

Assessment of the South African sardine resource using data from 1984-2015: Results at the joint posterior mode for the single stock hypothesis

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Introduction

The assessment of the South African sardine resource has been revised and updated using data available up to November 2015. Two primary hypotheses regarding the sardine stock structure have been agreed for investigation. The first considers sardine distributed off the west and south coasts of South Africa to form a single homogeneous “stock” (or “population”). The second considers the sardine to consist of a western stock and southern stock with some mixing between the two. While there is growing evidence supporting the existence of sub-population structure amongst sardine distributed off the west and south coasts of South Africa (e.g. Coetzee et al. 2008, van der Lingen et al. 2009, 2015, van der Lingen 2011, Weston et al. 2015), the single stock hypothesis continues to be modelled as it allows for easy comparison to past assessments and, in particular, to past risk statistics and previous Operational Management Procedures. It also reflects a limiting case of the mixing model as the extent of mixing becomes very large. This document presents results at the joint posterior mode for the single stock hypothesis only.

Population Dynamics Model

The same generalised operating model for the South African sardine resource is used for both the single and two mixing-stock hypotheses, and the data used in this assessment are listed in de Moor *et al.* (2016). The model is detailed in Appendix A of de Moor and Butterworth (2016) and all the parameters are defined in Tables A.1 and A.2 of that same Appendix. The single stock hypothesis uses abundance indices and proportion-at-length data for the whole west-south coast combined and excludes the parasite data used to inform mixing between the stocks in the two mixing-stock hypothesis.

Key features of this model include:

- The model is age-structured with a plus group of age 5. A distribution of length-at-age is used to model the length-structure of the population at fixed times during the year, and the length-at-age 0 differs by year to allow for variations in the time of peak recruitment (thus being able to accommodate early/late recruitment).
- Recruitment to each stock is dependent on the spawner biomass of that stock only (though the equations are generalised to allow for alternative assumptions to be made in robustness testing).

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Key differences in this model compared to those of de Moor and Butterworth (2015) include:

- Spawner biomass is calculated assuming a maturity-at-length ogive which changes over time, rather than assuming all sardine mature at age 2, and using weight-at-length rather than weight-at-age.
- The trawl survey selectivity-at-length is assumed to be logistic (hence allowing for some escapement of small fish); reduced availability (a decrease in selectivity) at larger lengths is no longer modelled.
- The estimated stock-specific commercial selectivity-at-length curve is described by a logistic distribution at greater lengths rather than an inverted lognormal distribution. Time-varying commercial selectivity is assumed, with selectivity varying by quarter and between four pre-specified periods (1984-1986, 1987-1997, 1998-2001, 2002-2015).
- Instead of assuming that the small (<14cm) sardine bycatch is measured without error, for numerical computation convenience a small error is allowed and a fishing mortality is estimated for this bycatch to assist with model convergence.
- The informative prior distribution for the bias associated with the acoustic survey has been recalculated assuming a lognormal rather than normal distribution.
- To aid stable parameter estimation, the stock-specific lengths at ages 1 and 3 are estimated instead of the von-Bertalanffy growth curve parameters themselves.
- To account for variation in the time of the recruitment peak each year, the annual length-at-age 0 is estimated to vary with additive normal error about a median value at 1st November.

In addition, a number of other prior distributions have been modified and/or parameters have been re-parameterised to assist with model convergence.

Stock recruitment relationship

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

- S_{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
- S_{HSpeak} – hockey stick stock-recruitment curve over all years except 2000-2004, 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; constant recruitment over the peak years of 2000-2004, with a uniform prior on the log of this constant.
- S_{BH} – Beverton Holt stock-recruitment curve, with uniform priors on steepness and carrying capacity
- S_R – Ricker stock-recruitment curve, with uniform priors on steepness and carrying capacity
- S_{ModR} – Modified Ricker stock-recruitment curve, with uniform priors on steepness, carrying capacity and a shape parameter

In all of the alternatives above the standard deviations of the residuals about the curve are estimated assuming a difference between peak (2000-2004) and non-peak years.

Natural mortality

A number of combinations of median juvenile and adult natural mortality values are examined, covering the range 0.6 to 1.2 year⁻¹, for the case where a Hockey Stick stock recruitment relationship is assumed. For realism, only combinations with $\bar{M}_j^S \geq \bar{M}_{ad}^S$ are considered.

Three alternatives were tested which allowed juvenile and/or adult natural mortality to change in 2000; with the amount of change being an estimable parameter.

Robustness Tests

The base case hypothesis estimates the initial (November 1983) numbers at age 1, and assumes age 2+ are negligible (zero), while age 0 are estimated using the stock-recruitment relationship (Table A.1 of Appendix A of de Moor and Butterworth 2016). Alternatives considered are:

S^{init1} – estimate $N_{j=1,NI,1983,a=2}^S \sim U(0,50)$

S^{init2} – estimates $N_{j=1,NI,1983,a=0}^S \sim U(0,50)$ and $N_{j=1,NI,1983,a=2}^S \sim U(0,50)$; thus does not use the stock-recruitment relationship in 1983

The base case hypothesis allows for differences in commercial selectivity-at-length by quarter and between four pre-specified time periods. Alternatives considered are:

S^{sel} – the same commercial selectivity-at-length for all years and quarters

The base case hypothesis allows for differences in the annual age at which length is zero. Alternatives considered are:

S^{l0} – the same age at which length is zero for all years

The base case hypothesis estimates the variability about the stock recruitment relationship during non-peak years. Alternatives considered are:

S^{sig1} – $\sigma_{j=1,r}^S = 0.4$

S^{sig2} – $\sigma_{j=1,r}^S = 0.5$

S^{sig3} – $\sigma_{j=1,r}^S = 0.6$

S^{sig4} – $\sigma_{j=1,r}^S = 0.7$

The base case hypothesis assumes no fish are lost to slippage or dumping. Alternatives considered are:

S^{slip1} – constant 10% of the catch is additionally lost to slippage (Somhlaba et al. 2015). This additional ‘catch’ is taken pro rata from all length classes.

S^{slip2} – 10% of the catch is additionally lost to slippage in years where the TAC is less than 100 000t¹. This

¹ There may be more pressure to discard unsuitable hauls in favour of landing only canable fish during years of low TAC.

additional ‘catch’ is taken pro rata from all length classes

$S^{\text{slip}3}$ – 10% of the catch tonnage is additionally lost to slippage in years where the TAC is less than 100 000t, this catch is assumed to be of lengths <13.5cm only. An additional ‘catch’ of X%, where:

$$X = 1.1 + 0.1 \frac{\sum_{l > 13.5 \text{cm}} C_{j,y,m,l}^{\text{fleet}=1+2} \times w_{j,l}^S}{\sum_{l \leq 13.5 \text{cm}} C_{j,y,m,l}^{\text{fleet}=1+2} \times w_{j,l}^S}$$

is taken from length classes <13.5cm, such that the total catch tonnage is ~10% higher than that reported.

The base case hypothesis assumes there is no additional survey variance. Alternatives considered are:

$$S^{\text{lam}1} - (\lambda_N^S)^2 \sim U(0,10)$$

$$S^{\text{lam}2} - (\lambda_R^S)^2 \sim U(0,10)$$

Results and Discussion

Natural mortality

Table 2a lists the various contributions to the objective function at the posterior mode for the full range of combinations of juvenile and adult natural mortality tested. Given the choice of prior distributions, the ratio k_r^S / k_N^S is by definition less than 1. Combinations of natural mortality which result in $k_r^S / k_N^S < 0.5$ are considered less plausible and are not considered further.

To maintain consistency with previous assessments, the base case hypothesis continues to assume $\bar{M}_j^S = 1.0$ and $\bar{M}_{ad}^S = 0.8$. This choice was made considering both the single and two-mixing stock hypotheses jointly. While there is some improvement in the objective function (joint posterior mode) for alternative natural mortality scenarios for the single stock hypothesis, those improvements were considered insufficiently large to warrant changing from the selection used in the most recent assessment, given also the major difficulties that a change would introduce for maintaining a comparable risk definition. To test the sensitivity of the results to this choice, three alternative natural mortality assumptions are retained for further robustness testing (Table 4):

$$S^{\text{M}1}: \bar{M}_j^S = 1.0 \text{ and } \bar{M}_{ad}^S = 1.0$$

$$S^{\text{M}2}: \bar{M}_j^S = 0.8 \text{ and } \bar{M}_{ad}^S = 0.8$$

$$S^{\text{M}3}: \bar{M}_j^S = 1.2 \text{ and } \bar{M}_{ad}^S = 1.0$$

Table 2b lists the various contributions to the objective function when either juvenile and/or adult natural mortality is estimated to increase after 2000. There is some improvement in the fit to the data for all alternatives, though note when only adult natural mortality is estimated to increase after 2000, the increased value is greater than that of juvenile natural mortality which is considered unrealistic. These results, together with the alternative

S^{M1} indicate that there may well have been an increase in adult natural mortality for sardine since the peak in biomass experienced in 2000.

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. While not strictly appropriate for models with prior distributions on residuals, AIC_c is used to compare coarsely amongst alternative stock-recruitment relationships, and suggests that the preferred stock-recruitment relationship is the Beverton Holt (S_{BH}), which is marginally preferred over the Hockey Stick assuming a different constant median recruitment during peak years, S_{2HS} . However, given the improved residual pattern (Figure 1) we recommend the base case hypothesis assumes a hockey stick stock-recruitment relationship with a different constant median recruitment during peak years (i.e. S_{2HS}). The alternative stock recruitment relationships are plotted in Figure 2. A much higher standard deviation about the curve is estimated for “peak” (2000-2004) years compared to non-peak years (Table 4).

S_{2HS} results at posterior mode

The estimated parameter values and other key outputs are listed in Table 4 together with the individual contributions to the negative log posterior probability density function (pdf) at the posterior mode.

The population model fits to the time series of abundance estimates of November biomass and May recruitment are shown in Figures 3 and 4, respectively. In both cases the fits to the survey data are reasonably good. The model does not predict as high a peak in early 2000's as given by the survey point estimates, though the predicted values are within the 95% CIs for the indices estimated by the surveys. The model also under-predicts recruitment in May 2010 as it is unable to reconcile the conflicting data of an above average recruitment estimate in May 2010, with almost no increase in the November biomass estimate from 2009 to 2010. This feature has been evident in previous assessments. The model is also not able to replicate the (statistically significant) annual switches from relatively high to relatively low west stock recruitment between 1994 and 1997, given the constraint of also fitting the November biomass during this same period. The model estimates that the May recruit survey covers 66% of the recruits compared to 100% coverage of the biomass in the November survey, and the bias in the acoustic survey is estimated to be 0.75 (Table 4).

The model estimated survey trawl selectivity is shown in Figure 5 with the average (over all years) model predicted November survey proportion-at-length given in Figure 6. While there appears to be some mis-fit in the average comparison around lengths 15-19cm, no systematic bias is evident from the residuals in Figure 7.

The model estimated commercial selectivity is shown in Figure 8. Some of the curves estimated during the early years are a consequence of poor estimability given low catches during some quarters prior to 1987. While the model is clearly able to fit the data better by allowing commercial selectivity to differ by quarter (perhaps due to changes between primarily fishing in the Gansbaai compared to the west coast at different times of the year) and

over time (Table 4), this variability does not remove all of the systematic residual patterns in the model fit to the commercial proportion-at-length data (Figures 9 and 10a). The average (over all years and quarters) model predicted commercial proportion-at-length matches the general pattern of that observed, when considering that the variability in the normal distribution for small lengths is the same for all years (Figure 10a). Further work could allow for time-varying changes in further commercial selectivity parameters or alternatively model some selectivity parameters with a random walk rather than pre-specified time blocks to see if an improved fit would be warranted given the additional parameters estimated.

A key factor in the model fits to the proportion-at-length data is the model estimated growth curve (Figure 11) and variability about this curve (Figure 12). The estimation of annual residuals about an average age at which length is zero, chosen to mimic differences between early or late recruitment, allowed a better fit to the model (compare S_{2HS} with S^{t0} in Table 4).

Figure 13 shows the model estimated harvest rates and instantaneous fishing mortality (calculation detailed in the Appendix of de Moor and Butterworth (2016)). Table 5 gives the model estimated loss to predation compared to loss to fishing mortality under S_{2HS} .

Robustness Tests

The estimated parameter values and other key outputs for the robustness tests together with the individual contributions to the negative log posterior probability density function (pdf) at the posterior mode, are compared to those for S_{2HS} in Table 4.

Many of the alternatives do not provide an improved fit to the data compared to S_{2HS} . Estimating additional parameters in the initial year (S^{init1} and S^{init2}) does improve the model fit, but not substantially given the extra parameters used.

Considering the results of the robustness tests to slippage of sardine, if slippage has been constant over time, the model rescales as expected such that S^{slip1} shows a similar fit to the data as S_{2HS2} . S^{slip2} also shows a similar fit to the data, with the stock-recruitment curve adjusted such that recruitment starts to drop below a higher spawner biomass level than under S_{2HS2} . The commercial proportion-at-length data change substantially for S^{slip3} (Figure 10b). Inspection of these proportions indicate that the ‘worse’ fit to the data for S^{slip3} compared to S_{2HS2} (Table 4) should not be taken to suggest a lower probability of the circumstances assumed for this robustness test actually applying, but rather to indicate a different parametric curve – perhaps a simpler logistic-only curve - being required to mimic commercial selectivity-at-length should slippage primarily occur from small sardine only.

Summary

This document has detailed the results for the updated assessment of the South African sardine resource, assuming a single stock hypothesis. It is recommended that a hockey stick stock recruitment relationship, with a different

constant median recruitment over the peak years of 2000-2004 be assumed for a base case hypothesis, together with $\bar{M}_j^s = 1.0$ and $\bar{M}_{ad}^s = 0.8$. To maintain comparability with past assessments and Operating Models used during OMP development, the baseline Operating Model posterior distributions will be simulated assuming $\sigma_{j=1,r}^s = 0.5$, because $\sigma_{j=1,r}^s \sim 0.4$ is considered to be too small for small pelagics with highly variable recruitment. This is consistent with the base case hypothesis proposed for the two mixing-stock hypothesis (de Moor and Butterworth 2016).

There is little indication of retrospective pattern for this assessment (Figure 14).

This updated assessment predicts the total sardine resource biomass to have been 783 000t in November 2015, below the long-term average of 1.1 million tons, and near the 1991-1994 average of 755 000t – a level historically used as a risk threshold for the total sardine resource. The resource has suffered below average recruitment in eleven of the last twelve years.

References

- Coetzee JC, van der Lingen CD, Hutchings L, and Fairweather TP. 2008. Has the fishery contributed to a major shift in the distribution of South African sardine? *ICES Journal of Marine Science*. 65: 1676-1688. doi: 10.1093/icesjms/fsn184.
- de Moor CL and Butterworth DS. 2015. Assessing the South African sardine resource: two stocks rather than one? *African Journal of Marine Science* 27:41-51.
- de Moor CL and Butterworth DS. 2016. Assessment of the South African sardine resource using data from 1984-2015: Results at the joint posterior mode for the two mixing-stock hypothesis. DAFF: Branch Fisheries Document FISHERIES/2016/JUL/SWG-PEL/22rev.
- 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/APR/SWG-PEL/13. 27pp.
- Somhlaba S, Brandão A, Butterworth DS and Glazer JP. 2015. A detailed look at the effect of observers on catch rates onboard the small pelagic vessels when sardine is the dominant species in catch landing. DAFF: Branch Fisheries Document FISHERIES/2015/FEB/SWG-PEL/01. 21pp.
- van der Lingen CD. 2011. The biological basis for hypothesizing multiple stocks in South African sardine *Sardinops sagax*. Report No. MARAM IWS/DEC11/P/OMP/P7. 2011 International Fisheries Stock Assessment Workshop, Cape Town.
- van der Lingen CD, Fréon P, Fairweather TP, van der Westhuizen JJ. 2006. Density-dependent changes in reproductive parameters and condition of southern Benguela sardine *Sardinops sagax*. *African Journal of Marine Science* 28(3&4): 625-636.

- van der Lingen CD, Durholtz MD, Fairweather TP, and Melo Y. 2009. Spatial variability in biological characteristics of southern Benguela sardine and the possible existence of two stocks. Report No. MCM/2009/SWG-PEL/39, Marine and Coastal Management, South Africa.
- van der Lingen CD, Weston LF, Ssempe NN, Reed CC. 2015. Incorporating parasite data in population structure studies of South African sardine *Sardinops sagax*. *Parasitology* 142:156-167.
- Weston LF, Reed CC, Hendricks MR, Winker H and van der Lingen CD. 2015. Stock discrimination of South African sardine (*Sardinops sagax*) using a digenean parasite biological tag. *Fisheries Research*. 164: 120-129. doi: 10.1016/j.fishres.2014.11.002.

Table 1. The alternative stock-recruitment relationships considered. The parameter h_j^S denotes the “steepness” of the stock-recruitment relationship for stock j , which is the proportion of the virgin recruitment that is realised at a spawning biomass level of 20% of average pre-exploitation (virgin) spawning biomass K_j^S (shown in units of thousands of tons). For the hockey stick model, $X_j = \sum_{a=1}^4 \bar{w}_{j,a}^S e^{-M_j^S - (a-1)\bar{M}_{ad}^S} + \bar{w}_{j,5+} e^{-M_j^S - 3\bar{M}_{ad}^S} \frac{1}{1 - e^{-\bar{M}_{ad}^S}}$, where $\bar{w}_{j,a}^S$ is the average of $w_{j,y,a}^S$ as defined in Appendix A of de Moor and Butterworth (2016). For this same model, a_j^S denotes the maximum recruitment (in billions) and b_j^S denotes the spawner biomass below which the expectation for recruitment is reduced below the maximum.

Test	Stock recruitment relationship	$f(SSB_{y,N}^S) =$	Parameters
S _{BH}	Beverton Holt	$\frac{\alpha_j^S SSB_{j,y}^S e^{\epsilon_{j,y}^S - 0.5(\sigma_{j,r}^S)^2}}{\beta_j^S + SSB_{j,y}^S}$	$h_j^S \sim U(0.2, 1)$ $K_j^S \sim U(0, 10\,000)$ $\alpha_j^S = \frac{4h_j^S}{5h_j^S - 1} \frac{K_j^S}{X_j}$ $\beta_j^S = \frac{K_j^S(1 - h_j^S)}{5h_j^S - 1}$
S _R	Ricker	$\alpha_j^S SSB_{j,y}^S e^{-\beta_j^S SSB_{j,y,N}^S} e^{\epsilon_{j,y}^S - 0.5(\sigma_{j,r}^S)^2}$	$h_j^S \sim U(0.2, 2)$ $K_j^S \sim U(0, 10\,000)$ $\alpha_j^S = \frac{1}{X_j} \left(\frac{h_j^S}{0.2} \right)^{1/0.8}$ $\beta_j^S = \frac{\ln(h_j^S / 0.2)}{0.8K_j^S}$
S _{ModR}	Modified Ricker	$\alpha_j^S SSB_{j,y}^S e^{-\beta_j^S (SSB_{j,y,N}^S)^c} e^{\epsilon_{j,y}^S - 0.5(\sigma_{j,r}^S)^2}$	$h_j^S \sim U(0.2, 2)$ $K_j^S \sim U(0, 10\,000)$ $c^S \sim U(0, 2)$ $\alpha_j^S = \frac{1}{X_j} \left(\frac{h_j^S}{0.2} \right)^{1/0.8}$ $\beta_j^S = \frac{\ln(h_j^S / 0.2)}{0.8K_j^S}$
S _{HS}	Hockey stick	$\begin{cases} a_j^S e^{\epsilon_{j,y}^S - 0.5(\sigma_{j,r}^S)^2} & , \text{if } SSB_{j,y}^S > b_j^S \\ \frac{a_j^S}{b_j^S} SSB_{j,y}^S e^{\epsilon_{j,y}^S - 0.5(\sigma_{j,r}^S)^2} & , \text{if } SSB_{j,y}^S \leq b_j^S \end{cases}$	$\ln(a_j^S) \sim U(0, 5.4)^2$ $b_j^S / K_j^S \sim U(0, 1)$ $K_j^S = a_j^S X_j^3$
S _{2HS}	Hockey stick (2 curves)	if $2000 \leq y \leq 2004$: $a_j^S e^{\epsilon_{j,y}^S - 0.5(\sigma_{j,r}^S)^2}$ else $\begin{cases} a_j^S e^{\epsilon_{j,y}^S - 0.5(\sigma_{j,r}^S)^2} & , \text{if } SSB_{j,y}^S > b_j^S \\ \frac{a_j^S}{b_j^S} SSB_{j,y}^S e^{\epsilon_{j,y}^S - 0.5(\sigma_{j,r}^S)^2} & , \text{if } SSB_{j,y}^S \leq b_j^S \end{cases}$	$\ln(a_j^S) \sim U(0, 5.4)^1$ $b_j^S / K_j^S \sim U(0, 1)$ $\ln(a_j^S) \sim U(0, 5.4)$ $K_j^S = a_j^S X_j^3$

² Given the lack of *a priori* information on the scale of a_j^S , a log-scale was used, with a maximum corresponding to about 10 million tons.

³ For consistency, mean rather than median estimates of K are used.

Table 2a. The contributions to the objective function at the posterior mode for a range of combinations of juvenile, \bar{M}_j^s , and adult, \bar{M}_{ad}^s , natural mortality for models assuming the Hockey Stick stock recruitment relationship with a different constant median recruitment during peak years. The ratio of the multiplicative bias in the recruit survey to that in the November survey, k_r^s/k_N^s , is given for diagnostic purposes. Shaded rows represent what are considered unrealistic values for this ratio.

\bar{M}_j^s	\bar{M}_{ad}^s	-ln(Posterior)	$\Delta \{-\ln(\text{Likelihood})\}$	-ln(Likelihood)				-ln(Prior)			k_N^s	k_r^s	k_r^s/k_N^s
				Nov	Rec	Com Prop-at-length	Survey Prop-at-length	k_{ac}^s	ε_y^s	ε_y^r			
0.6	0.6	-286.88	3.13	21.4	30.4	-186.5	-203.9	-1.32	13.39	40.62	0.77	0.70	0.91
0.8	0.6	-287.80	2.20	21.3	30.5	-187.7	-203.9	-1.30	13.49	40.62	0.77	0.65	0.84
0.8	0.8	-291.90	-1.89	20.7	30.7	-186.9	-208.2	-1.39	13.52	40.63	0.75	0.53	0.71
1.0	0.6	-285.57	4.43	22.4	31.2	-188.1	-206.4	-1.32	16.44	40.95	0.77	0.59	0.77
1.0	0.8	-290.01	0.00	20.5	30.5	-186.1	-208.4	-1.43	14.64	41.22	0.75	0.49	0.66
1.0	1.0	-293.02	-3.02	20.2	30.2	-186.8	-210.1	-1.44	14.31	41.58	0.74	0.45	0.61
1.2	0.6	-285.50	4.51	22.1	30.4	-187.0	-204.6	-1.39	14.28	41.59	0.76	0.56	0.74
1.2	0.8	-285.74	4.27	24.0	31.0	-184.4	-212.9	-1.44	15.89	42.92	0.73	0.46	0.64
1.2	1.0	-292.92	-2.92	21.9	32.2	-187.0	-215.0	-1.44	15.71	41.61	0.73	0.40	0.55
1.2	1.2	-292.56	-2.56	20.3	30.3	-185.6	-210.8	-1.44	14.01	41.50	0.74	0.38	0.52
1.4	0.6	-287.42	2.58	21.8	29.7	-187.4	-205.2	-1.41	14.69	41.33	0.75	0.50	0.66
1.4	0.8	-287.92	2.08	22.0	31.6	-187.1	-209.5	-1.43	15.54	41.71	0.74	0.41	0.55
1.4	1.0	-292.69	-2.69	22.2	32.0	-189.1	-211.8	-1.43	15.38	40.77	0.75	0.36	0.48
1.4	1.2	-293.58	-3.58	20.0	30.9	-186.8	-210.8	-1.44	14.22	41.20	0.73	0.34	0.47
1.4	1.4	-293.13	-3.12	19.9	31.5	-187.8	-208.7	-1.44	12.89	41.44	0.73	0.30	0.41

Table 2b. The contributions to the objective function at the posterior mode for a range of combinations of juvenile, \overline{M}_j^S , and adult, \overline{M}_{ad}^S , natural mortalities that differ over time or between stocks, for models assuming the Hockey Stick stock recruitment relationship with a different constant median recruitment during peak years. The bold row represents the baseline hypothesis, and the shaded cells indicate when natural mortality is estimated to increase after 2000.

\overline{M}_j^S	\overline{M}_{ad}^S	\overline{M}_j^S	\overline{M}_{ad}^S	-ln(Posterior)	$\Delta \{-\ln(\text{Likelihood})\}$	-ln(Likelihood)				-ln(Prior)			k_N^S	k_r^S	k_r^S/k_N^S	
						Nov	Rec	Com Prop-at-length	Survey Prop-at-length	k_{ac}^S	ε_y^S	ε_y^t				
$y \leq 2000$	$y \leq 2000$	$y > 2000$	$y > 2000$													
1.0	0.8	1.0	0.8	-290.01	0.00	20.5	30.5	-186.1	-208.4	-1.43	14.64	41.22	0.75	0.49	0.66	
1.0	0.8	1.45	0.8	-293.15	-1.86	19.74	29.6	-187.7	-207.0	-1.44	13.28	41.21	0.74	0.44	0.59	
1.0	0.8	1.0	1.16	-297.64	-6.47	19.73	31.4	-187.8	-213.3	-1.43	13.85	40.83	0.74	0.42	0.57	
1.0	0.8	1.12	0.92	-293.28	-2.80	20.1	30.9	-186.2	-211.1	-1.44	13.85	41.59	0.73	0.43	0.58	

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.

	S_{HS}	S_{2HS}	S_{BH}	S_R	S_{ModR}
$-\ln(\text{Posterior})$	-288.5	-290.1	-285.6	-290.7	-292.0
$-\ln L^{Nov}$	22.3	20.5	22.2	21.6	21.3
$-\ln L^{rec}$	31.3	30.5	30.4	30.3	30.4
$-\ln L^{comPropL}$	-187.3	-186.1	-184.1	-188.2	-187.5
$-\ln L^{SurPropL}$	-209.4	-208.4	-210.1	-208.6	-212.2
$-\ln \text{Prior}(k_{ac}^s)$	-1.4	-1.4	-1.4	-1.4	-1.4
$-\ln \text{Prior}(\varepsilon_y^s)$	15.8	14.6	15.9	14.7	16.4
$-\ln \text{Prior}(\varepsilon_y^t)$	41.1	41.2	41.6	40.9	41.0
# parameters	100	101	100	100	101
AIC	-486.1	-485.1	-483.1	-489.8	-494.0
AIC _C	-482.7	-481.6	-479.7	-486.3	-490.5

Table 4. The contributions to the negative log posterior pdf at the joint posterior mode, together with the values of various quantities at that mode, for the robustness tests considered.

	S ^{2HS}	S ^{HS}	S ^{BH}	S ^R	S ^{ModR}	S ^{M1}	S ^{M2}	S ^{M3}	S ^{init1}	S ^{init2}	S ^{sel}	S ^{t0}	S ^{sig1}	S ^{sig2}	S ^{sig3}	S ^{sig4}	S ^{slip1}	S ^{slip2}	S ^{slip3}	S ^{lam1}	S ^{lam2}
-ln(Posterior)	-290.0	-288.5	-285.6	-290.7	-292.0	-293.0	-291.9	-292.9	-292.3	-295.8	-276.1	-278.4	-292.4	-289.3	-288.5	-284.8	-288.4	-291.8	-283.0	-291.4	-291.4
-lnL ^{Nov}	20.5	22.3	22.2	21.6	21.3	20.2	20.7	21.9	20.6	20.4	22.3	21.1	22.7	21.5	21.2	20.8	23.0	19.7	20.2	20.3	20.3
-lnL ^{rec}	30.5	31.3	30.4	30.3	30.4	30.2	30.7	32.2	31.0	30.9	32.0	29.1	31.9	30.2	28.2	27.3	30.8	30.5	30.7	30.4	30.4
-lnL ^{comPropL}	-186.1	-187.3	-184.1	-188.2	-187.5	-186.8	-186.9	-187.0	-185.9	-186.8	-175.4	-187.9	-189.1	-187.5	-189.7	-188.2	-185.7	-184.8	-176.5	-187.3	-187.3
-lnL ^{SurPropL}	-208.4	-209.4	-210.1	-208.6	-212.2	-210.1	-208.2	-215.0	-210.2	-213.3	-209.2	-192.4	-212.0	-213.3	-212.0	-211.7	-210.1	-210.2	-209.9	-208.0	-208.0
-lnPrior(k_{ac}^S)	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4	-1.4
-lnPrior(ϵ_y^S)	14.6	15.8	15.9	14.7	16.4	14.3	13.5	15.7	13.5	14.1	15.4	13.5	15.6	21.3	25.3	28.7	14.1	13.7	13.2	14.3	14.3
-lnPrior(ϵ_y^t)	41.2	41.1	41.6	40.9	41.0	41.6	40.6	41.6	41.0	41.2	40.9	40.5	40.6	40.8	40.6	40.6	41.8	41.5	41.6	41.2	41.2
\overline{M}_j^S	1.0	1.0	1.0	1.0	1.0	1.0	0.8	1.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
\overline{M}_{ad}^S	0.8	0.8	0.8	0.8	0.8	1.0	0.8	1.0	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
$k_{j=1,N}^S = k_{ac}^S$	0.75	0.75	0.75	0.76	0.76	0.74	0.75	0.73	0.75	0.75	0.75	0.74	0.76	0.75	0.76	0.76	0.74	0.74	0.75	0.75	0.75
$k_{j=1,r}^S$	0.49	0.50	0.51	0.49	0.49	0.45	0.53	0.40	0.48	0.50	0.48	0.47	0.49	0.49	0.49	0.49	0.51	0.50	0.47	0.49	0.49
$k_{j=1,r}^S / k_{j=1,N}^S$ $= k_{cov}^S$	0.66	0.67	0.68	0.65	0.64	0.61	0.71	0.55	0.65	0.66	0.64	0.64	0.64	0.65	0.65	0.65	0.69	0.67	0.64	0.66	0.66
$(\lambda_N^S)^2$	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	0.00	0.00	0.00	0.00	0.00	0.00
$(\lambda_r^S)^2$	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	0.00	0.00	0.00	0.00	0.00	0.00
$N_{j=1,N,1983,a=0}^S$	1.35	1.38	1.27	1.58	1.56	1.80	1.17	1.49	2.47	2.51	1.26	3.05	0.89	1.15	0.97	1.35	1.50	1.50	1.63	1.30	1.30
$N_{j=1,I,1983,a=1}^S$	3.77	3.27	2.72	3.22	2.10	3.33	3.66	2.15	3.23	3.00	1.71	4.33	1.55	1.97	1.67	2.31	3.41	3.88	3.68	3.43	3.43
$N_{j=1,N,1983,a=2}^S$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$a_{j=1}^S$ or $\alpha_{j=1}^S$	30.8	34.1	48.1	0.20	>999	33.6	26.8	36.4	32.5	31.8	27.4	36.8	26.5	27.4	28.7	31.2	30.3	31.4	33.7	32.1	32.1
$a'_{j=1}^S$	91.2	-	-	-	-	105.5	69.2	123.6	87.1	87.3	90.3	86.3	81.7	82.7	81.0	81.6	90.7	88.1	91.0	91.6	91.6
$b_{j=1}^S$	165.4	189.0	167.4	0.002	56.5	162.2	182.2	66.7	189.4	186.2	66.2	260.6	37.8	45.0	38.0	62.4	165.6	171.0	169	176.2	176.2
c^S	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
$K_{j=1}^S$	1268	1417	1848	1134	4923	1231	1307	1063	1304	1319	1123	1439	1063	1114	1142	1241	1334	1293	1381	1321	1321
$h_{j=1}^S$	-	-	0.75	1.07	0.45	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 4 (continued).

	S ^{2HS}	S ^{HS}	S ^{BH}	S ^R	S ^{ModR}	S ^{M1}	S ^{M2}	S ^{M3}	S ^{init1}	S ^{init2}	S ^{sel}	S ^{t0}	S ^{sig1}	S ^{sig2}	S ^{sig3}	S ^{sig4}	S ^{slip1}	S ^{slip2}	S ^{slip3}	S ^{lam1}	S ^{lam2}	
$\sigma_{j=1,r}^S$	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.50	0.60	0.70	0.40	0.40	0.40	0.40	0.40	
$\sigma_{j=1,r,peak}^S$	0.98	0.92	0.93	0.79	0.96	0.92	0.88	0.90	0.89	0.97	0.94	0.89	0.87	0.87	0.88	0.88	0.97	0.97	0.91	0.98	0.98	
η_{2009}^S	-0.03	-0.14	-0.24	-0.31	-0.30	-0.05	-0.06	0.09	-0.07	-0.04	0.17	-0.23	0.17	0.18	0.17	0.14	-0.01	-0.05	-0.10	-0.08	-0.08	
s_{cor}^S	0.41	0.57	0.58	0.50	0.55	0.40	0.34	0.46	0.38	0.40	0.40	0.33	0.41	0.44	0.39	0.37	0.40	0.38	0.33	0.41	0.41	
$L_{j=1,\infty}$	19.1	19.1	19.1	19.0	19.1	19.1	19.0	19.3	19.1	19.1	19.2	19.5	19.1	19.2	19.2	19.1	19.2	19.0	19.0	19.0	19.0	
$\kappa_{j=1}$	1.4	1.5	1.4	1.5	1.5	1.5	1.5	1.5	1.4	1.5	1.7	1.2	1.5	1.6	1.4	1.5	1.4	1.5	1.5	1.5	1.5	
$t_{0,j=1}$	-1.0	-1.0	0.1	0.79	0.75	-1.0	0.06	-1.0	-0.04	-1.0	0.09	0.00	0.06	-0.23	0.07	0.08	-1.0	-1.0	-1.0	-1.0	-1.0	
$\mathcal{G}_{j=1,0}$	2.4	2.2	1.8	2.7	2.8	2.4	2.7	2.4	2.5	2.7	3.0	2.8	2.6	2.6	2.6	2.7	2.1	2.6	2.6	2.5	2.5	
$\mathcal{G}_{j=1,1}$	1.8	1.9	1.9	1.9	1.9	2.1	1.9	1.9	1.7	1.8	2.0	1.9	1.9	1.8	1.8	1.8	1.9	1.8	1.9	1.8	1.8	
$\mathcal{G}_{j=1,2+}$	1.3	1.2	1.2	1.2	1.2	1.2	1.2	1.1	1.3	1.2	1.2	1.1	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.3	1.3	
S_{50}	9.5	7.9	7.4	9.0	8.7	12.0	8.0	7.5	9.5	7.5	7.1	10.1	7.9	7.5	8.7	7.9	9.3	9.6	9.4	9.2	9.2	
δ	0.88	0.05	0.02	0.79	0.75	1.59	0.02	0.03	0.88	0.03	0.06	0.94	0.04	0.03	0.72	0.04	0.77	1.04	0.97	0.84	0.84	
$\bar{l}_{1,j=1}$	0.95	0.95	0.94	0.95	0.95	0.95	0.95	0.95	0.96	0.95	0.95	0.96	0.95	0.95	0.95	0.95	0.95	0.96	0.97	0.95	0.95	
$(\sigma_2^{sel})^2$	1.18	1.21	1.15	1.39	1.34	1.23	1.23	1.21	1.23	1.21	1.48	1.23	1.29	1.29	1.28	1.27	1.18	1.20	1.53	1.19	1.19	
$(\sigma_1^{sel})^2$	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0	
$\chi_{j=1}$	0.07	0.07	0.05	0.04	0.05	0.06	0.08	0.05	0.07	0.07	0.30	0.05	0.07	0.08	0.96	0.07	0.07	0.07	0.11	0.06	0.06	
$\bar{l}_{1,j=1,y,q}$	0.6- 1.1	0.6- 1.1	0.6- 1.1	0.6- 1.2	0.6- 1.2	0.6- 1.1	0.6- 1.1	0.6- 1.1	0.6- 1.1	0.6- 1.1	1.5	0.6- 1.1	0.6- 1.2	0.6- 1.1	0.6- 1.2	0.6- 1.1	0.6- 1.1	0.6- 1.1	0.6- 1.1	0.5- 1.2	0.6- 1.1	0.6- 1.1

Table 5. The annual estimated sardine loss to predation (in '000t), P (Appendix C of de Moor and Butterworth 2016), compared to the annual sardine directed and total catch (in '000t).

Year	Directed Catch	Total Catch	Loss to Predation
1984	27.178	27.178	74.497
1985	30.843	30.843	141.496
1986	30.639	30.639	146.742
1987	26.703	33.529	179.361
1988	28.338	34.527	216.377
1989	26.008	36.236	356.526
1990	49.286	56.870	558.109
1991	46.136	53.198	504.529
1992	41.060	54.190	601.692
1993	42.529	49.147	889.982
1994	81.049	96.264	976.609
1995	94.307	115.960	1192.540
1996	91.712	100.323	1105.579
1997	123.680	130.568	1379.307
1998	118.185	131.505	1254.212
1999	94.881	102.328	1379.943
2000	144.562	151.873	1494.744
2001	139.760	153.620	2690.323
2002	223.175	235.753	3926.179
2003	275.692	286.145	3185.229
2004	367.032	373.404	2340.635
2005	296.657	302.336	1370.446
2006	208.436	217.689	846.766
2007	157.453	161.392	529.649
2008	80.837	84.765	444.649
2009	102.614	105.688	680.939
2010	86.373	104.352	872.664
2011	109.364	120.768	1095.180
2012	97.120	104.797	837.042
2013	90.310	93.660	811.517
2014	90.082	96.171	824.546
2015	73.117	86.374	807.240

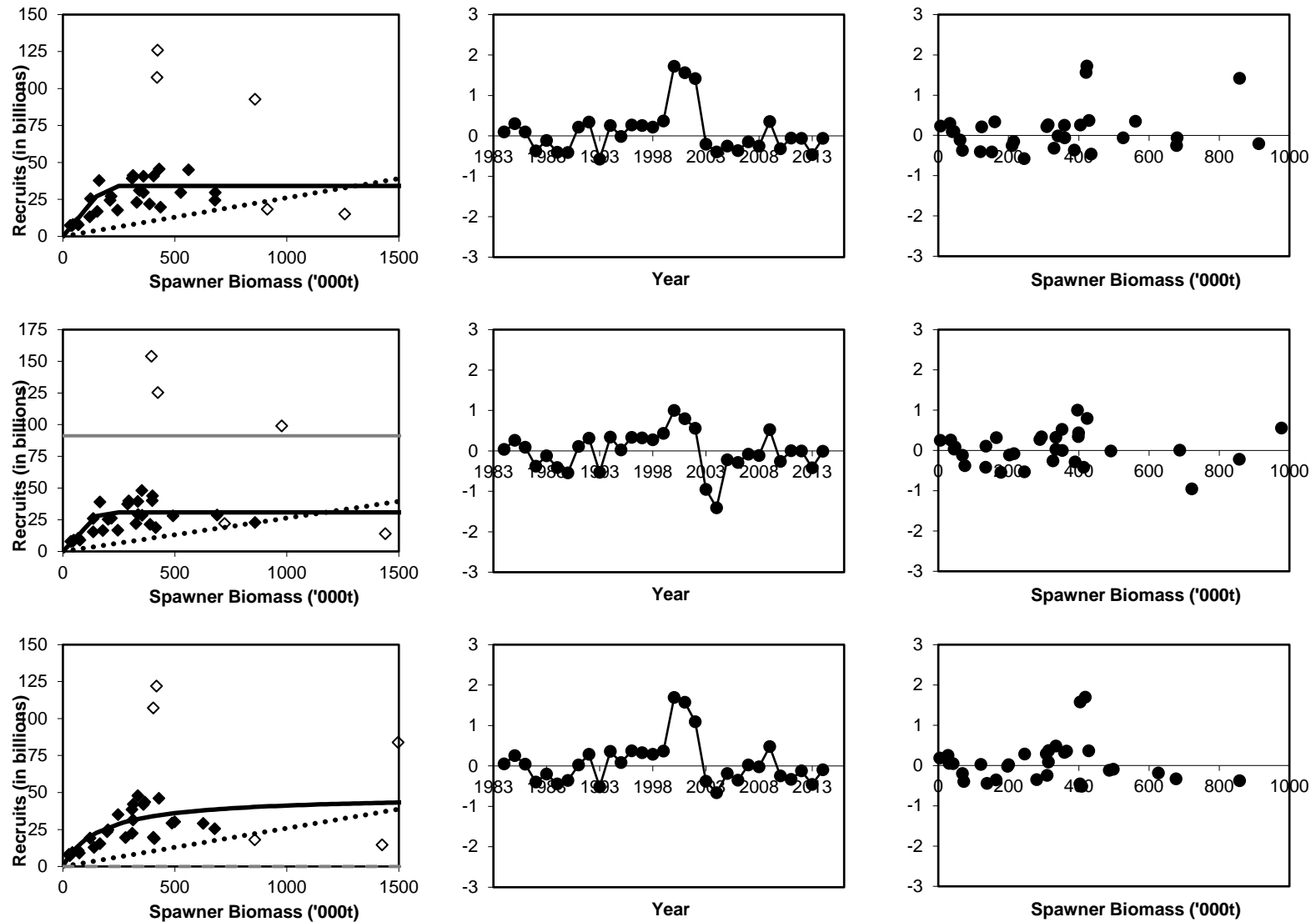


Figure 1. Model predicted sardine recruitment (in November) plotted against spawner biomass from November 1984 to November 2014 for S_{HS} (top row) with the Hockey stick stock recruitment relationship and S_{2HS} , with the grey line showing the median 2000-2004 recruitment (lower row). The dotted line indicates the replacement line. The open diamonds are those of the ‘peak years’ from November 2000 – 2004. The standardised residuals from the fit are given in the right hand plots, plotted against year and against spawner biomass.

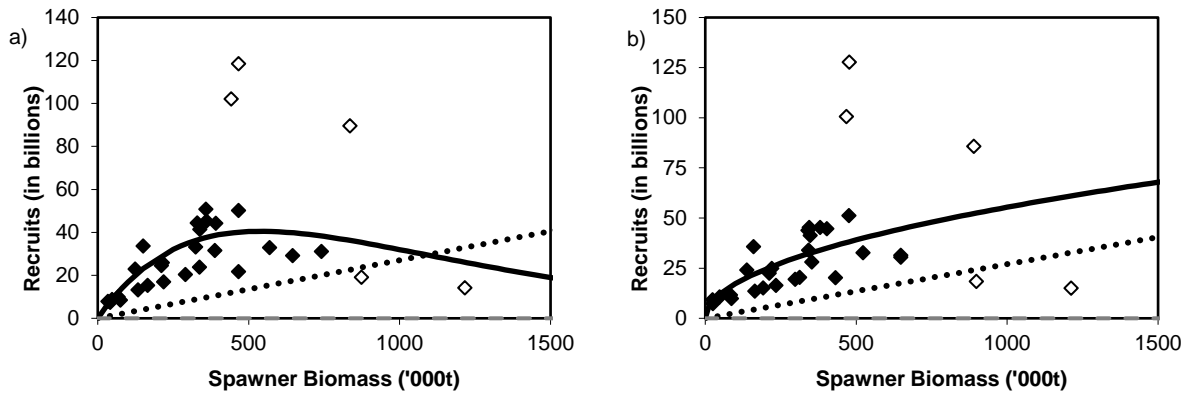


Figure 2. Stock-recruit relationships for a) S_R and b) S_{ModR} . The dotted line indicates the replacement line. The open diamonds are those of the ‘peak years’ from November 2000 – 2004.



Figure 3. Acoustic survey estimated and model predicted November sardine total biomass from 1984 to 2015 for S_{2HS} . The observed indices are shown with 95% confidence intervals. The standardised residuals (i.e. the residual divided by the corresponding standard deviation, including additional variance where appropriate) from the fits are given in the right hand plots.

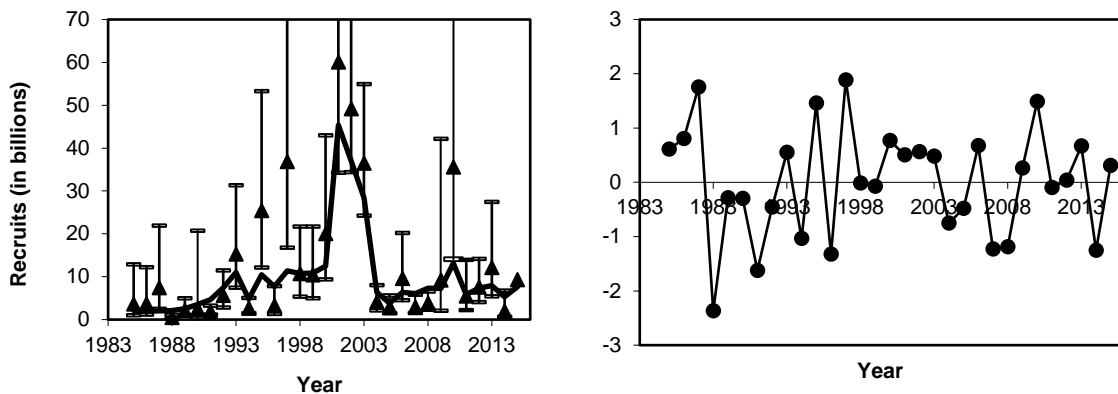


Figure 4. Acoustic survey estimated and model predicted sardine recruitment numbers from May 1985 to May 2015 for S_{2HS} . The survey indices are shown with 95% confidence intervals. The standardised residuals from the fit are given in the right hand plots.

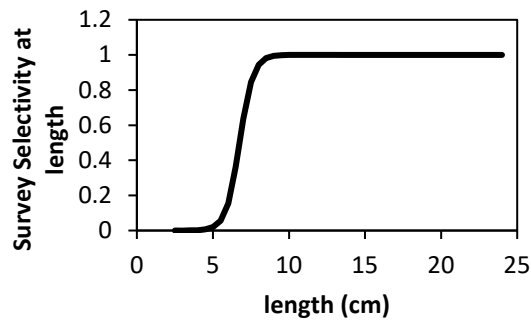


Figure 5. The model estimated November survey selectivity at length for S_{2HS} .

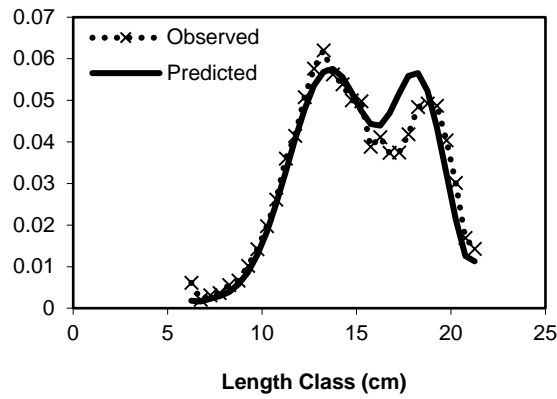


Figure 6. Average (over all years) model predicted and observed proportion-at-length in the November survey for S_{2HS} .

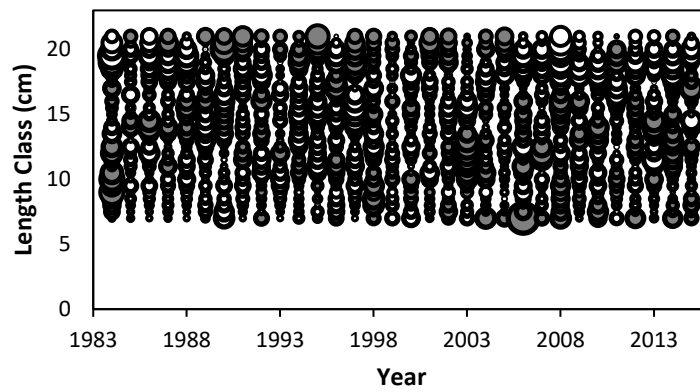


Figure 7. Residuals from the fit of the model predicted proportions-at-length in the November survey to the hydroacoustic survey estimated proportions for S_{2HS} .

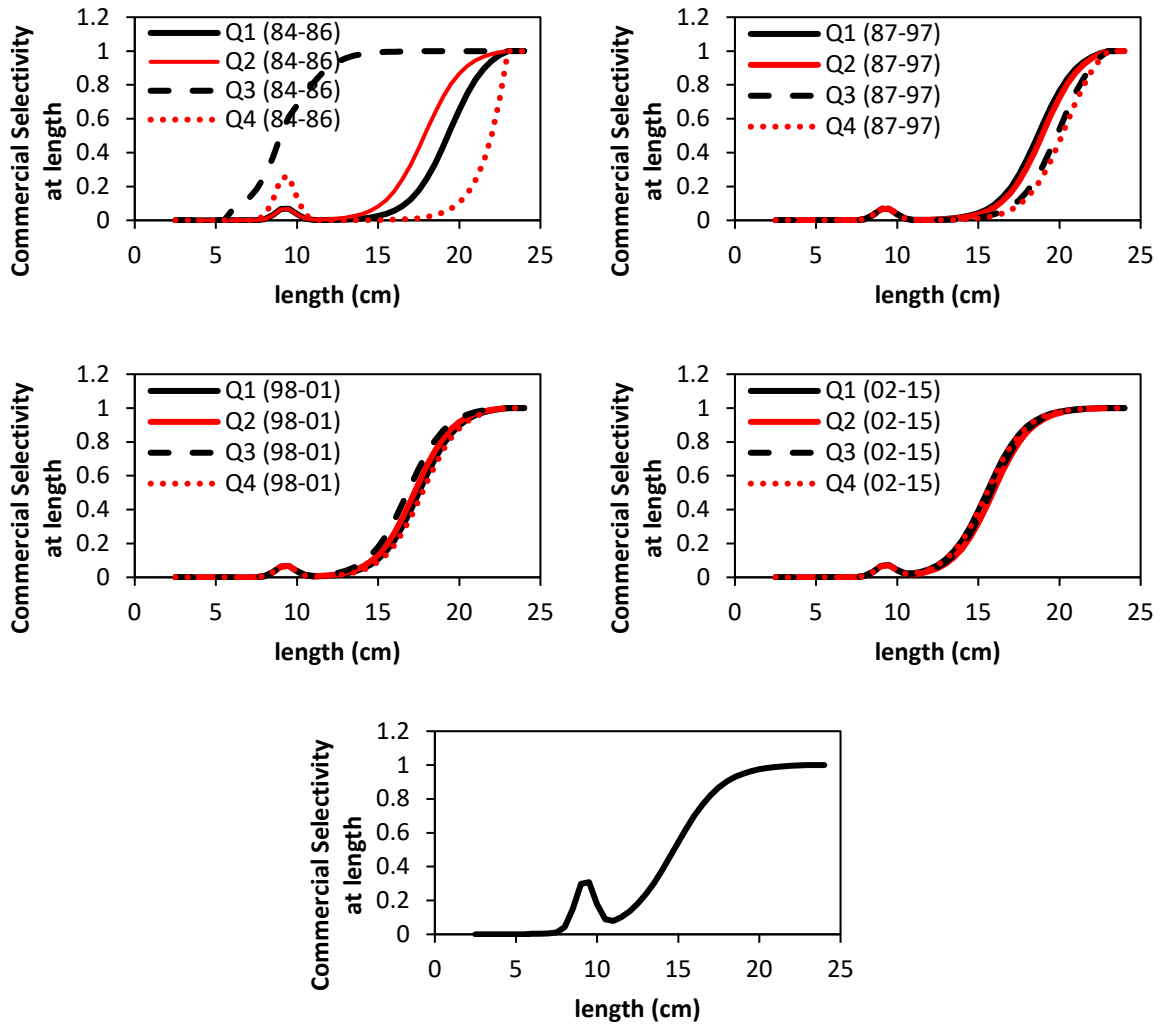


Figure 8. The model estimated commercial selectivity at length for S_{2HS} , which differs between four pre-specified time periods (the four plots) and quarters. The model estimated commercial selectivity at length for S^{sel} which is the same for all years and quarters is given in the lower plot.

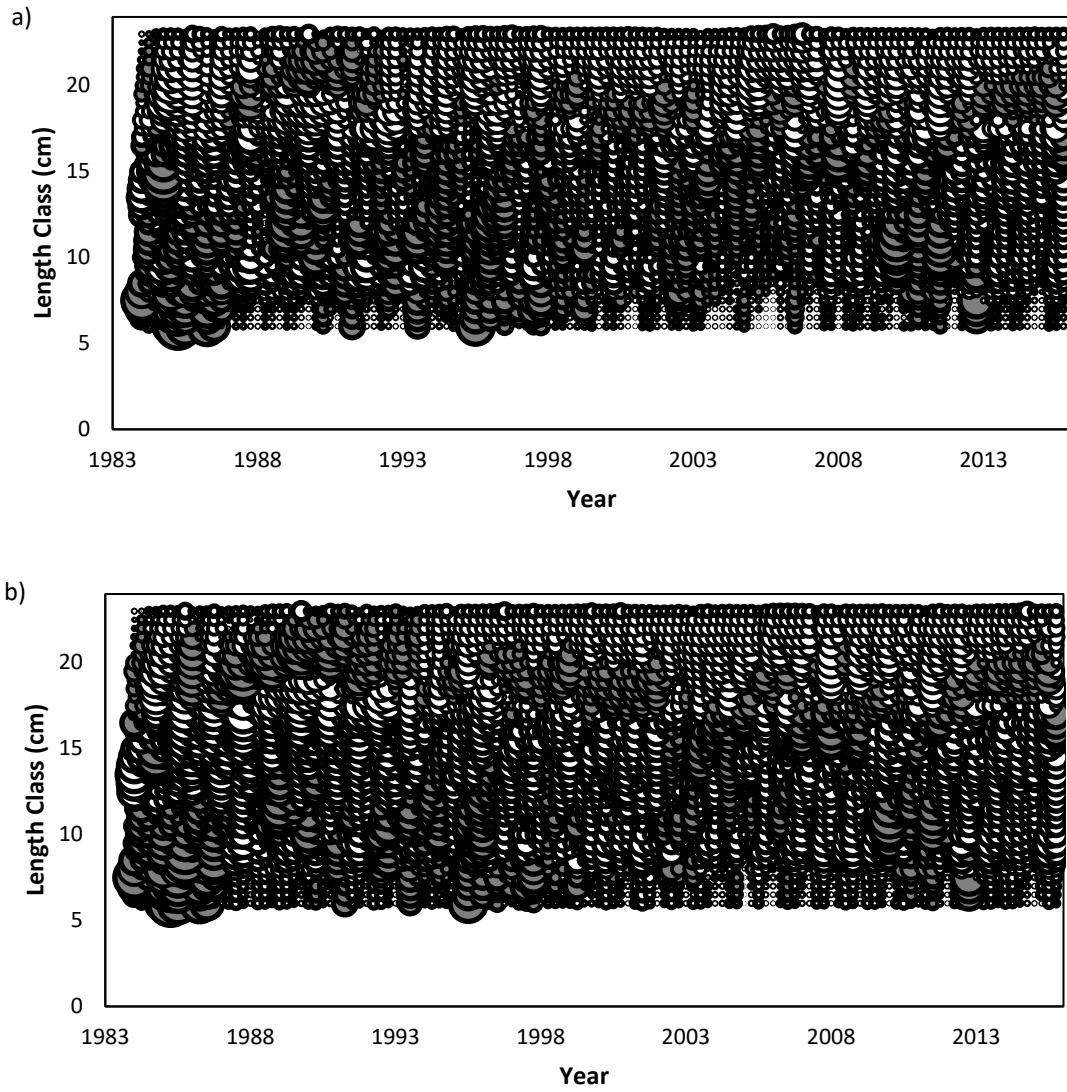


Figure 9. Residuals from the fit of the model predicted proportions-at-length in the quarterly commercial catch to the observed proportions for a) S_{2HS} and b) S_{sel} .

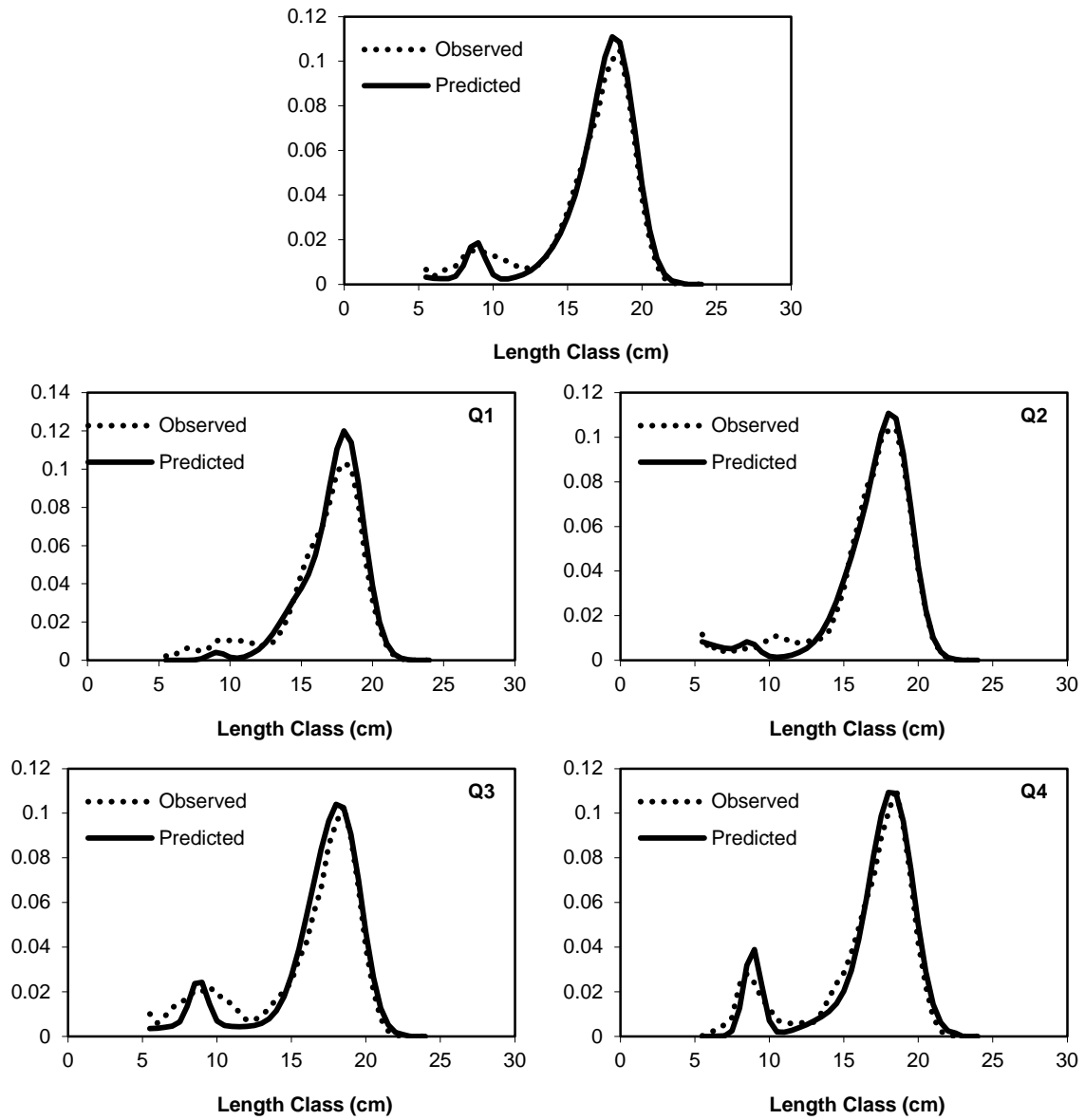


Figure 10a. Average (over all quarters and years) model predicted (S_{2HS}) and observed proportion-at-length in the commercial catch (top row), and average (over all years) quarterly model predicted (S_{2HS}) and observed proportions-at-length in the commercial catch (subsequent rows).

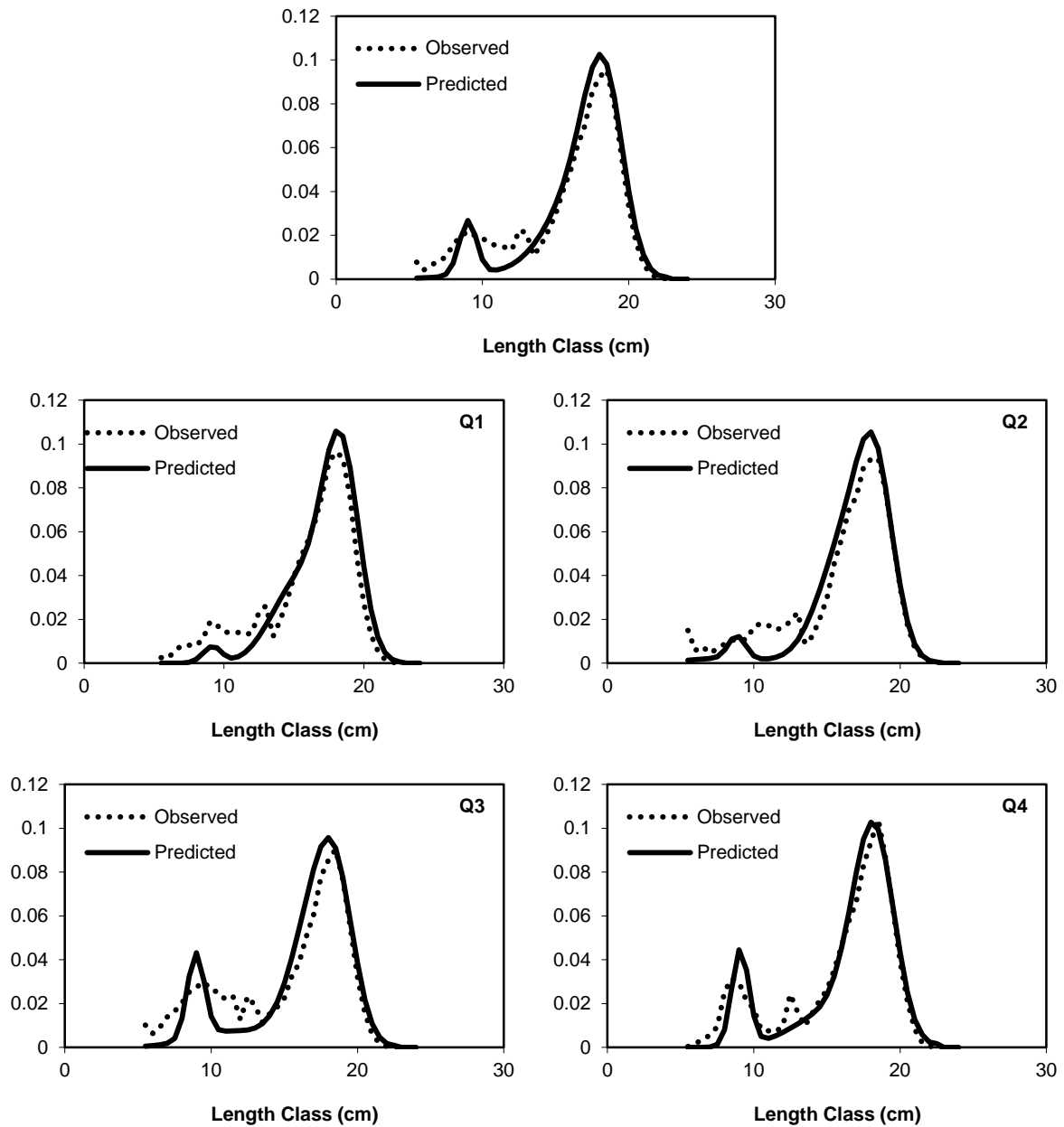


Figure 10b. Average (over all quarters and years) model predicted (S^{slip3}) and observed proportion-at-length in the commercial catch (top row), and average (over all years) quarterly model predicted (S^{slip3}) and observed proportions-at-length in the commercial catch (subsequent rows).

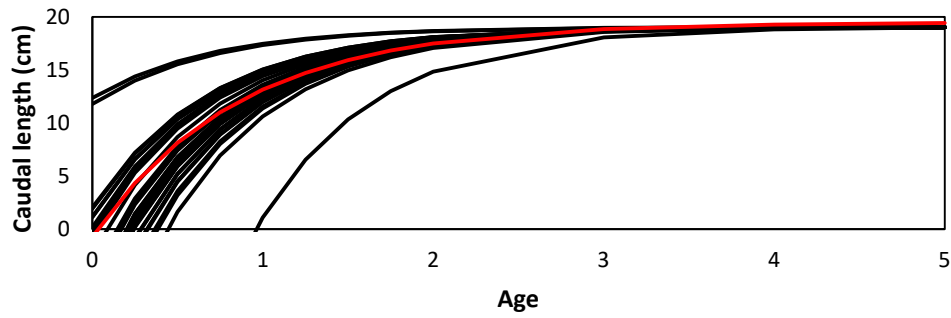


Figure 11. The annual von Bertalanffy growth curves estimated for S_{2HS} by allowing for auto-correlated residuals for variation about the age at which length is zero (black curves) and for the robustness test that assumes a time-invariant growth curve S^{10} (red curve).

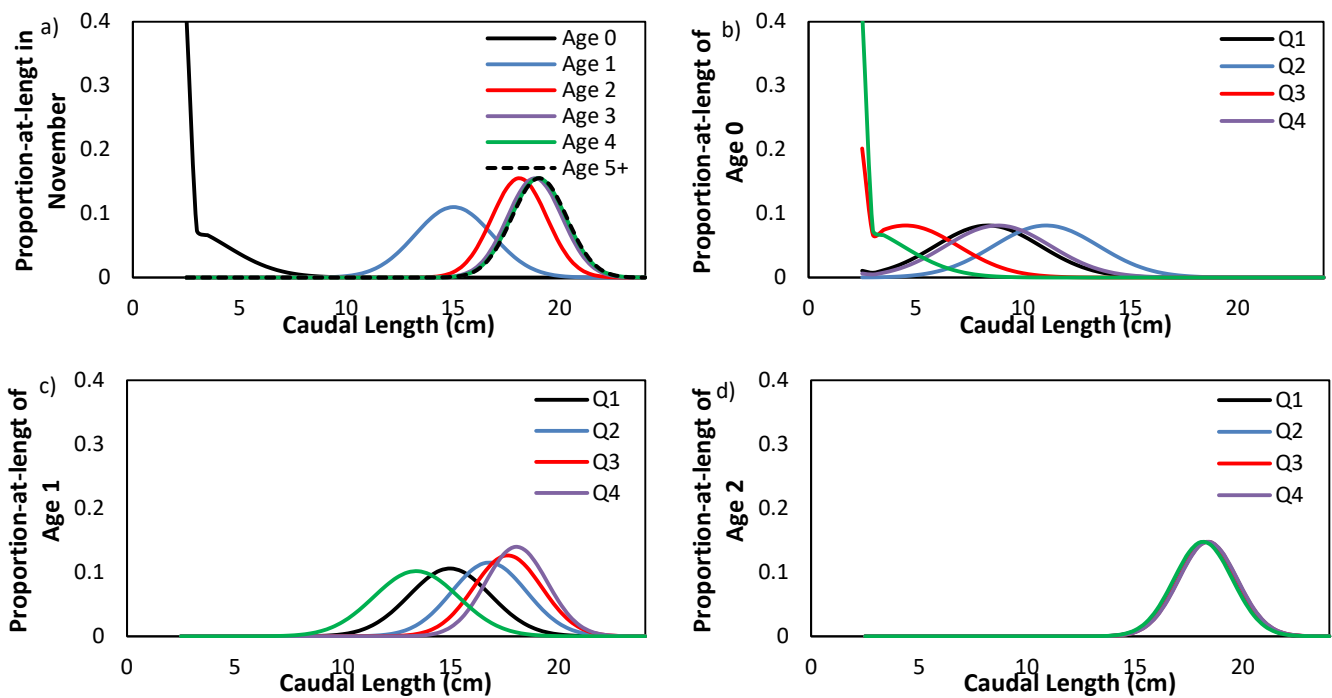


Figure 12. The model estimated distribution of length-at-age for S_{2HS} in 2014. The distributions vary between years (Figure 11), with greater variability for the smaller age groups (Table 4). The plots show a) the difference in length distributions at all ages at the time of the November hydro-acoustic survey, the difference in length distributions mid-way through each quarter for b) age 0, c) age 1 and d) age 2. The sudden increase in the proportion of the 2 cm length class is due to this being a minus group. The distribution at age 0 excludes any individuals not yet recruited to the population, and hence may not sum to 1 at the time of the survey.

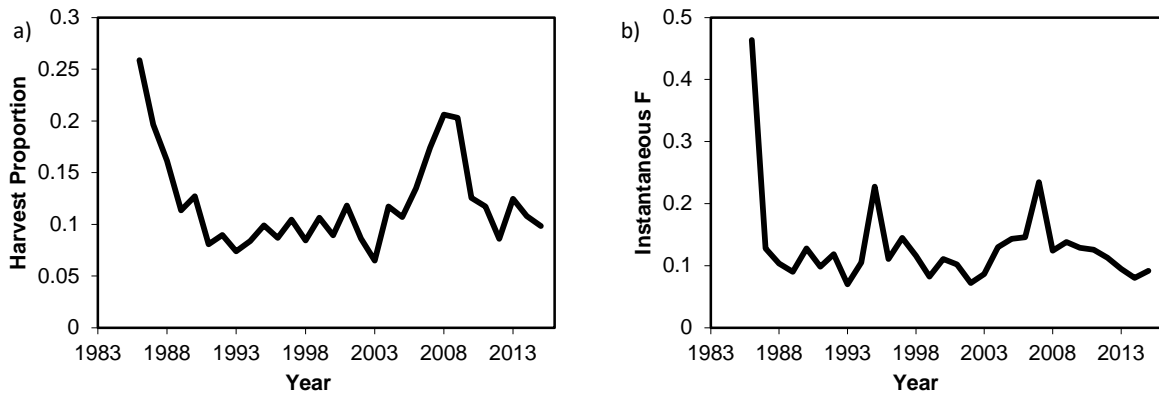


Figure 13. The a) harvest proportion (simply calculated as the observed annual (Nov-Oct) catch tonnage as a proportion of the model predicted total biomass) and b) the estimated approximate instantaneous fishing mortality rate (see Appendix C of de Moor and Butterworth (2016)) of the sardine single stock for S_{2HS} .

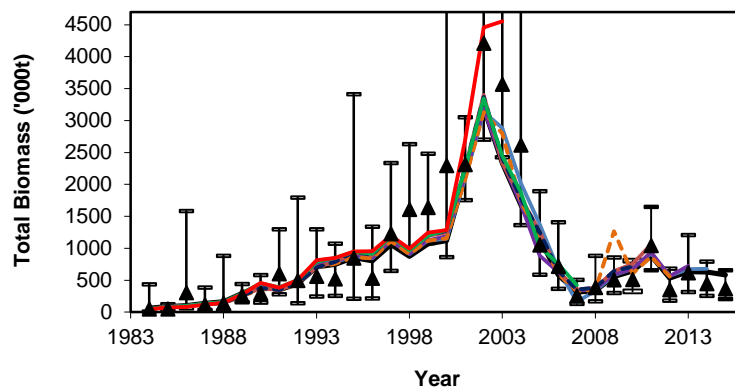


Figure 14a. Model predicted November sardine total biomass for retrospective runs considering data up to 2014, 2013, 2012, 2011, 2010, 2007 and 2003, compared to data up to 2015 as for S_{2HS} .

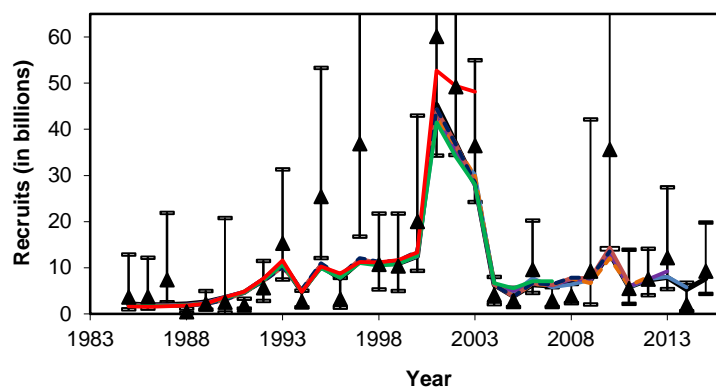


Figure 14b. Model predicted May sardine recruitment for retrospective runs considering data up to 2014, 2013, 2012, 2011, 2010, 2007 and 2003, compared to data up to 2015 as for S_{2HS} .