

**ASSESSMENT OF THE WEST AND EAST AUSTRALIAN BREEDING  
POPULATIONS OF SOUTHERN HEMISPHERE HUMPBACK WHALES USING A  
MODEL THAT ALLOWS FOR MIXING ON THE FEEDING GROUNDS AND  
TAKING ACCOUNT OF THE MOST RECENT ABUNDANCE ESTIMATES FROM  
JARPA**

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**ABSTRACT**

The most recent JARPA survey estimates of abundance are used to update the dynamic production model analyses of West and East Australian humpback breeding populations (Johnston and Butterworth 2002). These analyses take account of the results of both these surveys on the feeding grounds and of breeding area surveys, by applying a model that incorporates mixing of the two breeding populations on the feeding grounds of Areas IV and V. Results are quite precisely determined, with the available data providing a self-consistent picture of population recoveries well above their minima of the 1960's. Best estimates are projected under continuing zero harvest, and show approaches to pristine levels in some 10 years for the western and 15-20 years for the more depleted eastern breeding population.

**INTRODUCTION**

Initial assessments of breeding population of Southern Hemisphere humpback whales 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 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.

As in Johnston and Butterworth (2002), here we examine two breeding populations: breeding population W (West Australia, which has previously been denoted as stock “D”), and breeding population E (East Australia, which has previously been 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 by K. Matsuoka, pers. commn). Comparisons are made with IWC/IDCR SOWER-survey abundance estimates from these two feeding Areas.

## **DATA**

In this document the year, say 1950, refers to the austral summer season 1950/51. The following data are taken into account in the population model developed.

### **The catch series**

The catch series for both breeding populations W and E and Antarctic feeding Areas IV and V, and the bases for their development, are reported in the Appendix.

### **Relative abundance trends (breeding grounds)**

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 1.

### **CPUE data (breeding grounds)**

These data 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 2.

### **JARPA estimates of abundance (feeding Areas)**

Updated JARPA estimates of humpback whale abundance in feeding Areas IV and V (Matsuoka, K. pers. commn) are reported in Table 3. These data are available for every second year from 1989-2003 (Area IV) and 1990-2002 (Area V).

### **Recent estimates of absolute abundance - “targets” (breeding grounds)**

Recent estimates of abundance of humpback whales from the breeding grounds for stocks W (Bannister and Hedley 2001) and E (Brown *et al.* 1997) are reported in Table 4.

### **IWC/IDCR-SOWER estimates of abundance (feeding Areas)**

Estimates of abundance south of 60° S from the IWC/IDCR-SOWER sighting surveys were 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) – see Table 5.

These data are not used in the model fitting procedure, but instead for subsequent comparative purposes.

## METHODS

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 Table I in the Appendix) 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 *ad hoc* 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 described here 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.

### The Base Case population model

#### Breeding stock population dynamics

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

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

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,

$\mu$  is the “degree of compensation” parameter; this is set at 2.39, which fixes the MSY level to  $MSYL = 0.6K$ , 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  $y$ ,
- $\alpha$  is the proportion of breeding population W which feeds in feeding Area IV, and
- $\beta$  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:

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

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

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

$$\frac{C_y^{E,V}}{[C_y^{W,V} + C_y^{E,V}]} = \frac{\beta N_y^{B,E}}{N_y^{F,V}} \quad (10)$$

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  $y$ .

### The likelihood function

The estimable parameters of the model are:  $r^W$ ,  $r^E$ ,  $K^W$ ,  $K^E$ ,  $\alpha$  and  $\beta$ . The  $r$  parameters are constrained to be less than or equal to 0.126. This constraint is to force the model to respect demographically plausible bounds, as evaluated by Clapham *et al.* (2001) during the 2000 IWC Scientific Committee meeting.

The population model is fit to the following data:

- i) relative abundance data from breeding ground/migration route surveys (see Table 1),
- ii) CPUE data from breeding grounds (see Table 2),
- iii) updated JARPA abundance estimates from feeding Areas IV and V (see Table 3), and
- iv) absolute abundance estimates (treated as target population sizes) from the breeding grounds (for particular years) reported in Table 4.

Certain of the sensitivity tests conducted omit some of these data. Abundance estimates from the IWC/IDCR-SOWER sighting surveys (Branch and Butterworth (2002) are reported in Table 5. These data are not included in the likelihood, but

comparisons between the model estimated numbers in the feeding grounds and these abundance estimates are shown.

The Base Case model is fit to the relative abundances from the breeding ground surveys and CPUE trends as follows. It is assumed that the observed abundance index is log-normally distributed about its expected value:

$$I_y^A = q^A \hat{N}_y^{B,A} e^{\varepsilon_y} \quad (11)$$

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

The Base Case 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:

$$I_y^A = q_{JARPA}^A \hat{N}_y^{F,A} e^{\varepsilon_y} \quad (12)$$

where

$I_y^A$	is the JARPA abundance estimate for year $y$ and feeding stock $A$ (either IV or V),
$q_{JARPA}^A$	is 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
$\varepsilon_y$	is from $N(0, (\sigma_{JARPA}^A)^2)$ .

The contribution of the various data to the negative of the log-likelihood function is given by:

$$\begin{aligned}
-\ln L = & w_1 \sum_A \left( n_B^A \ln \sigma_B^A + \frac{1}{2\sigma_B^A} \sum_y \left( \ln I_y^A - \ln q_B^A - \ln \hat{N}_y^{B,A} \right)^2 \right) + \\
& w_2 \sum_A \left[ n_{CPUE}^A \ln \sigma_{CPUE}^A + \frac{1}{2\sigma_{CPUE}^A} \sum_y \left( \ln I_{CPUE,y}^A - \ln q_{CPUE}^A - \ln \hat{N}_y^{B,A} \right)^2 \right] + \\
& w_3 \sum_A \left[ n_{JARPA}^A \ln \sigma_{JARPA}^A + \frac{1}{2\sigma_{JARPA}^A} \sum_y \left( \ln I_{JARPA,y}^A - \ln q_{JARPA}^A - \ln \hat{N}_y^{F,A} \right)^2 \right] + \\
& w_4 \sum_A \left( N_Y^{A,obs} - \hat{N}_Y^{B,A} \right)^2
\end{aligned} \quad (13)$$

where

$w_1$  is the weight given to the breeding ground survey-based relative abundance data ( $w_1 = 1$  for the Base Case),

$w_2$  is the weight given to the CPUE data, which are heavily downweighted for the Base Case with a value of  $w_2 = 0.0001$  (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 fit itself, but their inclusion in the likelihood serves to provide an estimate of the associated catchability coefficient  $q$ ),

$w_3$  is the weight given to the JARPA absolute abundance data, ( $w_3 = 1$  for the Base Case) and

$w_4$  is the weight given to the population target size - a value of  $w_4 = \frac{1}{2\tilde{\sigma}^2}$  is used, where  $\tilde{\sigma} = 1000$ , so that the estimated population trajectory may not hit the target level exactly.

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

$$\hat{\sigma}^A = \sqrt{1/n \sum_y (\ln I_y^A - \ln q^A - \ln \hat{N}_y^{B,A})^2} \quad \text{for breeding survey/CPUE data (14)}$$

and

$$\hat{\sigma}_{JARPA}^A = \sqrt{1/n \sum_y (\ln I_{JARPA,y}^A - \ln q_{JARPA}^A - \ln \hat{N}_y^F)^2} \quad \text{for feeding ground (15)}$$

JARPA survey data

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:

$$\ln \hat{q}^A = 1/n \sum_y (\ln I_y^A - \ln \hat{N}_y^{B/F,A}) \quad (16)$$

## Sensitivity tests

Four sensitivity tests of the Base Case assumptions are considered and reported:

Sensitivity 1: JARPA estimates of abundance (Table 3) are treated as absolute rather than as relative indices of feeding stock numbers.

Sensitivity 2: As for Sensitivity 1, but exclude information on target abundances (i.e.  $w_4 = 0$ ).

Sensitivity 3: Information from the JARPA surveys is excluded (i.e.  $w_3 = 0$ ).

Sensitivity 4: The target abundance estimates are increased from 8000 to 13640 for breeding population W (this being the upper 95% confidence limit reported by Bannister and Hedley, 2001), and from 3200 to 6000 for

breeding population E (a somewhat arbitrary increase, being the same as used to reflect sensitivity in Johnston *et al.*, 2001).

A further sensitivity test was carried out in which no target abundance information was provided and the JARPA estimates of abundance were treated as relative indices. The results that followed were clearly unrealistic, suggesting an extremely small breeding population W (numbers an order of magnitude less than suggested by Bannister and Hedley, 2001), so that this approach was not pursued further.

## Confidence Intervals

A bootstrapping approach is used to calculate confidence intervals for the various population model estimates.

Details of the approach used to generate replicate data sets are as follows:

Replace  $I_y^A$  with  $I_y^{A,u} = \hat{q}\hat{N}_y e^{\varepsilon^u}$ , with  $\varepsilon^u$  from  $N(0, \sigma^{*2})$ , for the CPUE data, the relative abundance data from the feeding ground surveys and the JARPA estimates, and where  $\sigma^* = \sqrt{\frac{n}{n-2}}\sigma$ ,  $n$  is the number of data points, and  $\sigma$  is as estimated in the original fit for the series concerned.

The bootstrap procedure also replaces the “targets”  $N_y^{A,obs}$  with  $N_y^{A,u} = \hat{N}_y^{B,A} + \eta^u$  where  $\eta^u$  from  $N(0, 1000^2)$  (as  $\tilde{\sigma} = 1000$  – see  $w_4$ ).

Estimation is conducted from one hundred bootstrap replicates ( $u$ ), with the results ordered to provide distributions.

The 5<sup>th</sup> and 95<sup>th</sup> percentiles (as estimated by the 5<sup>th</sup> and 96<sup>th</sup> values in the ordered sequences) for various model estimates are reported in Table 6.

## RESULTS AND DISCUSSION

The results of the Base Case model fit to the data and the associated sensitivities are detailed in Table 6. Comparative results for the Base Case using instead the 2002 JARPA estimates of abundance are also reported. The estimates of  $\alpha$  are generally close to 1, whereas those of  $\beta$  are somewhat lower. This suggests that few animals from breeding population W feed in Area V, but a rather greater proportion of breeding population E feed in Area IV.

Figs 1-4 show how well the model results fit the available abundance-related information. The breeding ground survey trends are reflected closely (Fig. 1). 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 (Fig. 2). 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 1950's and early 1960's (Fig. 3) are also reasonably reflected. Agreement is not exact however, which is why these data are under-weighted in the model fit, as they cannot in any case be considered comparatively as reliable as the later scientific survey results as indices of population abundance. The IDCR-SOWER abundance estimates, although not used in the model fitting procedure, appear quite consistent with the model estimates given their large variances<sup>1</sup>(Fig. 4).

Trends in the estimated breeding and feeding stocks for the Base Case model fit are shown in Fig. 5. In terms of best estimates, near complete recoveries to pristine levels under zero harvest are suggested in some 10 years for stock W, and some 15-20 years for the currently more depleted (relative to pristine) stock E.

Comparison with the Base Case results with those prior to the availability of the updated JARPA estimates of abundance show little change (Table 6c). Breeding population W is now estimated to be marginally less productive (lower  $r$ ) and less recovered than previously thought.

Treating JARPA abundance estimates as reflecting absolute abundances increases the extent to which both W and E breeding populations are estimated to have recovered (Sensitivities 1 and 2, Table 6b). Similar results follow if the target abundance estimates for the breeding populations are increased (Sensitivity 4, Table 6c). Evidently (Table 6b, Sensitivity 2) the absolute estimates provided by the JARPA surveys suggest that the estimates of absolute abundance for the breeding grounds given in Table 4 are negatively biased estimates of overall abundance, more so for East Australia. Breeding ground population projections for Sensitivities 2 and 4 are compared to the Base Case in Figure 6, again indicating that approaches to pristine levels will occur earlier in the future.

However, if no account is taken of the JARPA abundance estimates (Sensitivity 3, Table 6c), the productivity ( $r$ ) for population W is notably less, as is the extent of recovery (there is little difference for population E). Bootstrap confidence intervals also generally show an increase (though only slight) compared to the Base Case; the reason the JARPA estimates have this relatively small impact on the model results is their greater variability, which leads to less weight placed upon them in the fitting procedure (note the  $\sigma_{JARPA}$  is typically 3-6 times larger than the  $\sigma_B$  for the abundance estimates from the feeding ground surveys).

## 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 1960's, with the recovery of the western stock likely the further advanced.

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<sup>1</sup> CV estimates are not immediately available for the Area-specific estimates given in Table 5. However, given that the associated circumpolar estimates have CVs of about 0.3 (Branch and Butterworth 2002), these Area-specific estimates will have CVs that are somewhat larger than this.

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## ACKNOWLEDGEMENTS

We thank K. Matsuoka for providing the most recent JARPA-based estimates of humpback abundance that were used in these analyses.

Table 1: Relative abundance estimates for breeding populations W (IWC 1996) and E (Brown *et al.* 1997).

<b>Year</b>	<b>Area W (West Australia)</b>
1982	10.2
1986	16.2
1988	12.7
1991	23.6
1994	36.0
	<b>Area E (East Australia)</b>
1981	381
1982	493
1986	1008
1987	879
1991	1533
1993	1807
1996	2872

Table 2: CPUE data off the west and east coasts of Australia (breeding populations W and E respectively) (from Chittleborough 1965).

<b>Year</b>	<b>Area W (West Australia)</b>	<b>Area E (East Australia)</b>
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 3: Updated JARPA estimates of abundance of humpback whales in feeding Areas IV and V (K. Matsuoka pers. commn).

<b>Year</b>	<b>Area IV</b>
1989	3873
1991	5203
1993	2740
1995	8850
1997	10874
1999	16211
2001	33010
2003	31750
	<b>Area V</b>
1990	767
1992	3837
1994	3567
1996	1543
1998	8301
2000	4720
2002	2735

Table 4: Estimates of breeding ground abundance of humpback whales used in the model (“targets”), together with the year to which they are taken to correspond.

<b>Breeding population</b>	<b>Abundance</b>	<b>Year</b>	<b>Source</b>
W (West Australia)	8000	1999	Bannister and Hedley (2001)
E (East Australia)	3200	1996	Brown <i>et al.</i> (1997)

Table 5: Estimates of abundance of humpback whales south of 60°S from the IWC/IDCR-SOWER sighting surveys (T.A. Branch pers. commn).

<b>YEAR</b>	<b>Circumpolar Survey</b>	<b>Area IV</b>	<b>Area V</b>
1978	I	1039	-
1980	I	-	966
1985	II	-	568
1988	II	3375	-
1991	III	-	2066

Table 6a: Base Case and 2002 (before JARPA update) results (the JARPA values are treated as relative indices and the model includes fitting to target abundance data). Note that the  $-\ln L$  contributions listed exclude the weighting factors  $w_1$  to  $w_4$  (see equation 13). Note also that the values in round brackets are the bootstrap medians, and the values in square brackets the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Note that  $\sigma_{JARPA}$  values apply respectively to Area IV and V rather than breeding populations W and E respectively.

	Base Case		2002 (before JARPA update)	
	Stock W	Stock E	Stock W	Stock E
$\alpha$	0.944 (0.898) [0.810; 0.999]		0.959	
$\beta$	0.671 (0.696) [0.622; 0.790]		0.667	
$r$	0.122 (0.121) [0.090; 0.126]	0.126 (0.123) [0.109; 0.126]	0.124	0.126
$K$	16879 (18212) [16109; 21316]	33857 (33072) [30842; 34939]	16365	34235
$q_{JARPA}$	1.56 (1.64) [1.10; 2.40]	1.18 (1.07) [0.54; 2.17]	1.20	1.41
$N_{lowest}$	236 (233) [169; 645]	114 (124) [64; 223]	225	116
$N_{target}^*$	7803 (7748) [6222; 3717]	3183 (3247) [1419; 4825]	7958	3213
$N_{2000}$	8601 (8548) [6893; 10139]	5104 (5039) [2192; 7703]	8771	5153
$N_{2003}$	11166 (11090) [9216; 12754]	7250 (6974) [3085; 10852]	-	-
$N_{2000}/K$	0.51 (0.46) [0.36; 0.57]	0.15 (0.15) [0.07; 0.23]	0.54	0.15
$N_{2003}/K$	0.66 (0.60) [0.47; 0.72]	0.21 (0.22) [0.09; 0.32]	-	-
$N_{lowest}/K$	0.014 (0.014) [0.009; 0.029]	0.003 (0.004) [0.002; 0.007]	0.014	0.003
$\sigma_{CPUE}$ (breeding)	0.378	0.343	0.376	0.336
$\sigma_B$ (relative abundance - breeding)	0.173	0.109	0.177	0.109
$\sigma_{JARPA}$ (feeding)	0.455	0.630	0.352	0.371
$-\ln L$ CPUE (breeding)	-6.14	-5.70	-6.21	-5.90
$-\ln L$ ( relative abundance - breeding)	-6.26	-12.00	-6.16	-12.00
$-\ln L$ JARPA (feeding)	-2.30	0.267	-3.25	-2.95
$-\ln L$ "targets" (breeding)	38774	281.9	1748	191
$-\ln L$ (total) (includes weights)	-20.27		-24.37	

\* the abundance "targets" of 8000 (W) and 3200 (E) – see Table 4 - are not hit exactly (as the fitting procedure assigns standard errors to each of 1000).

Table 6b: Base Case (JARPA treated as relative indices), Sensitivity 1 (JARPA treated as absolute indices) and Sensitivity 2 (target abundance data excluded in model fit; JARPA treated as absolute indices) results. Note that the  $-\ln L$  contributions listed exclude the weighting factors  $w_1$  to  $w_4$ .

	Base Case		Sensitivity 1 (JARPA absolute)		Sensitivity 2 (JARPA absolute, but exclude target abundance data)	
	Stock W	Stock E	Stock W	Stock E	Stock W	Stock E
$\alpha$	0.944		0.950		0.990	
$\beta$	0.671		0.735		0.628	
$r$	0.122	0.126	0.124	0.126	0.126	0.126
$K$	16879	33857	17332	33298	15363	35352
$q_{JARPA}$	1.56	1.18	1.0	1.0	1.0	1.0
$N_{lowest}$	236	114	254	127	276	217
$N_{target}^*$	7803	3183	8786	3539	9575	5934
$N_{2000}$	8601	5104	9659	5670	10392	9428
$N_{2003}$	11166	7250	12356	8041	12617	13188
$N_{2000}/K$	0.51	0.15	0.56	0.17	0.68	0.27
$N_{2003}/K$	0.66	0.21	0.71	0.24	0.82	0.37
$N_{lowest}/K$	0.014	0.003	0.015	0.004	0.018	0.006
$\sigma_{CPUE}$ (breeding)	0.378	0.343	0.378	0.350	0.370	0.307
$\sigma_B$ (relative abundance - breeding)	0.173	0.109	0.176	0.109	0.178	0.110
$\sigma_{JARPA}$ (feeding)	0.455	0.630	0.582	0.630	0.483	0.683
$-\ln L$ CPUE (breeding)	-6.14	-5.70	-6.15	-5.51	-6.42	-6.82
$-\ln L$ (relative abundance - breeding)	-6.26	-12.00	-6.19	-12.00	-6.11	-11.93
$-\ln L$ JARPA (feeding)	-2.30	0.267	-0.32	0.26	-1.82	-2.67
$-\ln L$ "targets" (breeding)	38774	281.9	618361	115324	-	-
$-\ln L$ (total) (includes weights)	-20.27		-17.88		-22.54	

\* the abundance "targets" of 8000 (W) and 3200 (E) – see Table 4 - are not hit exactly (as the fitting procedure assigns standard errors to each of 1000).

Table 6c: Base Case results compared to sensitivity results for which the JARPA abundance estimates are excluded from the model fitting procedure (Sensitivity 3) and for where the target abundance values are increased (to 13640 for stock W and 6000 for stock E) (Sensitivity 4). Note that the  $-\ln L$  contributions listed exclude the weighting factors  $w_1$  to  $w_4$ .

	Base Case		Sensitivity 3 (Exclude JARPA abundance estimates)		Sensitivity 4 (Increase target abundances)	
	Stock W	Stock E	Stock W	Stock E	Stock W	Stock E
$\alpha$	0.944 (0.898) [0.810; 0.999]		0.941 (0.897) [0.830; 0.999]		0.784	
$\beta$	0.671 (0.696) [0.622; 0.790]		0.662 (0.708) [0.573; 0.798]		0.718	
$r$	0.122 (0.121) [0.090; 0.126]	0.126 (0.123) [0.109; 0.126]	0.107 (0.110) [0.084; 0.126]	0.126 (0.124) [0.107; 0.126]	0.120	0.126
$K$	16879 (18212) [16109; 21316]	33857 (33072) [30842; 34939]	18145 (19017) [16791; 22668]	33613 (32900) [30340; 34061]	20783	29707
$q_{JARPA}$	1.56 (1.64) [1.10; 2.40]	1.18 (1.07) [0.54; 2.17]	-	-	1.05	0.45
$N_{lowest}$	236 (233) [169; 645]	114 (124) [64; 223]	357 (312) [182; 729]	115 (122) [68; 230]	455	218
$N_{target}^*$	7803 (7748) [6222; 3717]	3183 (3247) [1419; 4825]	7987 (7965) [6457; 9516]	3199 (3218) [1471; 4818]	13389	6023
$N_{2000}$	8601 (8548) [6893; 10139]	5104 (5039) [2192; 7703]	8723 (8685) [7067; 10430]	5129 (5077) [2294; 7688]	14439	9531
$N_{2003}$	11166 (11090) [9216; 12754]	7250 (6974) [3085; 10852]	11119 (11204) [9360; 13168]	7285 (7084) [3174; 10818]	17251	13209
$N_{2000}/K$	0.51 (0.46) [0.36; 0.57]	0.15 (0.15) [0.07; 0.23]	0.48 (0.45) [0.34; 0.57]	0.15 (0.16) [0.07; 0.23]	0.69	0.32
$N_{2003}/K$	0.66 (0.60) [0.47; 0.72]	0.21 (0.22) [0.09; 0.32]	0.61 (0.58) [0.44; 0.73]	0.22 (0.22) [0.10; 0.33]	0.83	0.44
$N_{lowest}/K$	0.014 (0.014) [0.009; 0.029]	0.003 (0.004) [0.002; 0.007]	0.020 (0.017) [0.010; 0.033]	0.003 (0.004) [0.002; 0.007]	0.022	0.007
$\sigma_{CPUE}$ (breeding)	0.378	0.343	0.378	0.353	0.399	0.372
$\sigma_B$ (relative abundance - breeding)	0.173	0.109	0.166	0.109	0.173	0.110
$\sigma_{JARPA}$ (feeding)	0.455	0.630	-	-	0.496	0.620
$-\ln L$ CPUE (breeding)	-6.14	-5.70	-6.14	-5.40	-5.45	-4.88
$-\ln L$ (relative abundance - breeding)	-6.26	-12.00	-6.47	-12.00	-6.28	- 11/97
$-\ln L$ JARPA (feeding)	-2.30	0.267	-	-	-1.60	0.154
$-\ln L$ "targets" (breeding)	38774	281.9	159	0.9	62789	555
$-\ln L$ (total) (includes weights)	-20.27		-18.48		-19.67	

\* the abundance "targets" are not hit exactly (as the fitting procedure assigns standard errors to each of 1000).

Figure 1: Base Case model fits to the relative abundance trends on the breeding grounds.

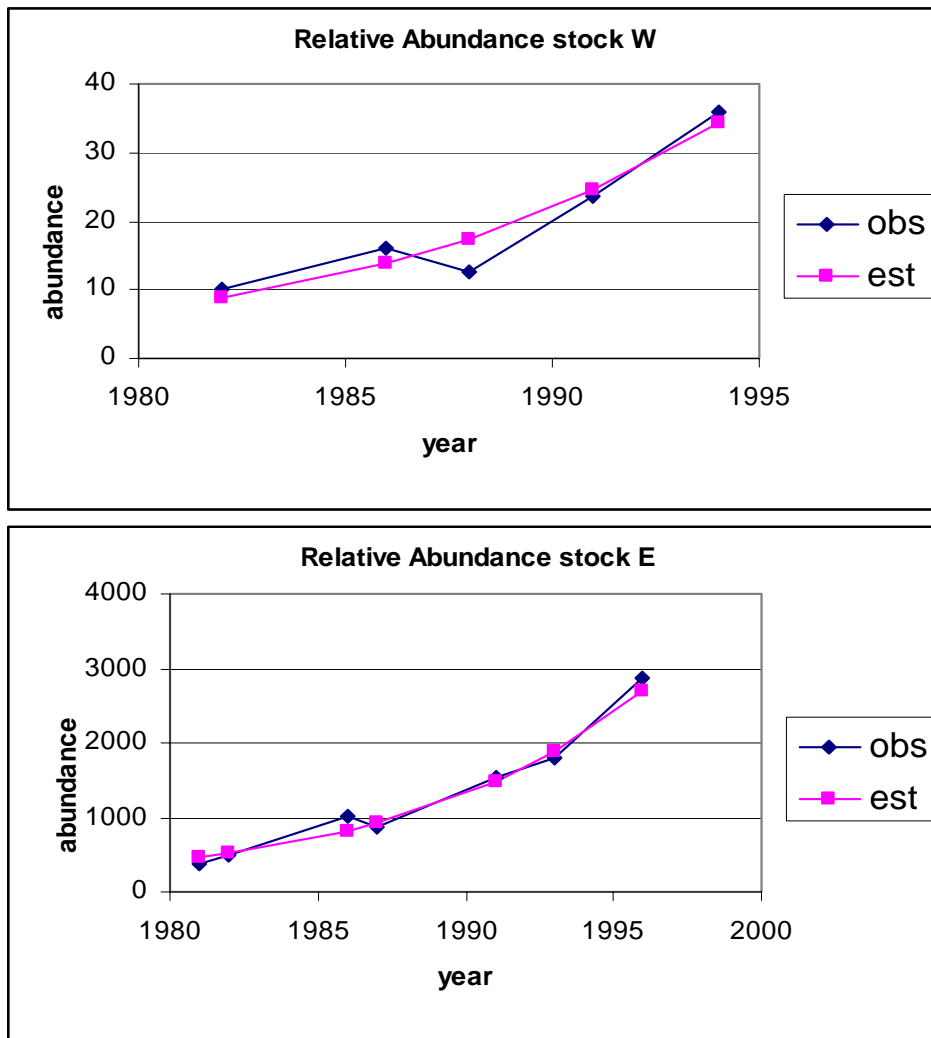
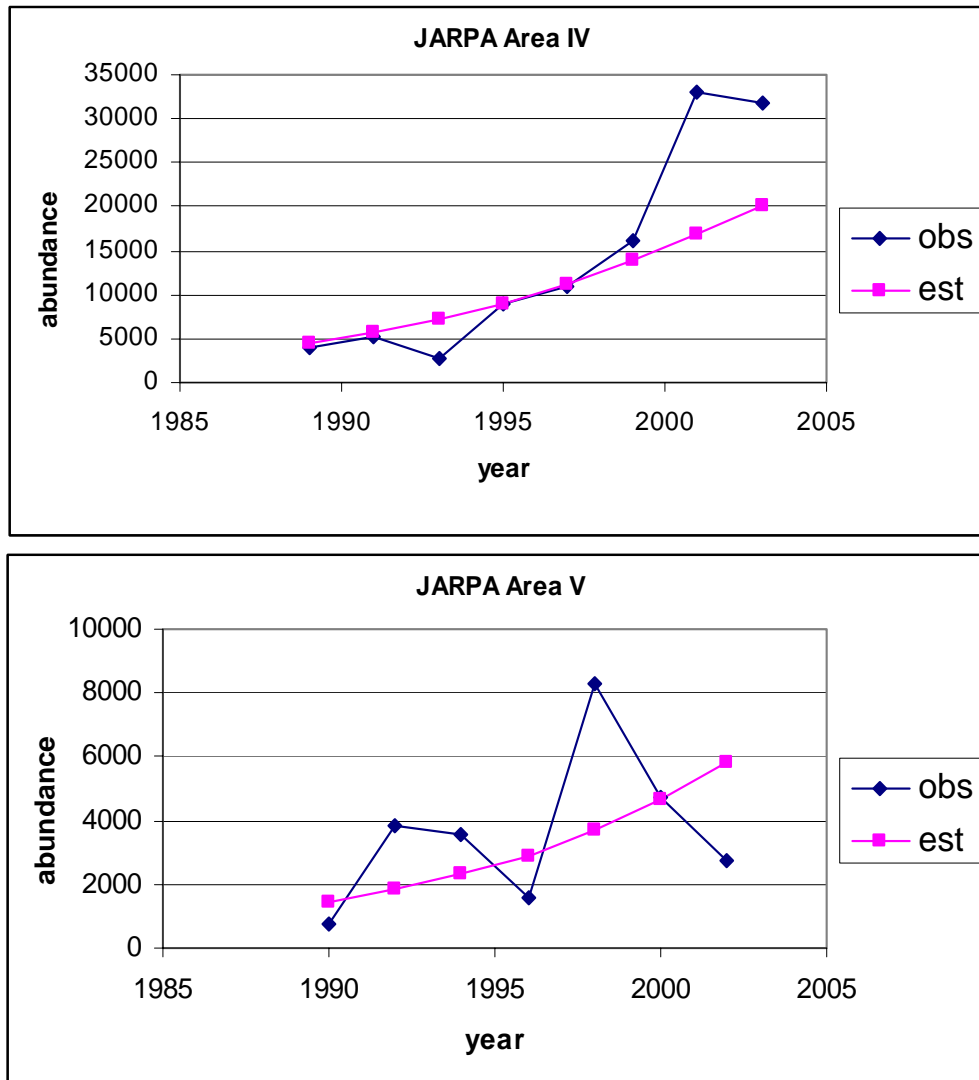




Figure 2: Base Case model fits to JARPA abundance estimates (for the feeding grounds).



Note: As the JARPA estimates are treated as indices of relative abundance, the model trajectory shown above is the true abundance multiplied by the estimated bias factor ( $q_{JARPA}$  - respectively 1.56 and 1.18 for Area IV and V).

Figure 3: Base Case model fits to breeding ground CPUE trends.

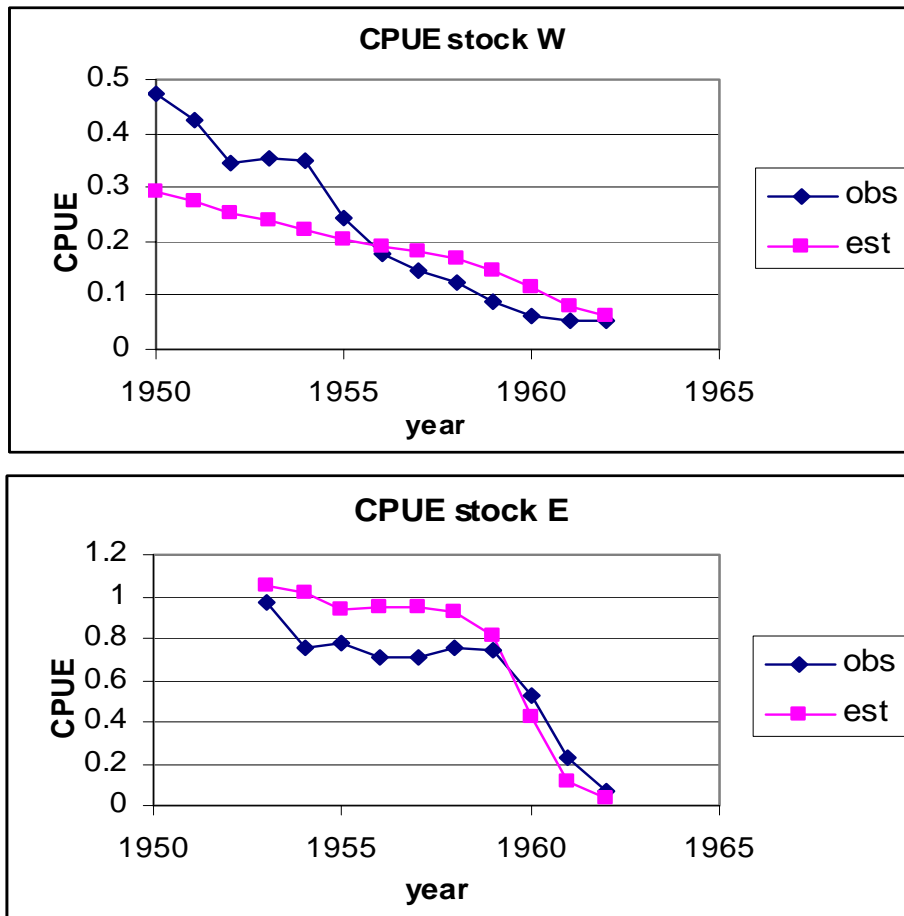


Figure 4: Comparisons between the IWC/IDCR-SOWER survey and Base Case model estimates of abundance in the feeding Areas.

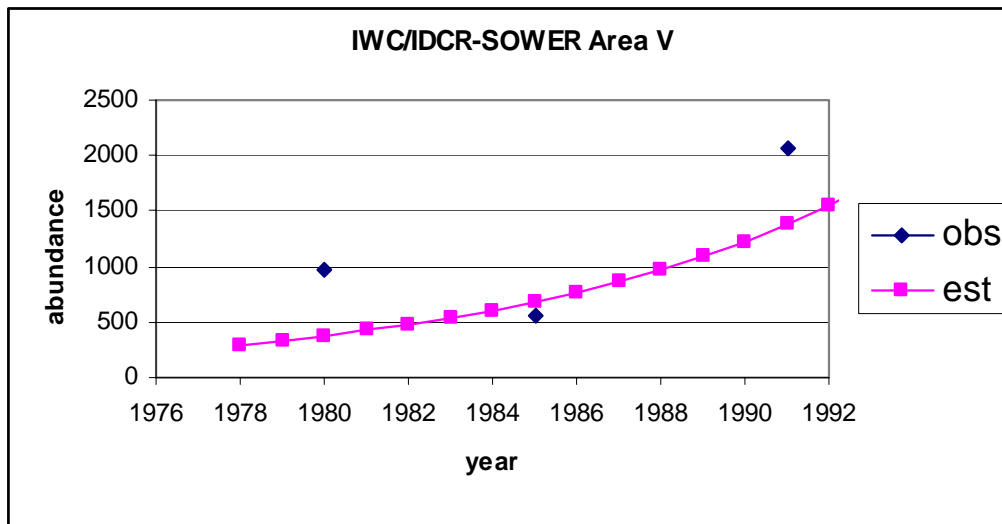
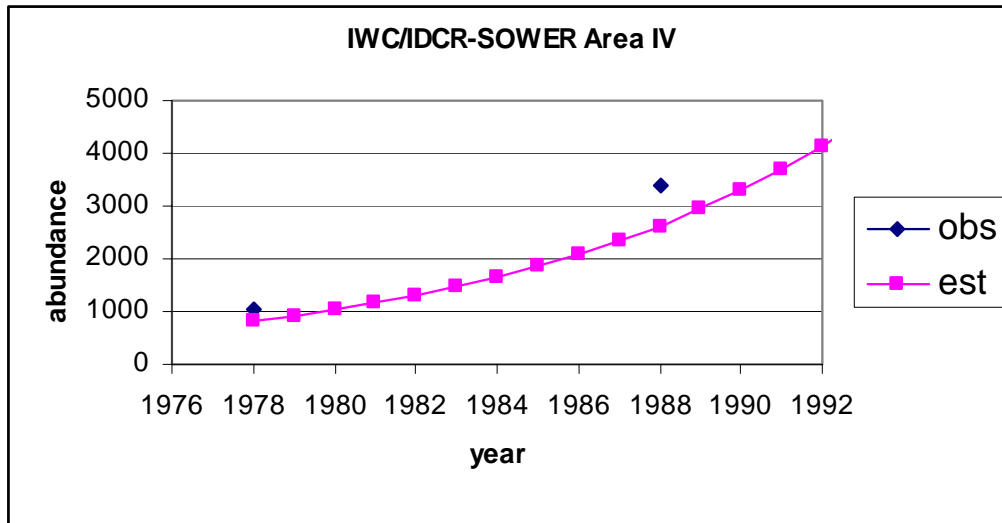


Figure 5a: Base Case estimated breeding population trends, with projected trajectories assuming a continued zero harvesting strategy. The vertical line indicates the start of the projection. The error bars denote a 90% bootstrap-based confidence interval for the 2000 population size (time precluded estimates of these intervals for other years).

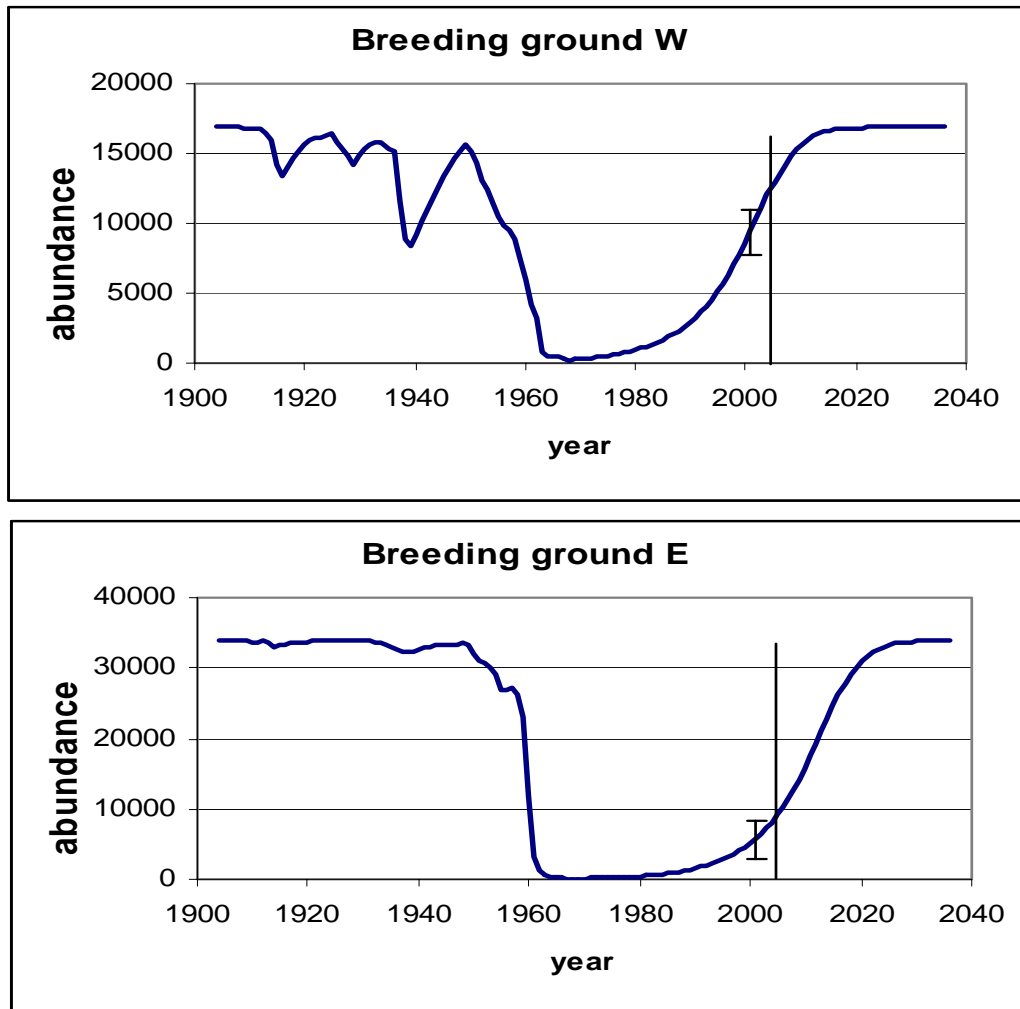


Figure 5b: Base Case estimated feeding stock trends, with projected trajectories assuming a continued zero harvesting strategy. The vertical line indicates the start of the projection.

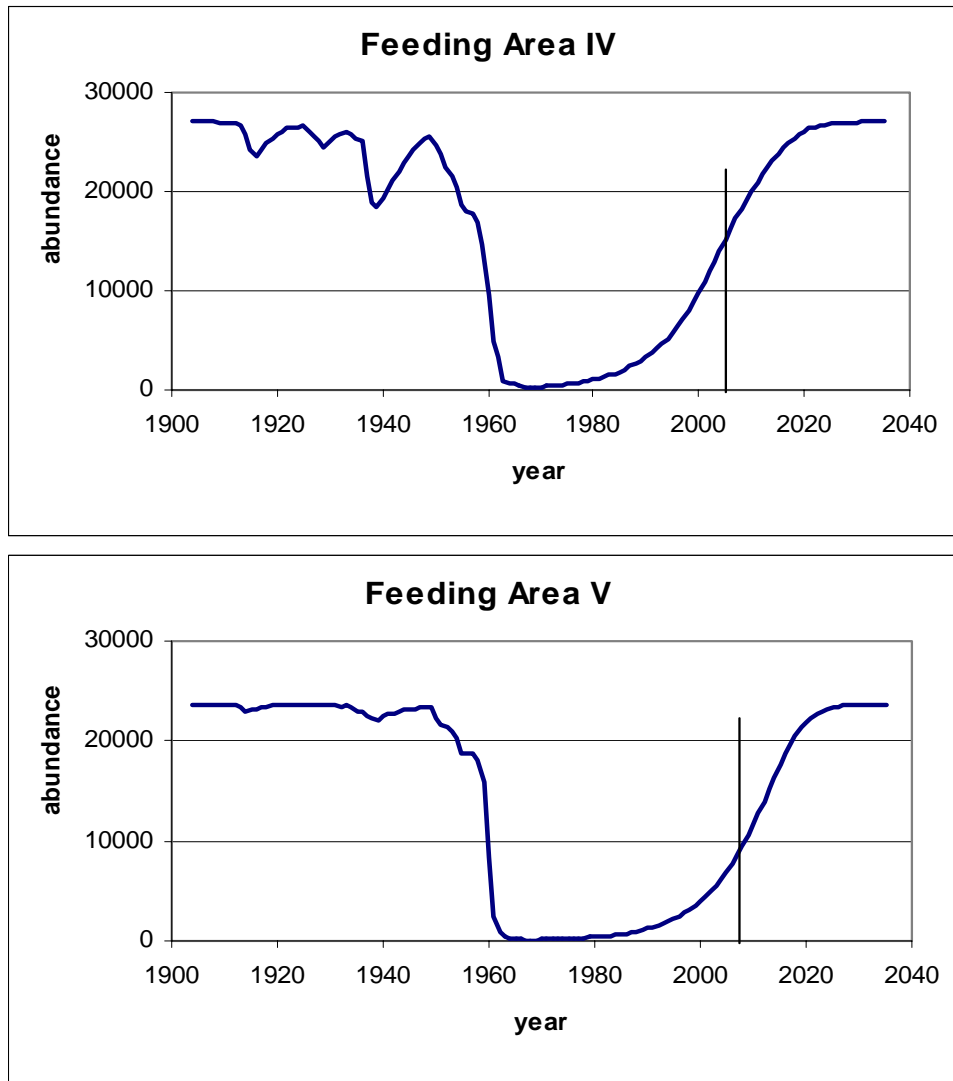
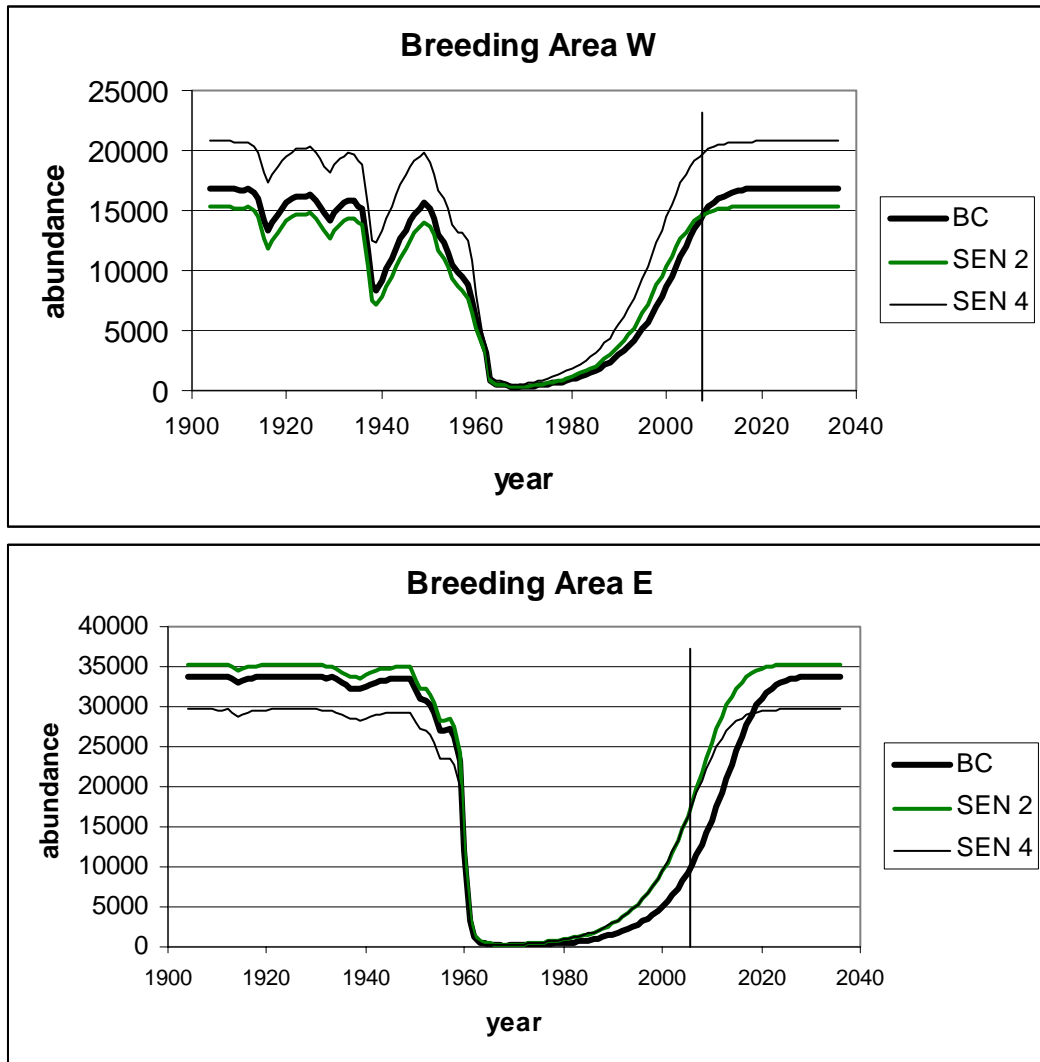


Figure 6a: Comparison between Base Case, Sensitivity 2 (excludes target abundance data and treats JARPA estimates as absolute) and Sensitivity 4 (target abundance data values increased) estimated breeding population trends, with projected trajectories assuming a continued zero harvesting strategy. The vertical line indicates the start of the projection.



## Appendix I. Allocation of Catches to Breeding Population and Feeding Stocks

All catches to the north of 40°S were allocated to breeding populations while all catches to the south of 40°S were allocated to feeding stocks. Tables I and II show the resulting catch series for the breeding grounds and for the feeding grounds respectively. Note that the feeding ground catches correspond to the catches for what has been previously described as the Naïve model (Findlay *et al.* 2000).

### Breeding Populations

Catches were allocated to breeding populations as follows (see Table I).

West: Land, floating factory and low latitude pelagic catches from the Australian West Coast, Soviet catches apportioned to Area IV (north of 40°S).

East: Land and floating factory catches from the Australian East Coast, New Zealand and Tonga, Soviet catches apportioned to Area V (north of 40°S).

### Feeding stocks

Catches were allocated to feeding stocks under the Naïve model. Catches are allocated to the two feeding Areas (IV and V) by year (see Table II).

Area IV: 60°E - 120°E : the 60°E - 120°E BIWS catches, Soviet catches apportioned to Area IV (south of 40°S), early Kerguelen Island catches, and the *Olympic Challenger* catches for 60°E - 120°E.

Area V: 120°E - 170°W : the 120°E - 170°W BIWS catches, Soviet catches apportioned to Area V (south of 40°S), the early Ross Sea catches, and the *Olympic Challenger* catches for 120°E - 170°W.

Table I. Southern Hemisphere humpback whale catches to the north of 40° S apportioned to breeding populations west and east of Australia. [Note that the year 1904, for example, represents the 1904/05 austral summer.]

<b>Year</b>	<b>West</b>	<b>East</b>	<b>Year</b>	<b>West</b>	<b>East</b>
1904	0	0	1953	1300.0	809.0
1905	0	0	1954	1320.0	898.0
1906	0	0	1955	1126.0	832.0
1907	0	0	1956	1119.0	1013.0
1908	0	0	1957	1120.0	1025.0
1909	0	0	1958	967.0	1023.0
1910	0	0	1959	737.0	1278.0
1911	0	0	1960	573.0	1341.0
1912	296.0	296.0	1961	587.0	981.0
1913	670.5	670.5	1962	548.0	209.0
1914	1968.0	0	1963	87.0	0
1915	1430.0	0	1964	1.0	0
1916	0	0	1965	5.0	0
1917	0	0	1966	28.0	0
1918	0	0	1967	12.0	0
1919	0	0	1968	0	0
1920	0	0	1969	0	0
1921	0	0	1970	0	0
1922	155.0	0	1971	0	0
1923	166.0	0	1972	0	0
1924	0	0	1973	0	0
1925	669.0	0	1974-	0	0
			2003		
1926	735.0	0			
1927	996.0	0			
1928	1033.0	0			
1929	0	0			
1930	0	78.0			
1931	0	110.0			
1932	0	18.0			
1933	0	44.0			
1934	0	52.0			
1935	0	57.0			
1936	3072.0	69.0			
1937	3242.0	55.0			
1938	917.0	75.0			
1939	0	80.0			
1940	0	107.0			
1941	0	86.0			
1942	0	71.0			
1943	0	90.0			
1944	0	88.0			
1945	0	107.0			
1946	0	110.0			
1947	2.0	101.0			
1948	4.0	92.0			
1949	193.0	141.0			
1950	388.0	79.0			
1951	1224.0	111.0			
1952	1187.0	721.0			



Table II. Southern Hemisphere humpback whale catches to the south of 40° S apportioned to the two feeding Areas IV and V. [Note that the year 1904, for example, represents the 1904/05 austral summer.]

Year	IV		Year	V	
	60-120E	120E-170W		60-120E	120E-170W
1904	0	0	1951	958.5	486.8
1905	0	0	1952	223.6	723.4
1906	0	0	1953	309.9	1120.9
1907	0	0	1954	379.5	2614.5
1908	217.0	0	1955	844.2	156.6
1909	118.0	0	1956	27.0	182.5
1910	83.0	0	1957	544.8	1158.7
1911	0	0	1958	1661.1	3182.1
1912	0	0	1959	66.0	13159.0
1913	0	0	1960	779.3	9846.7
1914	0	0	1961	468.0	1936.0
1915	0	0	1962	2352.0	290.6
1916	0	0	1963	288.8	321.7
1917	0	0	1964	91.5	70.7
1918	0	0	1965	76.3	265.8
1919	0	0	1966	172.0	112.0
1920	0	0	1967	98.0	27.0
1921	0	0	1968	0	0
1922	0	0	1969	0	0
1923	0	0	1970	0	0
1924	0	0	1971	0	0
1925	0	0	1972	0	0
1926	0	0	1973	0	0
1927	0	0	1974-2003	0	0
1928	11.0	0			
1929	0	0			
1930	0	0			
1931	159.0	0			
1932	82.0	0			
1933	593.0	0			
1934	1340.0	0			
1935	938.0	4.0			
1936	1435.0	0			
1937	832.0	0			
1938	835.0	24.0			
1939	0	0			
1940	0	0			
1941	0	0			
1942	0	0			
1943	0	0			
1944	0	0			
1945	0	0			
1946	0	0			
1947	1.0	0			
1948	11.0	74.3			
1949	725.2	1308.1			
1950	1207.9	998.1			

## ADDENDUM

This addendum reports Base Case results that have been re-run following advice received on some amendments of the JARPA abundance data after the computations of the main text had been completed. The amended data are reported in Table A.1 (compare to Table 3 of the main text) and were supplied by K. Matsuoka (pers. commn).

Table A.2 (compare to Table 6a of the main text) compares the Base Case results as reported in the paper, with those that have been re-run using the amended JARPA abundance estimates.

Figure A.1 (compare to Figure 2 of the main text) illustrates the revised Base Case fits to the JARPA abundance data.

Figure A.2 (compare to Figure 5a of the main text) compares the Base Case estimated breeding population trends as reported in the current paper, as well as those for which the JARPA data have been amended, with projected trajectories assuming a continued zero harvesting strategy. The error bars denote a 90% bootstrap-based confidence interval for the 2000 population size (for the estimates of the main text).

As is evident from these results, the amendments to the JARPA abundance data make little difference to the results presented in the main text.

Table A.1: Amended JARPA estimates of abundance of humpback whales in feeding Areas IV and V (K. Matsuoka pers. commn). The values in brackets refer to the values first supplied by K. Matsuoka and which have been used for the results reported in the main text.

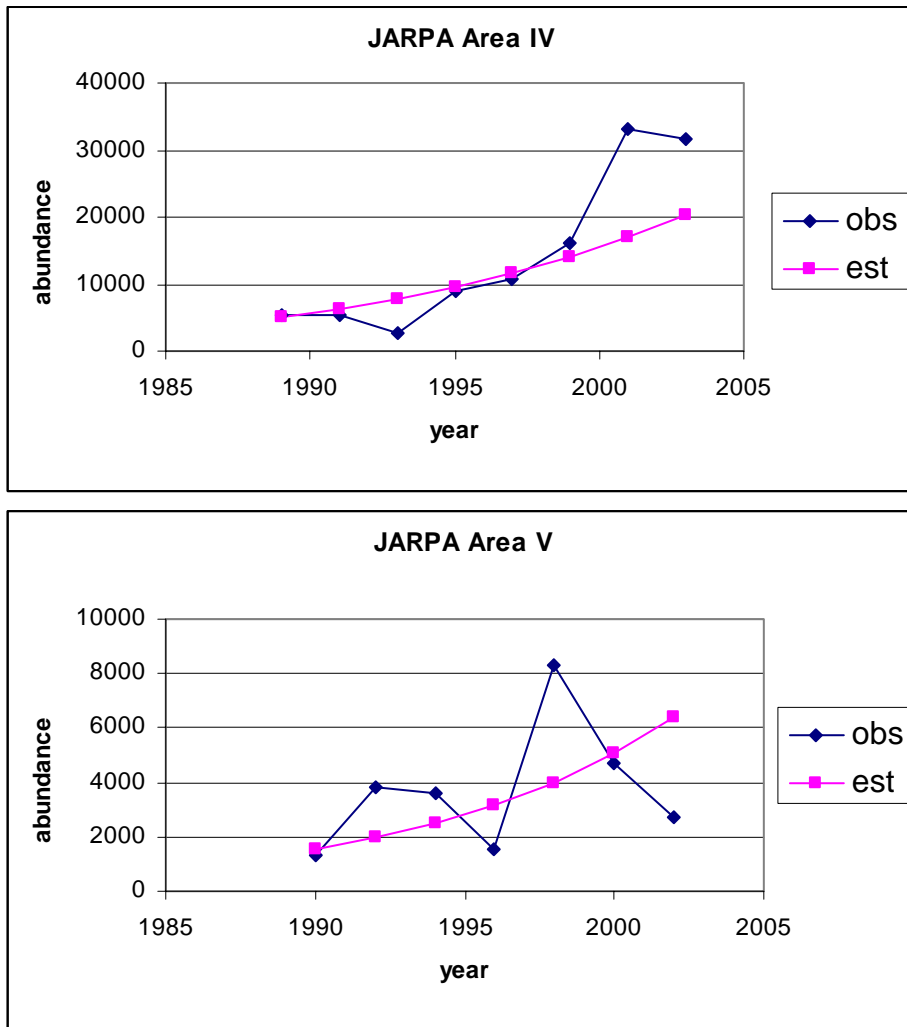
<b>Year</b>	<b>Area IV</b>
1989	5230 (3873)
1991	5350 (5203)
1993	2740
1995	8850
1997	10874
1999	16211
2001	33010
2003	31750
	<b>Area V</b>
1990	1354 (767)
1992	3837
1994	3567
1996	1543
1998	8301
2000	4720
2002	2735

Table A.2: Base Case results as reported in the current paper, as well as those for which the JARPA data have been amended (the JARPA values are treated as relative indices and the model includes fitting to target abundance data). Note that the  $-\ln L$  contributions listed exclude the weighting factors  $w_1$  to  $w_4$  (see equation 13). Note also that the values in round brackets are the bootstrap medians, and the values in square brackets the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Note that  $\sigma_{JARPA}$  values apply respectively to Area IV and V rather than breeding populations W and E respectively.

	Base Case – main text		Base Case – amended JARPA data	
	Stock W	Stock E	Stock W	Stock E
$\alpha$	0.944 (0.898) [0.810; 0.999]		0.996 (0.900) [0.834; 0.999]	
$\beta$	0.671 (0.696) [0.622; 0.790]		0.734 (0.708) [0.623; 0.849]	
$r$	0.122 (0.121) [0.090; 0.126]	0.126 (0.123) [0.109; 0.126]	0.113 (0.114) [0.088; 0.126]	0.123 (0.124) [0.109; 0.126]
$K$	16879 (18212) [16109; 21316]	33857 (33072) [30842; 34939]	17511 (18840) [16391; 22658]	33994 (32774) [30914; 34490]
$q_{JARPA}$	1.56 (1.64) [1.10; 2.40]	1.18 (1.07) [0.54; 2.17]	1.57 (1.65) [1.10; 2.54]	1.32 (1.14) [0.60; 2.55]
$N_{lowest}$	236 (233) [169; 645]	114 (124) [64; 223]	298 (274) [174; 648]	116 (122) [69; 246]
$N_{target}^*$	7803 (7748) [6222; 3717]	3183 (3247) [1419; 4825]	7836 (7804) [6251; 9406]	3225 (3289) [1450; 4934]
$N_{2000}$	8601 (8548) [6893; 10139]	5104 (5039) [2192; 7703]	8593 (8591) [6964; 10191]	5171 (5138) [2239; 7689]
$N_{2003}$	11166 (11090) [9216; 12754]	7250 (6974) [3085; 10852]	11050 (11042) [9025; 12647]	7346 (7142) [3101; 10819]
$N_{2000}/K$	0.51 (0.46) [0.36; 0.57]	0.15 (0.15) [0.07; 0.23]	0.49 (0.45) [0.32; 0.57]	0.15 (0.16) [0.07; 0.23]
$N_{2003}/K$	0.66 (0.60) [0.47; 0.72]	0.21 (0.22) [0.09; 0.32]	0.63 (0.58) [0.42; 0.72]	0.22 (0.22) [0.09; 0.32]
$N_{lowest}/K$	0.014 (0.014) [0.009; 0.029]	0.003 (0.004) [0.002; 0.007]	0.017 (0.014) [0.010; 0.033]	0.003 (0.004) [0.002; 0.007]
$\sigma_{CPUE}$ (breeding)	0.378	0.343	0.367	0.339
$\sigma_B$ (relative abundance - breeding)	0.173	0.109	0.167	0.109
$\sigma_{JARPA}$ (feeding)	0.455	0.630	0.466	0.581
$-\ln L$ CPUE (breeding)	-6.14	-5.70	-6.49	-5.81
$-\ln L$ ( relative abundance - breeding)	-6.26	-12.00	-6.44	-12.01
$-\ln L$ JARPA (feeding)	-2.30	0.267	-2.11	-0.30
$-\ln L$ “targets” (breeding)	38774	281.9	26764	654
$-\ln L$ (total) (includes weights)	-20.27		-20.84	

\* the abundance “targets” of 8000 (W) and 3200 (E) are not hit exactly (as the fitting procedure assigns standard errors to each of 1000).

Figure A.1: Revised Base Case model fits to JARPA abundance estimates (for the feeding grounds).



Note: As the JARPA estimates are treated as indices of relative abundance, the model trajectory shown above is the true abundance multiplied by the estimated bias factor ( $q_{JARPA}$  - respectively 1.57 and 1.32 for Area IV and V).

Figure A.2: Base Case estimated breeding population trends as reported in the current paper, as well as those for which the JARPA data have been amended, with projected trajectories assuming a continued zero harvesting strategy. The vertical line indicates the start of the projection. The error bars denote a 90% bootstrap-based confidence interval for the 2000 population size (for the estimates of the main text).

