The stock assessment model for South African sardine

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The stock assessment model for South African sardine is detailed in the Appendix. The following assumptions are made:

1) All infection occurs at 1 November; after all catch and before movement. Thus at the time of the recruit survey, all recruits are assumed to be uninfected.
2) All movement occurs at 1 November; after all catch is removed from the population and after infection by the parasite.
3) Permanent west-to-east movement is allowed for all ages.
4) No east-to-west movement is assumed[1].
5) Infection only happens to west stock fish (hypothesised region of parasite host)
6) No difference in growth, maturity, natural or fishing mortality or movement is assumed between sardine that are uninfected or infected with the parasite.

Initial results from fitting this model to available data are presented in de Moor and Butterworth (2015b).

References

de Moor CL, Butterworth DS. 2015a. Assessing the South African sardine resource: two stocks rather than one? African Journal of Marine Science. 37:41-51.

de Moor CL, Butterworth DS. 2015b. Initial results from fitting the revised sardine two-mixing stock model to data from 1984-2014, including consideration of parasite prevalence-by-length sampled from November surveys 2010-2014. MARAM International Fisheries Stock Assessment Workshop MARAM IWS/DEC15/Sardine/P3.

de Moor CL, Coetzee J, Merkle D, van der Westhuizen JJ, van der Lingen C. 2015. A record of the generation of data used in the 2015 sardine and anchovy assessments. Department of Agriculture, Forestry and Fisheries Report No FISHERIES/2015/NOV/SWG-PEL/42. 19pp. Also MARAM IWS/DEC15/Sardine/BG3.

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 28:625-636.

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[1] One two-mixing stock hypothesis allowed for south stock sardine to be distributed west of Cape Agulhas for some time each year, but that hypothesis is not considered here.

Appendix: Bayesian assessment for the South African sardine resource

The assessment is run from November $y_1 = 1984$ to November $y_n = 2014$, with 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. All parameters are defined in Tables A.1 and A.2.

The subscripts $j = W$ or $j = S$ denote the west and south stocks, respectively, where only the 'west' stock equations are used in the single stock hypothesis. The subscripts $p = NI$ or $p = I$ denote the sardine uninfected and infected with the digenean 'tetracotyle-type' metacercarian endoparasite, respectively.

<u>Population Dynamics</u>

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

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

$$y_1 \le y \le y_n,\ 1 \le a \le 4$$

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

$$y_1 \le y \le y_n \qquad \text{(A.1)}$$

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

$$N^{S**}_{W,NI,y,a} = (1 - I_y) N^{S*}_{W,NI,y,a} \qquad y_1 \le y \le y_n,\ 1 \le a \le 4$$

$$N^{S**}_{W,I,y,a} = N^{S+}_{W,I,y,a} + I_y N^{S*}_{W,NI,y,a} \qquad y_1 \le y \le y_n,\ 1 \le a \le 4$$

$$N^{S**}_{S,p,y,a} = N^{S*}_{S,p,y,a} \qquad p = I, NI,\ y_1 \le y \le y_n,\ 1 \le a \le 4 \qquad \text{(A.2)}$$

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

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

$$N^S_{S,p,y,a} = N^{S*}_{S,p,y,a} + move_{y,a} N^{S*}_{W,p,y,a} \qquad y_1 \le y \le y_n,\ 1 \le a \le 5^+ \qquad \text{(A.3)}$$

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

$$N^S_{j,p,y,1,a} = N^S_{j,p,y-1,a} e^{-M^S_{y,a}/8}$$

$$N^S_{j,p,y,2,a} = (N^S_{j,p,y,1,a} - C^S_{j,p,y,1,a}) e^{-M^S_{y,a}/4}$$

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

$$N^S_{j,p,y,4,a} = \left(N^S_{j,p,y,3,a} - C^S_{j,p,y,3,a}\right) e^{-M^S_{y,a}/4} \qquad y_1 \le y \le y_n,\ 1 \le a \le 5^+ \qquad \text{(A.4)}$$

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.

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

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

$$N^{S,1+}_{j,p,y,l} = \sum_{a=1}^{5+} A^{sur}_{j,a,l} N^S_{j,p,y,a} \qquad y_1 \le y \le y_n,\ 2.5^- cm \le l \le 24^+ cm \qquad \text{(A.6)}$$

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

$$A^{sur}_{j,a,l} \sim N\left(L_{j,\infty}\left(1 - e^{-\kappa_j (a - t_0)}\right), \vartheta^2_{j,a}\right) \qquad 0 \le a \le 5^+,\ 2.5^- cm \le l \le 24^+ cm \qquad \text{(A.7)}$$

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 – Table A.1):

$$M^S_{y,a=0} = \overline{M}^S_j e^{\varepsilon^j_y} \text{ with } \varepsilon^j_{1984} = \eta^j_{1984} \text{ and } \varepsilon^j_y = \rho \varepsilon^j_{y-1} + \sqrt{1-\rho^2}\,\eta^j_y,\ y > y_1 \qquad \text{(A.8)}$$

$$M^S_{y,a=1+} = \overline{M}^S_{ad} e^{\varepsilon^{ad}_y} \text{ with } \varepsilon^{ad}_{1984} = \eta^{ad}_{1984} \text{ and } \varepsilon^{ad}_y = \rho \varepsilon^{ad}_{y-1} + \sqrt{1-\rho^2}\,\eta^{ad}_y,\ y > y_1 \qquad \text{(A.9)}$$

Spawning biomass and biomass associated with the November survey

$$SSB^S_{j,y} = \sum_p \sum_{l=2.5^-}^{24^+} f^S_{j,y,l} N^{S,1+}_{j,p,y,l} w^S_{j,y,l} \qquad y_1 \le y \le y_n \qquad \text{(A.10)}$$

$$B^S_{j,y} = k^S_{j,N} \sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} w^S_{j,y,l} \qquad y_1 \le y \le y_n \qquad \text{(A.11)}$$

where $$w^S_{j,y,l} = w^S_{j,l} \times \frac{\tilde{w}_{j,y}}{\left(\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} w^S_{j,l}\right) \Big/ \left(\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l}\right)} \qquad y_1 \le y \le y_n, 2.5^- cm \le l \le 24^+ cm \qquad \text{(A.12)}$$

Commercial selectivity

$$S_{j,y,l} = \begin{cases} 0 & l \le 5.5cm \\ \chi_j \exp\left\{-\frac{\left(l+0.25-\bar{l}_{1,j}\right)^2}{\left(\sigma_1^{sel}\right)^2}\right\} + \exp\left\{-\frac{\left[\ln\left(\left(l+0.25-23.5\right)/\left(\bar{l}_{2,j}-23.5\right)\right)\right]^2}{\left(\sigma_2^{sel}\right)^2}\right\} & 6cm \le l \le 23cm \end{cases}$$

$$y_1 \le y \le y_n \qquad \text{(A.13)}$$

$$S_{j,y,q,a} = \sum_{l=3^-}^{23.5^+} A^{com}_{j,q,a,l} S_{j,y,l} \qquad y_1 \le y \le y_n\,,\ 1 \le q \le 4\,,\ 0 \le a \le 5^+ \qquad \text{(A.14)}$$

where $A^{com}_{j,q,a,l} \sim N\left(L_{j,\infty}\left(1-e^{-\kappa_j\left(a+(2q-1)/8-t_0\right)}\right), \vartheta^2_{j,a}\right)$ $\qquad 0 \le a \le 5^+\,,\ 2.5^- cm \le l \le 24^+ cm \qquad$ (A.15)

and the 23.5cm is one length class above the maximum for which observations can be predicted.

Bycatch in the anchovy directed fishery

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

$$C^{bycatch}_{j,p,y,q=1,a=1} = \frac{N^S_{j,p,y,q=1,a=1}}{\sum_p N^S_{j,p,y,1,1}} \times \left\{\sum_{m=11}^{12} \sum_{l>=lcut_{y,m}} C^{RLF,\,fleet=3}_{j,y-1,m,l} + \sum_{l>=lcut_{y,m}} C^{RLF,\,fleet=3}_{j,y,1,l}\right\}$$

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

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

$$C^{bycatch}_{j,p,y,q=4,a=0} = \frac{N^S_{j,p,y,q=4,a=0}}{\sum_p N^S_{j,p,y,4,0}} \times \sum_{m=8}^{10} \sum_{l<lcut_{y,m}} C^{RLF,\,fleet=3}_{j,y,m,l} \qquad C^{bycatch}_{j,p,y,q=4,a=1} = \frac{N^S_{j,p,y,q=4,a=1}}{\sum_p N^S_{j,p,y,4,1}} \times \sum_{m=8}^{10} \sum_{l>=lcut_{y,m}} C^{RLF,\,fleet=3}_{j,y,m,l}$$

$$C^{bycatch}_{j,p,y,q,a} = 0 \qquad y_1 \le y \le y_n\,,\ 1 \le q \le 4\,,\ 2 \le a \le 5^+ \qquad \text{(A.16)}$$

Catch in the directed sardine and round herring bycatch fisheries

$$C^{dir}_{j,p,y,q,a} = \left(N^S_{j,p,y,q,a} - C^{bycatch}_{j,p,y,q,a}\right) S_{j,y,q,a} F_{j,y,q} \qquad y_1 \le y \le y_n\,, 1 \le q \le 4\,, 0 \le a \le 5^+ \qquad \text{(A.17)}$$

Total catch

$$C^S_{j,p,y,q,a} = C^{bycatch}_{j,p,y,q,a} + C^{dir}_{j,p,y,q,a} \qquad y_1 \le y \le y_n\,, 1 \le q \le 4\,, 0 \le a \le 5^+ \qquad \text{(A.18)}$$

Fished proportion of the available biomass from the directed catch and round herring bycatch fisheries

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

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

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

$$F_{j,y,q=4} = \frac{\sum_{fleet=1}^{2}\sum_{m=8}^{10}\sum_{l\geq 6cm} C_{j,y,m,l}^{RFL,\,fleet}}{\sum_{p}\sum_{a=0}^{5+}\left(N_{j,p,y,4,a}^{S} - C_{j,y,4,a}^{bycatch}\right)S_{j,y,4,a}} \qquad \text{(A.19)}$$

A penalty is imposed within the model to ensure that $S_{j,y,l}F_{j,y,q} < 0.95$. Fish <6cm were caught in less than 10% of the quarters and were thus not used in fitting this model. Commercial selectivity-at-length is fixed to zero for length classes < 6cm (equation A.13)

Recruitment

$$N_{j,NI,y,a=0}^{S} = \begin{cases} a_j^S e^{\varepsilon_{j,y}^S - 0.5\left(\sigma_{j,r}^S\right)^2} & \text{if } SSB_{j,y}^S \geq b_j^S \\ \frac{a_j^S}{b_j^S} SSB_{j,y}^S e^{\varepsilon_{j,y}^S - 0.5\left(\sigma_{j,r}^S\right)^2} & \text{if } SSB_{j,y}^S < b_j^S \end{cases} \qquad y_1 \leq y \leq y_n \text{ [2]}$$

$$N_{j,I,y,a=0}^{S} = 0 \qquad \text{(A.20)}$$

Carrying Capacity

$$K_j^S = a_j^S e^{-0.5\left(\sigma_{j,r}^S\right)^2} \sum_{a=1}^{4} \overline{w}_{j,a}^S e^{-M_j^S - (a-1)\overline{M}_{ad}^S} + \overline{w}_{j,5+} e^{-M_j^S - 4\overline{M}_{ad}^S} \frac{1}{1-e^{-\overline{M}_{ad}^S}}$$

$$K_{peak}^S = a_j^S e^{-0.5\left(\sigma_{r,peak}^S\right)^2} \sum_{a=1}^{4} \overline{w}_{j,a}^S e^{-M_j^S - (a-1)\overline{M}_{ad}^S} + \overline{w}_{j,5+} e^{-M_j^S - 4\overline{M}_{ad}^S} \frac{1}{1-e^{-\overline{M}_{ad}^S}} \qquad \text{(A.21)}$$

[2] $\sigma_{j,r}^S$ is replaced with $\sigma_{r,peak}^S$ during the peak years of 2000-2004 in the single stock hypothesis (see Table A.1).

Number of recruits associated with the recruit survey

$$N^S_{j,y,r} = k^S_{j,r}\left(\sum_p \left(N^S_{j,p,y,2,0} - C^S_{j,p,y,2,0}\right)e^{-\left(1/8+0.5t^S_y/12\right)M^S_{y,0}} - \tilde{C}^S_{j,y,0bs}\right)e^{-0.5t^S_y \times M^S_{y,0}/12} \qquad y_1 \le y \le y_n \qquad \text{(A.22)}$$

Multiplicative survey bias

$$k^S_{j,N} = k^S_{ac} \qquad \text{(A.23)}$$

$$k^S_{1,r} = k^S_{\text{cov}} \times k^S_{ac} \qquad \text{(A.24)}$$

$$k^S_{2,r} = k^S_{\text{cov}\,S} \times k^S_{\text{cov}} \times k^S_{ac} \quad \text{(for the two stock hypothesis only)} \qquad \text{(A.25)}$$

Survey trawl selectivity

$$S_{j,y,l} = \begin{cases} 0 & l = 2.5^- cm \\ \left[1+\exp\{-\left(l - S_{50}\right)/\delta\}\right]^{-1} & 3cm \le l \le 24^+ cm \end{cases} \qquad y_1 \le y \le y_n \qquad \text{(A.26)}$$

Proportion-at-length associated with the November survey

$$p^S_{j,y,6^-} = \frac{\sum_p \sum_{l \le 6cm} N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=3}^{23.5} N^S_{j,p,y,l} S^{survey}_{j,l}} \qquad y_1 \le y \le y_n \qquad \text{(A.27)}$$

$$p^S_{j,y,l} = \frac{\sum_p N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=3}^{23.5} N^S_{j,p,y,l} S^{survey}_{j,l}} \qquad y_1 \le y \le y_n,\ 6.5cm \le l \le 20.5cm \qquad \text{(A.28)}$$

$$p^S_{j,y,21-23.3} = \frac{\sum_p \sum_{l=21}^{23.5} N^S_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=3}^{23.5} N^S_{j,p,y,l} S^{survey}_{j,l}} \qquad y_1 \le y \le y_n \qquad \text{(A.29)}$$

$$p^S_{j,y,24^+} = \frac{\sum_p N^S_{j,p,y,24^+} S^{survey}_{j,24^+}}{\sum_p N^S_{j,p,y,24^+} S^{survey}_{j,24^+}} \qquad y_1 \le y \le y_n \qquad \text{(A.30)}$$

[3]

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

$$P^S_{j,y,l} = \frac{N^S_{j,I,y,l}}{\sum_p N^S_{j,p,y,l}} \qquad y_1 \le y \le y_n,\ 5cm \le l \le 22.5cm \qquad \text{(A.31)}$$

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

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

$$C^{dir}_{j,p,y,q,l} = \sum_{a=0}^{5+} \left(N^S_{j,p,y,q,a} - C^{bycatch}_{j,p,y,q,a} \right) A^{com}_{j,q,a,l} S_{j,y,q,a} F_{j,y,q} \qquad y_1 \le y \le y_n \,, 1 \le q \le 4 \,, 2.5^- cm \le l \le 24^+ cm \quad \text{(A.32)}$$

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

$$p^{coml,S}_{j,y,q,l} = \frac{\sum_p C^{dir}_{j,p,y,q,l}}{\sum_p \sum_{l=3.5}^{23} C^{dir}_{j,p,y,q,l}} \qquad y_1 \le y \le y_n \,, 1 \le q \le 4 \,, 3.5cm \le l \le 23cm \quad \text{(A.33)}$$

Initial numbers-at-age

$$N^S_{1,NI,1983,a} = N^S_{1,NI,1983,a-1} e^{-Finit_1 - M^S_a} \qquad 3 \le a \le 4$$

$$N^S_{2,NI,1983,a} = N^S_{2,NI,1983,a-1} e^{-Finit_2 - M^S_a} \qquad 1 \le a \le 4$$

$$N^S_{j,NI,1983,a=5+} = N^S_{j,NI,1983,4} \frac{e^{-Finit_j - M^S_{5+}}}{1 - e^{-Finit_j - M^S_{5+}}}$$

$$N^S_{j,I,1983,a} = 0 \qquad 0 \le a \le 5^+ \quad \text{(A.34)}$$

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

$$-\ln L = -\ln L^{Nov} - \ln L^{rec} - \ln L^{sur\ propl} - \ln L^{com\ propl} - \ln L^{prev} \quad \text{(A.35)}$$

where

$$-\ln L^{Nov} = \tfrac{1}{2} \sum_j \sum_{y=y1}^{yn} \left\{ \left\{ \frac{5^5 \left(\frac{\left| \ln\left(\hat{B}^S_{j,y}\right) - \ln(B^S_{j,y}) \right|}{\sqrt{(\sigma^S_{j,y,Nov})^2 + \left(\phi^S_{ac}\right)^2 + (\lambda^S_{j,N})^2}} \right)^5}{5^5 + \left(\frac{\left| \ln\left(\hat{B}^S_{j,y}\right) - \ln(B^S_{j,y}) \right|}{\sqrt{(\sigma^S_{j,y,Nov})^2 + \left(\phi^S_{ac}\right)^2 + (\lambda^S_{j,N})^2}} \right)^5} \right\}^{2/5} + \ln\left[2\pi \left((\sigma^S_{j,y,Nov})^2 + \left(\phi^S_{ac}\right)^2 + (\lambda^S_{j,N})^2 \right) \right] \right\}$$

(A.36)

$$-\ln L^{rec} = \tfrac{1}{2} \sum_j \sum_{y=y1+1}^{yn} \left\{ \left\{ \frac{5^5 \left(\frac{\left| \ln\left(\hat{N}^S_{j,y,r}\right) - \ln(N^S_{j,y,r}) \right|}{\sqrt{(\sigma^S_{j,y,rec})^2 + \left(\phi^S_{ac}\right)^2 + (\lambda^S_{j,r})^2}} \right)^5}{5^5 + \left(\frac{\left| \ln\left(\hat{N}^S_{j,y,r}\right) - \ln(N^S_{j,y,r}) \right|}{\sqrt{(\sigma^S_{j,y,rec})^2 + \left(\phi^S_{ac}\right)^2 + (\lambda^S_{j,r})^2}} \right)^5} \right\}^{2/5} + \ln\left[2\pi \left((\sigma^S_{j,y,rec})^2 + \left(\phi^S_{ac}\right)^2 + (\lambda^S_{j,r})^2 \right) \right] \right\}$$

(A.37)

$$-\ln L^{sur\ propl} = w_{propl}^{sur} \sum_{y=y1}^{yn} \sum_{l=6}^{21} \left\{ \frac{\left(\sqrt{\hat{p}_{j,y,l}^{S}} - \sqrt{p_{j,y,l}^{S}} \right)^2}{2\left(\sigma_{j,ur}^{S}\right)^2} + \ln\left(\sigma_{j,sur}^{S}\right) \right\} \quad \text{(A.38)}$$

$$-\ln L^{com\ propl} = w_{propl}^{com} \sum_{y=y1}^{yn} \sum_{q=1}^{4} \sum_{l=5.5}^{21} \left\{ \frac{\left(\sqrt{\hat{p}_{j,y,q,l}^{S,coml}} - \sqrt{p_{j,y,q,l}^{S,coml}} \right)^2}{2\left(\sigma_{j,com}^{S}\right)^2} + \ln\left(\sigma_{j,com}^{S}\right) \right\} \quad \text{(A.39)}$$

$$-\ln L^{prev} = \sum_{j} \sum_{y=2010}^{2014} \sum_{l=5cm}^{23cm} \left\{ -\hat{N}_{j,y,l}^{prev} \ln\left(P_{j,y,l}^{S}\right) - \left(n_{j,y,l}^{prev} - \hat{N}_{j,y,l}^{S}\right) \ln\left(1 - P_{j,y,l}^{S}\right) \right\} \quad \text{(A.40)}$$

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.

Table A.1. Assessment model parameters and variables. 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 stock j that are uninfected ($p=0$) or infected ($p=1$) with the endoparasite	Billions		A.1 - A.3, A.20	
	$N^{S}_{j,p,y,q,a}$	Model predicted numbers-at-age a mid-way through quarter q of year y of stock j that are uninfected ($p=0$) or infected ($p=1$) with the endoparasite	Billions		A.4	
	I_y	Proportion of uninfected west stock sardine that are infected with the endoparasite in year y (two stock hypothesis only)		$I_y = I \sim U(0,1)$		
	$move_{y,a}$	Proportion of west stock sardine of age a which move to the south stock at the beginning of November of year y (two stock hypothesis only)	-	=0, $y_1 \le y \le 1993$ $move_{y,1} \sim U(0,1)$, $move_{y,2+} = \phi \times move_{y,1}$, $\phi \sim U(0,1)$, $1994 \le y \le y_n$		
	$SSB^{S}_{j,y}$	Model predicted spawning biomass of stock j at the beginning of November in year y	Thousand tons		A.10	
	$B^{S}_{j,y}$	Model predicted total biomass of stock j at the beginning of November in year y, associated with the November survey	Thousand tons		A.11	
	$f^{S}_{j,y,l}$	Proportion of sardine of stock j that are mature in length class l in year y	-	$[1+\exp\{-(l-17.2)/1.17\}]^{-1}$ $1984 \le y \le 1987$ $[1+\exp\{-(l-18.6)/1.26\}]^{-1}$ $1988 \le y \le 1995$ $[1+\exp\{-(l-19.4)/1.40\}]^{-1}$ $1996 \le y \le 2003$ $[1+\exp\{-(l-17.4)/0.95\}]^{-1}$ $2004 \le y \le 2014$		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

Table A.1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Annual numbers and biomass	$w_{j,l}$	Mean mass of sardine of stock j in length class l	Grams		$1.1639 \times 10^{-5} \times l^{3.03155}$	
	$w^S_{j,y,l}$	Mean mass of sardine of stock j in length class l at the beginning of November in year y	Grams		A.12	
	$\tilde{w}_{j,y}$	Mean mass of sardine sampled from stock j during the November survey of year y	Grams		$\dfrac{B^S_{j,y}}{\sum_{l=3}^{23.5} N^S_{j,y,l} \times \dfrac{\hat{B}^S_{j,y}}{\sum_{l=3}^{23.5} N^S_{j,y,l} w^S_{j,l}}}$	
	$\overline{w}^S_{j,a}$	Mean mass of age a from stock j sampled during each November survey, averaged over all years	Grams		$\sum_{l=2.5^-}^{24^+} A^{sur}_{j,a,l} w^S_{j,l}$	
Natural Mortality	$M^S_{y,a}$	Rate of natural mortality of age a in year y	Year^{-1}		A.8 and A.9	Selected based on maximized joint posterior, and subject to a compelling reason to modify from previous assessment
	$\overline{M}^S_j$	Median juvenile rate of natural mortality	Year^{-1}	1.0		
	$\overline{M}^S_{ad}$	Median rate of natural mortality for 1+ sardine	Year^{-1}	0.8		
	ε^j_y	Annual residuals about juvenile natural mortality rate	-		A.8	
	ε^{ad}_y	Annual residuals about natural mortality rate for 1+ sardine	-		A.9	
	η^j_y	Normally distributed error in calculating ε^j_y	-	$N(0,\sigma^2_j)$		
	η^{ad}_y	Normally distributed error in calculating ε^{ad}_y	-	$N(0,\sigma^2_{ad})$		
	σ_j	Standard deviation in the annual residuals about juvenile natural mortality	-	0		See robustness tests
	σ_{ad}	Standard deviation in the annual residuals about natural mortality for ages 1+	-	0		See robustness tests
	ρ	Annual autocorrelation coefficient	-	0		See robustness tests

Table A.1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Proportions-at-length and growth curve	$N^{S}_{j,p,y,l}$	Model predicted numbers-at-length l at the beginning of November in year y of stock j that are uninfected ($p=0$) or infected ($p=1$) with the endoparasite	Billions		A.5	
	$p^{S}_{j,y,l}$	Model predicted proportion-at-length l of stock j associated with the November survey in year y	-		A.27-A.30	
	$A^{sur}_{j,a,l}$	Proportion of age a of stock j that falls in the length group l in November	-		A.7	
	$L_{j,\infty}$	Maximum length (in expectation) of stock j	Cm	$\sim U(10,30)$		$\kappa_j \times L_{j,\infty}$ assumed same for both stocks. Bounds informed by data
	κ_j	Somatic growth rate parameter for stock j	Year^{-1}	$\kappa_j \times L_{j,\infty} \sim U(0,10)$		
	t_0	Age at which the length (in expectation) is zero	Year	$\sim U(-4,4)$		
	$\vartheta_{j,a}$	Standard deviation of the distribution about the mean length for age a of stock j	-	$\sim U(0.01,3)$, $a=0,1,2+$		Assumed same for both stocks. Upper bound chosen to preclude unrealistically large lengths for very young fish
	$p^{comlS}_{j,y,q,l}$	Model predicted proportion-at-length l of stock j in the directed catch and round herring bycatch during quarter q of year y	-		A.33	
	$A^{com}_{j,q,a,l}$	Proportion of age a of stock j that falls in the length group l mid-way through quarter q	-		A.15	
	$P^{S}_{j,y,l}$	Model predicted proportion-at-length l of stock j that are infected with the endoparasite, at the time of the November survey in year y			A.31	

Table A.1 (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 stock j	-		A.26	Some smaller fish escape through the trawl net
	S_{50}	Length at which survey selectivity is 50%	Cm	$\sim U(2.5,7)$		
	δ	Slope of survey selectivity-at-length ogive when selectivity is 50%	-	$\sim U(0.1,1)$		
	$S_{j,y,l}$	Commercial selectivity-at-length l during year y of stock j	-		A.13	
	$S_{j,y,q,a}$	Commercial selectivity-at-age a during quarter q of year y of stock j	-		A.14	
	χ_j	Height of the near-normal curve component for stock j relative to the height of the near-lognormal component	-	$\sim U(0,1)$		
	$\bar{l}_{1,j}$	Mean of the near-normal distribution for stock j	Cm	$\sim U(5,15)$		Bounds reflect a trade-off between not wanting to influence the data and ensuring that results remained realistic
	$\bar{l}_{2,j}$	Median of the near-lognormal distribution for stock j	Cm	$\bar{l}_{2,j} - \bar{l}_{1,j} \sim U(0,15)$		
	$\left(\sigma_1^{sel}\right)^2$	Variance parameter of the near-normal distribution	Cm	$\sim U(2,7)$		
	$\left(\sigma_2^{sel}\right)^2$	Variance parameter of the near-lognormal distribution	Cm	$\sim U(0,2)$		

Table A.1 (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 stock j caught during quarter q of year y that are uninfected ($p=0$) or infected ($p=1$) with the endoparasite	Billions		A.18	
	$lcut_{y,m}$	Cut off length for recruits in month m of year y	Cm	de Moor et al. 2015a		Differ by month and year as informed by the recruit surveys
	$C^{bycatch}_{j,p,y,q,a}$	Number of age a fish of stock j bycaught in the anchovy-directed fishery in quarter q of year y that are uninfected ($p=0$) or infected ($p=1$) with the endoparasite	Billions		A.16	
	$C^{dir}_{j,p,y,q,a}$	Number of age a fish of stock j caught in the sardine-directed and round herring bycatch fisheries in quarter q of year y that are uninfected ($p=0$) or infected ($p=1$) with the endoparasite	Billions		A.17	
	$C^{dir}_{j,p,y,q,l}$	Number of length l fish of stock j caught in the sardine-directed and round herring bycatch fisheries in quarter q of year y	Billions		A.32	
	$F_{j,y,q}$	Fished proportion in quarter q of year y for a fully selected age class a of stock j, by the directed and round herring bycatch fisheries	-		A.19	

Table A.1 (Continued).

	Parameter/ Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Recruitment	a_j^S	Maximum recruitment of stock j in the hockey stick model	Billions	$\ln\left(a_j^S\right) \sim U(0{,}5.6)$		Uninformative on log-scale as scale is not known *a priori*, with the maximum corresponding to about 10 million tons for K_j^S
	b_j^S	Spawner biomass below which the expectation for recruitment is reduced below the maximum for stock j	Thousand tons	$b_j^S / K_j^S \sim U(0{,}1)$		
	K_j^S	Carrying capacity for stock j	Thousand tons		A.21	
	K_{peak}^S	Carrying capacity during "peak" years (single stock hypothesis only)	Thousand tons		A.21	
	$\varepsilon_{j,y}^S$	Lognormal deviation of recruitment of stock j in year y	-	$\varepsilon_{j,y}^S \sim N\left(0,\left(\sigma_{j,r}^S\right)^2\right)$ Except for $\varepsilon_{1,y}^S \sim N\left(0,\left(\sigma_{r,peak}^S\right)^2\right)$, $2000 \le y \le 2004$ for single stock hypothesis		Reflects the assumption of a different distribution applying over the peak period
	$\left(\sigma_{j,r}^S\right)^2$	Variance in the residuals (lognormal deviation) about the stock recruitment curve of stock j	-	$\sim U(0.16,10)$		Lower bound chosen to restrict the influence of the stock recruitment curve on the assessment results
	$\left(\sigma_{r,peak}^S\right)^2$	Variance in the residuals (lognormal deviation) about the stock recruitment curve during "peak" years (single stock hypothesis only)	-	$\sim U(0.16,10)$		
	$N_{j,y,r}^S$	Model predicted number of juveniles of stock j at the time of the recruit survey in year y	Billions		A.22	

Table A.1 (Continued).

	Parameter/ Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Multiplicative bias	$k^S_{j,N}$	Multiplicative bias associated with the November survey of stock j	-		A.23	
	$k^S_{j,r}$	Multiplicative bias associated with the recruit survey of stock j	-		A.24 – A.25	
	k^S_{ac}	Multiplicative bias associated with the hydro-acoustic survey	-	$\sim N\left(0.714, 0.077^2\right)$		de Moor and Butterworth (2015a)
	k^S_{cov}	Multiplicative bias associated with the coverage of the recruits by the recruit survey in comparison to the 1+ biomass by the November survey	-	$\sim U\left(0.3,1\right)$		Lower bound selected in discussions with scientists on these surveys and their field experience
	$k^S_{\mathrm{cov}\,S}$	Multiplicative bias associated with the coverage of the south stock recruits by the recruit survey in comparison to the west stock recruits during the same survey	-	$\sim U\left(0,1\right)$		
Initial Values	$N^S_{j,1983,a}$	Initial numbers-at-age a in stock j	Billion	$N^S_{j,1983,a} \sim U\left(0,50\right)$ for $j=1$, $0 \le a \le 2$ and $j=2$, $a=0$	A.34	
	$Finit_j$	Rate of fishing mortality assumed in the initial year for stock j		$\sim U\left(0,1\right)$		

Table A.1 (Continued).

	Parameter / Variable	Description	Units / Scale	Fixed Value / Prior Distribution	Equation	Notes
Likelihood	$-\ln L^{Nov}$	Contribution to the negative log likelihood from the model fit to the November 1+ survey biomass data	-		A.36	
	$-\ln L^{rec}$	Contribution to the negative log likelihood from the model fit to the recruit survey data	-		A.37	
	$-\ln L^{sur\ propl}$	Contribution to the negative log likelihood from the model fit to the November survey proportion-at-length data	-		A.38	
	$-\ln L^{com\ propl}$	Contribution to the negative log likelihood from the model fit to the quarterly commercial proportion-at-length data	-		A.39	
	$-\ln L^{sur\ prev}$	Contribution to the negative log likelihood from the model fit to the November parasite prevalence-at-length data	-		A.40	
	ϕ_{ac}^{S}	CV associated with factors which cause bias in the acoustic survey estimates and which vary inter-annually rather than remain fixed over time	-	$=0.222$		de Moor and Butterworth (2015a)
	$\left(\lambda_{j,N/r}^{S}\right)^2$	Additional variance (over and above $\left(\sigma_{j,y,Nov/rec}^{S}\right)^2$ and $\left(\phi_{ac}^{S}\right)^2$) associated with the November/recruit surveys of stock j	-	$\sim U(0,10)$		
	w_{propl}^{sur}	Weighting applied to the remaining survey proportion-at-length data	-	$=0.167$		
	$\sigma_{j,sur}^{S}$	Standard deviation associated with the survey proportion-at-length data of stock j	-	$\sqrt{\sum_{y=y1}^{yn}\sum_{l=6}^{21}\left(\sqrt{\hat{p}_{j,y,l}^{S}}-\sqrt{p_{j,y,l}^{S}}\right)^2 \Big/ \sum_{y=y1}^{yn}\sum_{l=6}^{21}1}$		Closed form solution
	w_{propl}^{com}	Weighting applied to the commercial proportion-at-length data		0.04		To allow for autocorrelation[4]
	$\sigma_{j,com}^{S}$	Standard deviation associated with the commercial proportion-at-length data of stock j	-	$\sqrt{\sum_{y=y1}^{yn}\sum_{q=1}^{4}\sum_{l=5}^{12}\left(\sqrt{\hat{p}_{y,q,l}^{A,coml}}-\sqrt{p_{y,q,l}^{A,coml}}\right)^2 \Big/ \sum_{y=y1}^{yn}\sum_{q=1}^{4}\sum_{l=5}^{12}1}$		Closed form solution

[4] Based upon data being available ~4x6 times more frequently than annual age data which contain maximum information content on this

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

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