Assessment of the South African anchovy resource using data from 1984 – 2015: results at the posterior mode

C.L. de Moor*

Correspondence email: *carryn.demoor@uct.ac.za*

Abstract

The operating model (OM) for the South African anchovy resource has been updated from that used to develop OMP-14 given four more years of data. The model has been altered from previous assessments to now fit directly to length frequency data, removing the earlier need for estimates of proportions of anchovy-at-age 1 during the annual November hydroacoustic survey. A Beverton Holt stock recruitment relationship is used for the base case. Time-invariant natural mortality is assumed to be 1.2year^{-1} for both juvenile and adult natural mortality as before; this provides a better fit to the data than other options considered. The resource abundance is estimated to be near the historical (1984-2014) average, with a total biomass of 3.3 million tons in November 2015. Recruitment reflects three major peaks over the past 20 years, although the lowest points in these fluctuations were still large, being similar to the maximum recruitment prior to 2000.

Introduction

The operating model of the South African anchovy resource has been updated from the last assessment which used data collected up to an including November 2011 (de Moor and Butterworth 2012). There have been substantial changes in the model formulation, in particular to be able to fit directly to length-frequency data from the November survey and from commercial catches. The time series of estimates of proportions of 1 year old anchovy in the November survey (de Moor et al. 2013) which was used previously is now no longer required.

The updated model was originally fit to a revised time series of data up to an including November 2014 (de Moor and Butterworth 2015b). This document presents the updated base case operating model using data up to November 2015, and compares the associated results to those for a number of robustness tests. Results are given at the posterior mode only. A subsequent separate document will show the full posterior distributions.

Available Data

de Moor et al. (2016) detail all the data used in this assessment. Key changes from the data used by de Moor and Butterworth (2012), and how they are utilised in the model, include the following.

i) The incorporation of four more year's survey data from November 2012 to 2015.

ii) The model fits to November survey length-structured data, instead of estimates of proportions-at-age 1 in the November survey.

* MARAM (Marine Resource Assessment and Management Group), Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch, 7701, South Africa.

iii) The model fits to quarterly commercial length-structured data, instead of assuming catch-at-age (calculated using monthly and annually varying cut-off lengths) is observed without error.

Population Dynamics Model

The operating model used for the South African anchovy resource is detailed in Appendix A. All parameters used in this document are listed with definitions as well as parameter values, prior distributions or associated equations in Table A.1.

While the base case model structure is mostly unchanged from de Moor and Butterworth (2015), key changes in the population dynamics model from de Moor and Butterworth (2012) are still listed here for ease of reference, and include the following.

i) The model is still age-structured at its core, but has been extended using estimated length-at-age distributions (equations A.4 and A.21) to be able to fit directly to length- rather than age-structured data.

ii) Quarterly catches-at-age are estimated within the model (equations A.13 and A.16). Catches of ages older than 1 are thus allowed, while for de Moor and Butterworth (2012) the catch was split between ages 0 and 1 only, using monthly and annually varying cut-off lengths.

iii) A commercial selectivity curve is thus now also required, and changes in commercial selectivity between quarters is allowed in the estimation process (equation A.10).

iv) The assumption is made that the November survey estimate of biomass is an estimate of total (0+) biomass, i.e. all anchovy of lengths ≥2cm (equation A.7), rather than only 1+ biomass.

v) A logistic trawl survey selectivity-at-length is used, to reflect the lower selectivity on smaller anchovy in the trawls used to capture survey length-frequency data.

vi) Instead of assuming all 1+ anchovy to be mature, spawner biomass is calculated from 1+ anchovy after taking a maturity-at-length relationship (Melo, 1990) into account (equation A.9).

vii) Weight-at-length, rather than weight-at-age, is now used, being more appropriate for this revised formulation. In addition, the weight-at-length formula used in the assessment at the time of the November survey, and the monthly-varying weight-at-length formula used to re-adjust the monthly observed commercial catch length-frequency to a length-frequency consistent with the observed tonnage landed, are both new relationships (de Moor and Butterworth 2015a).

Larger anchovy are generally landed earlier in the year than smaller anchovy, resulting in changes in the commercial proportion-at-length distribution between the quarters of the year. This is primarily due to the targeting of larger anchovy early in the year before recruits become available to the fishery. This is taken into account in the model in a variety of ways. Modelling catch to be taken once a quarter allows account for quarterly changes in the length distribution of the population. This naturally has a greater effect on the fast growing juveniles. Secondly, as some fishing vessels turn their attention to target recruits mid-way through the year, the model allows for a change in fishing selectivity by quarter. This change in selectivity reflects a change in targeting (e.g. area) rather than a gear effect. One further advantage of modelling catch quarterly is that it allows for changes in the timing of the peak of anchovy catches[1] over the years.

de Moor and Butterworth (2015a) estimated new weight-at-length relationships for anchovy based separately on survey and commercial data. Although de Moor and Butterworth (2015a) found that these relationships could change from year-to-year, this assessment does not allow for such changes. This is because assumptions would need to be made regarding the relationship applied in past and future years for which no data exist to calculate the associated annual weight-at-length relationships. Such assumptions are premature while research continues to attempt to find environmental co-variates which explain these changes. In addition, the annually-varying relationships were shown to not differ to biologically meaningful extents from the time-invariant relationships (de Moor and Butterworth 2015a). Thus, in the meantime, a time-invariant relationship is used in this assessment. Allowance can be made for different commercial weights-at-length/age where necessary (only in projections) to the survey-based relationships used here-in.

<u>Stock recruitment relationship</u>

The following alternative stock recruitment relationships have been considered (Table 1):

A_{BH} – Beverton Holt stock-recruitment curve, with uniform priors on steepness and carrying capacity

A_{2BH} – two Beverton Holt stock-recruitment curves, with uniform priors on steepness and carrying capacity, one estimated using data from 1984 to 1999 and the other from 2000 to 2015

A_R – Ricker stock-recruitment curve, with uniform priors on steepness and carrying capacity

A_{HS} – hockey stick stock-recruitment curve, with uniform priors on the log of the maximum recruitment and on the ratio of the spawning biomass at the inflection point to carrying capacity

A_{2HS} – two hockey stick stock-recruitment curves, with uniform priors on the log of the maximum recruitment and on the ratio of the spawning biomass at the inflection point to carrying capacity, one estimated using data from 1984 to 1999 and the other from 2000 to 2015.

In cases where a second curve is estimated from 2000 to 2015, the variance about the stock recruitment curve over this time period, $\left(\sigma_{r,2000+}^{A}\right)^2$, is estimated separately from that for the earlier time period, $\left(\sigma_r^A\right)^2$.

<u>Time-invariant natural mortality</u>

---

[1] Following inspection of the raw data, de Moor and Butterworth (2012) assumed there was a shift in the timing of the annual pulse of age-0 anchovy catch between 1998 and 1999.

A number of combinations of time-invariant juvenile and median adult natural mortality values have been explored, covering the range 0.6 to 1.8 year^{-1}, and for the case where a Beverton Holt stock recruitment relationship is assumed. For realism, only combinations with $\overline{M}_j^A \geq \overline{M}_{ad}^A$ were considered.

Variable natural mortality

Alternatives to the assumption of constant natural mortality over time were considered through the following robustness tests:

A_{Mad} – annually varying adult natural mortality, i.e. random effects model with $\sigma_{ad} \sim U(0.2,0.5)$,[2], and $\rho \sim U(0,1)$.

A_{Mj} – annually varying juvenile natural mortality, i.e. random effects model with $\sigma_j \sim U(0.2,0.5)$, and $\rho \sim U(0,1)$.

A_{M2000+} – natural mortality is assumed to have increased at the turn of the century. In this case $\overline{M}_j^A = \overline{M}_{ad}^A = 0.9$ year^{-1} prior to 2000 and $\overline{M}_j^A = \overline{M}_{ad}^A = 1.2$ year^{-1} from 2000 onwards.

Further robustness tests

The following robustness tests to A_{BH} have also been considered:

A_{sur} – survey selectivity below 7cm is estimated to be a constant, and uniform (1) selectivity is assumed for lengths ≥7cm.

A_{com} – commercial selectivity is not estimated to decrease at higher lengths, i.e. $\delta_q = 0$.

A_{com2} – commercial selectivity is modelled using a double-logistic curve.

A_{kegg1} – negatively biased egg surveys, i.e., $k_g^A = 0.75$ (testing sensitivity to assumption 8 of Appendix A).

A_{kegg2} – positively biased egg surveys, i.e., $k_g^A = 1.25$ (testing sensitivity to assumption 8 of Appendix A).

A_{lamR} – fix the additional variance (over and above the survey sampling CV) associated with the recruit Survey, $(\lambda_r^A)^2$, to be 0.

A_{lamN} – estimate the additional variance (over and above the survey sampling CV) associated with the November survey, with the associated prior for $(\lambda_N^A)^2 \sim U(0,100)$.

A_{lamN2} – fix the additional variance (over and above the survey sampling CV) associated with the November Survey, $(\lambda_N^A)^2$, to be 0.02.

Retrospective runs

---

[2] The lower bound of 0.2 was chosen by de Moor and Butterworth (2012) from initial results by which indicated that there was a change in the model fit to the data when σ_{ad} decreased from 0.20 to 0.19, with a poorer fit obtained for the fit to the proportion-at-age 1 data. In general, the negative log posterior distribution decreases with decreasing σ_{ad}, primarily due to the contributions from the prior on η_y^{ad}. The prior bounds have not been retested here due to a lack of time and the low priority these robustness tests have received within the SPSWG.

A_{BH} is run using data from 1984 to 1999, to 2003, to 2006, and to 2011 to compare the base case model estimates to those which would have resulted from data corresponding to the years used as input to the OMs used for testing OMP-02, OMP-04, OMP-08 and OMP-14. Note that the data used in A_{BH} and the retrospective runs do NOT compare directly with those used for the former OMs due to methodological updates over time, corrections to historic time series of data and the replacement of proportion-at-age 1 inputs with length-structured data.

Results

Natural mortality

Table 2 lists the various contributions to the negative log posterior probability distribution function (pdf) at the posterior mode for the full range of combinations of juvenile and adult natural mortality explored. The new formulation of the prior distributions in this assessment implicitly forces one of the criteria that has traditionally been used to select appropriate natural mortality rates, i.e. that $k_r^A/k_N^A \leq 1$. Some of the fits to the data are thus rather poor, given this constraint. There is little change in the posterior distribution as $\overline{M}_j^A$ is changed for a given $\overline{M}_{ad}^A$. Given $\overline{M}_j^A$, however, the posterior distribution indicated an improved fit to the data for increasing $\overline{M}_{ad}^A$. This latter feature has been observed in previous assessments and may be an artefact of the assessment methodology in that a higher natural mortality results in a higher loss of "memory" of cohorts, making the November survey data easier to fit.

By preferring alternatives with $k_r^A/k_N^A \geq 0.5$, and avoiding a change in the baseline values for $\overline{M}_j^A$ and $\overline{M}_{ad}^A$ from that previously used in the interests of consistency over time in assessments, the following combinations were chosen for a set of robustness tests:

A_{BH} - $\overline{M}_j^A = 1.2$ and $\overline{M}_{ad}^A = 1.2$ (base case)

A_{M1} - $\overline{M}_j^A = 0.9$ and $\overline{M}_{ad}^A = 0.9$ (robustness test: for comparison with the base case assessment of 2007)

A_{M2} - $\overline{M}_j^A = 1.5$ and $\overline{M}_{ad}^A = 1.2$ (robustness test: alternative $\overline{M}_j^A$, similar to A_{BH} in terms of value of the negative log joint posterior mode)

Stock recruitment relationship

Table 3 lists the various contributions to the negative log posterior pdf at the posterior mode for the alternative stock-recruitment relationships considered. AIC_c is used to coarsely[3] compare amongst alternative stock-recruitment relationships, suggesting that the preferred stock-recruitment relationships are the Beverton Holt and Hockey Stick relationships. Models with different stock-recruitment relationships before and after the turn of the century were not favoured by AIC_c, even though they result in a better fits to the data. This is due to the additional number of estimable parameters required for these models. Both A_{2HS} and A_{2BH} estimate a higher recruitment for the same spawner

[3] Strictly AICc is for use in comparing between alternative frequentist models; the comparison here is made at the joint posterior mode.

biomass after 2000 than before (Figure 2). A_{BH} is chosen as the base case operating model to use during the development of the next OMP, with robustness being tested to A_R and A_{HS} (Figures 1 and 2). This curve reflects a more productive resource than was estimated at the joint posterior mode by de Moor and Butterworth (2012).

Base case (A_{BH}) results at posterior mode

The estimated parameter values and key outputs for A_{BH} are listed in Table 4. The fit to the November total biomass is very good (Figure 3). The joint posterior mode estimate of $k_N^A = 0.66$ indicates that the survey estimate of abundance is an over-estimate of total biomass, compared to the under-estimate of 1+ biomass indicated by the previous assessment (de Moor and Butterworth, 2012 had a joint posterior mode of $k_N^A = 1.16$). This is due firstly to the change in the assumption of the November survey being associated with total rather than 1+ biomass, together with the inclusion of a maturity-at-length ogive in the calculation of spawner biomass. de Moor and Butterworth (2012) assumed the time series of abundance estimates from the November hydroacoustic survey and DEPM reflected the same biomass. The model predicted SSB time series is higher than that estimated by de Moor and Butterworth (2012), but still reasonably within the range of DEPM estimates of abundance for most years (Figure 4). There is some slight trend in the residuals from the model fit to the May survey estimates of recruitment (Figure 5). The model projected posterior mode estimates of May recruitment in 2007, 2008 and 2010 fall outside the 95% CIs for the survey results (although within the 95% CI which reflects both the survey inter-transect and additional variance) as a result of the model also being required to fit to November survey estimates of total biomass which generally have smaller CVs.

The model fits the November survey estimates of proportions-at-length obtained from trawl samples well (Figures 7 and 8), allowing for a lower trawl net selectivity on anchovy of small lengths (Figure 6). The logistic selectivity curve results in an improved fit compared to one which assumes uniform selectivity above 7cm and a constant lower selectivity for all smaller lengths (A_{sur}), with uniform selectivity – which is expected given the survey design - still being estimated for lengths above 9.5cm (Table 4, Figure 6).

Initial model testing indicated that some commercial selectivity parameters could be assumed to be the same over quarters (see Table A.1). The model estimated commercial selectivity-at-length curves reflect a steep decrease in selectivity for lengths above the selected maximum (Figure 9). The selectivity-at-length estimated between February and April reflects the combination of the recruits of the year not yet being available to the fishery and the subsequent targeting of larger anchovy (Figure 9). The model estimated selectivity-at-length between May and October reflects the targeting of recruiting anchovy (Figures 9 and 10a). In general, the model fits to the commercial proportions-at-length are reasonable (Figures 10a and 11). The corresponding model fits assuming higher or lower values for the length classes above which selectivity is modelled to decrease were poorer than that of the base case, except for the change from 8.5cm to 9cm in quarter 1 (results not shown here). However, although there was an overall slightly better fit to all the data in this latter case, the fit to the commercial length frequencies in quarter 1 were poorer, hence the base case choice.

Alternative selectivity curves which did not allow for a decrease in selectivity for larger lengths (A_{com}) resulted in a poorer fit to all data, but particularly for the commercial length frequency data (Figures 9 and 10b, Table 4). Assuming a double-logistic commercial selectivity curve (A_{com2}) resulted in a slightly better fit to the data (Figures 9 and 10c, Table 4).

The model predicted catch-at-age is shown in Figure 12, indicating the majority of catch (by number) is estimated to be of age 0 and 1, although small amounts of age 2+ anchovy are estimated to have been landed.

Figure 13 shows the model estimated von Bertalanffy growth curve and Figure 14 shows the distributions about this curve, with a greater variability estimated for age 0 compared to older ages (Table 4). It is interesting to note that the growth curve estimated from proportion-at-length data from 1984 to 2015 has a steeper increase and thus greater length-at-ages 1 and 2 compared to that estimated directly from ageing data from the November surveys in 1990, 1992 to 1995 (that ageing was conducted by M. Kerstan, Deon Durholtz pers. comm.).

The historical annual harvest rates are plotted in Figure 15 and the annual losses of anchovy to predation are listed in Table 5, showing catch over the past two decades to be no more than a low fraction (seldom exceeding 5%) of anchovy lost to natural mortality.

Variable natural mortality

The alternative robustness test which allows for adult and juvenile natural mortality to vary with time through the use of random effects, A_{Mad} and A_{Mj}, result in better fits to the data (Table 4, Figures 16, 17), and the adult/juvenile natural mortality is estimated to remain within a reasonable range. The strong autocorrelation estimated by de Moor and Butterworth (2012) is no longer seen (Table 4, Figure 18). A slightly better fit to the hydroacoustic survey data is obtained if natural mortality is assumed to increase at the turn of the century (A_{M2000+}).

Further robustness tests

The model parameters, contributions to the negative log posterior pdf and key model outputs at the posterior mode for the robustness tests are given in Table 4. The remaining robustness tests, not discussed above, did not result in unanticipated changes from the parameter estimates for A_{BH}. Naturally, the magnitude of the resource biomass is dependent on the assumption made regarding the bias (if any) in the time series of abundance estimates resulting from the November egg surveys.

Retrospective analysis

There is little difference in the historical November biomass and May recruitment trajectories for the retrospective runs (Figure 19). These results indicate that the more productive stock-recruitment relationship estimated here for A_{BH} compared to that estimated by de Moor and Butterworth (2012), is primarily due to the change in methodology and change from using age- to length-structured data, rather than to the four further years of data.

Discussion

This document has refit the updated assessment of the South African anchovy resource, developed by de Moor and Butterworth (2015) to an additional year's data with only few further minor modifications to the model structure. The base case hypothesis assumes a Beverton Holt stock recruitment curve and time-invariant natural mortality, and is able to fit the new length-structured data reasonable well. Estimation of catch-at-age within the model results in the majority of catch being estimated to be of ages 0 and 1, in line with previous assumptions about anchovy landings. Results at the posterior mode have also been presented for a number of robustness tests to the base case hypothesis, A_{BH}. The total resource biomass in November 2015 is estimated under A_{BH} to be 3.3 million tons - near the historical (1984-2014) average of 3.4 million tons. Recruitment over the past 20 years reflects three major peaks, although the low points of these fluctuations were still large, being similar to the maximum recruitment observed prior to 2000. The harvest proportion over the past 20 years has only exceeded 0.10 once, in 2012 when the 305 000t of anchovy was landed(Figure 15).

References

de Moor CL and Butterworth DS. 2012. Finalised assessment of the South African anchovy resource using data from 1984-2011: results at the posterior mode. DAFF Branch Fisheries Document: FISHERIES/2012/SEP/SWG-PEL/47. 32pp.

de Moor CL and Butterworth DS. 2015a. A new length-weight relationship for South African anchovy. DAFF Branch Fisheries Document: FISHERIES/2015/JUN/SWG-PEL/26. 49pp.

de Moor CL and Butterworth DS. 2015b. Assessment of the South African anchovy resource using data from 1984 – 2014: base case results at the posterior mode. DAFF Branch Fisheries Document: FISHERIES/2015/AUG/SWG-PEL/31. 36pp.

de Moor CL, Butterworth DS and Coetzee JC. 2013. Can anchovy age structure be estimated from length distribution data collected during surveys? African Journal of Marine Science 35(3):335-342.

de Moor CL, Coetzee J, Merkle D, van der Westhuizen JJ and van der Lingen C. 2016. A record of the generation of data used in the 2016 sardine and anchovy assessments. DAFF Branch Fisheries Document: FISHERIES/2016/MAY/SWG-PEL/13. 28pp.

Melo YC. 1992. The biology of the anchovy *Engraulis capensis* in the Benguela Current region. PhD thesis, University of Stellenbosch, xii + 180pp.

Table 1. The alternative stock-recruitment relationships considered. The parameters are defined in Appendix A, Table A.1, with, $X = \sum_{a=1}^{3} \overline{w}_a^A e^{-M_j^A-(a-1)\overline{M}_{ad}^A} + \overline{w}_{4^+}^A e^{-M_j^A-3\overline{M}_{ad}^A} \Big/ \left(1-e^{-\overline{M}_{ad}^A}\right)$, where $\overline{w}_a^A$ is the average of $w_{y,a}^A = \sum_{l=2}^{16} A_{a,l}^{sur} w_{y,l}^A$, where $A_{a,l}^{sur}$ and $w_{y,l}^A$ are as defined in Appendix A.

Test	Stock recruitment relationship	$f\left(SSB_y^A\right)=$	Parameters
A_{BH}	Beverton Holt	$\dfrac{\alpha^A SSB_y^A}{\beta^A + SSB_y^A}$	$h^A \sim U(0.2,1)$ $K^A/1000 \sim U(0,10)$ $\alpha^A = \dfrac{4h^A}{5h^A-1}\dfrac{K^A}{X}$ $\beta^A = \dfrac{K^A\left(1-h^A\right)}{5h^A-1}$
A_{2BH}	Beverton Holt (2 curves)	$\dfrac{\alpha_1^A SSB_y^A}{\beta_1^A + SSB_y^A}$ if $y<2000$ $\dfrac{\alpha_2^A SSB_y^A}{\beta_2^A + SSB_y^A}$ if $y \ge 2000$	$h_t^A \sim U(0.2,1)$ $K_t^A/1000 \sim U(0,10)$ $\alpha_t^A = \dfrac{4h_t^A}{5h_t^A-1}\dfrac{K_t^A}{X}$ $\beta_t^A = \dfrac{K_t^A\left(1-h_t^A\right)}{5h_t^A-1}$ $t=1,2$
A_R	Ricker	$\alpha^A SSB_y^A e^{-\beta^A SSB_y^A}$	$h^A \sim U(0.2,1.5)$ $K^A/1000 \sim U(0,10)$ $\alpha^A = \dfrac{1}{X}\left(\dfrac{h^A}{0.2}\right)^{1/0.8}$ $\beta^A = \dfrac{\ln\left(h^A/0.2\right)}{0.8K^A}$
A_{ModR}	Modified Ricker	$\alpha^A SSB_y^A e^{-\beta^A\left(SSB_y^A\right)^{c^A}}$	$h^A \sim U(0.2,1.5)$ $K^A/1000 \sim U(0,10)$ $\alpha^A = \dfrac{1}{X}\left(\dfrac{h^A}{0.2}\right)^{\frac{1}{1-0.2^c}}$ $\beta^A = \dfrac{\ln\left(h^A/0.2\right)}{\left(K^A\right)^c\left[1-0.2^c\right]}$ $c^A \sim U(0,1)$
A_{HS}	Hockey stick	$\begin{cases} a^A & \text{if } SSB_y^A \ge b^A \\ a^A \dfrac{SSB_y^A}{b^A} & \text{if } SSB_y^A < b^A \end{cases}$	$\ln\left(a^A\right) \sim U(0,7.2)$[4] $b^A/K^A \sim U(0,1)$ $K^A = a^A X$[5]
A_{2HS}	Hockey stick (2 curves)	$\begin{cases} a_1^A & \text{if } SSB_y^A \ge b_1^A \\ a_1^A \dfrac{SSB_y^A}{b_1^A} & \text{if } SSB_y^A < b_1^A \end{cases}$ if $y<2000$ $\begin{cases} a_2^A & \text{if } SSB_y^A \ge b_2^A \\ a_2^A \dfrac{SSB_y^A}{b_2^A} & \text{if } SSB_y^A < b_2^A \end{cases}$ if $y \ge 2000$	$\ln\left(a_t^A\right) \sim U(0,7.2)$[4] $b_t^A/K_t^A \sim U(0,1)$ $K_t^A = a_t^A X$[5] $t=1,2$

[4] Given the lack of *a priori* information on the scale of a^A, a log-scale was used, with a maximum corresponding to about 10 million tons.
[5] For consistency, *K* relates throughout to corresponding means.

Table 2. The contributions to the negative log posterior pdf at the posterior mode for a range of combinations of juvenile, $\overline{M}_j^A$, and adult, $\overline{M}_{ad}^A$, natural mortality for models assuming the Beverton Holt stock recruitment relationship. The ratio of the multiplicative bias in the recruit survey to that in the November survey, k_r^A/k_N^A, is constrained to be less than 1.

$\overline{M}_j^A$	$\overline{M}_{ad}^A$	-ln (Posterior)	Δ{-ln(Likelihood)}	$-\ln L^{Nov}$	$-\ln L^{Egg}$	$-\ln L^{rec}$	$-\ln L^{sur\ pr}$	$-\ln L^{com\ pr}$	-ln(priors)	k_r^A	k_N^A	k_r^A/k_N^A
0.6	0.6	-580.0	45.4	-0.9	11.1	29.0	-393.8	-269.8	44.4	0.49	0.49	1.00
0.9	0.6	-582.9	42.8	0.3	11.1	25.1	-393.6	-270.0	44.1	0.48	0.48	1.00
0.9	0.9	-619.5	10.3	-9.2	9.1	18.7	-407.0	-271.1	40.0	0.64	0.64	1.00
1.2	0.6	-584.9	41.2	1.3	11.7	23.0	-394.2	-270.3	43.7	0.48	0.48	1.00
1.2	0.9	-619.4	9.9	-9.3	9.1	18.7	-407.1	-271.2	40.5	0.62	0.60	0.96
1.2	1.2	-631.8	0.0	-14.8	6.5	15.8	-406.5	-270.8	38.0	0.66	0.53	0.80
1.5	0.6	-585.5	40.6	2.0	12.4	22.3	-395.4	-270.5	43.7	0.49	0.49	1.00
1.5	0.9	-618.8	10.3	-8.8	9.1	18.7	-407.2	-271.2	40.7	0.62	0.52	0.85
1.5	1.2	-631.1	0.4	-14.3	6.5	15.8	-406.6	-270.7	38.3	0.66	0.47	0.71
1.5	1.5	-635.3	-1.7	-16.7	5.2	14.3	-404.0	-270.3	36.2	0.67	0.43	0.63
1.8	0.6	-586.8	39.6	5.2	15.4	22.3	-401.9	-271.3	43.4	0.52	0.52	1.00
1.8	0.9	-617.9	11.0	-8.0	9.1	18.7	-407.4	-271.2	40.9	0.61	0.46	0.76
1.8	1.2	-630.4	0.9	-13.7	6.5	15.8	-406.8	-270.6	38.5	0.65	0.41	0.63
1.8	1.5	-634.5	-1.2	-16.1	5.3	14.3	-404.2	-270.2	36.4	0.67	0.38	0.56
1.8	1.8	-634.4	0.7	-16.7	4.8	13.7	-401.1	-269.8	34.6	0.69	0.36	0.52

Table 3. The contributions to the negative log posterior pdf at the joint posterior mode, together with the values of various quantities at that mode, for alternative stock recruitment relationships.

	A_{BH}	A_{2BH}	A_R	A_{ModR}	A_{HS}	A_{2HS}
-ln(Posterior)	-631.8	-633.7	-631.5	-631.9	-630.9	-633.4
$-\ln L^{Nov}$	-14.8	-14.0	-14.7	-14.8	-15.3	-13.9
$-\ln L^{Egg}$	6.5	6.3	6.5	6.4	6.5	6.2
$-\ln L^{rec}$	15.8	15.8	15.6	15.8	16.4	16.0
$-\ln L^{sur\ propl}$	-406.5	-407.2	-406.4	-406.5	-406.9	-407.7
$-\ln L^{com\ propl}$	-270.8	-270.8	-270.8	-270.8	-270.8	-270.8
-ln(Priors)	32.4	36.2	38.2	37.9	39.2	36.8
# parameters	55	58	55	56	55	58
Sample size (i.e. data points)	3145	3145	3145	3145	3145	3145
AIC	-1230	-1224	-1229	-1228	-1230	-1224
AIC_c	-1228	-1222	-1227	-1226	-1228	-1222
h^A	0.50	0.64	0.50	0.44		
K^A	5251	2896	4868	6664	3702	2242
a^A	1349	654	0.61	38.5	718	435
b^A	1710	475	0.0002	2.19	1172	458
h_2^A	-	1.0	-	-		
K_2^A	-	4730	-	-	-	4727
a_2^A	-	917	-	-	-	917
b_2^A	-	0.006	-	-	-	964

Table 4. Key parameter values estimated at the joint posterior mode together with key model outputs. All robustness tests are defined in the main text and all parameters are defined in Table A.1. Fixed values are given in **bold**. Numbers are reported in billions and biomass in thousands of tons.

	A_{BH}	A_R	A_{HS}	A_{M1}	A_{M2}	A_{Mad}	A_{Mj}	A_{M2000+}	A_{sur}	A_{com}	A_{com2}	A_{kegg1}	A_{kegg2}	A_{lamR}	A_{lamN}	A_{lamN2}
-ln(Posterior)	-631.6	-631.5	-630.9	-619.5	-631.1	-683.1	-686.0	-627.4	-630.3	-559.4	-633.0	-630.7	-631.4	-617.7	-631.6	-628.4
$-\ln L^{Nov}$	-14.9	-14.7	-15.3	-9.2	-14.3	-16.1	-14.7	-12.7	-14.8	-11.6	-14.7	-14.7	-14.7	6.2	-14.9	-2.9
$-\ln L^{Egg}$	6.5	6.5	6.5	9.1	6.5	6.8	6.5	9.9	6.5	7.0	6.6	6.0	7.2	10.1	6.5	7.6
$-\ln L^{rec}$	15.8	15.6	16.4	18.7	15.8	10.5	14.8	14.1	15.6	15.9	15.8	16.0	15.7	6.1	15.8	8.8
$-\ln L^{sur\ propl}$	-406.1	-406.4	-406.9	-407.0	-406.6	-413.8	-406.8	-410.0	-404.6	-395.5	-406.8	-405.5	-406.6	-404.9	-406.1	-407.2
$-\ln L^{com\ propl}$	-270.7	-270.8	-270.8	-217.1	-270.7	-270.6	-270.6	-271.3	-270.3	-237.5	-272.9	-270.6	-270.7	-270.0	-270.7	-270.2
-lnPrior(ε_y^A)	32.3	32.5	33.5	34.2	32.6	32.6	31.0	37.0	32.2	32.2	32.5	32.5	32.1	29.0	32.3	29.9
-lnPrior(L_∞,κ, $t0$, ϑ_a)	-3.2	-3.0	-2.99	-3.1	-3.1	-2.7	-3.2	-3.1	-3.6	1.1	-3.2	-3.2	-3.2	-3.3	-3.2	-3.1
-lnPrior(δ_q)	-2.1	-2.1	-2.1	-2.0	-2.1	-2.1	-2.1	-2.1	-2.1	18.1	-1.2	-2.1	-2.1	-2.1	-2.1	-2.1
-lnPrior(Ninit)	10.8	10.8	10.8	10.9	10.8	10.8	10.8	10.9	10.8	10.8	10.8	10.8	10.8	10.8	10.8	10.8
-lnPrior(ε_y^j and ε_y^{ad})	0	0	0	0	0	-16.4	-43.3	0	0	0	0	0	0	0	0	0
$\overline{M}_j^A$	**1.2**	**1.2**	**1.2**	**0.9**	**1.5**	**1.2**	**1.1-1.3**	**0.9; 1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
$\overline{M}_{ad}^A$	**1.2**	**1.2**	**1.2**	**0.9**	**1.2**	**1.0-1.7**	**1.2**	**0.9; 1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**	**1.2**
$N_{1983,0}^A$	51.5	51.3	51.9	38.5	52.6	55.1	51.4	38.7	52.1	58.9	48.7	54.1	49.1	51.8	51.5	52.7
$N_{1983,1}^A$	142.3	142.4	142.7	136.9	142.5	143.3	142.3	136.0	142.1	148.5	142.2	145.0	140.1	142.9	142.3	1442.6
$N_{1983,2}^A$	349.4	349.4	349.4	348.9	349.4	349.4	349.4	348.7	349.4	350.1	349.4	349.7	349.2	349.5	349.4	349.4
$N_{1983,3}^A$	1.5.2	105.2	105.3	141.8	105.2	95.5	105.2	141.8	105.2	105.4	105.2	105.3	105.2	105.3	105.2	105.2
$N_{1983,4^+}^A$	45.4	45.4	45.4	97.2	45.4	35.9	45.4	97.1	45.4	45.4	45.4	45.4	45.3	45.4	45.4	45.4
k_N^A	0.66	0.66	0.68	0.64	0.66	0.67	0.66	0.63	0.66	0.45	0.66	0.52	0.79	0.59	0.66	0.62
k_r^A	0.53	0.52	0.54	0.64	0.47	0.51	0.53	0.58	0.54	0.27	0.53	0.42	0.62	0.45	0.53	0.49
k_r^A / k_N^A	0.80	0.80	0.80	1.00	0.71	0.77	0.80	0.92	0.81	0.60	0.80	0.82	0.78	0.77	0.80	0.79
k_g^A	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**0.75**	**1.25**	**1.00**	**1.00**	**1.00**
$\left(\lambda_N^A\right)^2$	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.00	**0.02**
$\left(\lambda_r^A\right)^2$	0.13	0.12	0.13	0.16	0.13	0.08	0.11	0.11	0.12	0.13	0.13	0.13	0.13	**0.00**	0.13	0.07

Table 4 (continued).

	A_{BH}	A_{R}	A_{HS}	A_{M1}	A_{M2}	A_{Mad}	A_{Mj}	A_{M2000+}	A_{sur}	A_{com}	A_{com2}	A_{kegg1}	A_{kegg2}	A_{lamR}	A_{lamN}	A_{lamN2}
σ_j	-	-	-	-	-	-	0.10	-	-	-	-	-	-	-	-	-
σ_{ad}	-	-	-	-	-	0.20	-	-	-	-	-	-	-	-	-	-
ρ	-	-	-	-	-	0.40	0.08	-	-	-	-	-	-	-	-	-
a^A	1349	0.61	718	778	1812	1737	1409	1621	1337	2760	1332	1752	1099	2311	1349	1809
b^A	1719	0.0002	1172	1371	1730	2537	1862	3498	1738	1726	1679	2404	1298	3878	1719	2725
K^A	5261	4868	3702	5000	5194	6488	5430	9999	5260	8682	5206	6690	4375	8147	5261	6645
h^A	0.50	0.50	-	0.54	0.50	0.47	0.49	0.49	0.50	0.60	0.51	0.49	0.52	0.44	0.50	0.46
σ_r^A	0.69	0.69	0.71	0.73	0.69	0.69	0.66	0.80	0.68	0.68	0.69	0.69	0.68	0.62	0.69	0.64
l^{sur}	11.8	11.9	11.9	11.9	11.9	11.8	11.8	11.8	0.26	19.9	11.8	11.8	11.8	11.8	11.8	11.8
δ^{sur}	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6		2.3	0.6	0.6	0.6	0.6	0.6	0.6
$l50_1$	6.7	6.5	6.5	6.4	6.6	6.5	6.7	6.6	6.2	7.5	6.6	6.7	6.7	6.8	6.7	6.6
$l50_2$	7.9	8.0	8.0	7.6	8.1	8.0	7.9	7.7	7.9	6.8	9.1	7.9	7.9	7.9	7.9	7.9
$l50_3 = l50_4$	6.7	6.7	6.7	6.6	6.7	6.8	6.7	6.6	6.7	5.6	6.8	6.7	6.7	6.7	6.7	6.7
ψ_1	-3.7	-4.1	-4.2	-4.4	-4.1	-4.2	-3.7	-3.8	-5.3	-0.7	-3.9	-3.7	-3.6	-3.4	-3.7	-3.8
$\psi_2 = \psi_3 = \psi_4$	-1.7	-1.7	-1.7	-1.9	-1.7	-1.8	-1.7	-1.8	-1.8	-3.1	-2.2	-1.7	-1.7	-1.7	-1.7	-1.7
$\delta_1 = \delta_2$	-0.3	-0.4	6.7	-0.4	-0.4	-0.4	-0.3	-0.3	-0.4	-	-	-0.3	-0.3	-0.3	-0.3	-0.4
$\delta_3 = \delta_4$	-0.8	-0.8	-0.8	-0.8	-0.7	-0.7	-0.8	-0.8	-0.8	-	-	-0.8	-0.8	-0.8	-0.8	-0.7
L_∞	11.1	11.1	11.1	10.9	11.1	11.2	11.1	11.0	11.1	10.0	11.1	11.1	11.1	11.1	11.1	11.1
t_0	0.09	0.09	0.10	0.09	0.10	0.10	0.09	0.09	0.13	0.17	0.10	0.09	0.09	0.09	0.09	0.10
κ	2.4	2.4	2.4	2.4	2.4	2.3	2.4	2.4	2.6	2.6	2.4	2.4	2.5	2.5	2.4	2.4
ϑ_0	2.0	2.0	2.0	2.0	2.0	2.1	2.0	2.1	2.0	1.8	2.0	2.0	2.0	2.0	2.0	2.0
ϑ_1	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3
ϑ_{2+}	0.9	0.9	0.9	1.0	0.9	0.9	0.9	1.0	0.9	1.2	0.9	0.9	0.9	0.9	0.9	0.9
η_{2013}^A	-0.39	-0.46	-0.20	-0.38	-0.38	-0.41	-0.38	-0.14	-0.39	-0.41	-0.39	-0.40	-0.39	-0.12	-0.39	-0.25
s_{cor}^A	0.13	0.11	0.19	0.18	0.13	0.13	0.13	0.25	0.13	0.22	0.13	0.15	0.12	0.08	0.13	0.13

Table 5. The annual estimated anchovy loss to predation (in '000t), P_y^A in Appendix C, compared to the annual anchovy catch (in '000t), and the annual total proportion fished, F_y^A in Appendix C. Note that these are calculated under the simplified assumption that catch is taken as a pulse mid-way through the year.

		A_{BH}			A_{Mad}			A_{Mj}		
Year	Catch	Loss to *M*	Catch / Loss to *M*	Annual proportion fished	Loss to *M*	Catch / Loss to *M*	Annual proportion fished	Loss to *M*	Catch / Loss to *M*	Annual proportion fished
1984	280	6456	0.04		6749	0.04		6453	0.04	
1985	300	3199	0.00	0.10	2933	0.00	0.11	3245	0.00	0.10
1986	600	4852	0.00	0.17	4586	0.00	0.17	4699	0.00	0.17
1987	570	5060	0.00	0.17	4978	0.00	0.18	5032	0.00	0.17
1988	297	4373	0.00	0.18	4295	0.00	0.18	4385	0.00	0.18
1989	152	2277	0.00	0.13	2285	0.00	0.13	2318	0.00	0.13
1990	151	1832	0.00	0.15	1875	0.00	0.15	1848	0.00	0.15
1991	349	4828	0.00	0.13	4539	0.00	0.13	4404	0.00	0.13
1992	236	5488	0.00	0.10	4823	0.00	0.11	5363	0.00	0.10
1993	156	3620	0.00	0.08	3643	0.00	0.08	3668	0.00	0.08
1994	177	1859	0.00	0.10	1770	0.00	0.10	1887	0.00	0.10
1995	42	1869	0.00	0.21	1956	0.00	0.21	1898	0.00	0.21
1996	60	1300	0.00	0.05	1370	0.00	0.05	1321	0.00	0.05
1997	108	2274	0.00	0.08	2124	0.00	0.08	2205	0.00	0.08
1998	179	2956	0.00	0.07	2855	0.00	0.07	2977	0.00	0.07
1999	268	4344	0.00	0.09	4301	0.00	0.09	4304	0.00	0.09
2000	285	9834	0.00	0.09	10037	0.00	0.09	9544	0.00	0.09
2001	216	15014	0.00	0.04	16534	0.00	0.04	14621	0.00	0.04
2002	256	12484	0.00	0.02	15264	0.00	0.02	12652	0.00	0.02
2003	192	9963	0.00	0.04	11199	0.00	0.04	10065	0.00	0.04
2004	282	6842	0.00	0.04	7521	0.00	0.04	6965	0.00	0.04
2005	136	6682	0.00	0.08	6087	0.00	0.08	6557	0.00	0.08
2006	251	5261	0.00	0.03	4852	0.00	0.03	5293	0.00	0.03
2007	259	6275	0.00	0.08	6572	0.00	0.08	6369	0.00	0.08
2008	181	8511	0.00	0.06	9262	0.00	0.06	8497	0.00	0.06
2009	220	8661	0.00	0.03	9961	0.00	0.03	8715	0.00	0.03
2010	120	6385	0.00	0.04	7884	0.00	0.04	6560	0.00	0.04
2011	305	3645	0.00	0.04	4136	0.00	0.04	3739	0.00	0.04
2012	77	6487	0.00	0.17	6327	0.00	0.19	6160	0.00	0.17
2013	243	11213	0.00	0.02	10721	0.00	0.02	10792	0.00	0.02
2014	238	8409	0.00	0.04	8416	0.00	0.05	8488	0.00	0.04
2015	280	5803	0.00	0.05	6166	0.00	0.05	5920	0.00	0.05

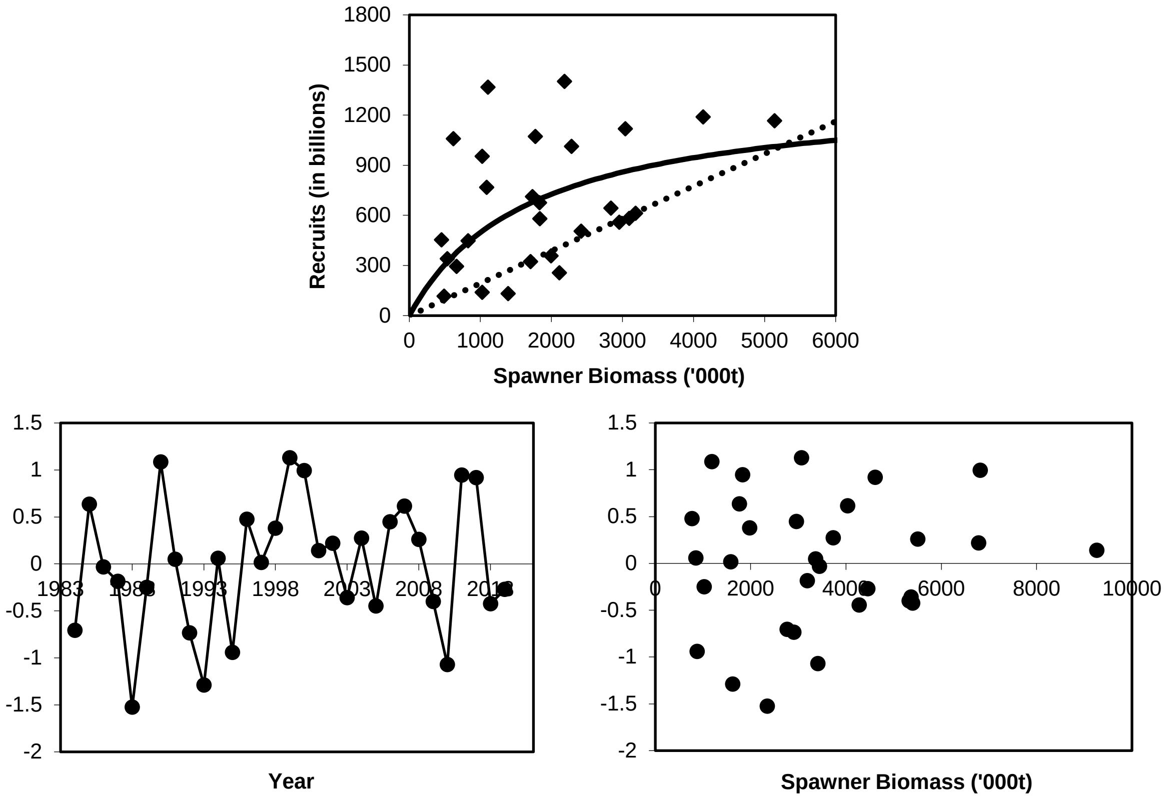

Figure 1. Model predicted anchovy recruitment (in November) plotted against spawner biomass from November 1984 to November 2014 for A_{BH} with the Beverton Holt stock recruitment relationship. The dotted line indicates the replacement line. The standardised residuals from the fit are given in the lower plots, against year and against spawner biomass.

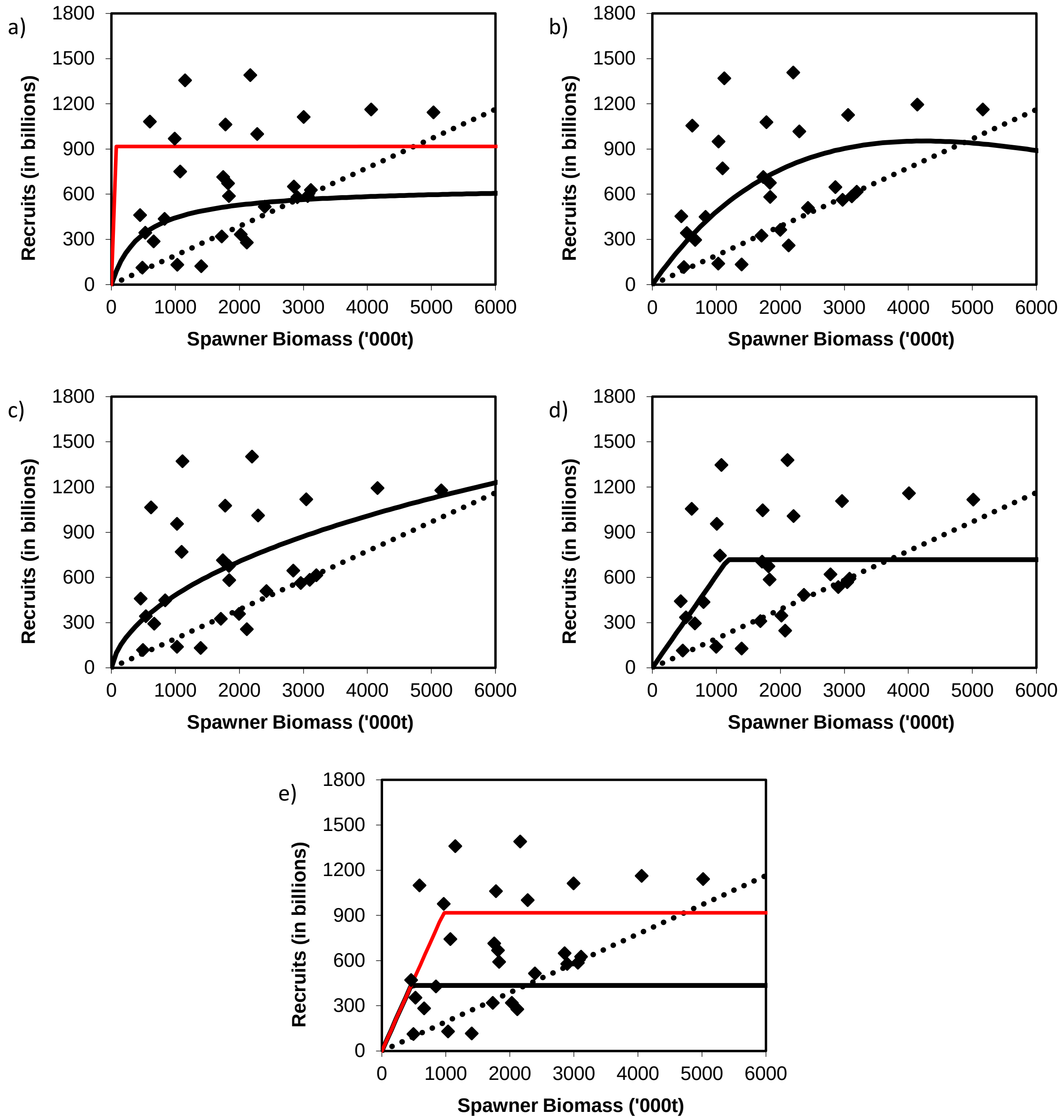

Figure 2. Stock-recruit relationships for a) A_{2BH} (red curve being the 2000+ relationship), b) A_R, c) A_{ModR}, d) A_{HS}, and e) A_{2HS} (red curve showing the 2000+ relationship).

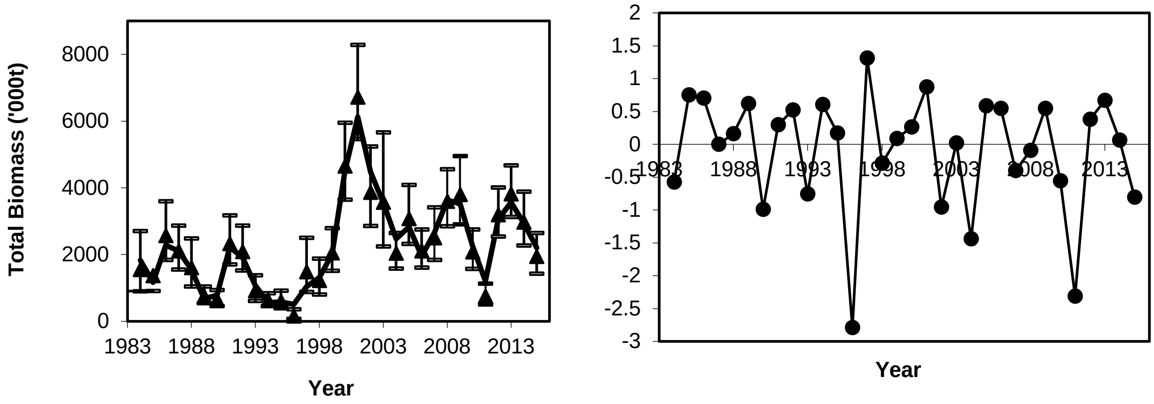

Figure 3. Acoustic survey results and model estimates for November anchovy spawner biomass from 1984 to 2015 for A_{BH}. The survey indices are shown with 95% confidence intervals reflecting survey inter-transect variance. The standardised residuals (i.e. the residual divided by the corresponding standard deviation, including additional variance where appropriate, calculated using equation (A.23)) are given in the right hand plot.

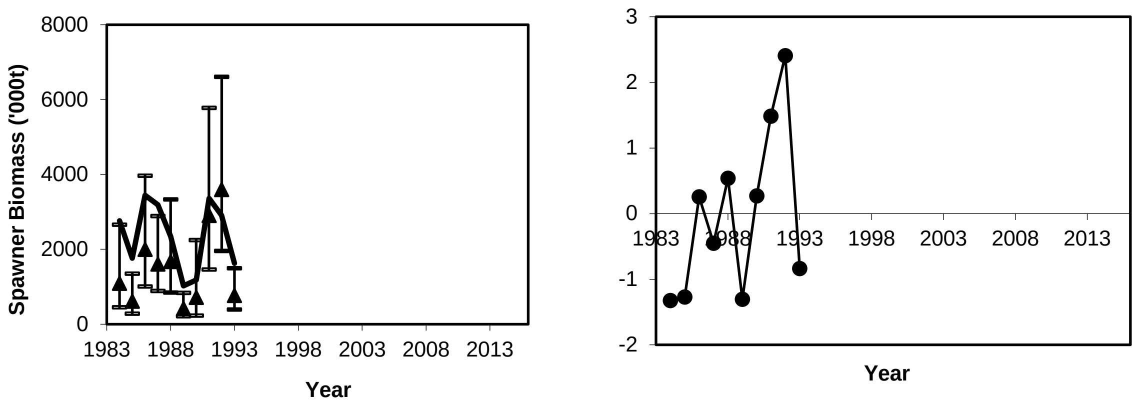

Figure 4. Egg survey results and model estimates for November anchovy spawner biomass from 1984 to 1993 for A_{BH}. The survey indices are shown with 95% confidence intervals. The standardised residuals are given in the right hand plot.

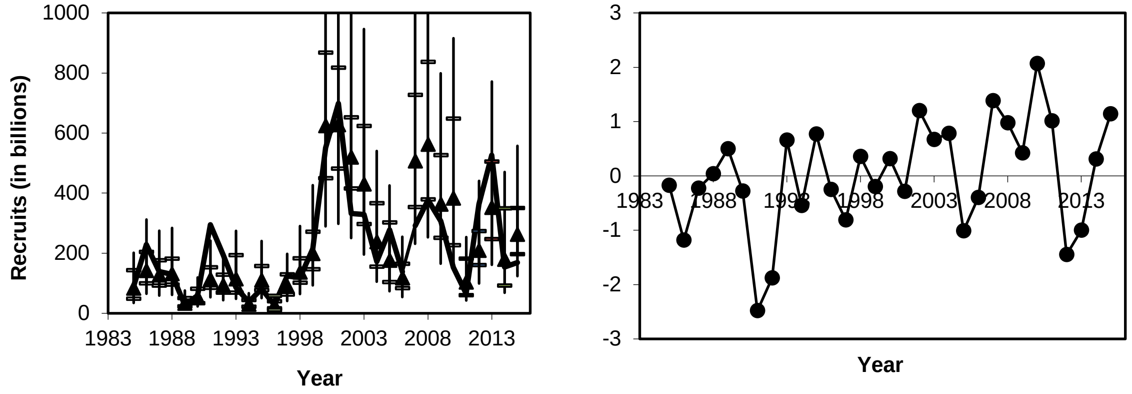

Figure 5. Acoustic survey results and model estimates for anchovy recruitment numbers from May 1985 to May 2015 for A_{BH}. The survey indices are shown with 95% confidence intervals reflecting survey inter-transect and additional variance. The horizontal bars on these vertical lines reflect the 95% confidence intervals from the survey inter-transect variance only. The standardised residuals (i.e. the residual divided by the corresponding standard deviation, including additional variance where appropriate, as specified in equation (A.25)) are given in the right hand plot.

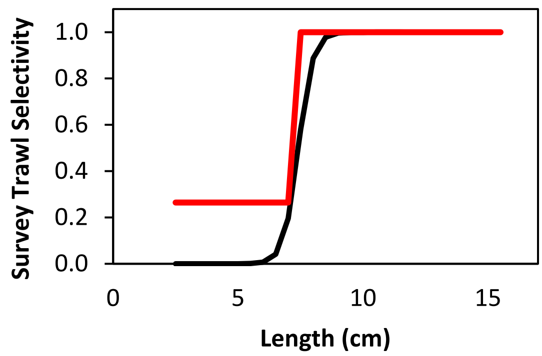

Figure 6. Model estimated trawl survey selectivity at length for A_{BH}.

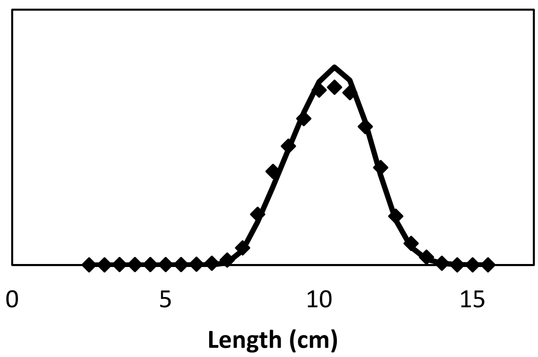

Figure 7. Average (over all years) model predicted and observed proportions-at-length in the November survey trawls for A_{BH}.

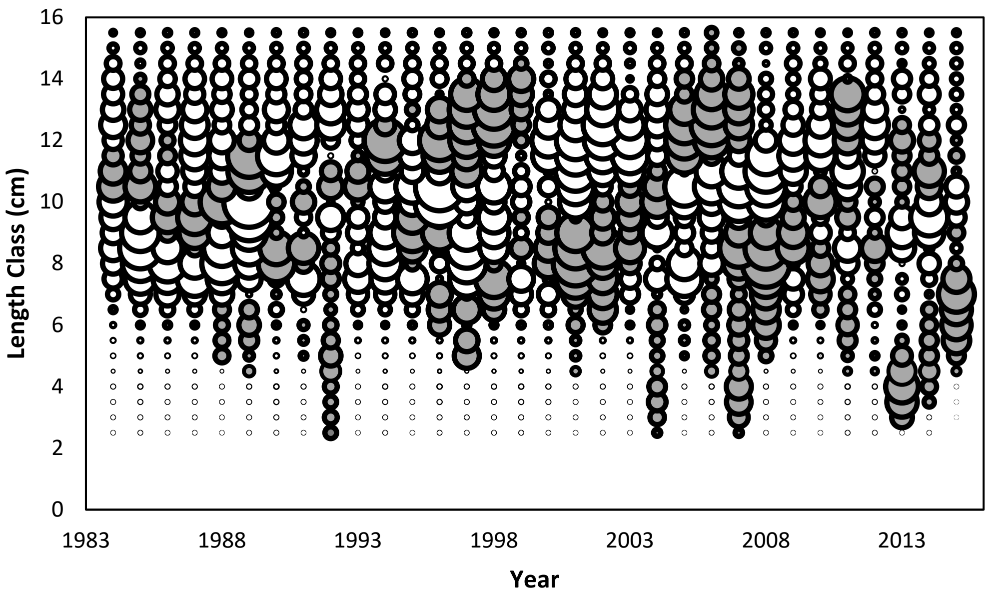

Figure 8. Standardised residuals for proportions-at-length in the November survey trawls for A_{BH}. The size of the bubbles are proportional to the absolute value of the residuals, while the shaded bubbles show positive and the unshaded bubbles show negative residuals.

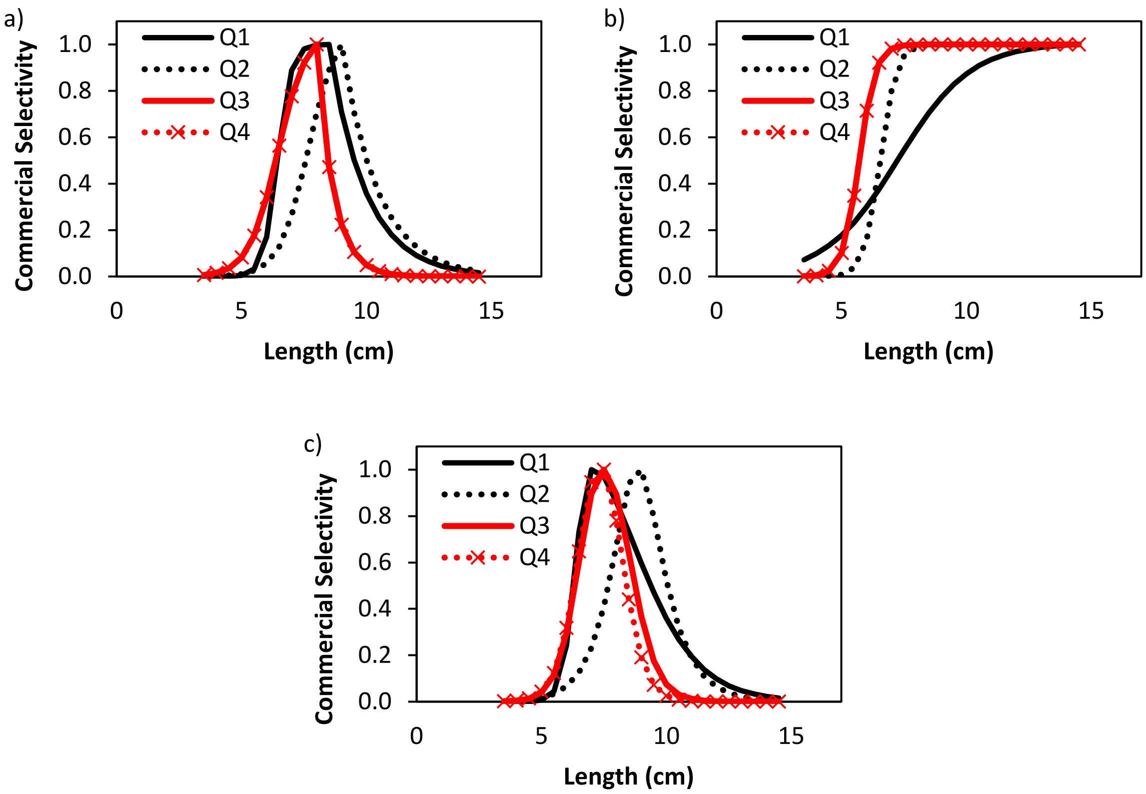

Figure 9. Model estimated quarterly commercial survey selectivity at length for a) A_{BH}, b) A_{com}, and c) A_{com2}.

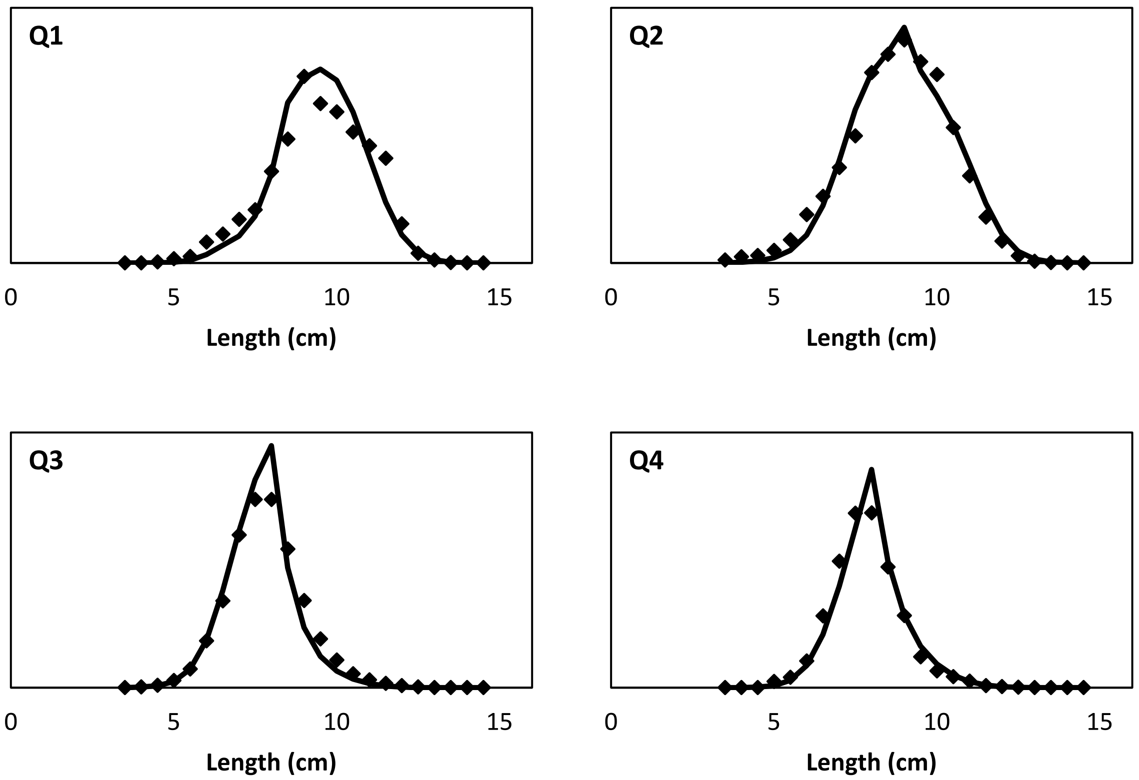

Figure 10a. Average (over all years) model predicted and observed proportions-at-length in the quarterly commercial catch for A_{BH}.

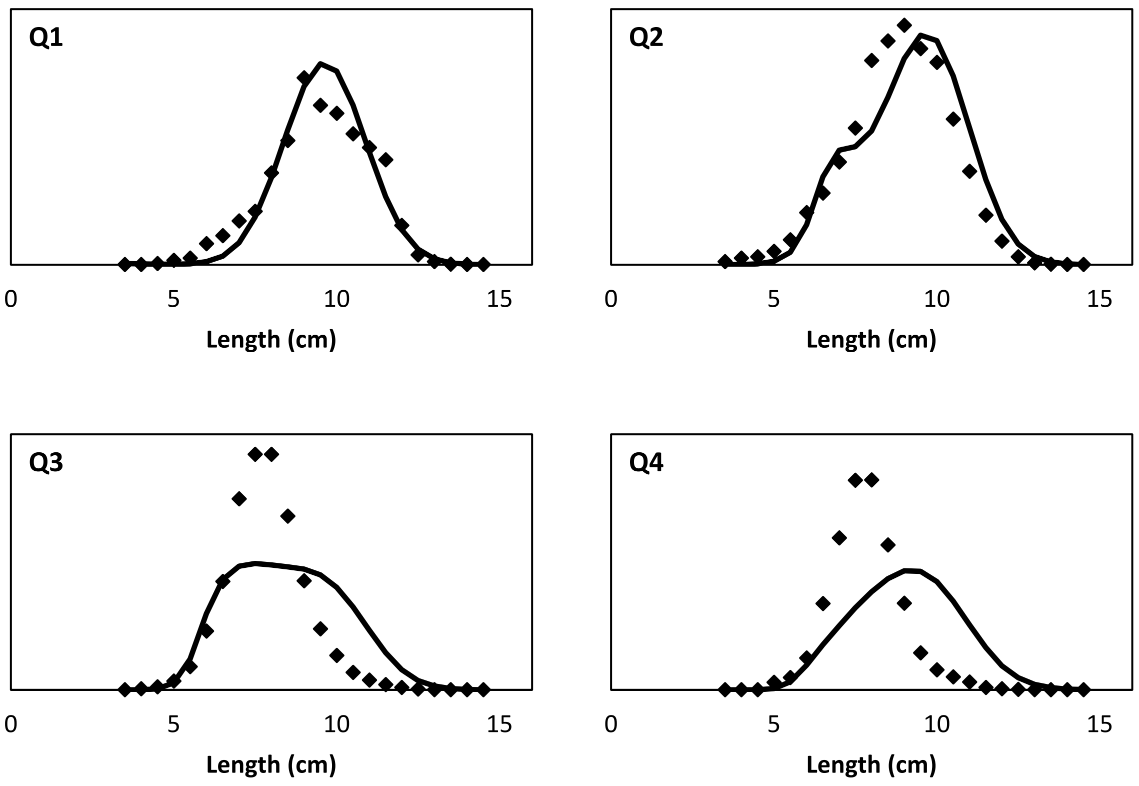

Figure 10b. Average (over all years) model predicted and observed proportions-at-length in the quarterly commercial catch for A_{Com}.

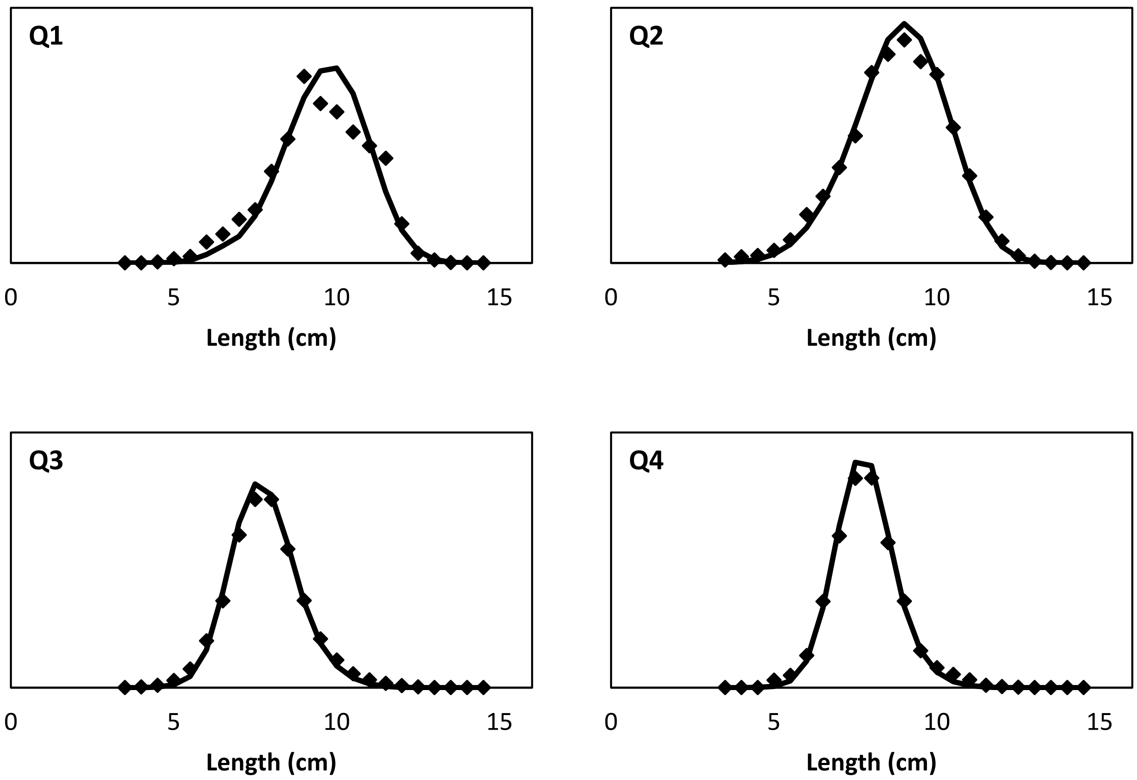

Figure 10c. Average (over all years) model predicted and observed proportions-at-length in the quarterly commercial catch for A_{Com2}.

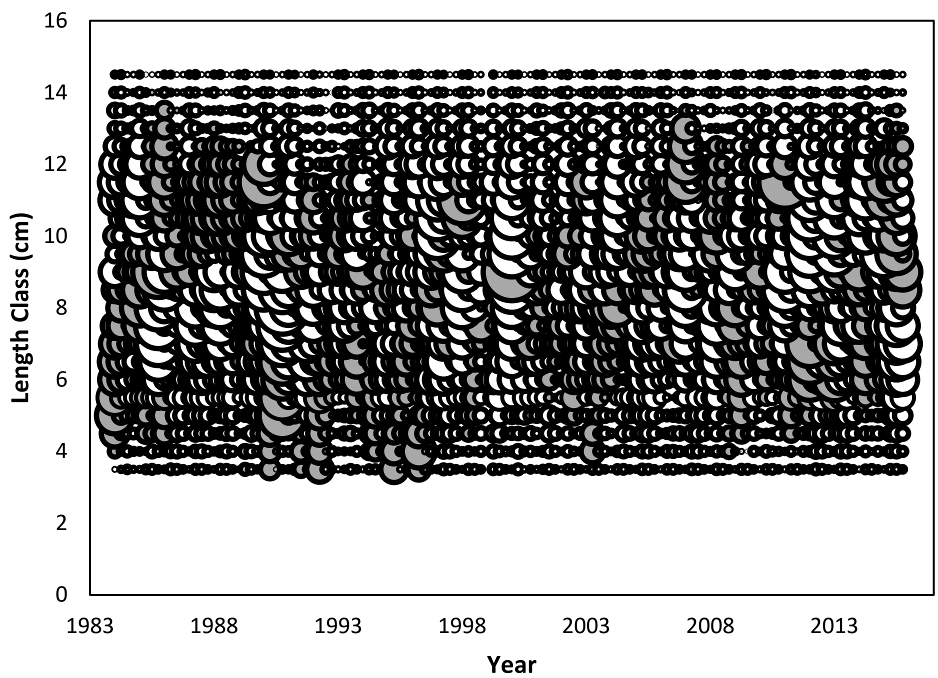

Figure 11. Standardised residuals for proportions-at-length in the quarterly commercial catch for A_{BH}. The size of the bubbles are proportional to the absolute value of the residuals, while the shaded bubbles show positive and the unshaded bubbles show negative residuals.

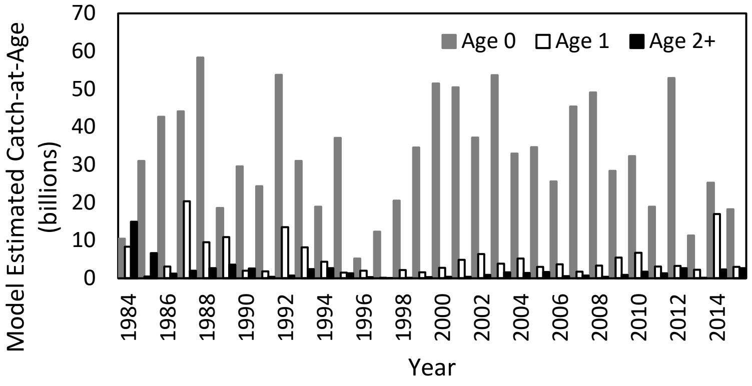

Figure 12. The model estimated quarterly catch-at-age for A_{BH}.

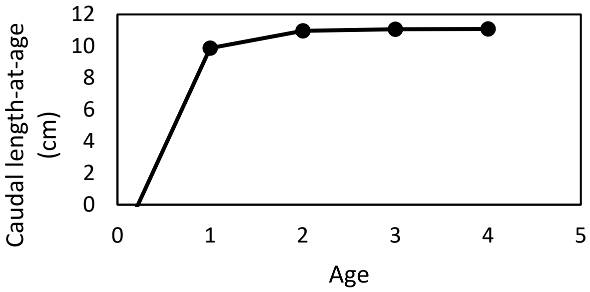

Figure 13. The model estimated von Bertalanffy growth curve, where integer ages are taken to correspond to November each year for A_{BH}.

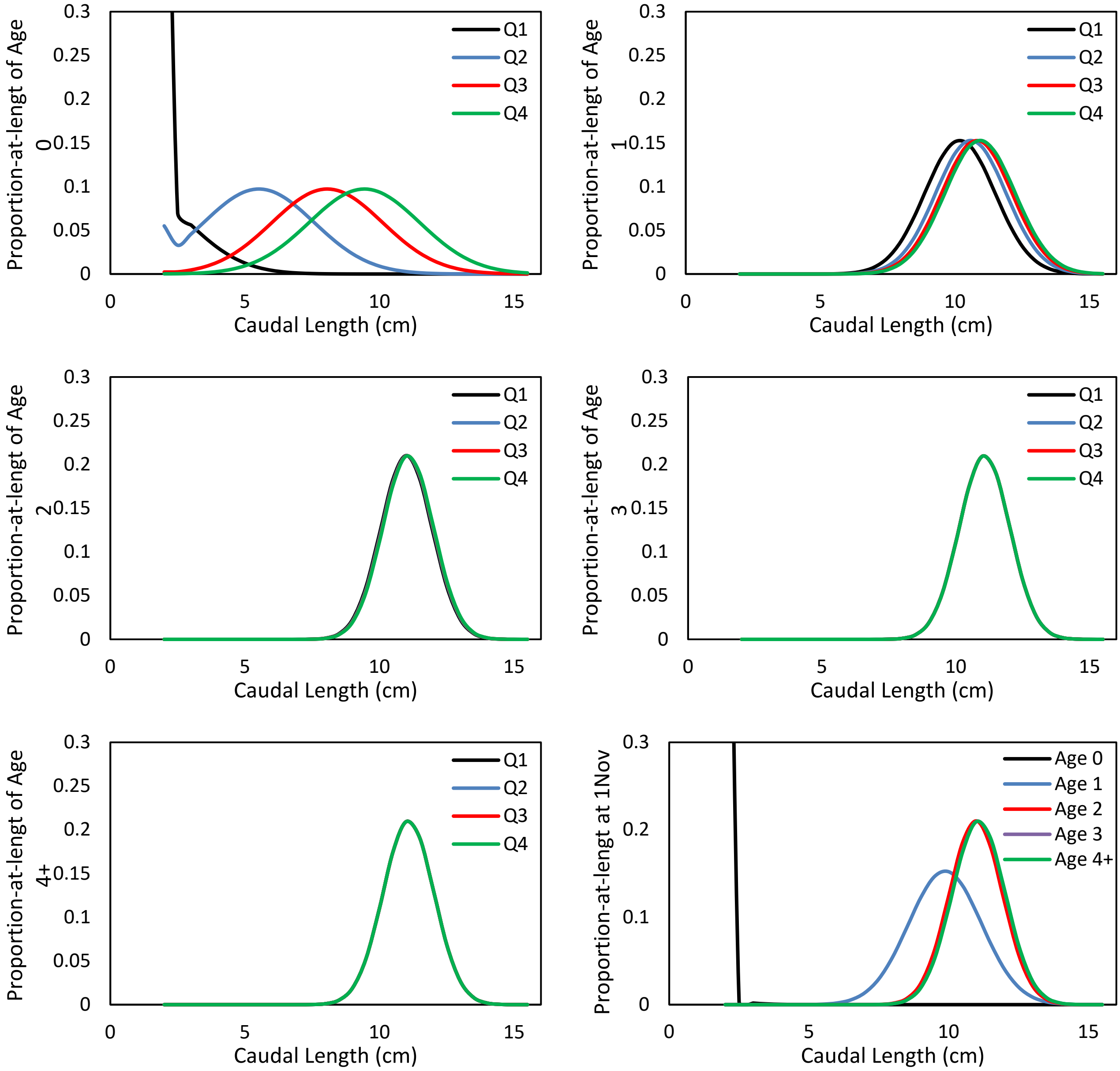

Figure 14. The model estimated distributions of proportions-at-length for each age for A_{BH}, given at the middle of each quarter of the year (corresponding to the times commercial catch is modelled to be taken). The last plot compares the distributions for all ages at 1 November.

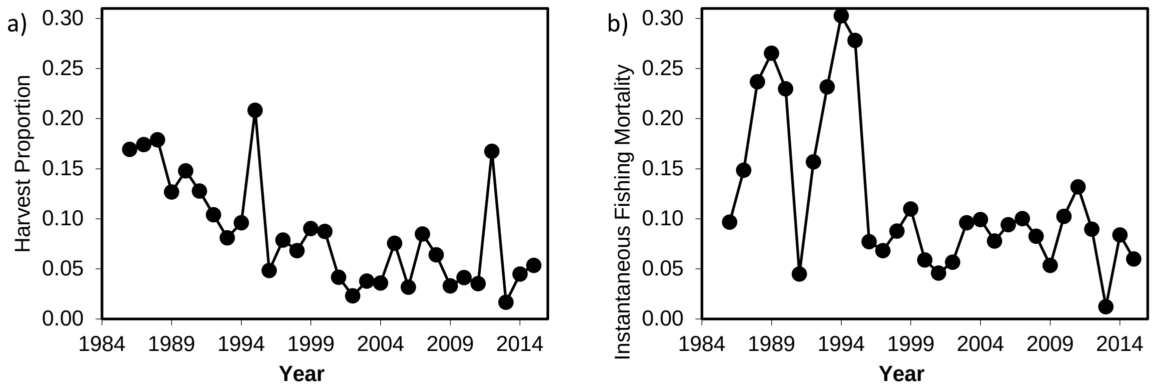

Figure 15. The model estimated historical harvest proportion (catch by mass as a proportion of total biomass) and approximated instantaneous fishing mortality for anchovy for A_{BH}.

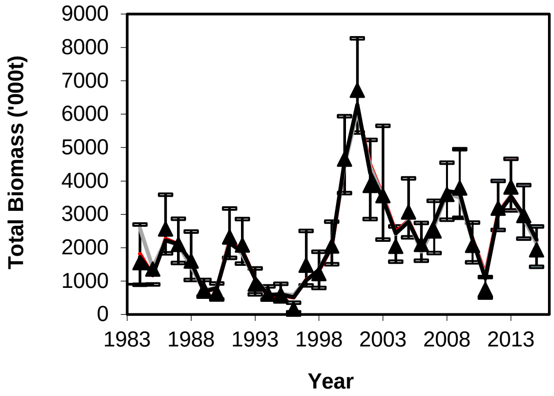

Figure 16. Acoustic survey results and model estimates for November anchovy spawner biomass from 1984 to 2015 for A_{Mad} (black), A_{Mj} (red) and A_{M2000+} (grey). The survey indices are shown with 95% confidence intervals reflecting survey inter-transect variance.

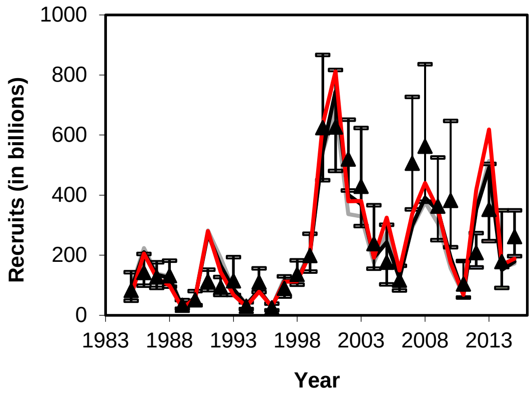

Figure 17. Acoustic survey results and model estimates for anchovy recruitment numbers from May 1985 to May 2015 for A_{Mad} (black), A_{Mj} (red) and A_{M2000+} (grey). The survey indices are shown with 95% confidence intervals reflecting survey inter-transect variance.

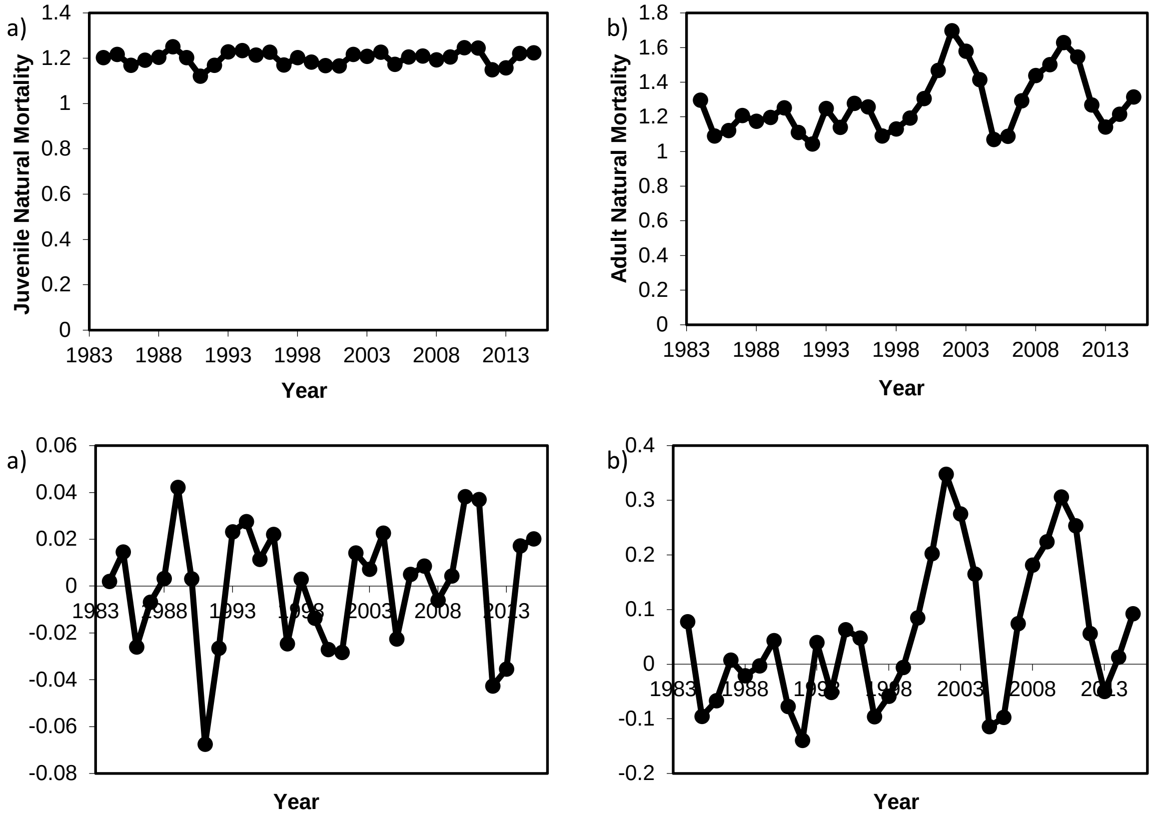

Figure 18. Model estimated annual a) juvenile and b) adult natural mortality for A_{Mj} and A_{Mad}, respectively. The random effects are shown in the lower panel.

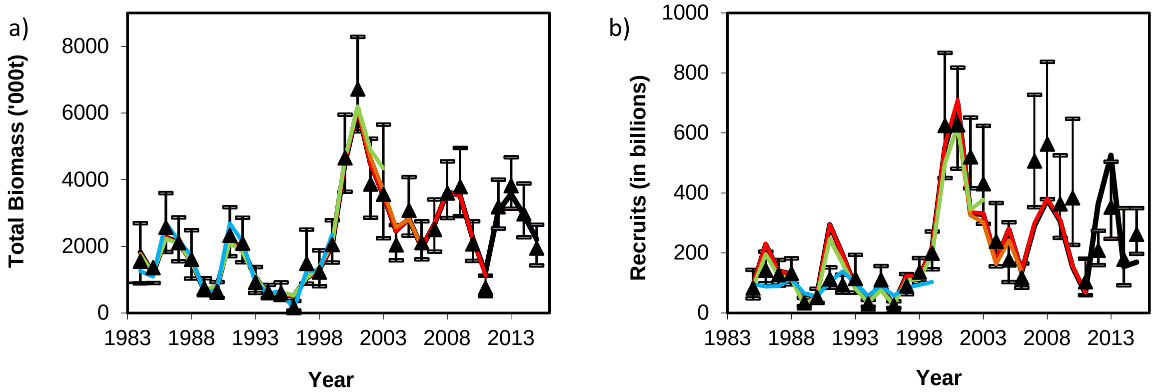

Figure 19. The model predicted a) November anchovy total biomass and b) May recruitment for A_{BH} and the retrospective runs using data up to 2011 (red line), A_{2006} using data up to 2006 (orange line), A_{2003} using data up to 2003 (green line), and A_{1999} using data up to 1999 (blue line).

Appendix A: Bayesian operating model for the South African anchovy resource

In the below equations a "^" is used to represent an estimate of a quantity (e.g. biomass) from a source external to this model (e.g. a survey). Model predicted quantities are represented by terms without any additional super-/sub-scripts other than dependencies on, for example, year, length etc.

Model Assumptions

1) All fish have a birthdate of 1 November.
2) Anchovy mature according to a length-based ogive with an L_{50} of 10.6cm.
3) A plus group of age 4 is used, thus assuming that all population dynamics aspects are the same for age 4 and older.
4) A minus length class of 2cm and a plus length class of 16cm is used.
5) Natural mortality is age-invariant for fish aged 1 and older.
6) Two acoustic surveys are held each year: the first takes place in November and provides an index of abundance of the total stock; the second is in May/June (known as the recruit survey) and provides an index of abundance of juvenile anchovy only.
7) The November and recruit acoustic surveys provide relative indices of abundance of unknown bias.
8) The egg survey observations (derived from data collected during the earlier November surveys) provide estimates of abundance in absolute terms.
9) The survey designs have been such that they result in survey estimates of abundance whose bias is invariant over time.
10) Pulse fishing occurs four times a year, in the middle of each quarter of the assessment year (November to October).

Population Dynamics

The basic dynamic equations for anchovy, based on Pope's approximation (Pope, 1984), are as follows, where $y_1 = 1984$ and $y_n = 2015$.

Numbers-at-age at 1 November

$$N^A_{y,a} = \left(\left(\left(\left((N^A_{y-1,a-1}e^{-M^A_{a-1,y}/8} - C^A_{y,1,a-1})e^{-M^A_{a-1,y}/4}\right) - C^A_{y,2,a-1}\right)e^{-M^A_{a-1,y}/4} - C^A_{y,3,a-1}\right)e^{-M^A_{a-1,y}/4} - C^A_{y,4,a-1}\right)e^{-M^A_{a-1,y}/8}$$

$$y_1 \le y \le y_n \ , \ 1 \le a \le 3$$

$$N^A_{y,4+a} = \left(\left(\left(\left((N^A_{y-1,3}e^{-M^A_{3,y}/8} - C^A_{y,1,3})e^{-M^A_{3,y}/4}\right) - C^A_{y,2,3}\right)e^{-M^A_{3,y}/4} - C^A_{y,3,3}\right)e^{-M^A_{3,y}/4} - C^A_{y,4,3}\right)e^{-M^A_{3,y}/8}$$
$$+\left(\left(\left(\left((N^A_{y-1,4+}e^{-M^A_{4+,y}/8} - C^A_{y,1,4+})e^{-M^A_{4+,y}/4}\right) - C^A_{y,2,4+}\right)e^{-M^A_{4+,y}/4} - C^A_{y,3,4+}\right)e^{-M^A_{4+,y}/4} - C^A_{y,4,4+}\right)e^{-M^A_{4+,y}/8}$$

$y_1 \le y \le y_n$ (A**Error! Bookmark not defined.**.1)

Numbers-at-length at 1 November

The model estimated numbers-at-length range from a 2cm minus group to a 16cm plus group, denoted 2^- and 16^+, respectively, in the remaining text. The model predicted numbers-at-length at the time of the survey are:

$$N_{y,l}^{A} = \sum_{a=0}^{4+} A_{a,l}^{sur} N_{y,a}^{A} \qquad y_1 \le y \le y_n,\ 2^- cm \le l \le 16^+ cm \qquad \text{(A.2)}$$

The model predicted numbers-at-length of ages 1+ only are given by:

$$N_{y,l}^{A,1+} = \sum_{a=1}^{4+} A_{a,l}^{sur} N_{y,a}^{A} \qquad y_1 \le y \le y_n,\ 2^- cm \le l \le 16^+ cm \qquad \text{(A.3)}$$

The proportion of anchovy of age a that fall in the length group l at 1 November matrix, $A_{a,l}^{sur}$, is calculated under the assumption that length-at-age is normally distributed about a von Bertalanffy growth curve:

$$A_{a,l}^{sur} \sim N\left(L_\infty\left(1 - e^{-\kappa(a-t0)}\right), \vartheta_a^2\right) \qquad 0 \le a \le 4^+,\ 2^- cm \le l \le 16^+ cm \qquad \text{(A.4)}$$ [6]

Natural mortality

Natural mortality is modelled to vary annually around a median as follows:

$$M_{0,y}^{A} = \overline{M}_j^{A} e^{\varepsilon j,y} \text{ with } \varepsilon_{1984}^{j} = \eta_{1984}^{j} \text{ and } \varepsilon_y^{j} = \rho\varepsilon_{y-1}^{j} + \sqrt{1-\rho^2}\,\eta_y^{j}, \quad y > y_1 \qquad \text{(A.5)}$$

$$M_{1+,y}^{A} = \overline{M}_{ad}^{A} e^{\varepsilon ad,y} \text{ with } \varepsilon_{1984}^{ad} = \eta_{1984}^{ad} \text{ and } \varepsilon_y^{ad} = \rho\varepsilon_{y-1}^{ad} + \sqrt{1-\rho^2}\,\eta_y^{ad}, \quad y > y_1 \qquad \text{(A.6)}$$

Biomass associated with the November survey

$$B_y^{A} = \sum_{l=2^-}^{16^+} N_{y,l}^{A} w_{y,l}^{A} \qquad y_1 \le y \le y_n \qquad \text{(A.7)}$$

where $w_{y,l}^{A} = w_l^{A,Nov} \times \frac{\hat{B}_y^{A}}{\sum_{l=2^-}^{16^+} \hat{N}_{y,l}^{A} w_l^{A,Nov}}$ $\qquad y_1 \le y \le y_n,\ 2^- cm \le l \le 16^+ cm$ (A.8)

November spawner biomass

Anchovy are assumed to mature from age 1 and thus the spawning stock biomass is:

$$SSB_y^{A} = \sum_{l=2^-}^{16^+} f_l^{A} N_{y,l}^{A,1+} w_{y,l}^{A} \qquad y_1 \le y \le y_n \qquad \text{(A.9)}$$

Commercial selectivity

Commercial selectivity-at-length is assumed to follow the logistic shape, with a dome at high lengths. Commercial selectivity is assumed to vary by quarter, but remain unchanged over time. Selectivity-at-lengths less than the smallest

[6] The proportion is calculated as the area under the curve between the mid-point of length class *l*-1 and length class *l*. The lower and upper tails are included in the proportions calculated for the minus and plus groups, respectively.

observed length class (3.5cm) and greater than the largest observed length class (14.5cm) are taken to be zero. Thus we have:

$$S_{y,q,l} = \begin{cases} 0 & if \quad 2^- cm \le l \le 3cm \\ 1/1+e^{\psi_q(l-l50_q)} & if \quad 3.5cm \le l \le S_q^{break} \\ S_{y,q,l-1}e^{\delta_q} & if \quad S_q^{break} < l \le 14.5cm \\ 0 & if \quad 15cm \le l \le 16^+ cm \end{cases} \qquad y_1 \le y \le y_n,\ 1 \le q \le 4 \qquad \text{(A.10)}$$

[7]

Commercial selectivity-at-age is given by:

$$S_{y,q,a} = \sum_{l=2^-}^{16^+} A_{q,a,l}^{com} S_{y,l} \qquad y_1 \le y \le y_n,\ 1 \le q \le 4,\ 0 \le a \le 4^+ \qquad \text{(A.11)}$$

Commercial catch

Anchovy quarterly pulse catches are split between ages using a model estimated selectivity:

$$C_{y,1,a}^A = N_{y-1,a}^A e^{-M_{a,y}^A/8} S_{y,1,a} F_{y,1}$$

$$C_{y,2,a}^A = \left(N_{y-1,a}^A e^{-M_{a,y}^A/8} - C_{y,1,a}^A\right) e^{-M_{a,y}^A/4} S_{y,2,a} F_{y,2}$$

$$C_{y,3,a}^A = \left(\left(N_{y-1,a}^A e^{-M_{a,y}^A/8} - C_{y,1,a}^A\right) e^{-M_{a,y}^A/4} - C_{y,2,a}^A\right) e^{-M_{a,y}^A/4} S_{y,3,a} F_{y,3}$$

$$C_{y,4,a}^A = \left(\left(\left(N_{y-1,a}^A e^{-M_{a,y}^A/8} - C_{y,1,a}^A\right) e^{-M_{a,y}^A/4} - C_{y,2,a}^A\right) e^{-M_{a,y}^A/4} - C_{y,3,a}^A\right) e^{-M_{a,y}^A/4} S_{y,4,a} F_{y,4}$$

$$y_1 \le y \le y_n,\ 0 \le a \le 4^+ \qquad \text{(A.12)}$$

In the equations above the difference in the year subscript between the catch-at-age and initial numbers-at-age is because these numbers-at-age pertain to November of the previous year.

The fished proportion of the available biomass from the anchovy fishery is estimated by:

$$F_{y,1} = \frac{\sum_{m=11}^{12}\sum_{l=3.5}^{14.5} C_{y-1,m,l}^{RLF} + \sum_{l=3.5}^{14.5} C_{y,1,l}^{RLF}}{\sum_{a=0}^{4+} N_{y-1,a}^A e^{-M_{a,y}^A/8} S_{y,1,a}}$$

$$F_{y,2} = \frac{\sum_{m=2}^{4}\sum_{l=3.5}^{14.5} C_{y,m,l}^{RLF}}{\sum_{a=0}^{4+} \left(N_{y-1,a}^A e^{-M_{a,y}^A/8} - C_{y,1,a}^A\right) e^{-M_{a,y}^A/4} S_{y,2,a}}$$

$$F_{y,3} = \frac{\sum_{m=5}^{7}\sum_{l=3.5}^{14.5} C_{y,m,l}^{RLF}}{\sum_{a=0}^{4+} \left(\left(N_{y-1,a}^A e^{-M_{a,y}^A/8} - C_{y,1,a}^A\right) e^{-M_{a,y}^A/4} - C_{y,2,a}^A\right) e^{-M_{y,a}^A/4} S_{y,3,a}}$$

[7] These selectivities-at-length are renormalized so that the maximum is 1.

$$F_{y,4} = \frac{\sum_{m=8}^{10}\sum_{l=3.5}^{14.5} C_{y,m,l}^{RLF}}{\sum_{a=0}^{4+}\left(\left(\left(N_{y-1,a}^{A} e^{-M_{a,y}^{A}/8} - C_{y,1,a}^{A}\right)e^{-M_{a,y}^{A}/4} - C_{y,2,a}^{A}\right)e^{-M_{y,a}^{A}/4} - C_{y,3,a}^{A}\right)e^{-M_{y,a}^{A}/4} S_{y,4,a}}$$ [8] $\quad y_1 \le y \le y_n$ (A.13)

A penalty is imposed within the model to ensure that $S_{y,l}F_{y,q} < 0.95$.

Recruitment

Recruitment at the beginning of November is assumed to fluctuate lognormally about a stock-recruitment curve (see Table 1):

$$N_{y,0}^{A} = f\left(SSB_{y}^{A}\right)e^{\varepsilon_{y}^{A} - 0.5(\sigma_{r}^{A})^{2}} \qquad y_1 \le y \le y_{n-1} \qquad \text{(A.14)}$$

Number of recruits at the time of the recruit survey

The following equation projects $N_{y,0}^{A}$ to the start of the recruit survey, taking natural and fishing mortality into account:

$$N_{y,r}^{A} = \left(\left(\left((N_{y-1,0}^{A} e^{-M_{0,y}^{A}/8} - C_{y,1,0}^{A})e^{-M_{0,y}^{A}/4}\right) - C_{y,2,0}^{A}\right)e^{-\left(1/8+0.5\times t_{y}^{S}/12\right)M_{y,0}^{A}} - C_{y,0bs}^{A}\right)e^{-0.5\times t_{y}^{A} x M_{0,y}^{A}/12} \qquad y_2 \le y \le y_n \qquad \text{(A.15)}$$

The juvenile catch from 1 May to the day before the survey is calculated as follows

$$C_{y,0bs}^{A} = \left(\left(N_{y-1,0}^{A} e^{-M_{0,y}^{A}/8} - C_{y,1,0}^{A}\right)e^{-M_{0,y}^{A}/4} - C_{y,2,0}^{A}\right)e^{-\left(1/8+0.5\times t_{y}^{A}/12\right)M_{0,y}^{A}} S_{y,3,0}F_{y,bs} \qquad y_2 \le y \le y_n \qquad \text{(A.16)}$$

where

$$F_{y,bs} = \frac{\sum_{l=3.5}^{14.5} C_{y,bs,l}^{RLF}}{\sum_{a=0}^{4+}\left(\left(N_{y-1,a}^{A} e^{-M_{a,y}^{A}/8} - C_{y,1,a}^{A}\right)e^{-M_{a,y}^{A}/4} - C_{y,2,a}^{A}\right)e^{-\left(1/8+0.5\times t_{y}^{A}/12\right)M_{y,a}^{A}} S_{y,3,a}} \qquad y_2 \le y \le y_n \qquad \text{(A.17)}$$

A penalty is imposed within the model to ensure that $S_{y,l}F_{y,bs} < 0.95$.

Proportion-at-length associated with the November survey

The model predicted proportion-at-length associated with the November survey is[9]:

$$p_{y,l}^{A} = \frac{N_{y,l}^{A} S_{l}^{survey}}{\sum_{l=2.5}^{15.5} N_{y,l}^{A} S_{l}^{survey}} \qquad y_1 \le y \le y_n,\ 2.5cm \le l \le 15.5cm \qquad \text{(A.18)}$$

Proportion-at-length associated with the commercial catch

---

[8] The range of length classes used in these summation matches the range of length classes in the observations which is a smaller range than the 2^{-}cm to 16^{+}cm used in the model.

[9] Note the model predicted survey proportion of lengths 2^{-}cm and 16^{+}cm is zero, given a zero survey trawl selectivity in Table A.1. This is consistent with the range of length classes in the observed trawl survey proportions-at-length.

The commercial catch-at-length from the anchovy fishery is:

$$C^A_{y,1,l} = \sum_{a=0}^{4+} N^A_{y-1,a} e^{-M^A_{a,y}/8} A^{com}_{1,a,l} S_{y,l} F_{y,1}$$

$$C^A_{y,2,l} = \sum_{a=0}^{4+} \left(N^A_{y-1,a} e^{-M^A_{a,y}/8} - C^A_{y,1,a} \right) e^{-M^A_{a,y}/4} A^{com}_{2,a,l} S_{y,l} F_{y,2}$$

$$C^A_{y,3,l} = \sum_{a=0}^{4+} \left(\left(N^A_{y-1,a} e^{-M^A_{a,y}/8} - C^A_{y,1,a} \right) e^{-M^A_{a,y}/4} - C^A_{y,2,a} \right) e^{-M^A_{a,y}/4} A^{com}_{3,a,l} S_{y,l} F_{y,3}$$

$$C^A_{y,4,l} = \sum_{a=0}^{4+} \left(\left(\left(N^A_{y-1,a} e^{-M^A_{a,y}/8} - C^A_{y,1,a} \right) e^{-M^A_{a,y}/4} - C^A_{y,2,a} \right) e^{-M^A_{a,y}/4} - C^A_{y,3,a} \right) e^{-M^A_{a,y}/4} A^{com}_{4,a,l} S_{y,l} F_{y,4}$$

$$y_1 \le y \le y_n,\ 2^- cm \le l \le 16^+ cm \qquad \text{(A.19)}$$

The model predicted proportion-at-length by quarter in the commercial catch[10] is:

$$p^{coml,A}_{y,q,l} = \frac{C^A_{y,q,l}}{\sum_{l=3.5}^{14.5} C^A_{y,q,l}} \qquad y_1 \le y \le y_n,\ 1 \le q \le 4,\ 3.5cm \le l \le 14.5cm \qquad \text{(A.20)}$$

The proportion of anchovy of age a that fall in the length group l in quarter *q*, $A^{com}_{q,a,l}$, is calculated under the assumption that length-at-age is normally distributed about a von Bertalanffy growth curve:

$$A^{com}_{q,a,l} \sim N\left(L_\infty \left(1 - e^{-\kappa(a+(2q-1)/8 - t_0)} \right), \vartheta_a^2 \right) \qquad 1 \le q \le 4,\ 0 \le a \le 4^+,\ 2^- cm \le l \le 16^+ cm \qquad \text{(A.21)[11]}$$

Fitting the Model to Observed Data (Likelihood)

The survey observations of abundance are assumed to be log-normally distributed. The standard errors of the log-distributions for the survey observations of adult biomass and recruitment numbers are approximated by the CVs of the untransformed distributions and a further additional variance parameter. A “sqrt(p)” formulation, rather than the “adjusted lognormal” (“Punt-Kennedy”, Punt and Kennedy 1997) error distribution formulation, is assumed for the estimated proportions-at-length particularly as it can deal with occasional zero observations more easily. This “sqrt(p)” formulation mimics a multinomial form for the error distribution by forcing near-equivalent variance-mean relationship for the error distributions. The negative log-likelihood function is given by:

$$-\ln L = -\ln L^{Nov} - \ln L^{Egg} - \ln L^{rec} - \ln L^{sur\ propl} - \ln L^{com\ propl} \qquad \text{(A.22)}$$

where

$$-\ln L^{Nov} = \tfrac{1}{2} \sum_{y=y1}^{yn} \left\{ \frac{\left(\ln \hat{B}^A_y - \ln(k^A_N B^A_y) \right)^2}{(\sigma^A_{y,N})^2 + (\lambda^A_N)^2} + \ln\left[2\pi \left((\sigma^A_{y,N})^2 + (\lambda^A_N)^2 \right) \right] \right\} \qquad \text{(A.23)}$$

$$-\ln L^{Egg} = \tfrac{1}{2} \sum_{y=y1}^{1993} \left\{ \frac{\left(\ln \hat{B}^A_{y,egg} - \ln(k^A_g SSB^A_y) \right)^2}{(\sigma^A_{y,egg})^2} + \ln\left[2\pi (\sigma^A_{y,egg})^2 \right] \right\} \qquad \text{(A.24)}$$

[10] Note there model predicted commercial catch of lengths <3.5cm and >14.5cm is zero, from a zero commercial selectivity in equation (A.9). This is consistent with the range of length classes in the observed commercial proportions-at-length.

[11] The proportion is calculated as the area under the curve between the mid-point of length class *l*-1 and length class *l*. The lower and upper tails are included in the proportions calculated for the minus and plus groups, respectively.

$$-\ln L^{rec} = \tfrac{1}{2}\sum_{y=y1+1}^{yn}\left\{\frac{\left(\ln \hat{N}^A_{y,r} - \ln(k^A_r N^A_{y,r})\right)^2}{(\sigma^A_{y,r})^2 + (\lambda^A_r)^2} + \ln\left[2\pi\left((\sigma^A_{y,r})^2 + (\lambda^A_r)^2\right)\right]\right\} \quad \text{(A.25)}$$

$$-\ln L^{sur\ propl} = w^{sur}_{propl}\sum_{y=y1}^{yn}\sum_{l=2.5}^{15.5}\left\{\frac{\left(\sqrt{\hat{p}^A_{y,l}} - \sqrt{p^A_{y,l}}\right)^2}{2\left(\sigma^A_{sur}\right)^2} + \ln\left(\sigma^A_{sur}\right)\right\} \quad \text{(A.26)}$$ [12]

$$-\ln L^{com\ propl} = w^{com}_{propl}\sum_{y=y1}^{yn}\sum_{q=1}^{4}\sum_{l=3.5}^{14.5}\left\{\frac{\left(\sqrt{\hat{p}^{A,coml}_{y,q,l}} - \sqrt{p^{A,coml}_{y,q,l}}\right)^2}{2\left(\sigma^A_{com}\right)^2} + \ln\left(\sigma^A_{com}\right)\right\} \quad \text{(A.27)}$$

[12] Although strictly there may be bias in the proportions of length-at-age data, no bias is assumed in this assessment. The effect of such a bias is assumed to be small.

Table A.1. Assessment model parameters and variables.

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Annual numbers and biomass	$N_{y,a}^{A}$	Model predicted numbers-at-age a at the beginning of November in year y	Billions		A.1	
	$N_{y,l}^{A}$	Model predicted numbers-at-length l at the beginning of November in year y	Billions		A.2	
	$N_{y,l}^{A,1+}$	Model predicted numbers-at-length length l at the beginning of November in year y of anchovy ages 1+ only	Billions		A.3	
	B_{y}^{A}	Model predicted total biomass at the beginning of November in year y, associated with the November survey	Thousand tons		A.7	
	$w_{y,l}^{A}$	Mean mass of anchovy of length l (in cm) sampled during the November survey of year y	Grams		A.8	
	$w_l^{A,Nov}$	Mean mass of anchovy of length l (in cm) during November	Grams	$w_l^{A,Nov} = 0.0079 \times l^{3.0979}$		de Moor and Butterworth (2015)
	SSB_{y}^{A}	Model predicted spawning biomass at the beginning of November in year y	Thousand tons		A.9	
	f_l^{A}	Proportion of anchovy of length l (in cm) that are mature	-	$f_l^{A} = 1/\left(1+e^{-(l-10.61)/0.66}\right)$		Figure A.1
Initial values	$N_{1983,a}^{A}$	Initial numbers-at-age a	Billions	$N_{1983,0}^{A} \sim N\left(51,30^2\right)$ $N_{1983,1}^{A} \sim N\left(143,20^2\right)$ $N_{1983,0}^{A} \sim N\left(349.6,5^2\right)$	$N_{1983,3}^{A} = N_{1983,2}^{A} e^{-M_{2,1983}^{A}}$ $N_{1983,4+}^{A} = N_{1983,3}^{A} \dfrac{e^{-M_{3,1983}^{A}}}{1-e^{-M_{3,1983}^{A}}}$	Assumed $M_{ad,1983}^{A} = M_{ad,1984}^{A}$

Table A.1 (continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Natural Mortality	M_a^A	Rate of natural mortality of age a	Year^{-1}		A.5 and A.6	Selected based on maximized joint posterior, and subject to a compelling reason to modify from previous assessment
	$\overline{M}_j^A$	Median juvenile rate of natural mortality	Year^{-1}	1.2		
	$\overline{M}_{ad}^A$	Median rate of natural mortality for 1+ anchovy	Year^{-1}	1.2		
	ε_y^j	Annual residuals about juvenile natural mortality rate	-		A.5	
	ε_y^{ad}	Annual residuals about natural mortality rate for 1+ anchovy	-		A.6	
	η_y^j	Normally distributed error in calculating ε_y^j	-	$N(0,\sigma_j^2)$		
	η_y^{ad}	Normally distributed error in calculating ε_y^{ad}	-	$N(0,\sigma_{ad}^2)$		
	σ_j	Standard deviation in the annual residuals about juvenile natural mortality	-	0		See robustness tests
	σ_{ad}	Standard deviation in the annual residuals about natural mortality for ages 1+	-	0		See robustness tests
	ρ	Annual autocorrelation coefficient	-	0		See robustness tests

Table A.1 (Continued).

	Parameter/ Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Recruitment	h^A	Steepness associated with the stock-recruitment curve[13]	-	Table 1		
	K^A	Carrying capacity	Thousand tons	Table 1		
	a^A	Maximum median recruitment in the Hockey Stick stock-recruitment curve	Billions	Table 1		
	b^A	Biomass above which median recruitment is constant and independent of spawning biomass in the Hockey Stock stock-recruitment curve	Thousand tons	Table 1		
	α^A	Stock-recruitment curve parameter, related to h^A and K^A, for Beverton Holt and Ricker curves	-		Table 1	
	β^A	Stock-recruitment curve parameter, related to h^A and K^A, for Beverton Holt and Ricker curves	-		Table 1	
	ε_y^A	Annual lognormal deviation of recruitment	-	$\sim N\left(0,\left(\sigma_r^A\right)^2\right)$, $y_1 \le y \le 1999$ $\sim N\left(0,\left(\sigma_{r,2000+}^A\right)^2\right)$, $2000 \le y \le y_{n-1}$		Reflects the assumption of a different distribution applying pre- and post-2000
	$\left(\sigma_r^A\right)^2$	Variance in the residuals (lognormal deviation) about the stock recruitment curve pre-2000	-	$\sim U(0.16,10)$		Lower bound chosen to restrict the influence of the stock recruitment curve on the assessment results
	$\left(\sigma_{r,2000+}^A\right)^2$	Variance in the residuals (lognormal deviation) about the stock recruitment curve post-2000	-	$\sim U(0.16,10)$		
	$N_{y,r}^A$	Model predicted number of juveniles at the time of the recruit survey in year y	Billions		A.14	

[13] The proportion of the median virgin recruitment that is realised at a spawning biomass level of 20% of average pre-exploitation (virgin) spawning biomass, K^A.

Table A.1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Multiplicative bias	k_N^A	Multiplicative bias associated with the November acoustic survey	-	$\ln(k_N^A) \sim U(-100, 0.7)$		Uninformative, corresponds to upper bound of $k_N^A \sim 2$
	k_g^A	Multiplicative bias associated with the November egg survey	-	1.0		See robustness tests
	k_r^A	Multiplicative bias associated with the recruit survey	-	$k_r^A / k_N^A \sim U(0,1)$		Recruit survey assumed to cover less of the recruits than the November survey covers of the total biomass
Proportions-at-length and growth curve	$p_{y,l}^A$	Model predicted proportion-at-length l associated with the November survey in year y	-		A.18	
	$A_{a,l}^{sur}$	Proportion of anchovy-at-age a that fall in the length group l in November	-		A.4	
	$p_{y,q,l}^{comA}$	Model predicted proportion-at-length l in the commercial catch during quarter q of year y	-		A.20	
	$A_{q,a,l}^{com}$	Proportion of anchovy-at-age a that fall in the length group l in quarter q	-		A.21	
	L_∞	Maximum length (in expectation) of anchovy	Cm	$\sim N(11.05, 1.105^2)$		See Appendix B
	κ	Annual somatic growth rate of anchovy	Year^{-1}	$\kappa \times L_\infty \sim N(2.915, 0.292^2)$		See Appendix B
	t_0	Age at which the length (in expectation) is zero	Year	$\sim N(0.112, 0.1^2)$		See Appendix B
	ϑ_a	Standard deviation of the distribution about the mean length for age a	-	$\vartheta_0 \sim N(2.0, 0.15^2)$ $\vartheta_1 \sim N(1.2, 0.18^2)$ $\vartheta_{2+} \sim N(1.0, 0.1^2)$		See Appendix B

Table A.1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Selectivity	S_l^{survey}	November survey trawl selectivity-at-length l	-	0, $l=2^- cm, 16^+ cm$ $= \frac{1}{1+exp(-(l-l^{sur})/\delta^{sur}}$		Set to 0 outside the length range observed. Estimated less than 1 for smaller length classes due to trawl net selectivity
	$S_{y,q,l}$	Commercial selectivity-at-length l during quarter q of year y	-		A.10	
	$S_{y,q,a}$	Commercial selectivity-at-age a during quarter q of year y	-		A.11	
	ψ_q	Steepness of ascending limb of logistic part of commercial selectivity curve during quarter q	-	$\sim U(-10,0)$, $\psi_2=\psi_3=\psi_4$		Uninformative
	$l50_q$	Length at which ascending limb of logistic part of commercial selectivity is 50% during quarter q	Cm	$\sim U(3,10)$, $l50_3=l50_4$		Uninformative
	δ_q	Rate of exponential decrease in commercial selectivity at large lengths during quarter q	-	$\delta_1=\delta_2 \sim N(0.38,0.5^2)$ $\delta_3=\delta_4 \sim N(0.75,0.04^2)$		See Appendix B
	S_q^{break}	Length at which commercial selectivity starts to decrease during quarter q	Cm	14, $q=1$; 15, $q=2$; 13, $q=3,4$		Informed by initial results

Table A.1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Catch	$C^A_{y,q,a}$	Model predicted number of anchovy of age a caught during quarter q [14] from 1 November $y-1$ to 31 October y	Billions		A.12	
	$F_{y,q}$	Fished proportion in quarter q of year y for a fully selected length class l	-		A.13	
	$C^A_{y,0bs}$	Number of juveniles caught between 1 May and the day before the start of the recruit survey in year y	Billions		A.16	
	$F_{y,bs}$	Fished proportion between 1 May and the day before the start of the recruit survey in year y	-		A.17	
Further output	s^A_{cor}	Recruitment serial correlation	-		$\frac{\sum_{y=y1}^{yn-2}\varepsilon_y\varepsilon_{y+1}}{\sqrt{\left(\sum_{y=y1}^{yn-2}\varepsilon_y^2\right)\left(\sum_{y=y1}^{yn-2}\varepsilon_{y+1}^2\right)}}$	
	η^A_{yn-1}	Standardised recruitment residual value for final year	-		$\frac{\varepsilon^A_{yn-1}}{\sigma^A_{r,2000+}}$	

[14] The quarters are $q=1$: November-January; $q=2$: February-April; $q=3$: May-July; $q=4$: August-October.

Table A.1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
	$-\ln L^{Nov}$	Contribution to the negative log likelihood from the model fit to the November total survey biomass data	-		A.23	
	$-\ln L^{Egg}$	Contribution to the negative log likelihood from the model fit to the November egg survey spawner biomass data			A.24	
	$-\ln L^{rec}$	Contribution to the negative log likelihood from the model fit to the recruit survey data	-		A.25	
	$-\ln L^{surpropl}$	Contribution to the negative log likelihood from the model fit to the November survey proportion-at-length data	-		A.26	
	$-\ln L^{compropl}$	Contribution to the negative log likelihood from the model fit to the quarterly commercial proportion-at-length data	-		A.27	
Likelihood	$\left(\lambda_N^A\right)^2$	Additional variance, over and above $\left(\sigma_{y,N}^A\right)^2$, associated with the November survey	-	0		See robustness tests
	$\left(\lambda_r^A\right)^2$	Additional variance, over and above $\left(\sigma_{y,r}^A\right)^2$, associated with the recruit survey		$\sim U\left(0{,}100\right)$		Uninformative
	w_{propl}^{sur}	Weighting applied to the survey proportion-at-length data	-	0.2		To allow for autocorrelation[15]
	σ_{sur}^A	Standard deviation associated with the survey proportion-at-length data	-	$\sqrt{\sum_{y=y1}^{yn}\sum_{l=7}^{13}\left(\sqrt{\hat{p}_{y,l}^A}-\sqrt{p_{y,l}^A}\right)^2 \Big/ \sum_{y=y1}^{yn}\sum_{l=7}^{13}1}$		Closed form solution[16]
	w_{propl}^{com}	Weighting applied to the commercial proportion-at-length data	-	0.05		To allow for autocorrelation[17]
	σ_{com}^A	Standard deviation associated with the commercial proportion-at-length data	-	$\sqrt{\sum_{y=y1}^{yn}\sum_{q=1}^{4}\sum_{l=5}^{12}\left(\sqrt{\hat{p}_{y,q,l}^{A,coml}}-\sqrt{p_{y,q,l}^{A,coml}}\right)^2 \Big/ \sum_{y=y1}^{yn}\sum_{q=1}^{4}\sum_{l=5}^{12}1}$ 8		Closed form solution[18]

[15] Based upon data being available ~5 times more frequently than annual age data which contain maximum information content on this

[16] A shorter range of lengths is used given the near absence of data outside this range, resulting in small/zero residuals, which would negatively bias this estimate.

[17] Based upon data being available ~4x5 times more frequently than annual age data which contain maximum information content on this

[18] A shorter range of lengths is used given the near absence of data outside this range, resulting in small/zero residuals, which would negatively bias this estimate.

Table A.2. Assessment model data, detailed in de Moor et al. (2015).

Quantity	Description	Units / Scale	Shown in Figure
$C^{RLF}_{y,m,l}$	Observed number of anchovy in length class l caught during month m of year y [19]	Billions	
$C^{RLF}_{y,bs}$	Observed number of anchovy in length class l caught from 1 May to the day before the start of the recruit survey in year y	Billions	
t^{A}_{y}	Time lapsed between 1 May and the start of the recruit survey in year y	Months	
$\hat{B}^{A}_{y}$	Acoustic survey estimate of total biomass from the November survey in year y	Thousand tons	Figure 3
$\sigma^{A}_{y,Nov}$	Survey sampling CV associated with $\hat{B}^{A}_{y}$ that reflects survey inter-transect variance	-	Figure 3
$\hat{B}^{A}_{y,egg}$	Egg survey estimate of spawner biomass from the November survey in year y	Thousand tons	Figure 4
$\sigma^{A}_{y,egg}$	Survey sampling CV associated with $\hat{B}^{A}_{y,egg}$ estimated from inter-transect variance		Figure 4
$\hat{N}^{A}_{y,r}$	Acoustic survey estimate of recruitment from the recruit survey in year y	Billions	Figure 5
$\sigma^{A}_{y,r}$	Survey sampling CV associated with $\hat{N}^{A}_{y,r}$ that reflects survey inter-transect variance	-	Figure 5
$\hat{p}^{A}_{y,l}$	Observed proportion (by number) of anchovy in length group l in the November survey of year y	-	
$\hat{p}^{A,coml}_{y,q,l}$	Observed proportion (by number) of anchovy commercial catch in length group l during quarter q of year y		

[19] This is the observed length-frequency adjusted such that the expected mass calculated using the weight-at-length relationship matches the observed catch in tons. The weight-at-length relationship applied to these commercial data is taken to vary by month, as obtained from fitting an inverted normal distribution for the “a parameter” to monthly commercial data from 1984 to 1996 (de Moor and Butterworth 2015a).

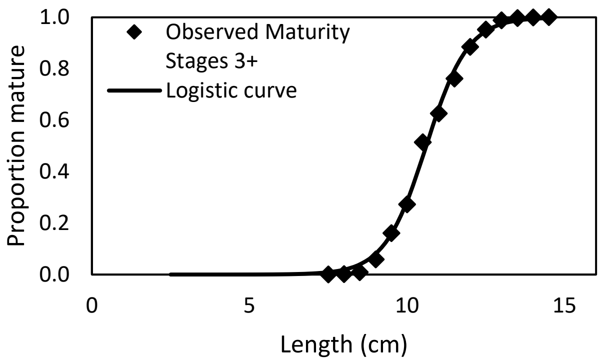

Figure A.1. The logistic curve fitted to stages 3+ proportions of sexually mature male and female anchovy sampled during the November surveys in 1985 and 1986 (Melo 1992). Sexual maturity was assumed for maturity stages 3 and higher (Melo pers. comm.). The four sets of data were combined for each length class into the single observation used in this plot. This was done by weighting each of the four observations of numbers of sexually mature males/females by the total numbers of males/females observed by length class, i.e. $f_l^{A,obs} = \frac{\sum_i mature^i \times total^i}{\sum_i total^i}$, where i=1,…,4 denotes each of the four data sets.

Appendix B: "Hardly informative" prior distributions

The model constantly demonstrated some problems attaining convergence to the joint posterior mode (a positive definite Hessian) for some parameters when initially these were given uninformative uniform prior distributions. Initial testing indicated estimation of these parameters was pushing the extremes of data limitation. "Hardly informative" prior distributions were thus used which do no more than simply aid the software to compute a Hessian and thus conduct MCMC simulations.

The process used was, while fixing other growth parameters, to separately develop likelihood profiles over the parameters L_∞, t_0, $\kappa \times L_\infty$ and ϑ_a. This was undertaken with the model and data available to de Moor and Butterworth (2015). Normal prior distributions were then assigned to these parameters with means roughly corresponding to the parameters values giving the minimum objective function value[20]. The standard deviations for these prior distributions were chosen such that the Hessian-based SE resulting from the model fit was less (as much less as possible) than that of the prior distribution.

Normal prior distributions chosen in a similar manner were used for the commercial selectivity parameters, δ_q, and for the initial numbers-at-ages 0, 1 and 2. Alternative formulations for the initial numbers-at-age were also attempted. This included assuming a decreasing equilibrium age structure based purely on natural mortality, or on both natural mortality and an estimated equilibrium fishing mortality. The formulation implemented offered the best fit to the data, which was likely informed by the decrease in survey estimated anchovy total biomass between Novembers 1984 and 1985, while recruitment was observed to increase from May 1984 to 1985.

For the parameters where the Hessian-based SE was close to the standard deviation of the distribution (and convergence to the joint posterior mode was not possible with a larger standard deviation), i.e. ϑ_0, $\delta_3 = \delta_4$, $N^A_{1983,2}$, robustness tests were undertaken for alternative fixed values for these parameters.

[20] With the reservation that estimating these parameters jointly will likely result in a different combination of 'best values' than when the likelihood profiles are estimated with the other parameters fixed.

Appendix C: Calculating instantaneous fishing mortality and loss to predation

Considering primarily age 0 and 1 anchovy contribute to the directed anchovy catch, and assuming that natural mortality, M, and the average annual commercial selectivity is constant over ages 0 and 1, the numbers of 1+ fish available at the end of the year is given by:

$$N^A_{y,1+} = N^A_{,y-1,0}e^{-\left(F^A_y S_0+M\right)} + N^A_{,y-1,1}e^{-\left(F^A_y S_1+M\right)} + N^A_{y-1,2+}e^{-M} \qquad \text{(C.1)}$$

where $N^A_{y,1+}$ denotes the total (over all ages 1^+) number of anchovy in November y (i.e. at the beginning of the year $y+1$), S_a denotes the relative selectivity at age a, averaged over all quarters and F^A_y denotes instantaneous annual fishing mortality of anchovy in year y.

The biomass of anchovy annually lost to predation, P^A_y, is calculated assuming for simplicity that catch is taken half way through the year:

$$\begin{aligned} P^A_y = \sum_{a=1}^{4}\left\{N^A_{y-1,a-1}\left(1-e^{-0.5M_{a-1,y}}\right)+\left(N^A_{y-1,a-1}e^{-0.5M_{a-1,y}}-\sum_q C^A_{y,q,a-1}\right)\left(1-e^{-0.5M_{a-1,y}}\right)\right\}\times 0.5\left(w_{a-1}+w_a\right) \\ +\left\{N^A_{y-1,4^+}\left(1-e^{-0.5M_{4^+,y}}\right)+\left(N^A_{y-1,5^+}e^{-0.5M_{4^+,y}}-\sum_q C^A_{y,q,4^+}\right)\left(1-e^{-0.5M_{4^+,y}}\right)\right\}\times 0.5\left(w_{4^+}+w_{4^+}\right) \end{aligned} \qquad \text{(C.2)}$$