The 2004 age-structured production model assessments and projections for the South Coast rock lobster resource

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Executive Summary

The assessment conducted in 2003 has been 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. Results are generally more optimistic than those for the 2003 assessment; this is shown to be a result of both the new abundance data now available as well as the revision of the historic catch series, with the former having slightly the larger effect. The Reference Case (RC) scenario suggests that a TAC of 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 appropriate level for the TAC is increased to 390 MT. On the other hand, the scenario which assumes the 1995+ 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.

Introduction

The age-structured production model applied previously to South Coast rock lobster 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 and 2003 assessments (Johnston and Butterworth 2001; 2002a; 2003a; 2003b). The age-structured model is reported in detail in the Appendix of Johnston and Butterworth (2002b) and is repeated here in the Appendix.

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

1. Standard priors for P, h[1], M, a_{50}, a_{95}.
2. Use of GLM-standardised CPUE from 1977-2002[2].

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[1] The prior for h is a truncated (at 1.0) normal distribution with mean of 0.95 and σ =0.2

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

3. Use of scientific-sample-based catch-at-age data from 1994-2002, with an 8- and 20+ grouping. Note that the 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.
4. A Beverton-Holt stock recruit relationship.
5. Deterministic recruitment, except for estimation of recruitment residuals from 1974-1994 with zero serial correlation ($\rho = 0$) and CV (σ_R) of 0.4.

Data

The annual total catch (by mass) (C_y) and relative abundance index ($CPUE_y$) data used are reported in Table 1a. One change to the 2004 RC assessment model is that the historic catch series now uses the TAC for each year where available (from 1995 to date) plus the larger and more comprehensive undeclared over-catch option as specified in WG/06/04/SCRL1. The 2003 assessment used the MCM catch records (rather than the TAC for 1994 to date) plus a series of undeclared catches for 1998-2000 only).

The relative abundance index corresponds to the standardised CPUE time series provided by Glazer (2004). The commercial catches-at-age ($C_{y,a}$) derived from the updated scientific length data (see Groeneveld 2004) 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 4a.

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

The effort saturation effect is taken into account by "de-trending" the observed CPUE series as described in the Appendix (see Equation 16 thereof) of Johnston and Butterworth (2002). This analysis includes fitting also 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 1995+ recruitment residuals are equal to the average of the preceding 10-year period (i.e. 1985-1994 average). The rationale for this analysis is that a ten-year average, rather than a shorter period, is used because the recent recruitments have been 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-weight

The catch-at-age data is down-weighted by a multiplicative factor of 0.10 in the likelihood function.

Projections

The resource is projected ahead from 2004 to 2013 under a number of constant catch (CC) levels: 270 MT, 300 MT, 330 MT, 360 MT, 390 MT and 420 MT.

Results

Assessment results

The assessment results for the RC model, and the five sensitivity analyses are presented in Table 4a. Table 4b compares the current results with those obtained from the 2003 assessment. Table 4c reports a summary of results to assist making comparisons more easily between the 2003 and 2004 assessments and to see what effects the new data alone (Sensitivity 1) have had on the results. Fits to CPUE data and catch-at-age data are illustrated in Figures 1 and 2 respectively. The effort saturation fit to the “de-trended” CPUE data is shown in Figure 1b. Figures 3a and 3b show the estimated exploitable biomass and spawning biomass trends for the RC and effort saturation scenarios.

The estimated stock-recruit residuals for the RC, effort saturation and catch-at-age down-weight scenarios are illustrated in Figure 4.

Projections

Table 5 presents results of projected spawning biomass trends for the RC and the three sensitivity analyses for a range of future constant catches. The projected exploitable biomass trends are also illustrated in Figures 5a-d for the different scenarios.

Discussion

The 2003 RC assessment of the south coast rock lobster resource estimated the resource at the start of 2002 to be 25% of carrying capacity for the exploitable portion of the stock, and 29% of capacity for the spawning biomass. The updated 2004 RC assessment estimates these values to be 30% and 32% respectively. Whilst these values are comparatively slightly higher than those estimates for the 2003 assessment, both the spawning biomass and exploitable biomass are estimated to have declined slightly between the years 2002 and 2003. The MSY for the resource is estimated to be 383 MT for the RC model, and between 368 and 454 for the five sensitivity analyses.

The RC MSY estimate (383 MT) is higher than that estimated by the 2003 assessment (347 MT) – see Table 4b. The 95% confidence interval for the 2004 MSY estimate as calculated using a likelihood profile method is [100; 451]; the corresponding interval for the 2003 assessment was [23; 362].

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 415 MT (RC = 383 MT).

The effort saturation scenario results are more positive than those for the RC model. The effects on estimates of management quantities (MSY, $\frac{B^{sp}}{K^{sp}}$) of the additional data available since last year are positive (see Table 4b).

Down-weighting the catch-at-age data once again results in a more optimistic appraisal of the resource. Through this down-weighting, this model is able to better fit the CPUE data, in particular, the recent upturn in CPUE (see Figure 1a). The fits to the catch-at-age data do however deteriorate substantially (see Figure 2), particularly for more recent years such as the 2002 season.

The projected spawning biomass trends estimated under different future constant catch scenarios, are rather different across the various scenarios (see Figures 5a-c for the RC and three of the sensitivity scenarios). The RC predicts catches above about 360 MT will result in a decline of the spawning biomass from its current (2003) level. Catches above 390 MT are shown to result in spawning biomass declines for the over-catch 87-97 set =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 larger than 300 MT will result in a spawning biomass decline, and the historic catch = 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 last year, are more optimistic.

Plots of exploitable biomass trajectories (Figures 5a) 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.

The effort saturation and catch-at-age down-weight scenarios are somewhat more optimistic (Figures 5b and d) and indicate that future CC of 390 MT or less will prevent further decline in the exploitable biomass.

The lower recruitment scenario (1995+ recruitment is assumed to equal the previous 10 year average) produces the least optimistic projection results (Figure 5c). This scenario suggests that a future TAC of 330 MT or less is needed to prevent further decline in the exploitable biomass.

The 2004 assessment results are thus more optimistic than those produced last year for similar scenarios. This is likely primarily the result of the continued increase in CPUE as well as the switch to using a historic catch record with slightly higher values (TAC rather than MCM records). Generally, the higher the historic catch record is assumed to be, the more “productive” the resource is estimated. Table 4c indicates that both the new abundance index data as well as the changed RC historic catch series contribute to more optimistic results compared to those of the 2003 assessment, with the former making slightly the greater contribution.

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Table 1: Total annual catch scenarios (data from WG/06/04/SCRL1) and GLM standardised CPUE (Glazer 2004) 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	0.2213
1978	461	461	461	0.2074
1979	122	122	122	0.1613
1980	176	176	176	0.2060
1981	348	348	348	0.1952
1982	407	407	407	0.1671
1983	524	524	524	0.1986
1984	450	450	450	0.1664
1985	450	450	450	0.1626
1986	450	450	450	0.2111
1987	452	452	552	0.1877
1988	452	452	552	0.2263
1989	452	452	552	0.2075
1990	477	477	577	0.1759
1991	524.54	524.54	577	0.1452
1992	529.96	529.96	577	0.1417
1993	524.27	524.27	577	0.1296
1994	507.89	507.89	552	0.1190
1995	504.89	472.99	527	0.1101
1996	442.69	428.39	515	0.0925
1997	416.39	384.09	502	0.0839
1998	516.03	460.73	516.03	0.0799
1999	512.16	514.86	512.16	0.0817
2000	423.4	378	423.4	0.0917
2001	288	288	288	0.1026
2002	340	325	340	0.1129
2003	350	350	350	

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**
0	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
2	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
4	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
6	0.0000	0.0000	0.0039	0.0000	0.0056	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
8	0.0029	0.0093	0.0266	0.0066	0.0484	0.0244	0.0069	0.0010	0.0190
9	0.0215	0.0554	0.0478	0.0609	0.0834	0.1229	0.0389	0.0105	0.0510
10	0.0709	0.1265	0.0819	0.1467	0.1233	0.2021	0.1166	0.0451	0.0767
11	0.1441	0.1838	0.1202	0.2080	0.1429	0.1958	0.2099	0.1119	0.0930
12	0.1537	0.1369	0.1256	0.1373	0.0939	0.1039	0.1648	0.1548	0.0986
13	0.1493	0.1110	0.1184	0.1079	0.0844	0.0800	0.1224	0.1552	0.1143
14	0.1343	0.0829	0.1054	0.0775	0.0744	0.0591	0.0782	0.1437	0.1242
15	0.0677	0.0440	0.0603	0.0412	0.0462	0.0372	0.0397	0.0762	0.0708
16	0.0786	0.0548	0.0782	0.0498	0.0637	0.0507	0.0461	0.0924	0.0927
17	0.0386	0.0342	0.0419	0.0262	0.0361	0.0265	0.0252	0.0459	0.0510
18	0.0293	0.0319	0.0349	0.0215	0.0315	0.0214	0.0213	0.0354	0.0434
19	0.0238	0.0274	0.0296	0.0192	0.0271	0.0171	0.0195	0.0290	0.0368
20+	0.0849	0.1013	0.1113	0.0968	0.1192	0.0579	0.1094	0.0990	0.1275

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 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 1994 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 (1995+ R = previous 10 year average)**	**Sensitivity 5: Catch-at-age down-weighted by 0.10 multiplier**
K^{sp}	8121	7959	8578	7588	8127	7093
h	0.851	0.843	0.867	0.905	0.854	0.932
M	0.115	0.113	0.116	0.135	0.116	0.142
a_{50}	10.07	10.07	10.08	10.01	10.07	11.04
a_{95}	12.47	12.47	12.48	12.31	12.47	13.55
$n*$	-	-	-	1.0 (fixed)	-	-
E'	-	-	-	2500 (fixed)	-	-
$E*$	-	-	-	7416	-	-
σ	0.168	0.164	0.154	0.090	0.168	0.079
σ_{age}	0.070	0.070	0.070	0.069	0.070	0.117
-*lnL* CPUE	-33.38	-34.02	-35.62	-49.91	-33.41	-52.96
-*lnL* age	-83.01	-83.27	-83.45	-84.37	-83.11	-23.66
-*lnL* S-R	1.81	1.87	1.98	3.42	1.86	4.81
-*lnL* effort expt	-	-	-	-1.35	-	-
-*lnL*(total)	**-115.13**	**-115.95**	**-117.68**	**-132.67**	**-115.21**	**-51.18**
MSY	383	368	415	441	387	454
$MSYL^{exp}/K$	0.216	0.220	0.209	0.184	0.215	0.145
$B^{\exp}_{2003}/K^{\exp}$	0.289	0.283	0.302	0.366	0.288	0.341
$B^{\exp}_{2003}/B^{\exp}_{msy}$	1.337	1.287	1.446	1.989	1.343	2.355
B^{sp}_{2003}/K^{sp}	0.315	0.310	0.328	0.388	0.315	0.425
B^{sp}_{2013}/K^{sp} **CC=330 MT**	0.354	0.336	0.388	0.455	0.303	0.497
$B^{sp}_{2013}/B^{sp}_{03}$ **CC=330 MT**	1.123	1.084	1.184	1.172	0.961	1.168

Table 4b: Stock assessment results for the Reference Case analysis and three of the sensitivity analyses. Units of mass-related quantities (e.g. *MSY*) are tons. The results in parenthesis are those for the corresponding 2003 assessment (note that here all $B^{\exp}$ estimates refer to 2002 rather than 2003). The values in square brackets are the 95% confidence intervals evaluated using a likelihood profile method.

	Reference Case	**Sensitivity 3: Effort saturation**	**Sensitivity 4: Lower recruitment (1995+ R = previous 10 year average)**	**Sensitivity 5: Catch-at-age down-weighted by 0.10 multiplier**
h	0.851 (0.795) [0.518; 0.981]	0.905 (0.886)	0.854 (0.800)	0.932 (0.912)
M	0.115 (0.112)	0.135 (0.135)	0.116 (0.123)	0.142 (0.139)
a_{50}	10.07 (10.2)	10.01 (10.2)	10.07 (10.2)	11.04 (10.8)
a_{95}	12.47 (11.8)	12.31 (12.5)	12.47 (12.6)	13.55 (13.2)
E*	-	7416 (7654)	-	-
σ	0.168 (0.135)	0.090 (0.090)	0.168 (0.135)	0.079 (0.078)
σ_{age}	0.070 (0.069)	0.069 (0.068)	0.070 (0.069)	0.117 (0.099)
MSY	383 (347) [100, 451]	441 (400) [441, 453]	387 (351)	454 (396)
$MSYL^{exp}/K$	0.216 (0.232)	0.184 (0.187)	0.215 (0.229)	0.145 (0.152)
$B_{2002}^{\exp}/K^{\exp}$	0.299 (0.253)	0.378 (0.331)	0.299 (0.253)	0.321 (0.280)
$B_{2002}^{\exp}/B_{msy}^{\exp}$	1.381 (1.095)	2.052 (1.765)	1.390 (1.107)	2.215 (1.842)
B_{2002}^{sp}/K^{sp}	0.323 (0.286)	0.400 (0.362)	0.323 (0.286)	0.410 (0.360)
B_{2010}^{sp}/K^{sp} **CC=330 MT**	0.340 (0.300)	0.436 (0.393)	0.304 (0.248)	0.483 (0.405)

Table 4c: Summary of stock assessment results for the 2003 and 2004 Reference Case analyses, as well as for the Sensitivity 1 scenario (for which the only change is new data).

	2003 Reference Case	**2004 Sensitivity 1: new data alone**	**2004 Reference Case: new data + new historic catch record**
h	0.795	0.843	0.851
M	0.112	0.113	0.115
MSY	347	368	383
$B^{\exp}_{2002}/K^{\exp}$	0.253	0.293	0.299
B^{sp}_{2002}/K^{sp}	0.286	0.317	0.323
B^{sp}_{2010}/K^{sp} **CC=330 MT**	0.300	0.325	0.340

Table 5: Projected 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 2003.]

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 (1995+ R = previous 10 year average)**	**Sensitivity 5: Catch-at-age down-weighted by 0.10 multiplier**
B^{sp}_{2003}/K^{sp}	**ALL**	0.315	0.310	0.328	0.388	0.315	0.425
B^{sp}_{2013}/K^{sp}							
	CC = 420	0.271	0.252	0.309	0.372	0.223	0.412
	CC = 390	0.298	0.279	0.336	0.399	0.249	0.440
	CC = 360	0.326	0.308	0.362	0.427	0.275	0.469
	CC = 330	0.354	0.336	0.388	0.455	0.303	0.497
	CC = 300	0.382	0.365	0.414	0.482	0.330	0.526
	CC = 270	0.410	0.394	0.441	0.510	0.358	0.554
$B^{sp}_{2013}/B^{2013}_{2003}$							
	CC = 420	0.857	0.808	0.942	0.957	0.702	0.966
	CC = 390	0.945	0.898	1.023	1.028	0.786	1.034
	CC = 360	1.033	0.990	1.103	1.100	0.873	1.101
	CC = 330	1.123	1.084	1.184	1.172	0.961	1.168
	CC = 300	1.212	1.177	1.264	1.243	1.050	1.236
	CC = 270	1.300	1.269	1.344	1.324	1.138	1.302

Figure 1a: Observed and estimated CPUE for the Reference Case, lower recruitment (1995+ R = previous 10 year average) and catch-at-age down-weight scenarios.

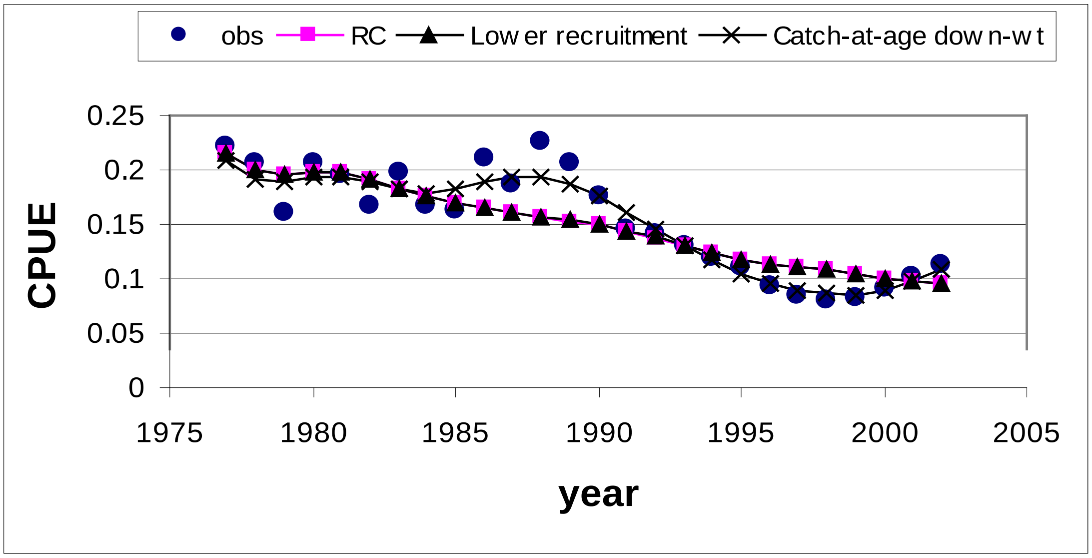


Figure 1b: “De-trended” and estimated CPUE for the effort saturation model.

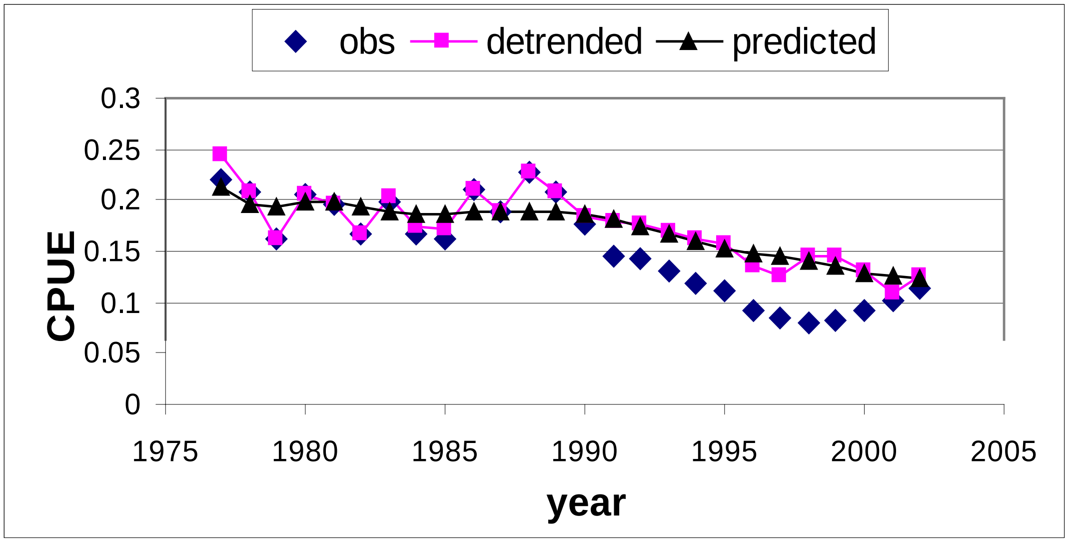


Figure 2: Observed and estimated catch-at-age proportions for the Reference Case and catch-at-age down-weight scenarios.

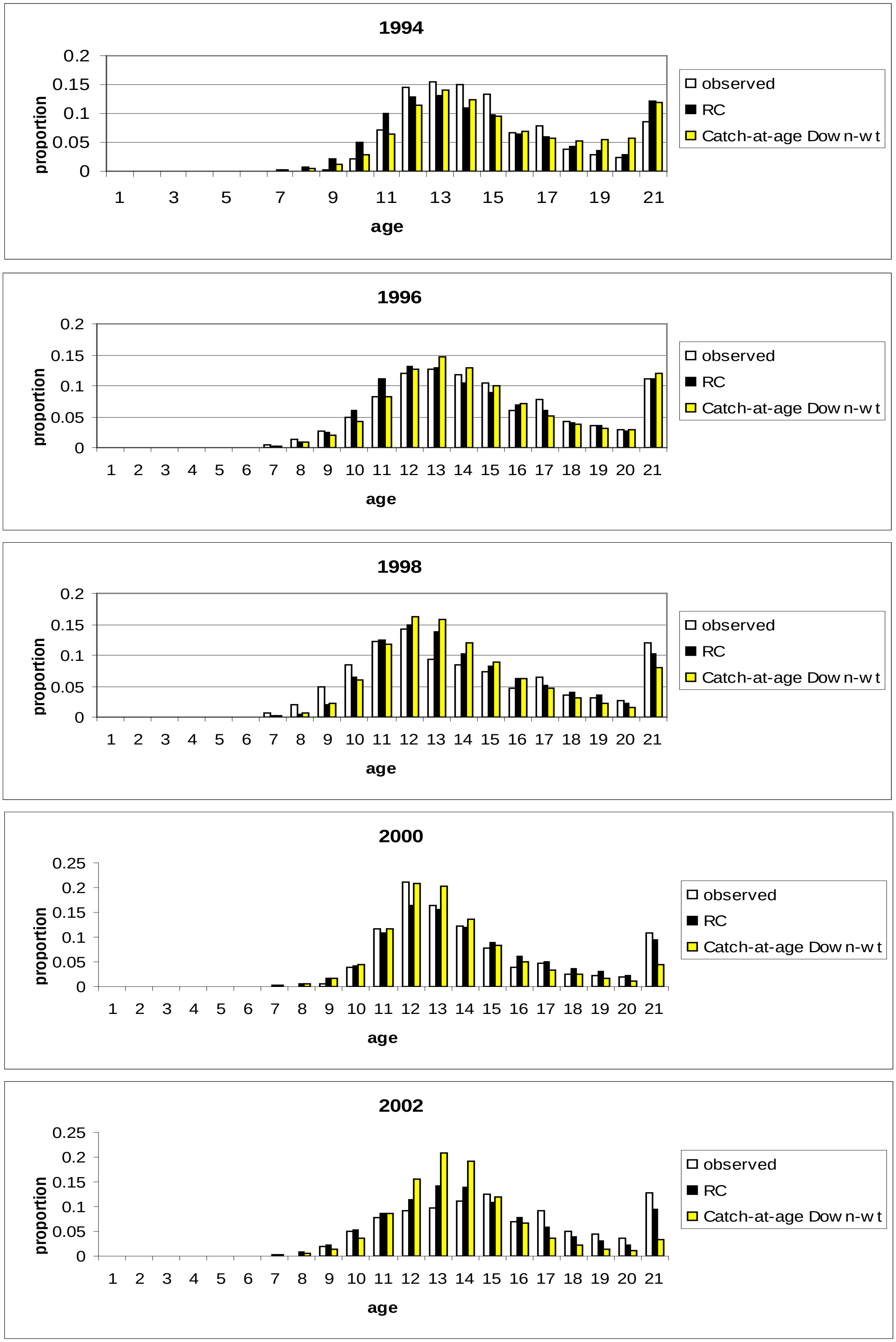


Figure 3a: Exploitable biomass trends for the Reference Case effort saturation scenarios.

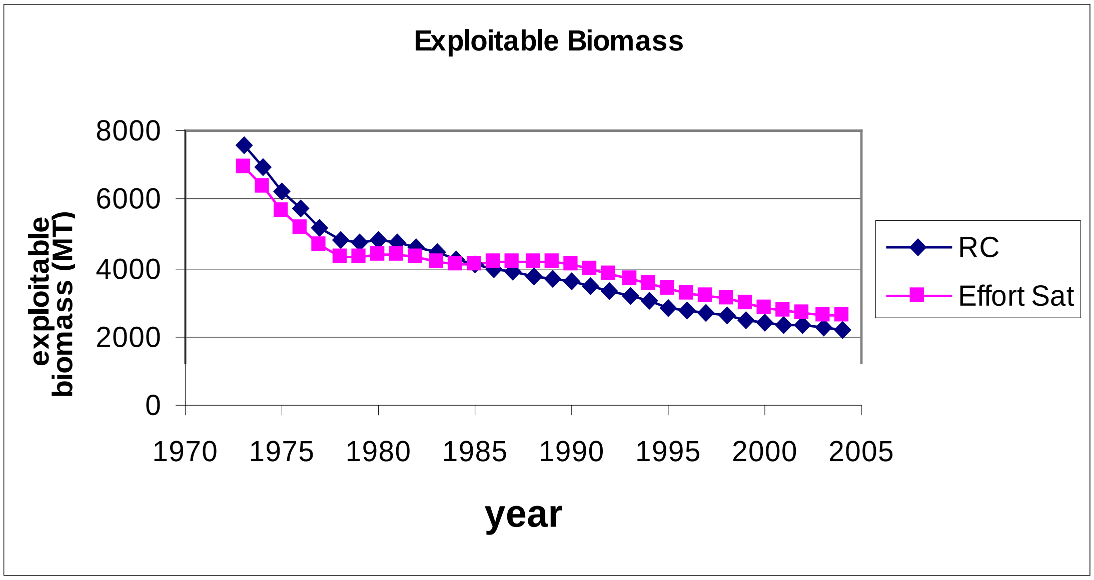


Figure 3b: Spawning biomass trends for the Reference Case and effort saturation scenarios.

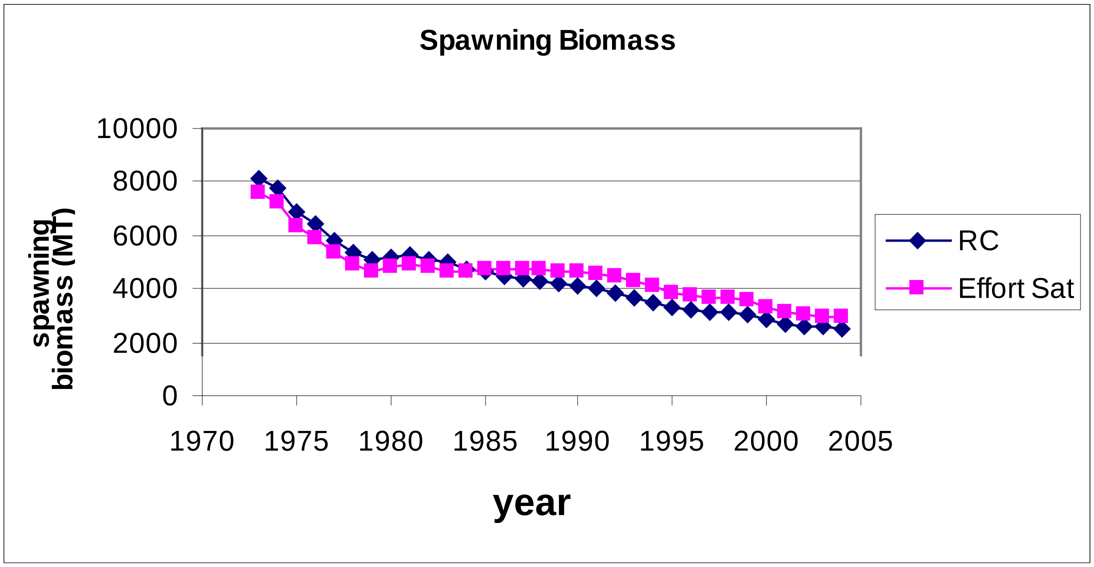


Figure 4: Stock-recruitment residuals for the Reference Case, effort saturation and catch-at-age down-weighting scenarios.

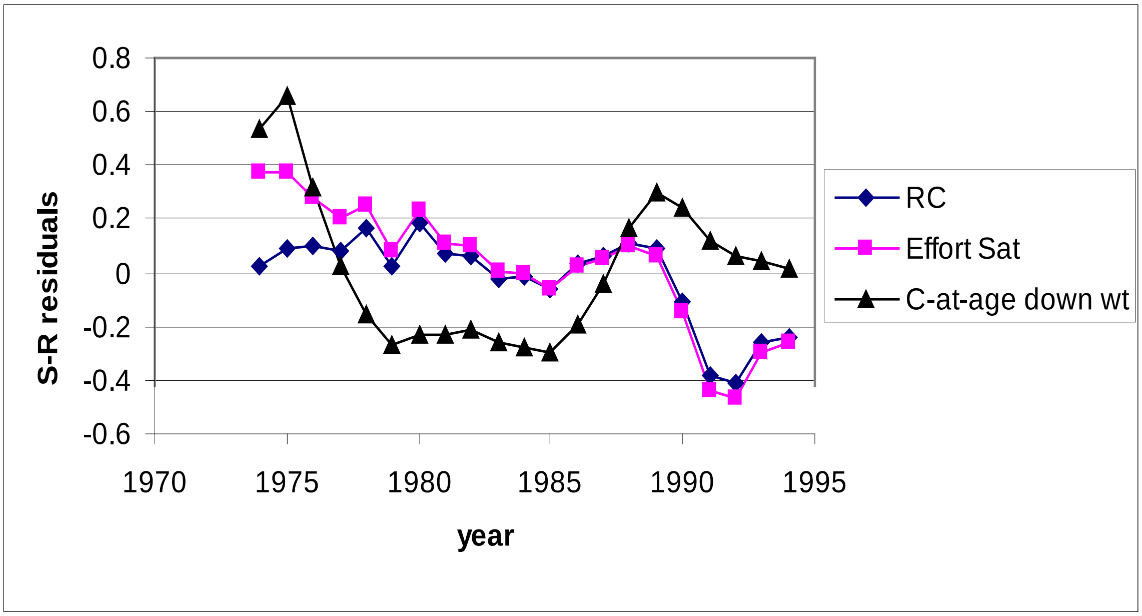


Figure 5a: Biomass (exploitable) projections for six different CC strategies for the Reference Case.

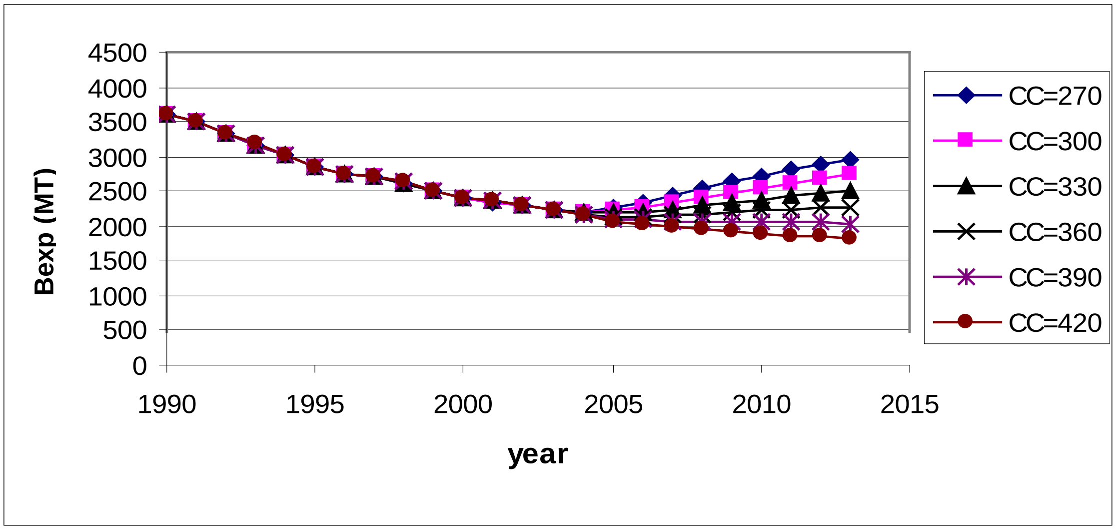


Figure 5b: Biomass (exploitable) projections for six different CC strategies for the effort saturation scenario.

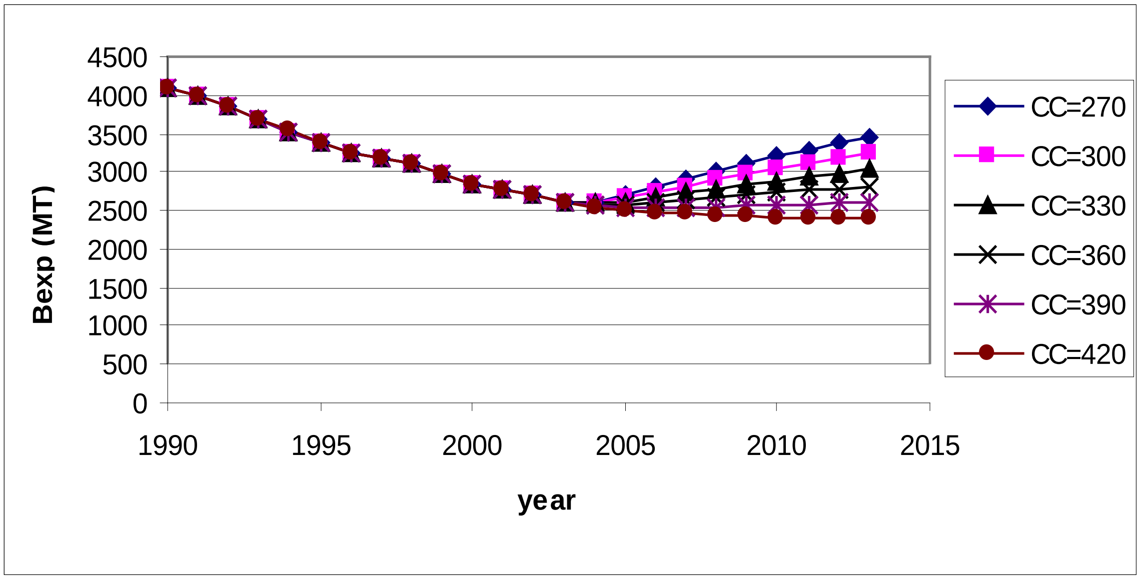


Figure 5c: Biomass (exploitable) projections for six different CC strategies for the lower recruitment scenario (1995+R = previous 10 year average).

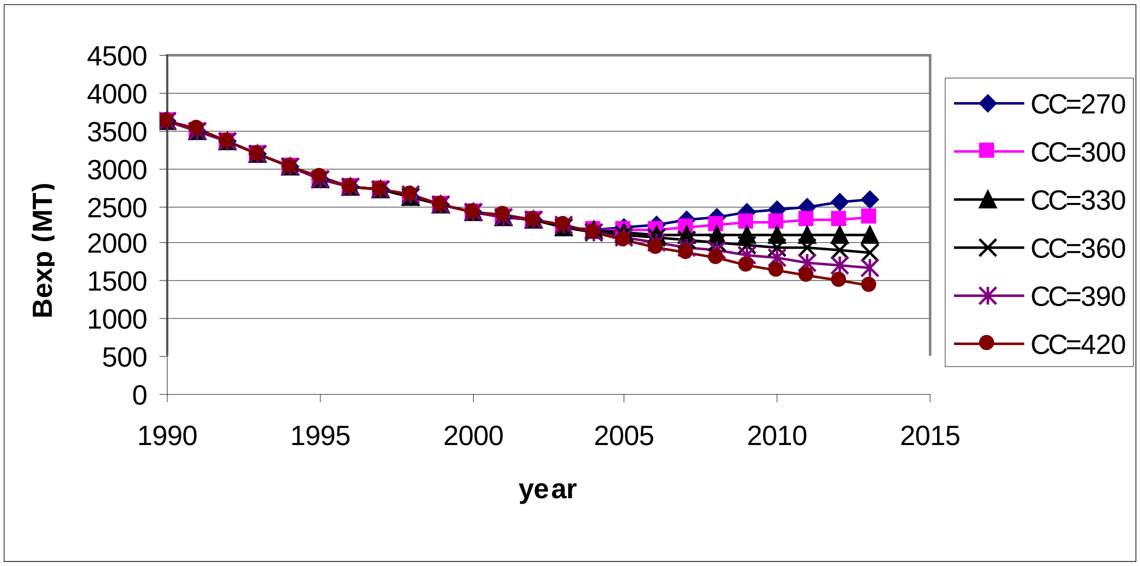
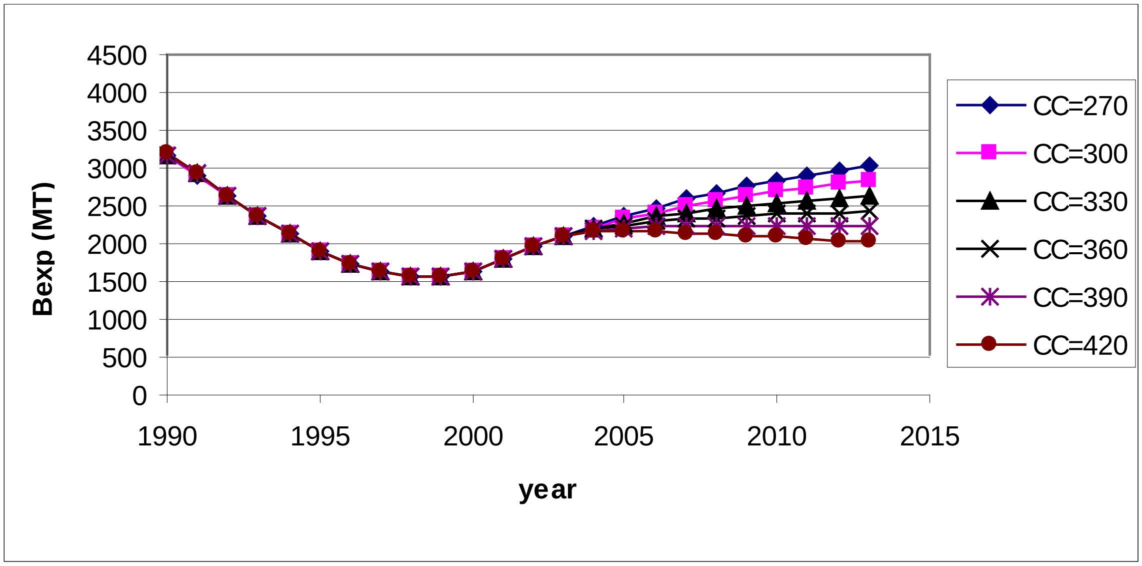


Figure 5d: Biomass (exploitable) projections for six different CC strategies for the catch-at-age down-weight scenario.



Appendix: The Age-structured production model for the South Coast rock lobster resource.

1. The population model:

The resource dynamics are modelled by the equations:

$$N_{y+1,0} = R_{y+1} \tag{1}$$

$$N_{y+1,a+1} = N_{y,a} e^{-(M_a + S_a F_y)} = N_{y,a} e^{-Z_{y,a}} \tag{2}$$

$$N_{y+1,m} = N_{y,m-1} e^{-(M_{m-1} + S_{m-1} F_y)} + N_{y,m} e^{-(M_m + S_m F_y)} \tag{3}$$

where

$N_{y,a}$ is the number of lobsters of age *a* at the start of year *y*,

M_a denotes the natural mortality rate on lobsters of age *a*,

S_a is the age-specific selectivity,

F_y is the fully selected fishing mortality in year *y*, and

m is the maximum age considered (taken to be a plus-group).

The number of recruits at the start of year y is related to the spawner stock size by a stock-recruitment relationship:

$$R_y = \frac{\alpha B_y^{sp}}{\beta + (B_y^{sp})^{\gamma}} e^{\varsigma_y} \tag{4}$$

where

α, β and γ are spawner biomass-recruitment parameters (γ =1 for a Beverton-Holt relationship),

ς_y reflects fluctuation about the expected recruitment for year *y*, and

B_y^{sp} is the spawner biomass at the start of year *y*, given by:

$$B_y^{sp} = \sum_{a=1}^{m} f_a w_a N_{y,a} \tag{5}$$

where w_a is the begin-year mass of fish at 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-recruit relationship is re-parameterised in terms of the pre-exploitation equilibrium spawning biomass, K^{sp}, and the "steepness" of the stock-recruit relationship (recruitment at $B^{sp} = 0.2K^{sp}$ as a fraction of recruitment at $B^{sp} = K^{sp}$):

$$\alpha = \frac{\left(5 - 0.2^{\gamma-1}\right) h R_1 \left(K^{sp}\right)^{\gamma-1}}{5h - 1} \tag{6}$$

and

$$\beta = \frac{\left(K^{sp}\right)^{\gamma} \left(1 - 0.2h\right)^{\gamma-1}}{5h - 1} \tag{7}$$

where

$$R_1 = K^{sp} / \left[\sum_{a=1}^{m-1} f_a w_a e^{-\sum_{a'=0}^{a-1} M_{a'}} + f_m w_m \frac{e^{-\sum_{a'=0}^{m-1} M_{a'}}}{1-e^{-M_m}} \right] \tag{8}$$

The total catch by mass in year *y* is given by:

$$C_y = \sum_{a=0}^{m} w_{a+\frac{1}{2}} N_{y,a} \frac{S_a F_y}{Z_{y,a}} (1-e^{-Z_{y,a}}) \tag{9}$$

where $w_{a+\frac{1}{2}}$ denotes the mid-year mass of a lobster at age *a*.

The model estimate of mid-year exploitable biomass is given by:

$$\hat{B}_y = \sum_{a=0}^{m} w_{a+\frac{1}{2}} S_a N_{y,a} e^{-(Z_{y,a})/2} \tag{10}$$

where

$\hat{B}_y$ is the model estimate of exploitable biomass for year *y*, and

S_a is the fishing selectivity-at-age for age *a*.

Models that do not allow for the possibility of fluctuations about the stock-recruitment relationship (i.e. those which set $\varsigma_y = 0$ in equation 4) assume that the resource is at the deterministic equilibrium that corresponds to an absence of harvesting at the start of the initial year ($B^{sp}_{1973} = K^{sp}$). For models that allow for that possibility, this assumption together with that of the associated equilibrium age-structure is made for 1973, with the biomass and age-structure thereafter potentially impacted by such fluctuations.

2. The likelihood function

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

2.1 Relative abundance data (CPUE):

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

$$CPUE_y = qB_y e^{\varepsilon_y} \text{ or } \varepsilon_y = \ln(CPUE_y) - \ln(qB_y) \tag{11}$$

where

$CPUE_y$ is the CPUE abundance index for year *y*,

B_y is the model estimate of mid-year exploitable biomass for year *y* given by equation 10,

q is the constant of proportionality (catchability coefficient), and

ε_y from $N(0,\sigma^2)$.

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

$$-\ln L = \sum_y \left[(\varepsilon_y)^2 / 2\sigma^2 + \ln \sigma \right] \tag{12}$$

where

σ is the residual standard deviation estimated in the fitting procedure by its maximum likelihood value:

$$\hat{\sigma} = \sqrt{1/n \sum_y \left(\ln CPUE_y - \ln \hat{q}\hat{B}_y \right)^2} \tag{13}$$

where

n is the number of data points in the CPUE series, and
q is the catchability coefficient, estiated by its maximum likelihood value:

$$\ln \hat{q} = 1/n \sum_y \left(\ln CPUE_y - \ln \hat{B}_y \right) \tag{14}$$

2.2 "Effort saturation"

When the possibility of "effort saturation" is taken into account, the CPUE abundance relationship of equation 11 is modified as follows:

$$CPUE_y^{adj} = qB_y e^{\varepsilon_y} \text{ or } \varepsilon_y = \ln(CPUE_y^{adj}) - \ln(qB_y) \tag{15}$$

where

$$CPUE_y^{adj} = CPUE_y \left[1 + \left(\frac{E - E'}{E^* - E'} \right)^{n^*} \right] \qquad \text{if } E > E' \tag{16}$$

$$CPUE_y^{adj} = CPUE_y \qquad \text{if } E \le E'$$

where

$CPUE_y$ is the GLM standardised CPUE data given in Table 1,

$CPUE_y^{adj}$ is the CPUE data "de-trended" to account for "effort saturation" in the fitting procedure,

E_y is the estimated effort given by $\dfrac{C_y}{CPUE_y}$,

E^* quantifies the extent of "effort saturation",
E' is the threshold effort above which "effort saturation" sets in, and
n^* allows for flexibility in the "effort saturation" relationship.

For this scenario, equations 13 and 14 are also modified by replacing $CPUE_y$ by the "de-trended" CPUE defined above.

2.3 Catches-at-age

The contribution of the catch-at-age data to the negative of the log-likelihood function when assuming a log-normal error distribution and when making an adjustment to effectively weight in proportion to sample size is given by:

$$-\ln L = \sum_y \sum_a \left[\ln(\sigma_{age} / \sqrt{\hat{p}_{y,a}}) + p_{y,a} \left(\ln p_{y,a} - \ln \hat{p}_{y,a} \right)^2 / 2(\sigma_{age})^2 \right] \tag{17}$$

where

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

$\hat{p}_{y,a} = \hat{C}_{y,a} / \sum_{a'} \hat{C}_{y,a'}$ is the model predicted proportion of fish caught in year *y* that are of age *a*, where:

$$\hat{C}_{y,a} = N_{y,a} \frac{S_{y,a} F_y}{Z_{y,a}} (1 - e^{-Z_{y,a}}) \tag{18}$$

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

$$\hat{\sigma}_{age} = \sqrt{\left[\sum_y \sum_a p_{y,a} (\ln p_{y,a} - \ln \hat{p}_{y,a})^2 / \sum_y \sum_a 1 \right]} \tag{19}$$

Note that allowance is made for a “minus” group (lobsters age 8 and younger) in the catch-at-age contribution to the likelihood function, as well as for a “plus” group (lobsters aged 20 and over).

2.4 Stock-recruitment function residuals:

The assumption that these residuals are log-normally distributed and could be serially correlated defines a corresponding joint prior distribution. This can be equivalently regarded as a penalty function added to the log-likelihood, which for fixed ρ is given by:

$$-\ln L = \sum_{y=y1}^{y2} \left[\frac{\varsigma_y - \rho \varsigma_{y-1}}{\sqrt{1-\rho^2}} \right]^2 / 2\sigma_R^2 \tag{20}$$

where

$\varsigma_y = \rho \tau_{y-1} + \sqrt{1-\rho^2} \varepsilon_y$ is the recruitment residual for year *y* (see equation 4), which is estimated for years *y1* to *y2* if $\rho = 0$, or *y1*+1 to *y2* if $\rho > 0$,

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

σ_R is the standard deviation of the log-residuals, which is input, and

ρ is their serial correlation coefficient, which is input.

Note that for the Reference Case assessment, ρ is set equal to zero, i.e. the recruitment residuals are assumed uncorrelated, and σ_R is set equal to 0.4. Because of the absence of informative age data for a wider period, recruitment residuals are estimated for years 1974 to 1994 only.

3 Model parameters

Natural mortality: Natural mortality, M_a, is assumed to be the same (*M*) for all age classes.

Commercial selectivity-at-age: The following time-invariant logistic curve is assumed for the commercial selectivity:

$$S_a = \frac{1}{1+e^{(-\ln(19)(a-a_{50})/(a_{95}-a_{50}))}} \tag{21}$$

where

a_{50} years is the age-at-50% selectivity which is estimated, and

a_{95} years is the age-at-95% selectivity which is estimated.

Age-at-maturity: The proportion of lobsters of age a that are mature is approximated by $f_a = 1$ for $a > 9$ years (i.e. $f_a = 0$ for a = 0, …,9).

Minimum age: Age 8 it taken to be a minus group.

Maximum age: $m = 20$, and is taken as a plus-group.

Mass-at-age: The mass w of a lobster at age a is given by:

$$w = \alpha\left[l_\infty\left(1-e^{-\kappa(a-t_0)}\right)\right]^\beta \tag{22}$$

where the values assumed for the growth parameters are shown in Table 3.

Stock-recruitment relationship: The shape parameter, γ, is fixed to 1, corresponding to a Beverton-Holt form.

4. The Bayesian approach

The Bayesian method entails updating prior distributions for model parameters according to the respective likelihoods of the associated population model fits to the CPUE, catch-at-age and tag-recapture data, to provide posterior distribution for these parameters and other model quantities.

In the case of an age-structured production model, the Bayesian computations require integration over the following priors:

- The 1993 harvest proportion ($P = C_{1993}/B_{1993}$),
- The "steepness" of the stock-recruit relationship (h), and
- Natural mortality (M_a), assumed independent of age.
- In addition, we integrate over the two parameters defining the shape of the selectivity-at-age curve (a_{50} and a_{95}).

Furthermore, priors for the parameters characterising the postulated "effort saturation" effects (E^*, E' and n^*) of equation 16 are also required. In applications considered thus far, E' and n^* have been taken as fixed. An effective prior based on the effort saturation experiment leads to the following term:

$$-\ln L = 4 \ln\sigma_E + 2 \tag{23}$$

where σ_E is estimated from the data such that:

$$\sigma_E = \sqrt{SS(E^*)/4} \tag{24}$$

where σ_E is the standard deviation of the residuals.

The $SS(E^*)$ term is developed as follows (Butterworth 2000): Considering the "full effort" exerted in Dec-Jan of the 1998/99 experiment as the standard, the extent of effort reduction (λ) and the associated relative change in CPUE (GLM-standardised to adjust for normal monthly trends), $f^{obs}(\lambda)$, were as follows for the four area-period combinations considered in the experiment:

Area-period	λ	$f^{obs}(\lambda)$
East – Feb/Mar	0.93	1.25
East – Apr/May	1.24	1.30
Agulhas – Feb/Mar	1.15	1.04
Agulhas – Apr/May	0.60	0.71

The effort "reduction" factors, λ, above are taken from Groeneveld *et al*. (1999), (specifically Table 2c) for effective effort. The $f^{obs}(\lambda)$ values follow from Tables 1 and 2 of an update of a section of that paper (WG/07/99/SCL16a), by dividing CPUE ratios (in relation to the Dec-Jan values taken as the standard) from the 1998/99 experiment by average values over the preceding 1991/92 to 1997/98 seasons.

To relate this "observed" information to a model for the extent of effort saturation, the formulation of Geromont (2000a), equation 16, is used:

$$\hat{f}(\lambda) = \frac{1 + \left[\left(E_{98/99} - E'\right)/\left(E^* - E'\right)\right]^{n^*}}{1 + \left[\left(\lambda E_{98/99} - E'\right)/\left(E^* - E'\right)\right]^{n^*}} \qquad (25)$$

Taking the effort for 1998/99, given by $C_{98/99}/\mathrm{CPUE}_{98/99}$, (see Geromont 2000a, equation 16 and Table 1) to be reflective of the full effort Dec-Jan period of the experiment, sets $E_{98/99}$ above to equal 5255. Geromont (pers. commn) advised values of $E'=2500$ and $n^* = 1$ to be typical of those obtained in her fits of the ASPM model with effort saturation. This leaves only the key E^* parameter unspecified, and this is estimated by minimizing the sums of squared differences between the observed $f(\lambda)$ values and those predicted by equation 25 above:

$$SS(E^*) = \sum_{i=1}^{4} \left[f^{obs}(\lambda_i) - \hat{f}(\lambda_i, E^*) \right]^2 \qquad (26)$$

The catchability coefficient (q) and the standard deviations associated with the CPUE and catch-at-age data (σ and σ_{age}) are estimated in the fitting procedure by their maximum likelihood values, rather than integrating over these three parameters as well. This is adequately accurate given reasonable large sample sizes (Walters and Ludwig 1994, Geromont and Butterworth 1995).

Modes of posteriors, obtained by finding the maximum of the product of the likelihood and the priors, are then estimated rather than performing a full Bayesian integration, due to the time intensiveness of the latter.

4.1 Priors

The following prior distributions for *P, h, M,* a_{50}, a_{95}, M_1^{tag}, M_2^{tag}, τ^{tag} and λ^{tag} are assumed, as previously agreed to by the Working Group (see also Butterworth 1997 and Groeneveld *et al*. 1997).

P: U[0,1]

h: N(0.95,SD) with SD=0.2, where the normal distribution is truncated at *h* = 1.

M: "tent shaped" function (P1,P2,P3,P4) = (0.05,0.1,0.2,0.3)

a_{50}: U[6,13] yr

a_{95}: U[9,17] yr subject to $a_{95} \geq a_{50}$