New Zealand Fisheries
Assessment Report
2008/5
January 2008
ISSN 1175-1584

The 2007 assessment for paua (*Haliotis iris*) stock PAU 5B (Stewart Island)

Paul A. Breen
Adam N. H. Smith

The 2007 assessment for paua (*Haliotis iris*) stock PAU 5B (Stewart Island)

Paul A. Breen
Adam N. H. Smith

NIWA
Private Bag 14901
Wellington

New Zealand Fisheries Assessment Report 2008/5
January 2008

Published by Ministry of Fisheries
Wellington
2008

ISSN 1175-1584

©
Ministry of Fisheries
2008

Citation:
Breen, P.A.; Smith, A.N.H. (2008).
The 2007 assessment for paua (*Haliotis iris*) stock PAU 5B (Stewart Island).
New Zealand Fisheries Assessment Report 2008/5. 64 p.

This series continues the informal
New Zealand Fisheries Assessment Research Document series
which ceased at the end of 1999.

EXECUTIVE SUMMARY

Breen, P.A.; Smith, A.N.H. (2008). The 2007 assessment for paua (*Haliotis iris*) stock PAU 5B (Stewart Island).

***New Zealand Fisheries Assessment Report 2008/5.* 64 p.**

This document presents the 2007 Bayesian stock assessment of blackfoot paua (New Zealand abalone, *Haliotis iris*) in PAU 5B (Stewart Island). This work was conducted by NIWA under Ministry of Fisheries (MFish) contract PAU200603, Objective 2.

The assessment used a purpose-built length-based Bayesian model that has been used for previous paua assessments; modifications were made only to the likelihood options for fitting length frequency and tag-recapture data. The model is described briefly and the modifications are explained.

The model was fit to six data sets: two abundance indices – one from commercial catch and effort data and one from independent research diver surveys, two sets of proportion-at-length data – one from commercial catch sampling and one from research diver surveys, a tag-recapture dataset and a maturity-at-length dataset. Data were presented to the Working Group.

Modelling choices and assumptions were mostly discussed by the Working Group and are presented here. The base case was found by iteratively weighting datasets to obtain standard deviations of normalised residuals close to 1. The model fit the data reasonably well and no problems were encountered in the exploratory runs, except that research diver selectivity parameters were fixed to values obtained in an earlier assessment in PAU 7, to exclude unrealistic model estimates.

The assessment is based on marginal posterior distributions of agreed fishery indicators; the indicators are based on spawning and recruited biomass at four levels: the minimum estimates in model trajectories, current levels, target levels from an agreed reference period, 1985–87, and projected levels in three-year projections with resampled recruitment and the current level of catch.

The assessment suggests that current biomass estimates (*S07* and *B07*) are well above the minimum reference levels *Smin* and *Bmin*. This was true in all MPD sensitivity trials and in the McMC. Second, projected biomass (*S10* and *B10*) is highly likely to remain above these reference levels – in the McMC projection, biomass never fell below *Bmin* or *Smin*.

The assessment suggests that both spawning and recruited biomass are below the target levels *Sav* and *Bav*. Spawning biomass was estimated at 75% of *Sav* (5th to 95th quantiles 66% to 85%), while recruited biomass was estimated as 87% of *Bav* (77% to 100%).

McMC projections suggest that spawning biomass was more likely (61%) to increase than decrease under current levels of total catch, and is likely to remain below *Sav* for the next three years. In contrast, recruited biomass shows a tendency to decrease (64%) and remain below *Bav*.

For recruited biomass, however, it cannot be concluded strongly that current biomass is less than the *Bav* reference level. The posterior touches 100% at the 95% confidence level. MPD sensitivity trials showed *B07/Bav* near 100% in several situations: when the CPUE dataset was removed, when the pre-1990 CPUE data were removed and when the lower-catch alternative series were used.

CONTENTS

EXECUTIVE SUMMARY 3
CONTENTS 4
1. INTRODUCTION 5
2. MODEL 5
2.1 Estimated parameters 5
2.2 Constants 6
2.3 New likelihood option 7
3. FINDING A BASE CASE 7
4. BASE CASE MPD RESULTS 9
5. MPD SENSITIVITY TRIALS 23
5.1 Dataset removal 24
5.2 Truncated abundance index series 27
5.3 Alternative commercial catch series 28
5.4 Multinomial likelihood 32
5.5 Retrospective trials 32
6. MCMC RESULTS 34
6.1 Diagnostics 34
6.2 Posterior distributions 44
6.3 Fits to data and trajectories 51
6.4 Parameter correlations 57
7. PAU 5B ASSESSMENT 59
8. MCMC SENSITIVITY TRIAL USING THE RAW DATA 59
9. DISCUSSION 62
9.1 Model fit 62
9.2 Stock assessment 62
9.3 Cautionary notes 63
9.3.1 The McMC process underestimates uncertainty 63
9.3.2 The data are not completely accurate 63
9.3.3 The model is homogeneous 63
9.3.4 The model assumptions may be violated 63
10. ACKNOWLEDGEMENTS 64
11. REFERENCES 64

1. INTRODUCTION

This document presents the 2007 Bayesian stock assessment of blackfoot paua (New Zealand abalone, *Haliotis iris*) in PAU 5B (Stewart Island). This work was conducted by NIWA under Ministry of Fisheries (MFish) contract PAU200603, Objective 2.

The assessment used a purpose-built length-based Bayesian model that has been used for previous paua assessments (e.g., Breen et al. 2003, Breen & Kim 2005, 2007); modifications were made only to the likelihood options for fitting length frequency data. The model is described briefly and the modification is explained.

The model was fit to six data sets: two abundance indices – one from commercial catch and effort data (CPUE) and an index from independent research diver surveys (RDSI), two sets of proportion-at-length data – one from commercial catch sampling (CSLF) and one from research diver surveys (RDLF), a tag-recapture dataset and a maturity-at-length dataset. Data were presented to the Shellfish Fisheries Assessment Working Group (SFWG) at two meetings.

Modelling choices and assumptions were also discussed by the Working Group and are presented below. This document describes the procedure used to find a base case and presents all the constants and assumptions used. The base case fit is described, and the document presents a number of sensitivity trials based on simple fits to variations of the base case.

The assessment is based on marginal posterior distributions of agreed fishery indicators. The document presents the indicators agreed by the SFWG, and describes the Markov chain – Monte Carlo (McMC) procedure used to estimate the marginal posterior distributions of model parameters and the indicators. One McMC sensitivity trial was made.

A population model is always a simplification of reality, and deviation from model assumptions may cause distortion of the model results. Cautionary notes are presented in the discussion.

2. MODEL

The model was initially developed for use in PAU 5B in 1999 (Breen et al. 2000) and has usually been revised each year for subsequent assessments, in many cases echoing changes made to the rock lobster assessment model (Breen et al. 2006), which is a similar but more complex length-based Bayesian model. The model was reviewed in 2003 by Dr. Andre Punt of the University of Washington, and was published in a primary journal by Breen et al. (2003).

The model has been documented fully in recent assessments such as Breen & Kim (2005, 2007). The description will not be repeated here, but some description of the model is necessary to enable understanding of the results presented here. Changes to the likelihood options will be described fully.

The model does not use age; instead it uses a number of length bins (51 in this assessment), each of width 2 mm shell length. The left-hand edge of the first bin is 70 mm and few, if any, paua are observed in the largest bin. Sexes are not distinguished; the time step is one year for the main dynamics; there is no spatial structure within the area modelled. The model is implemented in AD Model Builder™ (Otter Research Ltd., http://otter-rsch.com/admodel.htm) version 7.1.1.

2.1 Estimated parameters

Parameters that can be estimated by the model are as follows. The whole parameter vector is referred to as θ. "Shorthand" names for variables, used in tables and figure labels, are shown in parentheses; these are usually also the names used within the program.

$\ln(R0)$ natural logarithm of base recruitment

M instantaneous rate of natural mortality

g_α (*galpha*) expected annual growth increment at length α (*alpha*)

g_β (*gBeta*) expected annual growth increment at length β (*Beta*)

ϕ (*GrowthCV*) c.v. of the expected growth increment

q^I (*qCPUE*) scalar between recruited biomass and CPUE

q^J (*qRDSI*) scalar between numbers and the RDSI

L_{50} (*mat50*) length at which maturity is 50%

L_{95-50} (*mat95*) distance between L_{50} and L_{95}

T_{50} (*RD50*) length at which research diver selectivity is 50%

T_{95-50} (*RD95*) distance between T_{50} and T_{95}

D_{50} (*CS50*) length at which commercial diver selectivity is 50%

D_{95-50} (*CS95*) distance between D_{50} and D_{95}

$\tilde{\sigma}$ (*sigmatilde*) common component of error

h (*CPUEpow*) shape of CPUE *vs.* biomass relation

ε (*Eps*) vector of annual recruitment deviations, estimated from 1974 to 2006

2.2 Constants

Not all constants are shown – this list concentrates on those most likely to be encountered in the material below.

σ_{MIN} (*sigmaMin*) minimum standard deviation of the expected growth increment

σ_{obs} (*sigmaObs*) standard deviation of the observation error around the growth

MLS_t minimum legal size in year t (currently 125 mm)

a, b constants for the length-weight relation

ϖ^I (*CPUEwt*) relative weight assigned to the CPUE dataset.

ϖ^{tag} (*tagwt*) relative weight assigned to the tag-recapture dataset

ϖ^J (*RDSIwt*) relative weight assigned to the RDSI dataset

ϖ^r (*RDLFwt*) relative weight assigned to RDLF dataset

ϖ^s (*CSLFwt*) relative weight assigned to CSLF dataset

ϖ^{mat} (*matwt*) relative weight assigned to maturity-at-length data

$U^{\max}$ (*Umax*) exploitation rate above which a limiting function was invoked

μ_M (*meanMprior)* mean of the prior distribution for *M*,

σ_M (*stdevMprior*) assumed standard deviation of the prior distribution for *M*

σ_ε (*sigmaRdev*) assumed standard deviation of recruitment deviations in log space (part of the prior for recruitment deviations)

α (*alpha*) length associated with g_α (75 mm)

β (*Beta*) length associated with g_β (120 mm)

2.3 New likelihood option

In previous assessments, the proportion-at-length data have been fit with an *ad hoc* likelihood called Bentley-variance. The variance term used to compare observed and predicted proportions-at-length for the *k*th length bin in period *t* is

$$(1) \qquad \sigma_{k,t}^{s} = \frac{\tilde{\sigma}}{\kappa_t^s \varpi^s \sqrt{p_{k,t}^s + 0.1}}$$

where $\tilde{\sigma}$ is an estimated component of variance common to all datasets (fixed to 1 in this assessment), κ_t^s is the weight given to the data record for period *t* and ϖ^s is the weight given to the whole dataset. The negative log-likelihood for the comparison is then normal:

$$(2) \qquad -\ln(\mathbf{L})\left(\hat{p}_{k,t}^s \mid \theta\right) = \frac{\left(p_{k,t}^s - \hat{p}_{k,t}^s\right)^2}{2\left(\sigma_{k,t}^s\right)^2} + \ln\left(\sigma_{k,t}^s\right) + 0.5\ln\left(2\pi\right),$$

where $\hat{p}_{k,t}^s$ is the predicted proportion-at-length and $p_{k,t}^s$ is the observed. The Pearson residual is given by

$$(3) \qquad \frac{p_{k,t}^s - \hat{p}_{k,t}^s}{\sigma_{k,t}^s}.$$

The model (this version is p551) was modified to include an option to use multinomial likelihood:

$$(4) \qquad -\ln(\mathbf{L})\left(\hat{p}_{k,t}^s \mid \theta\right) = \frac{\kappa_t^s \varpi^s \left(p_{k,t}^s + 0.01\right)}{\tilde{\sigma}}\left(\ln\left(p_{k,t}^s + 0.01\right) - \left(\hat{p}_{k,t}^s + 0.01\right)\right)$$

with the Pearson residual given by

$$(5) \qquad \frac{\tilde{\sigma}\left(p_{k,t}^s - \hat{p}_{k,t}^s\right)}{\kappa_t^s \varpi^s \sqrt{\hat{p}_{k,t}^s + 0.01\left(1 - \hat{p}_{k,t}^s + 0.01\right)}}.$$

This option was made available to fitting the CSLF and RDLF datasets. No other likelihood options were altered.

3. FINDING A BASE CASE

For exploratory model runs, the available options included:

- whether to model the commercial fishery with a an estimated selectivity curve or with a fixed knife-edged minimum legal size (MLS) (we used a selectivity curve, again based on past experience),
- which year to use as the first year for estimating recruitment deviations (we used 1974, the first year for which we have estimated catch data),
- which likelihood to use for proportions-at-length data (after initial explorations we chose the multinomial)
- which length to specify as the smallest length used in fitting the two proportion-at-length datasets (we chose 120 and 86 for the CSLF and RDLF datasets respectively, based on inspection of the raw data),

- what value to use for (*sigmaRdev*), the standard deviation of recruitment deviations (we chose 0.4 based on previous practice),
- what priors to assume for each of the estimated parameters: for most parameters we assumed a uniform prior in arithmetic space with wide bounds; we used a lognormal prior for *M* and a normal prior for the recruitment deviations,
- whether to estimate *CPUEpow*, the relation between CPUE and biomass (based on exploratory fits, we estimated it) and
- what, if any, parameters to fix: we fixed *sigmatilde* at 1.0 to remove an unnecessary parameter, and we fixed the two growth parameters *sigmaMin* and *sigmaObs* to 1.0 and 3.0 after exploratory analyses of the tag-recapture data.

The constants used for the assessment are summarised in Table 1, excluding fixed parameters.

In exploratory fits, the estimates for the parameters of the research diver selectivity curve, *Select50RD* and *Select95RD* (the second is the *difference* between selectivity at 50% and 95% selectivity) were near 80 or 86 mm and 0.2 mm respectively, giving a very sharp curve with high selectivity at much smaller sizes was seen in other assessments – the estimated curve implies that paua of all lengths seen by divers are fully selected, which is unlikely. As Breen & Kim (2007) did for the PAU 5A assessment in 2006, we fixed the values to 100 and 19 mm.

The part of the input file dealing with estimated parameters is shown in Table 2.

Table 1: Constants used in the PAU 5B assessment base case. The length-weight constants *a* and *b* give weight in kg.

Constant	Value
CSLFminobs	120
RDLFminobs	86
FirstYear	1964
LastYear	2007
FirstRecYear	1974
ProjectYear	2010
Refl Year	1985
Refl Year	1987
number of bins	51
length firstbin	70 mm
bin width	2 mm
length-wt *a*	2.994E-08
length-wt *b*	3.303
alpha	75
Beta	120
maximum *ERate*	0.65
ERate penalty	1000000

Table 2: Base case specifications for estimated parameters for the PAU 5B assessment. Negative phases indicate fixed parameters. Prior types: zero uniform; 1 normal; 2 lognormal.

	Phase	Lower bound	Upper bound	Prior type	Prior mean	Prior std dev	Initial value
sigmatilde	-1	0.01	2	0	0	0	1
ln(*R0*)	1	5	50	0	0	0	25
M	3	0.01	0.5	2	0.1	0.1	0.1
Select50RDLF	-2	70	125	0	0	0	100
Select95RDLF	-2	0.001	50	0	0	0	19
Select50CSLF	2	70	145	0	0	0	125
Select95CSLF	2	0.01	50	0	0	0	3.3
Mat50	3	70	145	0	0	0	91
Mat95	3	1	50	0	0	0	22
Rdevs	3	-2.3	2.3	1	0	0.4	0
ln(*CPUE*)	1	-30	10	0	0	0	1
ln(*RDSI*)	1	-30	0	0	0	0	-13
galpha	1	1	80	0	0	0	30
gBeta	1	0.01	50	0	0	0	7
GroCV	1	0.001	2	0	0	0	0.27
sigmaMin	-2	0.001	5	0	0	0	1
sigmaObs	-1	0.001	5	0	0	0	3
CPUEpow	2	0.01	2	0	0	0	1

We found a base case by adjusting the dataset weights iteratively to balance the standard deviations of the normalised residuals (sdnrs). New weights were determined by dividing the trial weight by the sdnr for each dataset. Weights used for the base case, and the resulting sdnrs and medians of the absolute residuals (MARs), are shown in Table 3.

Table 3: Dataset weights used in the PAU 5B base case and their resulting diagnostics.

Dataset	Weight	Sdnr	MAR
CPUE	0.63	1.027	0.792
RDSI	0.37	0.999	0.448
CSLF	175.00	0.945	0.474
RDLF	356.00	0.992	0.605
Tags	1.04	0.971	0.666
Maturity	29.00	1.004	0.881

In the base case explorations, most exploratory runs had a positive definite Hessian matrix. Some early runs showed degenerate results: high recruitment and very very low exploitation rates, with essentially a flat fit to the CPUE. With such runs excluded, the range of values for parameters and indicators obtained during exploratory fits was not great.

4. BASE CASE MPD RESULTS

The base case parameter estimates and indicators are shown in Table 4. *M* was higher than the mean of the prior: 0.14 *vs.* 0.10, but was not unrealistically high. The estimated growth parameters were not far from the values estimated in exploratory fits that used only the tag-recapture data: *galpha* was 26.21 mm (28.6 in the exploratory fit) and *gBeta* was 7.15 mm (6.7); *GrowthCV* was slightly higher (0.323 *vs.* 0.273). *CPUEpow* reflected slight hyperstability at 0.856. The MPD trajectory came nowhere near the maximum exploitation rate, peaking at 30%, with current exploitation rate estimated near 10%.

Table 4: Base case MPD values for parameters and indicators in the PAU 5B assessment. Fixed parameters have been removed (see Table 2) and dataset weight diagnostics are shown in Table 3.

Quantity	Value
ln(*R0*)	14.01
M	0.138
Select50CSLF	125.1
Select95CSLF	2.7
Mat50	91.0
Mat95	22.8
ln(*CPUE*)	-6.501
ln(*RDSI*)	-11.60
galpha	26.21
gBeta	7.15
GroCV	0.323
CPUEpow	0.856
LikeCPUE	-18.28
LikeRDSI	1.59
LikeCSLF	134.76
LikeRDLF	155.56
LikeTags	888.59
LikeMat	-16.43
MPrior	3.69
Rdev prior	13.32
ERate penalty	0
LikeTotal	1162.80
max*Rdev*	1.682
min*Rdev*	0.461
Max*ERate*	0.301
ERate[LastYear]	0.099
Smin	913.5
Sav	1843.3
S07	1389.9
Bmin	561.4
Bav	1181.8
B07	1045.0
S07/Sav	75.4%
B07/Bav	88.4%
S07/Smin	152.2%
B07/Bmin	186.1%

The MPD fit to CPUE (Figure 1) showed a good fit except for the first four years, 1983–86, in which model predictions were smaller than the observed values, and the model's rate of decline was therefore more shallow. The fit to the RDSI (Figure 1) did not show such a good fit: it could not match the first survey index in 1994. In subsequent years, the model's predictions contained the decline from 1995 to 1998, although not as steeply as that in the observations; it contained the increase from 1998 to 2001 and the further increase from 2001 to 2007, fitting these last two data very well. Diagnostics for these fits are shown in Figure 2.

The model fit to the maturity data was good (Figure 3). Fits to proportions-at-length are shown in Figure 4 and their residuals in Figure 5. The model fit the CSLF data very well, save for the 1991 data which were given the lowest weight; the fit to RDLF data was acceptable but not as tight as that to the

CSLF. Residuals show considerable autocorrelation. Diagnostic q-q plots for these data (Figure 6) are good.

When the means of residuals are plotted against length for the two length frequency datasets (Figure 7), the RDLF shows a complex pattern with three areas of high mean residuals, approaching 1, and two low areas that approach 0.5. The plot for CSLF is better behaved, but does show one high spot and two low spots.

Figure 8 and Figure 9 compare the distributions of normalised (Pearson) residuals with the expected normal distribution for the two length frequency datasets. The distributions are reasonably good, but there is some tendency for them to show more very small and more very large residuals than expected. Figure 10 compares the model weights with the effective sample sizes, where effective sample is calculated from

$$N_j = \frac{\sum_s \left(\hat{p}_{s,j} \left(1 - \hat{p}_{s,j} \right) \right)}{\sum_j \left(p_{s,j} - \hat{p}_{s,j} \right)^2}. \tag{6}$$

The fits to tag-recapture data appear reasonable (Figure 11) and the diagnostics are good. The left-hand plot, for fish recovered after less than 300 days, shows Waituna recaptures (see Breen & Smith 2008); all others were recovered very close to one year after release. Figure 12 compares the distribution of normalised (Pearson) residuals with the expected normal distribution for this dataset; this comparison is harmonious.

A q-q plot of the residuals from all datasets combined (Figure 13) shows a good fit to the theoretical plot except for positive residuals above 2, which comes mostly from length frequencies, and especially from the RDLF dataset (Figure 4).

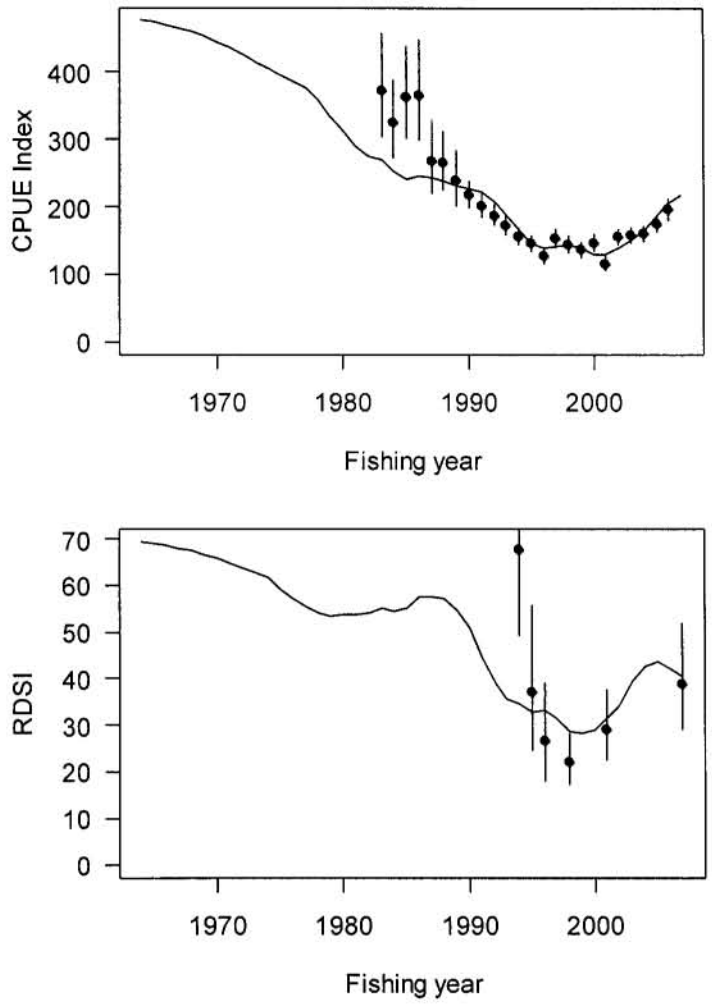


Figure 1: Observed and predicted CPUE (top) and RDSI (bottom) for the base case MPD fit for PAU 5B. Error bars show the standard error term used by the model in fitting, including the effects of the common error term and the dataset weights.

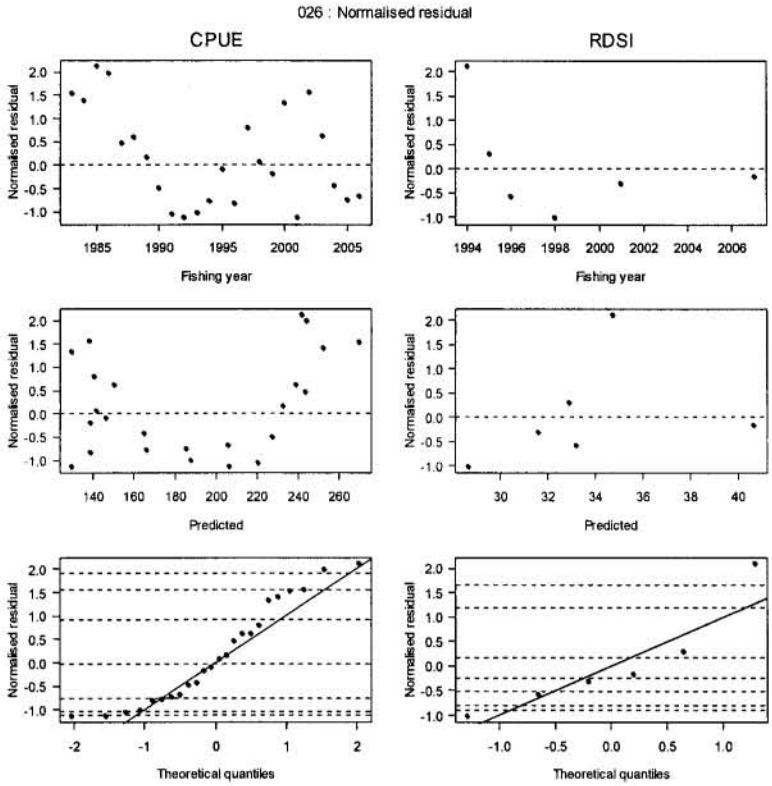


Figure 2: Normalised residuals for CPUE (left) and RDSI (right) for the base case MPD fit for PAU 5B. The horizontal lines on bottom plots are 5, 10, 25, 50, 75, 90 and 95th percentiles.

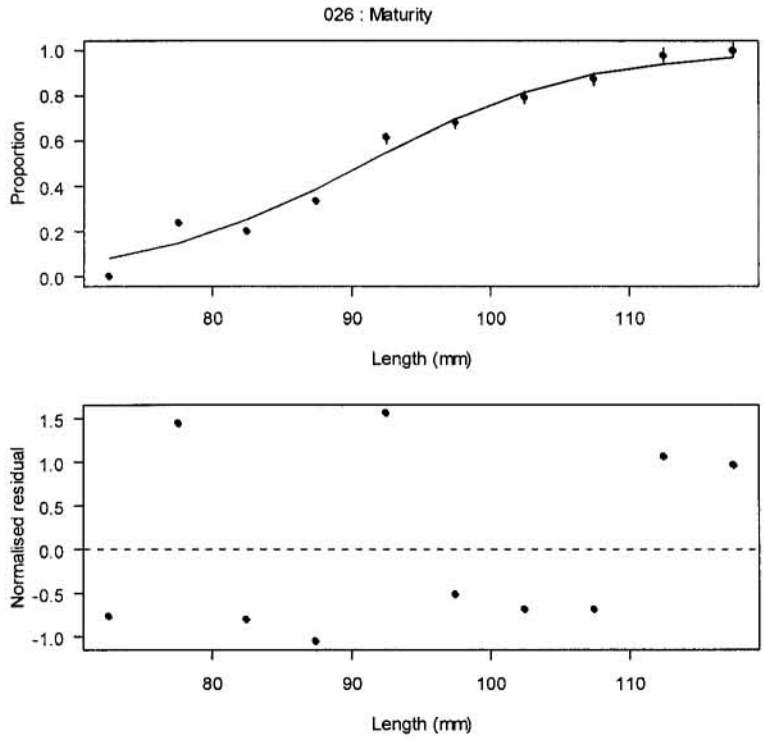


Figure 3: Observed (dots) and predicted (lines) proportions of maturity at length (top), and the normalised residuals plotted against length (bottom).

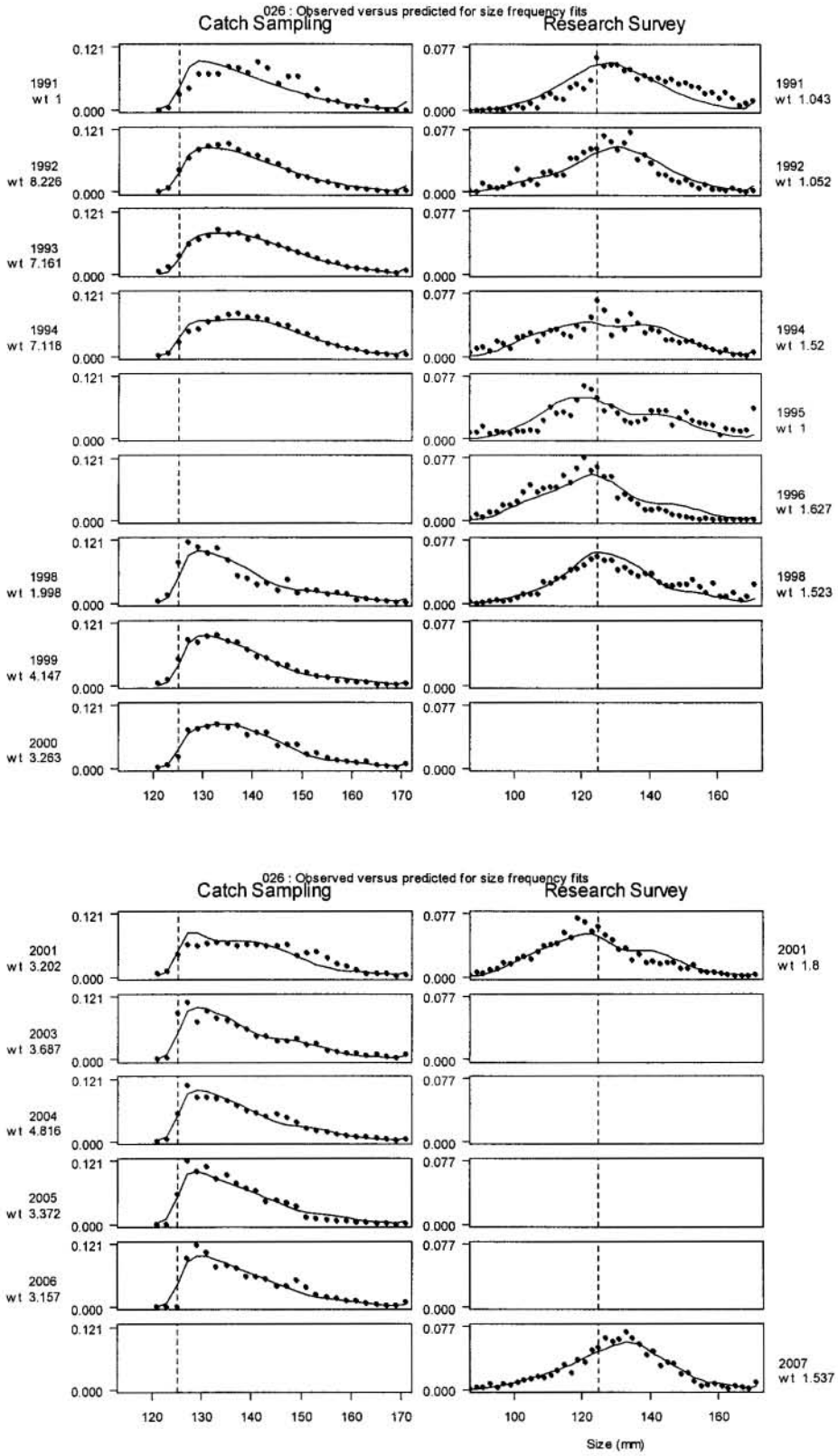


Figure 4: Observed (dots) and predicted (lines) proportion-at-length from commercial catch sampling (left) (CSLF) and research diver surveys (right) (RDLF) for the RDSI MPD fit.

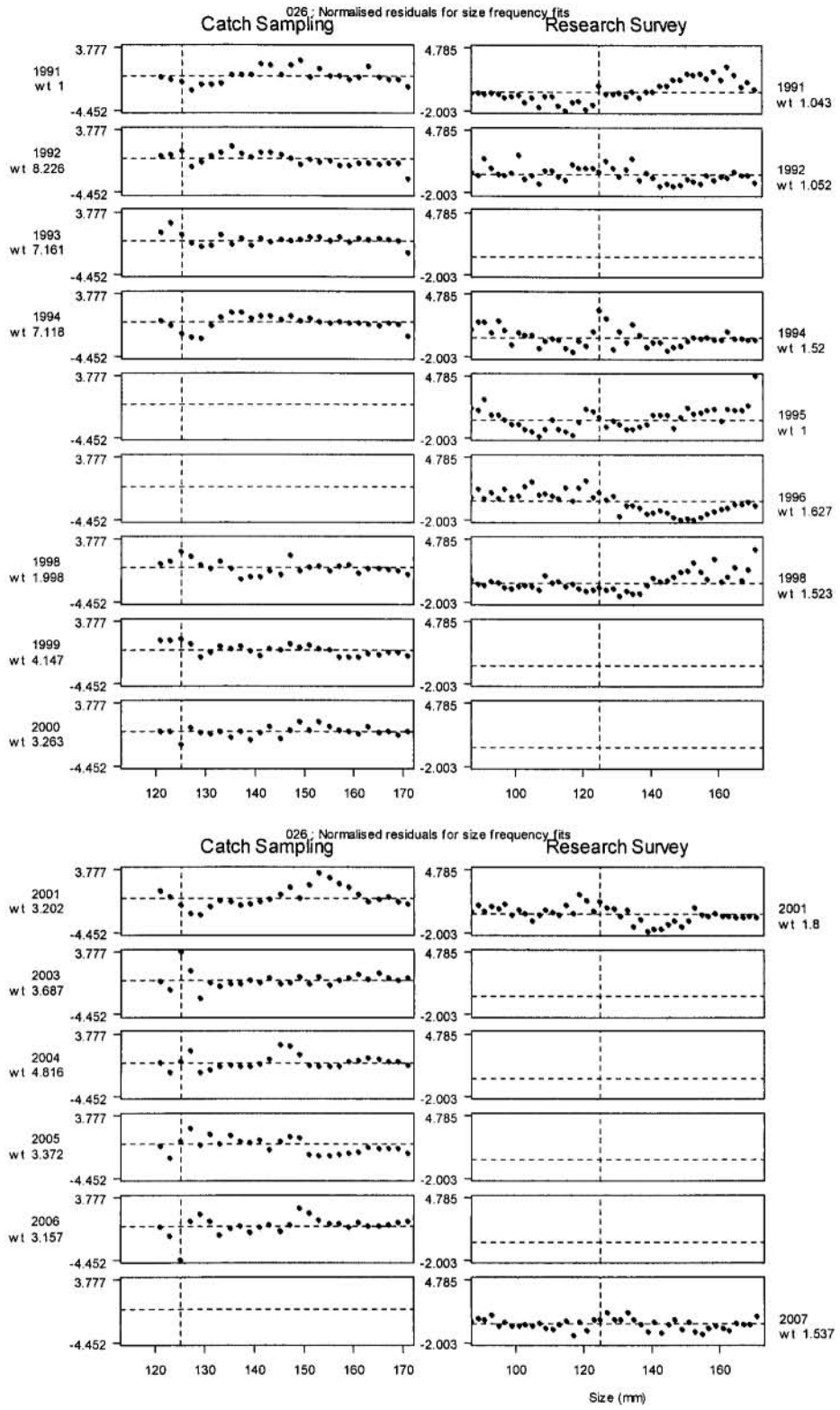


Figure 5: Residuals from base case MPD fits to CSLF (left) and RDLF (right) data seen in Figure 4.

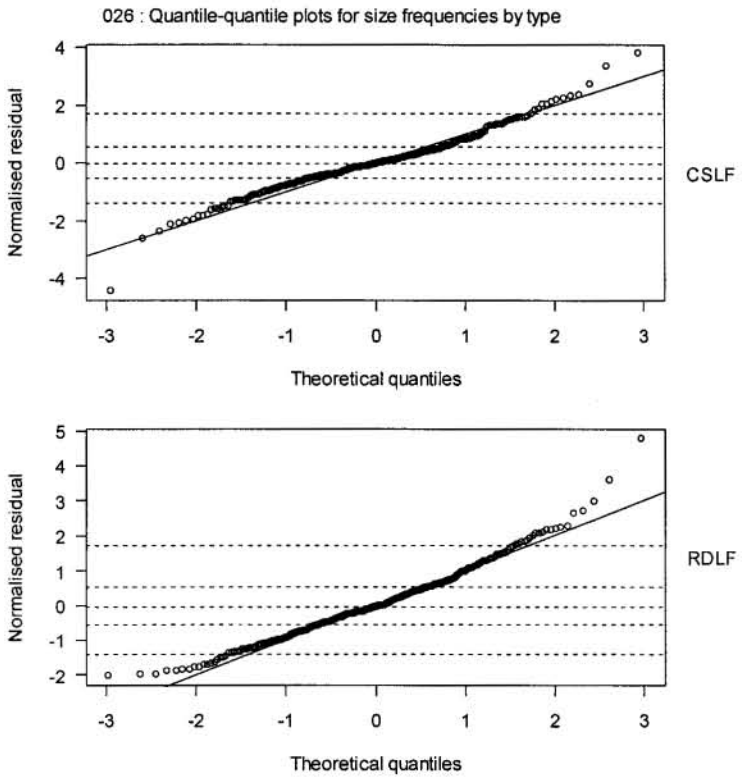


Figure 6: Q-Q plot of residuals for the fits to proportions-at-length from commercial catch sampling (top) and research diver surveys (bottom) from the base case MPD fit for PAU 5B.

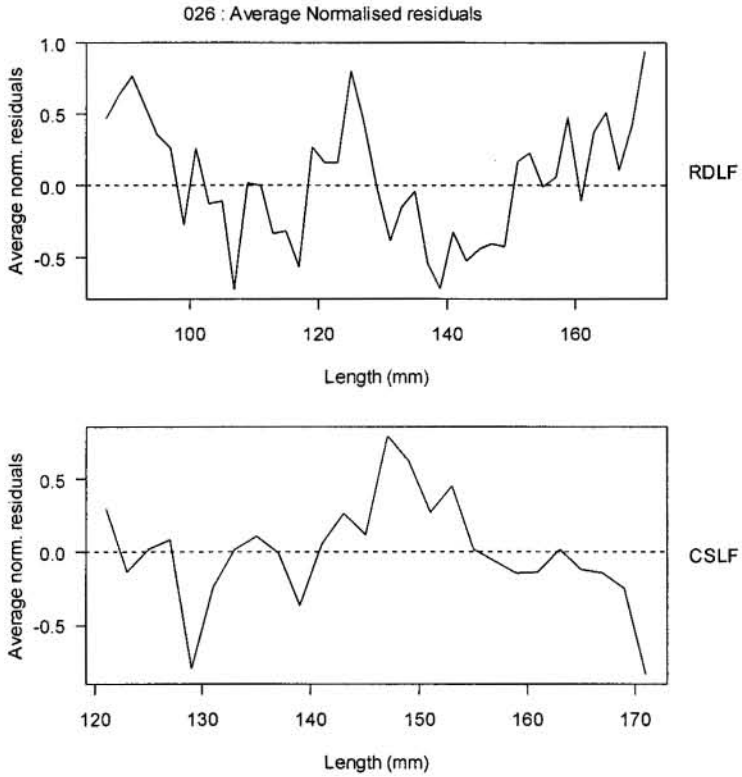


Figure 7: Means of normalised residuals at each length for the fits to the RDLF (upper) and CSLF (lower) datasets.

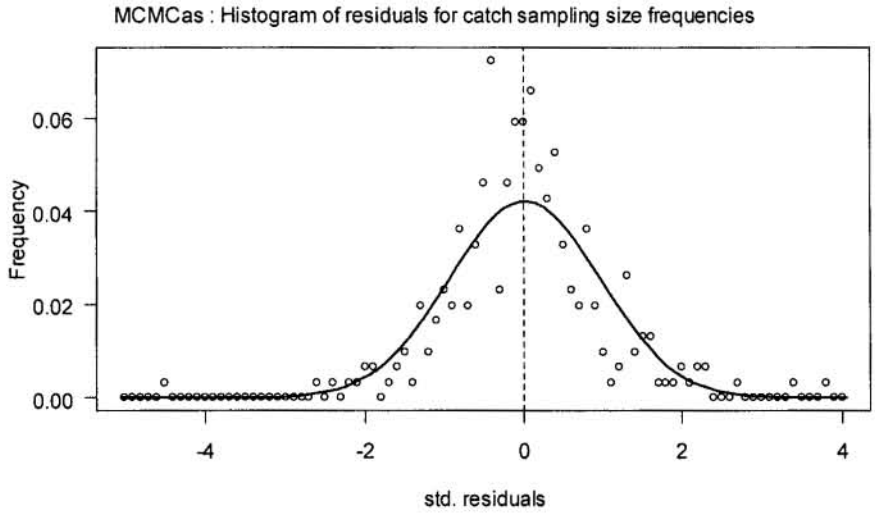


Figure 8: Histogram of Pearson residuals from the base case MPD fit to the CSLF dataset.

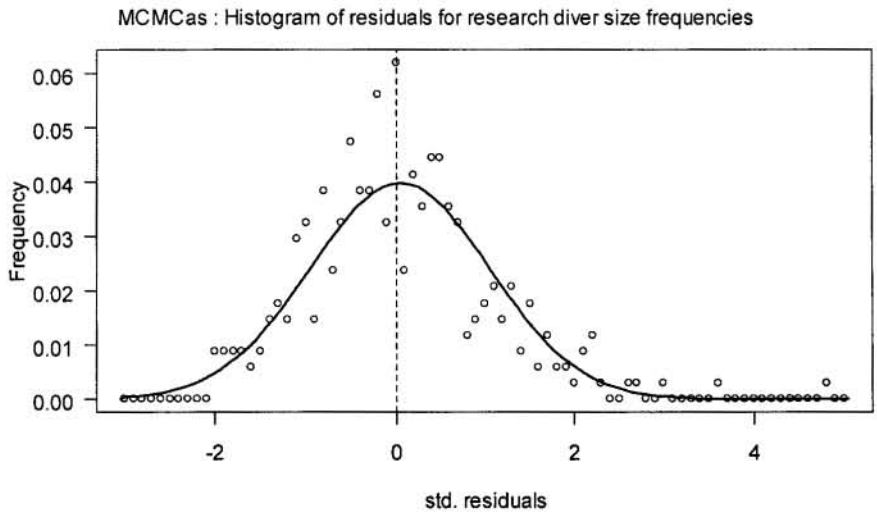


Figure 9: Histogram of Pearson residuals from the base case MPD fit to the RDLF dataset.

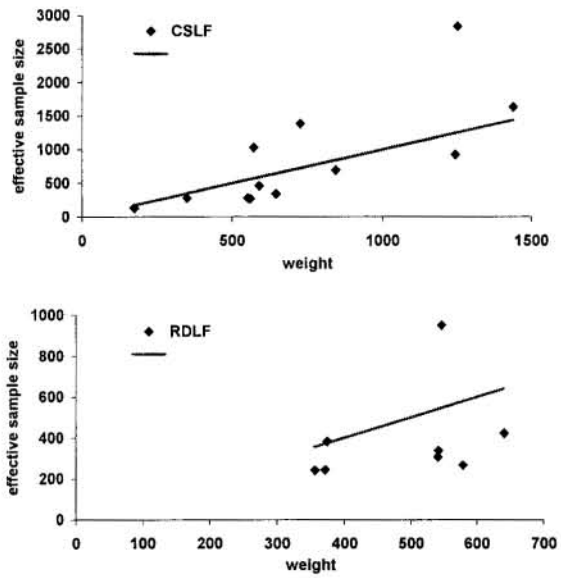


Figure 10: Effective sample size for the multinomial fits for the two proportion-at-length datasets, plotted against the model's weight.

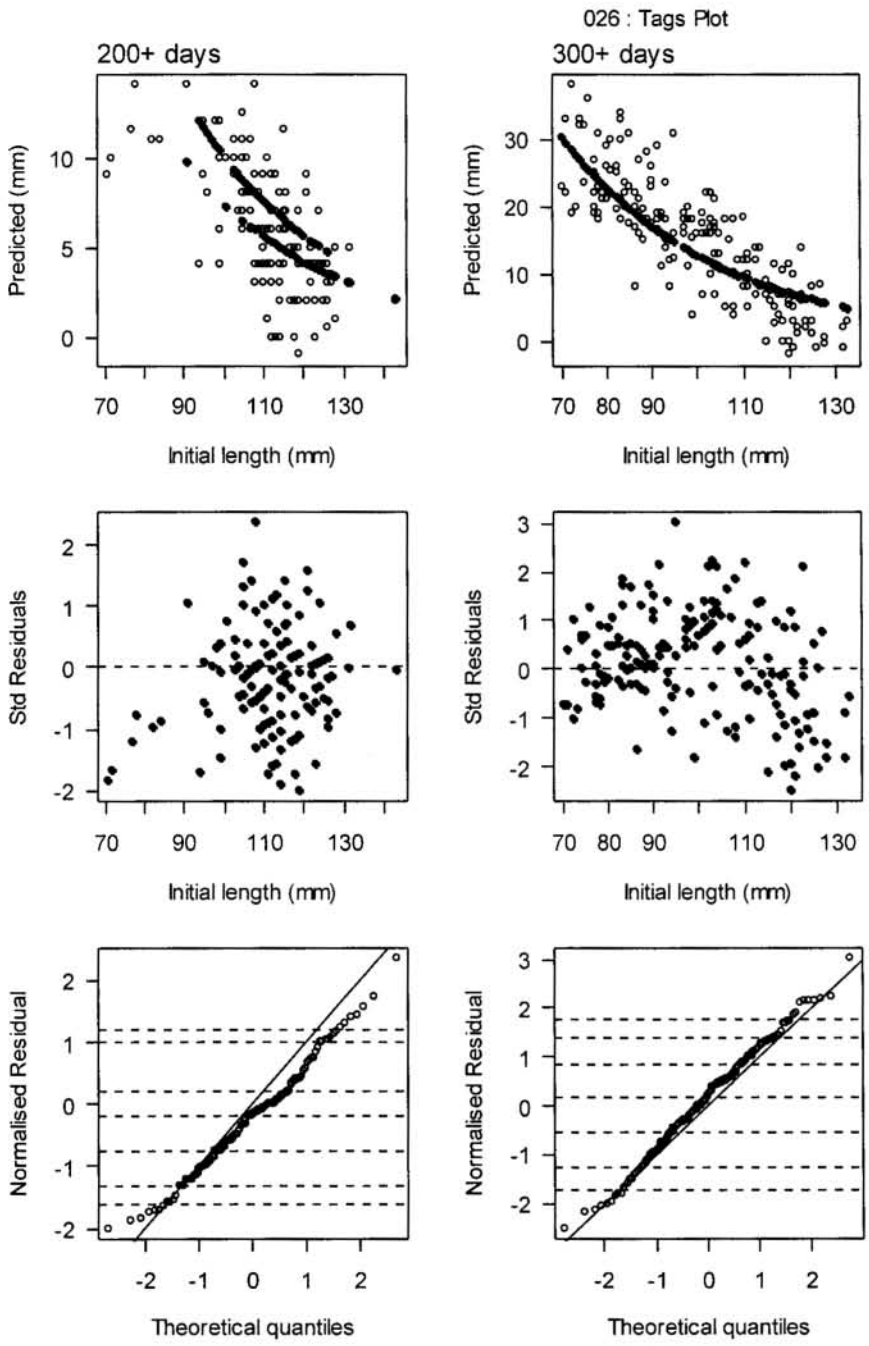


Figure 11: Top: predicted (closed circles) and observed (open circles) increments plotted against initial length of tagged paua from the base case MPD; middle: standardised residuals plotted against initial length; bottom: Q-Q plot of standardised residuals. The two columns are for 200+ and 300+ days.

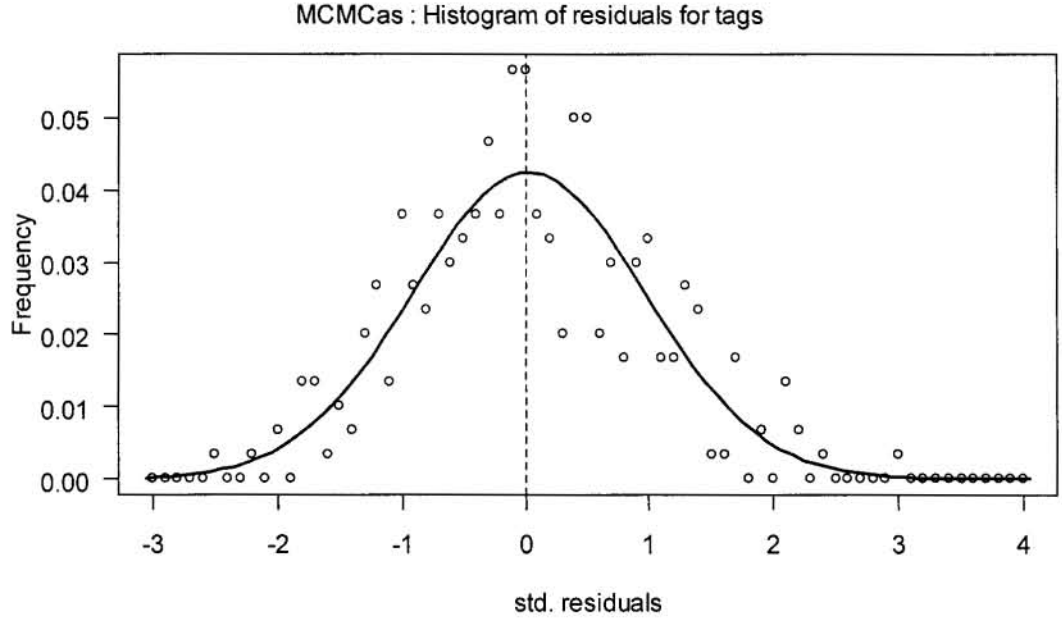


Figure 12: Histogram of Pearson residuals from the base case MPD fit to the tag-recapture dataset.

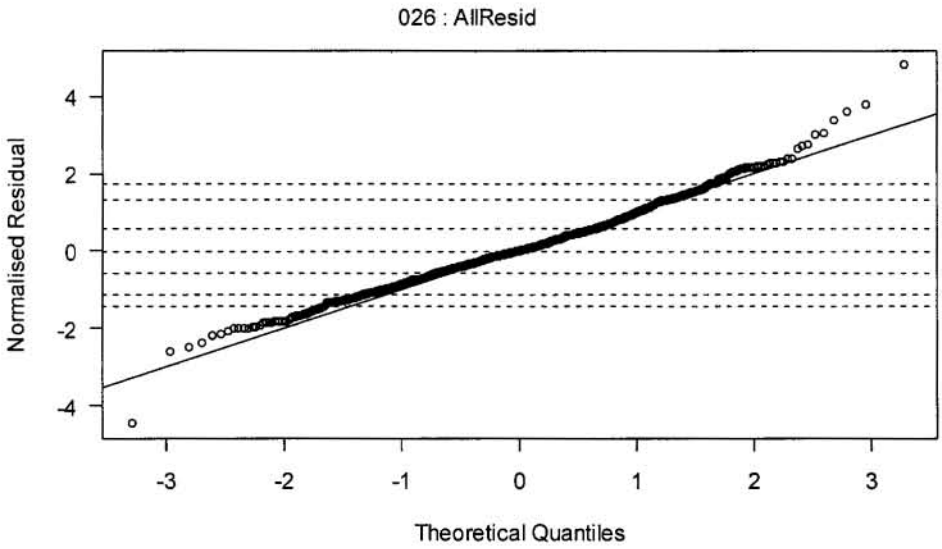


Figure 13: Q-Q plot of the normalised residuals from all datasets used by the model in the base case MPD fit.

The predicted annual growth increment is shown again in Figure 14, along with the fixed research diver selectivity curve and the estimated commercial fishery selectivity; the latter being steep and centred on 125 mm. Selected slices of the growth transition matrix are shown in Figure 15. The model's virgin size structure (assuming no effects of density-dependence) and the 1990 and 2007 size structure are shown in Figure 16, which suggests a large plus-group in the virgin equilibrium size structure.

The pattern of recruitment estimated by the model (Figure 17) shows high recruitment in the mid 1980s, then a decrease through the mid 1990s and a sharp spike in 2002. The model's annual exploitation rate estimates (Figure 16) show a steady increase to a peak near 30% in 1995, followed by a steady decline to the estimate near 10% for 2007, assuming the TACC is fully caught.

When estimated recruitment is plotted against estimated spawning biomass (Figure 18), no relation is apprehended.

Recruited and spawning biomass trajectories (Figure 19) are similar in shape, with spawning biomass being about 30% larger than recruited biomass. Surplus production (Figure 19) follows the same pattern as recruitment (Figure 17), displaced by several years. When surplus production is plotted against recruited biomass, the result suggests a dome-shaped curve with the position of its peak, although poorly determined, less than 50% of virgin biomass.

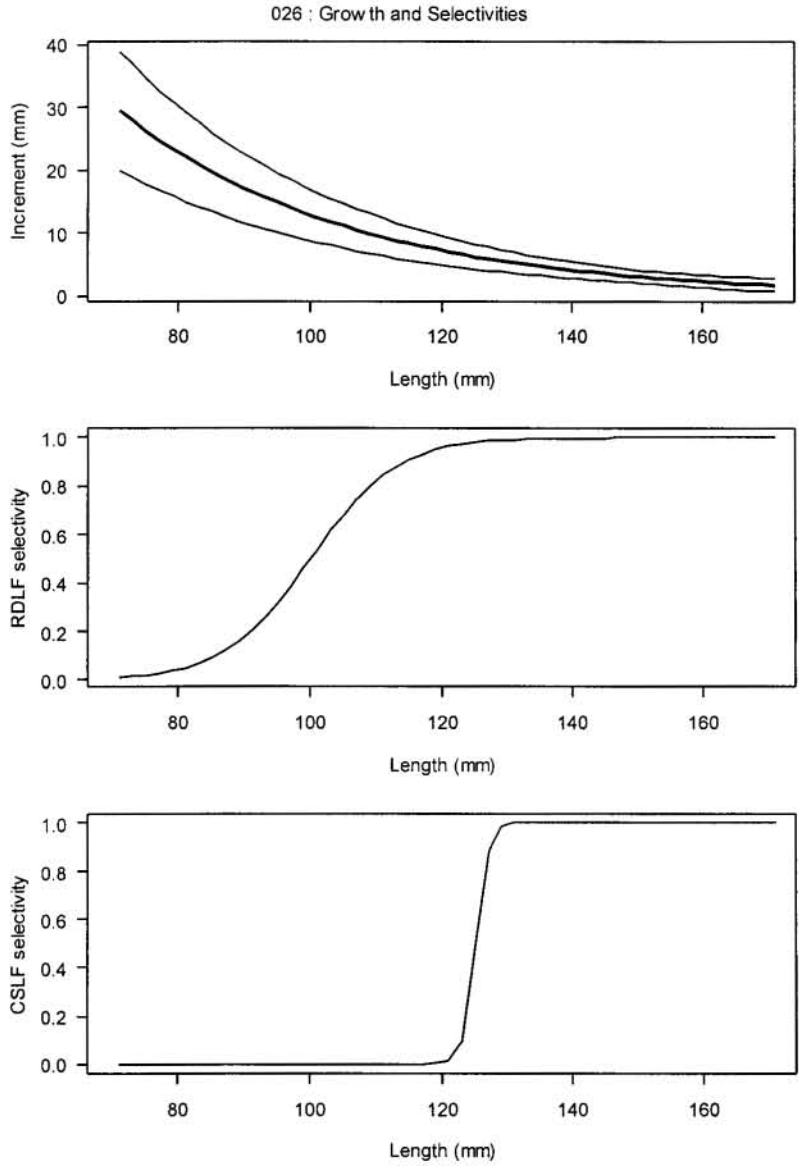


Figure 14: Top: predicted annual growth increment (thick line) vs. initial length of paua, shown with one standard deviation around the increment (thin line). Middle: estimated research diver survey selectivity. Bottom: estimated commercial catch sampling selectivity.

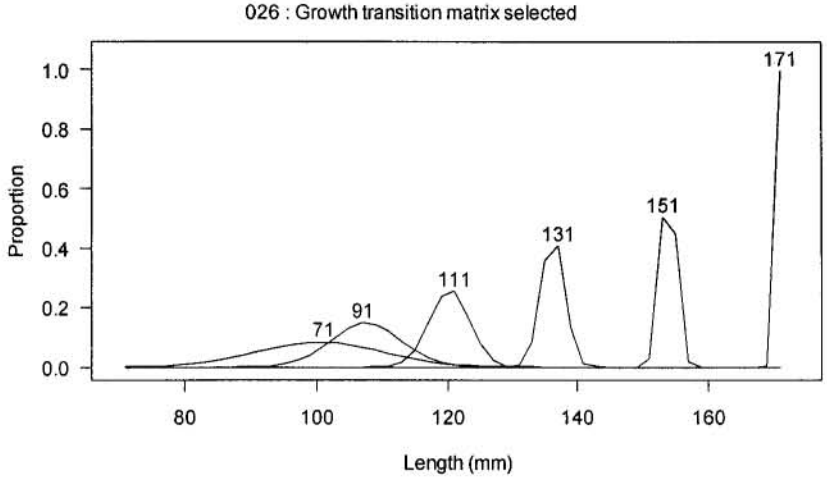


Figure 15: Growth transition matrix: selected slices from the PAU 5B MPD base case.

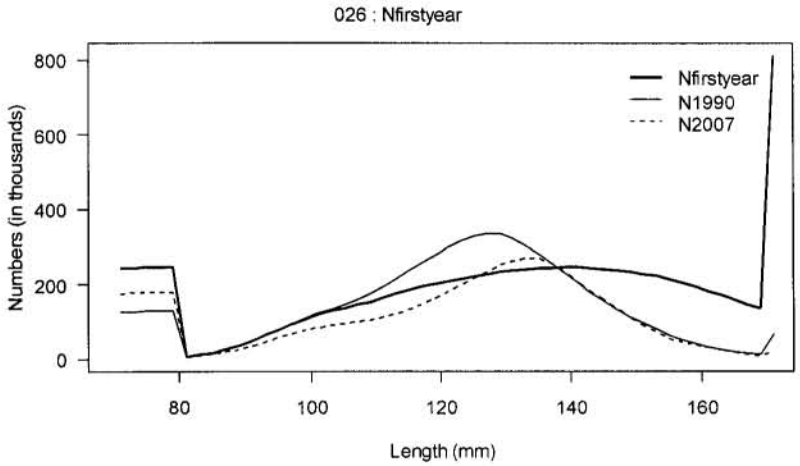


Figure 16: Comparison of size structures in the unfished population (heavy line) and the populations in 1990 (thin line) and 2007 (dashed line) from the base case MPD fit in PAU 5B.

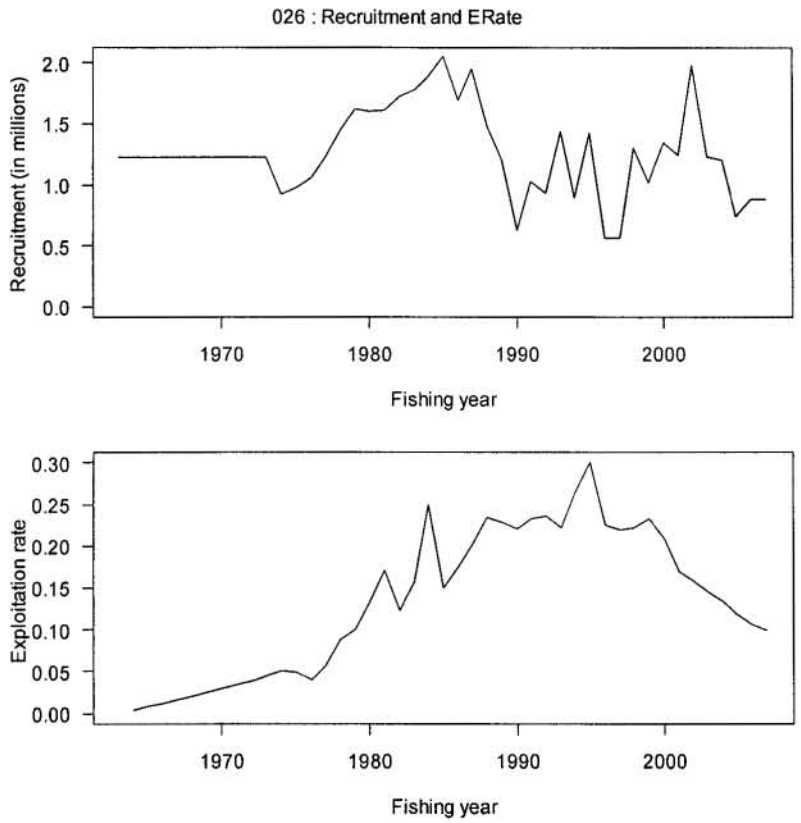


Figure 17: Recruitment to the model (top) and exploitation rate (bottom) from the base case MPD fit in PAU 5B.

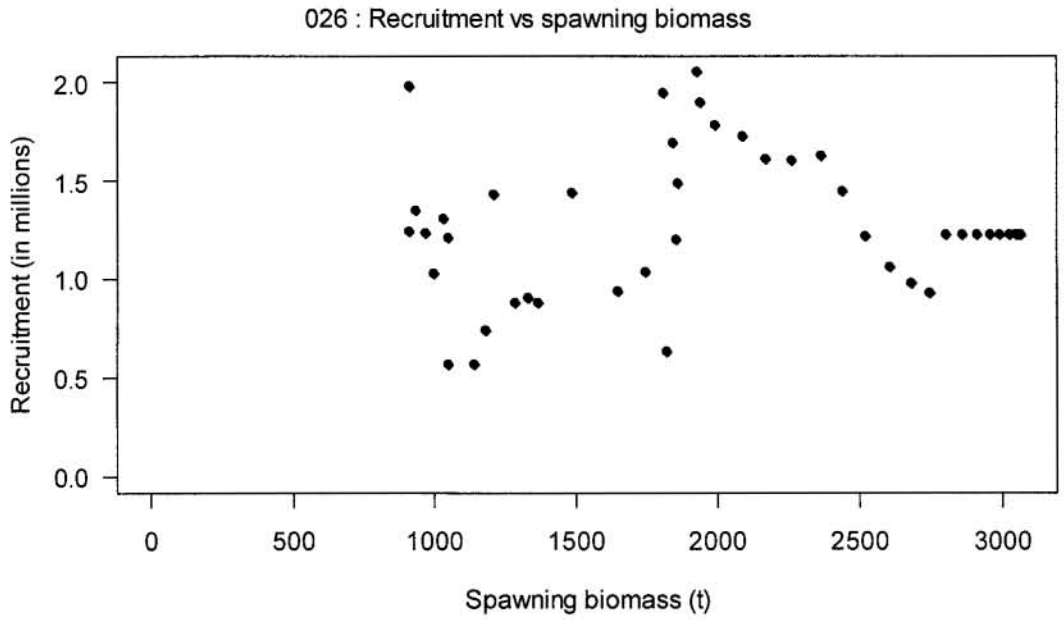


Figure 18: Recruitment plotted against spawning biomass two years earlier from the base case MPD fit in PAU 5B.

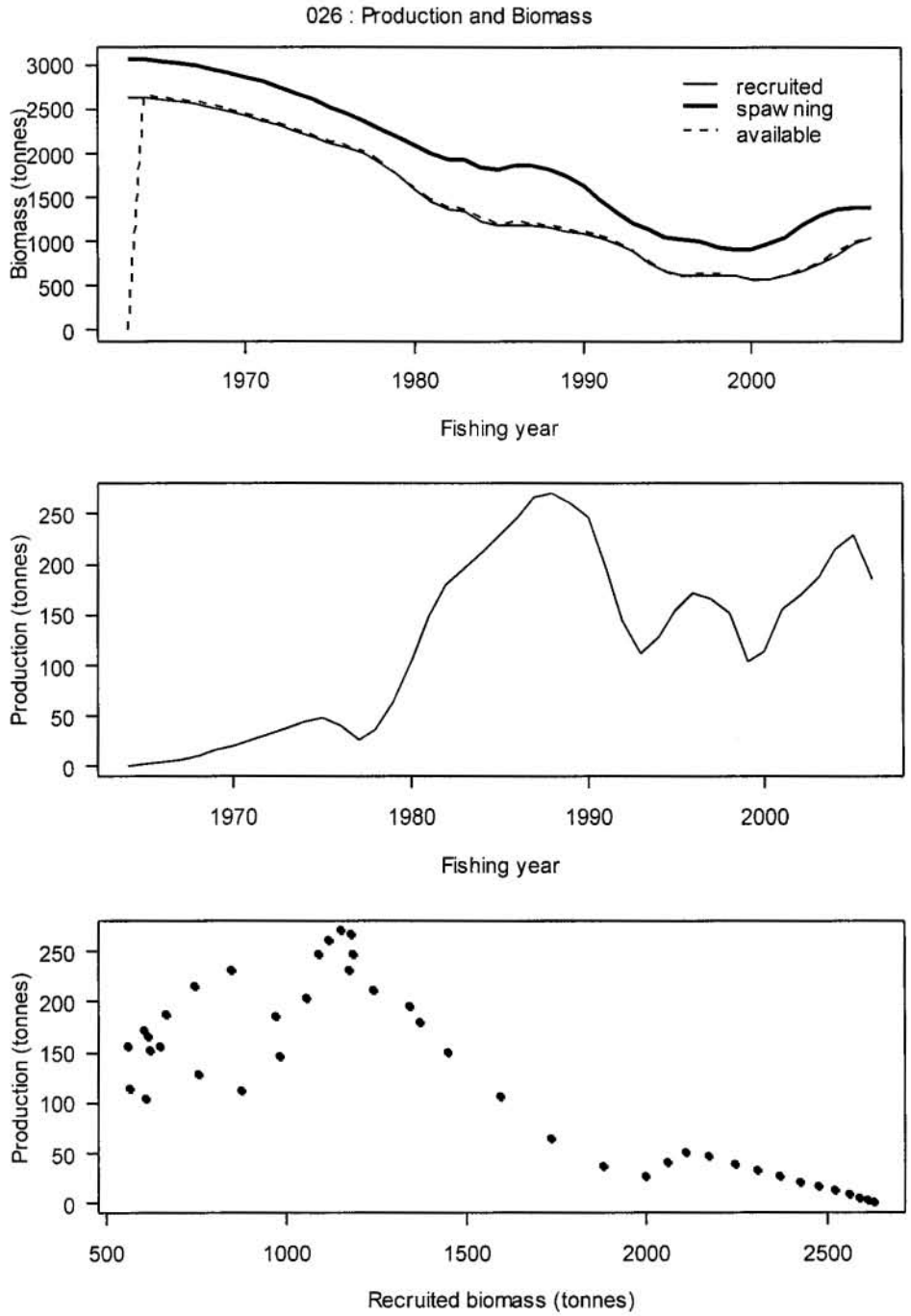


Figure 19: Top: recruited, spawning and available biomass trajectories, from the base case MPD fits. Recruited biomass includes all individuals above the MLS; spawning biomass includes all mature individuals; available biomass includes all recruited individuals that are selected by the commercial fishery. Middle: estimates of biomass production across years. Bottom: biomass production vs. recruited biomass.

5. MPD SENSITIVITY TRIALS

Sensitivity trials at the MPD level included those agreed by the SFWG. They comprised runs in which

- datasets were removed, one at a time and in combination, to explore the influence that was exerted by each dataset or data source,
- pre-1990 CPUE was removed,
- the first survey index datum was removed,

- alternative catch series were used for the years 1984 through 1995, to explore the effect of uncertainty in catches for these years,
- the effect of using multinomial likelihood was explored and
- recent data were removed one year (retrospective trials).

All sensitivity trials were begun from the MPD base case datafile; only the change indicated was made to this file. No re-weighting was attempted even though the sdnrs and MARs changed in some instances.

5.1 Dataset removal

Results from trials in which datasets were removed singly are shown in Table 5. Removal of CPUE had little effect on the fit to RDSI (as reflected in the likelihood contribution), but improved the fit to both length frequency datasets. There was limited effect on parameters or indicators: the biomass indicators were all reduced except for *B07* while the biomass ratio indicators all improved slightly.

Removal of the RDSI data had very little effect at all: parameter estimates were almost unchanged, and indicators changed but slightly.

Removal of the CSLF data resulted in a substantially better fit to the CPUE data (at a slight expense to the RDSI fit), a better fit to the RDLFs and a very slight improvement in the fit to tag-recapture data. *M* decreased to 0.12, with concomitant changes in recruitment and catchability. *CPUEpow* dropped to 0.64, an increase in hyperstability. Biomass indicators changed without a pattern: some increased and others decreased; both current biomass indicators increased a bit. Ratios involving minimum biomass became more optimistic while those involving the target reference levels became less optimistic. Differences were not great.

When the RDLF data were removed, the fit to CPUE and CSLFs improved and the fits to the tag-recapture data and RDSI worsened a small amount. The commercial selectivity was shifted left by 1 mm, and *galpha* increased by 4 mm while *GrowthCV* decreased to 0.28. *CPUEpow* increased to 1.24, reflecting estimated hyperdepletion. All biomass indicators were increased by 50% to 100%, but all biomass ratio indicators became less optimistic.

Finally, removal of the tag dataset gave an unsatisfactory result: the fit to CPUE was improved but all other data were fitted worse (except maturity, which did not vary in these trials), some datasets much worse. The growth parameters changed substantially, with *galpha* rising to 43 mm and *gBeta* becoming very small. Recruitment and biomass became very large, exploitation rate estimates very small. The run may have been improved with re-weighting, but this was not explored.

Removal of both abundance indices (Table 6) led to a high-recruitment, high-biomass, low exploitation rate run with high *M* thrown in. Removal of both length frequency datasets had less effect: *M* decreased to 0.10; biomass estimates changed without obvious pattern, sometimes slightly and sometimes by two and a half times; biomass remained less than target reference levels but above minimum levels; the indicators involving minimum biomass were more optimistic and those involving target biomass references were less optimistic. In this run the maximum exploitation rate was jammed against its upper bound.

When both datasets from research diver surveys were removed, biomass estimates increased by 50% to 100%, while biomass ratio indicators all became less optimistic. When both commercial datasets were removed, biomass indicators decreased except for the target reference levels; ratio indicators involving minimum biomass were more optimistic and those involving target biomass references were less optimistic.

The tag-recapture dataset is the most critical: without it, the model could not make good growth estimates and this problem led to a very poor fit elsewhere. The next most influential datasets were

the length frequencies. The RDLFs had a larger influence on indicators than CSLFs. However, without length frequency data the model produced results in the same general area as the base case.

Conversely, each of the abundance index datasets had apparently small influence, but removal of both indices led to unrealistic results dominated by high biomass.

Removal of all the research diver data, or conversely the commercially obtained data, gave results in roughly the same area as the base case.

In these trials, most of the runs that gave realistic results showed biomass above the minimum reference levels but below the target reference levels. The removal trials demonstrate, except for the tag data, a high redundancy of information content among the various datasets.

Table 5: MPD sensitivity trials for PAU 5B, wherein one or more datasets were removed from the model. Sdnrs: standard deviations of the normalised residuals. Shading indicates quantities that were fixed or irrelevant as a result of dataset removal.

	Base case	No CPUE	No RDSI	No CSLF	No RDLF	No tags
Serial	000	001	002	003	004	005
sdnrCPUE	1.027	29.765	1.024	0.755	0.887	0.927
sdnrRDSI	0.999	0.999	1.113	1.028	1.072	1.078
sdnrCSLF	0.945	0.928	0.945	1.331	0.898	1.225
sdnrRDLF	0.992	0.999	0.992	0.933	1.237	1.769
sdnrtags	0.971	0.974	0.971	0.990	1.031	2.162
sdnrmaturity	1.004	1.004	1.004	1.004	1.004	1.004
MARCPUE	0.792	103.4	0.794	0.629	0.740	0.461
MARRDSI	0.448	0.437	4.501	0.502	0.479	0.437
MARCSLF	0.474	0.478	0.473	0.806	0.490	0.638
MARRDLF	0.605	0.600	0.603	0.633	0.750	1.063
MARtags	0.666	0.646	0.669	0.665	0.670	1.987
MARmaturity	0.881	0.881	0.881	0.881	0.881	0.881
ln(*R0*)	14.01	13.94	14.02	13.91	14.24	19.70
M	0.14	0.13	0.14	0.12	0.14	0.15
Select50CSLF	125.12	125.13	125.12	125.00	124.86	126.07
Select95CSLF	2.72	2.73	2.72	3.30	2.47	3.70
Mat50	91.02	91.02	91.02	91.02	91.02	91.02
Mat95	22.83	22.83	22.83	22.83	22.83	22.83
ln(*qCPUE*)	-6.50	1.00	-6.59	-3.50	-12.43	-30.00
ln(*qRDSI*)	-11.60	-11.55	-13.00	-11.51	-12.05	-17.73
galpha	26.21	25.93	26.24	26.75	31.43	47.62
gBeta	7.15	7.34	7.14	6.93	6.02	0.33
GrowthCV	0.32	0.32	0.32	0.31	0.28	0.15
CPUEpow	0.86	1.00	0.86	0.64	1.24	1.80
LikeCPUE	-18.28	112319	-18.36	-24.35	-21.69	-20.87
LikeRDSI	1.59	1.58	63.65	1.76	2.04	2.08
LikeCSLF	134.8	129.6	134.8	280.3	121.8	220. 6
LikeRDLF	155.6	157.0	155.6	141.2	242.9	466.3
LikeTags	888.6	889.7	888.5	887.1	890.1	1800.7
LikeMat	-16.43	-16.43	-16.43	-16.43	-16.43	-16.43
MPrior	3.69	3.06	3.86	-0.40	3.18	7.20
Eps	13.32	14.73	13.18	10.45	9.55	7.68
ERate penalty	0	0	0	0	0	0
LikeTotal	1162.8	1179.2	1161.2	999.3	988.6	666.6
maxRdev	1.68	1.79	1.67	1.45	1.58	1.24
minRdev	0.461	0.459	0.465	0.408	0.529	0.553
MaxERate	0.301	0.315	0.298	0.331	0.177	0.001
ERate[LastYear]	0.099	0.099	0.098	0.100	0.068	0.000
Smin	913.5	854.8	925.1	794.5	1559.5	438388
Sav	1843.3	1701.1	1858.3	2062.5	2737.9	644876
S07	1389.9	1385.3	1412.1	1374.8	2032.3	550801
Bmin	561.4	520.7	570.3	458.1	1104.2	265125
Bav	1181.8	1039.7	1192.8	1584.4	1917.1	387494
B07	1045.0	1044.6	1061.5	1026.7	1545.2	330345
S07/Sav	75.4%	81.4%	76.0%	66.7%	74.2%	85.4%
B07/Bav	88.4%	100.5%	89.0%	64.8%	80.6%	85.3%
S07/Smin	152.2%	162.1%	152.6%	173.0%	130.3%	125.6%
B07/Bmin	186.1%	200.6%	186.1%	224.1%	139.9%	124.6%

Table 6: MPD sensitivity trials for PAU 5B, continued.

	Base case	No CPUE & RDSI	No CSLF & RDLF	No RDSI & RDLF	No CPUE & CSLF	No pre-1990 CPUE	No first RDSI
Serial	000	006	007	008	009	010	011
sdnrCPUE	1.027	127.8	0.571	0.884	28.446	0.675	1.025
sdnrRDSI	0.999	18.219	0.910	1.061	0.989	1.012	0.394
sdnrCSLF	0.945	0.918	3.328	0.897	1.328	0.929	0.945
sdnrRDLF	0.992	1.016	1.742	1.239	0.930	0.999	0.992
sdnrtags	0.971	0.980	1.001	1.031	0.988	0.975	0.971
sdnrmaturity	1.004	1.004	1.004	1.004	1.004	1.004	1.004
MARCPUE	0.792	446.3	0.248	0.740	102.756	0.382	0.801
MARRDSI	0.448	96.113	0.370	2.917	0.474	0.441	0.262
MARCSLF	0.474	0.538	2.117	0.485	0.777	0.464	0.473
MARRDLF	0.605	0.629	1.189	0.748	0.620	0.607	0.601
MARtags	0.666	0.654	0.663	0.668	0.663	0.653	0.668
MARmaturity	0.881	0.881	0.881	0.881	0.881	0.881	0.881
ln(*R0*)	14.01	44.92	13.72	14.26	13.86	13.97	14.02
M	0.14	0.24	0.10	0.14	0.11	0.14	0.14
Select50CSLF	125.12	125.02	125.00	124.86	125.00	125.13	125.12
Select95CSLF	2.72	2.59	3.30	2.47	3.30	2.72	2.72
Mat50	91.02	91.02	91.02	91.02	91.02	91.02	91.02
Mat95	22.83	22.83	22.83	22.83	22.83	22.83	22.83
ln(*qCPUE*)	-6.50	1.00	-0.97	-12.62	1.00	-3.46	-6.58
ln(*qRDSI*)	-11.60	-13.00	-11.17	-13.00	-11.45	-11.58	-11.74
galpha	26.21	28.12	28.56	31.48	26.61	25.97	26.24
gBeta	7.15	5.86	6.71	6.01	7.03	7.30	7.14
GrowthCV	0.32	0.33	0.29	0.28	0.31	0.32	0.32
CPUEpow	0.86	1.00	0.48	1.25	1.00	0.63	0.86
LikeCPUE	-18.28	2081900	-27.38	-21.75	110421	-22.18	-18.32
LikeRDSI	1.59	28483.7	1.07	30.80	1.52	1.66	-0.79
LikeCSLF	134.8	127.3	1533.5	121.8	277.8	129.9	134.9
LikeRDLF	155.6	163.9	451.9	244.0	140.0	156.8	155.6
LikeTags	888.6	891.6	885.8	890.2	887.4	889.5	888.5
LikeMat	-16.43	-16.43	-16.43	-16.43	-16.43	-16.43	-16.43
MPrior	3.69	36.61	-1.38	3.29	-0.56	3.39	3.83
Eps	13.32	12.13	0.92	9.44	11.03	14.50	13.18
ERate penalty	0	0	1.15E-06	0	0	0	0
LikeTotal	1162.8	1215.1	842.6	986.6	1023.0	1157.1	1160.4
maxRdev	1.68	2.08	1.10	1.57	1.45	1.77	1.67
minRdev	0.461	0.448	0.712	0.537	0.403	0.462	0.464
MaxERate	0.301	0.000	0.650	0.175	0.341	0.310	0.299
ERate[LastYear]	0.099	0.000	0.202	0.067	0.107	0.096	0.097
Smin	913.5	2.8E+16	483.6	1580.2	734.9	883.0	924.1
Sav	1843.3	2.9E+16	1554.8	2760.8	1991.4	1733.4	1856.3
S07	1389.9	3.7E+16	802.9	2056.4	1286.2	1438.1	1416.6
Bmin	561.4	1.9E+16	197.3	1121.8	409.3	541.3	569.5
Bav	1181.8	1.9E+16	1226.0	1935.6	1503.6	1062.4	1191.5
B07	1045.0	2.8E+16	474.7	1566.2	957.8	1085.5	1064.2
S07/Sav	75.4%	128.0%	51.6%	74.5%	64.6%	83.0%	76.3%
B07/Bav	88.4%	147.8%	38.7%	80.9%	63.7%	102.2%	89.3%
S07/Smin	152.2%	135.3%	166.0%	130.1%	175.0%	162.9%	153.3%
B07/Bmin	186.1%	151.3%	240.6%	139.6%	234.0%	200.5%	186.9%

5.2 Truncated abundance index series

When CPUE data before 1990 were discarded (Table 6), the fit to CSLF improved slightly. Parameter estimates were not much changed except for *CPUEpow* (0.63). Reference biomass estimates decreased while current biomass estimates increased, so ratio indicators were all more positive. This MPD suggested that current recruited biomass is at the target reference level, and is twice *Bmin*.

When the first RDSI datum was discarded (Table 6), the sdnr for this dataset decreased from 1.0 to 0.4; very little other effect can be discerned.

5.3 Alternative commercial catch series

Kendrick & Andrew (2000) presented three different trajectories for commercial catch (shown here in Table 7 and Figure 20), on one of which the base case catch series is based. Two sensitivity trials explored the effects of using their other two series. For each trial, the assumed commercial catch series was used in the same way as the base case, with the same non-commercial catches added to make a total catch series.

Catch series C had little effect (Table 8): this was to be expected because this series is, with two quite minor changes, the basis of the instant base case.

Catch series A and B, both with less catch from 1984 through 1994 than in the base case, gave parameter estimates quite similar to the base case estimates. Biomass indicators were all smaller for series A and a mixture of smaller and larger for series B. For both series, the ratio indicators involving minimum biomass were less optimistic and those involving target biomass references were more optimistic when compared with the base case.

Biomass and recruitment trajectories from these trials are shown in Figure 21 and Figure 22 respectively.

Table 7: Four catch trajectories: one is the basecase used here, and there three from Kendrick & Andrew (2000) used for sensitivity analyses. After 1995 the commercial catch trajectory for PAU 5B is known and is the same for all series.

	Kendrick & Andrew (2000)			
Fishing year	A "Base case 2000 sensitivity"	B "1999 Series 1"	C "1999 Series 2 2000 Base case"	2007 basecase
1974	110588	110588	110588	110588
1975	104614	104614	104614	104614
1976	83257	83257	83257	83257
1977	115128	115128	115128	115128
1978	173399	173399	173399	173399
1979	181979	181979	181979	181979
1980	225212	225212	225212	225212
1981	272657	272657	272657	272657
1982	180211	180211	180211	180211
1983	230350	230350	230350	230350
1984	287058	264000	356898	356898
1985	178981	169440	190884	190884
1986	112206	109440	147746	226982
1987	199915	201072	263080	263080
1988	214989	223200	305902	305902
1989	191494	205426	285099	285099
1990	198741	220541	268166	268166
1991	220590	253517	272344	272344
1992	196049	233645	255918	255918
1993	170720	211272	211137	211137
1994	164253	211387	222900	222900
1995	156168	209342	222593	222593

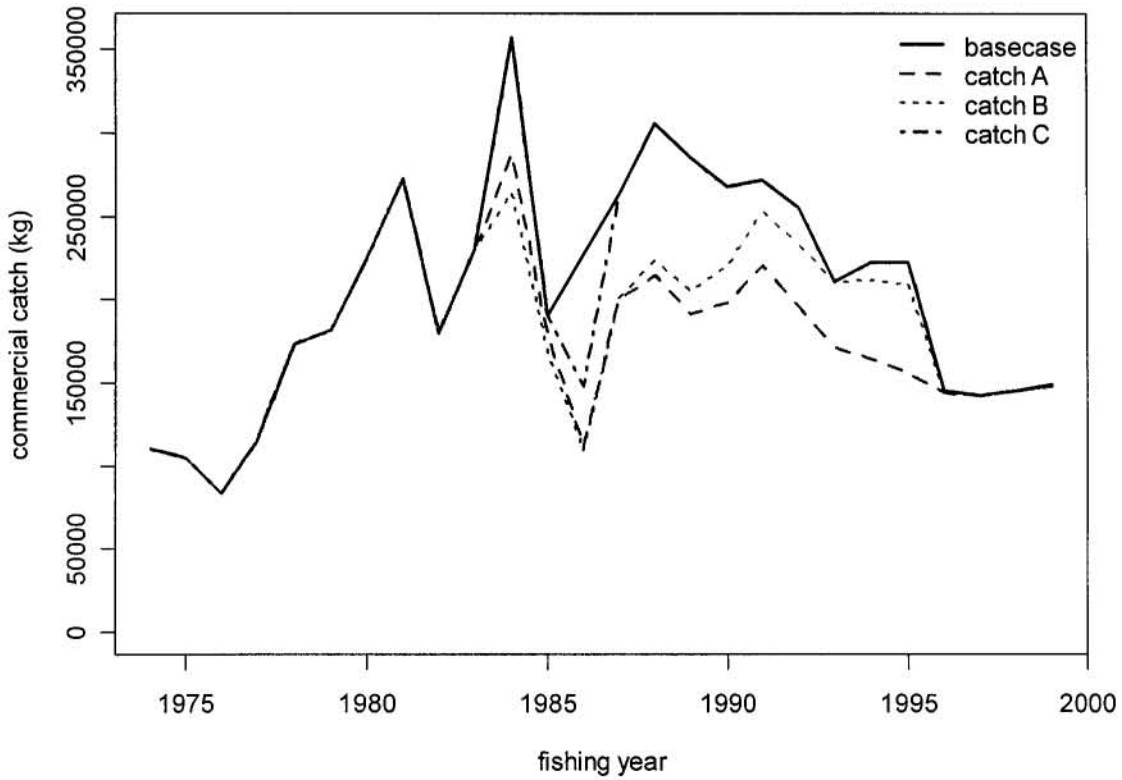


Figure 20: The three commercial catch series from Kendrick & Andrew (2000) used in sensitivity analyses, shown with the base case.

Table 8: MPD sensitivity trials with alternative commercial catch series obtained from Kendrick and Andrews (2000) were used. For run "019", the Bentley likelihood function was used for length frequencies.

	Base case	Catch series A	Catch series B	Catch series C	Bentley LF likelihood
Serial	000	016	017	018	019
sdnrCPUE	1.027	1.143	1.240	1.066	1.259
sdnrRDSI	0.999	1.056	1.006	1.000	1.019
sdnrCSLF	0.945	0.954	0.956	0.947	1.936
sdnrRDLF	0.992	0.995	0.989	0.991	1.472
sdnrtags	0.971	0.968	0.970	0.971	1.044
sdnrmaturity	1.004	1.004	1.004	1.004	1.004
MARCPUE	0.792	0.829	0.920	0.789	0.936
MARRDSI	0.448	0.516	0.482	0.453	0.435
MARCSLF	0.474	0.478	0.484	0.476	0.867
MARRDLF	0.605	0.606	0.599	0.604	0.777
MARtags	0.666	0.654	0.654	0.670	0.700
MARmaturity	0.881	0.881	0.881	0.881	0.881
ln(*R0*)	14.01	13.85	13.97	14.01	14.07
M	0.14	0.13	0.14	0.14	0.15
Select50CSLF	125.12	125.11	125.12	125.12	124.98
Select95CSLF	2.72	2.73	2.73	2.72	2.63
Mat50	91.02	91.02	91.02	91.02	91.02
Mat95	22.83	22.83	22.83	22.83	22.83
ln(*qCPUE*)	-6.50	-9.53	-7.23	-6.54	-6.90
ln(*qRDSI*)	-11.60	-11.52	-11.62	-11.61	-11.71
galpha	26.21	26.42	26.43	26.25	25.61
gBeta	7.15	7.10	7.03	7.13	7.03
GrowthCV	0.32	0.32	0.32	0.32	0.28
CPUEpow	0.86	1.09	0.91	0.86	0.88
LikeCPUE	-18.28	-15.17	-12.19	-17.27	-11.53
LikeRDSI	1.59	1.94	1.62	1.59	1.71
LikeCSLF	134.76	137.09	137.72	135.26	-836.41
LikeRDLF	155.56	157.00	155.12	155.34	-1074.69
LikeTags	888.59	888.21	887.98	888.46	890.02
LikeMat	-16.43	-16.43	-16.43	-16.43	-16.43
MPrior	3.69	2.75	4.29	3.86	5.74
Eps	13.32	10.48	11.12	13.04	19.73
ERate	0	0	0	0	0
LikeTotal	1162.80	1165.86	1169.23	1163.85	-1021.87
maxRdev	1.68	1.63	1.67	1.70	2.53
minRdev	0.461	0.500	0.482	0.466	0.336
MaxERate	0.301	0.257	0.279	0.299	0.276
ERate[LastYear]	0.099	0.117	0.103	0.099	0.089
Smin	913.5	850.5	933.9	921.3	1023.7
Sav	1843.3	1394.9	1604.4	1823.7	1910.2
S07	1389.9	1167.6	1339.9	1390.6	1537.7
Bmin	561.4	521.2	573.9	566.3	627.3
Bav	1181.8	904.5	1035.8	1166.7	1131.6
B07	1045.0	876.2	1006.8	1045.5	1165.6
S07/Sav	75.4%	83.7%	83.5%	76.3%	80.5%
B07/Bav	88.4%	96.9%	97.2%	89.6%	103.0%
S07/Smin	152.2%	137.3%	143.5%	150.9%	150.2%
B07/Bmin	186.1%	168.1%	175.4%	184.6%	185.8%

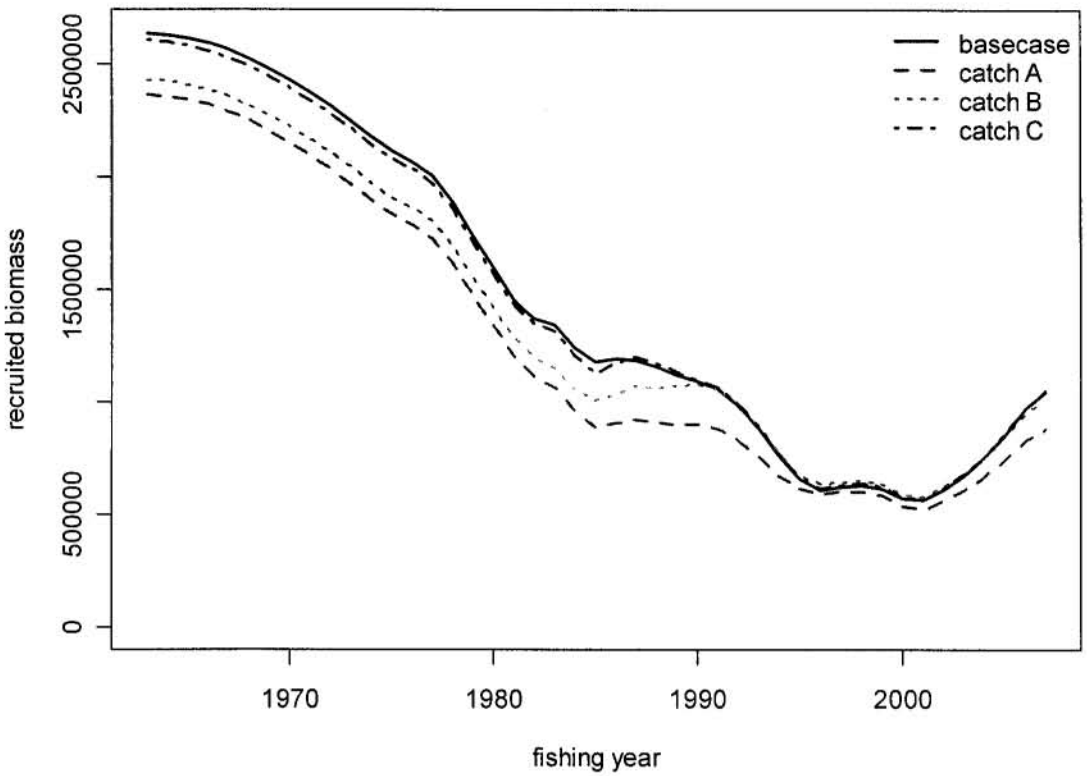


Figure 21: Recruited biomass trajectories for the base case and MPD sensitivity trials using three alternative commercial catch trajectories.

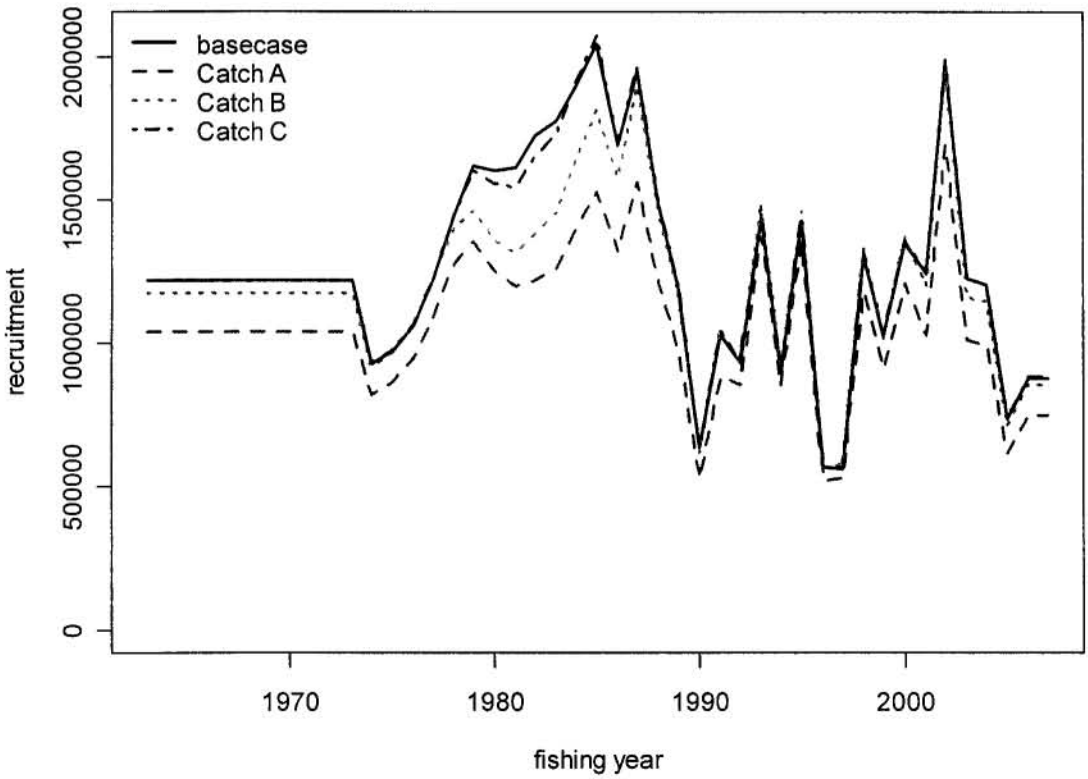


Figure 22: Recruitment trajectories for the base case and MPD sensitivity trials using three alternative commercial catch trajectories.

5.4 Multinomial likelihood

When multinomial likelihood was replaced by the previously used Bentley-variance formulation (Table 8), the relative dataset weighting changed, causing degradation of the CPUE fit. Biomass indicators changed slightly, except that B07/Bav was estimated near 100%.

5.5 Retrospective trials

MPD retrospective trials were made by removing one year of year-specific data at a time (thus not removing any maturity or tag-recapture data) to examine the effect of recent data on the results and to examine the stability of model estimates to the addition of a single year of data. No re-weighting was attempted.

Results are summarised in Table 9; recruited biomass and recruitment trajectories are shown in Figure 23 and Figure 24 respectively. This was a very stable set of retrospectives.

Table 9: Retrospective MPD sensitivity trials for PAU 5B.

	Base case "000	Fit through 2006 "012	Fit through 2005 "013	Fit through 2004 "014	Fit through 2003 "015
sdnrCPUE	1.027	1.032	1.038	1.003	0.982
sdnrRDSI	0.999	1.093	1.099	1.139	1.163
sdnrCSLF	0.945	0.939	0.911	0.886	0.877
sdnrRDLF	0.992	1.038	1.039	1.043	1.041
sdnrtags	0.971	0.978	0.966	0.965	0.968
sdnrmaturity	1.004	1.004	1.004	1.004	1.004
MARCPUE	0.792	0.806	0.819	0.966	0.905
MARRDSI	0.448	0.606	0.607	0.578	0.614
MARCSLF	0.474	0.498	0.477	0.483	0.483
MARRDLF	0.605	0.639	0.653	0.651	0.657
MARtags	0.666	0.655	0.666	0.666	0.663
MARmaturity	0.881	0.881	0.881	0.881	0.881
ln(*R0*)	14.01	13.99	14.06	14.05	14.03
M	0.14	0.137	0.140	0.139	0.137
Select50CSLF	125.12	125.08	125.01	124.97	125.06
Select95CSLF	2.72	2.695	2.715	2.901	3.247
Mat50	91.02	91.02	91.02	91.02	91.02
Mat95	22.83	22.83	22.83	22.83	22.83
ln(*qCPUE*)	-6.50	-6.524	-6.897	-8.725	-9.311
ln(*qRDSI*)	-11.60	-11.57	-11.62	-11.68	-11.68
galpha	26.21	26.22	26.29	26.23	26.36
gBeta	7.15	7.244	7.107	7.054	7.124
GrowthCV	0.32	0.316	0.326	0.328	0.324
CPUEpow	0.86	0.859	0.884	1.014	1.058
LikeCPUE	-18.28	-18.17	-16.96	-16.65	-15.93
LikeRDSI	1.59	1.887	1.921	2.151	2.290
LikeCSLF	134.76	132.43	111.65	95.25	84.48
LikeRDLF	155.56	148.80	149.06	150.37	149.64
LikeTags	888.59	888.79	888.46	888.45	888.36
LikeMat	-16.43	-16.43	-16.43	-16.43	-16.43
M Prior	3.69	3.53	4.28	3.97	3.66
Eps prior	13.32	12.91	11.95	11.24	11.43
ERate penalty	0	0	0	0	0
LikeTotal	1162.80	1153.74	1133.93	1118.35	1107.51
maxRdev	1.68	1.71	1.64	1.65	1.67
minRdev	0.461	0.461	0.453	0.476	0.465
MaxERate	0.301	0.307	0.294	0.283	0.288
ERate[LastYear]	0.099	0.110	0.113	0.117	0.123
Smin	913.5	893.2	938.9	1008.8	998.8
Sav	1843.3	1796.9	1883.4	1905.3	1864.4
Bmin	561.4	548.4	580.2	641.2	640.1
Bav	1181.8	1148.6	1209.4	1226.1	1202.0

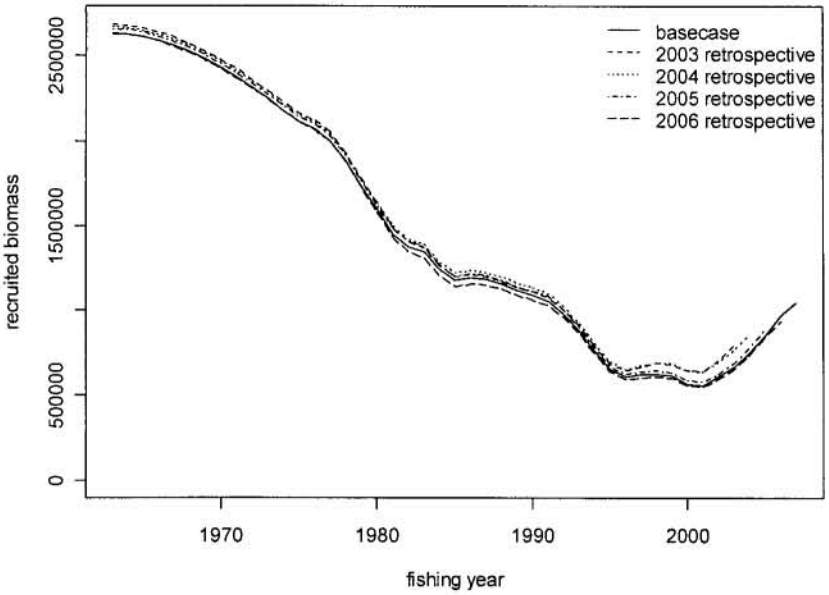


Figure 23: Recruited biomass trajectories from the MPD retrospective analysis for PAU 5B.

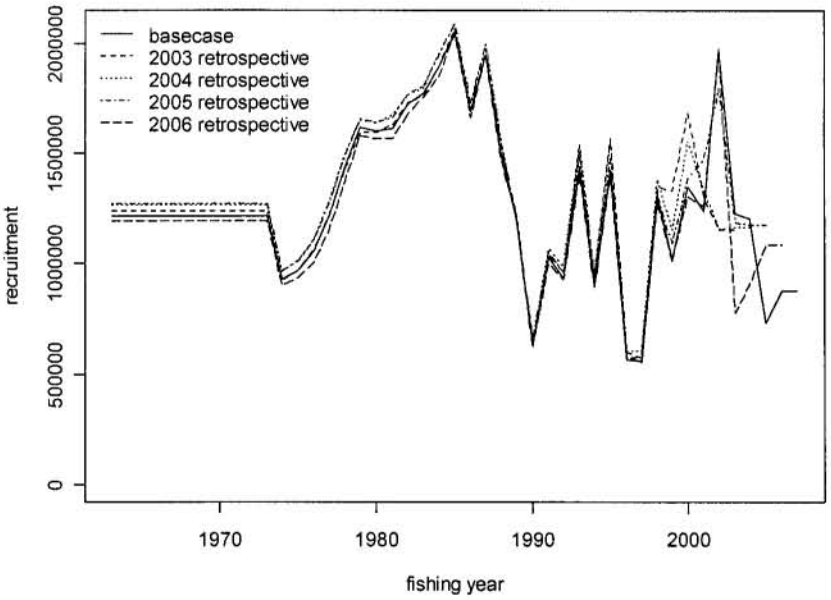


Figure 24: Recruitment trajectories from the MPD retrospective analysis for PAU 5B.

6. MCMC RESULTS

The base case McMC run was a single chain, started at the MPD. The chain was 5 million simulations long, with 5000 samples saved.

6.1 Diagnostics

Traces (Figure 25) were well mixed for all estimated and derived parameters. The only remotely suspect trace was that for the sdnr of the maturity data, which had a floor of 1.0 – this is the MPD value, obtained at the parameter values that give the maximum likelihood. Because the maturity is unrelated to other parameters and datasets, it is not possible to obtain a smaller sdnr.

In place of more formal diagnostics, which experience has shown to be less than useful in interpreting the McMC convergence (consequential non-convergence is evident from less formal diagnostics), for some time we have used informal diagnostics, including the traces and plots of the running median, running 5th and 95th percentiles, and a moving mean; these latter four items are shown in Figure 26. For no quantity do these plots suggest that there is any problem with convergence of the McMC chain.

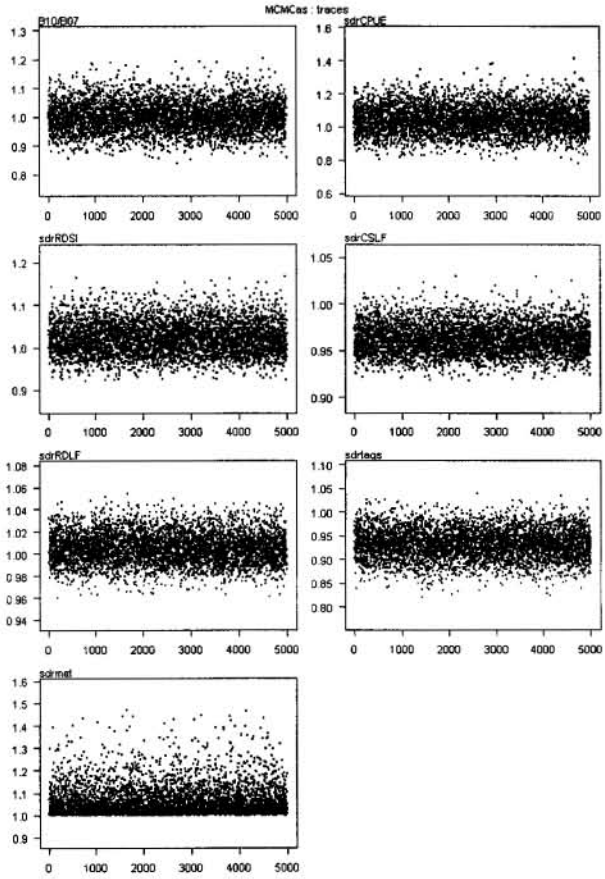


Figure 25: Traces for estimated and derived parameters from the PAU 5B base case. Some fixed parameters present themselves as flat lines.

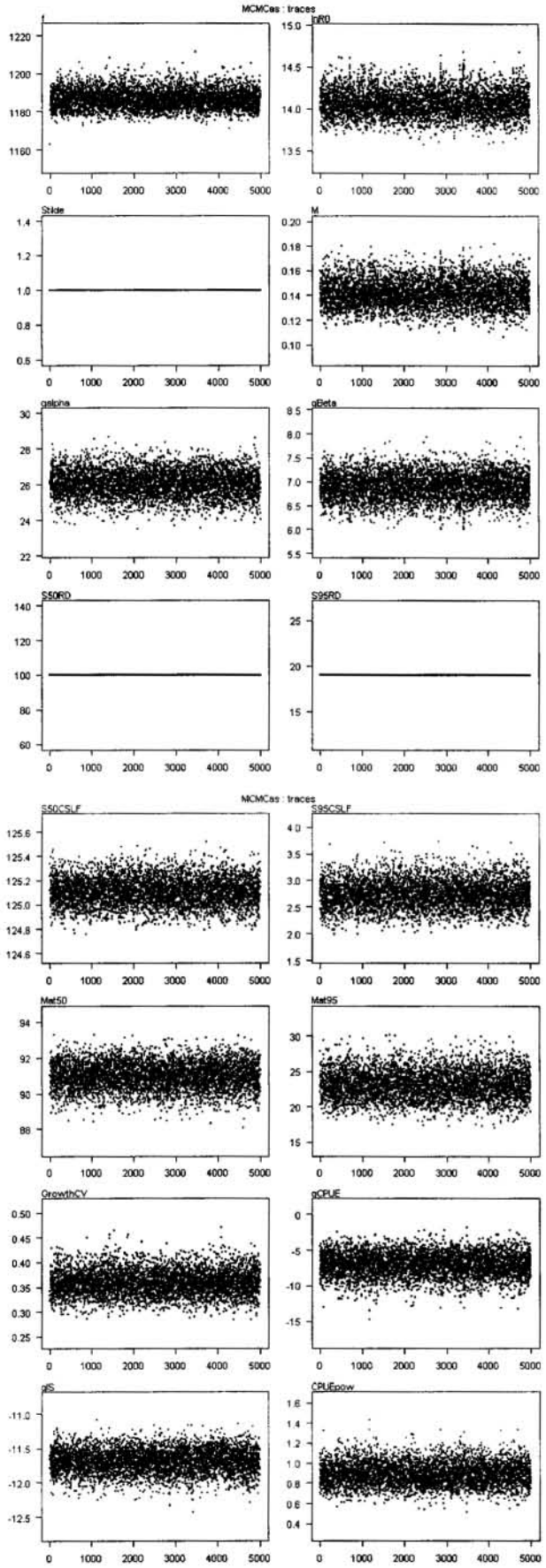
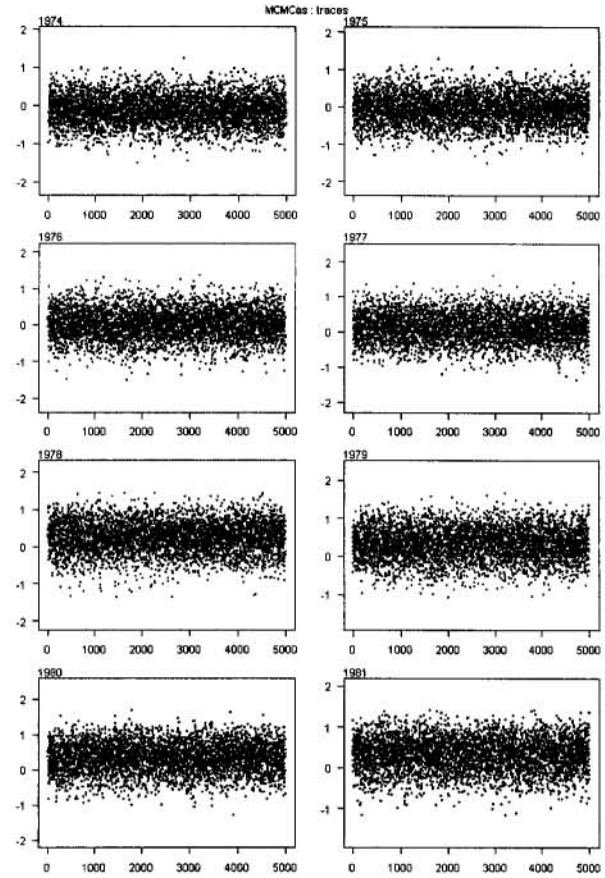


Figure 25 (continued).



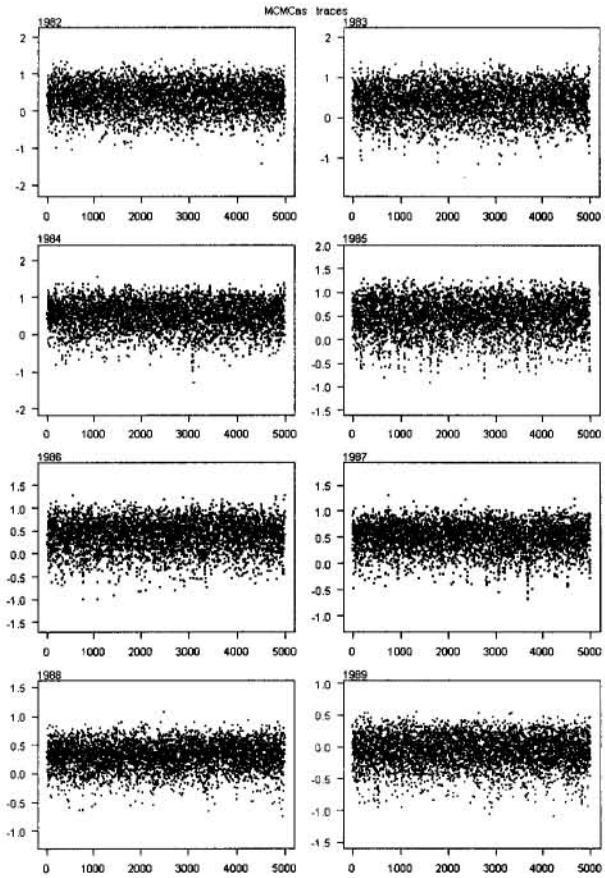


Figure 25 (continued).

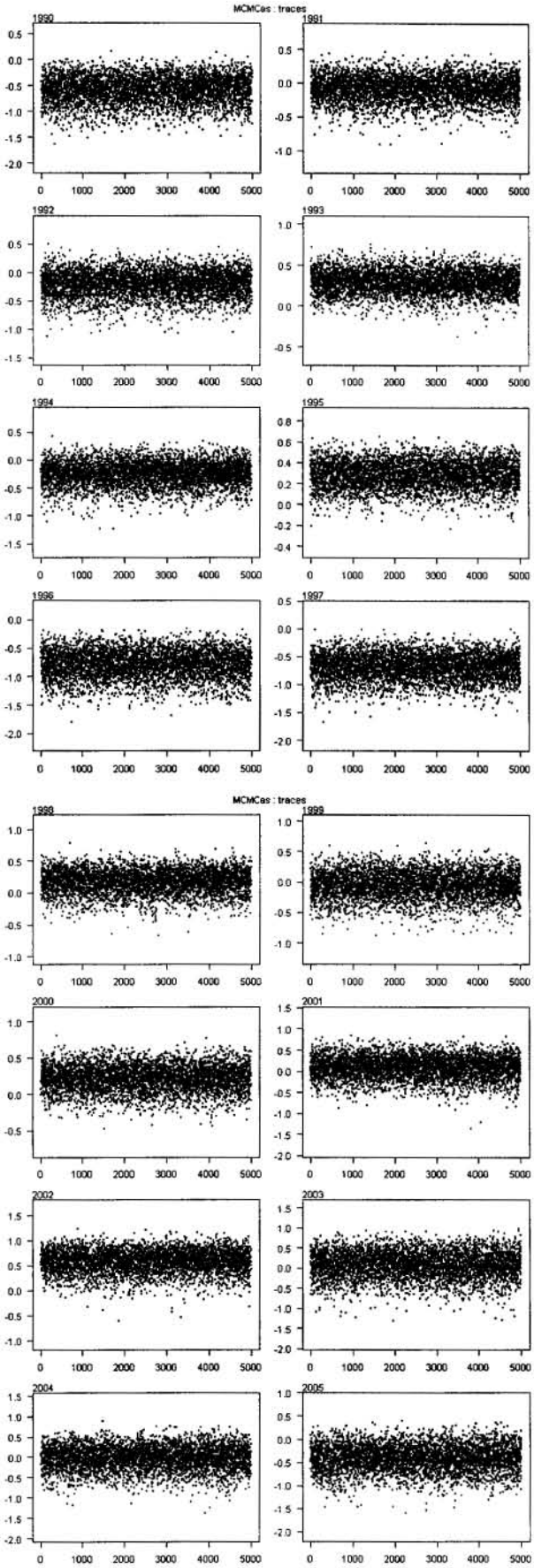


Figure 25 (continued).

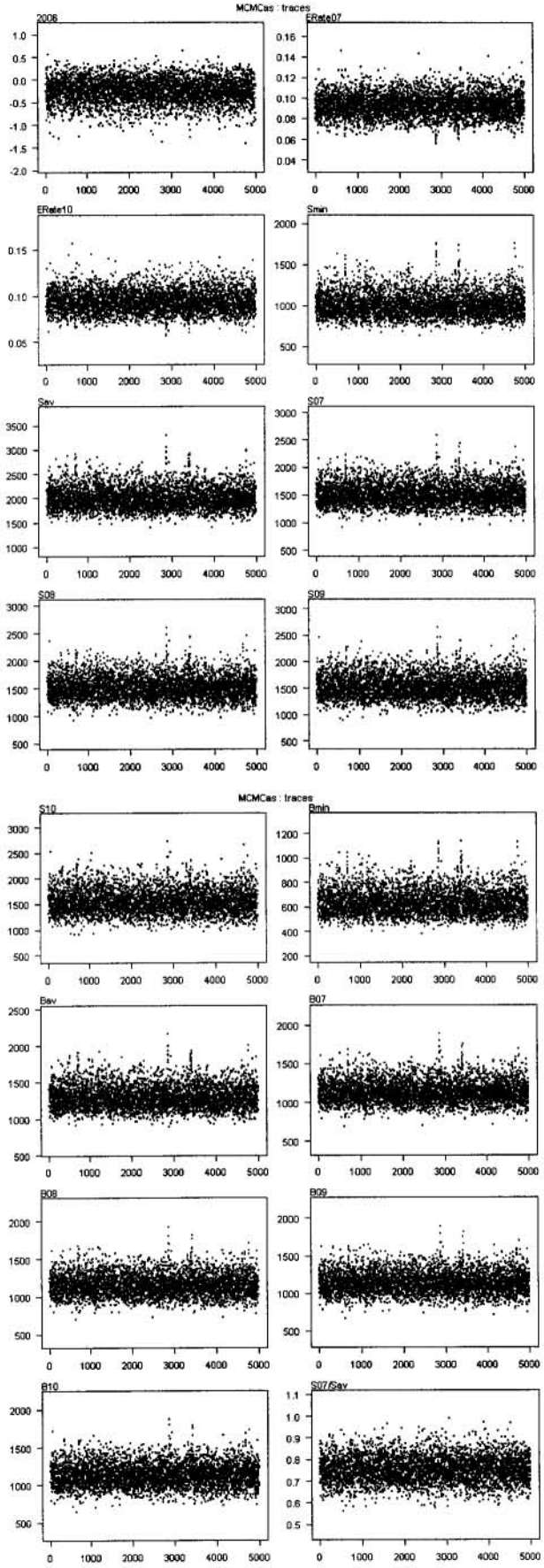


Figure 25 (continued).

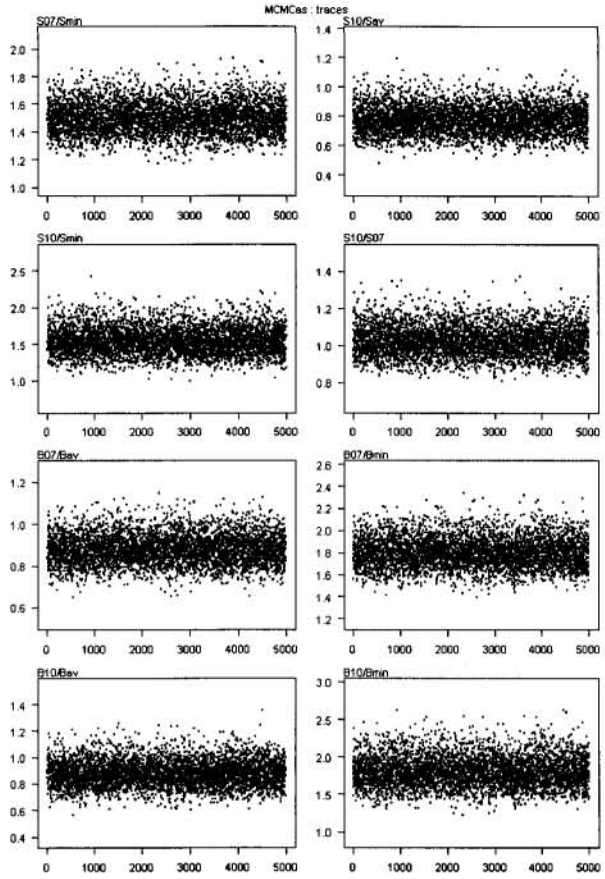


Figure 25 (continued).

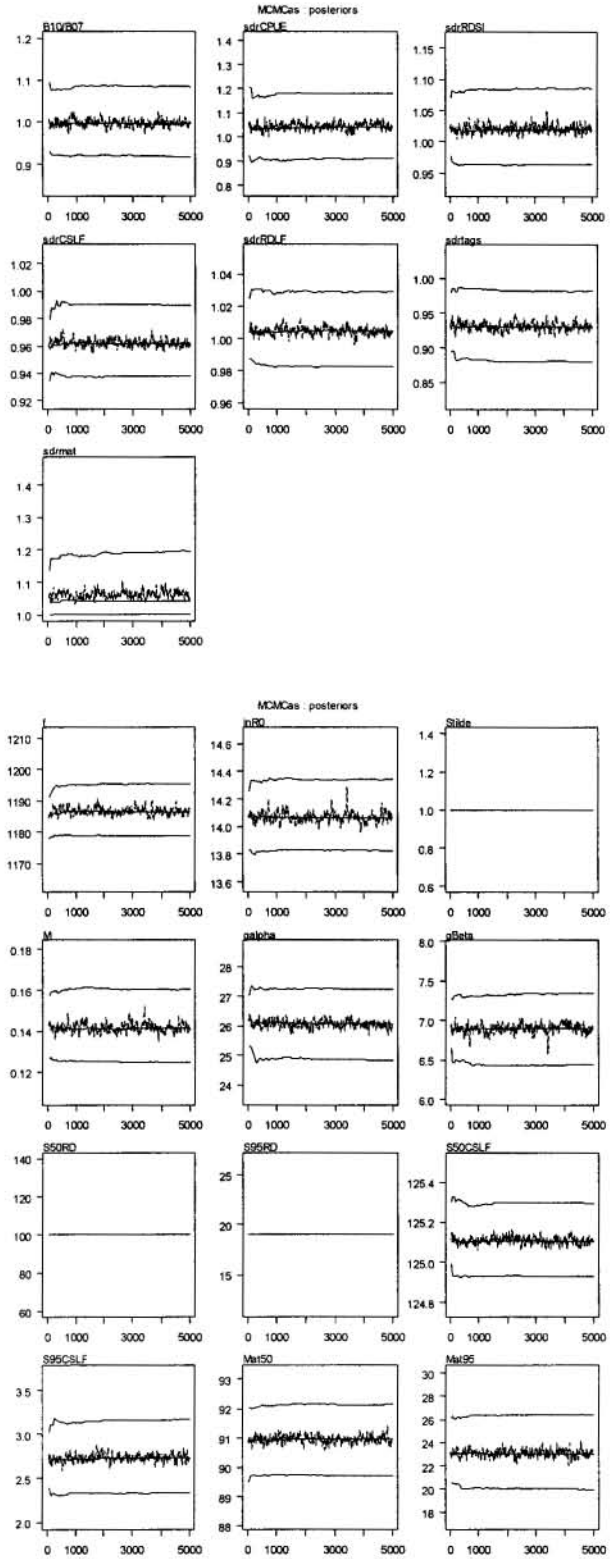


Figure 26: Diagnostic plots based on the traces shown in Figure 25. The solid lines show the running 5th and 95th percentiles and the median; the points show the moving mean, based on 40 contiguous samples.

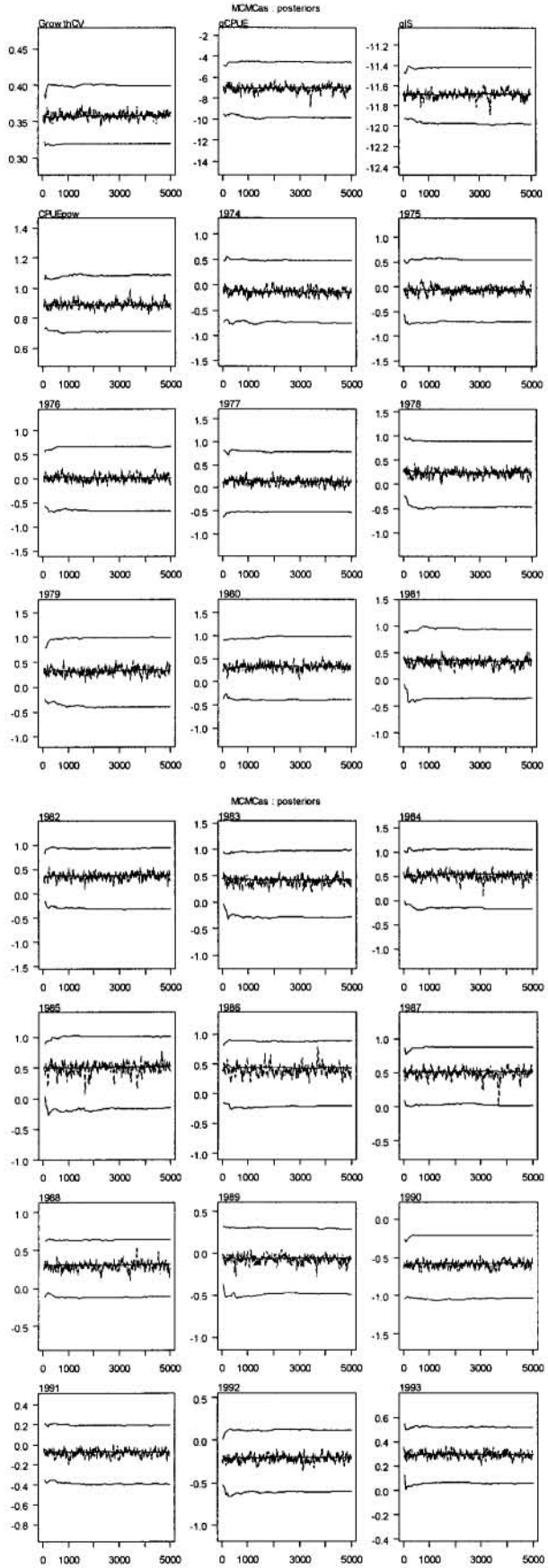


Figure 26 (continued).

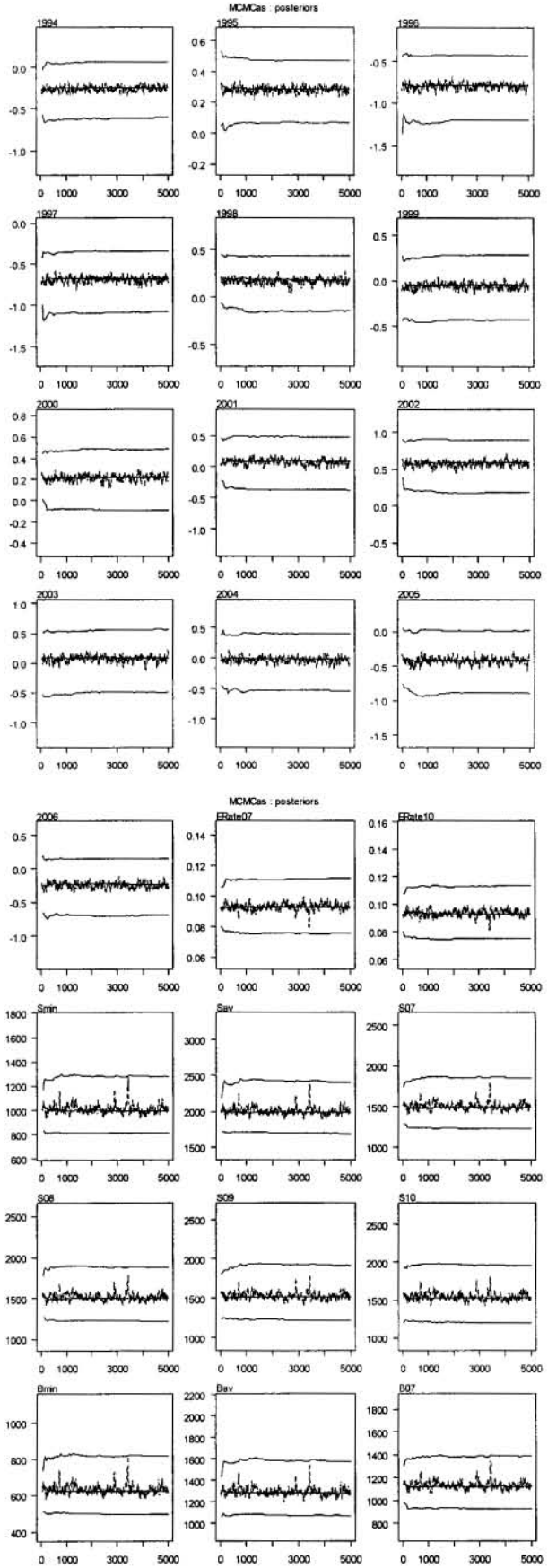


Figure 26 (continued).

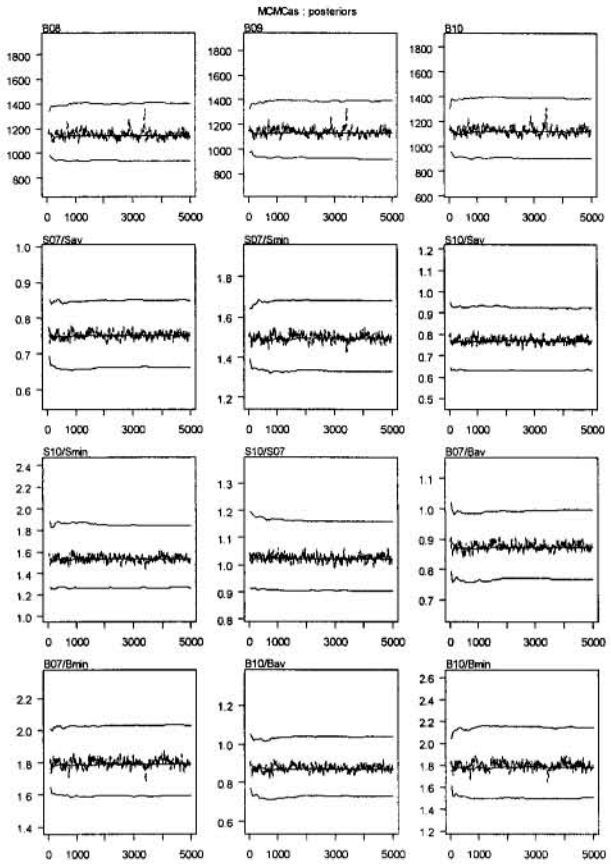


Figure 26 (continued).

6.2 Posterior distributions

Marginal posterior distributions for estimated and derived parameters are shown in Figure 27. These are mostly very nicely-formed posteriors, with the exception of that for the sdnr for maturity noted and discussed above. The MPD estimates, shown as a dot for each posterior, are generally close to the median: exclusions to this wholesale generalisation are the function value (for which the MPD is about 25 units smaller than the median of the marginal posterior, roughly 0.5 likelihood units per parameter), *GrowthCV*, for which the median was about 10% larger than the MPD value, the derived indicator values such as *Smin,*, *Sav*, *S07* etc., tending to be larger than the MPD, and the sdnrs, which have medians greater than the MPD for all except the tag-recapture datasets.

The marginal posterior distributions are summarised in Table 10. For estimated parameters, those showing the largest variation were as follows. *CPUEpow* ranged (5th to 95th quantile) from 0.70 to 1.10, suggesting that this is a poorly determined quantity. This variation magnifies the variation in ln(q*CPUE*). The difference between lengths at 50% and 95% maturity varied from 20 to 26.5 mm. *M* ranged from 0.125 to 0.160: although the range is 25% of the median, this variation is not alarming. *GrowthCV* varied from 0.32 to 0.40. All other parameters either had a range that was a small proportion of the median or (e.g. for the difference between lengths at 50% and 95% commercial selectivity) were small in absolute value.

As noted above, the medians of the posterior distributions for the biomass estimates tended to be larger than the MPDs. The biomass ratio indicators tend to be similar between the medians and the MPD, except for B07/Bmin, where the median was smaller (179%) than the MPD (186%).

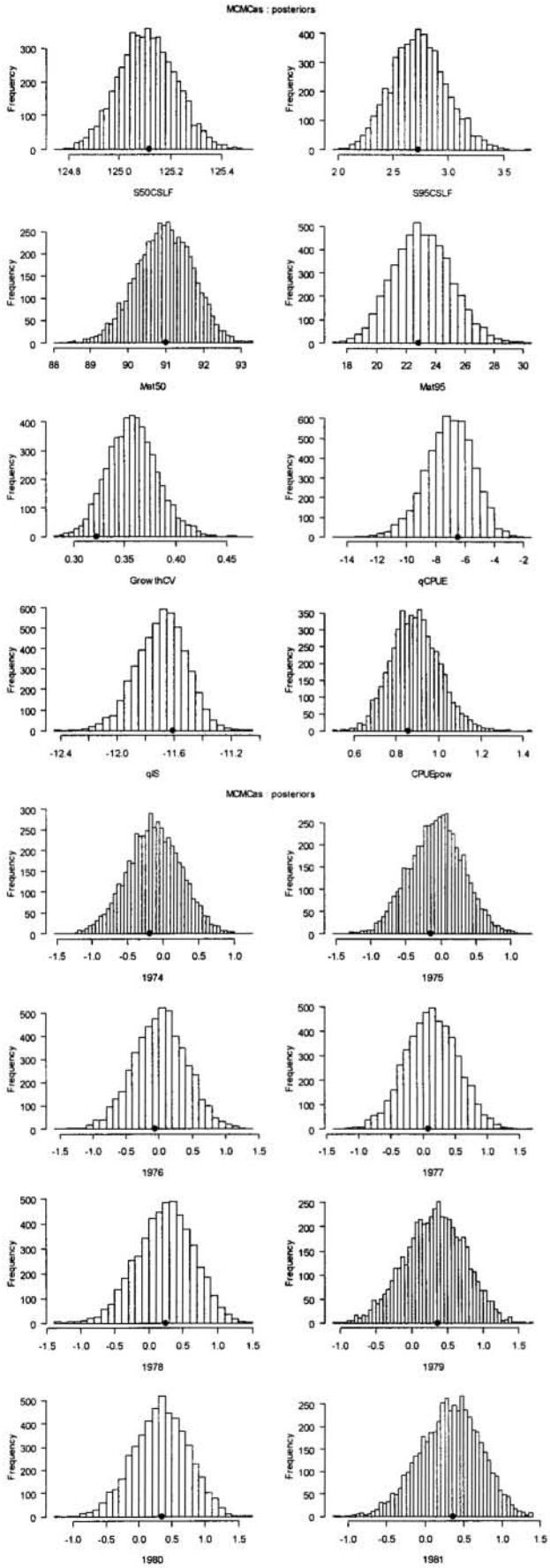


Figure 27: Marginal posterior distributions of estimated and derived parameters from the joint posterior distribution estimated by the base case McMC for the PAU 5B assessment.

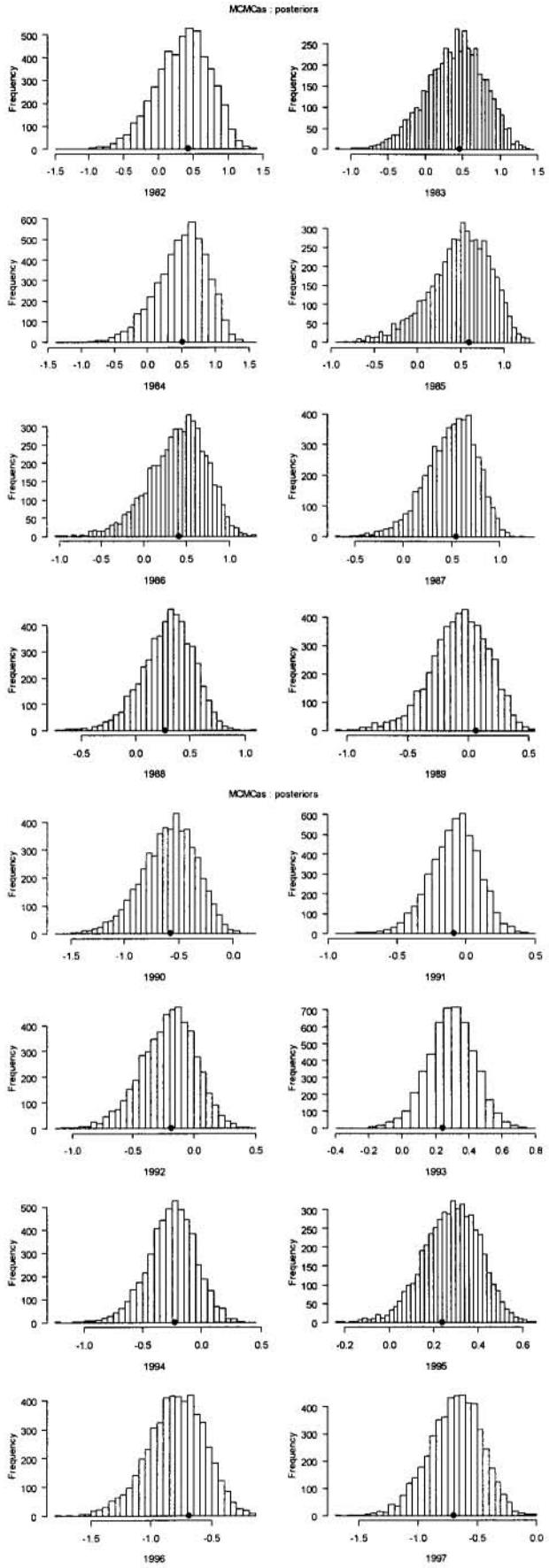


Figure 27 (continued).

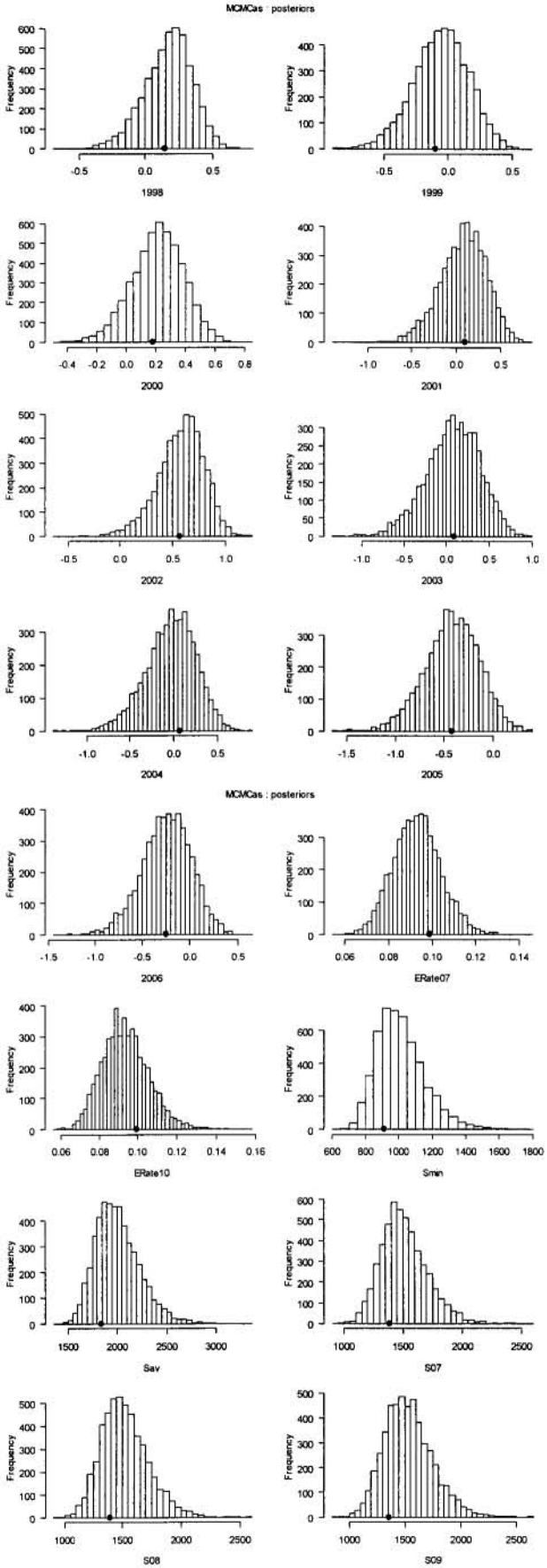


Figure 27 (continued).

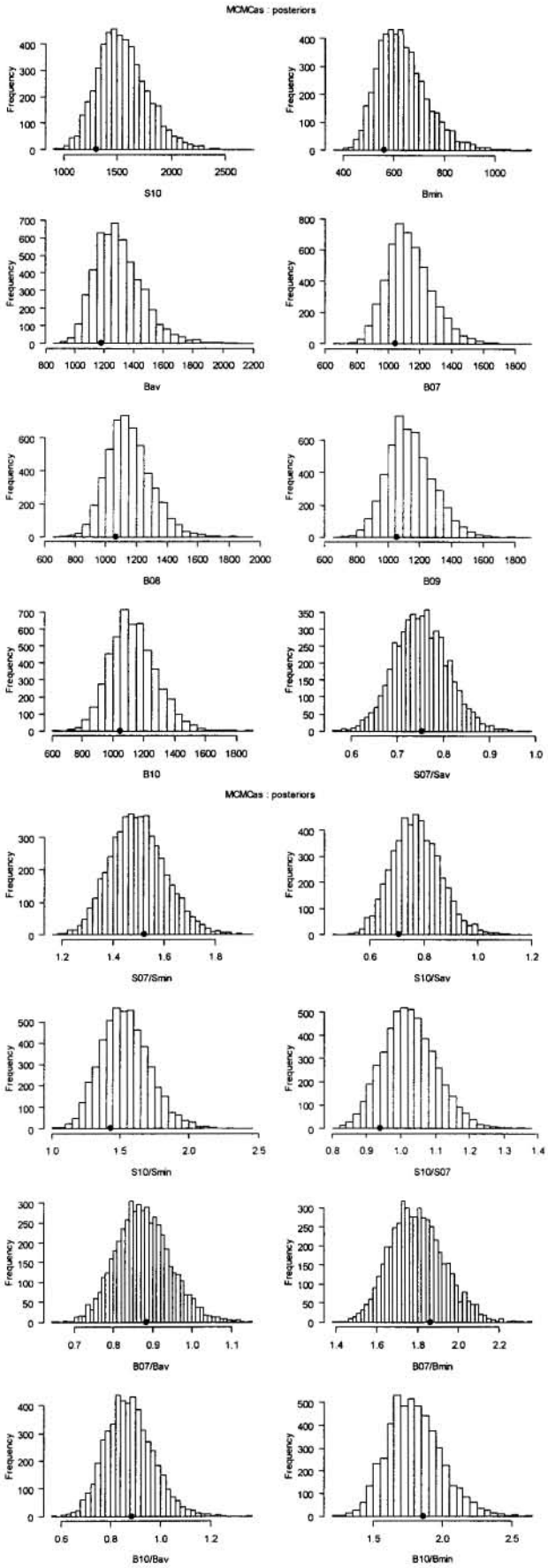


Figure 27 (continued).

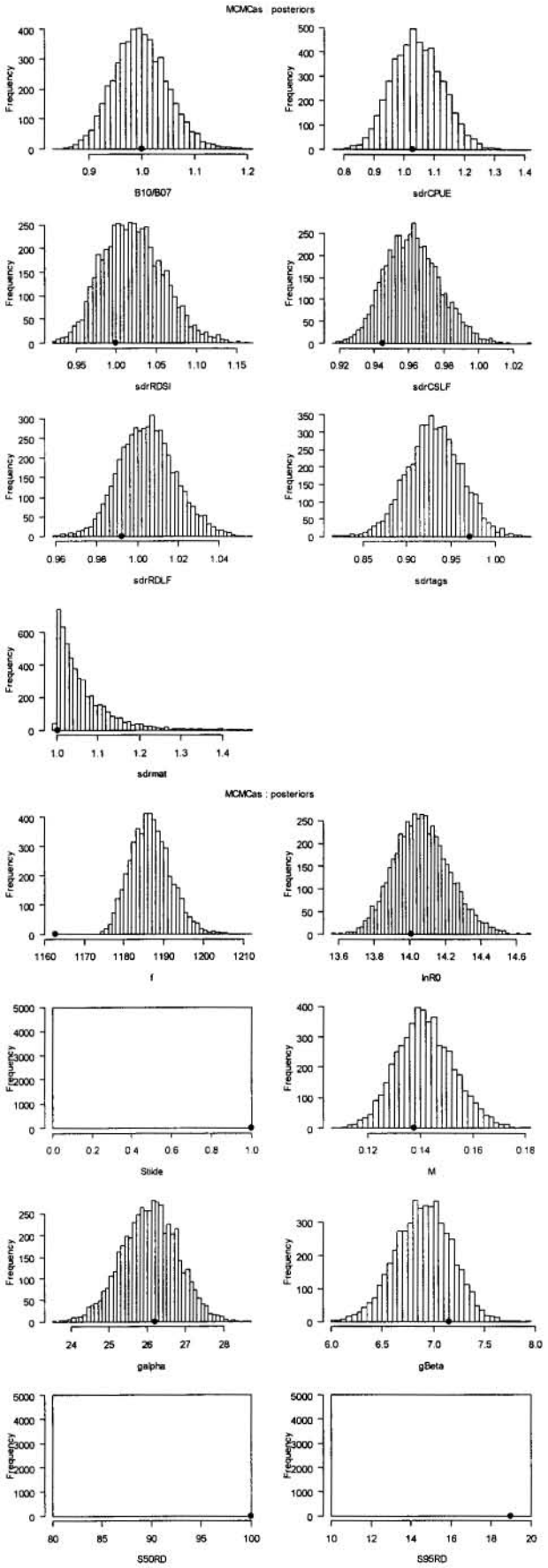


Figure 27 (continued).

Table 10: Summaries of the marginal posterior distributions of estimated parameters and derived parameters (indicators), including those from projections. Columns show the minimum, and maximum, 5th and 95th quantiles, median and mean of the marginal posterior distribution; the final column shows the exact position of the MPD value in the marginal posterior. The bottom part of the table shows the percentage of runs in which the indicated condition was true. All biomass values are in tonnes.

Parameter	Min	5%	Median	Mean	0.95	Max	%MPD
f	1162.8	1178.9	1186.47	1186.712	1195.271	1211.48	0.0%
sdrCPUE	0.779	0.912	1.041	1.044	1.182	1.411	43.7%
sdrRDSI	0.922	0.964	1.019	1.021	1.086	1.166	30.5%
sdrCSLF	0.918	0.938	0.962	0.962	0.990	1.030	13.4%
sdrRDLF	0.960	0.983	1.005	1.005	1.029	1.055	17.6%
sdrtags	0.820	0.881	0.931	0.931	0.982	1.040	89.8%
sdrmat	1.000	1.002	1.043	1.063	1.195	1.468	7.0%
ln(*R0*)	13.57	13.83	14.06	14.07	14.34	14.68	36.5%
M	0.1065	0.1248	0.1414	0.1418	0.1603	0.1816	35.3%
galpha	23.50	24.84	26.07	26.05	27.24	28.69	57.9%
gBeta	6.00	6.45	6.91	6.90	7.34	7.94	81.9%
S50CSLF	124.76	124.93	125.11	125.11	125.29	125.52	54.0%
S95CSLF	1.99	2.33	2.73	2.74	3.17	3.72	49.3%
Mat50	88.09	89.71	90.97	90.96	92.15	93.29	52.3%
Mat95	17.04	19.97	23.05	23.12	26.41	30.19	45.4%
GrowthCV	0.283	0.319	0.357	0.358	0.400	0.472	6.9%
qCPUE	-14.83	-9.86	-7.00	-7.07	-4.54	-1.78	61.8%
qRDSI	-12.43	-11.98	-11.68	-11.69	-11.42	-11.09	67.9%
CPUEpow	0.514	0.712	0.888	0.891	1.085	1.428	39.1%
ERate07	5.6%	7.6%	9.3%	9.3%	11.1%	14.6%	72.4%
ERate10	5.7%	7.5%	9.3%	9.3%	11.4%	15.7%	71.2%
Smin	631.3	807.2	992.7	1011.3	1276.6	1758.0	26.5%
Sav	1394.0	1688.3	1982.0	2006.0	2409.4	3301.4	24.3%
S07	908.0	1224.3	1487.7	1508.0	1853.0	2589.1	27.4%
S08	922.7	1222.3	1498.6	1518.1	1879.4	2597.9	28.4%
S09	897.7	1214.4	1512.3	1531.4	1916.4	2645.4	21.4%
S10	903.9	1199.5	1528.2	1546.9	1954.0	2714.3	14.2%
Bmin	378.9	495.3	622.4	634.5	817.9	1131.7	24.3%
Bav	887.6	1073.1	1280.5	1296.8	1580.5	2161.9	24.8%
B07	692.8	924.1	1119.6	1133.2	1386.2	1892.1	27.6%
B08	694.3	937.7	1140.3	1153.4	1408.2	1927.4	29.3%
B09	660.2	921.1	1129.4	1140.8	1392.5	1891.9	30.0%
B10	640.5	905.4	1120.1	1130.4	1389.9	1865.6	29.5%
S07/Sav	56.1%	66.3%	75.1%	75.2%	84.9%	98.8%	52.0%
S07/Smin	117.1%	133.3%	149.3%	149.8%	168.2%	192.9%	60.3%
S10/Sav	47.6%	63.3%	76.9%	77.2%	92.3%	119.2%	24.5%
S10/Smin	100.1%	126.5%	153.0%	153.8%	184.2%	242.3%	28.5%
S10/S07	81.2%	90.4%	102.1%	102.6%	116.0%	137.3%	13.9%
B07/Bav	64.6%	76.8%	87.3%	87.6%	99.7%	114.8%	56.1%
B07/Bmin	139.3%	159.6%	179.1%	179.8%	203.2%	234.1%	69.6%
B10/Bav	56.5%	73.0%	87.1%	87.6%	103.9%	135.5%	55.7%
B10/Bmin	122.5%	150.3%	178.3%	179.7%	214.3%	262.0%	65.2%
B10/B07	83.7%	91.7%	99.5%	99.8%	108.4%	120.1%	54.1%

S10<S07	38.8%	*B10<Bav*	90.2%
S10<Sav	98.9%	*S10<Smin*	0.0%
B10<B07	53.5%	*B10<Bmin*	0.0%

6.3 Fits to data and trajectories

The posterior distribution of the fit to CPUE (i.e., the posterior distribution of the predicted CPUE values compared with the observed values) and the residual posteriors are shown in Figure 28. The prediction posteriors are tight; they fit the observed pattern well but do not fit all the observed values well, hence a pattern in the residuals, and they do not fit the early values for 1983 to 1986.

The posterior of the fit to the RDSI fits the trend in the index, with the exception of the first survey index as discussed for the MPD results, but does not fit any except the most recent data very well (Figure 29), again generating a pattern in the residuals.

Figure 30 shows the posterior of the fit to one set of CSLF data, with its residuals, again showing a tight fit that is reasonably good for the trend in length but one that doesn't fit all the observations very well, generating a pattern in the residuals. Figure 31 shows a similar plot for one of the RDLF records. The posterior of the fit to maturity (Figure 32) shows a tight fit, being above some observations and below others.

Spawning and recruited biomass trajectories (Figure 33) show decreasing biomass from the beginning of the model runs to 1999 (spawning) or 2001 (recruited), then increases to the present, and a flat trend for the three-year projections. The recruited biomass posterior trajectory is shown for 1995 onwards in Figure 34.

The exploitation rate trajectory (Figure 35) is similar in form to the MPD, and shows greatest uncertainty in the 1980s and 1990s. Estimated recruitment (Figure 35) is also similar in form to the MPD. The surplus production trajectory (Figure 36) follows the shape of the recruitment trajectory as noted above for the MPD. Figure 37 shows the posterior of the surplus production *vs.* biomass function, which includes uncertainty in the production and biomass estimates and in the form of the relation.

We evaluated the assumption, encapsulated in the prior, that recruitment deviations have a standard deviation of 0.4. The distribution of standard deviations of estimated recruitment deviations (Figure 38) shows a mode near 0.45, which is slightly higher than the prior but not excessively divergent. The serial autocorrelation in recruitment deviations (Figure 39) has an absolute range of less than -0.2 to just over 0.6, with a mode near 0.25.

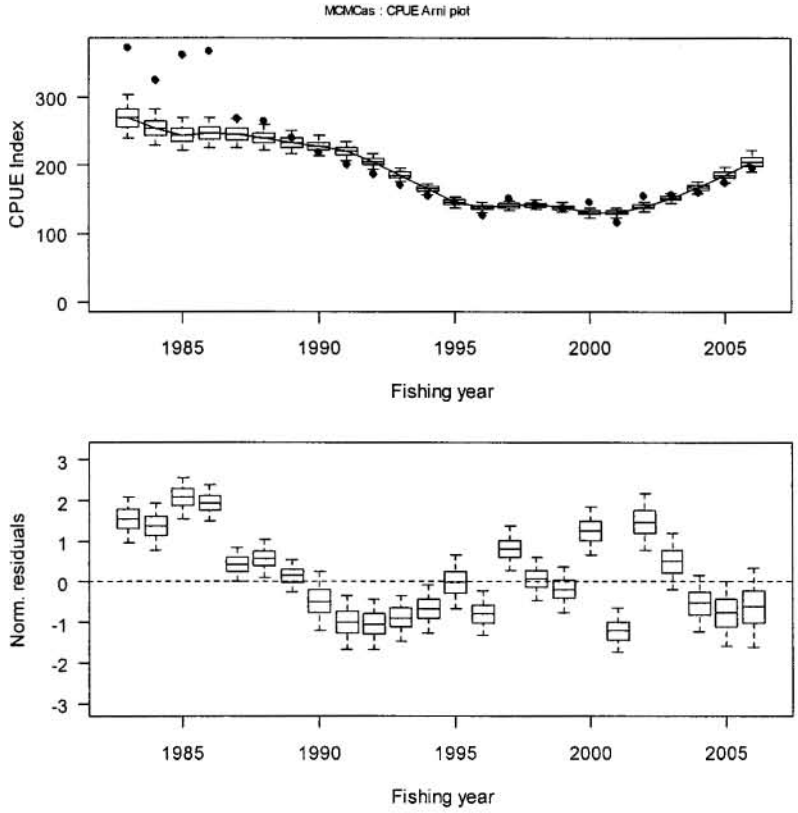


Figure 28: The posterior distributions of the fits to CPUE data (top) and the posterior distributions of the normalised residuals from the base case McMC for PAU 5B. In the upper plot, black dots show the observations. For each year, the figure shows the median of the posterior distribution (horizontal bar), the 25th and 75th percentiles (box) and 5th and 95th percentiles of the posterior.

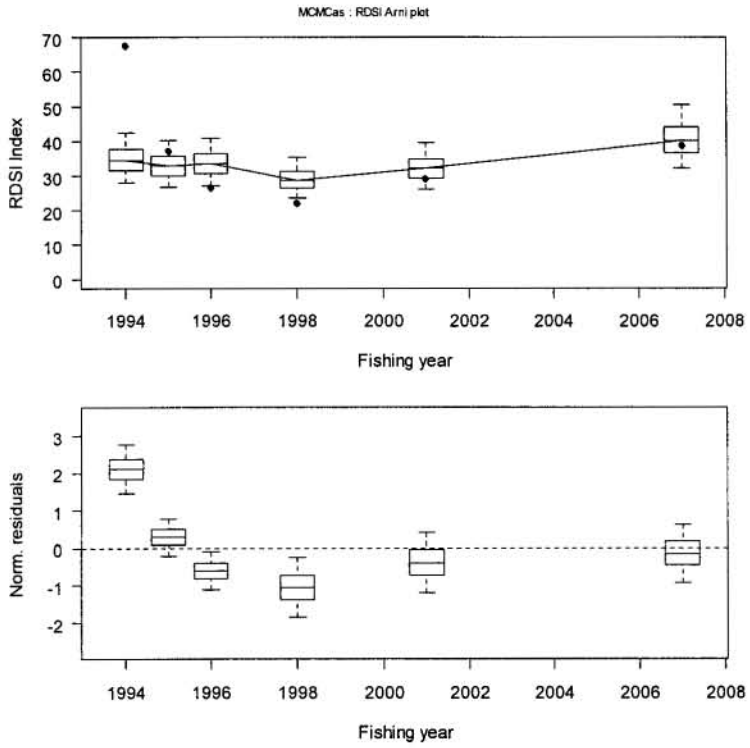


Figure 29: The posterior distributions of the fits to RDSI data (top) and the posterior distributions of the normalised residuals from the base case McMC for PAU 5B.

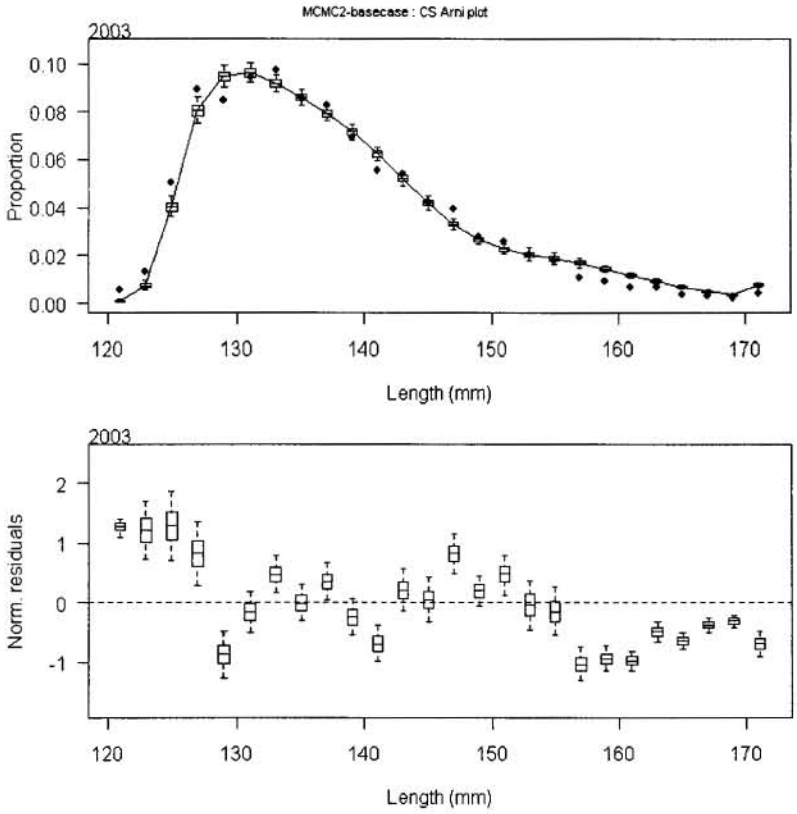


Figure 30: The posterior distribution of the base case McMC fit to the CSLF data from 2002 (top) and the posterior distributions of the normalised residuals.

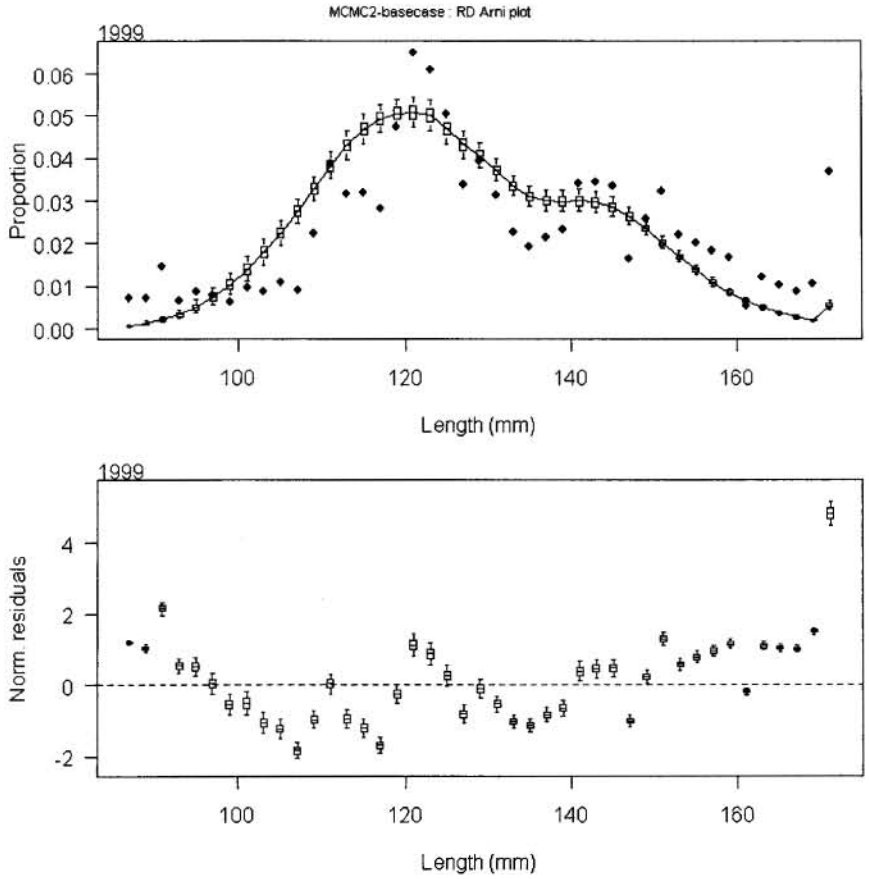


Figure 31: The posterior distribution of the base case McMC fit to the RDLF data from 1995 (top) and the posterior distributions of the normalised residuals.

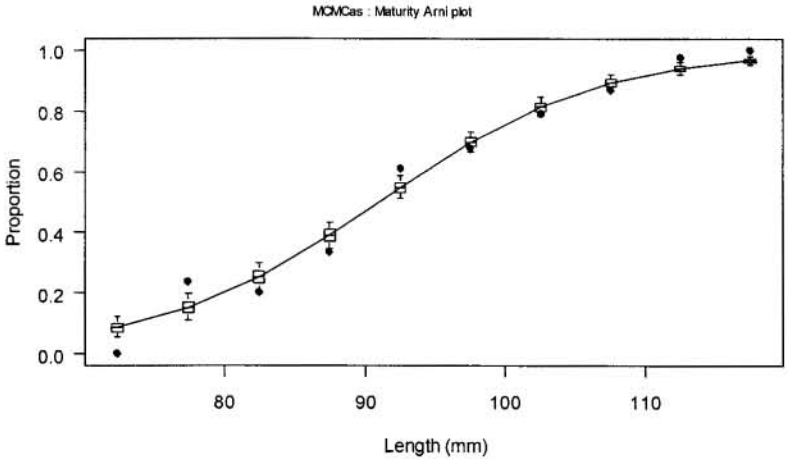


Figure 32: The posterior distribution of the base case McMC fit to maturity-at-length for PAU 5B. Dots show the observations and the box plots summarise the posterior as in previous captions.

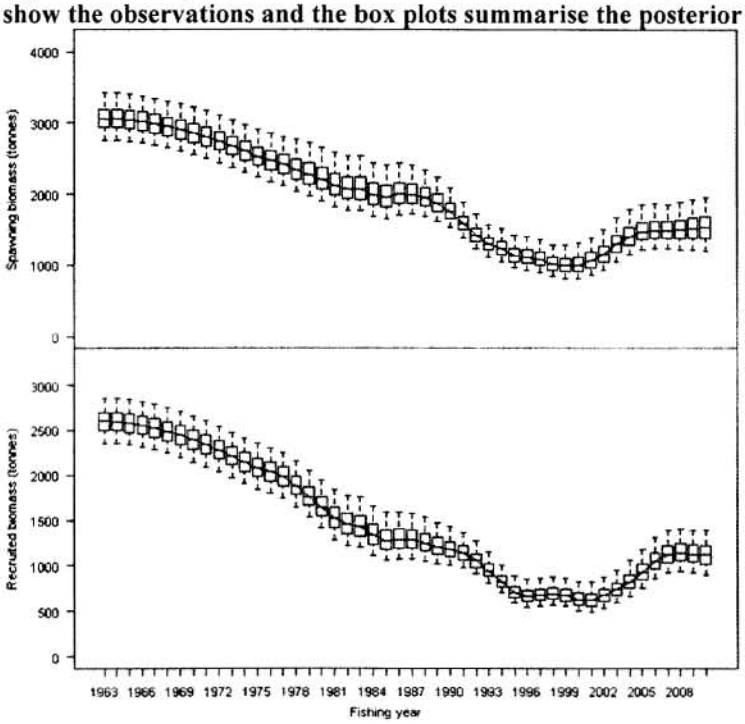


Figure 33: Posterior distributions for the spawning and recruited biomass trajectories. The box plots show, for the distribution for each year, the median, 25th-75% range and the 5%-95% range.

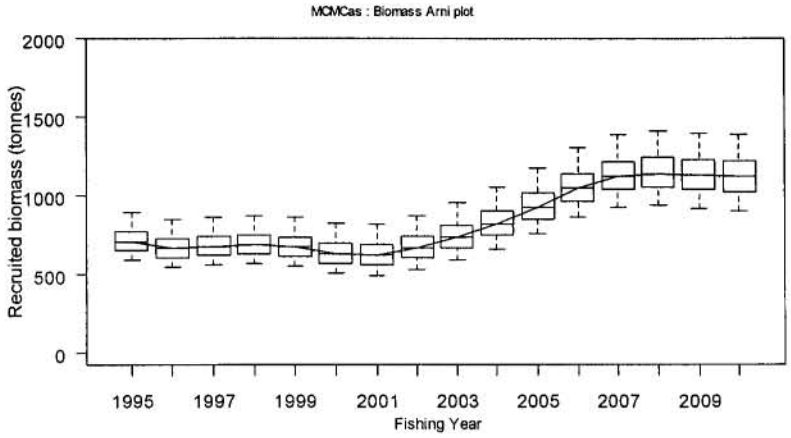


Figure 34: The posterior distribution of the base case McMC recruited biomass trajectory from 1995 onwards.

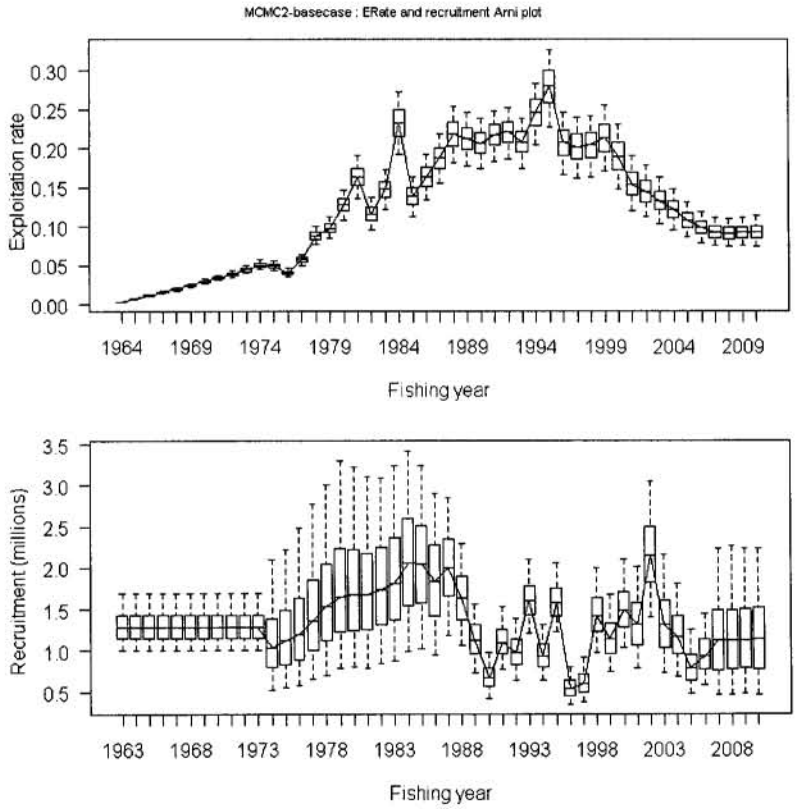


Figure 35: Posteriors of the exploitation rate (upper) and recruitment trajectories.

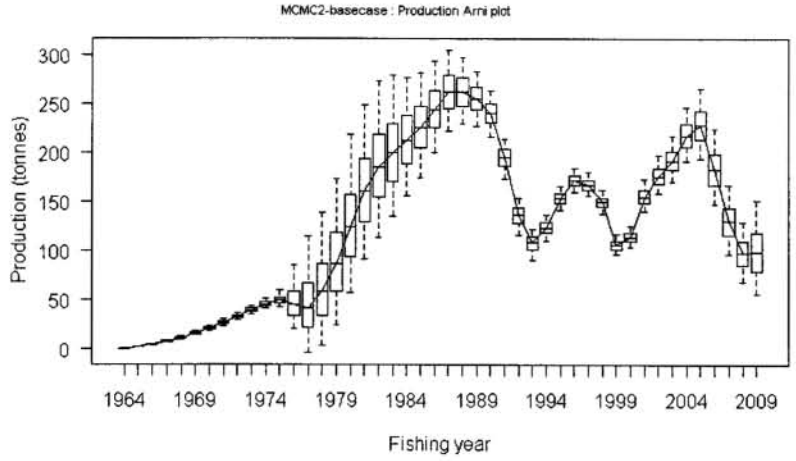


Figure 36: The posterior trajectory of estimated surplus production from the base case McMC for PAU 5B.

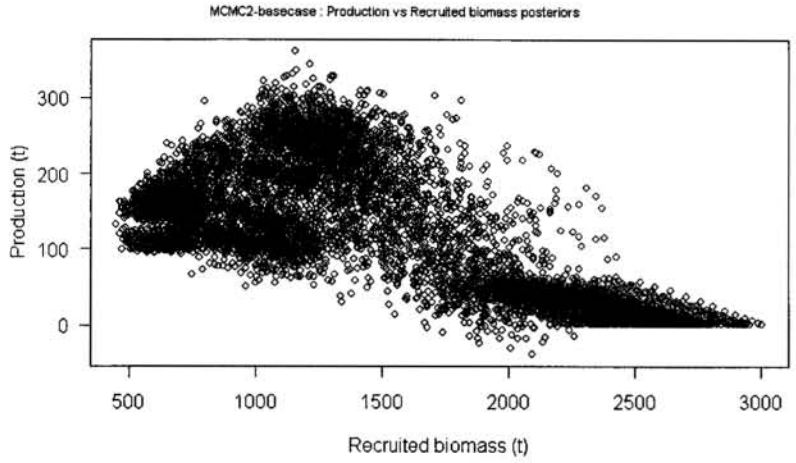


Figure 37: Surplus production plotted against mid-year recruited biomass from the base case McMC for PAU 5B. Each point represents one year in one sample from the joint posterior distribution. For this plot, samples were uniformly thinned from the total sample.

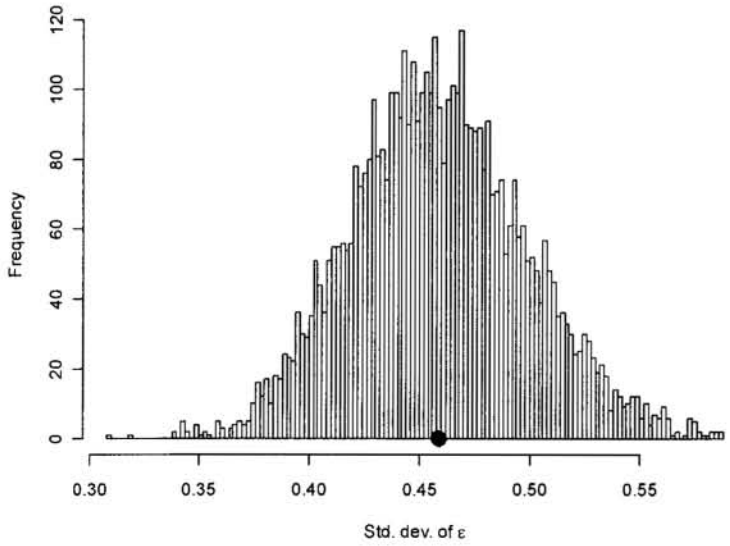


Figure 38: Marginal posterior distribution of the standard deviation of recruitment residuals.

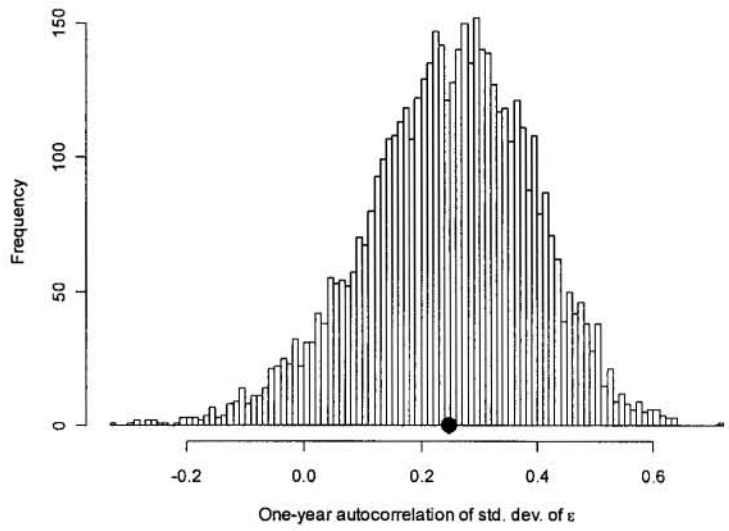


Figure 39: Marginal posterior distribution of the one-year autocorrelation in recruitment residuals.

6.4 Parameter correlations

Correlations among parameter posteriors distributions are shown in Table 11.
Of 1035 correlations, only 10 were greater than 0.50 in absolute value. The recruitment scale parameter was correlated with *M* (0.89) and negatively with *gBeta* and the RDSI catchability parameter. *gBeta* was correlated with the RDSI catchability parameter. The CPUE catchability was perfectly negatively correlated with the *CPUEpow* parameter.

Recruitment deviations were negatively correlated in four adjacent-year pairs from 1984–85 through 1987–88.

Overall, this is a low number of strong correlations among parameters. The interaction between *M* and recruitment is common and in previous assessments has been stronger than was seen here. For the rock lobster model (Breen, Kim & Fournier, unpub. data), re-parameterisation of *M* removed the correlation but changed nothing else. The strong correlation between CPUE catchability and *CPUEpow* suggests a bad parameterisation.

Table 11: Correlations among estimated parameters in the McMC base case posterior distributions. Absolute values greater than 0.50 are highlit. Some columns and rows have been omitted so as to show all highlighted correlations.

	f	ln(*R0*)	*M*	*galpha*	*gBeta*	*CS50*	*CS95*	*GCV*	qCPUE	qRDSI	1982	1983	1984	1985	1986	1987	1988	1989	1990
f	1.00																		
ln(*R0*)	0.06	1.00																	
M	0.05	0.89	1.00																
galpha	-0.10	0.19	0.23	1.00															
gBeta	-0.17	-0.50	-0.24	0.02	1.00														
S50CSLF	0.00	-0.05	-0.02	-0.18	0.10	1.00													
S95CSLF	0.03	-0.01	-0.01	-0.08	0.02	0.53	1.00												
GrowthCV	0.31	-0.02	-0.03	-0.42	-0.15	0.02	0.00	1.00											
qCPUE	-0.06	-0.44	-0.34	-0.11	0.50	0.12	0.05	0.02	1.00										
qRDSI	-0.08	-0.58	-0.47	-0.11	0.58	0.06	0.02	0.03	0.42	1.00									
CPUEpow	0.05	0.40	0.31	0.09	-0.46	-0.12	-0.05	-0.02	-1.00	-0.39									
Rdev1982	-0.06	-0.13	-0.10	-0.06	0.02	0.03	-0.01	-0.01	0.01	0.04	1.00								
Rdev1983	0.00	-0.13	-0.09	-0.07	-0.01	-0.01	0.00	0.04	0.04	0.05	-0.39	1.00							
Rdev1984	-0.02	-0.15	-0.12	-0.05	0.03	-0.01	0.00	0.01	0.05	0.06	-0.04	-0.49	1.00						
Rdev1985	-0.06	-0.22	-0.16	-0.05	0.13	0.03	0.01	-0.02	0.09	0.12	0.16	0.08	-0.52	1.00					
Rdev1986	0.00	-0.17	-0.12	-0.08	0.08	0.00	-0.01	0.04	0.06	0.10	0.00	0.15	0.14	-0.56	1.00				
Rdev1987	-0.03	-0.29	-0.21	-0.06	0.14	-0.03	-0.04	0.00	0.09	0.14	0.03	-0.02	0.15	0.29	-0.60	1.00			
Rdev1988	-0.01	-0.30	-0.19	-0.01	0.22	0.03	0.03	0.08	0.17	0.20	0.05	0.05	-0.03	0.06	0.41	-0.57	1.00		
Rdev1989	-0.11	-0.37	-0.22	0.09	0.37	0.02	0.00	-0.23	0.17	0.24	0.06	0.04	0.08	0.08	-0.02	0.44	-0.45	1.00	
Rdev1990	-0.03	-0.25	-0.19	-0.01	0.13	0.04	0.02	0.02	0.08	0.14	0.03	0.02	0.06	0.06	0.07	0.04	0.30	-0.37	1.00

7. PAU 5B ASSESSMENT

The assessment is based on the marginal posterior distributions of agreed indicators that include values from projections, using the 2007 catch levels. All the relevant values are shown in Table 10.

The assessment suggests that the spawning biomass reference points are: *Smin* near 1000 t, *Sav* about twice that, current spawning biomass near 1500 t, halfway between *Smin* and *Sav*, and projected spawning biomass *S10* roughly the same as current spawning biomass. The uncertainty associated with these estimates is tractable, although substantial: for all biomass indicators, the range between the 5th and 95th quantiles is near 40% of the median.

For recruited biomass, the assessment suggests that *Bmin* is just over 600 t, *Bav* again is about twice that, current biomass is just over 1100 t. Thus current biomass has a median of 87% of *Bav* (5th to 95th quantile range of 77% to 100%) and is well above *Bmin*. Projected recruited biomass is similar.

The results suggest that current exploitation rate is just over 9% (7.5% to 11%) and that projected exploitation rate is the same.

The probability indicators, comparing projected and reference levels, suggest that for spawning biomass, there is a 40% chance of decreasing spawning biomass over the next three years at current catch levels, and a high (98%) chance that projected biomass will remain below *Sav*. Recruited biomass shows a greater than 50% chance of decrease and a 90% chance of remaining below *Bav*. However, both the spawning and recruited biomass projections show no chance of the biomass falling below minimum reference levels.

8. MCMC SENSITIVITY TRIAL USING THE RAW DATA

An McMC sensitivity trial was undertaken in which, in place of standardised abundance indices and weighted length frequency datasets, raw CPUE and RDSI indices (calculated as the means of all records for each year) and the raw CSLF and RDLF datasets were used. Differences in the raw and standardised indices, and the raw and weighted length frequency datasets, were shown in the data documents.

The sensitivity trial otherwise used the base case datafile, and the simulation procedures were identical to those used for the base case.

The parameter estimates and indicators are summarised in Table 12. Parameter estimates differed but slightly. Biomass estimates were slightly larger in the sensitivity trial and exploitation rate was lower; biomass ratio indicators and probability indicators were all slightly less optimistic in the sensitivity trial. These differences were not very great.

The recruited biomass and recruitment trajectories from these two trials are compared in Figure 39 and Figure 40.

Table 12: Comparison of results from the McMC base case and sensitivity trial.

	Base case			Sensitivity		
	5%	Median	95%	5%	Median	95%
ln(*R0*)	13.83	14.06	14.34	13.83	14.09	14.39
M	0.125	0.141	0.160	0.123	0.138	0.156
galpha	24.84	26.07	27.24	26.64	27.91	29.17
gBeta	6.448	6.905	7.342	6.218	6.693	7.150
S50CSLF	124.93	125.11	125.29	124.72	124.89	125.06
S95CSLF	2.333	2.729	3.169	2.113	2.474	2.874
Mat50	89.71	90.97	92.15	89.68	90.99	92.18
Mat95	19.97	23.05	26.41	20.04	23.02	26.45
GrowthCV	0.319	0.357	0.400	0.336	0.376	0.419
qCPUE	-9.86	-7.00	-4.54	-10.56	-6.81	-3.84
qRDSI	-11.98	-11.68	-11.42	-12.20	-11.86	-11.57
CPUEpow	0.712	0.888	1.085	0.647	0.855	1.111
ERate07	0.076	0.093	0.111	0.063	0.081	0.101
ERate10	0.075	0.093	0.114	0.064	0.083	0.105
Smin	807.17	992.68	1276.63	952.97	1219.98	1638.49
Sav	1688.25	1982.02	2409.37	1879.56	2255.94	2814.82
S07	1224.34	1487.69	1853.04	1306.99	1645.12	2130.14
S08	1222.27	1498.64	1879.41	1293.52	1652.25	2140.02
S09	1214.38	1512.30	1916.36	1285.69	1658.83	2167.30
S10	1199.54	1528.17	1954.05	1281.26	1665.99	2198.35
Bmin	495.35	622.44	817.85	652.11	842.54	1141.24
Bav	1073.09	1280.51	1580.47	1283.43	1566.38	1985.76
B07	924.13	1119.59	1386.18	1023.69	1283.67	1662.44
B08	937.70	1140.34	1408.21	1019.09	1285.03	1658.13
B09	921.08	1129.41	1392.54	998.33	1269.27	1636.25
B10	905.44	1120.06	1389.93	979.22	1259.06	1631.23
S07/Sav	0.663	0.751	0.849	0.640	0.729	0.823
S07/Smin	1.333	1.493	1.682	1.210	1.339	1.501
S10/Sav	0.633	0.769	0.923	0.609	0.737	0.881
S10/Smin	1.265	1.530	1.842	1.139	1.356	1.616
S10/S07	0.904	1.021	1.160	0.900	1.011	1.133
B07/Bav	0.768	0.873	0.997	0.719	0.818	0.928
B07/Bmin	1.596	1.791	2.032	1.369	1.512	1.695
B10/Bav	0.730	0.871	1.039	0.671	0.801	0.947
B10/Bmin	1.503	1.783	2.143	1.273	1.479	1.741
B10/B07	0.917	0.995	1.084	0.907	0.978	1.060
S10<S07	-	38.8%	-	-	43.7%	-
S10<Sav	-	98.9%	-	-	99.8%	-
B10<B07	-	53.5%	-	-	67.5%	-
B10<Bav	-	90.2%	-	-	98.2%	-
S10<Smin	-	0.0%	-	-	0.1%	-
B10<Bmin	-	0.0%	-	-	0.0%	-

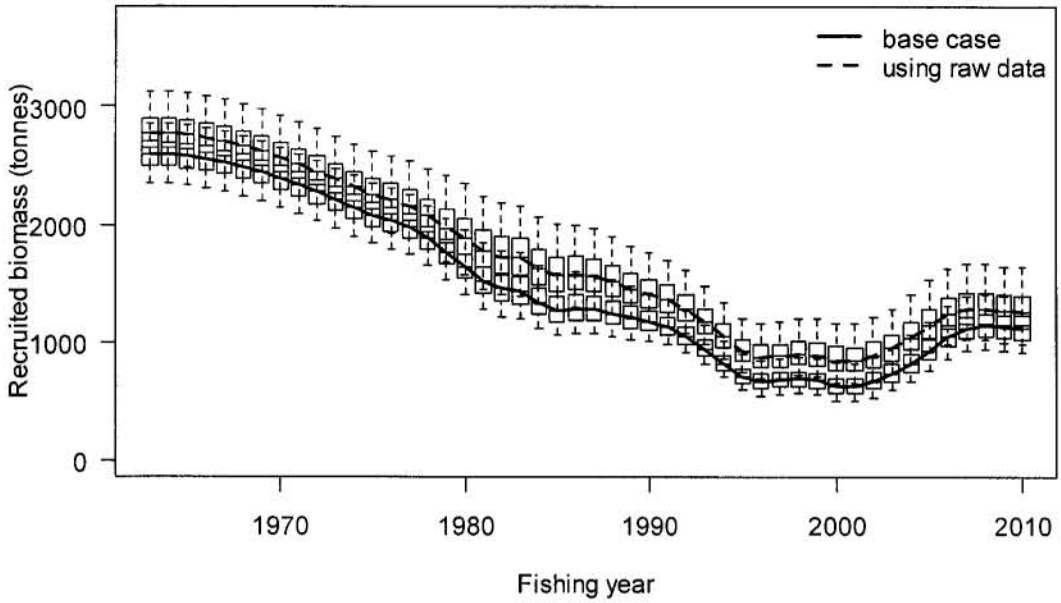


Figure 40: Comparison of the recruited biomass trajectories from the base case (solid line) McMC and the sensitivity trial (dashed line).

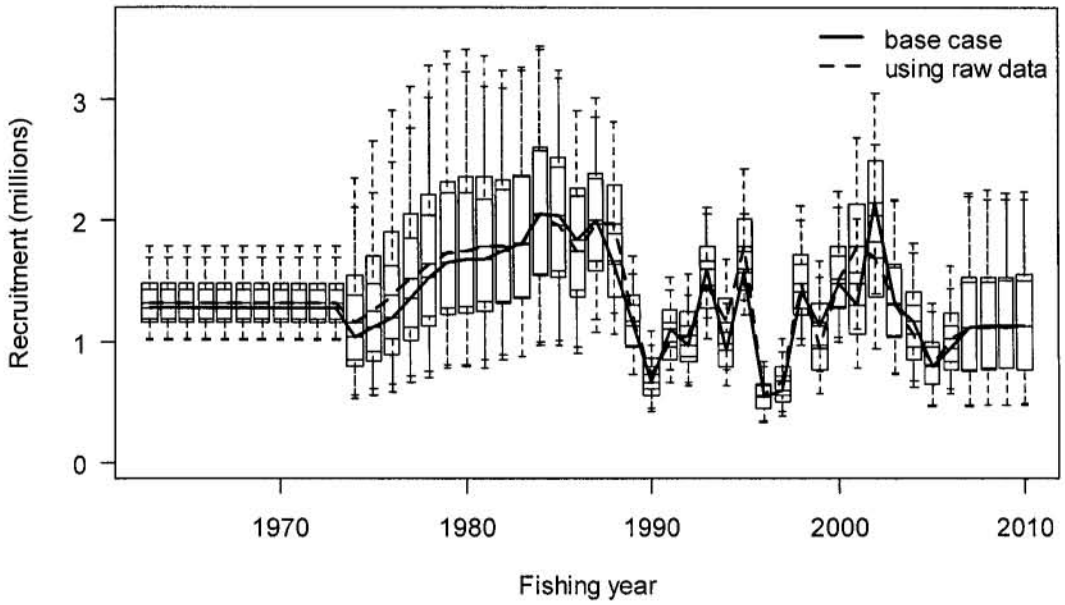


Figure 41: Comparison of the recruitment trajectories from the base case (solid line) McMC and the sensitivity trial (dashed line).

9. DISCUSSION

9.1 Model fit

The model fit the data reasonably well without much difficulty: exploratory runs showed little problem with the Hessian matrix and iterative re-weighting of datasets led to a fit in which the sdnrs were all close to 1. In this fit, the parameter estimates were all reasonable (except that research diver selectivity was fixed to avoid a problem) and the visual fits to data were acceptable, with RDSI showing the worst fit.

The sensitivity trials demonstrated that the tag data set was essential to obtaining a reasonable fit; the growth signal from the length frequency data alone did not allow a realistic fit. Apart from this, the trials suggested no undue influence of any of the other data sets.

Uncertainty about the catch data is moderate because of the change in stock definition in 1996 and the overlap of statistical areas. When this was explored with the alternatives presented by Kendrick & Andrew (2000), the alternative series, which both had less commercial catch in 1984 through 1994 than in the base case, gave ratio indicators involving target biomass references that were more optimistic when compared with the base case. *B07/Bmin* was 88% in the base case, but 97% in the two alternative catch trials.

The McMC results appeared to be acceptable, with good diagnostics and few correlations among parameters. They showed slightly higher biomass estimates than the MPD, but the biomass ratio indicators were not greatly different. Sensitivity of the McMC results to the various standardisation and weighting procedures used on the abundance index and length frequency data showed that their influence was small.

9.2 Stock assessment

The assessment suggests, first, that current biomass is well above minimum reference levels. This was true in all MPD sensitivity trials and in both McMCs. Second, projected biomass is highly likely to remain above these reference levels. In the McMC projections, there were no runs in the base case, and no more than 0.1% of runs in the sensitivity trial, where biomass fell below *Bmin* or *Smin*.

The assessment suggests that both spawning and recruited biomass are below the target levels based on the 1985–87 reference period agreed by the SFWG. Spawning biomass is estimated at 75% of *Sav*, (66% to 85%) while recruited biomass is estimated as 87% of *Bav* (77% to 100%).

For recruited biomass, however, it cannot be concluded strongly that current biomass is less than reference level. The posterior touches 100% at the 95% confidence level. MPD sensitivity trials showed *B07/Bav* near 100% in several situations: when the CPUE dataset was removed, when the pre-1990 CPUE data were removed, when the Bentley likelihood was used for length frequencies (this result may have stemmed from altered data weighting), and when the lower-catch alternative series were used. These results show that current biomass is uncertain with respect to *Bav*: it may be 70% to 85% of *Bav*, or it may be much closer to *Bav*, perhaps even above.

McMC projections from the base case and sensitivity trial suggest that spawning biomass is more likely (61% or 56%) to increase than decrease, and that spawning biomass is likely to remain below *Sav*. Recruited biomass shows a tendency to decrease (64% or 68%) and remain (this is tempered by the observations above) below *Bav*.

9.3 Cautionary notes

9.3.1 The McMC process underestimates uncertainty

The sensitivity trials described above illustrate that the variation in results among the various McMC trials can be much higher than variability within an McMC trial. The main sensitivities identified were the catch series, early CPUE data and data weighting issues.

9.3.2 The data are not completely accurate

The commercial catch before 1974 is unknown and differences may exist between the catches we assume and what was taken. In addition, non-commercial catch estimates are poorly determined and could be substantially different from what was assumed by the SFWG, although non-commercial catches appear to be generally small compared with commercial catch. The illegal catch is particularly suspect.

The tagging data may not reflect fully the average growth and range of growth in this population. Length frequency data collected from the commercial catch may not represent the commercial catch with high precision. The research diver data comprise six surveys, for some of which the standard errors are quite large, and length frequencies may not be fully representative of the population.

9.3.3 The model is homogeneous

The model treats the paua stocks as if they were single stocks with homogeneous biology, habitat and fishing pressures. The model assumes spatial homogeneity in recruitment, spatial and temporal homogeneity in natural mortality, and assumes that growth has the same mean and variance in all places and all years (we know this is violated because some areas are stunted and some are fast-growing).

To what extent does a homogenous model make biased predictions about a heterogeneous stock? Heterogeneity in growth can be a problem for this kind of model (Punt 2003). Variation in growth is addressed to some extent by having a stochastic growth transition matrix based on increments observed in several different places; similarly the length frequency data are integrated across samples from many places.

The effect is likely to make model results optimistic. For instance, if some local stocks are fished very hard and others not fished, recruitment failure can result because of the depletion of spawners, because spawners must breed close to each other and because the dispersal of larvae is unknown and may be limited. Recruitment failure is a common observation in overseas abalone fisheries. So local processes may decrease recruitment, which is an effect that the current model cannot account for.

9.3.4 The model assumptions may be violated

One suspect assumption made by the model is that CPUE is an index of abundance. There is a large abalone literature that suggests CPUE is difficult to use in abalone stock assessments because of serial depletion, which happens when fishers deplete unfished or lightly fished beds and maintain their catch rates: CPUE stays high while the biomass is actually

decreasing. Even when CPUE is not fitted by the model, if serial depletion is occurring, the model does not model serial depletion.

Another source of uncertainty is that fishing may cause spatial contraction of populations (e.g., Shepherd & Partington 1995), or that some populations become relatively unproductive after initial fishing (Gorfine & Dixon 2000). If this happens, the model will overestimate productivity in the population as a whole. Past recruitments estimated by the model might instead have been the result of serial depletion.

10. ACKNOWLEDGEMENTS

This work was conducted under MFish contract PAU2006-03. We are grateful to Reyn Naylor and Pete Notman for providing datasets they collected and working with us to collate them, Peter Todd for non-commercial catch estimates, and the Shellfish Working Group.

11. REFERENCES

Breen, P.A.; Andrew, N.L.; Kendrick T.H. (2000). Stock assessment of paua (*Haliotis iris*) in PAU 5B and PAU 5D using a new length-based model. *New Zealand Fisheries Assessment Report 2000/33*. 22 p.

Breen, P.A.; Kim, S.W. (2005). The 2005 stock assessment of paua (*Haliotis iris*) in PAU 7. *New Zealand Fisheries Assessment Report 2005/47*. 114 p.

Breen, P.A.; Kim, S.W. (2007). The 2006 assessments for paua (*Haliotis iris*) stocks PAU 5A (Fiordland) and PAU 5D (Otago). *New Zealand Fisheries Assessment Report 2007/9*. 164 p.

Breen, P.A.; Kim, S.W.; Andrew, N.L. (2003). A length-based Bayesian stock assessment model for the New Zealand abalone *Haliotis iris*. *Marine and Freshwater Research 54*: 619–634.

Breen, P.A., Kim, S.W.; Haist, V.; Starr, P.J. (2006). The 2005 stock assessment of red rock lobsters (*Jasus edwardsii*) in CRA 4. *New Zealand Fisheries Assessment Report 2006/17*. 133 p.

Breen, P.A.; Smith, A.N.H. (2008). The 2007 assessment for paua (*Haliotis iris*) stock PAU 5B (Stewart Island). *New Zealand Fisheries Assessment Report 2008/6*. 45 p.

Kendrick, T.H.; Andrew, N.L. (2000). Catch and effort statistics and a summary of standardised CPUE indices for paua (*Haliotis iris*) in PAU 5A, 5B, and 5D. New Zealand Fisheries Assessment Report 2000/47. 25 p.

Gorfine, H.K.; Dixon, C.D. (2000). A behavioural rather than resource-focused approach may be needed to ensure sustainability of quota managed abalone fisheries. *Journal of Shellfish Research 19*: 515–516.

Punt, A.E. (2003). The performance of a size-structured stock assessment method in the face of spatial heterogeneity in growth. *Fisheries Research 65:* 391–409.

Shepherd, S.A.;Partington, D. (1995). Studies on Southern Australian abalone (genus *Haliotis*). XVI. Recruitment, habitat and stock relations. *Marine and Freshwater Research 46:* 669–680.