OMP-04 Under Robustness Tests to the Base Case Assessments of the South African Anchovy and Sardine Resources

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Introduction

The results at the posterior mode for some robustness tests to the base case sardine and anchovy assessments were presented in Cunningham and Butterworth (2004x). These results are repeated here together with a few further tests, including a robustness test designed to mimic a perceived slower growth in sardine since 2000. New results presented in this document include those obtained from projecting the resource into the future using OMP-04 and the fishery management system outlined in Cunningham and Butterworth (2004c). The thresholds and rules for exceptional circumstances provisions as recommended in Cunningham and Butterworth (2004z) are used for all projections with OMP-04 in this document. Such projections are initially done using the results from the posterior modes in order that tests that show a substantial difference could be singled out. Bayesian analyses of these selected tests were then run and the resource projected using the Bayesian results.

Anchovy Robustness Tests

The robustness tests to the base case anchovy assessment considered are as follows (see Table 1 for a summary):

A_0 – base case assessment (Cunningham and Butterworth 2004a)

A_{M1} – adult and juvenile natural mortality of 0.6 year^{-1}

A_{M2} – adult and juvenile natural mortality of 1.2 year^{-1}

A_{M3} – adult and juvenile natural mortality of 1.5 year^{-1}

A_{M4} – juvenile natural mortality of 1.5 year^{-1}

A_{HS} – hockey stick stock-recruitment curve with the inflection point estimated (inflection point equal to 20% of K in base case)

A_{BH} – Beverton Holt stock-recruitment curve

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A_R – Ricker stock-recruitment curve

A_{10} – 10cm cut-off length for calculating the proportion of 1-year-olds in the November survey

$A_{10.5}$ – 10.5cm cut-off length for calculating the proportion of 1-year-olds in the November survey

A_{11} – 11cm cut-off length for calculating the proportion of 1-year-olds in the November survey

A_{kegg1} – negatively biased egg surveys, i.e., $k_g^A = 0.75$

A_{kegg2} – positively biased egg surveys, i.e., $k_g^A = 1.25$

A_{lam1} – fix $(\lambda_r^A)^2 = 0$, where $(\lambda_r^A)^2$ denotes the additional variance (over and above the survey sampling CV) associated with the recruit survey

A_{lam2} – estimate $(\lambda_N^A)^2$, where $(\lambda_N^A)^2$ denotes the additional variance (over and above the survey sampling CV) associated with the November survey

For A_{HS}, the prior distribution for the inflection point in the hockey stick curve as a proportion of carrying capacity $\frac{b^A}{K^A} \sim U(0,1)$ is introduced. For A_{BH}, the prior $\frac{b^A}{K^A} \sim U(0,1)$ is again used and equation (A.5) of Cunningham and Butterworth (2004a) is replaced with

$$N_{y,0}^A = \frac{a^A B_{y,N}^A}{b^A + B_{y,N}^A} e^{\varepsilon_y^A}, \qquad y = 1980, \ldots, 2002$$

and equation (A.9) is replaced with

$$K^A = a^A e^{\frac{1}{2}\left(0.4^2 + (\lambda_0^A)^2\right)} \left[\sum_{a=1}^{4} \overline{w}_a^A e^{-M_{ju}^A - (a-1)M_{ad}^A} \right] - b^A .$$

For A_R, equation (A.5) of Cunningham and Butterworth (2004a) is replaced with

$$N_{y,0}^A = a^A B_{y,N}^A e^{-b^A B_{y,N}^A} e^{\varepsilon_y^A}, \qquad y = 1980, \ldots, 2002$$

and equation (A.9) is replaced with

$$K^A = \frac{1}{b^A} \ln\left\{ a^A e^{\frac{1}{2}\left(0.4^2 + (\lambda_0^A)^2\right)} \left[\sum_{a=1}^{4} \overline{w}_a^A e^{-M_{ju}^A - (a-1)M_{ad}^A} \right] \right\}.$$

In addition, the prior distributions for the two stock-recruitment parameters in A_R are changed to $\ln(a) \sim U(-4,8)$ and $\ln\left(\frac{b^A}{1+b^A}\right) \sim U(-1000,1000)$.

<u>Sardine Robustness Tests</u>

The robustness tests to the base case sardine assessment considered are as follows (see Table 5 for a summary):

S_0 – base case assessment (Cunningham and Butterworth 2004b)

S_{kN1} – unbiased November spawner biomass surveys, i.e., $k_N^S = 1$

S_{kN2} – greater negatively biased November spawner biomass surveys, i.e., $k_N^S = 0.5$

S_{M1} – adult natural mortality of 0.3 year^{-1}

S_{M2} – adult natural mortality of 0.5 year^{-1}

S_{M3} – juvenile natural mortality of 0.6 year^{-1}

S_{M4} – juvenile natural mortality of 1.4 year^{-1}

S_{BH} – Beverton Holt stock-recruitment curve

S_R – Ricker stock-recruitment curve

S_{lam1} – fix $\left(\lambda_N^S\right)^2 = 0$, where $\left(\lambda_r^S\right)^2$ denotes the additional variance (over and above the survey sampling CV) associated with the recruit survey

S_{lam2} – fix $\left(\lambda_N^S\right)^2 = 0$ and $\left(\lambda_r^S\right)^2 = 0$, where $\left(\lambda_N^S\right)^2$ denotes the additional variance (over and above the survey sampling CV) associated with the November survey

S_{slow} – average age-length-keys representing a slower growth scenario for sardine are used

For S_{BH}, the prior distribution for a^S is modified to $a^S \sim N\left(50, 1^2\right)$, equation (A.4) of Cunningham and Butterworth (2004b) is replaced with

$$N_{y,0}^S = \frac{a^S B_{y,N}^S}{b^S + B_{y,N}^S} e^{\varepsilon_y^S}, \qquad y = 1979, \ldots, 2002$$

and equation (A.11) is replaced with

$$K^S = a^S e^{\frac{1}{2}\left(0.4^2 + \left(\lambda_0^S\right)^2\right)} \left[\sum_{a=1}^{5} \overline{w}_a^S e^{-M_{ju}^S - (a-1)M_{ad}^S}\right] - b^S .$$

For S_R, equation (A.4) of Cunningham and Butterworth (2004b) is replaced with

$$N_{y,0}^S = a^S B_{y,N}^S e^{-b^S B_{y,N}^S} e^{\varepsilon_y^S}, \qquad y = 1980, \ldots, 2002$$

and equation (A.11) is replaced with

$$K^S = \frac{1}{b^S} \ln\left\{a^S e^{\frac{1}{2}\left(0.4^2 + \left(\lambda_0^S\right)^2\right)} \left[\sum_{a=1}^{5} \overline{w}_a^S e^{-M_{ju}^S - (a-1)M_{ad}^S}\right]\right\}.$$

In addition, the prior distributions for the two stock-recruitment parameters in S_R are changed to $a^S \sim U(-1000, 1000)$ and $\ln\left(\frac{b^A}{1 + b^A}\right) \sim U(-1000, 1000)$.

In S_{slow}, the average age-length-keys used for commercial catches and November surveys since 2000 are replaced with age-length-keys that differ by 2cm. These new age-length-keys were constructed by simply 'moving' the old age-length-keys 2cm (or 4 length classes) 'up', i.e. an age-key relating to a length class under S_0, relates to a length class which is 2cm smaller in S_{slow}. The input files to the S_{slow} assessment robustness test therefore differ from S_0 in the catch-at-age, catch weight-at-age, sardine juvenile catch prior to the recruitment survey, November survey weight-at-age, and average weight-at-age for 2000 to 2003. Tests assuming a smaller (1cm) and greater (3cm) change were also conducted, although results from these tests are not shown in this document.

<u>Bayesian Integration</u>

The AD Model Builder package was used to perform the Bayesian integration. Due to time constraints, only one chain of 40 000 000 samples was simulated, begun at the posterior mode. A burn-in of 150 000 (more for A_R!) was discarded and the remaining chain was thinned by 1000 to decrease any autocorrelation. Convergence is tested using the BOA (Bayesian Output Analysis) package (Smith 2003). The diagnostics from the tests of Geweke (1992), Raftery and Lewis (1992) and Heidelberger and Welch (1983) were monitored.

A chain was only accepted as having converged once all of these diagnostic tests were passed for all parameters. The autocorrelations for each estimable parameter and cross-correlations between the parameters were also monitored to assess if further thinning or re-parameterisation was required.

The convergence diagnostics for A_R chain were unsatisfactory, but due to time constraints, OMP-04 was still run using a sample from this chain. This needs to be borne in mind when considering the results below.

<u>Results</u>

Anchovy robustness tests

The results at the posterior mode are given in Tables 1 to 4 (repeated from Cunningham and Butterworth, 2004x). Although the value at the posterior mode is greater for A_{M2} and A_{M3}, compared to A_0, the higher natural mortality cases are assumed to be unrealistically high. In addition, for ease of comparability with the assessments used to construct OMP-02, it is suggested that the base case assessment natural mortality remain at 0.9 year^{-1}.

The Beverton-Holt and Ricker stock-recruitment curves provide a better fit to the model at the posterior mode than A_0. In addition, estimating the inflection point, b, also results in a better fit. The stock-recruitment curves and the predicted spawner biomass and recruitment are shown in Figure 1.

For an initial comparison, the resource was projected forward using OMP-04 and the results at the posterior mode for all the anchovy robustness tests considered (Table 9, sardine base case MCMC results were used for these comparisons). The risk to the resource was highest under the cases of adult and juvenile natural mortality of 0.6 year^{-1} (A_{M1}), alternative stock-recruitment models (A_{HS}, A_{BH}, A_R) and positively biased egg surveys, i.e., $k_g^A = 1.25$ (A_{kegg2}).

From these results, Bayesian analyses were then performed on a few selected tests and the resource was projected forward using OMP-04 and the results from the posterior distributions of these robustness tests. Note that the risk for A_0 in Table 10 is now 0.238, even though OMP-04 was tuned for $Risk^A \leq 0.3$. This is because of the modification made to the exceptional circumstances provisions as documented in Cunningham and Butterworth (2004z), which results in a lower risk for anchovy under the base case assessment. Comparing the summary statistics resulting from these projections in Table 10, this shows that for A_{BH}, the robustness test resulting in greatest risk to the anchovy resource, the risk is estimated at 0.316. This is not substantially higher than the 30% for risk to which OMP-04 was initially tuned and average biomass at the end of the projection period is estimated to be almost 40% of carrying capacity. Were the anchovy resource to respond in such a manner reflecting a Beverton Holt stock-recruitment model over the next 2 decades, the average catch would decrease from 303 thousand tonnes under the base case to 268 thousand tonnes.

Sardine robustness tests

The results at the posterior mode are given in Tables 5 to 8 (repeated from Cunningham and Butterworth (2004x). The Beverton-Holt and Ricker stock-recruitment curves do not currently fit the stock-recruitment data well (Figure 2). This may be due to model mis-specification.

The resource was projected forward using OMP-04 and the results at the posterior mode for all the sardine robustness tests except S_{lam1} (poor fit to the data) and S_{lam2} (little difference to the results) (Table 11, anchovy base case MCMC results were used for these comparisons). Although the risk to the sardine resource was estimated to be higher under S_{BH} and S_R were higher, Bayesian analyses were not performed on these tests because of the poor fit of these curves to the stock-recruitment data at the posterior mode. Besides these tests, the risk to the resource was highest assuming unbiased November spawner biomass surveys, i.e., $k_N^S = 1$ (S_{kN1}).

Bayesian analyses were then performed on S_{kN1} and S_{Slow} and the resource was projected forward using OMP-04 and the results from the posterior distributions of these robustness tests. Comparing the summary statistics resulting from these projections in Table 12, this shows

<u>Discussion</u>

The results at the posterior mode for the robustness tests to the base case sardine and anchovy assessments have been presented in this document and MCMC chains have been simulated for some tests

(A_{M1}, A_{M2}, A_{HS}, A_{BH}, A_R, A_{kegg2}, S_{kN1} and S_{Slow}). These tests were selected as they indicated a higher risk when projecting using results from the posterior mode, they had a better fit to the data at the posterior mode, or for their potential to result in a greater difference in projection results from the base case

The results presented in this document show…

References

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Table 1. Assumptions and likelihood and prior values for the anchovy robustness tests at the posterior mode. Blank cells indicate no change from A_0. (Symbols and headings are defined in the appendix.)

Test	M^A_{ad}	M^A_{ja}	S-R curve	Ageing Method	k^A_g	$(\lambda^A_r)^2$	$(\lambda^A_N)^2$	Neg. Posterior	Neg. lnL	Neg. lnL_{Nov}	Neg. lnL_{Egg}	Neg. lnL_{Rec}	Neg. lnL_{Prop}	Neg. $lnPr(k_N)$	Neg. $lnPr(k_r)$	Neg. lnPr(del)	Neg. $lnPr(k_{prop})$
A_0	0.9	0.9	Hockey Stick	Prosch	1.0	estimated	fixed=0	45.86	20.62	-6.59	3.67	10.83	12.72	0.76	0.21	23.69	0.58
A_{M1}	0.6	0.6						50.43	27.02	-2.42	4.79	11.50	13.15	0.82	0.65	21.77	0.18
A_{M2}	1.2	1.2						43.34	17.18	-7.19	3.17	9.70	11.49	0.68	0.11	23.95	1.43
A_{M3}	1.5	1.5						42.67	15.02	-8.10	2.83	9.12	11.17	0.67	0.27	24.02	2.70
A_{M4}		1.5						47.15	21.57	-5.53	3.78	11.22	12.09	0.72	0.10	24.18	0.58
A_{HS}			Hockey Stick, b estimated					43.95	21.13	-5.44	4.18	10.40	12.00	0.79	0.21	21.23	0.59
A_{BH}			Beverton Holt					42.47	21.34	-4.49	4.37	9.56	11.90	0.74	0.20	19.60	0.59
A_R			Ricker					42.61	21.45	-4.42	4.46	9.59	11.83	0.75	0.20	19.62	0.60
A_{10}				10cm				47.20	19.96	-6.33	3.44	11.79	11.05	0.76	0.22	23.92	2.33
$A_{10.5}$				10.5cm				47.19	21.72	-6.88	3.45	10.98	14.16	0.74	0.21	23.99	0.54
A_{11}				11cm				47.63	22.56	-7.00	3.60	10.59	15.37	0.73	0.21	23.96	0.17
A_{kegg1}					0.75			47.05	21.79	-5.46	3.88	10.86	12.51	0.26	0.10	24.37	0.52
A_{kegg2}					1.25			44.95	19.84	-6.69	3.56	10.61	12.36	1.33	0.39	22.74	0.64
A_{lam1}						fixed=0		55.35	29.90	10.30	5.93	2.32	11.35	0.51	0.13	24.26	0.55
A_{lam2}							estimated	45.86	20.62	-6.59	3.67	10.83	12.72	0.76	0.21	23.69	0.58

Table 2. Key model parameters for the anchovy robustness tests at the posterior mode. (Symbols and headings are defined in the appendix.)

Test	k_N^A	k_r^A	k_r^A / k_N^A	k_q^A	$(\lambda_N^A)^2$	$(\lambda_r^A)^2$	$(\lambda_p^A)^2$	$(\lambda_0^A)^2$	$(\sigma_q^A)^2$
A_0	1.384	0.984	0.711	1.268	0.000	0.154	0.254	0.388	0.16
A_{M1}	1.416	1.315	0.929	0.945	0.000	0.167	0.283	0.292	0.16
A_{M2}	1.331	0.736	0.553	1.758	0.000	0.133	0.183	0.357	0.16
A_{M3}	1.325	0.583	0.440	2.435	0.000	0.123	0.167	0.360	0.16
A_{M4}	1.362	0.786	0.578	1.270	0.000	0.161	0.216	0.367	0.16
A_{HS}	1.398	0.987	0.706	1.279	0.000	0.145	0.211	0.243	0.16
A_{BH}	1.371	0.970	0.708	1.280	0.000	0.130	0.205	0.179	0.16
A_R	1.380	0.975	0.706	1.281	0.000	0.131	0.201	0.184	0.16
A_{10}	1.383	0.997	0.721	2.240	0.000	0.173	0.161	0.397	0.16
$A_{10.5}$	1.371	0.988	0.721	1.244	0.000	0.157	0.357	0.401	0.16
A_{11}	1.367	0.984	0.720	0.649	0.000	0.150	0.463	0.400	0.16
A_{kegg1}	1.035	0.791	0.764	1.233	0.000	0.154	0.241	0.377	0.16
A_{kegg2}	1.705	1.138	0.667	1.310	0.000	0.150	0.232	0.341	0.16
A_{lam1}	1.226	0.880	0.717	1.250	0.000	0.000	0.176	0.371	0.16
A_{lam2}	1.384	0.984	0.711	1.268	0.000	0.154	0.254	0.388	0.16

Table 3. Key outputs from the anchovy robustness tests at the posterior mode (numbers in billions and biomass in thousands of tonnes). (Symbols and headings are defined in the appendix.)

Test	$N_{2003,1}^A$	$N_{2003,2}^A$	$N_{2003,3}^A$	Average 84-99 Biomass
A_0	131.8	45.6	62.7	1022.6
A_{M1}	86.8	43.4	74.9	994.0
A_{M2}	178.0	46.1	44.8	1068.0
A_{M3}	214.9	42.3	28.5	1077.9
A_{M4}	130.7	45.2	63.1	1039.5
A_{HS}	130.5	46.5	61.1	1010.9
A_{BH}	141.6	52.1	61.6	1028.1
A_R	141.7	50.9	61.5	1022.6
A_{10}	129.2	43.5	63.0	1023.6
$A_{10.5}$	132.3	45.6	63.1	1030.4
A_{11}	133.5	46.5	62.7	1031.0
A_{kegg1}	173.1	61.0	82.8	1368.4
A_{kegg2}	106.4	36.8	51.1	829.2
A_{lam1}	198.1	105.2	67.2	1120.6
A_{lam2}	131.8	45.6	62.7	1022.6

Table 4. Key stock-recruitment parameters and outputs for the anchovy robustness tests at the posterior mode. (Symbols and headings are defined in the appendix.)

Test	K^A	a^A	b^A	$\sqrt{0.4^2+\left(\lambda_0^A\right)^2}$	ε_{2002}^A	s_{cor}^A
A_0	2306.6	227.7	461.3	0.740	0.877	0.565
A_{M1}	2492.3	145.9	498.5	0.672	0.812	0.548
A_{M2}	2082.1	342.7	416.4	0.719	1.041	0.581
A_{M3}	1987.8	507.3	397.6	0.721	1.101	0.596
A_{M4}	2111.4	383.6	422.3	0.726	0.913	0.564
A_{HS}	2475.8	262.7	1083.3	0.635	0.786	0.337
A_{BH}	2976.1	503.5	1619.5	0.582	0.472	0.307
A_R	3158.7	0.3	0.0	0.587	0.465	0.288
A_{10}	2306.0	226.6	461.2	0.746	0.857	0.537
$A_{10.5}$	2330.8	228.5	466.2	0.749	0.866	0.543
A_{11}	2338.0	229.4	467.6	0.748	0.871	0.545
A_{kegg1}	2747.9	272.7	549.6	0.733	0.926	0.566
A_{kegg2}	1973.0	199.4	394.6	0.707	0.887	0.561
A_{lam1}	2451.0	243.9	490.2	0.729	1.233	0.614
A_{lam2}	2306.6	227.7	461.3	0.740	0.877	0.565

Table 5. Assumptions and likelihood and prior values for the sardine robustness tests at the posterior mode. Blank cells indicate no change from S_0.. (Symbols and headings are defined in the appendix.)

Test	M^S_{ad}	M^S_{ju}	S-R curve	k^S_N	$(\lambda^S_r)^2$	$(\lambda^S_N)^2$	Neg. Posterior	Neg. lnL	Neg. lnL_{Nov}	Neg. lnL_{Rec}	Neg. lnL_{Prop}	Neg. $lnPr(k_r)$	Neg. lnPr(del)	Neg. $lnPr(k_{prop})$	Neg. $lnPr(var_{prop})$	Neg. lnPr(a)	Neg. $lnPr(a_2)$
S_0	0.4	1.0	Hockey Stick	0.7195	estimated	estimated	69.44	47.17	1.42	14.75	30.99	0.61	7.42	4.50	3.08	5.44	1.23
S_{kN1}				1.0			71.16	48.67	2.17	14.56	31.94	0.93	7.32	4.66	3.14	5.24	1.20
S_{kN2}				0.5			69.01	46.23	1.06	14.82	30.35	0.38	7.96	4.35	3.01	5.78	1.29
S_{M1}	0.3						74.67	48.07	1.52	14.75	31.80	0.75	10.44	4.09	3.14	7.75	0.44
S_{M2}	0.5						70.21	46.58	1.31	14.68	30.59	0.50	8.23	5.12	3.01	5.51	1.26
S_{M3}		0.6					68.01	47.28	1.85	14.34	31.09	0.80	6.36	4.48	3.07	5.21	0.81
S_{M4}		1.4					71.80	46.96	1.05	14.96	30.95	0.46	9.33	4.49	3.07	5.85	1.63
S_{BH}			Beverton Holt				92.50	47.55	3.06	14.94	29.56	0.65	32.55	4.41	2.96	4.38	N/A
S_R			Ricker				88.98	47.60	3.15	14.88	29.56	0.64	33.38	4.42	2.95	N/A	N/A
S_{lam1}						fixed=0	71.94	47.54	2.12	14.48	30.94	0.59	9.18	4.46	3.06	5.92	1.20
S_{lam2}					fixed=0	fixed=0	81.51	56.86	-0.01	15.04	41.83	0.72	8.88	4.53	4.08	5.53	0.91
S_{slow}							70.24	47.68	1.45	15.54	30.69	0.51	7.72	4.52	3.04	5.65	1.11

Note: Not all of the above results were obtained with a positive definite hessian using ADMB. However, tests on which Bayesian analyses were carried out did have a positive definite hessian.

Table 6. Key model parameters for the sardine robustness tests at the posterior mode. (Symbols and headings are defined in the appendix.)

Test	k_N^S	k_r^S	k_N^S/k_r^S	$k_{p,1}^S$	$k_{p,2}^S$	$k_{p,3}^S$	$k_{p,4}^S$	$k_{p,5}^S$	$(\lambda_N^S)^2$	$(\lambda_r^S)^2$	$(\lambda_0^S)^2$	$(\sigma_q^S)^2$
S_0	0.720	1.045	1.453	1.189	0.781	1.043	0.884	1.006	0.000	0.230	0.000	6.582
S_{kN1}	1.000	1.331	0.751	1.168	0.771	1.068	0.937	1.115	0.000	0.222	0.009	6.742
S_{kN2}	0.500	0.783	0.463	1.207	0.783	1.014	0.832	0.918	0.000	0.233	0.000	6.425
S_{M1}	0.720	1.174	0.613	1.298	0.783	0.942	0.724	0.736	0.000	0.236	0.035	6.733
S_{M2}	0.720	0.931	0.772	1.099	0.784	1.155	1.090	1.402	0.000	0.230	0.000	6.416
S_{M3}	0.720	1.221	0.589	1.189	0.778	1.036	0.877	0.998	0.000	0.219	0.000	6.573
S_{M4}	0.720	0.893	0.806	1.185	0.779	1.042	0.883	1.008	0.000	0.239	0.000	6.568
S_{BH}	0.720	1.081	1.502	1.193	0.783	1.026	0.856	0.957	0.000	0.248	0.668	6.289
S_R	0.720	1.071	1.489	1.192	0.783	1.028	0.858	0.964	0.000	0.243	0.918	6.271
S_{lam1}	0.720	1.025	0.702	1.190	0.776	1.035	0.867	0.991	0.000	0.219	0.016	6.534
S_{lam2}	0.720	1.152	0.625	1.241	0.759	1.018	0.902	1.008	0.000	0.000	0.000	9.258
S_{slow}	0.720	0.950	1.320	1.177	0.780	1.048	0.894	1.024	0.000	0.265	0.000	6.491

Table 7. Key outputs from the sardine robustness tests at the posterior mode (numbers in billions and biomass in thousands of tonnes). (Symbols and headings are defined in the appendix.)

Test	$N_{2003,1}^S$	$N_{2003,2}^S$	$N_{2003,3}^S$	$N_{2003,4}^S$	Average 91-94 Biomass	S_1	S_2	S_3	S_4
S_0	31.0	22.6	15.7	7.9	898.1	0.648	1.000	0.865	0.342
S_{kN1}	23.3	16.6	11.4	5.7	662.6	0.645	1.000	0.892	0.362
S_{kN2}	43.3	32.2	22.6	11.7	1288.9	0.653	1.000	0.842	0.325
S_{M1}	37.2	22.9	16.7	9.3	874.6	0.697	1.000	0.780	0.276
S_{M2}	34.7	23.7	14.7	6.6	912.5	0.587	1.000	0.959	0.422
S_{M3}	32.4	23.5	16.5	7.9	899.0	0.638	1.000	0.873	0.346
S_{M4}	30.6	22.3	15.6	7.9	901.2	0.650	1.000	0.864	0.341
S_{BH}	22.8	20.4	18.8	6.2	952.9	0.635	1.000	0.914	0.356
S_R	23.9	21.2	18.2	6.0	952.2	0.632	1.000	0.909	0.351
S_{lam1}	37.4	25.6	17.6	7.6	893.0	0.617	1.000	0.885	0.350
S_{lam2}	32.0	23.3	15.4	7.8	907.9	0.712	1.000	0.852	0.332
S_{slow}	38.6	28.4	21.5	11.5	901.5	0.204	0.516	0.782	1.000

Table 8. Key stock-recruitment parameters and outputs for the sardine robustness tests at the posterior mode. (Symbols and headings are defined in the appendix.)

Test	K^S	a^S	$a^S_{1979-1983}$	b^S	$\sqrt{0.4^2 + (\lambda^S_0)^2}$	ε^S_{2002}	s^S_{cor}
S_0	6267.0	91.811	3.273	2569.6	0.400	-0.037	0.236
S_{kN1}	4891.4	71.352	3.076	1953.1	0.411	-0.062	0.232
S_{kN2}	8581.2	125.713	3.559	3845.7	0.400	-0.035	0.204
S_{M1}	31775.7	380.609	2.715	12710.4	0.442	-0.645	0.282
S_{M2}	5694.8	98.550	3.393	2288.4	0.400	0.051	0.298
S_{M3}	6921.5	67.970	2.715	2928.2	0.400	-0.143	0.190
S_{M4}	6065.4	132.560	3.798	2572.0	0.400	-0.019	0.255
S_{BH}	2063.4	25.351		353.0	0.910	1.169	0.817
S_R	3148.8	0.045	N/A	0.0005	1.038	1.228	0.715
S_{lam1}	9678.1	140.632	3.262	3871.2	0.420	-0.631	0.206
S_{lam2}	6887.8	100.890	3.130	2757.3	0.400	-0.199	0.202
S_{slow}	7255.4	112.949	3.209	3159.2	0.400	-0.078	0.255

Table 9. Summary statistics resulting from running OMP-04 under the anchovy robustness tests, using anchovy results from the posterior mode only. Risk (the probability that adult anchovy biomass falls below 10% of the average adult anchovy biomass between November 1984 and November 1999 at least once during the projection period of 20 years), $Risk^A$*, average directed catch (in thousands of tons),* $\overline{C}^A$*, average proportional annual change in directed catch,* AAV^A*, average biomass at the end of the projection period as a proportion of carrying capacity, as a proportion of the risk threshold, and as a proportion of biomass at the beginning of the projection period, and average minimum biomass over the projection period as a proportion of carrying capacity and as a proportion of the risk threshold, for the OMP-04 trade-off point.*

	A_0	A_{M1}	A_{M2}	A_{M3}	A_{M4}	A_{HS}	A_{BH}	A_R	A_{10}	$A_{10.5}$	A_{11}	A_{kegg1}	A_{kegg2}	A_{lam1}	A_{lam2}
$Risk^A$	0.072	0.096	0.046	0.048	0.048	0.170	0.128	0.180	0.080	0.072	0.072	0.040	0.088	0.064	0.072
$\overline{C}^A$	333.1	323.2	333.4	335.5	334.3	304.7	294.7	291.1	332.7	333.2	333.5	334.4	329.3	337.7	333.1
AAV^A	0.273	0.286	0.266	0.261	0.272	0.285	0.287	0.285	0.281	0.276	0.273	0.270	0.276	0.243	0.273
$\overline{B^A_{2023}/K^A}$	0.675	0.550	0.755	0.808	0.721	0.485	0.364	0.324	0.675	0.678	0.679	0.735	0.621	0.701	0.675
$\overline{B^A_{2023}/Risk^A}$	1.523	1.379	1.471	1.490	1.465	1.187	1.054	1.002	1.520	1.534	1.541	1.477	1.478	1.533	1.523
$\overline{B^A_{2023}/B^A_{2004}}$	0.002	0.001	0.002	0.002	0.002	0.001	0.001	0.001	0.002	0.002	0.002	0.002	0.002	0.001	0.002
$\overline{B^A_{min}/K^A}$	0.188	0.164	0.223	0.231	0.218	0.164	0.123	0.117	0.183	0.184	0.186	0.226	0.171	0.218	0.188
$\overline{B^A_{min}/Risk^A}$	0.424	0.412	0.434	0.427	0.444	0.402	0.356	0.361	0.412	0.417	0.422	0.454	0.408	0.477	0.424

Table 10. Summary statistics resulting from running OMP-04 under some anchovy robustness tests, using results from the posterior distributions obtained using MCMC.

	A_0	A_{M1}	A_{M2}	A_{HS}	A_{BH}	A_R	A_{kegg2}
$Risk^A$	0.238		0.212		0.316	0.474	0.238
$\overline{C}^A$	303.1		311.3		268.1	245.6	301.0
AAV^A	0.337		0.318		0.348	0.368	0.337
$\overline{B^A_{2023}/K^A}$	0.695		0.765		0.382	0.285	0.624
$\overline{B^A_{2023}/Risk^A}$	1.521		1.664		1.000	0.889	1.433
$\overline{B^A_{2023}/B^A_{2004}}$	0.002		0.002		0.001	0.528	0.002
$\overline{B^A_{\min}/K^A}$	0.137		0.144		0.090	0.067	0.123
$\overline{B^A_{\min}/Risk^A}$	0.286		0.288		0.241	0.207	0.271

Table 11. Summary statistics resulting from running OMP-04 under the sardine robustness tests, using sardine results from the posterior mode only. Risk (the probability that adult anchovy biomass falls below 10% of the average adult anchovy biomass between November 1984 and November 1999 at least once during the projection period of 20 years), $Risk^S$, average directed catch (in thousands of tons), $\overline{C}^S$, average proportional annual change in directed catch, AAV^S, average biomass at the end of the projection period as a proportion of carrying capacity, as a proportion of the risk threshold, and as a proportion of biomass at the beginning of the projection period, and average minimum biomass over the projection period as a proportion of carrying capacity and as a proportion of the risk threshold, for the OMP-04 trade-off point.

	S_0	S_{kN1}	S_{kN2}	S_{M1}	S_{M2}	S_{M3}	S_{M4}	S_{BH}	S_R	S_{Slow}
$Risk^S$	0.020	0.046	0.010	0.000	0.034	0.016	0.022	0.928	0.736	0.010
$\overline{C}^S$	373.1	367.0	378.1	497.3	357.5	391.6	368.7	199.4	278.0	415.1
AAV^S	0.214	0.232	0.208	0.006	0.224	0.205	0.206	0.287	0.238	0.160
$\overline{B^S_{2023}/K^S}$	0.771	0.687	0.837	0.917	0.792	0.765	0.778	0.428	0.642	0.814
$\overline{B^S_{2023}/Risk^S}$	3.586	3.382	3.716	22.203	3.296	3.929	3.490	0.618	1.415	4.367
$\overline{B^S_{2023}/B^S_{2004}}$	0.565	0.542	0.614	2.962	0.545	0.586	0.560	0.133	0.248	0.563
$\overline{B^S_{\min}/K^S}$	0.496	0.430	0.556	0.308	0.499	0.495	0.503	0.224	0.279	0.537
$\overline{B^S_{\min}/Risk^S}$	2.309	2.114	2.469	7.465	2.078	2.541	2.256	0.323	0.616	2.880

Table 12. Summary statistics resulting from running OMP-04 under some sardine robustness tests, using results from the posterior distributions obtained using MCMC.

	S_0	S_{kN1}	S_{Slow}
$Risk^S$	0.096		
$\overline{C}^S$	365.9		
AAV^S	0.197		
$\overline{B^S_{2023}/K^S}$	0.728		
$\overline{B^S_{2023}/Risk^S}$	4.009		
$\overline{B^S_{2023}/B^S_{2004}}$	0.643		
$\overline{B^S_{\min}/K^S}$	0.451		
$\overline{B^S_{\min}/Risk^S}$	2.445		

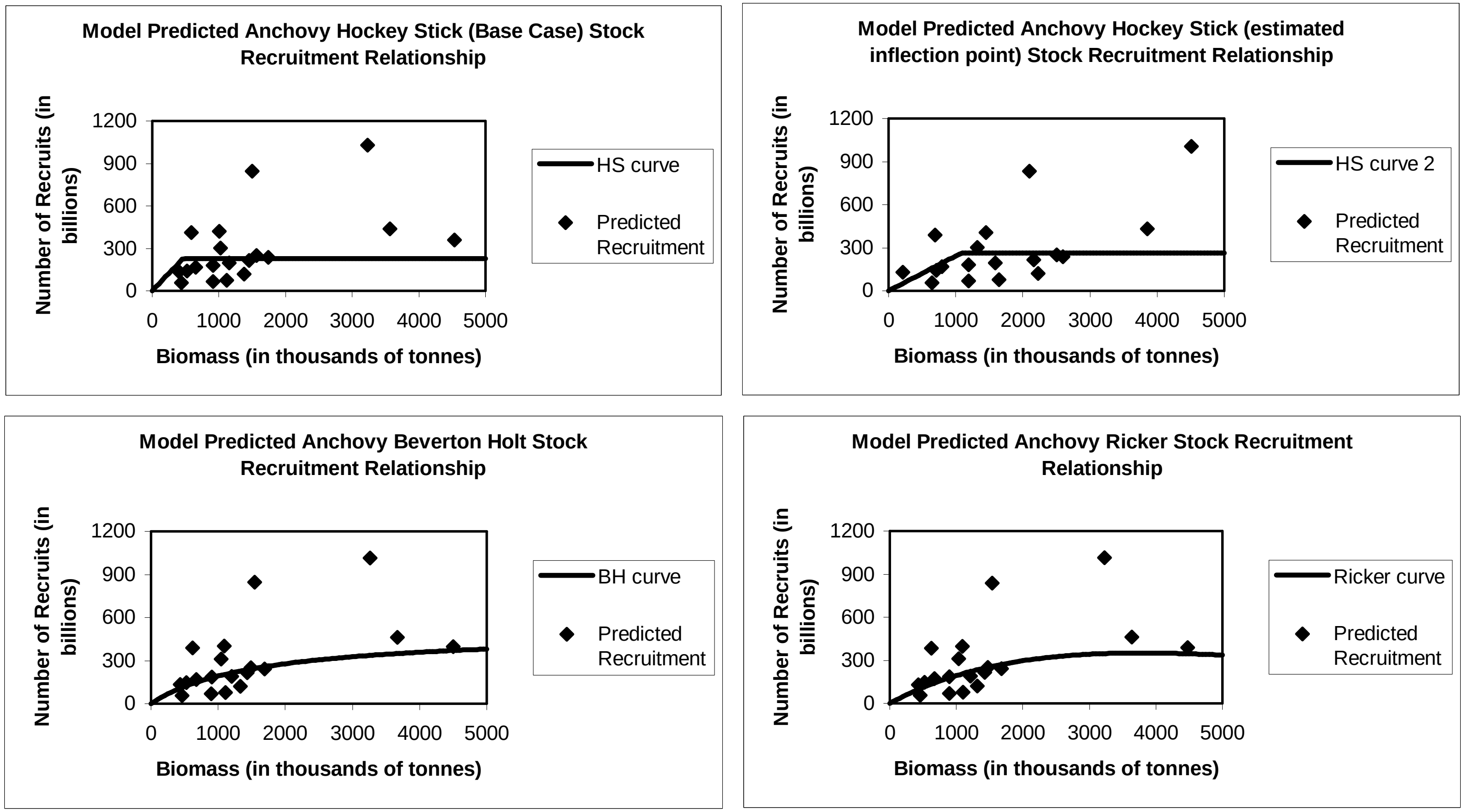

Figure 1. Model predicted November anchovy spawner biomass and recruitment with the fitted stock-recruitment curves.

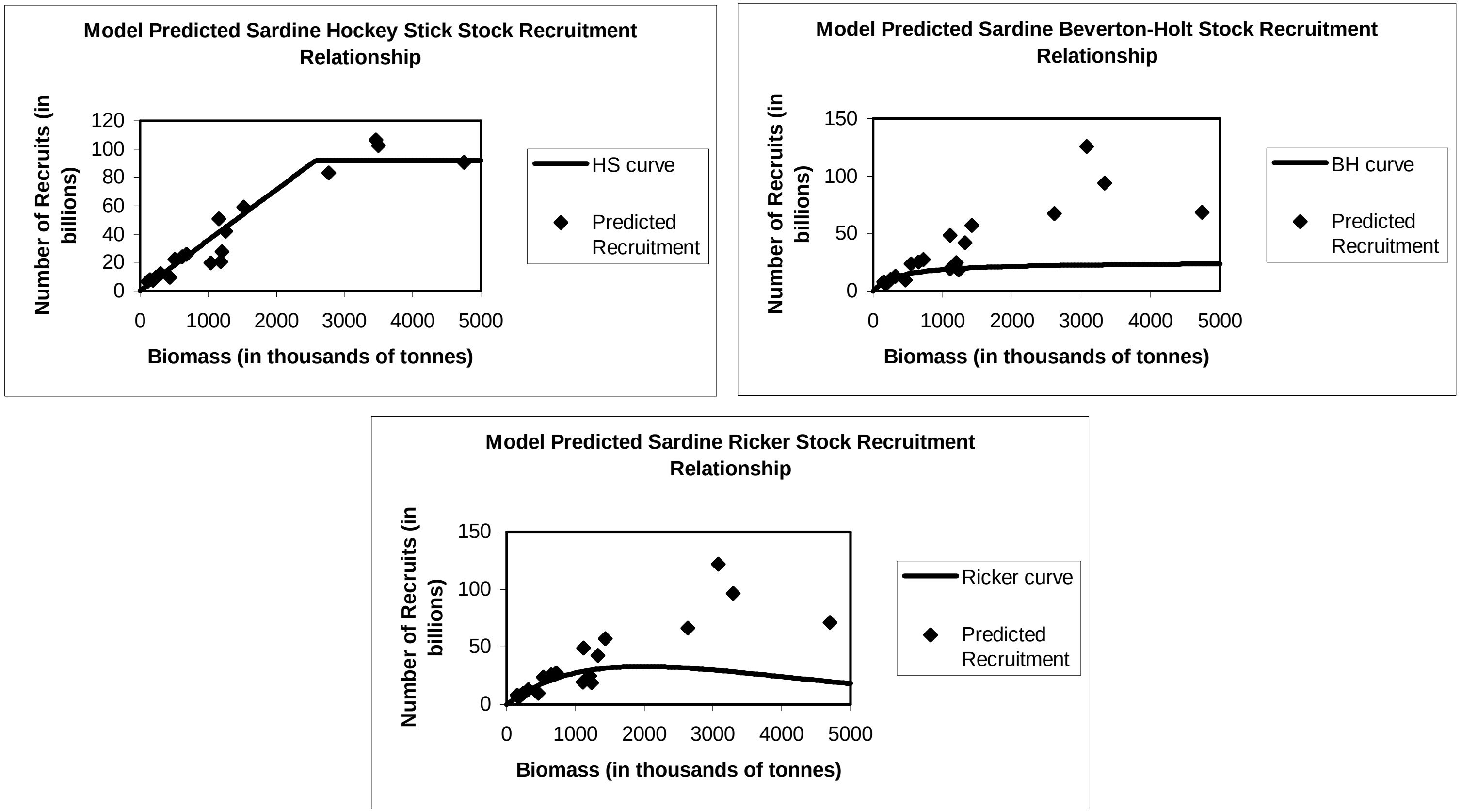

Figure 2. Model predicted November sardine spawner biomass and recruitment with the fitted stock-recruitment curves.

Appendix: Glossary of Terms Used in Tables

$M_{ad}^{A/S}$ - rate of natural mortality (in year^{-1}) of juvenile anchovy/sardine (i.e. fish of age 0).

$M_{ju}^{A/S}$ - rate of natural mortality (in year^{-1}) of adult anchovy/sardine (i.e. fish of age 1+).

k_g^A - constant of proportionality (multiplicative bias) in the November egg survey estimate of spawner biomass.

$k_N^{A/S}$ - constant of proportionality (multiplicative bias) in November acoustic survey estimate of spawner biomass.

$k_r^{A/S}$ - constant of proportionality (multiplicative bias) in the acoustic survey estimate of recruitment.

$k_{p,a}^S$ - constant of proportionality (multiplicative bias) in the estimate of the proportion (by number) of sardine of age a in the November survey.

k_q^A - is a multiplicative bias associated with the proportion of 1-year-olds in the November survey.

$\left(\lambda_r^{A/S}\right)^2$ - the additional variance (over and above the survey sampling CV that reflects survey inter-transect variance) associated with the recruit surveys.

$\left(\lambda_N^{A/S}\right)^2$ - the additional variance (over and above the survey sampling CV that reflects survey inter-transect variance) associated with the November surveys.

$\left(\lambda_p^A\right)^2$ - the additional variance (over and above the fixed variance of 0.4^2) associated with fitting the proportion of anchovy 1-year-olds in the November survey.

$\left(\lambda_0^{A/S}\right)^2$ - the additional variance (over and above the fixed variance of 0.4^2) associated with the recruitment residuals.

$(\sigma_p^S)^2$ - the overall variance-related parameter for the log-transformed sardine proportion-at-age observations, $p_{y,a,Nov}^S$ [note variance = $(\sigma_p^S)^2/(n_y\, p_{y,a,Nov}^S)$].

$\left(\sigma_q^A\right)^2$ - a minimum variance associated with the proportion of anchovy 1-year-olds in the likelihood.

Neg. Posterior - negative posterior (negative log-likelihood * negative log joint prior)

Neg. lnL - negative log-likelihood.

$\ln L_{Nov}$ - portion of the log-likelihood from fitting to the November acoustic survey estimates.

$\ln L_{Egg}$ - portion of the log-likelihood from fitting to the November egg survey estimates.

$\ln L_{Rec}$ - portion of the log-likelihood from fitting to the recruitment survey estimates.

$\ln L_{Prop}$ - portion of the log-likelihood from fitting to the proportion-at-age in the November survey lnPr(k_N) - log prior of k_N^A (anchovy only).

lnPr(k_r) - log prior of k_r^A (anchovy only).

lnPr(del) - log joint prior of the recruitment residuals.

lnPr(k_{prop}) - log prior of $k_{p,a}^S$ (sardine) or k_q^A (anchovy).

lnPr(var_{prop}) - log prior of the variance in the proportion-at-age.

lnPr(a) - log prior of $a^{A/S}$.

lnPr(a_2) - log prior of $a_{1979-1983}^S$ (sardine only).

$N_{2003,1}^{A/S}$ - number (in billions) of anchovy/sardine of age *a* at the beginning of November 2003.

S_a - recent sardine fishing selectivities-at-age.

$K^{A/S}$ - carrying capacity.

$a^{A/S}$ - maximum recruitment (in billions) in the hockey stick stock-recruitment curve (see pg 2 and X for definitions for other stock-recruitment curves).

$a_{1979-1983}^S$ - maximum recruitment (in billions) in the hockey stick stock-recruitment curve for 1979 to 1983.

$b^{A/S}$ - spawner biomass above which there should be no recruitment failure risk in the hockey stick stock-recruitment curve (see page 2 and X for definitions for other stock-recruitment curves).

$\sqrt{0.4^2 + \left(\lambda_0^{A/S}\right)^2}$ - standard deviation in recruitment residuals.

$\varepsilon_{2002}^{A/S}$ - lognormal deviation of anchovy/sardine recruitment in 2002.

$s_{cor}^{A/S}$ - recruitment serial correlation.