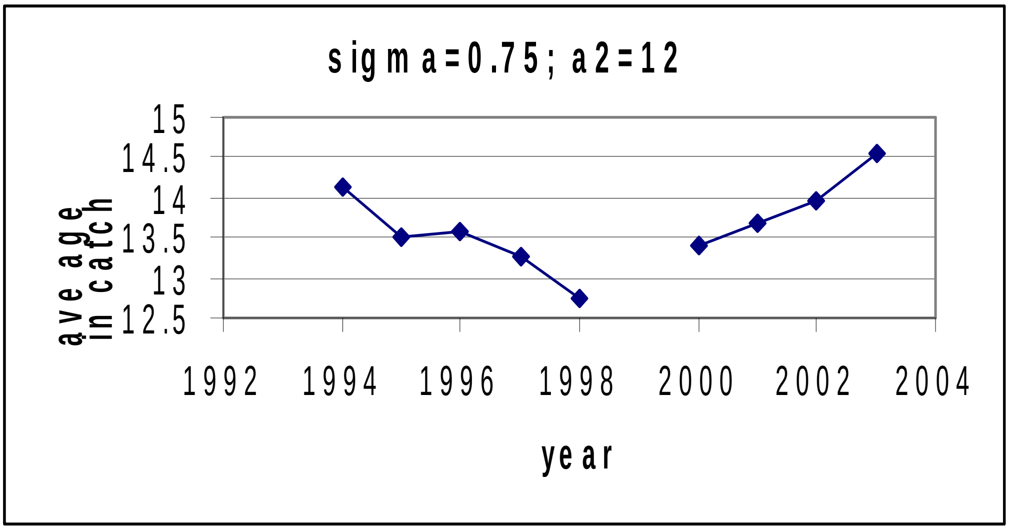


Figure 6: Plot comparing spawning biomass and model-estimated CPUE for the Model 2 time-varying selectivity scenario.

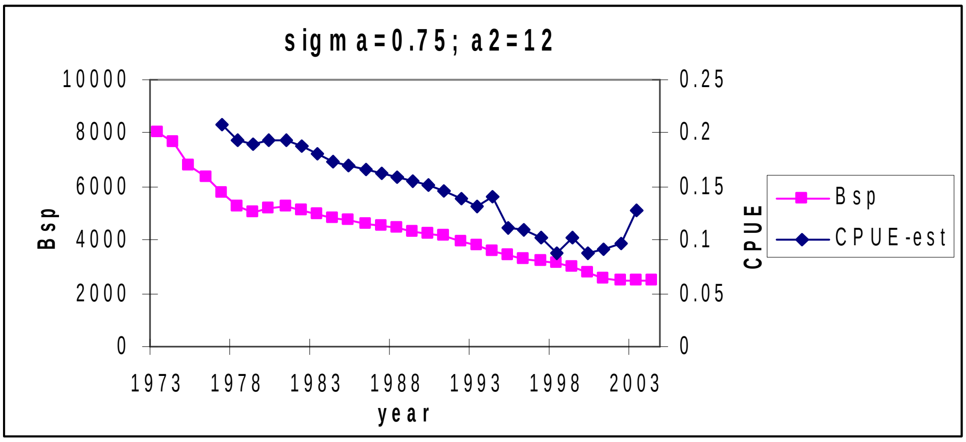


Figure 7: Observed and estimated catch-at-age proportions for the Reference Case (RC) and catch-at-age down-weight (cdw – Sensitivity 5) scenarios.

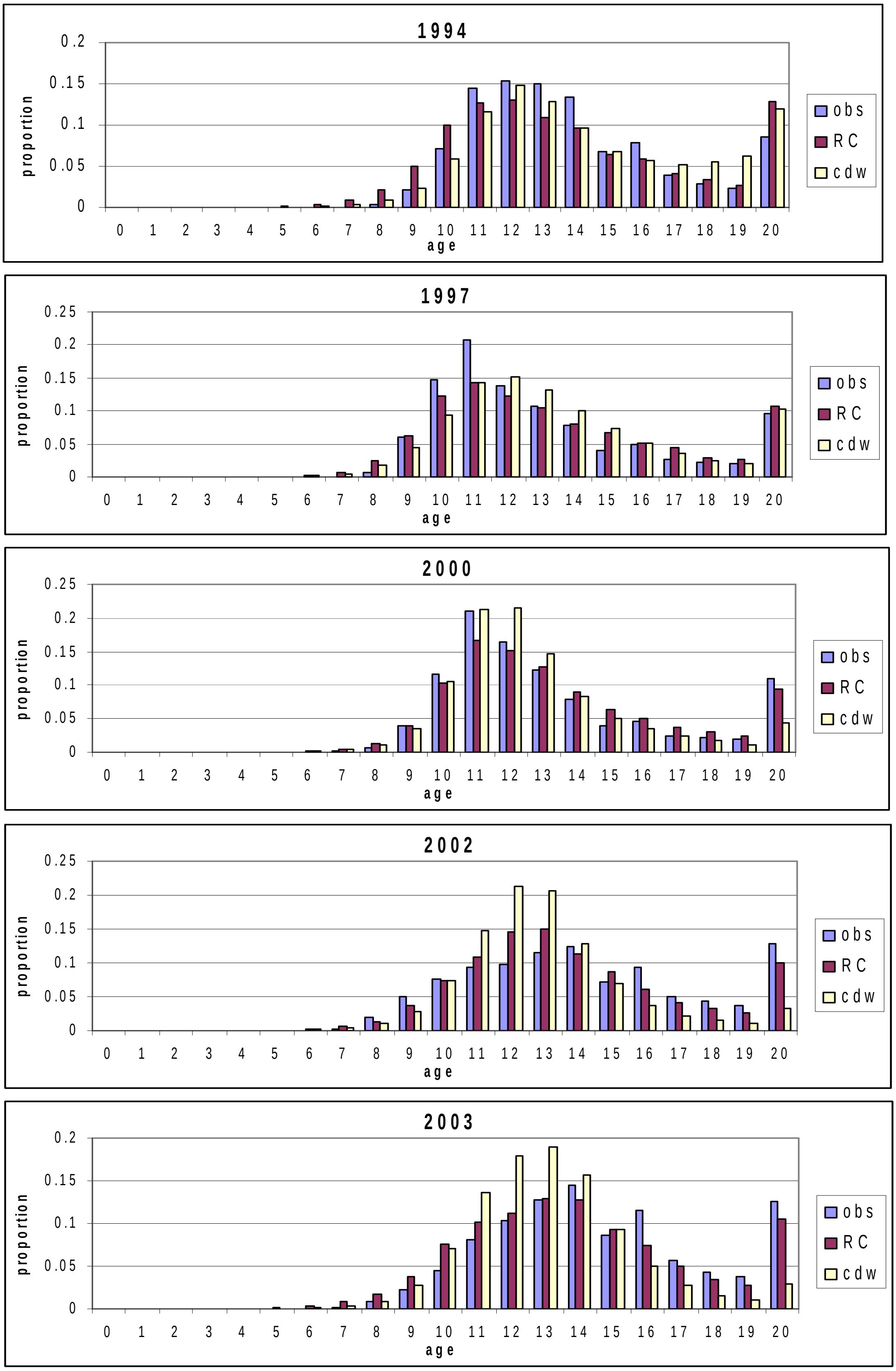


Figure 8a: Exploitable biomass trends for the Reference Case and effort saturation (Sensitivity 3) scenarios.

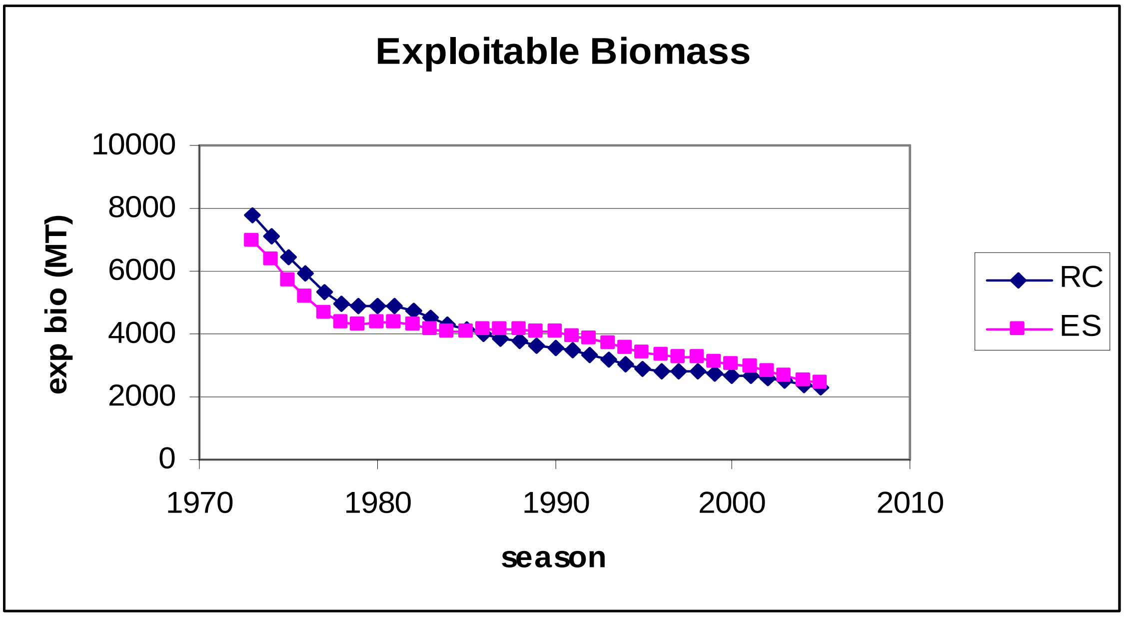


Figure 8b: Spawning biomass trends for the Reference Case and effort saturation (Sensitivity 3) scenarios.

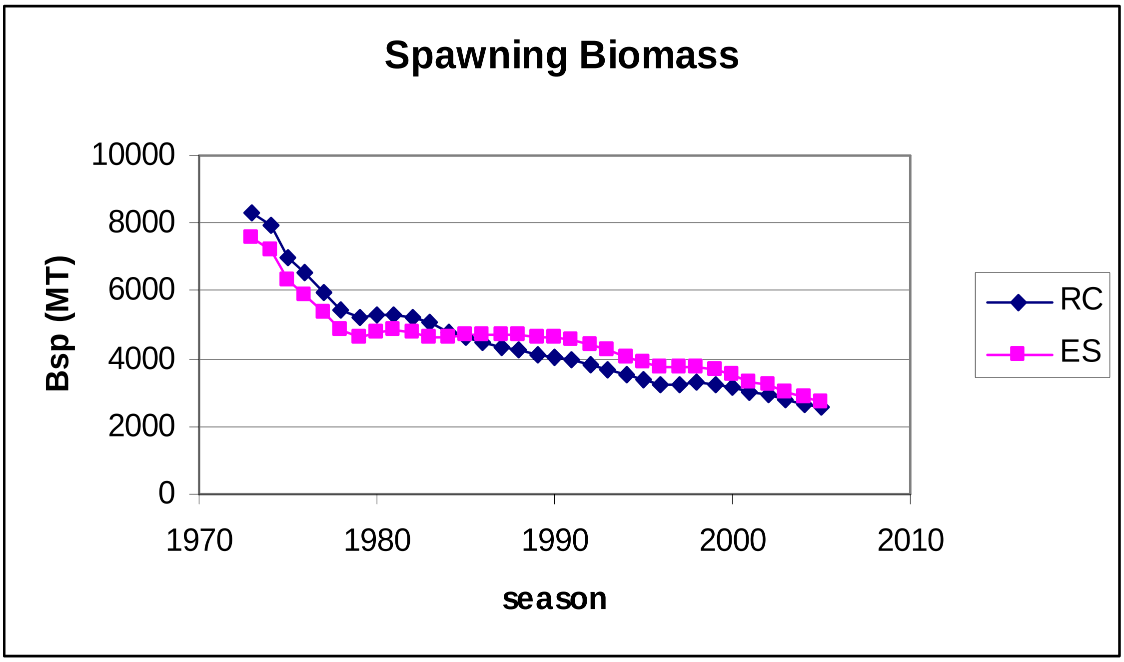


Figure 9a: Stock-recruitment residuals for the Reference Case, effort saturation (Sensitivity 3) and catch-at-age down-weighting (Sensitivity 5) scenarios.

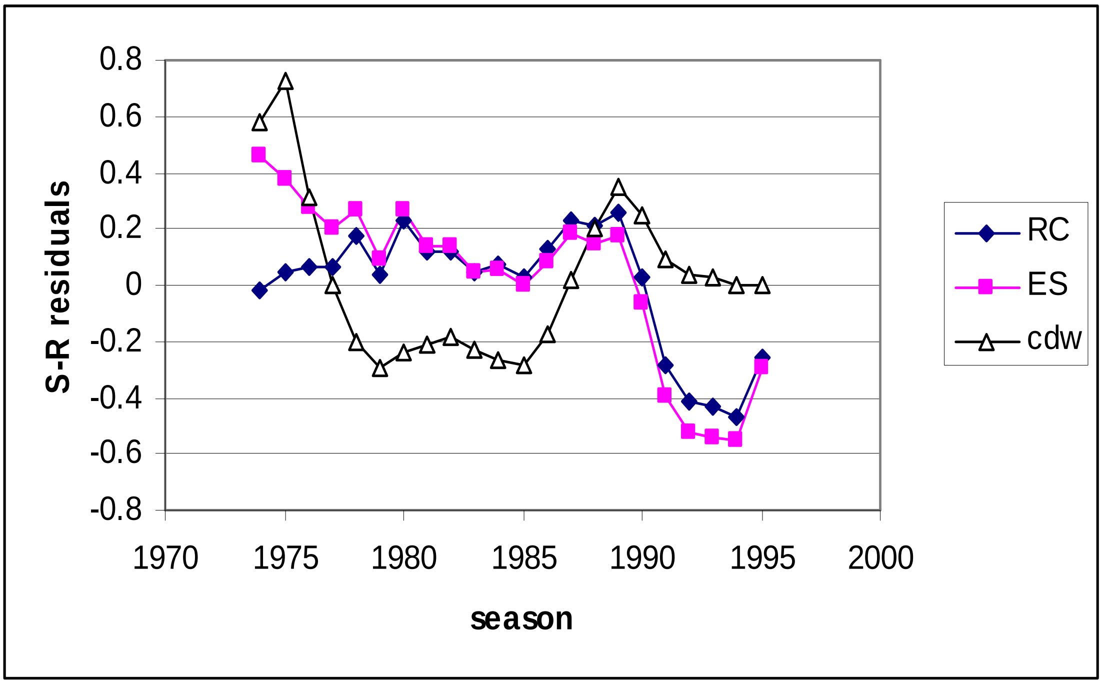


Figure 9b: Stock-recruitment residuals for Model 2 (time-varying selectivity) (the posterior medians of an MCMC analysis are shown).

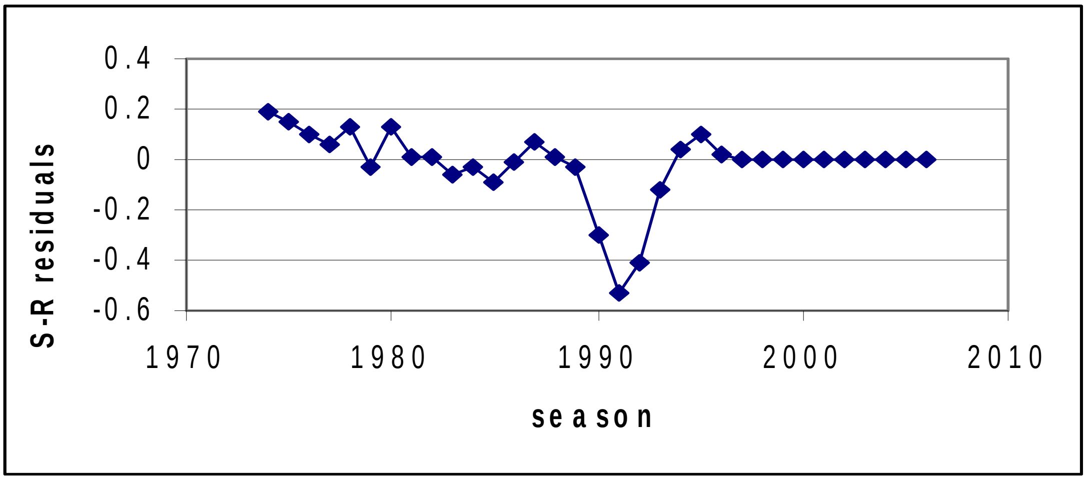


Figure 10a: Biomass (exploitable) projections for six different CC strategies for the Reference Case.

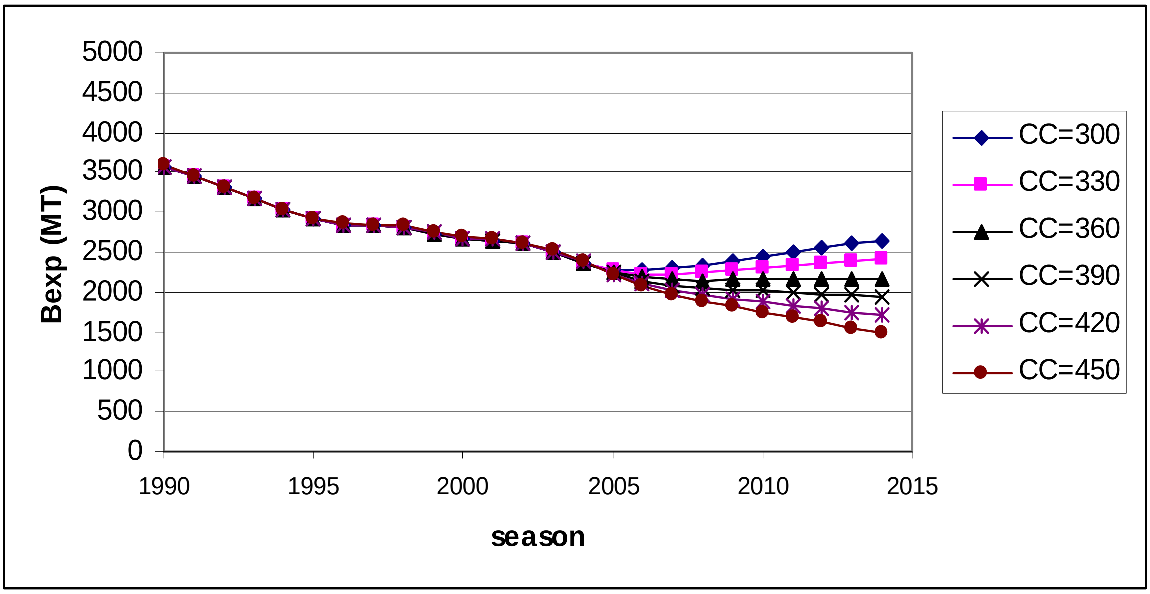


Figure 10b: Biomass (exploitable) projections for six different CC strategies for the effort saturation (Sensitivity 3) scenario.

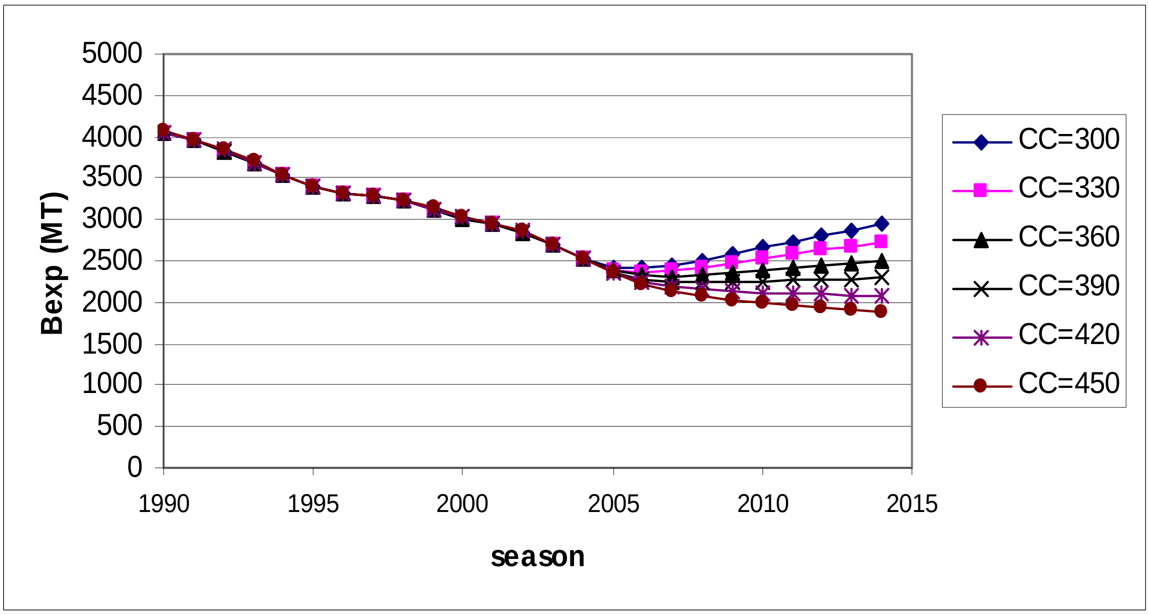


Figure 10c: Biomass (exploitable) projections for six different CC strategies for the lower recruitment scenario (Sensitivity 4: 1996+ R = previous 10 year average).

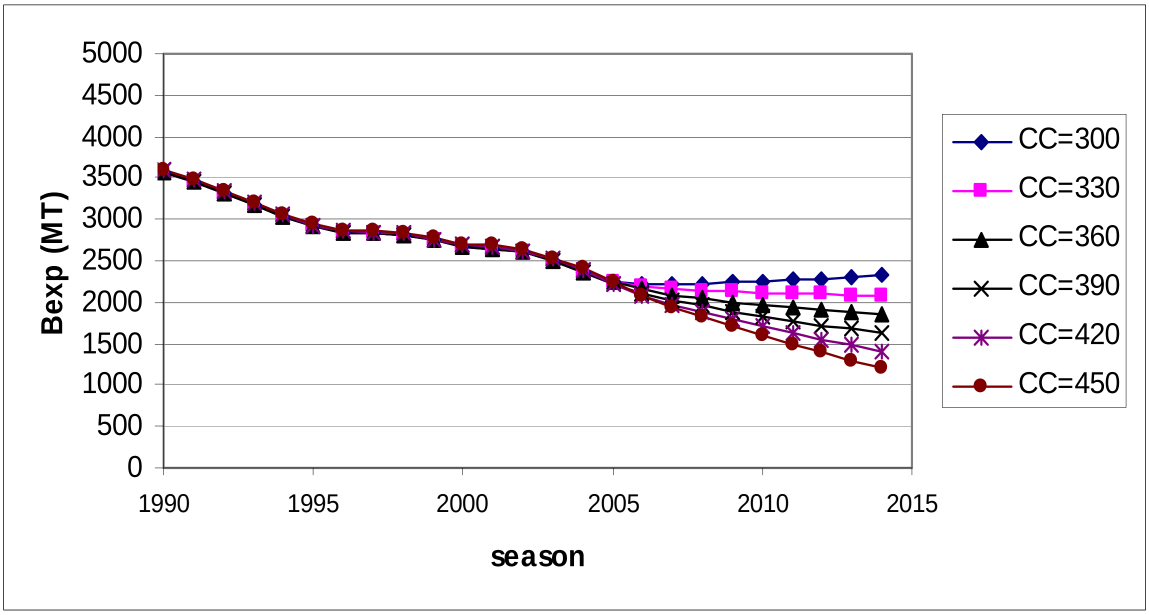


Figure 10d: Biomass (exploitable) projections for six different CC strategies for the catch-at-age down-weight (Sensitivity 5) scenario.

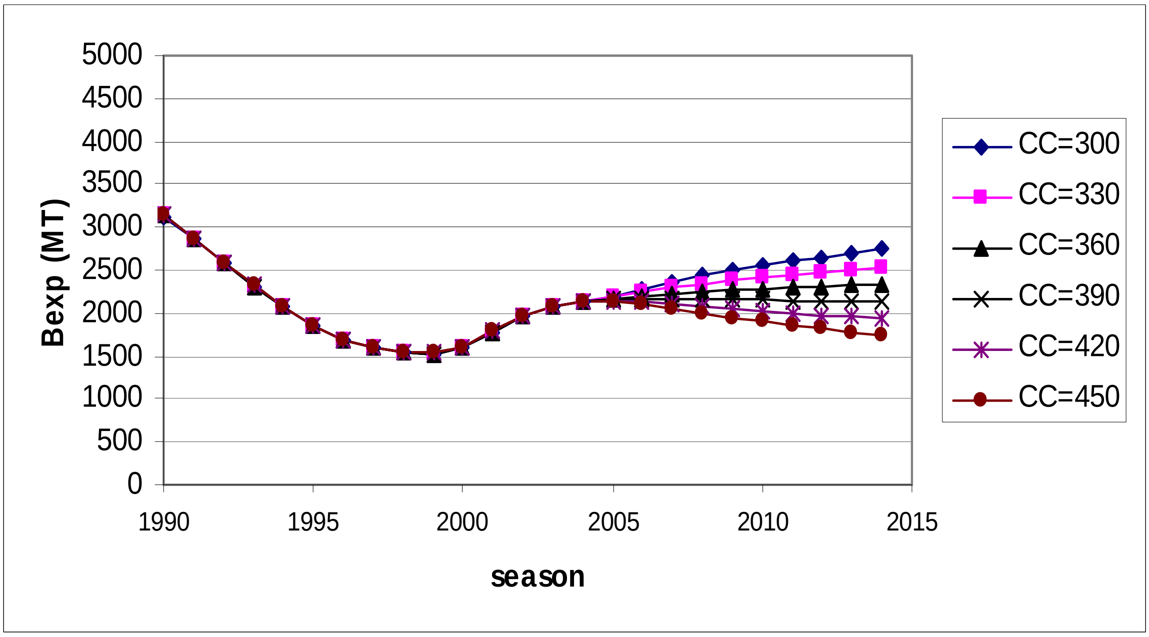


Figure 11a: Model 5 (fitting to catch-at-length directly) fit to CPUE data.

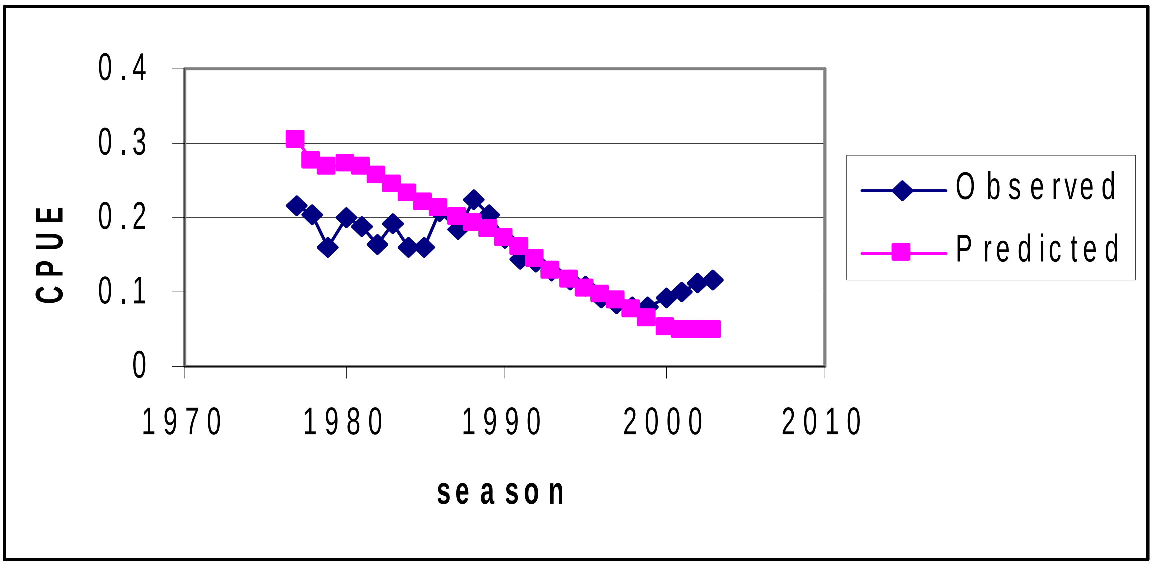


Figure 11b: Model 5 stock-recruit residuals.

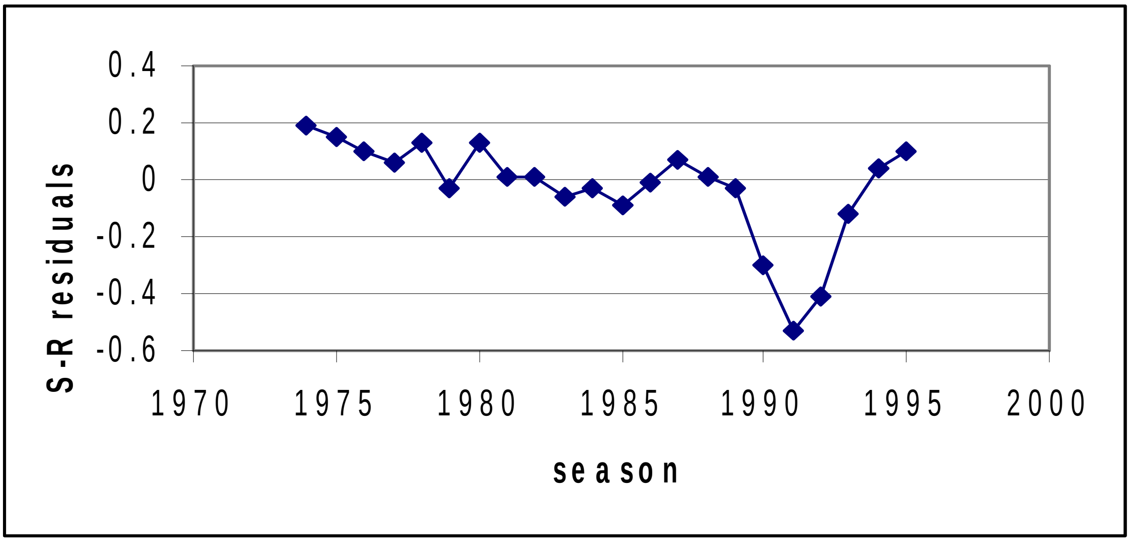


Figure 11c: Model 5 histogram plot of model fits to catch-at-length data (averaged over all years).

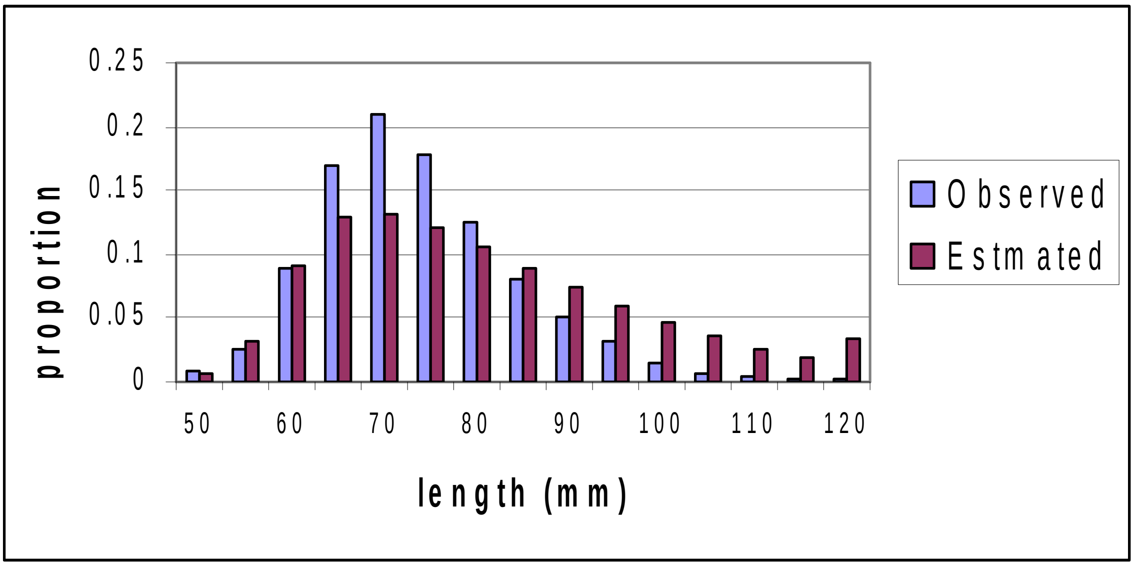


Figure 11d: Model 5 histogram plot of model estimated and observed catch-at-age data (averaged over all years). [Note that the model does not fit to these data!]