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Assessment of Antarctic Minke Whales using Statistical Catch-at-age Analysis

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ABSTRACT
Statistical Catch-at-age Analysis (SCAA) is applied to data for Antarctic minke whales. The SCAA model is spatially-structured, can model multiple stocks of minke whales, and can utilize several data types for parameter estimation. The application to Antarctic minke whales considers two stocks (I and P) in five areas which cover Antarctic Areas III-E to IV-W. The parameters of the model (annual deviations about the stock-recruitment relationship, density-dependence parameters (productivity and carrying capacity), and the parameters which determine growth by stock, age-specific natural mortality by stock, and vulnerability by area and 'fleet') are estimated by fitting the model to data on catches, catch-at-length, conditional age-at-length, and estimates of absolute and relative abundance. A reference case analysis is selected and sensitivity explored by varying the assumptions on which the reference case analysis is based. The reference case analysis is able to mimic all of the data sources adequately. Most of the analyses (reference and sensitivity) indicate that Antarctic minke whales in the assessed area increased from 1930 until the mid-1970s and have declined thereafter, with the extent of the decline greater for minke whales in Antarctic Areas III-E to V-W than for those further east. Natural mortality is consistently estimated to be higher for younger and older individuals. The estimates of $MSYR_{1+}$ are 5.3% for minke whales in Antarctic Areas III-E to V-W and 3.6% for minke whales in Areas V-E and VI-W, but these estimates are less well determined than other model outputs, and quite sensitive to the assumptions on which the SCAA is based.

KEYWORDS: CATCH-AT-AGE, ANTARCTIC MINKE WHALE, POPULATION MODEL; SOUTHERN HEMISPHERE

INTRODUCTION

Two classes of stock assessment method have been proposed for application to Antarctic minke whales. One of these (ADAPT-VPA; Butterworth *et al.* [1996, 1999, 2002]) is based on the assumption that the catches-at-age at measured with limited error compared to the indices of abundance used to estimate the values for the parameters of the model. The other is Statistical Catch-at-Age Analysis (SCAA; Punt and Polacheck [2005, 2006, 2007, 2008]; Punt [2011]). In contrast to ADAPT-VPA, SCAA does not assume that the age-structure of the catches is measured with limited error, and can account for both sampling error and age-reading error[1]. In addition, the SCAA developed for Antarctic minke whales can account for multiple stocks in the assessed area, time-varying growth,

[1] Age-reading error has been quantified for Antarctic minke whales by Kitakado and Punt (2010, 2013).

multiple areas, mixing of stocks in areas, environmental covariates, fleet-specific vulnerabilities, changes over time in the proportion of each stock in each area, and changes over time in vulnerability.

A question of considerable interest to the IWC Scientific Committee has been why the estimates of abundance from the IDCR/SOWER line transect survey exhibited declining trends in some Management Area. In addition, there has been interest in exploring the evidence for or against the hypothesis that there has been a recent decrease in carrying capacity for the Antarctic minke whales due to an increase in competition from other predators (IWC, 2005).

The paper applies SCAA to data for the Antarctic minke whales in Management Areas III-E, IV, V, and VI-W. It first outlines the mathematical specifications for the model and its associated estimation scheme. The paper then provides specifications for a 'reference' case analysis which uses all of the available index, catch length-composition, and conditional catch-at-age data. The reference case model considers five areas (III-E, IV, V-W, V-E, and VI-W), selected primarily because of the availability of data, and considers two stocks: the I stock - assumed to be found in areas III-E, IV, and V-W, and the P stock - assumed to be found in Areas V-E and VI-W. Full results for this reference case are provided based on suggestions for model outputs and fit diagnostics by the Scientific Committee. A series of sensitivity tests are outlined which examine the sensitivity of the results to the assumptions of the model, including that carrying capacity may have changed over time, and the weights assigned to each of the many data sources and penalties. Results for the sensitivity tests are restricted to a set of 'core' statistics to keep the volume of results to minimum. However, detailed results are available electronically for all of the sensitivity tests.

MATHEMATICAL SPECIFICATIONS OF THE POPULATION MODEL

A. Basic structure

The population dynamics model considers multiple stocks (indexed by '*s*') and represents each stock using an age- and sex-structured model. 'Fleets' in this model are combinations of 'fleet' (Japan before 1987/88, Japan from 1987/88[2], and ex-Soviet Union) and area. Each 'fleet' can have a different age- or length-specific vulnerability pattern (the combined effects of harvest selectivity and availability), which may change over time. Similarly growth, which depends on stock and sex, can change over time.

B. The population dynamics model

Under the assumption that harvesting occurs instantaneously at the start of the year, the number of animals of stock *s*, sex *g* and age *a* at the start of year *y*, $N^{g,s}_{y,a}$, is given by:

$$N^{g,s}_{y,a} = \begin{cases} 0.5\,\tilde{N}^{s}_{y,0} & \text{if } a = 0 \\ (N^{g,s}_{y-1,a-1} - C^{g,s}_{y-1,a-1})\,e^{-M^{s}_{a-1}} & \text{if } 1 \le a \le x-1 \\ (N^{g,s}_{y-1,x-1} - C^{g,s}_{y-1,x-1})\,e^{-M^{s}_{x-1}} + (N^{g,s}_{y-1,x} - C^{g,s}_{y-1,x})\,e^{-M^{s}_{x}} & \text{if } a = x \end{cases} \tag{B.1}$$

[2] Two Japanese 'fleets' are considered so that the data for commercial and Scientific Permit catches can be treated separately.

where $\tilde{N}^{s}_{y,0}$ is the number of births to stock *s* at the start of year *y* (the sex-ratio at birth is assumed to be 50:50), $C^{g,s}_{y,a}$ is the catch of animals of stock *s*, sex *g* and age *a* during year *y*, calculated as the sum of the catch of such animals over all fleets, i.e.:

$$C^{g,s}_{y,a} = \sum_{f} C^{g,s,f}_{y,a} \tag{B.2}$$

$C^{g,s,f}_{y,a}$ is the catch of animals of stock *s*, sex *g* and age *a* by fleet *f* during year *y*, M^{s}_{a} is the instantaneous rate of natural mortality on animals of stock *s* and age *a* (assumed to be time-invariant), and *x* is the plus-group (set equal to 54).

C. Natural mortality-at-age

The relationship between natural mortality and age is taken to be piecewise linear:

$$M^{s}_{a} = \begin{cases} \delta M^{s} & \text{if } a \le a_1 \\ M^{s}[\delta + (1-\delta)\dfrac{(a-a_1)}{(a_2-a_1)}] & \text{if } a_1 < a < a_2 \\ M^{s} & \text{if } a_2 \le a \le a_3 \\ M^{s}[1 + (\gamma-1)\dfrac{(a-a_3)}{(a_4-a_3)}] & \text{if } a_3 < a < a_4 \\ \gamma M^{s} & \text{if } a \ge a_4 \end{cases} \tag{C.1}$$

where δM^{s} is the rate of natural mortality for animals of stock *s* aged a_1 and younger, M^{s} is the rate of natural mortality for animals of stock *s* aged between a_2 and a_3, and γM^{s} is the rate of natural mortality for animals of stock *s* aged a_4 and older.

D. Births

The number of births to stock *s* during year *y* depends on the number of females that have reached the age-at-first-parturition at the start of year *y* and the extent of density-dependence in pregnancy rate and infant survival[3], i.e.:

$$B^{s}_{y} = B^{\mathrm{F},s}_{y}\ f^{s}_{0} e^{A^{s}(1-B^{1+,s}_{y}/K^{1+,s}_{y})}\ e^{\varepsilon^{s}_{y}} \tag{D.1a}$$

or

$$B^{s}_{y} = B^{\mathrm{F},s}_{y}\ f^{s}_{0} e^{A^{s}(1-B^{1+,s}_{y}/K^{1+,s}_{y})e^{\varepsilon^{s}_{y}}} \tag{D.1b}$$

where $B^{\mathrm{F},s}_{y}$ is the number of females of stock *s* that have reached the age-at-first-parturition at the start of year *y*, i.e.:

[3] As calves are not harvested, this formulation for density-dependence conceptually encompasses density-dependent effects in the survival rate of calves.

$$B_y^{\mathrm{F},s} = \sum_{a=1}^{x} \beta_{y,a}\, N_{y,a}^{g,s} \tag{D.2}$$

$B_y^{1+,s}$ is the number of animals aged 1 and older in stock *s* at the start of year *y*:

$$B_y^{1+,s} = \sum_g \sum_{a=1}^{x} N_{y,a}^{g,s} \tag{D.3}$$

$K_y^{1+,s}$ is the carrying capacity of stock *s* (expressed in terms of the size of the 1^+ component of the population) at the start of year *y*, $\beta_{y,a}$ is the proportion during year *y* of animals of age *a* that have reached the age-at-first-parturition, f_0^s is the pregnancy rate / infant survival rate in absence of harvesting for stock *s*, A^s is the resilience parameter for stock *s*, ε_y^s is the logarithm of the ratio of the expected to actual number of births for stock *s* during year *y* (Equation D.1a only), and σ_R is the standard deviation of ε_y^s.

Allowance is made for the possibility that carrying capacity has changed in a piecewise linear manner over the period considered in the analyses:

$$K_y^{1+,s} = \begin{cases} K_{1930}^{1+,s} & \text{if } y \le y_1 \\ K_{1930}^{1+,s}[1+(\tilde{K}_I^{1+,s}-1)\dfrac{(y-y_1)}{(y_2-y_1)}] & \text{if } y_1 < y < y_2 \\ K_{1930}^{1+,s}[\tilde{K}_I^{1+,s}+(\tilde{K}_{2002}^{1+,s}-\tilde{K}_I^{1+,s})\dfrac{(y-y_2)}{(y_3-y_2)}] & \text{if } y_2 \le y < y_3 \\ K_{1930}^{1+,s}\,\tilde{K}_{2002}^{1+,s} & \text{if } y \ge y_3 \end{cases} \tag{D.4}$$

where $K_{1930}^{1+,s}$ is the carrying capacity for stock *s* from 1930 to year y_1, $\tilde{K}_I^{1+,s}$ is the ratio of the carrying capacity for stock *s* in year y_2 to that in year y_1, and $\tilde{K}_{2002}^{1+,s}$ is the ratio of the carrying capacity for stock *s* in year y_3 to that in year y_1.

E. Catches and vulnerability

The model-estimate of the catch of animals of stock *s*, sex *g* and age *a* by fleet *f* during year *y* depends on the number of animals of stock *s*, sex *g* and age *a*, the exploitation rate by fleet *f* on animals of sex *s* during year *y*, the proportion of animals of stock *s* in the area where fleet *f* operates, and the relative vulnerability of animals of sex *g* and age *a* during year *y* to fleet *f* (assumed to be independent of stock). $C_{y,a}^{g,s,f}$ is computed using the formula:

$$C_{y,a}^{g,s,f} = \sum_l C_{y,a,l}^{g,s,f} \tag{E.1}$$

where $C_{y,a,l}^{g,s,f}$ is the catch during year *y* by fleet *f* of animals of stock *s*, sex *g* and age *a* that are in length-class *l*:

$$C_{y,a,l}^{g,s,f} = \begin{cases} \tilde{S}_a\, S_{y,l}^{g,f} F_y^{g,f}\, X_{y,a,l}^{g,s}\, P_y^{A,s} N_{y,a}^{g,s} & \text{if vulnerability is length-specific} \\ \tilde{S}_a\, S_{y,a}^{g,f}\, F_y^{g,f} X_{y,a,l}^{g,s}\, P_y^{A,s}\, N_{y,a}^{g,s} & \text{if vulnerability is age-specific} \end{cases} \tag{E.2}$$

$S_{y,l}^{g,f}$ is the vulnerability of animals of sex *g* and length *l* to fleet *f* during year *y*, $S_{y,a}^{g,f}$ is the vulnerability of animals of sex *g* and age *a* to fleet *f* during year *y*, $\tilde{S}_a$ is a factor to reduce the availability of animals of certain (younger) ages to the fishery, $F_y^{g,f}$ is the exploitation rate due to fleet *f* on fully-selected (i.e. $S_{y,l}^{g,f} \to 1$; $S_{y,a}^{g,f} \to 1$) animals of sex *g* during year *y*, $P_y^{A,s}$ is the proportion of stock *s* that is in the area *A* (where fleet *f* is found in area *A*) during year *y* (the model assumes that there is no sex- or age-structure to distribution),

$$P_y^{A,s} = \overline{P^{A,s}} e^{\varphi_y^{A,s}} \Big/ \sum_{A'} e^{\varphi_y^{A',s}} \tag{E.3}$$

$\overline{P^{A,s}}$ is the expected proportion of stock *s* that is in area *A*, $\varphi_y^{A,s}$ is the deviation from the expected proportion for stock *s* in area *A* during year *y*, and $X_{y,a,l}^{g,s}$ is the proportion of animals of stock *s*, sex *g* and age *a* that are in length-class *l* during year *y*.

Vulnerability by fleet is either assumed to be a function of length, fleet and sex, or a function of age, fleet and sex. The model has options which allow vulnerability to be uniform (Equations E.4a and E.5a), logistic (Equations E.4b and E.5b), or domed-shaped (Equations E.4c and E.5c), and can vary over time:

$$S_{y,l}^{g,f} = 1 \tag{E.4a}$$

$$S_{y,l}^{g,f} = (1 + e^{-\ell n 19 (L_l - L_{50,y}^{g,f})/L_{\text{diff}}^{g,f}})^{-1} \tag{E.4b}$$

$$S_{y,l}^{g,f} = \begin{cases} \exp(-(L_l - L_{50,y}^{g,f})^2 / L_{\text{left}}^{g,f}) & \text{if } L_l \le L_{50,y}^{g,f} \\ \exp(-(L_l - L_{50,y}^{g,f})^2 / L_{\text{right}}^{g,f}) & \text{otherwise} \end{cases} \tag{E.4c}$$

$$S_{y,a}^{g,f} = 1 \tag{E.5a}$$

$$S_{y,a}^{g,f} = (1 + e^{-\ell n 19 (a - a_{50,y}^{g,f})/a_{\text{diff}}^{g,f}})^{-1} \tag{E.5b}$$

$$S_{y,a}^{g,f} = \begin{cases} \exp(-(a - a_{50,y}^{g,f})^2 / a_{\text{left}}^{g,f}) & \text{if } a \le a_{50,y}^{g,f} \\ \exp(-(a - a_{50,y}^{g,f})^2 / a_{\text{right}}^{g,f}) & \text{otherwise} \end{cases} \tag{E.5c}$$

where $L^{g,f}_{50,y}$ is the length-at-50%-vulnerability (logistic vulnerability) / length-at-full-vulnerability (dome-shaped vulnerability) for fleet *f* during year *y* for animals of sex *g*:

$$L^{g,f}_{50,y} = L^{g,f}_{50,y-1} + \delta^{g,f}_{y} \tag{E.6a}$$

$a^{g,f}_{50,y}$ is the age-at-50%-vulnerability (logistic vulnerability) / age-at-full-vulnerability (dome-shaped vulnerability) for fleet *f* during year *y* for animals of sex *g*:

$$a^{g,f}_{50,y} = a^{g,f}_{50,y-1} + \delta^{g,f}_{y} \tag{E.6b}$$

$\delta^{g,f}_{y}$ is the "vulnerability deviation" during year *y* for fleet *f* for animals of sex *g*, $L^{g,f}_{\mathrm{diff}}$ is the width of the length-specific vulnerability ogive for fleet *f* for animals of sex *g*, $a^{g,f}_{\mathrm{diff}}$ is the width of the age-specific vulnerability ogive for fleet *f* for animals of sex *g*, $L^{g,f}_{\mathrm{left}}$ and $L^{g,f}_{\mathrm{right}}$ are the parameters that determine the extent of dome-shapedness for the length-specific vulnerability ogive for fleet *f* for animals of sex *g*, $a^{g,f}_{\mathrm{left}}$ and $a^{g,f}_{\mathrm{right}}$ are the parameters that determine the extent of dome-shapedness for the age-specific vulnerability ogive for fleet *f* for animals of sex *g*, and L_l is the length (in ft) corresponding to the mid-point of length-class *l*.

Time-dependence in vulnerability is modelled by allowing the length- (or age-)at-50%-/full-vulnerability to change from one year to the next, i.e. the shape of the vulnerability ogive is the same each year, but the point at which vulnerability first equals 1 changes. Time-dependence in vulnerability was modelled in this way to avoid the over-parameterization that might occur if allowance was also made for time-dependence in the parameters that determine the shape of the vulnerability ogive.

F. Growth

The proportion of animals of stock *s* and sex *g* in age-class *a* that are in length-class *l* during *y*, $X^{g,s}_{y,a,l}$, is given by:

$$X^{g,s}_{y,a,l} = \int_{L_l-\Delta L}^{L_l+\Delta L} \frac{1}{\sqrt{2\pi}\sigma^{g,s}_{\gamma}} e^{-\frac{(L-\bar{L}^{g,s}_{y,a})^2}{2(\sigma^{g,s}_{\gamma})^2}} dL \tag{F.1}$$

where ΔL is half of the width of each length-class (0.5 ft), $\sigma^{g,s}_{\gamma}$ is the extent of variability about the growth curve for sex *g* for animals of stock *s*, $\bar{L}^{g,s}_{y,a}$ is the expected length of an animal of stock *s*, sex *g* and age *a* during year *y*, assuming that length-at-age is governed by a von Bertalanffy growth curve and that the growth rate parameter $k^{g,s}_{y}$ varies over time, i.e.:

$$\bar{L}^{g,s}_{y,a} = \begin{cases} L^{g,s}_0 & \text{if } a = 0 \\ L^{g,s}_\infty - (L^{g,s}_\infty - \bar{L}^{g,s}_{y-1,a-1})e^{-k^{g,s}_{y-1}} & \text{otherwise} \end{cases} \tag{F.2}$$

$L^{g,s}_\infty$ is the asymptotic length for animals of stock *s* and sex *g*, $k^{g,s}_y$ is the value of the Brody growth coefficient for animals of stock *s* and sex *g* during year *y*:

$$k^{g,s}_y = k^{g,s}_{y-1}\, e^{\upsilon^s_y} \tag{F.3}$$

$L^{g,s}_0$ is the length of an animal of age zero for animals of stock *s* and sex *g*, and υ^s_y is the extent to which the growth rate changes from year *y*-1 to year *y* for stock *s*.

G. Initial conditions

The initial conditions (y_1=1930) correspond to a population at its unexploited equilibrium level, i.e.:

$$N^{g,s}_{y_1,a} = \begin{cases} 0.5\,\tilde{N}^s_{y,0} & \text{if } a = 0 \\ N^{g,s}_{y_1,a-1}\, e^{-M^s_{a-1}} & \text{if } 1 \le a \le x-1 \\ N^{g,s}_{y_1,x-1}\, e^{-M^s_{x-1}} / (1 - e^{-M^s_x}) & \text{if } a = x \end{cases} \tag{G.1}$$

where $\tilde{N}^s_{y,0}$ is the expected number of calves in the absence of exploitation for stock *s*.

The value of the parameter f^s_0 is chosen so that the population remains in balance in the absence of exploitation, i.e.:

$$f^s_0 = \left[\sum_{a=1}^{x-1} \beta_{y_1,a}\, e^{-\sum_{a'=0}^{a-1} M^s_{a'}} + \beta_{y_1,x} e^{-\sum_{a'=0}^{x-1} M^s_{a'}} / (1 - e^{-M^s_x}) \right]^{-1} \tag{G.2}$$

OBJECTIVE FUNCTION

The objective function contains contributions from the data and from penalties on some of the parameters, i.e.:

$$L = \sum_i O_i\, \ell n L_i + \sum_j P_j \tag{H.1}$$

where $\ell n L_i$ is the contribution of the i^th data source to the objective function, P_j is the contribution of the j^th penalty term to the objective function, and O_i is a factor to account for overdispersion.

The data included in the assessment are the annual catches (by fleet and sex), the estimates of abundance (IDCR and JARPA / JARPA II), the catch length-frequency data and the conditional age-at-length data, while there are penalties on the magnitudes of the deviations from the expected number of births (Equation D.1), on the inter-annual deviations in the growth rate (Equation F.3), on the inter-annual variation in the proportion of the population in each area (see Equation E.3), and on the inter-annual deviations in vulnerability (Equation E.6). Each of these contributions is discussed in turn below. The equations listed below assume that data for each data-type are available for every year, and for all areas and fleets. This is not the case in reality, and the equations are modified appropriately in the absence of data for specific years, areas and fleets.

H.1 Catches

The contribution of the catches to the objective function is based on the assumption that any errors when measuring the catch are log-normally distributed[4], i.e.:

$$\ell n L_1 = \sum_y \sum_g \sum_f \left\{ \tfrac{1}{2\sigma_C^2} \sum_y (\ell n \tilde{C}_y^{g,f} - \ell n C_y^{g,f})^2 \right\} + Const \qquad \text{(H.1)}$$

where $\tilde{C}_y^{g,f}$ is the actual catch by fleet *f* of animals of sex *g* during year *y*, $C_y^{g,f}$ is the model-estimate of total catch by fleet *f* of animals of sex *g* during year *y*:

$$C_y^{g,f} = \sum_s \sum_a C_{y,a}^{g,s,f} \qquad \text{(H.2)}$$

σ_C quantifies the extent of variation in catches.

H.2 Estimates of abundance

The estimates of abundance are assumed to be indices of 1^+ abundance, i.e.:

$$\ell n L_2 = \sum_A \sum_y \left\{ \tfrac{1}{2(\tilde{\sigma}_y^A)^2} (\ell n V_y^A - \ell n(\chi^A B_y^{\text{Surv},A}))^2 \right\} + Const \qquad \text{(H.3)}$$

where V_y^A is the estimate of abundance for area *A* and year *y*, χ^A is the bias factor for area *A*, $\tilde{\sigma}_y^A$ is the measurement error standard deviation, determined from the observation error standard deviation and the extent of additional variance, i.e.:

$$(\tilde{\sigma}_y^A)^2 = \tau^2 + (\phi_y^A)^2 \qquad \text{(H.4)}$$

τ^2 is the extent of additional variance, ϕ_y^A is the coefficient of variation of V_y^A, $B_y^{\text{Surv},A}$ is the model-estimate of the total (1+) abundance in area *A* at the start of year *y*, i.e.:

$$B_y^{\text{Surv},A} = \sum_s \sum_g \sum_{a>0} \sum_l P_y^{A,s} X_{y,a,l}^{g,s} S_{y,l}^{g,f*} N_{y,a}^{g,s} \qquad \text{(H.5)}$$

f^* is the fleet to which the abundance estimates pertain (set to the post-1987 Japanese fleet for the JARPA / JARPA II indices; set to uniform selectivity for the IDCR indices).

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[4] Note that very high weight is assigned to this component of the objective function so the model effectively replicates the actual catches exactly.

H.3 Length-frequency data

The contribution of the length-frequency data to the objective function is based on the assumption that the catch by sex and fleet is taken multinomially from the vulnerable population, i.e.:

$$\ell\mathrm{n}L_3 = -\sum_y \sum_f \sum_g M_y^{g,f} \sum_{l=l_{\min,y}}^{l_{\max,y}} \rho_{y,l}^{g,f} \,\ell\mathrm{n}(\hat{\rho}_{y,l}^{g,f} \,/\, \rho_{y,l}^{g,f}) + Const \tag{H.6}$$

where $M_y^{g,f}$ is the effective sample size for the length-frequency data for animals of sex *g* taken by fleet *f* during year *y* (set equal to the number of animals of sex *g* taken by fleet *f* during year *y* for which information on length is available multiplied by an overdispersion factor), $\rho_{y,l}^{g,f}$ is the observed fraction of the catch of animals of sex *g* taken by fleet *f* during year *y* that is in length-class *l*, $\hat{\rho}_{y,l}^{g,f}$ is the model-estimate of the fraction of the catch of animals of sex *g* taken by fleet *f* during year *y* that is in length-class *l*:

$$\hat{\rho}_{y,l}^{g,f} = \frac{\sum_s \sum_a C_{y,a,l}^{g,s,f}}{\sum_{s'} \sum_{a'} \sum_{l'} C_{y,a',l'}^{g,s',f}} \tag{H.7}$$

Lengths $l_{\min,y}$ and $l_{\max,y}$ define the plus and minus groups for the length-frequency data for year *y* (data and model-predictions for animals with length less than $l_{\min,y}$ are pooled in the $l_{\min,y}$ length-class while data and model-predictions for animals with length greater than $l_{\max,y}$ are pooled in the $l_{\max,y}$ length-class).

H.4 Conditional age-at-length data

The age data are included in the objective function under the assumption that sampling for age is multinomial conditioned on length, i.e.:

$$\ell\mathrm{n}L_4 = \sum_y \sum_f \sum_g \sum_{l=l_{\min,y}}^{l_{\max,y}} \tilde{M}_{y,l}^{g,f} \sum_{a=a_{\min,y}}^{a_{\max,y}} \theta_{y,a,l}^{g,f} \,\ell\mathrm{n}\left(\hat{\theta}_{y,a,l}^{g,f} \,/\, \theta_{y,a,l}^{g,f}\right) + Const \tag{H.8}$$

where $\tilde{M}_{y,l}^{g,f}$ is the effective sample size for the age breakup of the animals of sex *g* in length-class *l* taken by fleet *f* during year *y* (set equal to the number of animals of sex *g* in length-class *l* taken by fleet *f* during year *y* for which information on length and age is available multiplied by an overdispersion factor), $\theta_{y,a,l}^{g,f}$ is the observed fraction of the catch of animals in length-class *l* of sex *g* taken by fleet *f* during year *y* that were aged to be age *a*, $\hat{\theta}_{y,a,l}^{g,f}$ is the model-estimate of the fraction of the catch of animals in length-class *l* of sex *g* taken by fleet *f* during year *y* that were aged to be age *a*, i.e.:

$$\hat{\theta}^{g,f}_{y,a,l} = \frac{\sum_{s} \tilde{C}^{g,s,f}_{y,a,l}}{\sum_{s'} \sum_{a'} \tilde{C}^{g,s,f}_{y,a',l}} \tag{H.9}$$

$\tilde{C}^{g,s,f}_{y,a,l}$ is the model-estimate of the number of animals of sex *g* and stock *s* in length-class *l* caught by fleet *f* during year *y* that would have been aged to be age *a*:

$$\tilde{C}^{g,s,f}_{y,a,l} = \sum_{a'} Y_{a,a',y}\, C^{g,s,f}_{y,a',l} \tag{H.10}$$

$Y_{a,a',y}$ is the fraction during year *y* of animals of sex *g* and age *a*' that are aged to be age *a* (the age-reading error matrix), i.e.:

$$Y_{a,a',y} = \int_{a-0.5}^{a+0.5} \frac{1}{\sqrt{2\pi}\sigma''_{a',y}} e^{-\frac{(\lambda-\beta_{a',y})^2}{2(\sigma''_{a',y})^2}} d\lambda \tag{H.11}$$

$\beta_{a,y}$ is the expected age based on age-readings for an animal of true age *a* during year *y*, and $\sigma''_{a,y}$ is the standard error of the age-estimate for an animal of true age *a* during year *y*.

Ages $a_{\min,y}$ and $a_{\max,y}$ define the plus and minus groups for the ageing data for year *y*, i.e. data and model-predictions for animals with age greater than $a_{\max,y}$ are pooled at age $a_{\max,y}$ [5] and those with age less than $a_{\min,y}$ are pooled at age $a_{\min,y}$.

H.5 Penalties

The penalty on the deviations from the expected number of births is based on the assumption that these deviations are log-normally distributed, i.e.:

$$P_1 = \tfrac{1}{2\sigma_R^2} \sum_{s} \sum_{y} (\varepsilon^s_y)^2 \tag{H.12}$$

The penalty on the changes over time in the vulnerability deviations is based on the assumption that these deviations are normally distributed, i.e.:

$$P_2 = \tfrac{1}{2\sigma_S^2} \sum_{g} \sum_{y} \sum_{f} (\delta^{g,f}_y)^2 \tag{H.13}$$

where σ_S is the extent of inter-annual variation in the age-at-50%-vulnerability.

The penalty on the annual deviations in the proportion of each stock in each area is based on the assumption that these deviations are normally distributed, i.e.:

[5] Note that the evaluation of the impact of age-reading error is determined before the application of the plus-group.

$$P_3 = \frac{1}{2\sigma_P^2}\sum_s\sum_y\sum_A (\varphi_y^{A,s})^2 \tag{H.14}$$

where σ_P is the extent of variation in the distribution of the stock.

The penalty on the inter-annual changes in the von Bertalanffy growth rate parameter is based on the assumption that these deviations are normally distributed, i.e.:

$$P_4 = \frac{1}{2\sigma_k^2}\sum_s\sum_y (\upsilon_y^s)^2 \tag{H.15}$$

DATA UTILIZED

The data used when conducting assessments of the Antarctic minke whales consist of catches, abundance estimates, length frequency data, and conditional-at-age length data. The data include the catches and sighting survey information through the 2011/12 season.

I.1 Catches and length-frequency data

Table 1 lists the catches by sex, fleet (Japan and ex-Soviet Union) and Management Area (III-E, IV, V-W, V-E, and VI-W). The catches prior to 1971/72 are not allocated to fleet because these catches were taken by several nations. There is no information on the length-frequency of these catches so the vulnerability patterns for the years prior to 1971/72 are assumed to be equal to that for Japan in 1971/72, and the pre-1971/72 catches for Area V are split equally between Areas V-W and V-E. The results are unlikely to be sensitive to these assumptions given the small magnitude of the catches concerned.

I.2 Age-composition data

Age-composition data and hence conditional age-at-length data are only available for the Japanese catches. Table 2 lists the number of animals aged and the number of animals for which length data are available.

I.3 Indices of abundance

Table 3 lists the estimates of absolute abundance from the IDCR program (Okamura and Kitakado, 2012) and the indices of abundance based on the JARPA / JARPA II programme (Hakamada et al., in review; Hakamada, pers. comm).

THE REFERENCE CASE ANALYSIS

The reference case analysis matches the no-USSR length data analysis of Punt (2011), i.e. the length-frequency data for the USSR fleet are ignored, and selectivity for the USSR and the Japanese fleet are assumed to be the same. The primary specifications of this analysis are (note that the letters before each section match those in the previous sections) as follows.

C. Natural mortality

Natural mortality is assumed to change (in a piecewise linear fashion) at ages 3, 10, 30 and 35 (ages a_1, a_2, a_3 and a_4 in Equation C.1). Natural mortality for stock I is assumed to be a constant proportion of that for stock P.

D. Births

1. Process error in births is modelled using Equation D.1a.
2. Carrying capacity is assumed to have changed in 1930, 1960 and 1980 (years y_1, y_2 and y_3 in Equation D.4).
3. The proportion of animals that have reached the age-at-first-parturition is defined by a logistic curve where 50% of animals reach first parturition at 8.5 years and 95% by 11.5 years. The first age at which an animal may reach first parturition is set equal to 3 years. These specifications were made for consistency with the analyses conducted by Butterworth and Punt (1999).
4. The variation in births, σ_R, is set to 0.2.

E. Catches and vulnerability

1. Vulnerability is length- rather than age-specific.
2. Vulnerability for the ex-USSR fleet is assumed to be the same as that for the Japanese fleet because of concerns regarding possible mis-reporting of lengths by the ex-USSR (IWC, 2011).
3. Vulnerability for the Japanese fleets (before 1987/88) is assumed to be time-varying double-normal function of length (See Equation E.4c).
4. Vulnerability for the JARPA / JARPA II fleet is assumed to be a logistic function of length and to the constant over space.
5. An age-specific availability factor is estimated for age 1 only.

F. Growth

1. Values for the change in growth rate ($k_y^{g,s}$) are estimated for each year from 1963/64 until 2011/12.

G. Likelihood function

1. There is no survey bias for the IDCR/SOWER estimates (i.e. χ=1 for the IDCR estimates), and no additional variance for either IDCR/SOWER or JARPA/JARPA II (i.e. τ^2 =0 in Equation H.3)[6].
2. Separate survey bias parameters are estimated for the JAPRA / JARPA II indices in each of the five areas included in the analysis.
3. Age-reading error is modelled by assuming separate age-reading error matrices for each primary reader (Table 4)

$$\beta_a = \beta_L + (\beta_H - \beta_L)\frac{a}{70}; \qquad \sigma_a^{''} = \sigma_L^{''} + (\sigma_H^{''} - \sigma_L^{''})\frac{a}{70} \qquad \text{(J.1)}$$

4. The minus- and plus-group ages when fitting to the conditional age-at-length data, $a_{\min,y}$ and $a_{\max,y}$, are set to 1 and 45yr respectively.
5. The minus- and plus-group lengths, $l_{\min,y}$ and $l_{\max,y}$ for females are set to 22ft and 32ft for the period of commercial whaling, and 17ft and 32ft for JARPA /

[6] Additional variance is implicitly accounted for by allowing the proportion of the population in each area to change over time.

JARPA II while $l_{\min,y}$ and $l_{\max,y}$ for males are set to 22ft and 31ft for the period of commercial whaling and 17ft and 31ft for JARPA / JARPA II. [These choices were made to avoid fitting the model to length-classes with few data.]

6. The ex-USSR length-frequency data are ignored because of possible mis-reporting.
7. The standard deviation of the logarithms of measuring the catch, σ_C, is set to 0.05.
8. The parameter that determines the extent of variability in the vulnerability deviations, σ_S, is set to 10.
9. The parameter that determines the extent of variability in the proportion of each stock in each area, σ_P, is set to 0.3.
10. The parameter that determines the extent of variability in growth rate, σ_k, is set to 0.1.
11. The values for the overdispersion parameters for length-frequency and conditional age-length data (0.70 and 0.85 respectively) were selected as outlined by Punt and Polacheck (2006).

The reference case choices for σ_C, σ_R, σ_S, σ_P, and σ_k were made to force the model to replicate the catches closely, not to allow large deviations in births compared to those expected from the number of mature females, and to allow for large changes in vulnerability from one year to the next and in the proportion of the population in each area, if this suggested by the data.

Table 5 lists the estimable parameters of the reference case model and Table 6 lists the specifications for the sensitivity tests.

DIAGNOSTIC STATISTICS AND SENSTIVITY TESTS

Table 7 outlines a list of diagnostic statistics and plots. The statistics and some of the plots were originally selected by the Scientific Committee, but subsequently modified based on requests for additional analyses. The plots summarize the key outputs from the assessments (e.g. Figures 1 and 2) as well as plots to understand those outputs somewhat better (e.g. Figures 3, 4, and 5).

RESULTS

Reference case analysis

The estimates of natural mortality indicate that natural mortality is highest for the youngest and oldest animals (Figure 2; Table 8). Natural mortality for the I stock is estimated to be higher at large age than for the P stock (0.127yr^{-1} for animals 35yr and older, compared to 0.106yr^{-1}). Both stocks are estimated to have increased from 1930 until the early 1970s, with the I stock having declined subsequently thereafter (Figure 1). The increase in abundance is due primarily to an increase in recruitment owing to an increase in carrying capacity (Figure 2). Carrying capacity is estimated to have declined subsequently for both stocks, but the effect of this on recruitment and hence total population size is much smaller for the P than for the I stock (Figure 1). The I stock is estimated to have initially been larger than the P stock, but the P stock is currently the larger of the two stocks (Figure 1, Table 8). The recruitment deviations (Figure 1) suggest that there have been periods of good and poor recruitment since 1975. MSYR$_{1+}$ for the I stock is estimated to be higher than that for the P stock (5.3% compared to 3.6%; Table 8)

The estimates of the proportions of the total population in each area changes over time, and vary inter-annually to better fit the abundance estimates, while there is also evidence for time-varying growth (Figure 3). The initial declining trends in the proportion of the total population in Areas III-E, IV and V-W is due to the faster estimated rate of increase for the P stock. The von Bertalanffy growth rate is estimated to have peaked in the mid-1980s and to have declined thereafter (Figure 3). The number of calves per-mature female remains below the biological maximum (Figure 4); previous versions of the SCAA led to unrealistically high values for the number of calves per mature female (see Punt [2011] for reasons for this change in result, which relate to the implementation of a penalty early during the minimization process).

Figures 5 and 6 illustrate how well the model is able to mimic the estimates of absolute and relative abundance given the estimated changes in abundance as well as inter-annual variation in the proportion of the population in each area. The confidence intervals for the abundance estimates generally intersect the population trajectory, indicating that the extent of process error in the proportion of the stocks in each area is sufficient to capture additional variance. Figure 7 provides plots which summarise the fits to the length-frequency data using three commonly-used summary plots (bubble plots of Pearson residuals, input versus inferred effective sample sizes, and fits to data aggregated over year). Figure 8 provides a more detailed summary for one of the fleet-sex combinations. A full set of length-frequency diagnostics is not included in this document to keep its length down (but is available on request from the first author). The model is able to mimic the length-frequency data on average (Figure 7, right panels), except perhaps for females in Area V-E. The assumed extent of overdispersion (0.70; dotted lines in Figure 7) is not ideal for any one fleet, but (as expected) the model captures the average relationship between effective and observed sample sizes. The fits in Figure 8 are amongst the best. As expected, the fits are best when sample sizes are high.

The final diagnostic plot (Figure 9) summarizes the fit to the conditional age-at-length data (again results are only shown for one fleet-sex combination). There are no major concerns with the fits to the mean ages-at-length, suggesting that the extent of time-varying growth is sufficient to mimic the changes in growth over time (see Figure 10 for the model-predicted growth curves).

Figures 11 and 12 show the length- and age-specific selectivity curves.

Sensitivity tests

Assuming that process error impacts the density-dependent exponent (Equation D.1a; sensitivity test P1) leads qualitatively different trends for the P stock and a substantially larger size for the I stock (particularly between 1930 and the mid-1970s). However, the results for this sensitivity test should be considered with caution because it is unlikely that the minimization algorithm found the global minimum of the objective function. The marked difference in $MSYR_{1+}$ for the two stocks, as well as the very high rate of natural mortality for sensitivity test P1 are surprising, but are perhaps a reflection of convergence to a local minimum (Table 7).

As expected, the rate of increase in abundance is less for sensitivity test P5 in which no allowance is made for carrying capacity to increase (Figure 13). The assumption of no change in carrying capacity leads to a much poor fit to the data (Table 9).

Sensitivity test P2, which does not allow for process error in spatial distribution, is supported (in an AIC sense[7]) over the reference case (Table 9), suggesting that including an additional variance parameter in the reference case analysis may provide an adequate way to address overdispersion. Sensitivity test P2, however, leads to essentially the same results as the reference case analysis (Figure 13), suggesting that changing the way overdisperson is handled will not impact the overall conclusions of this study. Allowing natural mortality to differ among stocks is supported by AIC (a ΔAIC is 6.2), but this difference in AIC is not enormous, especially given the large amount of data and the way those data are weighted.

The results are quite sensitive to changes to how selectivity is modelled. Allowing g(0) to be less than 1 (sensitivity tests S5 and S6) does not change the quality of the fit of the model to the data (Table 9). However, as expected, population size is larger for these sensitivity tests (Figure 14). Sensitivity test S1 (selectivity depends on age not length) leads to qualitatively different results for the I stock. However, this sensitivity test led to a much poorer fit to the data (ΔAIC=1402). Sensitivity test S8 leads to a much poorer fit to the data (Table 8), although far fewer parameters are estimated. Overall, however, the estimated trends in abundance are similar for sensitivity tests S8 and the reference case analysis (Figure 14). Treating the JARPA indices of abundance as absolute (sensitivity test S9) leads to a poor fit to the data and overall to a lower trajectory of 1+ population size. This is not surprising because the estimates of the survey catchability coefficients (survey *q* in Table 8) for the JARPA surveys are generally substantially smaller than 1 (Table 8).

The trends in abundance are insensitive to whether separate selectivity patterns are estimated for JARPA and JARPA II (sensitivity test S10; Figure 14). As expected, the fit of the model is better (lower negative log-likelihood) when allowance is made for selectivity for JARPA and JARPA II to differ (Table 9). However, sensitivity test S10 involves nine additional parameters (four selectivity parameters and five survey catchability coefficients) so an improved fit (lower negative log-likelihood) is expected.

The results are insensitive to changes to how the data are weighted (Table 8, Figure 15). The one exception is when ageing error is ignored. Historical abundance is much larger for this sensitivity test, and the decline in abundance during the 1970s is even more pronounced than is case for the reference case analysis. Table 9 does not list the values for the negative log-likelihood function for the "D" sensitivity tests because changing the weights assigned to the data changes the likelihood function, which makes the values for the negative log-likelihood non-comparable among sensitivity tests.

DISCUSSION

Most of the analyses indicate that Antarctic minke whales in the assessed area increased from 1930 until the mid-1970s and have declined thereafter, with the extent of the decline greater for minke whales in Antarctic Areas III-E to V-W than those further east (Figures 13, 14 and 15). The trend in recent (last 20-odd) years is relatively flat or perhaps declining slowly. Natural mortality is consistently estimated to be higher for younger and older individuals. There are a few sensitivity tests for which these general conclusions do

[7] AIC should be interpreted with some caution given the somewhat ad hoc way the various data sources are weighted.

not hold, but one of those sensitivity tests are cases in which there is evidence for non-convergence[8].

The reference case estimates of $MSYR_{1+}$ are 5.3% for minke whales in Antarctic Areas III-E to V-W and 3.6% for minke whales in Areas V-E and VI-W, but these estimates are less well determined than other model outputs and quite sensitive to the assumptions on which the SCAA is based.

The estimates of the variances of the estimates of natural mortality are generally very low (CVs of 10% or less). These estimates should be interpreted with some caution given that they rely on asymptotic approximations and the weights assigned to the data / penalties.

The model on which the assessment is based is very complicated because it explicitly models five areas and two stocks, allows for time-varying selectivity, and consequently has over 1,000 parameters. The complexity arises because (a) some of the parameters (those related to natural mortality) are shared between stocks, necessitating that the two stocks are modelled simultaneously, and (b) the estimates of absolute abundance from IDCR are area-specific, which implies that the proportion of the population in each area needs to be modelled. In principle, the IDCR data could have been treated as relative indices of abundance, but then a constraint would have had to have been imposed on the survey catchability coefficients so that they sum to 1 over all areas in which a stock is found. The explicit allowance for spatial structure would also be needed if mixing of stocks was desired. If simulation testing of the assessment method is desired, it would be sensible to drop the area-structure and move to an parameterization where the catchability coefficients for IDCR add to 1 as this should substantial speed up the time it takes to fit the model.

The analyses are based on many assumptions, some of these have been explored in the tests of sensitivity. In general, the results are robust to those assumptions. Assumptions which could not be explored in detail in this study related to stock structure are perhaps of greatest concern. In particular, the analyses of this paper assume that there are two stocks of minke whales in Antarctic Areas III-E through VI-W and that there are no areas of mixing. Recently a transition area, where the two stocks mix with each other, has been suggested in part of Area VW (Pastene, 2006). The longitudinal sector of this transition area and the proportion of each stock in the transition area could change by year (Kitakado *et al*., 2012). The model has the capability to allow for such mixing but without agreed data to estimate mixing proportions, it is not currently possible to explore model configurations with mixing.

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[8] The analyses started from a parameter vector which was very far from the true minimum and changes to those values might resolve these non-convergence problems.

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Table 1
Catches by sex and Area

Table 1(a) – pre-1971/72 catches

Year	Area III*		Area IV		Area V*		Area VI*	
	Female	Male	Female	Male	Female	Male	Female	Male
1953/54	1	0	0	0	0	0	0	1
1954/55	0	0	0	0	0	0	0	0
1955/56	8	4	3	2	1	1	2	2
1956/57	5	2	0	1	0	0	6	3
1957/58	127	54	49	21	17	5	50	31
1958/59	28	10	20	9	7	3	5	3
1959/60	51	21	35	15	28	9	2	1
1960/61	55	24	8	4	15	4	12	7
1961/62	0	1	0	0	0	0	0	0
1962/63	8	3	1	1	0	1	0	0
1963/64	3	1	51	43	2	0	0	0
1964/65	1	2	0	1	0	0	0	0
1965/66	4	5	0	0	0	1	1	0
1966/67	10	5	1	1	0	1	1	2
1967/68	27	73	327	273	1	0	1	0
1968/69	43	72	27	23	2	1	0	1
1969/70	84	102	7	4	2	1	0	0
1970/71	0	0	16	10	1	1	0	0

* - split equally between the eastern and western half-Areas.

Table 1(b) – catches 1970/71 – 1986/87

Year	Area III-E				Area IV				Area V-W				Area V-E				Area VI-W			
	Japan		Soviet Union		Japan		Soviet Union		Japan		Soviet Union		Japan		Soviet Union		Japan		Soviet Union	
	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
1971/72	184	170	0	0	1728	929	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1972/73	0	0	351	298	975	1116	1172	1294	0	0	0	0	0	0	0	0	0	0	0	0
1973/74	818	260	86	50	1282	761	1526	1000	0	0	0	0	0	0	0	0	3	10	0	0
1974/75	751	519	0	0	410	430	913	477	310	190	165	69	0	0	0	0	0	0	0	0
1975/76	604	417	757	376	237	198	215	231	160	260	154	57	0	0	0	0	0	0	0	0
1976/77	940	445	1176	313	432	518	251	399	495	515	375	82	0	0	0	0	0	0	0	0
1977/78	614	398	656	133	353	128	359	123	316	298	189	27	22	32	0	0	83	156	74	110
1978/79	958	642	542	175	573	386	285	126	104	69	168	73	0	0	0	0	0	0	5	5
1979/80	395	308	641	132	482	1048	202	129	113	383	687	161	0	0	0	0	0	0	0	0
1980/81	292	327	343	275	664	529	841	352	330	105	132	114	156	34	335	42	99	100	10	48
1981/82	71	188	485	380	1043	582	0	0	779	369	0	0	11	18	0	0	67	218	0	0
1982/83	0	0	638	464	490	530	741	207	1480	416	0	0	0	0	0	0	170	137	319	150
1983/84	0	0	105	158	518	589	631	357	945	436	0	0	56	8	0	0	349	126	0	0
1984/85	0	0	377	142	364	137	659	328	573	337	0	0	0	0	0	0	92	277	0	0
1985/86	0	0	0	0	292	222	664	229	670	343	0	0	0	0	0	0	97	300	0	0
1986/87	0	0	41	21	321	193	628	322	851	162	0	0	0	0	0	0	285	129	0	0

Table 1(c) – catches by Japan post 1986/87

Year	Area III-E		Area IV		Area V-W		Area V-E		Area VI-W	
	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
1987/88	0	0	119	153	0	0	0	0	0	0
1988/89	0	0	0	0	0	0	151	85	0	0
1989/90	0	0	142	184	0	0	0	0	0	0
1990/91	0	0	0	0	77	110	68	54	14	0
1991/92	0	0	123	165	0	0	0	0	0	0
1992/93	0	0	0	0	87	118	53	45	20	4
1993/94	0	0	130	200	0	0	0	0	0	0
1994/95	0	0	0	0	27	113	103	87	0	0
1995/96	41	68	126	204	0	1	0	0	0	0
1996/97	0	0	0	0	72	55	80	77	82	74
1997/98	36	75	123	204	0	0	0	0	0	0
1998/99	0	0	0	0	88	95	34	111	20	41
1999/00	46	63	160	170	0	0	0	0	0	0
2000/01	0	0	0	0	45	95	73	87	64	76
2001/02	56	54	183	147	0	0	0	0	0	0
2002/03	0	0	0	0	46	54	116	114	43	67
2003/04	48	62	192	138	0	0	0	0	0	0
2004/05	0	0	0	0	47	35	137	75	79	67
2005/06	66	64	264	309	59	89	2	0	0	0
2006/07	0	0	0	0	0	0	233	88	118	66
2007/08	79	150	141	94	58	29	0	0	0	0
2008/09	0	0	0	0	57	77	106	67	141	231
2009/10	143	102	63	40	58	90	5	5	0	0
2010/11	0	0	0	0	0	0	20	26	88	36
2011/12	0	0	0	0	50	49	16	19	101	31

Table 2
Summary of the compositional data (number of animals aged and number of animals measured from the catch by Japan)

Year	Area III-E				Area IV			
	Age-composition		Length-frequency (Japan)		Age-composition		Length-frequency (Japan)	
	F	M	F	M	F	M	F	M
1971/72	12	6	184	170	487	235	1728	929
1972/73	0	0	0	0	413	418	975	1116
1973/74	250	85	818	260	436	272	1282	761
1974/75	468	285	751	519	235	257	410	430
1975/76	169	100	604	417	114	71	237	198
1976/77	352	146	940	445	156	168	432	518
1977/78	254	148	614	398	194	67	353	128
1978/79	643	439	958	642	428	274	573	386
1979/80	283	211	395	308	355	781	482	1048
1980/81	252	250	292	327	544	417	664	529
1981/82	62	149	71	188	864	491	1043	582
1982/83	0	0	0	0	392	398	490	530
1983/84	0	0	0	0	380	385	518	589
1984/85	0	0	0	0	303	110	364	137
1985/86	0	0	0	0	247	188	292	222
1986/87	0	0	0	0	293	177	321	193
1987/88	0	0	0	0	99	135	119	153
1988/89	0	0	0	0	0	0	0	0
1989/90	0	0	0	0	118	155	142	184
1990/91	0	0	0	0	0	0	0	0
1991/92	0	0	0	0	102	143	123	165
1992/93	0	0	0	0	0	0	0	0
1993/94	0	0	0	0	102	173	130	200
1994/95	0	0	0	0	0	0	0	0
1995/96	36	54	41	67	98	176	126	204
1996/97	0	0	0	0	0	0	0	0
1997/98	36	63	36	75	91	168	123	204
1998/99	0	0	0	0	0	0	0	0
1999/00	34	48	46	63	145	147	160	170
2000/01	0	0	0	0	0	0	0	0
2001/02	45	49	56	54	157	131	183	147
2002/03	0	0	0	0	0	0	0	0
2003/04	35	53	48	62	169	111	192	138
2004/05	0	0	0	0	0	0	0	0
2005/06	45	43	66	64	204	248	264	309
2006/07	0	0	0	0	0	0	0	0
2007/08	64	115	79	150	118	66	141	94
2008/09	0	0	0	0	0	0	0	0
2009/10	120	79	143	102	56	27	63	40
2010/11	0	0	0	0	0	0	0	0
2011.12	0	0	0	0	0	0	0	0

(Table 2 Continued)

	Area V-W				Area V-E				Area VI-W			
	Age-composition		Length-frequency (Japan)		Age-composition		Length-frequency (Japan)		Age-composition		Length-frequency (Japan)	
Year	F	M	F	M	F	M	F	M	F	M	F	M
1971/72	0	0	0	0	0	0	0	0	0	0	0	0
1972/73	0	0	0	0	0	0	0	0	0	0	0	0
1973/74	0	0	0	0	0	0	0	0	1	4	3	10
1974/75	145	54	310	190	0	0	0	0	0	0	0	0
1975/76	66	132	160	260	0	0	0	0	0	0	0	0
1976/77	263	237	495	515	0	0	0	0	0	0	0	0
1977/78	209	191	316	298	19	24	22	32	23	45	83	156
1978/79	93	54	104	69	0	0	0	0	0	0	0	0
1979/80	81	257	113	383	0	0	0	0	0	0	0	0
1980/81	257	71	330	105	119	28	156	34	68	78	99	100
1981/82	548	256	779	369	10	15	11	18	49	157	67	218
1982/83	1109	303	1480	416	0	0	0	0	130	98	170	137
1983/84	717	316	945	436	48	6	56	8	279	87	349	126
1984/85	485	274	573	337	0	0	0	0	79	240	92	277
1985/86	596	311	670	343	0	0	0	0	77	250	97	300
1986/87	743	143	851	162	0	0	0	0	242	112	285	129

(Table 2 Continued)

	Area V-W				Area V-E				Area VI-W			
	Age-composition		Length-frequency (Japan)		Age-composition		Length-frequency (Japan)		Age-composition		Length-frequency (Japan)	
Year	F	M	F	M	F	M	F	M	F	M	F	M
1987/88	0	0	0	0	0	0	0	0	0	0	0	0
1988/89	0	0	0	0	122	64	151	85	0	0	0	0
1989/90	0	0	0	0	0	0	0	0	0	0	0	0
1990/91	67	101	77	110	65	50	68	54	14	0	14	0
1991/92	0	0	0	0	0	0	0	0	0	0	0	0
1992/93	78	112	87	118	49	42	53	45	17	4	20	4
1993/94	0	0	0	0	0	0	0	0	0	0	0	0
1994/95	25	99	27	113	88	72	103	87	0	0	0	0
1995/96	0	1	0	1	0	0	0	0	0	0	0	0
1996/97	64	51	72	55	69	70	80	77	72	66	82	74
1997/98	0	0	0	0	0	0	0	0	0	0	0	0
1998/99	72	80	88	95	32	90	34	111	12	38	20	41
1999/00	0	0	0	0	0	0	0	0	0	0	0	0
2000/01	34	81	45	95	62	78	73	87	59	62	64	76
2001/02	0	0	0	0	0	0	0	0	0	0	0	0
2002/03	37	48	46	54	100	98	116	114	32	54	43	67
2003/04	0	0	0	0	0	0	0	0	0	0	0	0
2004/05	43	35	47	35	120	65	137	75	67	58	79	67
2005/06	45	70	59	89	2	0	2	0	0	0	0	0
2006/07	0	0	0	0	214	78	233	88	106	61	118	66
2007/08	54	21	58	29	0	0	0	0	0	0	0	0
2008/09	45	64	57	77	95	55	106	67	111	198	141	231
2009/10	41	71	58	90	2	4	5	5	0	0	0	0
2010/11	0	0	0	0	16	22	20	26	75	34	88	36
2011/12	38	44	50	49	13	17	16	19	96	29	101	31

Table 3
The estimates of abundance

(a) IDCR Estimates

Year	Estimate	Year	Estimate
Area III-E		Area IV	
1987/88	11 782 (0.440)	1988/89	46 763 (0.169)
1994/95	34 659 (0.237)	1998/99	55 873 (0.341)
Area V-W		Area V-E	
1985/86	105 951 (0.159)	1985/86	154 658 (0.189)
2001/02	43 640 (0.139)	2003/04	136 457 (0.134)
Area VI-W			
1990/91	20 438 (0.271)		
1995/96	48 206 (0.177)		

(b) JARPA / JARPA II indices of relative abundance

Area III-E		Area IV		Area V-W	
Year	Estimate	Year	Estimate	Year	Estimate
1995/96	9 614 (0.220)	1989/90	29 993 (0.228)	1990/91	35 108 (0.220)
1997/98	5 566 (0.367)	1991/92	32 418 (0.396)	1992/93	22 404 (0.350)
1999/00	12 404 (0.615)	1993/94	27 780 (0.147)	1994/95	12 805 (0.275)
2001/02	44 801 (0.582)	1995/96	31 601 (0.198)	1996/97	15 540 (0.293)
2003/04	18 927 (0.355)	1997/98*	16 590 (0.277)	1998/99	56 927 (0.538)
2005/06	29 261 0.379)	1999/00	43 673 (0.125)	2000/01	19 603 (1.031)
2007/08	9 406 (0.291)	2001/02	30 269 (0.218)	2002/03	66 544 (0.234)
		2003/04	34 701 (0.373)	2004/05	27 544 (0.243)
		2005/06	62 979 (0.334)	2005/06	45 541 (0.701)
		2007/08	14 739 (0.570)	2006/07	30 422 (0.534)
				2007/08	45 157 (0.408)
				2008/09	10 534 (0.638)
Area V-E		Area VI-W			
Year	Estimate	Year	Estimate		
1990/91	65 638 (0.353)	1996/97	7 530 (0.258)		
1992/93	43 743 (0.376)	1998/99	20 166 (0.280)		
1994/95	100 771 (0.254)	2000/01	12 571 (0.257)		
1996/97	82 155 (0.300)	2002/03	10 543 (0.218)		
1998/99	43 037 (0.286)	2004/05	14 843 (0.228)		
2000/01	88 274 (0.255)	2006/07	17 206 (0.556)		
2002/03	59 961 (0.244)	2008/09	26 364 (0.226)		
2004/05	45 177 (0.229)				
2006/07	26 418 (0.188)				
2008/09	97 563 (0.193)				

* Survey covered only a small part of Prydz Bay

Table 4

Parameters which determine the age-reading error matrix. These values correspond to the "Lockyer unbiased" analysis of Kitakado and Punt (2010) {model 3}. The values for L and H are 0 and 70 respectively.

Year	**Reader**	β_L	β_H	σ''_L	σ''_H
1971/72 – 1979/80	Masaki	3.0837	58.7940	1.5531	1.5531
1980/81 – 1989/90	Kato	2.4545	56.0060	0.5391	7.3718
1990/91 – 1991/92	Zenitani	1.0300	62.8530	0.4637	3.6614
1992/93	Kato	2.4545	56.0060	0.5391	7.3718
1993/94 – 2004/05	Zenitani	1.0300	62.8530	0.4637	3.6614
2005/06 – 2011/12	Bando	1.6355	63.6440	0.6588	3.4128

Table 5

The estimable parameters of the population dynamics model and the objective function.

Parameter	**Number of parameters**	
	Stock I	**Stock P**
Calves in the absence of exploitation, B_0	1	1
Natural mortality: M_0, M_1/M_0, M_2/M_1	4	
Resilience, A	1	1
Survival deviation, ε_y	83	83
Expected proportion in each Area, $\overline{P^{s,A}}$	2	1
Annual deviations about the expected proportions in each area, φ_y^A	69	26
Exploitation rate by year, sex and fleet, $F_y^{g,f}$	291	125
Changes in carrying capacity, $\tilde{K}_I^{1+}$, $\tilde{K}_{2002}^{1+}$	2	2
Parameters of the growth curve, L_∞^g, k^g, t_0^g, σ_γ^g	8	8
Inter-annual deviations in growth rate, υ_y	98	98
Parameters to define vulnerability, $L_{50,y}^{g,f}$, $\delta_y^{g,f}$, $L_{dff}^{g,f}$, $L_{\text{left}}^{g,f}$, $L_{\text{right}}^{g,f}$, $\tilde{S}_a$	14+72	8+22
JARPA survey bias, χ	3	2
Total	**1025**	

Table 6
The sensitivity tests.

Run	Description
0	Reference case
Related to the population dynamics model	
P1	Equation D.1b instead of Equation D.1a
P2	The proportion of each stock in each area is time-invariant
P3	No time-varying growth
P4	Natural mortality is independent of stock
P5	Carrying capacity (*K*) is time-invariant
P6	Carrying capacity changes in an auto-regressive manner
P7	Carrying capacity changes in 1960, 1980, and 2002
P8	JARPA indices pertain to 1+ abundance
Related to selectivity patterns	
S1	Selectivity is age- rather than length-specific
S2	The length frequency and age composition data for the years until1973/74 are down-weighted by 90%
S3	JARPA / JARPA II vulnerability is constant
S4	JARPA / JARPA II vulnerability is constant (and time-invariant); carrying capacity is time-invariant
S5	IDCR/SOWER estimates are assumed to be negatively biased, g(0) =0.60
S6	IDCR/SOWER estimates are assumed to be negatively biased, g(0) =0.80
S7	Ignore JARPA / JARPA II abundance estimates
S8	Time-invariant fishery selectivity
S9	JARPA / JARPA II abundance estimates are absolute
S10	Separate selectivity patterns for JARPA / JARPA II
Related to data selection and data weighting	
D1	Ignore JARPA II data (the area covered by JARPA II differs from that for JARPA)
D2	Ignore ageing error
D3	Decrease σ_s by 50%
D4	Increase σ_s by 50%
D5	Decrease σ_r to 0.10
D6	Increase σ_r to 0.30
D7	Decrease σ_p by 50%
D8	Increase σ_p by 50%
D9	Decrease σ_k by 50%
D10	Increase σ_k by 50%
D11	Double weight on length data
D12	Halve weight on length data
D13	Double weight on conditional age-at-length data
D14	Halve weight on conditional age-at-length data

Table 7
The summary statistics and plots

(a) Statistics

$b_{rec,1945\text{-}68}$ - slope of the linear regression of the estimates of the logarithms of the numbers of recruits (age 1 animals) on time (1945-68).
$b_{rec,1968\text{-}88}$ - slope of the linear regression of the estimates of the logarithms of the numbers of recruits on time (1968-88).
$b_{rec,1988\text{-}End}$ - slope of the linear regression of the estimates of the logarithms of the numbers of recruits on time (1988-last year).
$N_{tot,1945\text{-}68}$ - slope of the linear regression of the estimates of the logarithms of the numbers of 1+ animals on time (1945-68).
$N_{tot,1968\text{-}88}$ - slope of the linear regression of the estimates of the logarithms of the numbers of 1+ animals on time (1968-88).
$N_{tot,1988\text{-}Endr}$ - slope of the linear regression of the estimates of the logarithms of the numbers of 1+ animals on time (1988-last year).
$N_{\mathrm{End}\text{-}5,1}/N_{1968,1}$ – Ratio of the number of recruits in 1999 to that in 1968.
K_{1930} – Carrying capacity in 1930.
K_{2000}/K_{1960} – ratio of K in 2000 to that in 1960.
K_{1960}/K_{1930} – ratio of K in 1960 to that in 1930.
Natural mortality (ages 0-3, 10-30, 35+)
Average proportions in each management area
Survey q for JARPA.
MSYR (1+)

(b) Plots

Assessment outputs
Total (1+) population size versus year (by stock and by area)
Age 1 animals (recruits) versus time
Carrying capacity versus year
Natural mortality versus age
Number of females beyond the age-at-first parturition
Number of calves as a fraction of the number of females beyond the age-at-first parturition
Selectivity-at-age
Selectivity-at-length
Brody growth coefficient versus year
Diagnostic plots
Survey estimates of abundance from IDCR with the associated model predictions (by area)
Survey estimates of abundance from JARPA with the associated model predictions (by area)
Observed and model-predicted catches (by fleet and sex)
Observed and model-predicted length-frequencies (by fleet, sex and year)
Input and estimated effective sample sizes for the length-frequency data (by fleet and sex)
Fits to the length-frequency data in the form of bubble plots (by fleet and sex)
Fits to the summed length-frequency data (by fleet and sex)

Table 8

Results of the reference case analysis and the analyses to examine the sensitivity of the results to modifying some of the assumptions of the analysis method. The asymptotic standard errors for the estimates for natural mortality are given in parenthesis. The average proportions by area are given in parenthesis under the estimates for the JARPA *q*s.

(a) Stock I

Case	b_{rec} 1945-68	b_{rec} 1968-88	b_{rec} 1988-End	N_{tot} 1945-68	N_{tot} 1968-88	N_{tot} 1988-End	$N_{End\text{-}5,1}/N_{1968,1}$	K_{1930}	K_{2960}/K_{1930} (%)	K_{2000}/K_{1960} (%)	Natural mortality (ages) 0-3	10-30	35+	JARPA q / Mean proportion III-E	IV	V-W	MSYR (1+)
Reference	2.268	-2.736	0.387	2.943	-3.369	-0.609	0.576	118220	314.4	39.0	0.106 (0.010)	0.046 (0.003)	0.127 (0.003)	0.633 (0.161)	0.600 (0.369)	0.495 (0.470)	0.053
P1**	-3.634	-5.045	0.222	0.761	-6.704	-0.320	0.176	435751	23.3	165.6	0.436	0.067	0.143	4.592 (0.162)	3.894 (0.398)	3.750 (0.440)	0.244
P2	2.303	-2.843	0.418	2.98	-3.454	-0.581	0.572	109908	320.6	38.5	0.104 (0.008)	0.046 (0.002)	0.126 (0.003)	0.471 (0.204)	0.710 (0.546)	0.546 (0.453)	0.052
P3	3.927	-2.954	-0.338	4.385	-2.243	-0.852	0.528	89434	794.5	30.6	0.269 (0.008)	0.030 (0.003)	0.115 (0.003)	0.493 (0.146)	0.360 (0.424)	0.390 (0.429)	0.038
P4	2.671	-2.462	0.428	3.473	-3.079	-0.356	0.631	85825	398.9	42.7	0.101 (0.007)	0.042 (0.002)	0.119 (0.002)	0.622 (0.163)	0.604 (0.368)	0.495 (0.469)	0.055
P5	2.752	-1.84	0.191	1.672	-2.789	-0.36	0.666	219566	100	100	0.104 (0.008)	0.039 (0.002)	0.144 (0.002)	0.538 (0.162)	0.501 (0.382)	0.441 (0.455)	0
P6	2.618	-2.185	0.255	2.625	-3.188	-0.756	0.578	178026	177.7	52.8	0.121 (0.011)	0.045 (0.005)	0.130 (0.005)	0.571 (0.161)	0.517 (0.382)	0.461 (0.457)	0.216
P7	2.546	-2.502	0.64	3.272	-3.134	-0.314	0.637	101324	369.7	42.7	0.105 (0.010)	0.044 (0.006)	0.122 (0.006)	0.588 (0.161)	0.565 (0.373)	0.475 (0.464)	0.05
P8	2.265	-2.738	0.388	2.941	-3.371	-0.611	0.576	118453	314	38.9	0.106 (0.010)	0.046 (0.003)	0.127 (0.003	0.589 (0.161)	0.558 (0.369)	0.462 (0.469)	0.053
S1	-0.439	-2.725	0.298	0.098	-4.373	-0.097	0.700	349584	38.5	111.8	0.265 (0.020)	0.065 (0.005)	0.123 (.004)	1.136 (0.166)	1.114 (0.368)	0.917 (0.466)	0.094
S2	2.556	-2.829	0.381	3.24	-3.368	-0.589	0.539	101238	367	38.6	0.107 (0.010)	0.046 (0.003)	0.123 (0.003)	0.640 (0.162)	0.609 (0.368)	0.501 (0.470)	0.054
S3	2.353	-2.696	0.397	3.023	-3.301	-0.592	0.580	111208	39.5	324.6	0.094 (0.008)	0.045 (0.003)	0.126 (0.005)	0.601 (0.161)	0.574 (0.367)	0.469 (0.471)	0.052
S4	2.757	-1.881	0.182	1.651	-2.800	-0.384	0.659	213625	100	100	0.092 (0.008)	0.039 (0.002)	0.144 (0.003)	0.520 (0.162)	0.488 (0.379)	0.423 (0.458)	0.000
S5	2.130	-2.194	0.343	2.823	-2.903	-0.661	0.621	176171	292.8	42.3	0.110 (0.010)	0.047 (0.003)	0.128 (0.003)	0.419 (0.161)	0.404 (0.361)	0.320 (0.478)	0.056
56	2.207	-2.482	0.365	2.892	-3.152	-0.631	0.597	139161	304.7	40.5	0.108 (0.010)	0.046 (0.003)	0.127 (0.003)	0.533 (0.161)	0.510 (0.365)	0.412 (0.474)	0.054
S7	2.183	-2.789	0.352	2.835	-3.416	-0.694	0.563	128033	38.0	299.9	0.107 (0.010)	0.047 (0.003)	0.128 (0.005)	(0.169)	(0.364)	(0.466)	0.052
S8	2.222	-4.426	0.02	2.768	-3.731	-1.07	0.479	156796	303.1	31.0	0.128 (0.008)	0.047 (0.003)	0.131 (0.003)	0.625 (0.157)	0.551 (0.377)	0.476 (0.466)	0.046
S9	2.225	-3.687	0.418	2.830	-4.171	-0.733	0.484	95127	32.7	307.4	0.102 (0.010)	0.047 (0.003)	0.128 (0.005)	(0.173)	(0.379)	(0.447)	0.047
S10	2.093	-2.893	0.514	2.779	-3.535	-0.637	0.595	130843	37.6	294.4	0.118 (0.010)	0.048 (0.003)	0.128 (0.005)	0.673 (0.161)	0.623 (0.370)	0.521 (0.469)	0.054
D1	2.815	-2.801	0.438	3.605	-3.075	-0.683	0.488	88333	442.4	37.5	0.133 (0.009)	0.042 (0.003)	0.115 (0.003)	0.545 (0.162)	0.562 (0.369)	0.462 (0.469)	0.050
D2	1.959	-6.635	-0.202	2.654	-6.461	-0.83	0.243	254959	379.2	19.5	0.407 (0.025)	0.084 (0.005)	0.165 (0.003)	3.646 (0.151)	2.727 (0.404)	2.699 (0.444)	0.082
D3	2.268	-2.731	0.388	2.942	-3.367	-0.609	0.577	118286	314.1	39.0	0.105 (0.010)	0.046 (0.003)	0.127 (0.003)	0.632 (0.161)	0.598 (0.369)	0.495 (0.469)	0.053
D4	2.267	-2.737	0.387	2.943	-3.370	-0.610	0.576	118259	314.3	39.0	0.106 (0.010)	0.046 (0.003)	0.127 (0.003)	0.633 161)	0.600 (0.369)	0.496 (0.470)	0.053
D5	1.783	-3.484	0.450	3.001	-3.598	-0.531	0.534	99278	360.7	37.9	0.094 (0.009)	0.048 (0.002)	0.125 (0.002)	0.691 (0.160)	0.667 (0.361)	0.520 (0.479)	0.058
D6	2.545	-2.402	0.351	2.973	-3.233	-0.614	0.606	125928	298.6	39.6	0.112 (0.010)	0.045 (0.003)	0.127 (0.003)	0.605 (0.162)	0.569 (0.373)	0.485 (0.464)	0.050
D7	2.293	-2.813	0.408	2.971	-3.431	-0.589	0.573	112022	319.1	38.6	0.105 (0.010)	0.046 (0.003)	0.126 (0.003)	0.521 (0.188)	0.667 (0.347)	0.518 (0.465)	0.052
D8	2.237	-2.654	0.369	2.910	-3.301	-0.631	0.580	126129	308.8	39.3	0.107 (0.010)	0.046 (0.003)	0.127 (0.003)	0.705 (0.148)	0.549 (0.393)	0.493 (0.459)	0.053
D9	2.268	-2.736	0.387	2.943	-3.369	-0.609	0.576	118220	314.4	39.0	0.106 (0.010)	0.046 (0.003)	0.127 (0.003)	0.633 (0.161)	0.600 (0.369)	0.495 (0.470)	0.053
D10	2.268	-2.736	0.387	2.943	-3.369	-0.609	0.576	118220	314.4	39.0	0.106 (0.010)	0.046 (0.003)	0.127 (0.003)	0.633 (0.161)	0.600 (0.369)	0.495 (0.470)	0.053
D11	1.847	-3.062	0.391	2.517	-3.719	-0.718	0.537	157629	254.2	36.7	0.103 (0.007)	0.05 (0.002)	0.132 (0.002)	0.622 (0.162)	0.584 (0.372)	0.490 (0.466)	0.055
D12	2.523	-2.588	0.394	3.204	-3.155	-0.501	0.598	96689	364.8	40.5	0.110 (0.008)	0.044 (0.003)	0.123 (0.003)	0.651 (0.162)	0.625 (0.366)	0.509 (0.472)	0.052
D13	1.894	-2.869	0.450	2.435	-3.656	-0.643	0.576	157803	246.4	37.8	0.078 (0.007)	0.053 (0.002)	0.130 (0.003)	0.609 (0.162)	0.576 (0.371)	0.481 (0.467)	0.053
D14	2.575	-2.807	0.368	3.359	-3.221	-0.576	0.567	90864	389.5	39.1	0.123 (0.009)	0.041 (0.003)	0.124 (0.003)	0.664 (0.161)	0.638 (0.364)	0.514 (0.475)	0.052

(b) Stock P

Case		b_{rec}			N_{tot}		$N_{End-5,1}$/ $N_{1968,1}$	K_{1930}	K_{2960}/ K_{1930} (%)	K_{2000}/ K_{1960} (%)	Natural mortality (ages)			JARPA q / Mean proportion		MSYR (1+)
	1945-68	1968-88	1988-End	1945-68							0-3	10-30	35+	V-E	VI-W	
Reference											0.089	0.039	0.106	0.491	0.405	0.036
	3.608	-1.696	0.322	4.338	0.518	-0.499	0.671	36215	1000	45	(0.009)	(0.003)	(0.003)	(0.773)	(0.227)	
P1**											0.487	0.075	0.159	4.424	5.430	0.000
	-1.501	-6.501	-2.101	-0.985	-5.188	-2.981	0.198	762400	8.0	0.0				(0.817)	(0.183	
P2											0.088	0.038	0.106	0.455	0.412	0.036
	3.617	-1.667	0.329	4.355	0.540	-0.483	0.679	35976	1000	45.7	(0.008)	(0.003)	(0.002)	(0.789)	(0.211)	
P3											0.193	0.022	0.083	0.547	0.386	0.046
	4.326	0.282	0.212	4.796	2.079	0.389	0.977	19606	1000	100	(0.009)	(0.002)	(0.002)	(0.752)	(0.248)	
P4											0.101	0.042	0.119	0.494	0.440	0.028
	3.248	-2.519	0.058	3.792	-0.031	-0.984	0.548	52054	1000	28.0	(0.007)	(0.002)	(0.002)	(0.784)	(0.216)	
P5											0.094	0.035	0.131	0.495	0.404	0.002
	1.409	-1.001	0.286	0.461	0.013	-0.455	0.747	166325	100	100	(0.007	(0.002)	(0.002)	(0.772)	(0.228)	
P6											0.116	0.043	0.125	0.517	0.502	0.215
	3.254	-2.248	-0.884	2.756	-0.167	-1.598	0.419	116732	159.4	90.6	(0.012)	(0.005)	(0.004)	(0.795)	(0.205)	
P7											0.099	0.041	0.115	0.498	0.460	0.040
	3.497	-2.08	-0.425	4.492	0.237	-1.146	0.523	35916	1000	38.5	(0.009)	(0.004)	(0.004)	(0.789)	(0.211)	
P8											0.089	0.039	0.106	0.458	0.377	0.036
	3.607	-1.699	0.323	4.337	0.516	-0.5	0.671	36256	1000	44.9	(0.009)	(0.003)	(0.003)	(0.773)	(0.227)	
S1											0.198	0.049	0.092	0.800	0.561	0.025
	2.928	-0.555	0.452	3.315	0.703	0.306	0.965	44074.7	41.5	1000.0	(0.018)	(0.005)	(0.004)	(0.750)	(0.200)	
S2											0.091	0.039	0.105	0.492	0.407	0.036
	3.603	-1.738	0.3	4.32	0.483	-0.523	0.663	36782	1000	44.1	(0.009)	(0.003)	(0.003)	(0.774)	(0.226)	
S3											0.079	0.038	0.106	0.457	0.376	0.036
	3.635	-1.627	0.323	4.373	0.597	-0.486	0.675	35409	46.3	1000	(0.008)	(0.003)	(0.006)	(0.773)	(0.227)	
S4											0.084	0.035	0.131	0.461	0.377	0.002
	1.412	-0.987	0.278	0.452	0.033	-0.470	0.745	166262	100	100	(0.007)	(0.002)	(0.004)	(0.772)	(0.228)	
S5											0.091	0.039	0.106	0.300	0.247	0.036
	3.607	-1.673	0.323	4.356	0.536	-0.489	0.674	59130	1000	45.5	(0.009)	(0.003)	(0.003)	(0.773)	(0.277)	
S6											0.090	0.039	0.106	0.397	0.327	0.036
	3.608	-1.683	0.323	4.347	0.528	-0.493	0.673	44790	1000	45.3	(0.009)	(0.003)	(0.003)	(0.773)	(0.227)	
S7											0.089	0.039	0.107			0.035
	3.581	-1.781	0.280	4.289	0.461	-0.550	0.643	37223	43.0	1000	(0.009)	(0.003)	(0.006)	(0.807)	(0.193)	
S8											0.105	0.039	0.108	0.507	0.431	0.032
	3.500	-2.318	0.129	4.049	0.296	-0.659	0.622	43280	1000	36.2	(0.008)	(0.003)	(0.003)	(0.777)	(0.223)	
S9											0.087	0.040	0.110			0.032
	3.465	-2.136	0.232	4.088	0.225	-0.748	0.602	24575	35.9	1000	(0.009)	(0.003)	(0.006)	(0.805)	(0.195)	
S10											0.099	0.040	0.108	0.512	0.451	0.035
	3.533	-1.927	0.458	4.271	0.323	-0.558	0.658	38453.9	41.6	1000.0	(0.009)	(0.002)	(0.006)	(0.783)	(0.217)	
D1											0.128	0.040	0.111	0.490	0.409	0.031
	3.402	-2.797	0.631	3.964	-0.067	-0.778	0.599	47577	1000	31.7	(0.011)	(0.003)	(0.003)	(0.811)	(0.189)	
D2											0.360	0.074	0.146	3.277	3.167	0.028
	3.553	-4.120	-0.356	3.662	-2.480	-1.055	0.516	78510	1000	17.0	(0.025)	(0.006)	(0.003)	(0.789)	(0.211)	
D3											0.088	0.039	0.106	0.491	0.403	0.036
	3.602	-1.710	0.319	4.337	0.507	-0.505	0.669	36327	1000	44.8	(0.009)	(0.003)	(0.003)	(0.773)	(0.227)	
D4											0.089	0.039	0.106	0.491	0.405	0.036
	3.607	-1.698	0.322	4.337	0.518	-0.499	0.671	36234	1000	45.0	(0.009)	(0.003)	(0.003)	(0.773)	(0.227)	
D5											0.079	0.040	0.105	0.478	0.394	0.035
	3.462	-2.024	0.195	4.222	0.367	-0.425	0.692	38143	1000	43.8	(0.008)	(0.002)	(0.002)	(0.773)	(0.227)	
D6											0.095	0.038	0.107	0.498	0.414	0.037
	3.785	-1.591	0.250	4.498	0.602	-0.577	0.652	34556	1000	46.1	(0.010)	(0.003)	(0.003)	(0.774)	(0.226)	
D7											0.088	0.039	0.106	0.456	0.451	0.036
	3.604	-1.706	0.317	4.332	0.513	-0.506	0.671	36280	1000	44.7	(0.009)	(0.003)	(0.003)	(0.801)	(0.199)	
D8											0.089	0.038	0.106	0.524	0.348	0.036
	3.620	-1.659	0.334	4.360	0.542	-0.476	0.676	36573	1000	45.9	(0.009)	(0.003)	(0.003)	(0.743)	(0.257)	
D9											0.089	0.039	0.106	0.491	0.405	0.036
	3.608	-1.696	0.322	4.338	0.518	-0.499	0.671	36215	1000	45.0	(0.009)	(0.003)	(0.003)	(0.773)	(0.227)	
D10											0.089	0.039	0.106	0.491	0.405	0.036
	3.608	-1.696	0.322	4.338	0.518	-0.499	0.671	36215	1000	45.0	(0.009)	(0.003)	(0.003)	(0.773)	(0.227)	
D11											0.086	0.042	0.111	0.499	0.424	0.035
	3.585	-2.158	0.284	4.323	0.194	-0.721	0.590	39795	1000	39.3	(0.007)	(0.002)	(0.002)	(0.777)	(0.223)	
D12											0.091	0.037	0.102	0.493	0.394	0.037
	3.611	-1.311	0.360	4.410	0.752	-0.301	0.751	32665	1000	51.6	(0.009)	(0.003)	(0.003)	(0.769)	(0.231)	
D13											0.064	0.043	0.106	0.488	0.401	0.038
	3.505	-1.884	0.411	4.496	0.335	-0.537	0.626	35775	1000	45.0	(0.007)	(0.002)	(0.002)	(0.772)	(0.228)	
D14											0.105	0.035	0.106	0.487	0.401	0.035
	3.655	-1.626	0.268	4.235	0.629	-0.469	0.700	36542	1000	44.9	(0.009)	(0.003)	(0.003)	(0.773)	(0.277)	

Table 9

Negative log-likelihood for the model configurations which are comparable with the reference case model (the values in parenthesis are numbers of estimated parameters). Values indicated by asterisks are for model configurations for which the Hessian matrix was not positive definite. Results are not shown for model configurations S2 and S7 because the weightings of the likelihood function for these two configurations are not compatible with that for the reference case model.

Model Configuration	Negative log-likelihood	Model Configuration	Negative log-likelihood
Reference	20499.6 (1039)	S1	21200.6 (1039)
P1	20673.6 (1039)*	S3	20500.2 (1035)
P2	20532.3 (944)	S4	20626.4 (1031)
P3	22266.2 (749)	S5	20497.7 (1039)
P4	20503.7 (1038)	S6	20498.5 (1039)
P5	20626.0 (1035)	S8	21333.0 (947)
P6	20446.9 (1199)	S9	20532.2 (1034)
P7	20494.8 (1041)	S10	20496.1 (1048)
P8	20499.5 (1039)		

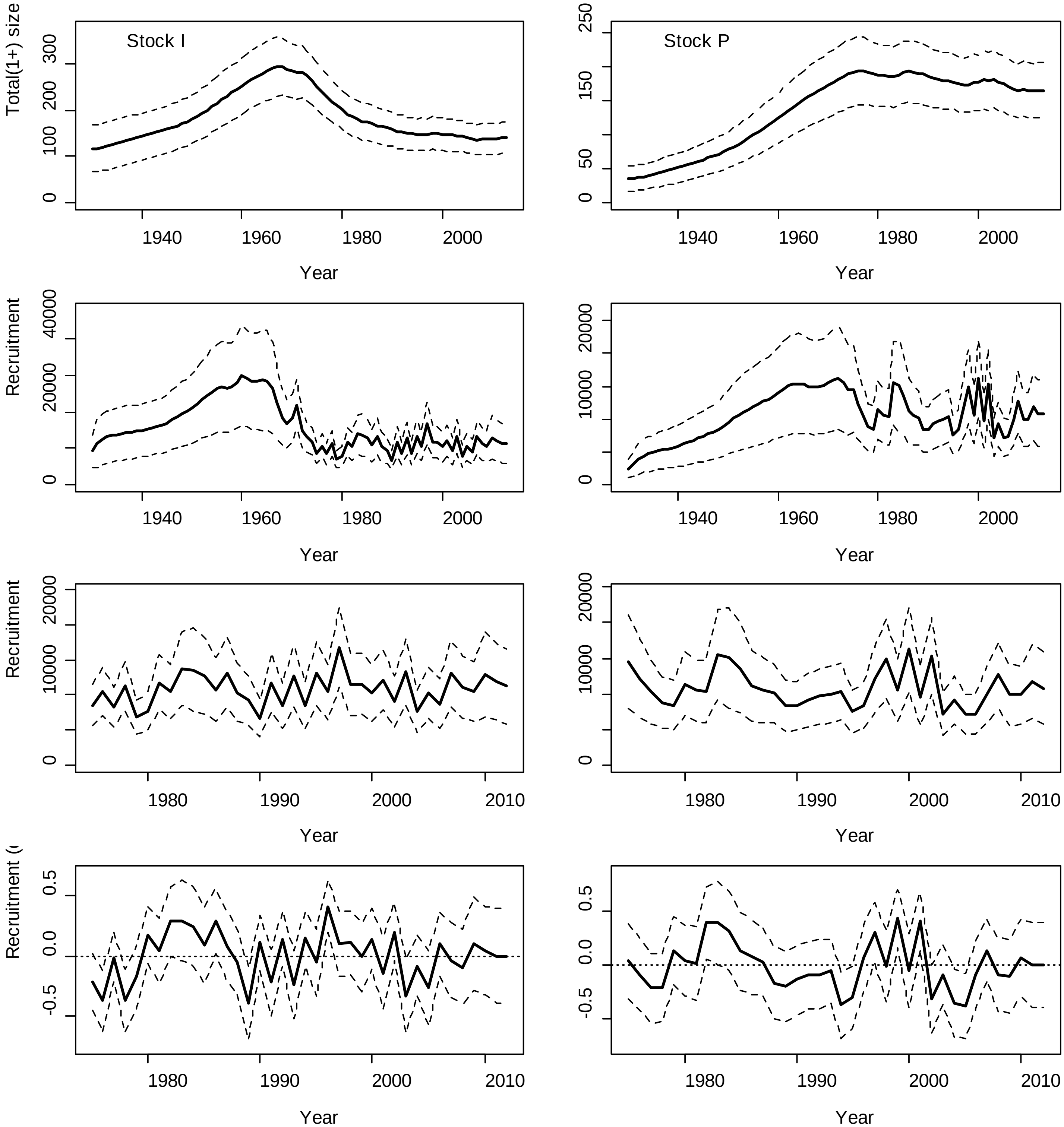


Figure 1. Time-trajectories of total (1+) population size, recruitment (from 1930 and from 1975), and recruitment deviations. The dotted lines indicate 95% asymptotic confidence intervals.

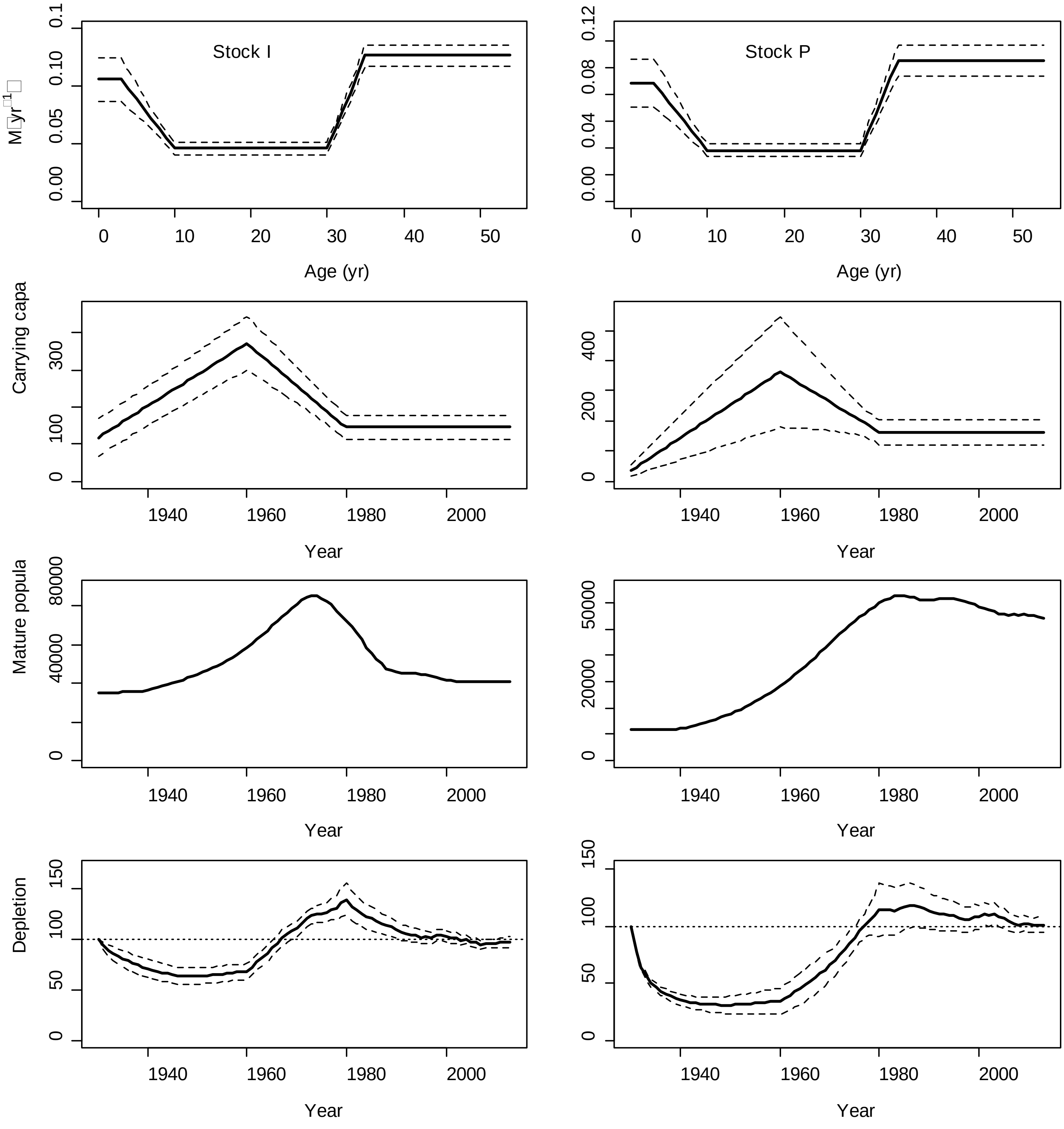


Figure 2. Age-specific natural mortality by stock, and time-trajectories of carrying capacity, the number of mature females, and total (1+) population size relative to carrying capacity. The dotted lines indicate 95% asymptotic confidence intervals.

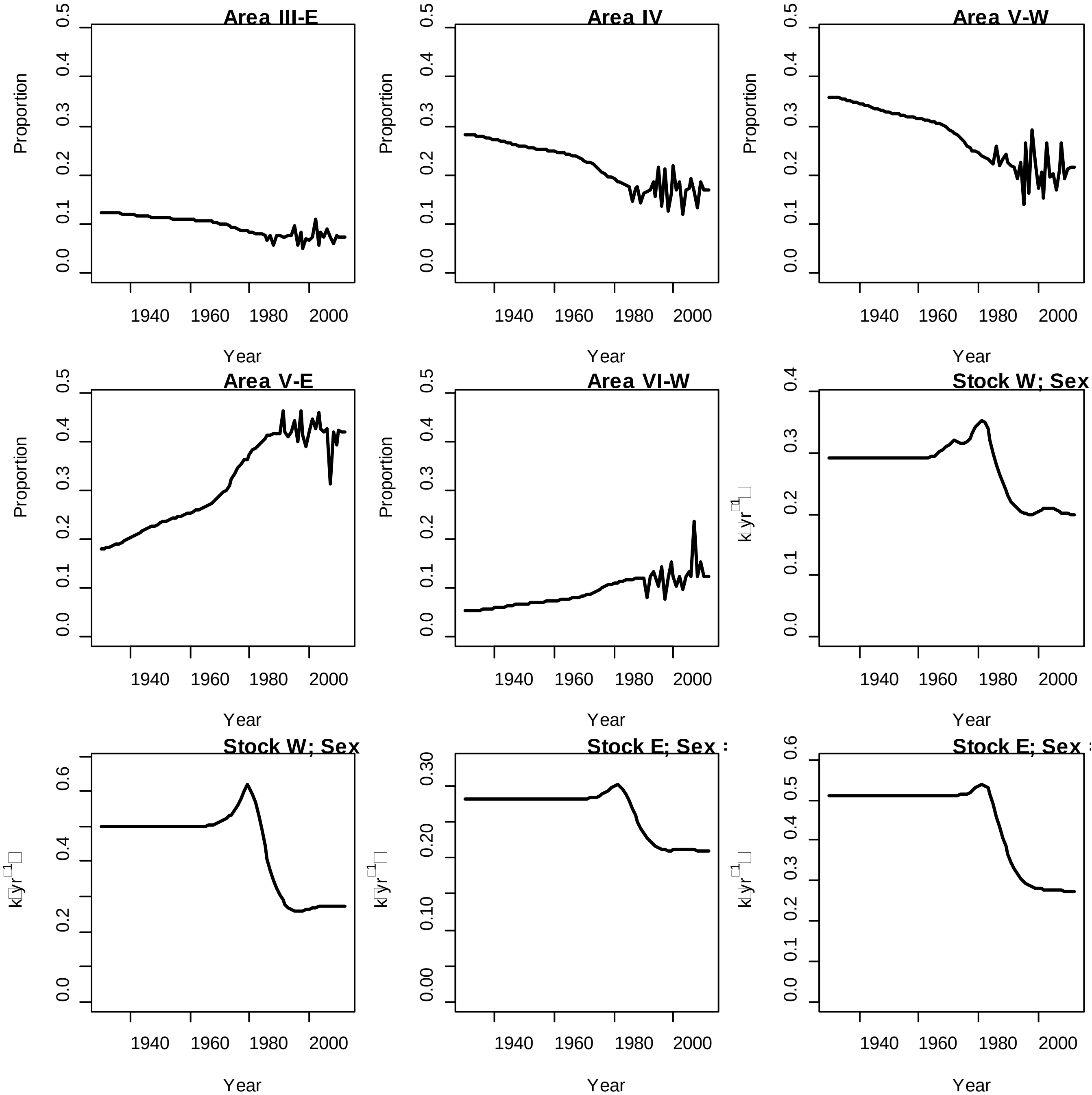


Figure 3. Time-trajectories of the proportion of the total population in each of the five areas considered in the model as well as those of the growth rate parameter *k* (by stock and sex).

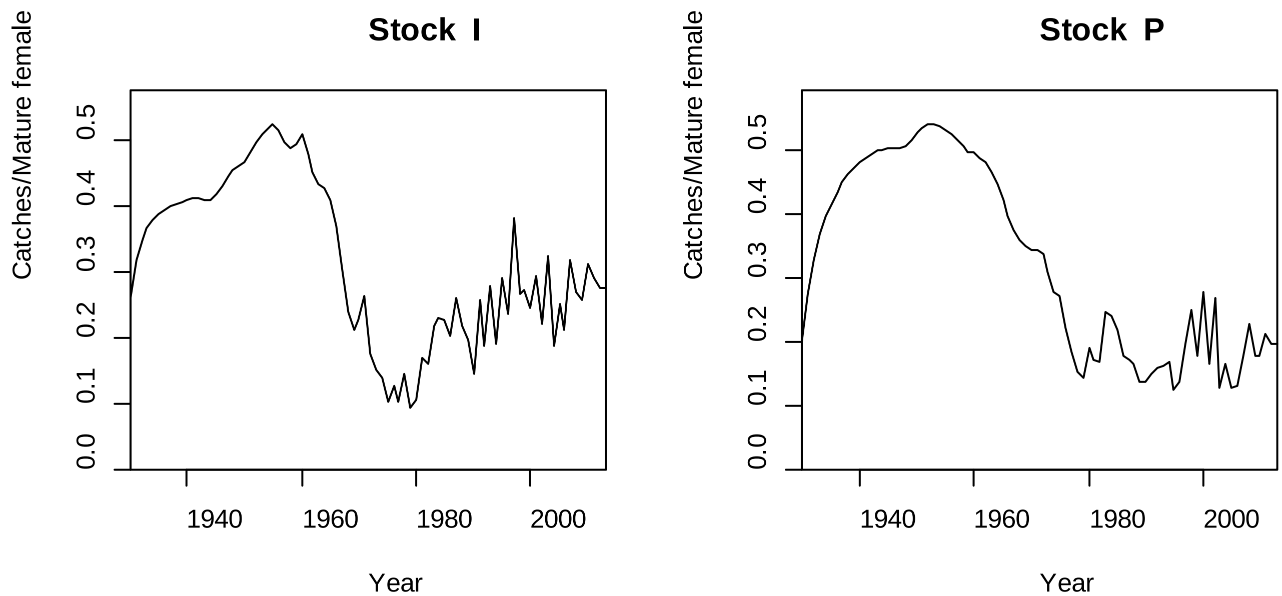


Figure 4. Time-trajectories of the number of calves-per-mature female by stock.

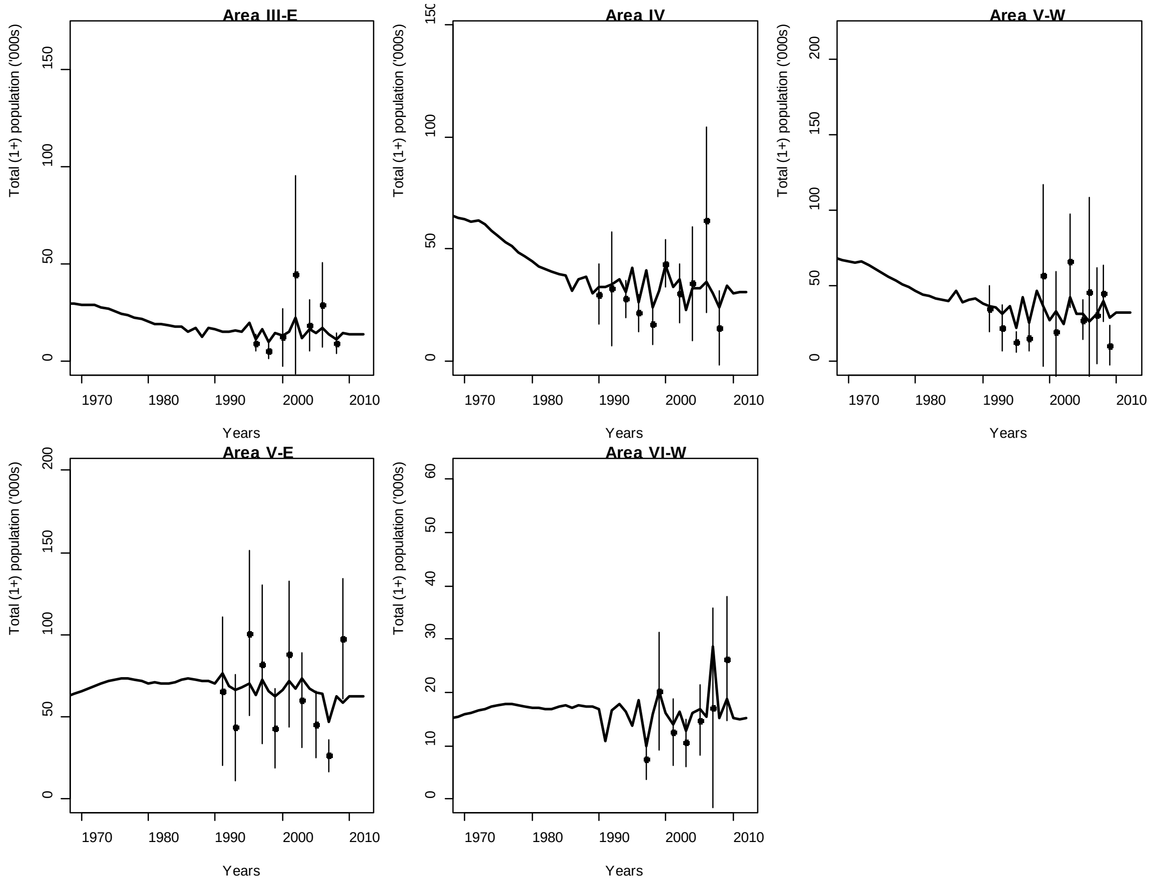


Figure 5. Fits to the indices of relative abundance (from JARPA). The bars indicate 95% confidence intervals based on the supplied sampling standard errors.

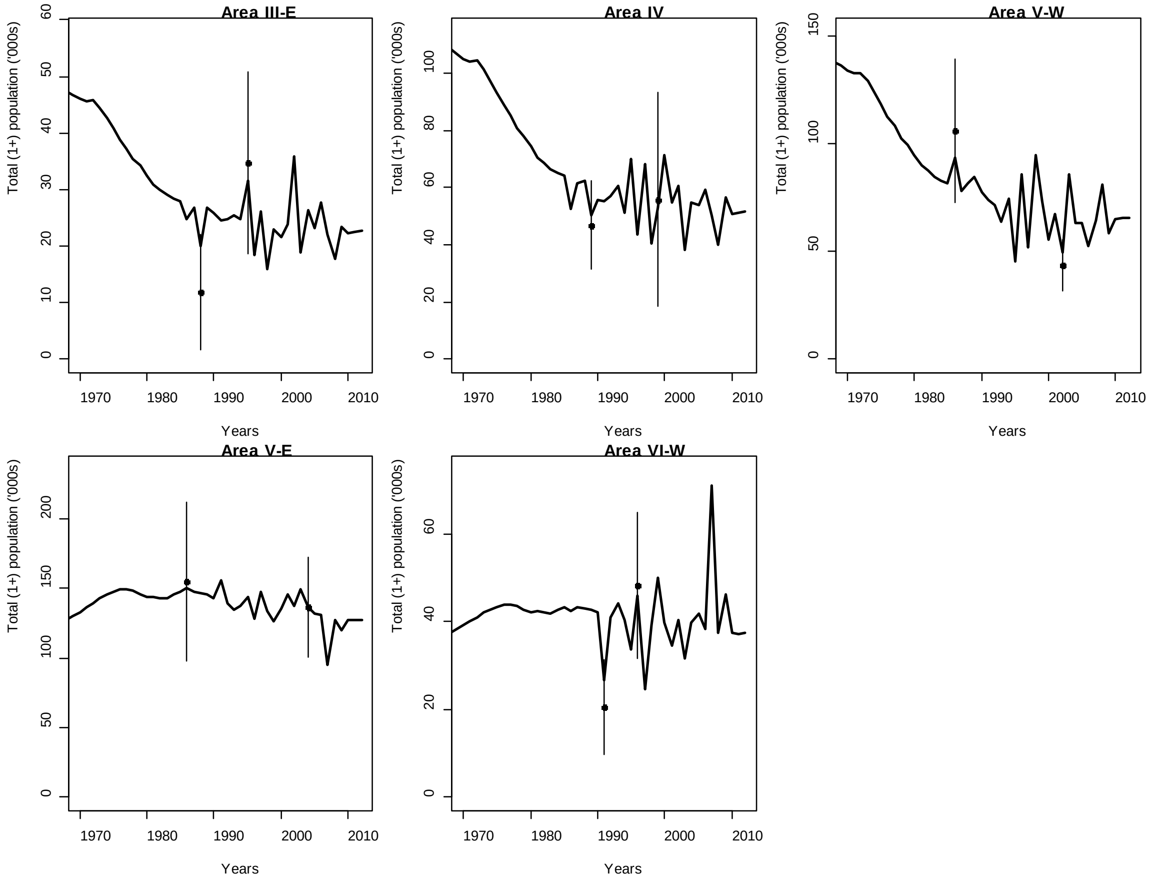
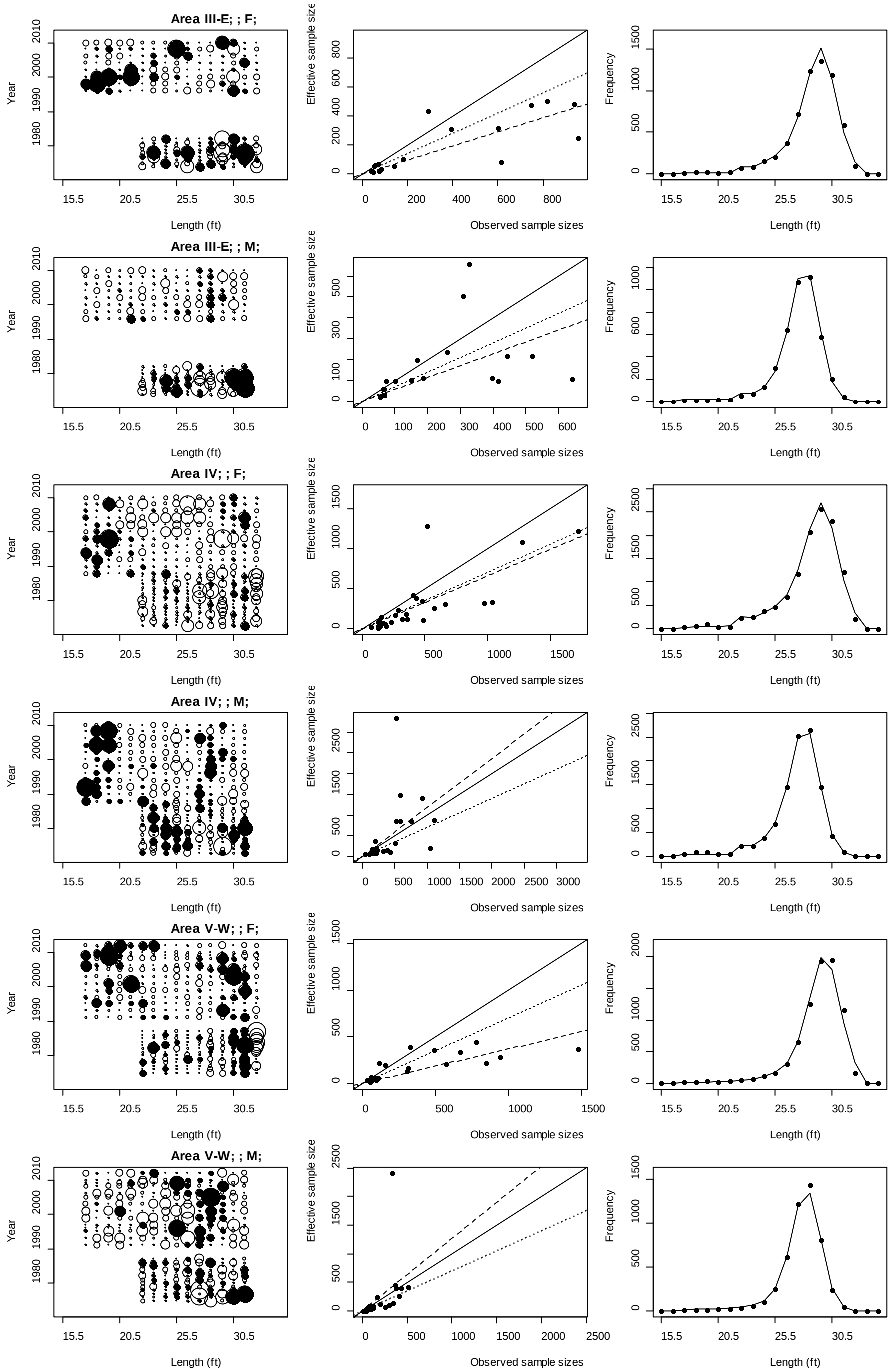


Figure 6. Fits to the indices of absolute abundance (from IDCR). The bars indicate 95% confidence intervals based on the supplied sampling standard errors.


Area III-E; ; F;
Area III-E; ; M;
Area IV; ; F;
Area IV; ; M;
Area V-W; ; F;
Area V-W; ; M;
Year
Length (ft)
Effective sample size
Observed sample sizes
Frequency

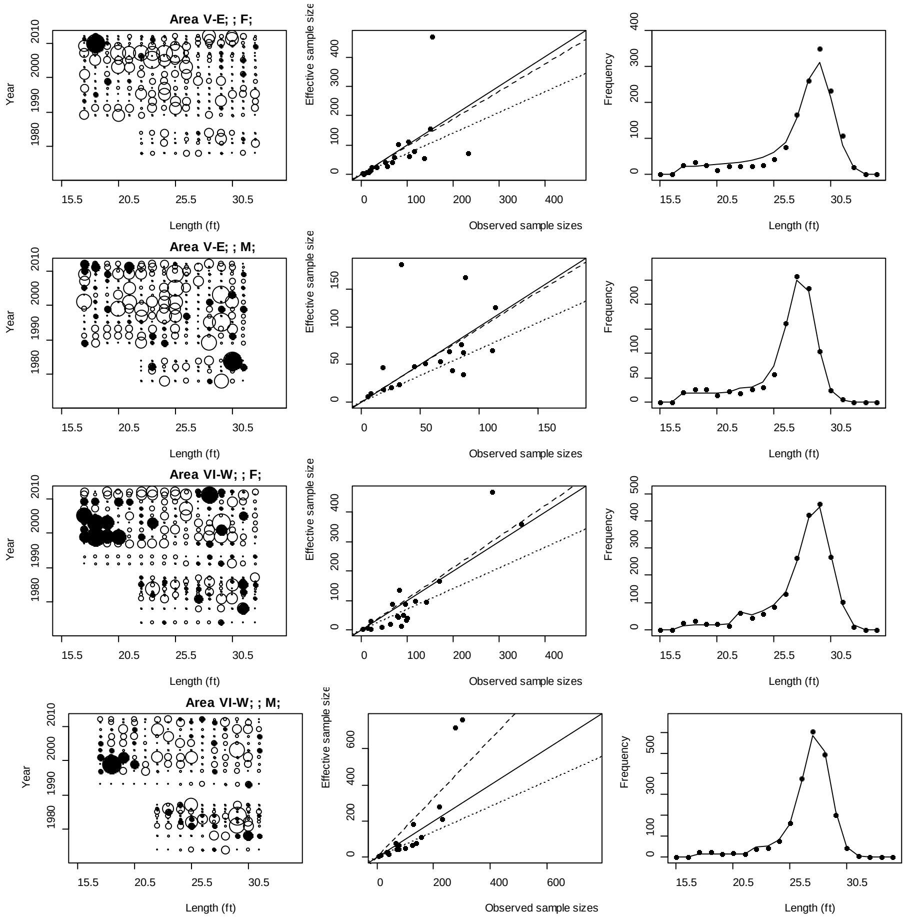


Figure 7. Summaries of the fits to the length-frequency data for each fleet and sex. The left panels show the standardized residuals by size-class and year in the form of a bubble plot, the centre panel plots the observed sample sizes (number of animals actually measured) against the computed effective sample size, and the right panel shows the fit of the model to the sum over years of the number of measured animals. The solid lines in the center panels are 1-1 lines, the dashed lines are the best linear relationships between observed and model-inferred expected sample sizes, and the dotted lines are the assumed relationships between observed and model-iinferred expected sample sizes (a slope of 0.7).

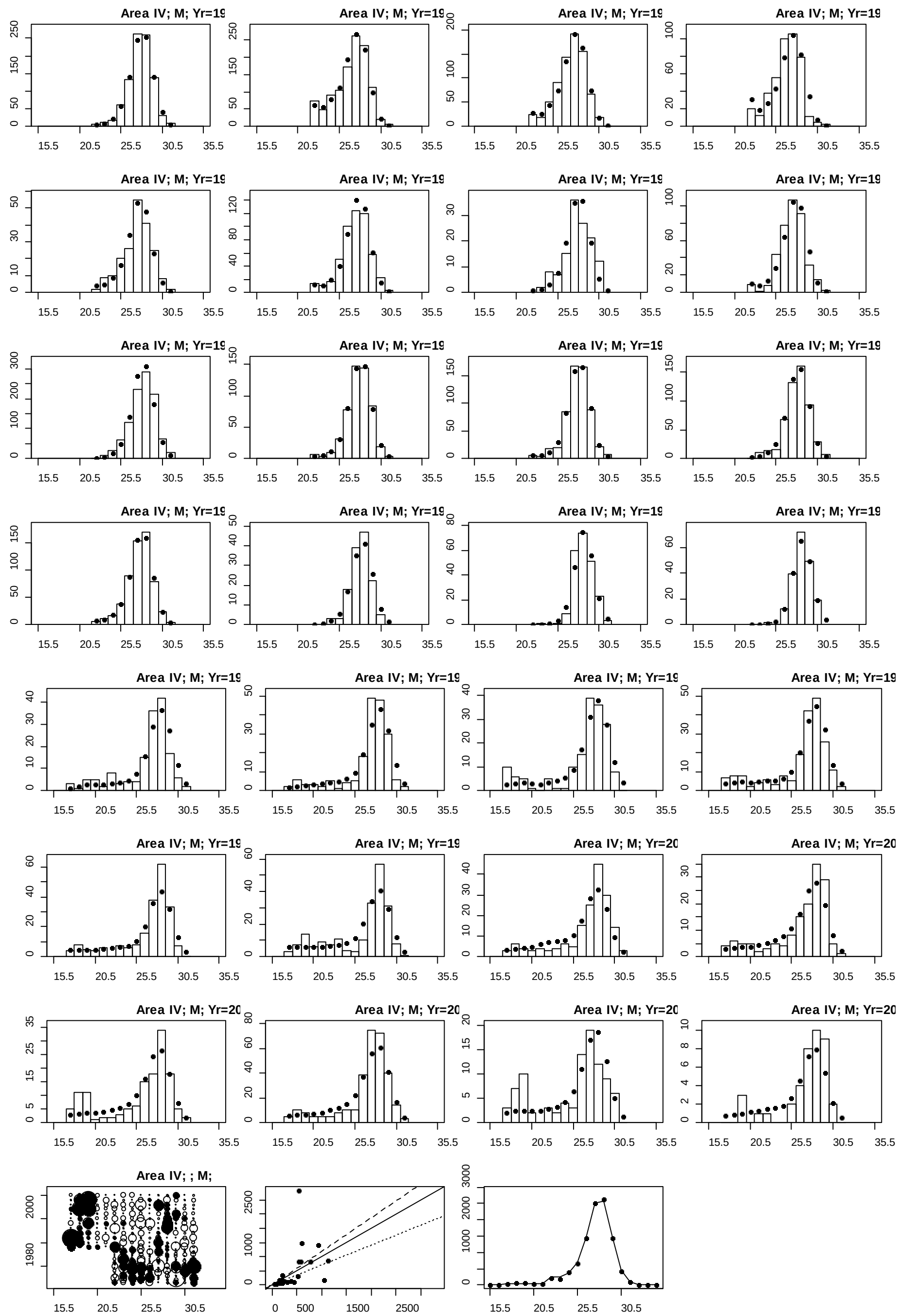


Figure 8. Detailed results of the fits to the length-frequency data for one fleet and sex. In the histograms, the bars indicate the raw data and the dots the model fits. The last three panels are the overall summaries of the fits.

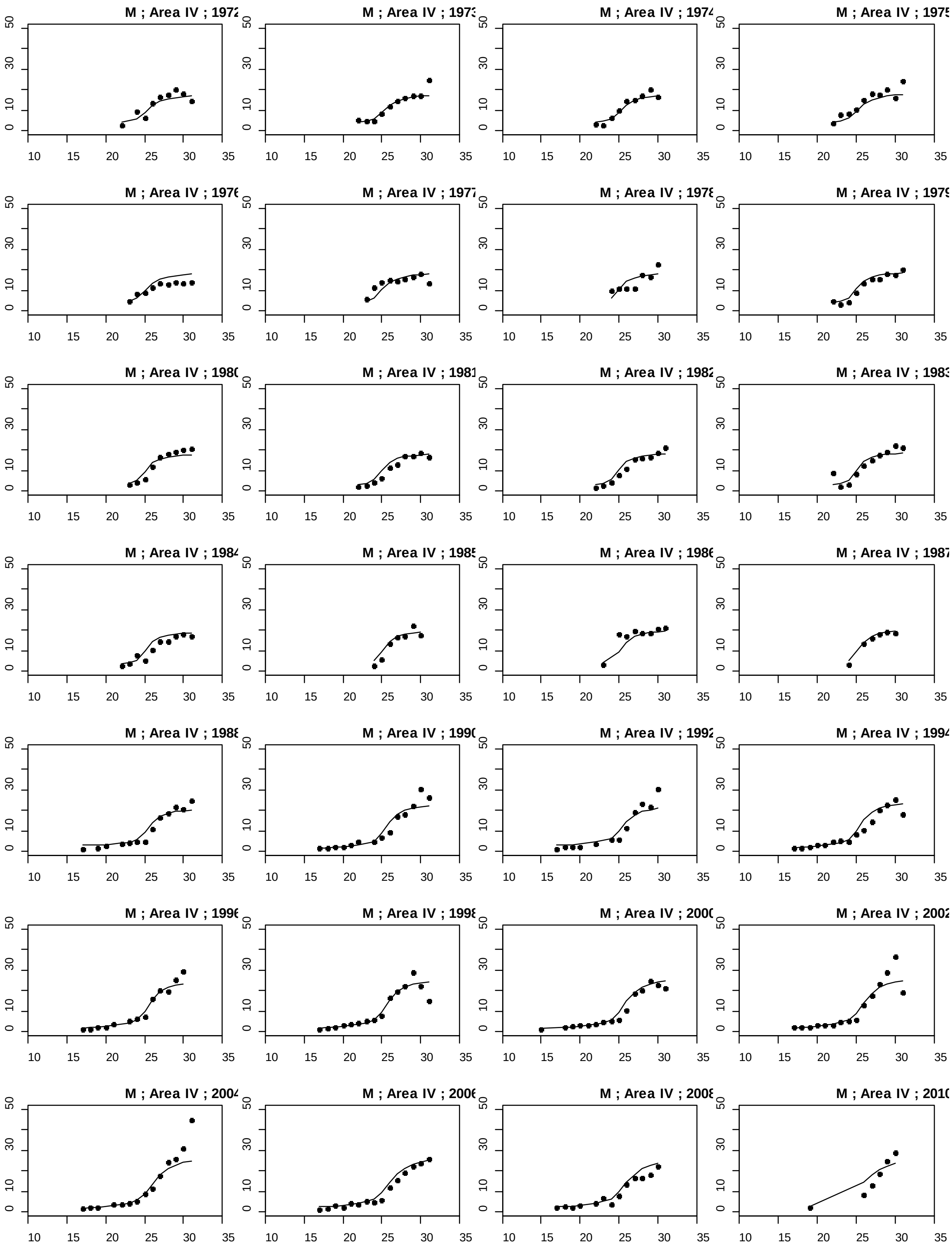


Figure 9. Observed (dots) and model-predicted (lines) mean ages versus length (ft) for one fleet-sex combination.

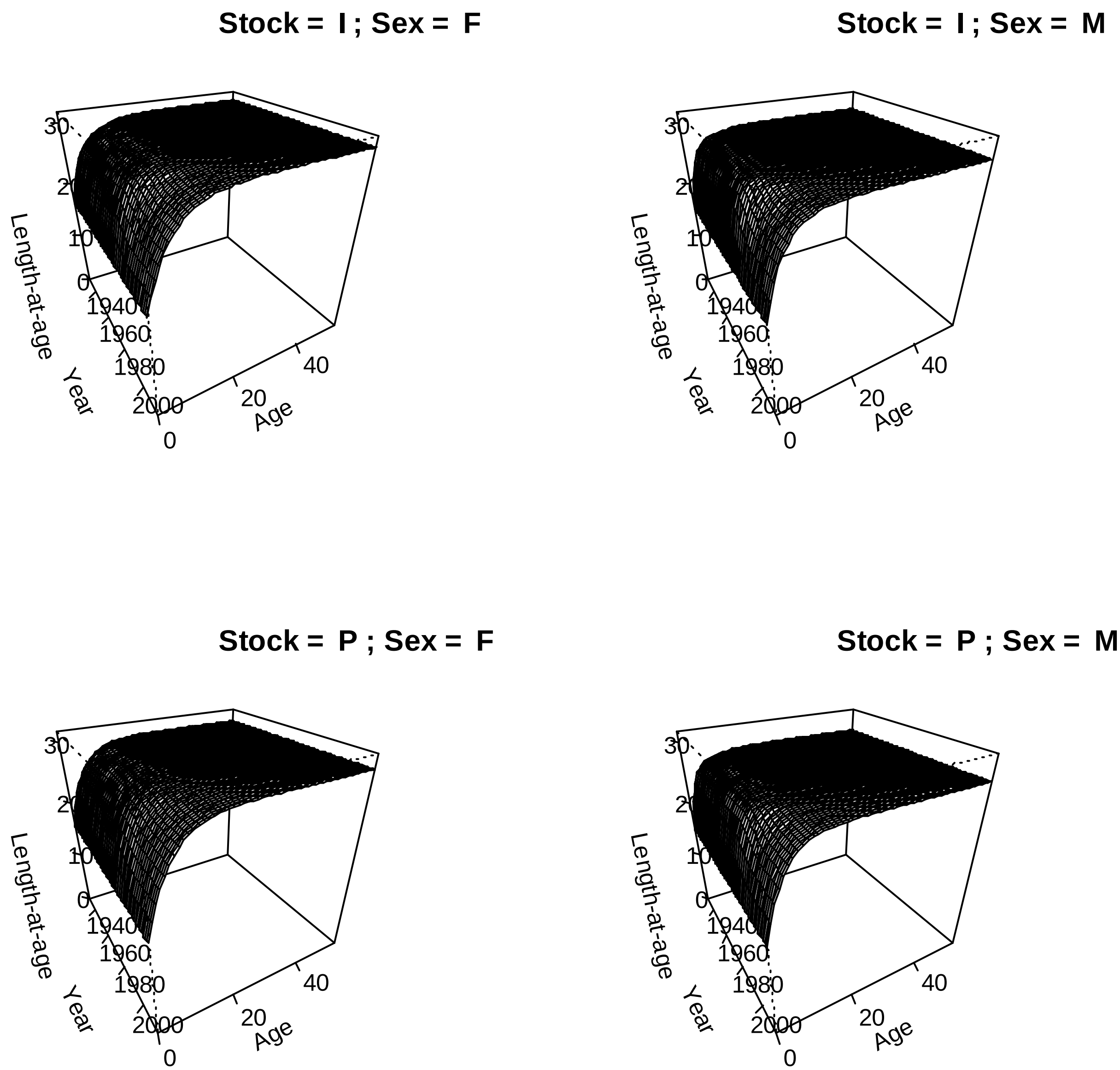


Figure 10. Length-at-age versus time by sex and stock.

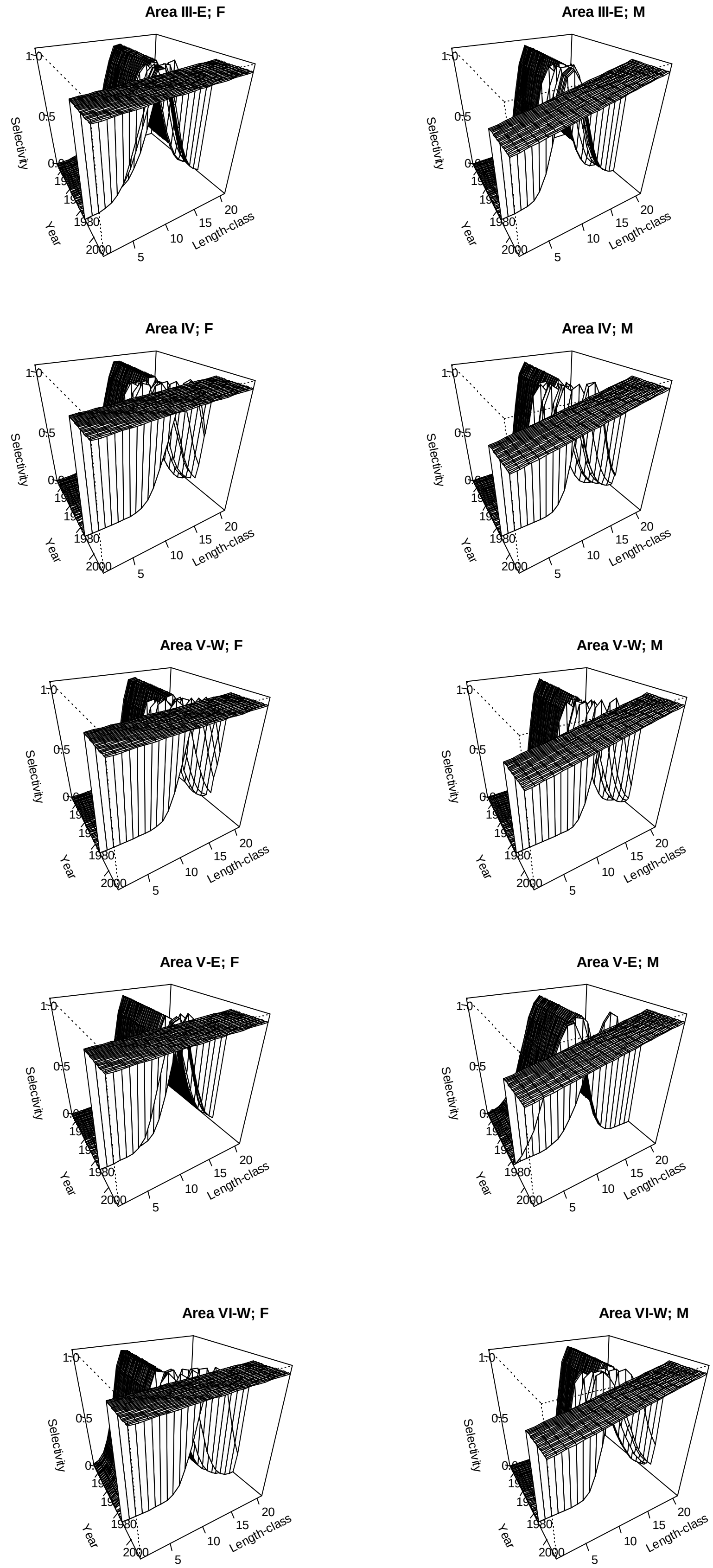


Figure 11. Length-selectivity patterns for five of the ten fleets (the Japanese fleets). Results are not shown for the ex-USSR fleets are they are identical to those for the Japanese fleets.

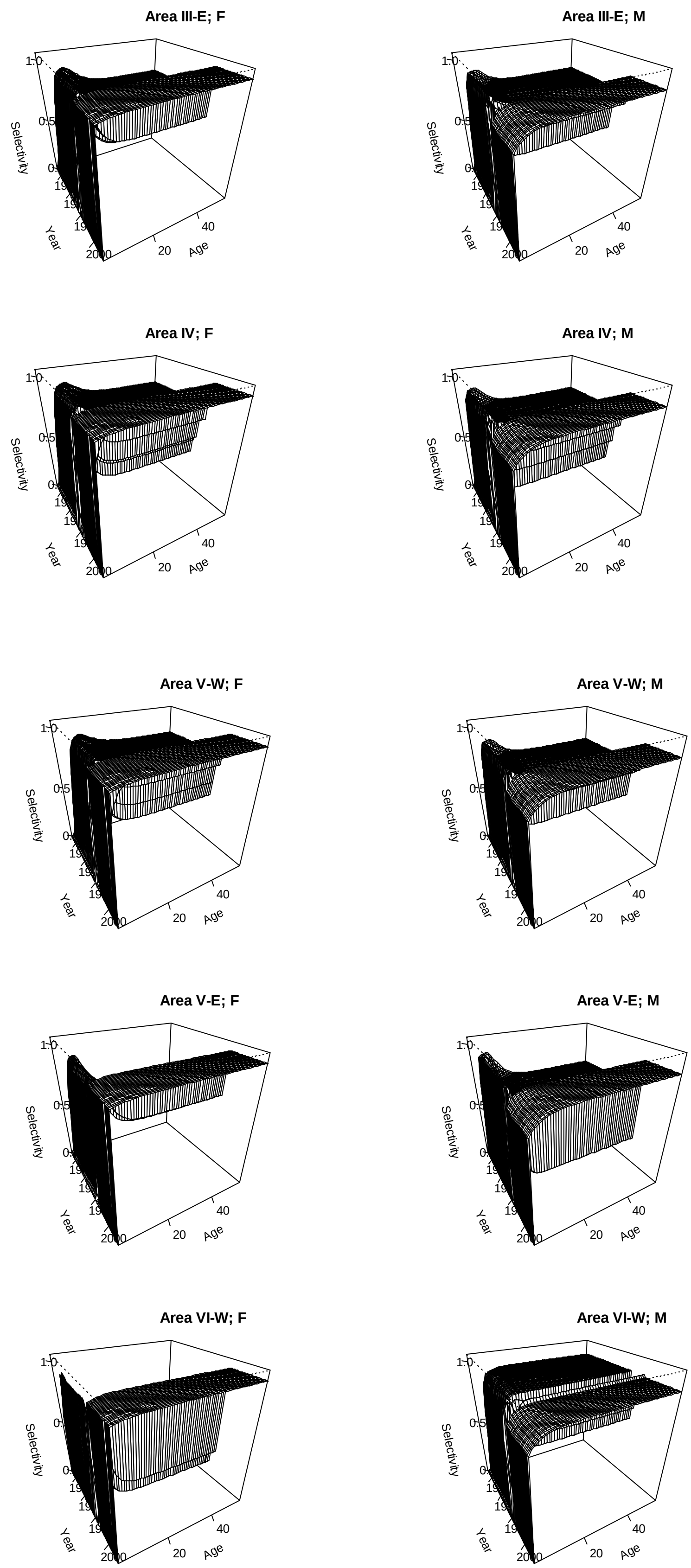


Figure 12. Age-selectivity patterns for five of the ten fleets (the Japanese fleets). Results are not shown for the ex-USSR fleets are they are identical to those for the Japanese fleets.

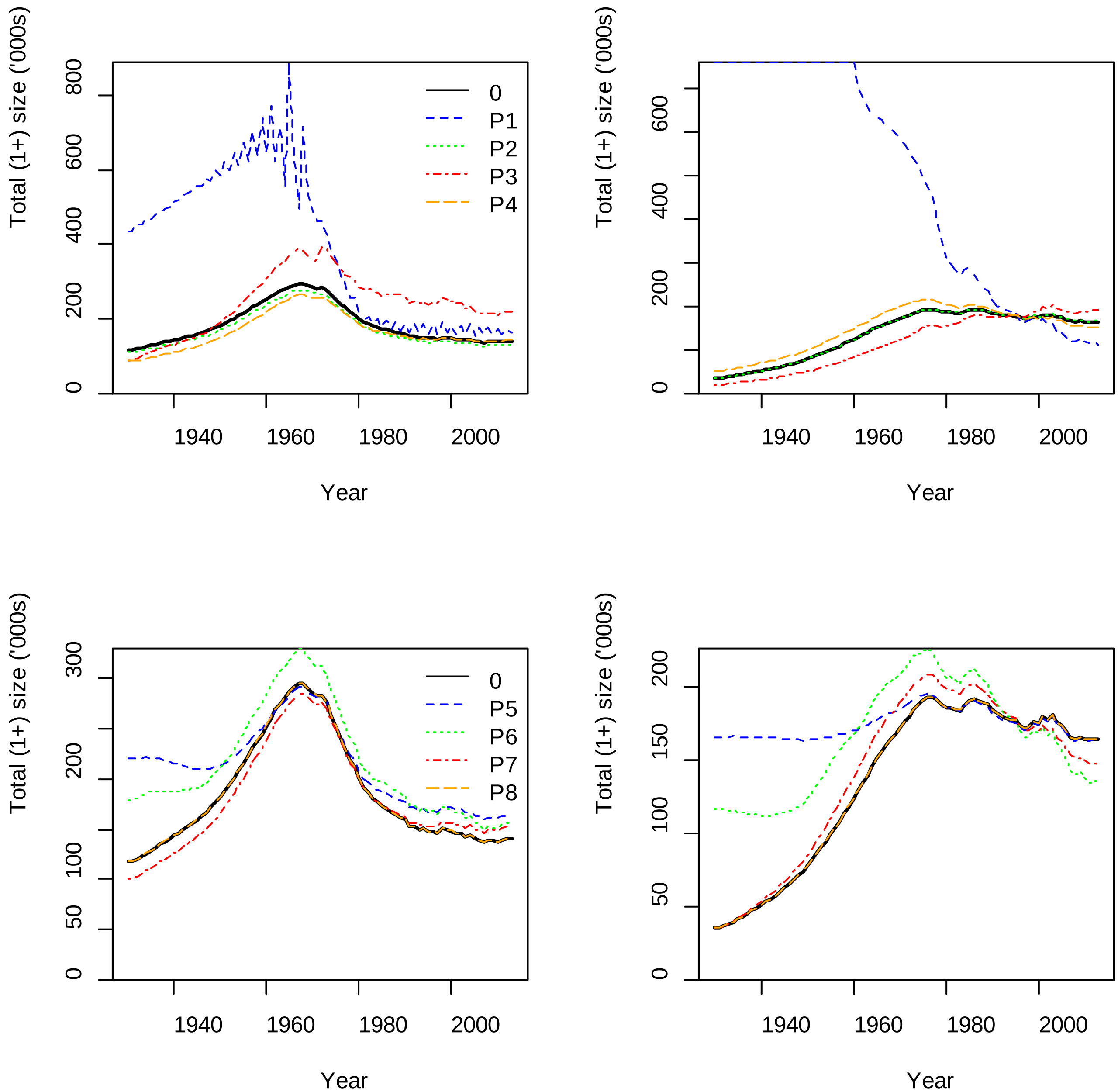


Figure 13. The time-trajectory of 1+ population size for the reference case analysis and the "P" sensitivity tests ("0" denotes the reference case analysis). Results are shown for the I stock in the left panels and for the P stock in the right panels.

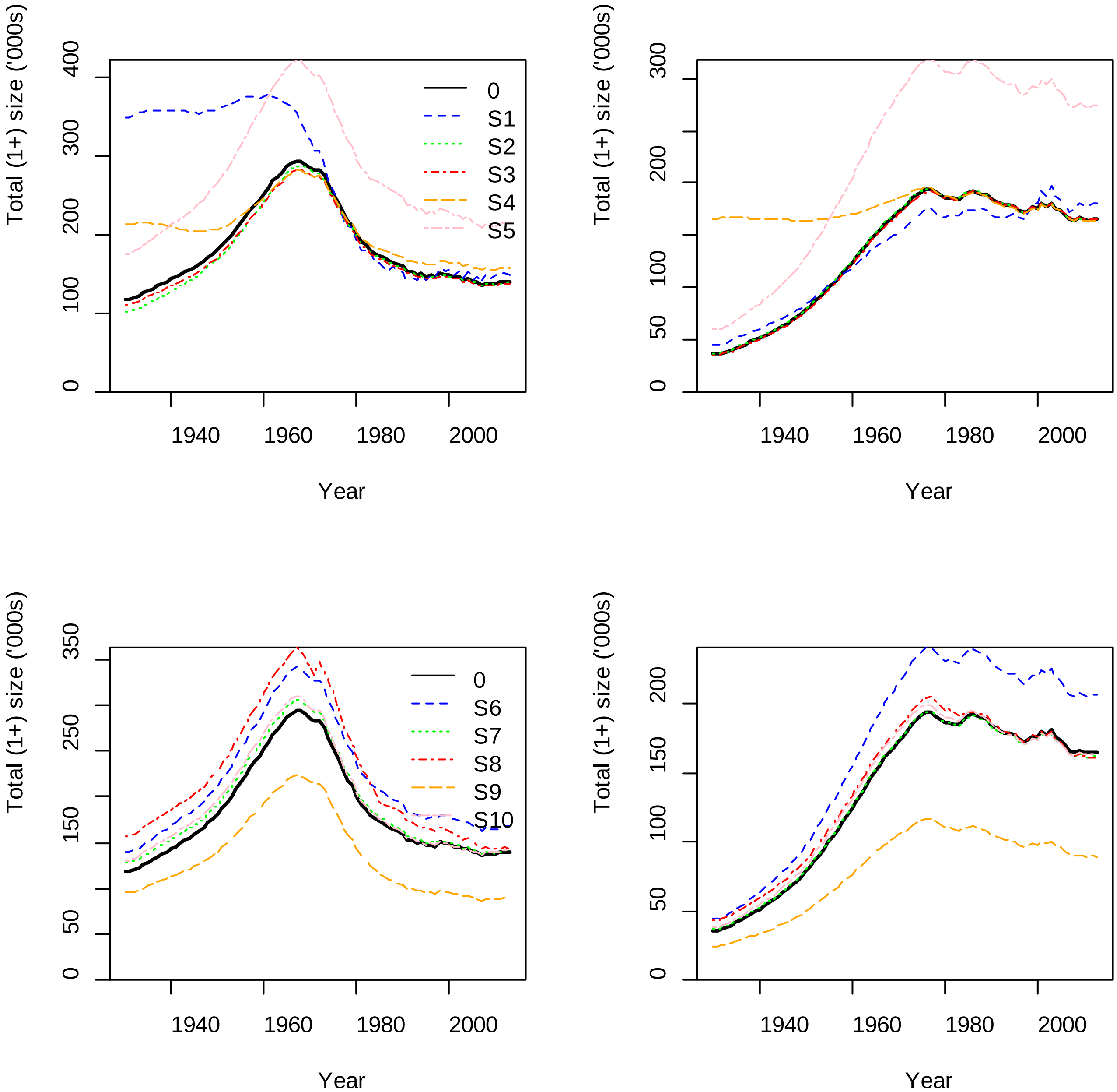


Figure 14. The time-trajectory of 1+ population size for the reference case analysis and the “S” sensitivity tests (“0” denotes the reference case analysis). Results are shown for the I stock in the left panels and for the P stock in the right panels. Sensitivity test S7 did lead to a positive definite Hessian matrix.

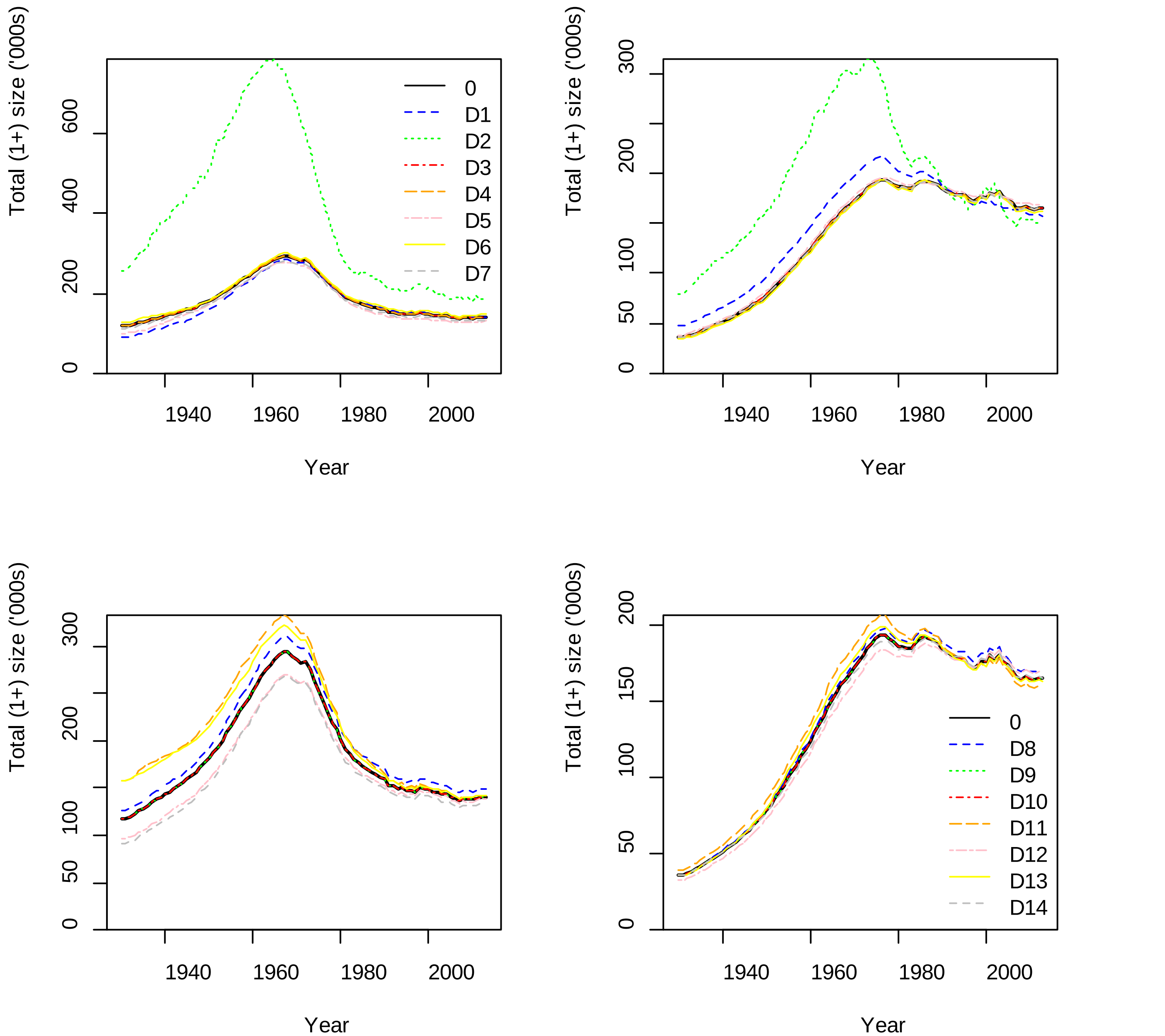


Figure 15. The time-trajectory of 1+ population size for the reference case analysis and the "D" sensitivity tests ("0" denotes the reference case analysis). Results are shown for the I stock in the left panels and for the P stock in the right panels.