South African sardine assessment posterior distributions and sensitivity tests

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A number of sensitivity tests to assumptions underlying the baseline assessment of South African sardine have been undertaken. Sardine recruitment is highly variable and there is no clear stock recruit relationship for the west or south components. A Beverton Holt stock recruitment relationship for the west component thus provides a very similar fit to that achieved by the Hockey Stick relationship assumed for the baseline model. These sensitivity tests also indicate that sardine natural mortality may have increased and remained at a higher rate after the peak recruitment years at the turn of the century.

Introduction

The most recent baseline assessment for South African sardine, conditioned to data available from 1984 – 2019, was presented by de Moor (2020a). This document contains the posterior distributions from the baseline assessment and considers a number of sensitivity tests to assumptions underlying the baseline assessment.

Methods

The baseline model is detailed in Appendix A and the data in de Moor *et al.* (2020). For ease of comparison, the changes in the model since de Moor (2020b) have been highlighted. The parameters are defined in Tables A1 and A2. Appendix B details the method used to estimate alternative stock recruitment relationships for the west component while Appendix C details the method used to estimate a 'two-step' stock recruitment relationship for the south component.

The following sensitivity tests were considered:

S_{HS} - $\bar{M}_j^S = \bar{M}_{ad}^S = 1.0$. Hockey Stick stock-recruitment curve fit after conditioning for west component, with the proportion of south component spawner biomass that contributes to the effective spawning biomass on the west coast $1 - \xi_S = 0.08$. Two-step recruitment model fit after conditioning for south component. **Baseline OM.**

S_{BH} - Beverton Holt stock-recruitment curve fit after conditioning, with $1 - \xi_S = 0.08$.

S_R - Ricker stock-recruitment curve fit after conditioning, with $1 - \xi_S = 0.08$.

$S_{0.2}$ - Hockey Stick stock-recruitment curve fit after conditioning, with $1 - \xi_S = 0.2$.

$S_{0.4}$ - Hockey Stick stock-recruitment curve fit after conditioning, with $1 - \xi_S = 0.4$.

S_M - $\bar{M}_j^S = \bar{M}_{ad}^S = 1.2$

S_{Mad} - Annually varying adult natural mortality, i.e. random effects model with $\sigma_{ad} = 0.1$ and 0.2 (2 alternatives) and $\rho \sim U(0,1)$.

S_{Mj} - Annually varying juvenile natural mortality, i.e. random effects model with $\sigma_j = 0.1$ and 0.2 (2 alternatives) and $\rho \sim U(0,1)$.

S_5 - No plus group, all remaining fish assumed to die as they reach age 6.

S_{mov1} - West-to-south movement and infection occurs on 1 August instead of 1 November.

S_{mov2} - West-to-south movement occurs on 1 August instead of 1 November.

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S_{sur} - standard deviation associated with the survey proportion-at-length data is estimated annually (through closed form solution and bounded between [0.04,0.1]) and not as a time-invariant standard deviation

S_{com} - standard deviation associated with the commercial proportion-at-length data is estimated annually (through closed form solution and bounded between [0.04,0.1]) and not as a time-invariant standard deviation

S_{prev} - Include samples from between 20 and 22°E in the south component prevalence at length data.

$S_{k0.6}$ - Acoustic survey bias fixed, $k_{ac}^{S} = 0.6$.

S_{k1} - Acoustic survey bias fixed, $k_{ac}^{S} = 1.0$.

S_{lamR} - Additional variance (over and above the survey sampling CV) associated with the recruit survey, fixed $(\lambda_r^S)^2 = 0.02$.

S_{lamN} - Additional variance (over and above the survey sampling CV) associated with the November survey, fixed $\left(\lambda_N^S\right)^2 = 0.02$.

S_{weight} - Down weight the survey and commercial proportion-at-length data, i.e. w_{propl}^{sur} and w_{propl}^{com} in equations A34 and A35 replaced with $0.3w_{propl}^{sur}$ and $0.3w_{propl}^{com}$.

For S_{mov1} the numbers-at-age at 1 August before movement or infection are:

$$N_{j,p,y,a}^{S*} = \left(\left(\left(N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/8} - C_{j,p,y,1,a}^{S}\right) e^{-M_{y,a}^{S}/4} - C_{j,p,y,2,a}^{S}\right) e^{-M_{y,a}^{S}/4} - C_{j,p,y,3,a}^{S}\right) e^{-M_{y,a}^{S}/8}$$

$$p = I, NI, y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

Infection of west component sardine at 1 August:

$$\mathrm{N}_{\mathrm{W,NI,y,a}}^{\mathrm{S**}} = \left(1 - \mathrm{I_y}\right)\mathrm{N}_{\mathrm{W,NI,y,a}}^{\mathrm{S*}} \qquad y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

$$\mathrm{N}_{\mathrm{W,I,y,a}}^{\mathrm{S**}} = \mathrm{N}_{\mathrm{W,I,y,a}}^{\mathrm{S*}} + \mathrm{I_y}\mathrm{N}_{\mathrm{W,NI,y,a}}^{\mathrm{S*}} \qquad y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

$$\mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S**}} = \mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S*}} \qquad p = I, NI, y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

Movement of west component (j = W) sardine to the south component (j = S) at 1 August:

$$\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S***}} = \left(1 - \mathrm{move_{y,a}}\right)\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S**}} \qquad p = I, NI, y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

$$\mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S***}} = \mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S**}} + \mathrm{move_{y,a}}\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S**}} \qquad p = I, NI, y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

The Numbers-at-age at 1 November are:

$$N_{j,p,y,a}^{S} = \left(N_{j,p,y,a-1}^{S***} e^{-M_{y,a-1}^{S}/8} - C_{j,p,y,4,a-1}^{S}\right) e^{-M_{y,a-1}^{S}/8} \qquad p = I, NI, y_1 \leq y \leq y_n, 1 \leq a \leq 4$$

$$N_{j,p,y,5^+}^{S} = \left(N_{j,p,y,4}^{S***} e^{-M_{y,4}^{S}/8} - C_{j,p,y,4,4}^{S}\right) e^{-M_{y,4}^{S}/8} + \left(N_{j,p,y,5^+}^{S} e^{-M_{y,5^+}^{S}/8} - C_{j,p,y,4,5^+}^{S}\right) e^{-M_{y,5^+}^{S}/8}$$

$$p = I, NI, y_1 \leq y \leq y_n$$

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

$$N_{j,p,y,1,a}^{S} = N_{j,p,y-1,a}^{S} e^{-M_{y,a}^{S}/8} \qquad p = I, NI, y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

$$N_{j,p,y,q,a}^{S} = \left(N_{j,p,y,q-1,a}^{S} - C_{j,p,y,q-1}^{S}\right)e^{-M_{y,a}^{S}/4} \qquad p = I, NI, y_1 \leq y \leq y_n, 2 \leq q \leq 3, 0 \leq a \leq 5^+$$

$$N_{j,p,y,4,a}^{S\prime} = \left(N_{j,p,y,3,a}^{S} - C_{j,p,y,3}^{S}\right)e^{-M_{y,a}^{S}/8} \qquad p = I, NI, y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

$$N_{W,NI,y,4,a}^{S\prime\prime} = \left(1 - \mathrm{I_y}\right)N_{W,NI,y,4,a}^{S\prime} \qquad y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

$$N_{W,I,y,4,a}^{S\prime\prime} = N_{W,I,y,4,a}^{S\prime} + \mathrm{I_y}N_{W,NI,y,4,a}^{S\prime} \qquad y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

$$\mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S}\prime\prime} = \mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S}\prime} \qquad p = I, NI, y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

$$\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S}\prime\prime\prime} = \left(1 - \mathrm{move_{y,a}}\right)\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S}\prime\prime} \qquad p = I, NI, y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

$$\mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S}\prime\prime\prime} = \mathrm{N}_{\mathrm{S,p,y,a}}^{\mathrm{S}\prime\prime} + \mathrm{move_{y,a}}\mathrm{N}_{\mathrm{W,p,y,a}}^{\mathrm{S}\prime\prime} \qquad p = I, NI, y_1 \leq y \leq y_n, 0 \leq a \leq 5^+$$

$$N^{S}_{j,p,y,4,a} = N^{S'''}_{j,p,y,4,a} e^{-M^{S}_{y,a}/8} \qquad p = I, NI, y_1 \le y \le y_n, 0 \le a \le 5^+$$

For S_{mov2} the numbers-at-age at 1 August before movement or infection are:

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

$$p = I, NI, y_1 \le y \le y_n, 0 \le a \le 5^+$$

Movement of west component (j = W) sardine to the south component (j = S) at 1 August:

$$\mathrm{N}^{S**}_{W,p,y,a} = \left(1 - \mathrm{move}_{y,a}\right)\mathrm{N}^{S*}_{W,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n, 0 \le a \le 5^+$$

$$\mathrm{N}^{S**}_{S,p,y,a} = \mathrm{N}^{S**}_{S,p,y,a} + \mathrm{move}_{y,a}\mathrm{N}^{S*}_{W,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n, 0 \le a \le 5^+$$

The Numbers-at-age at 1 November are:

$$N^{S***}_{j,p,y,a} = \left(N^{S**}_{j,p,y,a-1} e^{-M^{S}_{y,a-1}/8} - C^{S}_{j,p,y,4,a-1}\right) e^{-M^{S}_{y,a-1}/8} \qquad p = I, NI, y_1 \le y \le y_n, 1 \le a \le 4$$

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

$$p = I, NI, y_1 \le y \le y_n$$

Infection of west component sardine at 1 November:

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

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

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

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

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

$$N^{S}_{j,p,y,q,a} = \left(N^{S}_{j,p,y,q-1,a} - C^{S}_{j,p,y,q-1}\right) e^{-M^{S}_{y,a}/4} \qquad p = I, NI, y_1 \le y \le y_n, 2 \le q \le 3, 0 \le a \le 5^+$$

$$N^{S'}_{j,p,y,4,a} = \left(N^{S}_{j,p,y,3,a} - C^{S}_{j,p,y,3}\right) e^{-M^{S}_{y,a}/8} \qquad p = I, NI, y_1 \le y \le y_n, 0 \le a \le 5^+$$

$$\mathrm{N}^{S''}_{W,p,y,a} = \left(1 - \mathrm{move}_{y,a}\right)\mathrm{N}^{S'}_{W,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n, 0 \le a \le 5^+$$

$$\mathrm{N}^{S''}_{S,p,y,a} = \mathrm{N}^{S'}_{S,p,y,a} + \mathrm{move}_{y,a}\mathrm{N}^{S'}_{W,p,y,a} \qquad p = I, NI, y_1 \le y \le y_n, 0 \le a \le 5^+$$

$$N^{S}_{j,p,y,4,a} = N^{S''}_{j,p,y,4,a} e^{-M^{S}_{y,a}/8} \qquad p = I, NI, y_1 \le y \le y_n, 0 \le a \le 5^+$$

Appendices D and E detail the fitting of relationships to be used when projecting the sardine population forward in time (de Moor 2020c).

Results

Table 1 compares the fit to the data, the posterior (objective function) at the joint posterior mode and the posterior distributions for some key model parameters for all the sensitivity tests.

There is little difference in the fit to stock recruit data between S_{HS}, S_{BH}, S_{02} and S_{04}, although S_{HS} remains the best fit. The fit to the stock recruit data under S_R is worse than that of S_{HS}, but not significantly so (<2 -LnL points at the median). As expected, the hinge point increases as the south component's contribution to the west component effective spawning biomass increases (from S_{HS} to S_{02} to S_{04}) (Figure 1).

Assuming a higher time invariant juvenile and adult natural mortality rate (S_M) results in a better fit to the data. Only a small improvement in the fit to the data is achieved by allowing juvenile natural mortality to vary annually (S_{Mj}), while there is a substantial improvement in the fit to the data when adult natural mortality is allowed to vary (S_{Mad}). All four of these tests indicate a higher natural mortality since about 2003-2005 compared to the first half of the modelled time series (Figure 2). Furthermore, these autocorrelated changes in natural mortality may suggest that this model is not simply estimating changes to natural mortality to 'fit to noise' (Smith *et al*. 2011).

S_{mov1} and S_{mov2} resulted in substantially worse fits to the data which did not converge, and thus MCMC chains could not be run to estimate the posterior distributions. As there remains some interest in these sensitivity tests, attempting to obtain realistic fits to the data with these alternative assumptions might be re-attempted with a future assessment using a wider range of initial conditions.

Estimating an annual standard deviation associated with the survey or commercial proportion-at-length data, instead of estimating a time-invariant standard deviation, resulted in a lower objective function, but this was partially attributable to the different standard deviations rather than only from an improved fit to the data. Downweighting the survey and commercial proportion-at-length data (S_{weight}) results (as expected) in an improvement in the fit to the survey and parasite prevalence data, with a lower estimate of current biomass and a higher estimate of spawner biomass.

Including parasite prevalence samples from between 20 and 22°E in the south component prevalence at length data resulted in a substantial reduction in the fit to the May/June recruit survey. These data may include some west component fish mixed with south component fish.

The results from S_{k1} and S_{k06} indicate that is it likely that the acoustic survey bias is higher (and thus current biomass and spawner biomass estimates are lower than the baseline estimates), but less likely that the bias is lower.

The results were relatively insensitive to S_5, S_{lamR} and S_{lamN}. S_{lamR} and S_{lamN} will likely remain as long-term sensitivity tests; however, given the lack of sensitivity to the inclusion or exclusion of a plus-group, S_5 could be excluded from future assessments.

Discussion

This document has provided a number of sensitivity tests to assumptions underlying the baseline assessment of South African sardine. It has recently been decided that OMP-18rev will be an anchovy-only OMP, and thus it is unnecessary to test the robustness of this OMP to alternative sardine operating models. However, these sensitivity tests continue to highlight the uncertainty about a clear relationship between sardine effective spawning biomass and recruitment – this may be further explored with alternative stock structure hypotheses during the development of Operating Models for OMP-22.

These sensitivity tests indicate that it is likely that the sardine natural mortality rate has increased following the peak west component recruitments observed at the turn of the century and have remained high in recent years. This may reflect a density dependent response from predation by predators on a reduced stock size.

Four further sensitivity tests have previously been proposed, but were not considered due to time constraints. They may be considered for the next sardine assessment and/or OMP robustness testing:

S_{DD} - Component-specific density dependent natural mortality: $\bar{M}^S_{juv,j,y} = \bar{M}^S_{ad,j,y} = \bar{M} + e^{-\chi B^S_{j,y-1}}$.

S_{mat} - Alternative maturity-at-length relationships over time and between components

S_{Mpulse} - Natural mortality assumed to have increased between 2000 and 2005; i.e. $\bar{M}^S_j = \bar{M}^S_{ad} = 1.5$year^{-1} between 2000 and 2005 and $\bar{M}^S_j = \bar{M}^S_{ad} = 1.0$ year^{-1} in all other years. The Hockey Stick stock recruitment relationship was estimated to correspond to all years excluding 2000 to 2005.[1]

S_{sig} - The standard deviation about the west component Hockey Stick stock recruitment relationship is fixed $\sigma^S_{w,r} = 0.9$ (Bergh 2018).

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[1] It is possible this will not be considered further given the results of Mj and M_{ad}.

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Table 1. The posterior median and 95% probability intervals for key parameters and outputs. The value from the deterministic fit is given in *italics* and the individual contributions to the objective function from the deterministic fit at the joint posterior mode are shown. All robustness tests are defined in the main text and all parameters are defined in Table A.1 and Appendix B. Fixed values are given in **bold**. Numbers are reported in billions and biomass in thousands of tons.

	S_{HS}	S_{BH}	S_R	S_{02}	S_{04}	S_M
Obj fn			1147.4			1146.5
$-lnL$			1076.0			1073.5
$-lnL^{Nov}$			61.6			61.1
$-lnL^{rec}$			40.1			39.5
$-lnL^{com\ pro}$			-442.9			-440.8
$-lnL^{sur\ pro}$			-387.5			-391.5
$-lnL^{prev}$			1804.8			1805.2
$ln(k_{ac}^S)$			-1.3			-1.4
$move_{y,1}$			-30.8			-30.9
η_y^t			-14.5			-12.6
$\bar{l}_{1,y}$			117.7			117.6
ε_y^{ju} & ε_y^{ad}			0.0			0.0
$\bar{M}_j^S$			**1.0**			**1.2**
$\bar{M}_{ad}^S$			**1.0**			**1.2**
σ_j			-			-
σ_{ad}			-			-
ρ			-			-
$k_{j,N}^S$			*0.77* 0.74 [0.63,0.88]			*0.73* 0.72 [0.62,0.85]
$k_{w,r}^S$			*0.60* 0.74 [0.61,0.87]			*0.48* 0.70 [0.51,0.84]
$k_{s,r}^S$			*0.58* 0.49 [0.24,0.75]			*0.48* 0.63 [0.43,0.79]
$(\lambda_{w,N}^S)^2$			*0.00*			**0.00**
$(\lambda_{s,N}^S)^2$			*0.00*			**0.00**
$(\lambda_{w,r}^S)^2$			*0.00*			**0.00**
$(\lambda_{s,r}^S)^2$			*0.00*			**0.00**
α_w^S	12.98 [10.44,24.71]	14.90 [10.68,29.75]	0.38 [0.25,0.60]	12.94 [10.44,22.98]	12.85 [10.38,20.07]	17.33 [13.47,28.68]
β_w^S	18.0 [3.5,114.0]	10.0 [0.1,90.3]	0.008 [0.004,0.015]	23.1 [5.3,141.6]	29.1 [7.7,150.7]	12.7 [2.8,73.8]
K_w^S	193 [141,377]	213 [147,387]	215 [140,382]	193 [141,349]	192 [140,312]	159 [113,262]
$\sigma_{w,r}^S$	0.95 [0.78,1.10]	0.95 [0.78,1.09]	0.98 [0.80,1.15]	0.95 [0.79,1.10]	0.95 [0.79,1.10]	0.89 [0.76,1.04]
p^i			0.24 [0.15,0.35]			0.24 [0.15,0.35]
$exp(R_1^i)$			0.002 [0.000,0.018]			0.002 [0.000,0.028]
$exp(R_2^i)$			2.88 [1.66,5.14]			2.71 [1.50,5.19]
σ_1^S			1.93 [1.06,1.83]			1.86 [0.88,2.73]
σ_1^S			1.40 [1.04,1.83]			1.48 [0.99,2.18]
$B_{w,2019}^S$			*90* 62 [17,166]			*95* 48 [17,123]
$B_{s,2019}^S$			*385* 381 [207,584]			*319* 292 [178,427]
$B_{w,2019}^{sp,S}$			*7* 17 [6,49]			*6* 8 [3,23]
$B_{s,2019}^{sp,S}$			*184* 147 [69,263]			*145* 108 [57,182]

Table 1 (continued).

	S_{HS}	$S_{Mad0.1}$	$S_{Mad0.2}$	$S_{Mj0.1}$	$S_{Mj0.2}$	S_5
Obj fn	1147.4	1095.6	1117.7	1097.4	1122.0	1146.9
$-lnL$	1076.0	1073.1	1069.4	1075.7	1075.0	1075.5
$-lnL^{Nov}$	61.6	61.2	60.7	61.4	61.2	61.4
$-lnL^{rec}$	40.1	38.6	37.9	40.1	40.1	40.2
$-lnL^{com\ pro}$	-442.9	-442.2	-442.4	-442.8	-442.8	-442.9
$-lnL^{sur\ pro}$	-387.5	-389.3	-391.5	-387.7	-388.0	-387.7
$-lnL^{prev}$	1804.8	1804.7	1804.6	1804.7	1804.6	1804.4
$ln(k_{ac}^S)$	-1.3	-1.4	-1.4	-1.3	-1.3	-1.3
$move_{y,1}$	-30.8	-30.8	-30.8	-30.8	-30.8	-30.8
η_y^t	-14.5	-15.1	-15.1	-14.5	-14.5	-14.5
$\bar{l}_{1,y}$	117.7	117.6	117.6	117.7	117.7	117.7
ε_y^{ju} & ε_y^{ad}	0.0	-48.2	-22.4	-49.7	-24.4	0.0
$\bar{M}_j^S$	**1.0**	**1.0**	**1.0**	0.96-1.03	0.9-1.1	**1.0**
$\bar{M}_{ad}^S$	**1.0**	1.0-1.2	0.9-1.5	**1.0**	**1.0**	**1.0**
σ_j	-	-	-	**0.02**	**0.02**	-
σ_{ad}	-	**0.02**	**0.02**	-	-	-
ρ	-	0.90	0.87	0.86	0.85	-
$k_{j,N}^S$	*0.77* 0.74 [0.63,0.88]	*0.76* 0.74 [0.61,0.89]	*0.75* 0.73 [0.62,0.86]	*0.77* 0.74 [0.62,0.89]	*0.77* 0.76 [0.62,0.91]	*0.77* 0.76 [0.64,0.90]
$k_{w,r}^S$	*0.60* 0.74 [0.61,0.87]	*0.57* 0.74 [0.60,0.89]	*0.55* 0.72 [0.61,0.86]	*0.60* 0.74 [0.62,0.89]	*0.61* 0.75 [0.62,0.91]	*0.59* 0.76 [0.64,0.89]
$k_{s,r}^S$	*0.58* 0.49 [0.24,0.75]	*0.55* 0.49 [0.24,0.74]	*0.51* 0.48 [0.24,0.74]	*0.58* 0.48 [0.23,0.76]	*0.57* 0.48 [0.24,0.76]	*0.56* 0.50 [0.26,0.78]
$(\lambda_{w,N}^S)^2$	*0.00*	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
$(\lambda_{s,N}^S)^2$	*0.00*	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
$(\lambda_{w,r}^S)^2$	*0.00*	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
$(\lambda_{s,r}^S)^2$	*0.00*	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
α_w^S	12.98 [10.44,24.71]	13.23 [10.76,24.63]	13.46 [10.76,24.45]	12.31 [9.65,22.45]	11.54 [8.72,21.13]	12.44 [10.00,24.39]
β_w^S	18.0 [3.5,114.0]	18.9 [4.5,116.0]	20.8 [5.1,110.9]	16.0 [3.7,112.0]	17.1 [3.5,112.5]	17.4 [3.3,119.5]
K_w^S	193 [141,377]	191 [147,362]	197 [146,361]	182 [132,336]	168 [121,323]	181 [127,351]
$\sigma_{w,r}^S$	0.95 [0.78,1.10]	0.92 [0.78,1.06]	0.93 [0.77,1.07]	0.95 [0.80,1.10]	0.94 [0.78,1.08]	0.94 [0.79,1.09]
p^i	0.24 [0.15,0.35]	0.26 [0.15,0.35]	0.26 [0.15,0.35]	0.24 [0.15,0.35]	0.24 [0.15,0.35]	0.24 [0.15,0.35]
$exp(R_1^i)$	0.002 [0.000,0.018]	0.001 [0.000,0.010]	0.002 [0.000,0.016]	0.002 [0.000,0.012]	0.001 [0.000,0.011]	0.002 [0.000,0.017]
$exp(R_2^i)$	2.88 [1.66,5.14]	2.80 [1.51,4.95]	2.89 [1.55,5.16]	2.71 [1.44,5.12]	2.61 [1.33,4.88]	2.73 [1.38,5.19]
σ_1^S	1.93 [1.06,1.83]	1.88 [0.98,2.63]	1.93 [1.04,2.66]	1.87 [0.91,2.72]	1.88 [0.91,2.68]	1.90 [0.96,2.71]
σ_1^S	1.40 [1.04,1.83]	1.46 [1.04,2.16]	1.44 [1.04,2.15]	1.45 [1.03,2.17]	1.46 [1.05,2.15]	1.44 [1.02,2.20]
$B_{w,2019}^S$	*90* 62 [17,166]	*94* 53 [17,131]	*93* 58 [23,142]	*88* 58 [22,150]	*86* 56 [18,145]	*91* 59 [17,156]
$B_{s,2019}^S$	*385* 381 [207,584]	*330* 329 [169,508]	*264* 278 [119,441]	*380* 368 [207,570]	*368* 367 [194,647]	*380* 345 [193,541]
$B_{w,2019}^{sp,S}$	*7* 17 [6,49]	7 12 [3,29]	*6* 13 [5,32]	*8* 16 [6,42]	*6* 16 [5,40]	*7* 17 [5,46]
$B_{s,2019}^{sp,S}$	*184* 147 [69,263]	*155* 127 [56,228]	*110* 90 [30,184]	*293* 144 [71,248]	*179* 144 [65,277]	*181* 129 [59,230]

Table 1 (continued).

	S_{HS}	S_{mov}[2]	S_{sur}	S_{com}	S_{prev}
Obj fn	1147.4	1305.7	1128.7	1123.6	1432.0
$-lnL$	1076.0	1235.5	1054.3	1052.9	1362.1
$-lnL^{Nov}$	61.6	138.5	61.8	61.5	62.3
$-lnL^{rec}$	40.1	100.6	41.3	40.4	52.1
$-lnL^{com\ pro}$	-442.9	-432.7	-441.8	-466.6	-444.0
$-lnL^{sur\ pro}$	-387.5	-380.3	-410.1	-387.8	-386.0
$-lnL^{prev}$	1804.8	1809.4	1803.1	1805.4	2077.6
$ln(k_{ac}^S)$	-1.3	-1.1	-1.3	-1.3	-1.3
$move_{y,1}$	-30.8	-30.1	-30.6	-30.8	-31.4
η_y^t	-14.5	-16.7	-11.8	-14.5	-15.7
$\bar{l}_{1,y}$	117.7	117.8	117.7	117.0	117.7
ε_y^{ju} & ε_y^{ad}	0.0	0.0	0.0	0.0	0.0
$\bar{M}_j^S$	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
$\bar{M}_{ad}^S$	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
σ_j	-	-	-	-	-
σ_{ad}	-	-	-	-	-
ρ	-	-	-	-	-
$k_{j,N}^S$	*0.77* 0.74 [0.63,0.88]	*0.79*	*0.78* 0.75 [0.63,0.89]	*0.77* 0.74 [0.63,0.89]	*0.77* 0.71 [0.61,0.84]
$k_{w,r}^S$	*0.60* 0.74 [0.61,0.87]	*0.79*	*0.60* 0.75 [0.63,0.89]	*0.59* 0.74 [0.63,0.89]	*0.57* 0.71 [0.60,0.84]
$k_{s,r}^S$	*0.58* 0.49 [0.24,0.75]	*0.79*	*0.57* 0.50 [0.26,0.77]	*0.54* 0.48 [0.24,0.75]	*0.37* 0.35 [0.19,0.63]
$(\lambda_{w,N}^S)^2$	*0.00*	**0.00**	**0.00**	**0.00**	**0.00**
$(\lambda_{s,N}^S)^2$	*0.00*	**0.00**	**0.00**	**0.00**	**0.00**
$(\lambda_{w,r}^S)^2$	*0.00*	**0.00**	**0.00**	**0.00**	**0.00**
$(\lambda_{s,r}^S)^2$	*0.00*	**0.00**	**0.00**	**0.00**	**0.00**
α_w^S	12.98 [10.44,24.71]		12.67 [9.86,23.67]	13.08 [10.45,21.92]	13.24 [10.46,21.22]
β_w^S	18.0 [3.5,114.0]		18.6 [3.6,109.8]	17.5 [3.9,100.7]	16.5 [3.2,89.8]
K_w^S	193 [141,377]		184 [132,347]	191 [143,318]	208 [152,330]
$\sigma_{w,r}^S$	0.95 [0.78,1.10]		0.96 [0.80,1.09]	0.93 [0.78,1.06]	0.98 [0.83,1.14]
p^i	0.24 [0.15,0.35]		0.24 [0.15,0.38]	0.26 [0.15,0.35]	0.26 [0.15,0.38]
$exp(R_1^i)$	0.002 [0.000,0.018]		0.002 [0.000,0.022]	0.002 [0.000,0.015]	0.002 [0.000,0.012]
$exp(R_2^i)$	2.88 [1.66,5.14]		2.79 [1.42,5.47]	2.92 [1.50,5.56]	3.29 [1.84,6.00]
σ_1^S	1.93 [1.06,1.83]		1.90 [0.93,2.69]	1.87 [0.99,2.71]	1.94 [1.04,2.66]
σ_1^S	1.40 [1.04,1.83]		1.43 [0.98,2.17]	1.42 [0.99,2.14]	1.41 [0.95,2.15]
$B_{w,2019}^S$	*90* 62 [17,166]	*1*	*80* 53 [20,133]	*97 54 [20,133]*	*83* 52 [16,149]
$B_{s,2019}^S$	*385* 381 [207,584]	*322*	*352* 373 [226,570]	*398* 373 [226,570]	*416* 413 [271,586]
$B_{w,2019}^{sp,S}$	*7* 17 [6,49]	*1*	*9* 12 [4,32]	*8* 12 [4,32]	*7* 16 [5,40]
$B_{s,2019}^{sp,S}$	*184* 147 [69,263]	*150*	*163* 143 [76,346]	*180* 143 [76,246]	*143* 144 [74,258]

[2] The fit to the data for S_{mov2} was substantially worse than for S_{mov1}.

Table 1 (continued).

	S_{HS}	$S_{k0.6}$	S_{k1}	S_{lamR}	S_{lamN}	S_{weight}
Obj fn	1147.4	1151.2	1152.3	1148.1	1148.1	1717.7
$-lnL$	1076.0	1078.0	1076.7	1076.7	1076.8	1652.3
$-lnL^{Nov}$	61.6	61.6	61.0	61.5	62.5	58.1
$-lnL^{rec}$	40.1	40.1	39.5	41.1	40.0	37.2
$-lnL^{com\ pro}$	-442.9	-443.2	-441.5	-443.0	-442.9	-126.7
$-lnL^{sur\ pro}$	-387.5	-387.4	-388.4	-387.6	-387.5	-109.2
$-lnL^{prev}$	1804.8	1806.8	1806.1	804.7	1804.7	1792.9
$ln(k_{ac}^{S})$	-1.3	0.8	3.97	-1.3	-1.3	-1.1
$move_{y,1}$	-30.8	-30.9	-31.1	-30.8	-30.8	-31.0
η_y^t	-14.5	-14.5	-15.7	-14.5	-14.5	-18.8
$\bar{l}_{1,y}$	117.7	117.6	117.6	117.7	117.7	116.1
ε_y^{ju} & ε_y^{ad}	0.0	0.0	0.0	0.0	0.0	0.0
$\bar{M}_j^S$	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
$\bar{M}_{ad}^S$	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**	**1.0**
σ_j	-	-	-	-	-	-
σ_{ad}	-	-	-	-	-	-
ρ	-	-	-	-	-	-
$k_{j,N}^S$	*0.77* 0.74 [0.63,0.88]	**0.60**	**1.00**	*0.77* 0.76 [0.64,0.90]	*0.77* 0.75 [0.63,0.90]	*0.79* 0.76 [0.64,0.91]
$k_{w,r}^S$	*0.60* 0.74 [0.61,0.87]	*0.48* 0.60 [0.57,0.60]	*0.74* 1.00 [0.88,1.00]	*0.60* 0.76 [0.64,0.90]	*0.60* 0.75 [0.63,0.90]	*0.68* 0.75 [0.64,0.91]
$k_{s,r}^S$	*0.58* 0.49 [0.24,0.75]	*0.47* 0.41 [0.22,0.59]	*0.72* 0.57 [0.31,0.96]	*0.58* 0.49 [0.25,0.77]	*0.59* 0.49 [0.25,0.76]	*0.55* 0.53 [0.27,0.79]
$(\lambda_{w,N}^S)^2$	*0.00*	**0.00**	**0.00**	**0.00**	**0.02**	**0.00**
$(\lambda_{s,N}^S)^2$	*0.00*	**0.00**	**0.00**	**0.00**	**0.02**	**0.00**
$(\lambda_{w,r}^S)^2$	*0.00*	**0.00**	**0.00**	**0.02**	**0.00**	**0.00**
$(\lambda_{s,r}^S)^2$	*0.00*	**0.00**	**0.00**	**0.02**	**0.00**	**0.00**
α_w^S	12.98 [10.44,24.71]	15.50 [12.90,27.99]	10.16 [8.69,16.32]	12.46 [9.82,25.06]	12.49 [9.59,24.59]	12.10 [9.72,21.52]
β_w^S	18.0 [3.5,114.0]	24.9 [4.7,145.6]	12.7 [3.8,68.2]	17.6 [4.1,119.7]	17.8 [3.3,110.7]	12.9 [2.1,99.5]
K_w^S	193 [141,377]	225 [169,427]	149 [116,241]	178 [128,371]	180 [129,345]	179 [119,327]
$\sigma_{w,r}^S$	0.95 [0.78,1.10]	0.97 [0.79,1.11]	0.90 [0.76,1.03]	0.94 [0.80,1.09]	0.95 [0.79,1.07]	0.97 [0.82,1.12]
p^i	0.24 [0.15,0.35]	0.24 [0.15,0.35]	0.24 [0.15,0.35]	0.24 [0.15,0.35]	0.24 [0.15,0.35]	0.26 [0.15,0.38]
$exp(R_1^i)$	0.002 [0.000,0.018]	0.002 [0.000,0.016]	0.002 [0.000,0.012]	0.001 [0.000,0.014]	0.002 [0.000,0.025]	0.002 [0.000,0.010]
$exp(R_2^i)$	2.88 [1.66,5.14]	3.15 [1.66,6.33]	2.33 [1.30,4.26]	2.81 [1.46,5.50]	2.77 [1.44,5.49]	2.28 [1.22,4.29]
σ_1^S	1.93 [1.06,1.83]	1.94 [1.02,2.78]	1.85 [0.82,2.72]	1.82 [0.89,2.70]	1.89 [0.89,2.72]	1.91 [0.98,2.64]
σ_1^S	1.40 [1.04,1.83]	1.43 [0.93,2.14]	1.44 [1.06,2.14]	1.46 [1.03,2.14]	1.42 [1.03,2.15]	1.41 [0.99,2.11]
$B_{w,2019}^S$	*90* 62 [17,166]	*126* 72 [27,199]	*68* 40 [13,105]	*90* 59 [19,154]	*91* 58 [17,154]	*71* 50 [17,113]
$B_{s,2019}^S$	*385* 381 [207,584]	*462* 427 [249,632]	*312* 317 [178,493]	*384* 348 [203,539]	*386* 363 [190,556]	*214* 279 [120,555]
$B_{w,2019}^{sp,S}$	*7* 17 [6,49]	*9* 19 [7,50]	*6* 8 [3,23]	*7* 16 [4,42]	*7* 16 [5,46]	*23* 22 [7,51]
$B_{s,2019}^{sp,S}$	*184* 147 [69,263]	*226* 175 [93,293]	*148* 123 [63,211]	*184* 131 [64,231]	*186* 139 [63,241]	*133* 149 [68,327]

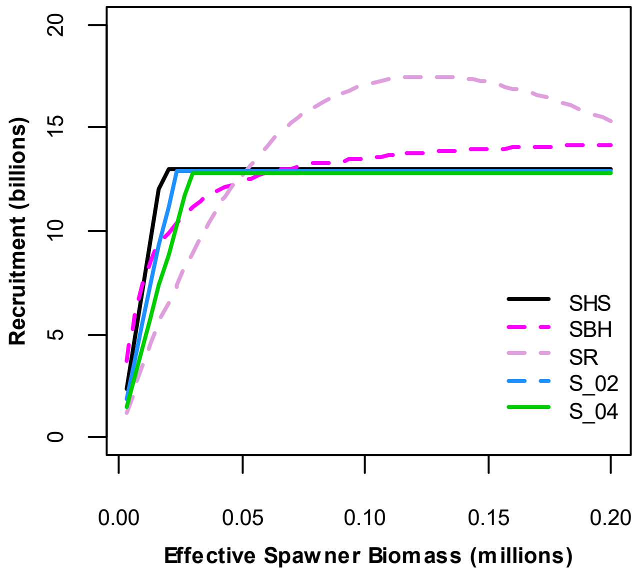

Figure 1. Posterior median stock recruitment relationships corresponding to S_{HS}, S_{BH}, S_R, S_{02} and S_{04}.

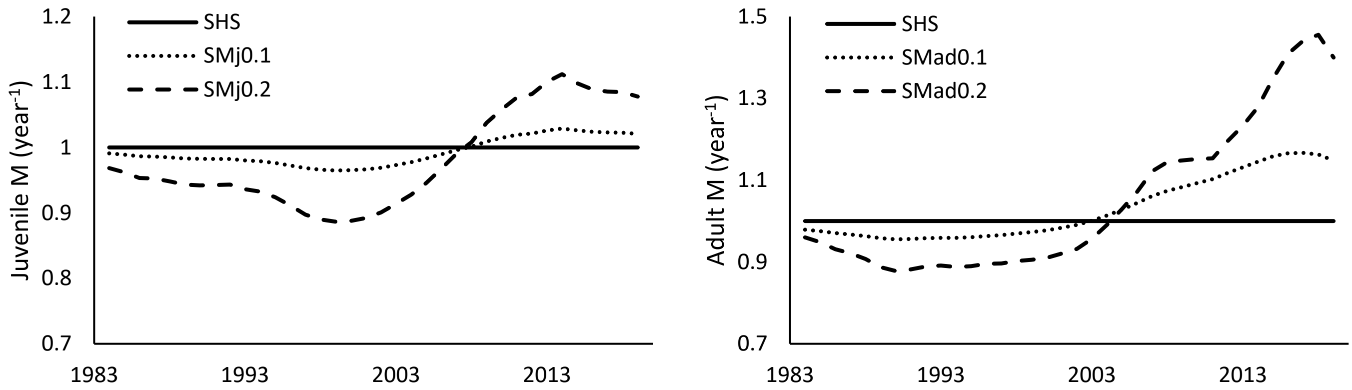

Figure 2. The annual juvenile and adult natural mortality rates estimated for S_{HS}, S_{Mj} (σ_j = 0.1 or 0.2) and S_{Mad} (σ_{ad}= 0.1 or 0.2).

Appendix A: Bayesian operating 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[3]). The assessment is run from November $y_1 = 1984$ to November $y_n = 2019$, 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 $\boldsymbol{a = 0}$ to a plus group of $\boldsymbol{a = 5^+}$;
- lengths from a minus group of $\boldsymbol{l = 2.5^- cm}$ to a plus group of $\boldsymbol{l = 24^+ cm}$;
- components $\boldsymbol{j = W}$ or $\boldsymbol{j = S}$ denote the west and south components, respectively, where only the west component equations are used in the single component hypothesis;
- infection $\boldsymbol{p = NI}$ or $\boldsymbol{p = I}$ denote the sardine uninfected and infected with the digenean 'tetracotyle-type' metacercarian endoparasite, respectively.

All parameters are defined in Tables A1 and A2.

Population Dynamics

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

$$N_{j,p,y,a}^{S*} = \left(\left(\left(\left(N_{j,p,y-1,a-1}^{S} e^{-M_{y,a-1}^{S}/8} - C_{j,p,y,1,a-1}^{S}\right) e^{-M_{y,a-1}^{S}/4} - C_{j,p,y,2,a-1}^{S}\right) e^{-M_{y,a-1}^{S}/4} - C_{j,p,y,3,a-1}^{S}\right) e^{-M_{y,a-1}^{S}/4} - C_{j,p,y,4,a-1}^{S}\right) e^{-M_{y,a-1}^{S}/8}$$

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

$$N_{j,p,y,5^+}^{S*} = \left(\left(\left(\left(N_{j,p,y-1,4}^{S} e^{-M_{y,4}^{S}/8} - C_{j,p,y,1,4}^{S}\right) e^{-M_{y,4}^{S}/4} - C_{j,p,y,2,4}^{S}\right) e^{-M_{y,4}^{S}/4} - C_{j,p,y,3,4}^{S}\right) e^{-M_{y,4}^{S}/4} - C_{j,p,y,4,4}^{S}\right) e^{-M_{y,4}^{S}/8} +$$

$$\left(\left(\left(\left(N_{j,p,y-1,5^+}^{S} e^{-M_{y,5^+}^{S}/8} - C_{j,p,y,1,5^+}^{S}\right) e^{-M_{y,5^+}^{S}/4} - C_{j,p,y,2,5^+}^{S}\right) e^{-M_{y,5^+}^{S}/4} - C_{j,p,y,3,5^+}^{S}\right) e^{-M_{y,5^+}^{S}/4} - C_{j,p,y,4,5^+}^{S}\right) e^{-M_{y,5^+}^{S}/8}$$

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

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

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

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

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

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

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

[3] 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.

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

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

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

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

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.

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

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

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

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

$A^{sur}_{j,y,a,l} \sim N\left(L_{j,y,a}, \vartheta_a^2\right)$ [4]

$$\text{where } L_{j=1,y,a} = \begin{cases} L^{small}_{j,y-a,\infty}\left(1 - e^{-1.5\kappa_j\left(a - t^{small}_{0,j,y-a}\right)}\right) & a \le 0.5 \\ L_{j,\infty}\left(1 - e^{-\kappa_j\left(a - t_{0,j,y-a}\right)}\right) & a \ge 0.5 \end{cases}$$

$$\text{and } L_{j=2,y,a} = L_{j,\infty}\left(1 - e^{-\kappa_j\left(a - t_{0,j,y-a}\right)}\right) \qquad y_1 \le y \le y_n, 0 \le a \le 5^+, 2.5^- cm \le l \le 24^+ cm \qquad \text{(A7)}^5$$

$$\text{with } t_{0,j,y} = t_{0,j} + \varepsilon^t_y \qquad \text{(A8)}^6$$

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

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

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

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

[4] 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.

[5] The proportion is calculated as the area under the curve between the lower limit and upper limit of length class l. The lower and upper tails are included in the proportions calculated for the minus and plus groups, respectively.

[6] 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.

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

$$B^S_{j,y} = k^S_{j,N}\sum_p \sum_{l=2.5^-}^{24^+} N^S_{j,p,y,l} w^S_{j,l} \qquad y_1 \le y \le y_n \qquad \text{(A13)}$$ [7][8]

Commercial selectivity

$$S_{j,y,q,l} = \begin{cases} 0 & l \le 5.5cm \\ \chi_{j,y,q} exp\left\{-\frac{\left(l+0.25-\bar{l}_{1,y}\right)^2}{(\sigma_1^{sel})^2}\right\} + \frac{1}{1+exp\{-\left(l+0.25-\bar{l}_{2,j,y,q}\right)/(\sigma_2^{sel})^2\}} & 6cm \le l \le l_{max} = 23cm \\ S_{j,y,q,lmax} & l > l_{max} \end{cases}$$ [9]

$$y_1 \le y \le y_n,\ 1 \le q \le 4 \qquad \text{(A14)}$$

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

$$A^{com}_{j,y,q,a,l} \sim N\left(L^{com}_{j,y,q,a}, \left[\left(1-\frac{(2q-1)}{8}\right)\vartheta_a + \frac{(2q-1)}{8}\vartheta_{a+1}\right]^2\right)$$

where $L^{com}_{j=1,y,q,a} = \begin{cases} L^{small}_{j,y-a,\infty}\left(1-e^{-1.5\kappa_j\left(a+(2q-1)/8-t^{small}_{0,j,y-a}\right)}\right) & a \le 0.5 \\ L_{j,\infty}\left(1-e^{-\kappa_j\left(a+(2q-1)/8-t_{0,j,y-a}\right)}\right) & a \ge 0.5 \end{cases}$

and $L^{com}_{j=2,y,q,a} = L_{j,\infty}\left(1-e^{-\kappa_j\left(a+(2q-1)/8-t_{0,j,y-a}\right)}\right)$

$$y_1 \le y \le y_n,\ 1 \le q \le 4, 0 \le a \le 5^+,\ 2.5^-cm \le l \le 24^+cm \qquad \text{(A16)}$$ [10]

Bycatch in the anchovy directed fishery

$$C^{bycatch}_{j,p,y,q,a} = \begin{cases} N^S_{j,p,y,q,a} F^{By}_{j,y,q,a} & 0 \le a \le 1 \\ 0 & 2 \le a \le 5^+ \end{cases} \qquad p = I, NI, y_1 \le y \le y_n,\ 1 \le q \le 4 \qquad \text{(A17)}$$ [11]

Catch in the directed sardine and round herring bycatch fisheries

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

Total catch

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

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

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

[7] The biomass in y_n excludes age 0 fish, although the contribution of age 0 fish to the total biomass should be minor.
[8] 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 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).
[9] The $l + 0.25$ denotes the middle of length class l. This function is renormalized to a maximum of 1.
[10] The proportion is calculated as the area under the curve between the lower limit and upper limit of length class l. The lower and upper tails are included in the proportions calculated for the minus and plus groups, respectively.
[11] "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.

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

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

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

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

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

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

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

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

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

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

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[12] 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

$$N^S_{j,y,r} = k^S_{j,r} \left(\left(N^S_{j,NI,y,2,0} - C^S_{j,NI,y,2,0}\right) e^{-(1/8 + 0.5 t^S_y/12) M^S_{y,0}} - \tilde{C}^S_{j,y,0bs} \right) e^{-0.5 t^S_y \times M^S_{y,0}/12} \quad 1985 \leq y \leq y_n \qquad \text{(A22)}$$

Multiplicative survey bias

$$k^S_{j,N} = k^S_{ac} \qquad \text{(A23)}$$

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

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

Survey trawl selectivity

$$S^{survey}_{j,l} = \begin{cases} 0 & l = 2.5^{-} cm \\ \left[1 + exp\{-\left(l + 0.25 - S_{50,j}\right)/\delta_j\}\right]^{-1} & 3cm \leq l \leq 24^{+} cm \end{cases} \qquad y_1 \leq y \leq y_n \qquad \text{(A26)}$$

[12] 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.

Proportion-at-length associated with the November survey

$$p^{S}_{j,y,l} = \begin{cases} \dfrac{\sum_p \sum_{l\leq 6cm} N^{S}_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^{S}_{j,p,y,l} S^{survey}_{j,l}} & l = 6^- cm \\ \dfrac{\sum_p N^{S}_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^{S}_{j,p,y,l} S^{survey}_{j,l}} & 6.5cm \leq l \leq 20.5cm \\ \dfrac{\sum_p \sum_{l=21}^{23.5} N^{S}_{j,p,y,l} S^{survey}_{j,l}}{\sum_p \sum_{l=2.5^-}^{24^+} N^{S}_{j,p,y,l} S^{survey}_{j,l}} & l = 21 - 23.5cm \\ \dfrac{\sum_p N^{S}_{j,p,y,l} S^{survey}_{j,24^+}}{\sum_p \sum_{l=2.5^-}^{24^+} N^{S}_{j,p,y,l} S^{survey}_{j,l}} & l = 24^+ cm \end{cases} \quad {}^{13} \quad y_1 \leq y \leq y_n \qquad \text{(A27)}$$

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

$$P^{S}_{j,y,l} = \frac{N^{S}_{j,I,y,l}}{\sum_p N^{S}_{j,p,y,l}} \qquad y_1 \leq y \leq y_n,\ 7.5cm \leq l \leq 23cm \qquad \text{(A28)}$$

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

$$C^{dir}_{j,p,y,q,l} = \sum_{a=0}^{5^+} \left(N^{S}_{j,p,y,q,a} - C^{bycatch}_{j,p,y,q,a}\right) A^{com}_{j,q,a,l} S_{j,y,q,l} F_{j,y,q} \quad {}^{14}$$

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

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

$$p^{coml,S}_{j,y,q,l} = \begin{cases} \dfrac{\sum_p C^{dir}_{j,p,y,q,l}}{\sum_p \sum_{l=6}^{24^+} C^{dir}_{j,p,y,q,l}} & 6cm \leq l \leq 22.5cm \\ \dfrac{\sum_p \sum_{l=23}^{24^+} C^{dir}_{j,p,y,q,l}}{\sum_p \sum_{l=6}^{24^+} C^{dir}_{j,p,y,q,l}} & l = 23^+ cm \end{cases} \quad {}^{15} \quad y_1 \leq y \leq y_n,\ 1 \leq q \leq 4 \qquad \text{(A30)}$$

Fitting the Model to Observed Data (Likelihood)

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

where

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

[13] 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.

[14] 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.

[15] 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.

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

$$-lnL^{sur\,propl} = w^{sur}_{propl} \sum_j \sum_{y=y_1}^{y_n} \left\{ \sum_{l=6-}^{21^+} \left\{ \frac{\left(\sqrt{\hat{p}^S_{j,y,l}} - \sqrt{p^S_{j,y,l}}\right)^2}{2\left(\sigma^S_{j,sur}\right)^2} + ln\left(\sigma^S_{j,sur}\right) \right\} + \frac{\left(0 - \sqrt{p^S_{j,y,24^+}}\right)^2}{2\left(\sigma^S_{j,sur}\right)^2} + ln\left(\sigma^S_{j,sur}\right) \right\} \quad \text{(A34)}$$

[16]

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

$$-lnL^{prev} = \sum_j \sum_{y=2010}^{2018} \sum_{l=7.5cm}^{23cm} -n^{prev}_{j,y,l}\, ln\left(P^S_{j,y,l}\right) - \left(N^{prev}_{j,y,l} - n^{prev}_{j,y,l}\right) ln\left(1 - P^S_{j,y,l}\right) \quad \text{(A36)}$$

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.

[16] 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	$ln(N^S_{j,NI,y,0})/10 \sim U(-10,3.2)$ $N^S_{j,I,y,0} = 0$	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		$\xi_W = 1$ $\xi_S = 0.92$		Alternative values considered in robustness tests
	$w^S_{j,l}$	Mean mass of sardine of component j in length class l	Grams	$5.6876 \times 10^{-6} \times l^{3.140026}$		OLSPS (2020)

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	-	$\left[1+e^{-(l-17.2)/1.17}\right]^{-1}$ $1984 \leq y \leq 1987$ $\left[1+e^{-(l-18.6)/1.26}\right]^{-1}$ $1988 \leq y \leq 1995$ $\left[1+e^{-(l-19.4)/1.40}\right]^{-1}$ $1996 \leq y \leq 2003$ $\left[1+e^{-(l-17.4)/0.95}\right]^{-1}$ $2004 \leq y \leq 2018$		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	-	$N(0, \sigma^2_j)$		
	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 A1 (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 component j that are uninfected ($p = NI$) or infected ($p = I$) with the endoparasite	Billions		A5	
	$p^{S}_{j,y,l}$	Model predicted proportion-at-length l of component j associated with the November survey in year y	-		A27	
	$A^{sur}_{j,y,a,l}$	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 $L_{j,a=1} \sim U(5,25)$ $L_{j,a=3} - L_{j,a=1} \sim U(5,25)$		
	$L^{small}_{j,\infty,y}$	Maximum length (in expectation) of component $j = 1$ for the growth curve below $a = 0.5$ years in year y	Cm	$= \frac{L_{j,\infty}\left(1 - e^{-\kappa_j(\acute{a} - t_{0,j,y})}\right)}{\left(1 - e^{-1.5\kappa_j\left(\acute{a} - t^{small}_{0,j,y}\right)}\right)}$		
	$t_{0,j,y}$	Age at which the length (in expectation) is zero for component j in year y	Year		A8	
	$t^{small}_{0,j,y}$	Age at which the length (in expectation) is zero for component $j = 1$ in year y for the growth curve below $a = 0.5$ years	Year	$= \frac{1}{1.5\kappa_j} ln\left(\frac{e^{1.5\kappa_j\acute{a} - \kappa_j(\acute{a} - t_{0,j,y})}}{1.5 + (1 - 1.5)e^{-\kappa_j(\acute{a} - t_{0,j,y})}}\right)$		
	$t_{0,j}$	Average age at which the length (in expectation) is zero	Year	$\frac{1}{\kappa_j} ln\left\{\frac{e^{\kappa_j}\left(L_{j,1} - L_{j,3}\right)}{L_{j,1}e^{-2\kappa_j} - L_{j,3}}\right\}$		
	ε^{t}_{y}	Annual autocorrelated residuals about the age at which the length is zero			A8	
	η^{t}_{y}	Annual uncorrelated residuals about the age at which the length is zero		$N(0, 0.2^2)$		
	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 precludes unrealistically large lengths for young fish
	$p^{com,S}_{j,y,q,l}$	Model predicted proportion-at-length l of component j in the directed catch and round herring bycatch during quarter q of year y	-		A30	
	$A^{com}_{j,y,q,a,l}$	Proportion of age a of component j sardine that falls in the length group l mid-way through quarter q of year y	-		A16	
	$P^{S}_{j,y,l}$	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 $0.3\le k_{cov}^S\le 1$		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*. 2020		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_{propl}^{sur}	Weighting applied to the remaining survey proportion-at-length data	-	$= 0.5 \times 0.167$		To allow for autocorrelation[17]
$\sigma_{j,sur}^{S}$	Standard deviation associated with the survey proportion-at-length data of component *j*	-		$\sqrt{\frac{\sum_{y=y_1}^{yn}\sum_{l=6^-}^{21^+}\left(\sqrt{\hat{p}_{j,y,l}^{S}}-\sqrt{p_{j,y,l}^{S}}\right)^2}{\sum_{y=y_1}^{yn}\sum_{l=6^-}^{21^+}1}}$[18]	Closed form solution
w_{propl}^{com}	Weighting applied to the commercial proportion-at-length data		$= 0.5 \times 0.04$		To allow for autocorrelation[19]
$\sigma_{j,com}^{S}$	Standard deviation associated with the commercial proportion-at-length data of stock *j*	-	$\sqrt{\frac{\sum_{y=y_1}^{yn}\sum_{q=1}^{4}\sum_{l=6}^{23^+}\left(\sqrt{\hat{p}_{j=1,y,q,l}^{comlS}}-\sqrt{}\right.}{\sum_{y=y_1}^{yn}\sum_{q=1}^{4}\sum_{l=6}^{23^+}1}}$ $\sqrt{\frac{\sum_{y=y_1}^{yn}\sum_{q=1}^{4}\sum_{l=13}^{23^+}\left(\sqrt{\hat{p}_{j=2,y,q,l}^{comlS}}-\sqrt{}\right.}{\sum_{y=y_1}^{yn}\sum_{q=1}^{4}\sum_{l=13}^{23^+}1}}$	Closed form solution[20]	$\sigma_{j,com}^{S}$

[17] Based upon data being available ~6 times more frequently than annual age data which contain maximum information content on this.
[18] The 21⁺ group in this equation consists of the length classes 21cm, 21.5cm, 22cm, 22.5cm, 23cm and 23.5cm.
[19] Based upon data being available ~4x6 times more frequently than annual age data which contain maximum information content on this.
[20] 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*. (2020)[21].

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 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 (2012-19) and $fleet = 3$ denotes the juvenile sardine bycatch with anchovy (1984-2011) or <14cm sardine bycatch (2012-19)	Billions
$\hat{B}_{j,y}^S$	Acoustic survey estimate of biomass of component 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 component 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 component j in length group l in the November survey of year y	-
$\hat{p}_{j,y,q,l}^{S,com}$	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	-
$n_{j,y,l}^{prev}$	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
$N_{j,y,l}^{prev}$	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

[21] Note that the expected mass by length class and month, used to calculate $C_{j,y,m,l}^{RLF,fleet}$ and $\tilde{C}_{j,y,0bs}^S$, is given by $EM_{y,l,m} = 0.0000090193 \times l_{mid}^{3.066305} \times N_{y,l,m}$ for the west component and $EM_{y,l,m} = 0.00023041 \times l_{mid}^{2.463739} \times N_{y,l,m}$ for the south component.

Appendix B: The procedure used to solve for west component stock recruitment parameters after conditioning, corrected and expanded from Bergh (2018)

The west component ($j = 1$) stock recruitment parameters, α^S and β^S, are estimated by minimising the sum of squares difference between the logarithm of the recruitment predicted by the stock recruitment relationship and that estimated by the assessment model from 1985[22] to 2018, excluding 2000 – 2002 as the peak recruitment years, i.e. minimising:

$$SS = \sum_{SSB_y}\left(ln\left(f\left(SSB_{j,y}^{eff}\right)\right) - ln\left(N_{j,NI,y,0}^S\right)\right)^2. \qquad \text{(B.1)}$$

For the three alternative stock recruitment relationships considered here, this gives:

$$\text{HS:}\;\; SS = \sum_{SSB_{j,y}^{eff}<\beta_y}\left(ln\left(\frac{\alpha^S SSB_{j,y}^{eff}}{\beta^S}\right) - ln\left(N_{j,NI,y,0}^S\right)\right)^2 + \sum_{SSB_{j,y}^{eff}\geq\beta_y}\left(ln(\alpha^S) - ln\left(N_{j,NI,y,0}^S\right)\right)^2$$

$$SS = \sum_{SSB_{j,y}^{eff}<\beta_y}\left(ln(\alpha^S) - \left\{ln\left(N_{j,NI,y,0}^S\right) - ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S}\right)\right\}\right)^2 + \sum_{SSB_{j,y}^{eff}\geq\beta_y}\left(ln(\alpha^S) - ln\left(N_{j,NI,y,0}^S\right)\right)^2$$

$$\text{BH:}\;\; SS = \sum_{SSB_{j,y}^{eff}}\left(ln\left(\frac{\alpha^S SSB_{j,y}^{eff}}{\beta^S + SSB_{j,y}^{eff}}\right) - ln\left(N_{j,NI,y,0}^S\right)\right)^2 = \sum_{SSB_{j,y}^{eff}}\left(ln(\alpha^S) - \left\{ln\left(N_{j,NI,y,0}^S\right) - ln\left(\frac{SSB_{j,y}^{eff}}{\beta_y + SSB_{j,y}^{eff}}\right)\right\}\right)^2$$

$$\text{R:}\;\; SS = \sum_{SSB_{j,y}^{eff}}\left(ln\left(\alpha^S SSB_y e^{-\beta^S SSB_{j,y}^{eff}}\right) - ln\left(N_{j,NI,y,0}^S\right)\right)^2 = \sum_{SSB_{j,y}^{eff}}\left(ln(\alpha^S) - \left\{ln\left(N_{j,NI,y,0}^S\right) - ln\left(SSB_{j,y}^{eff} e^{-\beta^S SSB_{j,y}^{eff}}\right)\right\}\right)^2$$

$$\text{(B.2)}$$

The multi-modal objective function can result in local rather than global solutions being produced, depending on the starting values used for α^S and β^S. To ensure a global solution is found when minimising equation (B.2), starting values for α^S and β^S are selected from the minimum SS' obtained over a grid over $\beta^S = 0, \ldots, 1000$[23] [24] in steps of 0.5[25], for which a corresponding extreme α^S can be calculated as follows.

Taking the derivative of SS with respect to $ln(\alpha^S)$ gives:

$$\text{HS:}\;\; \frac{d(SS)}{d\left(ln(\alpha^S)\right)} = \sum_{SSB_{j,y}^{eff}<\beta_y} 2\left(ln(\alpha^S) - \left\{ln\left(N_{j,NI,y,0}^S\right) - ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S}\right)\right\}\right) + \sum_{SSB_{j,y}^{eff}\geq\beta_y} 2\left(ln(\alpha^S) - ln\left(N_{j,NI,y,0}^S\right)\right)$$

$$= \sum_{SSB_{j,y}^{eff}<\beta_y} 2ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S}\right) + \sum_{SSB_{j,y}^{eff}} 2ln(\alpha^S) - \sum_{SSB_{j,y}^{eff}} 2ln\left(N_{j,NI,y,0}^S\right)$$

$$\text{BH:}\;\; \frac{d(SS)}{d\left(ln(\alpha^S)\right)} = \sum_{SSB_{j,y}^{eff}} 2\left(ln(\alpha^S) - \left\{ln\left(N_{j,NI,y,0}^S\right) - ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S + SSB_{j,y}^{eff}}\right)\right\}\right)$$

$$= \sum_{SSB_{j,y}^{eff}} 2ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S + SSB_{j,y}^{eff}}\right) + \sum_{SSB_{j,y}^{eff}} 2ln(\alpha^S) - \sum_{SSB_{j,y}^{eff}} 2ln\left(N_{j,NI,y,0}^S\right)$$

$$\text{R:}\;\; \frac{d(SS)}{d\left(ln(\alpha^S)\right)} = \sum_{SSB_{j,y}^{eff}} 2\left(ln(\alpha^S) - \left\{ln\left(N_{j,NI,y,0}^S\right) - ln\left(SSB_{j,y}^{eff} e^{-\beta^S SSB_{j,y}^{eff}}\right)\right\}\right)$$

$$= \sum_{SSB_{j,y}^{eff}} 2ln\left(SSB_y e^{-\beta^S SSB_{j,y}^{eff}}\right) + \sum_{SSB_{j,y}^{eff}} 2ln(\alpha^S) - \sum_{SSB_{j,y}^{eff}} 2ln\left(N_{j,NI,y,0}^S\right) \qquad \text{(B.3)}$$

[22] 1983 and 1984 are excluded to remove any inconsistencies associated with the non-equilibrium initial starting values.

[23] For the Hockey Stick relationship, $max\left(SSB_{j,y}^{eff}\right) \geq \beta^S \geq min\left(SSB_{j,y}^{eff}\right)$.

[24] For the Beverton Holt relationship, $\beta^S > 100$.

[25] For the Ricker relationship, the grid was $\beta^S = 0, \ldots, 10$ in steps of 0.005.

An extreme value for $ln(\alpha^S)$ can be obtained by setting $\frac{d(SS)}{d\left(ln(\alpha^S)\right)} = 0$ and solving for α^S in terms of β^S:

HS: $$\frac{d(SS)}{d\left(ln(\alpha^S)\right)} = \sum_{SSB_{j,y}^{eff}<\beta_y} 2ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S}\right) + \sum_{SSB_{j,y}^{eff}} 2ln(\alpha^S) - \sum_{SSB_{j,y}^{eff}} 2ln\left(N_{j,NI,y,0}^S\right) = 0$$

$$\sum_{SSB_{j,y}^{eff}} 2ln(\alpha^S) = \sum_{SSB_{j,y}^{eff}} 2ln\left(N_{j,NI,y,0}^S\right) - \sum_{SSB_{j,y}^{eff}<\beta_y} 2ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S}\right)$$

$$ln(\alpha^S) = \frac{1}{n}\left(\sum_{SSB_{j,y}^{eff}} ln\left(N_{j,NI,y,0}^S\right) - \sum_{SSB_{j,y}^{eff}<\beta_y} ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S}\right)\right)$$

BH: $$\frac{d(SS)}{d\left(ln(\alpha^S)\right)} = \sum_{SSB_{j,y}^{eff}} 2ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S+SSB_{j,y}^{eff}}\right) + \sum_{SSB_{j,y}^{eff}} 2ln(\alpha^S) - \sum_{SSB_{j,y}^{eff}} 2ln\left(N_{j,NI,y,0}^S\right) = 0$$

$$\sum_{SSB_{j,y}^{eff}} 2ln(\alpha^S) = \sum_{SSB_{j,y}^{eff}} 2ln\left(N_{j,NI,y,0}^S\right) - \sum_{SSB_{j,y}^{eff}} 2ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S+SSB_{j,y}^{eff}}\right)$$

$$ln(\alpha^S) = \frac{1}{n}\sum_{SSB_{j,y}^{eff}}\left(ln\left(N_{j,NI,y,0}^S\right) - ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S+SSB_{j,y}^{eff}}\right)\right)$$

R: $$\frac{d(SS)}{d\left(ln(\alpha^S)\right)} = \sum_{SSB_{j,y}^{eff}} 2ln\left(SSB_{j,y}^{eff} e^{-\beta^S SSB_{j,y}^{eff}}\right) + \sum_{SSB_{j,y}^{eff}} 2ln(\alpha^S) - \sum_{SSB_{j,y}^{eff}} 2ln\left(N_{j,NI,y,0}^S\right) = 0$$

$$\sum_{SSB_{j,y}^{eff}} 2ln(\alpha^S) = \sum_{SSB_{j,y}^{eff}} 2ln\left(N_{j,NI,y,0}^S\right) - \sum_{SSB_{j,y}^{eff}} 2ln\left(SSB_{j,y}^{eff} e^{-\beta^S SSB_{j,y}^{eff}}\right)$$

$$ln(\alpha^S) = \frac{1}{n}\sum_{SSB_{j,y}^{eff}}\left(ln\left(N_{j,NI,y,0}^S\right) - ln\left(SSB_{j,y}^{eff} e^{-\beta^S SSB_{j,y}^{eff}}\right)\right) \tag{B.4}$$

where n is the number of years over which $SSB_{j,y}^{eff}$ is available (1985 to 2018 in this case). Substituting (B.4) into (B.2) we get:

HS: $$SS' = \sum_{SSB_{j,y}^{eff}<\beta_y}\left(\frac{1}{n}\left\{\sum_{SSB_{j,y}^{eff}} ln\left(N_{j,NI,y,0}^S\right) - \sum_{SSB_{j,y}^{eff}<\beta_y} ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S}\right)\right\} - \left\{ln\left(N_{j,NI,y,0}^S\right) - ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S}\right)\right\}\right)^2$$

$$+\sum_{SSB_{j,y}^{eff}\geq\beta_y}\left(\frac{1}{n}\left\{\sum_{SSB_{j,y}^{eff}} ln\left(N_{j,NI,y,0}^S\right) - \sum_{SSB_{j,y}^{eff}<\beta_y} ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S}\right)\right\} - ln\left(N_{j,NI,y,0}^S\right)\right)^2$$

BH: $$SS' = \sum_{SSB_{j,y}^{eff}}\left(\frac{1}{n}\sum_{SSB_{j,y}^{eff}}\left(ln\left(N_{j,NI,y,0}^S\right) - ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S+SSB_{j,y}^{eff}}\right)\right) - \left\{ln\left(N_{j,NI,y,0}^S\right) - ln\left(\frac{SSB_{j,y}^{eff}}{\beta_y+SSB_{j,y}^{eff}}\right)\right\}\right)^2$$

R: $$SS' = \sum_{SSB_{j,y}^{eff}}\left(\frac{1}{n}\left\{\sum_{SSB_{j,y}^{eff}} ln\left(N_{j,NI,y,0}^S\right) - \sum_{SSB_{j,y}^{eff}<\beta_y} ln\left(\frac{SSB_{j,y}^{eff}}{\beta^S}\right)\right\} - \left\{ln\left(N_{j,NI,y,0}^S\right) - ln\left(SSB_{j,y}^{eff} e^{-\beta^S SSB_{j,y}^{eff}}\right)\right\}\right)^2 \tag{B.5}$$

The standard deviation associated with the stock recruitment relationship for use in projections is calculated as follows:

HS: $$\sigma_r^S = \sqrt{\frac{1}{n-2}\left\{\sum_{SSB_{j,y}^{eff}<\beta_y}\left(ln\left(\frac{\alpha^S SSB_{j,y}^{eff}}{\beta^S}\right) - ln\left(N_{j,NI,y,0}^S\right)\right)^2 + \sum_{SSB_{j,y}^{eff}\geq\beta_y}\left(ln(\alpha^S) - ln\left(N_{j,NI,y,0}^S\right)\right)^2\right\}}$$

BH: $$\sigma_r^S = \sqrt{\frac{1}{n-2}\left\{\sum_{SSB_{j,y}^{eff}}\left(ln\left(\frac{\alpha^S SSB_{j,y}^{eff}}{\beta^S+SSB_{j,y}^{eff}}\right) - ln\left(N_{j,NI,y,0}^S\right)\right)^2\right\}}$$

R: $$\sigma_r^S = \sqrt{\frac{1}{n-2}\left\{\sum_{SSB_{j,y}^{eff}}\left(ln\left(\alpha^S SSB_{j,y}^{eff} e^{-\beta^S SSB_{j,y}^{eff}}\right) - ln\left(N_{j,NI,y,0}^S\right)\right)^2\right\}} \tag{B.6}$$

Carrying capacity is approximated based on average maturity and weight in the last 5 years only as follows:

HS: $$K_w^S = \alpha^S\left(\sum_{a=1}^{4}\overline{f}_{w,a}^S\overline{w}_{w,a}^S e^{-\overline{M}_j^S-(a-1)\overline{M}_{ad}^S} + \overline{f}_{w,5+}^S\overline{w}_{w,5+}^S e^{-\overline{M}_j^S-4\overline{M}_{ad}^S}\Big/\left(1-e^{-\overline{M}_{ad}^S}\right)\right)$$

BH: $K_w^S = \alpha^S \left(\sum_{a=1}^{4} \overline{f}_{w,a}^S \overline{w}_{w,a}^S e^{-\overline{M}_j^S-(a-1)\overline{M}_{ad}^S} + \overline{f}_{w,5+}^S \overline{w}_{w,5+}^S e^{-\overline{M}_j^S-4\overline{M}_{ad}^S} / \left(1 - e^{-\overline{M}_{ad}^S}\right) \right) - \beta^S$

R: $K_w^S = ln \left[\left\{ \alpha^S \left(\sum_{a=1}^{4} \overline{f}_{w,a}^S \overline{w}_{w,a}^S e^{-\overline{M}_j^S-(a-1)\overline{M}_{ad}^S} + \overline{f}_{w,5+}^S \overline{w}_{w,5+}^S e^{-\overline{M}_j^S-4\overline{M}_{ad}^S} / \left(1 - e^{-\overline{M}_{ad}^S}\right) \right) \right\}^{0.8} \right] / 0.8\beta^S$

Appendix C: The procedure used to solve for south component 'two-step' recruitment parameters after conditioning, from de Moor (2018a)

For simulation i, having reordered $N^{i}_{j,NI,y,0}$, $1985 \leq y \leq 2018$ into ascending order $N^{i}_{j,t}$, $1 \leq t \leq N = 34$:

$$R^{i}_{1} = \frac{\sum_{\forall t<p^{i}N} ln\left(N^{i}_{j,t}\right)}{p^{i}N} \quad \text{(C1)}$$

$$R^{i}_{2} = \frac{\sum_{\forall t\geq p^{i}N} ln\left(N^{i}_{j,t}\right)}{(1-p^{i})N} \quad \text{(C2)}$$

parameter p^{i} was estimated by minimising: $\sum_{\forall t<p^{i}N}\left(ln\left(N^{i}_{j,t}\right) - R^{i}_{1}\right)^{2} + \sum_{\forall t\geq p^{i}N}\left(ln\left(N^{i}_{j,t}\right) - R^{i}_{2}\right)^{2}$. (C3)

Calculate $\sigma^{i}_{1} = \sqrt{\left(\frac{1}{p^{i}N-1}\right)\sum_{\forall t<p^{i}N}\left(ln\left(N^{i}_{j,t}\right) - R^{i}_{1}\right)^{2}}$ (C4)

and $\sigma^{i}_{2} = \sqrt{\left(\frac{1}{(1-p^{i})N-1}\right)\sum_{\forall t\geq p^{i}N}\left(ln\left(N^{i}_{j,t}\right) - R^{i}_{2}\right)^{2}}$ (C5)

$$ln\left(N^{i,pred}_{j=s,y,0}\right) = \begin{cases} R^{i}_{1} + \epsilon^{i}_{1,y} & if\ \varepsilon^{i}_{y} < p^{i} \\ R^{i}_{2} + \epsilon^{i}_{2,y} & if\ \varepsilon^{i}_{y} \geq p^{i}, \end{cases}$$

where $\varepsilon^{i}_{y} \sim Random[0,1]$, $\epsilon^{i}_{1,y} \sim N\left(0, {\sigma^{i}_{1}}^{2}\right)$ and $\epsilon^{i}_{2,y} \sim N\left(0, {\sigma^{i}_{2}}^{2}\right)$

and bounded to be within the historically estimated range.

Appendix D: Fitting a relationship between the proportion of directed sardine catch taken west of Cape Agulhas and the ratio of baseline sardine biomass to directed sardine TAC, from de Moor and Butterworth (2018)

For each simulation, i=1,…,1000, a relationship was estimated as follows:

$$p_y^{pred} = f\left(TAC_y^S / B_{1,y-1}^{S,i}\right) = g_1^i\left(1 - exp\left\{-g_2^i\, B_{1,y-1}^{S,i}/TAC_y^S\right\}\right) \quad (1)$$

by minimising a binomial likelihood:

$$-lnL = \sum_{y=1987}^{2019}\left\{-Np_y^{obs} ln\left(p_y^{pred}\right) - N\left(1-p_y^{obs}\right) ln\left(1-p_y^{pred}\right)\right\},$$

where p_y^{obs} is the historically observed proportion of directed sardine catch taken west of Cape Agulhas in year y. The value of the variance-determining parameter *N* was estimated by $N = \frac{\sum_{y=1987}^{2019} p_y^{pred}\left(1-p_y^{pred}\right)}{\sum_{y=1987}^{2019}\left(p_y^{obs}-p_y^{pred}\right)}$ (McAllister and Ianelli 1997), which yielded 3[26] for the time series of baseline posterior median biomass; it was assumed that this value could reasonably be applied to all simulations.

Fitting the relationship to the 1000 draws from the posterior distribution did not result in substantial changes in the relationship from that estimated using the time series of west component biomass at the posterior median (Figure D1). The median of g_1^i was 0.902, with a 90% probability interval of [0.901, 0.904], and the median of g_2^i was 0.408, with a 90% probability interval of [0.402,0.414].

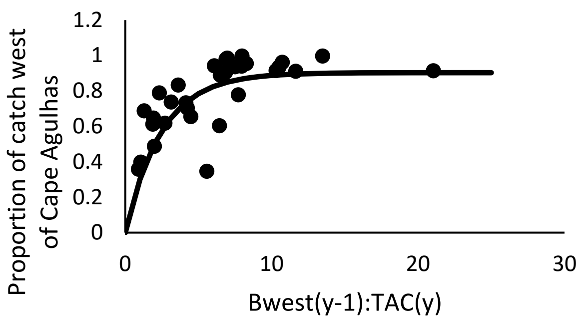

Figure D1. The proportion of catch west of Cape Agulhas in year *y* plotted against the ratio of the posterior median west coast biomass in November (*y*-1) : TAC in year *y*. This relationship (line) was estimated using the **posterior median**.

[26] Although this is a decrease from that estimated by de Moor and Butterworth (2018), in the absence of re-checking the appropriate N for generating future proportions, de Moor (2020c) uses a larger N to avoid generating proportions above 1.

Appendix E: Fitting a density dependent movement relationship for the proportion of west component 1-year-old sardine that move to the south component, from de Moor *et al*. (2018), using the baseline model

The density dependent movement hypothesis, "MoveD", assumes *a priori* that more sardine would move away from the west coast during years of high west coast biomass. The proportion of 1-year-olds that are modelled to move in November of year *y* is assumed to be related to the baseline model estimated biomass on the west coast in November of year *y*-1. The model fit is linear in logit space:

$$p^*_{1,y} = aB^S_{w,y-1} + b$$

and the parameters are estimated by minimising the sum of squares $\sum\left(p^*_{1,y} - ln\left(\frac{p^{mod}_{1,y}}{1-p^{mod}_{1,y}}\right)\right)^2$.

Fitting the relationship to the 1000 draws from the posterior distribution did not result in substantial changes in the relationship from that estimated using the time series of west component biomass and movement proportions at the posterior median (Figure E1). The median of a was 0.0012, with a 90% probability interval of [0.0006, 0.0022], and the median of b was -1.55, with a 90% probability interval of [-2.09,-1.04]. Figure E1 shows the fits of this linear relationship to historical posterior median values.

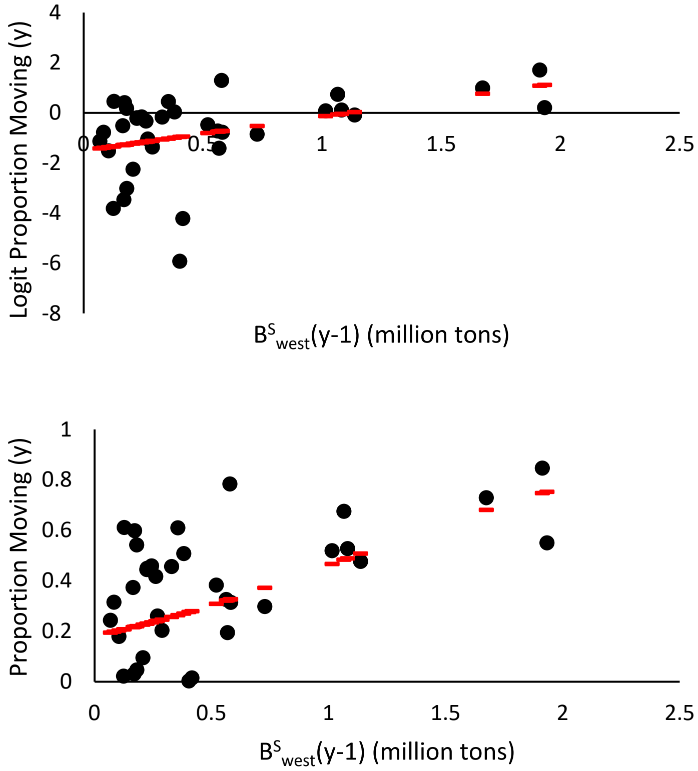

Figure E1. The baseline posterior median proportion of 1-year old sardine modelled to permanently move from the west to the south coast in November each year, plotted against the median west component biomass in November of the previous year. This is shown in a) logit-transformed space and b) in normal space, with estimated linear relationships in logit space ($p^*_{1,y} = 0.00136B^S_{w,y-1} - 1.5108$, with SD = 1.521).