Assessment of the US South Atlantic Wreckfish using primarily Statistical Catch-at-Age Assessment Methodology following the Recommendations of the November 2013 SAFMC SSC Wreckfish Assessment Workshop

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Summary

SCAA and dynamic Production Model assessments of the wreckfish resource are conducted following the specifications set out by a mid-November 2013 SAFMC SSC workshop. The results are generally rather robust across a wide range of scenarios. MSY for the Reference Case is estimated at 279 thousand lb. Dynamic Production models produce similar estimates for MSY. Adoption of the Lytton somatic growth curve removes an earlier conflict between the CPUE and CAL data, and leads to a relatively precise estimate of *M* of 0.037 yr^{-1}. For most scenarios considered, the resource is above its MSY abundance level, and overfishing is not taking place. Projections to 2020 indicate that for most scenarios, quotas could be increased from the current 235 thousand lb by up to 100 thousand lb at least, without the resource falling below its MSY abundance. The primary exception to these results is if a Ricker stock-recruitment function is assumed, which leads to a higher estimate of the abundance corresponding to MSY.

Introduction

This document carries out an assessment of the US South Atlantic wreckfish resource as originally proposed in Butterworth (2013), and then further elaborated as to the specifics desired by a workshop involving, in particular, some members of the SSC which took place in North Charleston in mid-November, 2013 (SAFMC, 2013).

The assessment models runs focus primarily on Statistical-Catch-at-Age (SCAA), though alternatives in the form of dynamic production models and the DCAC method previously applied (Anon., 2011a) are also considered. First the methods are detailed and the results obtained listed and discussed. Then ten year projections under different constant catch levels are reported as a basis from which advice may be developed.

Data and Methodology

The data and methods used are as described in Appendices A, B and C, except in a few cases where brief description in the main text suffices.

For the SCAA assessments, the Reference Case (RC) as agreed at the November 2013 workshop (SAFMC, 2013) incorporates the following key specifications:

1) Estimate natural mortality *M*;

2) Fix stock-recruitment steepness *h* = 0.75;

3) Use the existing CPUE series;

4) Use the Lytton growth curve (the freely estimated version);

5) The standard deviation of length at age is set constant;

6) A logistic curve fitted to available maturity-at-length information is input; and

7) Asymptotically flat selectivity at length at large lengths.

Sensitivities based on the RC are as follows, with further technical details provided in Appendix B where necessary:

S1) Alternative *h* values: S1a: *h*=0.6, S1b: *h*=0.9, S1c: beta distribution prior on *h* (mode of 0.84 with α=5.94, β=1.97.from a beta distribution fitted by maximum truncated likelihood in Shertzer and Conn, 2012)

S2) Alternative fixed *M* values: S2a: *M*=0.025, S2b: *M*=0.055, S2c: *M*=0.065.

S3) Increasing *M* at larger ages (linear from age 20 at the rates indicated) for:

a) *M* for ages 0 to 19 fixed to that estimated in the RC: S3a: 0.0025yr^{-1}, S3b: 0.005yr^{-1}and S3c: 0.075yr^{-1}; and

b) *M* for ages 0 to 19 estimated: S3d: 0.0025 yr^{-1}.

S4) CPUE:

a) S4a): Use the Vaughan *et al.* (2001) numbers per day series for the initial 1991-1998 period, renormalizing this for the same average as the series used for the RC over that period (see Table A2), and appending the RC series thereafter;

b) S4b): 1% p.a. increase in catchability.

S5) Catch: Vaughan trend variant over 2001-2008 (See Table A1).

S6) Selectivity-at-length:

a) S6a): Include dome (equation B28): *M* estimated: S6a1: dome slope=0.05, *M* fixed: S6a2: dome slope=0.05, S6a3: dome slope=0.10.

b) S6b): logistic selectivity (equation B29).

S7) Maturity: no sensitivity suggested for this.

S8) Down-weight CAL in –lnL (equation B22): S8a: W_{CAL}=0.6, S8b: W_{CAL}=0.3, S8c: W_{CAL}=0.1.

S9) Change –lnL form for CAL data changed to SQRT(proportion) as a multinomial surrogate (equation B25).

S10) Alternatives to Lytton growth curve (t_0=-1, L_{inf}=Base).

S11) SSB = B^{sp} = 0.8*K* at the start of the fishery (equation B12).

S12) Ricker S/R curve (equation B4b): S12a: *M* estimated, S12b: *M* fixed to that estimated for the RC.

S13) Alternatives to standard deviation constant for length-at-age distribution: $\theta_a = \beta^* L(a)$ (equation B10).

S14) Alternative stock structure:

a) S14a): *h*=1, corresponding to an external source for the bulk of the recruits;
b) S14b): Recruitment depends on time (linear decrease) rather than on SSB to mimic the effect of other fisheries on an ocean-wide stock as a whole (previous attempts to estimate catch series for the whole North Atlantic have not been successful).

The production models applied are detailed in Appendix C. A comparative application of the DCAC method used in Anon. (2011a) is also reported; the methodology for that is set out in Anon. (2011a).

Results and Discussion

SCAA assessments

The results of applications of the SCAA model for the RC are given in Table 1 with associated trajectories estimates and fits to the CPUE and CAL data shown in Fig. 1. The fits are generally good (without evidence of the data conflict shown in earlier analyses based on a growth curve from a different wreckfish stock – Butterworth and Rademeyer (2012), though the bubble plot for the CAL data does evidence some systematic patterns which could reflect changes in selectivity over time.

Details of the assumptions made for priors for extending these estimates to give the posterior distribution results shown in Table 1 are provided in Appendix B. Generally posterior median estimates for biomass related quantities are larger than their joint posterior mode counterparts (the MLEs): for example the MSY MLE of 279 thousand lb increases to 315 with a 90% PI of [236, 849]. The procedure is able to estimate natural mortality with reasonable precision, yielding an estimate of *M* = 0.037 with a Hessian based CV of 0.11 and a posterior 90% PI of [0.030, 0.058].

Changing the value of steepness *h* from the RC level of 0.75 (to 0.6 for sensitivity S1a or to 0.9 for S1b) makes little difference to the biomass trajectories estimated (Fig. 2) though the value of MSY is sensitive to these changes (see Table 2). The value of –lnL hardly changes across this range of values for *h*, indicating that there is insufficient information content in these data to estimate *h* unless a prior is also provided. This is done for sensitivity S1c, where a beta distribution prior is treated as a penalty function, with a resultant estimate for *h* of 0.758 which reflects some downward adjustment of the prior median of 0.84. The distribution of the estimate of *h* (even given this prior) is wide with a CV of 0.24.

Fixing instead of estimating natural mortality *M* (S2a to S2c) also makes relatively little difference to biomass trajectories except for the highest value of 0.065 considered, which leads to much higher estimates of biomass and of MSY, but to a clear statistical lack of fit to the CPUE data (Fig. 3). Essentially as *M* is increased above the RC estimate, the fit to the CAL data improves, but that to the CPUE data deteriorates (Table 2). Allowing for *M* to increase at large ages sees a compensating decrease in the value of *M* estimated to unrealistically low levels (S3d), whereas when *M* is fixed at its RC value, biomasses and MSY estimates increase as the value of M at higher ages is raised. However that leads to a worse overall fit, with improvements to fitting the CAL data unable to compensate for increasingly worse fits to the CPUE data (S3a, S3b and S3c in Table 2 and Fig. 4).

The mid-November workshop (SAFMC, 2013) discussed possibilities for alterative CPUE series in some detail, but eventually settled on only a few to consider in sensitivity tests. Results for those alternative CPUE series are listed in Table 3. Use of the Vaughan *et al.* (2001) series for 1991-98 (S4a) leads to a slight increase in the estimate of MSY, whereas (as might be expected) the estimated MSY falls more substantially when an increase in catchability is considered (S4b).The estimated biomass trajectories are scarcely affected by these changes (Fig. 5). Changes to the results when the alternative catch series for 2001-2008 is used (S5) are scarcely discernible (Table 3 and Fig. 6).

Allowing for the possibility of a dome in selectivity increases estimated abundance in absolute terms (S6a1 to S6a3) and can provide improvements in fits to the CAL data, though MSY estimates are mainly not too heavily impacted (Table 3 and Fig. 7). However, for the steepest doming assumed (S6a3: d =0.1) though abundance and MSY increase appreciably, the fit to the CPUE data shows a markeddeterioration. Assuming selectivity to have a logistic form (S6b) makes little difference to results (Table 3 and Fig. 8).

When the weighting given to the CAL data in –lnL is decreased (S8a, 8b and 8c in Table 3; Fig. 9), estimates of MSY and abundance drop, but only slightly. As might be expected, CVs of estimates increase as this weighting is decreased, though this effect is less marked for biomass-related quantities which are determined primarily by the combination of the CPUE and catch data. The impact of changing the form of the –lnL contribution by the CAL data from an "adjusted log-normal" to multinomial surrogate form is minimal (S9 in Table 4 and Fig. 10).

With the alternative somatic growth curve which reflects lower lengths at smaller ages (S10), the fit to the CAL data deteriorates appreciably (about 6 –lnL points); MSY is slightly higher but abundance estimates are lower (Table 4 and Fig. 11). For a starting spawning biomass of 0.8K, the fit deteriorates slightly, the MSY estimate is unchanged, and estimates of abundance increase slightly (Table 4 and Fig. 12).

Two results are shown for substituting the Beverton-Holt stock-recruitment functional form by a Ricker form: S12a re-estimates M (which increases), while for S12b M is kept fixed at the same value as estimated for the RC. Abundance estimates are hardly affected (Table 4 and Fig. 13). However, the estimated MSY drops appreciably, more so when M is re-estimated, although the precision of the estimate drops sharply with the CV increasing from 14% to about 30%. The spawning biomass at which MSY is achieved increases from about 1800 to 3100 tons.

For the distributions of CAL for each age having standard deviations proportional to mean length rather than constant (S13), the value of –lnL is unchanged, though biomass estimates increase slightly (Table 4 and Fig. 14).

For the two alternative stock-structure models for which the stock is assumed to be more widespread than the fishery considered here (S14a and S14b), abundance estimates are scarcely affected (Table 4 and Fig. 15).

A retrospective analysis for the RC shows no indications of any marked retrospective pattern (Fig. 16).

Dynamic production models and DCAC

Results for the Schaefer and Pella-Tomlinson dynamic production models are compared to those for the RC in Table 5 and Fig. 17. The abundance trajectories hardly differ, either within the range of the Pella-Tomlinson shape parameter μ considered, or when compared to the RC. What does change for different values of μ is the biomass at which MSY is achieved. The estimates for MSY itself are quite similar to that for the SCAA RC.

Anon. (2011a) provided estimates of sustainable yield for this wreckfish resource using the DCAC (Depletion-Corrected Average Catch Formula). That paper provides full details of the DCAC methodology. The deterministic equivalent of run 1 in Table 2 of that paper gives a sustainable yield estimate of 375 thousand lb. Using the natural mortality estimated in the RC (0.0366 instead of 0.05 in Run 1) results in a sustainable yield estimate of 325 thousand lb, i.e. the lower M suggests a less productive stock and reduces the sustainable yield estimate to a level more compatible with the MSY estimate for the SCAA RC.

Projections

Fig. 18 shows projections of the RC for 10 years under five different future catch scenarios: three years at the current quota of 235 thousand lb, followed by seven years at the same or a different higher constant catch level. The central constant catch value, 285 thousand lb, is close to the estimate of MSY for the SCAA RC. Figs 19a and b extend these RC results to a Bayesian framework. Table 6 lists these results, and extends them to include the SCAA sensitivities and the dynamic production models, while Fig. 20 shows those results graphically.

Most projection scenarios reflect an increase in abundance from 2010 to 2020. The few which reflect a drop of more than 10% for the highest catch level considered are the RC (at the lower 5%-ile), S2a (M=0.025), S4b (1% increase p.a. in catchability), S12a and b (Ricker stock-recruitment curves), and S14b (a linear decrease in recruitment in an ocean-wide stock). Declines are, however, not necessarily a concern in cases where the resource is indicated to be well above the biomass corresponding to MSY (B_{MSY}). In that context only the Ricker scenarios, and the Schaefer and some Pella-Tomlinson dynamic production models reflect biomasses in 2020 that are below B_{MSY} , but that is more a reflection of the higher values for B_{MSY}/K in those cases.

Conclusions

The SCAA assessment results are generally rather robust across a wide range of scenarios. MSY for the Reference Case is estimated at 279 thousand lb with a CV of 14%. Dynamic Production models produce similar estimates for MSY, which is determined essentially by the past catch data and CPUE trends.

Adoption of the Lytton somatic growth curve removes an earlier conflict between the CPUE and CAL data, and leads to a relatively precise estimate of M of 0.037 yr^{-1} with a CV of 11%. For most scenarios considered, the resource is above its MSY abundance level, and overfishing is not taking place. The primary exception to this is if a Ricker stock-recruitment function is assumed, which leads to a higher estimate of the abundance corresponding to MSY.

Projections to 2020 indicate that for most of the scenarios considered, quotas could be increased from the current 235 thousand lb by up to 100 thousand lb at least, without the resource falling below its MSY abundance. Again the primary exception to this is if a Ricker stock-recruitment function applies.

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Table 1: Results for the RC. Values fixed on **input are bolded**.

	MLE	Hessian CVs	Posterior Median	Posterior 5%-ile	Posterior 95%-ile
'-lnL:overall	-68.2				
'-lnL:CPUE	-31.2				
'-lnL:CAL	-37.0				
'-lnL:RecRes	-				
-lnL:h	-				
θ	**1**	**-**	**1**	1	1
ϕ	**0**	**-**	**0**	0	0
h	**0.75**	**-**	**0.75**	0.75	0.75
M	0.03664	(0.11)	0.039	0.030	0.058
K^{sp} (tons)	7105	(0.08)	7816	6587	14981
B^{sp}_{2010} (tons)	2864	(0.22)	3607	2331	11610
B^{sp}_{2010}/K^{sp}	0.40	(0.15)	0.46	0.34	0.78
$MSYL^{sp}$	0.25	(0.11)	0.25	0.25	0.26
B^{sp}_{MSY} (tons)	1809	(0.14)	1997	1672	3771
$B^{sp}_{2010}/B^{sp}_{MSY}$	1.58	(0.12)	1.82	1.35	3.09
$B^{sp}_{2010}/0.75B^{sp}_{MSY}$	2.11	(0.12)	2.42	1.80	4.12
MSY ('000 lb)	279	(0.14)	315	236	849
F_{MSY}	0.065	-	0.068	0.051	0.104
F_{2010}	0.038	(0.22)	0.030	0.009	0.047
F_{2010}/F_{MSY}	0.583	(0.22)	0.449	0.098	0.800
σ_{com}	0.13	(0.05)	0.14	0.13	0.18
σ_{len}	0.09	(0.01)	0.09	0.08	0.09

Table 2: Results for the RC and sensitivities. Values fixed on **input are bolded**. Values in parenthesis are Hessian-based CVs.

Run	RC	S1a	S1b	S1c	S2a	S2b	S2c	S3a	S3b	S3c	S3d
		h =0.6	*h* =0.9	*h* estimated (beta prior)	*M* =0.025	*M* =0.055	*M* =0.065	*M* incr. 0.0025 yr^{-1} from age 20, *M* fixed to RC level	*M* incr. 0.005 yr^{-1} from age 20, *M* fixed to RC level	M incr. 0.0075 yr^{-1} from age 20, *M* fixed to RC level	*M* incr. 0.0025 yr^{-1} from age 20, *M* estimated
'-lnL:overall	-68.2	-68.5	-67.8	-69.1	-64.6	-65.4	-64.3	-66.2	-65.4	-65.3	-69.2
'-lnL:CPUE	-31.2	-31.0	-31.3	-31.2	-30.4	-25.7	-23.5	-26.2	-23.9	-22.9	-31.5
'-lnL:CAL	-37.0	-37.5	-36.5	-37.0	-34.1	-39.7	-40.9	-40.0	-41.6	-42.3	-37.6
'-lnL:RecRes	-	-	-	-	-	-	-	-	-	-	-
-lnL:h	-	-	-	-0.9	-	-	-	-	-	-	-
θ	**1** -	**1** -	**1** -	**1**	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -
ϕ	**0** -	**0** -	**0** -	**0**	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -
h	**0.75** -	**0.60** -	**0.90** -	0.758 (0.24)	**0.75** -	**0.75** -	**0.75** -	**0.75** -	**0.75** -	**0.75** -	**0.75** -
M	0.037 (0.11)	0.039 (0.15)	0.035 (0.16)	0.037 (0.12)	**0.025** -	**0.055** -	**0.065** -	**0.037** -	**0.037** -	**0.037** -	0.014 (0.50)
K^{sp} (tons)	7105 (0.08)	7115 (0.10)	7188 (0.10)	7106 (0.08)	7693 (0.07)	9200 (0.22)	15437 (0.50)	8391 (0.24)	11934 (0.48)	18696 (0.74)	7177 (0.10)
B^{sp}_{2010} (tons)	2864 (0.22)	2830 (0.24)	2961 (0.23)	2867 (0.22)	2713 (0.21)	5911 (0.34)	12577 (0.61)	5098 (0.40)	9175 (0.62)	16284 (0.85)	2876 (0.22)
B^{sp}_{2010}/K^{sp}	0.40 (0.15)	0.40 (0.15)	0.41 (0.15)	0.40 (0.15)	0.35 (0.13)	0.64 (0.12)	0.81 (0.11)	0.61 (0.16)	0.77 (0.15)	0.87 (0.10)	0.40 (0.14)
$MSYL^{sp}$	0.25 (0.11)	0.31 (0.17)	0.19 (0.20)	0.25 (0.22)	0.26 (0.03)	0.25 (0.02)	0.25 (0.02)	0.28 (0.04)	0.29 (0.04)	0.30 (0.02)	0.29 (0.16)
B^{sp}_{MSY} (tons)	1809 (0.14)	2213 (0.15)	1354 (0.18)	1786 (0.24)	1972 (0.06)	2312 (0.21)	3841 (0.49)	2341 (0.21)	3462 (0.44)	5530 (0.73)	2068 (0.13)
$B^{sp}_{2010}/B^{sp}_{MSY}$	1.58 (0.12)	1.28 (0.20)	2.19 (0.19)	1.61 (0.21)	1.38 (0.15)	2.56 (0.13)	3.27 (0.13)	2.18 (0.19)	2.65 (0.18)	2.94 (0.12)	1.39 (0.18)
$B^{sp}_{2010}/0.75B^{sp}_{MSY}$	2.11 (0.12)	1.71 (0.20)	2.92 (0.19)	2.14 (0.21)	1.83 (0.15)	3.41 (0.13)	4.37 (0.13)	2.90 (0.19)	3.53 (0.18)	3.93 (0.12)	1.85 (0.18)
MSY ('000 lb)	279 (0.14)	233 (0.14)	328 (0.16)	282 (0.24)	205 (0.06)	543 (0.20)	1076 (0.49)	493 (0.22)	824 (0.46)	1418 (0.73)	291 (0.12)
F_{MSY}	0.065 -	0.045 -	0.102 -	0.067 -	0.043 -	0.102 -	0.122 -	0.090 -	0.102 -	0.109 -	0.059 -
F_{2010}	0.038 (0.22)	0.039 (0.24)	0.037 (0.23)	0.038 (0.22)	0.040 (0.21)	0.019 (0.33)	0.009 (0.61)	0.021 (0.40)	0.012 (0.63)	0.007 (0.84)	0.037 (0.22)
F_{2010}/F_{MSY}	0.583 (0.22)	0.864 (0.24)	0.359 (0.23)	0.569 (0.22)	0.924 (0.21)	0.183 (0.33)	0.072 (0.61)	0.237 (0.40)	0.117 (0.63)	0.061 (0.84)	0.635 (0.22)
σ_{com}	0.13 (0.05)	0.13 (0.04)	0.13 (0.06)	0.13 (0.05)	0.13 (0.01)	0.17 (0.05)	0.19 (0.04)	0.16 (0.06)	0.18 (0.04)	0.19 (0.03)	0.13 (0.04)
σ_{len}	0.09 (0.01)	0.09 (0.01)	0.09 (0.02)	0.09 (0.02)	0.09 (0.00)	0.08 (0.01)	0.08 (0.01)	0.08 (0.02)	0.08 (0.01)	0.08 (0.01)	0.09 (0.01)

Table 3: Results for the RC and sensitivities. Values fixed on **input are bolded**. Values in parenthesis are Hessian-based CVs.

Run	RC	S4a	S4b	S5	S6a1	S6a2	S6a3	S6b	S8a	S8b	S8c
		Other 1991-1998 series	1% p.a. increase in catchability	Other 2001-2008 catch series	Selectivity domed 0.05, *M* estimated	Selectivity domed 0.05, *M* fixed	Selectivity domed 0.1, *M* fixed	Logistic selectivity	W_{CAL}=0.6	W_{CAL}=0.3	W_{CAL}=0.1
'-lnL:overall	-68.2	-62.3	-66.9	-68.3	-72.5	-71.9	-71.6	-68.6	-53.5	-42.5	-35.3
'-lnL:CPUE	-31.2	-24.7	-31.5	-31.4	-31.2	-30.4	-27.4	-31.1	-31.5	-31.6	-31.7
'-lnL:CAL	-37.0	-37.6	-35.4	-37.0	-41.3	-41.6	-44.3	-37.5	-22.0	-10.9	-3.6
'-lnL:RecRes	-	-	-	-	-	-	-	-	-	-	-
-lnL:h	-	-	-	-	0	0	0	0	-	-	-
γ	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -
θ	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -	**1** -
ϕ	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -
h	**0.75** -	**0.75** -	**0.75** -	**0.75** -	**0.75** -	**0.75** -	**0.75** -	**0.75** -	**0.75** -	**0.75** -	**0.75** -
M	0.037 (0.11)	0.039 (0.15)	0.029 (0.10)	0.037 (0.11)	0.032 (0.11)	**0.037** -	**0.037** -	0.040 (0.14)	0.036 (0.11)	0.035 (0.13)	0.035 (0.17)
K^{sp} (tons)	7105 (0.08)	7409 (0.13)	6888 (0.05)	7092 (0.08)	7398 (0.08)	7528 (0.11)	9761 (0.27)	6755 (0.09)	6951 (0.08)	6841 (0.08)	6736 (0.12)
B^{sp}_{2010} (tons)	2864 (0.22)	3276 (0.36)	2201 (0.18)	2849 (0.22)	2881 (0.22)	3271 (0.25)	5472 (0.48)	2721 (0.22)	2657 (0.20)	2520 (0.21)	2418 (0.22)
B^{sp}_{2010}/K^{sp}	0.40 (0.15)	0.44 (0.24)	0.32 (0.14)	0.40 (0.15)	0.39 (0.15)	0.43 (0.14)	0.56 (0.21)	0.40 (0.15)	0.38 (0.14)	0.37 (0.14)	0.36 (0.14)
$MSYL^{sp}$	0.25 (0.11)	0.25 (0.15)	0.26 (0.10)	0.25 (0.11)	0.25 (0.11)	0.25 (0.01)	0.24 (0.01)	0.25 (0.17)	0.25 (0.11)	0.25 (0.13)	0.25 (0.21)
B^{sp}_{MSY} (tons)	1809 (0.14)	1886 (0.24)	1757 (0.11)	1806 (0.14)	1851 (0.13)	1876 (0.10)	2381 (0.27)	1717 (0.16)	1770 (0.12)	1741 (0.12)	1714 (0.15)
$B^{sp}_{2010}/B^{sp}_{MSY}$	1.58 (0.12)	1.74 (0.15)	1.25 (0.12)	1.58 (0.12)	1.56 (0.14)	1.74 (0.15)	2.30 (0.22)	1.58 (0.17)	1.50 (0.14)	1.45 (0.16)	1.41 (0.24)
$B^{sp}_{2010}/0.75B^{sp}_{MSY}$	2.11 (0.12)	2.32 (0.15)	1.67 (0.12)	2.10 (0.12)	2.08 (0.14)	2.32 (0.15)	3.06 (0.22)	2.11 (0.17)	2.00 (0.14)	1.93 (0.16)	1.88 (0.24)
MSY ('000 lb)	279 (0.14)	305 (0.24)	218 (0.10)	279 (0.14)	257 (0.14)	297 (0.10)	382 (0.26)	293 (0.15)	267 (0.12)	260 (0.12)	257 (0.13)
F_{MSY}	0.065 -	0.068 -	0.052 -	0.065 -	0.055 -	0.063 -	0.061 -	0.074 -	0.064 -	0.063 -	0.063 -
F_{2010}	0.038 (0.22)	0.033 (0.36)	0.049 (0.18)	0.038 (0.22)	0.036 (0.22)	0.032 (0.24)	0.019 (0.46)	0.041 (0.23)	0.041 (0.20)	0.043 (0.20)	0.045 (0.23)
F_{2010}/F_{MSY}	0.583 (0.22)	0.486 (0.36)	0.948 (0.18)	0.586 (0.22)	0.654 (0.22)	0.507 (0.24)	0.312 (0.46)	0.550 (0.23)	0.643 (0.20)	0.686 (0.20)	0.711 (0.23)
σ_{com}	0.13 (0.05)	0.18 (0.07)	0.13 (0.04)	0.13 (0.05)	0.13 (0.04)	0.13 (0.06)	0.15 (0.11)	0.13 (0.06)	0.13 (0.03)	0.12 (0.01)	0.12 (0.01)
σ_{len}	0.09 (0.01)	0.09 (0.02)	0.09 (0.01)	0.09 (0.01)	0.08 (0.01)	0.08 (0.02)	0.08 (0.03)	0.09 (0.02)	0.09 (0.01)	0.09 (0.01)	0.09 (0.02)

Table 4: Results for the RC and sensitivities. Values fixed on **input are bolded**. Values in parenthesis are Hessian-based CVs.

Run	RC	S9	S10	S11	S12a	S12b	S13	S14a	S14b
		sqrt(p)	Alt. growth curve	SSB_{1987}=0.8K	Ricker	Ricker, *M* fixed to RC level	std(LAA)= β*LAA	*h* =1	Linear decrease for recruitment
'-lnL:overall	-68.2	-113.5	-62.0	-66.1	-68.3	-68.1	-68.2	-67.5	-68.3
'-lnL:CPUE	-31.2	-31.1	-30.2	-31.3	-30.5	-31.0	-31.1	-31.3	-30.9
'-lnL:CAL	-37.0	-82.4	-31.7	-34.7	-37.7	-37.1	-37.1	-36.3	-37.5
'-lnL:RecRes	-	-	-	-	-	-	-	-	-
-lnL:*h*	-	-	-	-	-	-	-	-	-
θ	**1** -	**1** -	**1** -	**0.8** -	**1** -	**1** -	**1** -	**1** -	**1** -
ϕ	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -	**0** -
h	**0.75** -	**0.75** -	**0.75** -	**0.75** -	0.446 (0.30)	0.509 (0.21)	**0.75** -	**1** -	-
M	0.037 (0.11)	0.037 (0.15)	0.043 (0.14)	0.029 (0.10)	0.041 (0.22)	**0.037** -	0.035 (0.11)	0.033 (0.16)	0.039 (0.14)
K^{sp} (tons)	7105 (0.08)	7278 (0.10)	6618 (0.07)	8989 (0.07)	7167 (0.11)	7194 (0.10)	7459 (0.08)	7284 (0.10)	7154 (0.08)
B^{sp}_{2010} (tons)	2864 (0.22)	2995 (0.23)	2523 (0.23)	2858 (0.21)	2868 (0.25)	2808 (0.24)	3110 (0.23)	3047 (0.23)	2853 (0.23)
B^{sp}_{2010}/K^{sp}	0.40 (0.15)	0.41 (0.15)	0.38 (0.17)	0.32 (0.15)	0.40 (0.16)	0.39 (0.15)	0.42 (0.15)	0.42 (0.15)	0.40 (0.15)
$MSYL^{sp}$	0.25 (0.11)	0.25 (0.19)	0.26 (0.14)	0.26 (0.10)	0.44 (0.36)	0.43 (0.31)	0.26 (0.11)	-	-
B^{sp}_{MSY} (tons)	1809 (0.14)	1854 (0.17)	1701 (0.15)	2292 (0.12)	3178 (0.33)	3121 (0.27)	1933 (0.15)	-	-
$B^{sp}_{2010}/B^{sp}_{MSY}$	1.58 (0.12)	1.62 (0.20)	1.48 (0.14)	1.25 (0.12)	0.90 (0.39)	0.90 (0.34)	1.61 (0.12)	-	-
$B^{sp}_{2010}/0.75B^{sp}_{MSY}$	2.11 (0.12)	2.15 (0.20)	1.98 (0.14)	1.66 (0.12)	1.20 (0.39)	1.20 (0.34)	2.15 (0.12)	-	
MSY ('000 lb and tons)	279 (0.14)	284 (0.15)	299 (0.15)	279 (0.12)	201 (0.33)	218 (0.27)	277 (0.15)	-	-
F_{MSY}	0.065 -	0.067 -	0.074 -	0.051 -	0.027 -	0.030 -	0.062 -	-	-
F_{2010}	0.038 (0.22)	0.037 (0.24)	0.043 (0.23)	0.038 (0.21)	0.038 (0.26)	0.039 (0.24)	0.036 (0.23)	0.036 (0.23)	0.038 (0.23)
F_{2010}/F_{MSY}	0.583 (0.22)	0.558 (0.24)	0.583 (0.23)	0.741 (0.21)	1.427 (0.26)	1.315 (0.24)	0.575 (0.23)	-	-
σ_{com}	0.13 (0.05)	0.13 (0.05)	0.13 (0.08)	0.13 (0.05)	0.13 (0.06)	0.13 (0.04)	0.13 (0.05)	0.13 (0.06)	0.13 (0.05)
σ_{len}	0.09 (0.01)	0.04 (0.02)	0.09 (0.02)	0.09 (0.01)	0.09 (0.02)	0.09 (0.01)	0.09 (0.02)	0.09 (0.02)	0.09 (0.02)

Table 5: Results for the RC and the Schaefer and Pella-Tomlinson production models. Values in parenthesis are Hessian-based CVs.

Run	RC		Schaefer		Pella-Tomlinson					
μ			1		-0.5		0.5		1.5	
'-lnL:overall	-68.2		-32.2		-32.0		-32.1		-32.2	
'-lnL:CPUE	-31.2		-32.2		-32.0		-32.1		-32.2	
'-lnL:CAL	-37.0		-		-		-		-	
'-lnL:RecRes	-		-		-		-		-	
-lnL:h	-		-		-		-		-	
M	0.037	(0.11)	-		-		-		-	
r	-		0.072	(0.22)	0.033	(0.17)	0.057	(0.20)	0.090	(0.23)
K^{sp} (tons)	7105	(0.08)	7382	(0.09)	7678	(0.09)	7478	(0.09)	7294	(0.09)
B^{sp}_{2010} (tons)	2864	(0.22)	2901	(0.19)	3011	(0.19)	2936	(0.19)	2869	(0.19)
B^{sp}_{2010}/K^{sp}	0.40	(0.15)	0.39	(0.12)	0.39	(0.12)	0.39	(0.12)	0.39	(0.12)
$MSYL^{sp}$	0.25	(0.11)	0.50	-	0.25	-	0.44	-	0.54	-
B^{sp}_{MSY} (tons)	1809	(0.14)	3691	(0.09)	1919	(0.09)	3323	(0.09)	3960	(0.09)
$B^{sp}_{2010}/B^{sp}_{MSY}$	1.58	(0.12)	0.79	(0.12)	1.57	(0.12)	0.88	(0.12)	0.72	(0.12)
$B^{sp}_{2010}/0.75B^{sp}_{MSY}$	2.11	(0.12)	1.05	(0.12)	2.09	(0.12)	1.18	(0.12)	0.97	(0.12)
MSY ('000 lb)	279	(0.14)	294	(0.14)	276	(0.13)	277	(0.13)	314	(0.15)
σ_{com}	0.13	(0.05)	0.12	(0.00)	0.12	(0.00)	0.12	(0.00)	0.12	(0.00)

Table 6: Projections results for the RC and the sensitivities under various future constant catches. Biomass ratios below 1, and fishing mortality ratios above 1, are shown shaded. Similar results are also shown for the dynamic production models, for which *F* refers to the *C/B* ratio.

		$B^{sp}_{2020}/B^{sp}_{2010}$					$B^{sp}_{2020}/B^{sp}_{MSY}$					F_{2020}/F_{MSY}				
		Future constant catch from 2014 ('000 lb):					Future constant catch from 2014 ('000 lb):					Future constant catch from 2014 ('000 lb):				
Run		235	260	285	310	335	235	260	285	310	335	235	260	285	310	335
RC	MLE	1.026	1.007	0.987	0.967	0.948	1.624	1.593	1.562	1.531	1.500	0.518	0.585	0.655	0.729	0.805
	Posterior median	1.030	1.018	1.004	0.989	0.973	1.886	1.858	1.829	1.800	1.770	0.396	0.445	0.496	0.548	0.603
	5%-ile	0.983	0.961	0.939	0.916	0.893	1.342	1.311	1.277	1.245	1.212	0.087	0.097	0.106	0.116	0.126
	95%-ile	1.060	1.046	1.035	1.024	1.015	3.175	3.160	3.146	3.133	3.119	0.736	0.836	0.942	1.055	1.174
S1a	h=0.6	0.985	0.966	0.946	0.926	0.906	1.260	1.235	1.210	1.184	1.159	0.800	0.905	1.014	1.129	1.249
S1b	h=0.9	1.054	1.035	1.016	0.997	0.978	2.306	2.264	2.222	2.180	2.138	0.311	0.351	0.392	0.435	0.481
S1c	h est. (beta prior)	1.028	1.009	0.989	0.969	0.950	1.650	1.619	1.587	1.556	1.524	0.505	0.571	0.639	0.710	0.785
S2a	M=0.025	0.942	0.920	0.898	0.876	0.854	1.296	1.266	1.235	1.205	1.175	0.894	1.014	1.141	1.275	1.417
S2b	M=0.055	1.055	1.046	1.037	1.028	1.019	2.698	2.675	2.652	2.629	2.606	0.158	0.177	0.195	0.214	0.234
S2c	M=0.065	1.031	1.027	1.023	1.019	1.014	3.376	3.362	3.349	3.335	3.322	0.063	0.071	0.078	0.085	0.092
S3a	M fixed, incr. 0.0025 yr^{-1}	1.084	1.073	1.062	1.052	1.041	2.360	2.337	2.314	2.290	2.267	0.200	0.224	0.248	0.273	0.298
S3b	M fixed, incr. 0.005 yr^{-1}	1.061	1.055	1.049	1.043	1.038	2.811	2.796	2.781	2.765	2.750	0.100	0.112	0.123	0.135	0.147
S3c	M *fixed*, incr. 0.0075 yr^{-1}	1.036	1.033	1.029	1.026	1.023	3.052	3.043	3.034	3.024	3.015	0.053	0.059	0.065	0.071	0.077
S3d	M est., incr. 0.0025 yr^{-1}	1.066	1.045	1.025	1.004	0.984	1.482	1.453	1.425	1.396	1.368	0.545	0.615	0.689	0.766	0.847
S4a	Other 1991-1998 series	1.036	1.019	1.002	0.985	0.968	1.800	1.770	1.740	1.711	1.681	0.428	0.482	0.538	0.596	0.656
S4b	1% p.a. incr. in q	0.961	0.934	0.908	0.882	0.855	1.203	1.170	1.137	1.104	1.071	0.900	1.026	1.160	1.303	1.456
S5	Other 01-08 catches	1.026	1.006	0.987	0.967	0.947	1.619	1.588	1.557	1.526	1.494	0.521	0.588	0.659	0.733	0.810
S6a1	Sel. domed 0.05, M est.	0.955	0.937	0.919	0.900	0.882	1.510	1.481	1.453	1.424	1.395	0.743	0.839	0.939	1.043	1.152
S6a2	Sel. domed 0.05, M fixed	1.029	1.012	0.995	0.978	0.961	1.795	1.765	1.735	1.705	1.675	0.450	0.507	0.566	0.627	0.691
S6a3	Sel. domed 0.10, M fixed	1.027	1.017	1.006	0.996	0.986	2.361	2.337	2.314	2.290	2.266	0.278	0.311	0.345	0.379	0.414
S6b	Logistic selectivity	1.042	1.022	1.002	0.982	0.962	1.652	1.620	1.588	1.556	1.524	0.481	0.544	0.609	0.678	0.750
S8a	W_{CAL}=0.6	1.019	0.998	0.977	0.956	0.935	1.531	1.499	1.467	1.435	1.403	0.575	0.651	0.730	0.814	0.901
S8b	W_{CAL}=0.3	1.015	0.992	0.970	0.948	0.925	1.468	1.436	1.403	1.371	1.339	0.616	0.698	0.785	0.876	0.971
S8c	W_{CAL}=0.1	1.013	0.990	0.967	0.944	0.920	1.430	1.397	1.364	1.331	1.299	0.640	0.726	0.817	0.913	1.014
S9	sqrt(p)	1.028	1.008	0.989	0.970	0.951	1.660	1.629	1.598	1.567	1.536	0.495	0.560	0.627	0.696	0.769
S10	Alt. growth curve	1.064	1.041	1.017	0.994	0.971	1.578	1.544	1.509	1.474	1.440	0.500	0.567	0.636	0.710	0.787
S11	SSB_{1987}=0.8K	1.050	1.030	1.009	0.989	0.969	1.309	1.284	1.258	1.233	1.208	0.644	0.728	0.815	0.907	1.002
S12a	Ricker	0.950	0.931	0.912	0.892	0.873	0.858	0.840	0.823	0.805	0.788	1.369	1.549	1.737	1.934	2.141
S12b	Ricker, M fixed	0.970	0.949	0.929	0.909	0.889	0.872	0.854	0.836	0.818	0.800	1.236	1.399	1.569	1.748	1.936
S13	std(LAA)=β^{*}LAA	1.019	1.000	0.982	0.963	0.944	1.639	1.609	1.579	1.549	1.519	0.514	0.581	0.650	0.722	0.797
S14a	h=1	1.066	1.048	1.029	0.991	0.991	-	-	-	-	-	-	-	-	-	-
S14b*	Linear decr. recr.	0.895	0.875	0.855	0.836	0.816	-	-	-	-	-	-	-	-	-	-
Schaefer		1.072	1.047	1.023	0.999	0.974	0.8421	0.8231	0.804	0.7849	0.7658	0.950	1.075	1.207	1.344	1.489
Pella-Tomlinson, μ=-0.5		1.030	1.008	0.987	0.965	0.943	1.6159	1.5816	1.5473	1.513	1.4786	0.527	0.596	0.667	0.742	0.821
Pella-Tomlinson, μ=0.5		1.058	1.034	1.011	0.987	0.964	0.9344	0.9137	0.8929	0.8721	0.8513	0.909	1.029	1.154	1.285	1.423
Pella-Tomlinson, μ=1.5		1.085	1.060	1.035	1.010	0.985	0.7858	0.7678	0.7497	0.7315	0.7133	0.951	1.077	1.209	1.348	1.494

* For the projections, recruitment is assumed to continue constant at its lower level at the end of the assessment period in 2011.

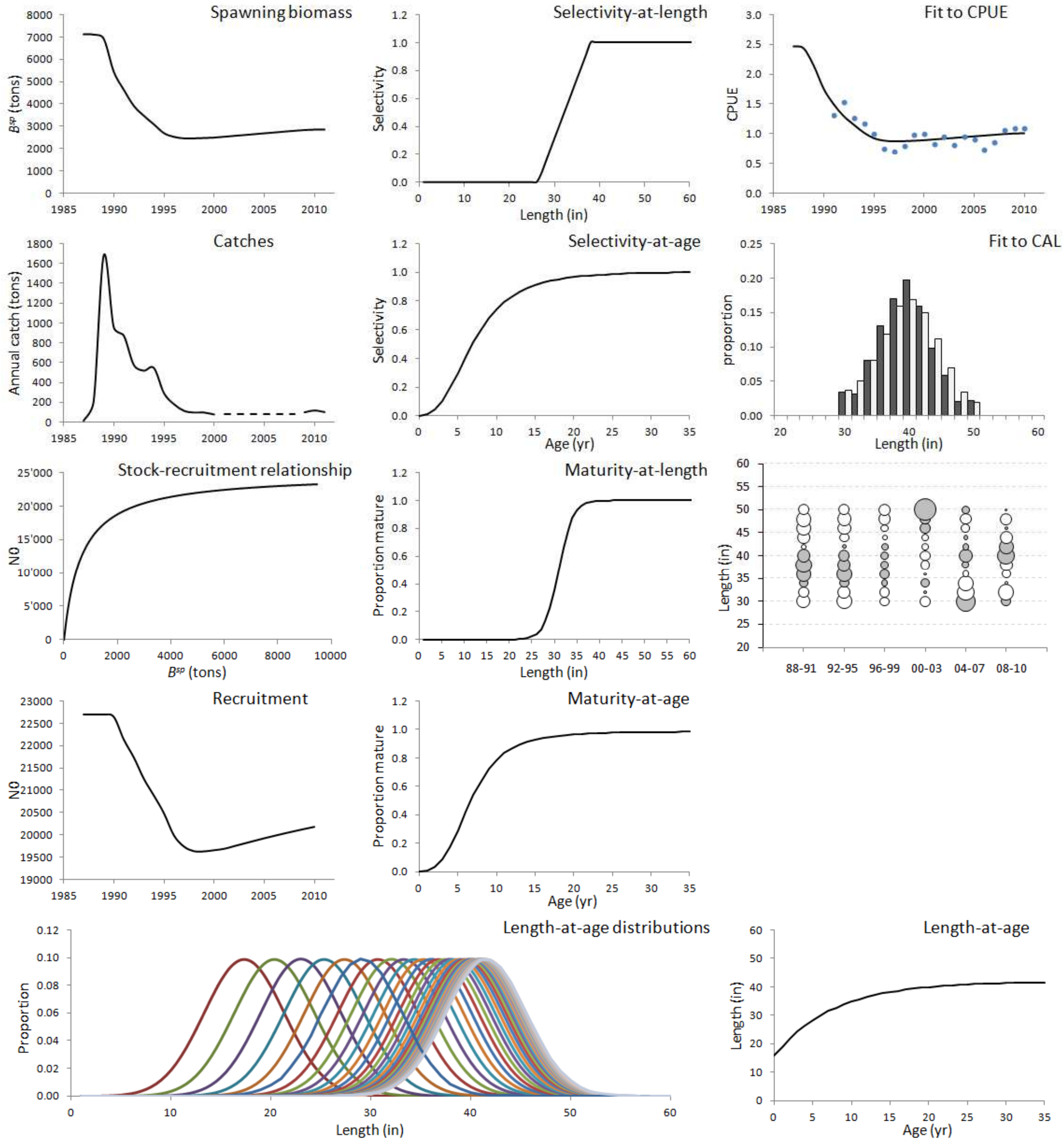

Figure 1: Results for the RC. The fit to the CAL data is shown aggregated over all the data available (second row, left column) and the corresponding standardised residuals are shown in the bubble plot (third row, left column). The area of the bubble is proportional to the magnitude of the corresponding standardised residuals. For positive residuals the bubbles are grey, whereas for negative residuals the bubbles are white.

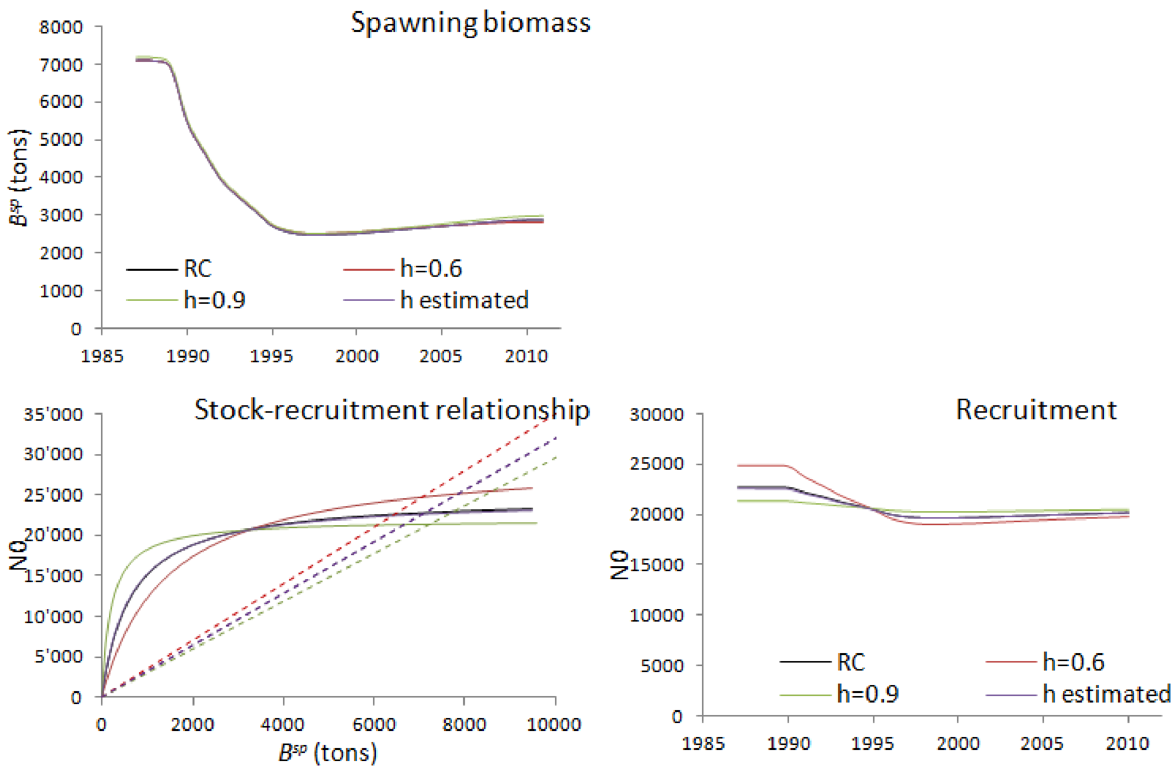

Figure 2: Trajectories of spawning biomass and recruitment, as well as the stock-recruitment relationship for the RC (*h*=0.75), two sensitivities with different fixed values for the steepness parameter (**S1a**: *h*=0.6 and **S1b**: *h*=0.9) and a sensitivity in which a prior for *h* is provided and *h* is estimated (**S1c**: *h*=0.758). The replacement lines are shown as dotted line in the plot of the stock-recruitment relationships.

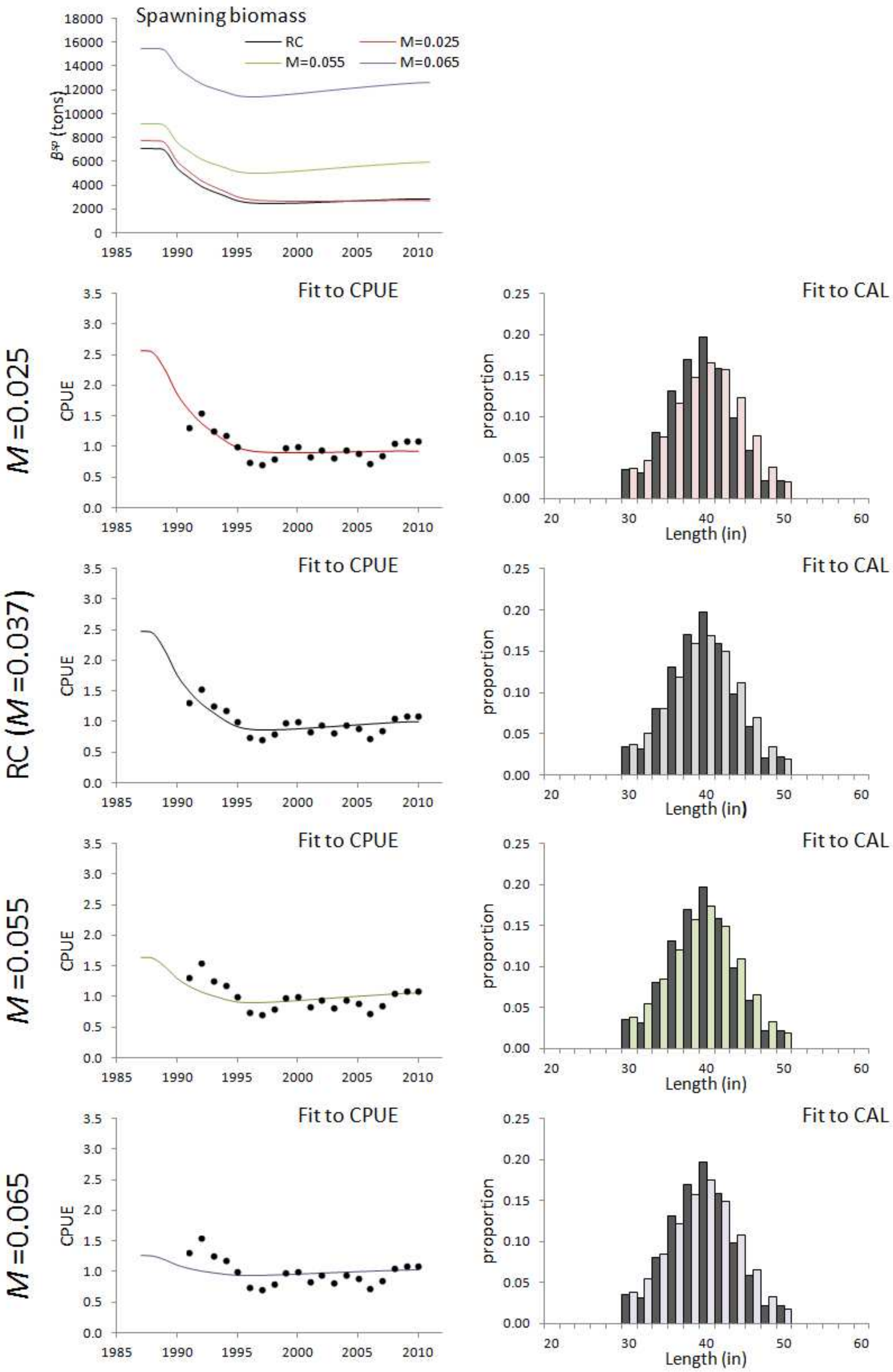

Figure 3: Spawning biomass trajectories showing fits to the CPUE data , together with fits to the CAL data (averaged over all the years for which data are available) for the RC and three sensitivities with different fixed values of natural mortality (**S2a**: *M*=0.025; **S2b**: *M*=0.055 and **S2c**: *M*=0.065).

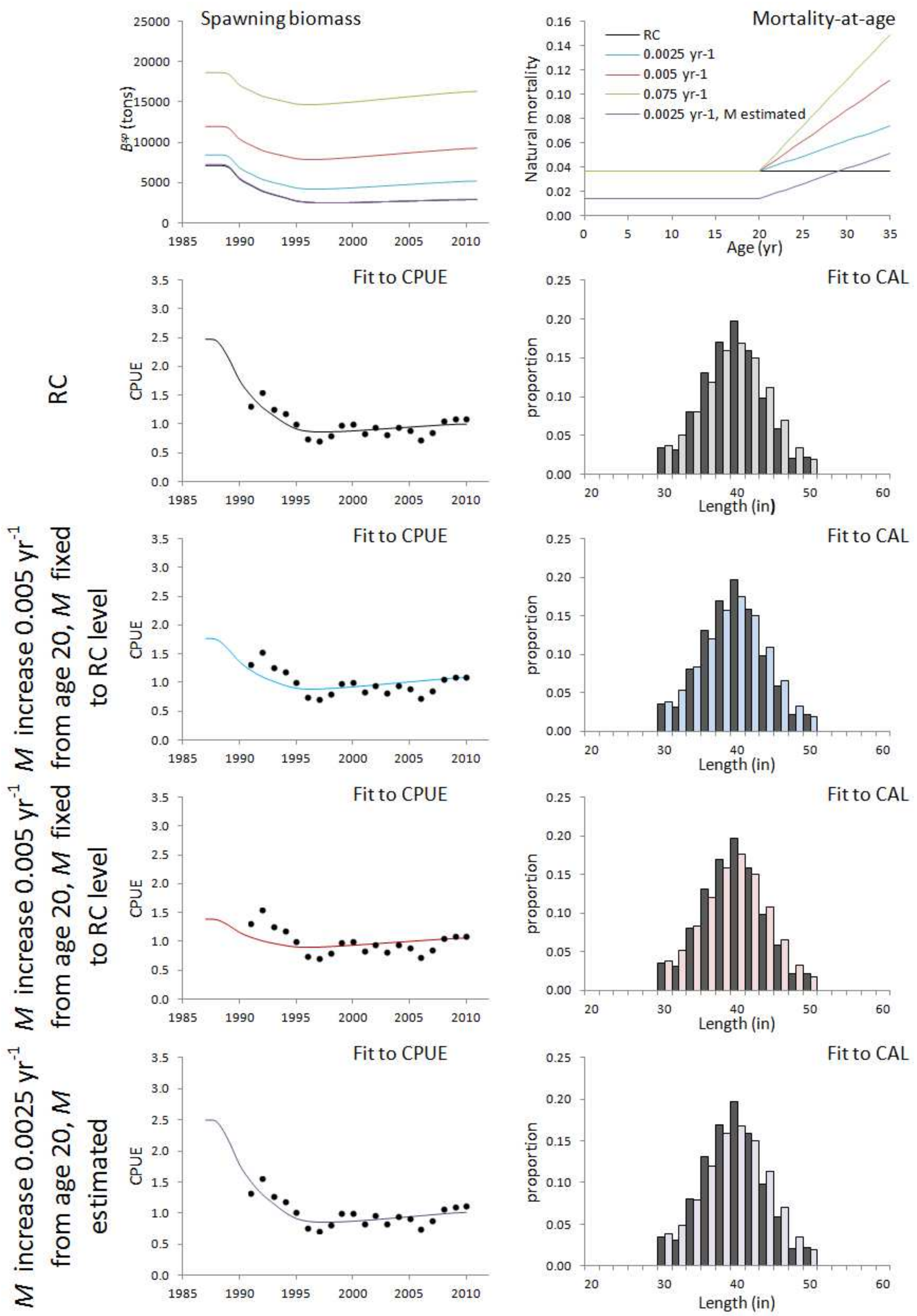

Figure 4: Spawning biomass trajectories for different specifications for natural mortality-at-age showing fits to the CPUE and CAL data (averaged over all the years for which data are available) for the RC and four sensitivities with increasing natural mortality for older ages (*M* increases from the **RC level** by 0.0025 yr^{-1} for **S3a**, 0.005 yr^{-1} for **S3b**, and 0.0075 yr^{-1} for **S3c**; and for **S3d**, *M* increases from an **estimated level** by 0.0025 yr^{-1})..

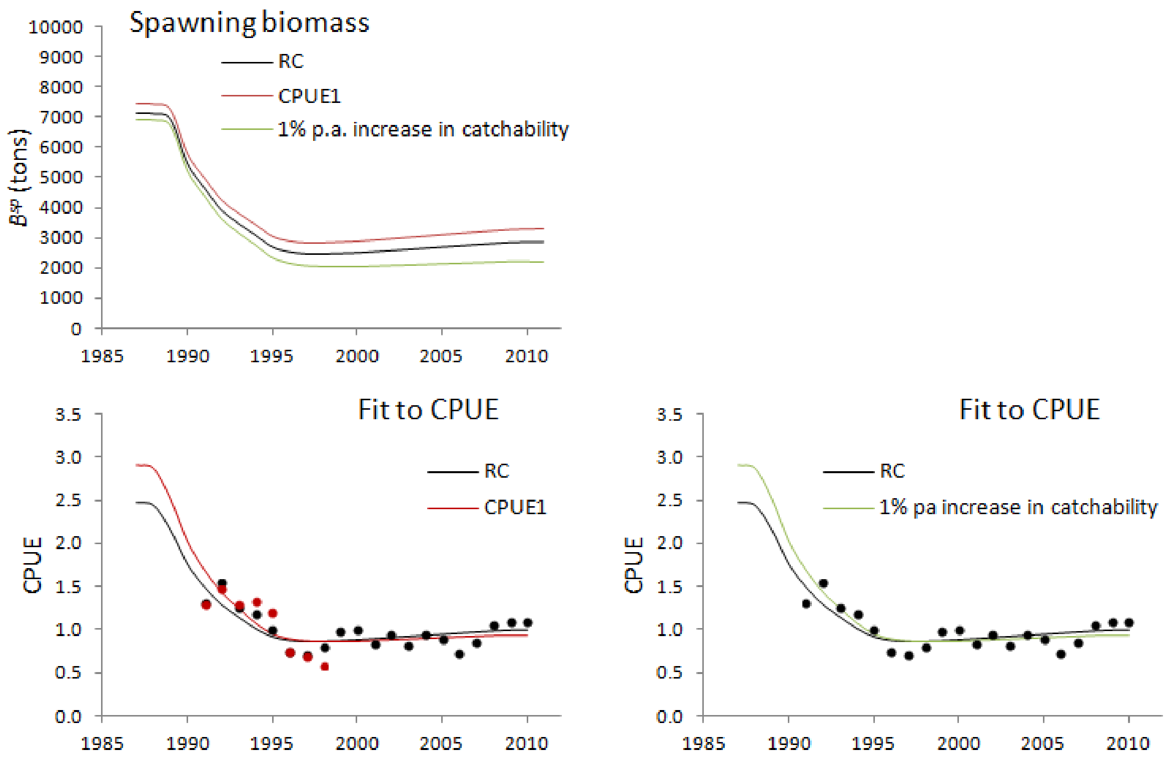

Figure 5: Spawning biomass trajectories, with fits to the CPUE data for the RC and two sensitivities involving CPUE. For CPUE1, the 1991-1998 CPUE data points have been replaced by the Vaughan *et al*. (**S4a**) (2001) series, renormalized to the average of the RC series over the same period. The new CPUE data points are shown as red dots in the left-hand plot. The 1% p.a. increase in catchability run corresponds to **S4b**.

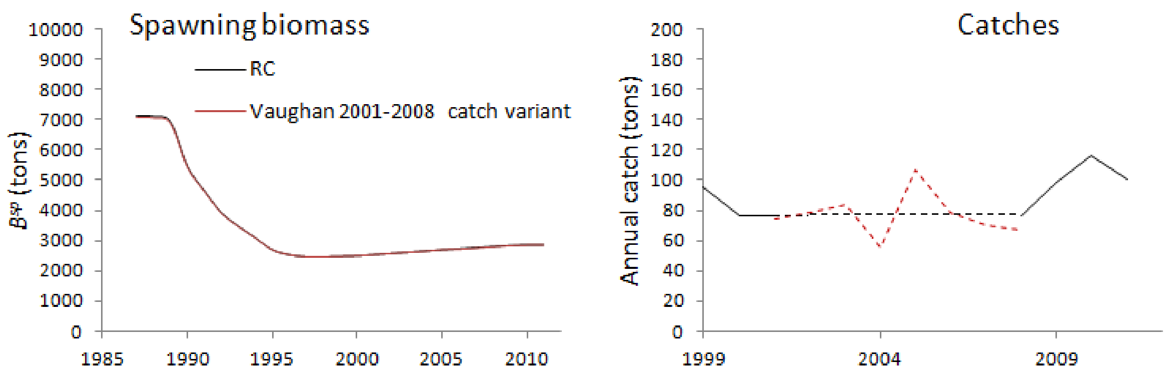

Figure 6: Spawning biomass and catch trajectories for the RC and the sensitivity in which a different catch series is assumed for the 2001-2008 period (**S5**).

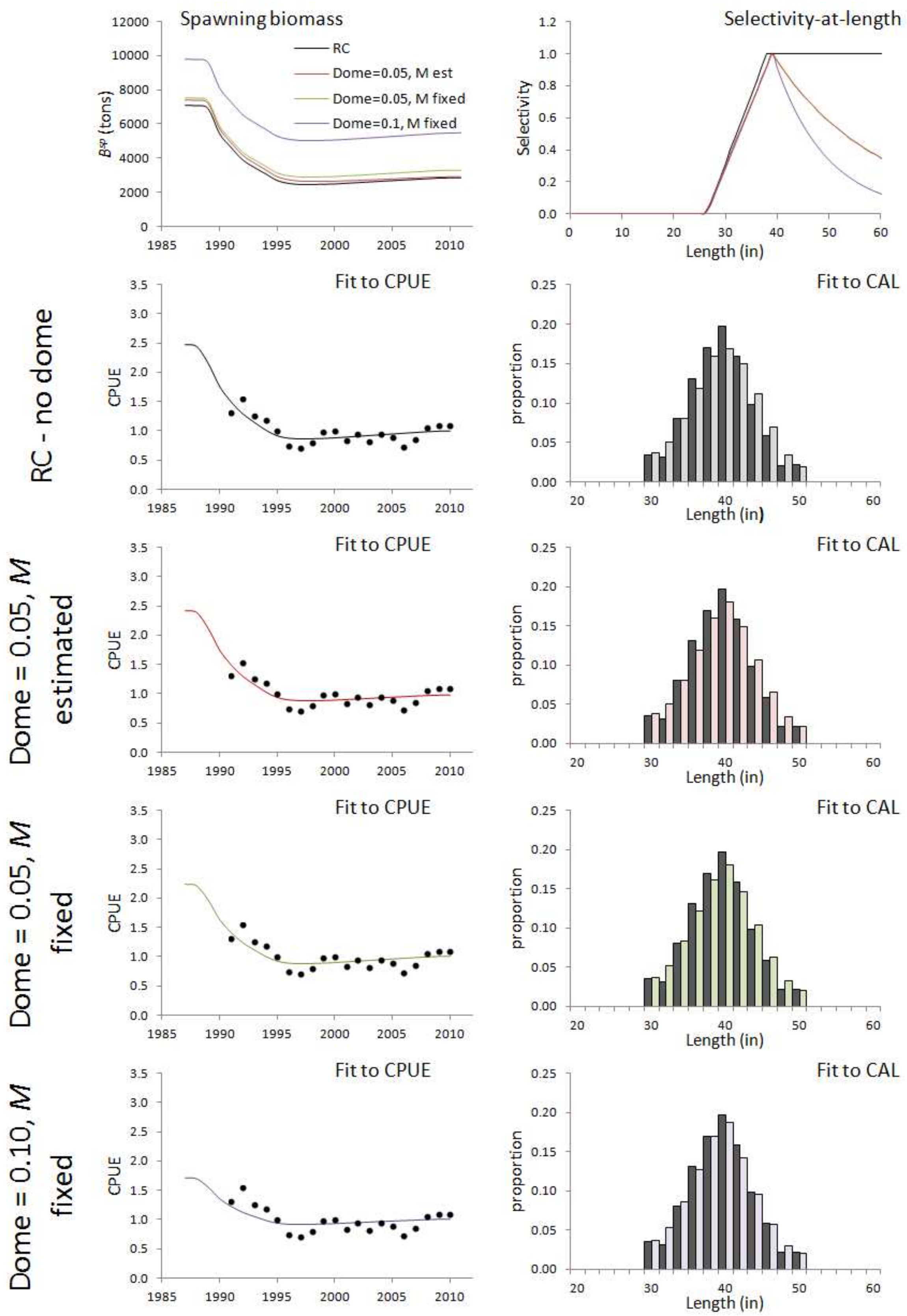

Figure 7: Spawning biomass trajectories, selectivity-at-length and fits to the CPUE and CAL data (averaged over all the years for which data are available) for the RC and three sensitivities with fixed rates of decreasing selectivity (“dome”) at larger lengths (**S6a**).

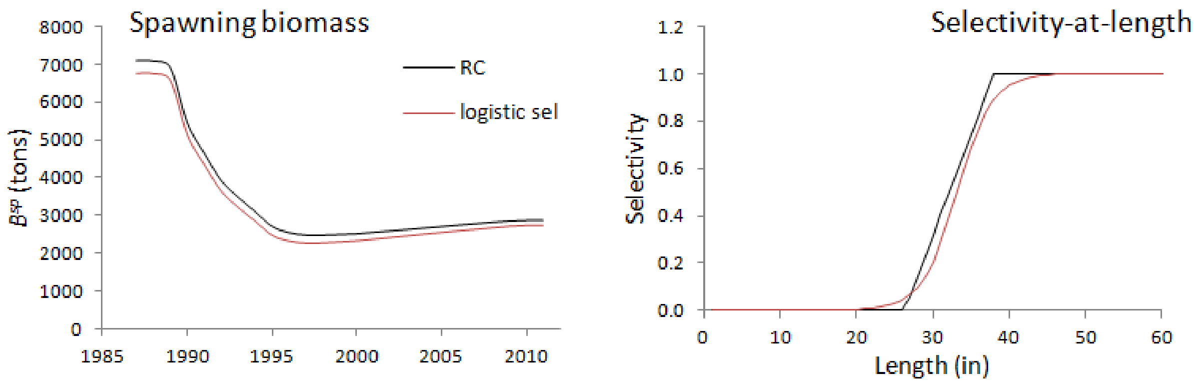

Figure 8: Spawning biomass trajectories and selectivity-at-length for the RC and a sensitivity with an estimated logistic selectivity-at-length function (**S6b**).

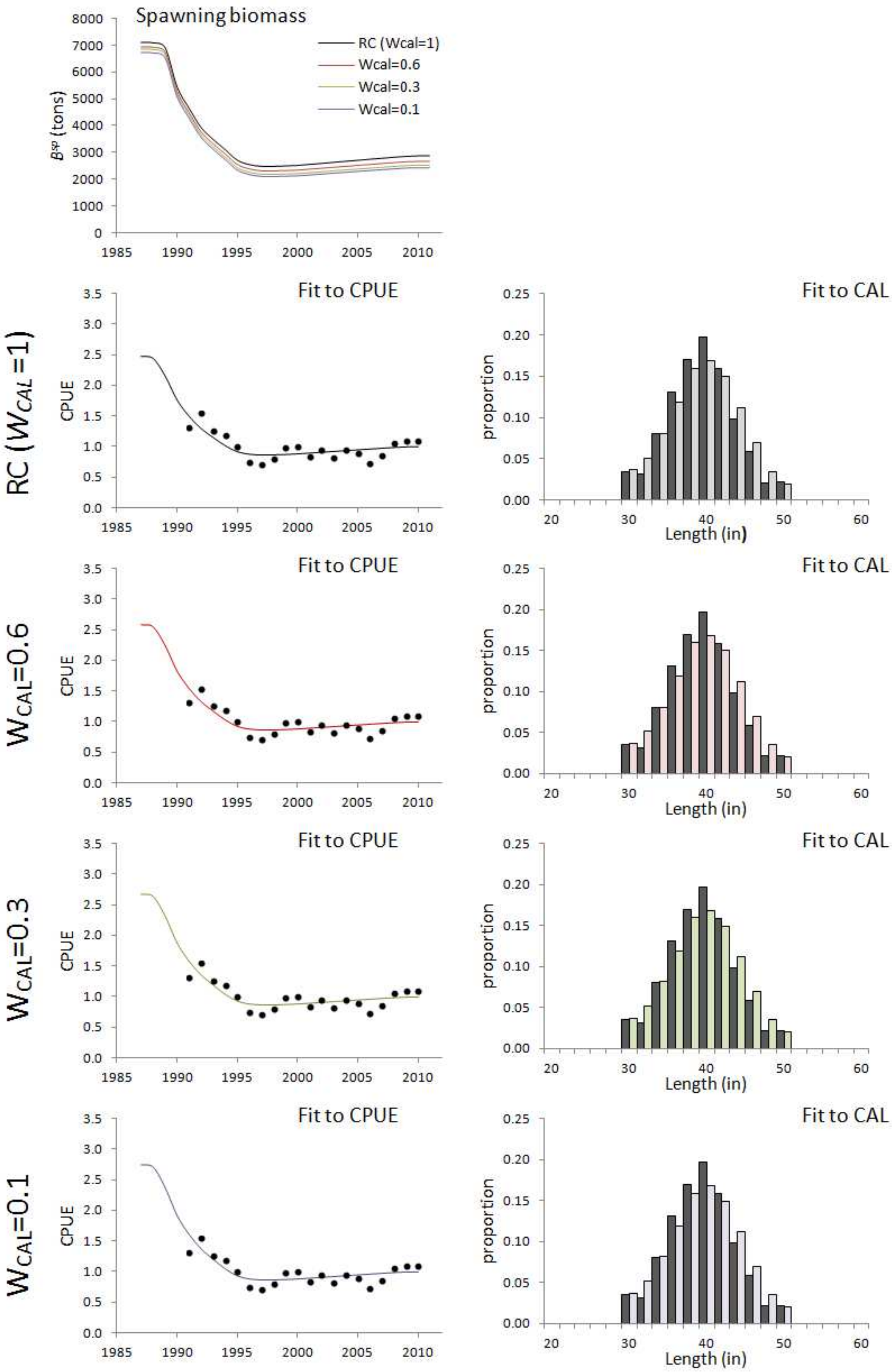

Figure 9: Spawning biomass trajectories, selectivity-at-length and fits to the CPUE and CAL data (averaged over all the years for which data are available) for the RC and three sensitivities with different weighting for the CAL component of -lnL (**S8**).

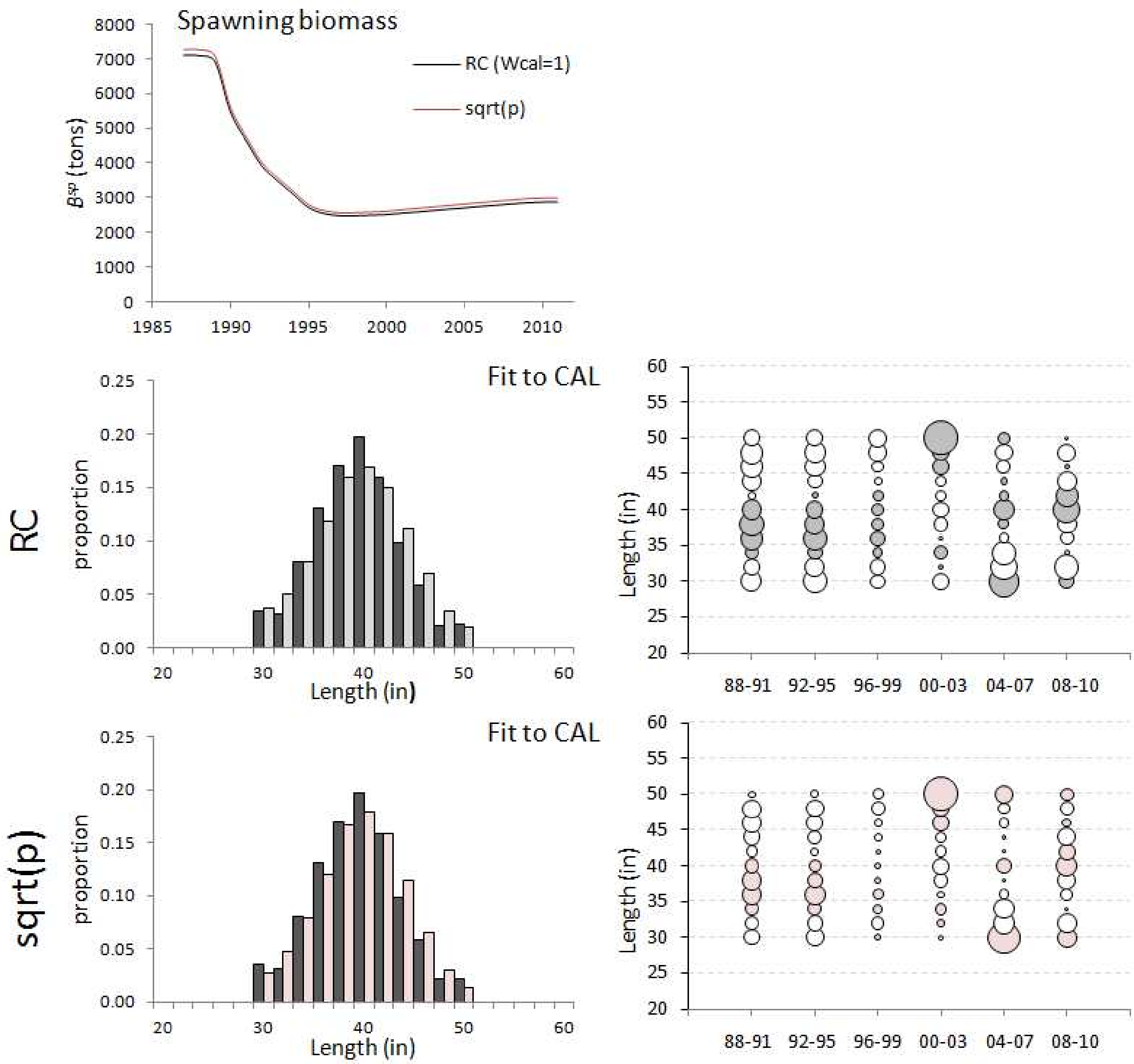

Figure 10: Spawning biomass trajectories and fits to the CAL data (averaged over all the years for which data are available together with bubble plots of residuals) for the RC and the sensitivity using a surrogate of the multinomial for the CAL component of -lnL (sqrt(p)) (**S9**).

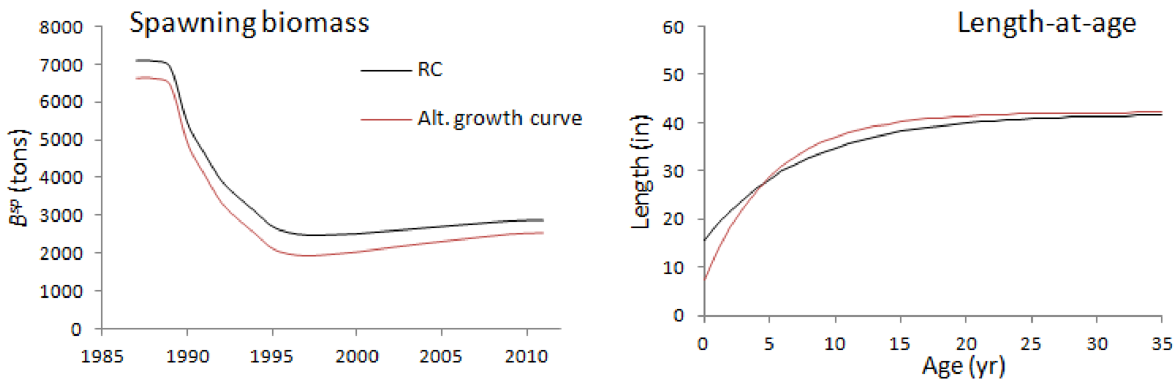

Figure 11: Spawning biomass trajectories and length-at-age for the RC and the sensitivity using an alternative growth curve (**S10**).

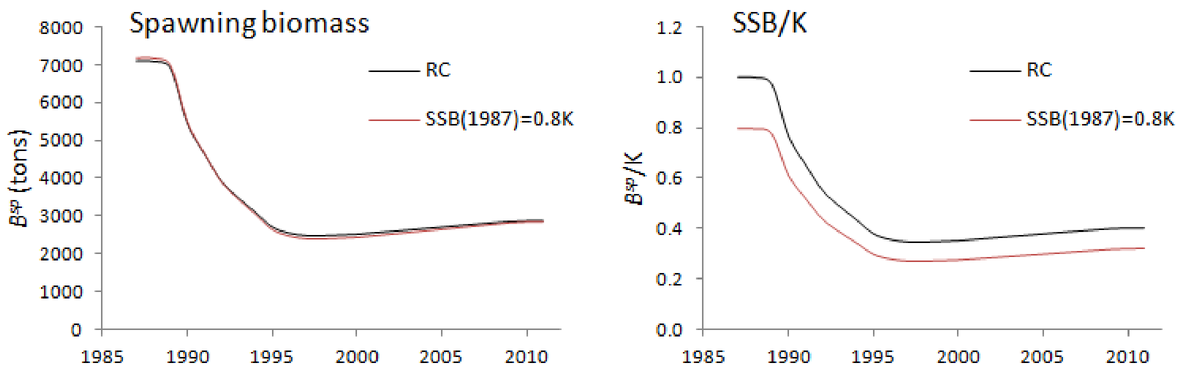

Figure 12: Spawning biomass trajectories in absolute terms and relative to pre-exploitation level for the RC and the sensitivity which fixes the starting 1987 spawning biomass at 0.8 of *K* (**S11**).

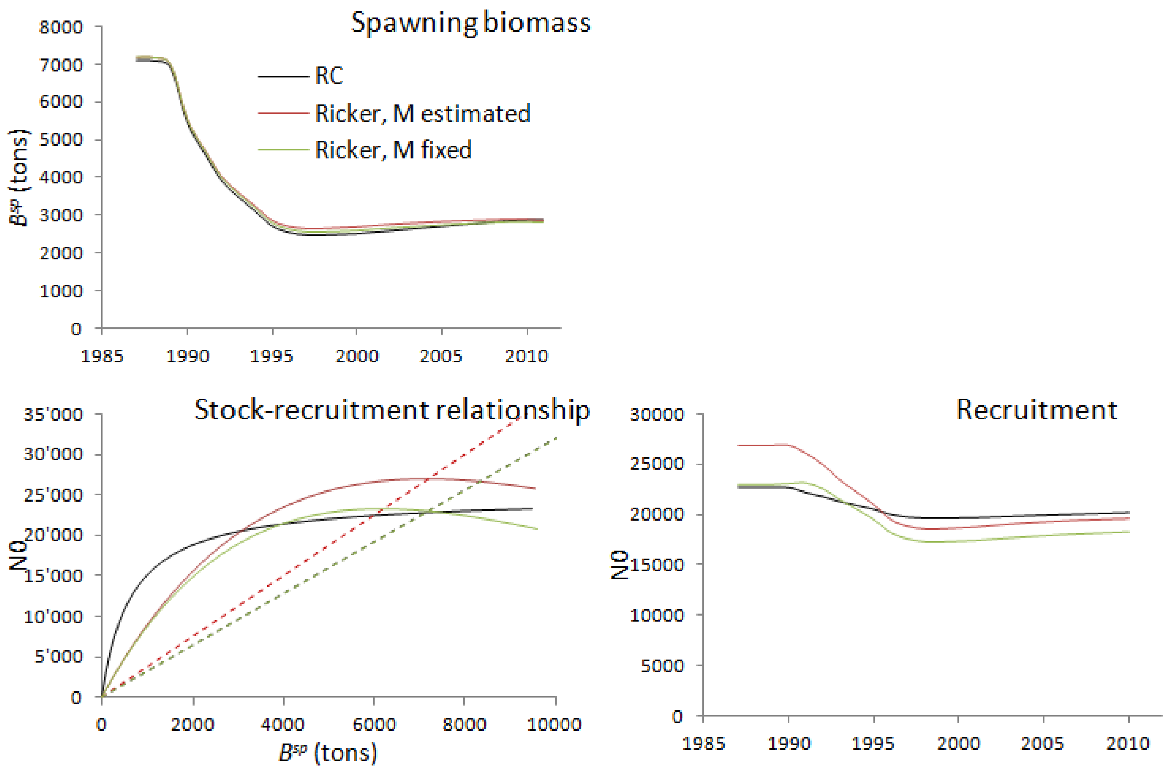

Figure 13: Trajectories of spawning biomass and recruitment, as well as the stock-recruitment relationship for the RC (Beverton-Holt, h=0.75) and the two sensitivities using a Ricker stock-recruitment curve with h estimated (**S12a**: M is estimated, **S12b**: M is fixed to the RC level). The replacement lines are shown as dotted lines in the plot of the stock-recruitment relationships.

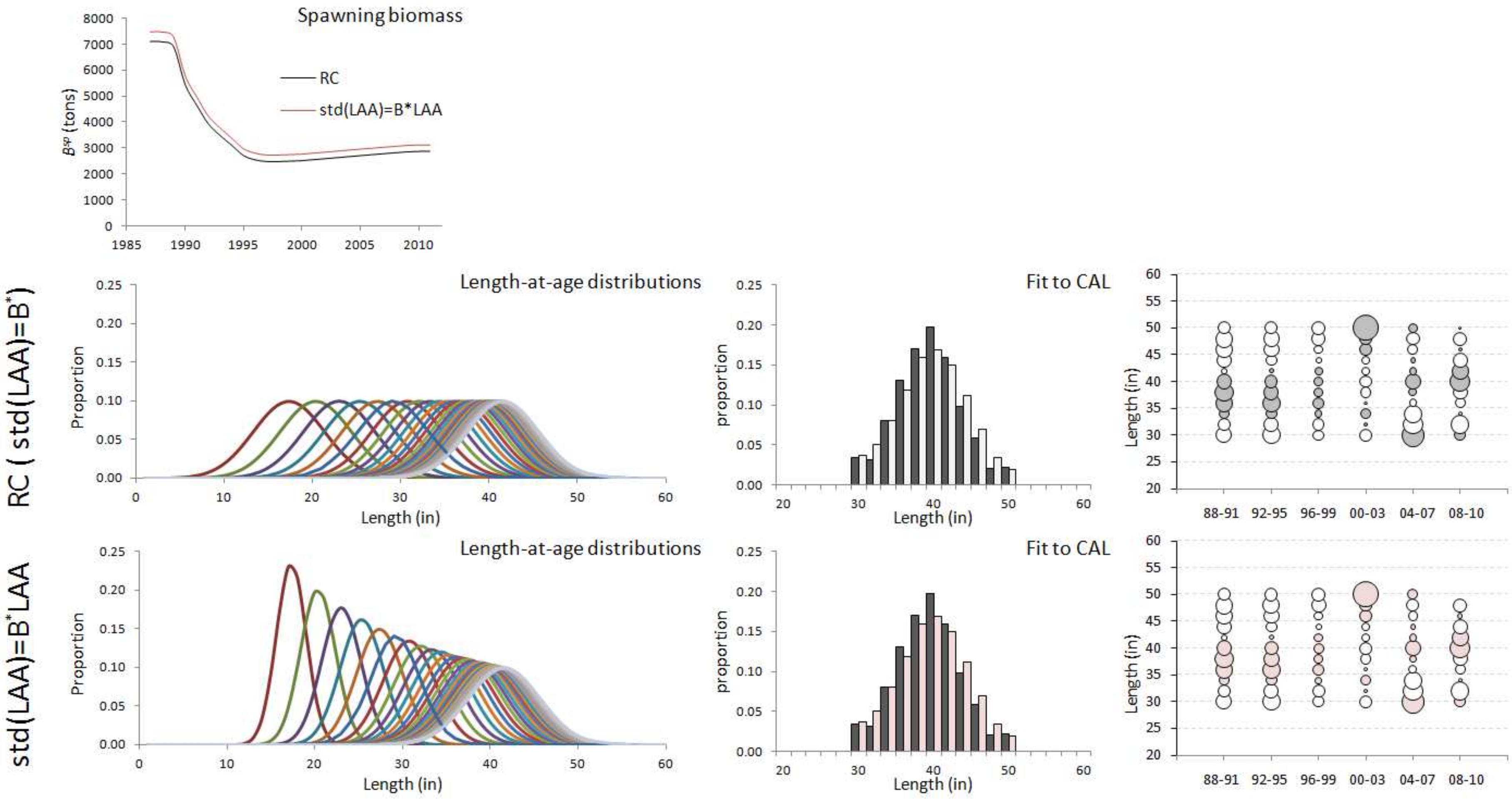

Figure 14: Trajectories of spawning biomass, length-at-age distribution, and fits to the CAL data for the RC and the sensitivity in which the standard deviation of the length-at-age distribution is length dependent (**S13**).

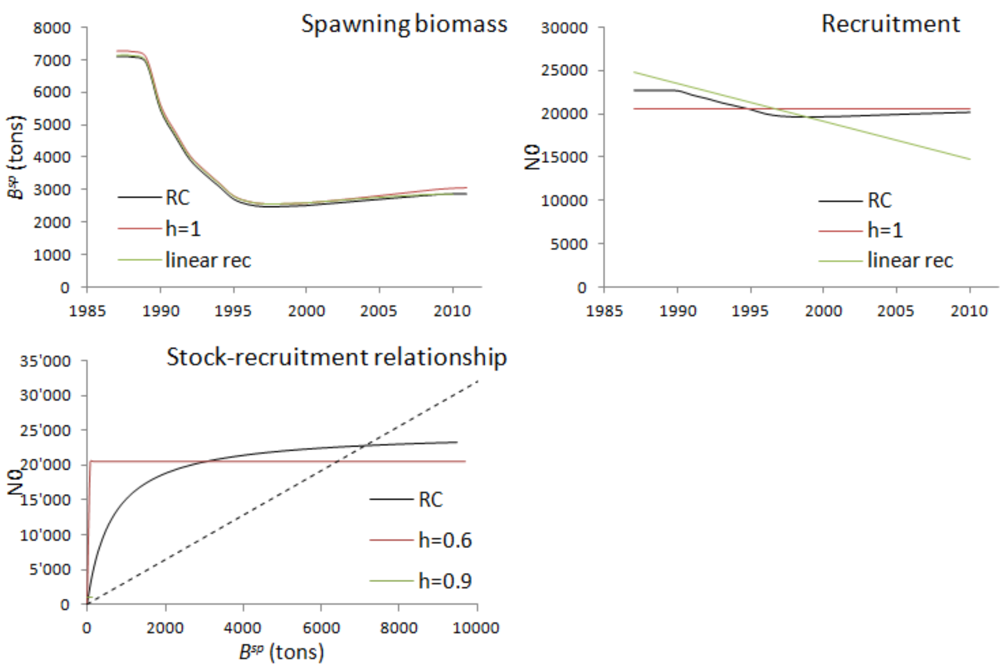

Figure 15: Trajectories of spawning biomass and recruitment for the RC and two alternative stock-structure (**S14a**: *h*=1; **S14b**: linear decrease in recruitment).

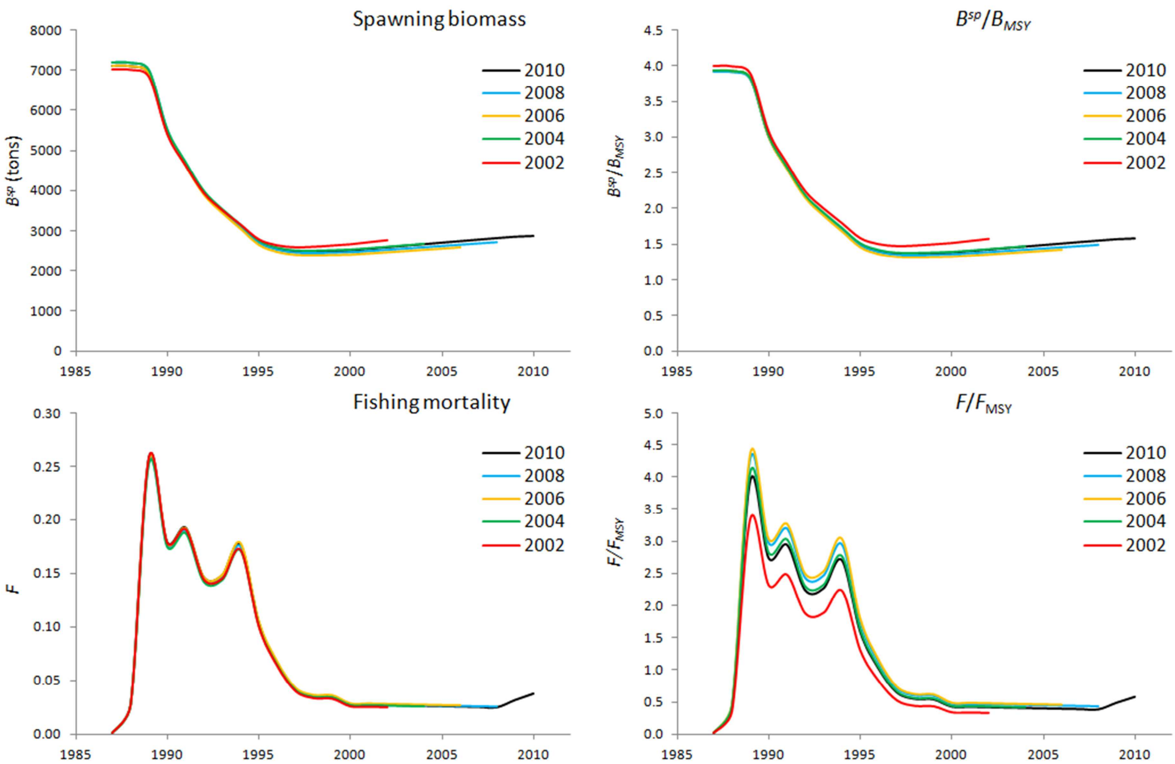

Figure 16: Retrospective results for the RC.

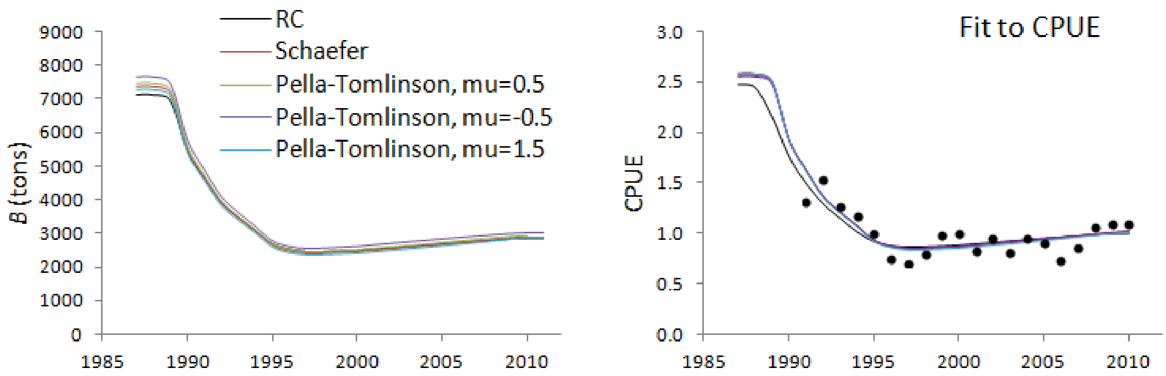

Figure 17: Trajectories of spawning biomass and fit to the CPUE data for the RC, and for the Schaefer and Pella-Tomlinson production models.

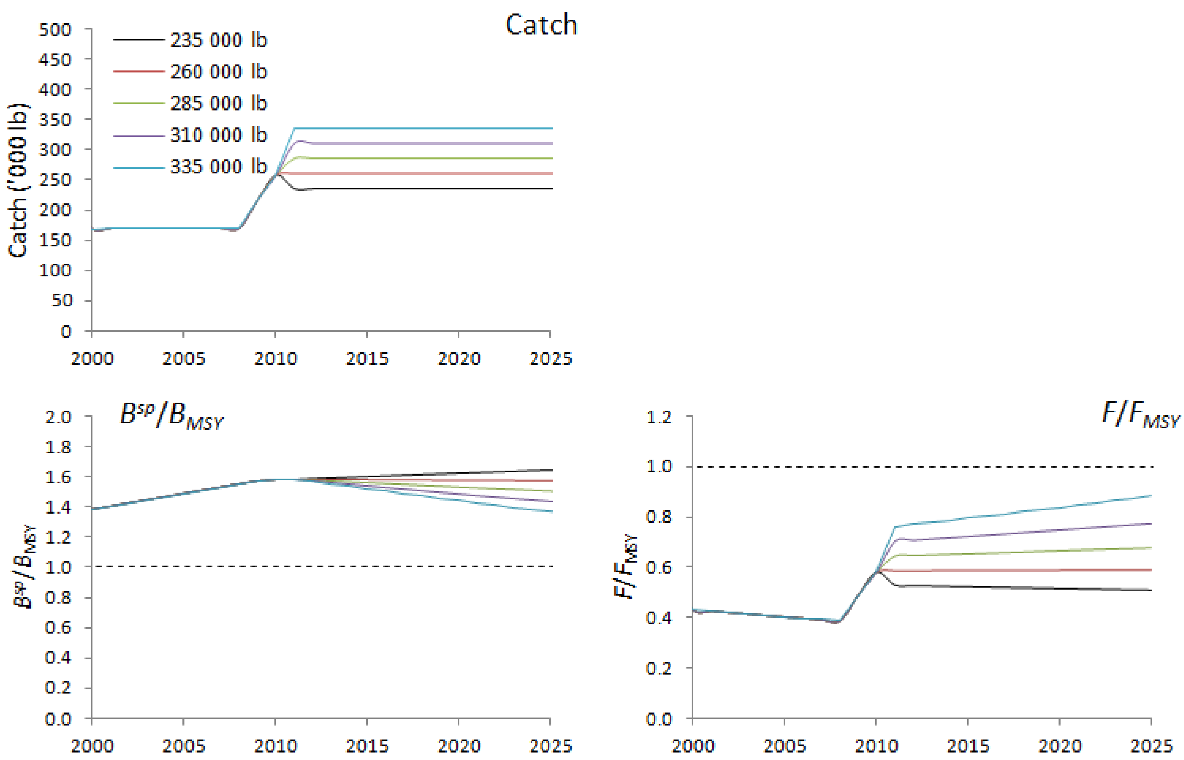

Figure 18: Catch, spawning biomass (relative to B_{MSY}) and fishing mortality (relative to F_{MSY}) trajectories under a series of constant catch projections for the RC.

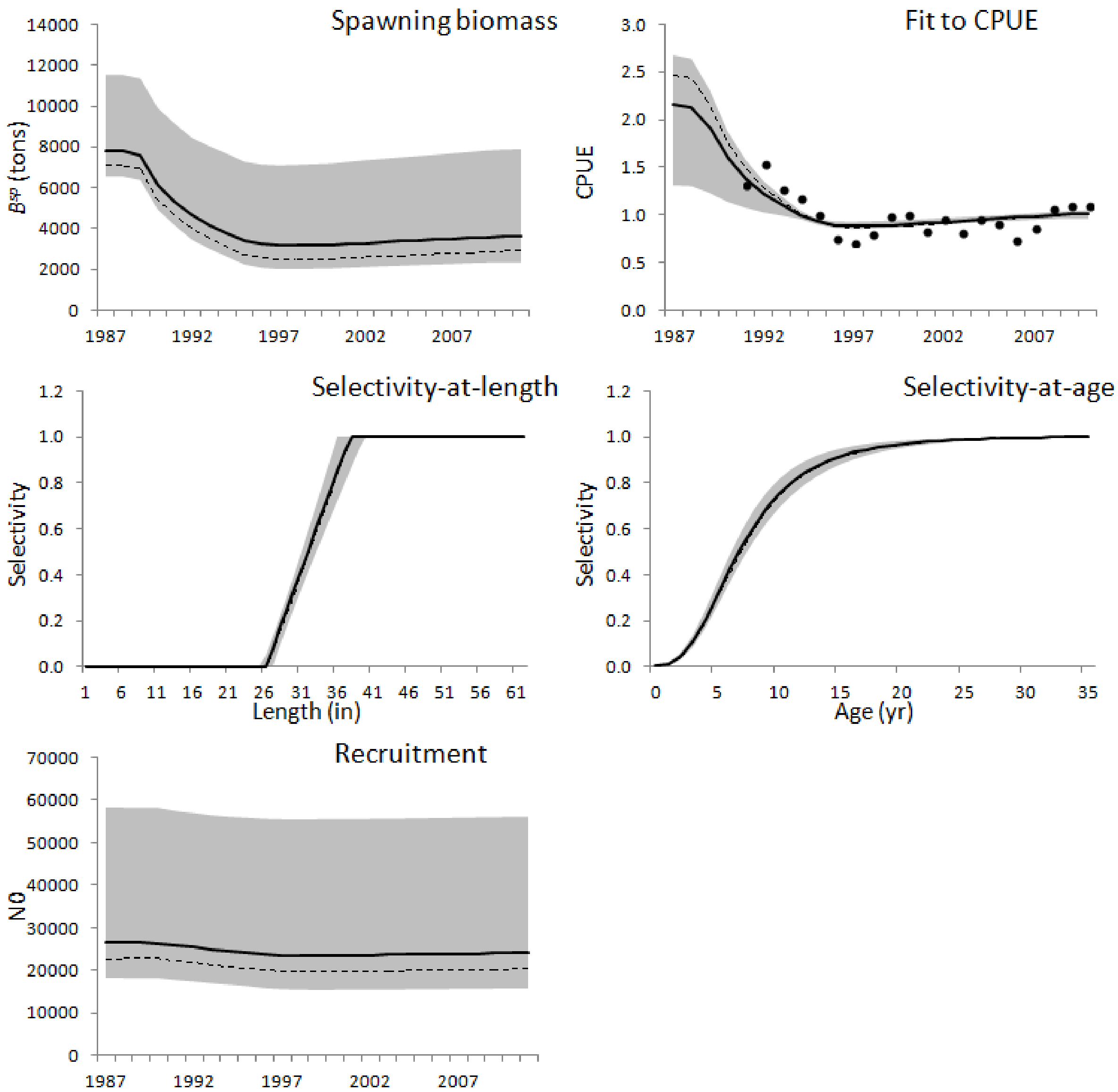

Figure 19a: Median and lower and upper 5%iles trajectory projections for the Bayesian RC. The dashed curves show the MLEs, and the solid curves reflect the posterior medians, while the shading shows the 90% posterior probability envelopes.

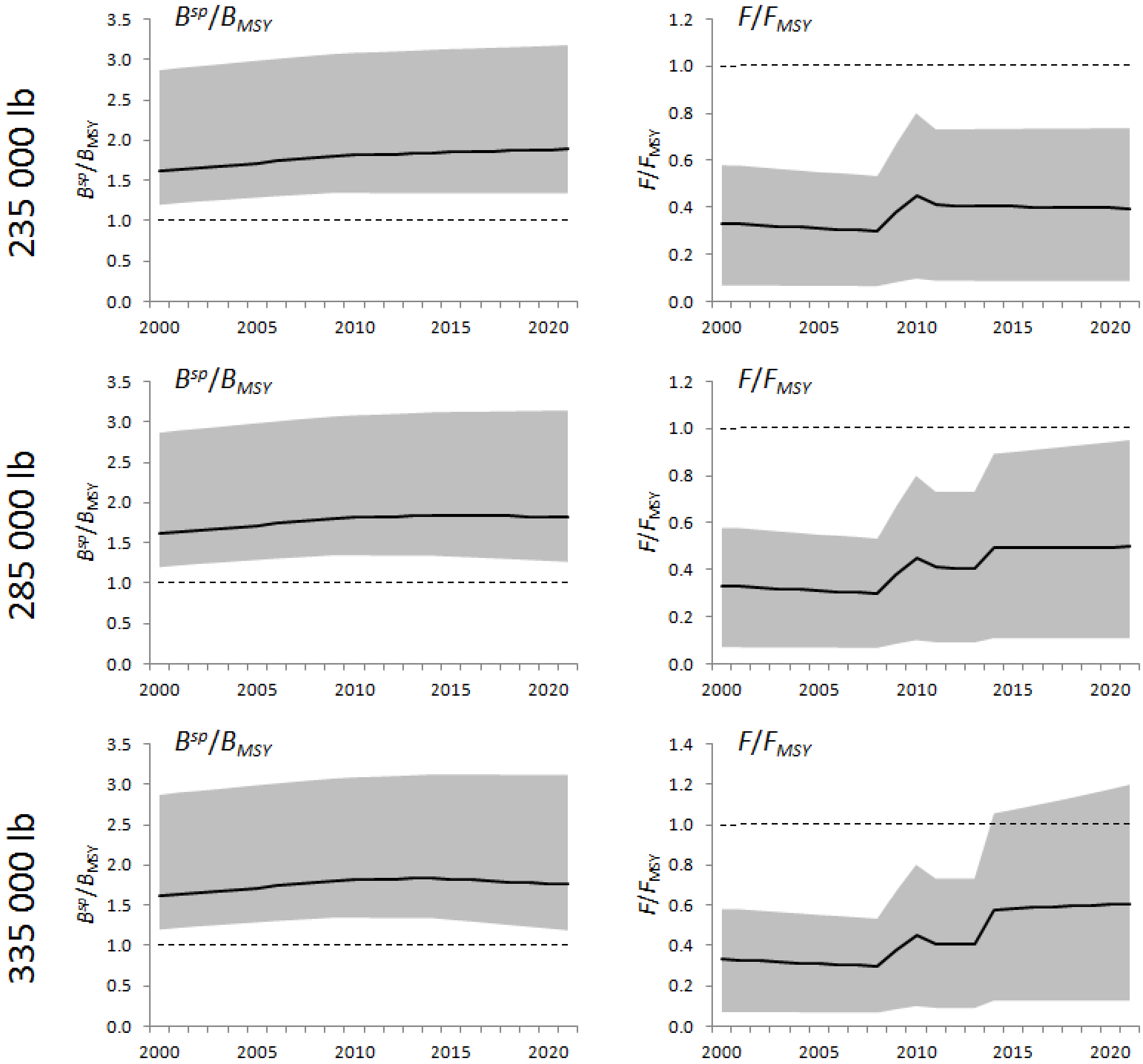

Figure 19b: Spawning biomass (relative to B_{MSY}) and fishing mortality (relative to F_{MSY}) median and lower and upper 5%iles trajectory projections under a series of constant catch projections commencing in 2011 for the Bayesian RC. The solid curves reflect the posterior medians, while the shading shows the 90% posterior probability envelopes.

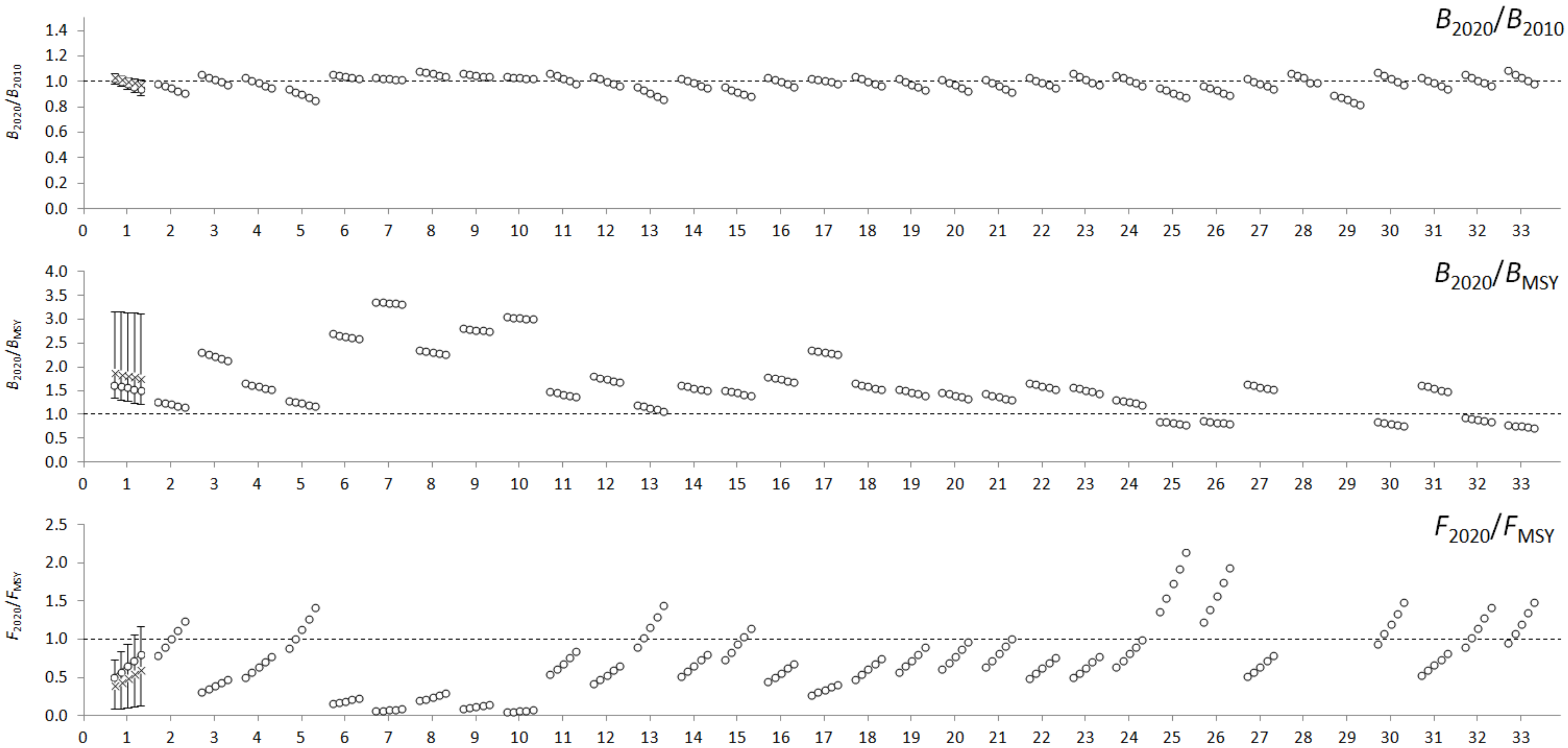

Figure 20: Projections results for the RC and the sensitivities under various future constant catches (235, 260, 285, 310 and 335 thousand lb from left to right respectively). Similar results are also shown for the dynamic production models, for which *F* refers to the *C/B* ratio. For the RC, the MLE and posterior median (crosses) with 90% PI as error bars are shown. The runs are shown in the following order:

1	RC		10	S3c	*M fixed*, incr. 0.0075 yr^{-1}	18	S6b	Logistic selectivity	26	S12b	Ricker, *M* fixed
2	S1a	h=0.6	11	S3d	*M* est., incr. 0.0025 yr^{-1}	19	S8a	W_{CAL}=0.6	27	S13	std(LAA)=β^{*}LAA
3	S1b	h=0.9	12	S4a	Other 1991-1998 series	20	S8b	W_{CAL}=0.3	28	S14a	h=1
4	S1c	h est. (beta prior)	13	S4b	1% p.a. incr. in q	21	S8c	W_{CAL}=0.1	29	S14b*	Linear decr. recr.
5	S2a	M=0.025	14	S5	Other 01-08 catches	22	S9	sqrt(p)	30	Schaefer	
6	S2b	M=0.055	15	S6a1	Sel. domed 0.05, *M* est.	23	S10	Alt. growth curve	31	Pella-Tomlinson, μ=-0.5	
7	S2c	M=0.065	16	S6a2	Sel. domed 0.05, *M* fixed	24	S11	SSB_{1987}=0.8K	32	Pella-Tomlinson, μ=0.5	
8	S3a	*M* fixed, incr. 0.0025 yr^{-1}	17	S6a3	Sel. domed 0.10, *M* fixed	25	S12a	Ricker	33	Pella-Tomlinson, μ=1.5	
9	S3b	*M* fixed, incr. 0.005 yr^{-1}									

APPENDIX A – Data

Table A1: Annual landings (thousand metric tons) of US south Atlantic wreckfish, 1967-2010 (Anon. 2011b, Table 3-2). Values in parenthesis are those used for sensitivity **S5**.

Year	Landing (tons)	Year	Landing (tons)	
1987	12.701	1999	95.481	
1988	206.824	2000	76.246	
1989	1680.54	2001	76.879*	(74.327)
1990	957.885	2002	76.879*	(78.972)
1991	873.658	2003	76.879*	(83.617)
1992	576.315	2004	76.879*	(55.745)
1993	519.243	2005	76.879*	(106.844)
1994	545.793	2006	76.879*	(78.972)
1995	292.562	2007	76.879*	(69.681)
1996	180.017	2008	76.879*	(66.894)
1997	113.268	2009	98.179	
1998	95.618	2010	116.718	

*Landings for 2001/2002 through 2008/2009 are confidential because there were fewer than three vessels that fished wreckfish and/or fewer than three dealers purchased wreckfish during those years. Anon. (2011a) gives the sum of landings for 1989-2010 as 15.220 million pounds, so that the remainder of the catch was attributed equally to the years 2001-2008.

Table A2: Wreckfish standardized catch-per-unit-effort data (summarized in Figure 1 of Anon. 2011a). Values in parenthesis are a renormalisation of the Vaughan *et al.* (2001)numbers-at-age series which is used for sensitivity **S4a**.

Year	Standardized CPUE		Year	Standardized CPUE
1991	1.325	(1.293)	2001	0.837
1992	1.552	(1.472)	2002	0.965
1993	1.272	(1.290)	2003	0.827
1994	1.190	(1.343)	2004	0.957
1995	1.009	(1.198)	2005	0.908
1996	0.755	(0.753)	2006	0.737
1997	0.712	(0.687)	2007	0.872
1998	0.810	(0.588)	2008	1.066
1999	0.991		2009	1.101
2000	1.003		2010	1.110

Table A3: Wreckfish size frequency data (summarized in Figure 3 of Anon. 2011a).

Total Length (in)	Frequency of Measured Lengths by Fishing Year					
	88-91	92-95	96-99	00-03	04-07	08-10
20	0	0	0	0	0	0
22	0	0	0	1	0	0
24	0	0	1	1	22	0
26	3	5	5	3	14	0
28	7	18	35	9	8	3
30	22	37	59	17	15	6
32	93	205	130	64	10	4
34	316	635	276	110	34	16
36	626	1125	406	137	85	21
38	937	1388	501	157	126	25
40	979	1456	526	152	149	46
42	745	1196	455	142	108	36
44	469	785	308	101	75	14
46	226	381	175	82	36	12
48	76	126	55	43	13	3
50	36	54	13	21	8	3
52	14	12	8	18	2	0
54	10	15	4	11	3	0
56	8	10	1	5	1	0
58	1	7	1	4	0	0
60	1	0	0	0	1	0
>60	1	0	0	0	0	0

Appendix B - The Statistical Catch-at-Age Model

The text following sets out the equations and other general specifications of the SCAA model, followed by details of the contributions to the (penalised) log-likelihood function from the different sources of data available and assumptions concerning the stock-recruitment relationship. Quasi-Newton minimization is then applied to minimize the total negative log-likelihood function to estimate parameter values (the package AD Model Builder™, Otter Research, Ltd is used for this purpose).

B.1. Population dynamics

B.1.1 Numbers-at-age

The resource dynamics are modelled by the following set of population dynamics equations:

$$N_{y+1,0} = R_{y+1} \tag{B1}$$

$$N_{y+1,a+1} = \left(N_{y,a}\, e^{-M_a/2} - C_{y,a}\right) e^{-M_a/2} \qquad \text{for } 0 \le a \le m-2 \tag{B2}$$

$$N_{y+1,m} = \left(N_{y,m-1}\, e^{-M_{m-1}/2} - C_{y,m-1}\right) e^{-M_{m-1}/2} + \left(N_{y,m}\, e^{-M_m/2} - C_{y,m}\right) e^{-M_m/2} \tag{B3}$$

where

$N_{y,a}$ is the number of fish of age *a* at the start of year *y* (which refers to a calendar year),

R_y is the recruitment (number of 0-year-old fish) at the start of year *y*,

M_a denotes the natural mortality rate for fish of age *a*,

$C_{y,a}$ is the predicted number of fish of age *a* caught in year *y*, and

m is the maximum age considered (*m*=35, taken to be a plus-group).

B.1.2. Recruitment

The number of recruits (i.e. new 0-year old) at the start of year *y* is assumed to be related to the spawning stock size (i.e. the biomass of mature fish) by either a deterministic Beverton-Holt stock-recruitment relationship:

$$R_y = \frac{\alpha B_y^{sp}}{\beta + B_y^{sp}} \tag{B4a}$$

or a deterministic Ricker stock recruitment relationship:

$$R_y = \alpha B_y^{sp} \exp\left(-\beta B_y^{sp}\right) \tag{B4b}$$

where

α and β are spawning biomass-recruitment relationship parameters,

B_y^{sp} is the spawning biomass at the start of year *y*, computed as:

$$B_y^{sp} = \sum_{a=0}^{m} f_a w_a^{\text{strt}} N_{y,a} \tag{B5}$$

where

w_a^{strt} is the mass of fish of age *a* at the beginning of the year, 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", *h*, of the stock-recruitment relationship, which is the proportion of the virgin recruitment that is realized at a spawning biomass level of 20% of the virgin spawning biomass. In the fitting procedure applied in this paper, K^{sp} is estimated, while *h* is fixed at 0.75 for the RC.

B.1.3. Catches-at-age

The catches at age in number in year *y* are given by:

$$C_{y,a} = N_{y,a}\, e^{-M_a/2}\, S_{y,a}\, F_y^* \tag{B6}$$

where

$C_{y,a}$ is the catch-at-age, i.e. the number of fish of age *a*, caught in year *y*,

F_y^* is the proportion of a fully selected age class that is fished, and

$S_{y,a}$ is the commercial selectivity (i.e. combination of availability and vulnerability to fishing gear) at age *a* for year *y*; when $S_{y,a} = 1$, the age-class *a* is said to be fully selected.

Selectivity is estimated as a function of length (see section B3.1) and then converted to selectivity-at-age:

$$S_{y,a} = \sum_l S_{y,l} A_{a,l} \tag{B7}$$

where $A_{a,l}$ is the proportion of fish of age *a* that fall in the length group *l* (i.e., $\sum_l A_{a,l} = 1$ for all ages).

The matrix $A_{a,l}$ is calculated under the assumption that length-at-age is normally distributed about a mean given by the von Bertalanffy equation, i.e.:

$$L_a \sim N\left[L_\infty\left(1 - e^{-\kappa(a-t_o)}\right); \theta_a^2\right] \tag{B8}$$

where

θ_a is the standard deviation of length-at-age *a*, which is taken as a constant in the RC, i.e.:

$$\theta_a = \beta^* \tag{B9}$$

with β^* an estimable parameter.

For sensitivity S13, the standard deviation of length-at-age *a* is modelled to be proportional to the expected length-at-age *a*, i.e.:

$$\theta_a = \beta^* L_\infty \left(1 - e^{-\kappa(a - t_o)}\right) \tag{B10}$$

with β^* an estimable parameter.

The model estimate of the mid-year exploitable ("available") component of biomass is calculated by converting the numbers-at-age into mid-year mass-at-age (using the individual weights of the landed fish) and applying natural and fishing mortality for half the year:

$$B_y^{\mathrm{ex}} = \sum_{a=0}^{m} \tilde{w}_{y,a}^{\mathrm{mid}} S_{y,a} N_{y,a} e^{-M_a/2} (1 - S_{y,a} F_y^* / 2) \tag{B11}$$

where

$\tilde{w}_{y,a}^{\mathrm{mid}}$ is the selectivity-weighted mid-year weight-at-age *a* landed in year y, and

$$\tilde{w}_{y,a}^{\mathrm{mid}} = \sum_l S_{y,l} w_l A_{a,l} \Big/ \sum_l S_{y,l} A_{a,l}$$

with

w_l being the weight of fish of length *l*.

B.1.4. Initial conditions

In general, the first year for which annual catch data are available may not correspond to the first year of (appreciable) exploitation, so that one cannot necessarily make the assumption in the application of this SCAA model that this initial year reflects a population (and its age-structure) at pre-exploitation equilibrium. For the first year (y_0) considered in the model therefore, the stock is assumed to be at a fraction (θ) of its pre-exploitation biomass, i.e.:

$$B_{y_0}^{sp} = \theta \cdot K^{sp} \tag{B12}$$

with the starting age structure:

$$N_{y_0,a} = R_{\mathrm{start}} N_{\mathrm{start},a} \qquad \text{for } 1 \le a \le m \tag{B13}$$

where

$$N_{\mathrm{start},0} = 1 \tag{B14}$$

$$N_{\mathrm{start},a} = N_{\mathrm{start},a-1} e^{-M_{a-1}} (1 - \phi S_{a-1}) \qquad \text{for } 1 \le a \le m-1 \tag{B15}$$

$$N_{\mathrm{start},m} = N_{\mathrm{start},m-1} e^{-M_{m-1}} (1 - \phi S_{m-1}) \Big/ (1 - e^{-M_m} (1 - \phi S_m)) \tag{B16}$$

where ϕ characterises the average fishing proportion over the years immediately preceding y_0.

For the RC and all but one sensitivity (S11, $\theta = 0.8$ and $\phi = 0$) considered here however, the population starts in 1987 at its pre-exploitation equilibrium level (*K*) with an equilibrium age-structure, where:

$$R_0 = K^{sp} \Bigg/ \left[\sum_{a=1}^{m-1} f_a w_a^{\mathrm{strt}} e^{-\sum_{a'=0}^{a-1} M_{a'}} + f_m w_m^{\mathrm{strt}} e^{\sum_{a'=0}^{m-1} M_{a'}} \right] \tag{B17}$$

B.2. The likelihood function

The model is fit to a CPUE index and commercial catch-at-length data to estimate model parameters. Contributions by each of these to the negative of the (penalised) log-likelihood (-lnL) are as follows.

B.2.1 CPUE relative abundance data

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

$$I_y = \hat{I}_y \exp(\varepsilon_y) \quad \text{or} \quad \varepsilon_y = \ell n(I_y) - \ell n(\hat{I}_y) \tag{B18}$$

where

I_y is the CPUE abundance index for year *y*,

$\hat{I}_y = \hat{q}\ \hat{B}_y^{\mathrm{ex}}$ is the corresponding model estimate, where $\hat{B}_y^{\mathrm{ex}}$ is the model estimate of exploitable resource biomass as described in equation B11,

$\hat{q}$ is the constant of proportionality (catchability) for the CPUE abundance series, and

ε_y from $N\left(0, (\sigma_y)^2\right)$.

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

$$-\ell n L^{\mathrm{CPUE}} = \sum_y \left\{ \ell n(\sigma_{com}) + (\varepsilon_y)^2 / (2\sigma_{com}^2) \right\} \tag{B19}$$

where

σ_{com} is the standard deviation of the residuals for the logarithm of the CPUE index, which is estimated in the fitting procedure by its maximum likelihood value:

$$\sigma_{com} = \sqrt{\frac{1}{n}\sum_y \left[\ell n(I_y) - \ell n(\hat{I}_y)\right]^2} \tag{B20}$$

where *n* is the number of data points for the CPUE index.

The catchability coefficient q for the CPUE abundance index is estimated by its maximum likelihood value:

$$\ell n\,\hat{q} = 1/n \sum_y \left(\ln I_y - \ln \hat{B}_y^{\mathrm{ex}}\right) \tag{B21}$$

B.2.2. Commercial catches-at-length

The contribution of the catch-at-length data to the negative of the log-likelihood function under the assumption of an "adjusted" (or “Punt-Kennedy (1997)”) lognormal error distribution is given by:

$$-\ell n L^{\mathrm{CAL}} = W_{CAL} \sum_{y^*} \sum_l \left[\ell n\left(\sigma_{\mathrm{CAL}} / \sqrt{p_{y^*,l}}\right) + p_{y^*,l}\left(\ell n\, p_{y^*,l} - \ell n\, \hat{p}_{y^*,l}\right)^2 / 2(\sigma_{\mathrm{CAL}})^2 \right] \tag{B22}$$

$p_{y*,l} = C_{y*,l} \Big/ \sum_{l'} C_{y*,l'}$ is the average observed proportion of fish caught between years y_1 and y_2 that are of length l,

$\hat{p}_{y*,l} = \sum_{y=y_1}^{y_2} \hat{C}_{y,l} \Big/ \sum_{y=y_1}^{y_2} \sum_{l'} \hat{C}_{y,l'}$ is the model-predicted average proportion of fish caught between years y_1 and y_2 that are of length l,

where

$$\hat{C}_{y,l} = N_{y,a}\ A_{a,l}\ S_{y,l} e^{-M_a/2} F_y \quad \text{(B23)}$$

and

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

$$\hat{\sigma}_{\mathrm{CAL}} = \sqrt{\sum_{y*}\sum_{l} p_{y*,l}\left(\ell n\ p_{y*,l} - \ell n\ \hat{p}_{y*,l}\right)^2 / \sum_{y*}\sum_{a} 1} \quad \text{(B24)}$$

The log-normal error distribution underlying equation (B22) is chosen on the grounds that (assuming no ageing error) variability is likely dominated by a combination of interannual variation in the distribution of fishing effort, and fluctuations (partly as a consequence of such variations) in selectivity-at-length, which suggests that the assumption of a constant coefficient of variation is appropriate. However, for lengths poorly represented in the sample, sampling variability considerations must at some stage start to dominate the variance. To take this into account in a simple manner, motivated by binomial distribution properties, the observed proportions are used for weighting so that undue importance is not attached to data based upon a few samples only.

Commercial catches-at-length are incorporated in the likelihood function using equation (B22), for which the summation over length l is taken from age l_{minus}= 30 in (considered as a minus group) to l_{plus}=50 in (a plus group).

The W_{CAL} weighting factor may be set to a value less than 1 to downweight the contribution of the catch-at-length data (which tend to be positively correlated between adjacent length groups) to the overall negative log-likelihood compared to that of the CPUE data. The calculations reported in this paper have, however, all been carried out with $W_{CAL} = 1$ except for sensitivity S8.

For sensitivity S9, equations B22 and B24 are replaced by:

$$-\ell\mathrm{n}\, L^{\mathrm{CAL}} = W_{CAL}\sum_{y*}\sum_{l}\left[\ell n\left(\sigma_{\mathrm{CAL}}\right) + \left(\sqrt{p_{y*,l}} - \sqrt{\hat{p}_{y*,l}}\right)^2 / 2\left(\sigma_{\mathrm{CAL}}\right)^2\right] \quad \text{(B25)}$$

$$\hat{\sigma}_{\mathrm{CAL}} = \sqrt{\sum_{y*}\sum_{l}\left(\sqrt{p_{y*,l}} - \sqrt{\hat{p}_{y*,l}}\right)^2 / \sum_{y*}\sum_{a} 1} \quad \text{(B26)}$$

B.3. Model parameters

B.3.1. Fishing selectivity-at-length:

The commercial fishing selectivity, S_l , takes on the following form:

$$S_l = \begin{cases} 0 & \text{if } l < l_1 \\ (l-l_1)/(l_2-l_1) & \text{if } l_1 \le l \le l_2 \\ 1 & \text{if } l > l_1 \end{cases} \quad \text{(B27)}$$

with l_1 and l_2 estimated in the fitting procedure.

The selectivity is assumed to stay constant over time.

For sensitivity S6a, the selectivity is modified to include a decrease in selectivity at larger lengths ("dome"), as follows:

$$S_l = S_{l-1}e^{-d} \qquad \text{for } l > 40 \text{ in} \quad \text{(B28)}$$

where *d* is a fixed parameter that measures the rate of decrease in selectivity with length for fish longer than 40 in., and the subscript notation indicates an increase of 1 in. in the length class considered.

For sensitivity S6b, the selectivity is assumed to follow a logistic curve by:

$$S_l = \frac{1}{1+\exp((l-l^c)/\delta)} \quad \text{(B29)}$$

l^c cm is the length-at-50% selectivity, and

δ cm^{-1} defines the steepness of the ascending limb of the selectivity curve.

B.3.2. Biological parameters

Growth curve:

$$l_a^{FL} = l_\infty\left(1-e^{-\kappa(a-t_o)}\right) \quad \text{(B30)}$$

where

l_a^{FL} is the fork length at age *a*, converted to total length using:

$$l_a^{TL} = \left(1.0451 l_a^{FL} - 1.1221\right)/25.4$$

l_∞=101.7 cm, κ=0.132 yr^{-1} and t_0=-3.56 yr^{-1} (from Lytton, pers commn).

For sensitivity S10, the following parameters have been used:

l_∞=102.6 cm, κ=0.1903 yr^{-1} and t_0=-1.0 yr^{-1} (from Lytton, pers commn).

Weight-at-age:

Begin-year:

$$w_a^{\text{strt}} = \alpha(l_a)^\beta \quad \text{(B31)}$$

and mid-year:

$$w_a^{\text{mid}} = \alpha\left(l_{a+1/2}\right)^\beta$$

where α=1.00x10^{-5} and β=3.0778 (from Lytton, pers. commn), and units in terms of gm and cm.

Percentage maturity-at-age:

Maturity-at-length is assumed to take on a logistic form,

$$f_l = \frac{1}{1+e^{(l-l_{50})/\delta}} \qquad \text{(B32)}$$

with the parameters obtained from fitting to the female percentage maturity-at-length from Wyanski and Meister, 2002). It is then converted to maturity-at-age within the model through the use of the age-length distribution matrix.

The fitting leads to the following estimates:

$$l_{50} = 30.95cm$$

$$\delta = 1.57cm^{-1}$$

Natural mortality M:

Taken as age-independant and estimated directly in the model fitting procedure if not indicated otherwise.

B.4. Bayesian extension

The RC is extended to a Bayesian formulation by first specifying priors for all the estimated parameters. All priors are uniform with the intent of being uninformative, except for one of the selectivity parameters (l_1 - see equation B27) and the carrying capacity *K*, for which the following prior was used to exclude unrealistically high values:

$$prior = \exp\left(\frac{-(x_i-\mu)^p}{2\sigma^p}\right) \qquad \text{(B33)}$$

where μ=23, p=6 and σ=4 for l_1 and μ=8.5, p=4 and σ=1.5 for ln*K*.

The Bayesian computations were effected by using the MCMC capability of ADMB. A chain of 3 million was used, with a burn in period of 300 thousand excluded. Convergence of the MCMC was checked using three tests - Geweke, Heidelberg and Welch, and Raftery and Lewis. These confirmed convergence with the possible exception of one selectivity parameter.

Appendix C - The Dynamic Production Models

B.1. The resource dynamics

The resource dynamics are modelled by the Pella-Tomlinson form of the biomass-production function:

$$B_{y+1} = \frac{r}{\mu} B_y \left[1 - \left(\frac{B_y}{K} \right)^{\mu} \right] - C_y \tag{C1}$$

where

B_y is the biomass in year *y*,

r is the intrinsic growth rate parameter,

K is the unexploited equilibrium biomass, and

μ is the shape parameter.

The Schaefer form of the biomass-production function corresponds to the Pella-Tomlinson form with $\mu = 1$.

C.2. The likelihood function

The model is fit to a CPUE index. The likelihood is calculated by assuming that the observed CPUE indices are log-normally distributed about their expected values:

$$I_y = \hat{I}_y \exp(\varepsilon_y) \quad \text{or} \quad \varepsilon_y = \ell\text{n}(I_y) - \ell\text{n}(\hat{I}_y) \tag{C2}$$

where

I_y is the CPUE abundance index for year *y*,

$\hat{I}_y = \hat{q}\ \hat{B}_y$ is the corresponding model estimate, where $\hat{B}_y$ is the model estimate of resource biomass as used in equation C1,

$\hat{q}$ is the constant of proportionality (catchability) for the CPUE abundance series, and

ε_y from $N\left(0, (\sigma_y)^2\right)$.

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

$$-\ell\text{n}\, L^{\text{CPUE}} = \sum_y \left\{ \ell\text{n}(\sigma_{com}) + (\varepsilon_y)^2 / \left(2\sigma_{com}^2\right) \right\} \tag{C3}$$

where

σ_{com} is the standard deviation of the residuals for the logarithm of the CPUE index, which is estimated in the fitting procedure by its maximum likelihood value:

$$\sigma_{com} = \sqrt{\frac{1}{n}\sum_y \left[\ell n\left(I_y\right) - \ell n\left(\hat{I}_y\right)\right]^2} \tag{C4}$$

where *n* is the number of data points for the CPUE index.

The catchability coefficient q for the CPUE abundance index is estimated by its maximum likelihood value:

$$\ell n\,\hat{q} = 1/n \sum_y \left(\ln I_y - \ln \hat{B}_y\right) \tag{C5}$$

ADDENDUM

Introduction

During the wreckfish peer review discussions in March 2014, which considered the main text of this paper, a number of further calculations were requested. The results of these are reported in this Addendum.

The peer reviewers also requested a list of the model parameters estimated when fitting the RC; this list is given in Table Add.1 below.

Further sensitivities requested

Table Add.2 gives results for the following sensitivities requested by the peer reviewers.

S15) Allow for a change in the commercial selectivity between 1999 and 2000.
S16) Make use of a "mixed" growth curve, this being a combination of the two curves plotted in Figure 11 of the main text, with the faster growth up to age 4 (red curve) followed by the slower growth (black curve – the original curve provided by Lytton) at higher ages.
S17) Fixing the standard deviation of the length-at-age distributions on input.

Allowing for a change in the commercial selectivity between 1999 and 2000 improves the negative log-likelihood by over 6 points (i.e. this refinement is AIC justified) (Table Add.2), but does not result in any appreciable difference to results of pertinence to management (Figure Add.1).

Similarly, using the "mixed" growth curve makes virtually no difference to the results (Table Add.2 and Figure Add.2).

In Figure Add.3, the observed standard deviations of the length-at-age data (Lytton, pers. commn) are compared to the estimated values for the RC (constant standard deviations for all ages) and to sensitivity S10 in which the standard deviations are assumed proportional to the mean length-at-age. Since the observed values are lower than those estimated in the RC and sensitivity S10, the standard deviation is fixed in sensitivity S17 to correspond to the average of the observed values (78.3 mm fork length). The resultant fit to the CAL data deteriorates substantially (Table Add.2 and Figure Add.4). It is not altogether surprising that the model prefers a larger standard deviation in length-at-age than indicated by Lytton's age readings, as a number of additional factors could lead to such an effect. For example, the wreckfish birthdates are not all on exactly the start of each year as assumed by the model, but are spread over a longer period; the model the effectively adds variance to the length-at-age distributions to account for that.

Negative log likelihood profiles for the RC and sensitivity S8c in which the CAL is downweighted by a factor of 0.1 are plotted in Figure Add.5, as requested by the peer reviewers. It is evident that the CPUE data play the dominant role in the model's ability to estimate natural mortality, *M*.

F_{MSY} Projections requested

Projections of the RC for 10 years under F_{MSY} (after three years assumed to have been at the current catch limit of 235 thousand lb) have been run as requested by the peer reviewers. Tables Add.3 and Add.4 give MLE and Bayesian results, which are compared to a series of constant catch projections. Figures Add.6 and Add.7 plot the projections.

Table Add.1: List of the model parameters estimated for the RC.

Parameter	Comments
K^{sp}	Pre-exploitation spawning biomass
M	Age-independent natural mortality
Selectivity l_1	eqn B27
Selectivity l_2	eqn B27
β^*	sd of length-at-age, eqn B9

Table Add.2: Results for the RC and the further sensitivities requested. Values fixed on **input are bolded**. Values in parenthesis are Hessian-based CVs.

Run	RC	S15) Change in selectivity 1999/2000	S16) Mixed growth curves	S17) Fixed SD of length-at-age
'-lnL:overall	-68.2	-74.8	-68.2	-50.8
'-lnL:CPUE	-31.2	-31.3	-31.2	-30.6
'-lnL:CAL	-37.0	-43.4	-37.0	-20.1
'-lnL:RecRes	-	-	-	-
-lnL:h	-	-	-	-
θ	**1** **-**	**1** **-**	**1** **-**	**1**
ϕ	**0** **-**	**0** **-**	**0** **-**	**0**
h	**0.75** **-**	**0.75** **-**	**0.75** **-**	**0.75**
M	0.037 (0.11)	0.037 (0.11)	0.037 (0.11)	0.029 (0.13)
K^{sp} (tons)	7105 (0.08)	7065 (0.07)	7098 (0.08)	8401 (0.10)
B^{sp}_{2010} (tons)	2864 (0.22)	2832 (0.21)	2854 (0.22)	3526 (0.24)
B^{sp}_{2010}/K^{sp}	0.40 (0.15)	0.40 (0.14)	0.40 (0.15)	0.42 (0.15)
$MSYL^{sp}$	0.25 (0.11)	0.26 (0.13)	0.25 (0.11)	0.26 (0.16)
B^{sp}_{MSY} (tons)	1809 (0.14)	1813 (0.14)	1807 (0.14)	2183 (0.17)
$B^{sp}_{2010}/B^{sp}_{MSY}$	1.58 (0.12)	1.56 (0.14)	1.58 (0.12)	1.62 (0.18)
$B^{sp}_{2010}/0.75B^{sp}_{MSY}$	2.11 (0.12)	2.08 (0.14)	2.11 (0.12)	2.15 (0.18)
MSY ('000 lb)	279 (0.14)	282 (0.13)	279 (0.14)	249 (0.15)
F_{MSY}	0.065 -	0.067 -	0.065 -	0.049 -
F_{2010}	0.038 (0.22)	0.039 (0.21)	0.038 (0.22)	0.031 (0.25)
F_{2010}/F_{MSY}	0.583 (0.22)	0.581 (0.21)	0.585 (0.22)	0.647 (0.25)
σ_{com}	0.13 (0.05)	0.13 (0.04)	0.13 (0.05)	0.13 (0.05)
σ_{len}	0.09 (0.01)	0.08 (0.01)	0.09 (0.01)	0.11 (0.01)

Table Add.3: Projections results (MLE and Bayesian) for the RC under various future constant catches and constant *F* projections. Biomass ratios below 1, and fishing mortality ratios above 1, are shown shaded.

		$B^{sp}_{2020}/B^{sp}_{2010}$						$B^{sp}_{2020}/B^{sp}_{MSY}$						F_{2020}/F_{MSY}					
		Future constant catch from 2014 ('000 lb):						Future constant catch from 2014 ('000 lb):						Future constant catch from 2014 ('000 lb):					
		235	260	285	310	335	F_{MSY}	235	260	285	310	335	F_{MSY}	235	260	285	310	335	F_{MSY}
RC	MLE	1.026	1.007	0.987	0.967	0.948	0.884	1.624	1.593	1.562	1.531	1.500	1.403	0.518	0.585	0.655	0.729	0.805	1.000
	Posterior median	1.030	1.018	1.004	0.989	0.973	0.852	1.886	1.858	1.829	1.800	1.770	1.548	0.396	0.445	0.496	0.548	0.603	1.000
	5%-ile	0.983	0.961	0.939	0.916	0.893	0.671	1.342	1.311	1.277	1.245	1.212	1.243	0.087	0.097	0.106	0.116	0.126	1.000
	95%-ile	1.060	1.046	1.035	1.024	1.015	0.920	3.175	3.160	3.146	3.133	3.119	2.078	0.736	0.836	0.942	1.055	1.174	1.000

Table Add.4: MLE and Hessian-based CV projections results for the RC under constant $F = F_{MSY}$ (from 2014) after assumed constant catches of 235 thousand lb for 2011-2013. Catch units are ‘000 lb.

	MLE	CV
$B^{sp}_{2020}/B^{sp}_{2010}$	0.88	(0.03)
$B^{sp}_{2020}/B^{sp}_{MSY}$	1.40	(0.09)
F_{2020}/F_{MSY}	1.00	-
C_{2013}	235.0	-
C_{2014}	439.7	(0.22)
C_{2015}	429.4	(0.22)
C_{2016}	419.7	(0.21)
C_{2017}	410.6	(0.21)
C_{2018}	402.0	(0.20)
C_{2019}	394.0	(0.20)
C_{2020}	386.6	(0.19)

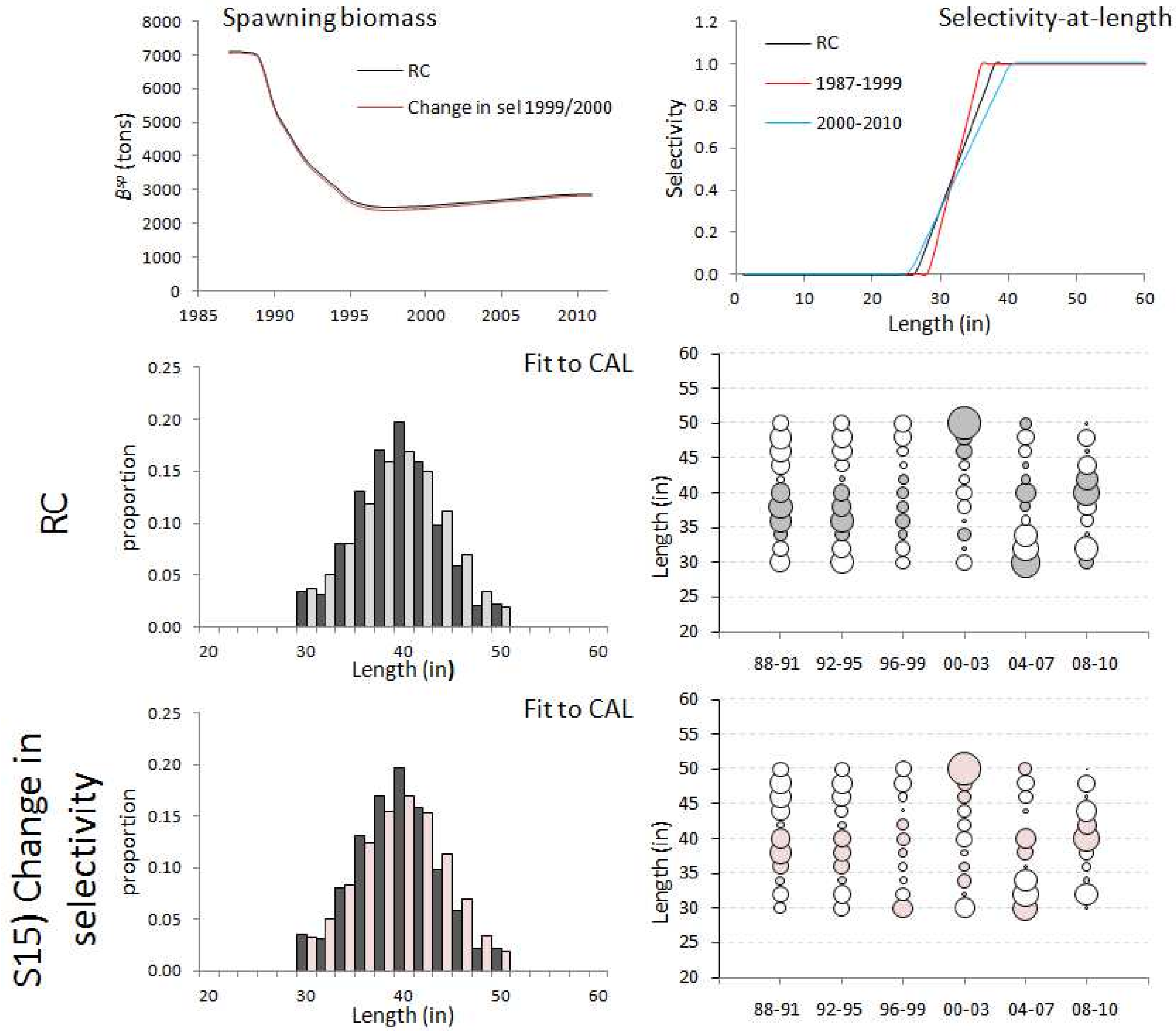

Figure Add.1: Spawning biomass trajectories, selectivities-at-length and fits to the CAL data (averaged over all the years for which data are available together with bubble plots of residuals) for the RC and the sensitivity which allows for a change in the commercial selectivity between 1999 and 2000 (S15).

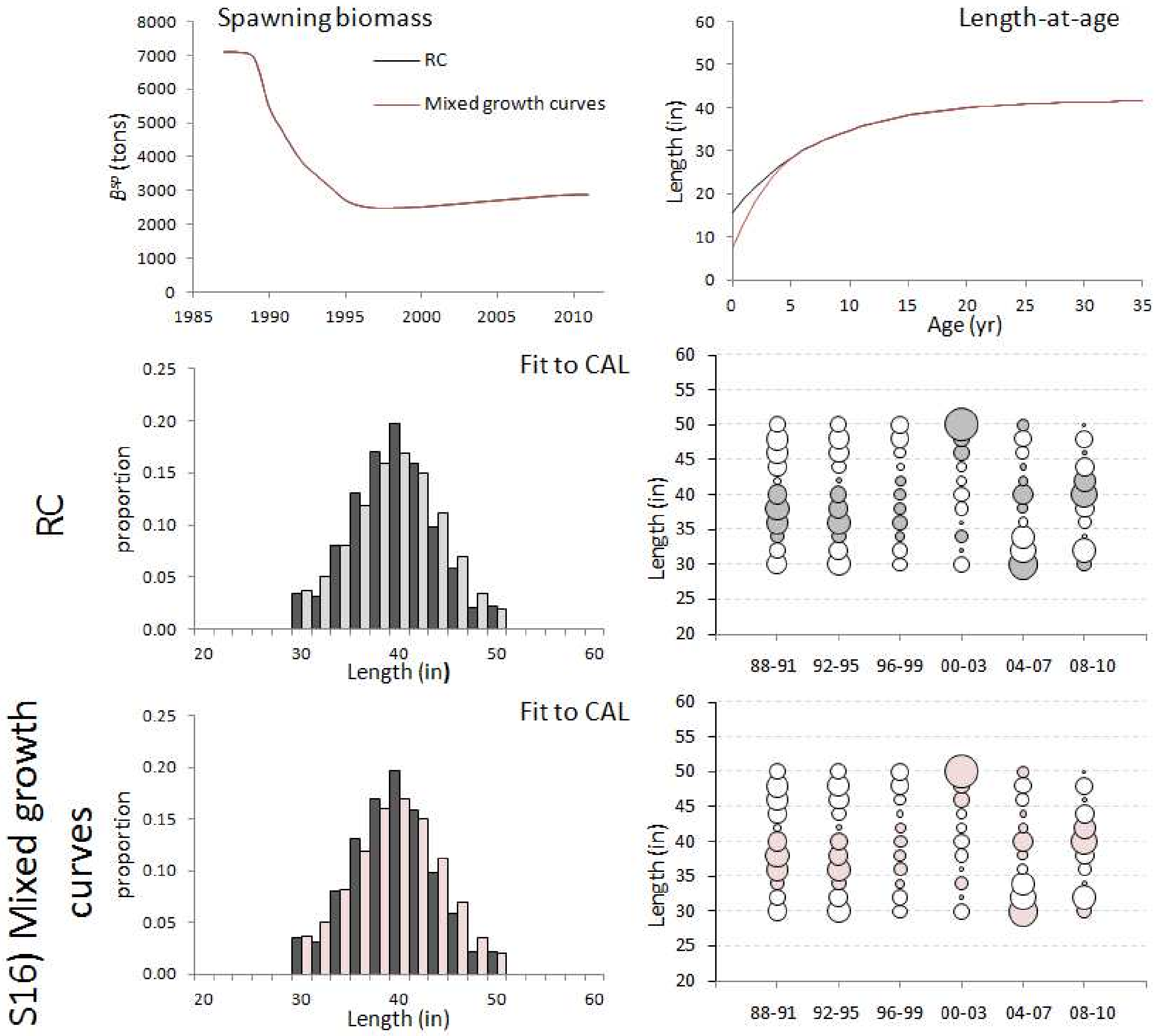

Figure Add.2: Spawning biomass trajectories, growth curves and fits to the CAL data (averaged over all the years for which data are available together with bubble plots of residuals) for the RC and the sensitivity with mixed growth curves (S16).

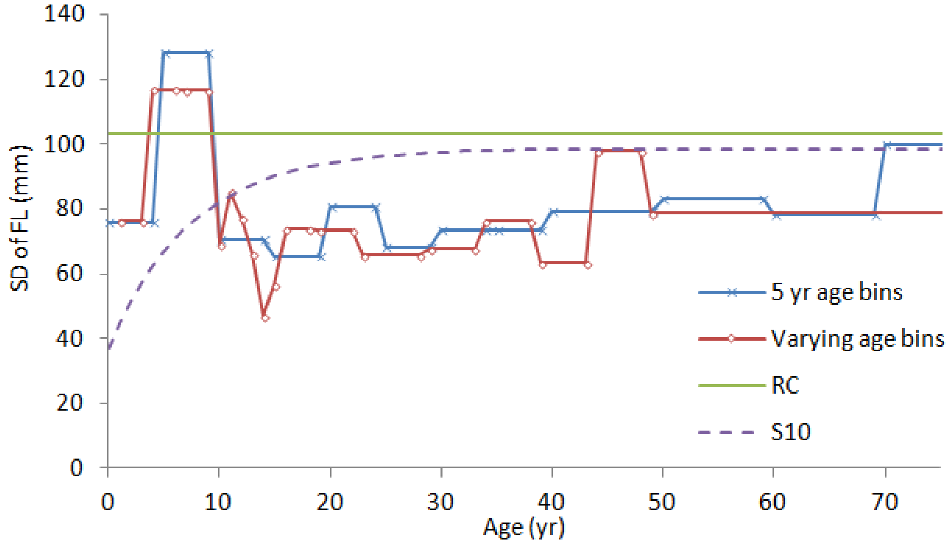

Figure Add.3: Observed standard deviations for the length-at-age distribution for observed ageing data grouped into 5-year age bins and grouped into age bins of varying widths (Lytton, pers. commn) and corresponding estimated values for the RC (constant standard deviation for all ages) and sensitivity S10 in which the standard deviations are assumed proportional to the mean length-at-age.

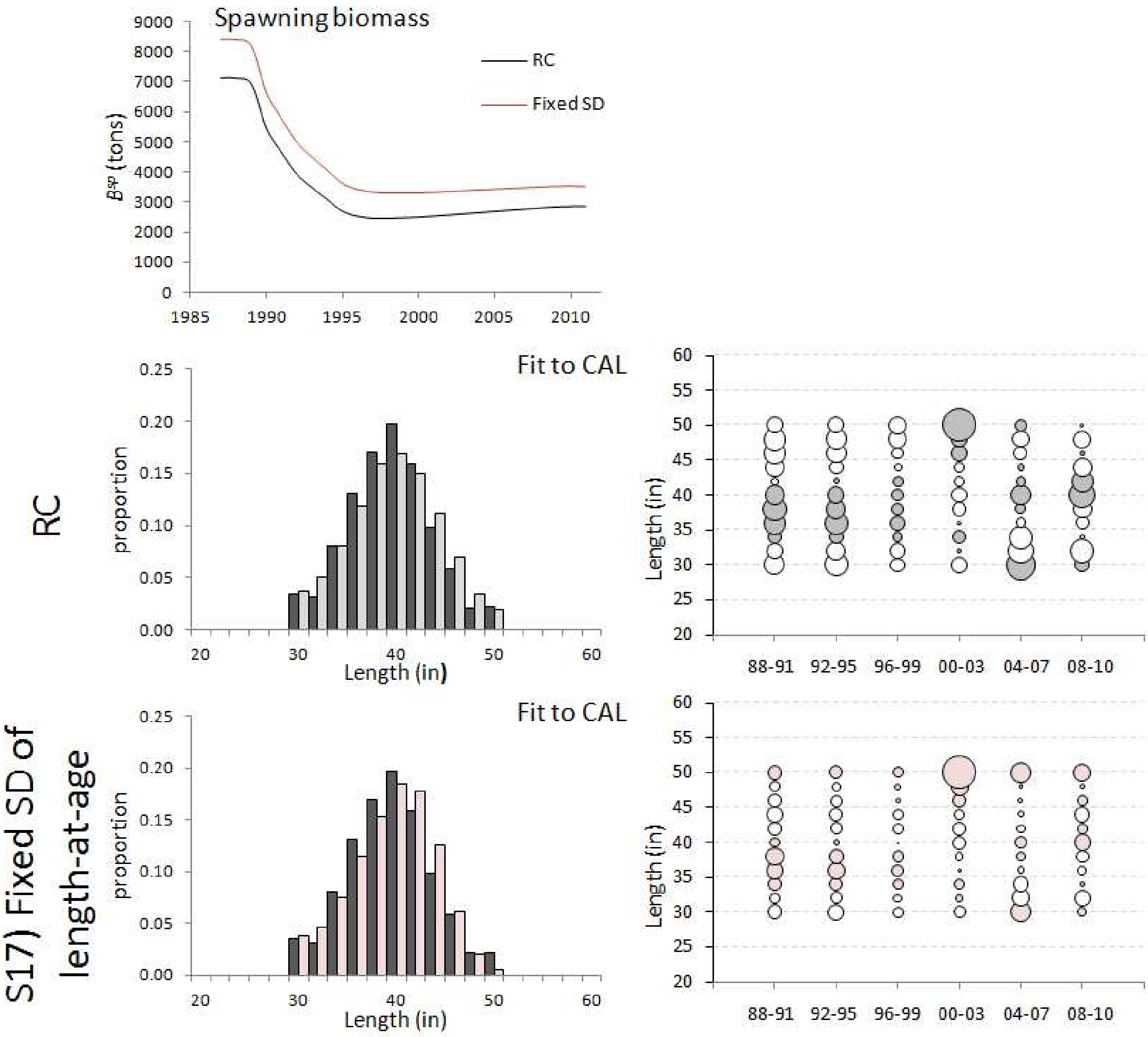

Figure Add.4: Spawning biomass trajectories, and fits to the CAL data (averaged over all the years for which data are available together with bubble plots of residuals) for the RC and the sensitivity fixing the standard deviation of the length-at-age distribution to 78.3 mm based on the Lytton ageing data (S17).

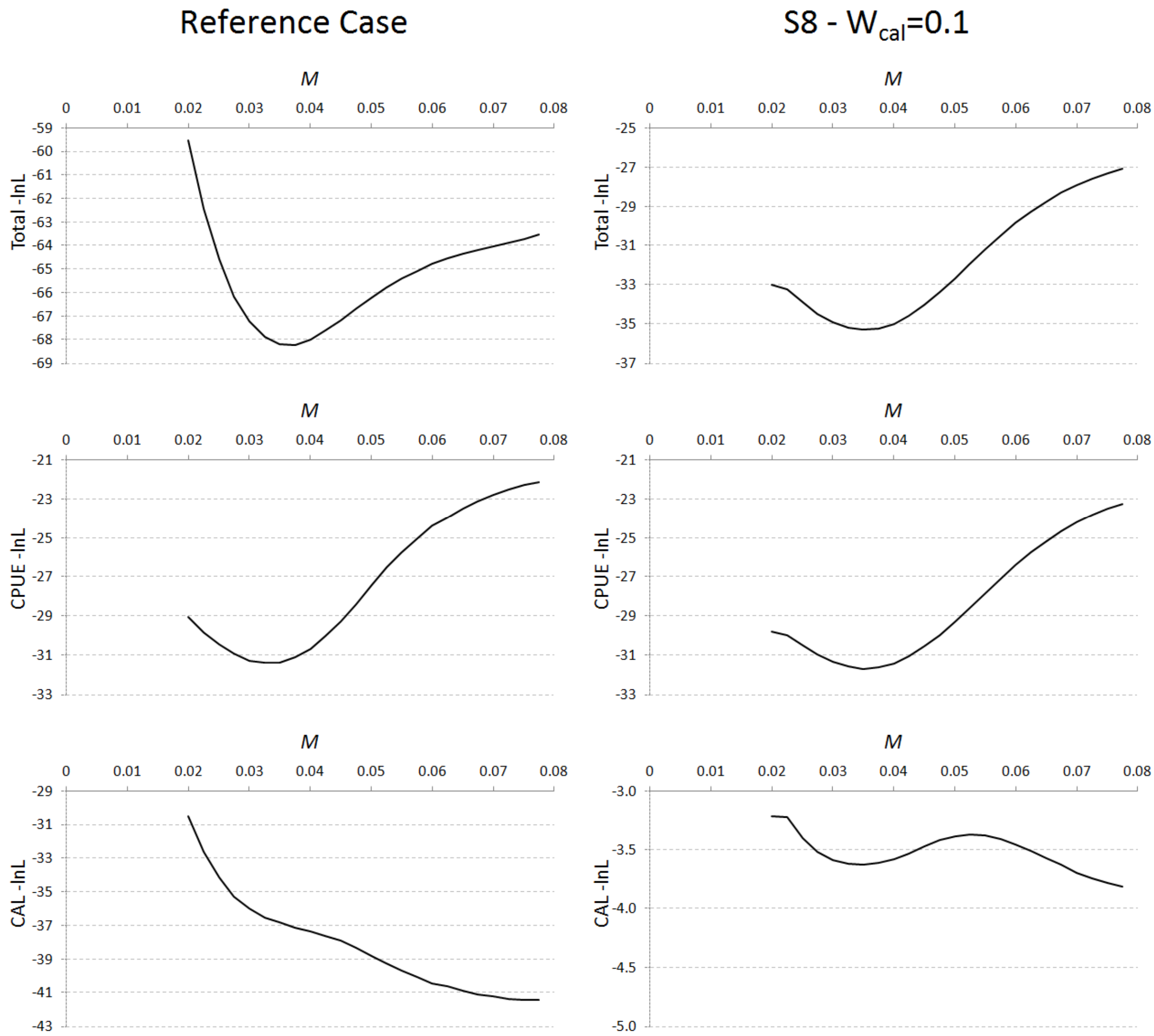

Figure Add.5: Negative log-likelihood profiles for *M* for the RC and for sensitivity S8c in which the CAL data are downweighted by a multiplicative factor of 0.1.

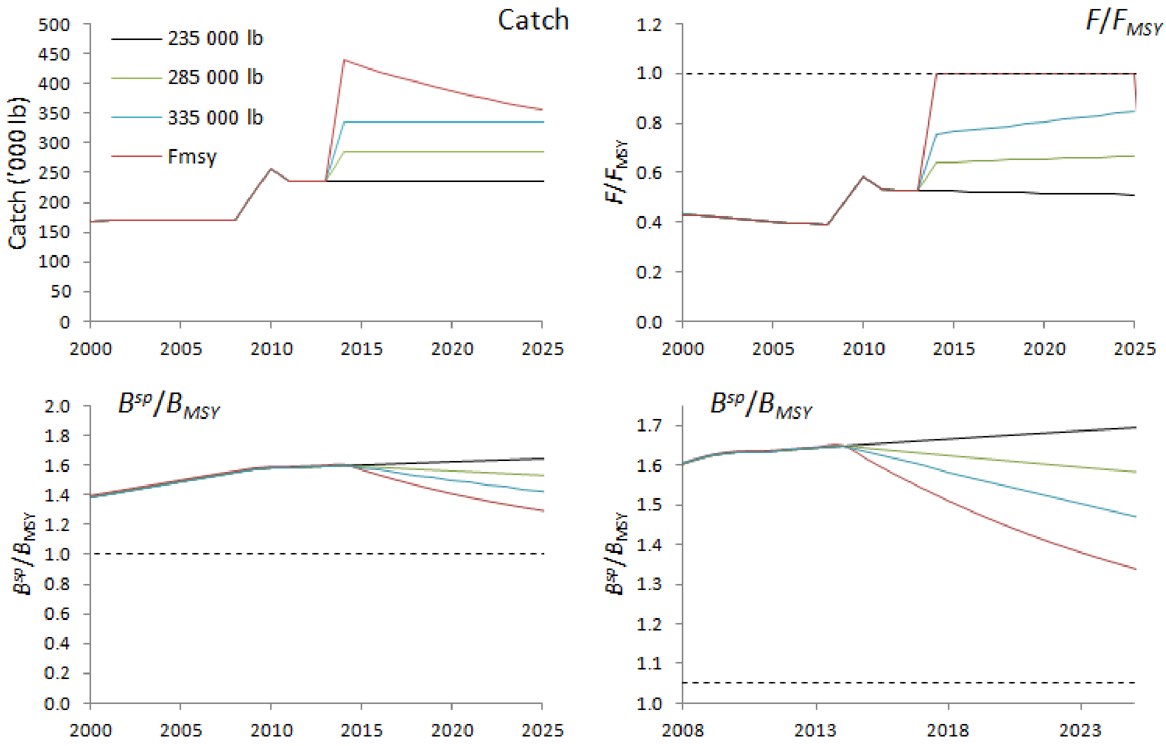

Figure Add.6: MLE catch, spawning biomass (relative to B_{MSY}) and fishing mortality (relative to F_{MSY}) trajectories under a series of constant catch and F_{MSY} projections for the deterministic RC.

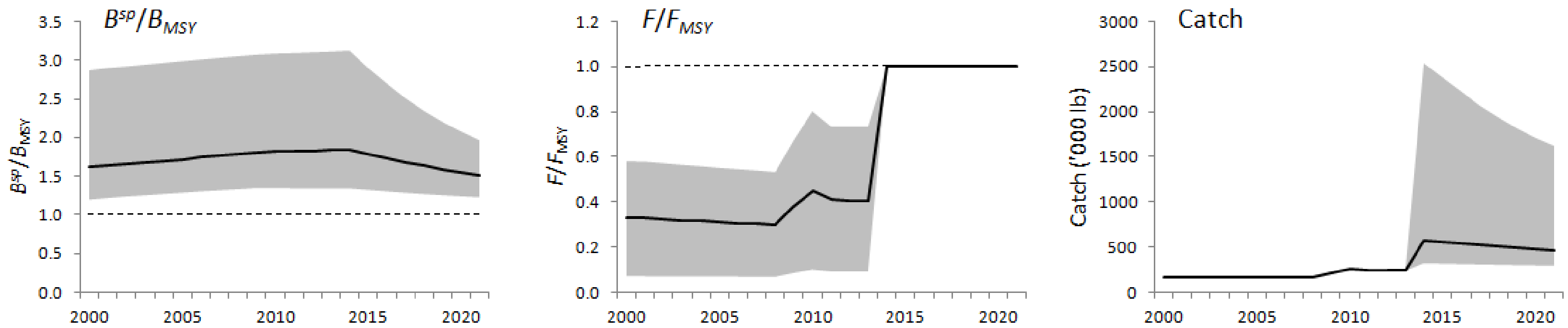

Figure Add.7: Spawning biomass (relative to B_{MSY}), fishing mortality (relative to F_{MSY}) and catches median and lower and upper 5%iles Bayesian trajectory projections under constant F_{MSY} projections commencing in 2014 for the Bayesian RC. The solid curves reflect the posterior medians, while the shading shows the 90% posterior probability envelopes.