Results from the updated stock assessment model of the revised South African sardine stock structure hypothesis

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Results from the model for the updated South African sardine assessment are shown. The results show that the new way of modelling coast-dependent – and no longer stock-dependent – growth has only a small impact on the results and the standard deviation about the mean length-at-age off the south coast is not much larger than that off the west coast, despite immigration of sardine of a different mean length from the west coast. The fit to the data whether parametric stock recruitment relationships are estimated during conditioning or not is similar. In the former case a Beverton Holt stock recruitment relationship is assumed for Cool Temperate sardine (CTS) while a Hockey Stick stock recruitment relationship is assumed for Warm Temperate sardine (WTS). In the latter case, historical annual recruitments are estimated independently. This allows for the option of fitting a stock recruitment relationship after conditioning.

Keywords: growth curves, multi-stocks, population dynamics, recruitment, sardine, South Africa

Background

The updated stock assessment model for the revised stock structure hypothesis for South African sardine was detailed in de Moor (2025a). This document shows the results from fitting two versions of this model to the available data (de Moor *et al*. 2024, Appendix A) and is a summary of other documents to the Small Pelagic Scientific Working Group in which a range of model assumptions and potential key robustness tests have been explored. The two models considered herein are: (i) S_{noSR} – recruitment is estimated independently each year and no stock recruitment relationship is considered during the conditioning of the model to the data and (ii) S_{SR} – recruitment is estimated about parametric stock recruitment relationships, with a Beverton Holt relationship estimated for Cool Temperate sardine (CTS) and a Hockey Stick relationship estimated for Warm Temperate sardine (WTS).

Results and Discussion

Figures 1 to 8 show the model fits to the data, together with some key estimated parameters. The S_{noSR} model fits most of the data reasonably well, and slightly better overall than that achieved for S_{17} of de Moor (2024) (Table 1, Figures 1, 2, 4, 7). The fit to the data by S_{SR} is slightly poorer (Figures 1, 2, 4, 7) given the additional requirement of fitting the stock-recruitment relationships.

The model estimated growth curves are shown in Figure 9, with a West Coast peak recruitment time of approximately 1.5 months after 1 October ($t_{0,w} = 0.14$), and a South Coast peak recruitment of less than 2.5 months before 1 October ($t_{0,s} = -0.20$). These correspond well with the peak spawning period of September to February indicated by the gonadosomatic index (GSI) of sardine sampled from commercial catches off the west coast and the peak spawning period of June to November indicated by the GSI of sardine sampled from commercial catches off the south coast (Coetzee and de Moor 2024).

The estimated coast-specific standard deviation about the growth curve is shown in Figure 10. The approximate method of Appendix B (de Moor 2025a) results in only a small difference in standard deviations between the west and south coasts,

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with the largest difference at the time of the sardine moving before they turn age 2; the difference at the time of movement before the turn age 1 is estimated insignificant.

Figure 11 shows the corresponding distributions of mean length-at-age at different times during the year, with the distributions being wider for age 0, likely reflecting the combination of an extended spawning season and rapid growth in their first year. Given the substantially smaller length-at-age off the west coast compared to the south coast for age 0 (Figure 9), the mean length-at-age 0 off the south coast in the middle of quarter 3, is reduced from the 'base underlying' length-at-age, due to the immigration of fish from the west coast (de Moor 2025a). The extent of reduction is year-dependent, depending on the number of WTS which immigrate to the south coast compared to the number already distributed off the south coast (de Moor 2025a).

Active movement of WTS from the west to the south coast is estimated to vary annually, with almost the same proportion of <2year olds estimated to move as that of <1 year olds (Figure 12). Very few CTS are estimated to move from the west coast to the east coast, via the south coast (Figures 12,13), which was expected *a priori*. Figure 13 shows the vast majority of sardine moving from the west to the south coast each year are WTS recruits after they complete their southwards migration from the nursery area down the west coast.

Peak recruitment at the turn of the century is estimated to be WTS off the west coast (as expected), though it is not possible with the data and this model parameterisation to distinguish in which years that primarily arose from spawning off the west coast, or from passive transport from spawning off the south coast (Figures 14,15). In many years the vast majority of WTS recruits are estimated to recruit to the west rather than south coast (Figure 14). The recruitment of WTS off the west coast is commonly estimated to be higher than that of CTS (Figure 15), even though – except for the pulse years at the turn of the century - the spawning biomass of WTS is often much lower than that of CTS off the west coast (Figure 15). Recruitment in the final year is likely poorly determined as it can only be informed by the March/April 2025 survey and October – December 2024 commercial length frequencies, during which few ≤14cm sardine are typically landed.

Recruitment is plotted against spawner biomass in Figure 16, with the estimated stock recruitment relationships estimated for S_{SR} shown.

The historical harvest proportions by coast are shown in Figure 17.

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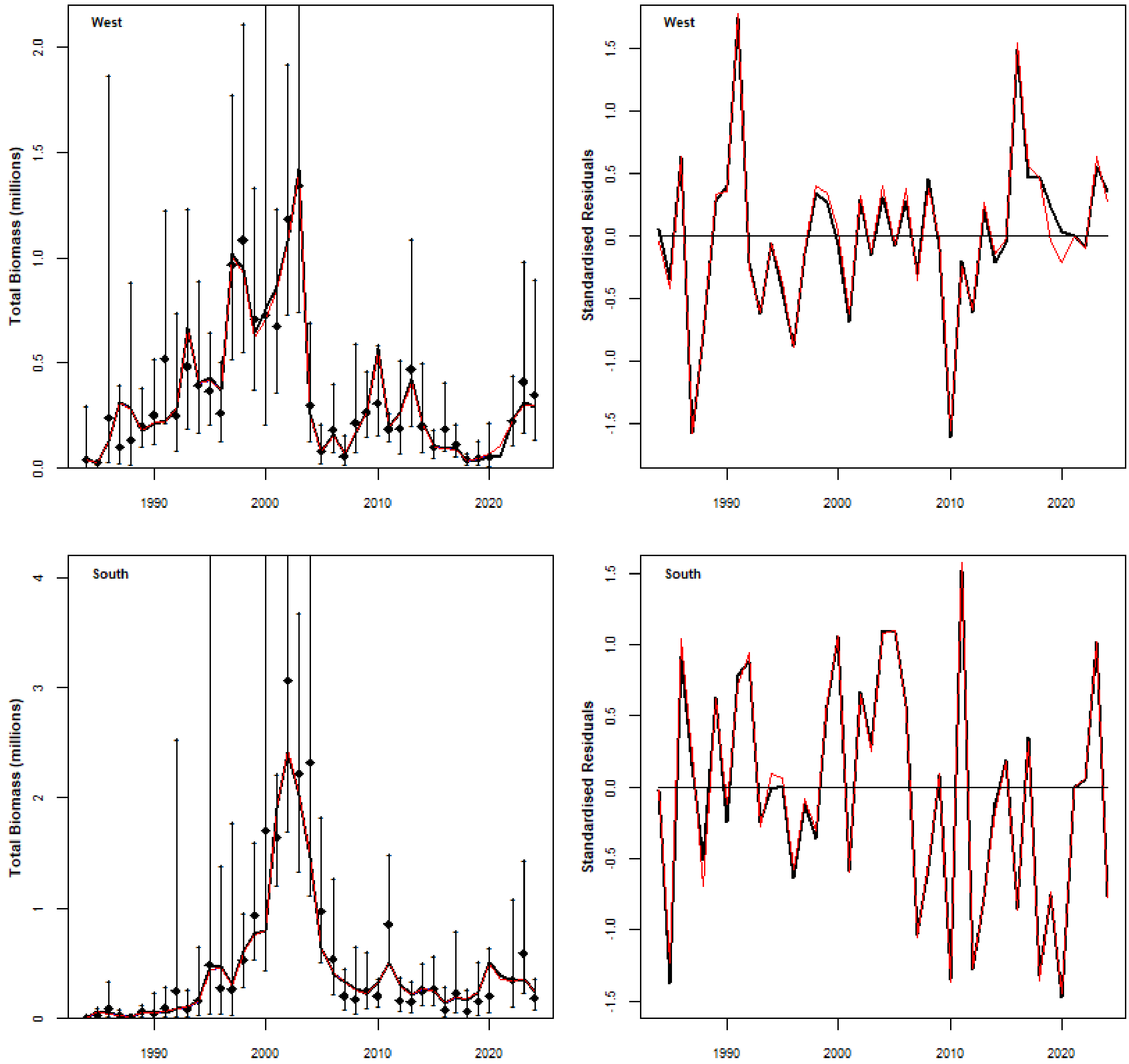


Figure 1. Acoustic survey estimated and model predicted November sardine total biomass from 1984 to 2024 for S_{noSR} (black solid line) and S_{SR} (red line). The observed indices are shown with 95% confidence intervals. The standardised residuals (i.e. the residual divided by the corresponding standard deviation, including additional variance where appropriate) from the fits are given in the right hand plots.

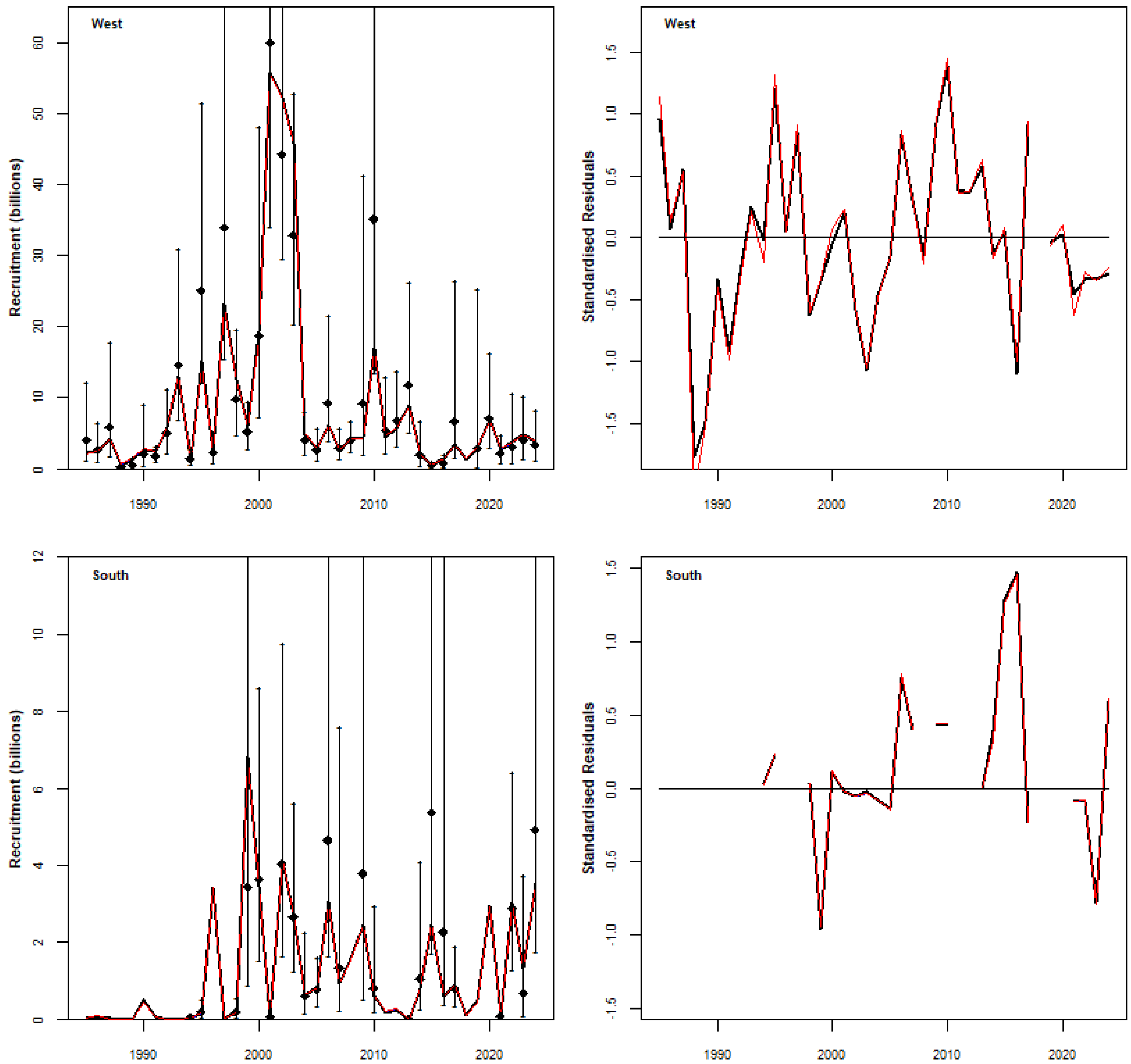


Figure 2. Acoustic survey estimated and model predicted sardine recruitment numbers from May/June 1985 to 2024 for S_{noSR} (black solid line) and S_{SR} (red line). There was no survey observation in 2018; the model predicted value corresponds to the recruitment predicted at 8th June 2018 which is the average start date of the survey from 2016, 2017 and 2019 surveys. The survey indices are shown with 95% confidence intervals. The standardised residuals from the fit are given in the right hand plots.

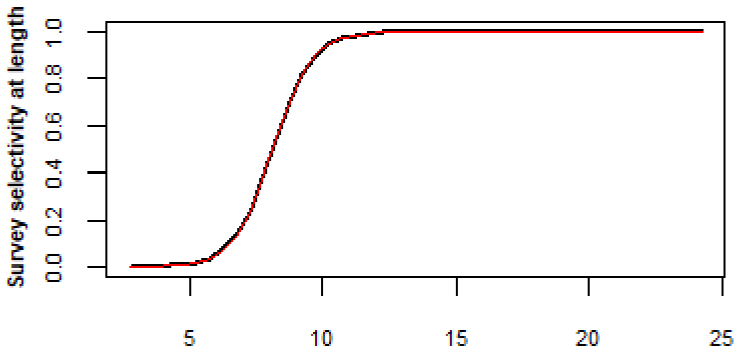


Figure 3. The model estimated November survey selectivity at length for S_{noSR} (black solid line) and S_{SR} (red line).

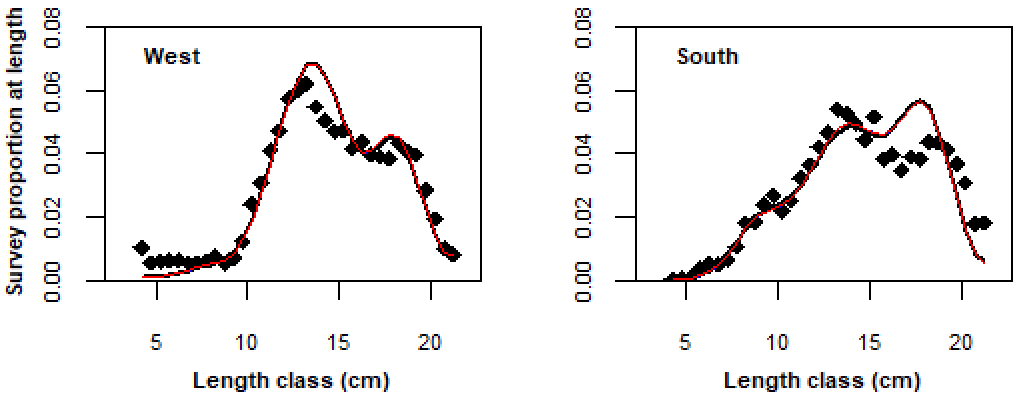


Figure 4. Average (over all years) model predicted and observed proportion-at-length in the November survey for S_{noSR} (black solid line) and S_{SR} (red line). See Appendix B for annual data.

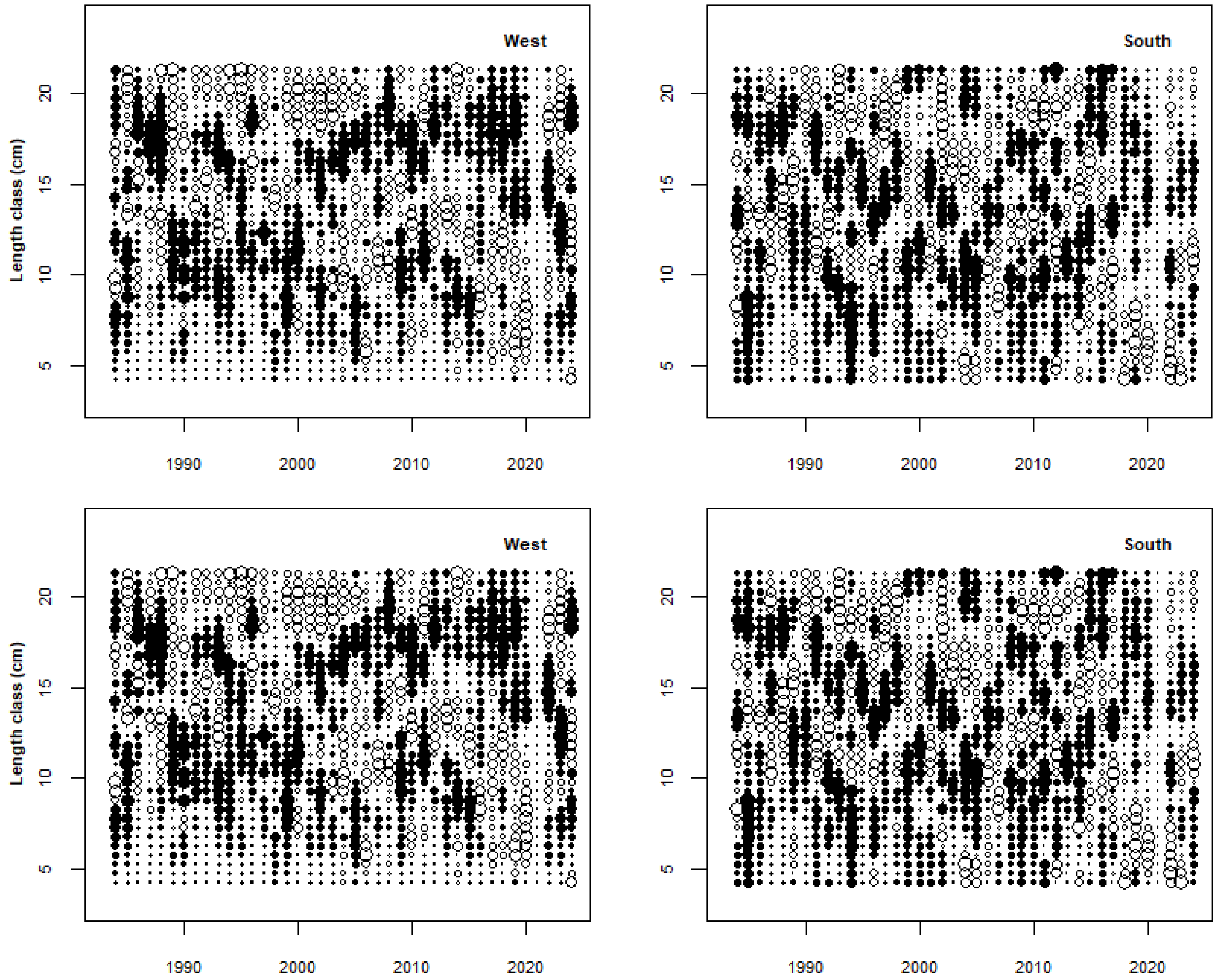


Figure 5. Residuals from the fit of the model predicted proportions-at-length in the November survey to the hydroacoustic survey estimated proportions for S_{noSR} (top row) and S_{SR} (lower row).

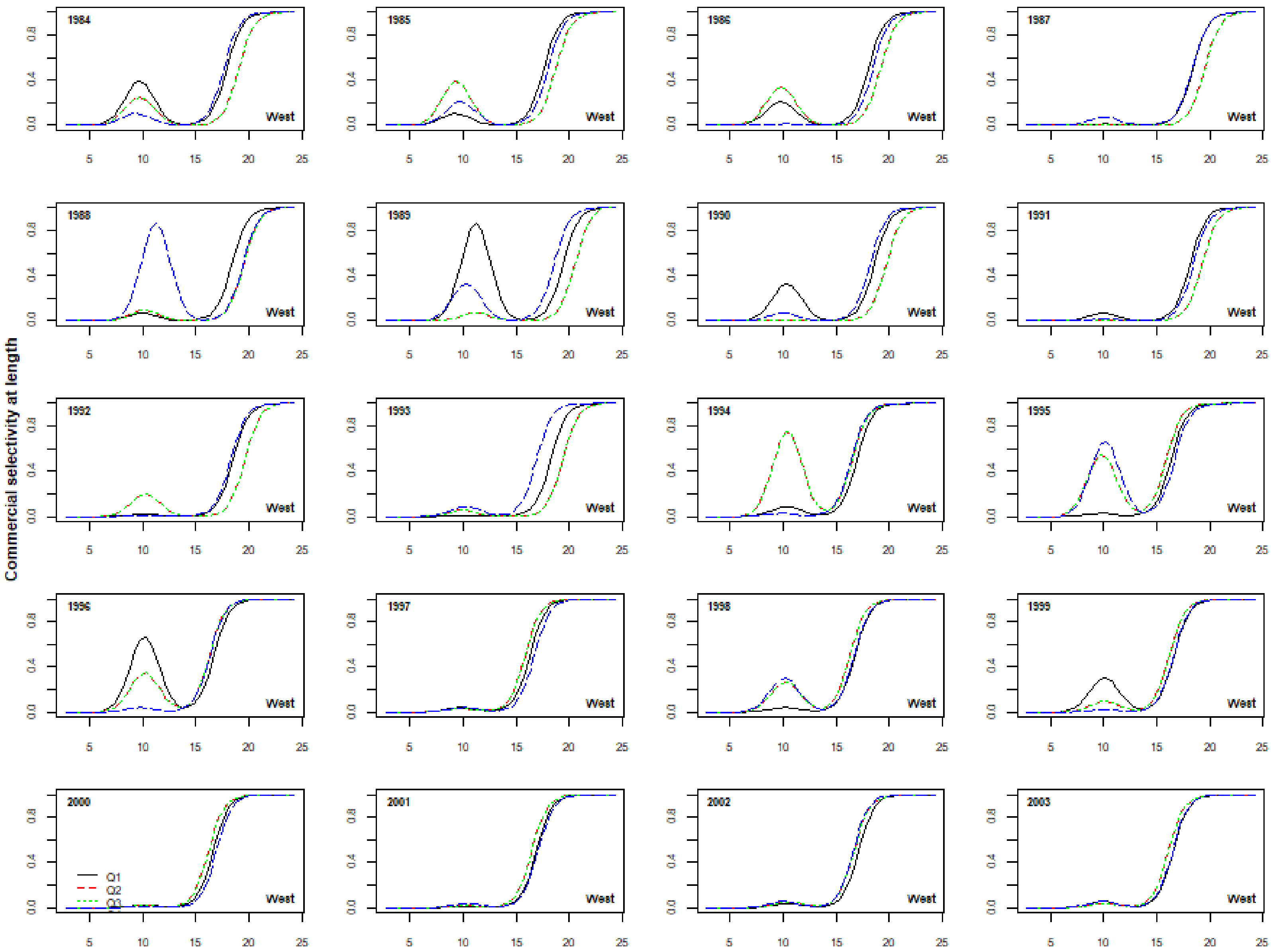


Figure 6. The model estimated commercial selectivity at length for S_{noSR}.

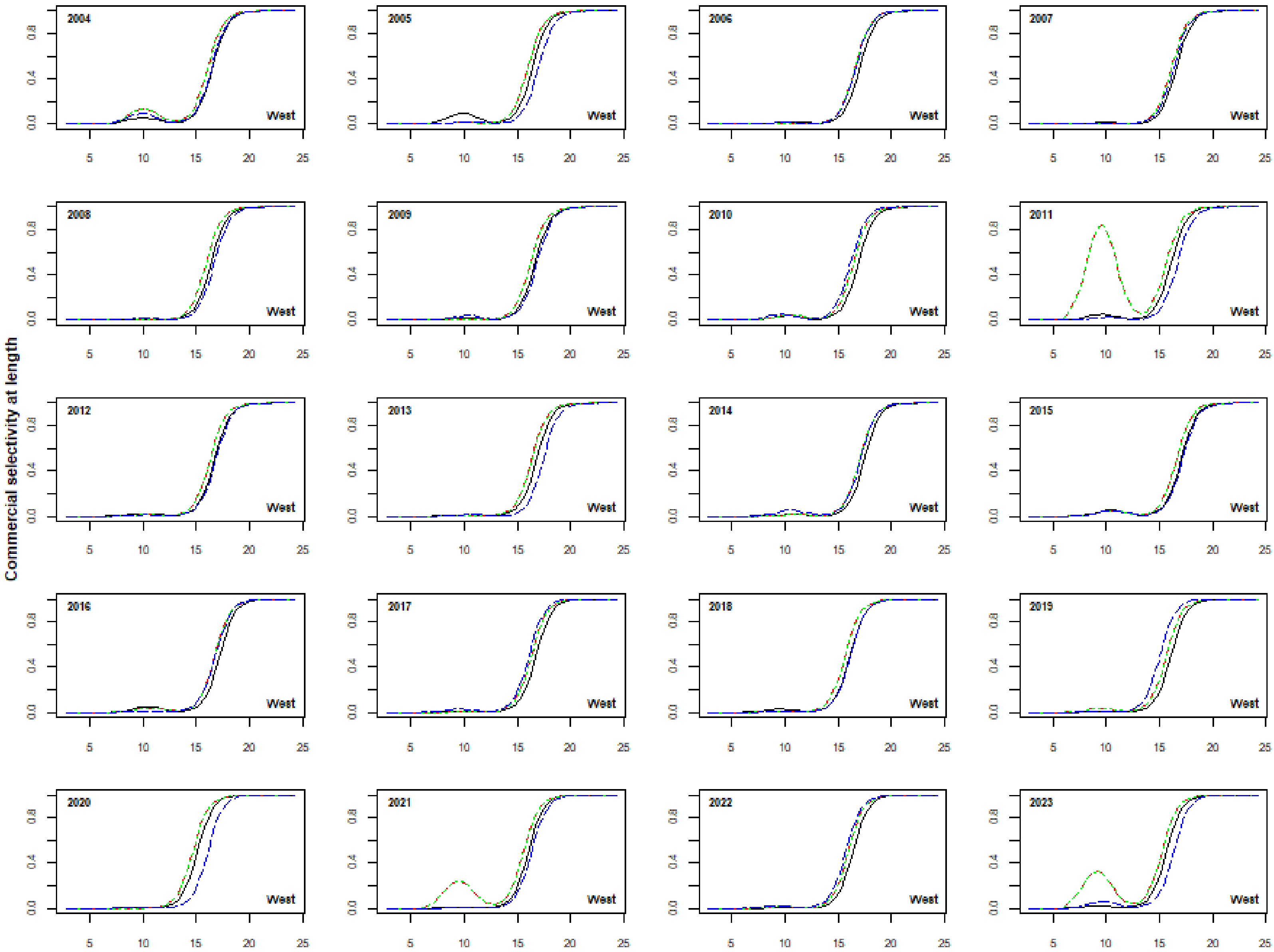


Figure 6 (continued).

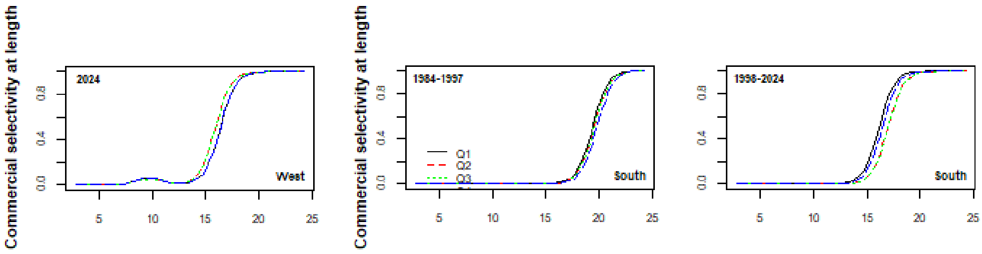


Figure 6 (continued).

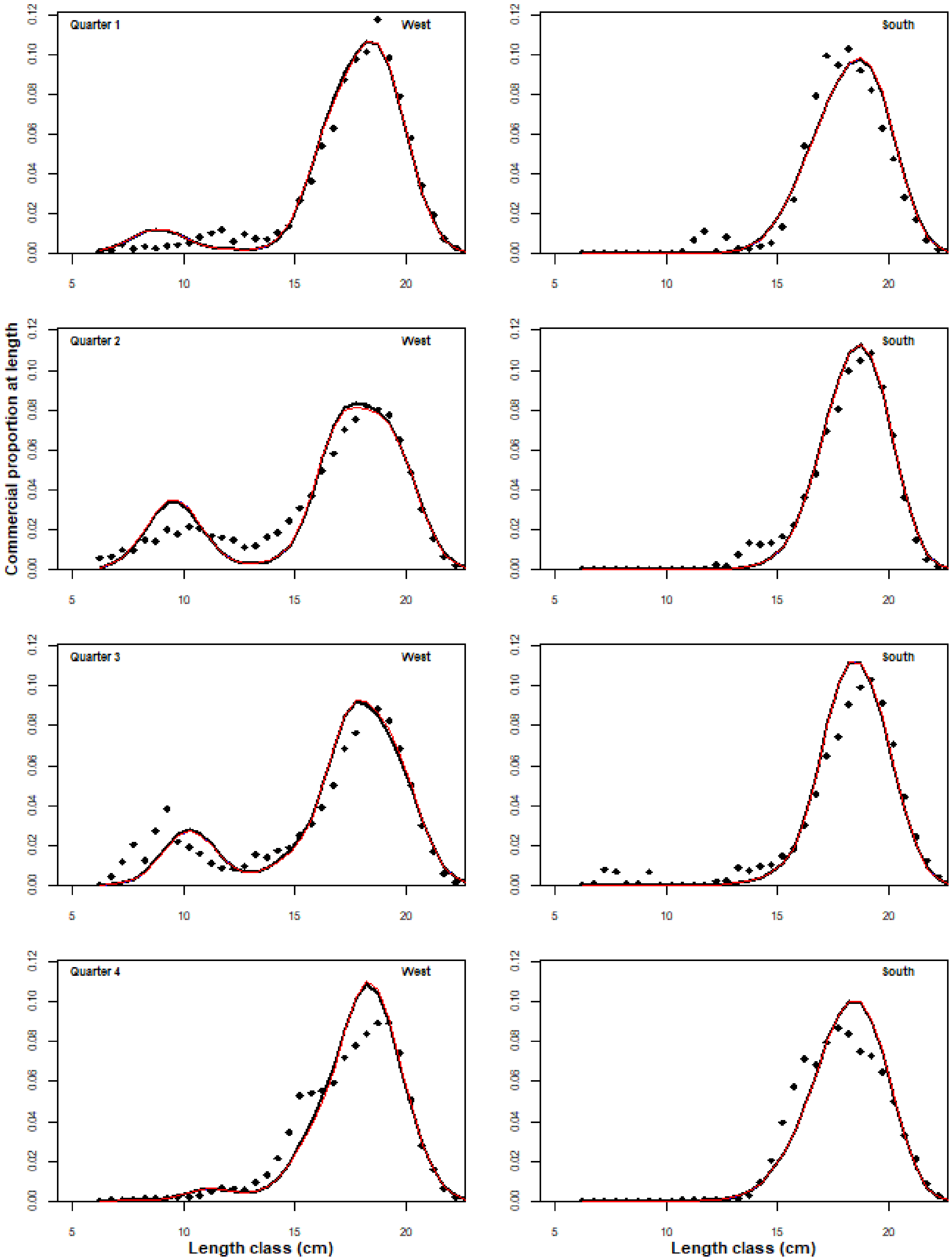


Figure 7. Average (over all years) quarterly model predicted and observed proportions-at-length in the commercial catch for S_{noSR} (black solid line) and S_{SR} (red line). See Appendix B for annual data.

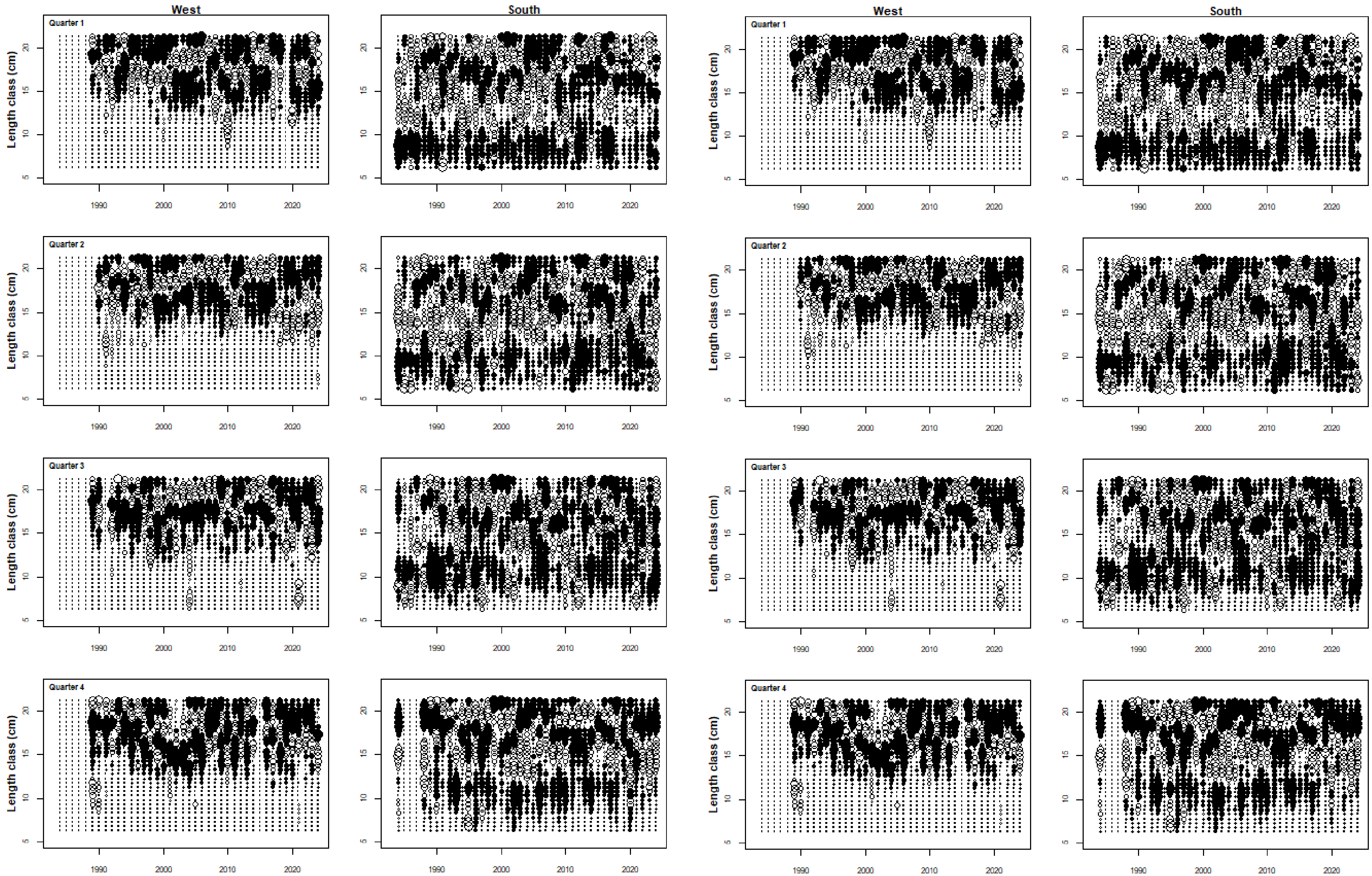


Figure 8. Residuals from the fit of the model predicted proportions-at-length in the quarterly commercial catch to the observed proportions for S_{base}.

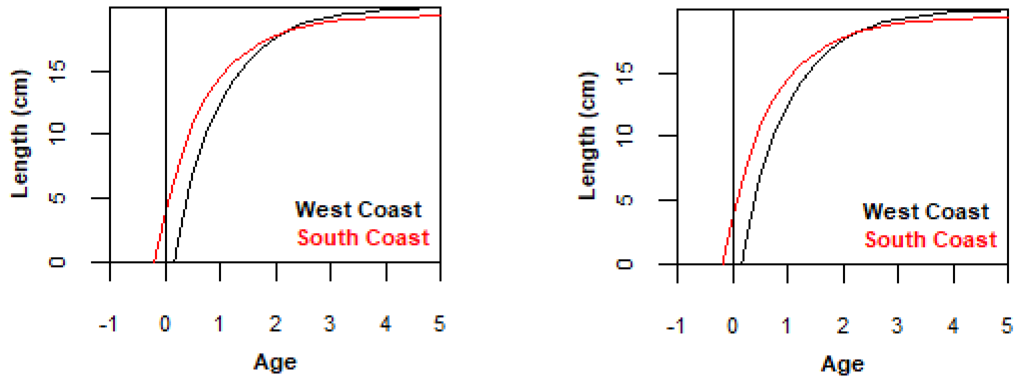


Figure 9. The von Bertalanffy growth curves for S_{noSR} (left) and S_{SR} (right). (No differences in co-horts assumed).

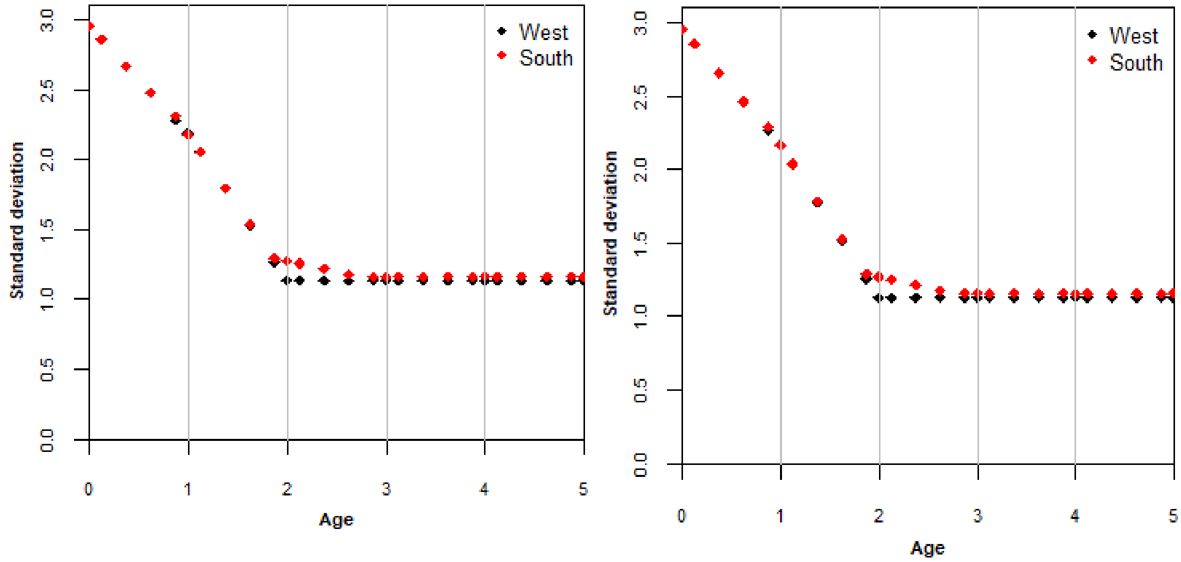


Figure 10. The estimated standard deviation about the mean length-at-age for S_{noSR} (left) and S_{SR} (right).

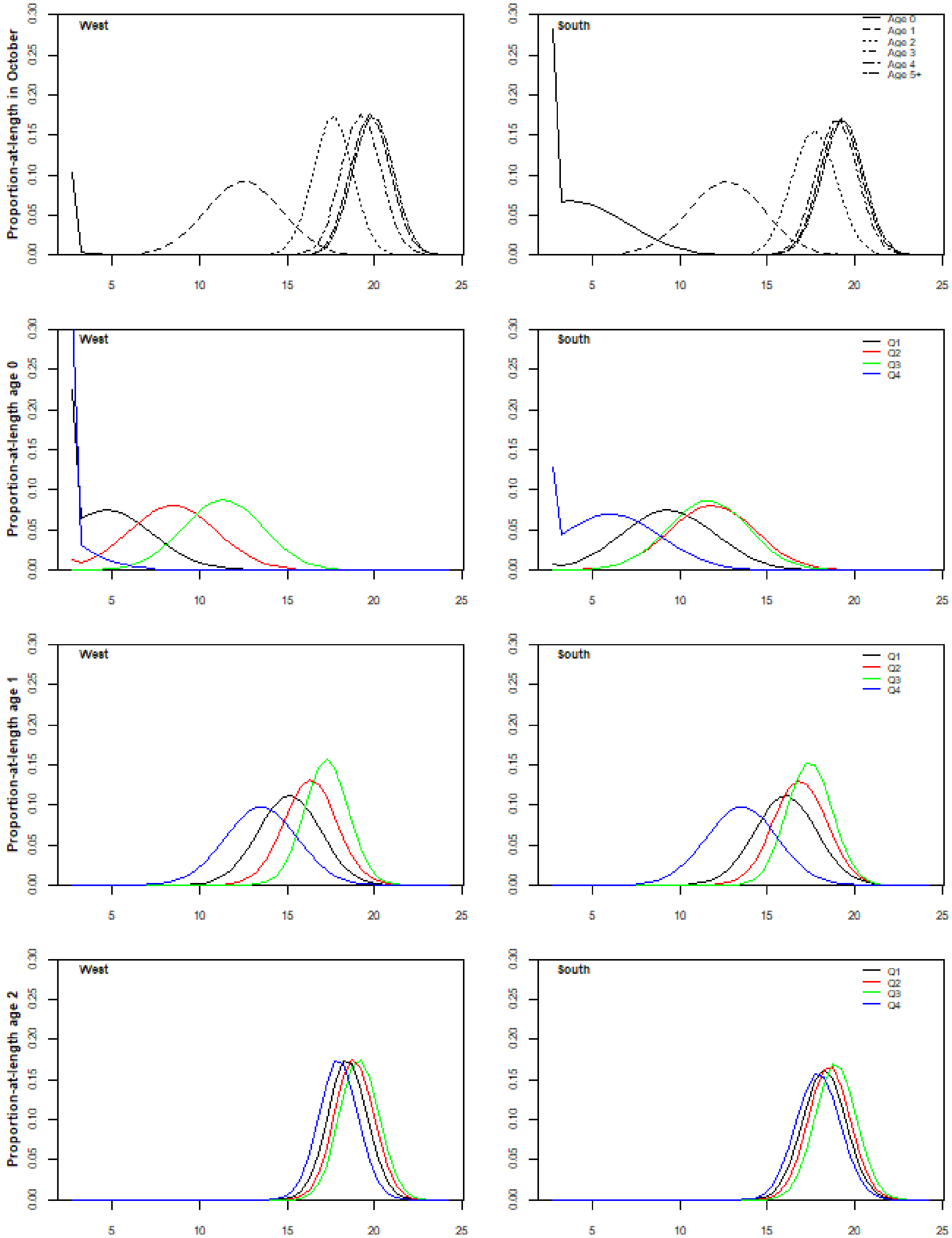


Figure 11. The model S_{noSR} estimated distributions of proportions-at-length for each age in 2010, given at the time of spawning (1 October, top row), and middle of each quarter of the year (corresponding to the times commercial catch is modelled to be taken for ages 0, 1 and 2) (subsequent rows). The November survey is also modelled at the middle of quarter 4.

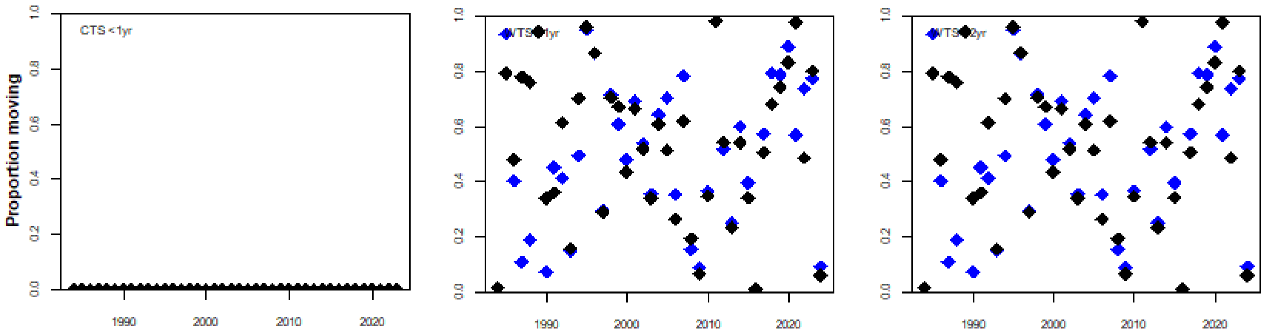


Figure 12. Model estimated proportion of <1-year-olds and <2-year-olds which move from the West Coast to the South Coast in mid-August for S_{noSR} (black) and S_{SR} (blue).

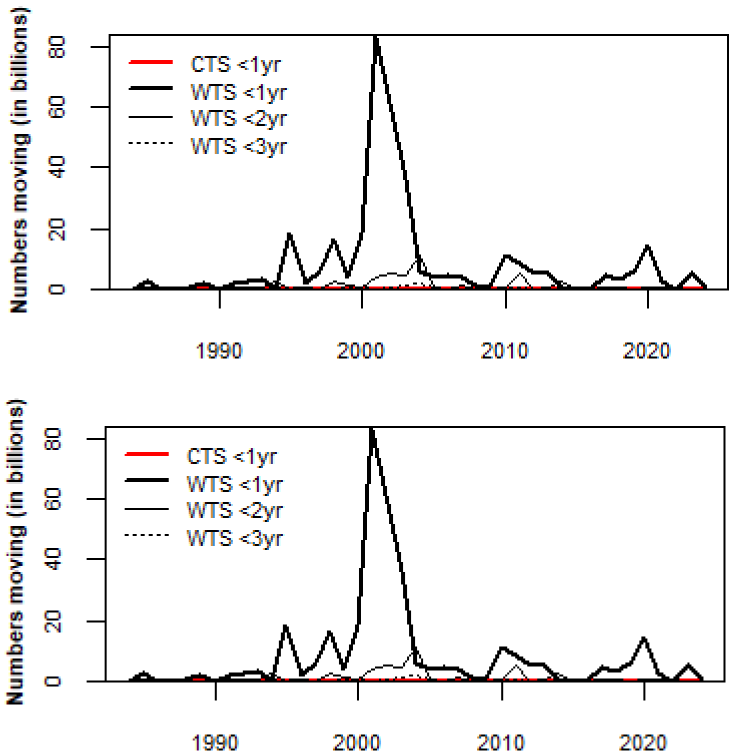


Figure 13. Model estimated number of <1-year-olds, <2-year-olds and <3-year-olds which move from the West Coast to the South Coast in mid-August for S_{noSR} (top plot) and S_{SR} (lower plot).

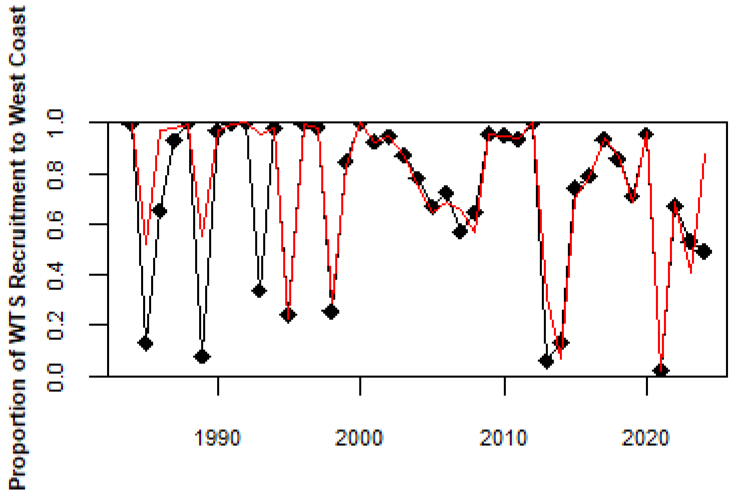


Figure 14. Model estimated proportion of WTS recruits which are recruited to the West Coast, either from spawning off the West Coast or from passive transport of spawning products from the South Coast for S_{noSR} (black solid line) and S_{SR} (red line).

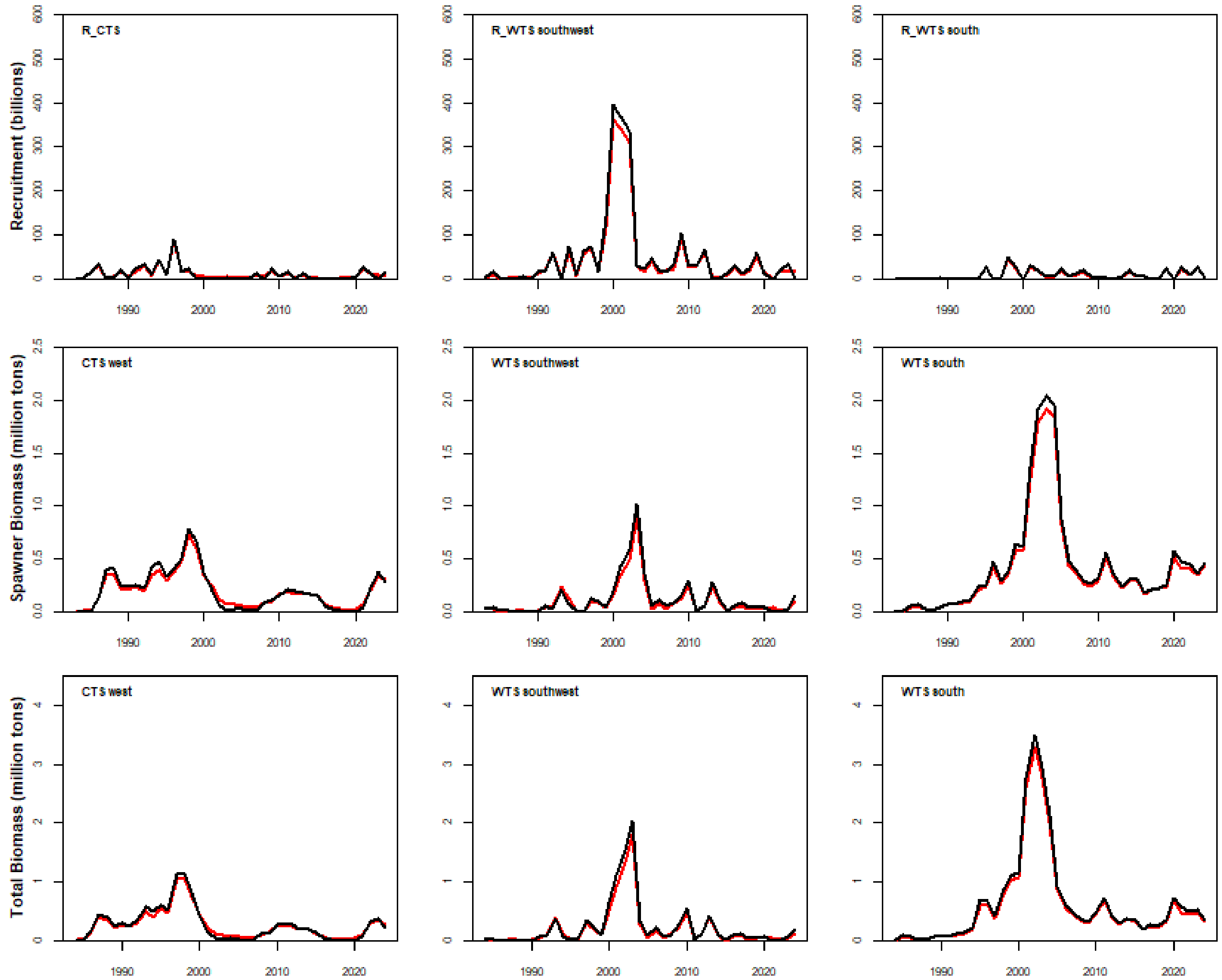


Figure 15. Model predicted sardine recruitment (top row), spawner biomass (2nd row) and total biomass (lower row) from November 1983 to November 2024 for S_{noSR} (black) and S_{SR} (red).

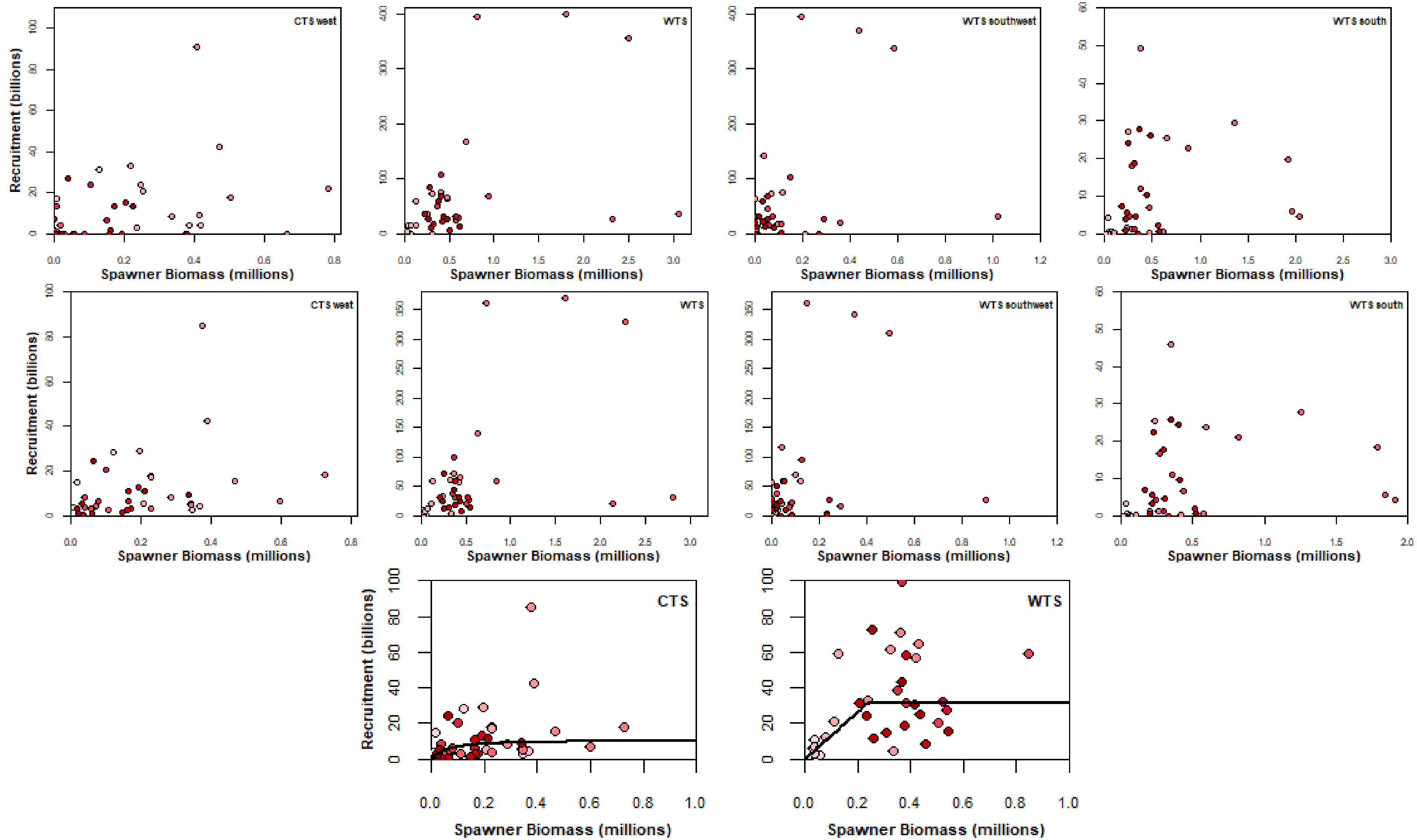


Figure 16. Model predicted sardine recruitment plotted against spawner biomass, with colouring indicating earlier (lighter) to more recent (darker) years for S_{noSR} (top row) and S_{SR} (middle row). Stock recruitment relationships might be considered for the left two columns. The right two columns show the resultant WTS recruitment by coast, which is due both to spawning by coast and passive transport of spawning products from south coast spawning to west coast recruitment. The lower row shows the stock recruitment relationships estimated for S_{SR}.

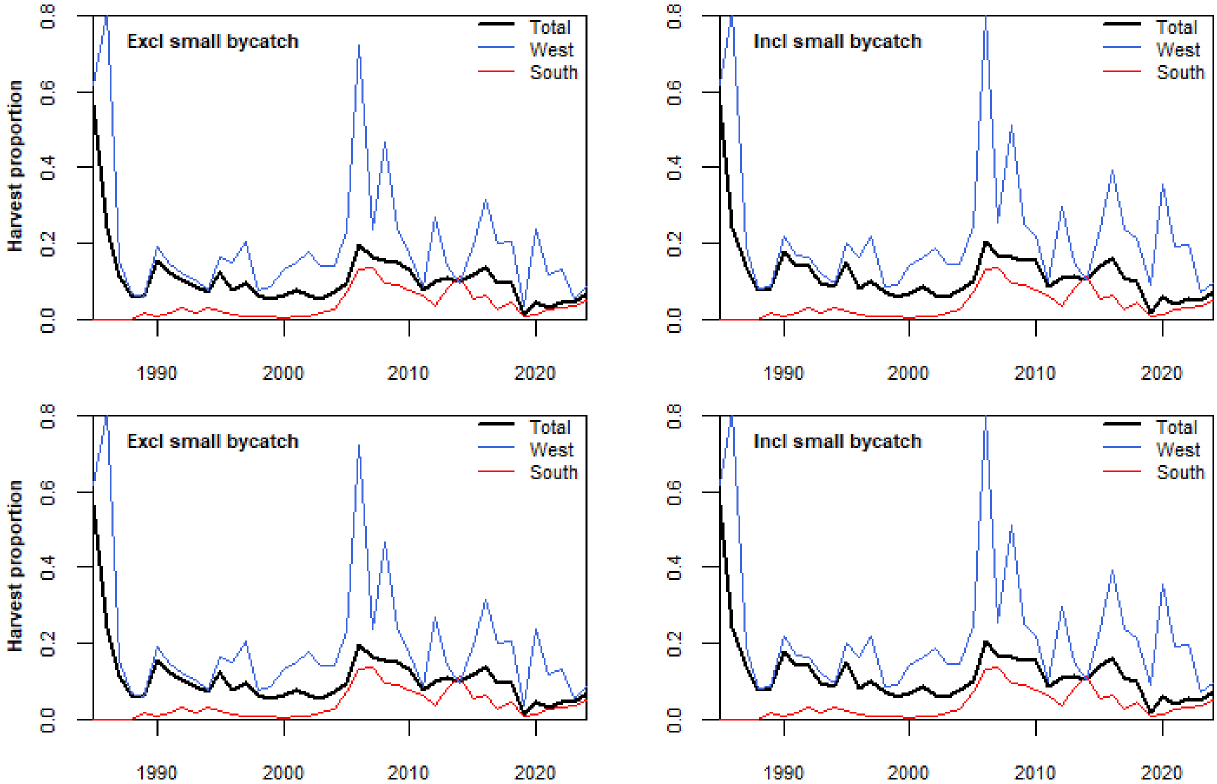


Figure 17. Historical exploitation rates by coast for S_{noSR} (top row) and S_{SR} (lower row) calculated as the annual (January – December) catch tonnage as a proportion of the November biomass of the previous year. Exploitation rates are shown excluding (left) and including (right) the small sardine bycatch.

Appendix A: Sardine data for 2024 (repeated from de Moor (2025b))

The following data are available for 2024 (Merkle *et al*. 2024, Coetzee *et al*. 2025, Merkle pers comm):

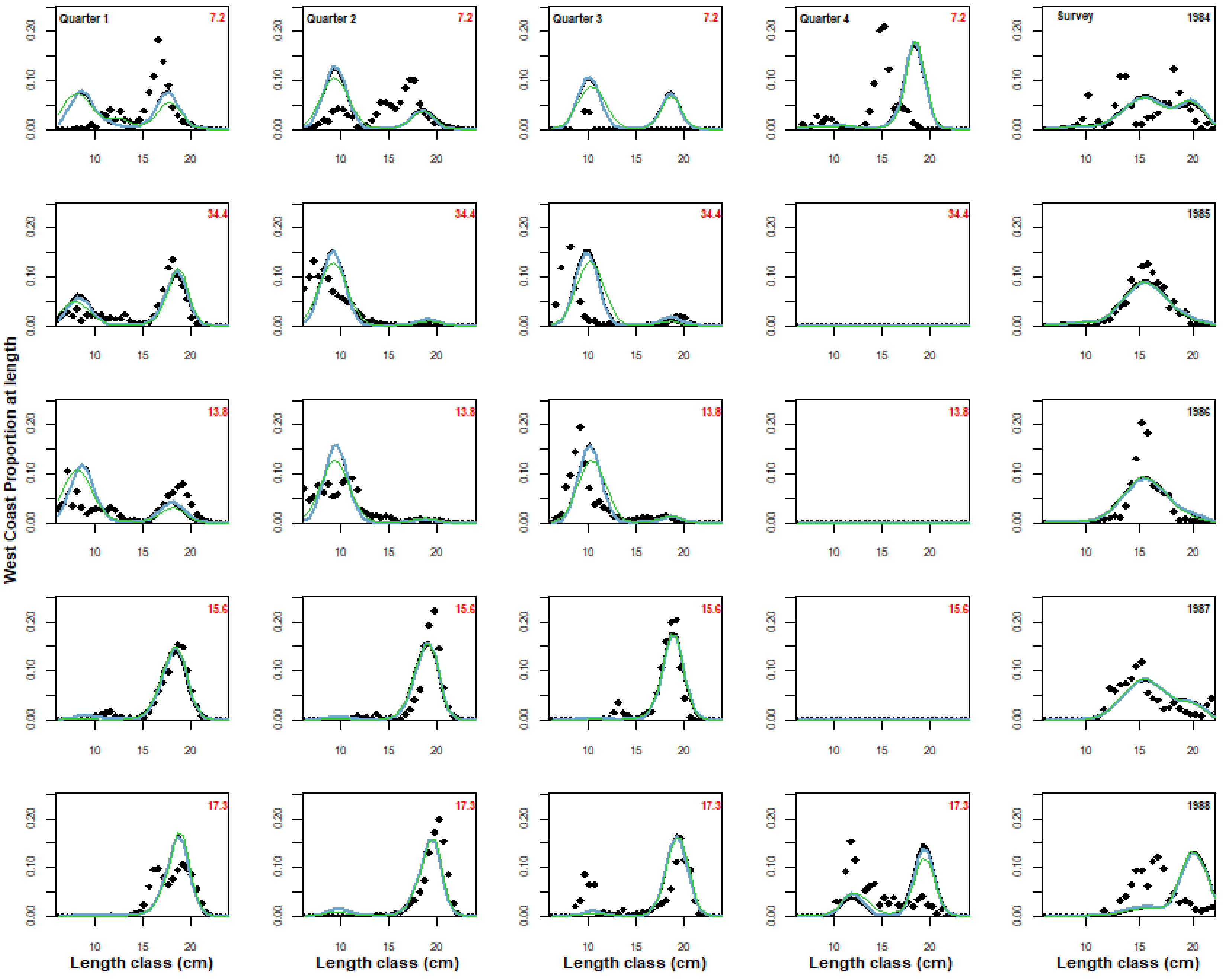
- May 2024 recruitment survey began at 1st June, i.e. $t_y = 1.067$.
- May 2024 recruit cut-off length was <11.5cm.
- May 2024 recruit numbers and inter-transect CVs were 3.365 billion (0.466) and 4.931 billion (0.524) for west and east of Cape Agulhas, respectively.

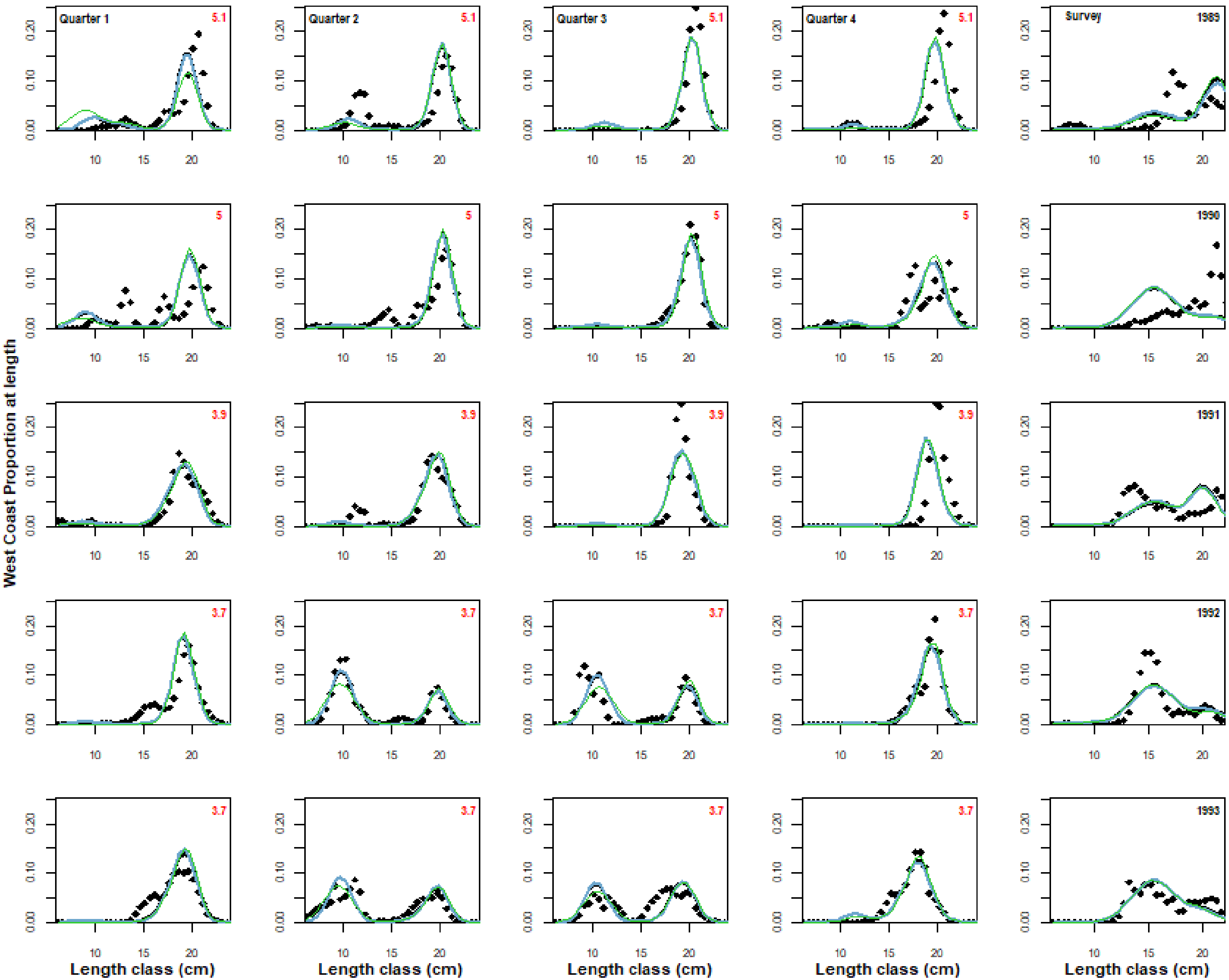
- November 2024 total biomass survey took place over March-April 2025 and is modelled to have occurred on 1 April 2025 instead of 15th November 2024.
- The total biomass and inter-transect CVs were 322 756t (0.490) and 164 873t (0.348) for west and east of Cape Agulhas, respectively.
- The March-April 2025 survey length frequencies for west and east of Cape Agulhas.

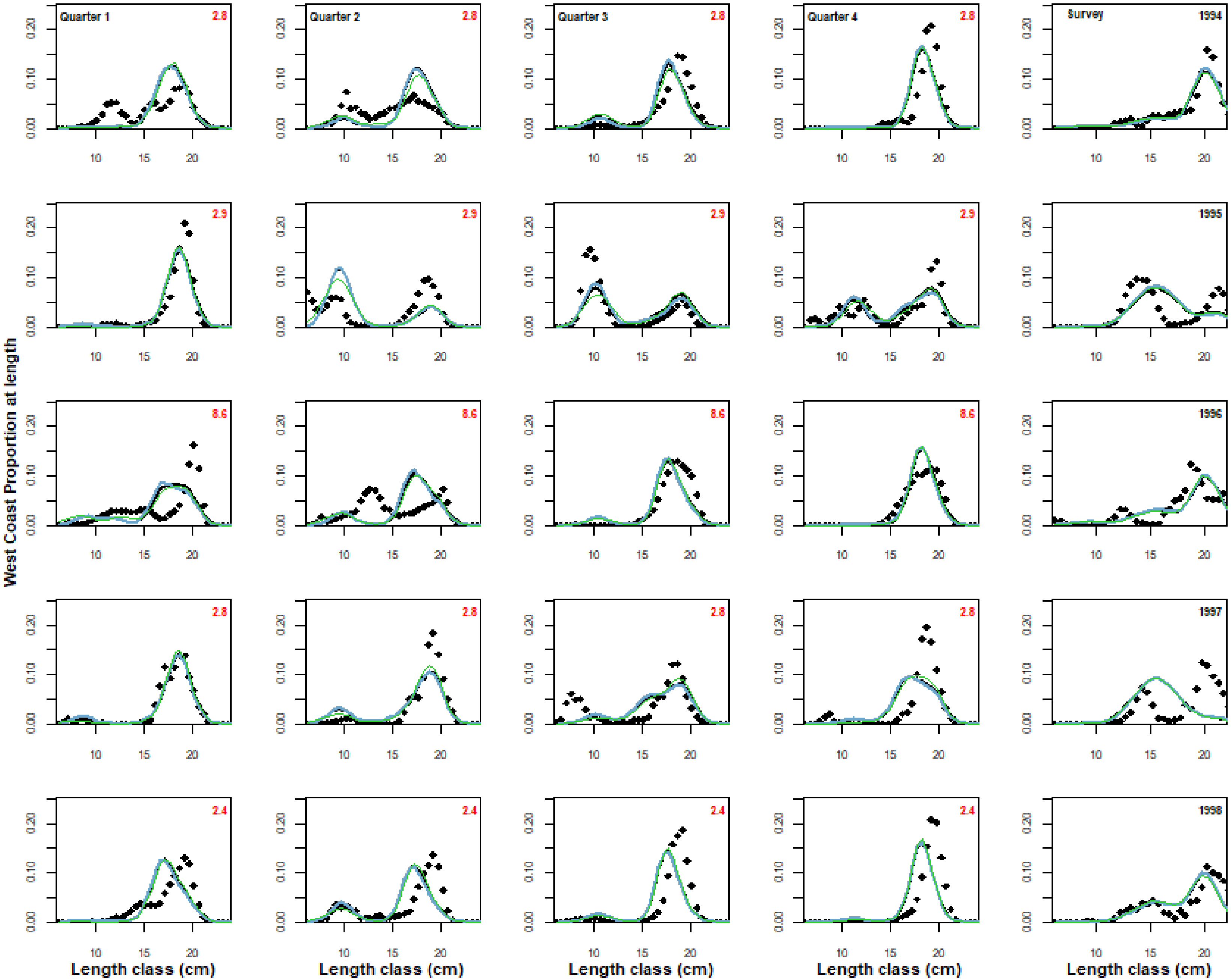
- Commercial catch tonnages and length frequencies from January 2024 to March 2025, for west of Cape Point, Cape Point to Cape Agulhas and east of Cape Agulhas.
- (By)Catch tonnage is available for all January – March months, areas and size classes in 2025. However, length frequency data are not available for all months/areas in 2025:
- For the ≤14cm sardine bycatch in January – March 2025, the weighted average relative length frequency from 2022-2024 in the same months/areas are used.
- For the >14cm sardine bycatch with round herring and anchovy in March 2025, the corresponding relative length frequency from the >14cm directed sardine in March 2025 is used.
- Catch from 1-2 June 2025 (to contribute to recruit catch from 1 April to the day before the survey) consisted only of ≤14cm and >14cm bycatch in the area north of Cape Point.
- As maturity data could not be collected during November 2024, the average 2017-2020,2022 $L_{50,y}$ and δ_y^{mat} were used for November 2024, as assumed for November 2023 (de Moor *et al*. 2024).

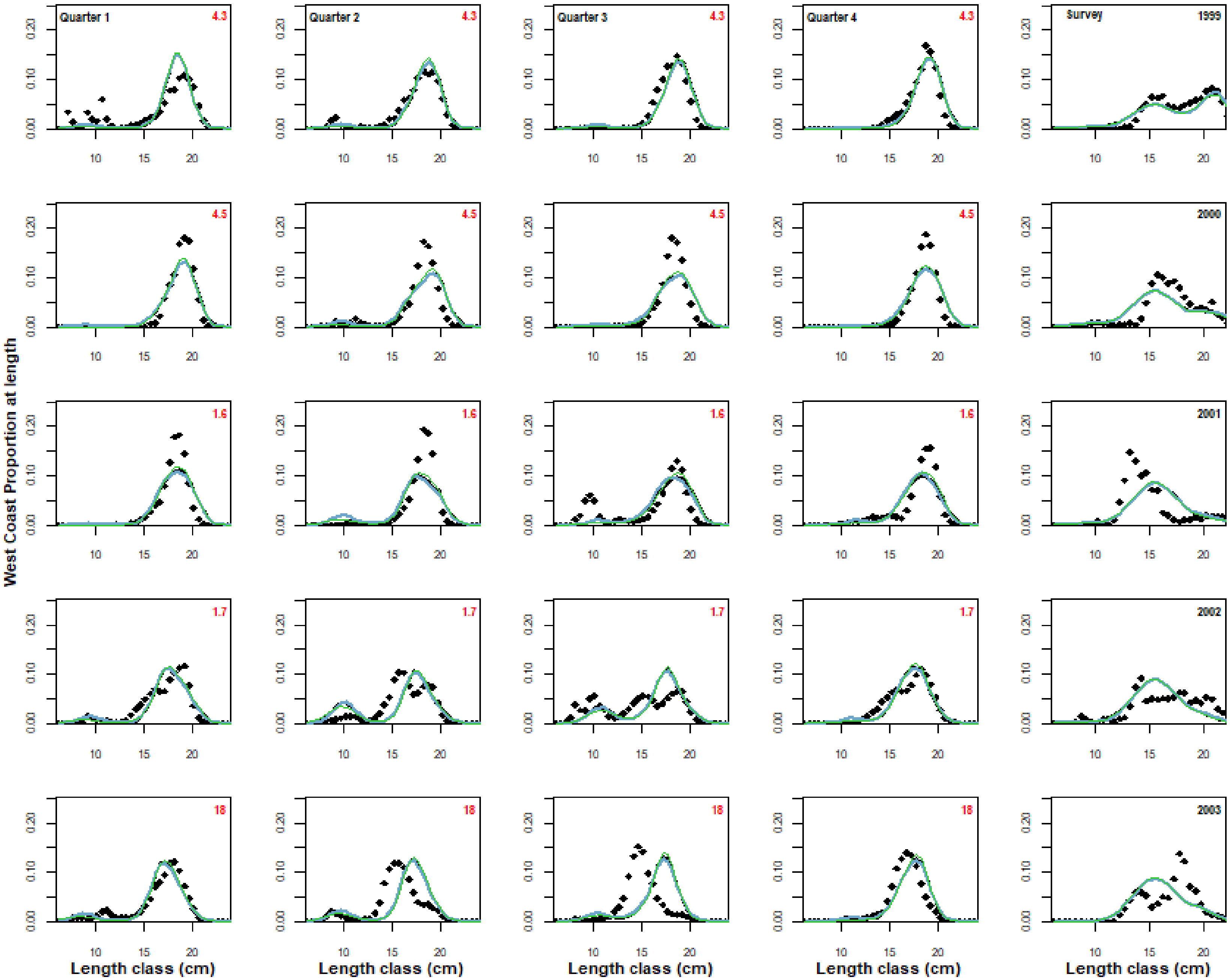
Appendix B: Quarterly commercial and November survey length frequencies

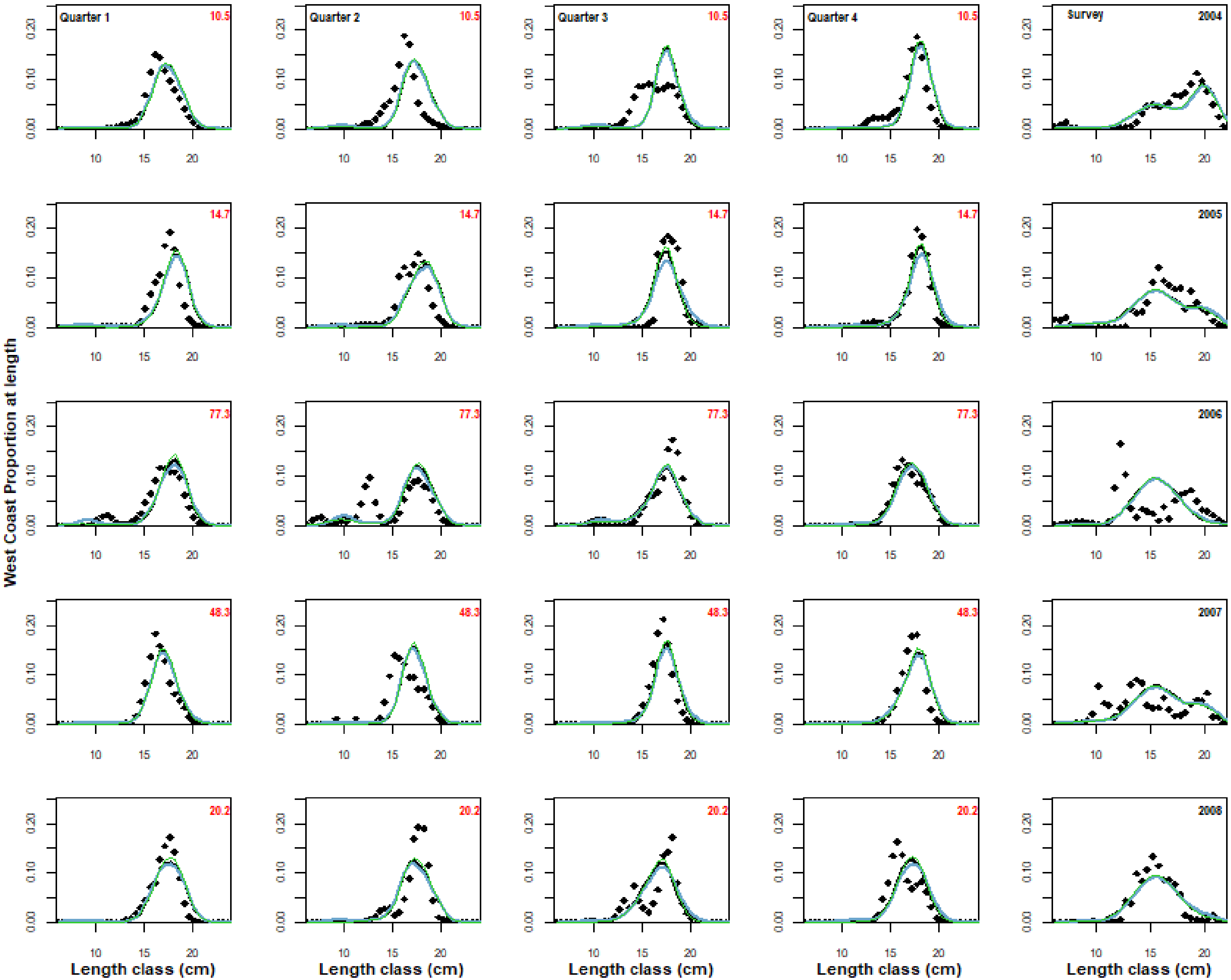
Data are shown by the diamonds, the black lines are S_{noSR} model predicted length frequencies while the green lines are S_{SR} model predicted length frequencies. Each row shows the data and model fits for a year. The catch tonnage by quarter is shown in red.

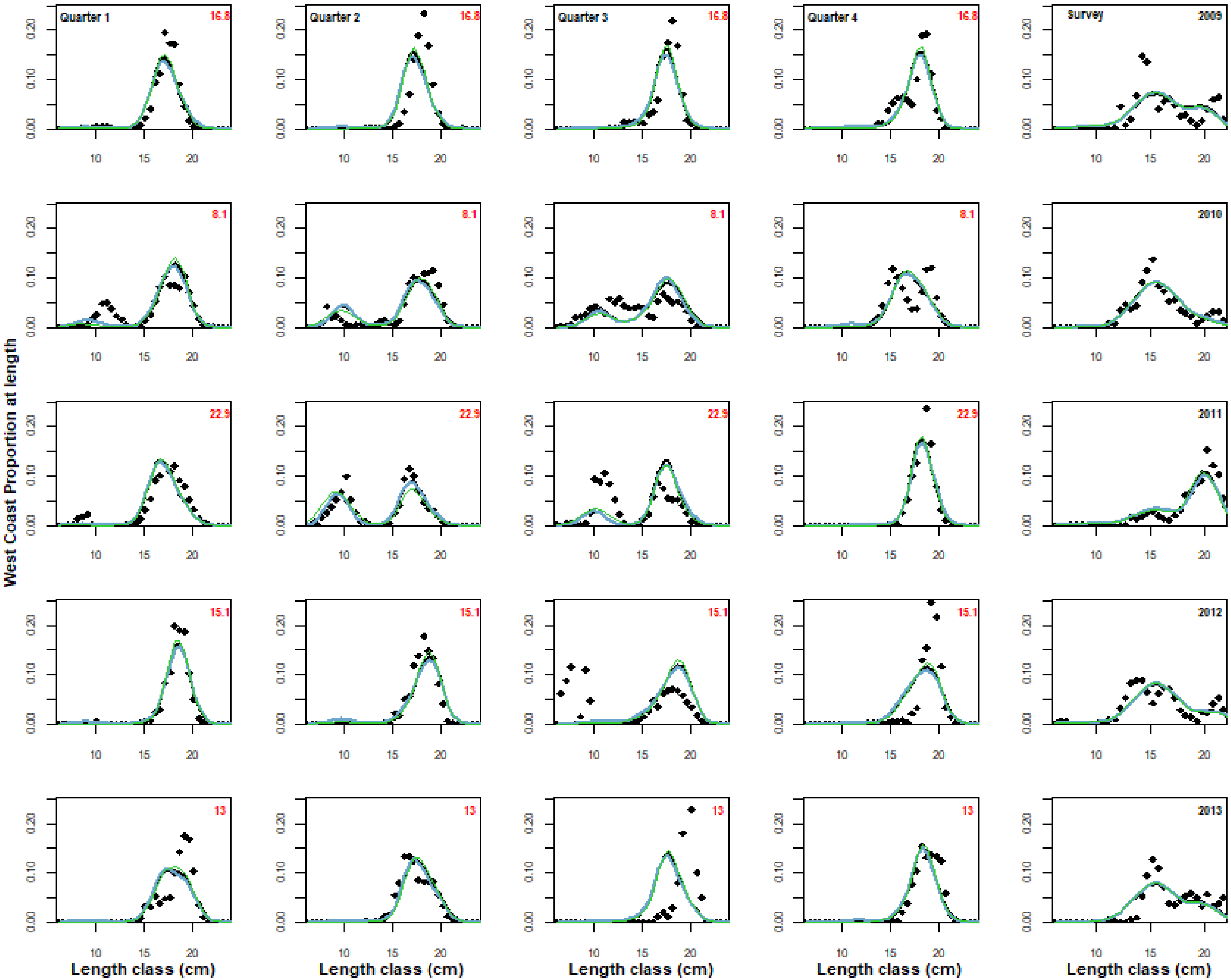

Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
7.2
1984
34.4
1985
13.8
1986
15.6
1987
17.3
1988
West Coast Proportion at length
Length class (cm)

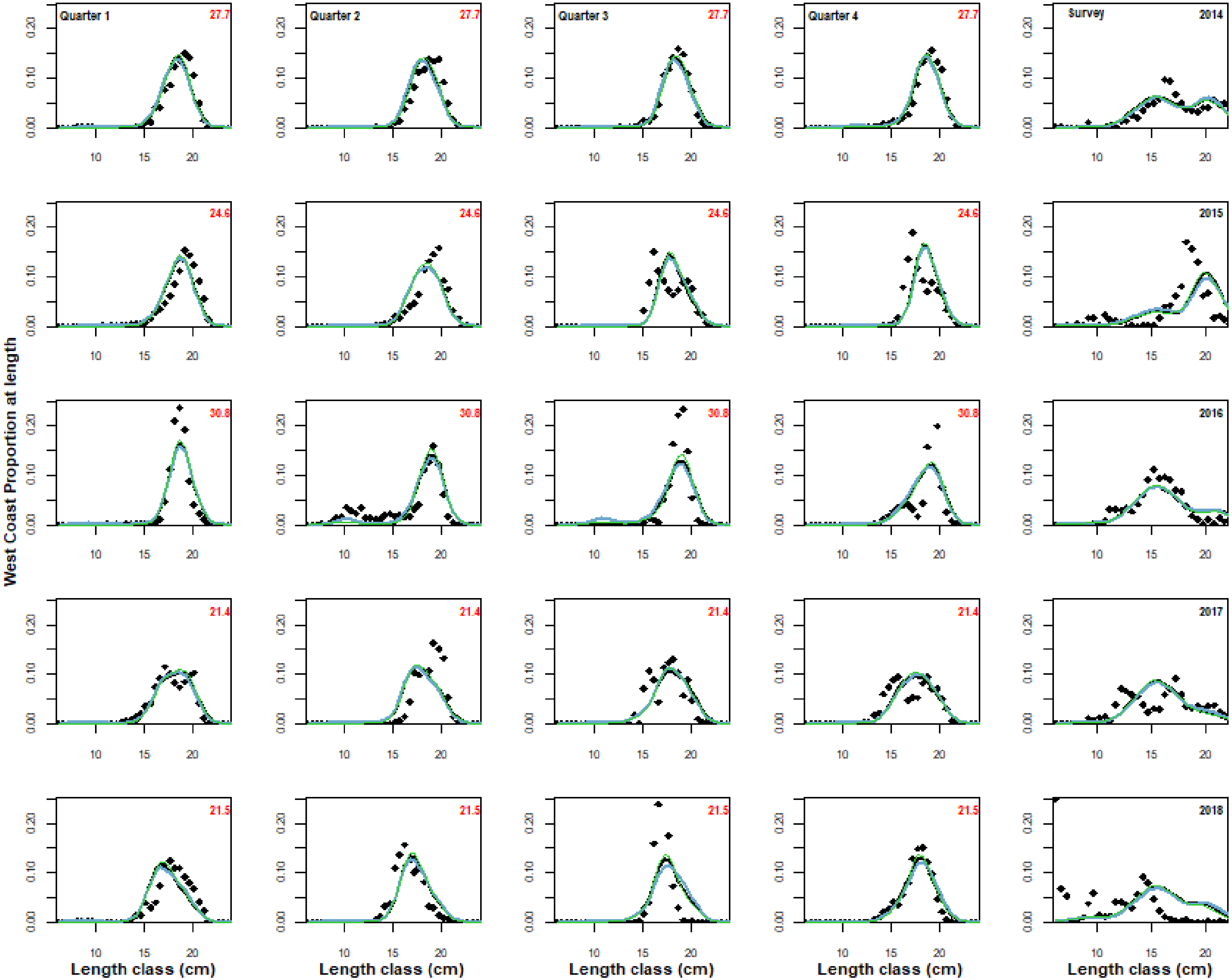

West Coast Proportion at length
Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
1989
1990
1991
1992
1993
5.1
5
3.9
3.7
Length class (cm)

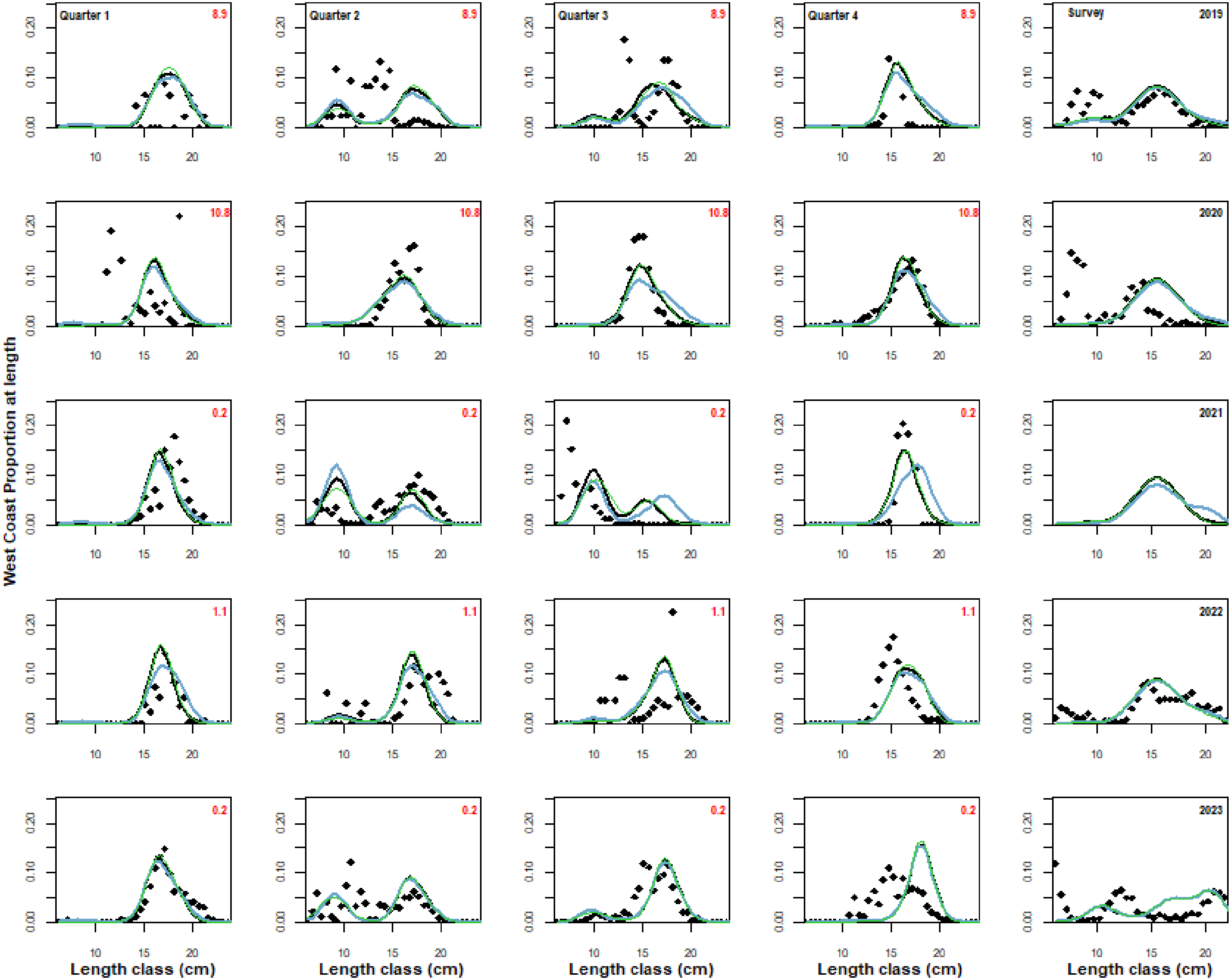

Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
1994
1995
1996
1997
1998
2.8
2.9
8.6
2.8
2.4
West Coast Proportion at length
Length class (cm)
0.00
0.10
0.20
10
15
20

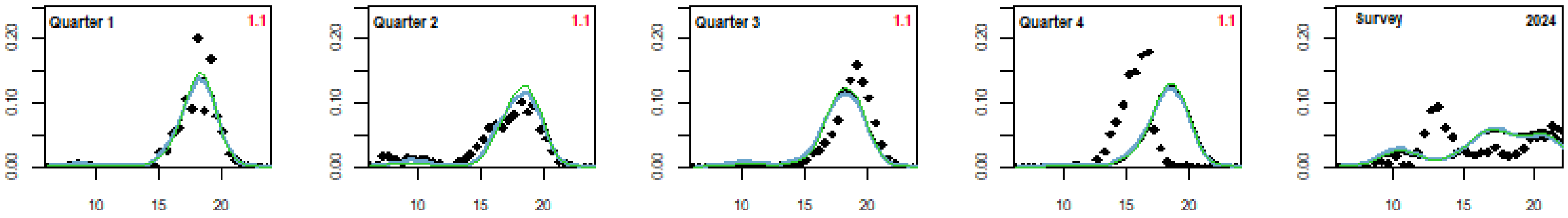

West Coast Proportion at length
Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
4.3
4.5
1.6
1.7
18
1999
2000
2001
2002
2003
Length class (cm)
Length class (cm)
Length class (cm)
Length class (cm)
Length class (cm)

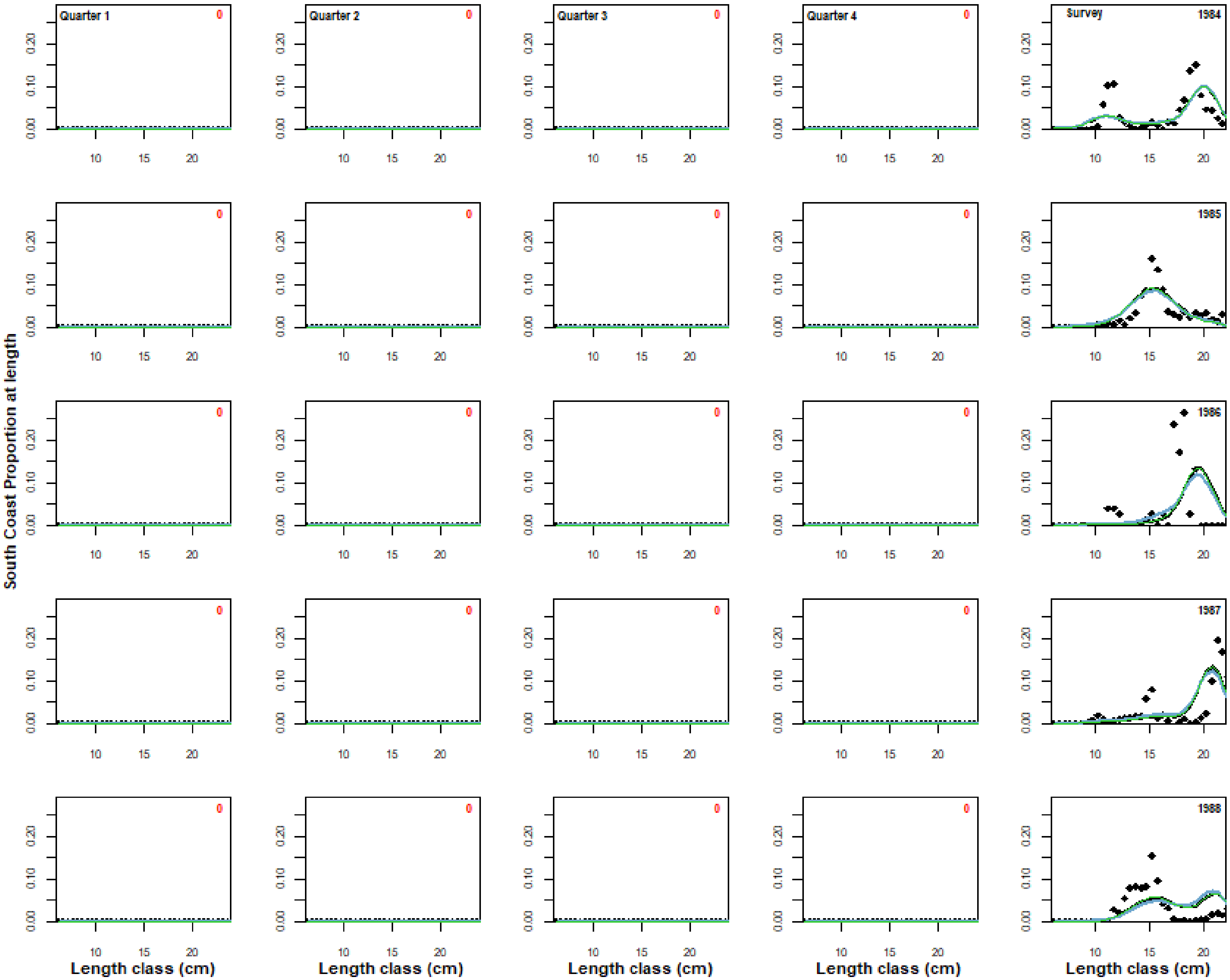

Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
10.5
14.7
77.3
48.3
20.2
2004
2005
2006
2007
2008
West Coast Proportion at length
Length class (cm)

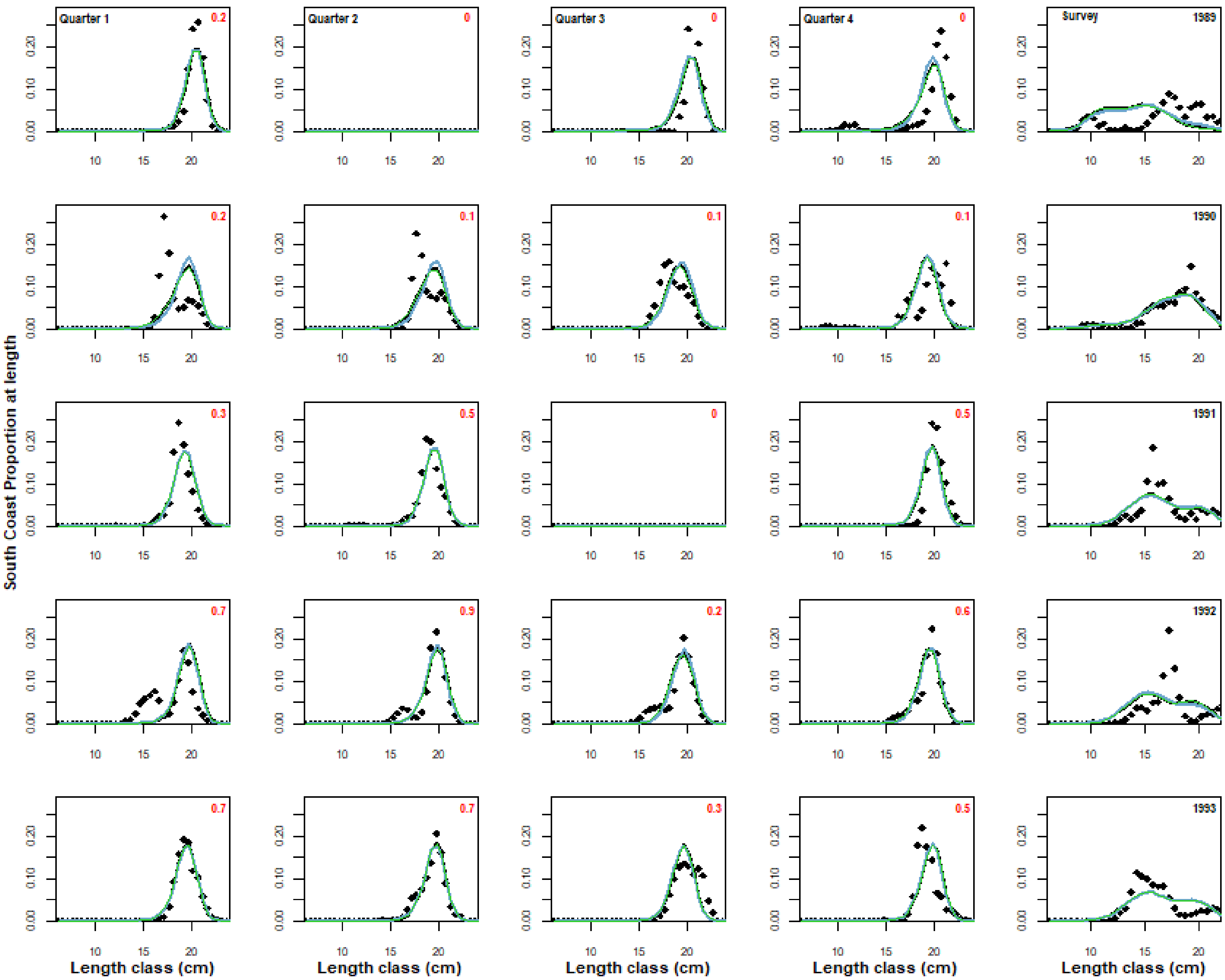

West Coast Proportion at length
Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
16.8
2009
8.1
2010
22.9
2011
15.1
2012
13
2013
0.00
0.10
0.20
10
15
20
Length class (cm)

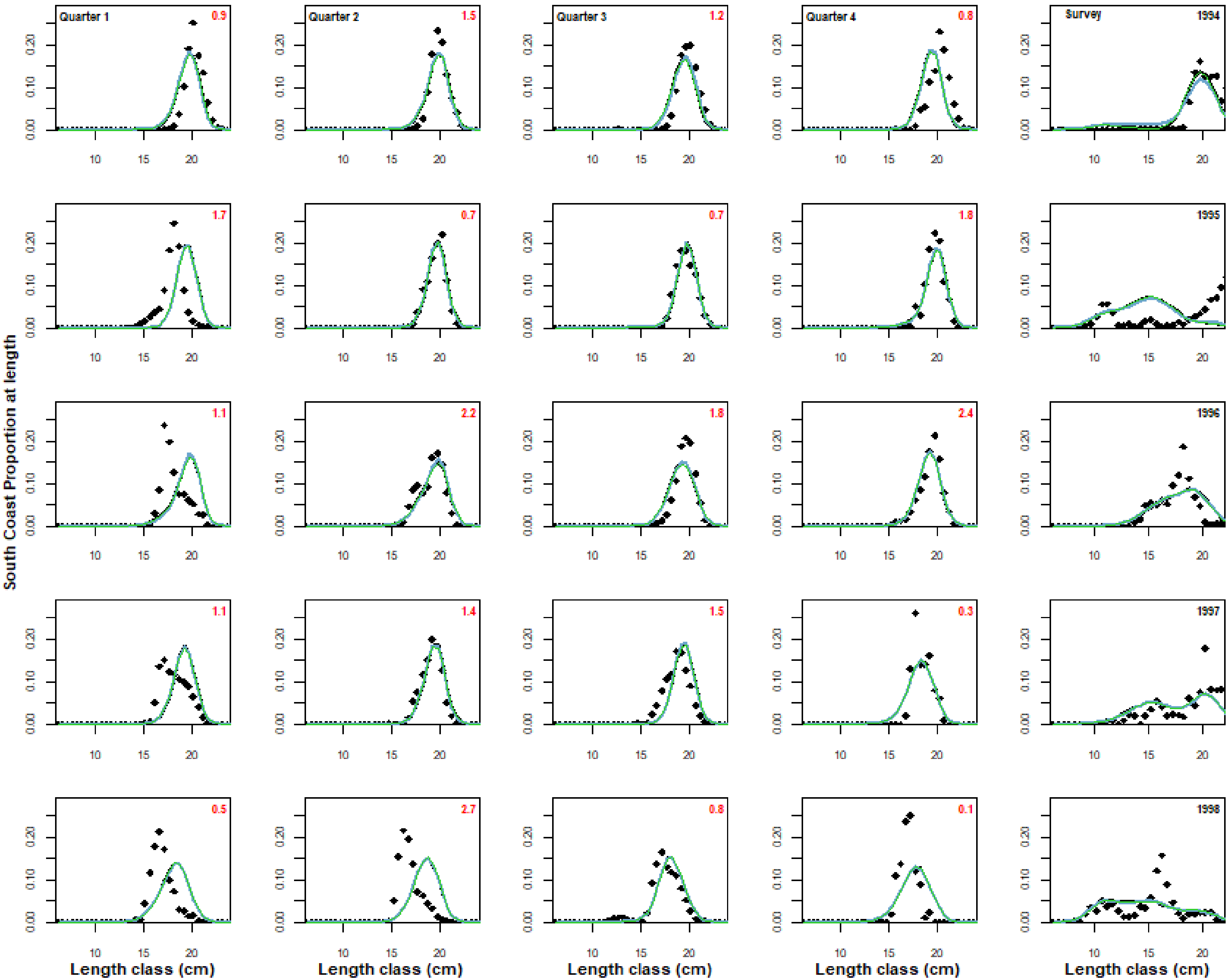

Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
27.7
24.6
30.8
21.4
21.5
2014
2015
2016
2017
2018
West Coast Proportion at length
Length class (cm)

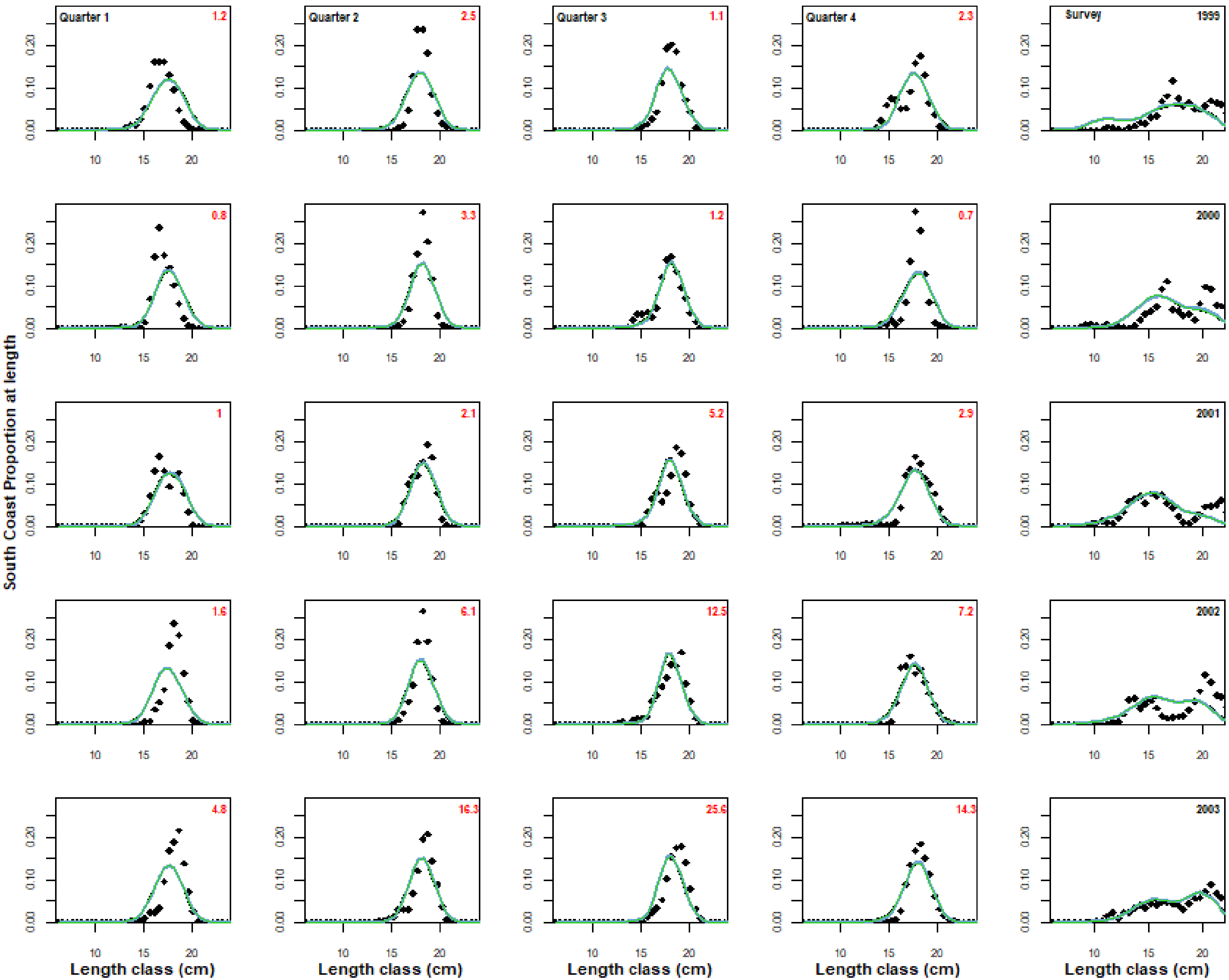

Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
8.9
10.8
0.2
1.1
2019
2020
2021
2022
2023
West Coast Proportion at length
Length class (cm)

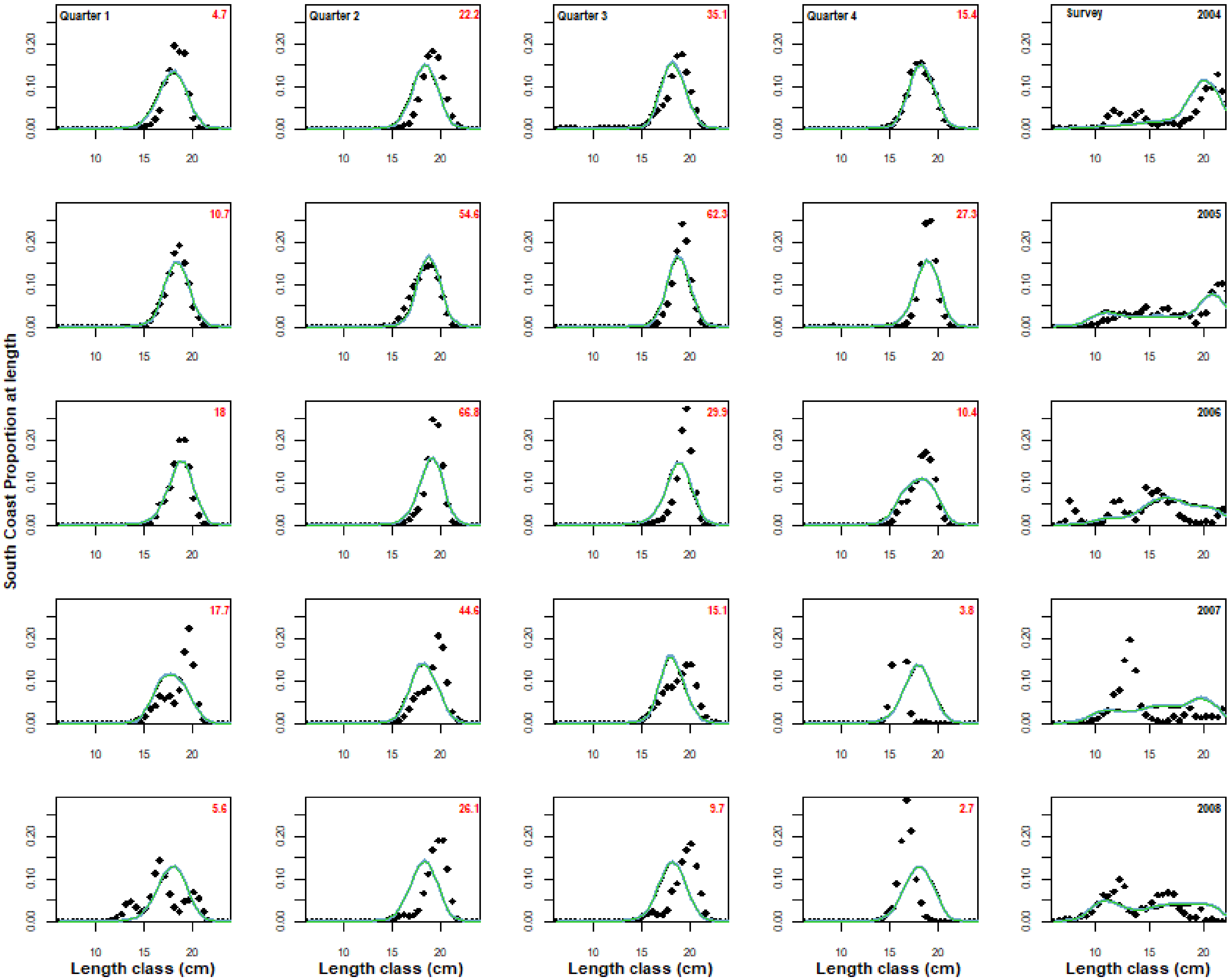

Quarter 1
1.1
Quarter 2
1.1
Quarter 3
1.1
Quarter 4
1.1
Survey
2024
0.00
0.10
0.20
10
15
20

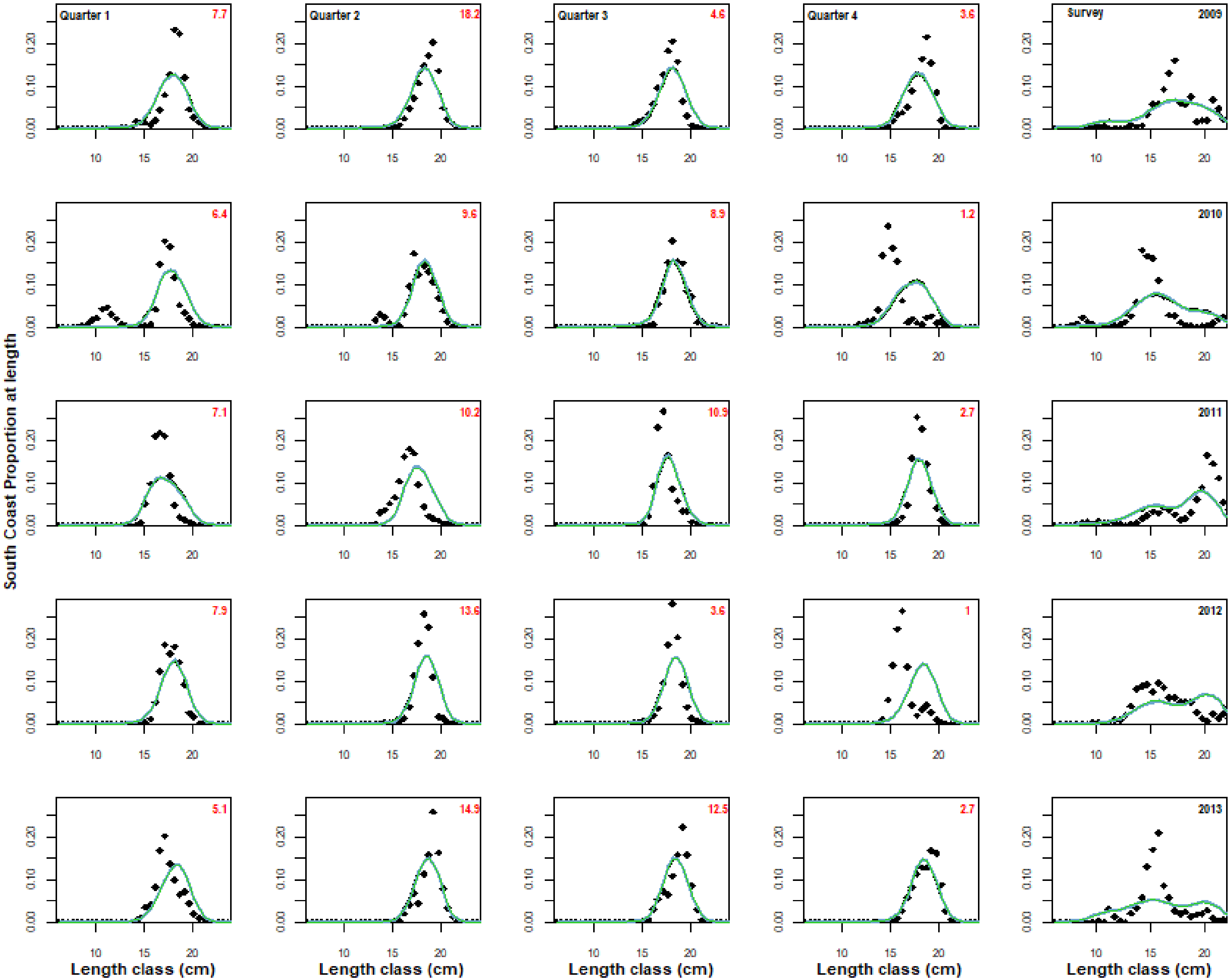

Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
1984
1985
1986
1987
1988
South Coast Proportion at length
Length class (cm)

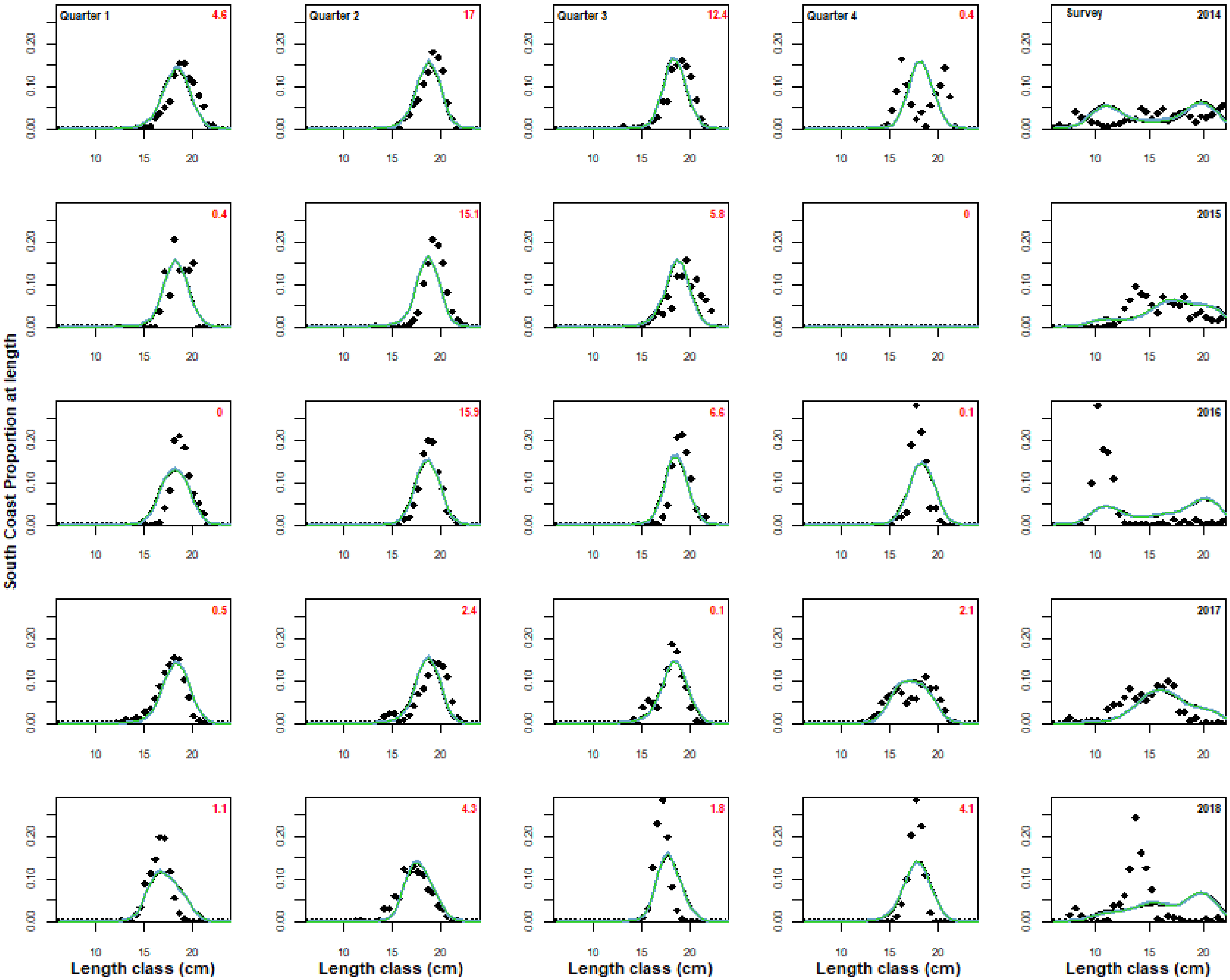

Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
1989
1990
1991
1992
1993
South Coast Proportion at length
Length class (cm)
Length class (cm)
Length class (cm)
Length class (cm)
Length class (cm)

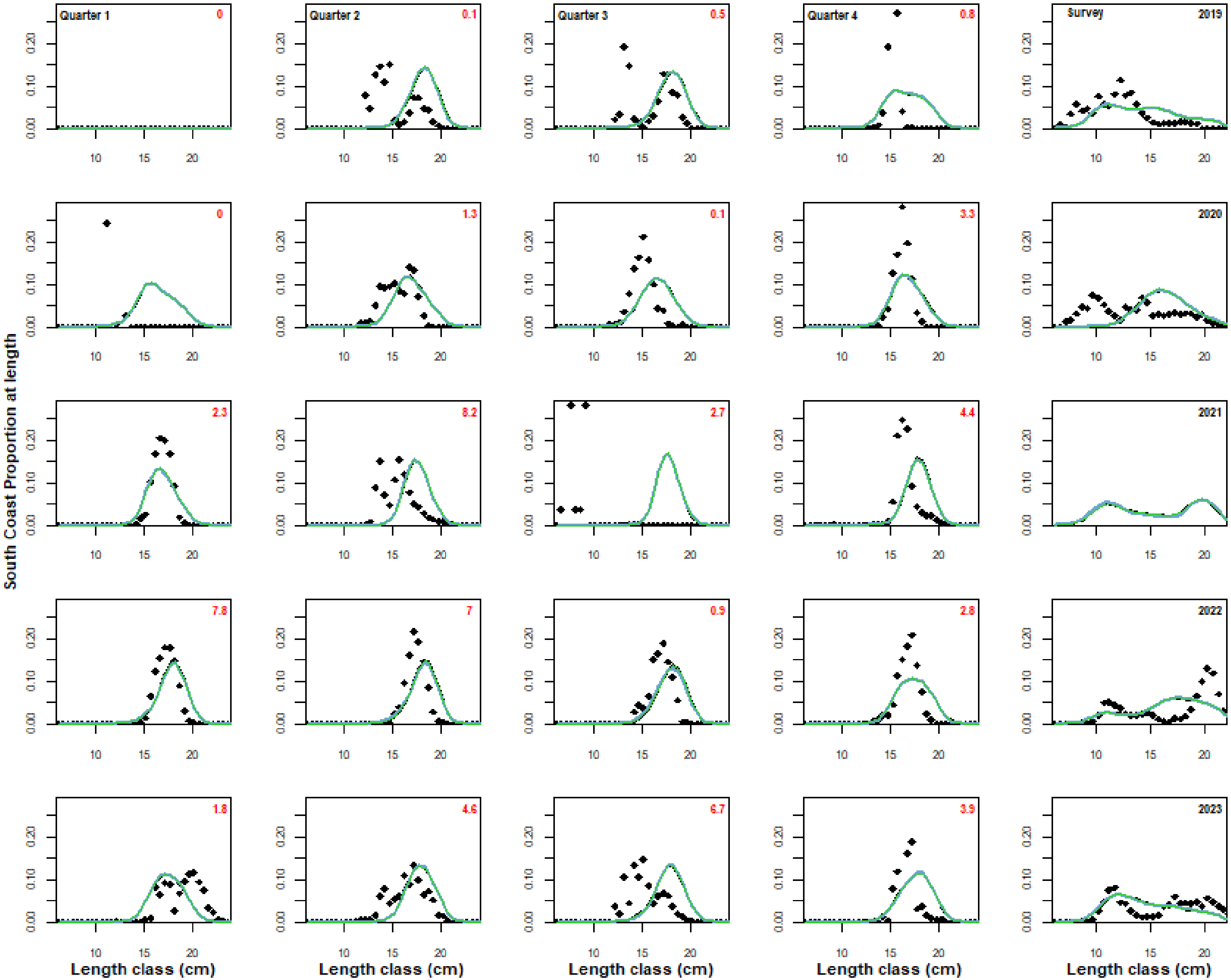

Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
1994
1995
1996
1997
1998
0.9
1.5
1.2
0.8
1.7
0.7
0.7
1.8
1.1
2.2
1.8
2.4
1.1
1.4
1.5
0.3
0.5
2.7
0.8
0.1
South Coast Proportion at length
Length class (cm)
0.00
0.10
0.20
10
15
20

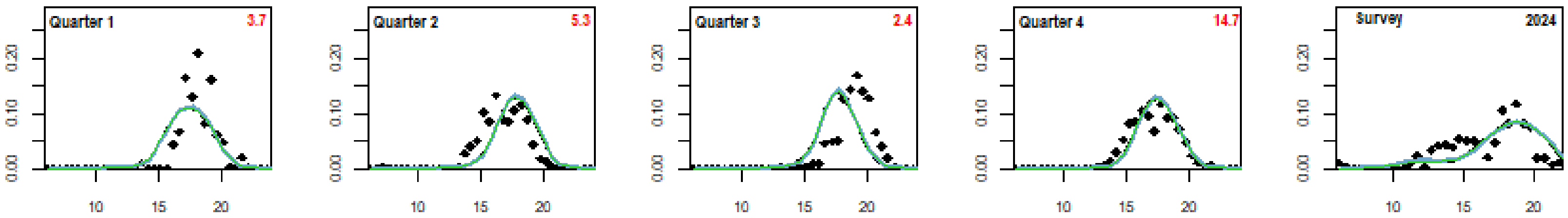

Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
1999
2000
2001
2002
2003
1.2
2.5
1.1
2.3
0.8
3.3
1.2
0.7
1
2.1
5.2
2.9
1.6
6.1
12.5
7.2
4.8
16.3
25.6
14.3
South Coast Proportion at length
0.00
0.10
0.20
10
15
20
Length class (cm)


Quarter 1
4.7
Quarter 2
22.2
Quarter 3
35.1
Quarter 4
15.4
Survey
2004
10.7
54.6
62.3
27.3
2005
18
66.8
29.9
10.4
2006
17.7
44.6
15.1
3.8
2007
5.6
26.1
9.7
2.7
2008
South Coast Proportion at length
Length class (cm)
0.00
0.10
0.20
10
15
20


South Coast Proportion at length
Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
2009
2010
2011
2012
2013
Length class (cm)


Quarter 1
4.6
Quarter 2
17
Quarter 3
12.4
Quarter 4
0.4
Survey
2014
0.4
15.1
5.8
0
2015
0
15.9
6.6
0.1
2016
0.5
2.4
0.1
2.1
2017
1.1
4.3
1.8
4.1
2018
South Coast Proportion at length
Length class (cm)
Length class (cm)
Length class (cm)
Length class (cm)
Length class (cm)


South Coast Proportion at length
Quarter 1
Quarter 2
Quarter 3
Quarter 4
Survey
2019
2020
2021
2022
2023
Length class (cm)


Quarter 1
3.7
Quarter 2
5.3
Quarter 3
2.4
Quarter 4
14.7
Survey
2024
0.00
0.10
0.20
10
15
20