Progress towards updating the assessment of the South African sardine resource using data from 1984-2018

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Results are given for the current baseline assessment of the South African sardine resource, using data from 1984 to 2018. Some model assumptions are still under investigation and therefore this is not the finalised assessment.

Introduction

The assessment of the South African sardine resource is in the process of being revised and updated using data available up to November 2018. The assessment model considers the sardine population to consist of two mixing 'components', with a west component distributed west of Cape Agulhas and a south component distributed south-east of Cape Agulhas. Mixing occurs via movement from the west to the south component in November each year and via some contribution from the south component spawning biomass towards west component recruitment.

Population Dynamics Model

The population dynamics model for the South African sardine resource is given in Appendix A. All model parameters are defined in Tables A1 and A2. The data used in this assessment are listed in de Moor *et al*. (2019), which is a corrected and updated time series of data compared to that used in the initial 2019 assessment (de Moor *et al*. 2019b, de Moor 2019).

Updates to the model from that used by de Moor (2019) include a revision to the autocorrelated age at which length is zero (equation A8) and a substantial reduction in the range of the prior on these associated residuals (η_y^t). The task team expects a reasonable range for $t_{0,j,y}$ to be about 4 months per component (see further work below). A time-invariant survey weight-at-length is now used (see footnotes associated with equations A11 and A13). While the shape of the commercial selectivity-at-length relationship has remained unchanged with a normal distribution used to account for small sardine bycatch in the directed sardine fishery and a logistic distribution used to account for directed sardine fishing, substantial investigation into improving the fit to the commercial length frequency data (Appendix B) has resulted in year- and quarter-specific relationships on the west component (Figure 7).

Results

The model fit to available data and key estimated relationships are given in Figures 1 to 15 and Appendix B for the current baseline model. Given the provisional nature of these results they are not discussed extensively herein.

Discussion and Further Work

Two model assumption are currently undergoing investigation. The first is the extent of variability in the $t_{0,j,y}$ parameters for each component (modified by the range in the prior on the residuals, η_y^t) and the shape of the growth curve. Table 1 shows the fit to the data (in particular – as expected – the fit to the length frequency data) improves as a greater range is

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allowed, but the task team currently considers a range of approximately 4 months in the $t_{0,j,y}$ to be reasonable (Figure 16). However, a narrower range results in a mean $t_{0,j,y}$ that is substantially different from 1 November ($t_{0,j,y} = 0$). A modification to the shape of the growth curve is thus also being investigated. An alternative scenario in which the somatic growth rate parameter (κ_j) was doubled for ages ≤ 1 while maintaining both continuity and derivative continuity at $a = 1$ indicates that factors of κ_j between 1 and 2 may provide improvement for the west component (Table 1, Figure 17).

The second model assumption currently undergoing investigation is whether the standard deviation associated with the survey and commercial proportion-at-length data should be calculated as a time-invariant close form solution (as per Appendix A), or be calculated separately for each year. Table 1 shows that annual standard deviations associated with the survey proportion-at-length data (Figure 18) result in a (somewhat) poorer fit to survey abundance data; the 'gain' does not necessarily indicate a better fit to the proportion-at-length data given different standard deviations. Annual standard deviations associated with the commercial proportion-at-length data (Figure 19) have minimal impact on the fit to survey abundance data, but frequently cause convergence difficulties. The bounding of these estimates of standard deviation does impact results and requires further investigation.

Two further adjustments to the model remain high priority. The first is an incorporation of a new weight-at-length relationship that is expected to be stock-dependent and may potentially allow for differences between these relationships as estimated by commercial and survey data. The second is an investigation of an alternative hypothesis which accounts for winter spawning on the South Coast (to be initially modelled as two cohorts of recruitment to the south component).

Further sensitivity tests (some of which may result in changes to baseline specifications) will likely only be undertaken once the data for 2019 are available. These include, among others, alternative natural mortality scenarios including the testing of a density-dependent natural mortality hypothesis, alternative maturity-at-length relationships over time and between components and movement occurring at 1 August and/or 1 November.

Acknowledgements

The SWG-PEL Task Team is thanked for discussions aiding the development of this assessment.

References

de Moor CL. 2019. Revision to the Initial Assessment of the South African sardine resource using data from 1984-2018. DAFF: Branch Fisheries Document FISHERIES/2019/MAR/SWG-PEL/06.

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/22REV2.

de Moor CL, Coetzee J, Merkle D and van der Lingen C. 2019b. The data used in the 2019 initial sardine assessment. DAFF: Branch Fisheries Document FISHEREIS/2019/APR/SWG-PEL/14.

de Moor CL, Merkle D, Coetzee J and van der Lingen C. 2019a. The data used in the 2019 sardine assessment. DAFF: Branch Fisheries Document FISHEREIS/2019/SEP/SWG-PEL/22.

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.

Table 1. The contributions to the objective function at the joint posterior mode for the current baseline (1st row) and alternative scenarios. The current baseline is given in bold

				-ln(Likelihood)						-ln(Prior)				
	Growth curve	Closed form SD	-ln(Post-erior)	Total	Nov	Rec	Com Prop-at-length	Survey Prop-at-length	Prev-at-length	k_{ac}^{S}	$move_{1,y}$	η_y^t	$\bar{l}_{1,y}$	Penalty
$\boldsymbol{\eta_y^t \sim N(0, 0.2^2)}$	**Standard**	**Time-invariant**	**981.3**	**913.4**	**60.6**	**39.7**	**-432.2**	**-383.4**	**1628.7**	**-1.4**	**-30.3**	**-15.4**	**114.5**	**0.5**
$\eta_y^t \sim N(0, 0.7^2)$	Standard	Time-invariant	1010.0	904.0	58.2	38.8	-433.6	-387.6	1628.3	-1.4	-30.4	23.1	114.5	0.3
$\eta_y^t \sim N(0, 0.1^2)$	Standard	Time-invariant	968.5	924.6	61.4	38.3	-428.1	-374.8	1627.9	-1.3	-30.4	-39.7	114.4	0.7
$\eta_y^t \sim N(0, 0.7^2)$	$2 \times \kappa$ for $a \leq 1$	Time-invariant	1056.9	947.8	56.0	39.1	-430.7	-389.6	1672.9	-1.2	-30.5	26.4	114.0	0.4
$\eta_y^t \sim N(0, 0.1^2)$	$2 \times \kappa$ for $a \leq 1$	Time-invariant	1001.1	961.8	58.1	42.0	-435.5	-385.7	1683.0	-1.3	-30.2	-43.3	114.1	0.1
$\eta_y^t \sim N(0, 0.7^2)$	Standard	Annual survey	987.1	880.1	60.0	42.3	-430.4	-413.5	1621.7	-1.2	-30.2	23.2	114.4	0.8
$\eta_y^t \sim N(0, 0.7^2)$	Standard	Annual comm	987.4	882.3	58.2	39.0	-455.3	-388.0	1628.4	-1.4	-30.4	23.0	113.7	0.3

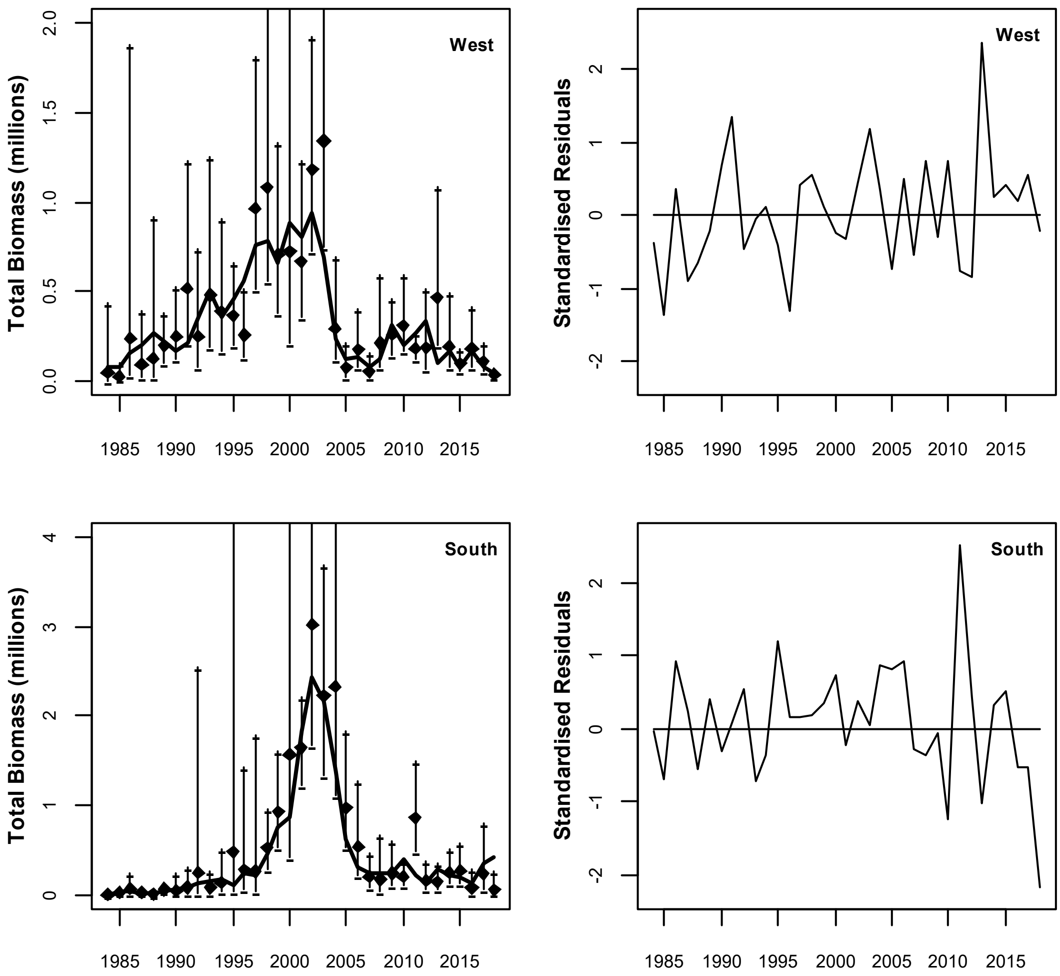


Figure 1. Acoustic survey estimated and model predicted November sardine total biomass from 1984 to 2018. The observed indices are shown with 95% confidence intervals. The standardised residuals (i.e. the residual divided by the corresponding standard deviation, including additional variance where appropriate) from the fits are given in the right hand plots.

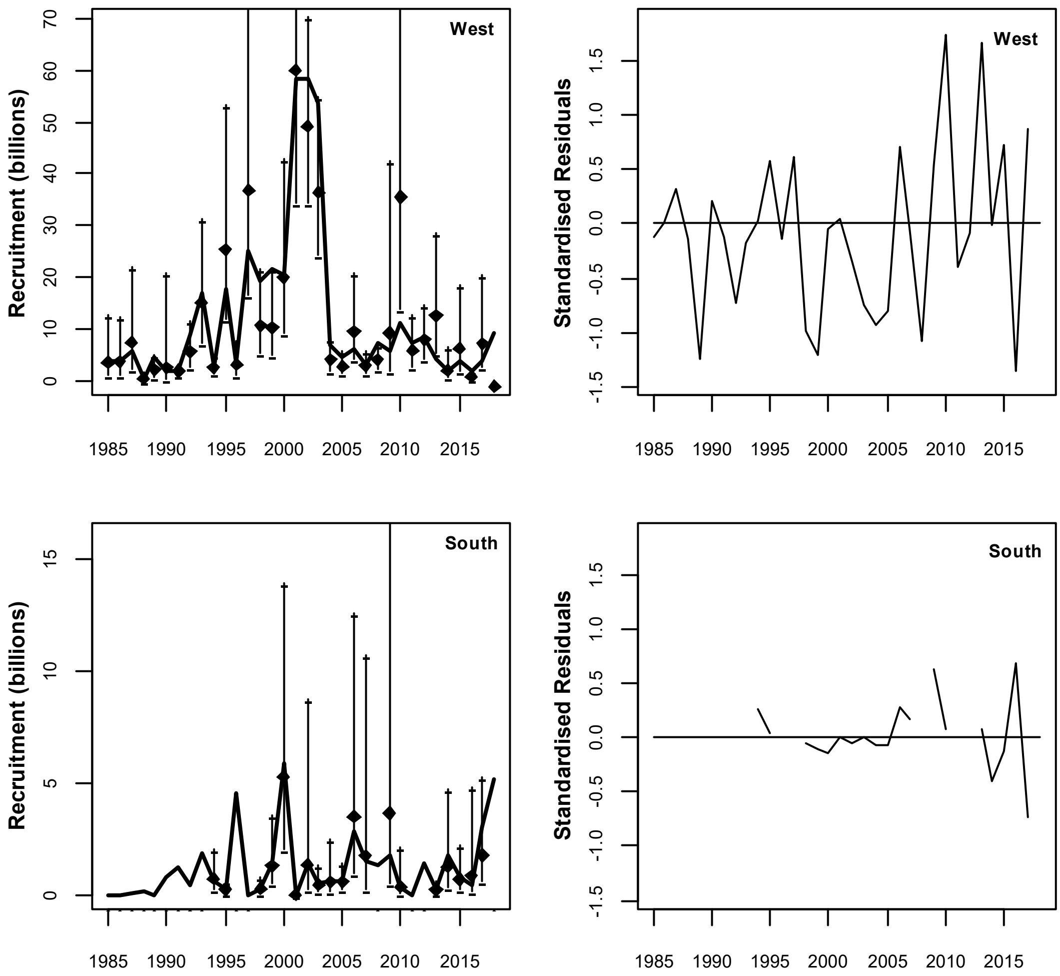


Figure 2. Acoustic survey estimated and model predicted sardine recruitment numbers from May 1985 to May 2018. The survey indices are shown with 95% confidence intervals. The standardised residuals from the fit are given in the right hand plots.

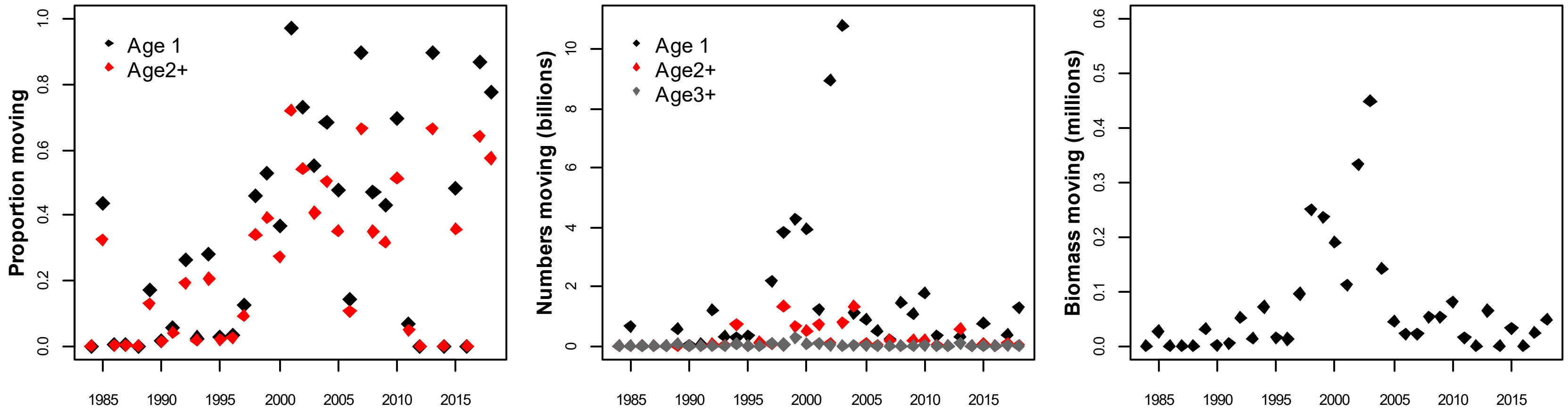


Figure 3. Model estimated proportion of 1-year-olds and 2+-year-olds which move from the "west" component to the "south" component in November. The middle plot shows the numbers of 1-, 2- and 3-year olds moving while the right hand plot shows rough[1] estimates of the annual biomass moving from the west to south component.

[1] Calculated using the average of west and south component weights-at-age.

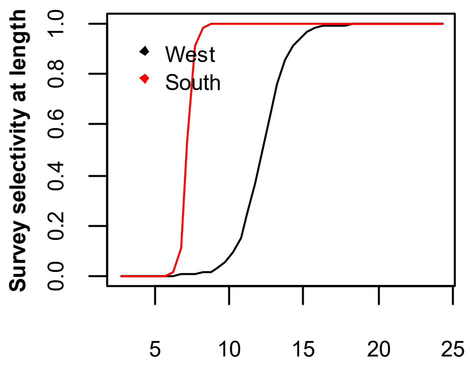


Figure 4. The model estimated November survey selectivity at length.

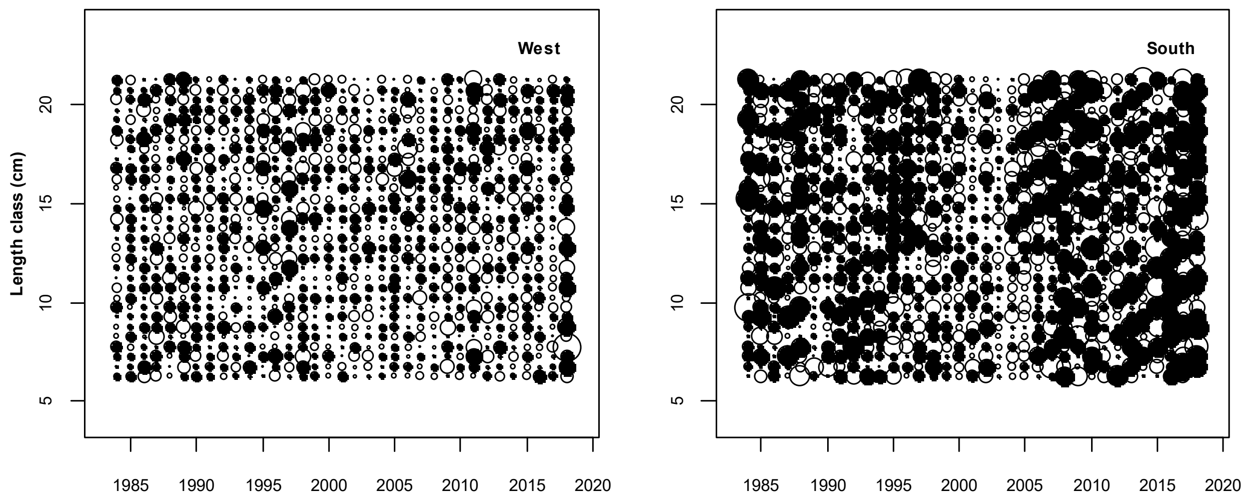


Figure 5. Residuals from the fit of the model predicted proportions-at-length in the November survey to the hydroacoustic survey estimated proportions.

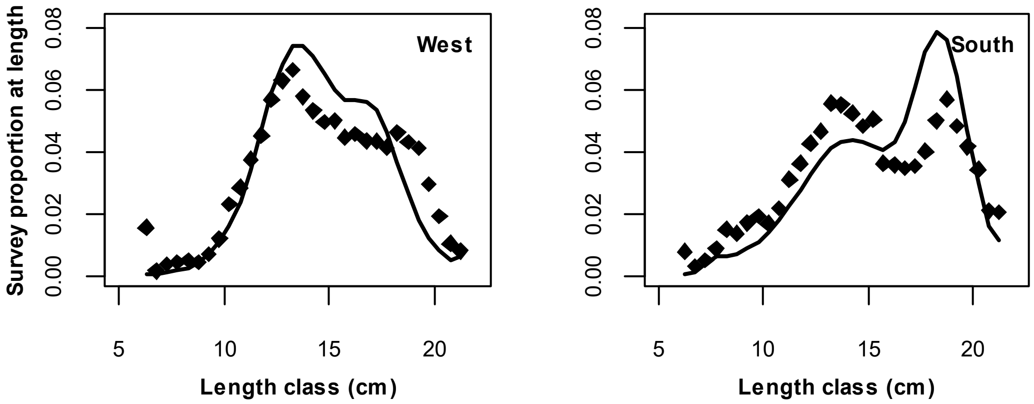


Figure 6. Average (over all years) model predicted and observed proportion-at-length in the November survey.

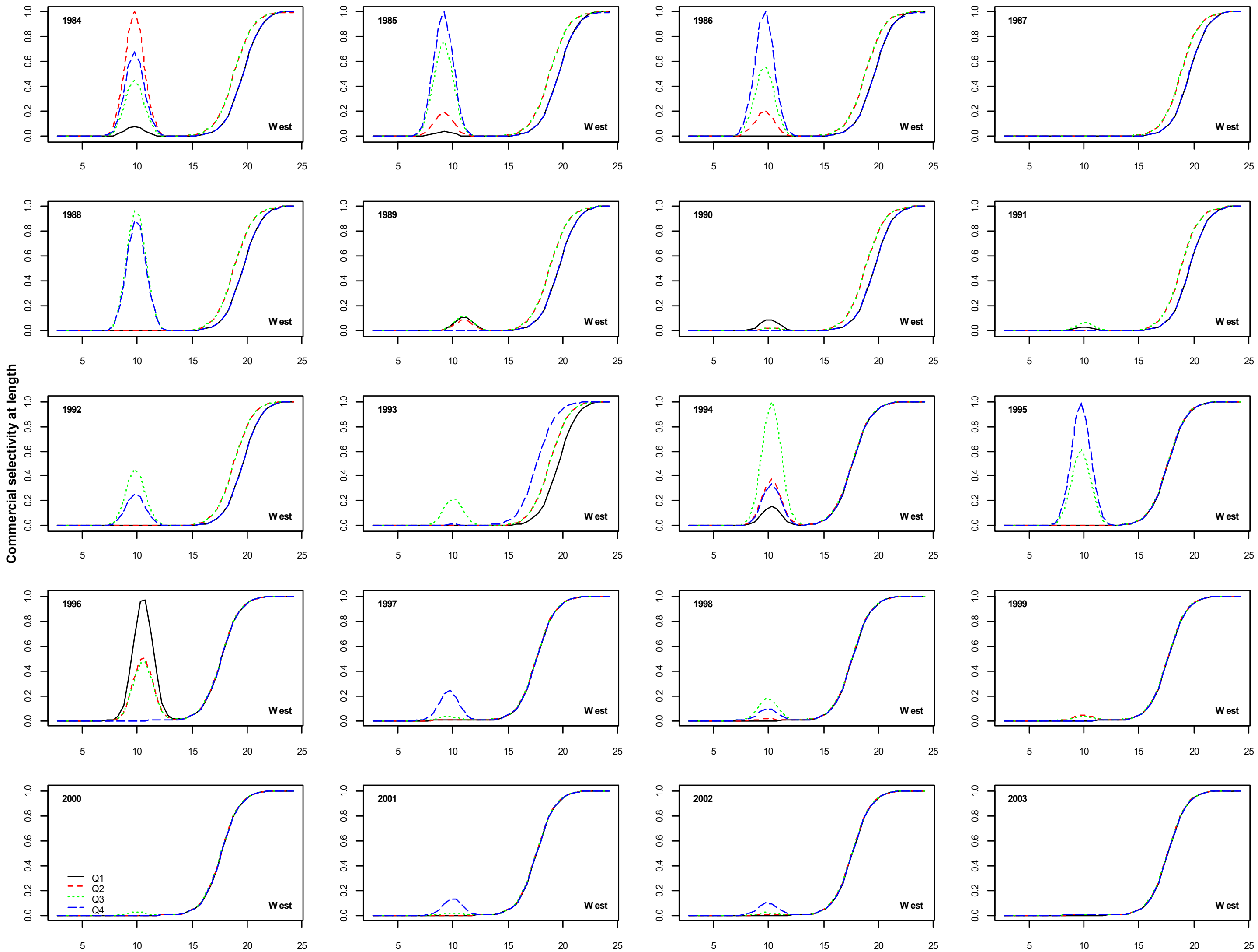


Figure 7. The model estimated commercial selectivity at length.

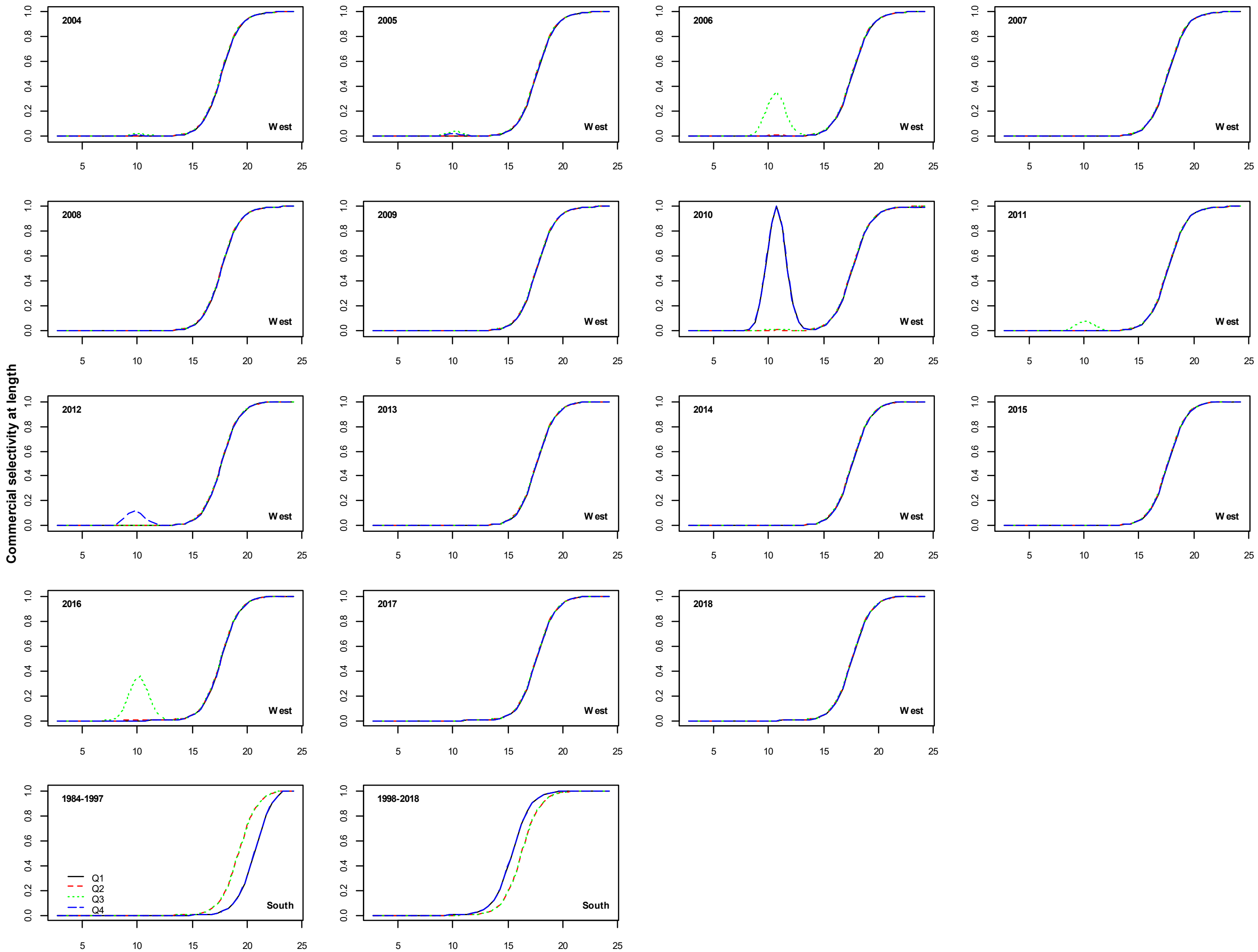


Figure 7 (continued).

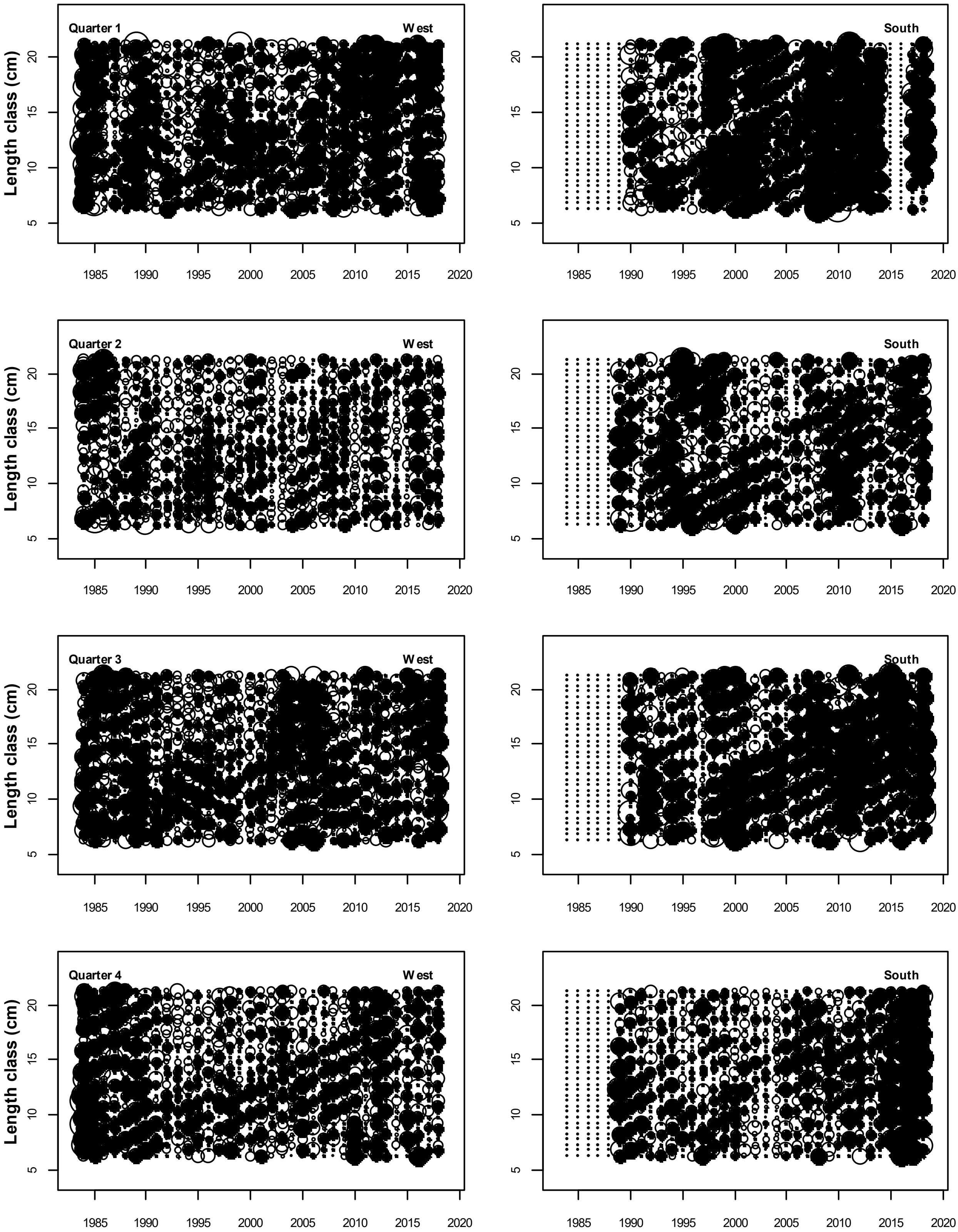


Figure 8. Residuals from the fit of the model predicted proportions-at-length in the quarterly commercial catch to the observed proportions.

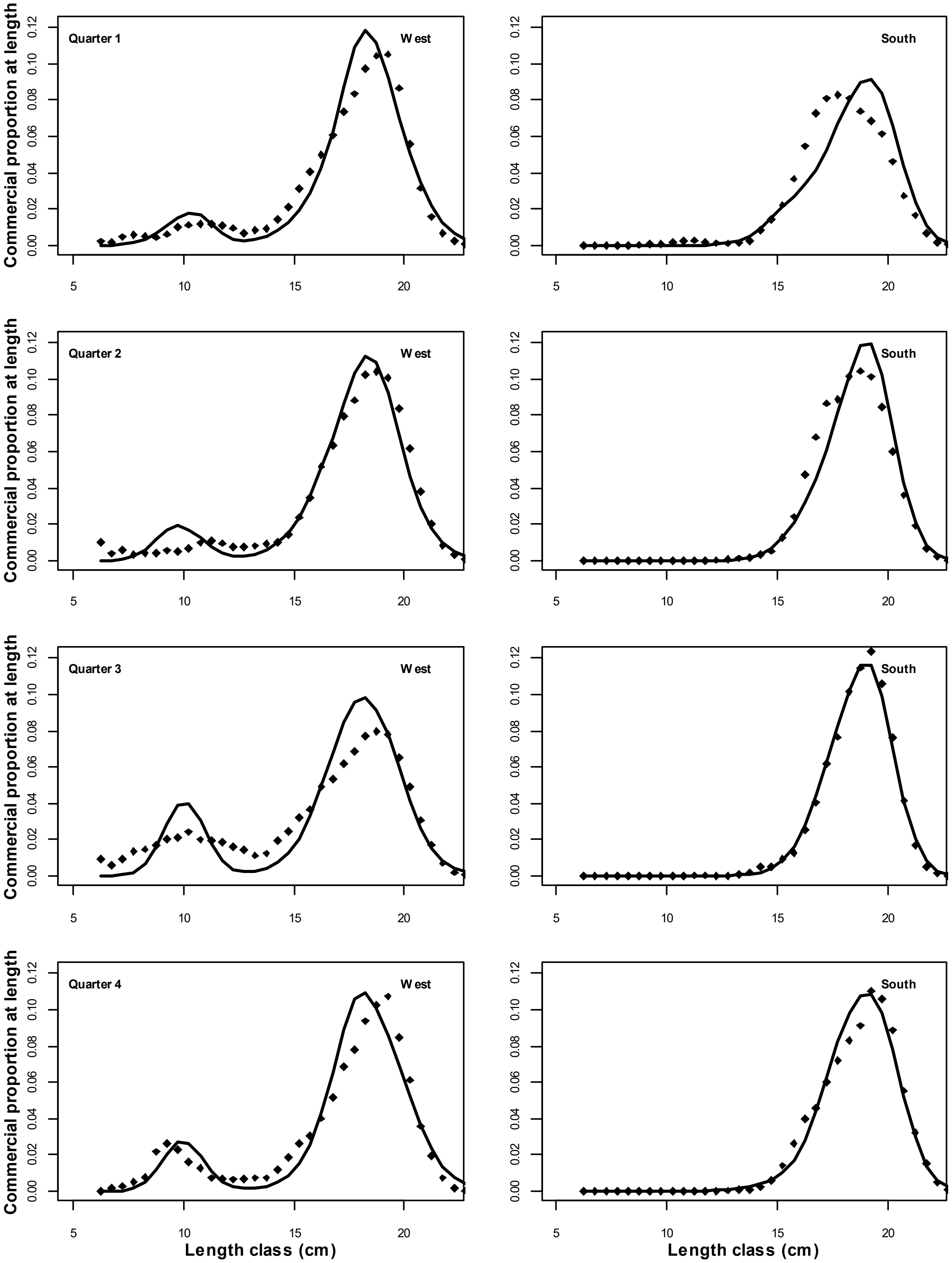


Figure 9. Average (over all quarters and years) model predicted and observed proportion-at-length in the commercial catch (top row), and average (over all years) quarterly model predicted and observed proportions-at-length in the commercial catch (subsequent rows). See Appendix B for plots for each year and quarter.

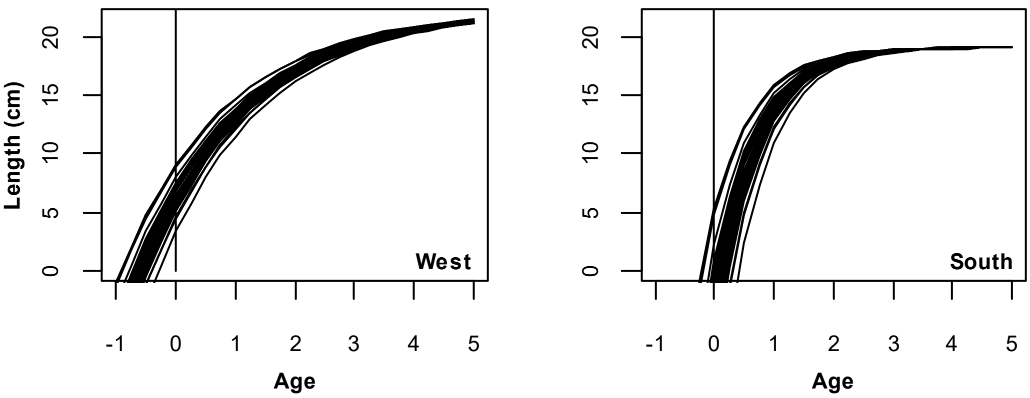


Figure 10. The annual von Bertalanffy growth curves estimated by allowing for auto-correlated residuals for the variation about the age at which length is zero.

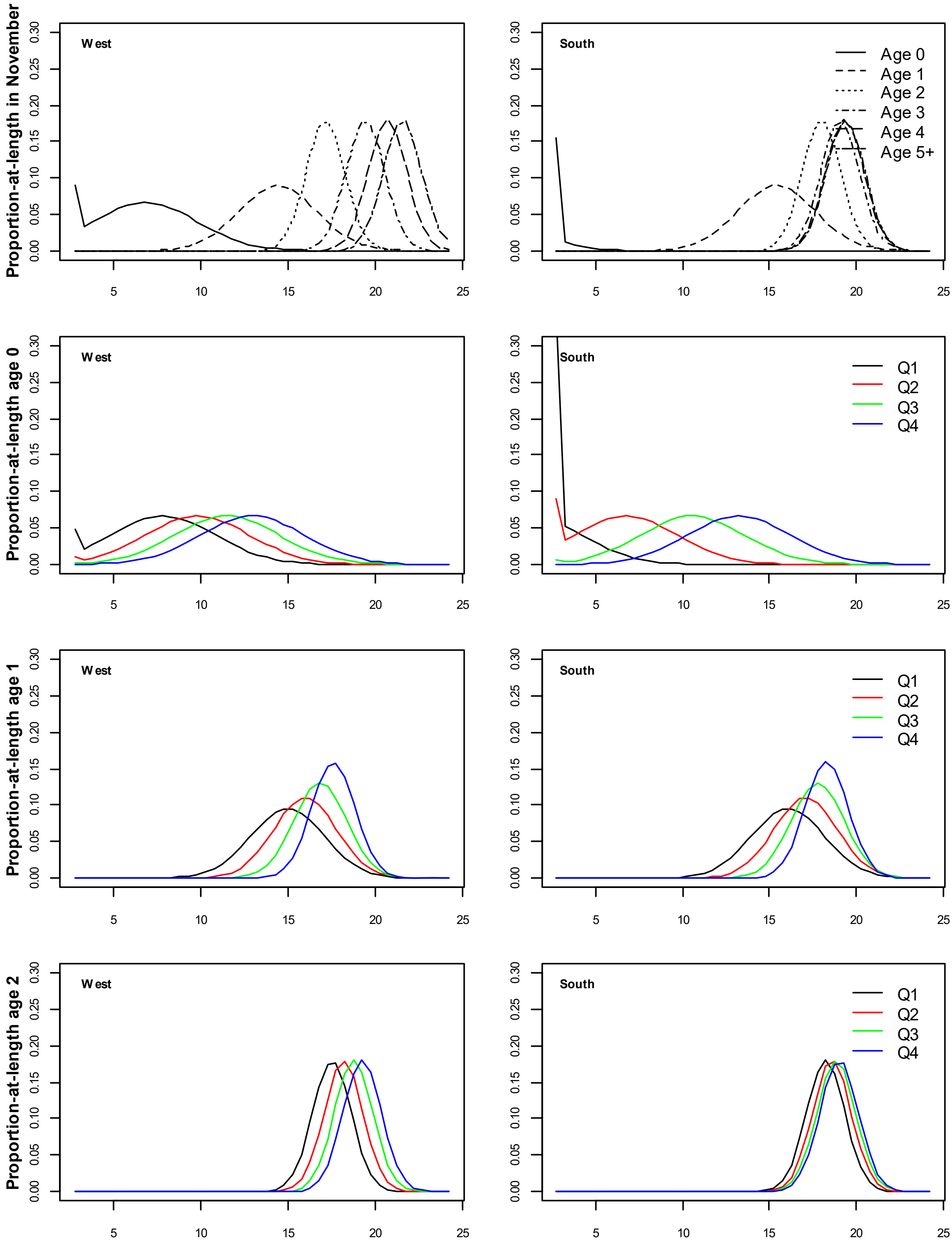


Figure 11. The model estimated distributions of proportions-at-length for each age **in 2010**, given at the time of the biomass survey (1 November, top row), and middle of each quarter of the year (corresponding to the times commercial catch is modelled to be taken) for age 0, 1 and 2 (subsequent rows).

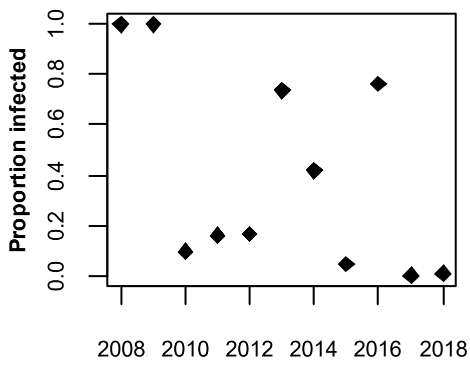


Figure 12. The model estimated proportion of west component sardine infected with the parasite between 2008 and 2018. (Annual infection rate is arbitrarily assumed to be 0 prior to 2008.)

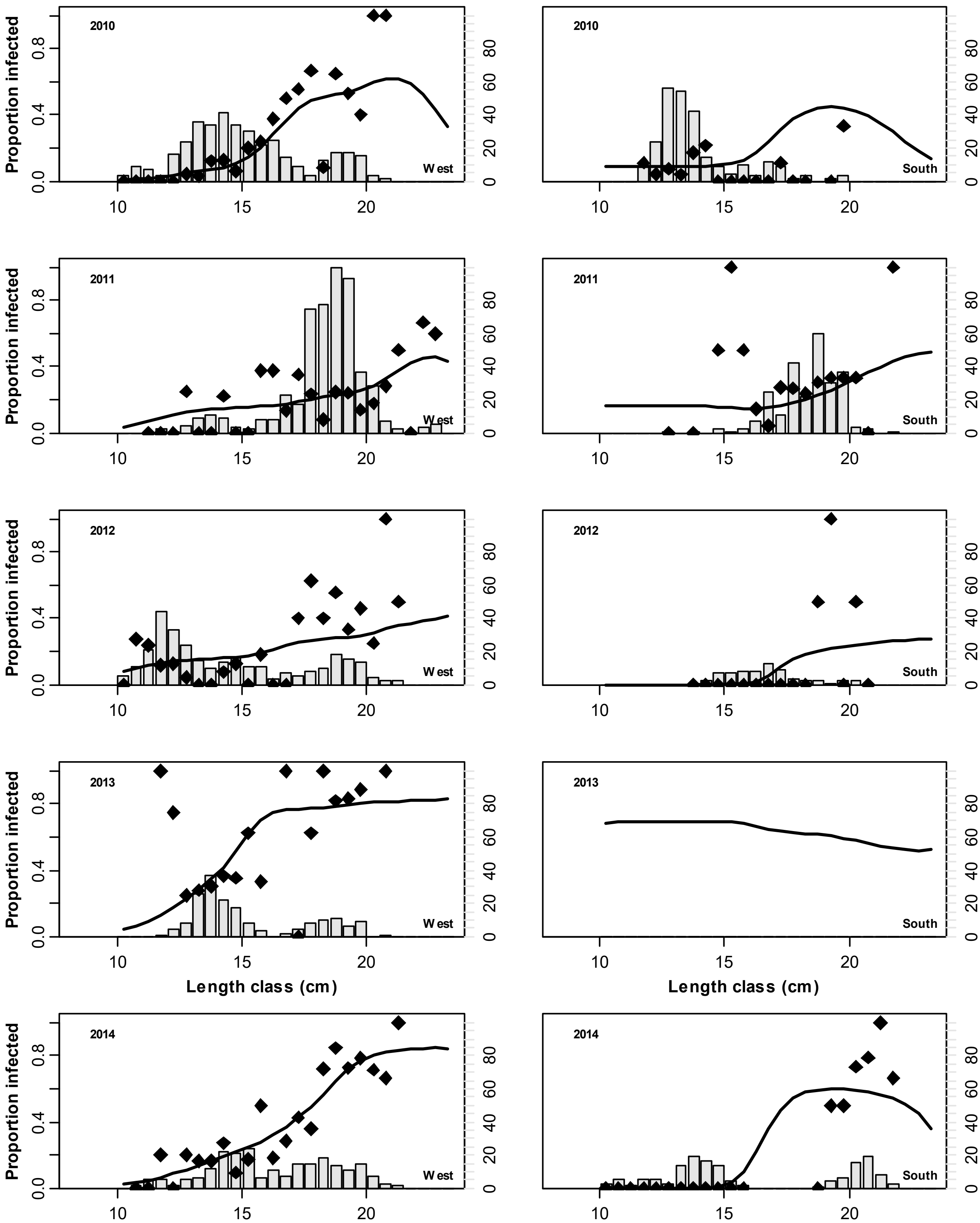


Figure 13. The model estimated proportions-at-length of west and south stock sardine infected with the parasite (i.e. parasite prevalence-by-length) between 2010 and 2018 together with the observed proportions-at-length. The sample size for each length class is given by the grey bars, plotted against the right vertical axis.

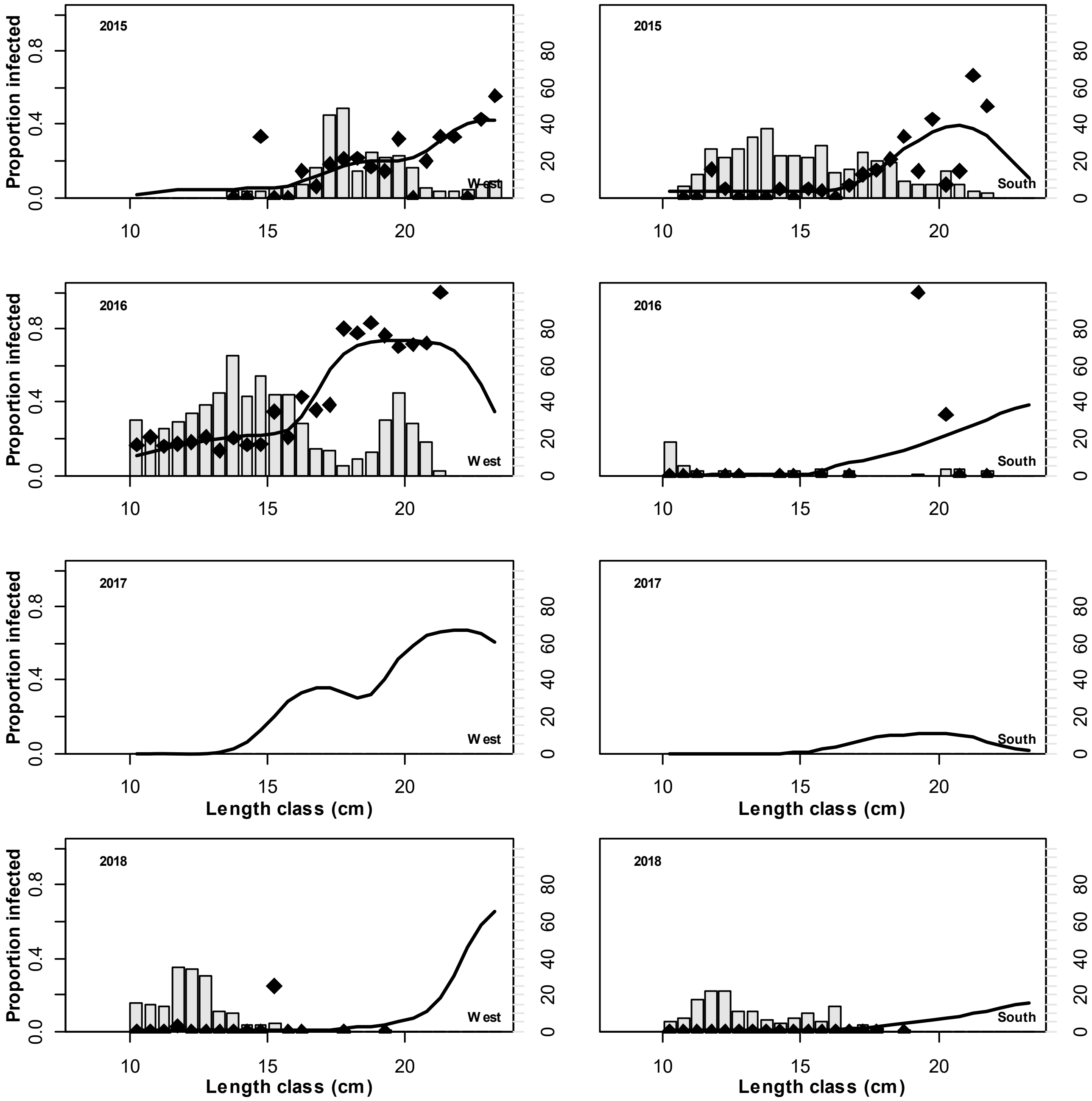


Figure 13 (continued).

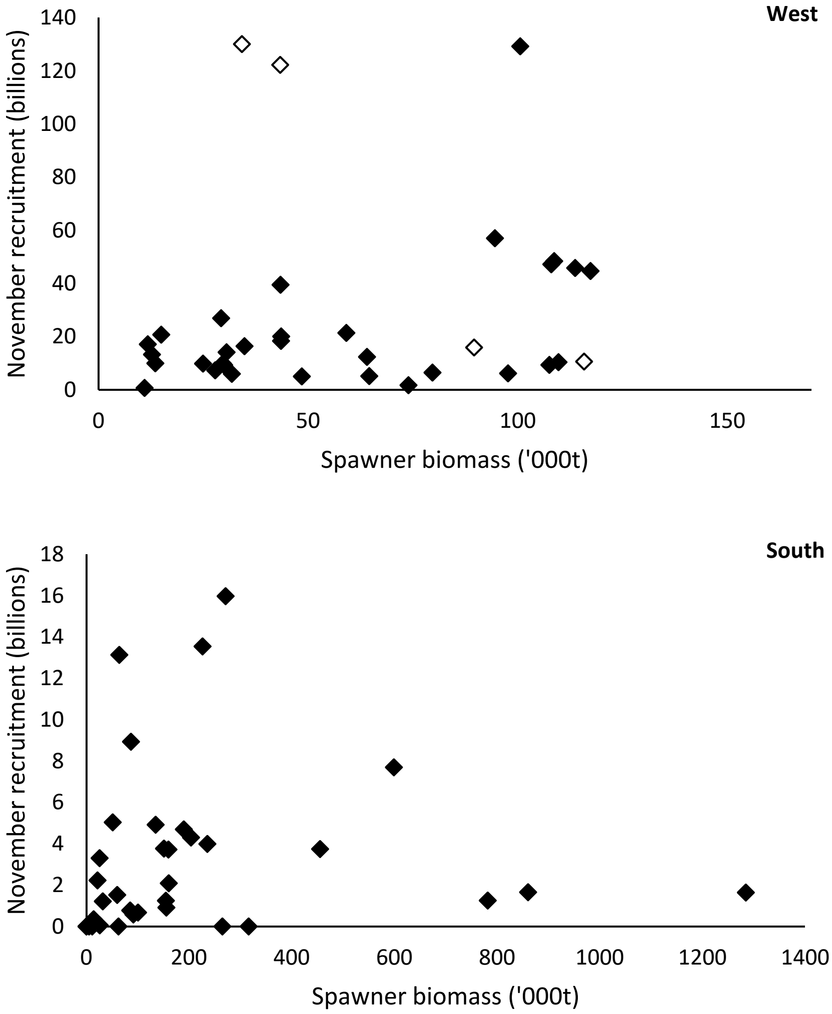


Figure 14. Model predicted sardine recruitment (in November) plotted against spawner biomass from November 1983 to November 2017.

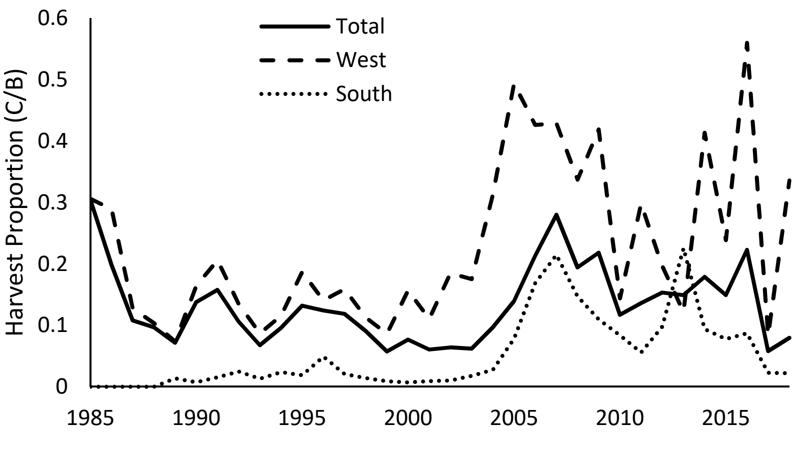
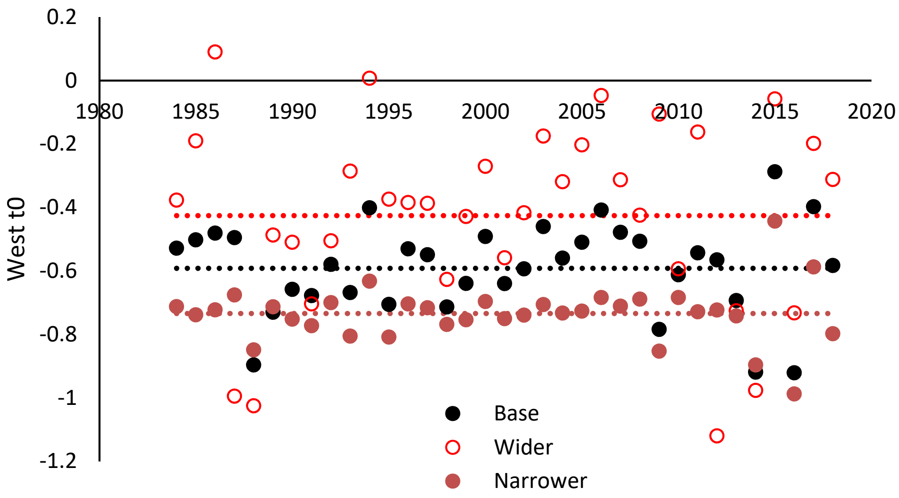


Figure 15. The exploitation rate (simply calculated as the observed annual (Nov-Oct) catch tonnage as a proportion of the model predicted total biomass).



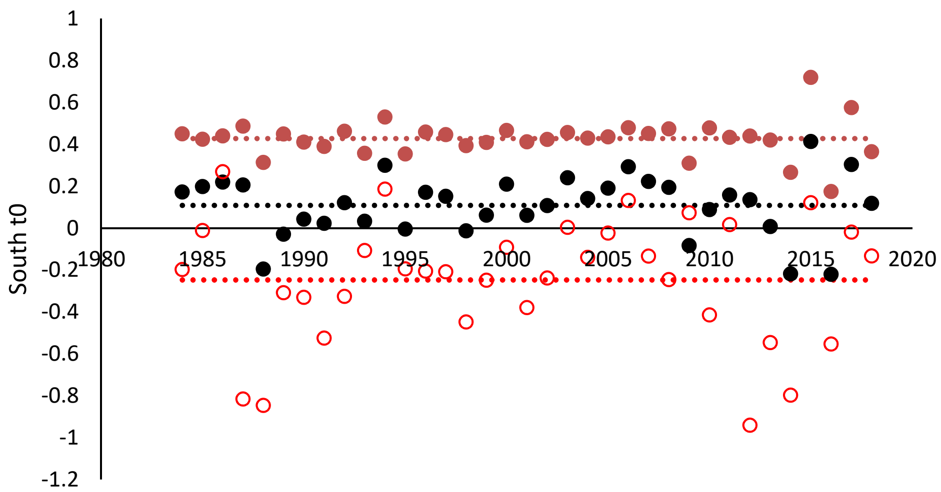
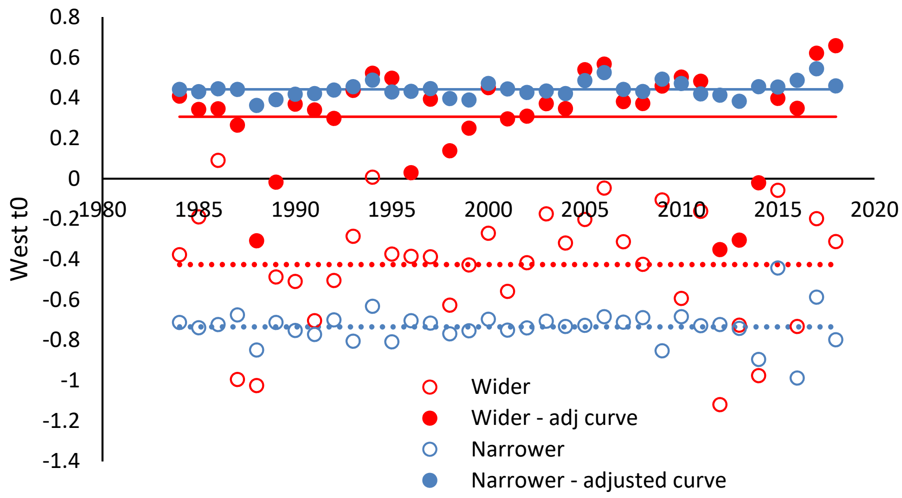


Figure 16. The time series of estimated $t_{0,j,y}$ (in months) for the current baseline model and for alternatives with a narrower and wider range on η_y^t.



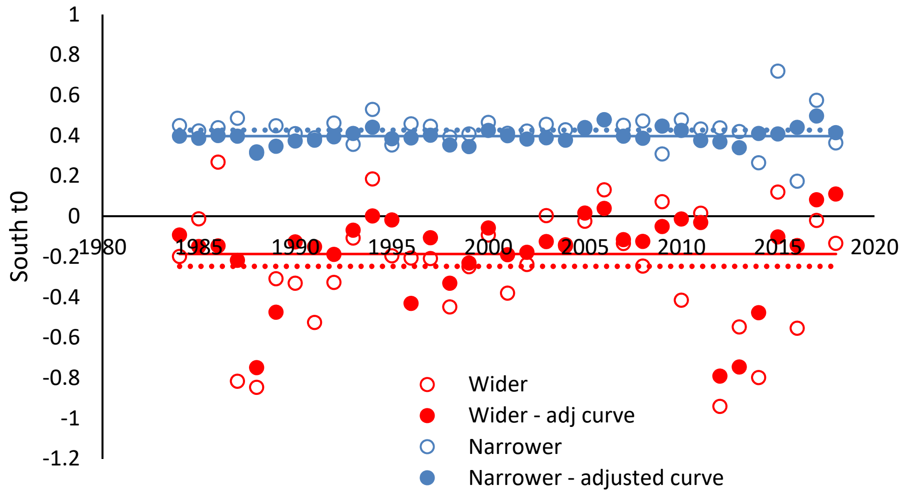


Figure 17. The time series of estimated $t_{0,j,y}$ (in months) for alternatives with a narrower and wider range on η_y^t using the standard von Bertalanffy growth curve, and with double the somatic growth rate for $a \leq 1$.

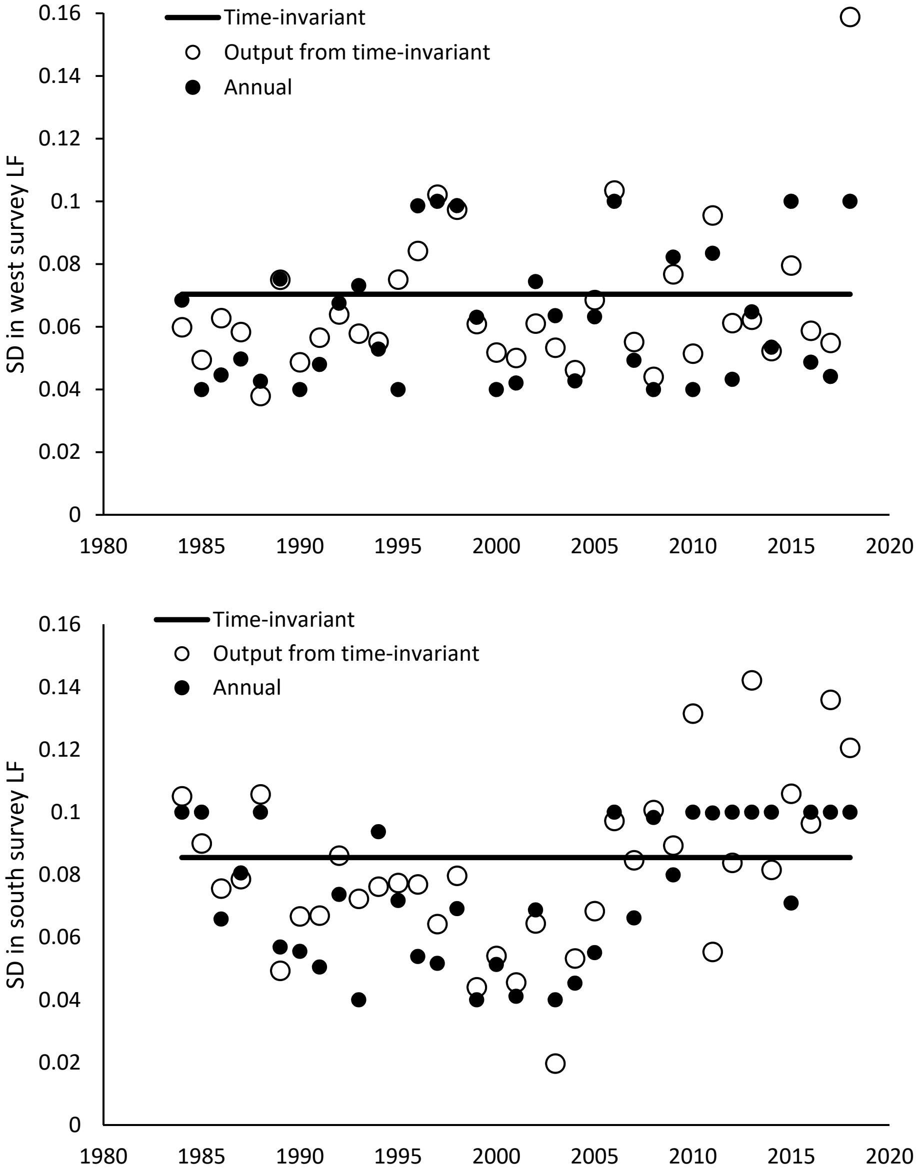


Figure 18. The time series of standard deviations associated with the survey length frequencies as calculated over all years (baseline), calculated annually based on the output of that baseline run and calculated annually during conditioning, and constrained between [0.04,0.1]. Note $\eta_y^t \sim N(0, 0.7^2)$.

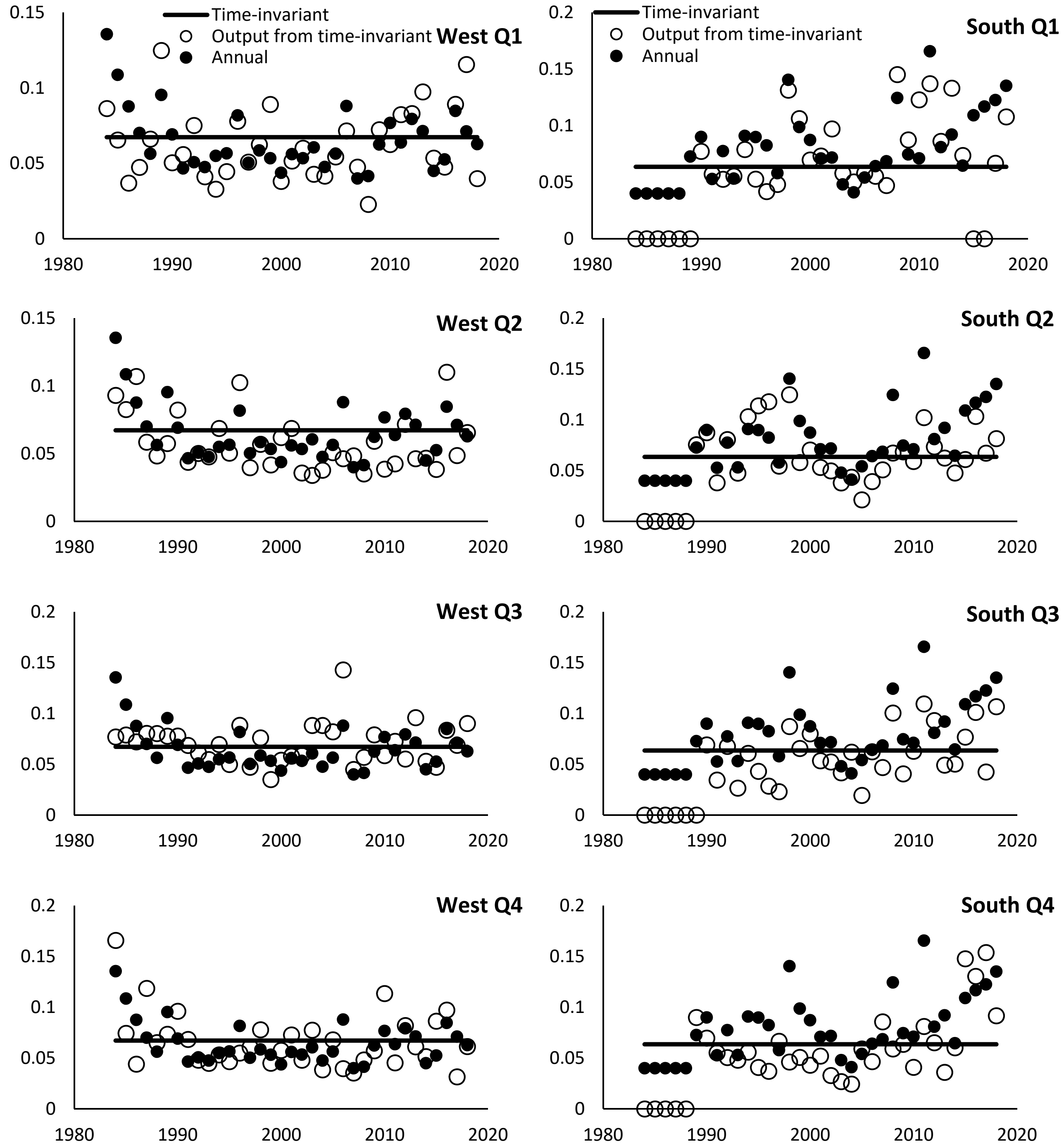


Figure 19. The time series of standard deviations associated with the commercial length frequencies as calculated over all years (baseline), calculated annually based on the output of that baseline run and calculated annually during conditioning, and constrained between [0.04,0.1]. Note $\eta_y^t \sim N(0, 0.7^2)$.

Appendix A: Bayesian assessment model for the South African sardine resource

This assessment provides the generalised operating model for the South African sardine resource (used for this baseline two mixing-component hypothesis as well as a single stock hypothesis[2]). The assessment is run from November $y_1 = 1984$ to November $y_n = 2018$, with the following subscript notation:

- quarters $q = 1$ denoting November $y-1$ to January y, $q = 2$ denoting February to April y, $q = 3$ denoting May to July y and $q = 4$ denoting August to October y;
- ages $a = 0$ to a plus group of $a = 5^+$;
- lengths from a minus group of $l = 2.5^- cm$ to a plus group of $l = 24^+ cm$;
- components $j = W$ or $j = S$ denote the west and south components, respectively, where only the west component equations are used in the single component hypothesis;
- infection $p = NI$ or $p = I$ denote the sardine uninfected and infected with the digenean 'tetracotyle-type' metacercarian endoparasite, respectively.

All parameters are defined in Tables A1 and A2.

<u>Population Dynamics</u>

Numbers-at-age at 1 November before movement or infection

$$N^{S*}_{j,p,y,a} = \left(\left(\left(\left(N^S_{j,p,y-1,a-1}e^{-M^S_{y,a-1}/8} - C^S_{j,p,y,1,a-1}\right)e^{-M^S_{y,a-1}/4} - C^S_{j,p,y,2,a-1}\right)e^{-M^S_{y,a-1}/4} - C^S_{j,p,y,3,a-1}\right)e^{-M^S_{y,a-1}/4} - C^S_{j,p,y,4,a-1}\right)e^{-M^S_{y,a-1}/8}$$

$$p = I, NI, y_1 \le y \le y_n, 1 \le a \le 4$$

$$N^{S*}_{j,p,y,5^+} = \left(\left(\left(\left(N^S_{j,p,y-1,4}e^{-M^S_{y,4}/8} - C^S_{j,p,y,1,4}\right)e^{-M^S_{y,4}/4} - C^S_{j,p,y,2,4}\right)e^{-M^S_{y,4}/4} - C^S_{j,p,y,3,4}\right)e^{-M^S_{y,4}/4} - C^S_{j,p,y,4,4}\right)e^{-M^S_{y,4}/8} +$$

$$\left(\left(\left(\left(N^S_{j,p,y-1,5^+}e^{-M^S_{y,5^+}/8} - C^S_{j,p,y,1,5^+}\right)e^{-M^S_{y,5^+}/4} - C^S_{j,p,y,2,5^+}\right)e^{-M^S_{y,5^+}/4} - C^S_{j,p,y,3,5^+}\right)e^{-M^S_{y,5^+}/4} - C^S_{j,p,y,4,5^+}\right)e^{-M^S_{y,5^+}/8}$$

$$p = I, NI, y_1 \le y \le y_n \qquad \text{(A1)}$$

Infection of west component sardine in the two mixing-component hypothesis; in the single component hypothesis $I_y = 0$ as the parasite data have no influence so that they are not included in the likelihood

$$\mathrm{N^{S**}_{W,NI,y,a}} = (1 - \mathrm{I_y})\mathrm{N^{S*}_{W,NI,y,a}} \qquad y_1 \le y \le y_n, 1 \le a \le 5^+$$

$$\mathrm{N^{S**}_{W,I,y,a}} = \mathrm{N^{S*}_{W,I,y,a}} + \mathrm{I_y N^{S*}_{W,NI,y,a}} \qquad y_1 \le y \le y_n, 1 \le a \le 5^+$$

$$\mathrm{N^{S**}_{S,p,y,a}} = \mathrm{N^{S*}_{S,p,y,a}} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le a \le 5^+ \qquad \text{(A2)}$$

Movement of west component ($j = W$) sardine to the south component ($j = S$) in the two mixing-component hypothesis; in the single component hypothesis $move_{y,a} = 0$

$$\mathrm{N^{S}_{W,p,y,a}} = (1 - \mathrm{move_{y,a}})\mathrm{N^{S**}_{W,p,y,a}} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le a \le 5^+$$

[2] For the single stock hypothesis, both abundance indices and proportion-at-length data are combined for the full area and parasite prevalence-by-length is excluded from the likelihood.

$$\mathrm{N}^{\mathrm{S}}_{\mathrm{S,p,y,a}} = \mathrm{N}^{\mathrm{S**}}_{\mathrm{S,p,y,a}} + \mathrm{move}_{\mathrm{y,a}} \mathrm{N}^{\mathrm{S**}}_{\mathrm{W,p,y,a}} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le a \le 5^+ \qquad \text{(A3)}$$

Numbers-at-age mid-way through each quarter (for use in catch equations)

$$N^S_{j,p,y,1,a} = N^S_{j,p,y-1,a} e^{-M^S_{y,a}/8} \qquad p = I, NI, y_1 \le y \le y_n,\ 0 \le a \le 5^+$$

$$N^S_{j,p,y,q,a} = \left(N^S_{j,p,y,q-1,a} - C^S_{j,p,y,q-1}\right) e^{-M^S_{y,a}/4} \qquad p = I, NI, y_1 \le y \le y_n,\ 2 \le q \le 4, 0 \le a \le 5^+ \qquad \text{(A4)}$$

Numbers-at-length at 1 November (after infection and movement)

The model estimated numbers-at-length range from a 2.5cm minus group to a 24cm plus group, denoted 2.5^- and 24^+, respectively, in the remaining text.

$$N^S_{j,p,y,l} = \sum_{a=0}^{5^+} A^{sur}_{j,y,a,l} N^S_{j,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n,\ 2.5^- cm \le l \le 24^+ cm \qquad \text{(A5)}$$

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

$$N^{S,1+}_{j,p,y,l} = \sum_{a=1}^{5^+} A^{sur}_{j,y,a,l} N^S_{j,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n,\ 2.5^- cm \le l \le 24^+ cm \qquad \text{(A6)}$$

The proportion of sardine of age a in component j that fall in length group l at 1 November, $\mathrm{A}^{\mathrm{sur}}_{\mathrm{j,y,a,l}}$, is calculated under the assumption that length-at-age is normally distributed about a von Bertalanffy growth curve:

$$A^{sur}_{j,y,a,l} \sim N\left(L_{j,\infty}\left(1 - e^{-\kappa_j(a - t_{0,j,y-a})}\right), \vartheta_a^2\right) \ ^{3} \qquad y_1 \le y \le y_n,\ 0 \le a \le 5^+,\ 2.5^- cm \le l \le 24^+ cm \qquad \text{(A7)}$$

with

$$t_{0,j,y} = t_{0,j} + \varepsilon^t_y \ ^{4} \qquad \text{(A8)}$$

And $\varepsilon^t_y = \begin{cases} \eta^t_y & y = y_1 \\ \rho^t \varepsilon^t_{y-1} + \sqrt{1 - (\rho^t)^2}\,\eta^t_y & y_1 < y \le y_n \end{cases}$

Natural mortality

Natural mortality is modelled to vary annually in an autocorrelated manner around a median as follows (although the baseline assumes no such correlation – see Table A.1):

$$M^S_{y,a=0} = \bar{M}^S_{ju} e^{\varepsilon^{ju}_y} \text{ with } \varepsilon^{ju}_{1984} = \eta^{ju}_{1984} \text{ and } \varepsilon^{ju}_y = \rho \varepsilon^{ju}_{y-1} + \sqrt{1 - \rho^2}\,\eta^{ju}_y,\ y_1 \le y \le y_n \qquad \text{(A9)}$$

$$M^S_{y,a=1+} = \bar{M}^S_{ad} e^{\varepsilon^{ad}_y} \text{ with } \varepsilon^{ad}_{1984} = \eta^{ad}_{1984} \text{ and } \varepsilon^{ad}_y = \rho \varepsilon^{ad}_{y-1} + \sqrt{1 - \rho^2}\,\eta^{ad}_y,\ y_1 \le y \le y_n \qquad \text{(A10)}$$

Spawning biomass and biomass associated with the November survey

$$SSB^S_{j,y} = \sum_p \sum_{l=2.5^-}^{24^+} f^S_{j,y,l} N^{S,1+}_{j,p,y,;} w^S_{j,l} \qquad y_1 \le y \le y_n \qquad \text{(A11)}$$

$$SSB^{eff,S}_{j=W,y} = \xi_W SSB^S_{W,y} + (1 - \xi_S) SSB^S_{S,y} \qquad y_1 \le y \le y_n$$

$$SSB^{eff,S}_{j=S,y} = (1 - \xi_W) SSB^S_{W,y} + \xi_S SSB^S_{S,y} \qquad y_1 \le y \le y_n \qquad \text{(A12)}$$

$$B^S_{j,y} = k^S_{j,N} \sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} w^S_{j,l} \ ^{56} \qquad y_1 \le y \le y_n \qquad \text{(A13)}$$

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[3] Given the allowance for early/late recruitment in varying $t_{0,y}$ estimates annually, there may be some proportion of this distribution below a length of zero (due to late recruitment). In these cases, this proportion is removed from the proportion-at-length of the minus length class.

[4] Additive error allows for early or late recruitment. While the timing of recruitment may vary between stocks due to differing environmental conditions on the west and south coasts, the same autocorrelation parameters are assumed here for simplicity reasons.

[5] The biomass in $y_n = 2018$ excludes age 0 fish, although the contribution of age 0 fish to the total biomass should be minor.

[6] A time invariant weight-at-length is used in this equation. Previous assessments adjusted the November weight-at-length annually, informed by the average weight of sardine sampled during the survey, to account for the differing condition factor of sardine at the time of the survey. However, recent discussions have clarified that the hydro-acoustic survey estimate of total biomass depends on the size

Commercial selectivity

$$S_{j,y,q,l} = \begin{cases} 0 & l \leq 5.5cm \\ \chi_{j,y,q} exp\left\{-\frac{\left(l+0.25-\bar{l}_{1,y}\right)^2}{(\sigma_1^{sel})^2}\right\} + \frac{1}{1+exp\left\{-\left(l+0.25-\bar{l}_{2,j,y,q}\right)/(\sigma_2^{sel})^2\right\}} & 6cm \leq l \leq l_{max} = 23cm \\ S_{j,y,q,lmax} & l > l_{max} \end{cases}$$ [7]

$$y_1 \leq y \leq y_n,\ 1 \leq q \leq 4 \quad \text{(A14)}$$

$$S_{j,y,q,a} = \sum_{l=2.5^-}^{24^+} A^{com}_{j,y,q,a,l} S_{j,y,q,l} \qquad y_1 \leq y \leq y_n,\ 1 \leq q \leq 4,\ 0 \leq a \leq 5^+ \quad \text{(A15)}$$

where $A^{com}_{j,y,q,a,l} \sim N\left(L_{j,\infty}\left(1-e^{-\kappa_j(a+(2q-1)/8-t_{0,j,y-a})}\right), \left[\left(1-\frac{(2q-1)}{8}\right)\vartheta_a + \frac{(2q-1)}{8}\vartheta_{a+1}\right]^2\right)$

$$y_1 \leq y \leq y_n,\ 1 \leq q \leq 4, 0 \leq a \leq 5^+,\ 2.5^- cm \leq l \leq 24^+ cm \quad \text{(A16)}$$

Bycatch in the anchovy directed fishery

$$C^{bycatch}_{j,p,y,q,a} = \begin{cases} N^S_{j,p,y,q,a} F^{By}_{j,y,q,a} & 0 \leq a \leq 1 \\ 0 & 2 \leq a \leq 5^+ \end{cases}$$ [8]

$$p = I, NI, y_1 \leq y \leq y_n,\ 1 \leq q \leq 4 \quad \text{(A17)}$$

Catch in the directed sardine and round herring bycatch fisheries

$$C^{dir}_{j,p,y,q,a} = \left(N^S_{j,p,y,q,a} - C^{bycatch}_{j,p,y,q,a}\right) S_{j,y,q,a} F_{j,y,q} \qquad p = I, NI, y_1 \leq y \leq y_n,\ 1 \leq q \leq 4, 0 \leq a \leq 5^+ \quad \text{(A18)}$$

Total catch

$$C^S_{j,p,y,q,a} = C^{bycatch}_{j,p,y,q,a} + C^{dir}_{j,p,y,q,a} \qquad p = I, NI, y_1 \leq y \leq y_n,\ 1 \leq q \leq 4, 0 \leq a \leq 5^+ \quad \text{(A19)}$$

Fished proportion of the available biomass from the sardine bycatch with the anchovy directed fishery

$$F^{By}_{j,y,q=1,a=0} = \frac{\sum_{m=11}^{12} \sum_{l<lcut_{y-1,m}} C^{RLF,fleet=3}_{j,y-1,m,l} + \sum_{l<lcut_{y,m}} C^{RLF,fleet=3}_{j,y,1,l}}{\sum_p N^S_{j,p,y,q=1,a=0}}$$

$$F^{By}_{j,y,q=1,a=1} = \frac{\sum_{m=11}^{12} \sum_{l\geq lcut_{y-1,m}} C^{RLF,fleet=3}_{j,y-1,m,l} + \sum_{l\geq lcut_{y,m}} C^{RLF,fleet=3}_{j,y,1,l}}{\sum_p N^S_{j,p,y,q=4,a=1}}$$

$$F^{By}_{j,y,q=2,a=0} = \frac{\sum_{m=2}^{4} \sum_{l<lcut_{y,m}} C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=2,a=0}} \qquad F^{By}_{j,y,q=2,a=1} = \frac{\sum_{m=2}^{4} \sum_{l\geq lcut_{y,m}} C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=2,a=1}}$$

$$F^{By}_{j,y,q=3,a=0} = \frac{\sum_{m=5}^{7} \sum_{l<lcut_{y,m}} C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=3,a=0}} \qquad F^{By}_{j,y,q=3,a=1} = \frac{\sum_{m=5}^{7} \sum_{l\geq lcut_{y,m}} C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=3,a=1}}$$

$$F^{By}_{j,y,q=4,a=0} = \frac{\sum_{m=8}^{10} \sum_{l<lcut_{y,m}} C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=4,a=0}} \qquad F^{By}_{j,y,q=4,a=1} = \frac{\sum_{m=8}^{10} \sum_{l\geq lcut_{y,m}} C^{RLF,fleet=3}_{j,y,m,l}}{\sum_p N^S_{j,p,y,q=4,a=1}} \quad \text{(A20)}$$

A penalty is imposed within the model to ensure that $F^{By}_{j,y,q,a} < 0.95$.

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of the fish swim bladder which depends (through the time invariant target strength relationship) on fish length only but not on the condition (skinniness/fattiness) of the fish at the time of the survey. A time-invariant weight-at-length therefore provides most appropriate basis to estimate biomass from the population model to correspond to the time series of biomasses from the survey (which is independent of sardine condition factor).

[7] The $l + 0.25$ denotes the middle of length class l. This function is renormalized to a maximum of 1.

[8] "Selectivity" is incorporated in $F^{By}_{j,y,q,a}$, as the sardine bycaught is typically independent of sardine abundance, but rather correlated with anchovy recruitment which varies from year to year.

Fished proportion of the available biomass from the directed sardine catch and sardine bycatch with round herring fishery

$$F_{j,y,q=1}=\frac{\sum_{fleet=1}^{2}\sum_{m=11}^{12}\sum_{l\geq 6cm}C_{j,y-1,m,l}^{RLF,fleet}+\sum_{fleet=1}^{2}\sum_{l\geq 6cm}C_{j,y,1,l}^{RLF,fleet}}{\sum_{p}\sum_{a=0}^{5+}\left(N_{j,p,y,1,a}^{S}-C_{j,y,1,a}^{bycatch}\right)S_{j,y,1,a}}$$

$$F_{j,y,q=2}=\frac{\sum_{fleet=1}^{2}\sum_{m=2}^{4}\sum_{l\geq 6cm}C_{j,y,m,l}^{RLF,fleet}}{\sum_{p}\sum_{a=0}^{5+}\left(N_{j,p,y,2,a}^{S}-C_{j,y,2,a}^{bycatch}\right)S_{j,y,2,a}}$$

$$F_{j,y,q=3}=\frac{\sum_{fleet=1}^{2}\sum_{m=5}^{7}\sum_{l\geq 6cm}C_{j,y,m,l}^{RLF,fleet}}{\sum_{p}\sum_{a=0}^{5+}\left(N_{j,p,y,3,a}^{S}-C_{j,y,3,a}^{bycatch}\right)S_{j,y,3,a}}$$

$$F_{j,y,q=4}=\frac{\sum_{fleet=1}^{2}\sum_{m=8}^{10}\sum_{l\geq 6cm}C_{j,y,m,l}^{RLF,fleet}}{\sum_{p}\sum_{a=0}^{5+}\left(N_{j,p,y,4,a}^{S}-C_{j,y,4,a}^{bycatch}\right)S_{j,y,4,a}} \qquad \text{(A21)}$$

A penalty is imposed within the model to ensure that $S_{j,y,a,l}F_{j,y,q}<0.95$. Fish <6cm were seldom[9] caught and were thus not used in fitting this model. Commercial selectivity-at-length is fixed to zero for length classes <6cm (equation A12).

Number of recruits associated with the recruit survey

$$N_{j,y,r}^{S}=k_{j,r}^{S}\left(\left(N_{j,NI,y,2,0}^{S}-C_{j,NI,y,2,0}^{S}\right)e^{-(1/8+0.5t_{y}^{S}/12)M_{y,0}^{S}}-\tilde{C}_{j,y,0bs}^{S}\right)e^{-0.5t_{y}^{S}\times M_{y,0}^{S}/12} \quad 1985\leq y\leq y_{n} \qquad \text{(A22)}$$

Multiplicative survey bias

$$k_{j,N}^{S}=k_{ac}^{S} \qquad \text{(A23)}$$

$$k_{j=W,r}^{S}=k_{cov}^{S}\times k_{ac}^{S} \qquad \text{(A24)}$$

$k_{j=S,r}^{S}=k_{covS}^{S}\times k_{cov}^{S}\times k_{ac}^{S}$ (for the two mixing-component hypothesis only) (A25)

Survey trawl selectivity

$$S_{j,l}^{survey}=\begin{cases}0 & l=2.5^{-}cm\\ \left[1+exp\left\{-\left(l+0.25-S_{50,j}\right)/\delta_{j}\right\}\right]^{-1} & 3cm\leq l\leq 24^{+}cm\end{cases} \qquad y_{1}\leq y\leq y_{n} \text{(A26)}$$

Proportion-at-length associated with the November survey

$$p_{j,y,l}^{s}=\begin{cases}\frac{\sum_{p}\sum_{l\leq 6cm}N_{j,p,y,l}^{S}S_{j,l}^{survey}}{\sum_{p}\sum_{l=2.5^{-}}^{24^{+}}N_{j,p,y,l}^{S}S_{j,l}^{survey}} & l=6^{-}cm\\ \frac{\sum_{p}N_{j,p,y,l}^{S}S_{j,l}^{survey}}{\sum_{p}\sum_{l=2.5^{-}}^{24^{+}}N_{j,p,y,l}^{S}S_{j,l}^{survey}} & 6.5cm\leq l\leq 20.5cm\\ \frac{\sum_{p}\sum_{l=21}^{23.5}N_{j,p,y,l}^{S}S_{j,l}^{survey}}{\sum_{p}\sum_{l=2.5^{-}}^{24^{+}}N_{j,p,y,l}^{S}S_{j,l}^{survey}} & l=21-23.5cm\\ \frac{\sum_{p}N_{j,p,y,l}^{S}S_{j,24^{+}}^{survey}}{\sum_{p}\sum_{l=2.5^{-}}^{24^{+}}N_{j,p,y,l}^{S}S_{j,l}^{survey}} & l=24^{+}cm\end{cases} \text{[10]} \qquad y_{1}\leq y\leq y_{n} \qquad \text{(A27)}$$

Proportion-at-length of fish infected with the parasite in November

$$P_{j,y,l}^{S}=\frac{N_{j,I,y,l}^{S}}{\sum_{p}N_{j,p,y,l}^{S}} \qquad y_{1}\leq y\leq y_{n}, 10cm\leq l\leq 23cm \qquad \text{(A28)}$$

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[9] Less than 6% of the quarters west of Cape Agulhas, less than 2% of the quarters south-east of Cape Agulhas and less than 4% of the quarters for the whole coast.

[10] The inclusion of model predicted proportion-at-length 24+cm is deliberate to take into account the zero samples of 24+cm sardine in the survey.

Catch-at-length from the directed and round herring bycatch fisheries

$$C^{dir}_{j,p,y,q,l} = \sum_{a=0}^{5^+} \left(N^S_{j,p,y,q,a} - C^{bycatch}_{j,p,y,q,a}\right) A^{com}_{j,q,a,l} S_{j,y,q,l} F_{j,y,q}$$ [11]

$$p = I, NI, y_1 \leq y \leq y_n,\ 1 \leq q \leq 4,\ 2.5^{-}cm \leq l \leq 24^{+}cm \quad \text{(A29)}$$

Proportion-at-length associated with the directed catch and round herring bycatch

$$p^{coml,S}_{j,y,q,l} = \begin{cases} \dfrac{\sum_p C^{dir}_{j,p,y,q,l}}{\sum_p \sum_{l=6}^{24^+} C^{dir}_{j,p,y,q,l}} & 6cm \leq l \leq 22.5cm \\ \dfrac{\sum_p \sum_{l=23}^{24^+} C^{dir}_{j,p,y,q,l}}{\sum_p \sum_{l=6}^{24^+} C^{dir}_{j,p,y,q,l}} & l = 23^{+}cm \end{cases}$$ [12]

$$y_1 \leq y \leq y_n,\ 1 \leq q \leq 4 \quad \text{(A30)}$$

<u>Fitting the Model to Observed Data (Likelihood)</u>

$$-lnL = -lnL^{Nov} - lnL^{rec} - lnL^{sur\ propl} - lnL^{com\ propl} - lnL^{prev} \quad \text{(A31)}$$

where

$$-lnL^{Nov} = 0.5 \sum_j \sum_{y=y_1}^{y_n} \left\{ \frac{5^5 \left(\dfrac{\left|ln\left(\hat{B}^S_{j,y}\right) - ln\left(B^S_{j,y}\right)\right|}{\sqrt{\left(\sigma^S_{j,y,Nov}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,N}\right)^2}} \right)^5}{5^5 + \left(\dfrac{\left|ln\left(\hat{B}^S_{j,y}\right) - ln\left(B^S_{j,y}\right)\right|}{\sqrt{\left(\sigma^S_{j,y,Nov}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,N}\right)^2}} \right)^5} \right\}^{2/5} + ln\left[2\pi \left(\left(\sigma^S_{j,y,Nov}\right)^2 + (\phi^S_{ac})^2 + \left(\lambda^S_{j,N}\right)^2 \right)\right] \quad \text{(A32)}$$

$$-lnL^{rec} = 0.5 \sum_j \sum_{y=y_2}^{y_n} \left\{ \frac{5^5 \left(\dfrac{\left|ln\left(\hat{N}^S_{j,y,r}\right) - ln\left(N^S_{j,y,r}\right)\right|}{\sqrt{\left(\sigma^S_{j,y,rec}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,r}\right)^2}} \right)^5}{5^5 + \left(\dfrac{\left|ln\left(\hat{N}^S_{j,y,r}\right) - ln\left(N^S_{j,y,r}\right)\right|}{\sqrt{\left(\sigma^S_{j,y,rec}\right)^2 + \left(\phi^S_{ac}\right)^2 + \left(\lambda^S_{j,r}\right)^2}} \right)^5} \right\}^{2/5} + ln\left[2\pi \left(\left(\sigma^S_{j,y,rec}\right)^2 + (\phi^S_{ac})^2 + \left(\lambda^S_{j,r}\right)^2 \right)\right] \quad \text{(A33)}$$

$$-lnL^{sur\ propl} = w^{sur}_{propl} \sum_j \sum_{y=y_1}^{y_n} \left\{ \sum_{l=6^-}^{21^+} \left\{ \frac{\left(\sqrt{\hat{p}^S_{j,y,l}} - \sqrt{p^S_{j,y,l}}\right)^2}{2\left(\sigma^S_{j,sur}\right)^2} + ln\left(\sigma^S_{j,sur}\right) \right\} + \frac{\left(0 - \sqrt{p^S_{j,y,24^+}}\right)^2}{2\left(\sigma^S_{j,sur}\right)^2} + ln\left(\sigma^S_{j,sur}\right) \right\}$$ [13]

$$\text{(A34)}$$

$$-lnL^{com\ propl} = w^{com}_{propl} \sum_j \sum_{y=y_1}^{y_n} \sum_{q=1}^{4} \sum_{l=6}^{23^+} \left\{ \frac{\left(\sqrt{\hat{p}^{S,coml}_{j,y,q,l}} - \sqrt{p^{S,coml}_{j,y,q,l}}\right)^2}{2\left(\sigma^S_{j,com}\right)^2} + ln\left(\sigma^S_{j,com}\right) \right\} \quad \text{(A35)}$$

$$-lnL^{prev} = \sum_j \sum_{y=2010}^{2018} \sum_{l=10cm}^{23cm} -n^{prev}_{j,y,l}\, ln\left(P^S_{j,y,l}\right) - \left(N^{prev}_{j,y,l} - n^{prev}_{j,y,l}\right) ln\left(1 - P^S_{j,y,l}\right) \quad \text{(A36)}$$

A "robustified likelihood" is used for the contributions from the hydro-acoustic surveys to ensure no undue influence from any extreme (outlying) values for residuals. The functional form chosen to robustify makes negligible difference for standardised residuals of magnitude three or less, but essentially treats large standardised residuals as if they do not exceed five in magnitude.

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[11] Note the model predicted commercial catch of lengths <6cm is zero, from a zero commercial selectivity in equation A.13. This is consistent with the range of length classes in the observed commercial proportions-at-lengths.

[12] Note the model predicted commercial catch of lengths <6cm is zero, from a zero commercial selectivity in equation A.13. This is consistent with the range of length classes in the observed commercial proportions-at-lengths.

[13] The 21^+ group in this equation consists of the length classes 21cm, 21.5cm, 22cm, 22.5cm, 23cm and 23.5cm.

Table A1. Assessment model parameters and variables with associated fixed values or prior distributions and, for derived variables, associated equation numbers. As the majority of prior distributions are uninformative, notes are provided only for informative priors and/or bounds.

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Annual numbers and biomass	$N^S_{j,p,y,a}$	Model predicted numbers-at-age a at the beginning of November in year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions	$ln(N^S_{j,NI,y,0})/10 \sim U(-10,3.$ $N^S_{j,I,y,0} = 0$	A1 - A3	
	$N^S_{j,p,1983,a}$	Initial numbers-at-age a in component j	Billions	$N^S_{j,NI,1983,a=1} \sim U(0,50)$ $N^S_{j,NI,1983,a} = 0,\ 2 \le a \le 5^+$ $N^S_{j,I,1983,a} = 0,\ 0 \le a \le 5^+$		
	$N^S_{j,p,y,q,a}$	Model predicted numbers-at-age a mid-way through quarter q of year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A4	
	I_y	Proportion of uninfected west component sardine that are infected with the endoparasite in year y (two mixing-component hypothesis only)		$= 0,\ y_1 \le y \le 2007$ $\sim U(0,1),\ 2008 \le y \le y_n$		
	$move_{y,a}$	Proportion of west component sardine of age a which move to the south component at the beginning of November of year y (two mixing-component hypothesis only)	-	$move_{y,1} \sim Beta(1.05,1.05)$ $move_{y,2+} = \phi move_{y,1}$ $\phi \sim U(0,1)$		
	$SSB^S_{j,y}$	Model predicted spawning biomass of component j at the beginning of November in year y	Thousand tons		A11	
	$SSB^{eff,S}_{j,y}$	Model predicted effective spawning biomass of component j at the beginning of November in year y	Thousand tons		A12	
	$B^S_{j,y}$	Model predicted total biomass of component j at the beginning of November in year y, associated with the November survey	Thousand tons		A13	
	ξ_j	Proportion of j-component spawner biomass that contributes to the effective spawning biomass on the same coast		0.08		Alternative values considered in robustness tests
	$w^S_{j,l}$	Mean mass of sardine of component j in length class l	Grams	$1.1639 \times 10^{-5} \times l^{3.03155}$		van der Lingen *et al.* (2006)

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Annual numbers and biomass	$f^S_{j,y,l}$	Proportion of component j sardine that are mature in length class l in year y	-	$\left[1+e^{-(l-17.2)/1.17}\right]^{-1}$ $1984 \le y \le 1987$ $\left[1+e^{-(l-18.6)/1.26}\right]^{-1}$ $1988 \le y \le 1995$ $\left[1+e^{-(l-19.4)/1.40}\right]^{-1}$ $1996 \le y \le 2003$ $\left[1+e^{-(l-17.4)/0.95}\right]^{-1}$ $2004 \le y \le 2018$		Refit from data used by van der Lingen *et al*. (2006) using midpoints of length classes. Assuming maturity post-2003 reflects that of 1965-1975 as maturity is hypothesized to be density dependent (van der Lingen *et al*. 2006) and both these periods correspond to low biomass following a peak in abundance
	$N^S_{j,y,r}$	Model predicted number of juveniles of component j at the time of the recruit survey in year y	Billions		A23	
Natural mortality	$M^S_{y,a}$	Rate of natural mortality of age a in year y	Year^{-1}	$M^S_{y,0} = 1.0$ $M^S_{y,1+} = 1.0$	A9 and A10	Selected based on maximized joint posterior, and subject to a compelling reason to modify from previous assessment
	$\bar{M}^S_{ju}$	Median juvenile rate of natural mortality	Year^{-1}	1.0		
	$\bar{M}^S_{ad}$	Median rate of natural mortality for 1+ sardine	Year^{-1}	0.8		
	ε^{ju}_y	Annual residuals about juvenile natural mortality rate	-		A9	
	ε^{ad}_y	Annual residuals about natural mortality rate for 1+ sardine	-		A10	
	η^{ju}_y	Normally distributed error in calculating ε^{ju}_y	-	$N(0,\sigma_j^2)$		
	η^{ad}_y	Normally distributed error in calculating ε^{ad}_y	-	$N(0,\sigma_{ad}^2)$		
	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 A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Proportions-at-length and growth curve	$N_{j,p,y,l}^{S}$	Model predicted numbers-at-length l at the beginning of November in year y of component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A5	
	$p_{j,y,l}^{S}$	Model predicted proportion-at-length l of component j associated with the November survey in year y	-		A27	
	$A_{j,y,a,l}^{sur}$	Proportion of age a of component j sardine that falls in the length group l in November of year y	-		A7	
	κ_j	Somatic growth rate parameter for component j	$Year^{-1}$	$U(0,3)$		
	$L_{j,\infty}$	Maximum length (in expectation) of component j	Cm	$L_{j,\infty} = \frac{L_{j,1}e^{-2\kappa_j} - L_{j,3}}{e^{-2\kappa_j} - 1}$ where $L_{j,a=1} \sim U(5,25)$ $L_{j,a=3} - L_{j,a=1} \sim U(5,25)$		
	$t_{0,j,y}$	Age at which the length (in expectation) is zero in year y	Year		A8	
	$t_{0,j}$	Average age at which the length (in expectation) is zero	Year	$\frac{1}{\kappa_j} ln\left\{\frac{e^{\kappa_j}(L_{j,1} - L_{j,3})}{L_{j,1}e^{-2\kappa_j} - L_{j,3}}\right\}$		
	ε_y^t	Annual residuals about the age at which the length is zero		$\eta_y^t \sim N(0, 0.2^2)$		
	ρ^t	Autocorrelation coefficient in these residuals		$U(-1,1)$		
	ϑ_a	Standard deviation of the distribution about the mean length for age a	-	$U(0,3)$, $a = 0,1,2^+$		Upper bound chosen to preclude unrealistically large lengths for very young fish
	$p_{j,y,q,l}^{com,S}$	Model predicted proportion-at-length l of component j in the directed catch and round herring bycatch during quarter q of year y	-		A30	
	$A_{j,y,q,a,l}^{com}$	Proportion of age a of component j sardine that falls in the length group l mid-way through quarter q of year y	-		A16	
	$P_{j,y,l}^{S}$	Model predicted proportion-at-length l of component j that are infected with the endoparasite, at the time of the November survey in year y			A28	

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Selectivity	$S_{j,l}^{survey}$	Survey selectivity-at-length l in the November survey for component j	-		A26	Some smaller fish escape through the trawl net
	$S_{50,j}$	Length at which survey selectivity is 50% for component j	Cm	$U(2.5,20)$		
	δ_j	Inverse of slope of survey selectivity-at-length ogive when selectivity is 50% for component j	-	$U(0.05,50)$		
	$S_{j,y,q,l}$	Commercial selectivity-at-length l during quarter q of year y of component j	-		A14	
	$S_{j,y,q,a}$	Commercial selectivity-at-age a during quarter q of year y of component j	-		A15	
	$\chi_{j,y,q}$	Height of the Gaussian component for component j relative to the height of the logistic component in quarter q of year y	-	$U(0,1)$ for $j = 1$ = 0 for $j = 2$		No bycatch modelled for south component
	$\bar{l}_{1,y}$	Mean of the Gaussian distribution for in year y	mm	$N(100, 10^2)$		
	$\bar{l}_{2,j,y,q}$	Length at 50% selectivity in the logistic component for component j in quarter q of year y	mm	$\bar{l}_{2,j,y,1} - \bar{l}_{1,2000} \sim U(0,150)$ $\bar{l}_{2,j,y,2} - \bar{l}_{1,2000} \sim U(0,150)$ $\bar{l}_{2,j,y,3} = \bar{l}_{2,j,y,2}$ $\bar{l}_{2,j,y-1,4} = \bar{l}_{2,j,y12}$		Estimated for two time periods per component: 1984-1993, 1994-2018 (west) and 1984-1997, 1998-2018 (south)
	$(\sigma_1^{sel})^2$	Variance parameter of the Gaussian distribution	mm	$U(20,150)$		
	$(\sigma_2^{sel})^2$	Variance parameter of the logistic distribution	mm	$U(0,100)$		
Multiplicative bias	$k_{j,N}^S$	Multiplicative bias associated with the November survey of component j	-		A23	
	$k_{j,r}^S$	Multiplicative bias associated with the recruit survey of component j	-		A24 – A25	
	k_{ac}^S	Multiplicative bias associated with the hydro-acoustic survey	-	$ln(k_{ac}^S) \sim N(-0.311, 0.094^2)$		Appendix B of de Moor and Butterworth (2016)
	k_{cov}^S	Multiplicative bias associated with the coverage of the recruits during the recruit survey in comparison to the coverage of the biomass during the November survey	-	Uniform prior on logit transpose of k_{cov}^S, such that $0.3 \leq k_{cov}^S \leq 1$		Lower bound selected in discussions with scientists on these surveys and their field experience
	k_{covS}^S	Multiplicative bias associated with the coverage of the south component recruits in comparison to the west component recruits during the recruit survey		$U(0,1)$		

Table A1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Catch	$C^{S}_{j,p,y,q,a}$	Model predicted number of age a fish of component j caught during quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A19	
	$lcut_{y,m}$	Cut off length for recruits in month m of year y	Cm	de Moor *et al*. 2019		Differ by month and year as informed by the recruit surveys
	$C^{bycatch}_{j,p,y,q,a}$	Number of age a fish of component j bycaught in the anchovy-directed fishery in quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A17	
	$C^{dir}_{j,p,y,q,a}$	Number of age a fish of component j caught in the sardine-directed and round herring bycatch fisheries in quarter q of year y that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A18	
	$C^{dir}_{j,p,y,q,l}$	Number of length l fish of component j caught in the sardine-directed and round herring bycatch fisheries in quarter q of year y	Billions		A29	
	$F^{By}_{j,y,q,a}$	Fished proportion in quarter q of year y for age class a of component j, of bycatch in the anchovy-directed fishery	-		A20	
	$F_{j,y,q}$	Fished proportion in quarter q of year y for a fully selected age class a of component j, by the directed and round herring bycatch fisheries	-		A21	
Likelihood	$-lnL^{Nov}$	Contribution to the negative log likelihood from the model fit to the November survey biomass data	-		A32	
	$-lnL^{rec}$	Contribution to the negative log likelihood from the model fit to the recruit survey data	-		A33	
	$-lnL^{surpropl}$	Contribution to the negative log likelihood from the model fit to the November survey proportion-at-length data	-		A34	
	$-lnL^{compropl}$	Contribution to the negative log likelihood from the model fit to the quarterly commercial proportion-at-length data	-		A35	
	$-lnL^{surprev}$	Contribution to the negative log likelihood from the model fit to the November parasite prevalence-at-length data	-		A36	
	ϕ^{S}_{ac}	CV associated with factors which cause bias in the acoustic survey estimates and which vary inter-annually rather than remain fixed over time	-	=0.227		Appendix B of de Moor and Butterworth (2016)
	$\left(\lambda^{S}_{j,N/r}\right)^2$	Additional variance (over and above $\left(\sigma^{S}_{j,y,Nov/rec}\right)^2$ and $(\phi^{S}_{ac})^2$) associated with the November/recruit surveys of component j	-	$U(0,10)$		

Table A1 (Continued).

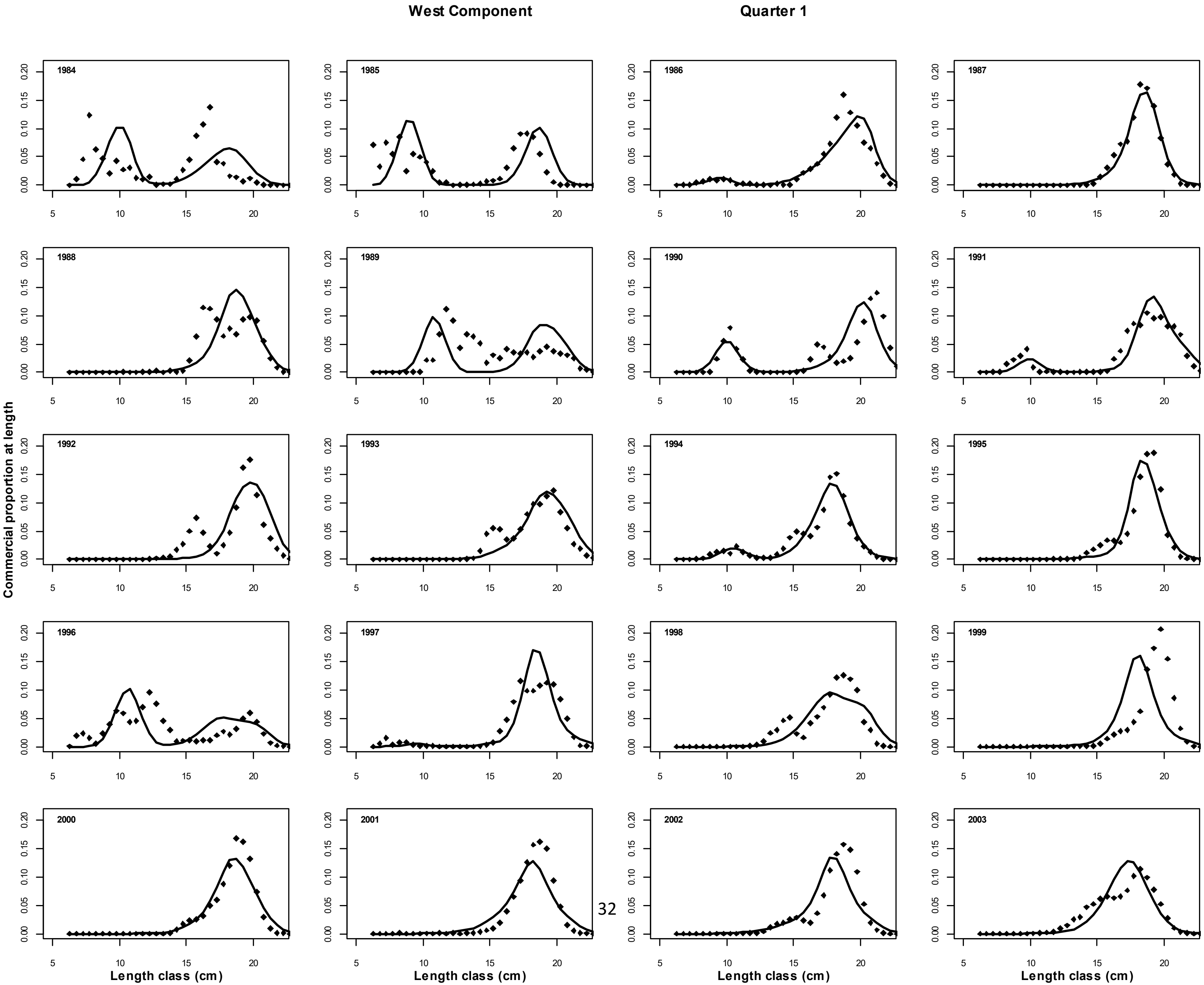
Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
w^{sur}_{propl}	Weighting applied to the remaining survey proportion-at-length data	-	$= 0.5 \times 0.167$		To allow for autocorrelation[14]
$\sigma^{S}_{j,sur}$	Standard deviation associated with the survey proportion-at-length data of component *j*	-		$\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{l=6}^{21^+}\left(\sqrt{\hat{p}^{S}_{j,y,l}}-\sqrt{p^{S}_{j,y,l}}\right)^2}{\sum_{y=y_1}^{y_n}\sum_{l=6}^{21^+}1}}$ [15]	Closed form solution
w^{com}_{propl}	Weighting applied to the commercial proportion-at-length data		$= 0.5 \times 0.04$		To allow for autocorrelation[16]
$\sigma^{S}_{j,com}$	Standard deviation associated with the commercial proportion-at-length data of stock *j*	-	$\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=6}^{23^+}\left(\sqrt{\hat{p}^{comlS}_{j=1,y,q,l}}-\sqrt{\cdots}\right.}{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=6}^{23^+}1}}$ $\sqrt{\frac{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=13}^{23^+}\left(\sqrt{\hat{p}^{comlS}_{j=2,y,q,l}}-\sqrt{\cdots}\right.}{\sum_{y=y_1}^{y_n}\sum_{q=1}^{4}\sum_{l=13}^{23^+}1}}$	Closed form solution[17]	$\sigma^{S}_{j,com}$

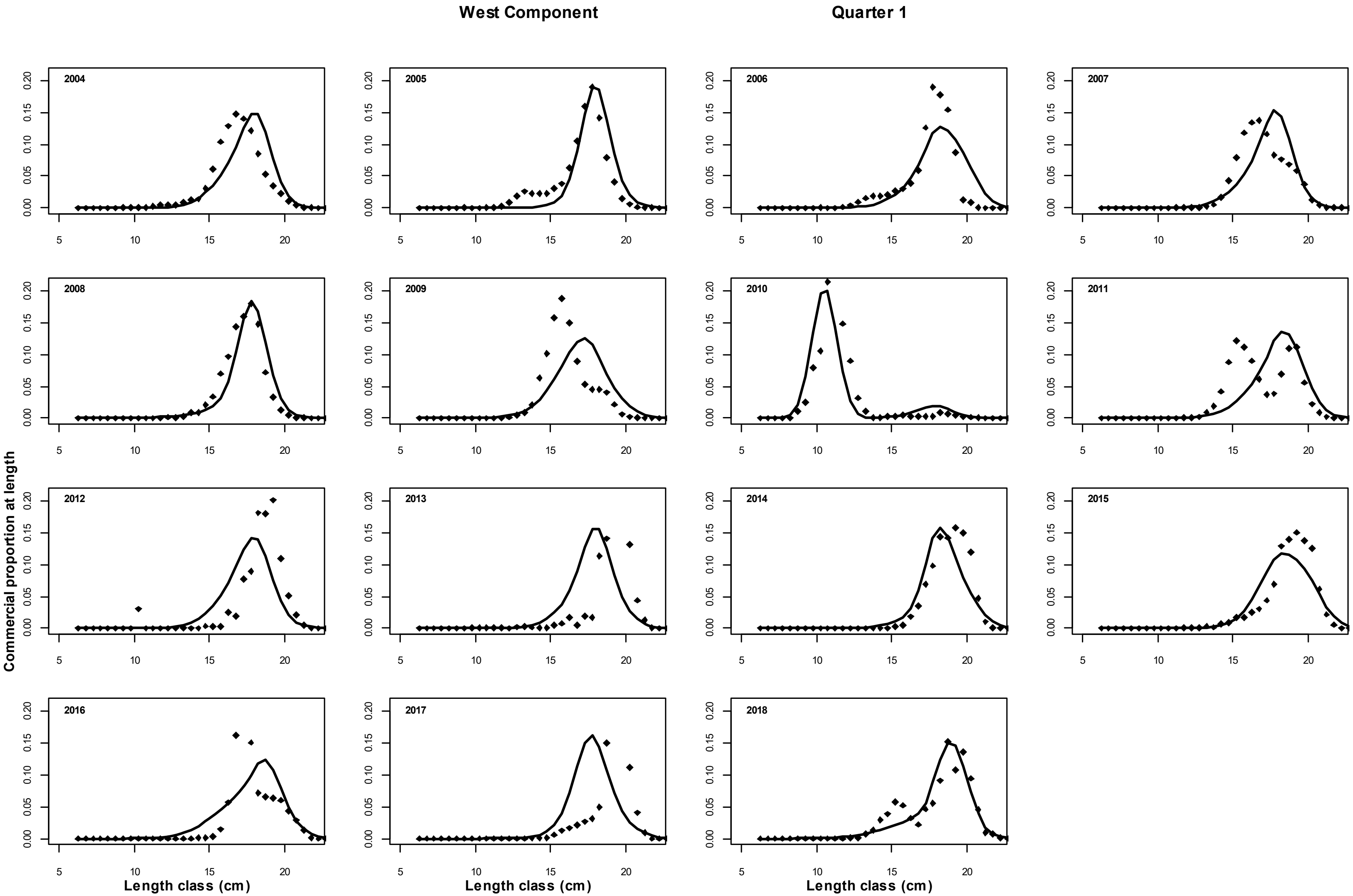
[14] Based upon data being available ~6 times more frequently than annual age data which contain maximum information content on this.
[15] The 21⁺ group in this equation consists of the length classes 21cm, 21.5cm, 22cm, 22.5cm, 23cm and 23.5cm.
[16] Based upon data being available ~4x6 times more frequently than annual age data which contain maximum information content on this.
[17] A shorter range of lengths is used for the south component given the near absence of data outside this range, resulting in small/zero residuals, which would negatively bias this estimate.

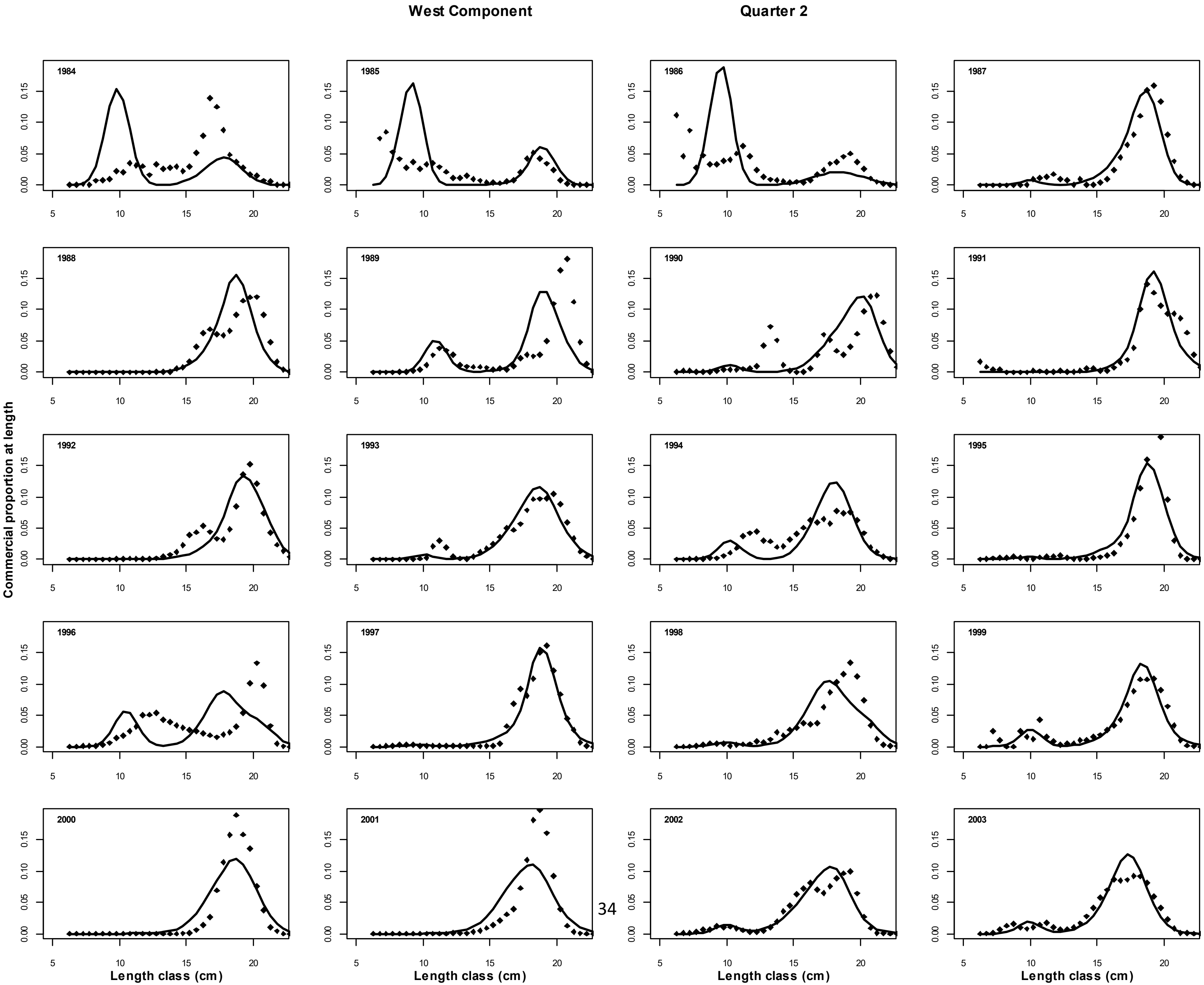
Table A2. Assessment model data, detailed in de Moor *et al*. (2019).

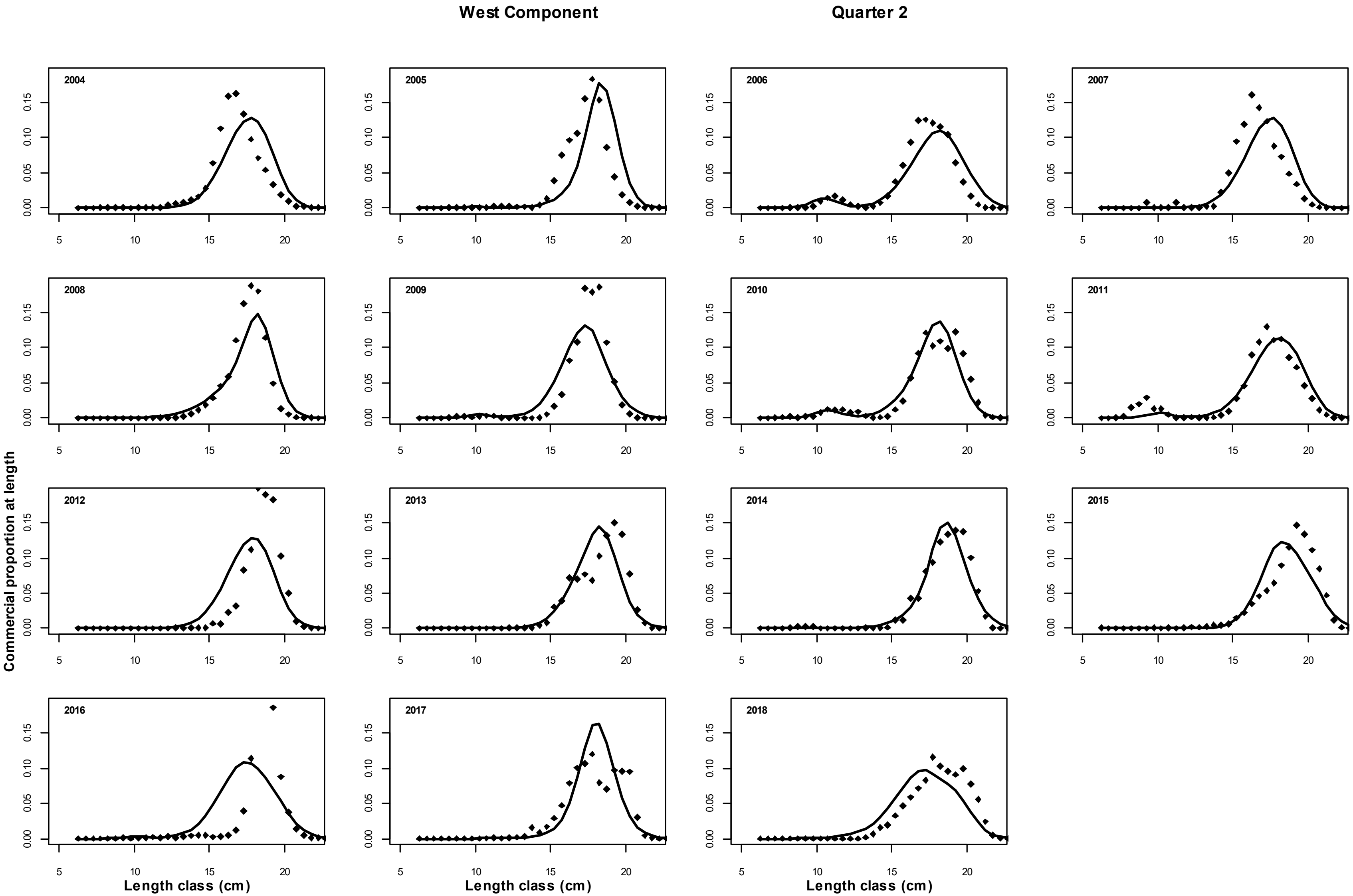
Quantity	Description	Units / Scale	Shown in Figure
t_y^S	Time lapsed between 1 May and the start of the recruit survey in year y	Months	
$\tilde{C}_{j,y,0bs}^S$	Number of juveniles of component j caught between 1 May and the day before the start of the recruit survey in year y	Billions	
$C_{j,y,m,l}^{RLF,fleet}$	Number of fish in length class l landed by $fleet$ in month m of year y of component$j$. $fleet = 1$ denotes the sardine directed fishery, $fleet = 2$ denotes the sardine bycatch with round herring (1984-2011) or ≥14cm sardine bycatch (2012-18) and $fleet = 3$ denotes the juvenile sardine bycatch with anchovy (1984-2011) or <14cm sardine bycatch (2012-18)	Billions	
$\hat{B}_{j,y}^S$	Acoustic survey estimate of biomass of component j from the November survey in year y	Thousand tons	Fig. 1
$\sigma_{j,y,Nov}^S$	Survey sampling CV associated with $\hat{B}_{j,y}^S$ that reflects survey inter-transect variance	-	Fig. 1
$\hat{N}_{j,y,r}^S$	Acoustic survey estimate of recruitment of component j from the recruit survey in year y	Billions	Fig. 2
$\sigma_{j,y,rec}^S$	Survey sampling CV associated with $\hat{N}_{j,y,r}^S$ that reflects survey inter-transect variance	-	Fig. 2
$\hat{p}_{j,y,l}^S$	Observed proportion (by number) of component j in length group l in the November survey of year y	-	Fig. 6
$\hat{p}_{j,y,q,l}^{S,com}$	Observed proportion (by number) of the directed catch and round herring bycatch of fish of component j and length group l during quarter q of year y	-	Fig. 9
$n_{j,y,l}^{prev}$	Number of sardine of component j in length class l sampled from the November survey in year y that were tested and found to be infected with the endoparasite	Numbers	Fig. 13
$N_{j,y,l}^{prev}$	Number of sardine of component j in length class l sampled from the November survey in year y that were tested for infection with the endoparasite	Numbers	Fig. 13

Appendix B: Detailed comparison between model predicted and observed commercial length frequencies

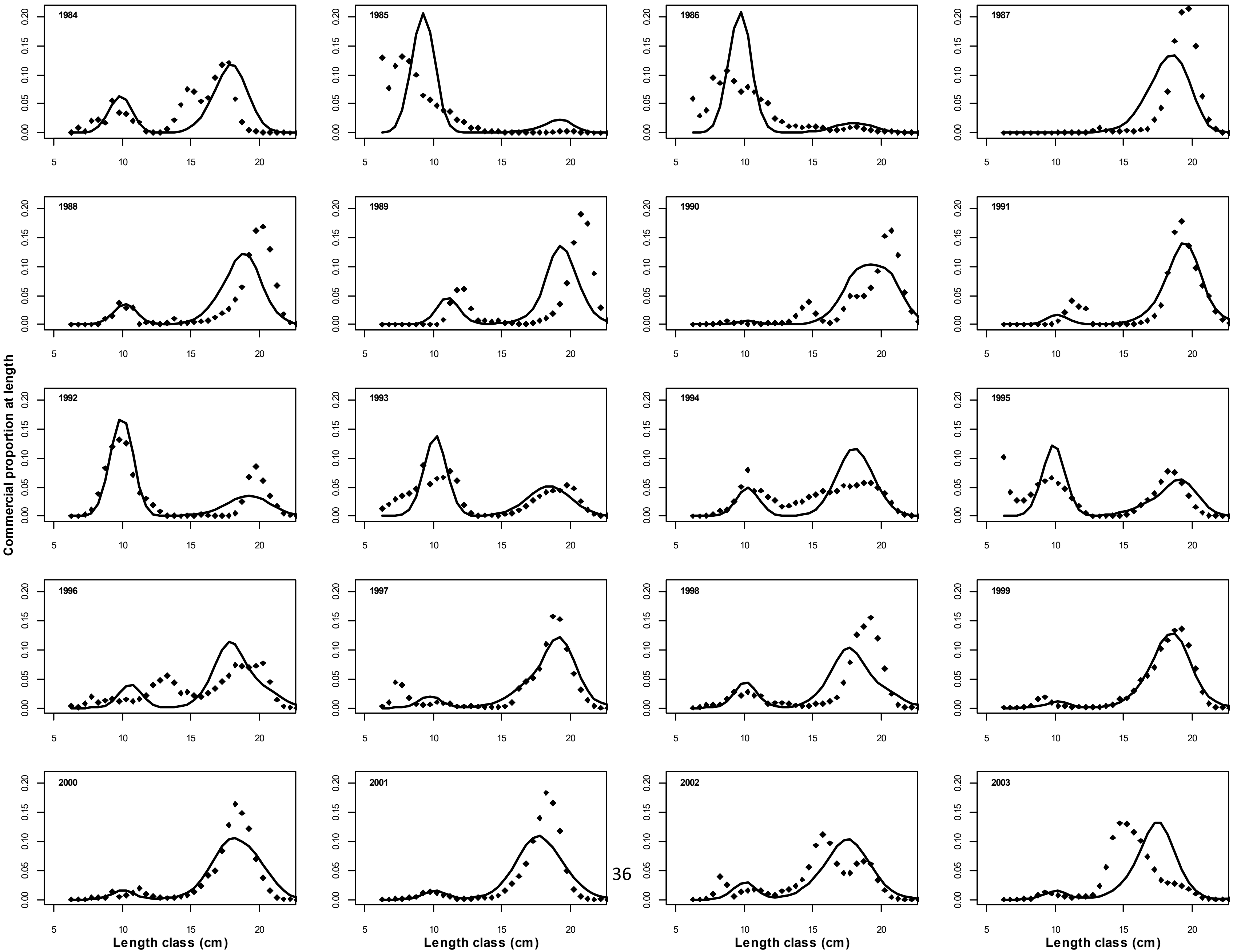

West Component
Quarter 1
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
Commercial proportion at length
Length class (cm)

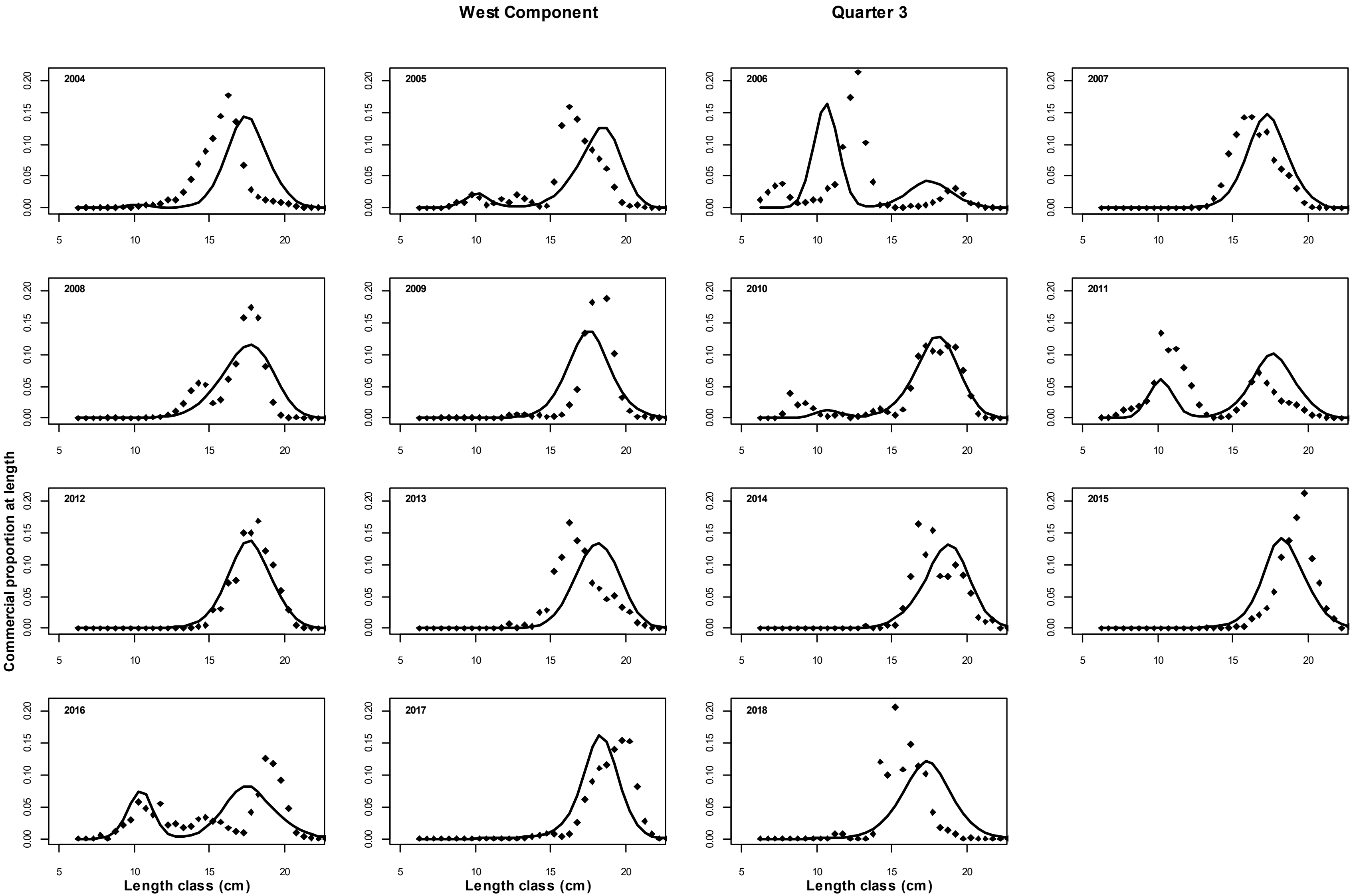

West Component
Quarter 1
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Commercial proportion at length
Length class (cm)
0.00
0.05
0.10
0.15
0.20
5
10
15
20

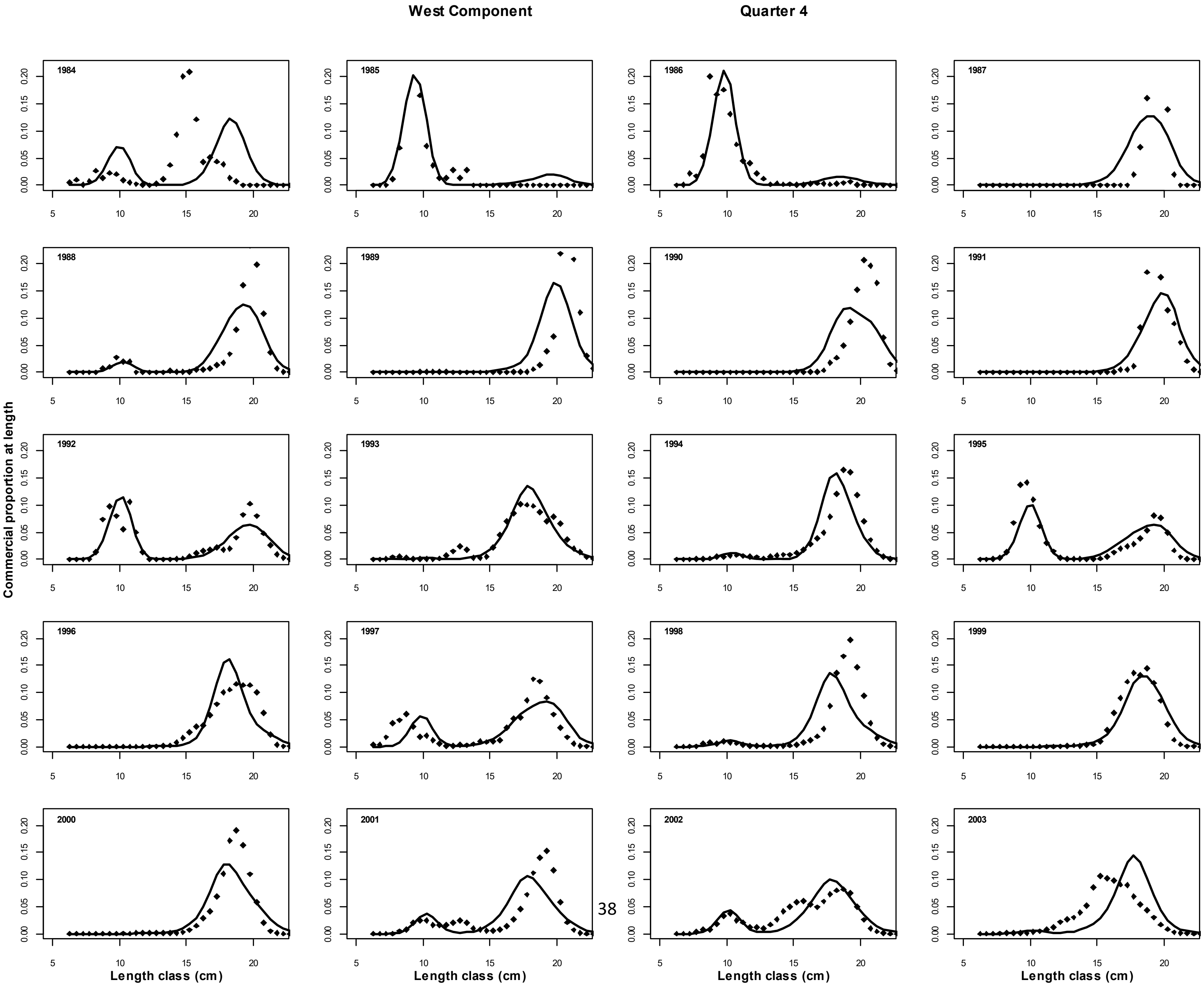

West Component
Quarter 2
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
Commercial proportion at length
Length class (cm)

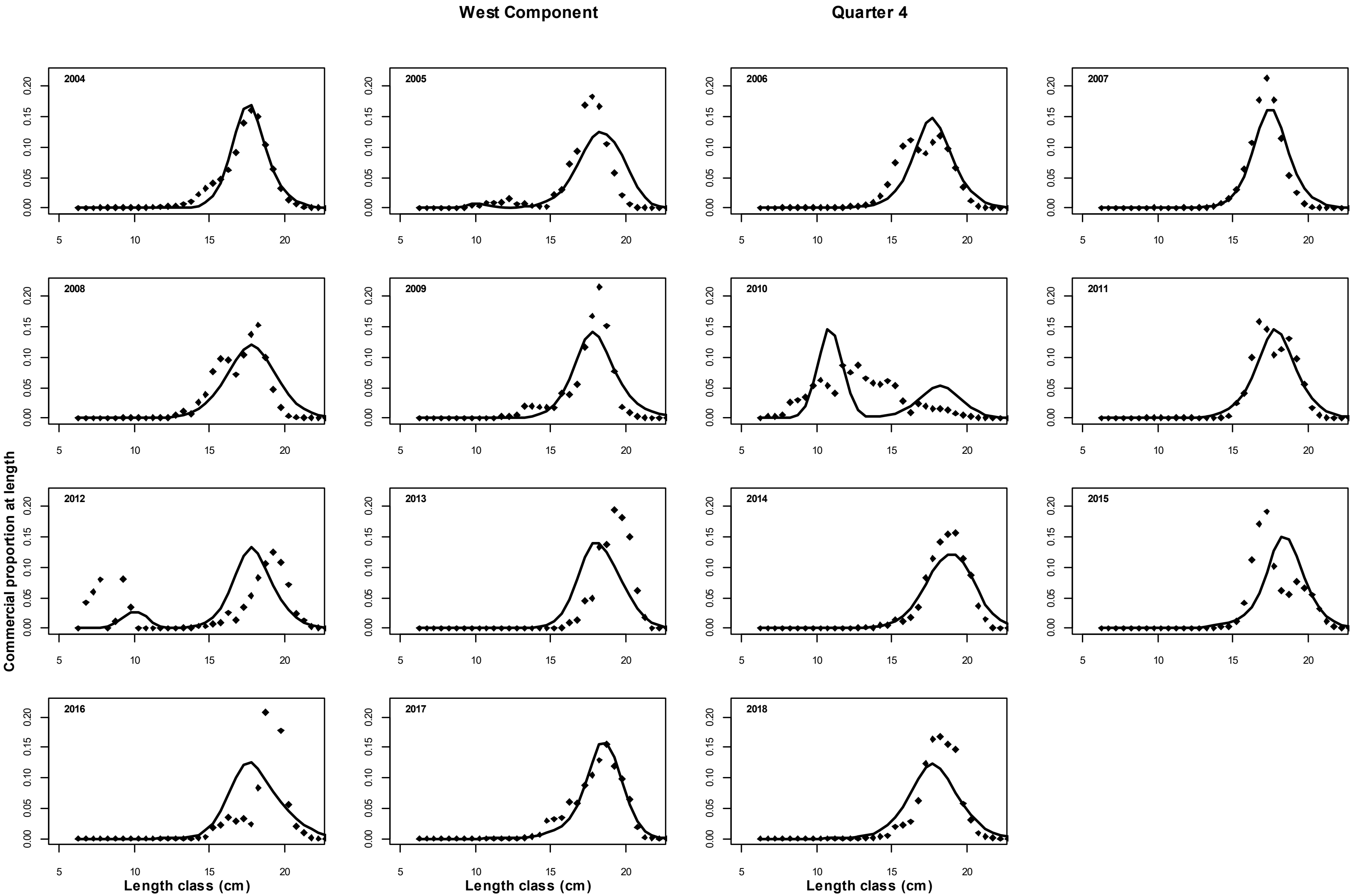

West Component
Quarter 2
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Commercial proportion at length
Length class (cm)
0.00
0.05
0.10
0.15
5
10
15
20

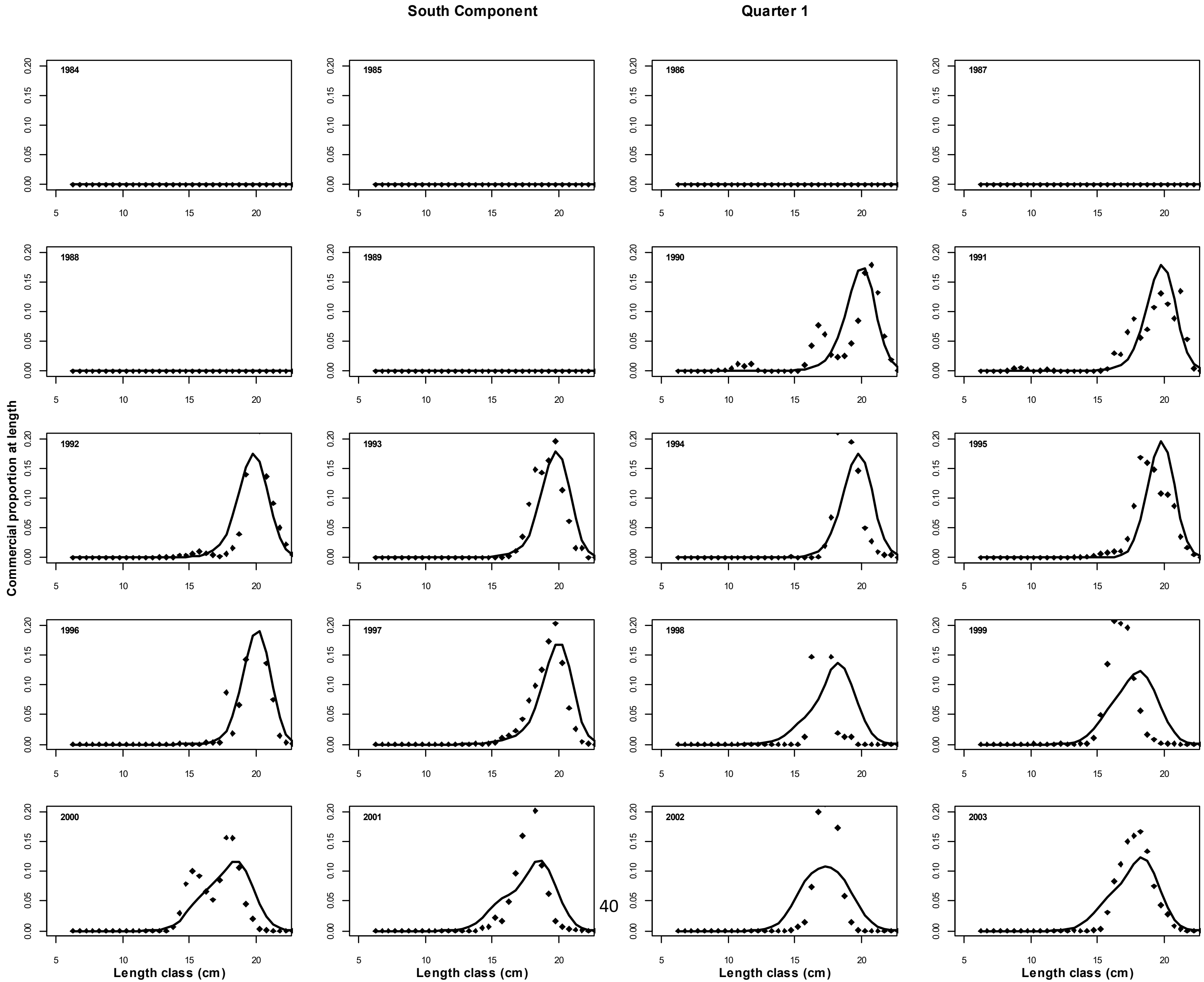
West Component **Quarter 3**



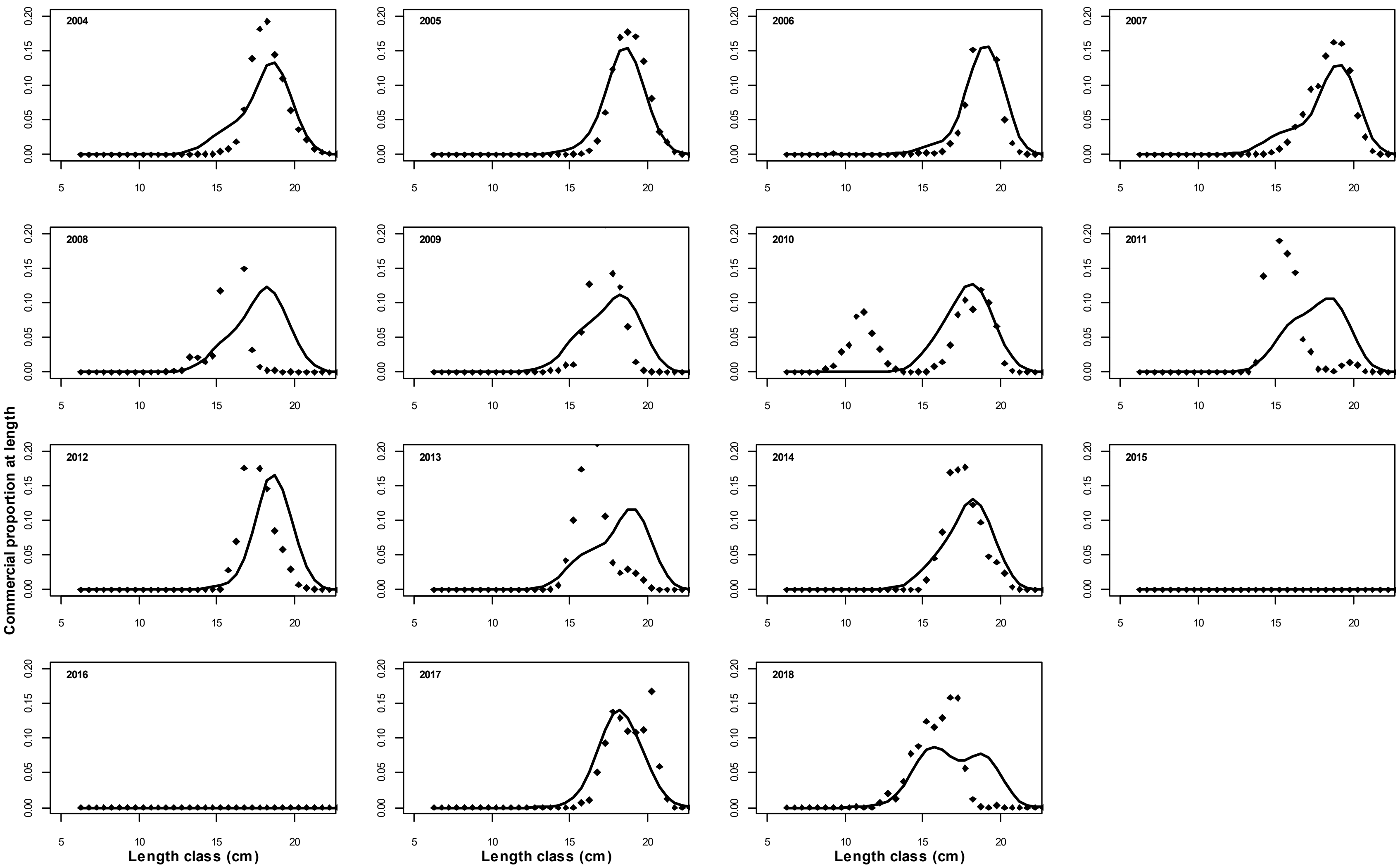

West Component
Quarter 3
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Commercial proportion at length
Length class (cm)

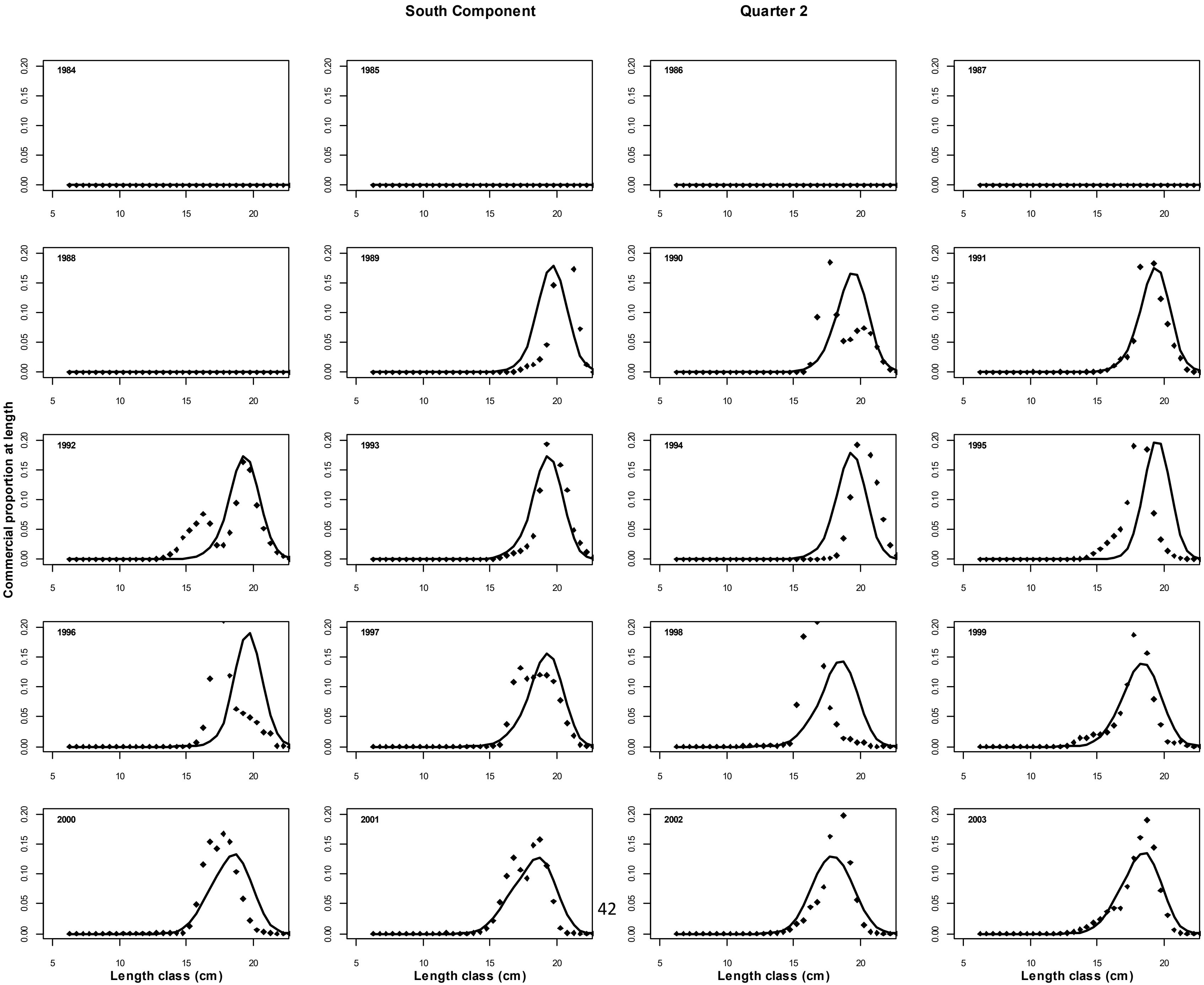

West Component
Quarter 4
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
Commercial proportion at length
Length class (cm)
0.00
0.05
0.10
0.15
0.20
5
10
15
20

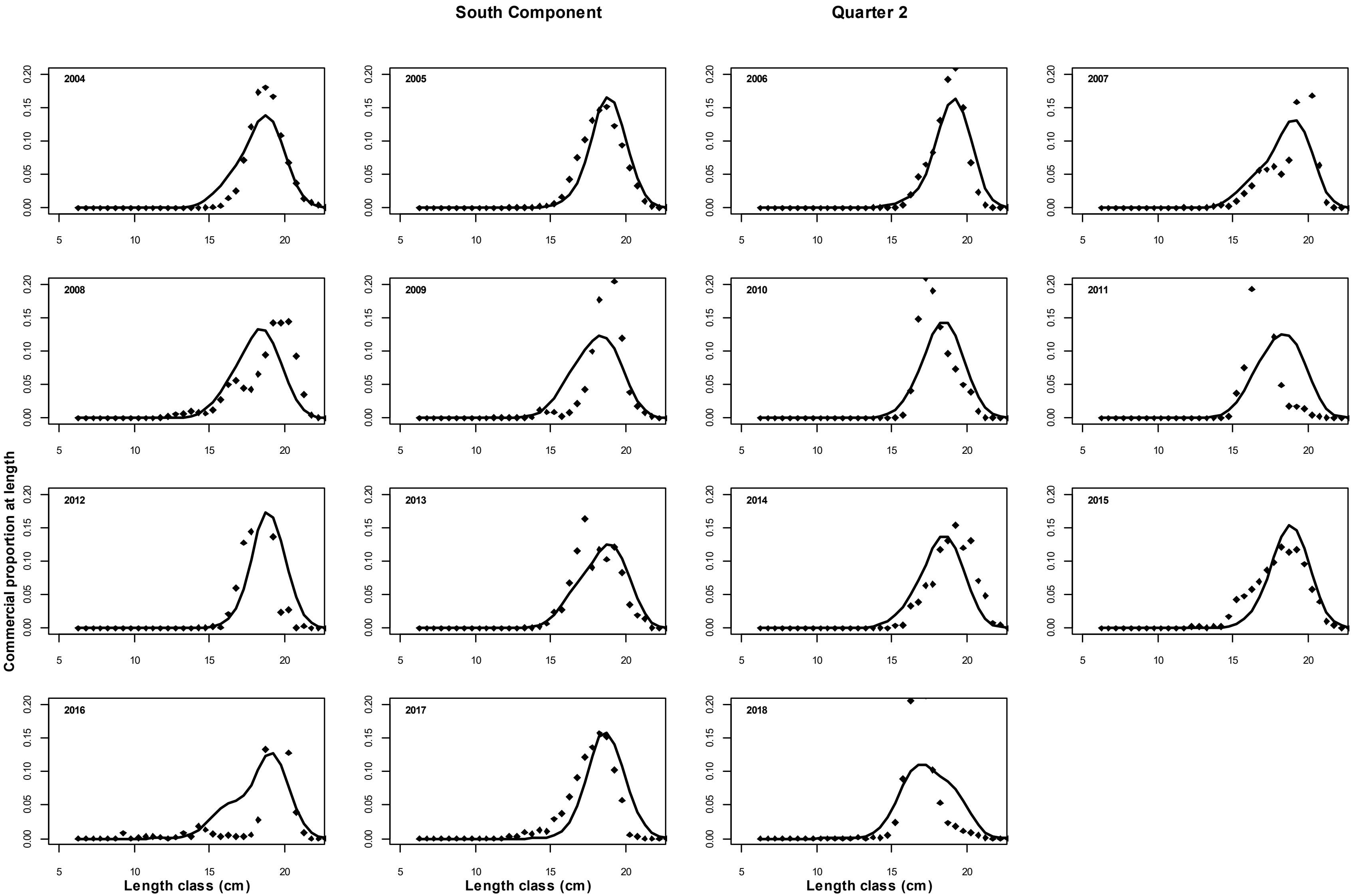

West Component
Quarter 4
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Commercial proportion at length
Length class (cm)


South Component
Quarter 1
Commercial proportion at length
Length class (cm)
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003

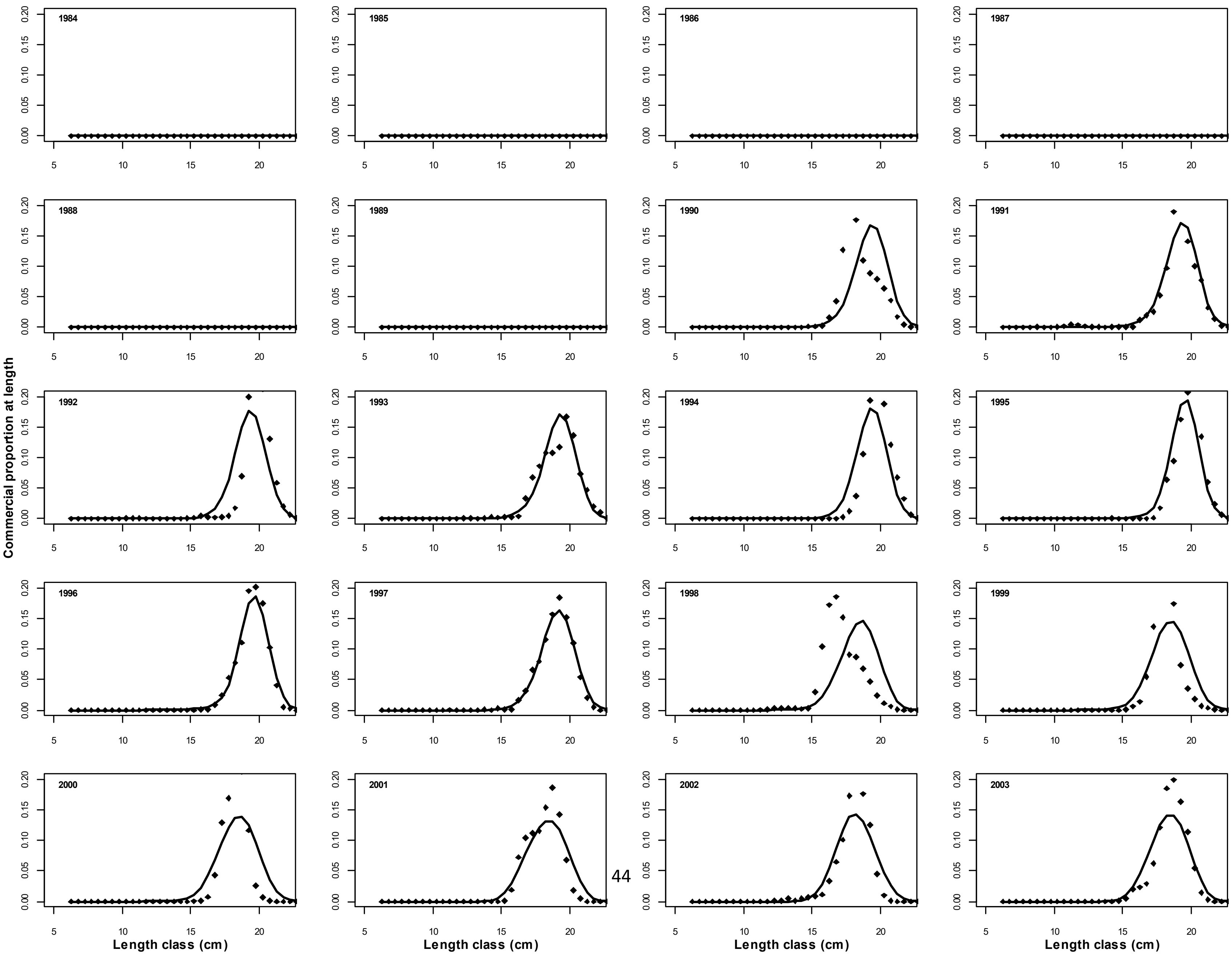
South Component **Quarter 1**

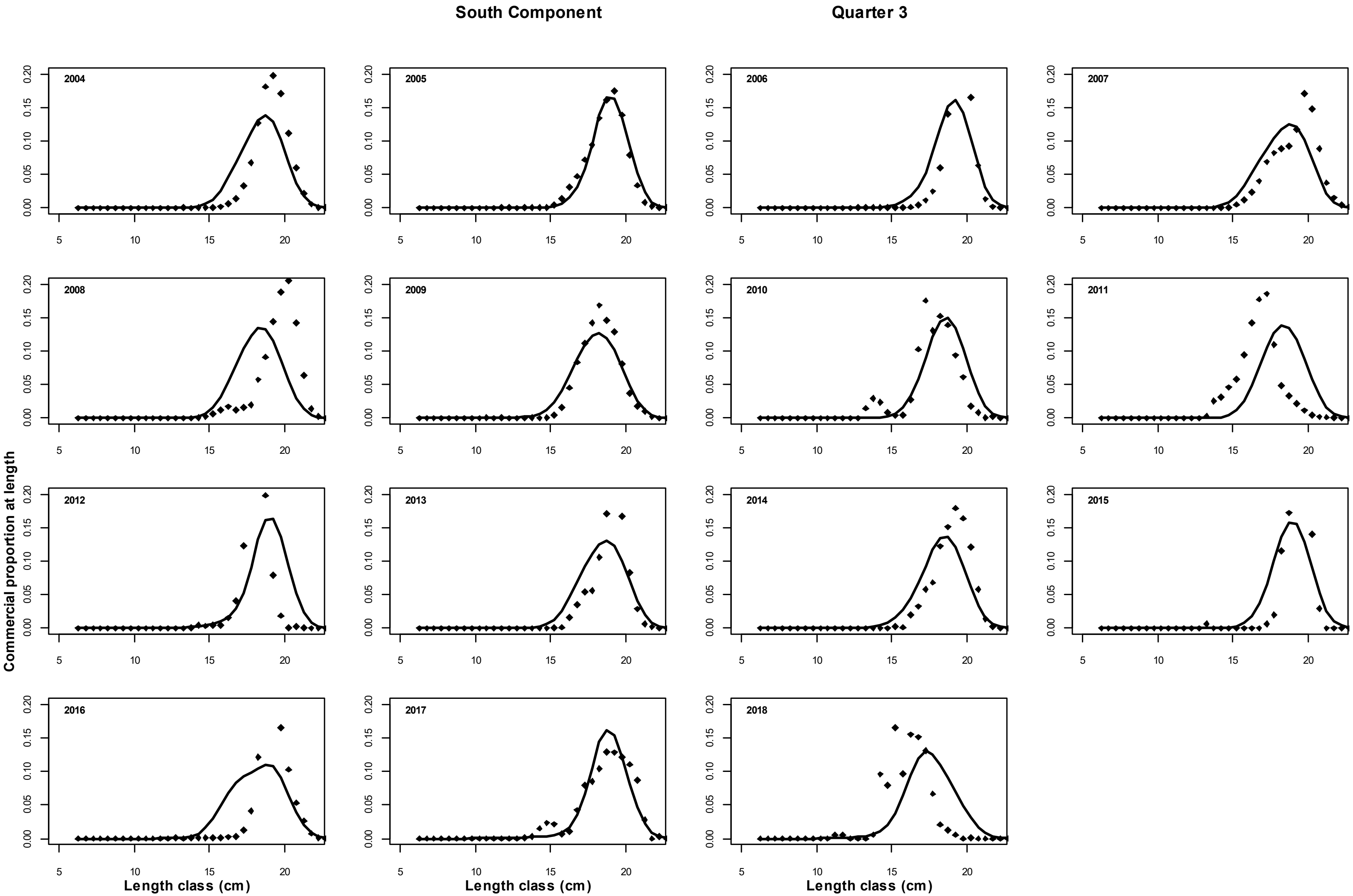


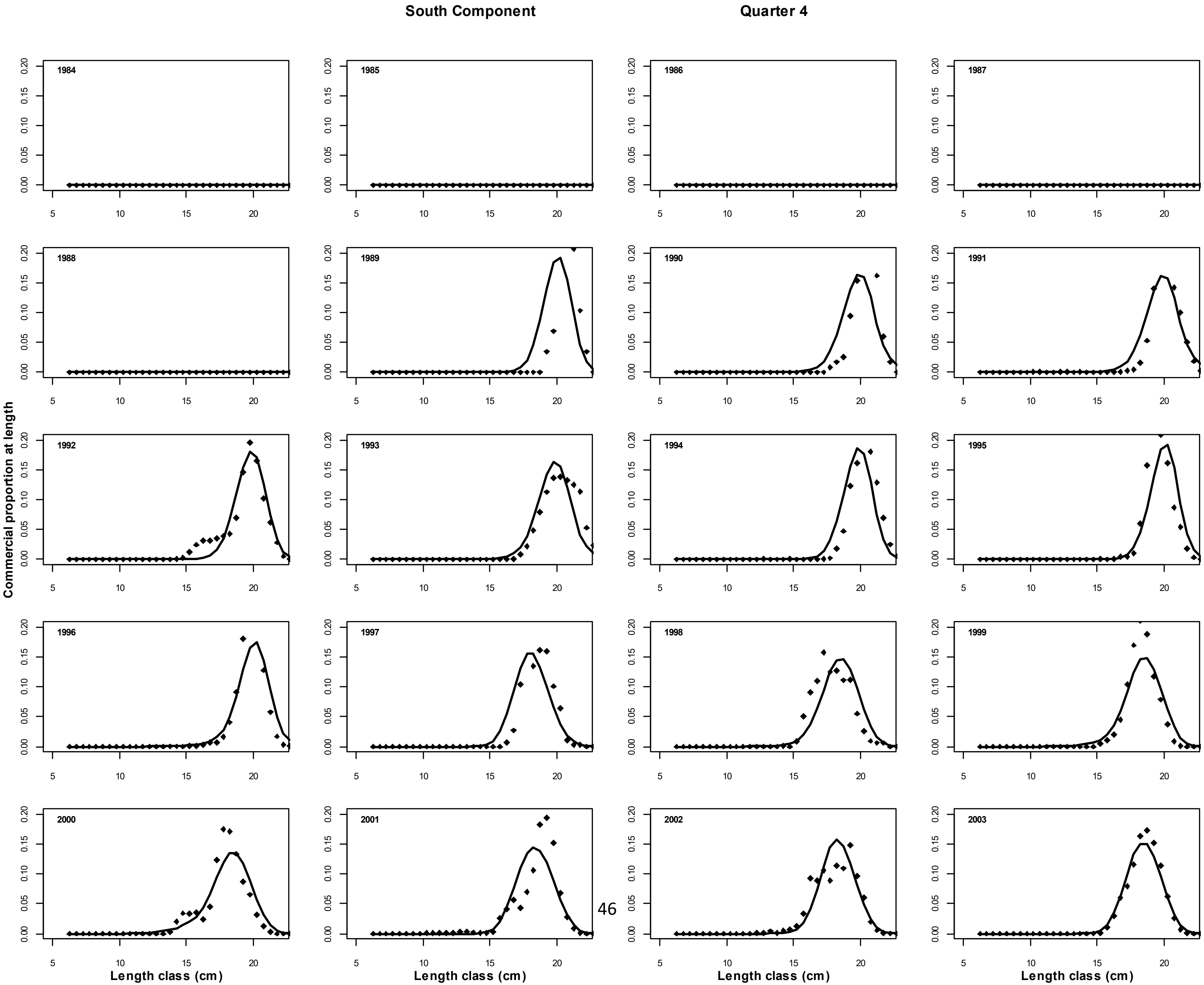

South Component
Quarter 2
Commercial proportion at length
Length class (cm)
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003

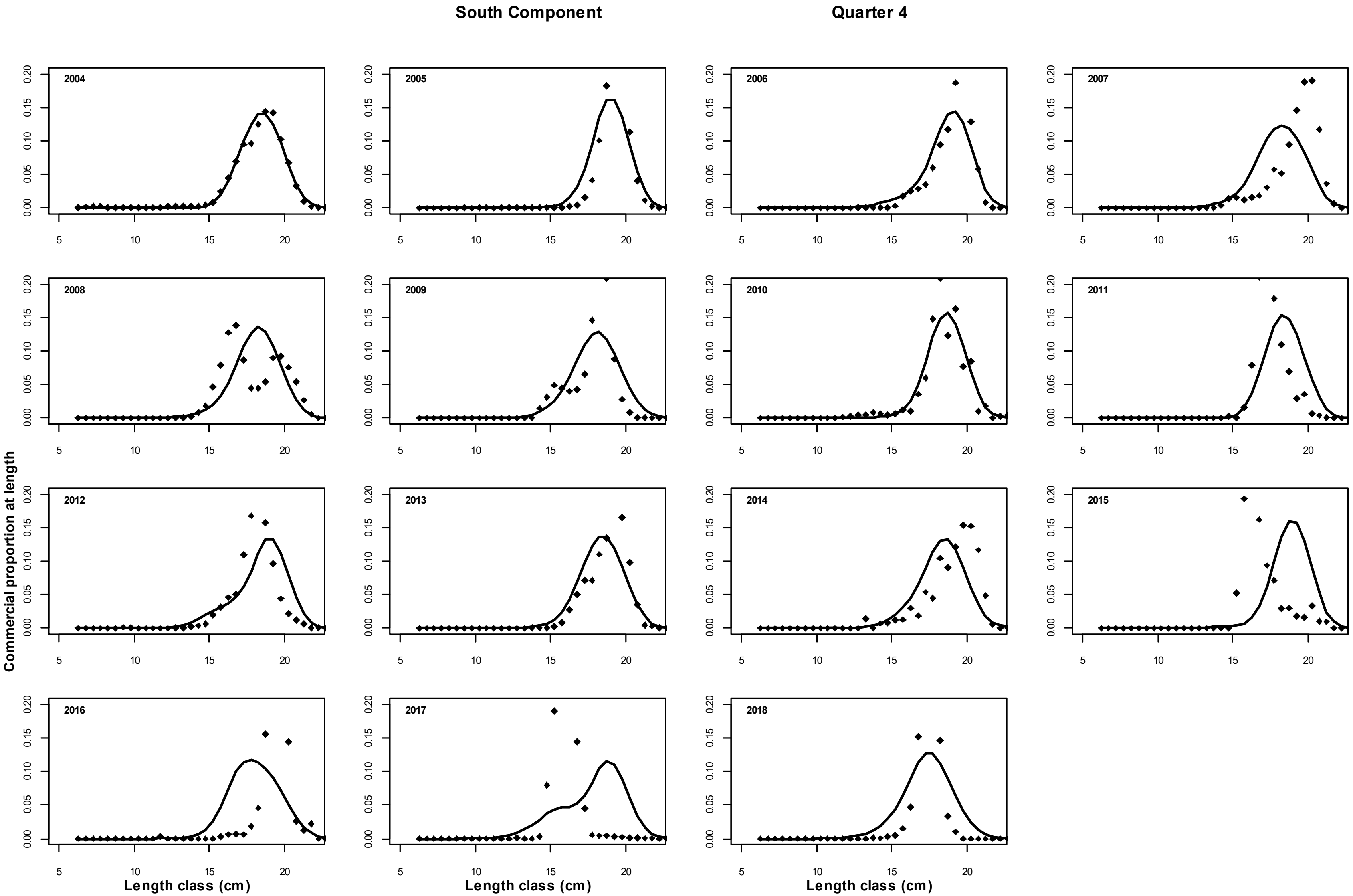

South Component
Quarter 2
Commercial proportion at length
Length class (cm)
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018

South Component **Quarter 3**




South Component
Quarter 3
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Commercial proportion at length
Length class (cm)
0.00
0.05
0.10
0.15
0.20
5
10
15
20


South Component
Quarter 4
Commercial proportion at length
Length class (cm)
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003


South Component
Quarter 4
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Commercial proportion at length
Length class (cm)
0.00
0.05
0.10
0.15
0.20
5
10
15
20