APPLICATION OF ADAPT-VPA TO ANTARCTIC MINKE WHALES IN THE JARPA RESEARCH AREA

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ABSTRACT

The ADAPT-VPA assessment methodology originally developed by Butterworth *et al*. (1999) has been greatly improved by taking into account various comments made during a series of IWC-SC meetings and is applied here to abundance estimates (from both IDCR/SOWER and JARPA surveys) as well as catch at age data (both commercial and scientific) for the I and P-stocks of Antarctic minke whales. The improvements to the methodology allow account to be taken of various further aspects, primarily: 1) inter-annual differences in the distribution of the population between different management Areas, 2) a stock-recruitment relationship, and 3) the effects of possible ageing-error. Furthermore sensitivities to various functional forms for selectivity and natural mortality with age are explored. The general pattern shown by the results for both stocks is of a minke whale abundance trend that increased over the middle decades of the 20th Century to peak at about 1970, and then stabilized or declined somewhat for the next three decades. The recruitment trend is similar, though with its peak slightly earlier. The annual natural mortality rate, *M*, is estimated to be 0.056 with a CV of 0.16 for the I-stock, and 0.069 with a CV of 0.15 for the P-stock for the "Reference case" assessments. When only the JARPA abundance estimates are used for tuning, *M* is estimated as 0.038 and 0.060 for the I- and P-stocks, respectively. The estimation of *M* is fairly robust to the various assumptions of the model. The CVs of these *M* estimates for the "Reference case" assessments, when compared with those of typically 0.35 for the Area-specific assessments of Butterworth *et al*. (1999) which were based on fewer data, indicate an improvement in the precision of these estimates due to the accumulation of data over the long-term of the JARPA surveys. The fits of the stock-recruitment model generally require a carrying capacity for minke whales that first increased and then stabilized or declined somewhat during the last century, and suggest *MSYR(1+)* values in the 4-6% range. The improved precision in the estimation of *M* may contribute in the improvement of management and assessment of this species on a stock-specific basis, since it can reduce the uncertainty concerning the value of *M* and can provide an improved prior distribution for *MSYR*. The latter in particular, in the context of providing a measure of the productivity of which the species is capable, is essential information for effective RMP implementation through reduction of the range of plausible scenarios which need to be considered in *Implementation Simulation Trials.*

KEYWORD ADAPT-VPA, CATCH-AT-AGE, NATURAL MORTALITY, ANTARCTIC MINKE WHALE

INTRODUCTION

This study is a continuation of the series of studies since Butterworth *et al*. (1999) (Butterworth *et al*. 2002, Mori and Butterworth 2005, Mori *et al*. 2006a) and has modified the most recent analyses (Mori *et al*. 2006a) in response to suggestions made during the 58th International whaling Commission (IWC)' Scientific Committee (SC) (IWC 2006). The major areas of refinement are:

1) Inclusion of the estimation of the stock-recruitment relationship within the ADAPT-VPA model;
2) Consideration of the effects of ageing-error;
3) Consideration of various functional forms for selectivity and natural mortality in relation to age;
4) Inclusion of the catch-at-age data obtained from the most recent (2004/05) JARPA survey; and
5) Use of the most recent abundance estimates of minke whales from the JARPA surveys as calculated by Hakamada *et al*. (2006).

For the application of ADAPT-VPA information on abundance as well as catches-at-age is necessary, and there are two series of abundance estimates available: one is obtained from the IDCR-SOWER surveys and the other from the JARPA surveys. Mori *et al*. (2006a) showed that some of the results obtained from the ADAPT-VPA method are quite sensitive to the abundance estimates input to the model. However, the abundance estimates to be used in any final application of this model remain under discussion in the IWC-SC. Thus, the results obtained from this study using currently available abundance estimates from these sets of surveys should be regarded as preliminary, with the main focus rather on development of the estimation method itself and how sensitive the results are to changes in assumptions concerning features such as the selectivity and natural mortality functions and ageing errors. A further focus is the extent to which the accumulation of catch-at-age data by the JARPA surveys has contributed towards improving the precision of various quantities (e.g. natural mortality and the past trend in recruitment).

The analyses are conducted for the two possible stocks identified by Pastene *et al.* (2005), which are the I-stock (distributed from Area IIIE to Area VW) and P-stock (distributed from Area VE to Area VIW). IWC (2006) also suggested restricting further catch-at-age analyses to these two possible stocks. This followed consideration of results in Mori *et al.* (2006a) and Punt and Polacheck (2006), which investigated alternative stock structure hypotheses and concluded that results were relatively insensitive to such scenario modifications.

DATA

Table 1 lists the catch-at-age matrices constructed from Russian and Japanese catches for Areas IIIE to VIW. These reflect commercial catches from 1971[1] to 1986, and scientific research catches by Japan from 1987 to 2004. The commercial and scientific catch-related information has been developed as described in Butterworth *et al.* (1999), using ageing information kindly provided by R. Zenitani. For the lengths for which there are no age data that year, the 'nearest' length-class is used; in cases where the upper and lower lengths for which there are data are equidistant, the age distributions for those two lengths are averaged.

Table 2 list the abundance estimates by sighting survey for Areas IIIE to VIW that are used in the analyses, together with the associated survey sampling CVs. The estimates from the IDCR/SOWER surveys were kindly provided by T. A. Branch; Appendix 1 gives some details of their development. The estimates from the JARPA surveys listed in Table 2 were kindly provided by T. Hakamada. Hakamada *et al.* (2006) produced three series of abundance estimates for Antarctic minke whales: 1) using Haw's method, 2) using GLM, and 3) using GLM with a bootstrap method. Because the abundance estimation method using Haw's method is most comparable methodologically to that used to obtain the IDCR/SOWER abundance estimates used in these analyses, the abundance estimate series using method 1) are shown in Table 2 and are used as "Reference case" abundance estimates. Sensitivity tests of the results are also conducted using the other two abundance estimate series (i.e. from the GLM and the GLM with a bootstrap method).

METHODOLOGY

The basic methodology used is same as in Mori *et al.* (2006a), except that some modifications have been introduced to take account of the stock-recruitment relationship, and also to be able to take account of ageing error.

Population model

The basic population dynamics are taken to be governed by the equations:

$$N_{y+1,a+1} = \left(N_{y,a} - C_{y,a}\right)\cdot e^{-M_a} \qquad 1 \le a \le m-1 \tag{1}$$

$$F_{y,a} = C_{y,a} \big/ N_{y,a} \tag{2}$$

$$C_{y,a} = C^R_{y,a} + C^J_{y,a} \quad \text{(thus } F^R_{y,a} = C^R_{y,a} \big/ N_{y,a} \text{ and } F^J_{y,a} = C^J_{y,a} \big/ N_{y,a}\text{)} \tag{3}$$

where

$N_{y,a}$ is the number of minke whales (here of both sexes combined) of age *a* present at the start of year *y*;

$C_{y,a}$ is the number of such whales taken during year *y*, where $C^R_{y,a}$ is the number taken by the Russian vessels[2] and $C^J_{y,a}$ is the number taken by the Japanese vessels;

M_a is the (possibly age-dependent) rate of natural mortality;

$F_{y,a}$ is the proportion of the whales of age *a* present at the start of year *y* that are taken (the "fishing proportion"); and

m is the oldest age considered in the full likelihood of the model.

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[1] In this paper, the convention is that 1971 refers to the 1971/72 austral summer season.

[2] These operated only during the commercial period.

Consistent with previous analyses (Butterworth *et al*. 1999, 2002; Mori and Butterworth 2005; Mori *et al*. 2006a), most of the analyses of this paper take m=30. However, results are also shown for the alternative choice for m of 45. When m=45, the methodology still continues to treat the $N_{y,a}$ with a=30 (rather than a=45) as the estimable parameters, and then to project both backward and forward along the cohort, but now taking contributions from catch-at-age data for a=31 to 45 to the full likelihood into account; this is to avoid problems associated with very small or zero $C_{y,m}$ values. For analysis purposes, the natural mortality rate M_a is presumed infinite at age 45 and above, so that animals captured above this age are ignored. For choices of m < 45, results are projected forward from age m to age 45 using equation (1) and known catches, so that all the analyses take account of minke whales up to age 45 irrespective of the choice made for m.

A key aspect of the parameterization of the ADAPT-VPA model applied is the assumption that the fishing proportion F for both Japanese commercial and scientific takes is separable (in expectation). Different selectivity patterns are assumed for the years of commercial and scientific catches:

$$F_{y,a}^{E,J} = \begin{cases} S_a^{c,J} F_y^{E,J} & y \le 1986 \\ S_a^s F_y^{E,J} & y \ge 1987 \end{cases} \tag{4}$$

where

$S_a^{c,J}$ is the selectivity-at-age for the period of commercial catches by Japanese vessels ($S_m^{c,J}$ =1);

S_a^s is the selectivity-at-age for the period of scientific catches (S_m^s =1);

$F_y^{E,J}$ is the Japanese fishing proportion (in expectation) for year y on age m (i.e. the fully selected fishing proportion in cases where $S_a^{c,J/s} \le 1$ for all a); and

$F_{y,a}^{E,J}$ is the expected Japanese fishing proportion on animals of age a for year y; this differs from the actual proportion $F_{y,a}^J$ because actual catches $C_{y,a}^J$ differ from their expectations ($C_{y,a}^{E,J} = F_{y,a}^{E,J} N_{y,a}$) as a result of sampling variability (at least).

Note that the Russian commercial catches $C_{y,a}^R$ enter the computations only through equation (1); these are calculated by application of Japanese age-length keys to length distribution data for the Russian commercial catches.

The parameters of primary interest in the model (thus far) are:

- The natural mortality M_a (usually taken to be age-independent).
- The oldest-age (as considered in the model-fitting process) numbers-at-age $N_{y,m}$ (though the $N_{y,30}$ are the parameters estimated – see above).
- The most-recent-year numbers-at-age $N_{n,a}$, where n is the last year for which data are available.

Given these values, the complete numbers-at-age matrix ($N_{y,a}$) for the population can then be computed by use of equation (1).

Stock-recruitment model

A stock-recruitment model of the Pella-Tomlinson form as described in Mori *et al*. (2006a), though with some minor modification, is introduced in the ADAPT-VPA framework to investigate the extent of changes in carrying capacity[3] and to estimate the *MSYR* for the stocks considered.

The “adult” (reproductive) population is taken to be:

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[3] Here carrying capacity is expressed in terms of the number of adult female minke whales.

$$N_y^A = \sum_{a=7}^{45} N_{y,a} \tag{5}$$

and the number of adult females $N_y^f = 0.5 \cdot N_y^A$, i.e. an age at first parturition of 7 is assumed (Bando *et al.* 2006)[4].

Recruitment is assumed to follow a Pella-Tomlinson form:

$$N_{y+1,1} = \lambda \cdot N_y^f \left[1 + A \left\{ 1 - \left(\frac{N_y^f}{K_y^f} \right)^z \right\} \right] \tag{6}$$

where

$N_{y,1}$ is the recruitment (1-year-olds) in year y,

λ is the combined pregnancy and first year survival rate when the population is at carrying capacity,

N_y^f is the number of adult (past the age of first parturition) females, taken to be given by $0.5\sum_{a=7}^{45} N_{y,a} = 0.5N_y^A$ (i.e. equal numbers of males and females are assumed),

A is the resilience parameter (related to *MSYR*),

K_y^f is the carrying capacity for adult females, which may change over time, and

z is the degree of compensation parameter, which is set here at 2.39, as conventional in the Scientific Committee.

When $N^f = K^f$, the recruitment must equal the number of 1+ whales that die annually due to the natural mortality, i.e:

$$\lambda \cdot K_y^f = K^{1+} \left[\left(1 - e^{-M}\right) + \frac{e^{-46M}}{\sum_{a=1}^{45} e^{-aM}} \right] \qquad \text{(when } M \text{ is constant)} \tag{7}$$

$$\lambda \cdot K_y^f = K^{1+} \left[\frac{e^{-M_1}}{\sum_{a=1}^{45} T_a} \right] \qquad \text{(when } M \text{ is age dependent)}$$

$$\text{where } T_a = \exp\left(-\sum_{a'=1}^{a} M_{a'} \right)$$

Further, expressions for unexploited equilibrium numbers at age values yield:

$$\frac{K^{1+}}{K^f} = \frac{\sum_{a=1}^{45} e^{-M \cdot a}}{0.5 \cdot \sum_{a=7}^{45} e^{-M \cdot a}} = \mu \qquad \text{(when } M \text{ is constant)} \tag{8}$$

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[4] Future refinements of this approach could take into account indications of changes in the age at first parturition over time (Mori *et al.* 2006b, Zenitani and Kato 2006)

$$\frac{K^{1+}}{K^{f}} = \frac{\sum_{a=1}^{45} T_a}{0.5 \cdot \sum_{a=7}^{45} T_a} = \mu \qquad \text{(when } M \text{ is age dependent)}$$

where μ can be computed given the value of M (or of the M_a). Thus equation (6) can be rewritten:

$$N_{y+1,1} = \mu \cdot \left[\left(1 - e^{-M}\right) + \frac{e^{-46M}}{\sum_{a=1}^{45} e^{-aM}} \right] \cdot N_y^f \left[1 + A \left\{ 1 - \left(\frac{N_y^f}{K_y^f} \right)^{2.39} \right\} \right] \qquad \text{(when } M \text{ is constant)} \tag{9}$$

$$N_{y+1,1} = \mu \cdot \left[\frac{e^{-M_1}}{\sum_{a=1}^{45} T_a} \right] \cdot N_y^f \left[1 + A \left\{ 1 - \left(\frac{N_y^f}{K_y^f} \right)^{2.39} \right\} \right] \qquad \text{(when } M \text{ is age dependent).}$$

The unknown parameters of this model are A and the parameters describing K and its temporal variation. These are estimated by minimizing the negative likelihood function shown in equation (23) below. It is assumed here that the stock was in unexploited equilibrium in the year 1930.

The following functional form adopted for K_y^f is as in Mori *et al.* (2006a):

$$\tilde{K}_y^f = \begin{cases} K_1^f & y \le y_1 \\ K_1^f + \dfrac{\left(K_2^f - K_1^f\right)}{\left(y_2 - y_1\right)^{\gamma}} \left(y - y_1\right)^{\gamma} & y_1 + 1 \le y \le y_2 \\ K_2^f + \dfrac{\left(K_3^f - K_2^f\right)}{\left(y_3 - y_2\right)} \left(y - y_2\right) & y_2 + 1 \le y \le y_3 \\ K_3^f & y_3 + 1 \le y \end{cases} \tag{10}$$

with the following choices made for the "change" years: $y_1 = 1930$, $y_2 = 1960$ and $y_3 = 2000$. These years were used since similar previous analyses had indicated them to give better fits in terms of maximum likelihood values. K_y^f is set to be

$$K_y^f \rightarrow \tilde{K}_y^f \cdot e^{\varepsilon_y} \tag{11}$$

where the ε_y are estimable parameters which are constrained to change somewhat smoothly over time under the assumption:

$$\varepsilon_y = \varepsilon_{y-1} + \eta_y \text{, where } \eta_y \sim N\left(0, \sigma^2\right) \tag{12}$$

which was implemented by adding a term to the negative log likelihood function as shown in equation (25). This describes an auto-correlated model error as time proceeds. It is assumed here that $\varepsilon_{1930} = 0$.

The primary estimable parameters from the stock-recruitment model are effectively:

- The resilience parameter A,
- K_1^f, K_2^f, K_3^f, γ and
- $N_{y,1}$ where y=1931 to 1941, the remaining recruitments being determined by the $N_{y,m}$ oldest-age numbers-at-age parameters following back-projection using equation (1).

Note that the value of $N_{1930,1}$ follows from the assumption of deterministic unexploited equilibrium that year.

The Likelihood function

For single Area assessments, the likelihood function has four components related to the IDCR/SOWER estimates of abundance, the JARPA estimates of abundance, the catch-at-age data and the stock-recruitment relationship. The contribution of the first of these to the negative of the log likelihood (ignoring constants) is given by:

$$-\ln L_1 = \sum_y \frac{1}{2\sigma_y^2}\left(\ln N_y^{obs} - \ln \hat{N}_y\right)^2 \qquad (13)$$

where

N_y^{obs} is the abundance estimate for year y;

σ_y is the known standard error for the logarithm of N_y^{obs}, which is approximated by $\sqrt{{CV_y}^2 + {CV_{add}}^2}$;

CV_y is the known survey sampling CV estimated for N_y^{obs} ;

CV_{add} is an additional CV to reflect the fact that survey sampling error is not the only factor contributing to the difference between N_y^{obs} and $\hat{N}_y$ (though here we set CV_{add} =0 – see subsequent discussion in the "Specifications" section) ; and

$\hat{N}_y$ is the model estimate of 1+ abundance for year y[5], given by:

$$\hat{N}_y = \sum_{a=1}^{45} \hat{N}_{y,a} \qquad (14).$$

The contribution of the JARPA estimates of abundance is similar, except that these are treated as indices of relative abundance:

$$-\ln L_2 = \sum_y \frac{1}{2\sigma_y^2}\left(\ln N_y^{obs} - \ln\left(q\hat{N}_y\right)\right)^2 \qquad (15)$$

where

q is the multiplicative bias associated with abundance estimates from JARPA compared to those from IDCR/SOWER, and is given by its maximum likelihood estimate:

$$\ln \hat{q} = \left\{\sum_y \frac{\ln\left(N_y^{obs}/\hat{N}_y\right)}{\sigma_y^2}\right\} \Big/ \left\{\sum_y 1/\sigma_y^2\right\} \qquad (16).$$

The contributions of the commercial and the scientific catch-at-age data are given by:

$$-\ln L_3^{c,J} = -\lambda^{c,J} \sum_{y=1971}^{1986} \sum_{a=16}^{m} C_{y,a}^{J,*} \ln\left(\hat{\rho}_{y,a}^{J} / \rho_{y,a}\right) \qquad (17)$$

$$-\ln L_3^{s} = -\lambda^{s} \sum_{y=1987}^{lstyr} \sum_{a=1}^{m} C_{y,a}^{J,*} \ln\left(\hat{\rho}_{y,a} / \rho_{y,a}\right) \qquad (18)$$

where

$lstyr$ is the most recent year in the scientific survey series for which data are available;

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[5] In previous papers using this ADAPT-VPA methodology the model did not provide abundance estimates of the older of the age groups in this summation, so that some *ad hoc* adjustments were required as explained in Mori and Butterworth (2005). Given now the inclusion of a stock-recruitment relationship within the estimation methodology, the need for this adjustment falls away.

$C^{J,*}_{y,a}$ is the effective number of animals of age *a* caught by Japan during year *y*, computed as $C^{J}_{y,a} C^{J,*}_{y} \big/ C^{J}_{y}$;

C^{J}_{y} is the total Japanese catch in numbers during year *y*;

$C^{J,*}_{y}$ is the number of animals actually aged by Japan for year *y*, as also taken into account in the L_3 calculation for that year (i.e. with ages from 16 to *m* for the commercial, and from 1 to *m* for the scientific catches);

$\lambda^{c,J/s}$ is a factor to account for overdispersion in the Japanese commercial/scientific catch-at-age distribution (underdispersion is not admitted, so that the constraint $0 < \lambda \le 1$ is applied); and

$\hat{\rho}_{y,a}$ is the model-estimate of the expected proportion of the catch in year *y* that consists of animals of age *a*, which from equation (4) is given by:

$$\hat{\rho}_{y,a} = \begin{cases} N^{*}_{y,a} \Big/ \sum\limits_{a'=16}^{m} N^{*}_{y,a'} & y \le 1986 \\ N^{*}_{y,a} \Big/ \sum\limits_{a'=1}^{m} N^{*}_{y,a'} & y \ge 1987 \end{cases} \tag{19}$$

where, $N^{*}_{y,a}$ denotes the relative numbers of whales expected to be available for capture in relation to ages as observed with error and is defined by:

$$N^{*}_{y,a} = \sum_{a'=1}^{m} E_{a,a'} \cdot S_{a'} \cdot N_{y,a'} \tag{20}$$

where $E_{a,a'}$ is the ageing error matrix, for example as defined in equation (35). When ageing error is not considered, $E_{a,a'} = \delta_{a,a'}$.

A time-invariant commercial selectivity-at-age pattern ($S^{J,c}_{a}$) is assumed to apply only above age 15, on the basis of arguments by Sakuramoto and Tanaka (1985) that the pattern below this age varies appreciably from year to year. The overdispersion factors λ are estimated by iterative application of the formula:

$$\lambda^{c/s} = \sum_{y} 1 \Bigg/ \sum_{y} \left\{ \frac{C^{J,*}_{y} \sum\limits_{a} \left(\rho_{y,a} - \hat{\rho}_{y,a}\right)^2}{\sum\limits_{a} \hat{\rho}_{y,a}\left(1 - \hat{\rho}_{y,a}\right)} \right\} \tag{21}$$

where the years and ages in the summations are as adopted above for $L^{c,J}_{3}$ and L^{s}_{3}, and $\rho_{y,a}$ is the observed proportion of the catch during year *y* which consists of animals of age *a*:

$$\rho_{y,a} = \begin{cases} C^{J,*}_{y,a} \Big/ \sum\limits_{a'=16}^{m} C^{J,*}_{y,a'} & y \le 1986 \\ C^{*}_{y,a} \Big/ \sum\limits_{a'=1}^{m} C^{*}_{y,a'} & y \ge 1987 \end{cases} \tag{22}$$

The contribution of the stock-recruitment model to the likelihood is given by:

$$-\ln L_4 = \sum_{y=1931}^{lstyr} \frac{1}{2\sigma^2_{R,y}} \cdot \left(\ln\left(N^{VPA}_{y,1}\right) - \ln\left(N^{\text{S-R}}_{y,1}\right)\right)^2 \tag{23}$$

where

$N^{VPA}_{y,1}$ is the recruitment for year *y* estimated from the ADAPT-VPA assessment,

$N^{S-R}_{y,1}$ is the recruitment for year *y* predicted by the model of equation (9), which is implemented under the assumption that $N^f_{1930} = K^f_{1930}$, and

$\sigma_{R,y}$ is a factor to downweight the contribution of the stock-recruitment relationship in year y to the likelihood function depending on how informative the catch-at-age data are to estimate $N^{VPA}_{y,1}$, which is defined by:

$$\sigma_{R,y} = \begin{cases} w & n_y \geq 15 \\ v + (w-v)\cdot\dfrac{n_y}{15} & n_y \leq 15 \end{cases} \tag{24}$$

where

n_y is the number of times the cohort concerned appears in the catch-at-age matrix and contributes to the catch-at-age log likelihood term. For example $n_{1942} = 1$, $n_{1943} = 2$, … etc. It is assumed here that w=0.3, and v=0.01, which leads to the standard deviation of the log recruitments about the stock-recruitment relationship as estimated by the ADAPT-VPA for well-represented cohorts (i.e. n_y>15) to be about the same magnitude as this choice for w implies.

Fish can show large variations about a stock-recruitment relationship as there is so much (potentially varying) mortality between eggs and juveniles, so that σ_R values of typically 0.4 up to even 1.0 occur. However for whales the number of calves is very tightly tied to the number of mature females - certainly in Antarctic minke whales where the direct observations of average pregnancy rate show this to be near constant from year to year. Thus, σ_R =0.2-0.3 should be an empirically realistic maximum value to assume here.

The purpose of allowing $\sigma_{R,y}$ to vary with year in this manner is on the one hand to give appropriate "Bayesian prior" weight to the stock-recruitment function for years where the catch-at-age data do provide good information on recruitment strength, but on the other to increase this weight for years for which there is little such information, and estimates need to be shrunk towards the mean provided by this relationship, in particular to counter-act the destabilising effect that the introduction of ageing-error can have on estimation.

In addition, the following contribution is added to the total negative log likelihood to secure smoothness over time in the estimated carrying capacity:

$$-\ln L_5 = \sum_{y=1930}^{lstyr} \left(\varepsilon_{y+1} - \varepsilon_y\right)^2 \Big/ 2\sigma^2 \tag{25}$$

Here σ is taken to be 0.01 as was assumed previously, since it was found to yield reasonably smooth results for carrying capacity while not compromising the flexibility the form assumed allowed.

Allowance for more than two areas assessed in combination

When two areas (e.g. Area IV and Area V) are assessed in combination, allowance needs to be made for the fact that the survey estimates now apply to only a portion of the minke whale abundance in the two areas combined. If the proportion in Area IV in year y is p^1_y, and hence the proportion in Area V that year is $p^2_y = \left(1 - p^1_y\right)$, then equation (13) is adjusted to read:

$$-\ln L_1 = \sum_{y(IV)} \frac{1}{2\sigma^2_y}\left[\ln N^{obs,IV}_y - \ln\left(p^1_y \hat{N}_y\right)\right]^2 + \sum_{y(V)} \frac{1}{2\sigma^2_y}\left[\ln N^{obs,V}_y - \ln\left\{\left(1 - p^1_y\right)\hat{N}_y\right\}\right]^2 \tag{26}$$

where the two summations are over years with IDCR/SOWER surveys in Area IV and in Area V respectively.

Equation (15) for the contribution from the JARPA survey abundance estimates is adjusted similarly. The p^i_y s become estimable parameters of the model, though note that in years with a survey in both Areas, the same p^i_y is taken to apply (as any difference arising from the JARPA and IDCR/SOWER surveys taking place at slightly different times during the season seems likely to be relatively small).

When three areas (e.g. Areas IIIE, IV and VW) are assessed in combination, equation (26) becomes:

$$-\ln L_1 = \sum_{y(IV)} \frac{1}{2\sigma_y^2}\left[\ln N_y^{obs,IV} - \ln\left(p_y^1 \hat{N}_y\right)\right]^2 + \sum_{y(IIIE)} \frac{1}{2\sigma_y^2}\left[\ln N_y^{obs,IIIE} - \ln\left(p_y^2 \hat{N}_y\right)\right]^2 + \sum_{y(VW)} \frac{1}{2\sigma_y^2}\left[\ln N_y^{obs,VW} - \ln\left\{\left(1 - p_y^1 - p_y^2\right)\hat{N}_y\right\}\right]^2 \qquad (27)$$

where the proportion in Area IV in year *y* is p_y^1, the proportion in Area IIIE that year is p_y^2, and the proportion in Area VW that year is $p_y^3 = \left(1 - p_y^1 - p_y^2\right)$. Equation (27) is extended naturally if four or more areas are assessed in combination.

Allowing the p_y^i s to be unconstrained (other than $0 \le p_y^i \le 1$) would lead to an over-parameterized model, in the sense that the p_y^i s could then adjust for the model to match each abundance estimate exactly (except in years with surveys in more than one area). On the other hand, setting $p_y^i = p^i$ (constant) is unrealistic as it does not allow for changes in the distribution of whales between the areas from year to year. Accordingly for the case of two areas assessed in combination, the p_y^i s have been assumed to follow a beta distribution with parameters u^1 and u^2:

$$\mathrm{p}_y = \left(p_y^1, p_y^2\right) \sim \mathrm{B}\left(u^1, u^2\right) \qquad (28)$$

with the estimation approach then used (within the MLE context applied) being the addition of the following further contribution to the negative of the log likelihood:

$$-\ln L_6 = Y \cdot \left\{\ln\Gamma\left(u^1\right) + \ln\Gamma\left(u^2\right) - \ln\Gamma\left(u^1 + u^2\right)\right\} + \sum_y \left[-\left(u^1 - 1\right)\ln p_y^1 - \left(u^2 - 1\right)\ln\left(1 - p_y^1\right)\right] \qquad (29)$$

where the summation extends over the years for which there is a survey in at least one of the two areas and *Y* is the total number of corresponding years.

When more than two areas are assessed in combination, the p_y^i s have been assumed to follow a Dirichlet distribution. For example, when three areas are assessed in combination:

$$\mathrm{p_y} \sim Dirichlet\left(u^1, u^2, u^3\right) \qquad (30)$$

with the addition of the following further contribution to the negative of the log likelihood:

$$-\ln L_6 = Y \cdot \left\{\ln\Gamma\left(u^1\right) + \ln\Gamma\left(u^2\right) + \ln\Gamma\left(u^3\right) - \ln\Gamma\left(u^1 + u^2 + u^3\right)\right\} + \sum_y \left[-\left(u^1 - 1\right)\ln p_y^1 - \left(u^2 - 1\right)\ln p_y^2 - \left(u^3 - 1\right)\ln\left(1 - p_y^1 - p_y^2\right)\right] \qquad (31)$$

Again this equation is extended naturally if four or more areas are assessed in combination.

In implementation, the parameters:

$$E\left[p^i\right] = \frac{u^i}{u^{tot}} \qquad (32)$$

$$\text{where } u^{tot} = \sum\nolimits_{i=1}^{n} u^i$$

which are the average proportions of the combined abundance to be found in each area *i* of a total of *n* areas considered are treated as estimable parameters of the model, except that the parameter u^1 is fixed externally, with different values being chosen to achieve different levels of inter-annual variability (in terms of CVs) of p^i:

$$CV\left(p^i\right) = \sqrt{\frac{u^{tot} - u^i}{u^i\left(u^{tot} + 1\right)}} \qquad (33).$$

Once u^1 is fixed externally, other parameters such as the u^i s and the p_y^i s are estimated from the model fit.

In summary, the estimable parameters in the model are as follows (see also Butterworth *et al.* (1999) for further details):

(i) the age-independent natural mortality, *M* (or age-dependent M_a);

(ii) numbers-at-age for all ages for the final year considered;

(iii) numbers-at-age for the maximum age considered in the likelihood for every year;

(iv) one selectivity-at-age (for ages 16-21) for the period of commercial catches;

(v) two selectivities-at-age (for ages 1 and 2-6) for the period of scientific catches;

(vi) u^i s, which define the beta (or Dirichlet) distributions (except that u^1 is input, being varied to meet a criterion that is specified in the next Section);

(vii) p_y^i s which are the proportions of the whales in area *i* in year *y*;

(viii) The resilience parameter *A* for the stock-recruitment relationship;

(ix) K_1^f , K_2^f , K_3^f , γ for the stock-recruitment relationship; and

(x) $N_{y,1}$ where *y*=1931 to 1941.

Ageing-error introduced in the model

One of the major tasks identified by the working group on population modelling at the 58th IWC-SC meeting is to develop an appropriate error model for the catch-at-age data to be used to take account of potential errors and biases in the ageing and length data and how these may have been changed over time (IWC 2006 – Appendix 4 of Annex G). This model is in the process of development within this working group and is not yet available. Thus, in this study we assume the ageing-error identified by Kato *et al*. (1991) and subsequently used in Butterworth *et al*. (1999).

Kato *et al*. (1991) examined the effect of differences in age-reader on age readings of earplugs obtained from Antarctic minke whales. They calculated the standard deviation (*s*) of the differences in age-reading between the two different readers by the following equation:

$$s^2 = \sum_{i=1}^{n} (X_i - Y_i)^2 / 2n \tag{34}$$

where X_i and Y_i denote the layer counts for the earplug *i* by readers *X* and *Y* respectively and *n* is the number of samples. The results of this study by Kato *et al*. (1991) are shown in Table 3.

Table 3 indicates that as the absolute age of minke whales increases, the value of *s* increases, which means that the differences in age-reading between the readers get larger with age. Thus, we assumed the following ageing-error model which assumes ageing-error to increase proportionally to the age of the animal:

$$a' = a \cdot (1+\varepsilon) \qquad \varepsilon \sim N(0; \sigma_e^2) \tag{35}$$

where *a'* is the observed age of an animal of actual age *a*, and σ_e reflects the extent of ageing-error. Here the assumption is made that σ_e =0.066, based on the result of Kato *et al*. (1991). The ageing-error matrix elements $E_{a,a'}$ (see equation 20) give the probabilities of animals with true age *a* being assigned to age *a'*; the matrix elements are evaluated by integration based on equation 35, with ages assigned larger than the maximum age (i.e. 54) all considered to be age 54 (in the actual catch-at-age data, ages are assigned up to age 54+).

A sensitivity test is run for a case when $C_{y,a}$ in equation (1) is substituted by $\hat{C}_{y,a}$ for ages considered in the contribution of the catch-at-age data to the likelihood function as shown in equation (17) and (18). This is to investigate the consequences of using data for catches-at-age that are in error in the basic dynamics equation.

Specifications of the scenarios considered

For reasons explained in the "Introduction" section, we conduct analyses only for the separate I-stock (Area IIIE+IV+VW) and P-stock (Area VE+VIW) scenarios, with no mixing across the boundary.

The parameter u^1 of the beta/Dirichlet distributions (see equations 28 and 30) was chosen so that the standard deviation of the standardised[6] residuals for the survey estimates of abundance was (about) 1. In other words, variability in the distribution of the population between the areas over which it ranges is assumed to account for all variance in excess of the survey sampling CV, so that CV_{add} (see following equation 13) is effectively set to zero.

Reference case and sensitivity tests

Given that attempts to estimate q (the relative bias of the JARPA compared to the IDCR abundance estimates) generally provide results less than 1 (typically close to q=0.7) for the most recent abundance estimates from JARPA (Hakamada *et al*. 2006), q is estimated for the "Reference case"[7] Assessments. Since earlier analyses have used all the available abundance estimates and catch-at-age data for most of their results, this paper continues that practice for this "Reference case". Runs are also conducted omitting some of these data, but in the interests of keeping to a manageable set of results, sensitivities are not run for every possible combination of such factors, but rather for convenience results are shown for modifications to the "Reference case" which generally alter only one factor at a time.

The sensitivity tests run for each stock involve some or all of the following:

1. Maximum age m considered in the likelihood is 45 rather than 30.
2. $\hat{C}_{y,a}$ is used instead of $C_{y,a}$ in equation (1) for ages considered in the catch-at-age data contribution to the likelihood.
3. Set q=1 (i.e. use JARPA abundance estimate as absolute abundance estimates rather than relative).
4. Use different series of abundance estimates for JARPA (detailed in the Data section above). A scenario that increases the abundance estimates from the IDCR/SOWER and JARPA by 50% is also considered to preliminarily investigate the implications of g(0)<1.
5. Either the JARPA or the IDCR/SOWER estimates of abundance are omitted.
6. For the commercial period, only data for the later half (i.e. collected only after 1979) are used since they seem to have lesser age/length measurement errors.
7. Retrospective analyses for the periods ending 1995, 1998, 2001.
8. Ageing error as given by equation (35) is introduced.
9. Various selectivity function scenarios:

   The selectivity functions for the "Reference case" are shown in Figure 1. Examples of other selectivity functions assumed for sensitivity tests are illustrated in Figure 2 and are similar to those considered in Butterworth *et al.* (1999). These include scenarios that consider different commercial selectivity slopes (left hand side plots in Figure 2) and the possibility of older animals hidden (from the surveys) in the pack ice for both commercial and scientific selectivity (two of the right hand side plots in Figure 2).
10. The relationship between natural mortality and age is taken to be piecewise linear as defined below (this function is kept of the same form as that used by Punt and Polacheck (2006) to make comparisons of results between the two methods easier):

$$M_a = \begin{cases} M_0 & \text{if} \quad a \le a_1 \\ M_0 + (M_1 - M_0)\cdot\dfrac{(a-a_1)}{(a_2-a_1)} & \text{if} \quad a_1 \le a < a_2 \\ M_1 & \text{if} \quad a_2 \le a \le a_3 \\ M_1 + (M_x - M_1)\cdot\dfrac{(a-a_3)}{(a_4-a_3)} & \text{if} \quad a_3 \le a < a_4 \\ M_x & \text{if} \quad a \ge a_4 \end{cases} \qquad (36)$$

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

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

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

Computations here take a_1=3, a_2=10, a_3=30, and a_4=35, as implemented in Punt and Polacheck (2006).

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[6] The standardisation is in terms of the sampling CV estimated for the survey in question.

[7] This term is used deliberately, rather than to call this a "Base Case", to reflect that there is no intention to imply that the selection of data used for this Reference case is necessarily the best.

Calculation of *MSYR*

When M is constant, the equilibrium number of animals of age a under a fishing proportion F for fully selected ages can be expressed as:

$$N_a(F) = N_1(F) \cdot \left(\prod_{a'=1}^{a-1} (1 - S_{a'} \cdot F) \right) \cdot e^{-\sum_{a'=1}^{a-1} M_{a'}} \qquad (37).$$

The catch of animals of age a can be expressed as $C(F) = \sum_{a=1}^{m} F \cdot S_a \cdot N_a(F)$, and the F value that gives the maximum $C(F)$ (=*MSY*) is F_{MSY} (solved by setting $\frac{dC}{dF} = 0$). This value of F_{MSY} is alternatively termed *MSYR* for the component of the population specified by the selectivity function.

RESULTS

Various output statistics[8] for the I and P-stocks are shown in Tables 4 and 5 respectively, which includes both “Reference case” and various sensitivity results. It should further be noted that –*ln*L values shown are not always comparable within sensitivities for a particular scenario (e.g. when age-dependence in *M* is estimated compared to the “Reference case” with an age-invariant *M*, because the catch-at-age overdispersion parameters (the $\lambda^{c,J/s}$’s –see equations 17 and 18) are re-estimated for each fit. Various plots for the “Reference case” results for the I-stock are shown in Figure 3 and plots for the sensitivity results for this stock are shown in Figures 4a-b. Corresponding plots for the P-stock are shown in Figures 5 and 6a-b. The 95% CI’s shown in these plots are Hessian based.

The estimated natural mortality (*M*) for the “Reference case” assessment for the I-stock is 0.056 (CV=0.16). This varies from 0.038 (CV=0.27) when only the JARPA abundance estimates are considered in the model fit, to 0.065 (CV=0.19) when only the IDCR/SOWER abundance estimates are taken into account (Table 4). The estimated *M* for the “Reference case” assessment for the P-stock is 0.069 (CV=0.15). When the JARPA abundance estimates are the only abundance series contributing to the likelihood, *M* is estimated to be 0.060 (CV=0.27), and when it is only the IDCR/SOWER abundance estimates contributing in this way, *M* is estimated to be 0.070 (CV=0.15).

These estimates of *M* are not particularly sensitive to the choice between the alternative JARPA abundance estimate series (Hakamada *et al.* 2006), whether the ageing-error (of the form assumed) is considered or not, or the selectivity slope assumed for the commercial and scientific catches (see Figures 4a-b for I-stock, and Figures 6a-b for P-stock). When *M* is treated as age-dependent, *M* for ages 10-30 for both stocks is estimated to be lower (*M*=0.045 (CV=0.19) for the I-stock and *M*=0.066 (CV=0.15) for the P-stock) than when a constant *M* is assumed, and higher for ages <10 or >30.

The estimated *MSYR(1+)* for the “Reference case” assessment for the I-stock is 0.055, and this varies from 0.030 to 0.073 depending on the assumptions of the model (Table 4). *MSYR(1+)* for the “Reference case” for the P-stock is 0.036 and this varies from 0.029 to 0.092 depending on the assumptions (Table 5).

The estimated trend in recruitment shows an increase until about the mid 1960s for all the scenarios considered in the model for both stocks, followed by a decline then stabilization (Figures 3-6). The trends in total population size are similar, but the peak is a little later (around the early 1970s) than in the case of the recruitment.

One notable difference between the results for the two stocks is that while there is little retrospective pattern in the assessments for the I-stock, those for the P-stock (and hence also of *M* and *MSYR(1+)*) have stabilised only recently, and with trends and parameter estimates the more similar to those for the I-stock.

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[8] These particular statistics are as have been agreed for standardisation purposes by the catch-at-age analyses intersessional email correspondence group.

DISCUSSION

Comparing with earlier assessments using this methodology (Butterworth *et al*. 1999, 2002), CVs on estimates of *M* as data have accumulated have decreased roughly speaking from about 0.35 to 0.15. For the I-stock assessment, estimates of *M* are typically in the range 0.05-0.06 with CVs of about 0.15-0.20. For the P-stock, *M* estimates are a little higher, at about 0.06-0.07 with CVs ranging over 0.12-0.17. The "Reference case" estimates of *MSYR(1+)* are about 6% for the I-stock and 4% for the P-stock. The considerable increase in precision for the results from these analyses compared to the earlier ones is closely linked to the long-term accumulation of data from the JARPA surveys. This improved precision in the estimation of *M* may contribute in the improvement of management and assessment of this species, since it can reduce the uncertainty concerning the value of *M* and can provide an improved prior distribution for *MSYR*. The latter in particular, in the context of providing a measure of the productivity of which the species is capable, is essential information for effective RMP implementation through reduction of the range of plausible scenarios which need to be considered in *Implementation Simulation Trials.* Estimation of *M* and other parameters by biological stock is also a major advance compared to previous earlier work which was based on Management Area-specific assessments.

The *M* values have also been estimated by Tanaka *et al*. (2006), who use the method proposed by Tanaka (1990) and annual abundance estimates from JARPA stratified by area and school size, together with estimates of age composition by area, school size and sex. Their estimates of *M* are 0.038 and 0.040 for the I-stock and P-stock respectively. When only the JARPA abundance estimates are used for the methodology of this paper, the estimated *M* is 0.038 (95%CI: 0.018-0.058) and 0.060 (95%CI: 0.027-0.093) for the I- and P-stocks respectively, so that the results from the two approaches are reasonably compatible. The estimation method of Tanaka *et al*. (2006) is much simpler than that used in this paper and does not allow for age dependent selectivity for the catches, i.e. it assumes that the catch-at-age data exactly reflect the age composition of the total population.

As regards to the estimated population and recruitment trend, most results show an initial increase in recruitment estimates of about 4-6% pa until about 1970, followed either by a stock decline (typically at between about 1-3% pa over recent decades) or sometimes stabilisation. These latter trends are very sensitive to the estimation of *M*, which in turn depends on the time-series of abundance estimates selected for input to the model fitting process. For the fits to the stock-recruitment model, carrying capacity generally shows an increase up to about 1960, followed by a decline. The estimated trend in recruitment and abundance of this species is supported by the analysis of trend in age-at sexual maturity of this species calculated by Zenitani and Kato (2006) and Mori *et al*. (2006b), which indicated that the age at sexual maturity of the Antarctic minke whales declined from about 11 years for the late 1940s cohorts to 7 years for the late 1960s cohorts, and further that this has since increased slightly before stabilising for cohorts since the early 1980s for both the I- and the P-stock. This may in turn suggest that improved feeding conditions for Antarctic minke whales due to the krill-surplus extended to the late 1960s, but that these have now come to an end as a result perhaps of increased intra- and inter-species competition for krill (Mori and Butterworth 2006).

FURTHER WORK

As discussed in the "Introduction" section, the abundance estimates to be used in the final application of this model remain under discussion in the IWC-SC. The estimated *M* from this approach is quite sensitive to trends in these estimates of abundance, and once they are finalised by the IWC-SC, the analyses should be re-run to provide *M* and *MSYR* estimates based on those agreed abundance estimates.

In addition, as noted in the "Methodology" section, the working group on population modelling in the IA sub-group of the IWC/SC is currently in the process of developing an appropriate error model for the catch-at-age data to be used to take account of potential errors and biases in the ageing and length data and how these may have been changed over time. Once these error models are available, the corresponding error structures will be incorporated in updates of these analyses.

The full likelihood function incorporates components of two rather different types: the one relates to the genuine likelihood functions based on observed data such as catches-at-age and abundance estimates; the other reflects prior information on unknown parameters (or latent variables), which can incorporate further hierarchical parametric structures. The latter can be regarded as penalties for constraining the overall parameter space. To handle these latent variables, essentially a penalized likelihood approach has been employed. Although parameters related to weights for these penalties were estimated or specified in somewhat *ad hoc* ways, the values used are considered either to be reasonably well motivated or (to the extent to which tests have been possible) such that key results are not too sensitive to their reasonable variation. The use of the marginal likelihood function of the observed data, in which latent variables are integrated out, is another possible way for estimating such weights as well as hyperparameters. Although there are some computational difficulties with such an approach, it would nevertheless seem to warrant further investigation.

CONCLUDING REMARKS

The combined analysis of catch-at-age data and survey abundance estimates, combined with an assumed stock-recruitment relationship, provides considerable and important insights into the dynamics of minke whales by stock over the middle and final decades of the 20th century. Information from the JARPA programme has played a key role in improving the precision of estimates of these trends as time has progressed, and with this also improving the precision with which natural mortality *M* and *MSYR (1+)* can be estimated.

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APPENDIX 1

IDCR/SOWER ESTIMATES FOR SH MINKE CATCH-AT-AGE ANALYSES

T.A. BRANCH

Preliminary minke whale abundance estimates calculated from the IDCR/SOWER cruise data for use in catch-at-age analyses are as follows.

Area	Longitudinal coverage	Surveys	N	CV	Year to which applies (as per convention of this paper)
IIIE	35°-70°E	1979/80	80,551	0.381	1979/80 (1979)
IIIE		1987/88	37,428	0.426	1987/88 (1987)
IIIE		1992/93+1994/95	20,465	0.238	1994/95 (1994)
IV	70°-130°E	1978/79	130,333	0.178	1978/79 (1978)
IV		1988/89	84,815	0.288	1988/89 (1988)
IV		1994/95+1998/99	13,409	0.279	1998/99 (1998)
VW	130°-165°E	1980/81	78,093	0.470	1980/81 (1980)
VW		1985/86	77,194	0.249	1985/86 (1985)
VW		1991/92	10,055	0.282	1991/92 (1991)
VW		2001/02 + 2002/03	46,169	0.174	2001/02 (2001)
VE	165°E-170°W	1980/81	164,993	0.328	1980/81 (1980)
VE		1985/86	172,828	0.147	1985/86 (1985)
VE		1991/92	187,266	0.210	1991/92 (1991)
VE		2002/03 + 2003/04	100,658	0.170	2003/04 (2003)
VIW	170°-145°W	1983/84	67,161	0.227	1983/84 (1983)
VIW		1990/91	8,394	0.294	1990/91 (1990)
VIW		1995/96	33,323	0.230	1995/96 (1995)

Note that these (sub-)Areas correspond to the regions covered by the JARPA surveys (see, for example, ICR document JA/J05/JR3 on the ICR website); in particular the VW/VE division here is at 165°E to correspond to an hypothesised stock division line based on genetic analyses and agreed for use in these catch-at-age analyses.

The "Year to which applies" is the year to which the estimate should be assumed to apply in the model fitting process. In cases where two survey seasons are involved, it is that one of the two during which the greater part of the (sub-)Area was covered.

These estimates have been based on the approach of Branch (2005), and have the following broad features/specifications:

- Estimates are standardised to IO mode assuming $g(0)=1$, and combining modes using inverse variance weighting with a constant inter-mode calibration factor R=0.826 (CV=0.089) from Branch and Butterworth (2001).
- Where the survey stratum spans a sub-Area boundary, the abundance estimate required has been obtained by pro-rating proportional to longitudinal coverage.
- Pro-rating was conducted prior to combining survey modes.

- For the first two circumpolar cruises for which coverage did not always extend as far north as 60°S, the estimates given include extrapolation for this unsurveyed area by assuming a density equal to that in the corresponding northern stratum of the survey.
- There is little by way of common factors used to generate the estimates listed, so that any additions required can adequately assume independence for computing the associated CV.

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Table 1 Catch at age matrices by Area and by nation. For economy of space, ages have been grouped by 3, so that age 5 (for example) combines ages 4-6. Note that 1971 reflects the 1971/72 season.

Area IIIE – Japan

Year/Age	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	54+
1971	3	11	18	96	18	26	85	28	19	52	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1973	78	133	131	124	135	118	115	80	74	32	25	12	8	3	6	0	0	3
1974	53	159	251	236	191	131	87	65	42	27	14	8	4	0	0	1	0	0
1975	20	123	133	169	132	122	139	80	46	10	17	14	6	4	0	0	4	0
1976	23	120	148	207	202	206	158	121	55	60	29	34	7	7	6	0	2	0
1977	5	60	86	98	194	143	105	105	79	53	16	30	16	11	5	2	0	5
1978	34	102	207	245	273	238	176	134	63	50	31	22	7	10	3	4	0	1
1979	20	63	63	70	74	93	58	70	68	50	24	17	14	8	5	3	3	1
1980	19	75	102	103	90	70	64	42	24	15	6	7	0	1	0	1	0	0
1981	10	36	33	47	38	34	23	17	6	2	7	4	0	0	1	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	12	12	6	13	13	9	1	11	5	8	8	6	1	2	0	0	0	0
1996	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	20	10	20	15	5	11	7	7	5	5	2	2	2	0	1	0	0	0
1998	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1999	24	28	11	12	12	8	3	4	3	3	1	1	0	0	0	0	0	0
2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Area IIIE – USSR

Year/Age	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	54+
1971	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1973	12	25	18	17	16	11	14	8	5	4	2	3	1	0	1	0	0	1
1974	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1975	10	85	133	187	170	143	168	100	60	13	23	25	8	3	0	0	3	0
1976	16	67	134	271	253	226	186	130	62	69	27	29	7	8	3	0	2	0
1977	6	72	97	84	150	109	60	79	39	32	14	17	18	3	4	1	0	3
1978	5	35	81	119	123	105	87	67	30	25	15	13	3	5	0	2	0	0
1979	9	57	94	74	71	97	61	72	87	55	27	25	20	12	8	2	3	2
1980	9	54	97	97	99	81	76	46	26	17	7	8	0	1	0	1	0	0
1981	11	86	151	216	121	93	64	51	33	6	18	14	0	0	2	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. Cont.

Area IV – Japan

Year/Age	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	54+
1971	123	255	313	309	351	318	283	234	146	95	98	45	30	25	3	7	13	8
1972	128	374	401	306	272	216	143	123	50	39	18	13	3	4	0	0	0	0
1973	261	246	278	305	230	185	170	96	92	76	39	26	26	2	6	5	0	0
1974	38	88	138	132	116	108	57	58	49	27	15	6	4	1	2	0	2	0
1975	6	77	63	80	62	63	32	17	11	11	5	3	5	0	0	0	0	0
1976	15	126	112	193	188	122	73	68	18	13	12	0	2	4	0	0	0	4
1977	25	31	62	61	77	82	41	35	33	17	8	3	5	0	0	2	0	0
1978	34	91	137	172	153	116	92	66	39	22	19	11	1	1	1	0	3	0
1979	84	164	152	184	199	214	148	109	78	62	47	28	20	15	11	11	3	3
1980	77	148	153	137	150	135	116	94	53	48	21	25	13	8	9	4	2	1
1981	65	155	195	221	211	239	171	119	106	59	41	15	17	5	4	3	1	0
1982	55	85	92	134	115	160	138	93	65	37	13	11	6	10	1	3	1	0
1983	89	152	140	167	138	145	93	85	48	36	7	4	2	3	0	0	0	0
1984	18	38	44	65	73	60	63	52	39	21	13	8	0	2	2	0	0	0
1985	8	19	36	50	70	79	79	68	42	29	13	10	11	1	0	1	0	0
1986	12	22	42	53	68	88	65	56	43	29	13	11	7	3	2	1	0	0
1987	28	44	33	24	29	25	31	14	17	13	3	6	2	1	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	35	53	48	23	15	36	30	19	27	14	8	7	5	5	1	0	0	0
1990	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1991	39	39	39	24	20	21	18	12	16	20	15	9	7	2	2	2	1	1
1992	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1993	58	47	46	42	22	25	16	11	17	12	14	7	6	1	1	2	1	1
1994	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	34	34	34	50	26	17	20	18	27	12	12	17	7	5	3	7	3	4
1996	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1997	87	36	36	27	20	19	14	17	10	10	15	13	9	2	5	6	0	2
1998	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
1999	40	42	37	32	28	28	22	17	10	15	17	11	13	8	7	3	0	0
2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
2001	42	39	38	21	26	24	27	17	14	18	9	16	14	10	8	3	1	2
2002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2003	39	30	45	21	28	30	23	16	12	13	18	8	18	7	8	8	4	1

Area IV – USSR

Year/Age	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	54+
1971	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1972	224	563	537	347	254	195	133	114	37	31	22	8	1	2	0	0	0	0
1973	342	348	388	364	273	210	197	109	99	81	40	23	35	2	7	8	0	0
1974	3	65	173	234	199	229	122	142	109	55	26	12	11	2	2	0	6	0
1975	10	49	87	88	67	78	26	14	10	10	4	2	4	0	0	0	0	0
1976	7	57	80	140	137	83	55	52	11	7	10	0	3	4	0	0	0	4
1977	31	37	72	75	74	83	31	25	30	12	6	1	5	0	0	0	0	0
1978	4	24	49	79	73	58	44	33	19	11	9	5	1	1	0	0	1	0
1979	2	18	35	43	44	49	39	28	21	17	11	8	6	3	3	3	1	0
1980	26	92	144	154	167	153	126	109	63	56	25	30	19	10	11	2	4	2
1981	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	23	63	90	137	106	162	134	95	63	41	9	9	5	8	2	1	1	0
1983	31	113	137	168	131	144	93	83	45	30	7	2	1	4	0	0	0	0
1984	31	70	96	135	143	125	127	94	72	40	29	17	0	3	5	0	0	0
1985	11	42	88	91	131	138	113	117	58	44	17	17	24	1	0	1	0	0
1986	20	51	87	111	142	149	114	99	70	47	20	16	14	8	2	1	0	0

Table 1. Cont.

Area VW – Japan

Year/Age	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	54+
1971	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1973	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1974	17	46	90	92	87	58	47	32	20	2	7	2	0	0	0	0	0	0
1975	10	63	56	70	66	58	44	24	17	6	4	4	0	0	0	0	0	0
1976	7	101	112	143	180	152	95	64	53	48	19	18	4	6	6	0	0	2
1977	11	51	106	116	82	81	66	36	31	18	6	1	2	3	3	0	0	0
1978	7	13	22	30	27	29	7	15	11	7	1	3	0	1	0	0	0	0
1979	36	56	83	71	75	58	34	21	17	20	6	8	3	4	3	1	0	0
1980	4	40	41	46	57	53	38	44	36	30	10	14	12	6	4	1	0	0
1981	13	82	95	108	165	182	151	102	102	50	31	30	14	9	7	4	2	0
1982	26	114	216	258	281	295	244	175	117	72	48	16	17	12	3	1	0	1
1983	79	170	151	203	244	189	124	93	61	27	22	12	3	3	1	0	0	0
1984	24	67	88	104	112	173	128	84	56	39	13	14	5	1	1	0	0	0
1985	33	52	66	102	128	182	128	105	101	44	31	24	6	7	1	2	1	0
1986	4	32	48	102	117	141	171	125	118	80	31	25	5	6	1	2	1	3
1987	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	3	31	18	13	19	16	18	19	13	9	8	6	7	2	2	3	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	10	13	29	23	20	10	13	16	23	10	16	13	7	1	2	1	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	20	10	15	12	16	12	7	9	10	7	1	8	3	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	10	15	8	15	17	4	9	6	8	7	6	7	6	4	2	0	4	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1998	13	9	28	12	19	18	11	8	17	13	5	14	6	5	1	2	0	0
1999	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2000	9	17	6	10	13	16	4	11	11	5	11	11	9	0	2	2	0	3
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	3	7	9	11	10	12	13	7	10	5	5	0	4	0	0	1	1	1
2003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2004	0	5	12	7	5	14	7	3	3	4	3	4	4	1	3	2	1	2

Area VW – USSR

Year/Age	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	54+
1971	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1973	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1974	8	24	41	47	43	24	21	12	10	1	3	1	0	0	0	0	0	0
1975	4	29	28	36	35	33	24	10	9	1	1	1	0	0	0	0	0	0
1976	5	37	44	64	100	70	46	30	22	19	6	6	2	2	2	0	0	0
1977	1	11	40	48	32	32	25	9	11	3	0	0	2	1	0	0	0	0
1978	5	10	26	48	42	41	10	20	22	9	1	2	0	2	0	0	0	0
1979	10	48	115	89	96	124	105	59	72	39	47	15	10	3	12	4	0	0
1980	1	20	23	33	38	27	21	23	22	15	7	7	6	2	1	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. Cont.

Area VE – Japan

Year/Age	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	54+
1971	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1973	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1974	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1975	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1976	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1977	1	3	15	10	6	4	6	4	2	0	1	1	0	0	0	0	0	0
1978	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1979	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1980	5	18	31	22	13	24	14	13	15	16	6	6	3	0	3	2	0	0
1981	0	4	4	3	4	6	1	2	3	1	1	1	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	1	10	12	10	7	6	6	5	2	0	1	3	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	13	34	27	28	39	25	21	15	8	10	5	5	5	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	1	9	11	9	16	19	21	10	10	4	3	4	2	1	2	1	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	12	5	10	16	3	6	6	11	9	8	6	1	3	1	0	0	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	22	14	21	21	21	21	10	12	15	11	5	9	4	2	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	11	9	9	21	15	15	15	13	13	8	13	3	3	7	2	0	1	1
1997	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1998	24	5	11	8	20	12	9	12	14	8	10	5	4	0	1	1	1	1
1999	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2000	8	9	19	18	15	17	4	10	14	15	8	5	6	2	3	1	3	5
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	19	26	19	27	22	26	16	15	12	12	14	8	5	3	5	1	2	2
2003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2004	12	15	23	17	16	24	18	15	14	17	11	11	2	5	5	3	1	2

Area VE – USSR

Year/Age	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	54+
1971	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1973	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1974	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1975	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1976	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1977	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1978	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1979	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1980	0	37	62	49	23	50	29	28	32	30	12	9	6	0	5	3	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. Cont.

Area VIW - Japan

Year/Age	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	54+
1971	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1973	0	0	0	3	5	0	5	0	0	0	0	0	0	0	0	0	0	0
1974	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1975	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1976	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1977	3	35	41	27	32	20	32	23	15	4	2	0	0	3	0	0	0	0
1978	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1979	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1980	5	37	36	34	18	14	17	7	12	5	6	2	3	1	1	0	0	0
1981	42	33	50	44	27	26	23	15	12	4	5	1	1	1	0	0	0	0
1982	14	32	42	55	45	48	20	21	20	8	1	3	0	0	0	0	0	0
1983	26	57	77	98	63	51	45	22	18	5	7	1	3	0	0	0	2	0
1984	21	49	52	57	61	48	36	22	15	6	2	1	0	0	0	0	0	0
1985	66	57	40	50	63	41	24	20	18	9	3	3	0	0	1	0	0	0
1986	13	35	34	47	65	66	49	47	27	18	8	3	2	0	0	0	0	0
1987	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1990	0	0	2	2	0	4	3	2	0	0	1	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1992	0	1	0	2	5	2	1	2	1	6	0	1	1	0	0	1	0	0
1993	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1994	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1996	8	6	15	16	18	17	11	11	16	11	7	5	5	6	1	3	1	0
1997	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1998	31	4	5	1	3	3	1	2	3	2	1	0	2	0	0	1	0	0
1999	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2000	37	2	9	12	12	17	6	7	15	6	5	5	4	4	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2002	26	25	6	6	9	8	8	3	6	2	3	5	0	3	0	1	0	0
2003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2004	16	22	17	7	7	14	9	8	10	6	12	2	6	4	5	0	0	0

Area VIW – USSR

Year/Age	2	5	8	11	14	17	20	23	26	29	32	35	38	41	44	47	50	54+
1971	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1972	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1973	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1974	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1975	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1976	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1977	2	28	20	21	27	18	32	17	13	5	0	0	0	2	0	0	0	0
1978	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1979	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1980	1	5	11	10	4	5	6	3	5	2	3	1	1	1	1	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1982	11	36	72	100	66	76	30	35	25	13	1	4	0	0	0	0	0	0
1983	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1985	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1986	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2 Abundance estimates from sightings surveys (see text for source details).

Area IIIE

Survey	Year to which applies	Estimate (CV)
IDCR 1979/80	1979	80551 (0.381)
IDCR 1987/88	1987	37428 (0.426)
IDCR 1992/93 + 1994/95	1994	20465 (0.238)
JARPA 1995/96	1995	10262 (0.388)
JARPA 1997/98	1997	5618 (0.637)
JARPA 1999/00	1999	12940 (0.837)
JARPA 2001/02	2001	54717 (0.488)
JARPA 2003/04	2003	35241 (0.352)

Area IV

Survey	Year to which applies	Estimate (CV)
IDCR 1978/79	1978	130333 (0.178)
IDCR 1988/89	1988	84815 (0.288)
IDCR 1994/95+1998/99	1998	13409 (0.279)
JARPA 1989/90	1989	48167 (0.203)
JARPA 1991/92	1991	52467 (0.274)
JARPA 1993/94	1993	41398 (0.192)
JARPA 1995/96	1995	42363 (0.203)
JARPA 1997/98	1997	25922 (0.220)
JARPA 1999/00	1999	44931 (0.151)
JARPA 2001/02	2001	48280 (0.188)
JARPA 2003/04	2003	44564 (0.291)

Area VW

Survey	Year to which applies	Estimate (CV)
IDCR 1980/81	1980	78093 (0.470)
IDCR 1985/86	1985	77194 (0.249)
IDCR 1991/92	1991	10055 (0.282)
IDCR 2001/02+2002/03	2001	46169 (0.174)
JARPA 1990/91	1990	56381 (0.210)
JARPA 1992/93	1992	41922 (0.227)
JARPA 1994/95	1994	20113 (0.248)
JARPA 1996/97	1996	23719 (0.241)
JARPA 1998/99	1998	84405 (0.319)
JARPA 2000/01	2000	19608 (0.321)
JARPA 2002/03	2002	100775 (0.205)
JARPA 2004/05	2004	38790 (0.192)

Table 2 cont.

Area VE

Survey	Year to which applies	Estimate (CV)
IDCR 1980/81	1980	164993 (0.328)
IDCR 1985/86	1985	172828 (0.147)
IDCR 1991/92	1991	187266 (0.210)
IDCR 2002/03+2003/04	2003	100658 (0.170)
JARPA 1990/91	1990	105409 (0.248)
JARPA 1992/93	1992	82137 (0.282)
JARPA 1994/95	1994	143596 (0.256)
JARPA 1996/97	1996	118335 (0.256)
JARPA 1998/99	1998	40755 (0.277)
JARPA 2000/01	2000	141389 (0.210)
JARPA 2002/03	2002	75210 (0.201)
JARPA 2004/05	2004	53387 (0.177)

Area VIW

Survey	Year to which applies	Estimate (CV)
IDCR 1983/84	1983	67161 (0.227)
IDCR 1990/91	1990	8394 (0.294)
IDCR 1995/96	1995	33323 (0.230)
JARPA 1996/97	1996	12533 (0.317)
JARPA 1998/99	1998	38355 (0.296)
JARPA 2000/01	2000	21873 (0.261)
JARPA 2002/03	2002	12358 (0.297)
JARPA 2004/05	2004	18700 (0.247)

Table 3. Estimated standard deviations (*s*) of reading differences between readers A and B (extracted from Table 1 of Kato *et al*. 1991). The sample size is given by *n*, and *A* is the mean. The age-interval corresponds to reader A's reading.

Interval	*n*	*A*	*s*	CV(%)
-10	73	7.1575	0.43004	6.008
11-20	150	15.1533	1.03602	6.837
21-30	95	24.5053	1.40675	5.741
31-	38	36.4342	2.00984	5.516
Total	356	18.2809	1.20393	6.586

Table 4. Results of various statistics for the "Reference case" and sensitivity tests for the **I-stock**. Increase rates are given as annual proportions. Estimated CVs where given, are based upon the Hessian approximation – this was cross-checked against likelihood profile estimation for the CV of *M* in an earlier analysis, and was found there to have achieved good accuracy.

											Average proportions in each management area					
I-stock	$b_{rec,1945\text{-}68}$	$b_{rec,1968\text{-}88}$	$b_{rec,1988\text{-}lastyr}$	$N_{tot,1945\text{-}68}$	$N_{tot,1968\text{-}88}$	$N_{tot,1988\text{-}lastyr}$	$N_{\text{lstyr-5,1}}/N_{1968,1}$	K_{1930}	K_{2000}/K_{1960}	K_{1960}/K_{1930}	M (CV)	IIIE	IV	VW	Survey q	MSYR (1+)	-lnL
Reference case (m=30)	0.052	−0.032	−0.010	0.057	−0.020	−0.007	0.374	26860	0.626	5.820	0.056 (0.162)	0.205	0.425	0.371	0.713	0.055	321.021
Reference case (m=45)	0.074	−0.035	−0.017	0.083	−0.017	−0.004	0.368	10225	0.724	13.596	0.052 (0.184)	0.204	0.425	0.371	0.719	0.073	498.789
Use Cexpect (m=30)	0.051	−0.034	−0.012	0.037	−0.022	−0.011	0.336	72262	0.556	2.364	0.060 (0.157)	0.305	0.310	0.385	0.783	0.049	297.940
q=1 (m=30)	0.047	−0.040	−0.018	0.051	−0.028	−0.014	0.292	31155	0.486	4.894	0.061 (0.126)	0.214	0.413	0.373	1.000	0.050	323.305
q=1 (m=45)	0.067	−0.044	−0.021	0.075	−0.026	−0.012	0.278	12996	0.535	11.021	0.059 (0.131)	0.213	0.414	0.374	1.000	0.066	501.155
JARPA abun is "GLM+boot" (m=30)	0.053	−0.031	−0.011	0.058	−0.019	−0.006	0.383	25772	0.646	5.981	0.055 (0.186)	0.163	0.465	0.373	0.551	0.056	317.994
JARPA abun is "GLM" (m=30)	0.060	−0.025	−0.006	0.064	−0.014	0.001	0.481	19906	0.820	7.029	0.048 (0.191)	0.240	0.412	0.349	0.550	0.062	326.843
g(0)<1 (abundance x 1.5) (m=30)	0.048	−0.032	−0.007	0.052	−0.018	−0.010	0.368	42800	0.599	5.123	0.061 (0.162)	0.199	0.427	0.374	0.771	0.052	320.387
Fit only JARPA (m=30)	0.069	−0.024	−0.013	0.065	−0.016	0.008	0.500	39155	0.849	2.592	0.038 (0.269)	0.204	0.405	0.391	−	0.056	320.384
Fit only IDCR (m=30)	0.046	−0.042	−0.024	0.045	−0.025	−0.022	0.242	78077	0.460	2.304	0.065 (0.194)	0.273	0.434	0.292	−	0.046	129.397
Delete early commercial data (m=30)	0.032	−0.031	−0.010	0.014	−0.018	−0.013	0.373	100478	0.518	1.540	0.062 (0.158)	0.307	0.305	0.389	0.879	0.030	
Retrospective (lstyr=2001) (m=30)	0.048	−0.038	0.004	0.037	−0.025	−0.011	0.436	75338	0.530	2.378	0.062 (0.135)	0.201	0.453	0.346	0.617	0.048	281.113
Retrospective (lstyr=1998) (m=30)	0.043	−0.044	−0.009	0.034	−0.029	−0.020	0.277	82861	−	2.285	0.067 (0.132)	0.172	0.458	0.370	0.600	0.044	240.734
Retrospective (lstyr=1995) (m=30)	0.052	−0.032	−0.053	0.037	−0.021	−0.015	0.433	77201	−	2.390	0.057 (0.205)	0.172	0.531	0.298	0.537	0.047	199.328
With ageing error (m=30)	0.050	−0.032	−0.009	0.055	−0.021	−0.009	0.371	28817	0.594	5.776	0.057 (0.155)	0.207	0.424	0.370	0.700	0.053	319.466
With ageing error (m=45)	0.075	−0.035	−0.016	0.083	−0.018	−0.005	0.358	9824	0.702	14.637	0.052 (0.183)	0.205	0.425	0.370	0.716	0.073	488.198
With ageing error (m=30) (use Cexpect)	0.049	−0.033	−0.010	0.038	−0.023	−0.011	0.348	71252	0.553	2.431	0.059 (0.156)	0.305	0.310	0.385	0.778	0.049	296.257
Sc26=0.80 (Sc30=1)	0.089	−0.031	−0.015	0.065	−0.014	−0.001	0.410	31393	0.834	3.875	0.052 (0.174)	0.295	0.318	0.387	0.783	0.072	293.771
Est Select Slope (Sc30=1)	0.037	−0.031	−0.011	0.041	−0.023	−0.009	0.374	45561	0.565	3.777	0.055 (0.166)	0.303	0.311	0.385	0.776	0.044	298.617
Sc26=1.20 (Sc30=1)	0.035	−0.028	−0.011	0.023	−0.024	−0.007	0.400	101675	0.569	1.717	0.052 (0.171)	0.302	0.312	0.385	0.765	0.040	298.348
Sc26=1.40 (Sc30=1)	0.024	−0.024	−0.008	0.013	−0.025	−0.005	0.456	127860	0.564	1.366	0.046 (0.191)	0.301	0.312	0.387	0.784	0.032	297.167
Animals in the pack ice (Sc30=1)																	
Sc26=Ss26=0.9	0.065	−0.030	−0.012	0.049	−0.019	−0.005	0.396	49248	0.674	2.941	0.059 (0.164)	0.300	0.314	0.386	0.774	0.058	296.186
Est Select Slope	0.042	−0.031	−0.011	0.029	−0.023	−0.008	0.376	88710	0.578	1.951	0.052 (0.188)	0.303	0.312	0.385	0.764	0.044	298.421
Sc26=Ss26=1.1	0.046	−0.033	−0.012	0.032	−0.022	−0.008	0.361	82676	0.585	2.094	0.051 (0.189)	0.303	0.313	0.385	0.764	0.046	298.599
											M0 (CV) M1(CV) M2(CV)						
M linear by age (m=30)	0.062	−0.028	−0.009	0.046	−0.020	−0.005	0.408	47190	0.677	2.939	0.111 (0.239) 0.045 (0.189) 0.150 (0.107)	0.209	0.423	0.368	0.715	0.056	322.056
M linear by age (m=45)	0.078	−0.030	−0.018	0.068	−0.018	−0.003	0.388	24284	0.775	5.272	0.117 (0.234) 0.042 (0.206) 0.081 (0.183)	0.209	0.423	0.368	0.708	0.067	500.114

Table 5. Results of various statistics for the "Reference case" and sensitivity tests for the **P-stock**. Increase rates are given as annual proportions. Estimated CVs where given, are based upon the Hessian approximation – this was cross-checked against likelihood profile estimation for the CV of M in an earlier analysis, and were found there to have achieved good accuracy.

														Average proportions in each				
P-stock	$b_{rec,1945-68}$	$b_{rec,1968-88}$	$b_{rec,1988-lastyr}$	$N_{tot,1945-68}$	$N_{tot,1968-88}$	$N_{tot,1988-lastyr}$	$N_{lstyr-5,1}/N_{1968,1}$	K_{1930}	K_{2000}/K_{1960}	K_{1960}/K_{1930}	M (CV)			p(VE)	p(VIW)	Survey q	MSYR (1+)	-lnL
Reference case (m=30)	0.039	−0.051	0.023	0.039	−0.007	−0.022	0.438	33143	0.484	5.610	0.069 (0.150)			0.821	0.179	0.712	0.036	167.238
Reference case (m=45)	0.066	−0.054	0.031	0.051	−0.006	−0.020	0.442	41353	0.477	4.482	0.076 (0.165)			0.821	0.179	0.720	0.050	278.667
Use Cexpect	0.038	−0.051	0.022	0.038	−0.007	−0.023	0.430	34863	0.475	5.437	0.070 (0.145)			0.823	0.178	0.709	0.035	166.696
q=1 (m=30)	0.034	−0.059	0.017	0.033	−0.014	−0.030	0.338	37787	0.383	4.489	0.078 (0.106)			0.842	0.158	1.000	0.032	169.137
q=1 (m=45)	0.058	−0.063	0.025	0.046	−0.015	−0.029	0.331	43844	0.367	4.007	0.085 (0.092)			0.847	0.153	1.000	0.046	279.540
JARPA abun is "GLM+boot" (m=30)	0.040	−0.051	0.028	0.039	−0.006	−0.020	0.429	32766	0.501	5.780	0.068 (0.141)			0.847	0.153	0.599	0.037	157.020
JARPA abun is "GLM" (m=30)	0.041	−0.048	0.026	0.041	−0.004	−0.019	0.479	29631	0.525	6.186	0.067 (0.148)			0.837	0.163	0.586	0.038	159.618
g(0)<1 (abundance x 1.5) (m=30)	0.038	−0.051	0.023	0.038	−0.007	−0.022	0.434	51447	0.481	5.423	0.070 (0.149)			0.821	0.179	0.713	0.035	167.287
Fit only JARPA (m=30)	0.048	−0.042	0.031	0.048	0.003	−0.012	0.594	12808	0.652	8.154	0.060 (0.273)			0.768	0.232	−	0.043	175.329
Fit only IDCR (m=30)	0.041	−0.050	0.026	0.040	−0.006	−0.021	0.449	31472	0.496	6.004	0.070 (0.151)			0.858	0.142	−	0.037	164.690
Retrospective (lstyr=2001) (m=30)	0.070	−0.011	0.097	0.042	0.037	0.022	1.036	28059	4.918	1.579	0.024 (0.235)			0.859	0.141	0.494	0.092	136.462
Retrospective (lstyr=1998) (m=30)	0.072	−0.041	0.103	0.063	0.017	−0.007	0.467	22573	−	6.197	0.049 (0.537)			0.853	0.147	0.573	0.061	127.800
Retrospective (lstyr=1994) (m=30)	0.068	−0.026	0.152	0.037	0.037	0.015	0.632	32627	−	1.475	0.020 (0.360)			0.907	0.093	0.522	0.089	101.602
With ageing error (m=30)	0.040	−0.052	0.025	0.034	−0.007	−0.022	0.409	54547	0.483	3.434	0.069 (0.146)			0.821	0.179	0.710	0.035	171.403
With ageing error (m=45)	0.065	−0.057	0.032	0.048	−0.009	−0.021	0.393	45840	0.456	4.172	0.077 (0.151)			0.821	0.180	0.725	0.049	280.785
With ageing error (m=30) (use Cexpect)	0.038	−0.052	0.024	0.037	−0.008	−0.022	0.403	36003	0.474	5.295	0.070 (0.141)			0.822	0.178	0.708	0.035	170.754
Sc26=0.80 (Sc30=1)	0.053	−0.056	0.022	0.030	−0.010	−0.025	0.382	70819	0.435	2.763	0.076 (0.128)			0.822	0.178	0.731	0.038	171.078
Est Select Slope (Sc30=1)	0.031	−0.048	0.021	0.031	−0.007	−0.021	0.454	44761	0.498	4.131	0.066 (0.159)			0.823	0.177	0.701	0.032	165.595
Sc26=1.20 (Sc30=1)	0.031	−0.048	0.021	0.031	−0.007	−0.021	0.455	44976	0.499	4.110	0.066 (0.153)			0.823	0.177	0.700	0.032	165.592
Sc26=1.40 (Sc30=1)	0.024	−0.046	0.020	0.026	−0.007	−0.021	0.471	56559	0.510	3.228	0.063 (0.158)			0.823	0.177	0.695	0.029	165.868
Animals in the pack ice (Sc30=1)																		
Sc26=Ss26=0.9	0.047	−0.050	0.023	0.038	−0.007	−0.023	0.441	44463	0.468	3.654	0.077 (0.123)			0.887	0.113	0.809	0.038	167.856
Est Select Slope	0.030	−0.051	0.022	0.030	−0.007	−0.021	0.440	48198	0.506	3.917	0.060 (0.211)			0.823	0.177	0.697	0.031	165.521
Sc26=Ss26=1.1	0.035	−0.053	0.023	0.035	−0.007	−0.021	0.426	35285	0.499	4.748	0.061 (0.174)			0.887	0.113	0.789	0.034	166.342
											M0 (CV)	M1(CV)	M2(CV)					
M linear by age (m=30)	0.039	−0.049	0.019	0.036	−0.011	−0.020	0.444	47142	0.475	3.230	0.167 (0.327)	0.066 (0.152)	0.149 (0.353)	0.887	0.113	0.801	0.034	169.258
M linear by age (m=45)	0.064	−0.050	0.030	0.047	−0.007	−0.017	0.476	44283	0.516	3.955	0.117 (0.208)	0.068 (0.223)	0.120 (0.216)	0.822	0.178	0.695	0.047	277.801

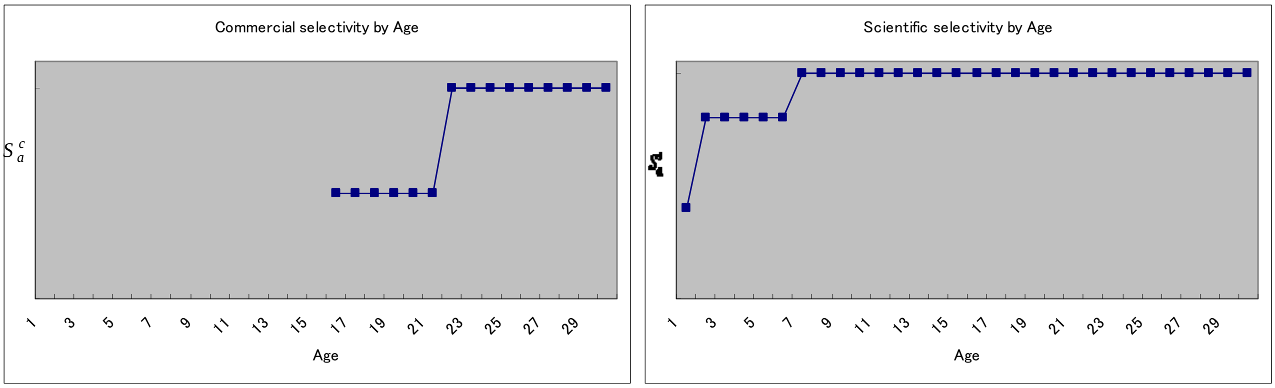

Figure 1. Assumed commercial and scientific selectivities by age for the “Reference case” scenario. S^c_{16-21}, S^s_1 and S^s_{2-6} are estimated.

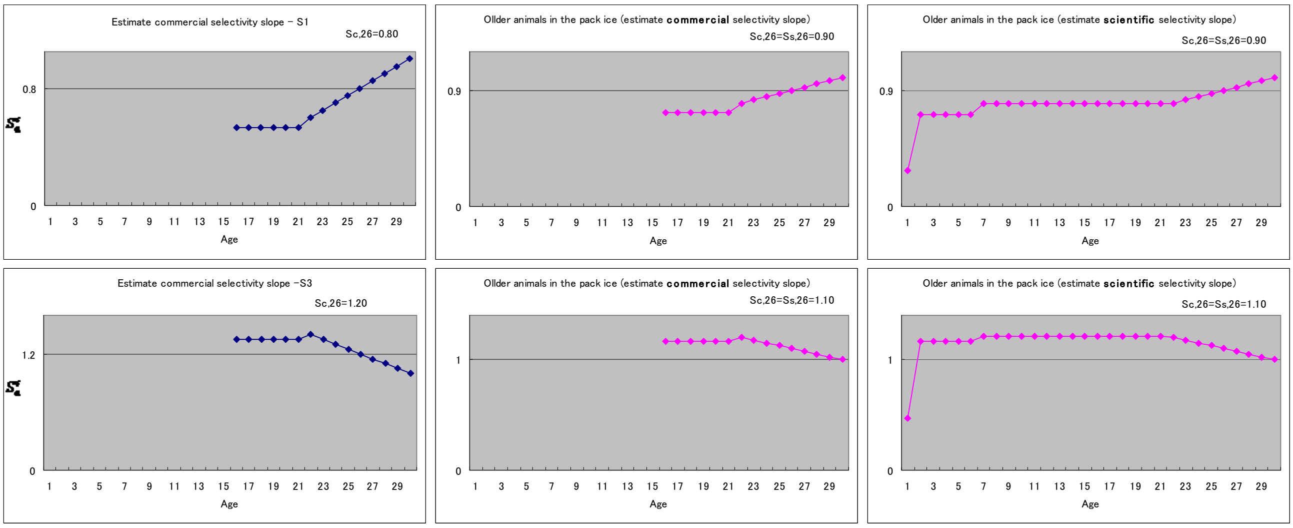

Figure 2. Illustration of selectivity functions considered in the sensitivity tests.

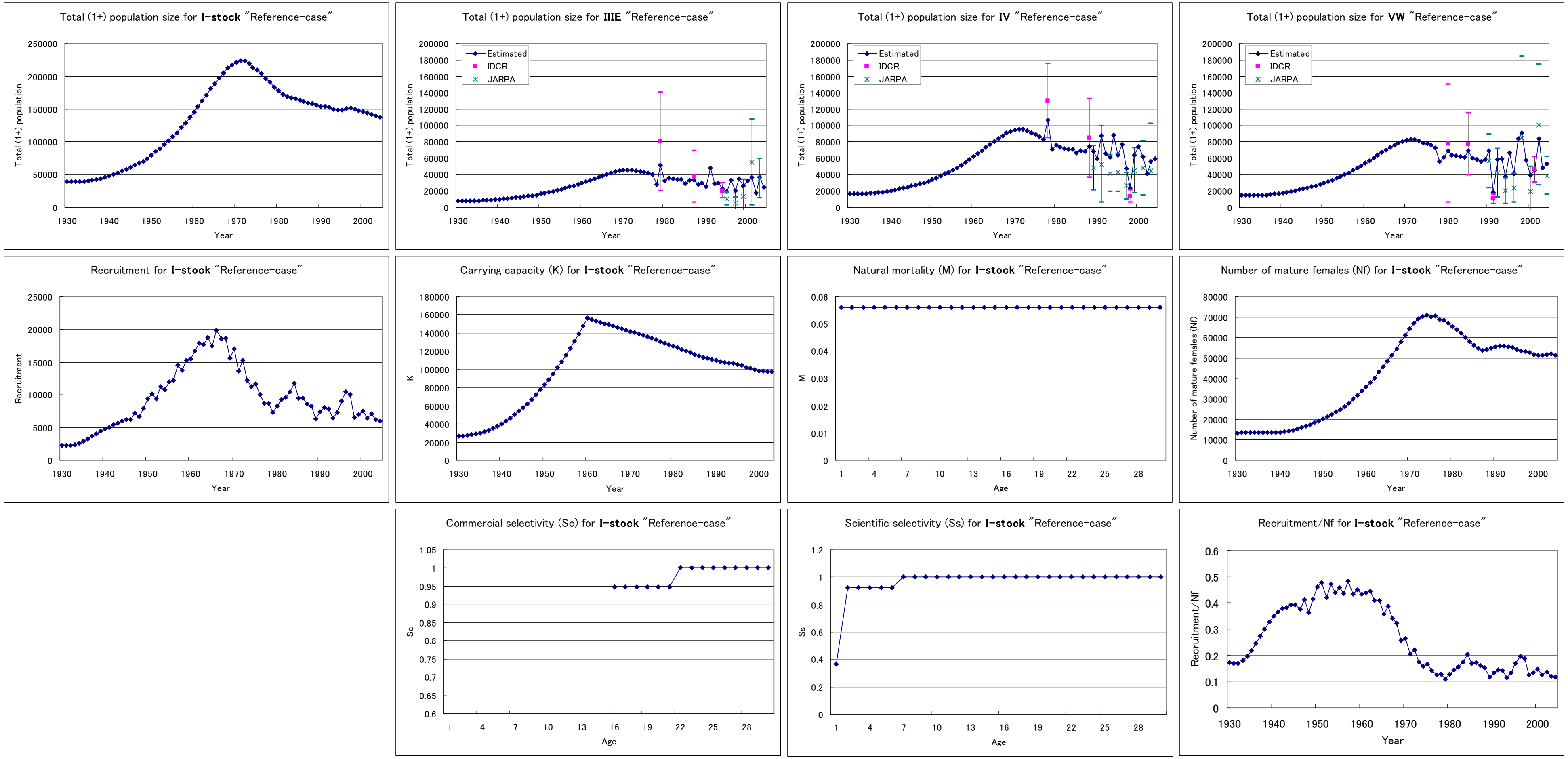

Figure 3. Various plots (including trends in total population size by stock and by area, recruitment, carrying capacity, number of mature females, recruitment rate, selectivity estimates and natural mortality) for the "Reference case" results for the **I-stock**. Error bars reflect 95% CIs on the abundance estimates.

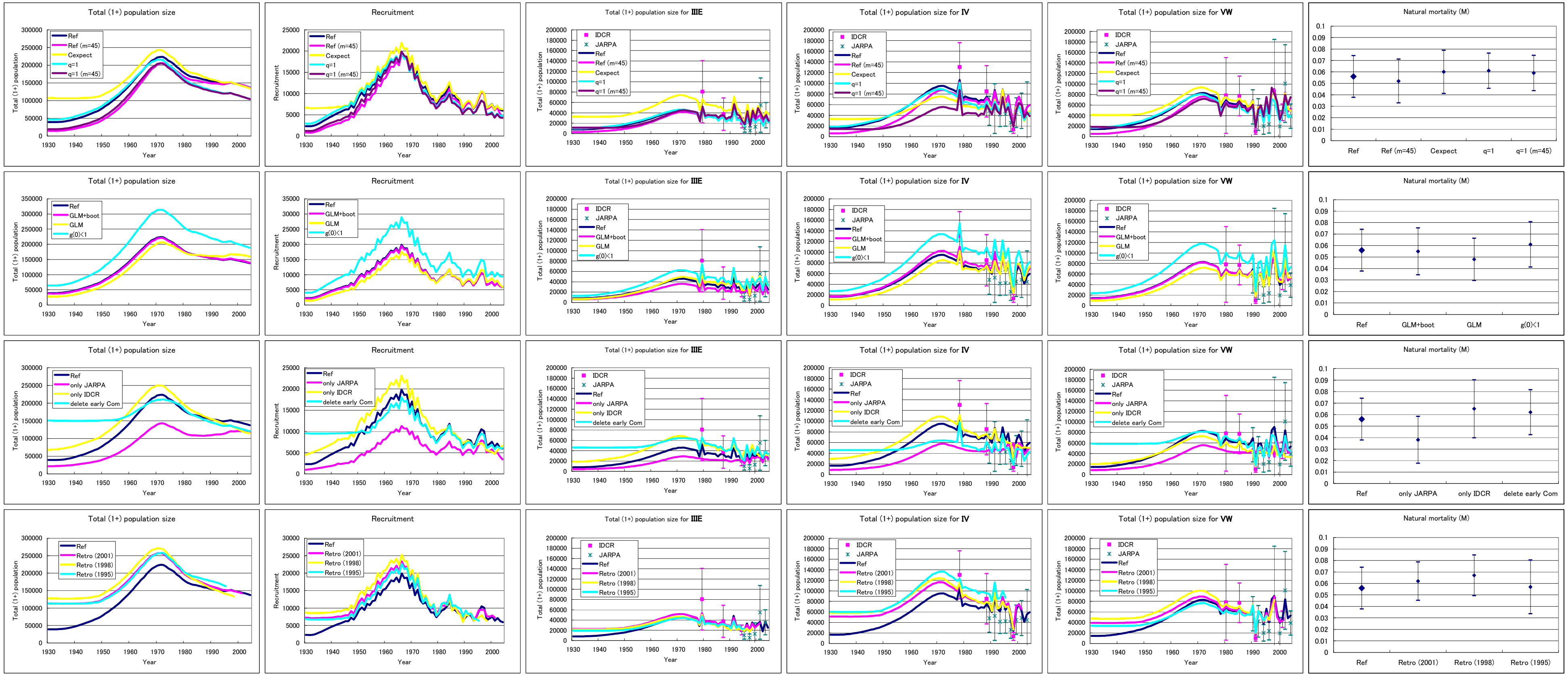

Figure 4a. Plots of total population size by stock and by Area, recruitment, and estimated *M* for the **I-stock** for various sensitivity test runs, including 1) Maximum age *m* considered in the likelihood is 45 rather than 30; 2) $\hat{C}_{y,a}$ is used instead of $C_{y,a}$ in equation (1) for ages considered in the catch-at-age likelihood; 3) Set *q*=1 (i.e. use JARPA abundance estimate as absolute abundance estimates rather than relative); 4) Use different series of abundance estimates for JARPA (detailed in the Data section above), including a 50% increase in the abundance estimates to preliminarily consider the implications of g(0)<1; 5) Either the JARPA or the IDCR/SOWER estimates of abundance are omitted; 6) For the commercial period, only data from the later half (i.e. collected only after 1979) are used since they seem to have lesser age/length measurement errors; and 7) Retrospective analyses for the periods ending 1995, 1998, and 2001. Error bars reflect 95% CIs on the abundance estimates.

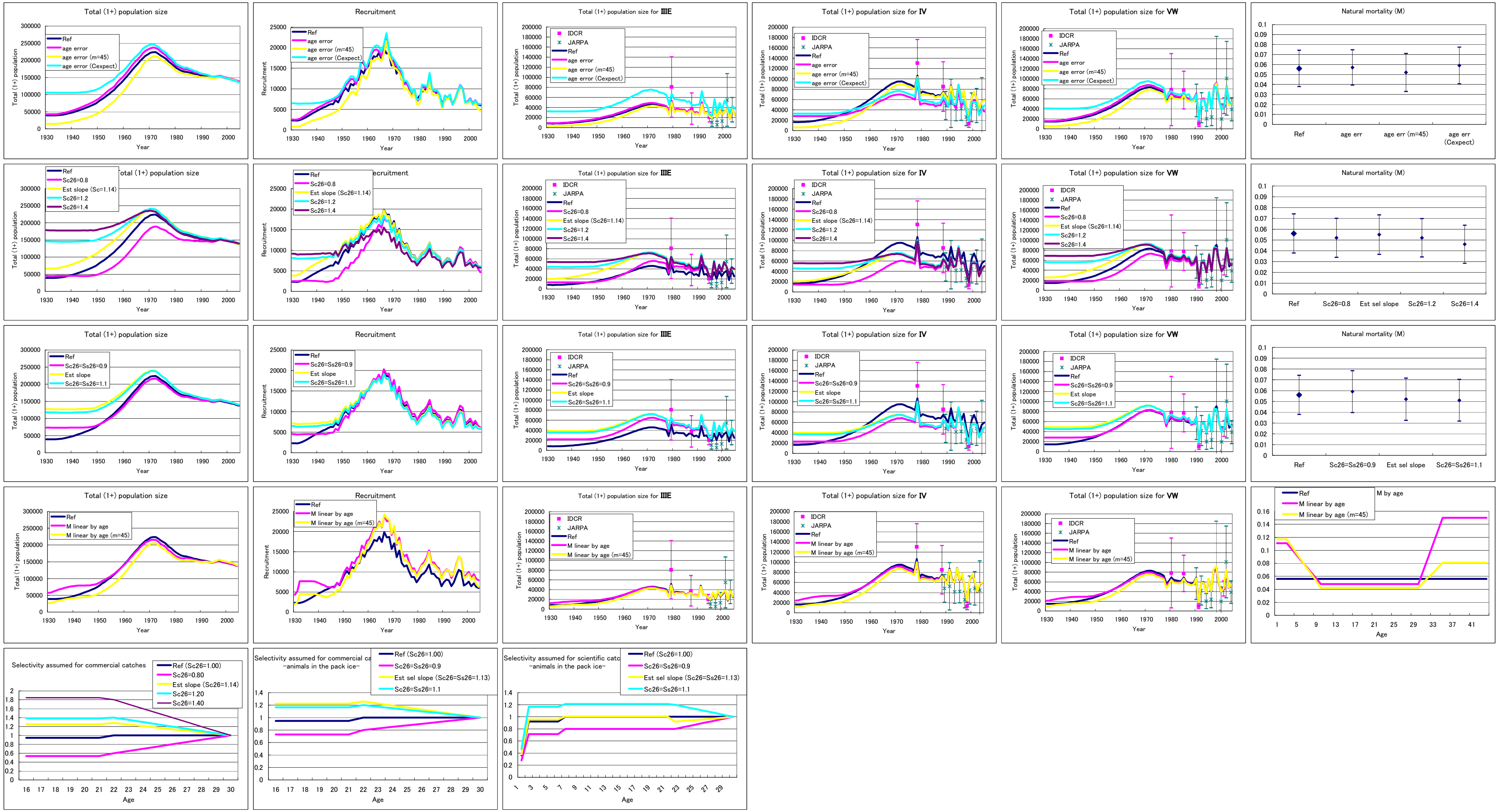

Figure 4b. Plots of total population size by stock and by Area, recruitment, estimated *M* and selectivities for the **I-stock** for various sensitivity test runs, such as 1) Ageing error is introduced; 2)Various alternative selectivity functions are assumed; and 3) The relationship between natural mortality and age is taken to be piecewise linear.

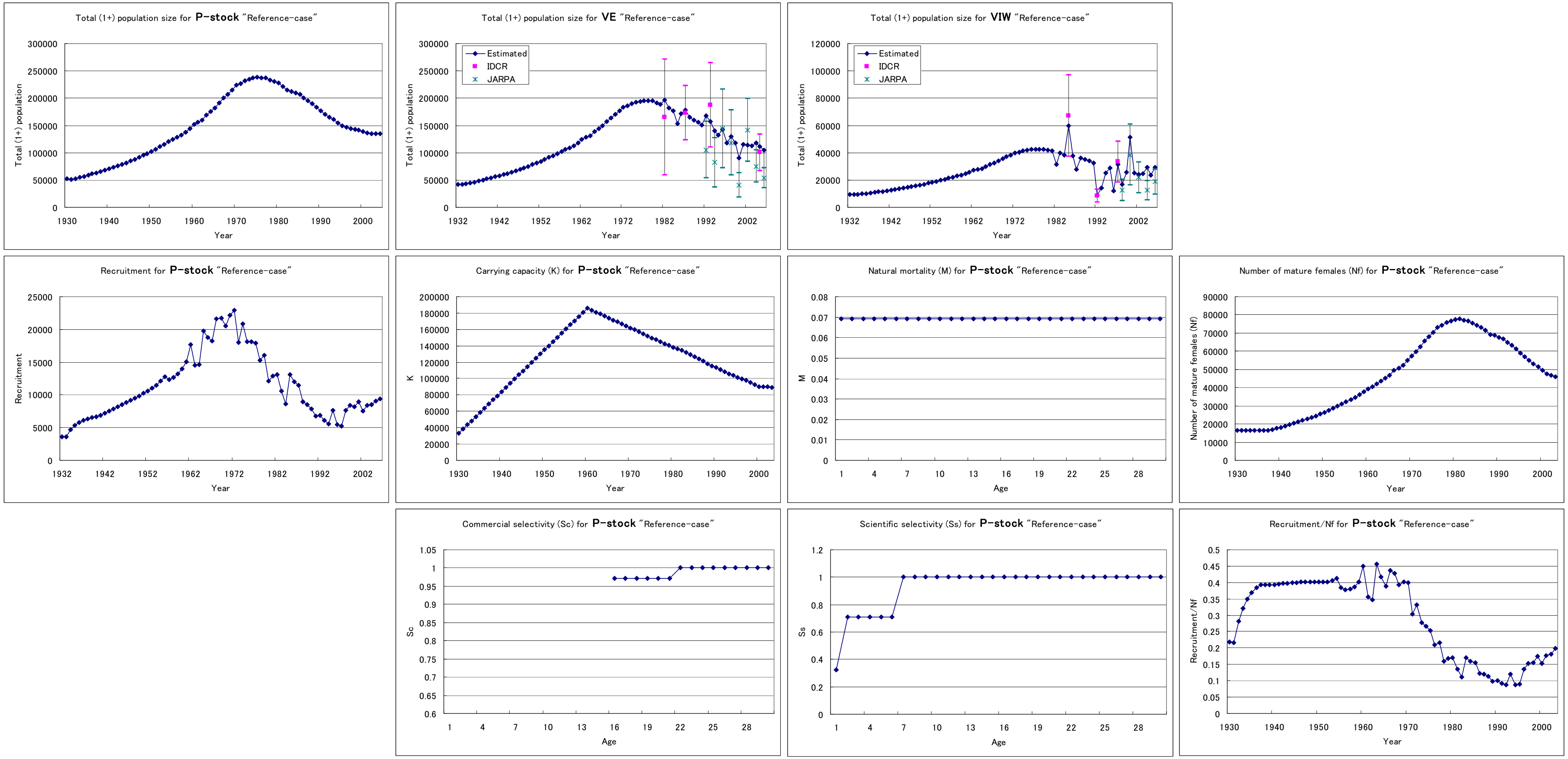

Figure 5. Various plots (including trends in total population size by stock and by area, recruitment, carrying capacity, number of mature females, recruitment rate, selectivity estimates and natural mortality) for the "Reference case" result for the **P-stock**. Error bars reflect 95% CIs on the abundance estimates.

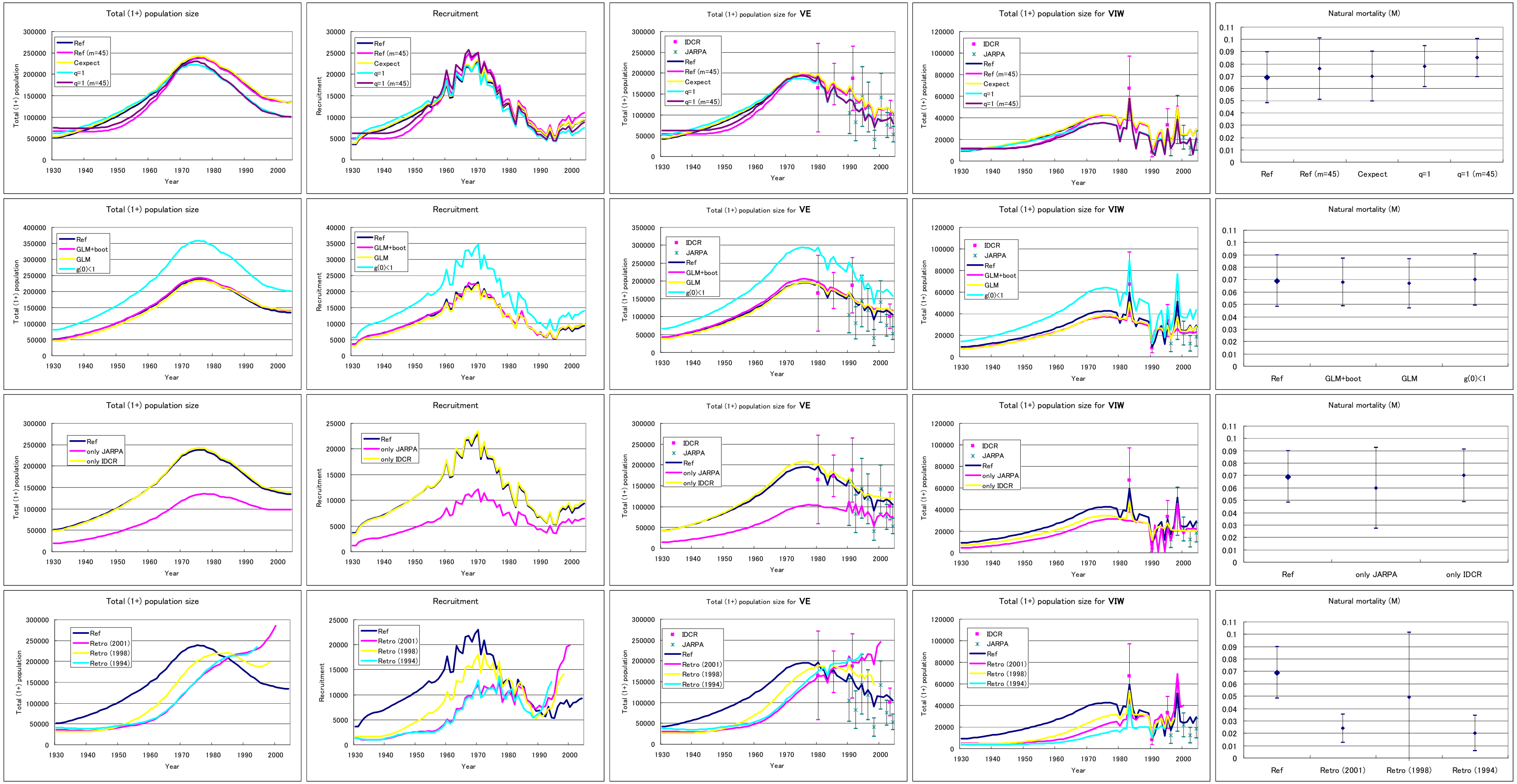

Figure 6a. Plots of total population size by stock and by Area, recruitment, and estimated *M* for the **P-stock** for various sensitivity test runs, including 1) Maximum age *m* considered in the likelihood is 45 rather than 30; 2) $\hat{C}_{y,a}$ is used instead of $C_{y,a}$ in equation (1) for ages considered in the catch-at-age likelihood; 3) Set *q*=1 (i.e. use JARPA abundance estimate as absolute abundance estimates rather than relative); 4) Use different series of abundance estimates for JARPA (detailed in the Data section above), including a 50% increase in the abundance estimates to preliminarily consider the implications of g(0)<1; 5) Either the JARPA or the IDCR/SOWER estimates of abundance are omitted; 6) For the commercial period, only data for the later half (i.e. collected only after 1979) are used since they seem to have lesser age/length measurement errors; and 7) Retrospective analyses for the periods ending 1995, 1998, and 2001. Error bars reflect 95% CIs on the abundance estimates.

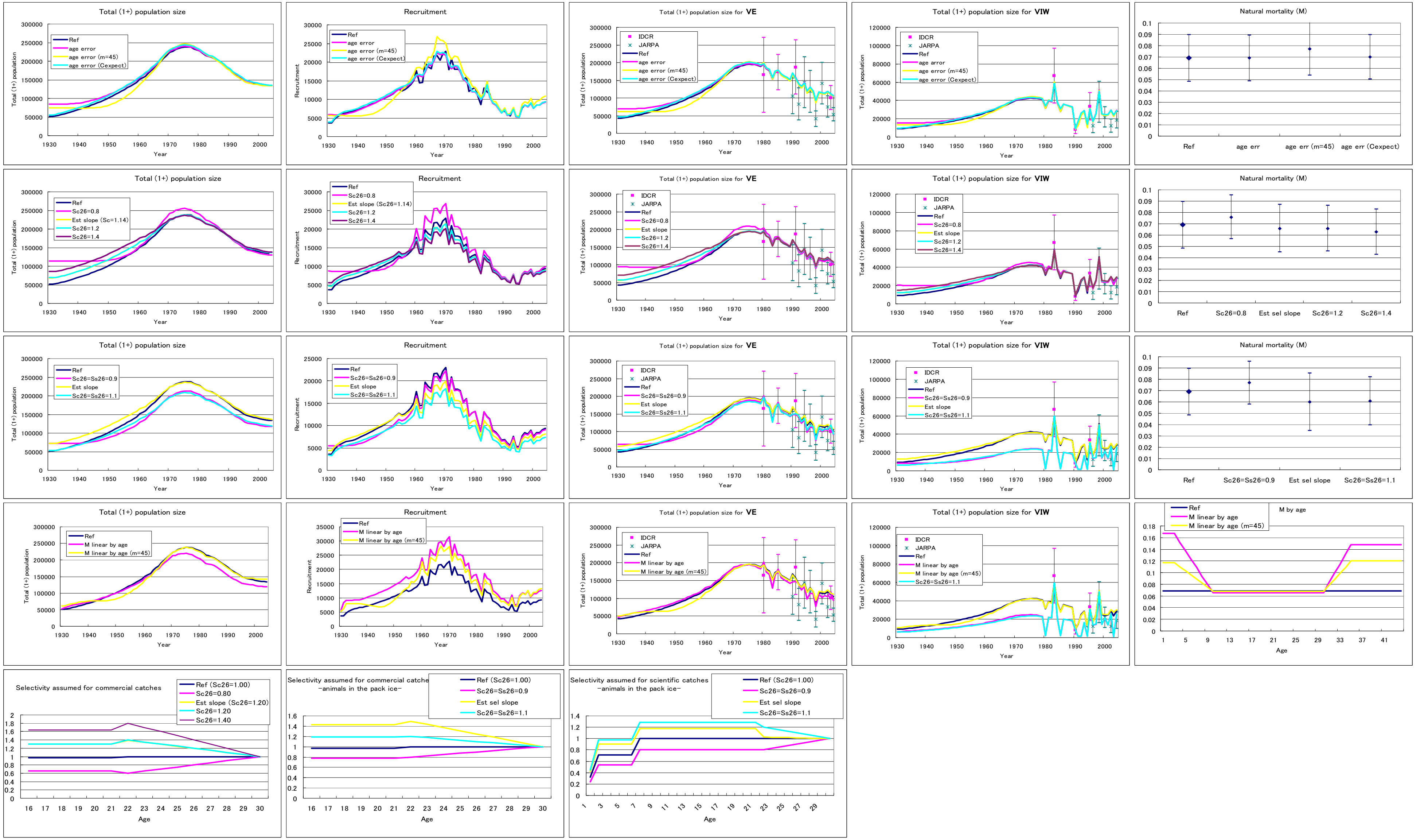

Figure 6b. Plots of total population size by stock and by Area, recruitment, estimated *M* and selectivities for the **P-stock** for various sensitivity test runs, such as 1) Ageing error is introduced; 2)Various alternative selectivity functions are assumed; and 3) The relationship between natural mortality and age is taken to be piecewise linear.