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Further Development of Statistical Catch-at-age Models for Southern Hemisphere Minke Whales

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ABSTRACT
The statistical catch-at-age approach developed by Punt and Polacheck (2005, 2006) is applied to catch, catch-at-length, and age-length keys as well as indices of relative and absolute abundance in order to identify a "reference case" set of specifications related to vulnerability, examine the sensitivity to using reduced portions of the commercial catch-at-age data for assessment purposes, and to examine an alternative density- dependence function. The results confirm results obtained by Punt and Polacheck (2005, 2006) that the data support a non-uniform vulnerability pattern for JARPA and dome-shaped vulnerability for the period of commercial harvest. It is proposed that these types of vulnerability curves should be used in reference case analyses so that the reference case analysis is centered well within the range of possible parameter and model options. The results again confirm the result from earlier studies that the recruitment of Southern Hemisphere minke whales in Areas III-W, IV, V and VI-W increased until about the early- to mid-1960s and declined thereafter. This result is generally robust to assumptions about the form of the vulnerability patterns for the catches by JARPA and during the period of commercial whaling, the density-dependence function, and the weight assigned to the early ageing data. However, we had difficulty in achieving biologically reasonable estimates for stock E and had convergence problems when vulnerabilities were assumed to be age-specific – both of these issues require further analyses. As with previous analyses, the model predicts large changes in carrying capacity and somatic growth rates. There are no obvious known sources or causes to associate with these changes, particularly the large decline in estimated carrying capacity between 1960 and 1980.

KEYWORDS: CATCH-AT-AGE, MINKE WHALE, SOUTHERN HEMISPSHERE

INTRODUCTION

The IWC Scientific Committee has been conducting a multi-year IDCR/SOWER line transect survey for minke whales in the Antarctic, and is aiming to understand the reason or reasons for the apparent large declines in abundance indicated by estimates produced from these surveys. One hypothesis that has been suggested is that the declines are due to "a decrease in carrying capacity due to increase in competition from other predators (e.g. other whales)" (IWC, 2005). It has been suggested that population modelling could provide an approach for addressing the plausibility of this and other population dynamic-related hypotheses for the decline. The ADAPT-VPA approach of Butterworth *et al.* (1996, 1999, 2002) was identified as one approach that would be useful for assessing the plausibility of this hypothesis. However, it was also considered useful to develop alternative modelling approaches.

Punt and Polacheck (2005, 2006) developed a statistical catch-at-age model for Southern Hemisphere minke whales that allows for errors in catch-at-age data, more than a single stock, time-varying growth, multiple areas, environmental covariates, fleet-specific vulernabilities, and changes over time in vulnerability. They applied this model to data for the Southern Hemisphere minke whales and found that the scenario of a resource that increased after 1930 and declined recently is fairly robust to changes to the specifications of the assessment. However, some of the scenarios identified by Punt and Polacheck (2005), particularly those in which allowance was made for dome-shaped vulnerability and when vulnerability is assumed to be age-based, suggest a different conclusion regarding historical trends

Analyses of the length-at-age data from the commercial and JARPA Antarctic minke whale catches suggested apparent inconsistency in these data (Punt and Polacheck, 2005; Polacheck and Punt, 2006). Aging and/or length measurement errors have been identified as one possible hypothesis contributing to this apparent inconsistency. The catch-at-age data are the fundamental input into the population modelling of Southern Hemisphere minke whales, and consequently the development of appropriate error models for these data and the implementation of these models was considered the highest priority for the intersessional work related to the population modelling of Southern Hemisphere minke whales at last year's meeting of the Scientific Committee (IWC, 2007). Unfortunately no substantive progress was made on the development of error models for the catch-at-age data. As such, it was not possible to undertake any additional work along these lines in developing population models.

In addition to the development and implementation of error models for the catch-at-age data, a number of other priority tasks for further developing the population modelling work were identified by the Working Group on Population Modelling at last year's meeting of the Scientific Committee (IWC, 2007). The objective of this paper is to document progress with respect to these tasks using the statistical catch-at-age modelling approach of Punt and Polacheck (2005, 2006). In particular, the purpose of this paper is to a) select a reference case set of specifications related to vulnerability patterns for the commercial catches by Japan and the ex-Soviet Union and for JARPA, b) to examine the sensitivity to using reduced portions of the commercial catch-at-length/age data for assessment purposes, and c) to examine an alternative density- dependence function.

The analyses of the paper are based on the stock hypotheses identified by IWC (2007), namely that there are separate stocks in Areas III-E, IV and V-W (Stock W) and Areas V-E and IV-W (Stock E). Unlike Punt and Polacheck (2006), all of the analyses of this paper are based on allowing the von Bertalanffy growth rate parameter, κ, to vary over time and involve including the JARPA age-composition data in the analyses in the same way that the commercial data are included in the analyses (length-frequencies and age-length keys).

MATERIALS AND METHODS

Data utilized

The data used in this paper are the same as those used by Punt and Polacheck (2006), and consist of catch, abundance estimates, length frequency and age-composition data. The

data include the catches and sighting surveys information through the 2003/04 season as no additional data were provided to the Intersessional Working Group on VPA Analysis during the 2006/07 intersessional period.

Catches and length-frequency data
Table 1 lists the catches by sex, fleet (Japan and Soviet Union) and 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.

Age-composition data
Age-composition 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. Note that any final conclusions to be drawn from the application of this and other population models will depend upon conclusions from reviews of potential uncertainties (particularly biases) in these data by the Scientific Committee.

Indices of abundance
Table 3 lists the estimates of absolute abundance (from the IDCR programme; supplied by T. Branch, University of Washington) and the indices of abundance based on the JARPA programme (supplied by T. Hakamada, Institute of Cetacean Research). Note that, as is also the case for the age-composition data, any final conclusions to be drawn from the application of population models will depend on the conclusions of the current Scientific Committee review of these minke whale abundance estimates and the set of hypotheses for how these estimates should be interpreted.

The population dynamics model
Under the assumption that harvesting occurs instantaneously at the start of the year, the number of animals of sex *g* and age *a* at the start of year *y*, $N^g_{y,a}$, is given by:

$$N^g_{y,a} = \begin{cases} 0.5\,B_y & \text{if } a = 0 \\ (N^g_{y-1,a-1} - C^g_{y-1,a-1})\,e^{-M^g_{a-1}} & \text{if } 1 \le a \le x-1 \\ (N^g_{y-1,x-1} - C^g_{y-1,x-1})\,e^{-M^g_{x-1}} + (N^g_{y-1,x} - C^g_{y-1,x})\,e^{-M^g_x} & \text{if } a = x \end{cases} \qquad (1)$$

where B_y is the number of births at the start of year *y* (the sex-ratio at birth is assumed to be 50:50),

$C^g_{y,a}$ is the catch of animals of sex *g* and age *a* during year *y*, calculated as the sum of the catch over all fleets, i.e.:

$$C^g_{y,a} = \sum_f C^{g,f}_{y,a} \qquad (2)$$

$C_{y,a}^{g,f}$ is the catch of animals of sex g and age a by fleet f during year y (the analyses treat the fleets in each area in which a stock is assumed to be found as separate fleets, and assume that there are three fleets in each of these areas: Japan before 1987/88, Japan from 1987/88, and Soviet Union (see Table 1 for the catches concerned)),

M_a^g is the instantaneous rate of natural mortality on animals of sex g and age a (assumed to be time-invariant), and

x is the plus-group (set equal to 54 for the analyses of this paper).

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

$$M_a^g = \begin{cases} M_0 & \text{if } a \le a_1 \\ M_0 + (M_1 - M_0)\dfrac{(a-a_1)}{(a_2-a_1)} & \text{if } a_1 < a < a_2 \\ M_1 & \text{if } a_2 \le a \le a_3 \\ M_1 + (M_x - M_1)\dfrac{(a-a_3)}{(a_4-a_3)} & \text{if } a_3 < a < a_4 \\ M_x & \text{if } a \ge a_4 \end{cases} \tag{3}$$

where M_0 is the rate of natural mortality for animals aged a_1 and younger,

M_1 is the rate of natural mortality for animals aged between a_2 and a_3, and

M_x is the rate of natural mortality for animals aged a_4 and older.

Births

The number of births 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[1], i.e.:

$$B_y = B_y^{\mathrm{F}}\ f_0\, e^{A(1-B_y^{1+}/K_y^{1+})}\ e^{\varepsilon_y - \sigma_R^2/2} \tag{4}$$

where B_y^{F} is the number of females that have reached the age-at-first-parturition at the start of year y, i.e.:

$$B_y^{\mathrm{F}} = \sum_{a=1}^{x} \beta_{y,a}\, N_{y,a}^g \tag{5}$$

B_y^{1+} is the number of animals aged 1 and older at the start of year y:

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

$$B_y^{1+} = \sum_g \sum_{a=1}^{x} N_{y,a}^g \tag{6}$$

K_y^{1+} is the carrying capacity (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 is the pregnancy rate / infant survival rate in absence of harvesting,

A is the resilience parameter (assumed to be independent of stock),

ε_y is the logarithm of the ratio of the expected to actual number of births for year *y*, and

σ_R is the standard deviation of ε_y.

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

$$K_y^{1+} = \begin{cases} K_{1930}^{1+} & \text{if } y \le y_1 \\ K_{1930}^{1+}[1+(\tilde{K}_I^{1+}-1)\dfrac{(y-y_1)}{(y_2-y_1)}] & \text{if } y_1 < y < y_2 \\ K_{1930}^{1+}[\tilde{K}_I^{1+}+(\tilde{K}_{2002}^{1+}-\tilde{K}_I^{1+})\dfrac{(y-y_2)}{(y_3-y_2)}] & \text{if } y_2 \le y < y_3 \\ K_{1930}^{1+}\,\tilde{K}_{2002}^{1+} & \text{if } y \ge y_3 \end{cases} \tag{7}$$

where K_{1930}^{1+} is the carrying capacity from 1930 to year y_1,

K_I^{1+} is ratio of the carrying capacity in year y_2 to that in year y_1, and

K_{2002}^{1+} is ratio of the carrying capacity from year y_3 to that in year y_1.

Catches

The model-estimate of the catch of animals of sex *g* and age *a* by fleet *f* during year *y* depends on the number of animals of sex *g* and age *a*, the exploitation rate by fleet *f* on animals of sex *s* during year *y*, and the relative vulnerability (the combined effects of harvest selectivity and availability) of animals of sex *g* and age *a* during year *y* to fleet *f*. $C_{y,a}^{g,f}$ is computed using the formula:

$$C_{y,a}^{g,f} = \sum_l C_{y,a,l}^{g,f} \tag{8}$$

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

$$C_{y,a,l}^{g,f} = \begin{cases} \tilde{S}_a \, S_{y,l}^{g,f} \, X_{y,a,l}^{g} \, N_{y,a}^{g} \, F_y^{g,f} & \text{if vulnerability is length-specific} \\ \tilde{S}_a \, S_{y,a}^{g,f} \, X_{y,a,l}^{g} \, N_{y,a}^{g} \, F_y^{g,f} & \text{if vulnerability is age-specific} \end{cases} \tag{9}$$

$S_{y,l}^{g,f}$ 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*, and

$X_{y,a,l}^{g}$ is the proportion of animals of sex *g* and age *a* that are in length-class *l* during year *y*.

Vulnerability

Vulnerability is either assumed to be a function of length, fleet and sex, or a function of age, fleet and sex. Recall that separate fleets are defined for each area in which each stock is assumed to be found. Thus, separate vulnerability curves are estimated for each area and operational type. Note, however, that for the JARPA catches it is assumed that the vulnerability function is the same in all areas for each stock. This is because there are insufficient data to support the estimation of area-specific vulnerability curves for JARPA. The model has options which allow vulnerability to be uniform (Equations 10a and 11a), logistic (Equations 10b and 11b), or domed-shaped (Equations 10c and 11b), and can vary over time:

$$S_{y,l}^{g,f} = 1 \tag{10a}$$

$$S_{y,l}^{g,f} = (1 + e^{-\ell n 19 (L_l - L_{50,y}^{g,f}) / L_{\text{diff}}^{g,f}})^{-1} \tag{10b}$$

$$S_{y,l}^{g,f} = \begin{cases} \exp(-(L_l - L_{50,y}^{g,f})^2 / L_{\text{left}}^{g,f}) & \text{if } L_l \le L_{50,y}^{g,f} \\ \exp(-(L_l - L_{50,y}^{g,f})^2 / L_{\text{right}}^{g,f}) & \text{otherwise} \end{cases} \tag{10c}$$

$$S_{y,a}^{g,f} = 1 \tag{11a}$$

$$S_{y,a}^{g,f} = (1 + e^{-\ell n 19 (a - a_{50,y}^{g,f}) / a_{\text{diff}}^{g,f}})^{-1} \tag{11b}$$

$$S_{y,a}^{g,f} = \begin{cases} \exp(-(a - a_{50,y}^{g,f})^2 / a_{\text{left}}^{g,f}) & \text{if } a \le a_{50,y}^{g,f} \\ \exp(-(a - a_{50,y}^{g,f})^2 / a_{\text{right}}^{g,f}) & \text{otherwise} \end{cases} \tag{11c}$$

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

$$L_{50,y}^{g,f} = L_{50,y-1}^{g,f} + \delta_y^{g,f} \tag{12a}$$

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

$$a_{50,y}^{g,f} = a_{50,y-1}^{g,f} + \delta_y^{g,f} \tag{12b}$$

$\delta_y^{g,f}$ is the "vulnerability deviation" during year *y* for fleet *f* fishing for animals of sex *g*,

$L_{\text{diff}}^{g,f}$ is the width of the length-specific vulnerability ogive for fleet *f* fishing for animals of sex *g*,

$a_{\text{diff}}^{g,f}$ is the width of the age-specific vulnerability ogive for fleet *f* fishing for animals of sex *g*,

$L_{\text{left}}^{g,f}$ and $L_{\text{right}}^{g,f}$ are the parameters that determine the extent of dome-shapedness for the length-specific vulnerability ogive for fleet *f* fishing for animals of sex *g*,

$a_{\text{left}}^{g,f}$ and $a_{\text{right}}^{g,f}$ are the parameters that determine the extent of dome-shapedness for the age-specific vulnerability ogive for fleet *f* fishing 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. Note that vulnerability is assumed to be time invariant for the JARPA catches.

Growth

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

$$X_{y,a,l}^{g} = \int_{L_l-\Delta L}^{L_l+\Delta L} \frac{1}{\sqrt{2\pi}\sigma_\gamma^g} e^{-\frac{(L-\tilde{L}_{y,a}^g)^2}{2(\sigma_\gamma^g)^2}} dL \tag{13}$$

where ΔL is half of the width of each length-class (0.5 ft),

σ_γ^g is the extent of variability about the growth curve for sex *g*,

$\tilde{L}_{y,a}^g$ is the expected length of an animal of 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_y^g varies for every year from 1963/64 until 2003/03, i.e.:

$$L_{y,a}^g = \begin{cases} L_\infty^g (1 - e^{-k_y^g t_0^g}) & \text{if } a = 0 \\ L_\infty^g - (L_\infty^g - L_{y-a,a-1}^g)(1 - e^{-k_{y-1}^g}) & \text{otherwise} \end{cases} \tag{14}$$

L_∞^g is the asymptotic length for animals of sex *g*,

k_y^g is the value of the Brody growth coefficient for animals of sex *g* during year *y*:

$$k_y^g = k_{y-1}^g e^{\upsilon_y} \tag{15}$$

t_0^g is the theoretical age at which length is zero for animals of sex *g*, and

υ_y is the extent to which the growth rate changes from year *y*-1 to year *y*.

Initial conditions

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

$$N_{y_1,a}^g = \begin{cases} 0.5\, B_0 & \text{if } a = 0 \\ N_{y_1,a-1}^g\, e^{-M_{a-1}^g} & \text{if } 1 \le a \le x-1 \\ N_{y_1,x-1}^g\, e^{-M_{x-1}^g} / (1 - e^{-M_x^g}) & \text{if } a = x \end{cases} \tag{16}$$

where B_0 is the expected number of calves in the absence of exploitation.

The value of the parameter f_0 is chosen so that the population remains in balance in the absence of exploitation, i.e.:

$$f_0 = \left[\sum_{a=1}^{x-1} \beta_{y_1,a}\, e^{-\sum_{a'=0}^{a-1} M_{a'}^{\mathrm{f}}} + \beta_{y_1,x} e^{-\sum_{a'=0}^{x-1} M_{a'}^{\mathrm{f}}} / (1 - e^{-M_x^{\mathrm{f}}}) \right]^{-1} \tag{17}$$

The objective function

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

$$L = \sum_i O_i\, \ell\mathrm{n} L_i + \sum_j P_j \tag{18}$$

where $\ell\mathrm{n} L_i$ is the contribution of the ith data source to the objective function,

P_j is the contribution of the jth penalty term to the objective function, and

O_i is a factor to account for overdispersion.

The data included in the analyses are the annual catches (by fleet and sex), the estimates of abundance (IDCR and JARPA), the catch length-frequency data and the age-length keys, while there are penalties on the magnitudes of the deviations from the expected number of births (Equation 4), on the inter-annual deviations in the growth rate (Equation 15), on the inter-annual variation in the proportion of the population in each area (see Equation 23), and on the inter-annual deviations in vulnerability (Equation 12). 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.

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[2], i.e.:

$$\ell \mathrm{n} L_1 = \sum_y \sum_g \sum_f \left\{ \ell \mathrm{n} \sigma_C + \tfrac{1}{2\sigma_C^2} \sum_y (\ell \mathrm{n} \tilde{C}_y^{g,f} - \ell \mathrm{n} C_y^{g,f})^2 \right\} + Const \tag{19}$$

where $\tilde{C}_y^{g,f}$ is the actual catch by fleet *f* of animals of sex *g* during year *y* (see Table 1), and

σ_C quantifies the extent of variation in catches.

Estimates of abundance

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

$$\ell \mathrm{n} L_2 = \sum_A \sum_y \left\{ \ell \mathrm{n} \tilde{\sigma}_y^A + \tfrac{1}{2(\tilde{\sigma}_y^A)^2} (\ell \mathrm{n} V_y^A - \ell \mathrm{n}(\chi^A B_y^{1+,A}))^2 \right\} + Const \tag{20}$$

where V_y^A is the estimate of abundance for Area *A* and year *y* (see Table 3),

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.:

$$(\tilde{\sigma}_y^A)^2 = \tau^2 + (\phi_y^A)^2 \tag{21}$$

τ^2 is the extent of additional variance,

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

ϕ_y^A is the coefficient of variation of V_y^A (see Table 3),

$B_y^{1+,A}$ is the model-estimate of the total (1+) abundance in Area A at the start of year y, i.e.:

$$B_y^{1+,A} = P_y^A B_y^{1+} \tag{22}$$

P_y^A is the proportion of the population that is in the region A during year y:

$$P_y^A = \overline{P^A} e^{\varphi_y^A} / \sum_{A'} e^{\varphi_y^{A'}} \tag{23}$$

$\overline{P^A}$ is the expected proportion of the population that is in the Ath region, and

φ_y^A is the deviation from the expected proportion in Area A for year y.

Length-frequency data

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

$$\ell \text{n} L_3 = -\sum_y \sum_f \sum_g M_y^{g,f} \sum_{l=l_{\min,y}}^{l_{\max,y}} \rho_{y,l}^{g,f} \ell \text{n}(\hat{\rho}_{y,l}^{g,f} / \rho_{y,l}^{g,f}) + Const \tag{24}$$

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),

$\rho_{y,l}^{g,f}$ 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:

$$\hat{\rho}_{y,l}^{g,f} = \frac{\sum_a C_{y,a,l}^{g,f}}{\sum_{a'} \sum_{l'} C_{y,a',l'}^{g,f}} \tag{25}$$

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).

Age-length keys

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

$$\ell \mathrm{n} L_4 = \sum_y \sum_f \sum_g \sum_{l=l_{\min,y}}^{l_{\max,y}} \tilde{M}_{y,l}^{g,f} \sum_{a=a_{\min,y}}^{a_{\max,y}} \theta_{y,a,l}^{g,f} \ell \mathrm{n}\left(\hat{\theta}_{y,a,l}^{g,f} / \theta_{y,a,l}^{g,f}\right) + Const \tag{26}$$

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),

$\theta_{y,a,l}^{g,f}$ 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.:

$$\hat{\theta}_{y,a,l}^{g,f} = \frac{\tilde{C}_{y,a,l}^{g,f}}{\sum_{a'} C_{y,a',l}^{g,f}} \tag{27}$$

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

$$\tilde{C}_{y,a,l}^{g,f} = \sum_{a'} Y_{a,a'}^{g} C_{y,a',l}^{g,f} \tag{28}$$

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

$$Y_{a,a'}^{g} = \int_{a-0.5}^{a+0.5} \frac{1}{\sqrt{2\pi}\alpha a'} e^{-\frac{(\lambda - a')^2}{2(\alpha a')^2}} d\lambda \tag{29}$$

α is the coefficient of variation of the age-reading error.

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 $a_{\max,y}$ [3] and those with age less than $a_{\min,y}$ are pooled at age $a_{\min,y}$.

Penalties

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

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.:

$$P_1 = \tfrac{1}{2\sigma_R^2} \sum_y (\varepsilon_y)^2 \tag{30}$$

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

$$P_2 = \tfrac{1}{2\sigma_S^2} \sum_g \sum_y \sum_f (\delta_y^{g,f})^2 \tag{31}$$

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.:

$$P_3 = \tfrac{1}{2\sigma_P^2} \sum_y \sum_A (\varphi_y^A)^2 \tag{32}$$

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

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

$$P_4 = \tfrac{1}{2\sigma_k^2} \sum_y \upsilon_y^2 \tag{33}$$

Parameter estimation for the reference case analyses

The primary aim of the reference case analyses is to contrast alternative assumptions about vulnerability. Table 4 lists the estimable parameters of the model for each choice for an assumption about the vulnerability ogive considered in this paper. The values for the other parameters of the model are pre-specified. The alternative assumptions regarding vulnerability considered in this paper are:

(1) Should vulnerability be a function of length or of age (the availability of animals of age 1 is always treated as an estimable parameter of the model)?
(2) Is the vulnerability pattern for JARPA uniform (model A), asymptotic as a function of length/age (model B), or a dome-shaped function of length/age (models C & D)?
(3) Is the vulnerability pattern for the period of commercial whaling a logistic (models A, B & C) or a dome-shaped (model D) function of length/age?

Early analyses indicated that parameter estimation could be unstable when the length/age-at-50%-/full-vulnerability for JARPA was treated as an estimable parameter. Therefore, in addition to presenting results when the length/age-at-50%-/full-vulnerability for JARPA is treated an estimable parameter, results are also shown when

the length-at-50%-/full-vulnerability is set to 28, 30 and 32ft and when the age-at-50%-/full-vulnerability is set to 10, 15 and 20 years.

The values for the other parameters of the model are specified as follows

- The age-reading error CV is set to 10% (i.e. α=0.1 in Equation 29).
- There is no survey bias for the IDCR estimates (i.e. χ=1 for the IDCR estimates), and no additional variance for either IDCR or JARPA (i.e. τ^2 =0 in Equation 21).
- The minus- and plus-group ages when fitting to the age-composition data, $a_{\min,y}$ and $a_{\max,y}$, are set to 1 and 45yr respectively.
- 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 JAPRA 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 JAPRA. These choices were made to avoid fitting the model to length-classes with few data.
- Carrying capacity changed in 1930, 1960 and 1980 (years y_1, y_2 and y_3 in Equation 7).
- Natural mortality changes (in a piecewise linear fashion) at ages 3, 10, 30 and 35 (ages a_1, a_2, a_3 and a_4 in Equation 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).
- An age-specific availability factor is estimated for age 1 only (exploratory analyses, not shown here, indicate that little improvement in fit occurs if availability is estimated for additional ages).
- The extent of variation in births, σ_R, is set to 0.2.
- The standard deviation of the logarithms of measuring the catch, σ_C, is set to 0.05.
- The parameter that determines the extent of variability in the vulnerability deviations, σ_S, is set to 10.
- The parameter that determines the extent of variability in the proportion of each stock in each area, σ_P, is set to 0.2.
- The parameter that determines the extent of variability in growth rate, σ_k, is set to 0.1.

The reference case choices for σ_R, σ_C, 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. The values for the overdispersion parameters O_3 and O_4 (0.65 and 0.8) were selected as outlined by Punt and Polacheck (2006).

Sensitivity to the nature of the density-dependence function

Sensitivity to whether density-dependence acts on the rate of natural mortality for all ages rather than the pregnancy rate and infant survival rate is explored by setting the parameter *A* in Equation 4 to 0, and allowing natural mortality to depend on year as well as on age, i.e.:

$$M_{y,a}^{g} = M_{1930,a}^{g}\, e^{-\tilde{A}(1-B_y^{1+}/K_y^{1+})} \tag{34}$$

where $M_{y,a}^{g}$ is the instantaneous rate of natural mortality on animals of sex *g* and age *a* during year *y*, and

$\tilde{A}$ is the parameter that determines the extent of density-dependence in natural mortality.

Sensitivity to omitting some of age-length keys

The sensitivity of the results to ignoring all of the age-length keys (but not length-composition information) for the years prior to (a) 1976 and (b) 1981 is explored to determine the impact of the ageing data for the early (and less intensively sampled) years.

Summary statistics

The summary statistics and plots for which results are reported (Table 5) represent a set of common output statistics to facilitate comparisons among alternative analyses of these data. The set of output statistics was developed by the authors in conjunction with Butterworth and Mori, and then reviewed by the Intersessional Working Group on VPA Analysis.

RESULTS AND DISCUSSION

Selection of a reference case vulnerability pattern

Table 6 lists the values for the summary statistics for the analyses that examine the implications of different assumptions regarding vulnerability. Results are shown in Tables 6(a) and 6(c) for the analyses in which vulnerability is assumed to be a function of length, and in Tables 6(b) and 6(d) for the analyses in which vulnerability is assumed to be a function of age. The estimates of the time-trajectories of 1+ abundance and recruitment are shown for all of the analyses in Table 6 in Figure 1.

There is evidence in Table 6 that some of the analyses did not converge to the global minimum of the objective function. For example, several of the model runs based on age-specific vulnerability, and dome-shaped vulnerability for the commercial fleets did not lead to a Hessian matrix that was positive definite (indicated by asterisks in Table 6), and, in some cases, models that are nested within other models did not lead to a value for the objective function that was lower than that for the less complicated model (indicated by ampersands in Table 6).

The most complicated model in which vulnerability is length-based ("D-Est") led to the best fit to the data for stock W. It should be noted, however, that many of the models in which vulnerability was age-based failed to converge when applied to the data for stock W (Table 6(b)). Detailed examination of the results for the models that failed to provide

positive definite Hessian matrices revealed that the "best fits" occurred when some of the parameters hit bounds (e.g. knife-edged vulnerability when vulnerability was assumed to be a logistic function of age). Time did not permit us to explore whether the problems encountered were due to the initial starting values or related to more fundamental problems (e.g. a mis-match between the data and the assumptions of the model). In particular, it is not clear why the convergence problems were primarily associated with the scenarios with age-specific vulnerability.

The results for the best-fit model for stock W (Figures 2 and 3) indicate that the number of 1+ animals increased from 1930 to about the mid-1970s and has declined since. This is attributed to a large change in carrying capacity (an increase from 1930 to about 1960 by nearly 900% followed by a substantial decline thereafter). Recruitment is also estimated to have increased from 1930, peaked, declined, and to have been relatively stable since 1980. The estimate of the maximum sustainable yield rate (MSYR) for this analysis is 5.4% (asymptotic standard deviation 0.53%). The fits to the JARPA data are good. However, the model is not able to fit the most recent IDCR estimates. The fits to the length frequency data and the age-length keys are similar to those achieved by Punt and Polacheck (2006) who used similar models and the same data set and, given the focus of the current paper, we have not repeated the figures showing the fits to these data. As expected from the results of Punt and Polacheck (2006), there is substantial variation over time in the Brody growth rate parameter. Length-specific vulnerability for the ex-Soviet fleets (fleets 2, 4 and 6) is more dome-shaped than for the Japanese fleets (fleets 1, 3 and 5) during the period of commercial whaling (Figure 3). The reasons for dome-shaped vulnerability remain unclear; this could reflect either biological processes (such as large animals being less available to whalers) or the impact of ageing error (e.g. negative bias in the estimates of age for the older animals). As expected, the vulnerability pattern during the period of JAPRA catches is flatter than during the period of commercial catches (Figure 3, fleets 1, 3 and 5), but the vulnerability pattern for JARPA is clearly not uniform.

In contrast to the situation for stock W, the lowest value for the objective function for stock E occurs for one of the models with age-based vulnerability ("D-Est"; Table 6(d)). However, the Hessian matrix for this model is not positive definite. Moreover, this model, and the other models in which commercial vulnerability is dome-shaped (the D models), imply very low rates of natural mortality for older ages and occasionally very high (and unrealistic) rates of natural mortality for young animals. For these reasons, we do not consider that the "D-Est" model with length-based vulnerability provides a reliable choice for a reference case. In addition, the "D-Est" model with age-based vulnerability (and models "D-10yr" and "D-15yr" in Table 6(d)) indicate that MSYR=0% so that the time-trajectory of 1+ population size is a one-way trip of stable followed by declining abundance (Figure 1). An MSYR equal to zero is not viable for a population over extended periods. However, an estimate of zero in this case may be an alternative way for the model to reflect the fact that that carrying capacity declines after 1960. The zero MSYR values may also be due to the fact that there is very little information for the model to estimate pre-1960 trends (i.e. essentially no age or length data prior to 1977/78 followed by another two years with no catches, combined with the fact that samples sizes for stock E are relatively small).

Among the length-based vulnerability models for stock E, the "D-Est" model provides the best fit, and the Hessian matrix is positive definite. The estimates of natural mortality from the D models when vulnerability is length-based seem more realistic than those from these models when vulnerability is assumed to be age-based (although the estimates of natural mortality for young animals still seem very high for the models with length-based vulnerability). As such, model "D-est" with length-based vulnerability would seem to currently provide the best choice for a reference case for stock E. The detailed results for model "D-Est" for stock E (Figure 4) are qualitatively the same was those for stock W. The vulnerability pattern for JARPA for stock E is less flat than was the case for stock W (Figure 5); this may be due in part to the high rate of natural mortality for young animals. However, one consequence of the high rate of natural mortality for young (ages 0-3) animals is that the number of calves-per-mature female is estimated to exceed 1 for most of the years 1930-2002 (Figure 4). Clearly, this is not biologically plausible. The problems in fitting to the stock E data may reflect problems in the stock definition and/or the fact that there are simply insufficient data to provide reliable information on, for example, natural mortality. In any case, further work is required in order to provide a biologically plausible reference case.

Sensitivity to the nature of the density-dependence function

The time-trajectories of 1+ population size and recruitment when density-dependence acts on all ages (rather than on the pregnancy rate and infant survival rate) are qualitatively the same as those for the reference case analysis (Figure 6). However, the trajectories differ quantitatively, particularly for stock E, as the increase in recruitment between 1940 and 1960 for this stock is substantially less than for the reference case analysis. It should be noted, however, that the fits of the model in which density-dependence acts on the rate of natural mortality for all ages are poorer than those for the reference case analyses (although the models have the same number of parameters) (Table 7).

Sensitivity of omitting some of the age-length keys

Somewhat surprisingly, the time-trajectories of total (1+) population size and recruitment are not very sensitive to omitting the age-length keys for the years prior to 1980 (Figure 7). For stock W, removing the early age-length keys exacerbates the increase and then decline in recruitment and hence total (1+) population size. The impact of ignoring the early age-length keys is much less for stock E than for stock W owing to there being far fewer early age-length keys for stock E. The fits for these sensitivity tests all led to positive definite Hessian matrices. As expected, the estimates of the key model outputs (such as the rate of natural mortality) are somewhat less precise when the early age-length keys are omitted from the analyses.

General discussion and future work

The results reported in this paper again confirm the result from earlier studies that the recruitment of Southern Hemisphere minke whales in Areas III-W, IV, V and VI-W increased until about the early- to mid-1960s and declined thereafter. This result is generally robust to assumptions about the form of the vulnerability patterns for the catches by JARPA and during the period of commercial whaling, the density-dependence function, and the weight assigned to the early ageing data. As in Punt and Polacheck

(2005), some of the models with age-specific dome-shaped vulnerability yielded different historical trends in recruitment. However, problems were encountered with these models in terms of convergence and the biological plausibility of some of the parameter estimates.

As in previous analyses (e.g. Punt and Polacheck, 2005, 2006), the model continues to predict large changes in carrying capacity and somatic growth rates. There are no obvious known sources or causes to associate with these changes (particularly the large decline in estimated carrying capacity between 1960 and 1980). This is a question that warrants further consideration and discussion.

The results of the analyses confirm results obtained by Punt and Polacheck (2005, 2006) that the data support a non-uniform vulnerability pattern for JARPA and dome-shaped vulnerability for the period of commercial harvest. Use of these types of vulnerability curves in reference case analyses should begin to satisfy the suggestion of Punt and Polacheck (2006) that that any reference case analysis should be centered well within the range of possible parameter and model options, and also priority task four identified by the Working Group on Population Modelling (i.e. "determine a revised 'reference case' analysis reflecting what has been learned with respect to the most likely assumptions about selectivity, etc", IWC (2007)).

The estimated vulnerability patterns are perhaps somewhat surprising and have potential implications for the interpretation of the abundance estimates as well as biological data collected from catch samples. If the estimated vulnerability patterns do not reflect problems in the age and/or length data, the fact that they are dome-shaped suggests that portions of the population are relatively less available to capture in the area where commercial harvesting and JARPA catches have taken place. It seems unlikely that dome-shaped vulnerability would be the result of the harvesting/targeting practices of the whaling fleet as larger animals were certainly preferable targets during the period of commercial whaling and the JARPA programme has been designed to capture a random sample of the whales encountered. Differential age/size spatial patterns of distribution would be a likely source for dome-shaped vulnerability, possibility related to animals inside or outside the pack ice. This question has been discussed previously within the Scientific Committee. Polacheck *et al* (1999) found no evidence for spatial or temporal structure in the age-distribution of the commercial catches that would suggest differential vulnerability among older animals within the areas where commercial catches were actually taken, As such, if differential age/size spatial distributional patterns are the source for the dome-shaped vulnerability patterns, this would suggest that there is substantial differential availability by age or size inside and outside the areas where whaling took place, although why the extent of dome-shapeness would then differ so markedly between the Japanese and Soviet fleets (see Figures 3 and 5) is perhaps somewhat surprising. Such differential distribution patterns have implications for the interpretation of the sightings data and how they are included in the population model assessments. For example, the sighting survey estimates may be providing an estimate of only the vulnerable portion of the stock and, for example, any trend estimates would then be confounded by changes in the age/length structure of the population unless account could be taken of this when population models are fitted.

The reasons why there were substantially more problems in fitting the models with age-specific in contrast to length-specific vulnerability are not clear and this needs to be investigated further. The underlying factors responsible for the differential vulnerability is unknown and it is unclear whether it is likely to be more age- or length-driven. Nevertheless, given the correlation between age and length, one might have anticipated relatively similar results for these two assumptions regarding vulnerability. In this regard, it would be informative to calculate and examine the implicit annual age-specific vulnerabilities patterns for the models based on length-specific vulnerability.

The analyses of this paper assume the vulnerability pattern for JARPA is the same across sub-Areas, but that country-specific vulnerability patterns during the period of commercial harvest are area-specific. It may be possible to simplify the model further by investigating models in which vulnerability depends on national fleet, but not area. This may resolve some of the convergence problems encountered when fitting the models with age-specific vulnerability Similarly, the possibility that vulnerability for some fleets (e.g. Japan) is asymptotic, but that vulnerability for other fleets (e.g. USSR) is dome-shaped could be examined further.

The model has difficulty in achieving biologically reasonable estimates for stock E. The best fits tend to lead to high estimated rates of natural mortality, calving rates greater then one and/or estimates of MSYR of 0 (Tables 6(c) and 6(d) and Figure 4). This may simply represent the relative paucity of data for this stock as defined, or possibly a stock definition problem. The analyses of this paper have treated stocks W and E completely separately. Future analyses should explore the extent to which the analyses for stock E can “borrow strength” from those for stock W (e.g. by assuming similar natural mortality rates).

In common with previous papers on this subject, the focus of this paper has been on examining uncertainty by means of sensitivity tests (i.e. exploring model uncertainty). Although there is a large amount of data, the models considered in this paper also have a large number of parameters (although fewer than in the models considered by Punt and Polacheck (2006) because the models in this paper are somewhat simplified compared to those considered by Punt and Polacheck (2006)). Nevertheless, it is important to understand the degree of estimation uncertainty associated with the “best” fit parameter estimates for each model scenario. We attempted to apply the Markov Chain Monte Carlo (MCMC) algorithm to obtain estimates of the uncertainty associated with the parameter estimates. However, no meaningful results were obtained even after a week of continuous computing for the “D-Est” scenario for stock E. This is an area requiring further investigation

An original aim of the research for this year was to explore the implications of ageing error on the results from analyses of abundance and catch-at-age data for Southern Hemisphere minke whales. However, as noted above, owing to lack of progress developing hypotheses related to how ageing of Southern Hemisphere minke whales could be in error and quantifying these hypotheses in ways in which they could included in statistical catch-at-age analysis, it was not possible to do any work on this issue.

The results in this paper remain preliminary, not only because of the lack of information to quantify ageing error, but also because the Scientific Committee has yet to finalize the estimates of abundance, their interpretation in terms of trends, their relationship to absolute population size, and how they should be treated within the catch-at-age modelling framework.

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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

Table 2
Summary of the age-composition 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	68	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

(Table 2 Continued)

Year	Area V-W				Area V-E				Area VI-W			
	Age-composition		Length-frequency (Japan)		Age-composition		Length-frequency (Japan)		Age-composition		Length-frequency (Japan)	
	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	190	54	310	144	0	0	0	0	0	0	0	0
1975/76	260	132	160	66	0	0	0	0	0	0	0	0
1976/77	515	237	495	263	0	0	0	0	0	0	0	0
1977/78	298	191	316	209	32	24	32	18	23	45	83	156
1978/79	69	54	104	93	0	0	0	0	0	0	0	0
1979/80	383	257	113	81	0	0	0	0	0	0	0	0
1980/81	105	71	330	257	34	28	156	119	68	78	99	100
1981/82	369	256	779	548	18	15	11	10	49	157	67	218
1982/83	416	303	1480	1109	0	0	0	0	130	98	170	137
1983/84	436	316	945	717	8	6	56	48	279	87	349	126
1984/85	337	274	573	485	0	0	0	0	79	240	92	277
1985/86	343	311	670	596	0	0	0	0	77	250	97	300
1986/87	162	143	851	743	0	0	0	0	242	112	285	129

(Table 2 Continued)

Year	Area V-W				Area V-E				Area VI-W			
	Age-composition		Length-frequency (Japan)		Age-composition		Length-frequency (Japan)		Age-composition		Length-frequency (Japan)	
	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	85	64	151	122	0	0	0	0
1989/90	0	0	0	0	0	0	0	0	0	0	0	0
1990/91	110	101	77	67	54	50	68	65	14	0	14	0
1991/92	0	0	0	0	0	0	0	0	0	0	0	0
1992/93	118	112	87	78	45	42	53	49	17	4	20	4
1993/94	0	0	0	0	0	0	0	0	0	0	0	0
1994/95	113	99	27	25	87	72	103	88	0	0	0	0
1995/96	1	1	0	0	0	0	0	0	0	0	0	0
1996/97	55	51	72	64	77	70	80	69	72	66	82	74
1997/98	0	0	0	0	0	0	0	0	0	0	0	0
1998/99	95	80	88	72	111	90	34	32	12	38	20	41
1999/00	0	0	0	0	0	0	0	0	0	0	0	0
2000/01	95	81	45	34	87	78	73	62	59	62	64	76
2001/02	0	0	0	0	0	0	0	0	0	0	0	0
2002/03	54	48	46	37	114	98	116	100	32	54	43	67
2003/04	0	0	0	0	0	0	0	0	0	0	0	0

Table 3
The estimates of abundance

(a) IDCR Estimates

Year	Estimate	Year	Estimate
Area III-E		Area IV	
1979/80	80 551 (0.381)	1978/79	130 333 (0.178)
1987/88	37 428 (0.426)	1988/89	84 815 (0.288)
1994/95	20 465 (0.238)	1998/99	13 409 (0.279)
Area V-W		Area V-E	
1980/81	78 093 (0.470)	1980/81	164 993 (0.328)
1985/86	77 194 (0.249)	1985/86	172 828 (0.147)
1991/92	10 055 (0.282)	1991/92	187 266 (0.210)
2001/02	46 169 (0.174)	2001/02	100 658 (0.170)
Area VI-W			
1983/84	67 161 (0.227)		
1990/91	8 394 (0.294)		
1995/96	33 323 (0.230)		

(b) JARPA indices of relative abundance

Area III-E		Area IV		Area V-W	
Year	Estimate	Year	Estimate	Year	Estimate
1995/96	12 766 (0.323)	1989/90	54 772 (0.231)	1990/91	65 129 (0.279)
1997/98	7 710 (0.445)	1991/92	56 774 (0.258)	1992/93	44 047 (0.291)
1999/00	15 580 (0.687)	1993/94	41 895 (0.211)	1994/95	21 601 (0.322)
2001/02	58 169 (0.413)	1995/96	42 882 (0.245)	1996/97	26 333 (0.373)
2003/04	34 949 (0.295)	1997/98	29 683 (0.266)	1998/99	87 626 (0.311)
		1999/00	49 922 (0.168)	2000/01	20 548 (0.290)
		2001/02	67 954 (0.169)	2002/03	108 783 (0.230)
		2003/04	47 818 (0.358)		

Area V-E		Area VI-W	
Year	Estimate	Year	Estimate
1990/91	124 758 (0.287)	1996/97	13 556 (0.284)
1992/93	81 466 (0.284)	1998/99	40 430 (0.273)
1994/95	141 017 (0.297)	2000/01	23 426 (0.236)
1996/97	142 304 (0.293)	2002/03	13 426 (0.269)
1998/99	38 230 (0.378)		
2000/01	152 580 (0.236)		
2002/03	83 136 (0.197)		

Table 4
The estimable parameters of the population dynamics model and the objective function, except those related to vulnerability (a), and the number of vulnerability parameters for each of the parameterizations of vulnerability considered in this paper (b). Results are shown for each of the two stock hypotheses.

(a) Parameters other than those related to vulnerability

Parameter	**Number of parameters**	
	Stock W	**Stock E**
Calves in the absence of exploitation, B_0	1	1
Natural mortality: M_0, M_1/M_0, M_2/M_1	3	3
Resilience, A	1	1
Survival deviation, ε_y	75	75
Expected proportion in each Area, $\overline{P^{s,A}}$	2	1
Annual deviations about the expected proportions in each area, φ_y^A	63	26
Exploitation rate by year, sex and fleet, $F_y^{g,f}$	267	102
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	82	82
JARPA survey bias, χ	3	2
Total	**507**	**301**

(Table 4 Continued)

(b) Parameters related to vulnerability*

Parameter	Number of parameters	
	Stock W	**Stock E**
A-JARPA = Uniform; Commercial = Logistic	1+134+12+12	1+28+8+8
Pre-specified length-(age-) at-modal selection (28, 30, 32ft, / 10 ,15, 20 yr)		
B-JARPA = Dome-shaped (pre-specified RHS); Commercial = Logistic	1+134+12+14	1+28+8+10
C-JARPA = Dome-shaped (estimated RHS); Commercial = Logistic	1+134+12+16	1+28+8+12
D-JARPA = Dome-shaped (estimated RHS); Commercial = Dome-shaped	1+134+12+28	1+28+8+20
Estimated length-(age-) at-modal selection		
B-JARPA = Dome-shaped (pre-specified RHS); Commercial = Logistic	1+134+13+14	1+28+9+10
C-JARPA = Dome-shaped (estimated RHS); Commercial = Logistic	1+134+13+16	1+28+9+12
D-JARPA = Dome-shaped (estimated RHS); Commercial = Dome-shaped	1+134+13+28	1+28+9+20

* The JARPA vulnerability ogive is always assumed to be time-invariant and the same among Areas; the vulnerability patterns for Japan and the ex-Soviet Union are always assumed to change over time and to differ among Areas.

& Only the selectivity parameter for age 1 is estimated.

Table 5
The summary statistics and plots reported in this paper

(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).
$N_{\text{End-5,1}}/N_{1968,1}$ – 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

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 (*)

* Final reference runs only

Table 6
Results of the alternative model runs to select a reference case analysis

(a) Stock W (length-specific vulnerability)

Case	-LnL	b_{rec}			N_{tot}			$N_{End\text{-}5,1}/N_{1968,1}$	K_{1930}	K_{2000}/K_{1960} (%)	K_{1960}/K_{1930} (%)	Natural mortality (ages)			JARPA q / Mean proportion			MSYR
		1945-68	1968-88	1988-End	1945-68	1968-88	1988-End					0-3	10-30	35+	III-E	IV	V-W	
A	12731.60	4.60	-5.06	0.42	5.13	-3.58	-1.40	0.32	51152	24	1000	0.11	0.06	0.16	0.72/0.24	0.83/0.44	1.11/0.32	0.043
B-28ft	12726.90	4.50	-5.16	0.50	5.09	-3.73	-1.34	0.31	52061	24	1000	0.12	0.06	0.16	0.71/0.24	0.82/0.44	1.10/0.32	0.044
C-28ft	12721.10	4.51	-5.27	0.49	5.09	-3.77	-1.36	0.30	52722	24	1000	0.12	0.06	0.16	0.71/0.24	0.83/0.44	1.10/0.32	0.044
D-28ft	12621.40	4.28	-4.78	0.79	5.07	-3.56	-1.04	0.36	44405	28	1000	0.06	0.06	0.16	0.74/0.24	0.87/0.44	1.14/0.32	0.048
B-30ft	12711.90	4.42	-5.33	0.49	5.06	-3.90	-1.31	0.30	53763	24	1000	0.13	0.07	0.16	0.69/0.24	0.81/0.44	1.08/0.32	0.046
C-30ft	12711.90	4.42	-5.33	0.49	5.06	-3.90	-1.31	0.30	53762	24	1000	0.13	0.07	0.16	0.69/0.24	0.81/0.44	1.08/0.32	0.046
D-30ft	12616.70	4.22	-4.85	0.81	5.05	-3.65	-1.02	0.35	44916	28	1000	0.06	0.06	0.16	0.73/0.24	0.86/0.44	1.14/0.32	0.049
B-32ft	12697.20	4.05	-5.80	0.63	4.87	-4.64	-1.06	0.29	56209	22	1000	0.19	0.07	0.16	0.70/0.24	0.84/0.44	1.09/0.32	0.052
&C-32ft	12704.70	4.06	-5.58	0.66	4.91	-4.48	-1.05	0.31	54501	23	1000	0.18	0.07	0.16	0.70/0.24	0.84/0.44	1.09/0.32	0.052
D-32ft	12614.60	4.18	-4.87	0.78	5.03	-3.71	-1.01	0.35	45747	28	1000	0.07	0.06	0.16	0.72/0.24	0.85/0.44	1.13/0.32	0.049
B-Est	12663.50	3.19	-6.62	0.48	4.15	-5.99	-0.78	0.26	77241	20	827	0.29	0.08	0.16	0.69/0.24	0.87/0.43	1.07/0.33	0.067
C-Est	12663.50	3.19	-6.62	0.48	4.15	-5.99	-0.78	0.26	77236	20	827	0.29	0.08	0.16	0.69/0.24	0.87/0.43	1.07/0.33	0.067
D-Est	12609.70	3.84	-5.26	0.80	4.80	-4.31	-0.92	0.33	50767	26	948	0.13	0.07	0.16	0.73/0.24	0.87/0.44	1.13/0.32	0.054

& Could not have converged.

(Table 6 Continued)

(b) Stock W (age-specific vulnerability)

Case	-LnL	b_{rec}			N_{tot}			$N_{End\text{-}5,1}/N_{1968,1}$	K_{1930}	K_{2000}/K_{1960} (%)	K_{1960}/K_{1930} (%)	Natural mortality (ages)			JARPA q / Mean proportion			MSYR
		1945-68	1968-88	1988-End	1945-68	1968-88	1988-End					0-3	10-30	35+	III-E	IV	V-W	
A	13053.70	4.68	-7.01	0.36	4.98	-4.37	-2.26	0.23	69285	15	1000	0.12	0.09	0.13	0.79/0.24	0.95/0.42	1.16/0.33	0.034
B-10yr	13010.10	4.40	-7.58	0.49	4.84	-5.14	-1.91	0.22	77210	14	1000	0.18	0.09	0.13	0.74/0.25	0.91/0.42	1.11/0.33	0.037
&C-10yr	13113.20	4.30	-7.43	0.50	4.86	-5.14	-1.91	0.25	76309	15	1000	0.17	0.09	0.13	0.73/0.25	0.90/0.42	1.10/0.33	0.038
*D-10yr	12705.60	4.22	-5.05	0.55	4.08	-3.09	-0.95	0.34	66703	22	949	0.10	0.07	0.10	0.62/0.24	0.73/0.45	1.03/0.31	0.032
&B-15yr	13081.80	4.17	-7.22	0.53	4.86	-5.28	-1.64	0.25	71297	16	1000	0.17	0.10	0.13	0.72/0.25	0.90/0.42	1.10/0.33	0.043
&C-15yr	13072.10	3.99	-7.34	0.45	4.72	-5.49	-1.60	0.27	77696	15	1000	0.20	0.10	0.12	0.69/0.25	0.87/0.42	1.07/0.33	0.042
*D-15yr	12703.80	3.92	-5.11	0.47	3.77	-3.27	-1.03	0.33	79322	21	788	0.10	0.07	0.10	0.62/0.24	0.73/0.45	1.03/0.31	0.032
&B-20yr	13116.40	4.03	-7.05	0.51	4.85	-5.30	-1.54	0.26	69316	17	1000	0.15	0.10	0.12	0.71/0.25	0.88/0.43	1.09/0.33	0.045
&C-20yr	13057.90	3.80	-7.09	0.41	4.65	-5.56	-1.43	0.27	76382	16	1000	0.19	0.11	0.12	0.66/0.25	0.83/0.43	1.04/0.33	0.046
*D-20yr	12700.8	3.42	-5.18	0.37	3.2	-3.38	-1.16	0.32	104995	21	590	0.1	0.07	0.09	0.61/0.24	0.72/0.45	1.01/0.31	0.029
B-Est	12948.30	3.34	-5.22	0.48	4.36	-4.77	-0.58	0.34	59857	24	1000	0.16	0.12	0.12	0.59/0.25	0.74/0.44	1.00/0.31	0.056
&C-Est	13010.20	3.22	-5.38	0.44	4.34	-4.96	-0.69	0.37	63984	23	1000	0.16	0.12	0.12	0.58/0.25	0.73/0.44	0.98/0.31	0.056
*D-Est	12694.30	2.46	-5.07	0.16	2.03	-3.52	-1.30	0.31	172743	21	345	0.10	0.07	0.06	0.60/0.24	0.70/0.45	1.00/0.30	0.022

* The Hessian matrix was not positive definite
& Could not have converged.

(Table 6 Continued)

(c) Stock E (length-specific vulnerability)

Case	-LnL	b_{rec}			N_{tot}			$N_{End-5,1}$/ $N_{1968,1}$	K_{1930}	K_{2000}/ K_{1960} (%)	K_{1960}/ K_{1930} (%)	Natural mortality (ages)			JARPA q / Mean proportion		MSYR
		1945-68	1968-88	1988-End	1945-68	1968-88	1988-End					0-3	10-30	35+	V-E	VI-W	
A	3292.36	3.36	-5.26	0.91	3.09	-1.05	-2.20	0.54	84490	12	1000	0.07	0.08	0.17	0.82/0.84	0.90/0.16	0.020
B-28ft	3289.60	3.33	-5.75	0.84	3.13	-1.64	-2.10	0.52	90172	11	1000	0.13	0.08	0.17	0.82/0.84	0.89/0.16	0.020
C-28ft	3289.58	3.33	-5.75	0.84	3.13	-1.64	-2.10	0.52	90165	11	1000	0.13	0.08	0.17	0.82/0.84	0.89/0.16	0.020
D-28ft	3254.19	3.52	-5.24	1.27	3.44	-0.92	-2.00	0.59	72266	15	1000	0.03	0.07	0.18	0.80/0.84	0.88/0.16	0.024
B-30ft	3281.81	3.32	-6.43	0.49	3.27	-2.76	-1.89	0.49	98751	10	1000	0.22	0.08	0.17	0.83/0.83	0.87/0.17	0.022
C-30ft	3281.81	3.32	-6.43	0.49	3.27	-2.76	-1.89	0.49	98751	10	1000	0.22	0.08	0.17	0.83/0.83	0.87/0.17	0.022
D-30ft	3252.92	3.53	-5.22	1.23	3.46	-0.97	-1.97	0.60	71908	15	1000	0.03	0.07	0.18	0.80/0.84	0.87/0.16	0.024
B-32ft	3272.11	3.34	-7.12	-0.09	3.45	-4.27	-1.68	0.44	109318	9	1000	0.35	0.09	0.17	0.83/0.83	0.84/0.17	0.025
C-32ft	3272.11	3.34	-7.12	-0.09	3.45	-4.27	-1.68	0.44	109318	9	1000	0.35	0.09	0.17	0.83/0.83	0.84/0.17	0.025
D-32ft	3252.67	3.46	-5.63	0.95	3.49	-1.68	-1.86	0.57	77887	14	1000	0.11	0.07	0.17	0.81/0.84	0.87/0.16	0.024
B-Est	3257.82	3.39	-8.00	-0.88	3.62	-6.38	-1.57	0.38	123671	8	1000	0.53	0.10	0.16	0.84/0.83	0.83/0.17	0.032
C-Est	3257.82	3.39	-8.00	-0.88	3.62	-6.38	-1.57	0.38	123671	8	1000	0.53	0.10	0.16	0.84/0.83	0.83/0.17	0.032
D-Est	3250.90	3.39	-6.42	0.27	3.56	-3.31	-1.64	0.50	91188	11	1000	0.27	0.08	0.17	0.82/0.83	0.84/0.17	0.026

(Table 6 Continued)

(d) Stock E (age-specific vulnerability)

Case	-LnL	b_{rec}			N_{tot}			$N_{End-5,1}$/ $N_{1968,1}$	K_{1930}	K_{2000}/ K_{1960} (%)	K_{1960}/ K_{1930} (%)	Natural mortality (ages)			JARPA q / Mean proportion		MSYR
		1945-68	1968-88	1988-End	1945-68	1968-88	1988-End					0-3	10-30	35+	V-E	VI-W	
A	3331.73	3.54	-5.30	1.06	3.32	-1.07	-2.14	0.55	77756	14	1000	0.05	0.08	0.17	0.81/0.84	0.89/0.16	0.022
B-10yr	3317.41	3.37	-6.43	0.10	3.43	-3.88	-1.53	0.48	102793	10	1000	0.37	0.08	0.17	0.82/0.83	0.82/0.17	0.025
C-10yr	3316.51	3.36	-6.18	0.18	3.41	-3.54	-1.53	0.49	98867	10	1000	0.35	0.08	0.17	0.82/0.83	0.82/0.17	0.024
D-10yr	3238.08	-1.29	-4.91	0.91	-0.25	-1.55	-1.69	0.57	275710	16	1	0.17	0.01	0.04	0.77/0.84	0.83/0.16	0.000
B-15yr	3286.42	3.42	-6.96	-0.80	3.72	-6.26	-1.14	0.43	101237	12	1000	0.66	0.10	0.15	0.82/0.82	0.80/0.18	0.045
C-15yr	3286.06	3.43	-6.81	-0.77	3.72	-6.09	-1.12	0.44	99261	12	1000	0.65	0.10	0.15	0.82/0.82	0.80/0.18	0.044
*D-15yr	3238.68	-1.69	-5.26	-0.18	-0.73	-3.40	-2.17	0.48	440508	15	0	0.31	0.05	0.07	0.82/0.83	0.88/0.17	0.000
B-20yr	3294.95	3.53	-5.41	0.06	4.08	-3.84	-1.12	0.54	70312	18	1000	0.34	0.10	0.15	0.79/0.83	0.79/0.17	0.042
C-20yr	3287.42	3.48	-5.39	-0.16	3.99	-4.21	-1.04	0.54	72850	18	1000	0.41	0.10	0.15	0.79/0.83	0.78/0.17	0.044
*D-20yr	3250.74	0.95	-4.62	0.36	1.00	-2.02	-1.78	0.61	205775	14	271	0.14	0.07	0.11	0.80/0.83	0.85/0.17	0.011
B-Est	3285.11	3.43	-6.68	-0.69	3.75	-5.91	-1.10	0.44	95790	13	1000	0.63	0.10	0.15	0.82/0.82	0.80/0.18	0.045
C-Est	3284.16	3.43	-6.59	-0.68	3.74	-5.83	-1.09	0.45	95203	13	1000	0.63	0.10	0.15	0.82/0.82	0.79/0.18	0.044
*D-Est	3236.16	-1.58	-5.39	-0.33	-0.90	-3.85	-1.80	0.48	478755	13	0	0.47	0.05	0.07	0.82/0.83	0.83/0.17	0.000

* The Hessian matrix was not positive definite

Table 7

Results of the alternative models based on varying the density-dependence function. The vulnerability assumption for these analyses is “D-Est” and vulnerability is a function of length. MSYR was not calculated for the model in which density-dependence impacts the rate of natural mortality for all ages.

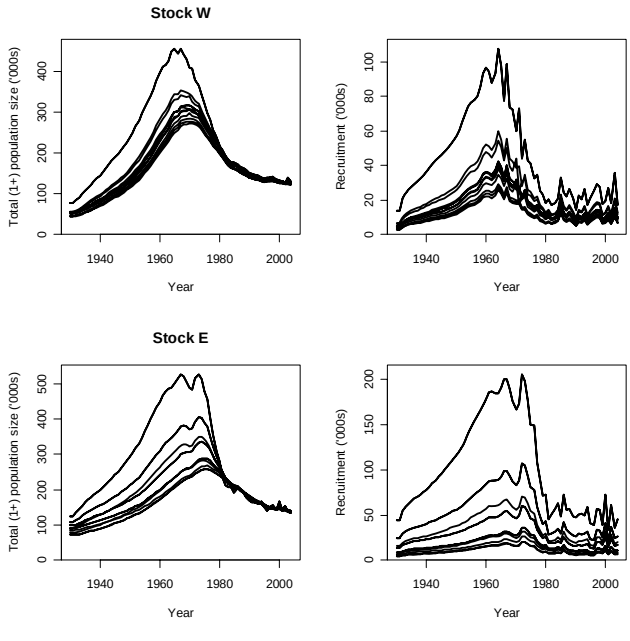
(a) Stock W

Density-dependence	-LnL	b_{rec}			N_{tot}			$N_{End-5,1}/N_{1968,1}$	K_{1930}	K_{2000}/K_{1960} (%)	K_{1960}/K_{1930} (%)	Natural mortality (ages)			JARPA q / Mean proportion			MSYR
		1945-68	1968-88	1988-End	1945-68	1968-88	1988-End					0-3	10-30	35+	III-E	IV	V-W	
Base	12609.70	3.84	-5.26	0.80	4.80	-4.31	-0.92	0.33	50768	26	948	0.13	0.07	0.16	0.73/0.24	0.87/0.44	1.13/0.32	0.054
M	12648.20	4.66	-6.70	-0.90	4.19	-7.38	-2.01	0.19	153067	5	1000	0.21	0.07	0.18	0.94/0.25	1.39/0.36	1.24/0.39	N/A

(b) Stock E

Density-dependence	-LnL	b_{rec}			N_{tot}			$N_{End-5,1}/N_{1968,1}$	K_{1930}	K_{2000}/K_{1960} (%)	K_{1960}/K_{1930} (%)	Natural mortality (ages)			JARPA q / Mean proportion		MSYR
		1945-68	1968-88	1988-End	1945-68	1968-88	1988-End					0-3	10-30	35+	V-E	VI-W	
Base	3250.90	3.39	-6.42	0.27	3.56	-3.31	-1.64	0.50	91188	11	1000	0.27	0.08	0.17	0.82/0.83	0.84/0.17	0.026
M	3274.69	1.50	-4.31	-2.08	1.13	-4.19	-2.89	0.45	311097	1	1000	0.31	0.08	0.18	0.96/0.83	0.99/0.17	N/A

(a) Length-based vulnerability



(b) Age-based vulnerability

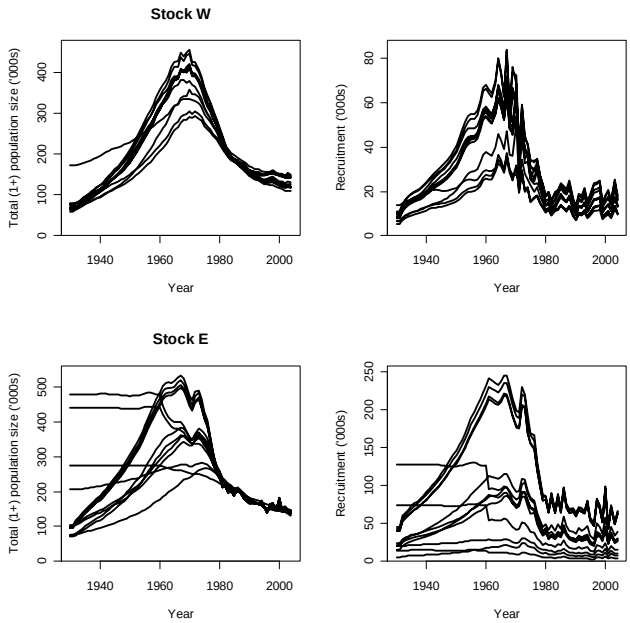


Figure 1: Time-trajectories of total (1+) population size and recruitment for the analyses reported on in Table 6. Results are shown for stocks W and E and for analyses in which vulnerability is assumed to be length- and age-based.

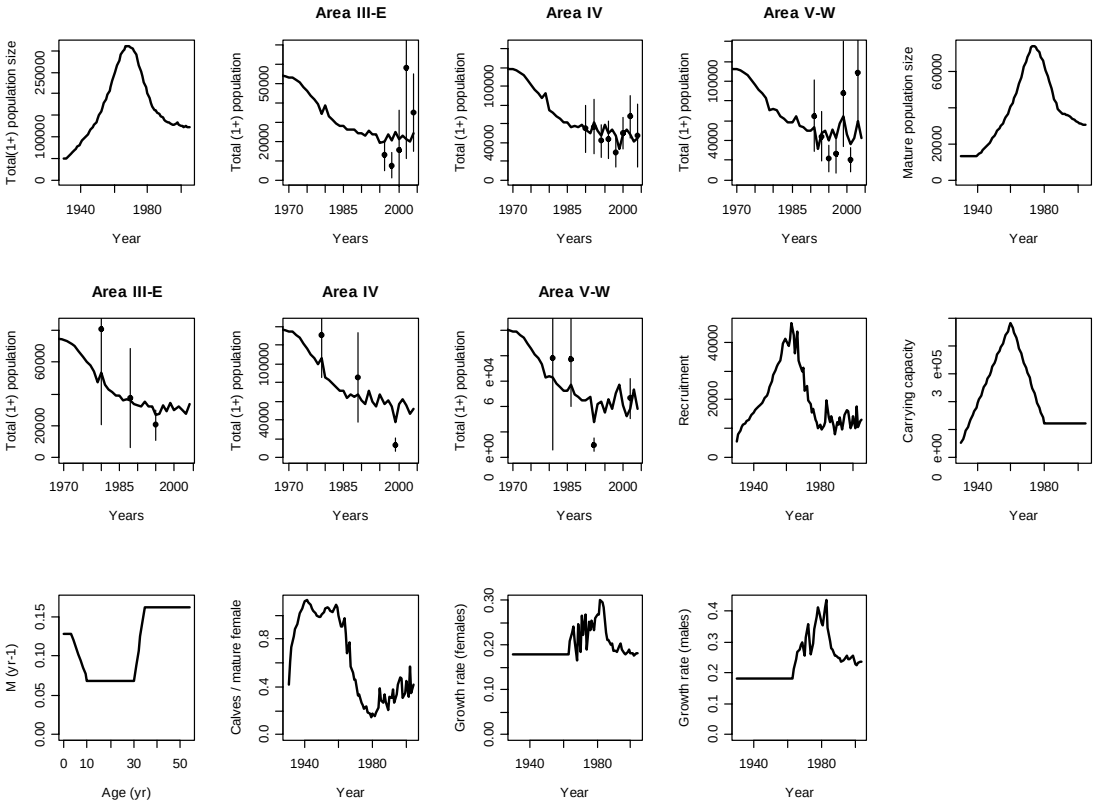


Figure 2 : Detailed output statistics for model D-Est for Stock W.

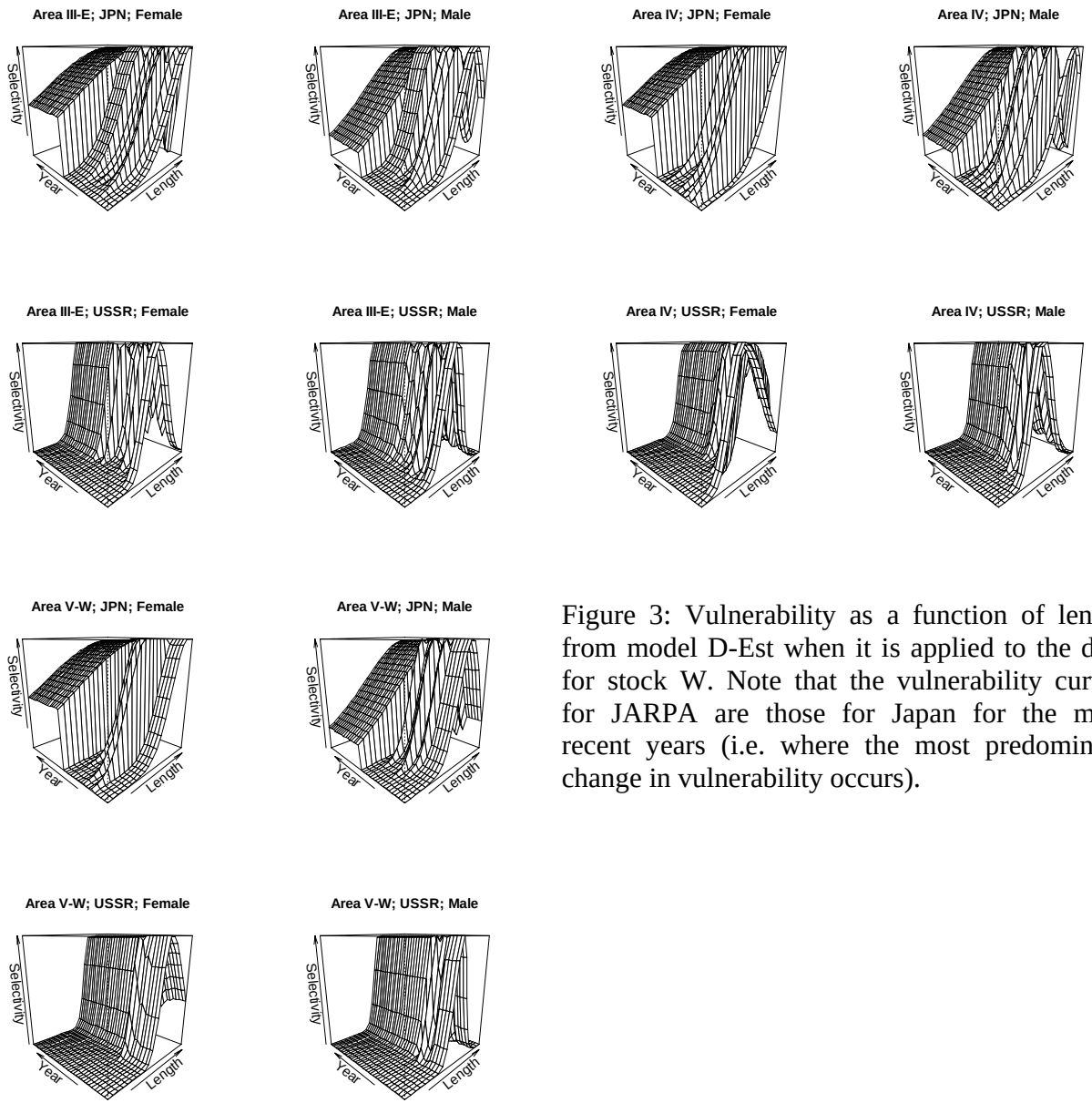


Figure 3: Vulnerability as a function of length from model D-Est when it is applied to the data for stock W. Note that the vulnerability curves for JARPA are those for Japan for the most recent years (i.e. where the most predominant change in vulnerability occurs).

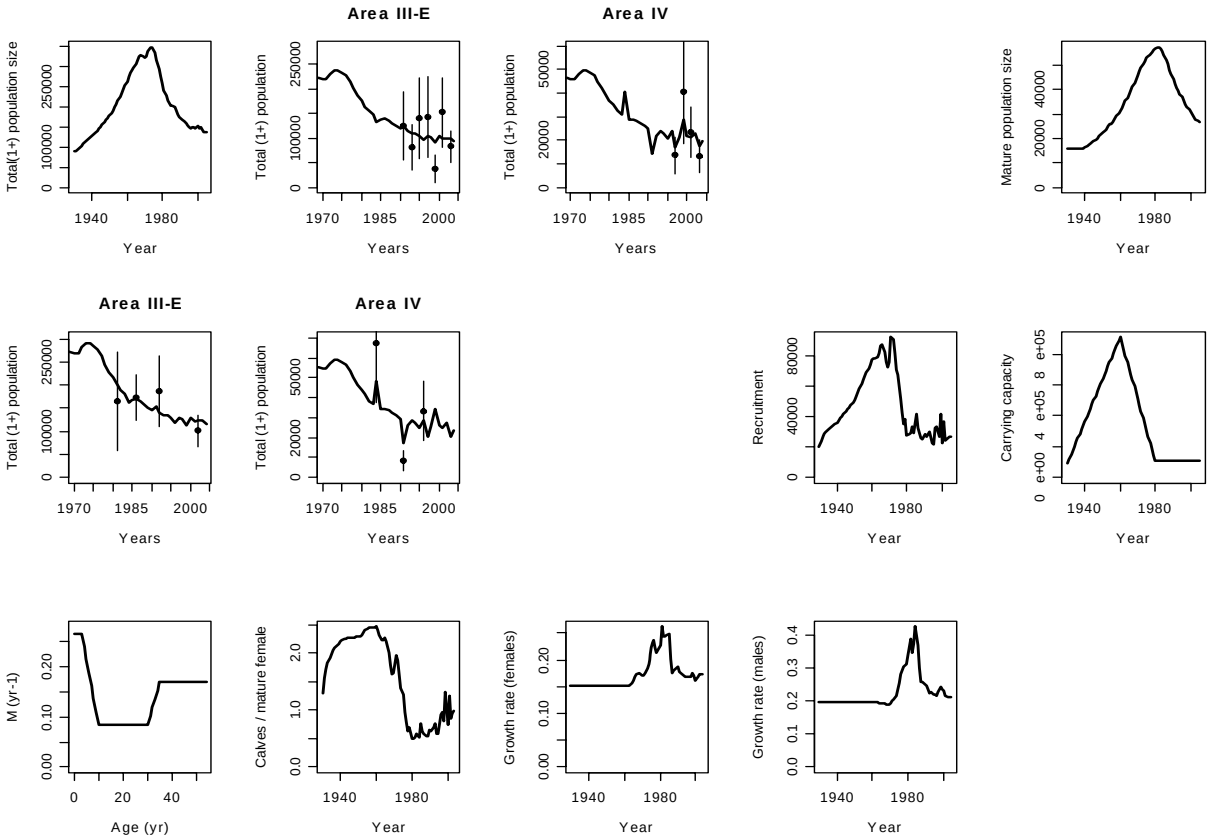


Figure 4 : Detailed output statistics for model D-Est for Stock E.

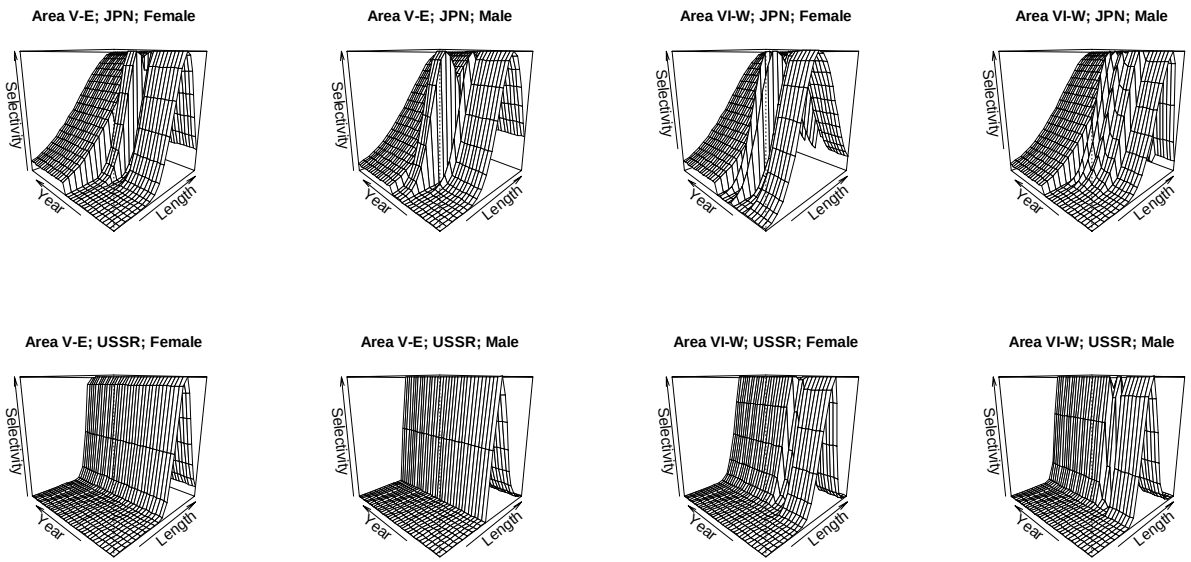


Figure 5 : Vulnerability as a function of length from model D-Est when it is applied to the data for stock E.
Note that the vulnerability curves for JARPA are those for Japan for the most recent years.

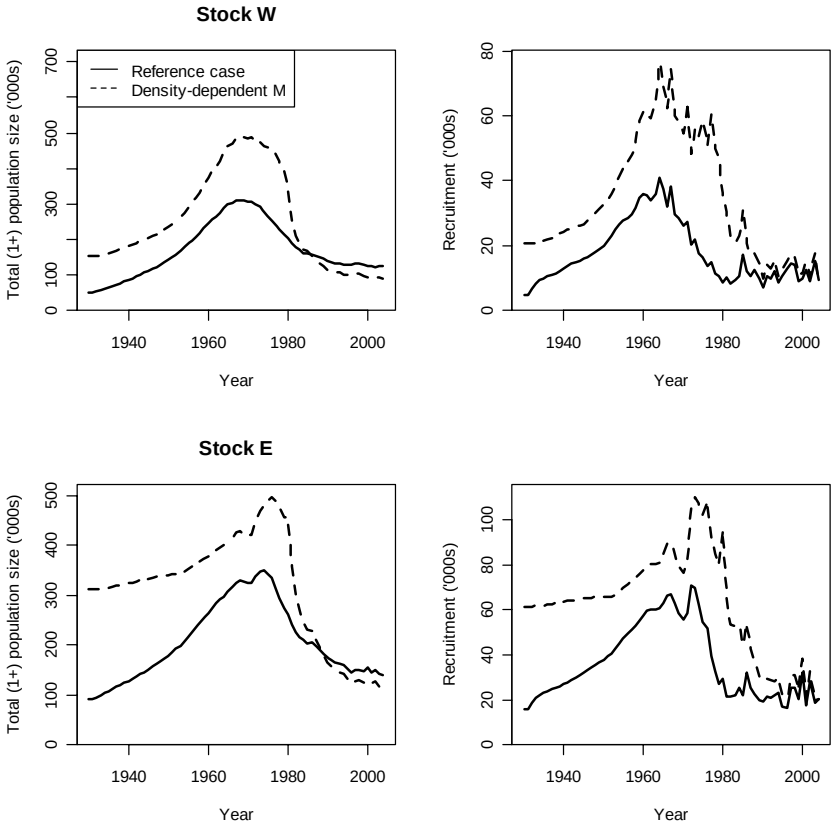


Figure 6 : Time-trajectories of total (1+) population size and recruitment. Results are shown for the reference case analyses and analyses in which the rate of natural mortality for all ages is assumed to be density-dependent.

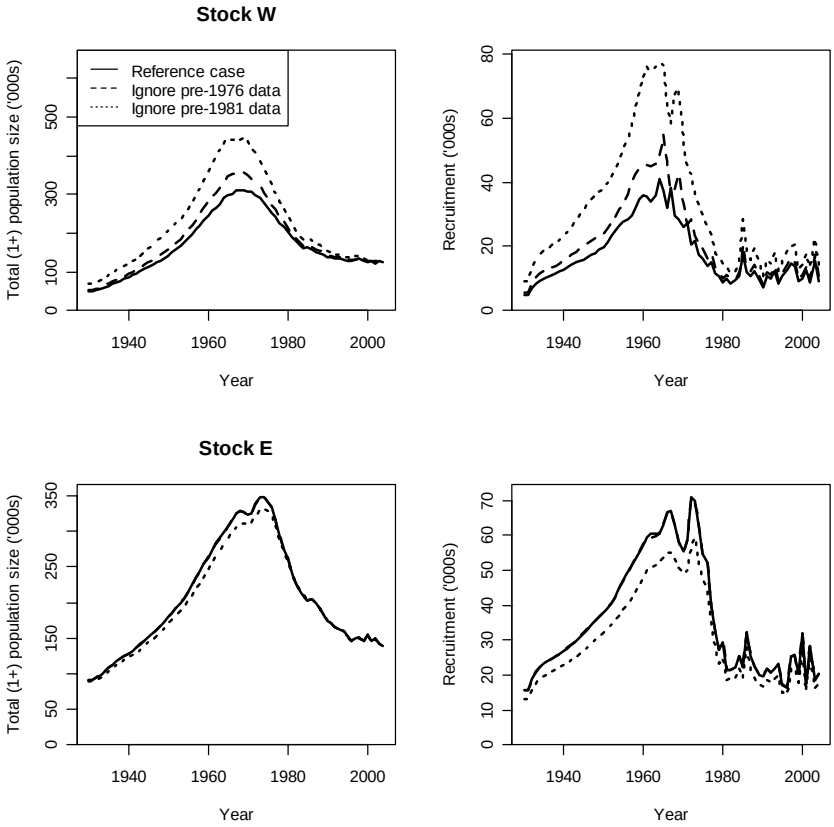


Figure 7: Time-trajectories of total (1+) population size and recruitment. Results are shown for the reference case analyses and analyses in which age-length keys are available from 1976 and 1981 respectively.