FOR CONSIDERATION BY THE INTER-SESSIONAL WORKSHOP FOR
THE COMPREHENSIVE ASSESSMENT OF SOUTHERN HEMISPHERE HUMPBACK WHALES
HOBART, TASMANIA 3 – 7 APRIL 2006. SC/A06/HW52

A Bayesian assessment of humpback whales on breeding grounds of Eastern Australia and Oceania (IWC Stocks E, E1, E2 and F)

Jennifer A. Jackson, Alex Zerbini, Phil Clapham, Claire Garrigue, Nan Hauser, Michael Poole, C. Scott Baker

Abstract

Humpback whales breeding along the coast of eastern Australia and near islands of Oceania (South Pacific) are thought to feed in Antarctic Areas V and VI (110W to 120E). These populations were subject to intensive exploitation by pelagic and coastal whaling operations during the 20th century. Some known breeding populations, including those around Fiji and those that migrate past New Zealand, virtually disappeared and have yet to show signs of recovery. A Bayesian statistical method was used to estimate probability distributions for the carrying capacity (K), maximum growth rate (r_{max}) and current abundance (N2005) parameters for whales breeding throughout eastern Australia and Oceania (E1+E2+E3+F), as well as for two divisions, represented by eastern Australia and New Caledonia (E1+E2) and east Oceania (E3+F). A density-dependent (age- and sex-aggregated) logistic population model was applied, incorporating the recently revised Antarctic catch series supplied by the IWC Secretariat. Three prior distributions were imposed on growth rates for these analyses; two informative (N[0.067, 0.042]), N[0.106, 0.032] and one uninformative U[0, 12.6%]. Estimates of current abundance were based on capture-recapture models using individual identification photographs collected for the years 1999-2004 (SPWRC 2006). Sensitivity of the model parameters to prior distribution choice, catch allocation (Naïve, Fringe and Overlap) and estimates of current abundance was investigated. Median posterior estimates of carrying capacity for eastern Australia and Oceania ranged from 40,595-44,476. Current recovery estimates (N2005/K) for the combined stocks were low (median, 0.16-0.26K; 95% probability interval, 0.10-0.33K) across all models tested.

Introduction

Commercial fleets have been hunting humpbacks in the Southern Ocean from the start of the 20th century. Coastal whaling was also active in New Zealand, Norfolk Islands, East and West Australia and locally across a number of the Pacific islands. While whaling officially ceased in 1966, the Soviet Union continued illegal whaling throughout the Southern Ocean until 1973. Many of the regional populations of South Pacific humpbacks underwent a severe decline in abundance.

Pelagic catch data from the Soviet Antarctic whaling operation, detailing the magnitude and location of catches made in the 1960s, have recently been made available (Yablokov et al., 1998). The present updated catch series (Allison 2006) represents the most comprehensive catch information covering 20th century whaling in the Antarctic so far.

Seven breeding populations of humpback whales are currently recognised in the Southern Hemisphere (Figure 1). Breeding stock E encompasses animals breeding from eastern Australia (E1), New Caledonia (E2) and Tonga (E3), while breeding stock F encompasses animals breeding in French Polynesia and the Cook Islands. These stocks are thought to feed in Antarctic Areas V and VI. Discovery marks have linked eastern Australian stock E with these areas, while the primary feeding areas of the other three stocks (E2, E3 and F) remain uncertain. As a result, appropriate catch allocation is difficult for these stocks.

Recent analyses of the current recovery of whales breeding in the South Pacific have focused on eastern Australia (Johnston and Butterworth 2002, 2005). Shore-based counts along this coast over the last 25 years have provided estimates of population growth of 10.6% ± 0.5% (Noad et al., 2005). Recent Bayesian logistic analyses of this population (Johnston and Butterworth 2005) suggest an even higher growth rate (r_{max}) estimate of 12.1% (95% CI = 10.6-12.6%). Recovery of this population in 2004 (relative to pristine) was estimated at 37% (95% CI = 26% - 52%).

However, the final breeding grounds of whales migrating past east Australia remain unknown and at present genetic and photo ID data are not available to link these whales with known breeding grounds to the north and east. While it is almost certain that a proportion of these migratory whales breed in the waters around NE Australia (Great Barrier Reef), the alternative hypothesis that some of these migrants also travel to other breeding regions in Oceania, such as New Caledonia, must be considered.

Here we explore a number of scenarios for allocation of catch, abundance estimates and population structuring across the region.

Bayesian logistic modelling was used to provide a preliminary assessment of the status of breeding stocks E1, E2, E3 and F, following the approach of Zerbini (2004, 2005). Uniform and normally distributed priors on the maximum growth rate (r_{max}) were imposed. The effect of various stock allocation scenarios for east and west Oceania were explored. Three different abundance scenarios were investigated for east Australia and west Oceania, (E1, E1 + E2, E1 + E2 + E3) and two for east Oceania (E3 + F, F) under the Naïve, Fringe and Overlap catch allocation scenarios for Areas V and VI respectively.

Methods

Catch Data

In this paper we use the updated historical whale catches for high latitudes provided by Allison (2006). Three catch allocation scenarios are analysed for the whole Oceania region using the combined catch series' for Areas V and VI; Naïve, Fringe and Overlap (as described by the IWC, 1998). In addition, Naïve and Overlap allocation scenarios were applied to pooled breeding stocks for east Australia and west Oceania, exploring the effect of allocating Area V catch to stock E1, stocks E1 + E2, and stocks E1 + E2 +E3. Naïve and Overlap allocation scenarios were also applied to stocks with breeding grounds in west Oceania, and the effect of including stocks E3 + F as opposed to F alone was explored.

The effect of varying the catch series for Tonga was also explored (see *Abundance Estimates* Section). Local whaling was ongoing in Tonga until 1978, but few records are available (Dawbin 1997, Cook 1982). Since scant information exists as to the extent of these catches, a conservative alternative Tongan catch series was generated (Scenario 4, Table 2), wherein 16 whales were added to the catch series for this region for each year from 1900-1956. Thereafter 3-4 whales were added every year from 1957-1978.

Abundance estimates
Abundance estimates from 2004 were used to provide realistic boundaries on recovery calculations. A number of capture-recapture analyses have been reported, for Oceania in combination, and by region (SPWRC 2006). The Mth closed capture-recapture model was chosen to provide the abundance estimates used in this analysis (Table 1).
Oceania plus east Australia (E, E1, E2, F)- Areas V and VI
Two abundance estimates were chosen for this analysis

1. Combined abundance scenario: This is a sum of the CRC Mth closed model estimate for French Polynesia, Cook Islands, New Caledonia and Tonga (3,827, see Table 1) with the east Australian count of 6,555 under the assumption that both estimates are normally distributed. Under this scenario, east Australian counts are assumed to encompass whales not already counted in the other breeding grounds in Oceania, and so provides a maximal abundance estimate (Scenario 1; Table 2).
2. East Australian coastal count (Noad et al., 2005) only, which assumes that all whales breeding in Oceania migrate past this region. A total count of 6,555 ± 389 whales provides a minimal abundance estimate (Scenario 2; Table 2).

Eastern Oceania (E3, F)- Area VI plus coastal Tongan counts

1. Abundance of breeding stocks from Tonga, Cook Islands and French Polynesia was estimated at 3,772 (CV 0.15) using the Mth capture-recapture model. The east Oceania simulation was run twice with variation in the catch series detail for Tonga (as described in the *Catch Data* Section). This estimate provides a maximal abundance estimate of whales feeding in Antarctic Area VI (Scenarios 3 and 4; Table 2).
2. Abundance of French Polynesia alone was estimated at 1,057 (CV 0.22). This was used to provide a minimal abundance estimate of whales feeding in Antarctic Area VI (Scenario 5; Table 2). This is termed here the 'True Naïve' scenario, as it encompasses the only breeding ground found longitudinally within Area VI for which abundance estimates are available. No data on abundance is currently available for the Cook Islands and they are thought to represent a largely migratory, rather than breeding, population.

Western Oceania and east Australia (E1, E2, E3)- Area V
Three estimates of the abundance of stocks breeding on grounds from east Australia and west Oceania were tested in order to explore the effect of including Tonga:

1. East Australian counts alone (6555 ± 389; Scenario 6 (Table 2)).
2. Combination of east Australian count estimates (6555± 389; Noad et al., 2005) and capture-recapture estimates from New Caledonia under Mth (472, CV 0.18). This is Scenario 7, Table 2.

3. Combination of east Australian count estimates (6555± 389; Noad et al., 2005) and capture-recapture estimates from New Caledonia and Tonga under Mth (2236, CV 0.14). This is termed here the 'True Naïve' scenario, as it encompasses all known SH breeding grounds which are found longitudinally within Area V (Scenario 8, Table 2).

Population Dynamics Model

The logistic population dynamics model used in this study is the same as that presented by Zerbini (2004). Integration of prior distributions on the parameters and the likelihood function was approximated using the Sampling-Importance-Resampling algorithm of Rubin (1988), as described in Zerbini (2004). An initial sample of 40,000 parameter combinations from the data was re-sampled 5,000 times in order to provide a random sample from the joint posterior distributions of the model parameters.

Prior distributions

Three priors for the maximum growth rate were used: one uninformative (U[0.00-0.126]) and two informative (N[0.067, 0.04^2] and N[0.106, 0.03^2]). The uninformative prior upper bound recognises that humpback growth rates over 12.6% are extremely unlikely (e.g. Brandão et al., 2000). Prior N[0.067, 0.04^2] is as used by Zerbini (2004, 2005) based on the average growth rate estimated from a hierarchical meta-analysis of growth rates of large baleen whales (Branch et al., 2004). Prior N[0.106, 0.03^2]) approximates the current estimated growth rate for east Australian humpbacks as determined by coastal counts (Noad et al., 2005).

The prior distribution on N2004 for combined estimates was U[ln(2000); ln(15000)]. For east and west Oceania the prior distribution was set at U[ln(1000); ln(9000)].

Genetic constraints

Humpbacks of the South Pacific have maintained a notably large number of mitochondrial haplotypes, and a high level of underlying haplotype diversity (Olavarria et al., in review). We infer from this that the minimum female population size estimated from these trajectories should remain greater than the number of haplotypes present in the population (Baker and Clapham 2004). A total of 79 mitochondrial haplotypes are found in populations from east Australia, New Caledonia, Tonga, French Polynesia and the Cook Islands. The effective female population size (N_{ef}) is generally considered to be (at it's most conservative) an estimate of 0.25N (where N is the total population size). In view of this, the effect on posterior parameter estimates, when trajectories for which N1968 < $4N_e$ (316) were removed, was quantified. Results are shown in Table 3.

Results

East Australia and Oceania (E1, E2, E3, F)

Median estimates of carrying capacity for Oceania under the three scenarios described in Table 2 ranged from 40,595 – 44,476 (95% probability range 36,642 – 66,129). A population trajectory is shown in Figure 4. Despite lower median posterior K under the N[0.106] r_{max}

prior (Table 3), posterior estimates of K and current status (N2005/K) for each scenario did not conflict (i.e. 95% posterior probabilities overlapped) for Fringe, Naïve and Overlap catch allocations, the three abundance estimates and the three prior distributions for r_{max}. The recovery status of the combined populations was estimated at 14.8-25.5% (95% probability range 10.4 – 32.2%; Figure 3). For the normally distributed priors, posterior R_{max} estimates for all models were found to be close (>0.03) to the mean of the specified distribution, indicating that this parameter is plastic for the given combinations of current abundance and catch series. Removal of samples for which N1968 < 316 reduced the allowed range of this estimate, however; growth rates of > 11.3% were rejected by this constraint for the higher abundance estimate (Scenario 1). The effect of the N1968 constraint on median parameter estimates is shown in red in Table 3. Despite the large median difference between N1968 estimates under the N[0.106] prior and the other distributions, confidence intervals overlapped for both scenarios. In summary, no one model rejected the output of any other model for this dataset. Given the extensive intermixing of the populations under scrutiny, and the lack of a designated fringe between Areas V and VI it is considered that the Overlap model of catch allocation should provide a better model for the divided regions of Oceania than the Naïve model. For the combined estimates, the output estimates of the Fringe and Overlap models cannot be distinguished from those of the Naïve model, however.

East Oceania (E3, F vs F)

The median estimate of K within east Oceania when Tonga, French Polynesia and the Cook Islands are pooled (E3 + F; Scenarios 3 and 4) ranged between 6581-9721. The recovery status of this combined population is estimated at between 41.2-61.5%. There was no conflict between the estimates provided by these models, and the inclusion of a modified catch series for Tonga did not significantly affect the estimates of key parameters in terms of probability distributions. Given the evident intermixing of this population outside Area VI, the Overlap model is considered to be most suitable IWC allocation here. The Overlap model provides a median posterior K of 9,608 (CI 8,383-14,851) and median recovery status at 41.7% (CI 26.1-56.5%) for the base case.

When the 'True Naïve' hypothesis was employed, (Scenario 5; F alone), the 3-fold reduction of input parameter N2004 relative to Scenarios 3 and 4 (Table 2) predictably reduced recovery estimates by the same magnitude (Table 3). The effect of this allocation under the Overlap model is shown in Figure 3. Posterior estimates of K were similar across all three scenarios, with median range of 7302-9721. In constrast, Nmin and recovery (N2005/K) estimates were significantly smaller under Scenario 5, when compared with Scenarios 3 and 4 (see Figure 2).

West Oceania (E1, E1 +E2, E1 +E2 + E3)

The median estimate of K for west Oceania ranged from 33,278 to 37,573. Median recovery status for the Overlap model was 22% (CI 14.9-27.7%) under Scenarios 6 and 7 (E1 and E1 + E2) and 28% under Scenario 8 (E1 + E2 + E3). The three abundance estimates provided overlapping probability intervals under the various scenarios, again with no conflict between estimates in terms of output parameter probability distributions.

Discussion

Catch allocations across Oceania

Pelagic catch

Two alternative catch allocation schemes, under-reporting (all catch in the Naïve region increased by 20%) and mis-allocation (catch reduced by 20%), as explored by Zerbini (2004) have not been considered in the current study but their impact on these analyses is likely to be considerable, given the extremely heavy catch records documented for these Areas. An additional limitation to the present analyses is the lack of a designated IWC Fringe region between Antarctic Areas V and VI. It is hoped that this omission will be rectified in the near future, as it will enable more appropriate allocation models for a region where high levels of inter-population migration are apparent.

Coastal catch

The accurate allocation of coastal (north of 40°S) catches to breeding stocks E1, E2 and E3 in Oceania remains problematic, since the final breeding grounds of whales migrating past east Australia and New Zealand (both regions of intensive shore-based whaling) are not known. Comparison of genetic and photo ID data from these migratory regions with data from Oceania will hopefully resolve this allocation problem in the near future.

Allocation of catch to Tonga (E3)

Tonga is the largest humpback breeding stock in Oceania, according to current abundance estimates. Geographically it lies just west of the demarcation line (170W) between Antarctic Areas V and VI, and so should be considered within Area V under an IWC naïve model. This study has demonstrated the impact of including the Tongan population in each Area, with respect to abundance and recovery estimates. However, neither of the approaches taken here are appropriate to account for the likely presence of this population in both feeding Areas during the summer. Bayesian modelling approaches such as Johnston and Butterworth (2005), wherein a prior is placed on the proportion of whales feeding in each Area for each breeding stock, may enable us to approximate mixed feeding Area allocations more appropriately.

As noted in the Methods section, the whaling industry in Tonga cannot be fully accounted for by the IWC (Allison 2006) due to a lack of records. Hence the current catch allocation for this region is likely to be an underestimate.

Abundance estimates for Oceania

Overall abundance estimates presented in the current study are confounded a lack of information as to the migratory destinations of whales counted in the eastern Australia coastal surveys. A catalogue comparison between photos from this region and those from the rest of Oceania will be underway by November 2006. This will hopefully enable more appropriate abundance estimates to be made, encompassing east Australia and Oceania under one model of capture-recapture in order to provide one estimate for the whole region, rather than the combined approximates used in this study. It is also possible that the abundance estimates reported here are slightly biased, as closed models were used, which do not take mortality rates into account (thereby providing an upward bias). These models also fail to account for heterogeneity of between-years estimates, and so will be downwardly biased by this omission.

Whales unaccounted for in Oceania (those breeding outside the survey areas) may also downwardly bias the overall abundance estimate.

Impact of whaling on small populations in Oceania

The impact of whaling on individual humpback breeding grounds in Oceania has not been fully explored in this study. Breeding grounds are known historically from Fiji, for example, and small numbers of humpbacks have also been observed in Niue. Kiribati and American Samoa among others. In the absence of genetic data from these populations, it is very difficult to quantify the true impact of whaling, since the numbers of recent colonisers from other breeding grounds to these small populations (relative to the number of animals who show site fidelity and would have undergone a recent bottleneck) is unquantified.

Impact of Western Australia

Genetic and capture-recapture evidence suggests that the Western Australia humpback population (D) is large (N1999 = 8000-14000, Bannister and Hedley 2001) in comparison to the stocks described in this study. Discovery mark data suggests that stock D shares feeding Areas IV and V with humpbacks from group E regions. Johnston and Butterworth (2005) modelled the mixing of groups D and E1 on feeding Areas IV and V. Under the assumption that no humpbacks from other breeding stocks feed in these Areas, ~32% of whales from group D were estimated to feed in Area V and ~28% of whales from group E1 were estimated to feed in Area IV. We account for this catch allocation heterogeneity only in the IWC Fringe and Overlap models. If the true overlap or shift in distributions of whales between feeding Areas is much larger than these adjustments, it represents a shortcoming for these analyses.

References

Allison, C. 2006. Documentation of the Creation of the S. Hemisphere Humpback Catch Series Feb 2006, Cambridge, UK.

Baker, C. S., and P. J. Clapham. 2004. Modelling the past and future of whales and whaling. Trends in Ecology and Evolution **19**:365-371.

Bannister, J. L., and S. L. Hedley. 2001. Southern Hemisphere Group IV humpback whales: their status from recent aerial surveys. Memoirs of the Queensland Museum **47**:587-598.

Branch, T. A., K. Matsuoka, and T. Miyashita. 2004. Evidence for increases in Antarctic blue whales based on Bayesian modelling. Marine Mammal Science **20**:726-754.

Cook, B. 1982. Interview with Benny Cook (2/6/82). Pp. 2.

Dawbin, W. H. 1997. Temporal segregation of humpback whales during migration in southern hemisphere waters. Memoirs of the Queensland Museum **42**:105-138.

IWC. 1998. Report of the Scientific Committee of the International Whaling Commission. 50th Annual Meeting of the International Whaling Commission, Muscat, Oman.

Johnston, S. J., and D. S. Butterworth. 2002. An Assessment of the west and east Australian breeding stocks of Southern Hemisphere humpback whales using a model that allows for mixing in the feeding grounds. 54th Annual Meeting of the International Whaling Commission, Document SC/54/H17 submitted to the IWC Scientific Committee.

Johnston, S. J., and D. S. Butterworth. 2005. A Bayesian Assessment of the West and East Australian Breeding Populations (Stocks D and E) of Southern Hemisphere Humpback whales. 57th Annual Meeting of the International Whaling Commission, Document SC/57/SH15 submitted to the IWC Scientific Committee. 31pp.

Johnston, S. J., D. S. Butterworth, and K. P. Findlay. 2001. Further results from a preliminary assessment of Southern Hemisphere Humpback whales. 53rd Annual Meeting of the International Whaling Commission, Document SC/53/IA20 submitted to the IWC Scientific Committee. 31pp.

Noad, M. J., D. H. Cato, and D. Paton. 2005. Absolute and relative abundance estimates of Australian east coast humpback whales (*Megaptera novaeangliae*). 57th Annual Meeting of the International Whaling Commission, Ulsan, Republic of Korea.

Olavarría, C., C. S. Baker, C. Garrigue, M. Poole, N. Hauser, S. Caballero, L. Flórez-González, L. Brasseur, M. Bannister, J. Capella, P. J. Clapham, R. Dodemont, M. Donoghue, C. Jenner, M. N. Jenner, D. Moro, M. Oremus, D. A. Paton, and R. K. 2005. Population Structure of humpback whales throughout the Southern Pacific and the origins of the eastern Polynesian breeding grounds. In review.

Rubin, D. B. 1988. Using the SIR algorithm to simulate posterior distributions. Pp. 805 *in* J. M. Bernado, M. H. DeGroot, D. V. Lindlley, and A. F. M. Smith, eds. Bayesian Statistics 3: Proceedings of the Third Valencia International Meeting. Clarendon Press, Oxford.

Ruhen, O. 1966. Harpoon in My Hand. Angus and Robertson, Sydney.

South Pacific Whale Research Consortium (SPWRC) 2006. Abundance of humpback whales in Oceania (South Pacific), 1999-2004. Report submitted for the consideration of the Inter-sessional Workshop for the Comprehensive Assessment of Southern Hemisphere Humpback whales, Hobart, Tasmania.

Yablokov, A. V., V. A. Zemsky, Y. A. Mikhalev, V. V. Tormosov, and A. A. Berzin. 1998. Data on Soviet whaling in the Antarctic in 1947-1972 (population aspects). Russian Journal of Ecology **29**:38-42.

Zerbini, A. N. 2005. An updated Bayesian assessment of the Southern Hemisphere humpback whale Breeding Stock A. Document SC/57/SH17 presented to the IWC Scientific Committee.:7pp.

Zerbini, A. N. 2004. Status of the Southern Hemisphere humpback whale breeding stock A: preliminary results from a Bayesian assessmet. 56th Annual Meeting of the International Whaling Commission, Document SC/56/SH17 submitted to the IWC Scientific Committee.

Table 1- Estimates of the 2004 abundance of humpback whales used in this study. Numbers under the Model column indicate those regions (from the left-hand column) which have been summed to generate a combined estimate. EA = east Australia, NC = New Caledonia, Tg = Tonga

Region	Model	Year	Estimate	CV	Reference
1. Oceania (E2, E3, F)	Mth	1999-2004	3827	0.12	SPWRC report 2006
2. East Oceania (E3, F)	Mth	1999-2004	3772	0.15	SPWRC report 2006
3. NC + Tg (E2+E3)	Mth	1999-2004	2236	0.14	SPWRC report 2006
4. New Caledonia (E2)	Mth	1999-2004	472	0.18	SPWRC report 2006
5. French Polynesia (F)	Mth	1999-2004	1057	0.22	SPWRC report 2006
6. East Australia (E1)	Survey	2004	6555	0.06	Noad et al., 2005
7. EA + Oceania (E1, E2, E3, F)	1 + 6	2004	10390	0.12	
8. EA + NC (E1+E2)	4 + 6	2004	7025	0.06	
9. EA + NC + Tg (E1+E2+E3)	3 + 6	2004	8784	0.07	

Table 2 – Scenarios tested for population assessments across Oceania. Numbers in brackets in the 'Abundance' column relate to regional estimates detailed in Table 1.** indicates the scenario wherein Tongan catch was estimated as described in the methods section.

Scenario	Breeding Stocks	Abundance (2004)	Feeding Area	Allocation type
1	All (E1, E2, E3, F)	10390 (7)	V and VI	Naïve, fringe, overlap
2	All (E1, E2, E3, F)	6555 (6)	V and VI	Naïve, fringe, overlap
3	East Oceania (E3+F)	3772 (2)	VI	Naïve, overlap
4	East Oceania (E3+F)	3772 (2)	VI **	Naïve, overlap
5	East Oceania (F- true Naïve)	1057 (5)	VI	Naïve, overlap
6	EA (E1)	6555 (6)	V	Naïve, overlap
7	EA + West Oceania (E1+E2)	7025 (7)	V	Naïve, overlap
8	EA + West Oceania (E1+E2+E3 – true Naïve)	8784 (9)	V	Naïve, overlap

Table 3- Summary of posterior median estimates for five parameters across all scenarios, as depicted in Figure 2. For more detailed information see Tables 4-6. Numbers in brackets are posterior median estimates after trajectories where N1968 < 316 have been removed. Note that the Fringe model is not available for analyses of Areas V and VI individually.

Oceania Scenarios	**Rmax**	**K**	**Abundance 2005**	**N1968**	**Status 2005**
1 Naïve	U	44476	11000	1233	24.6%
1 Naïve	(0.062) N(0.067)	(44546) 44178	(10983) 11019	1139	(24.5%) 24.8%
1 Naïve	(0.085) N(0.106)	(41724) 40595	(11243) 11332	412	(26.6%) 27.8%
1 Fringe	N(0.067)	42727	11018	1137	25.7%
1 Overlap	N(0.067)	42017	11016	1139	26.1%
2 Naïve	U	44267	6959	785	15.7%
2 Naïve	(0.054) N(0.067)	(46837) 43799	(6908) 6985	699	(15.2%) 15.9%
2 Naïve	(0.074) N(0.106)	(42768) 40605	(7039) 7160	272	(16.3%) 17.6%
2 Fringe	N(0.067)	42464	6975	713	16.4%
2 Overlap	N(0.067)	41857	6971	735	16.7%

Area Scenarios	**Rmax**	**K**	**Abundance 2005**	**N1968**	**Status 2005**
East Oceania (E3 + F)					
3 Naïve Area VI	U	7209	4011	479	54.8%
3 Naïve Area VI	N(0.067)	7142	4024	440	55.6%
3 Naïve Area VI	N(0.106)	6581	4071	164	61.5%
3 Fringe Area VI	N/A	N/A	N/A	N/A	N/A
3 Overlap Area VI	N(0.067)	9608	4048	417	41.7%
Variation in Tongan catch series					
4 Naïve Area VI	N(0.067)	7302	4024	483	54.4%
4 Overlap Area VI	N(0.067)	9721	4049	451	41.2%
East Oceania (F) 'True' Area VI stocks					
5 Naïve Area VI	N(0.067)	6978	1140	115	16.1%
5 Naïve Area VI	N(0.106)	6533	1166	43	17.7%
5 Overlap Area VI	N(0.067)	9458	1142	117	11.9%

EA + West Oceania base case (E1)					
6 Naïve	N(0.067)	37142	6983	697	18.8%
6 Naïve	N(0.106)	34376	7156	267	20.8%
6 Fringe	N/A	N/A	N/A	N/A	N/A
6 Overlap	N(0.067)	33257	6982	699	20.9%
EA + West Oceania (E1+E2)					
7 Naïve	N(0.067)	37169	7483	747	20.1%
7 Naïve	N(0.106)	34370	7666	283	22.3%
7 Fringe	N/A	N/A	N/A	N/A	N/A
7 Overlap	N(0.067)	33278	7480	743	22.4%
EA + West Oceania (E1+E2+E3)- 'True' Area V stocks					
8 Naïve	N(0.067)	37246	9352	924	25.0%
8 Naïve	N(0.106)	34285	9570	334	27.9%
8 Fringe	N/A	N/A	N/A	N/A	N/A
8 Overlap	N(0.067)	33364	9344	927	27.9%

Scenario 1

Allocation	r	current r	K	N2004	N2005	N2020	Nmin/K	N2005/K	N2020/K	Nmin
Naïve	Uniform									
median	0.062	0.060	44475.6	10389.8	11000.4	24759.0	0.028	0.246	0.557	1232.7
mode	0.056	0.054	45517.0	10495.3	11060.6	23164.1	0.034	0.243	0.509	1546.5
mean	0.063	0.061	46879.2	10391.5	11018.7	24366.1	0.044	0.242	0.558	2069.1
sd	0.036	0.035	7702.1	556.1	688.5	8326.2	0.041	0.044	0.251	317.2
2.5%	0.003	0.003	38464.5	9317.6	9724.9	10796.8	0.005	0.156	0.164	188.5
97.5%	0.122	0.118	66128.8	11505.3	12413.2	35975.2	0.142	0.314	0.934	9403.1

Naïve	0.106									
median	0.096	0.093	40594.9	10402.7	11332.0	32885.1	0.010	0.278	0.810	412.4
mode	0.101	0.098	40130.6	10427.0	11441.5	33789.3	0.009	0.285	0.842	351.1
mean	0.093	0.090	41233.8	10412.4	11341.3	31397.3	0.014	0.276	0.770	586.2
sd	0.022	0.021	2610.1	550.6	634.1	4520.1	0.012	0.025	0.145	32.2
2.5%	0.043	0.041	38336.9	9353.4	10119.7	19623.9	0.005	0.222	0.409	176.8
97.5%	0.124	0.120	48045.8	11512.5	12627.5	36126.5	0.050	0.322	0.939	2424.7

Naïve	0.067									
median	0.064	0.062	44177.5	10390.9	11019.3	25229.6	0.026	0.248	0.571	1139.1
mode	0.053	0.051	45993.2	10439.4	10973.9	22292.8	0.037	0.239	0.485	1689.8
mean	0.064	0.063	45261.3	10386.9	11033.8	25051.3	0.034	0.247	0.573	1554.3
sd	0.027	0.026	4920.6	557.8	648.8	6397.6	0.027	0.032	0.191	134.5
2.5%	0.013	0.013	38973.8	9270.1	9775.7	12853.4	0.006	0.179	0.219	231.9
97.5%	0.116	0.111	58700.4	11489.6	12313.1	35443.6	0.112	0.305	0.908	6590.2

Fringe	0.067									
median	0.064	0.062	42726.9	10390.2	11018.1	25079.3	0.027	0.257	0.586	1136.5
mode	0.053	0.051	44494.1	10439.4	10972.6	22184.6	0.038	0.247	0.499	1688.5
mean	0.064	0.063	43805.0	10386.8	11032.1	24789.5	0.035	0.255	0.585	1550.8
sd	0.027	0.025	4793.0	558.5	648.4	6173.4	0.028	0.033	0.192	135.2
2.5%	0.013	0.013	37752.7	9270.0	9774.1	12828.7	0.006	0.184	0.225	228.7
97.5%	0.116	0.111	56956.1	11497.2	12310.5	34597.2	0.116	0.315	0.915	6591.3

Allocation	r	current r	K	N2004	N2005	N2020	Nmin/K	N2005/K	N2020/K	Nmin
Overlap	**0.067**									
median	0.064	0.062	42017.0	10390.9	11016.0	24944.6	0.027	0.261	0.593	1139.0
mode	0.053	0.051	43837.8	10439.4	10972.0	22133.9	0.039	0.250	0.505	1690.2
mean	0.064	0.062	43150.5	10386.2	11030.1	24613.8	0.036	0.259	0.591	1546.7
sd	0.027	0.025	5023.3	558.3	648.0	6014.3	0.028	0.035	0.193	141.5
2.5%	0.013	0.013	36863.8	9268.0	9772.5	12828.7	0.006	0.184	0.225	230.1
97.5%	0.115	0.111	56986.5	11489.7	12309.1	33973.8	0.116	0.322	0.920	6597.8

Scenario 2

Naïve	Uniform									
median	0.062	0.061	44266.5	6557.0	6959.2	16638.1	0.018	0.157	0.375	784.7
mode	0.043	0.042	47463.4	6772.4	7059.1	13040.6	0.032	0.149	0.275	1537.6
mean	0.063	0.062	46236.5	6558.5	6966.1	17735.1	0.029	0.154	0.414	1335.1
sd	0.037	0.036	6933.0	276.2	377.4	7800.6	0.028	0.027	0.223	191.0
2.5%	0.003	0.003	38385.7	6013.4	6247.2	6843.2	0.003	0.104	0.109	122.6
97.5%	0.123	0.122	63068.4	7111.9	7709.3	31045.7	0.095	0.197	0.808	6022.4

Naïve	0.067									
median	0.066	0.065	43799.4	6564.7	6985.4	17434.9	0.016	0.159	0.398	698.3
mode	0.057	0.057	47747.1	6715.6	7095.0	15866.7	0.021	0.158	0.353	1000.1
mean	0.065	0.065	45117.8	6566.9	6991.1	18029.0	0.024	0.157	0.420	1071.2
sd	0.031	0.031	5344.6	274.2	354.6	6702.2	0.021	0.022	0.191	114.4
2.5%	0.008	0.008	38579.0	6030.6	6323.4	7466.6	0.003	0.111	0.126	132.5
97.5%	0.121	0.119	59295.8	7111.6	7710.2	30577.1	0.082	0.195	0.792	4882.9

Naïve	0.106									
median	0.095	0.094	40604.7	6567.2	7160.2	24852.9	0.007	0.176	0.612	271.9
mode	0.124	0.123	38319.0	6562.0	7364.9	31168.7	0.003	0.192	0.813	118.9
mean	0.092	0.091	41230.6	6568.2	7164.7	23932.4	0.010	0.175	0.590	391.8
sd	0.022	0.022	2545.6	275.9	334.4	5313.7	0.008	0.015	0.156	21.0
2.5%	0.041	0.040	38312.2	6035.5	6519.0	12250.5	0.003	0.141	0.256	118.6
97.5%	0.124	0.123	47811.3	7134.5	7813.2	31398.2	0.034	0.200	0.817	1602.7

Allocation	r	current r	K	N2004	N2005	N2020	Nmin/K	N2005/K	N2020/K	Nmin
Fringe	**0.067**									
median	0.065	0.064	42464.4	6558.5	6975.1	17164.0	0.017	0.164	0.404	713.2
mode	0.072	0.072	41546.4	6662.2	7138.2	19204.6	0.014	0.172	0.462	565.0
mean	0.065	0.064	43776.3	6561.4	6979.8	17730.0	0.025	0.162	0.426	1092.3
sd	0.031	0.030	5267.6	272.5	350.8	6536.1	0.022	0.023	0.193	118.5
2.5%	0.007	0.007	37399.3	6043.5	6311.8	7322.7	0.003	0.113	0.125	129.2
97.5%	0.120	0.119	58285.0	7101.5	7679.2	30012.9	0.089	0.201	0.803	5180.2
Overlap	**0.067**									
median	0.064	0.063	41856.5	6557.9	6971.4	16957.5	0.018	0.167	0.405	734.2
mode	0.073	0.072	40752.1	6828.7	7317.9	19634.4	0.014	0.180	0.482	576.2
mean	0.064	0.063	43277.7	6562.0	6973.7	17448.7	0.026	0.164	0.425	1114.4
sd	0.030	0.030	5602.0	274.4	351.6	6328.6	0.023	0.024	0.192	126.7
2.5%	0.007	0.007	36641.6	6031.0	6306.8	7251.6	0.004	0.112	0.123	141.2
97.5%	0.118	0.116	58739.7	7106.4	7668.3	29377.4	0.088	0.205	0.800	5159.7

Table 4- Posterior estimates of key logistic parameters for Scenarios 1 and 2 (whole of Oceania).

Scenario 3

	r	current r	K	N2004	N2005	N2020	Nmin/K	N2005/K	N2020/K	N1968
Naïve	**Uniform**									
median	0.062	0.049	7208.7	3828.0	4010.9	6276.3	0.067	0.548	0.895	478.9
mode	0.111	0.092	6382.7	3291.7	3581.7	6277.5	0.013	0.561	0.984	83.6
mean	0.063	0.049	7748.4	3865.9	4043.6	5917.5	0.102	0.540	0.802	921.4
sd	0.037	0.027	1474.0	407.9	420.6	802.5	0.091	0.112	0.208	997.1
2.5%	0.003	0.003	6258.6	3183.6	3318.2	3828.6	0.011	0.328	0.347	67.7
97.5%	0.123	0.095	11490.5	4824.2	5011.7	6774.5	0.308	0.744	0.996	3523.0
Naïve	**0.067**									
median	0.065	0.051	7141.7	3827.6	4023.8	6340.4	0.062	0.556	0.906	440.3
mode	0.082	0.067	6779.4	3561.1	3791.7	6422.7	0.034	0.559	0.947	227.2
mean	0.065	0.051	7491.3	3875.8	4061.4	6106.0	0.087	0.554	0.839	729.7
sd	0.030	0.022	1126.7	419.3	429.8	649.7	0.072	0.097	0.168	758.6
2.5%	0.008	0.007	6293.1	3196.7	3360.3	4249.0	0.012	0.357	0.404	77.1
97.5%	0.119	0.091	10736.4	4824.2	5031.8	6830.4	0.278	0.742	0.995	2991.2
Naïve	**0.106**									
median	0.096	0.072	6580.7	3815.5	4070.6	6375.4	0.025	0.615	0.979	164.4
mode	0.115	0.086	6347.9	3872.4	4179.8	6300.4	0.014	0.658	0.993	91.4
mean	0.093	0.071	6687.6	3856.4	4110.4	6369.6	0.034	0.617	0.956	237.9
sd	0.022	0.016	422.1	409.9	413.3	201.3	0.028	0.074	0.062	230.0
2.5%	0.044	0.036	6243.3	3182.3	3417.1	5924.9	0.010	0.477	0.767	63.6
97.5%	0.124	0.098	7824.8	4824.2	5066.9	6702.5	0.115	0.778	0.997	898.8
Overlap	**0.067**									
median	0.065	0.059	9607.5	3824.7	4048.3	7806.3	0.043	0.417	0.811	417.3
mode	0.082	0.075	9113.3	3561.0	3823.6	8046.1	0.024	0.420	0.883	218.3
mean	0.065	0.058	10086.9	3874.1	4092.9	7294.3	0.062	0.415	0.754	705.4
sd	0.030	0.026	1604.8	418.7	445.2	1240.1	0.052	0.077	0.202	749.3
2.5%	0.008	0.008	8383.7	3196.2	3370.9	4285.3	0.009	0.261	0.294	72.9
97.5%	0.119	0.105	14851.6	4824.2	5104.9	8592.8	0.199	0.565	0.985	2965.6

	r	current r	K	N2004	N2005	N2020	Nmin/K	N2005/K	N2020/K	N1968
Scenario 4										
Naïve	**0.067**									
median	0.065	0.052	7302.0	3824.6	4024.0	6443.3	0.066	0.544	0.900	482.9
mode	0.082	0.068	9670.5	3561.1	3794.7	6532.5	0.039	0.548	0.944	266.8
mean	0.065	0.051	7665.7	3874.0	4062.8	6189.4	0.090	0.542	0.833	771.9
sd	0.030	0.023	1179.5	418.7	430.6	683.9	0.070	0.097	0.172	764.9
2.5%	0.008	0.007	6405.3	3196.1	3360.9	4253.7	0.017	0.348	0.392	110.3
97.5%	0.119	0.092	11037.7	4824.2	5038.8	6944.0	0.275	0.730	0.994	3052.6
Overlap	**0.067**									
median	0.065	0.059	9720.7	3824.3	4049.0	7851.9	0.046	0.412	0.806	450.9
mode	0.082	0.075	10185.9	3561.0	3824.3	8107.0	0.027	0.415	0.880	248.7
mean	0.065	0.058	10209.5	3873.6	4093.4	7339.1	0.064	0.411	0.750	738.4
sd	0.030	0.026	1641.3	418.4	445.5	1264.6	0.051	0.077	0.204	753.1
2.5%	0.008	0.008	8467.9	3194.9	3370.8	4285.6	0.012	0.257	0.289	98.7
97.5%	0.119	0.105	15092.9	4824.2	5107.0	8667.2	0.198	0.560	0.984	3010.9
Scenario 5										
Naïve	**0.067**									
median	0.065	0.064	6978.3	1069.9	1140.4	2807.1	0.016	0.161	0.402	115.4
mode	0.082	0.082	6702.3	969.8	1049.0	3224.6	0.009	0.157	0.481	58.9
mean	0.065	0.064	7115.1	1075.4	1143.9	2904.4	0.025	0.162	0.424	196.9
sd	0.031	0.030	645.8	161.3	174.4	1122.4	0.025	0.030	0.191	215.6
2.5%	0.007	0.007	6281.5	776.2	819.9	1133.0	0.003	0.109	0.131	20.9
97.5%	0.119	0.118	8752.1	1410.1	1504.9	5073.1	0.097	0.224	0.802	847.9
Naïve	**0.106**									
median	0.096	0.095	6533.2	1069.7	1165.8	3982.2	0.007	0.177	0.611	42.7
mode	0.101	0.100	6266.0	1145.8	1260.2	4475.3	0.006	0.195	0.692	38.3
mean	0.092	0.091	6614.7	1075.7	1173.3	3882.8	0.010	0.178	0.594	65.9
sd	0.022	0.022	330.7	162.6	178.1	925.0	0.009	0.029	0.161	70.8
2.5%	0.042	0.042	6229.0	776.4	846.2	1940.7	0.003	0.124	0.263	17.4
97.5%	0.124	0.123	7433.2	1415.5	1542.4	5334.1	0.034	0.238	0.850	254.0

	r	current r	K	N2004	N2005	N2020	Nmin/K	N2005/K	N2020/K	N1968
Overlap	**0.067**									
median	0.065	0.065	9457.6	1070.4	1141.5	2870.5	0.012	0.119	0.303	117.0
mode	0.082	0.082	10755.7	969.9	1049.5	3332.0	0.007	0.116	0.369	60.6
mean	0.065	0.064	9731.4	1075.9	1145.1	3049.1	0.018	0.119	0.330	198.1
sd	0.031	0.031	1146.6	160.3	173.5	1288.6	0.017	0.024	0.165	215.0
2.5%	0.007	0.007	8374.3	778.2	821.1	1134.6	0.003	0.076	0.090	22.2
97.5%	0.119	0.118	12901.2	1407.7	1504.8	5760.4	0.066	0.167	0.683	842.8

Table 5- Posterior estimates of key logistic parameters for Scenarios 3, 4 and 5 (east Oceania)

Scenario 6

	r	current r	K	N2004	N2005	N2020	Nmin/K	N2005/K	N2020/K	N1968
Naïve	**0.067**									
median	0.066	0.065	37142.7	6564.6	6983.4	17091.5	0.019	0.188	0.461	697.2
mode	0.057	0.056	38178.2	6715.6	7093.1	15658.0	0.025	0.186	0.410	939.6
mean	0.065	0.064	38407.8	6567.2	6988.5	17359.3	0.028	0.185	0.475	1183.9
sd	0.031	0.030	4840.0	273.4	352.1	5986.6	0.025	0.027	0.205	1260.5
2.5%	0.008	0.008	32668.0	6030.8	6325.8	7462.9	0.004	0.128	0.145	128.0
97.5%	0.121	0.119	51486.0	7108.2	7701.1	27810.7	0.095	0.229	0.850	4893.9
Naïve	**0.106**									
median	0.095	0.094	34376.1	6567.2	7156.1	23618.7	0.008	0.208	0.686	267.1
mode	0.124	0.122	32449.5	6562.1	7359.1	28175.9	0.004	0.227	0.868	114.4
mean	0.092	0.091	34936.1	6568.5	7161.3	22585.2	0.011	0.206	0.656	408.4
sd	0.022	0.022	2225.6	275.3	332.9	4476.0	0.010	0.018	0.159	421.1
2.5%	0.040	0.040	32443.6	6036.8	6521.5	12171.1	0.004	0.165	0.298	114.2
97.5%	0.124	0.122	40795.7	7134.6	7814.5	28338.4	0.039	0.236	0.871	1604.1
Naïve	**U**									
median	0.062	0.061	37573.1	7027.8	7455.5	17408.6	0.022	0.198	0.462	835.6
mode	0.043	0.042	40481.6	7254.3	7559.3	13826.8	0.041	0.187	0.342	1645.1
mean	0.063	0.062	39530.2	7030.0	7463.2	17858.6	0.036	0.194	0.488	1630.0
sd	0.037	0.036	6425.2	292.4	399.5	7067.2	0.034	0.035	0.244	1805.8
2.5%	0.003	0.003	32501.3	6451.3	6702.5	7333.5	0.004	0.127	0.133	125.2
97.5%	0.123	0.121	55426.4	7616.7	8251.6	28762.1	0.116	0.249	0.884	6427.3
Overlap	**0.067**									
median	0.065	0.064	33257.3	6565.6	6982.3	16808.0	0.021	0.209	0.506	698.5
mode	0.057	0.056	34254.6	6715.7	7091.4	15475.0	0.027	0.207	0.452	941.2
mean	0.065	0.064	34502.0	6567.5	6986.6	16826.0	0.031	0.206	0.514	1184.2
sd	0.031	0.030	4679.1	273.7	352.0	5437.0	0.027	0.031	0.214	1258.1
2.5%	0.008	0.008	29000.2	6030.8	6324.7	7465.9	0.004	0.139	0.159	128.7
97.5%	0.120	0.118	47164.4	7109.1	7702.0	25707.0	0.103	0.258	0.885	4869.1

	r	current r	K	N2004	N2005	N2020	Nmin/K	N2005/K	N2020/K	N1968
Scenario 7										
Naïve	**0.067**									
median	0.065	0.064	37169.3	7035.6	7483.2	18145.4	0.020	0.201	0.488	746.7
mode	0.057	0.056	38214.9	7194.6	7597.9	16657.1	0.026	0.199	0.436	1005.9
mean	0.065	0.064	38448.2	7037.8	7488.6	18284.8	0.030	0.198	0.500	1262.5
sd	0.031	0.030	4900.2	289.1	373.0	6065.6	0.026	0.029	0.209	1344.8
2.5%	0.008	0.008	32669.9	6472.7	6786.1	8028.0	0.004	0.136	0.156	136.1
97.5%	0.121	0.118	51730.4	7614.5	8245.5	28504.4	0.101	0.246	0.872	5217.3
Naïve	**0.106**									
median	0.096	0.094	34369.9	7036.5	7665.7	24678.0	0.008	0.223	0.717	282.6
mode	0.081	0.080	35582.9	7270.8	7847.6	22161.8	0.013	0.221	0.623	463.2
mean	0.092	0.091	34927.0	7037.0	7671.5	23574.9	0.012	0.221	0.685	432.5
sd	0.022	0.022	2233.9	290.1	350.9	4382.9	0.010	0.019	0.158	449.0
2.5%	0.041	0.040	32447.8	6477.3	6995.4	13071.8	0.004	0.177	0.319	121.3
97.5%	0.124	0.122	40837.6	7624.9	8353.3	28962.1	0.042	0.253	0.890	1706.3
Overlap	**0.067**									
median	0.066	0.064	33277.8	7035.5	7480.1	17829.6	0.022	0.224	0.536	743.2
mode	0.057	0.056	34291.3	7194.6	7595.7	16432.1	0.029	0.222	0.479	1007.9
mean	0.065	0.064	34537.8	7037.7	7485.8	17678.9	0.033	0.221	0.539	1262.0
sd	0.031	0.030	4743.3	289.2	371.3	5451.1	0.029	0.033	0.216	1344.7
2.5%	0.008	0.008	29001.9	6472.0	6788.2	8025.1	0.005	0.149	0.169	136.4
97.5%	0.121	0.117	47478.2	7613.4	8234.8	26218.8	0.110	0.277	0.903	5219.2
Scenario 8										
Naïve	**0.067**									
median	0.066	0.064	37245.7	8799.5	9351.7	21782.1	0.025	0.250	0.585	924.4
mode	0.010	0.010	51940.3	9020.4	9111.4	10587.0	0.121	0.175	0.204	6306.1
mean	0.065	0.063	38695.2	8802.9	9357.4	21293.6	0.037	0.246	0.578	1588.1
sd	0.031	0.030	5231.8	435.4	525.9	6126.7	0.033	0.037	0.218	1698.6
2.5%	0.009	0.008	32713.9	7951.3	8364.0	10004.0	0.005	0.167	0.190	167.3
97.5%	0.120	0.116	52871.6	9672.4	10420.8	30288.0	0.124	0.309	0.925	6523.9

	r	current r	K	N2004	N2005	N2020	Nmin/K	N2005/K	N2020/K	N1968
Naïve	**0.106**									
median	0.097	0.094	34285.3	8784.5	9569.9	27958.2	0.010	0.279	0.816	334.2
mode	0.105	0.101	33731.6	8701.3	9575.9	28839.8	0.008	0.284	0.855	264.2
mean	0.093	0.091	34861.5	8797.8	9587.9	26662.7	0.014	0.276	0.774	512.7
sd	0.022	0.021	2224.9	436.5	506.2	3825.7	0.012	0.025	0.145	532.8
2.5%	0.043	0.042	32484.0	7950.1	8607.9	16404.7	0.005	0.221	0.405	150.2
97.5%	0.124	0.120	40547.6	9678.3	10588.9	30550.4	0.049	0.318	0.938	1980.5
Overlap	**0.067**									
median	0.066	0.063	33364.1	8799.0	9344.4	21169.3	0.028	0.279	0.634	927.4
mode	0.010	0.010	47707.6	9020.4	9111.1	10579.9	0.132	0.191	0.222	6311.2
mean	0.065	0.063	34793.8	8802.1	9350.3	20383.4	0.041	0.275	0.616	1592.2
sd	0.031	0.029	5079.8	435.0	522.8	5342.8	0.035	0.043	0.221	1700.5
2.5%	0.009	0.008	29042.5	7951.2	8362.2	9998.5	0.006	0.181	0.207	168.0
97.5%	0.120	0.115	48622.3	9671.5	10409.5	27487.4	0.134	0.347	0.945	6528.2

Table 6- Posterior estimates of key logistic parameters for each of the chosen scenarios for east Australia and west Oceania