A BAYESIAN ASSESSMENT OF THE WEST AND EAST AUSTRALIAN BREEDING POPULATIONS (STOCKS D AND E) OF SOUTHERN HEMISPHERE HUMPBACK WHALES

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ABSTRACT

A Bayesian assessment of breeding stocks D and E shows qualitatively similar results to those presented previously using maximum likelihood methodology, although (in posterior median terms) breeding stock D is indicated to be a little less recovered than in these previous assessments. Current estimates of abundance relative to pristine are shown to be somewhat sensitive to the two alternate historic catch records currently put forward for south of 40^0 S. A posterior distribution for the maximum growth rate parameter *r* is developed. This posterior could be used as a prior for similar Bayesian assessments of other southern hemisphere humpback populations for which little or no information on increase rates is available.

KEYWORDS: HUMPBACK WHALES, BAYESIAN ASSESSMENT

INTRODUCTION

Initial assessments of breeding populations of Southern Hemisphere humpback whales *(Megaptera novaengliae)* were presented at the 2000 IWC Scientific Committee meeting (Findlay *et al.* 2000; Findlay and Johnston 2001). These assessments were updated the following year (Johnston *et al.* 2001), and covered seven distinct Southern Hemisphere breeding populations, coupled with three sets of hypotheses as to how historic catches from mixtures of these breeding populations on the high latitude feeding grounds are to be allocated to such breeding populations; results were shown to be relatively insensitive across these hypotheses. Johnston *et al.* (2001) further reported results for models for two of the breeding populations for which the models were fitted to CPUE trends as well as to relative abundance indices. Johnston and Butterworth (2002) presented a model for breeding stocks D and E (the east and west Australian populations) which was an extension of these previous assessments, in that links between feeding grounds and breeding grounds were explored. An age-aggregated production model approach continued to form the basis of these assessments. The assessments mentioned above were structured so as to provide maximum likelihood estimates, with bootstrapping used to obtain confidence intervals.

A Bayesian stock assessment of breeding stock A was produced by Zerbini (2004). This paper applies a similar Bayesian methodological approach for breeding stocks D and E, using the population model of Johnston and Butterworth (2002) that allows for mixing on the feeding grounds.

One of the aims of this study is to provide a suitable prior distribution for *r* (the maximum growth rate), for use in assessments of other breeding stocks of southern hemisphere humpback whales (see Johnston and Butterworth 2005; Zerbini 2005).

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METHODS

Data

Historic catch data
The historic catch record for Southern Hemisphere humpback whales can be broken into two categories: catches taken north of 40^0 S and catches taken south of 40^0 S. The updated catch record of whales caught north of 40^0 S is reported in Table 1a. Two alternate catch records exist however, for the catches south of 40^0 S. The first is here termed the "KP" record (reported in Table 2b). The second, here termed the "CA" record and reported in Table 2c, includes both different data sources and new information available in 2005. Recent attempts by Allison and Findlay have been made to update both these catch records. In particular, following the 2004 meeting of the IWC Scientific Committee, the catches from the 60-70^0W longitude band (including those from the South Shetland and "West Antarctica") have been assigned to breeding stock G. In this study, the "KF" series is used for the "base-case" and a sensitivity analysis for the "CA" series is run. These catches have been apportioned to each of the seven hypothesised feeding areas that are associated with breeding stocks A-G under what has previously been termed the "naïve" model (this simply means that each breeding stock is assumed to correspond to a single feeding area), although as stated above, the catches from the 60-70^0W longitude band have been assigned to the G stock, whereas previously they were assigned to the A stock.

Recent absolute abundance estimates
Estimates of recent (in both cases 1999) absolute stock abundance for each of the two breeding stocks considered here are reported in Table 2, along with their associated estimated CVs.

"Trend" data
Relative abundance trend data for breeding population E are from Brown *et al.* (1997) and cover surveys spanning the period 1981-1996. Data for breeding population W are from IWC (1996) cover five surveys spanning the period 1982-1994. These data are reproduced here in Table 3a.

CPUE data from the breeding grounds are from Chittleborough (1965) and span the period 1950-1962 (breeding population W) and 1953-1962 (breeding population E). They are reproduced here in Table 3b.

Updated JARPA estimates of abundance of humpback whales feeding Areas IV and V (Matsuoka *et al*. 2005) are reported in Table 3c. These data are available for every second year from 1989-2003 (Area IV) and 1990-2002 (Area V).

IWC/IDCR-SOWER estimates of abundance (from the feeding area) have been provided by T.A. Branch (pers. commn). These are the Area specific estimates that are summed to give the corresponding circumpolar abundance estimates reported in Branch and Butterworth (2002). These data are available for two years for Area IV (1978 and 1988) and three years for Area V (1980, 1985 and 1991) and are reported here in Table 3d. These data are not used in the model fitting procedure, but instead for subsequent comparative purposes.

The population dynamics models

As in Johnston and Butterworth (2002), we examine two breeding populations: breeding population W (West Australia, which is also denoted as stock "D"), and breeding population E (East Australia, which is also denoted as stock "E"). The models are fit not only to CPUE (though heavily down-weighted) and relative abundance data from the breeding grounds, but also to the recently updated JARPA abundance estimates from feeding Areas IV and V (kindly provided earlier by K. Matsuoka, pers. commn, and now reported in Matsuoka *et al.* 2005). [Comparisons are made later with IWC/IDCR SOWER-survey abundance estimates from these two feeding areas.]

The West (W) and East (E) Australian breeding populations are assumed to feed exclusively in both Antarctic feeding Areas IV (70°E-130°E) and V (130°E-170°E), with no humpback whales from other breeding populations in those Areas.

The catch records for the two feeding grounds (reported in Tables 1b and 1c) correspond to 70°E-120°E (most of Area IV) and 120°E-170°E (mainly Area V). An *ad hoc* adjustment is made to these catches to make allowance for the extra 10 degrees of the latter set of catches which should correspond to the Area IV catch. This adjustment simply removes 20% of the recorded latter set of catches and adds them to the former set. [Data are available to make this adjustment exactly, but it was not possible to pursue this in the time available.]

The population model allows for mixing of the two breeding populations in the feeding areas. Catches taken in the feeding areas are apportioned to each breeding population relative to the numbers present in that feeding area.

Population model and estimation procedure

Breeding stock population dynamics

$$N_{y+1}^{B,W} = N_y^{B,W} + r^W N_y^{B,W}\left(1-(\frac{N_y^{B,W}}{K^w})^{\mu}\right) - C_y^W \quad (1)$$

$$N_{y+1}^{B,E} = N_y^{B,E} + r^E N_y^{B,E}\left(1-(\frac{N_y^{B,E}}{K^E})^{\mu}\right) - C_y^E \quad (2)$$

where

$N_y^{B,W}$ is the number of whales in the breeding population W at the start of year *y*,

$N_y^{B,E}$ is the number of whales in the breeding population E at the start of year *y*,

r^W is the intrinsic growth rate (the maximum per capita the population can achieve, when its size is very low) for breeding population W,

r^E is the intrinsic growth rate for breeding population E,

K^W is the carrying capacity of breeding population W,

K^E is the carrying capacity of breeding population E,

μ is the "degree of compensation" parameter; this is set at 2.39, which fixes the MSY level to MSYL = 0.6*K*, as conventionally assumed by the IWC Scientific Committee,

C_y^W is the total catch (in terms of animals) in year *y* from breeding population W, and

C_y^E is the total catch (in terms of animals) in year *y* from breeding population E.

Feeding stocks

Mixing of the breeding populations in the feeding Areas is described by:

$$N_y^{F,IV} = \alpha N_y^{B,W} + (1-\beta)N_y^{B,E} \quad (3)$$

$$N_y^{F,V} = (1-\alpha)N_y^{B,W} + \beta N_y^{B,E} \quad (4)$$

where

$N_y^{B,IV}$ is the number of whales in feeding Area IV at the start of year *y*,

$N_y^{B,V}$ is the number of whales in feeding Area V at the start of year *y*,

α is the proportion of breeding population W which feeds in feeding Area IV, and

β is the proportion of breeding population E which feeds in feeding Area V.

Thus it follows that:

$1-\alpha$ is the proportion of breeding population W which feeds in feeding Area V, and

$1-\beta$ is the proportion of breeding population E which feeds in feeding Area IV.

Catches

$$C_y^W = C_y^{W,IV} + C_y^{W,V} + C_y^{W,BW} \quad (5)$$

$$C_y^E = C_y^{E,IV} + C_y^{E,V} + C_y^{E,BE} \quad (6)$$

where

$C_y^{W,IV}$ are the catches of animals in year *y* in the western feeding Area (Area IV) which come from the breeding population W,

$C_y^{W,V}$ are the catches of animals in year *y* in the eastern feeding Area (Area V) which come from the breeding population W,

$C_y^{W,BW}$ are the catches of animals in year *y* taken from breeding population W, either in the breeding area or on the migration route,

$C_y^{E,IV}$ are the catches of animals in year *y* in the western feeding Area (Area IV) which come from the breeding population E,

$C_y^{E,V}$ are the catches of animals in year *y* in the eastern feeding Area (Area V) which come from the breeding population E, and

$C_y^{W,BE}$ are the catches of animals in year *y* taken from breeding population E, either in the breeding Area or on the migration route.

We can calculate the breakdown by breeding population of the catches in a feeding Area, *viz.* $C_y^{W,IV}, C_y^{W,V}, C_y^{E,IV}$ and $C_y^{E,V}$, from the assumption that catches by stock are in the same ratio as the numbers of each breeding population present:

$$\frac{C_y^{W,IV}}{\left[C_y^{W,IV} + C_y^{E,IV}\right]} = \frac{\alpha N_y^{B,W}}{N_y^{F,IV}} \quad (7)$$

$$\frac{C_y^{E,IV}}{\left[C_y^{W,IV} + C_y^{E,IV}\right]} = \frac{(1-\beta) N_y^{B,E}}{N_y^{F,IV}} \quad (8)$$

$$\frac{C_y^{W,V}}{\left[C_y^{W,V} + C_y^{E,V}\right]} = \frac{(1-\alpha) N_y^{B,W}}{N_y^{F,V}} \quad \text{and} \quad (9)$$

$$\frac{C_y^{E,V}}{\left[C_y^{W,V} + C_y^{E,V}\right]} = \frac{\beta N_y^{B,E}}{N_y^{F,V}} \tag{10}$$

where we know

$[C_y^{W,IV} + C_y^{E,IV}]$ = Area IV catches recorded for year *y*, and

$[C_y^{W,V} + C_y^{E,V}]$ = Area V catches recorded for year *y*.

Bayesian estimation framework

Priors

Prior distributions were defined for the following parameters:

i) $r^W \sim U[0, 0.126]$

ii) $r^E \sim U[0, 0.126]$

iii) $\alpha \sim U[0, 1]$

iv) $\beta \sim U[0, 1]$

v) $\ln N_{1999}^{A,obs} * \sim U[\ln N_{1999}^{A,obs} - 4CV, \ln N_{1999}^{A,obs} + 4CV]$

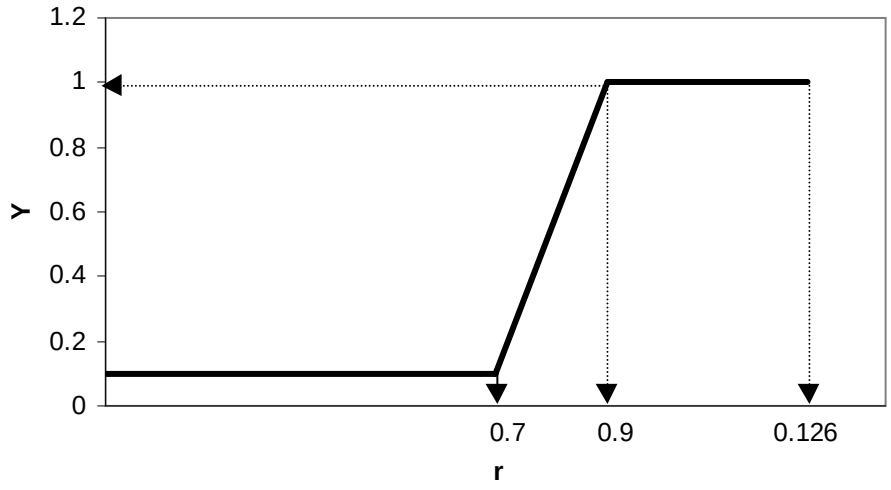
The uninformative r^W and r^E priors were bounded by zero (negative rates of growth are biologically implausible) and 0.126 (this corresponds to the maximum growth rate for the species as evaluated by Clapham *et al.* 2001). The prior distribution from which target abundance estimates ($N_y^{A,obs} *$) are drawn at random is uniform on a natural logarithmic scale. The lower and upper bounds are set by four times the CV. The CV is 0.122 for stock E (Paterson *et al.* 2001) and 0.111 for stock W (Bannister and Hedley 2001). (This latter CV takes no account of uncertainty about $g(0)$ as the Table 2 estimate for stock W abundance is taken as the lowest value in the corresponding range of uncertainty quoted by Bannister and Hedley (2001)).

A constraint needs to be placed on the values of α and β generated from the priors above. The reason is that priors of that form do not exclude the possibility that nearly all breeding stock W feed in Area V, and nearly all E breeders feed in Area IV: such a cross-over would clearly not be biologically plausible. We accordingly add the assumption that the proportion of E whales going to Area V must be greater than the proportion of Ws, and *vice versa* for Area IV. Mathematically this amounts to requiring:

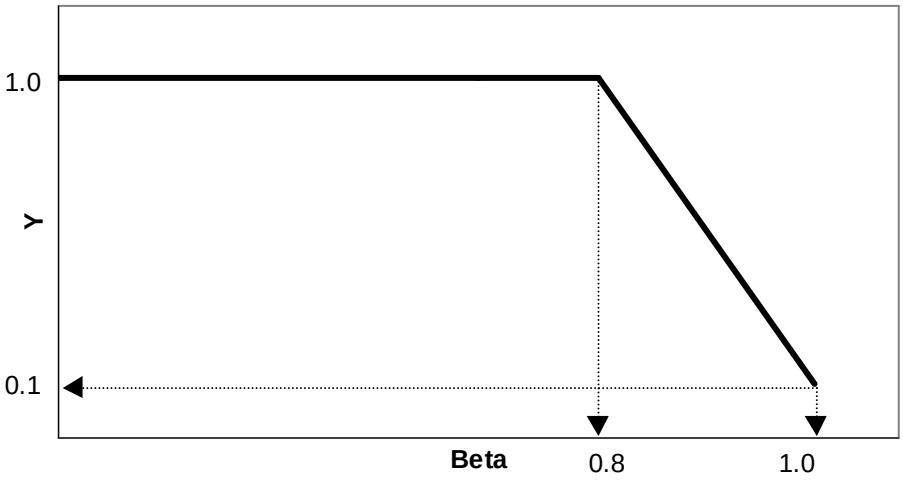
$$\alpha + \beta > 1$$

For each of n_1 simulations, values of $N_{1999}^{W,obs} *$ and $N_{1999}^{E,obs} *$, r^W and r^E, and α and β are drawn from their prior distributions. As the population model and associated minimization of its parameter is considerably more complex than that used for the other breeding stocks (see Johnston and Butterworth 2005; Zerbini 2004, 2005), a method for reducing the number of "unlikely" parameter vectors drawn from the various priors was needed to speed computations. The authors thus defined simple importance functions for the r^W and r^E and β parameters based on previous modeling results.

For the r^W and r^E priors this took the form:



and for the β prior:



These importance functions modified the probabilities of generation of values from the uniform priors across their ranges. To compensate, a weight (W_{prior}) is then assigned to values generated from each of these three priors, which then multiplies the likelihood function value resulting from the model fit using the various values generated from the priors. These weights are calculated as follows:

$$W_{prior} = 1/Y \tag{11}$$

where Y is the value of the importance function in question (see above).

Using the randomly drawn vector of values of $N_{1999}^{W,obs}*$, $N_{1999}^{E,obs}*$, r^W, r^E, α and β, a downhill simplex method of minimization is used to calculate K^W and K^E such that the model estimates of $\hat{N}_{1999}^{W}$ and $\hat{N}_{1999}^{E}$ are identical to the randomly drawn values $N_{1999}^{W,obs}*$ and $N_{1999}^{E,obs}*$.

For each simulation, using the r^W, r^E, α, β and calculated K^W and K^E values, a negative log likelihood is then calculated by comparing the population model to observed data - these being the target abundance estimates from the breeding grounds (see Table 2), CPUE data from the breeding grounds (see Table 3b), relative abundance trend data from the breeding ground/migration route surveys (see Table 3a) and JARPA abundance estimates from feeding Areas IV and V (see Table 3c). The components of the negative log likelihood are calculated as follows:

It is assumed that the observed abundance index is log-normally distributed about its expected value:

$$I_y^A = q^A \hat{N}_y^{B,A} e^{\varepsilon_y} \tag{12}$$

where

I_y^A is either the survey-based relative abundance or CPUE index for year *y* for breeding population *A* (either W or E),

q^A is the multiplicative bias/catchability coefficient for that index for breeding population *A*,

$\hat{N}_y^{B,A}$ is the model estimate of population size at the start of year *y* for breeding population *A*, and

ε_y is from $N(0, \sigma_{B,A}^2)$.

The model treats the JARPA abundance estimates as relative indices as follows. It is assumed that the observed abundance index is log-normally distributed about its expected value:

$$I_y^A = q_{JARPA}^A \hat{N}_y^{F,A} e^{\varepsilon_y} \tag{13}$$

where

I_y^A is the JARPA abundance estimate for year *y* and feeding stock *A* (either IV or V),

q_{JARPA}^A it the multiplicative bias of the JARPA abundance estimate for feeding stock *A*, which is set equal to 1 when this is treated as an index of absolute abundance,

$\hat{N}_y^{F,A}$ is the model estimate of population size at the start of year *y* for feeding stock *A*, and

ε_y is from $N(0, (\sigma_{JARPA}^A)^2)$.

The contributions of the various data to the negative of the log-likelihood function are then given by:

$$\begin{aligned} -\ln L = & \sum_A \left(n_B^A \ln \sigma_B^A + \frac{1}{2\sigma_B^{A\,2}} \sum_y \left(\ln I_y^A - \ln q_B^A - \ln \hat{N}_y^{B,A} \right)^2 \right) + \\ & w_{cpue} \sum_A \left[n_{CPUE}^A \ln \sigma_{CPUE}^A + \frac{1}{2\sigma_{CPUE}^{A\,2}} \sum_y \left(\ln I_{CPUE,y}^A - \ln q_{CPUE}^A - \ln \hat{N}_y^{B,A} \right)^2 \right] + \\ & \sum_A \left[n_{JARPA}^A \ln \sigma_{JARPA}^A + \frac{1}{2\sigma_{JARPA}^{A\,2}} \sum_y \left(\ln I_{JARPA,y}^A - \ln q_{JARPA}^A - \ln \hat{N}_y^{F,A} \right)^2 \right] + \\ & \frac{1}{2CV^2} \left(\ln N_Y^{A,obs} - \ln \hat{N}_Y^{B,A} \right)^2 \end{aligned} \tag{14}$$

where

w_{cpue} is the weight given to the CPUE data, which are heavily downweighted here

with a value of $w_{\text{cpue}} = 0.0001$ (due to the fact that the CPUE data are considered to be less reliable than the survey-based relative abundance data – effectively this means that these CPUE data do not influence the likelihood itself, but their inclusion in the likelihood serves to provide an estimate of the associated catchability coefficient *q*),

The σ parameters are the residual standard deviations which are estimated in the fitting procedure by their maximum likelihood values:

$$\hat{\sigma}^A = \sqrt{1/n \sum_y \left(\ln I_y^A - \ln q^A - \ln \hat{N}_y^{B,A} \right)^2} \quad \text{for breeding survey/CPUE data} \tag{15}$$

and

$$\hat{\sigma}^A_{JARPA} = \sqrt{1/n \sum_y \left(\ln I^A_{JARPA,y} - \ln q^A_{JARPA} - \ln \hat{N}_y^F \right)^2} \quad \text{for feeding ground JARPA survey data} \tag{16}$$

where

n is the number of data points in the abundance index or CPUE series, and

q is the multiplicative bias/catchability coefficient, estimated by its maximum likelihood value:

$$\ln \hat{q}^A = 1/n \sum_y \left(\ln I_y^A - \ln \hat{N}_y^{B/F,A} \right) \tag{17}$$

(This is a short cut to avoid integrating over priors for the *q*'s and σ^2's, and in fact corresponds to the assumption that these priors are uniform in log-space and proportional to σ^{-3} respectively (Walters and Ludwig 1994)).

The negative log likelihood is then converted into a likelihood value (*L*). This likelihood value is subsequently multiplied by the various importance function weights as described above to take account of the use of importance functions, yielding a modified likelihood L^m:

$$L^m = L\, W_{r^W} W_{r^E} W_\beta \tag{18}$$

The integration of the prior distributions of the parameters and the likelihood function then essentially follows the Sampling-Importance-Resampling (SIR) algorithm presented by Rubin (1988) as described in Zerbini (2004). For a vector of parameter values θ_i, the (importance function modified) likelihood of the data associated with this vector of parameters (L^m) as described above is calculated and stored. This process is repeated until an initial sample of n_1 θ_is is generated. This sample is then resampled with replacement n_2 times with probability equal to weight w_j, where:

$$w_j = \frac{L^m(\theta_j / data)}{\sum_{j=1}^{n1} L^m(\theta_j / data)} \tag{19}$$

The resample is thus a random sample of size n_2 from the joint posterior distribution of the parameters (Rubin 1988).

Values of n_1 (original number of simulations) are 100 000 and the value of n_2 (number of resamples) is 1000. Note that the number of n_1 and n_2 are lower than have been used for the other breeding stocks (see Johnston and Butterworth 2005, Zerbini 2004, 2005) – but the method described above using importance functions allowed the use of these lower values of simulations without compromising precision. Convergence was tested by examining results for different random number seeds. For an earlier version of the base case, convergence was examined for n_1 = 250 000 and by ensuring that no sample contributed more than 0.05% of the total weight. For this version of the base case, 94% of the resamples were unique values. [Note however that this earlier base case took 48 computing hours to run!]

Projections
The populations are projected into the future under a continuation of a zero harvesting strategy.

Sensitivity analyses
Two sensitivity analyses are explored here. The first is where the "CA" historic catch series is used (instead of the "KF" series). The second analysis relates to how the priors on the α and β are modified by the constraint $\alpha + \beta > 1$. The impact of this constraint results in effective priors for α and β that are no longer uniform: higher values of α and β are preferred suggesting that *a priori* the probability of, say, whales from breeding stock W going to Area IV is more likely to be large. To our knowledge, the only joint prior on the space defined by this constraint that maintains uniform marginal probabilities on α and β is a uniform distribution of delta functions along the line $\alpha + \beta = 1$, i.e. effectively select α from U[0, 1] and then fix $\beta = 1 - \alpha$. While this is clearly not a realistic assumption to make for these analyses, we have shown results for this option as indicative of the direction and extent that a defensible modification of the priors for α and β for the base case might cause.

RESULTS AND DISCUSSION

The results of the analyses for both sets of historic catch records are reported in Table 4a. Table 4b reports results for the sensitivity analyses that used an alternate form for an uninformative prior for α and β. The base case posterior median for α (0.68) is similar to that for β (0.71), suggesting that around 30% of each breeding population crosses over to feed in the other's primary feeding Area. Results for the sensitivity test using the "CA" historic catch series are very similar to those for the "KF" series (Table 4a), except that the former indicates lower carrying capacity *K*, and hence yields higher estimates for the current depletions (N_{2004}/K). This is a consequence of the higher total historic catches for the "KF" series compared to the "CA": series (see Tables 1b and c). The alternative joint uninformative prior for α and β leads to wider probability intervals for these quantities with lower posterior medians, but the posteriors for other quantities are scarcely affected.

The results are qualitatively similar to the MLE results of Johnston and Butterworth (2002) except in two consequential respects: posterior medians of N_{2004}/K tend to be larger than MLE, indicating a greater degree of recovery, and the precision of the estimates of α and β is poorer (we suspect this last result is a consequence of the bootstrap procedure used for confidence interval estimation in earlier papers having failed to converge satisfactorily for all bootstrap replicates).

Figure 1a illustrates the posterior probability distributions for the base case r^W and r^E parameters, as well as for the combined distribution for both parameters. Figure 1b illustrates the base case posterior probability distributions of various other model parameters and management related quantities.

Figures 2a-c illustrate how well the base case model (in terms of its posterior median) fits to the available abundance-related information. The breeding ground survey trends are reflected closely (Figure 2a). The fits to the JARPA feeding ground trends show greater variability – for feeding Area IV, the model is unable to reproduce the two high most recent estimates (Figure 2b). This greater variability is, however, not unexpected, as unlike for the breeding grounds, numbers in feeding grounds from year to year would be expected to change to a greater extent as food distribution patterns change. In qualitative terms, the CPUE trends over the 1950s and 1960s (Figure 2c) are also reasonably reflected. Agreement is not exact however, which is why these data are under-weighted in the likelihood, as they cannot in any case be considered comparatively as reliable as the later scientific survey results as indices of population abundance. Figure 2d provides a comparison between the IWC/IDCR-SOWER estimates of abundance in the two feeding areas with those estimated by the base case model, again reflecting reasonable agreement.

Projections
Trends in the estimated breeding and feeding stocks for the base case model fit are shown in Figure 3a. In terms of the median, near complete recoveries to pristine levels under zero harvest are suggested in some 15 years for stock W, and some 20 years for the currently more depleted (relative to pristine) stock E.

Posteriors
Posterior distribution histograms of various parameters are illustrated in Figure 1. One of the aims of this study was to be able to produce information from the posterior distributions of r^W and r^E, in order to provide a prior for

use in studies of other southern hemisphere humpback breeding populations, for which little or no information on increase rates are available. An average of the two posteriors is suggested for this purpose, and is illustrated in the lowest plot within Figure 1.

CONCLUDING REMARKS

The available data continue to give a self consistent picture of breeding populations to the west and east of Australia that are recovering well from their minima in the 1960s with the recovery of the western stock likely the further advanced.

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Table 1a: Catches taken north of 40^0 S for southern hemisphere humpback whales. Catches are reported for the seven hypothesised breeding stocks (BS).

	BS A	BS B	BS C	BS D	BS E	BS F	BS G
1904	0	0	0	0	0	0	0
1905	0	0	0	0	0	0	0
1906	0	0	0	0	0	0	0
1907	0	0	0	0	0	0	0
1908	0	0	104	0	0	0	0
1909	0	272	155	0	0	0	0
1910	0	962	640	0	0	0	0
1911	102	2506	1576	0	0	0	0
1912	342	4076	2106	240	250	0	86
1913	352	6456	1562	940	400	0	0
1914	317	2269	824	1950	18	0	23
1915	0	5	122	1460	0	0	10
1916	0	3	83	450	0	0	15
1917	0	7	7	0	0	0	15
1918	0	19	9	0	0	0	23
1919	0	14	91	0	0	0	24
1920	0	20	148	0	0	0	21
1921	0	30	190	0	0	0	21
1922	0	626	285	155	0	0	19
1923	0	899	183	166	0	0	16
1924	0	537	187	0	0	0	34
1925	0	843	167	669	0	0	248
1926	0	442	124	735	0	0	261
1927	0	47	84	996	0	0	22
1928	0	68	62	1033	0	0	36
1929	0	50	99	0	0	0	26
1930	0	622	131	0	78	0	33
1931	0	0	71	0	110	0	53
1932	0	0	309	0	18	0	21
1933	0	0	162	0	44	0	11
1934	0	724	514	0	52	0	13
1935	0	2479	418	0	57	0	73
1936	0	1639	301	6148	69	0	22
1937	0	625	4476	6492	55	0	37
1938	0	0	1927	1834	75	0	6
1939	0	0	2441	0	80	0	7
1940	0	0	176	0	107	0	0
1941	0	0	79	0	86	0	0
1942	0	0	0	0	71	0	0
1943	0	0	80	0	90	0	0
1944	0	0	115	0	88	0	0
1945	0	0	46	0	107	0	0
1946	0	0	93	0	110	0	15
1947	11	5	90	2	101	0	21
1948	21	14	182	4	92	0	5
1949	15	2704.4	1523.6	193	141	0	6
1950	24	2128.4	862.6	388	79	0	5
1951	28	791.4	103.6	1224	111	0	24
1952	10	313	111	1187	721	0	27
1953	8	9	89	1300	809	0	27
1954	18	0	27	1320	898	0	106
1955	9	0	49	1126	832	0	7
1956	14	3	36	1119	1013	0	10
1957	0	3.8	35.2	1120	1025	0	5
1958	5	3.9	42.1	967	1023	0	0
1959	8	169.2	41.8	737	1315	0	3
1960	13	6.25	39.8	573	1369	0	2
1961	13	13	47	587	988	0	3
1962	13	10.5	39.3	548	214	0	4
1963	0	7.8	39.2	87	0	0	1
1964	0	3.4	5.6	1	1	0	35
1965	1	0	5	5	5	0	143
1966	9	0	2	28	28	0	58
1967	192	2	64	12	12	0	3
1968	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0
1970	0	0	0	0	0	0	0
TOTALS	**1525**	**32427**	**23583**	**35796**	**12742**	**0**	**1686**

Table 1b: "KF" (Ken Findlay pers. commn) record of catches taken south of 40^0S for southern hemisphere humpback whales. Catches have been apportioned into seven feeding areas.

	Area A	Area B	Area C	Area D	Area E	Area F	Area G
	60W-20W	20W-10E	10E-60W	60E-120E	120E-170E	170E-110W	110W-60W-
1904	180	0	0	0	0	0	0
1905	288	0	0	0	0	0	23
1906	240	0	0	0	0	0	492
1907	1261	0	0	0	0	0	336
1908	1858	0	0	217	0	0	1240
1909	3485	0	0	118	0	0	1481
1910	6197	0	0	83	0	0	2370
1911	5777	0	0	0	0	0	2056
1912	2525	0	0	0	0	0	976
1913	653	0	0	0	0	0	1089
1914	845	0	0	0	0	0	656
1915	1578	0	0	0	0	0	219
1916	378	0	0	0	0	0	21
1917	50	0	0	0	0	0	71
1918	68	0	0	0	0	0	81
1919	79	0	0	0	0	0	182
1920	103	0	0	0	0	0	157
1921	9	0	0	0	0	0	0
1922	329	0	0	0	0	0	188
1923	133	0	0	0	0	0	100
1924	262	0	0	0	0	0	197
1925	240	0	0	0	0	0	124
1926	4	0	0	0	0	0	103
1927	1	0	0	0	0	0	6
1928	15	0	0	11	0	0	16
1929	46	0	0	0	0	0	34
1930	66	0	0	0	0	0	339
1931	18	3	2	159	0	0	0
1932	23	18	37	82	0	0	0
1933	132	83	54	593	0	0	0
1934	57	38	541	1340	0	0	0
1935	48	300	1868	938	4	0	0
1936	106	250	2683	1435	0	0	0
1937	241	188	774	832	32	0	0
1938	0	0	0	835	48	0	0
1939	2	0	4	0	0	0	0
1940	37	242	0	0	0	0	0
1941	16	0	0	0	0	0	0
1942	0	0	0	0	0	0	0
1943	4	0	0	0	0	0	0
1944	60	0	0	0	0	0	0
1945	238	0	0	0	0	0	0
1946	30	1	0	0	0	0	0
1947	24	1	0	1	0	0	0
1948	21	4.7	12.8	43.2	61.3	0	0
1949	66	161.7	221.5	871.9	1296.8	0	0
1950	281	14.3	69.1	1479.1	684.5	292	0
1951	11	41	44.9	1129.2	914.8	38	0
1952	18	61.7	63.2	312.8	687.3	13	0
1953	19	12.8	31.1	356.5	152.5	136	0
1954	2	5.5	47.8	165.1	1137.7	340	0
1955	0	3.6	34.3	1255.9	2503.2	334	14
1956	5	9.2	17.3	106	150.6	37	629
1957	0	49.1	153.5	842.2	1220.1	198	59
1958	0	135.2	230.8	2820.2	2826.8	0	0
1959	182	126.2	459.8	2772.3	6160.9	3861.8	0
1960	7	165.3	305.1	2172.5	6734.2	3474.9	86
1961	0	41.9	117.9	1067.5	2518.1	1492.9	288.6
1962	0	11.3	70.6	1343.5	981.6	468.4	50.6
1963	0	3.5	16.8	216.3	250.9	185.3	13.2
1964	0	0	48.3	47.9	80.6	34.4	12.9
1965	52	915.1	83.4	117.9	442.6	415.3	19.7
1966	0	147	198.5	50.8	184.8	164.0	13.9
1967	0	365	61.2	33.2	113.9	87.7	11
1968	0	0	0	0	0	0	0
1969	0	0	0	0	0	0	0
1970	0	0	0	0	0	0	0
1971	0	0	0	0	0	3	0
1972	0	1	0	0	2	0	0
TOTALS	**28370**	**3399**	**8251**	**23848**	**29189**	**11576**	**13755**

Table 1c: "CA" (Cherry Allison pers. commn) record of catches taken south of 40^0 S for southern hemisphere humpback whales. Catches have been apportioned into seven feeding areas.

	Area A	**Area B**	**Area C**	**Area D**	**Area E**	**Area F**	**Area G**
	60W-20W	20W-10E	10E-60W	60E-120E	120E-170E	170E-110W	110W-60W-
1904	180	0	0	0	0	0	0
1905	288	0	0	0	0	0	23
1906	240	0	0	0	0	0	229.1
1907	1261	0	0	0	0	0	130
1908	1849	0	0	217	0	0	1248.3
1909	3391	0	0	118	0	0	1575
1910	4976	0	0	0	0	0	2246
1911	4381.5	0	0	0	0	0	1689
1912	2054	0	0	0	0	0	984
1913	546	0	0	0	0	0	1045.6
1914	896	0	0	0	0	0	610
1915	1667	0	0	0	0	0	167
1916	379	0	0	0	0	0	21
1917	59	0	0	0	0	0	69
1918	67	0	0	0	0	0	81
1919	106	0	0	0	0	0	157
1920	115	0	0	0	0	0	136
1921	9	0	0	0	0	0	0
1922	437	0	0	0	0	0	116
1923	136	0	0	2	0	0	91
1924	276	0	0	0	0	0	92
1925	264.1	0.4	7	6.4	0	0	139
1926	35.1	0.3	4.5	4.1	0	82	64
1927	1	0	0	0	0	16	3
1928	16.1	0.2	3	15.8	0	17	10
1929	49	11	7	11	33	743	3
1930	103	76	188	39	59	105	12
1931	20	3	2	159	0	0	0
1932	23	13	37	82	0	0	0
1933	132	84	57	595	0	0	4
1934	57	43	541	1340	0	0	0
1935	48	301	1869	759	4	0	181
1936	106	250	2683	1435	0	0	0
1937	241	189	781	833	32	0	1
1938	0	0	0	835	48	0	0
1939	2	0	4	0	0	0	0
1940	37	242	0	0	2401.0	0	0
1941	13	0	0	0	0	0	0
1942	0	0	0	0	0	0	0
1943	4	0	0	0	0	0	0
1944	60	0	0	0	0	0	0
1945	238	0	0	0	0	0	0
1946	30	0	0	0.3	0.2	0.5	0
1947	24	1	0	1	0	0	0
1948	21	3.3	8.8	34.7	24.3	50.8	0.4
1949	66	155.4	203.3	832.7	1127.5	231.3	1.8
1950	10	2.7	35.3	1406.6	204.3	915.8	274.3
1951	11	33.7	23.6	1083.6	427.6	599.4	2.1
1952	23	53.9	52.0	289.0	233.2	504.8	1.1
1953	19	9.7	22.1	337.1	54.7	264.5	0.9
1954	2	1.0	34.8	137.4	834.0	687.4	1.3
1955	0	0.7	127.4	1088.8	2424.0	440.8	63.3
1956	0	5.8	7.4	84.9	59.4	161.5	635.0
1957	0	28.5	84.4	673.9	640.2	1078.1	65.8
1958	0	85.4	86.3	2510.5	1488.1	1828.6	14.2
1959	9.7	95.6	323.4	2894.4	2702.1	5228.8	2315.5
1960	12.2	142.3	203.0	2260.3	3396.0	5263.4	1667.8
1961	0	18	28	363	1106	2797	1211
1962	14.2	180.7	74.8	945.6	932.9	688.4	92.5
1963	0	2	32.0	347.0	279.8	22.7	2.4
1964	0.9	15	1.9	63.0	89.6	33.4	3.2
1965	52	914	75.4	97.2	180.7	699.6	20.2
1966	4.5	65.9	16.4	301.2	322.6	663.0	168.5
1967	7.0	110.8	22.9	169.6	305.1	459.0	79.6
1968	0	0	0	0.3	0.8	0.7	0.2
1969	0	0	0	0	0	0	0
1970	0	0	0	0	0	0	0
1971	0	0	0	0	0	3	0
1972	2	1	0	0	0	0	0
TOTALS	**25071**	**3139**	**7646**	**22373**	**19410**	**23586**	**17748**

Table 2
Recent absolute abundance estimates used for each breeding stock.

Breeding Stock	Year	Abundance estimate	Source
D	1999	8000 (CV=0.111)	Bannister and Hedley (2001)
E	1999	3600 (CV=0.122)	Paterson *et al.* (2001)

Table 3a
Breeding stocks W (D) and E: Relative abundance estimates for breeding populations W (IWC 1996) and E (Brown et al. 1997).

Year	**Breeding stock W (West Australia)**
1982	10.2
1986	16.2
1988	12.7
1991	23.6
1994	36.0
	Breeding stock E (East Australia)
1981	381
1982	493
1986	1008
1987	879
1991	1533
1993	1807
1996	2872

Table 3b
Breeding stocks W (D) and E: CPUE data (Chittleborough 1965).

Year	**Breeding stock W**	**Breeding stock E**
1950	0.475	
1951	0.424	
1952	0.347	
1953	0.353	0.972
1954	0.351	0.755
1955	0.244	0.779
1956	0.178	0.704
1957	0.146	0.714
1958	0.123	0.750
1959	0.090	0.740
1960	0.062	0.522
1961	0.055	0.230
1962	0.051	0.069

Table 3c
Feeding Areas IV and V: JARPA estimates of abundance (Matsuoka *et al.* 2005).

Year	Feeding Area IV
1989	5230
1991	5350
1993	2740
1995	8850
1997	10874
1999	16211
2001	33010
2003	31750
	Feeding Area V
1990	1354
1992	3837
1994	3567
1996	1543
1998	8301
2000	4720
2002	2735

Table 3d
Estimates of abundance of humpback whales south of 60^{0} S from the IWC/IDCR-SOWER sightings surveys (T.A. Branch, pers. commn).

Year	Circumpolar Survey	Area IV	Area V
1978	I	1039	-
1980	I	-	966
1985	III	-	568
1988	II	3375	-
1991	III	-	2066

Table 4a

Results using both the base case ("KF") and the "CA" historic catch series. Note the –ln*L* contributions listed exclude the weighting factors (see eqn 13). Posterior median values are presented with the values in square brackets the 5th and 95th percentiles. Note that σ_{JARPA} values apply respectively to Areas IV and V rather than to breeding populations W and E respectively.

	Base Case: "KF" historic catch series		**Sensitivity test: "CA" catch series**	
	Stock W	**Stock E**	**Stock W**	**Stock E**
α	0.679 [0.193, 0.966]		0.672 [0.193, 0.970]	
β	0.712 [0.231, 0.972]		0.717 [0.212, 0.977]	
r	0.109 [0.078, 0.123]	0.122 [0.108, 0.126]	0.109 [0.079, 0.124]	0.121 [0.106, 0.126]
K	28230 [20494, 36837]	21825 [15043, 31716]	23127 [20663, 31276]	16612 [12163, 22336]
q_{JARPA}	2.14 [1.34, 7.33]	0.86 [0.45, 2.80]	2.13 [1.32, 6.97]	0.84 [0.44, 2.98]
N_{lowest}	334 [212, 822]	104 [82, 158]	331 [208, 817]	107 [83, 166]
N_{target}	8007 [6547, 9625]	3580 [2947, 4546]	8015 [6588, 9697]	6133 [5065, 7492]
N_{2004}	12656 [10251, 15103]	6203 [5088,7562]	12571 [10263, 15004]	6162 [5125, 7522]
N_{2004}/K	**0.46 [0.30, 0.63]**	**0.29 [0.19, 0.42]**	**0.50 [0.34, 0.64]**	**0.37 [0.26, 0.52]**
σ_{CPUE}	0.401 [0.365, 0.415]	0.184 [0.154, 0.230]	0.374 [0.339, 0.381]	0.192 [0.171, 0.217]
σ_B (relative abundance)	0.168 [0.165, 0.197]	0.118 [0.110, 0.160]	0.169 [0.166, 0.197]	0.120 [0.110, 0.169]
σ_{JARPA}	0.460 [0.433, 0.527]	0.564 [0.545, 0.575]	0.463 [0.436, 0.527]	0.562 [0.544, 0.574]
-*lnL* CPUE	-5.36	-11.94	-6.30	-11.48
-*lnL* relative abundance	-6.40	-11.44	-6.38	-11.34
-*lnL JARPA*	-2.21	-0.51	-2.16	-0.54
-*lnL "targets"*	0.209	0.236	0.204	0.226
-*lnL (TOTAL) (includes weights)*	-19.50		-19.27	

Table 4b

Comparison of base case results with results of the sensitivity analysis for which $\beta = 1 - \alpha$ to mimic uninformative marginal priors for α and β. Note the –ln*L* contributions listed exclude the weighting factors (see eqn 13). Posterior median values are presented with the values in square brackets the 5th and 95th percentiles. Note that σ_{JARPA} values apply respectively to Areas IV and V rather than to breeding populations W and E respectively.

	Base Case: "KF" historic catch series		$\beta = 1 - \alpha$	
	Stock W	**Stock E**	**Stock W**	**Stock E**
α	0.679 [0.193, 0.966]		0.504 [0.059, 0.959]	
β	0.712 [0.231, 0.972]		0.496 [0.0.041, 0.941]	
r	0.109 [0.078, 0.123]	0.122 [0.108, 0.126]	0.108 [0.075, 0.124]	0.121 [0.107, 0.126]
K	28230 [20494, 36837]	21825 [15043, 31716]	28773 [25439, 36991]	20759 [17825, 23490]
q_{JARPA}	2.14 [1.34, 7.33]	0.86 [0.45, 2.80]	2.40 [1.23, 19.15]	0.74 [0.38, 8.83]
N_{lowest}	334 [212, 822]	104 [82, 158]	343 [214, 868]	106 [82, 159]
N_{target}	8007 [6547, 9625]	3580 [2947, 4546]	7997 [6543, 9610]	3591 [2942, 4402]
N_{2004}	12656 [10251, 15103]	6203 [5088,7562]	12686 [10287, 15347]	6219 [5103, 7603]
N_{2004}/K	**0.46 [0.30, 0.63]**	**0.29 [0.19, 0.42]**	**0.44 [0.29, 0.57]**	**0.30 [0.24, 0.38]**
σ_{CPUE}	0.401 [0.365, 0.415]	0.184 [0.154, 0.230]	0.408 [0.403, 0.410]	0.191 [0.173, 0.235]
σ_B (relative abundance)	0.168 [0.165, 0.197]	0.118 [0.110, 0.160]	0.169 [0.165, 0.205]	0.119 [0.110, 0.163]
σ_{JARPA}	0.460 [0.433, 0.527]	0.564 [0.545, 0.575]	0.457 [0.432, 0.517]	0.560 [0.541, 0.572]
-*lnL* CPUE	-5.36	-11.94	-5.17	-11.55
-*lnL* relative abundance	-6.40	-11.44	-6.39	-11.41
-*lnL JARPA*	-2.21	-0.51	-2.27	-0.56
-*lnL "targets"*	0.209	0.236	0.208	0.229
-*lnL (TOTALl) (includes weights)*	-19.50		-19.51	

Figure 1a
Base case posterior probability distributions of the r^W and r^E model parameters. The bottom plot shows the posterior distribution for the two parameters r^W and r^E combined used in Johnston and Butterworth (2005) as a prior for r for other breeding populations, and taken to be the average of the priors for r^W and r^E.

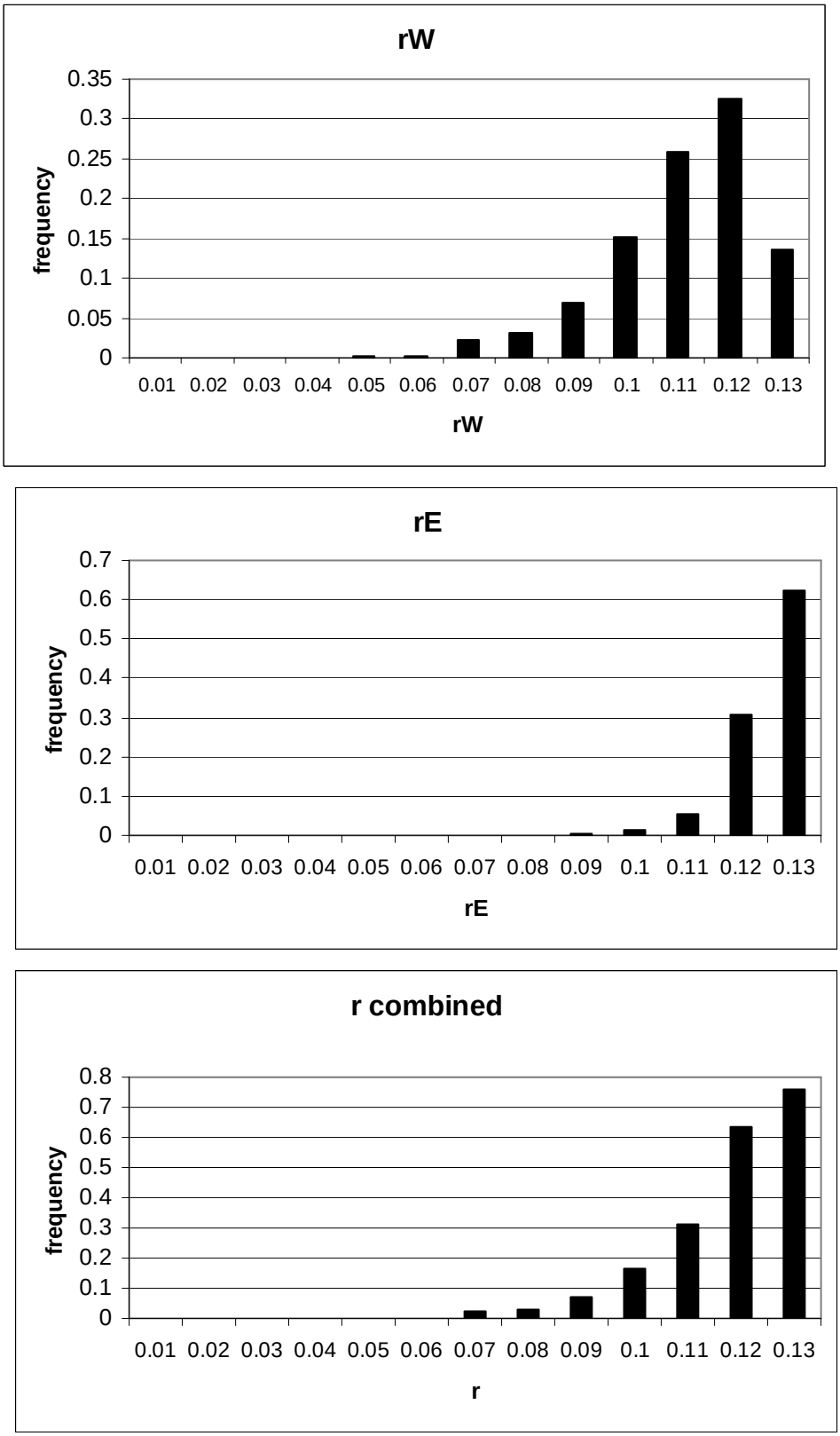


Figure 1b
Base case posterior probability distributions of various parameters and management related quantities.

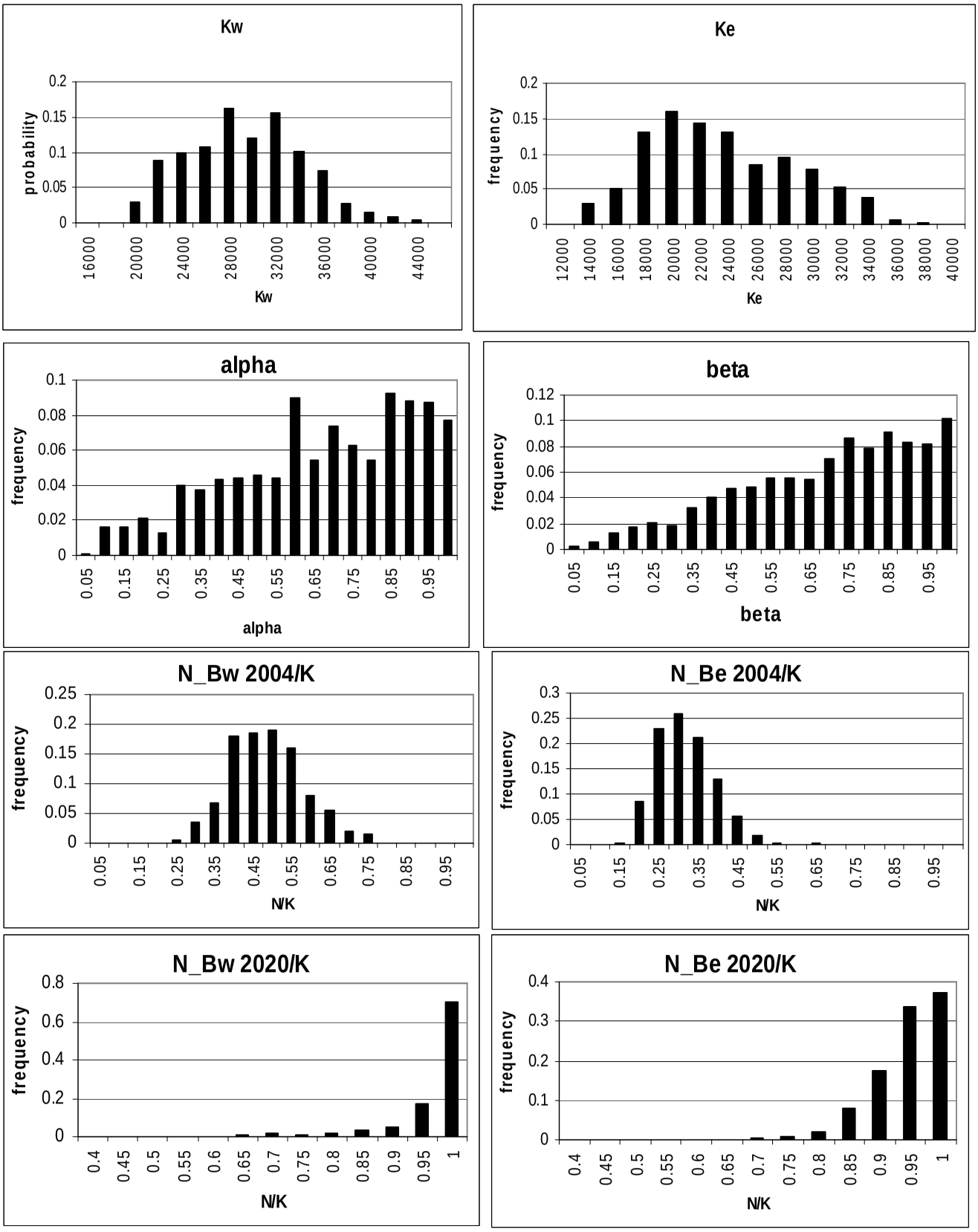


Figure 2a
Base case model fits to the relative abundance trends on the breeding grounds. The curve shown joins the posterior medians.

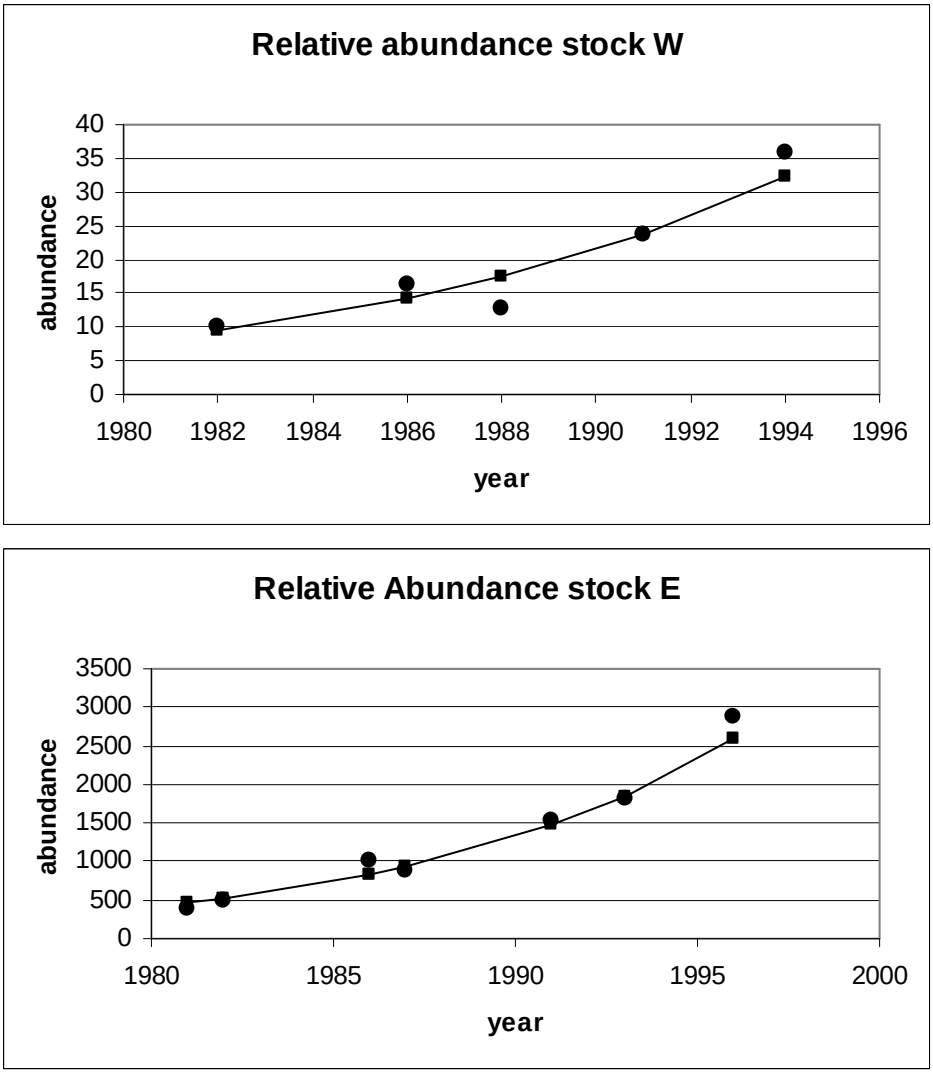
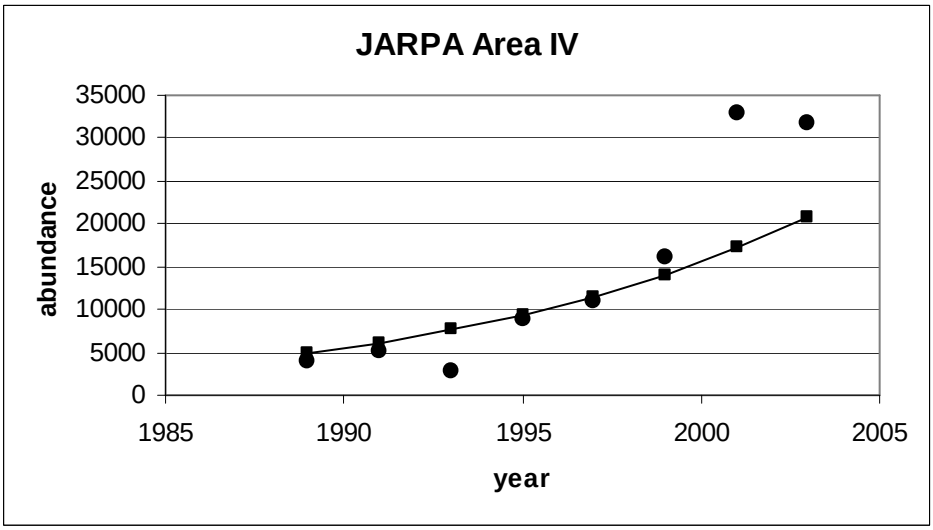


Figure 2b
Base case model fits to JARPA abundance estimates (for the feeding grounds). The curve shown joins the posterior medians.



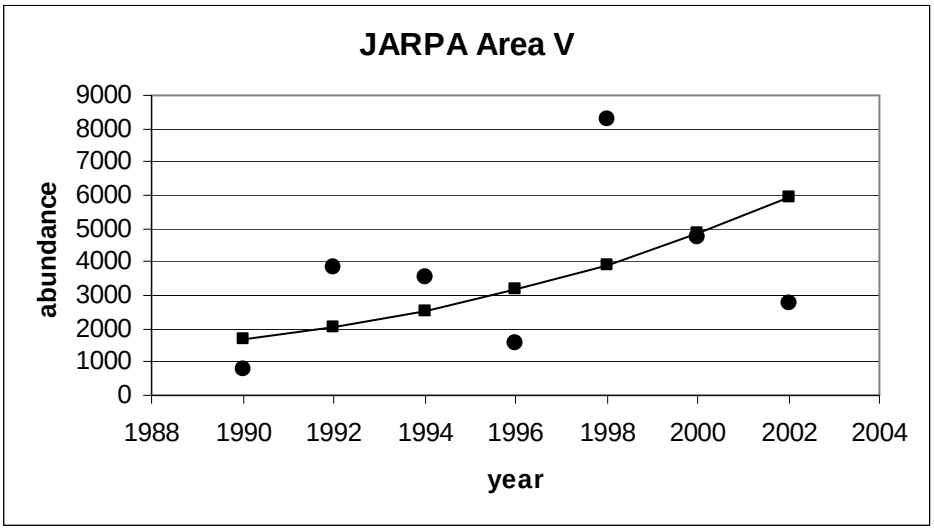


Figure 2c
Base case model fits to CPUE trends from the breeding grounds. The curve shown joins the posterior medians.

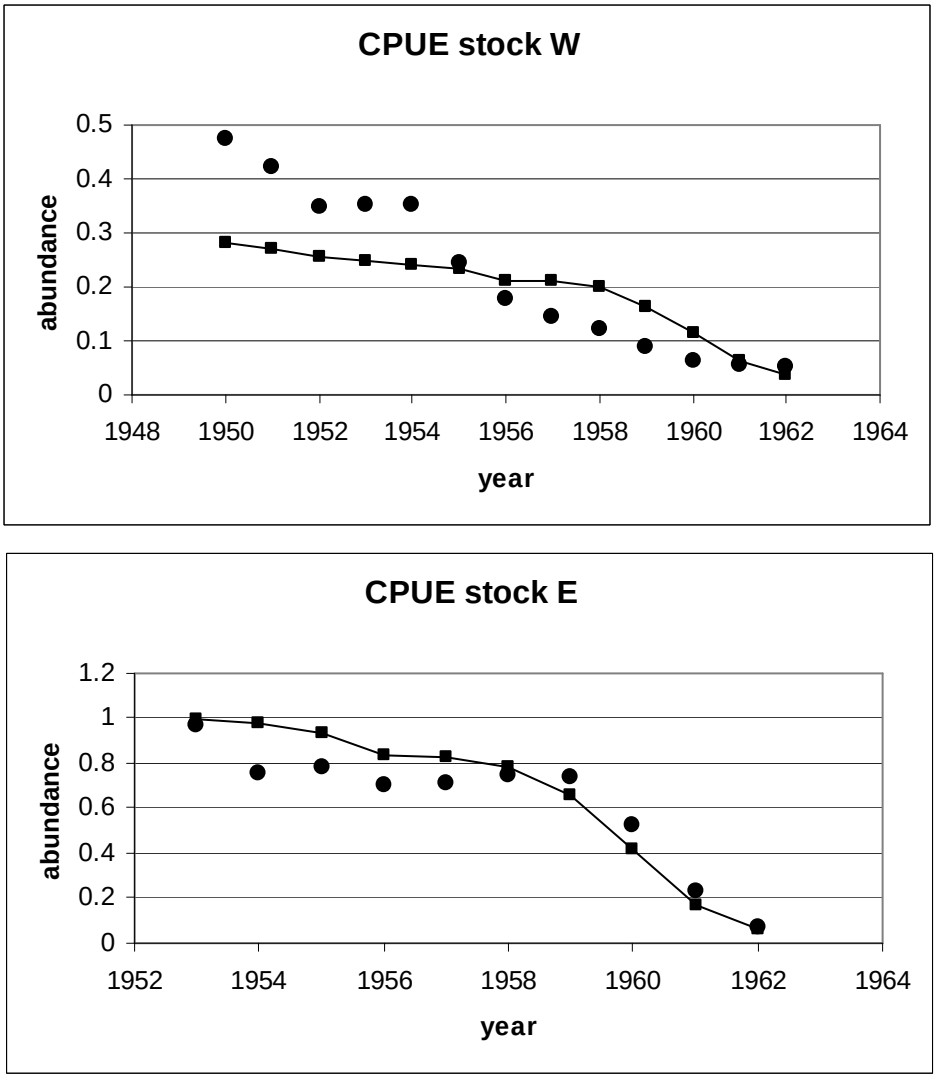
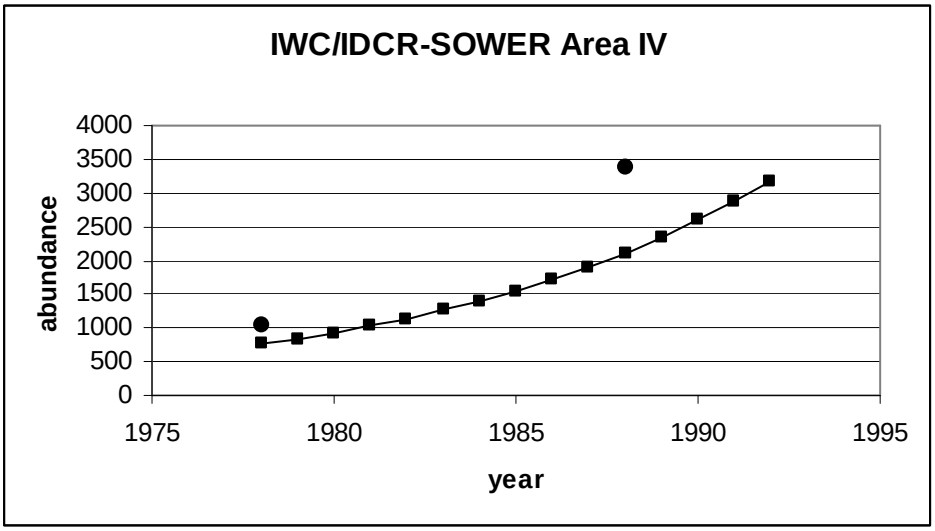


Figure 2d
Comparisons between the IWC/IDCR-SOWER survey and the Base case posterior medians (joined by the curve shown).



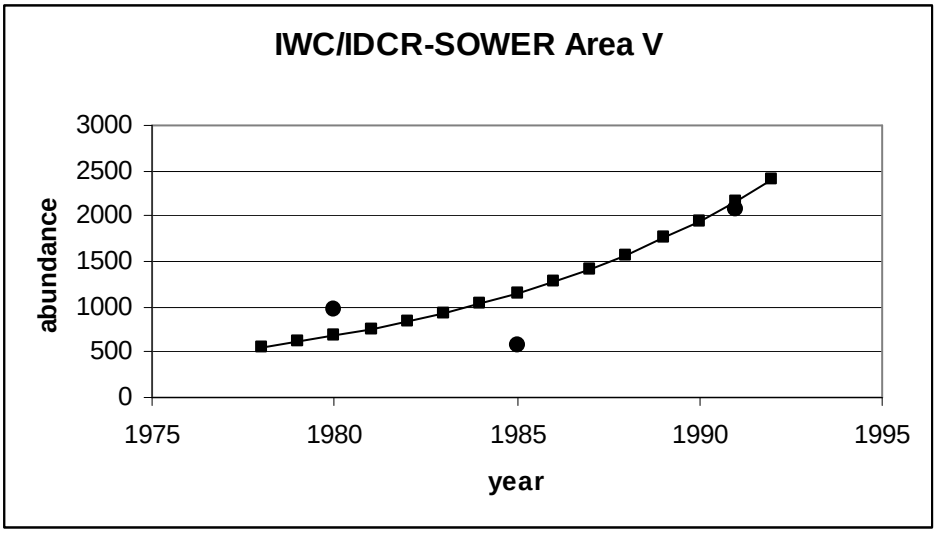


Figure 3a
Base case model estimated breeding population trends, with projected trajectories assuming a continued zero harvesting strategy. The posterior medians with the 90% probability intervals are illustrated. The vertical dashed lines are at 2004, after which the projections shown assume zero catch.

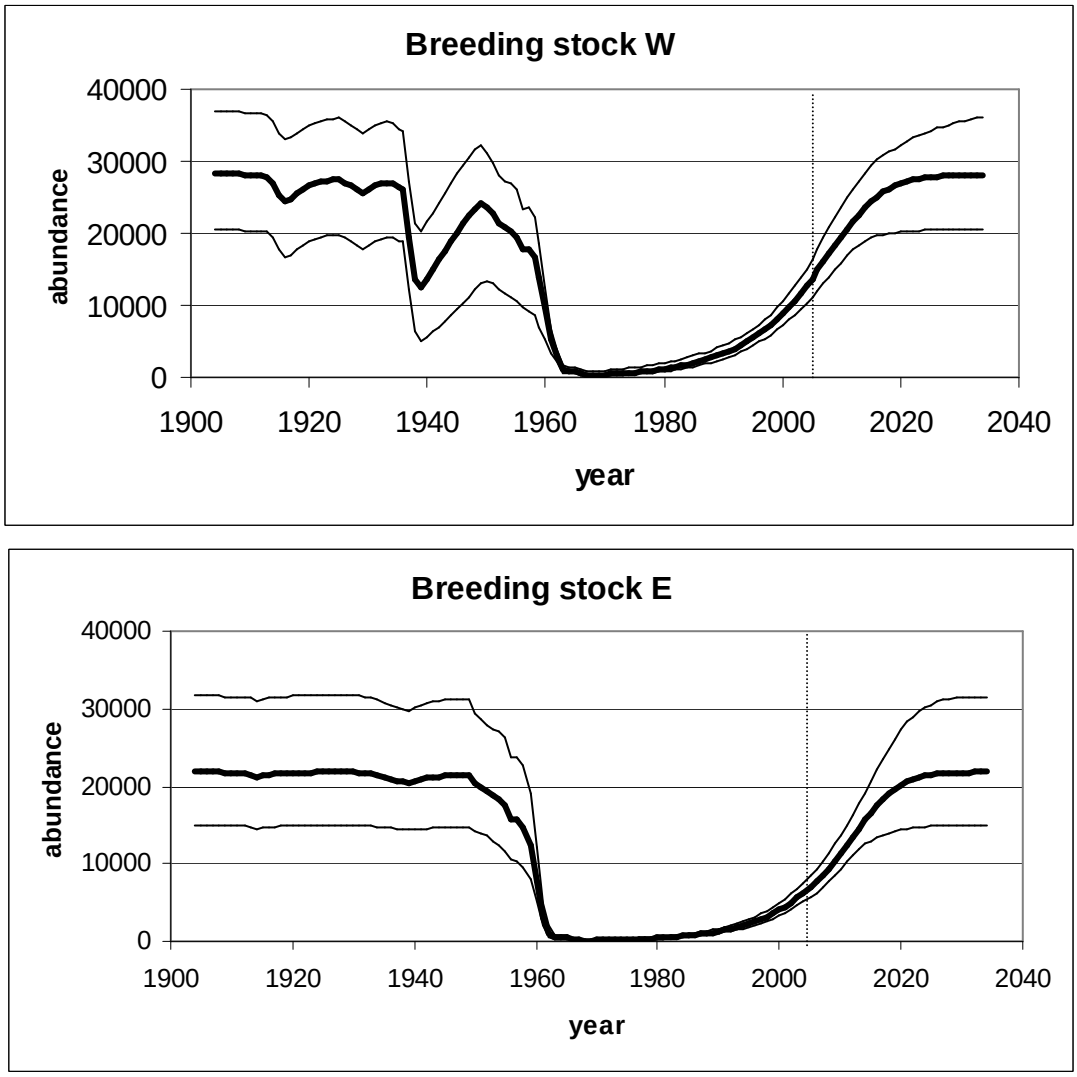


Figure 3b
Base case model estimated feeding population trends, with projected trajectories assuming a continued zero harvesting strategy. The posterior medians with the 90% probability intervals are illustrated. The vertical dashed lines are at 2004, after which the projections shown assume zero catch.