Base Case Assessment of the South African Sardine Resource

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Introduction

The assessment of the South African sardine resource is in the process of being updated. This document outlines the base case assessment which has been updated from the last assessment (Cunningham and Butterworth 2004) to take account of new data:

i) an update in the time series of November spawner biomass and May recruitment estimates from acoustic surveys, such that the new time series reflects uncapped estimates of biomass based on new target strength calculations,

ii) new data for 2004 to 2006,

iii) proportion-at-age data from the November spawner biomass surveys for years for which revised ALKs are available (see Durholtz and Cunningham 2007) (previously proportions-at-age in the November surveys estimated using ALKs from Michael Kerstan for 1988 to 1999 were used),

iv) proportion-at-length data from the November spawner biomass surveys for years for which ALKs are not available (see Durholtz and Cunningham 2007)

v) quarterly proportion-at-length data from the commercial catches (previously annual catch-at-age data, derived using ALKs from Michael Kerstan prior to 1999 and an 'average' ALK from 2000 to 2003, was assumed observed without error)

In addition, this assessment has been updated from previous assessments to include:

vi) a plus group of age 5 (previously sardine were assumed to spawn at age 5 and then die),

vii) catch now assumed to be taken in a pulse mid-way between each quarter November-January, February-April, May-July, August-October (previously assumed to be taken on 1 May).

viii) an estimate of length-at-age using a von-Bertananffy growth curve, estimated at 5 stages during the year: 1 November for calculating predicted proportions-at-length in the November survey, and mid-point of each quarter for calculating predicted proportions-at-length in the commercial catch,

ix) an allowance for a difference in the growth rate between 2000 and 2004 (years of peak sardine abundance) in the von-Bertalanffy growth curves and in the mean weights-at-age in the November survey.

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Bayesian Assessment Model

The population dynamics model used for the South African sardine resource is detailed in Appendix A and the data and biological parameters used in the sardine assessment model are listed in Appendix B. The objective function consisting of the negative log likelihood equations (A.14), (A.15) and (A.16) added to the negative of the 39 prior distributions was minimised using AD Model Builder (Otter Research Ltd. 2000) to fit the model and estimate the parameters at the posterior mode. The results from the fit of this model at the posterior mode are given in Cunningham and Butterworth (2007b)

Ongoing Work

This document has detailed the model being used to assess the South African sardine resource and provided results of the current base case hypothesis at the posterior mode. Further work is still required, including:

i) beginning the model in 1984, thereby removing all data prior to 1983 which is considered less reliable. The estimation of numbers at age in 1984 will replace the estimation of recruitment residuals from 1979 to 1983;

ii) testing alternative fixed values for juvenile and adult natural mortality, especially given the addition of a plus-group (alternative sets of fixed values will also be retained as robustness tests);

iii) testing robustness to alternative stock-recruitment models including Ricker and Beverton-Holt models as well as a mixture model in which the recent years of good recruitment are treated as part of a different "regime" (see Cunningham and Butterworth 2007a);

iv) assuming a maturity ogive rather than maturity at age 1. A robustness test may also include alternative maturity ogives for peak and non-peak years;

v) modelling an alternative hypothesis assuming two sardine stocks distributed over three areas (western, southern and eastern) areas (see Cunningham and Butterworth 2007a);

The posterior distributions resulting from the finalised base case hypothesis and alternative hypothesis of stock structure and some key robustness tests will be used as input into the testing framework for the combined management procedure for sardine and anchovy to be finalised by the end of this year.

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Appendix A: Bayesian Assessment Model for the South African Sardine Resource

Model Assumptions

1) All fish have a theoretical birthdate of 1 November.
2) Sardine spawn for the first time (and are called adult sardine) when they turn one year old.
3) A plus group of age five is chosen.
4) Two surveys are held each year: the first takes place in November (known as the November survey) and surveys the adult stock; the second is in May/June (known as the recruit survey) and surveys juvenile sardine (also called recruits or 0-year-old sardine).
5) The November survey provides a relative index of abundance of known bias.
6) The recruit survey provides a relative index of abundance of unknown bias.
7) The survey strategy is such that it results in surveys of invariant bias over time.
8) Pulse fishing occurs 4 times a year, in the middle of each quarter after the birthdate.
9) Natural mortality is year-invariant for juvenile and adult fish, and age-invariant for adult fish.

Population Dynamics

Numbers-at-age at 1 November

$$N^S_{y+1,a+1} = \left(\left(\left(\left((N^S_{y,a}e^{-M^S_a/8} - \hat{C}^S_{y+1,1,a})e^{-M^S_a/4}\right) - \hat{C}^S_{y+1,2,a}\right)e^{-M^S_a/4} - \hat{C}^S_{y+1,3,a}\right)e^{-M^S_a/4} - \hat{C}^S_{y+1,4,a}\right)e^{-M^S_a/8}$$

$y = 1979$, $a = 0$;

$y = 1980$, $a = 0,1$;

$y = 1981$, $a = 0,1,2$;

$y = 1982$, $a = 0,1,2,3$;

and $y = 1983,\ldots,2006$, $a = 0,1,\ldots,3$

$$N^S_{y+1,5+} = \left(\left(\left(\left((N^S_{y,4}e^{-M^S_4/8} - \hat{C}^S_{y+1,1,4})e^{-M^S_4/4}\right) - \hat{C}^S_{y+1,2,4}\right)e^{-M^S_4/4} - \hat{C}^S_{y+1,3,4}\right)e^{-M^S_4/4} - \hat{C}^S_{y+1,4,4}\right)e^{-M^S_4/8}$$
$$+ \left(\left(\left(\left((N^S_{y,5+}e^{-M^S_4/8} - \hat{C}^S_{y+1,1,5+})e^{-M^S_4/4}\right) - \hat{C}^S_{y+1,2,5+}\right)e^{-M^S_4/4} - \hat{C}^S_{y+1,3,5+}\right)e^{-M^S_4/4} - \hat{C}^S_{y+1,4,5+}\right)e^{-M^S_4/8}$$

$y = 1983,\ldots,2006$ (A.1)

where

$N^S_{y,a}$ is the number (in billions) of sardine of age *a* at the beginning of November in year *y*;

$\hat{C}^S_{y,q,a}$ is the estimated number (in billions) of sardine of age *a* caught during quarter q of year y ($q=1$ for November $y-1$ to January y, $q=2$ for February to April y, $q=3$ for May to July y and $q=4$ for August to October y);

M^S_a is the rate of natural mortality (in year^{-1}) of sardine of age a.

Biomass associated with the November survey

$$\hat{B}^S_{y,N} = k^S_N \sum_{a=1}^{5+} N^S_{y,a} w^S_{y,a} \qquad y = 1984,\ldots,2006 \qquad \text{(A.2)}$$

where

$\hat{B}^S_{y,N}$ is the biomass (in thousand tonnes) of adult sardine at the beginning of November in year *y*, associated with the November survey;

k^S_N is the constant of proportionality (multiplicative bias) associated with the November survey; and

$w^S_{y,a}$ is the mean mass (in grams) of sardine of age *a* sampled during the November survey of year *y*.

Age composition associated with the November survey

$$\hat{p}^S_{y,a,N} = \frac{k^S_{p,a}\tilde{p}^s_{y,a}}{\sum_{a=1}^{5+} k^S_{p,a}\tilde{p}^s_{y,a}} \qquad y = 1984,\ldots,2006 \qquad \text{(A.3)}$$

where $\tilde{p}^S_{y,a} = \frac{N^S_{y,a}}{\sum_{a=1}^{5+} N^S_{y,a}}$ and

$\hat{p}^S_{y,a,N}$ is the re-normalised proportion (by number) of sardine of age *a* at the beginning of November in year *y*, associated with the November survey; and

$k^S_{p,a}$ is the multiplicative bias for each age group.

Length composition associated with the November survey

The proportions at age are then converted into proportions at length using the von Bertalanffy growth equation, assuming that the length-at-age distribution in the November survey differs during the period of peak abundance from 2000-2004 from that of remaining years:

$$\hat{p}^S_{y,l,N} = \sum_{a=1}^{5+} \hat{p}^S_{y,a,N} A_{y,a,l} \qquad y = 1984,\ldots,2006 \qquad \text{(A.4)}$$

where

$A_{y,a,l}$ is the proportion of sardine of age a that fall in the length group l (thus $\sum_{l=1}^{7} A_{a,l} = 1$ for all ages) in year y.

The matrix A is calculated under the assumption that length-at-age is normally distributed about a mean given by the Von Bertalanffy equation (Brandão *et al*. 2002):

$$L_{y,a}^{Sur} \sim N^*\left(L_{\infty,y}\left(1-e^{-\kappa_y\left(a-t_{0,y}\right)}\right);\vartheta_a^2\right) \quad \text{(A.5)}$$

N^* is the normal distribution truncated at ± 3 standard deviations, and

ϑ_a is the standard deviation of length-at-age a, which is modelled to be proportional to the expected length-at-age a, i.e.: $\vartheta_a = \beta_y L_{\infty,y}\left(1-e^{-\kappa_y\left(a-t_{0,y}\right)}\right)$

In this analysis, the growth curve and extent of variability about it have been assumed to change between ‘normal’ years and years of peak abundance. The latter set of years is pre-determined to be 2000 – 2004.

Catch

The catch at age by number is calculated using Pope’s approximation (Pope 1984):

$$\hat{C}_{y,1,a}^S = N_{y-1,a}^S e^{-M_a^S/8} S_{1,a} F_{y,1}, \; a = 0,\ldots,5+$$

$$\hat{C}_{y,2,a}^S = \left(N_{y-1,a}^S e^{-M_a^S/8} - \hat{C}_{y,1,a}^S\right) e^{-M_a^S/4} S_{2,a} F_{y,2}, \; a = 0,\ldots,5+$$

$$\hat{C}_{y,3,a}^S = \left(\left(N_{y-1,a}^S e^{-M_a^S/8} - \hat{C}_{y,1,a}^S\right) e^{-M_a^S/4} - \hat{C}_{y,2,a}^S\right) e^{-M_a^S/4} S_{3,a} F_{y,3}, \; a = 0,\ldots,5+$$

$$\hat{C}_{y,4,a}^S = \left(\left(\left(N_{y-1,a}^S e^{-M_a^S/8} - \hat{C}_{y,1,a}^S\right) e^{-M_a^S/4} - \hat{C}_{y,2,a}^S\right) e^{-M_a^S/4} - \hat{C}_{y,3,a}^S\right) e^{-M_a^S/4} S_{4,a} F_{y,4}, \; a = 0,\ldots,5+ \quad \text{(A.6)}$$

where

$S_{q,a}$ is the commercial selectivity at age a during quarter q which is assumed to be the same for all years; when $S_{y,q,a} = 1$ the age-class a is said to be fully selected; and

$F_{y,q}$ is the fished proportion in quarter q of year y for a fully selected age class a.

In the above equations the difference in the year subscript between the catch-at-age and initial numbers-at-age is because the numbers-at-age are calculated in November of the previous year.

The commercial fishing selectivity is assumed to take the form of a logistic curve:

$$S_{q,a} = \begin{cases} \dfrac{1}{1+\exp\left(-\left(a-a'_q\right)/\delta_q\right)} & \text{if a} < 3 \\ \dfrac{1}{1+\exp\left(-\left(a-a'_q\right)/\delta_q\right)}\exp\left(-\gamma(a-3)\right) & \text{if a} \geq 3 \end{cases} \quad \text{(A.7)}$$

where

a'_q is the age at 50% selectivity;

δ_q defines the steepness of the ascending limb of the selectivity curve; and

γ defines the extent to which selectivity is decreased after age 3.

The fished proportion is estimated by:

$$F_{y,1} = \frac{C_{y,1}^{ObsTon}}{\sum_{a=0}^{5+}\left(\frac{7}{8}w_{y-1,a}^S + \frac{1}{8}w_{y,a+1}^S\right)N_{y-1,a}^S e^{-M_a^S/8} S_{1,a}} \quad 1$$

$$F_{y,2} = \frac{C_{y,2}^{ObsTon}}{\sum_{a=0}^{5+}\left(\frac{5}{8}w_{y-1,a}^S + \frac{3}{8}w_{y,a+1}^S\right)\left(N_{y-1,a}^S e^{-M_a^S/8} - \hat{C}_{y,1,a}^S\right)e^{-M_a^S/4} S_{2,a}}$$

$$F_{y,3} = \frac{C_{y,3}^{ObsTon}}{\sum_{a=0}^{5+}\left(\frac{3}{8}w_{y-1,a}^S + \frac{5}{8}w_{y,a+1}^S\right)\left(\left(N_{y-1,a}^S e^{-M_a^S/8} - \hat{C}_{y,1,a}^S\right)e^{-M_a^S/4} - \hat{C}_{y,2,a}^S\right)e^{-M_a^S/4} S_{3,a}}$$

$$F_{y,4} = \frac{C_{y,4}^{ObsTon}}{\sum_{a=0}^{5+}\left(\frac{1}{8}w_{y-1,a}^S + \frac{7}{8}w_{y,a+1}^S\right)\left(\left(\left(N_{y-1,a}^S e^{-M_a^S/8} - \hat{C}_{y,1,a}^S\right)e^{-M_a^S/4} - \hat{C}_{y,2,a}^S\right)e^{-M_a^S/4} - \hat{C}_{y,3,a}^S\right)e^{-M_a^S/4} S_{4,a}} \quad \text{(A.8)}$$

where

$C_{y,q}^{ObsTon}$ is the observed catch tonnage for quarter q of year y from the RLFs.

Given the predicted proportion-at-age in the quarterly commercial catch

$$\hat{p}_{y,q,a}^{com} = \frac{\hat{C}_{y,q,a}^S}{\sum_{a=0}^{5+}\hat{C}_{y,q,a}^S} \quad \text{(A.9)}$$

the predicted proportion-at-length is then estimated by

$$\hat{p}_{y,q,l}^{com} = \sum_{a-0}^{5+}\hat{p}_{y,q,a}^{com} A_{y,q,a,l}^{com} \quad \text{(A.10)}$$

where

$A_{y,q,a,l}^{com}$ is the proportion of sardine catch-at-age *a* that fall in the length group l (thus $\sum_{l=1}^{7} A_{a,l} = 1$ for all ages) in quarter q of year y.

The matrix A^{com} is calculated under the assumption that length-at-age is normally distributed about a mean given by the Von Bertalanffy equation, (Brandão *et al*. 2002):

$$L^{com}_{y,q,a} \sim N^*\left(L_{\infty,y}\left(1-e^{-\kappa_y\left(a+1/8+(q-1)*0.25-t_{0,y}\right)}\right);\vartheta^2_{a+1/8+(q-1)*0.25}\right) \quad \text{(A.11)}$$

Recruitment

For the base case assessment a Hockey-Stock (or Single-Sloped) stock-recruitment curve is assumed. Recruitment at the beginning of November is assumed to fluctuate lognormally about the stock-recruitment curve. Thus recruitment in November is given by:

$$N^S_{y,0} = \begin{cases} a^S e^{\varepsilon^S_y} & , \text{ if } B^S_{y,N} \geq b^S \\ \dfrac{a^S}{b^S} B^S_{y,N} e^{\varepsilon^S_y} & , \text{ if } B^S_{y,N} < b^S \end{cases} \qquad y = 1979,\ldots,2006 \quad \text{(A.12)}$$

where

a^S is the maximum recruitment (in billions);

b^S is the spawner biomass above which there should be no recruitment failure risk in the hockey stick model; and

ε^S_y is the annual lognormal deviation of sardine recruitment.

Number of recruits at the time of the recruit survey

The number of recruits at the time of the recruit survey is calculated taking into account the recruit catch during quarters 1 and 2 (November to April) and an estimate of the recruit catch between 1 May and the start of the survey:

$$\hat{N}^S_{y,r} = k^S_r\left(\left((N^S_{y-1,0}e^{-M^S_0/8} - \hat{C}^S_{y,1,0})e^{-M^S_0/4} - \hat{C}^S_{y,2,0}\right)e^{-0.5t^S_y \times M^S_0/12} - \tilde{C}^S_{y,0bs}\right)e^{-0.5t^S_y \times M^S_0/12} \quad y = 1984,\ldots,2006 \quad \text{(A.13)}$$

where

$\hat{N}^S_{y,r}$ is the number (in billions) of juvenile sardine at the time of the recruit survey in year *y*;

k^S_r is the constant of proportionality (multiplicative bias) associated with the recruit survey;

$\tilde{C}^S_{y,0bs}$ is the observed number (in billions) of juvenile sardine caught between 1 May and the day before the start of the recruit survey, assuming a 15.5cm cut-off length; and

t^S_y is the time lapsed (in months) between 1 May and the start of the recruit survey in year *y*.

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

The survey observations are assumed to be lognormally distributed. The standard errors of the log-distributions for the survey observations of adult biomass and recruitment numbers are approximated by

[1] As no survey weight-at-age is available for 1983, it is assumed that $w^S_{1983,a} = w^S_{1984,a}$ and $w^S_{y,0} = 0$.

the CVs of the untransformed distributions. Thus the contribution of the survey abundance data to the negative log-likelihood function is given by:

$$-\ln L^{surv} = \tfrac{1}{2}\sum_{y=1984}^{2006}\left\{\frac{\left(\ln B^S_{y,N} - \ln(\hat{B}^S_{y,N})\right)^2}{(\sigma^S_{y,Nov})^2 + (\lambda^S_N)^2} + \ln\left[2\pi\left((\sigma^S_{y,Nov})^2 + (\lambda^S_N)^2\right)\right]\right\}$$
$$+ \tfrac{1}{2}\sum_{y=1985}^{2006}\left\{\frac{\left(\ln N^S_{y,r} - \ln(\hat{N}^S_{y,r})\right)^2}{(\sigma^S_{y,rec})^2 + (\lambda^S_r)^2} + \ln\left[2\pi\left((\sigma^S_{y,rec})^2 + (\lambda^S_r)^2\right)\right]\right\} \quad \text{(A.14)}$$

where

$B^S_{y,N}$ is the uncapped acoustic survey estimate (in thousands of tonnes) of adult sardine biomass from the November survey in year y, with associated CV $\sigma^S_{y,Nov}$;

$N^S_{y,r}$ is the uncapped acoustic survey estimate (in billions) of sardine recruitment numbers from the recruit survey in year y, with associated CV $\sigma^S_{y,rec}$; and

$(\lambda^S_{N/r})^2$ is the additional variance (over and above the survey sampling CV $\sigma^S_{y,Nov/rec}$ that reflects survey inter-transect variance) associated with the November/recruit surveys;

The survey proportions at age for years in which survey ALKs are available and the survey proportions at length for years in which survey ALKs are not available are assumed to be lognormally distributed. Thus the contribution of the survey proportions at age/length to the negative log-likelihood function is given by:

$$-\ln L^{prop} = \frac{1}{2}\sum_{y=yi}\sum_{a=1}^{5}\left\{\frac{n_y\, p^S_{y,a,N}\left(\ln p^S_{y,a,N} - \ln\left(\hat{p}^S_{y,a,N}\right)\right)^2}{(\sigma^S_p)^2} + \ln\left[2\pi(\sigma^S_p)^2/(n_y\, p^S_{y,a,N})\right]\right\}$$
$$+ w_{len}\sum_{y=yj}\sum_{l=1}^{7}\left\{\frac{p^S_{y,l,N}\left(\ln p^S_{y,l,N} - \ln \hat{p}^S_{y,l,N}\right)^2}{2\left(\sigma^S_{len}\right)^2} + \ln\left(\frac{\sigma^S_{len}}{\sqrt{p^S_{y,l,N}}}\right)\right\} \quad \text{(A.15)}$$

yi are the 8 years for which November survey ALKs are available (1993, 1994, 1996, 2001, 2002, 2003, 2004, 2006);

yj are the 15 years for which November survey ALKs are not available;

$p^S_{y,a,N}$ is the re-normalised estimate of the proportion (by number) of sardine of age *a* in the November survey of year y;

n_y is the number of fish from the November survey trawls in year y used to compile the age-length key for calculating $p^S_{y,a,Nov}$;

$(\sigma^S_p)^2$ is the overall variance-related parameter for the log-transformed proportion-at-age observations,

$p^S_{y,a,Nov}$ [note variance = $(\sigma^S_p)^2/(n_y p^S_{y,a,Nov})$].

$p^S_{y,l,N}$ is the observed proportion (by number) in length group l in the November survey of year y;

σ^S_{len} is the standard deviation associated with the length-at-age data in the November survey, which is estimated in the fitting procedure by:

$$\sigma^S_{len} = \sqrt{\sum_{y=yj}\sum_{l=1}^{7} p^S_{y,l,N}\left(\ln p^S_{y,l,N} - \ln \hat{p}_{y,l,N}\right)^2 \Big/ \sum_{y=yj}\sum_{l=1}^{7} 1}$$

The raw data is recorded by 0.5cm length classes from 3.0cm to 23cm. The data were combined to form seven length groups: a minus group of 11.499cm, 11.5cm - 12.999cm, 13.0cm – 14.499cm, 14.5cm – 15.499cm, 15.5cm – 17.499cm, 17.5cm – 18.999cm and a plus group of 19.0cm. The data are given in Table B.5.

The associated variance in equation (A.15) s taken to be inversely proportional to the observed proportion-at-age/length to downweight contributions from observed small proportions which will correspond to small predicted sample sizes. The w_{len} weighting factor may be set at a value less than 1 to downweight the contribution of the survey proportion-at-length data to the overall negative log-likelihood compared to that of the spawner biomass and recruit survey data.

The commercial proportions at length from the raised length frequencies are assumed to be lognormally distributed; the contribution to the negative log-likelihood function is given by:

$$-\ln L^{prop} = w_{com} \sum_{y=1984}^{2006} \sum_{q=1}^{4} \sum_{l=1}^{l\max(y,q)} \left\{ \frac{p^{com}_{y,q,l}\left(\ln p^{com}_{y,q,l} - \ln \hat{p}^{com}_{y,q,l}\right)^2}{2\left(\sigma^S_{com}\right)^2} + \ln\left(\frac{\sigma^S_{com}}{\sqrt{p^{com}_{y,q,l}}} \right) \right\}^2 \qquad \text{(A.16)}$$

approach to ignore the difference $p^{com}_{y,q,l}$ is the normalised observed proportion (by number) of the commercial catch in length group

l of during quarter q ($q=1$ for Nov-Jan, $q=2$ for Feb-Apr, $q=3$ for May-Jul, $q=4$ for Aug-Oct) of year y;

σ^S_{com} is the standard deviation associated with the proportion-at-length data in the commercial catch, which is estimated in the fitting procedure by:

$$\sigma^S_{com} = \sqrt{\sum_{y=1984}^{2006} \sum_{q=1}^{4} \sum_{l=1}^{l\max(y,q)} p^{com}_{y,q,l}\left(\ln p^{com}_{y,q,l} - \ln \hat{p}^{com}_{y,q,l}\right)^2 \Big/ \sum_{y=1984}^{2006} \sum_{q=1}^{4} \sum_{l=1}^{l\max(y,q)} 1} \; .$$

No proportion-at-length was fitted for the fourth quarter in 1984, 1985, 1986 and 1989 as the tonnage landed during this quarter is less than 4% of that for the year. The raw data is recorded by 0.5cm length classes from 3.5cm to 23cm. The data were combined to form seven length groups: a minus group of 8.499cm, 8.5cm - 10.499cm, 10.5cm – 13.999cm, 14.0cm – 17.499cm, 17.5cm – 18.499cm, 18.5cm – 19.499cm and a plus group of 19.5cm. In some quarters, the proportion-at-length in these length groups was small (<2%) and so some length groups were further combined. The data are given in Table B.3.

Fixed Parameters

Fourteen parameters are fixed externally in this assessment:

$M_{ju}^{S}=1$ and $M_{ad}^{S}=0.4$ (De Oliveira 2003)

$w_{len}=w_{com}=0.5$

$k_{p,2}^{S}=k_{p,3}^{S}=k_{p,4}^{S}=k_{p,5+}^{S}=1$

$k_{N}^{S}=1$

The parameters for the Von Bertalanffy growth curves were estimated separately for peak (2000 – 2004) and non-peak years using the combined ALKs from 1993, 1994, 1996 and 2006 for 'normal' years and 2001 to 2004 for 'peak' years, giving:

$L_{\infty,normal}=19.12$ $\qquad$ $L_{\infty,peak}=18.95$

$\kappa_{normal}=0.73$ $\qquad$ $\kappa_{normal}=0.78$

$t_{0,normal}=t_{0,peak}=-1/6$ (fixed, giving recruits between 2-3cm in November)

Estimable Parameters and Prior Distributions

The recruitments are assumed to fluctuate lognormally about the stock-recruitment curve. The prior pdfs for the recruitment residuals are given by:

$$\varepsilon_{y}^{S}\sim N\left(0,\left(\sigma_{r}^{S}\right)^{2}\right) \quad , \qquad y=1979,...,2005$$

where $\left(\sigma_{r}^{S}\right)^{2}=0.4^{2}+\left(\lambda_{0}^{S}\right)^{2}$

$(\lambda_{0}^{S})^{2}$ is the additional variance (over and above the fixed variance of 0.4^2) associated with the recruitment residuals, where the fixed variance has been introduced to avoid the overall variance being estimated to be unrealistically small.

The remaining estimable parameters are defined as having the following near non-informative prior distributions:

$k_{r}^{S}\sim\log N\left(1,0.7^{2}\right)$

$k_{p,1}^{S}\sim\log N\left(1,1\right)$

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[2] Although strictly there may be bias in the proportions of commercial length-at-age (as for the survey length-at-

$\lambda_N^S \sim U(0,1)$

$\left(\lambda_r^S\right)^2 \sim U(0,10000)$

$\left(\lambda_0^S\right)^2 \sim U(0,10000)$

$\sigma_p^S \sim \log N\left(3, 0.7^2\right)$

$a^S \sim N\left(100, 1^2\right)$

$b^S / K^S \sim U(0,1)$

$a_1' = a_2' = a_3' = a_4' = a'$, $a' \sim N\left(1, 2^2\right)$

$\delta_1 = \delta_2 = \delta_3 = \delta_4 = \delta$, $\delta \sim Exp(-5\delta)$

$\gamma \sim U(0,10)$

$\beta_{peak} \sim U(0,100)$

$\beta_{normal} \sim U(0,100)$

Further Outputs

Recruitment serial correlation:

$$s_{cor}^S = \frac{\sum_{y=1984}^{2004} \varepsilon_y \varepsilon_{y+1}}{\sqrt{\left(\sum_{y=1984}^{2004} \varepsilon_y^2\right)\left(\sum_{y=1984}^{2004} \varepsilon_{y+1}^2\right)}} \tag{A.8}$$

and the standardised recruitment residual value for 2005:

$$\eta_{2005}^S = \frac{\varepsilon_{2005}^S}{\sigma_r^S} . \tag{A.9}$$

are also required as input into the OMP.

A separate carrying capacity, K^S (essentially the B_N^S value where the replacement line and the function describing expected recruitment intersect) is calculated representing the period of peak abundance (2000 – 2004) to that for the remaining years:

$$K_{normal}^S = a^S e^{\frac{1}{2}\sigma_r^2} \left[\sum_{a=1}^{5+} \overline{w}_{normal,a}^S e^{-M_0^S - (a-1) M_a^S} \right] \tag{A.17}$$

$$K_{peak}^S = a^S e^{\frac{1}{2}\sigma_r^2} \left[\sum_{a=1}^{5+} \overline{w}_{peak,a}^S e^{-M_0^S - (a-1) M_a^S} \right] \tag{A.18}$$

where:

age), no bias is assumed in this assessment. The effect of such a bias is assumed to be small.

$\overline{w}^{S}_{normal,a}$ is the mean mass (in grams) of sardine of age *a* sampled during each November survey, averaged over all November surveys for which an estimate of mean mass-at-age is available outside of the peak years (i.e. 1993, 1994, 1996 and 2006).

$\overline{w}^{S}_{peak,a}$ is the mean mass (in grams) of sardine of age *a* sampled during each November survey, averaged over all November surveys for which an estimate of mean mass-at-age is available during the peak period (i.e. 2001 – 2004).

The $e^{\frac{1}{2}\left(\sigma_r^S\right)^2}$ factor in the above equation is a bias correction factor, needed given the assumption that recruitment is log-normally distributed about an underlying stock-recruit curve.

Appendix B: Tables of Data Used in the Sardine Assessment

Table B.1. Catch-at-age data (in millions)

	$C^P_{y,0}$	$C^P_{y,1}$	$C^P_{y,2}$	$C^P_{y,3}$	$C^P_{y,4}$
1980	625.634	172.418	201.631	65.045	4.300
1981	908.200	206.432	144.387	66.128	7.688
1982	236.902	144.131	167.696	48.004	17.224
1983	1803.579	151.879	246.975	72.060	5.050

Table B.2. Quarterly catch tonnage (in thousands of tonnes)

	Nov-Jan	Feb-Apr	May-Jul	Aug-Oct
1984	1.980	18.297	6.485	0.261
1985	3.641	16.168	10.878	0.025
1986	1.310	19.496	9.611	0.222
1987	3.693	20.853	7.083	1.895
1988	1.855	14.405	14.812	3.450
1989	3.311	19.412	12.517	0.989
1990	3.341	22.182	23.767	7.570
1991	3.389	21.122	21.765	6.911
1992	1.569	17.577	18.961	16.068
1993	6.288	21.683	15.396	5.768
1994	5.411	31.747	37.418	21.673
1995	5.126	26.617	38.335	45.869
1996	11.176	30.847	29.914	28.372
1997	16.112	32.986	38.717	42.740
1998	5.955	33.096	46.689	45.754
1999	8.285	12.713	41.157	40.160
2000	34.950	25.830	47.350	43.731
2001	20.689	44.025	38.669	50.219
2002	56.332	56.611	41.703	81.092
2003	85.797	84.535	63.896	51.898
2004	94.181	99.331	97.132	82.743
2005	86.266	90.401	74.368	51.286
2006	32.324	55.581	79.781	49.929

Table B.3. Proportion-at-length in the quarterly commercial catch. A blank cell indicates that the length group is combined with the length group directly smaller than it. The fourth quarter in 1984, 1985, 1986 and 1989 is ignored in the model fit as the tonnage landed during this quarter is less than 4% of that landed for the year. Quarter 1 refers to November – January, Quarter 2 to February to April, Quarter 3 to May to July, and Quarter 4 to August to October.

Year	Quarter	$3.5cm \le l < 8.5cm$	$8.5cm \le l < 10.5cm$	$10.5cm \le l < 14cm$	$14cm \le l < 17.5cm$	$17.5cm \le l < 18.5cm$	$18.5cm \le l < 19.5cm$	$1 \ge 19.5cm$
1984	1	0.373	-1	-1	0.522	0.062	0.024	0.019
	2	0.068	-1	0.206	0.482	0.134	0.063	0.047
	3	0.056	0.142	0.072	0.724	-1	-1	0.006
	4	-1	-1	-1	-1	-1	-1	-1
1985	1	0.534	-1	-1	0.198	0.18	0.08	0.007
	2	0.599	-1	0.133	0.055	0.097	0.079	0.036
	3	0.576	0.268	0.139	0.011	-1	-1	0.005
	4	-1	-1	-1	-1	-1	-1	-1
1986	1	0.061	-1	-1	0.155	0.193	0.288	0.304
	2	0.469	-1	0.231	0.069	0.066	0.089	0.077
	3	0.297	0.355	0.252	0.088	-1	-1	0.008
	4	-1	-1	-1	-1	-1	-1	-1
1987	1	0.002	-1	-1	0.253	0.291	0.313	0.142
	2	0.062	-1	0.243	0.124	0.155	0.225	0.191
	3	0.377	0.389	0.116	0.071	-1	-1	0.049
	4	0.323	0.471	0.187	0.014	-1	-1	0.006
1988	1	0.05	-1	-1	0.392	0.135	0.155	0.267
	2	0.087	-1	0.055	0.244	0.105	0.174	0.333
	3	0.368	0.361	0.078	0.078	-1	-1	0.115
	4	0.173	0.324	0.316	0.09	-1	-1	0.096
1989	1	0.381	-1	-1	0.258	0.067	0.1	0.195
	2	0.202	-1	0.415	0.071	0.023	0.033	0.258
	3	0.47	0.29	0.135	0.022	-1	-1	0.082
	4	-1	-1	-1	-1	-1	-1	-1
1990	1	0.317	-1	-1	0.108	0.042	0.04	0.494
	2	0.565	-1	0.099	0.051	0.036	0.029	0.22
	3	0.515	0.287	0.015	0.067	-1	-1	0.116
	4	0.008	-1	-1	-1	0.047	0.144	0.802

1991	1	0.122	-1	-1	0.149	0.17	0.195	0.365
	2	0.688	-1	0.063	0.032	0.033	0.063	0.122
	3	0.127	0.304	0.16	0.236	-1	-1	0.174
	4	0.024	-1	-1	-1	0.089	0.413	0.474
1992	1	0.135	-1	-1	0.259	0.051	0.176	0.379
	2	0.506	-1	0.139	0.099	0.03	0.079	0.148
	3	0.397	0.416	0.094	0.034	-1	-1	0.06
	4	0.17	0.405	0.186	0.04	0.018	0.056	0.124
1993	1	0.086	-1	-1	0.277	0.152	0.19	0.295
	2	0.216	-1	0.125	0.198	0.114	0.133	0.213
	3	0.343	0.285	0.152	0.051	0.042	0.049	0.078
	4	0.621	0.269	0.036	0.019	0.017	0.014	0.023
1994	1	0.331	-1	-1	0.236	0.221	0.145	0.067
	2	0.254	-1	0.283	0.214	0.078	0.086	0.085
	3	0.323	0.291	0.115	0.115	0.047	0.051	0.057
	4	0.063	0.357	0.117	0.091	0.096	0.151	0.125
1995	1	0.238	-1	-1	0.127	0.157	0.282	0.196
	2	0.455	-1	-1	0.047	0.098	0.204	0.195
	3	0.493	0.375	-1	0.031	0.041	0.041	0.019
	4	0.236	0.566	-1	0.032	0.031	0.064	0.071
1996	1	0.766	-1	-1	0.056	0.029	0.052	0.098
	2	0.547	-1	-1	0.14	0.035	0.056	0.222
	3	0.362	0.296	-1	0.09	0.066	0.076	0.109
	4	0.001	0.004	-1	0.254	0.199	0.231	0.313
1997	1	0.098	-1	-1	0.231	0.183	0.219	0.27
	2	0.016	-1	-1	0.214	0.188	0.304	0.278
	3	0.369	0.085	-1	0.097	0.114	0.197	0.138
	4	0.365	0.242	-1	0.104	0.114	0.112	0.063
1998	1	0.09	-1	-1	0.295	0.205	0.238	0.172
	2	0.513	-1	-1	0.143	0.099	0.126	0.119
	3	0.455	0.313	-1	0.039	0.057	0.079	0.056
	4	0.218	0.052	-1	0.063	0.161	0.277	0.228
1999	1	0.002	-1	-1	0.143	0.122	0.297	0.435
	2	0.361	-1	-1	0.17	0.166	0.15	0.152

	3	0.063	0.395	-1	0.135	0.131	0.156	0.119
	4	0.208	0.132	-1	0.211	0.178	0.174	0.097
2000	1	0.017	-1	-1	0.148	0.207	0.36	0.268
	2	0.548	-1	-1	0.077	0.119	0.147	0.109
	3	0.049	0.32	-1	0.148	0.208	0.19	0.084
	4	0.038	0.035	-1	0.157	0.27	0.325	0.175
2001	1	0.005	-1	-1	0.239	0.289	0.307	0.159
	2	0.207	-1	-1	0.159	0.237	0.281	0.115
	3	0.297	0.344	-1	0.095	0.12	0.11	0.034
	4	0.156	0.401	-1	0.063	0.097	0.163	0.12
2002	1	0.04	-1	-1	0.22	0.252	0.301	0.187
	2	0.147	-1	-1	0.403	0.163	0.191	0.097
	3	0.28	0.256	-1	0.262	0.075	0.089	0.038
	4	0.07	0.413	-1	0.238	0.102	0.11	0.066
2003	1	0.083	-1	-1	0.428	0.219	0.177	0.093
	2	0.26	-1	-1	0.378	0.163	0.133	0.067
	3	0.228	0.302	-1	0.293	0.066	0.07	0.04
	4	0.102	0.116	-1	0.414	0.152	0.137	0.079
2004	1	0.045	-1	-1	0.596	0.216	0.099	0.044
	2	0.083	-1	-1	0.605	0.168	0.099	0.046
	3	0.11	0.189	-1	0.508	0.057	0.069	0.066
	4	0.092	0.036	-1	0.332	0.246	0.19	0.105
2005	1	0.079	-1	-1	0.422	0.33	0.134	0.036
	2	0.114	-1	-1	0.391	0.294	0.144	0.058
	3	0.06	0.164	-1	0.146	0.176	0.254	0.2
	4	0.036	0.118	-1	0.057	0.142	0.351	0.296
2006	1	0.101	-1	-1	0.16	0.267	0.355	0.117
	2	0.093	-1	-1	0.303	0.211	0.256	0.137
	3	0.252	0.23	-1	0.014	0.045	0.202	0.256
	4	0.244	0.14	-1	0.269	0.128	0.125	0.093

Table B.4. Summary of annual uncapped estimates for the sardine spawner biomass surveys (in thousands of tonnes), using new target strength expressions and including corrections for attenuation. Values have been estimated from 1984 to 1997 and are as observed since 1998. Mean masses-at-age, $w^{P}_{y,a}$*, observed during the November spawner biomass survey, together with proportions-at-age estimates from the November survey,* $p^{S}_{y,a,N}$*, and the sample size,* n_y*, (number of fish) used to compile age-length keys underlying these estimates.*

Year	Acoustic 1+ Biomass	CV	$w^S_{y,1}$	$w^S_{y,2}$	$w^S_{y,3}$	$w^S_{y,4}$	$w^S_{y,5+}$	$p^S_{y,1,N}$	$p^S_{y,2,N}$	$p^S_{y,3,N}$	$p^S_{y,4,N}$	$p^S_{y,5+,N}$	n_y
1984	48.378	1.118	32.378[3]	58.563[3]	83.612[3]	92.696[3]	108.815[3]						
1985	45.013	0.509	32.378	58.563	83.612	92.696	108.815						
1986	299.797	0.848	32.378	58.563	83.612	92.696	108.815						
1987	111.285	0.630	32.378	58.563	83.612	92.696	108.815						
1988	134.362	0.957	32.378	58.563	83.612	92.696	108.815						
1989	256.655	0.274	32.378	58.563	83.612	92.696	108.815						
1990	289.931	0.352	32.378	58.563	83.612	92.696	108.815						
1991	597.858	0.395	32.378	58.563	83.612	92.696	108.815						
1992	494.157	0.658	32.378	58.563	83.612	92.696	108.815						
1993	560.019	0.427	25.483	39.937	74.304	77.632	110.329	0.0976	0.473	0.2157	0.1535	0.0603	587
1994	518.354	0.370	42.281	61.340	81.786	89.778	96.285	0.0226	0.3606	0.2687	0.1989	0.1493	620
1995	843.944	0.713	32.378	58.563	83.612	92.696	108.815						
1996	529.456	0.471	29.412	72.304	96.520	111.277	126.697	0.1295	0.3464	0.2945	0.1453	0.0842	335
1997	1224.632	0.329	32.378	58.563	83.612	92.696	108.815						
1998	1607.328	0.251	32.378	58.563	83.612	92.696	108.815						
1999	1635.410	0.212	32.378	58.563	83.612	92.696	108.815						
2000	2292.380	0.500	25.464[4]	43.466[4]	75.165[4]	84.813[4]	96.486[4]						
2001	2309.600	0.142	19.896	29.992	72.327	82.142	95.360	0.5254	0.3422	0.0386	0.0583	0.0355	526
2002	4206.250	0.227	22.750	33.187	66.104	77.252	88.508	0.1287	0.2717	0.2316	0.1931	0.1749	570
2003	3564.171	0.197	38.804	53.252	81.420	93.045	105.959	0.5049	0.1974	0.1481	0.0994	0.0502	145
2004	2615.715	0.334	20.408	57.433	80.811	86.814	96.115	0.3249	0.1436	0.2294	0.1626	0.1395	322
2005	1048.991	0.300	32.378	58.563	83.612	92.696	108.815						
2006	712.553	0.346	30.232	65.055	85.564	94.835	103.858	0.8687	0.0584	0.0356	0.024	0.0134	442

[3] Average over 1993, 1994, 1996 and 2006.
[4] Average over 2001 to 2004.

Table B.5. Proportion-at-length in the survey (for years for which ALKs are not available).

Year	$3cm \le l < 11.5cm$	$11.5cm \le l < 13cm$	$13cm \le l < 14.5cm$	$14.5cm \le l < 15.5cm$	$15.5cm \le l < 17.5cm$	$17.5cm \le l < 19cm$	$1 \ge 19cm$
1984	0.095	0.034	0.084	0.095	0.565	0.102	0.024
1985	0.020	0.116	0.333	0.233	0.138	0.069	0.091
1986	0.002	0.176	0.631	0.065	0.037	0.071	0.017
1987	0.090	0.158	0.216	0.040	0.104	0.076	0.316
1988	0.017	0.045	0.220	0.219	0.287	0.116	0.096
1989	0.078	0.019	0.154	0.201	0.164	0.150	0.235
1990	0.017	0.064	0.133	0.060	0.215	0.149	0.363
1991	0.083	0.199	0.259	0.165	0.070	0.069	0.155
1992	0.025	0.106	0.263	0.360	0.178	0.034	0.035
1995	0.133	0.246	0.114	0.012	0.070	0.091	0.334
1997	0.035	0.127	0.097	0.034	0.175	0.386	0.145
1998	0.164	0.149	0.266	0.081	0.067	0.084	0.188
1999	0.002	0.060	0.159	0.150	0.276	0.177	0.175
2000	0.032	0.063	0.239	0.164	0.171	0.058	0.273
2005	0.111	0.053	0.103	0.111	0.116	0.141	0.365

Table B.6. Summary of annual uncapped estimates of sardine recruitment (in billions), using the new target strength expression and including corrections for attenuation. Recruitment and CVs from 1985 to 1997 have been calibrated on a regression of data from 1998 to 2006. The mean weight of the recruits during the survey is given (in grams) together with the time of the recruit survey after 1 May, t_y^S, and the recruit catch taken between 1 May and the commencement of the recruit survey (in billions), $C_{y,0bs}^S$.

Year	Recruitment	CV	t_y^S	$C_{y,0bs}^S$
1985	3.60	0.595	0.613	0.050[5]
1986	3.71	0.586	1.300	0.050[5]
1987	8.06	0.598	2.613	0.063
1988	0.44	0.402	1.867	0.195
1989	2.26	0.616	1.233	0.045
1990	2.50	0.906	1.700	0.010
1991	1.90	0.276	0.194	0.009
1992	5.59	0.325	0.387	0.029
1993	15.43	0.358	0.645	0.045
1994	2.70	0.311	0.129	0.071
1995	26.04	0.345	1.300	0.161
1996	3.49	0.372	1.133	0.081
1997	40.72	0.42	0.516	0.036
1998	10.72	0.354	0.613	0.428
1999	10.38	0.378	0.290	0.021
2000	60.07	0.359	0.452	0.076
2001	49.15	0.285	0.129	0.002
2002	36.45	0.183	0.129	0.031
2003	4.09	0.217	0.419	0.073
2004	1.69	0.324	0.226	0.078
2005	9.56	0.303	0.387	0.105
2006	3.60	0.379	0.581	0.037

[5] To be finalised.