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EXECUTIVE SUMMARY

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A revised length-based model was used to assess the PAU 5A stock of paua (abalone) (*Haliotis iris*). The assessment used Bayesian techniques to estimate model parameters, the state of the stock, future states of the stock and their uncertainties. The assessment was based on marginal posterior distributions generated from Markov chain-Monte Carlo simulations (McMC).

The 2003 assessment model was reviewed by Andre Punt in December 2003 and then was revised by making the growth model more general, reverting to calculating one of the catchability coefficients as a nuisance parameter, re-parameterising recruitment to avoid high correlation with natural mortality and making a number of minor changes. A full description of the revised model is provided.

The model was applied to five datasets from PAU 5A: standardised CPUE, a standardised index of relative abundance from research diver surveys, proportions-at-length from commercial catch sampling and population surveys, and tag-recapture data. Maturity data were too sparse to permit of maturity parameter estimation.

Data were relatively limited in this assessment, and importantly there were but two data from the research diver survey index (RDSI). These RDSI data were antagonistic in their effects to the CPUE data and it was comparatively difficult to find a workable base case.

Once a base case was found, the marginal posterior distributions of interest appeared to be converged. Sensitivity analyses confirmed the effects of conflict between the RDSI and CPUE data, and showed that assessment modelling was also dependent on the tag and commercial length frequency data sets. Retrospective analyses were reasonably stable until three years of data had been removed, but they underscored the paucity of data.

The assessment results suggest that current catch is not sustainable: at the current level of catch the stock is certain to decline over the next years, assuming that annual recruitment is within its recent estimated range. The assessment may be too optimistic: possible mechanisms causing such a result are discussed.

CONTENTS

1. INTRODUCTION

1.1 Overview

This document presents a Bayesian stock assessment of blackfoot paua (abalone) (*Haliotis iris*) in PAU 5A (Fiordland) using data to the end of 2002–03 and some data from the 2003–04 fishing season. The assessment is made with a further revision of the length-based model first used in 1999 for PAU 5B (Breen et al. 2000a) and revised for subsequent assessments in PAU 5B (Stewart Island) and PAU 7 (Andrew et al. 2000a, Breen et al. 2000b, 2001, Breen & Kim 2003). This model is driven by estimated commercial catches from 1974 to 2003 and is fitted to five sets of data described below: standardised CPUE, a standardised research diver survey index (RDSI) based on work described for other areas by Andrew et al. (2000b, 2002), proportion-at-length data from commercial catch sampling (CSLF), proportion-at-length data from research diver surveys (RDLF) (Andrew et al. 2000a) and a set of growth increment data.

This document contains a full description of the current model and describes the datasets used in the assessment, assumptions made in fitting and the basic fit of the model to the data in sensitivity trials and projections. The assessment is based on posterior distributions of model and derived parameters obtained from Markov chain-Monte Carlo (McMC) simulations. Diagnostics from these are discussed and results are summarised.

1.2 Description of the fishery

The New Zealand paua fishery was summarised by Schiel (1992), Annala et al. (2003) and in numerous previous assessment documents (e.g., Schiel 1989, Breen et al. 2000a, 2000b, 2001, Breen & Kim 2003).

The fishing year for paua is from 1 October to 30 September. In what follows we refer to fishing year by the second portion; viz. the 1997–98 fishing year is called "1998".

2. MODEL

This section describes the model used for stock assessment of PAU 5A in 2004. The model was originally developed for use in PAU 5B in 1999 and has been revised each year for subsequent assessments, in many cases echoing changes made to the rock lobster assessment model (Kim et al. 2004), which is a similar but more complex length-based Bayesian model. Some changes in 2004 were made in response to an external review by Dr. Andre Punt, University of Washington, in December 2003.

2.1 Changes to the 2003 assessment model

Revised equations are provided when the model is described below.

2.1.1 Plus group

Previous models used a plus group near the largest size observed in the data. In his review Dr. Punt suggested that the virgin population may have substantial numbers above this size, thus that these models underestimate *B0*. We altered the dynamics so that the model keeps track of paua up to a size well above the maximum observed, and calculates a plus-group proportion-at-size for comparison with the data.

2.1.2 Growth model

The growth model was made more general, as in the rock lobster model (Kim et al. 2004). This change has no effect on model estimates unless the shape parameter is estimated.

2.1.3 Estimated *qs*

In assessments before 2003, catchability coefficients were treated as nuisance parameters and were calculated as the weighted geometric mean of the ratios of observed and predicted CPUE and RDSI annual estimates obtained from the observed abundance estimates. In 2004 we estimated the logarithms of catchability coefficients as simple parameters: q^I for CPUE and q^J for RDSI. However, for PAU 5A there was a very large correlation between these two parameters, and we reverted to the use of a nuisance parameter for q^J.

2.1.4 Recruitment parameterisation

In runs leading to the choice of a final base case, we observed very high correlations ($r = 0.98$) between the natural log of base recruitment, ln(*R0*) and *M*. To remedy this, for PAU 5A we reparameterised the former, defining a new parameter *z* and calculating ln(*R0*):

$$\ln(R0) = zM^{0.9687}$$

where the exponent and the initial value (15.5) for *z* were determined from analysis of a preliminary McMC posterior from PAU 5A (Figure 1).

2.1.5 Catch and biomass units

We incorporated a suggestion from D.A. Fournier (Otter Research, pers. comm.) and normalised observed catches:

$$C'_t = \frac{C_t}{\sum_t C_t / n_C}$$

where n_C is the number of years of catch. Because the model is driven by catch, the model's biomass is now calculated in units of mean catch and recruitment is scaled commensurately. The true biomass and recruitment are recovered from model biomass for output using the mean catch:

$$B_t = B'_t \sum_t C_t / n_C$$

2.2 Model description

The model (BLEPSAM: Bayesian Length-based Paua Stock Assessment Model) does not use age; instead it uses a number of length bins (55 in this assessment), each of 2 mm shell length. The left-hand edge of the first bin is 71 mm (this was changed from 70 mm in previous assessments so that the MLS of 125 mm falls between two bins rather than in the centre of a bin); the largest bin is well above the maximum size observed and a plus-group is calculated from the bins of abalone 171 mm and larger. 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 6.2.1, compiled with the Borland 5.01 compiler.

2.2.1 Estimated parameters

Parameters estimated by the model are as follows. The whole parameter vector is referred to as θ.

z	parameter relating $\ln(R0)$ to M
M	instantaneous rate of natural mortality
g_α	expected annual growth increment at length α
g_β	expected annual growth increment at length β
δ	shape of the relation between growth increment and initial length
ϕ	c.v. of the expected growth increment
q^I	scalar between recruited biomass and CPUE
L_{50}	length at which maturity is 50%
L_{95-50}	distance between L_{50} and L_{95}
T_{50}	length at which research diver selectivity is 50%
T_{95-50}	distance between T_{50} and T_{95}
D_{50}	length at which commercial diver selectivity is 50%
D_{95-50}	distance between D_{50} and D_{95}
$\tilde{\sigma}$	common component of error
h	shape of CPUE *vs* biomass relation
ε	vector of annual recruitment deviations

2.2.2 Constants

l_k	length of an abalone at the midpoint of the *k*th length class (l_k for class 1 is 72 mm, for class 2 is 74 mm and so on)
σ_{MIN}	minimum standard deviation of the expected growth increment
σ_{obs}	standard deviation of the observation error around the growth increment
MLS_t	minimum legal size
$P_{k,t}$	a switch based on whether abalone in the *k*th length class in year *t* are above the MLS ($P_{k,t} = 1$) or below ($P_{k,t} = 0$)

a,b	constants for the length-weight relation, taken from Schiel & Breen (1991)
w_k	the weight of an abalone at length l_k
ϖ^I	relative weight assigned to the CPUE dataset. This and the following relative weights are specified in the data file, but can be varied between runs
ϖ^J	relative weight assigned to the RDSI dataset
ϖ^r	relative weight assigned to RDLF dataset
ϖ^s	relative weight assigned to CSLF dataset
ϖ^{mat}	relative weight assigned to maturity-at-length data
κ_t^s	normalised square root of the number measured greater than the MLS in CSLF records for each year, normalised by the lowest year
κ_t^r	normalised square root of the number measured greater than 90 mm in RDLF records for each year, normalised by the lowest year
$U^{\max}$	exploitation rate above which a limiting function was invoked
μ_M	mean of the prior distribution for M, based on a literature review by Shepherd & Breen (1992)
σ_M	assumed standard deviation of the prior distribution for M
σ_ε	assumed standard deviation of recruitment deviations in log space (part of the prior for recruitment deviations)
n_ε	number of recruitment deviations
α	length associated with g_α
β	length associated with g_β

2.2.3 Observations

C_t	observed catch in year t after normalisation
I_t	standardised CPUE in year t
σ_t^I	standard deviation of the estimate of observed CPUE in year t, obtained from the standardisation model
J_t	standardised RDSI in year t
σ_t^J	the standard deviation of the estimate of RDSI in year t, obtained from the standardisation model
$p_{k,t}^r$	observed proportion in the kth length class in year t in RDLF
$p_{k,t}^s$	observed proportion in the kth length class in year t in CSLF
l_j	initial length for the jth tag-recapture record
d_j	observed length increment of the jth tag-recapture record
Δt_j	time at liberty for the jth tag-recapture record
p_k^{mat}	observed proportion mature in the kth length class in the maturity dataset

2.2.4 Derived variables

$R0$	base number of annual recruits
q^J	scalar between model numbers and the RDSI
$N_{k,t}$	number of abalone in the *k*th length class at the start of year *t*
$N_{k,t+0.5}$	number of abalone in the *k*th length class in the mid-season of year *t*
$R_{k,t}$	recruits to the model in the *k*th length class in year *t*
g_k	expected annual growth increment for abalone in the *k*th length class
σ^{g_k}	standard deviation of the expected growth increment for abalone in the *k*th length class, used in calculating **G**
G	growth transition matrix
B_t	biomass of abalone available to the commercial fishery at the beginning of year *t*
$B_{t+0.5}$	biomass of abalone above the MLS in the mid-season of year *t*
$S_{t+0.5}$	biomass of mature abalone in the mid-season of year *t*
U_t	exploitation rate in year *t*
A_t	the complement of exploitation rate
$SF_{k,t}$	finite rate of survival from fishing for abalone in the *k*th length class in year *t*
V_k^r	relative selectivity of research divers for abalone in the *k*th length class
V_k^s	relative selectivity of commercial divers for abalone in the *k*th length class
$\sigma_{k,t}^r$	error of the predicted proportion in the *k*th length class in year *t* in RDLF data
$\sigma_{k,t}^s$	error of the predicted proportion in the *k*th length class in year *t* in CSLF data
σ_j^d	standard deviation of the predicted length increment for the *j*th tag-recapture record
σ_j^{tag}	total error predicted for the *j*th tag-recapture record
σ_k^{mat}	error of the proportion mature-at-length for the *k*th length class
$-\ln(\mathbf{L})$	negative log-likelihood
f	total function value

2.2.5 Predictions

$\hat{I}_t$	predicted CPUE in year *t*
$\hat{J}_t$	predicted RDSI in year *t*
$\hat{p}_{k,t}^r$	predicted proportion in the *k*th length class in year *t* in research diver surveys
$\hat{p}_{k,t}^s$	predicted proportion in the *k*th length class in year *t* in commercial catch sampling
$\hat{d}_j$	predicted length increment of the *j*th tag-recapture record
$\hat{p}_k^{mat}$	predicted proportion mature in the *k*th length class

2.2.6 Initial conditions

The initial population is assumed to be in equilibrium with zero fishing mortality and the base recruitment. The model is run for 60 years with no fishing to obtain near-equilibrium in numbers-at-length. Recruitment is evenly divided among the first five length bins:

(1) $\ln(R0) = zM^{0.9687}$

(2) $R_{k,t} = 0.2R0 \qquad \text{for } 1 \le k \le 5$

(3) $R_{k,t} = 0 \qquad \text{for } k > 5$

A growth transition matrix is calculated inside the model from the estimated growth parameters. Two intermediate variables are defined from the estimated growth parameters:

(4) $x = (\beta^{\delta} - \alpha^{\delta}) / \left((\beta + g_{\beta})^{\delta} - (\alpha + g_{\alpha})^{\delta}\right)$ and

(5) $$y = \frac{\left(\beta^{\delta}(\alpha + g_{\alpha})^{\delta} - \alpha^{\delta}(\beta + g_{\beta})^{\delta}\right)}{\left((\alpha + g_{\alpha})^{\delta} - \alpha^{\delta} + \beta^{\delta} - (\beta + g_{\beta})^{\delta}\right)}$$

and then the expected increment g_k for the kth length is

(6) $$g_k = -l_k + \left[\frac{l_k^{\delta}}{x} + y\left(1 - \frac{1}{x}\right)\right]^{(1/\delta)}$$

The model uses the AD ModelBuilder™ function *posfun*, with a dummy penalty, to ensure a positive expected increment at all lengths, using a smooth differentiable function. The standard deviation of g_k is assumed to be proportional to g_k with minimum σ_{MIN}:

(7) $$\sigma^{g_k} = (g_k\phi - \sigma_{MIN})\left(\frac{1}{\pi}\tan^{-1}\left(10^6(g_k\phi - \sigma_{MIN})\right) + 0.5\right) + \sigma_{MIN}$$

From the expected increment and standard deviation for each length class, the probability distribution of growth increments for an abalone of length l_k is calculated from the normal distribution and translated into the vector of probabilities of transition from the kth length bin to other length bins to form the growth transition matrix **G**. Zero and negative growth increments are permitted, i.e. the probability of staying in the same bin or moving to a smaller bin can be non-zero.

In the initialisation, the vector $\mathbf{N}_t$ of numbers-at-length is determined from numbers in the previous year, survival from natural mortality, the growth transition matrix **G** and the vector of recruitment $\mathbf{R}_t$:

(8) $$\mathbf{N}_t = \left(\mathbf{N}_{t-1}e^{-M}\right) \bullet \mathbf{G} + \mathbf{R}_t$$

where the dot (•) denotes matrix multiplication.

2.2.7 Dynamics

2.2.7.1 Sequence of operations

After initialising, the first model year is 1964 and the model is run through 2004. In the first 10 years, the model is run with an assumed catch vector, because it is unrealistic to assume that the fishery was in a virgin state when the first catch data became available in 1974. The assumed catch vector rises linearly from zero to the 1974 catch. These years can be thought of as an additional part of the initialisation, but they use the dynamics described in this section.

Model dynamics are sequenced as follows:

- numbers at the beginning of year t-1 are subjected to fishing, then natural mortality, then growth to produce the numbers at the beginning of year t;
- recruitment is added to the numbers at the beginning of year t;
- biomass available to the fishery is calculated and used with catch to calculate the exploitation rate, which is constrained if necessary; then
- half the exploitation rate (but no natural mortality) is applied to obtain mid-season numbers, from which the predicted abundance indices and proportions-at-length are calculated. Mid-season numbers are not used further.

2.2.7.2 Main dynamics

For each year t, the model calculates the start-of-the-year biomass available to the commercial fishery. Biomass above the MLS at the start of the year is:

$$(9)\qquad B_t = \sum_k N_{k,t} P_{k,t} w_k$$

or, if the commercial selectivity is used instead of the MLS,

$$(10)\qquad B_t = \sum_k N_{k,t} V_k^s w_k$$

where

$$(11)\qquad V_k^s = \frac{1}{1+19^{-\left((l_k - D_{50}) / D_{95-50} \right)}}$$

The observed catch is then used to calculate exploitation rate, constrained for all values above U^{max} with the *posfun* function of AD Model Builder™. If the ratio of catch to available biomass exceeds U^{max}, then exploitation rate is constrained and a penalty is added to the total negative log-likelihood function. Let minimum survival rate A_{min} be 1-U^{max} and survival rate A_t be 1-U_t:

$$(12)\qquad A_t = 1 - \frac{C_t}{B_t} \qquad\qquad \text{for } \frac{C_t}{B_t} \le U^{\max}$$

$$(13) \quad A_t = 0.5A_{\min}\left[1+\left(3-\frac{2\left(1-\frac{C_t}{B_t}\right)}{A_{\min}}\right)^{-1}\right] \quad \text{for } \frac{C_t}{B_t} > U^{\max}$$

The penalty invoked when the exploitation rate exceeds U^{max} is:

$$(14) \quad 1000000\left(A_{\min}-\left(1-\frac{C_t}{B_t}\right)\right)^2$$

In this assessment, this has no effect on the final estimates, but it prevents the model from exploring parameter combinations that give unrealistically high exploitation rates. Survival from fishing is calculated as:

$$(15) \quad SF_{k,t} = 1-(1-A_t)P_{k,t}$$

or

$$(16) \quad SF_{k,t} = 1-(1-A_t)V_k^s$$

The vector of numbers-at-length in year t is calculated from numbers in the previous year:

$$(17) \quad \mathbf{N}_t = \left(\left(\mathbf{SF}_{t-1} \otimes \mathbf{N}_{t-1}\right)e^{-M}\right) \bullet \mathbf{G} + \mathbf{R}_t$$

where $\otimes$ denotes the element-by-element vector product. The vector of recruitment $\mathbf{R}_t$ is determined from $R0$ and the estimated recruitment deviations:

$$(18) \quad R_{k,t} = 0.2R0e^{\left(\varepsilon_t - 0.5\sigma_\varepsilon^2\right)} \qquad \text{for } 1 \le k \le 5$$

$$(19) \quad R_{k,t} = 0 \qquad \text{for } k > 5$$

The recruitment deviation parameters ε_t were estimated for all years after 1973 except the two most recent ones; there was no constraint for deviations to have a of 1 in arithmetic space except for the constraint of the prior, which had a mean of zero in log space, and we assumed no stock-recruit relation.

2.2.8 Model predictions

The model predicts CPUE in year t from mid-season recruited biomass, the scaling coefficient and the shape parameter:

$$(20) \quad \hat{I}_t = q^I\left(B_{t+0.5}\right)^h$$

Available biomass $B_{t+0.5}$ is the mid-season vulnerable biomass after half the catch has been removed (no natural mortality is assumed, because the time over which half the catch is removed might be short). It is calculated as in equation (9) or (10), but using the mid-year numbers, $N_{k,t+0.5}$:

$$(21) \qquad N^{vuln}_{k,t+0.5} = N_{k,t}\left(1 - \frac{(1-A_t)}{2}P_{k,t}\right)$$

or if commercial selectivity is used instead of MLS:

$$(22) \qquad N^{vuln}_{k,t+0.5} = N_{k,t}\left(1 - \frac{(1-A_t)}{2}V^s_k\right)$$

Similarly the predicted research diver survey index is calculated from the mid-season model numbers in bins greater than 90 mm length, taking into account research diver selectivity-at-length:

$$(23) \qquad N^{res}_{k,t+0.5} = N_{k,t}\left(1 - \frac{(1-A_t)}{2}V^r_k\right)$$

$$(24) \qquad \hat{J}_t = q^J \sum_{k=11}^{55} N^{res}_{k,t+0.5}$$

where the scalar is calculated as the geometric mean of the logs of the ratios of predicted and observed:

$$(25) \qquad q^J = 0.5 \sum_t \ln\left(\frac{J_t}{\sum_{k=11}^{55} N^{res}_{k,t+0.5}}\right)$$

and the research diver selectivity V^r_k is calculated from:

$$(26) \qquad V^r_k = \frac{1}{1 + 19^{-\left((l_k - T_{50})/T_{95-50}\right)}}$$

The model predicts proportions-at-length for the RDLF from numbers in each length class for lengths greater than 90 mm:

$$(27) \qquad \hat{p}^r_{k,t} = \frac{N^{res}_{k,t+0.5}}{\sum_{k=11}^{55} N^{res}_{k,t+0.5}} \qquad \text{for } 11 \le k < 51$$

and

(28) $$\hat{p}^{r}_{51,t} = \frac{\sum_{k=51}^{55} N^{res}_{k,t+0.5}}{\sum_{k=11}^{55} N^{res}_{k,t+0.5}}$$ for the plus group.

Predicted proportions-at-length for CSLF are similar:

(29) $$\hat{p}^{s}_{k,t} = \frac{N^{vuln}_{k,t+0.5}}{\sum_{k=11}^{55} N^{vuln}_{k,t+0.5}}$$ for $11 \le k < 51$

and

(30) $$\hat{p}^{s}_{51,t} = \frac{\sum_{k=51}^{55} N^{vuln}_{k,t+0.5}}{\sum_{k=11}^{55} N^{vuln}_{k,t+0.5}}$$ for the plus group.

The predicted increment for the jth tag-recapture record is

(31) $$\hat{d}_j = \Delta t_j \left(-l_j + \left[\frac{l_j^{\delta}}{x} + y\left(1 - \frac{1}{x}\right) \right]^{\left(1/\delta\right)} \right)$$

where Δt_j is in years and the error around this expected increment is

(32) $$\sigma_j^{d} = \left(\hat{d}_j \phi - \sigma_{MIN}\right)\left(\frac{1}{\pi}\tan^{-1}\left(10^{6}\left(\hat{d}_j \phi - \sigma_{MIN}\right)\right) + 0.5\right) + \sigma_{MIN}$$

Predicted maturity-at-length is

(33) $$\hat{p}^{mat}_{k} = \frac{1}{1 + 19^{-\left((l_k - L_{50}) / L_{95-50} \right)}}$$

2.2.9 Fitting

2.2.9.1 Likelihoods

The distribution of CPUE is assumed to be lognormal and the negative log-likelihood is:

(34) $$-\ln(\mathrm{L})\left(\hat{I}_t \mid \theta\right) = \frac{\left(\ln(I_t) - \ln(\hat{I}_t) + 0.5\left(\sigma_t^{I} \tilde{\sigma} / \varpi^{I} \right)^2 \right)^2}{2\left(\sigma_t^{I} \tilde{\sigma} / \varpi^{I} \right)^2} + \ln(I_t) + \ln\left(\sigma_t^{I} \tilde{\sigma} / \varpi^{I} \right) + 0.5\ln(2\pi)$$

The distribution of the RDSI is also assumed to be lognormal and the negative log-likelihood is:

$$(35)\qquad -\ln(\mathrm{L})\left(\hat{J}_t \mid \theta\right)=\frac{\left(\ln(J_t)-\ln\left(\hat{J}_t\right)+0.5\left(\sigma_t^J\tilde{\sigma}/\varpi^J\right)^2\right)^2}{2\left(\sigma_t^J\tilde{\sigma}/\varpi^J\right)^2}+\ln(J_t)+\ln\left(\sigma_t^J\tilde{\sigma}/\varpi^J\right)+0.5\ln(2\pi)$$

The proportions-at-length from CSLF data are assumed to be normally distributed, with a standard deviation that depends on the proportion, the number measured and the weight assigned to the data:

$$(36)\qquad \sigma_{k,t}^s=\frac{\tilde{\sigma}}{\kappa_t^s\varpi^s\sqrt{p_{k,t}^s+0.1}}$$

The negative log-likelihood is:

$$(37)\qquad -\ln(\mathrm{L})\left(\hat{p}_{k,t}^s \mid \theta\right)=\frac{\left(p_{k,t}^s-\hat{p}_{k,t}^s\right)^2}{2\sigma_{k,t}^{s\;2}}+\ln\left(\sigma_{k,t}^s\right)+0.5\ln(2\pi)$$

The likelihood for RDLF data is analogous. The model was revised to accept alternative likelihoods for proportions-at-age, but after experimentation these were not used in the PAU 5A assessment and need not be described.

Errors in the tag-recapture dataset were also assumed to be normal. For the *j*th record, the total error is a function of the predicted standard deviation (equation (32)) and the observation error:

$$(38)\qquad \sigma_j^{tag}=\sqrt{\sigma_{obs}^{\;2}+\left(\sigma_j^d\right)^2}$$

and the negative log-likelihood is:

$$(39)\qquad -\ln(\mathrm{L})\left(\hat{d}_j \mid \theta\right)=\frac{\left(d_j-\hat{d}_j\right)^2}{2\left(\sigma_j^{tag}\right)^2}+\ln\left(\sigma_j^{tag}\right)+0.5\ln(2\pi)$$

The proportion mature-at-length was assumed to be normally distributed, with standard deviation analogous to proportions-at-length:

$$(40)\qquad \sigma_k^{mat}=\frac{\tilde{\sigma}}{\varpi^{mat}\sqrt{p_k^{mat}+0.1}}$$

The negative log-likelihood (not used for this assessment) is:

$$(41)\qquad -\ln(\mathrm{L})\left(\hat{p}_k^{mat} \mid \theta\right)=\frac{\left(p_k^{mat}-\hat{p}_k^{mat}\right)^2}{2\left(\sigma_k^{mat}\right)^2}+\ln\left(\sigma_k^{mat}\right)+0.5\ln(2\pi)$$

2.2.9.2 Normalised residuals

These are calculated as the residual divided by the relevant σ term used in the likelihood. For CPUE, the normalised residual is

$$(42)\qquad \frac{\ln(I_t)-\ln(\hat{I}_t)}{\left(\sigma_t^I\tilde{\sigma}\big/\varpi^I\right)}$$

and similarly for the RDSI. For the CSLF data proportions-at-length, the residual is

$$(43)\qquad \frac{p_{k,t}^s-\hat{p}_{k,t}^s}{\sigma_{k,t}^s}$$

and similarly for proportions-at-length from the RDLF data. Because the vectors of observed proportions contain many empty bins (e.g., the bins for large and very small paua), the residuals for proportions-at-length include large numbers of very small residuals that distort the frequency distribution of residuals. When presenting normalised residuals from proportions-at-length, we arbitrarily ignore normalised residuals less than 0.05.

For tag-recapture data, the residual is

$$(44)\qquad \frac{d_j-\hat{d}_j}{\sigma_j^{tag}}$$

and for the maturity-at-length data the residual is

$$(45)\qquad \frac{p_k^{mat}-\hat{p}_k^{mat}}{\sigma_k^{mat}}$$

2.2.9.3 Dataset weights

The relative weights used for each dataset, ϖ, are relative to the tagging dataset, which is unweighted. Weights were chosen experimentally in choosing a base case. Ideally they should be changed iteratively to obtain standard deviations of the normalised residuals (sdnr) close to unity for each dataset, but for this assessment the weights were adjusted to obtain reasonable fits and a well-formed Hessian.

2.2.9.4 Priors and bounds

Bayesian priors were established for all parameters. Most were incorporated simply as bounded uniform distributions with upper and lower bounds arbitrarily set wide so as not to restrict the estimation. For $\tilde{\sigma}$ the prior was uniform in log space. The prior probability density for M was a normal-log distribution with mean μ_M and standard deviation σ_M. The contribution to the objective function of estimated M = x is:

(46) $$-\ln(\mathrm{L})(x \mid \mu_M, \sigma_M) = \frac{\left(\ln(M) - \ln(\mu_M)\right)^2}{2\sigma_M^{\ 2}} + \ln\left(\sigma_M \sqrt{2\pi}\right)$$

The prior probability density for the vector of estimated recruitment deviations, ε , was assumed to be normal with a mean of zero. The contribution to the objective function for the whole vector is:

(47) $$-\ln\left(\mathbf{L}\right)(\varepsilon \mid \mu_\varepsilon, \sigma_\varepsilon) = \frac{\sum_{i=1}^{n_\varepsilon} (\varepsilon_i)^2}{2\sigma_\varepsilon^{\ 2}} + \ln\left(\sigma_\varepsilon\right) + 0.5\ln\left(2\pi\right).$$

2.2.9.5 Penalty

A penalty is applied to exploitation rates higher than the assumed maximum (equation (14)); it is added to the objective function after being multiplied by an arbitrary weight determined by experiment.

AD ModelBuilder™ also has internal penalties that keep estimated parameters within their specified bounds, but these should have no effect on the final outcome, because choice of a base case excludes the situations where parameters are estimated at or near a bound.

2.2.10 Fishery indicators

The assessment is based on the following indicators calculated from their posterior distributions: the model's mid-season recruited and spawning biomass from 2004 (current biomass, *B04* and *S04*), from 2007 (*B04* and *S04*) and from a reference period, 1991–93. This was a period when the biomass was stable and production was good, and before a subsequent period when the fishery flourished. The means of values from the three years were called *Sav* and *Bav*. We also used annual exploitation rate in 2004, *U04*, and in 2007, *U07*. Ratios of these are also used.

Four additional indicators are calculated as the percentage of runs in which:

- spawning biomass in 2007 had decreased from 2004: *S07<S04*
- spawning biomass in 2007 was less than the reference level: *S07<Sav*
- recruited biomass in 2007 had decreased from 2004: *B07<B04*
- recruited biomass in 2007 was less than the reference level: *B07<Bav*

2.2.11 Markov chain Monte Carlo (McMC) procedures

AD ModelBuilder™ uses the Metropolis-Hastings algorithm. The step size is based on the standard errors of the parameters and their covariance relationships, estimated from the Hessian matrix.

For the McMCs in this assessment we ran single long chains that started at the estimated mode of the joint posterior distribution (MPD). The base case was 6 million simulations long and we saved 5000 regularly spaced samples. For sensitivity and retrospective analyses we saved 5000 samples from chains of one million simulations.

2.2.12 Projections

Stochastic projections were made through 2007 by running the dynamics forward in time with each of the 5000 parameter vectors, driving the model with a specified catch (assumed to be the 2004 TACC). The sequence of operations is as described for the main dynamics.

Stochastic recruitment in projections was obtained by re-sampling the estimated recruitment from the years 1993 to 2002. Because the 2003 and 2004 recruitment deviations are poorly determined by the data (they have no effect on any of the quantities being fitted), the estimated values are inappropriate for projections; we over-write them with values obtained by re-sampling the deviations from 1993 through 2002.

Projected exploitation rate is limited by simply truncating it at the specified maximum.

3. DATA

3.1 Catch data

3.1.1 Commercial catch

The commercial catch history before 1989 is from FSU data. Fishery data from PAU 5 were described by Kendrick & Andrew (2000): the division of PAU 5 into three new stocks created some difficulty in dividing the reported catches into the new stocks. Catches have been reported for each of the new stocks (5A, 5B, 5D) since 1996. From 1984 through 1995, catches from each stock were estimated from the proportion of catches reported by statistical area (Figure 2 and Figure 3). However, some statistical areas used during that period overlapped the new stock boundaries, so this division was not straightforward. Before 1984, catches must be estimated from the total PAU 5 catch under some assumption about proportionality. The methodology was described by Kendrick & Andrew (2000) for PAU 5B and 5D; for this assessment PAU 5A catch was determined by subtracting their estimates from the total PAU 5 catch.

It may be unrealistic to start the model in 1974 under an assumption of unfished equilibrium, as in previous assessments. There may have been some fishing before 1974 from which the catches were unknown, although they are likely have been small. We assume that catches increased linearly from zero in 1963 to the observed 1974 catch (Table 1 and Figure 4).

3.1.1.1 TACC

The TACC for PAU 5 was set at 445 t when paua entered the QMS in 1987. This increased to 492 t in 1992 but was reduced to 443 t in 1993. When the new substocks were created in 1995 the quota for PAU 5A was set at 147.66 t, one third of the total. It is now 149 t (Table 1).

3.1.2 Recreational catch

The estimate of recreational catch in PAU 5 from the 1999 - 2000 National Recreational Fishing Survey was 53.1 t. We assumed that 10 t was taken from PAU 5A and assumed that this had increased linearly from 1 t in 1974 (Table 1).

3.1.3 Illegal catch

MFish was unable to provide illegal catch estimates, so we assumed 0 t for the illegal catch estimate for the assessment.

3.1.4 Customary catches

MFish was unable to provide customary catch estimates, so we assumed 0 t for the illegal catch estimate for the assessment.

3.2 CPUE

The data come from three sources: the Fisheries Statistics Unit (FSU), Catch and Effort Landing Returns (CELR) and Paua Catch and Effort Landing Returns (PCELR). The period of data from each source for PAU 5A is shown in Table 2. As for catches, effort in PAU 5A was reported for large statistical areas that straddled the new substocks created in 1996. Kendrick & Andrew (2000) described this problem and their solution to it. Data up until the 1999 fishing year extracted for the 1999 assessment were simply retained.

The FSU data included the fields: form type, method, vessel key, event key, landing date, number of divers, number of hours, statistical area, species caught (all recorded as PAU), state code (GRE for green weight, SHU for meat only), unit type (kg or bag), number of units and green weight (kg). The green weight was used as the estimated catch for the FSU data.

For PAU 5A, FSU data were extracted from the NIWA-managed database for January 1983 through September 1988. There is a gap for the 1989 fishing year (transition period from FSU data to CELR data), and the 1983 and 1988 fishing years are incomplete but were used for the analysis because most data are included.

From 1 October 1989, the CELR form was used and from 1 October 2001, the Ministry of Fisheries changed its form type from CELR to PCELR so that the paua fishery has its own special form.

The CELR (from 1 October 1989 to 28 February 2002) and PCELR forms (from 1 October 2001 to the present) are separated into two parts: catch and effort section and landing section. Both sections were extracted from the MFish database. In the catch and effort section, the CELR form includes the fields: form type, form number, trip key, starting date of trip, ending date of trip, date of effort, method, statistical area, fishing duration (in hours), number of divers (we called this diver day), estimated catch, species caught (recorded as PAU for most of them), vessel key and client key.

The PCELR form includes the fields: form type, form number, event key (trip key in CELR form), starting date of trip (effort date in CELR form), statistical area, diver key (new field in PCELR form), time in water (fishing duration in CELR form), diving conditions (new field in PCELR form), species caught, catch weight (estimated catch in CELR form), vessel key and client key. In the landing section, both the CELR and PCELR forms include the fields: form type, form number, trip number, first day of trip, last day of trip, landing date, point of landing, fish stock, destination type, green weight (kg), vessel key and client key.

The data were groomed to remove obvious errors and to maintain consistency. There were minor errors in both the effort and landing sections of the form. The most common error was mismatching statistical area and fishstock; we corrected the fishstock from its corresponding statistical area after merging the effort and landing part of the form. The trip length (days) was not used as a variable because fishers recorded estimated catch on each day of effort.

The PCELR form has estimated catch recorded for each diver and it has a good record of hours. The CELR form does not have a reliable record of diving hours and it records the number of divers and the sum of catch for all divers instead of recording estimated catch for each diver. Therefore, we used catch per diver day as our unit of CPUE. To maintain the same error structure for both types of forms, PCELR data were collapsed by form number and statistical area so that the data have the same format as the CELR data.

Specifically,
PCELR catch in area a on form y = sum of catch in statistical area a.
PCELR number of divers in area a on form y = count of divers in statistical area a.
PCELR diving hours in area a on form y = sum of diving hours in statistical area a.

The PCELR extracts identify yellowfoot paua (*Halitois australis*, species code PAA) and these records were excluded. The FSU and the CELR data do not separate the two species, so all FSU and CELR data were included in grooming; they may contain small quantities of *H. australis*.

There appeared to be some duplicated records in the extracted data in CELR form (possibly because they used species code PAU for both yellowfoot and blackfoot paua), but it was not possible sort them out reliably and they were left in place.

There were 3134 records for PAU 5A. Of these, 1 record was deleted because the statistical area was missing, 2 records because the number of divers in CELR form was missing, 4 because the number of divers was greater than 8, 12 because diving hours per diver was greater than 10 for post 1990 data (for pre-1990 data, we ignored the diving hours because many were extremely large, up to 120 hours per diver), 5 records were deleted because CPUE (estimated catch per diver in one day) was greater than or equal to 2000 kg, and 25 records from the 1983 fishing year because 1983 data are not usable (Kendrick & Andrew 2000). This grooming process left 3085 records, but this became 2312 after collapsing PCELR data by form number and stat area so that the data are in the same form as CELR data. One record was deleted because it was a duplicate.

Of these 2311 records, there were 17 records (1% of data) with zero and "NULL" catches. Since there was only a small percentage of zero catches and no information on catch is available for "NULL", these data were not included in the analysis. This process left 2295 records.

Historically, for the paua CPUE standardisation, vessel was one of the important variables. We have two options to calculate the number of years that the vessel has operated. First we used vessel data from the three fisheries - PAU 5A, PAU 5B and PAU 5D - to calculate the number of years each vessel operated in the fishery (Option 1). Some vessels that operated in PAU 5A also operated in PAU 5B or PAU 5D; of these, some may have operated less than 5 years in PAU 5A but operated longer in other PAU 5 fisheries. Under Option 1, data from vessels that fished for 5 years or longer in any of the PAU 5 fisheries were used for the analysis.

The second option used vessel data only from the PAU 5A fishery data after grooming (Option 2). With this option, if a vessel did not fish for 5 years or longer in PAU 5A, data from that vessel were not used. This option leaves fewer records than Option 1.

Using these two options, we removed all data recorded by vessels that operated less than 5 fishing years. At the end of this process we had 1482 records using Option 1 and 1245 records Option 2. The final groomed data did not have any records with vessel code "NULL".

CPUE was standardised with the method of Vignaux (1993) as described by Kendrick & Andrew (2000), then changed into canonical form as described by Francis (1999), giving estimates that are independent of the reference year. Standardisation used the natural logarithm of catch per diver day.

Because no area effect is included in the model, we explored the interaction between area and month (Andre Punt, University of Washington, pers. comm.). For PAU 5A the interaction term was not significant for either the Option 1 or 2 models. The variables offered to the model were vessel, fishing year, month and statistical area, with fishing year forced to be an explanatory variable. The order in which variables were selected into the model and their effect on the model r^2 are shown in Table 3. In all standardisations, statistical area did not increase the r^2 substantially (greater than 1%) and was not used. The model explained 17.9% and 14.7% of the variation in CPUE for PAU 5A with Options 1 and 2 respectively.

The raw and standardised CPUE for PAU 5A from Option 1 are shown in Figure 5 (raw CPUE is the sum of catch divided by the sum of diver days). Option 1 shows a better fit to the data and was chosen. *The standardised CPUE is similar to raw CPUE after 1990; before 1990,* standardised CPUE has a different pattern from the raw CPUE and has higher uncertainty. There are two peaks of CPUE: at the beginning of the series and in 1987.

The raw and standardised year effects on CPUE from Option 1, using the interaction term, are shown in Table 4. After preliminary model fits we arbitrarily down-weighted the first four years by tripling the standard error in response to concerns that the quality of data in these years was poor and for consistency with the parallel assessment in PAU 4.

3.3 Research diver survey index (RDSI)

The timed-swim survey index method was described by Andrew et al. (2000b). Divers make a timed swim of 10 minutes after sighting the first paua and they record the patch size by grade (in the older data) or by actual count (in the new data). The timed-swim index for a swim is the product of numbers of patches and numbers per patch, by patch type.

In calculating the index before this assessment, the average size of each patch type was the simple median of the size range of each patch type. Because research divers now count the numbers in all patches, we calculated the mean size for each patch type for use in calculating the index for the older data (Table 5). For the newer data, the index is based on the number counted.

We explored using searching time to refine the estimates of relative abundance. When divers are underwater it takes some time to count the number of paua in a patch, collect a sample from that patch and record the patch size. This was studied by McShane et al. (1996) and found to average 7.8 seconds per patch. Although divers count patches now, this does not increase patch handling time much, and divers stop their stopwatch when the patch size looks larger than 20. So total time spent searching in the *a*th 10-minute swim can be estimated as:

$$t_a^{searching} = 600 - 7.8 n_i^{patches}$$

The raw timed-swim index IS'_a is then modified by rescaling:

$$IS_a = \frac{600 IS'_a}{t_a^{searching}}$$

where IS_a is the new index.

Exploratory analyses showed that incorporating estimated searching time gave a better fit, so this was approach adopted.

Visibility code 1 is for very clear water (Table 6) and code 5 is for murky water. In PAU 5A, code 5 visibility occurred only in the 2002 survey (Table 7).

There were three research strata in PAU 5A (Table 7): Chalky, Dusky and South Coast (Figure 2). The Dusky stratum was surveyed only in 2002. The South Coast stratum was surveyed in March 2003 and these data were included as if they were 2002 data. One swim of only 5 minutes was excluded, leaving 135 swims: 44 records from 1996 and 91 records from 2002. A number of timed swims had zero abundance: two records in 1996 (4.5%) and 14 records in 2002 (15.4%). These zeroes were replaced with one paua to allow their use in the log-normal standardisation model.

The standardisation used the same method as for the CPUE. The variables offered to the model were fishing year, stratum and visibility, with fishing year forced to be an explanatory variable. Diver was not offered as variable because only one researcher dove for both years' surveys. The order in which variables were selected into the model and their effect on the model r^2 are shown in Table 8. All variables were important in both models for the relative abundance index for PAU 5A. With searching time, the model explains 21.6% of the variation in RDSI and without searching time the model explains 21.7% of the variation in RDSI.

Raw and standardised diver survey indices with confidence intervals are shown in Figure 6 (the raw index is the arithmetic mean of the indices from each swim). The standardised index of relative abundance decreased from 1996 to 2002 whereas the raw index increased. The Dusky stratum has a higher stratum effect than other strata and visibility code 5 (poor visibility) has a higher effect than others.

The residuals to the PAU 5A research diver survey model are shown in Figure 7. The records with smallest residuals are those with abundance of zero replaced with one paua. This procedure does not appear to have distorted the fitting.

The raw and standardised RDSIs for each stratum are shown in Table 9. The decline in RDSI between 1996 and 2002 was examined further, outside the assessment model, with a GLM coded in AD ModelBuilder™. The likelihood profile and posterior of the ratio J_{2002}/J_{1996} both had less than 1% of their distribution above 1.0, so the decline could be considered significant.

3.4 Commercial catch sampling length frequency data (CSLF)

The number of days sampled in each statistical area in each fishing year is shown in Table 10. In 1993 and 1998, few days were sampled and in 1994 there was only one sample in statistical area 030. The number of paua measured in each area for each fishing year is shown in Table 11. Statistical area for some paua measured is unknown because some divers or quota owners are sensitive to giving out this information.

Length frequencies were measured in samples of shells from the commercial fishery from 1992 to 1994, 1998, and 2000 to 2004 (Table 11). As with the CSLF data used for the 2003 PAU 7 assessment (Breen & Kim 2003), the samples were simply added together for each year. Data were not stratified by catch.

The CSLF in PAU 5A in each fishing year (Figure 8) show little pattern across years. The distribution was very different in 1993, with smaller paua than in other years, a result most likely caused by the sampling pattern. The length frequencies by statistical area (Figure 9) suggest little difference among areas, with a slight tendency for area 032 to have more larger paua.

Each year's CSLF data were weighted by the normalised square root of numbers measured greater than MLS:

$$\kappa_i^s = \frac{\sqrt{n_i^{paua \geq MLS}}}{\min_i\left(\sqrt{n_i^{paua \geq MLS}}\right)}.$$

3.5 Research diver survey length frequency data (RDLF)

Research divers remove some paua from each surveyed patch for measuring at the surface; thus there are length data from each swim. After the analysis of research diver survey indices, we linked the calculated abundance from each timed swim to the length frequency data for that timed swim. We calculated the weighted length frequency at size s from the ath timed swim, $L_{s,a}$, by scaling the raw frequency at size s, $L'_{s,a}$, by the normalised abundance from sample a:

$$L_{s,a} = L'_{s,a} \frac{IS_a}{\sum_a IS_a / n_a}.$$

where n_a is the number of swims involved. For those length frequency samples without timed-swim data (older data where the divers made a collection without doing a timed swim), we assumed a normalised abundance of 1.

Length frequency bins are defined differently from previous years, starting from 71 mm instead of 70, although they are still 2 mm bins. This change was made because MLS is 125 mm; the old approach caused the MLS to occur in the centre of a length bin. This change might improve the model's fit to the length frequency data.

During the two research diver surveys, 4,553 paua were measured. One was less than 71 mm and was not included in the length frequency data. The number of paua measured in each stratum in each year is shown in Table 12. The data include a research survey in 1991 that measured paua but did not conduct timed-swims.

The weighted RDLF data by stratum, pooled over years (Figure 10), show strong differences among the three strata. Further south, fewer large paua are found (i.e. many large paua are observed in Dusky, but only small paua are observed in the South Coast.) The weighted length frequencies and cumulative frequencies by fishing year, pooled over strata (Figure 11), show that sampled paua were larger in 1991, with little difference between 1996 and 2002.

For 2002, a year with both CSLF and RDLF data, very little difference is seen in proportions-at-length for lengths above the MLS in the two datasets (Figure 12 and Figure 13).

3.6 Growth increment data

This section describes tag-recapture data used for the assessment and describes explorations of the tagging data made outside the model. We describe the data, grooming and experimental fitting.

3.6.1 Data

Paua were tagged (Reyn Naylor, NIWA, pers. comm.) to measure growth of paua in various locations.

In May 2000, 2307 tagged paua were released in Poison Bay (statistical area 32) and, in early November 2000, 1463 paua were tagged in Landing Bay and Red Head (both in research stratum Chalky, statistical area 30). No sex and maturity information were recorded for these data. About a year later, they were recovered by research divers (Table 13).

Because the model does not represent paua less than 70 mm in length, we removed a small number of paua tagged at smaller sizes.

3.6.2 Growth models

In preliminary analyses, tagging data were fitted using Schnute's growth model (Schnute 1981) outside the population model. First we fitted to tag data for each area separately, then fitted to all tag data from PAU 5A. In all fits, α and β were fixed at 75 and 120 respectively.

At Poison Bay, where a relatively large number of tags were collected, paua grew more slowly than at the other sites (Table 14). The shape parameter was estimated as 5.5. Fits are shown in Figure 14 through Figure 17.

3.7 Maturity data

In July 1996, 33 paua were measured and observed for a study of maturity-at-size in Chalky Inlet (Reyn Naylor, pers. comm.). The number of paua measured and mature are shown in Table 15. This sample size is very small and no paua were greater than 100 mm. Because of the small sample size, the model was not fitted to these data. The maturity parameters affect only the model's estimates of spawning biomass, by modifying the numbers-at-length by the maturity curve. In the assessment we used assumed values that appeared to fit the data well, because the estimation phase was unstable when these parameters were estimated.

4. MODEL RESULTS

In this section we first describe, in a greatly condensed fashion, finding a base case and then we show MPD results. We describe a set of sensitivities to datasets and modelling options that were explored by comparing MPD runs in the search for a base case, but we do not explore MPD sensitivities from the final base case. Second, we show diagnostics from one long McMC chain. Third, we show the Bayesian fits and residuals from these fits. The assessment is obtained from the posterior distributions of the indicators (Section 2.2.10).

4.1 Finding a base case

The base case for PAU 7 (Breen & Kim 2003) was chosen by altering the relative weights for each dataset until the standard deviations of normalised residuals were close to 1.0 for each dataset. For PAU 5A this simple approach could not be used. Many runs were characterised by M on its upper bound, very high recruitment, trifling exploitation rates and a flat biomass trajectory. Other runs had Hessian matrices that were not positive definite and thus could not be used to run McMC.

Part of the trouble was caused by the antagonism between CPUE and RDSI indices (this is explored more fully below): CPUE shows a decline and then an increase; RDSI shows a decline; it is difficult for the model to fit both. We experimented with fitting to one without regard to the other, but in the end chose to persist with a combination base case.

Excluding the earliest trials, 224 trials were made before choosing a base case to use for McMC simulations. To obtain this candidate we fixed δ and h to 1 and 0.62 respectively: the latter value came from the PAU 7 assessment (Breen & Kim 2003). Although it fit the data well, unfortunately this candidate produced McMC traces with pathological behaviour.

More trials and model changes to produce the parameterisation described above were made and a credible base case McMC obtained. The specifications for this base case are given in Table 16. The parameter δ was fixed to 2.5, based on trials in which it was estimated and h was fixed to 0.8 after experimentation. It was necessary to fix D_{50}, the length at which commercial diver selectivity is 50%, to 126 mm: this was well determined in most trials.

4.2 MPD results

Parameter estimates and some indicators are shown in Table 17. The MPD estimate of M was 0.262, *substantially larger than the assumed mean of the prior distribution*, 0.10. The estimate of z, 15.23, was close to the value of 15.5 estimated empirically from the preliminary McMC (Figure 1). Means of normalised residuals varied from 0.5 for RDLF to 2.5 for CPUE (ignoring the RDSI, for which there are only two data).

The model fitted the observed CPUE reasonably well, except for the earliest years (Figure 18) and fits the decline in RDSI, although with a lag. Fits to proportions-at-length were reasonably good (Figure 19) and there was little consistent relation between the residuals and length (Figure 20) for CSLF; the RDLF residuals show some problems that may indicate mis-specification of the research diver selectivity (Figure 21). The q-q plot is generally better from the commercial catch sampling data (Figure 22).

The fit to growth increment data (Figure 23) was different from the preliminary fits (Figure 14 though Figure 18): the population model estimates higher growth rates for larger paua and concomitant lower growth for small paua. This reflects the large sizes of paua seen in the length frequencies. The predicted annual growth increment and the variability around this are also shown in Figure 24 (top) and sections of the growth transition matrix are shown in Figure 25.

The selectivity curves (assumed for research divers; partially estimated for commercial divers) are shown in Figure 24. Total numbers of model paua are shown for 1964, 1990 and 2002 (Figure 26), showing the effects of the model's variable recruitment estimates (Figure 27), which were strong in the late 1970s and mid 1990s, low in the 1980s and recently.

The recruitment pattern shown in Figure 27 may be misleading: the model uses recruitment estimates to enable it to fit the data and the data are sparse. There are no abundance indices before 1984, so the early estimates of recruitment are flat and the estimated deviations are zero. The model creates high recruitment in the late 1970s, followed by a long period of declining recruitment, so that it can fit the decline observed in CPUE.

Exploitation rate (Figure 27) increased steadily over the history of the fishery, then increased sharply when catches increased in 1995 (Figure 3), reaching a peak of 19% in 1997 (Table 17).

Biomass trajectories, the production trajectory and surplus production plotted against recruited biomass are shown in Figure 28. Surplus production is defined as change in biomass plus the catch, i.e.:

$$SP_t = B_{t+1} - B_t + C_t$$

Biomass shows a general decline but with large increases caused by the recruitment pattern (Figure 27).

The years 1991 to 1993 were chosen as the reference period, containing the low point to which the population fell in the early 1990s and from which it then recovered. The MPD fit suggests (Table 17) that the current biomass is near the reference levels and that current exploitation rate is 16%.

4.3 MPD sensitivity trials

MPD sensitivity trials were made only from an early base case candidate, one that produced a flawed McMC. Because base case sensitivities were later run as McMC trials, MPD sensitivities were not repeated. Trials from the early base case can be summarised as follows:

- when a Cauchy prior likelihood (Chen et al. 2001) on M was used instead of a lognormal prior, estimates for M and ln($R0$) (which was estimated as an independent parameter) were both much higher than in the early base case;
- similarly, relaxing the standard deviation of the prior on M allowed the estimate to go near the upper bound of 0.50;
- when h was estimated, it went to the upper bound of 2 with greatly increased ln($R0$).
- when δ was estimated it was 2.33; larger than the 1.0 assumed in that early base case;
- when both h and δ were estimated, estimates were 2 and 2.8 respectively. In all these trials, current biomass was substantially higher than the early base case, exploitation rate was lower, but the ratio of projected to current biomass didn't change much;
- estimating the research diver selectivity parameters did not give credible estimates;
- when we estimated T_{50} and T_{95-50}, the latter went to the upper bound; with T_{95-50} fixed and T_{50} estimated, T_{50} was estimated as low as 78.1 and biomass indicators were higher (these estimates improved the fit to RDLF slightly); and
- when data sets were removed one at a time, removal of CPUE led to much smaller biomass estimates and removal of RDSI led to much higher estimates, illustrating the conflict between these data; removal of RDLF or CSLF data singly did not have gross effects; removal of the tag data led to very small ϕ and a blow-out in biomass.

Thus these trials support our decision to fix the research diver selectivity parameters, and they show that results are sensitive to the relative weights given to the CPUE vs RDSI indices, which are contradictory and have opposing effects.

4.4 McMC results: diagnostics

A single chain of 6 million McMC simulations was run, starting at the MPD, with 5000 samples. Traces from the chain are shown in Figure 29. We examined the chain for each parameter with five tests – Raftery & Lewis (1992), Geweke (1992), stationary and half width tests by Heidelberger & Welch (1983) and the single chain Gelman – to test the single chains for stationarity and convergence (see Brooks & Roberts 1998). Diagnostics on the chain (Table 18) were poor for some derived parameters in two tests and generally good for the others, as is usual.

The matrix of correlations among parameter posteriors (Table 19) shows interactions between z and the growth parameters and $\ln(q^I)$, among the growth parameters and between M and $\ln(q^I)$. The largest is -0.85. Although not perfect, this situation is far better than that that obtained before we re-parameterised the model.

4.5 McMC results: posteriors and fits

Posteriors (Figure 30) were generally well formed and MPDs were mostly near the centres. Relevant posteriors are summarised in Table 20. Some parameter posteriors have narrow ranges, for instance the growth parameter g_β, ranges from 4.7 to 5.4 (5th to 95th quantiles) (Table 20), and others are broader, for instance M ranges from 0.23 to 0.32. Biomass indicators tend to be loosely estimated: for instance *Bav* has a range from 740 to 3972 t; *B04* from 713 to 3871. The ratio indicators are tighter: for instance *B07/B04* ranges from 59% to 80% and *B04/Bav* from 92% to 102%.

The posteriors of predicted CPUE (Figure 31) show that variation is greatest for the early years, where data are weakest, and then is low. The early years and final year have predictions that do not encompass the observed values. There is no pattern in the residuals. The fit to the two RDSI data (Figure 32) is strongly biased towards a weaker decline than that seen in the data. This is probably caused by the antagonistic effects of CPUE, which shows no decline after 1990.

The posteriors of the fit to CSLFs for 2002 (Figure 33) are very tight and sometimes do not include the observed values. Proportions near the MLS tend to be overestimated and proportions near 150 mm tend to be underestimated. The residual pattern is worse for RDLFs in the same year (Figure 34), although the overall fit is acceptable. The selectivity curve may be mis-specified in some parts of the size range because the selectivity parameters were assumed.

The posteriors of the fits to tagging data are difficult to show; instead we show the posterior of the q-q plot of the residuals (Figure 35). This is well formed between the -1 and 1 quantiles.

The biomass trajectory posteriors (Figure 36) are generally wide, reflecting high variability in these absolute abundance estimates. Variability is least for recruited biomass and greatest for total biomass. Variability for spawning biomass would be much greater if the maturity parameters had been estimated: assuming fixed values greatly reduces the uncertainty.

In all three biomass measures, the stock declined from the mid 1980s to late 1990s, increased to 2002 and then declined again in projections. Uncertainty in projections is high. The recruited biomass trajectory is shown in more detail in (Figure 37).

Exploitation rate (Figure 38, top) also has least uncertainty in the early years, when it was low, and most in the most recent years. Estimates tended to be lower in the McMC than they were in the MPD (Table 20).

Recruitment (Figure 38, bottom) has an underlying form similar to the MPD, but with high uncertainty.

The surplus production trajectory tends to follow catch (Figure 39) but without the steep 1995 increase. Estimates are least variable when the production is changing rapidly and most variable when it is static.

4.6 McMC sensitivities

MPD sensitivities from a preliminary base case are discussed above (Section 4.3). From the final base case we made a small set of McMC sensitivity trials, each a short chain of a million simulations started from the MPD. These are summarised in Table 21.

In the first trial we arbitrarily decreased the decline in the RDSI (based on the two data) from 34% to 26%. Biomass indicators were slightly more optimistic, but this change had only a small effect.

In the next set of trials we removed each of the five data sets one at a time. Removing the RDSI led to higher *M*, higher recruitment, faster growth and far higher biomass estimates. This was the only run in which any of the projections showed an increase in recruited biomass. Conversely, removing CPUE led to far more pessimistic results, with low biomass and high exploitation rates.

Removing the CSLF data or the tag-recapture data gave the most extreme result, with absurdly high biomass estimates, a flat biomass trajectory and only trifling exploitation rates. Probably this resulted from an inability to estimate the growth rates. Removing the RDLF data led to more pessimistic results (this trial would not run without some tinkering, the successful version of which involved reducing σ_M). Estimating δ or h or both together had little effect on the biomass ratio indicators.

4.7 McMC retrospectives

Retrospective trials, in which data were removed one year at a time, were also made with a million McMCs. The tagging data were not removed - there are tag-recapture data only from one year, and sensitivity of the model to its removal has already been seen.

The biomass retrospective (Figure 40, Table 21) for 2003 was very similar to that for 2004; the 2002 retrospective had considerably lower biomass but retained the same shape; the 2001 retrospective had still lower biomass and a different shape. Exploitation rate followed the converse pattern (Figure 41). The 2001 retrospective did not use the second RDSI data point, so this trial had relatively few data. Given that, these retrospective results do not seem unreasonably sensitive.

4.8 Assessment of PAU 5A

The results (Table 20) suggest that current recruited biomass is 1230 t (5% to 95% range 713 to 3871 t) and that the current exploitation rate is 13% (4% to 21%). This is a relatively wide range of uncertainty. Optimum exploitation rate is unknown.

The reference period, 1991 to 1993, was chosen by inspecting the biomass and exploitation rate trajectories from the MPD. This was a period after which exploitation rates increased and then levelled off, and after which biomass declined somewhat and then stabilised. The assessment suggests that current recruitment biomass is near *Bav*, (92% to 102% of *Bav*) (Figure 36). Current spawning biomass is also near *Sav*, but the uncertainty is artificially low with maturity parameters not estimated, and the conclusion may be sensitive to maturity ogives. More maturity data are obviously required for estimating spawning biomass; this should have a high priority.

Projections suggest a decreasing recruited biomass, with a median of 30% decrease (41% to 20% decrease). In projections made with current catch levels, recruited biomass declined and was less than *Bav* in 100% of the runs. This suggests that the current catch is not sustainable.

5. DISCUSSION

5.1 PAU 5A assessment

In this assessment the model did not fit the data comfortably. We had considerable trouble in finding a base case that appeared to fit the data satisfactorily, had a well-formed Hessian matrix and produced a converged estimate of the marginal posterior distributions.

Compared with other New Zealand paua assessments, data for this assessment were limited; there were only two RDSI data and two sets of RDLF data. There appeared, based on sensitivity trials, to be a strong conflict between the CPUE and RDSI data: the CPUE data suggest a stable and lightly fished stock while the RDSI data suggest a strong decline between 1996 and 2002. Sensitivity trials showed that the tag-recapture and CSLF datasets were essential to our obtaining reasonable estimates, whereas in other paua assessments we have been able to obtain robust results without these.

Successful modelling required some parameters to be fixed. The parameter h was fixed because when estimated it went to the upper bound, 2. This implies hyperdepletion, which is most unlikely for abalone. The research diver selectivity parameters T_{50} and T_{95-50} were fixed because unrealistic estimates resulted: evidently the data contain poor information about these. Although the commercial selectivity should be well determined, we were forced to fix D_{50}. Maturity parameters were fixed because there were essentially no data. The parameter δ was fixed to stabilise the estimation, but the McMC sensitivity trials suggest it may have been possible to estimate this. Ideally, none of these parameters should be fixed; fixing them reduces the estimated uncertainty from its real levels; that we had to fix them is another indication that this assessment was data-limited.

Once we found a suitable base case under the conditions described, results appeared to be reasonable: the diagnostics indicated that we could consider the marginal posteriors, especially those of greatest management interest, to be converged. The retrospective results were acceptable, considering the very small amount of data left after three years' data were deleted.

Although we don't show them, McMC results from another late-stage candidate base case also showed convergence of the chain, similar parameter estimates, somewhat lower biomass and higher exploitation rate estimates (median 20%). As in the present base case, 100% of runs declined to below *Bav*.

The assessment is a pessimistic one: we chose the period for *Bav* partly because it showed the lowest biomass in the estimated trajectory. This assessment suggests that biomass will decline below this level in three years; i.e., to its lowest observed point, with 100% certainty at the current catch level. Current catches are thus not sustainable.

The credibility of this assessment is strongly related to the RDSI data. The projected decline in biomass depends absolutely on the RDSI data. The RDSI data have only two points, from 1996 and 2002 surveys, and nearly all the 1996 survey was conducted in Chalky Inlet, one of three survey strata in the southernmost of three statistical areas. To what extent is Chalky Inlet likely to be representative of fishing patterns and population trends elsewhere in PAU 5A? Even if Chalky Inlet is a typical stratum, the limited data are a cause for some caution in accepting these results, although the declining RDSI and the possibility of serial depletion discussed below are grounds for concern.

5.2 Cautionary notes

5.2.1 The McMC process underestimates uncertainty

The assessment results just described have more uncertainty than that reflected in the posterior distributions. These results come from a single base case chosen from a wide range of possibilities. Sensitivity trials suggest that data weighting has an effect on the results. Choice of likelihoods may also have an effect, and we did not explore this avenue fully. The effect of assuming maturity parameters has already been discussed; other assumed parameters also cause uncertainty to be underestimated.

5.2.2 The data are not completely accurate

The next source of uncertainty comes from the data. Commercial catch data show large fluctuations in 1983 to 1986 that may suggest anomalies in data capture. The period before 1974 is unknown. Non-commercial catch estimates are unavailable.

The tagging data are from only three locations, which may not reflect fully the average growth and range of growth in this population. They show considerable spatial variability. Similarly, length frequency data collected from the commercial catch may not represent the commercial catch with much precision: only 132 days have been sampled in nine years and less than 1000 paua were measured in some years.

The research diver data are sparse. Only two surveys have been conducted and the indices were uncertain and sensitive to standardisation. It is difficult to sample heterogeneous populations to obtain estimates that are representative of the whole population. The 136 survey sites may not be fully representative of Fiordland paua habitat.

5.2.3 The model is homogeneous, the world heterogeneous

The model treats the whole of PAU 5A as if it were a single stock with homogeneous biology, habitat and fishing pressures. This means: in the model, recruitment affects all areas of PAU 5A in the same way. Natural mortality, which does not vary by size or year, is the same in all areas of PAU 5A. Growth has the same mean and variance in all parts of PAU 5A (we know this is violated because we know some that areas are stunted and grow quickly).

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, an effect that the current model cannot account for.

5.2.4 The model assumptions may be violated

The most suspect assumption made is that CPUE is an index of abundance. There is a large literature for abalone that suggests CPUE is difficult to use in abalone stock assessments because of *serial depletion*. This happens when fishers can deplete unfished or lightly fished beds and maintain their catch rates. So CPUE stays high while the biomass is actually decreasing.

In fully developed fisheries such as PAU 7 this is not such a serious problem, at least if Cape Campbell and the West Coast strata are excluded, because spatial variation in density is lower: high exploitation rates have depleted most of the stock. The difference is illustrated by CPUE itself: for PAU 7 it was 64 kg per diver day in 2002; for PAU 5A it was 240 kg in 2003 (both are standardised estimates).

If CPUE is not an index of abundance, it may mislead the model, although this assessment was not grossly changed when CPUE was excluded. However, the same problem occurs in the commercial length frequencies, CSLF. If the fishery depletes areas serially, the size structure of the commercial catch does not reflect the population size structure. The PAU 5A length frequencies show no systematic trends among the years sampled.

If serial depletion occurs in the current PAU 5A fishery, then these assessment results may be misleading. Biomass may be declining much faster than CPUE indicates; the size structure may be shifting to smaller paua much more quickly than the CSLF data indicate. The research diver data are somewhat sparse to overcome these other data sources. Whether serial depletion is a problem cannot be determined with the current data.

Another significant source of uncertainty in this assessment 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.

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Table 1: Commercial and recreational catch data (kg) for the PAU 5A assessment, and the PAU 5A TACC. Catches before 1974 are assumed.

Fishing year	Commercial catch	Recreational catch	TACC
1964	4 538		
1965	9 075		
1966	13 613		
1967	18 151		
1968	22 688		
1969	27 226		
1970	31 764		
1971	36 301		
1972	40 839		
1973	45 376		
1974	48 914	1 000	–
1975	46 272	1 346	–
1976	36 825	1 692	–
1977	50 922	2 038	–
1978	76 696	2 385	–
1979	80 491	2 731	–
1980	99 613	3 077	–
1981	120 598	3 423	–
1982	79 709	3 769	–
1983	101 886	4 115	–
1984	49 594	4 462	–
1985	66 073	4 808	–
1986	15 677	5 154	–
1987	31 601	5 500	–
1988	17 021	5 846	–
1989	7 334	6 192	–
1990	40 659	6 538	–
1991	76 766	6 885	–
1992	60 397	7 231	–
1993	69 979	7 577	–
1994	53 457	7 923	–
1995	46 225	8 269	–
1996	139 530	8 615	147 660
1997	141 910	8 962	147 660
1998	145 220	9 308	148 980
1999	147 360	9 654	148 980
2000	143 910	10 000	148 980
2001	147 700	10 000	148 980
2002	148 530	10 000	148 980
2003	148 764	10 000	148 980
2004	148 983	10 000	148 980

Table 2: Data sources, periods and number of records for data used for the CPUE standardisation for the PAU 5A assessment.

Data source	Data periods	Extracted in	Records
FSU & CELR	13 February 1983 – 30 September 1998	1999 (Kendrick)	1 317
CELR	1 October 1998 – 28 February 2002	December 2003	643
PCELR	1 October 2001 – 30 September 2003	December 2003	1 174
Total			3 134

Table 3: The order in which variables were selected into the GLM model of CPUE and their cumulative effect on the model r^2 for PAU 5A (Option 1).

	Model r^2	
Variable	Option 1	Option 2
Fishing year	2.9%	1.9%
Vessel	16.1%	12.5%
Month	17.9%	14.7%

Table 4: Standardised CPUE indices for PAU 5A. Standard errors (SE) for the first four years were arbitrarily tripled in obtaining a base case.

Year	Year effect	SE
1984	1.727	1.016
1985	1.559	1.072
1986	1.322	1.064
1987	1.877	1.122
1988	1.743	0.312
1989	1.221	0.288
1990	1.074	0.165
1991	0.917	0.144
1992	0.885	0.159
1993	0.761	0.148
1994	0.710	0.137
1995	0.766	0.140
1996	0.735	0.120
1997	0.675	0.119
1998	0.746	0.112
1999	0.743	0.113
2000	0.861	0.120
2001	0.910	0.125
2002	0.893	0.124
2003	1.016	0.124

Table 5: Definition of research diver survey patch type by number of paua, the old assumed mean number and the observed mean for PAU 5A.

		Average patch size	
Patch type	Patch size	Old	New
1	1-4	1.28	1.65
2	5-10	7.5	6.98
3	11-20	15.5	14.31
4	21-40	30.5	27.78
5	41-80	60.5	48.88
6	>80	120.5	128.50

Table 6: Definition of research diver survey visibility codes.

Visibility code	Definition
1	>10 m
2	6 to 10 m
3	3 to 6 m
4	1.5 to 3 m
5	<1.5 m

Table 7: Summary of research diver survey data for PAU 5A, showing the number of timed swim surveys made in each stratum in each year (a) and each visibility level in each year (b). The mean abundance based on estimated time searching is shown by stratum in (c) and by visibility in (d).

(a)

Number of swims			Stratum
Fishing year	Chalky	Dusky	South Coast
1996	42		2
2002	32	30	30

(b)

Number of swims					visibility
Fishing year	1	2	3	4	5
1996	24	8	10	2	
2002	28	52	8	2	2

(c)

Mean			Stratum
Fishing year	1	2	3
1996	53.7		15.6
2002	51.5	150.1	59.3

(d)

Mean					Visibility
Fishing year	1	2	3	4	5
1996	52.0	16.0	80.3	54.3	
2002	72.0	101.8	29.9	37.3	153.3

Table 8: The order in which variables were selected into the GLM model of RDSI that includes searching time, and their cumulative effect on the model r^2 for PAU 5A.

Variable	Model r^2
Fishing year	0.2%
Stratum	17.5%
Visibility	21.6%

Table 9: Standardised RDSI for PAU 5A.

Fishing year	Index	SE
1996	1.250	0.200
2002	0.800	0.200

Table 10: Number of sample days in each statistical area in each fishing year for commercial catch sampling in PAU 5A.

Fishing year	030	031	032	Unknown	All
1992	3	4	1		8
1993	2	1			3
1994	1				1
1998	1	1	2		4
2000		2		19	21
2001	1		2	29	29
2002		7	18	11	32
2003	14	7	4	11	28
2004				6	6
Total	22	22	27	76	132

Table 11: Numbers of paua measured in commercial catch sampling in PAU 5A by year and statistical area.

Fishing year	030	031	032	Unknown	Total
1992	967	3 222	326		4 515
1993	831	331			1 162
1994	348				348
1998	157	121	249		527
2000		201		3 420	3 621
2001	120		245	4 069	4 434
2002		830	2 768	1 532	5 130
2003	3,278	1 070	482	1 634	6 464
2004				878	878
Total	5,701	5 775	4 070	11 533	27 079

Table 12: Numbers of paua above 71 mm measured in research diver surveys in PAU 5A by year and stratum.

Fishing year	Chalky	Dusky	South Coast	Total
1991		1 273		1 273
1996	798		13	811
2002	657	1 174	638	2 469
Total	1 455	2 447	651	4 553

Table 13: Summary of tag-recapture datasets from PAU 5A.

Area	Release	Recovery	Tagged	Recovered	% Recovery
Landing Bay	06 Nov 2000	10 Nov 2001	629	73	11.6%
Red Head	05 Nov 2000	09 Nov 2001	834	91	10.9%
Poison Bay	12 May 2000	28 May 2001	843	135	16.0%
Total			2 306	299	13.0%

Table 14: Estimated value for growth model parameters from fits to the tag data from PAU 5A made outside the population model. For parameters see section 2.2.

Quantity	Landing Bay	Red Head	Poison Bay	All PAU 5A
g_α	33.28	20.85	11.35	20.70
g_β	7.62	7.10	1.67	4.84
δ	5.68	2.40	1.00	5.54
ϕ	0.06	0.49	0.79	0.72
σ_{MIN}	2.98	1.64	1.64	2.49
$-\ln(L)$	183.3	224.1	242.3	834.1

Table 15: Numbers of paua examined and mature in PAU 5A.

Length (mm)	Examined	Mature
71	1	0
73	0	0
75	0	0
77	2	1
79	1	0
81	2	0
83	4	3
85	1	0
87	1	0
89	3	3
91	3	3
93	4	4
95	3	3
97	4	4
99	4	4
Total	33	25

Table 16: PAU 5A final base case: for estimated parameters, the phase of estimation (negative indicates fixed), lower bound, upper bound, type of prior (0 uniform, 1 normal, 2 lognormal), mean of the prior, standard deviation of the prior and initial values; for other variables, values used for the base case. "Varied" means fixed in the base case, varied between runs to find a base case.

Variable	Source	Phase	LB	UB	Prior	Mean	StdDev	Initial
z	est	1	0.01	100	0	-	-	15.5
M	est	1	0.01	0.5	2	0.1	0.1	0.22
g_α	est	2	1	50	0	-	-	15
g_β	est	2	0.01	50	0	-	-	8
ϕ	est	2	0.001	1	0	-	-	0.5
$\ln(q^I)$	est	1	-30	0	0	-	-	-13
δ	fixed	-	0.001	5	0	-	-	2.5
L_{50}	fixed	-	70	145	0	-	-	90
L_{95-50}	fixed	-	1	50	0	-	-	7
T_{50}	fixed	-	70	125	0	-	-	107
T_{95-50}	fixed	-	0.001	50	0	-	-	26
D_{50}	fixed	-	70	145	0	-	-	126
D_{95-50}	est	2	0.01	50	0	-	-	6
$\ln(\tilde{\sigma})$	est	1	-10	10	0	-	-	-1
h	fixed	-	0.01	2	0	-	-	0.8
ε	est	3	-2.3	2.3	1	0	0.4	0
σ_{MIN}	fixed	-	0.001	5	0	-	-	1
σ_{obs}	fixed	-	0.001	5	0	-	-	0.25
MLS								125
ϖ^I	varied							1
ϖ^J	varied							1
ϖ^r	varied							15
ϖ^s	varied							10
ϖ^{mat}	fixed							[1]
$U^{\max}$	fixed							0.8
α	fixed							75
β	fixed							120
a	fixed							2.99E-8
b	fixed							3.303

Table 17: Base case MPD results for PAU 5A. "sdnr" indicates the standard deviation of normalised residuals. Shading indicates a fixed parameter.

	Quantity	value
Std dev of normalised residuals	sdnrCPUE	2.527
	sdnrRDSI	4.208
	sdnrCSLF	0.897
	sdnrRDLF	0.480
	sdnrTags	0.990
Parameters	$\tilde{\sigma}$	0.182
	z	15.23
	M	0.262
	D_{50}	126
	D_{95-50}	6.12
	$\ln(q^I)$	-2.179
	g_α	12.7
	g_β	5.2
	ϕ	0.749
	δ	25
	h	0.80
Likelihoods	CPUE	20.4
	RDSI	12.9
	CSLF	-653.7
	RDLF	-320.1
	Tags	849.1
Prior contributions	M	43.6
	ε	18.9
	Total	-28.9
Indicators	*U(04)*	0.163
	Bav	978
	B(04)	946
	B(04)/Bav	0.967
	B(07)	624
	B(07)/Bav	0.638
	S(04)	1827
	S(07)	1705
	maxU	0.186
	Year of maxU	1997

Table 18: Convergence diagnostics from the base case McMC for PAU 5A for estimated and derived parameters. An asterisk indicates that the test statistic was significantly different (P=0.05) from that indicating convergence. RL: Raftery & Lewis; HW: Heidleberger & Welsh.

Quantity	RL	Geweke	HW Stationarity	HW Halfwidth	Gelman
z		*	*		
$\tilde{\sigma}$					
M			*		
g_α					
g_β					
D_{95-50}					
φ					
$\ln(q^I)$	*	*	*		
U_{07}	*		*		
Sav		*	*		
S(04)		*	*		
S(05)		*	*		
S(06)		*	*		
S(07)		*	*		
Bav		*	*		
B(04)		*	*		
B(05)		*	*		
B(06)		*	*		
B(07)		*	*		
S04/Sav					
S07/Sav					
S07/S04					
B04/Bav					
B07/Bav					
B07/B04			**		

Table 19: Correlations among parameters in the base case PAU 5A McMC. Boxes indicate absolute values grater than 0.50. Correlations among the ε are not shown: the largest was -0.41.

	z	$\ln(\tilde{\sigma})$	M	g_α	g_β	D_{95-50}	φ	$\ln(q^I)$
z	1.00							
$\ln(\tilde{\sigma})$	-0.20	1.00						
M	0.36	-0.58	1.00					
g_α	-0.54	0.17	-0.14	1.00				
g_β	-0.73	0.12	-0.17	0.79	1.00			
D_{95-50}	-0.28	0.15	-0.26	0.15	0.11	1.00		
φ	0.39	-0.04	0.00	-0.64	-0.74	-0.06	1.00	
$\ln(q^I)$	-0.85	0.43	-0.76	0.38	0.55	0.35	-0.24	1.00

Table 20: Summary of posterior distributions for the PAU 5A base case. For each quantity is shown the minimum and maximum values in the 5000 runs, the 5th and 95th quantiles, and the mean and median. The last column shows the position of the MPD estimate in the posterior distribution. The last four rows show the percentage of runs for which the stated criterion was true.

Quantity	Min	0.05	Median	Mean	0.95	Max	%MPD
z	12.94	14.35	15.65	15.86	18.09	22.99	31.3
ln(*R0*)	2.86	3.65	4.42	4.52	5.74	7.68	32.2
$\tilde{\sigma}$	0.153	0.170	0.183	0.183	0.197	0.216	48.3
M	0.171	0.228	0.273	0.273	0.318	0.366	34.3
g_α	10.21	11.39	12.40	12.40	13.44	14.61	68.8
g_β	4.15	4.67	5.04	5.04	5.42	5.78	76.1
D_{95-50}	4.2	5.1	6.0	6.0	7.1	8.6	57.2
φ	0.64	0.70	0.78	0.78	0.87	0.97	28.6
$\ln\left(q^I\right)$	-4.59	-3.29	-2.38	-2.47	-1.96	-1.65	75.5
$\ln\left(q^J\right)$	-7.65	-5.96	-4.84	-4.94	-4.31	-3.90	74.9
sdnrCPUE	2.097	2.309	2.544	2.544	2.779	3.278	44.8
sdnrRDSI	2.128	3.269	4.152	4.153	5.020	5.866	54.4
sdnrCSLF	0.755	0.826	0.889	0.889	0.951	1.016	58.9
sdnrRDLF	0.374	0.432	0.487	0.489	0.552	0.652	42.0
sdnrTags	0.849	0.919	0.985	0.985	1.053	1.162	53.7
U04	0.9%	4.2%	12.7%	12.7%	21.1%	31.9%	75.3
U07	1.1%	5.4%	17.6%	18.0%	32.2%	61.6%	74.2
Sav	836	1331	2384	3228	7690	42265	25.0
S04	853	1357	2360	3167	7497	40364	25.2
S05	749	1289	2326	3141	7571	45392	28.7
S06	636	1238	2345	3176	7810	47287	37.0
S07	537	1212	2393	3228	7949	46303	44.8
Bav	498	740	1265	1684	3972	20014	24.4
B04	448	713	1230	1645	3871	19237	24.6
B05	354	611	1087	1466	3519	17302	24.2
B06	271	517	959	1302	3186	15796	24.3
B07	200	439	863	1188	2971	15381	25.6
S04/Sav	80.7%	89.5%	99.2%	99.6%	110.8%	126.1%	60.0
S07/Sav	57.8%	76.3%	98.0%	99.9%	129.4%	178.1%	91.3
S07/S04	62.8%	79.3%	98.3%	100.3%	128.6%	182.5%	91.2
B04/Bav	86.7%	92.2%	97.2%	97.3%	102.3%	109.1%	43.2
B07/Bav	39.4%	56.0%	68.2%	68.0%	79.0%	90.3%	35.6
B07/B04	42.3%	59.1%	70.1%	69.9%	79.6%	89.9%	35.3
S07<S04				54.5%			
S07<Sav				54.7%			
B07<B04				100.0%			
B07<Bav				100.0%			

Table 21: McMC sensitivity trials and retrospective results for PAU 5A. Grey shading indicates a fixed parameter.

	Base case			less decline in RDSI			no RDSI data			no CPUE data			no CSLF data		
	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95
z	14.35	15.65	18.09	14.31	15.72	17.66	15.40	18.24	24.06	12.83	13.80	14.91	19.66	62.14	94.63
ln(*R0*)	3.65	4.42	5.74	3.79	4.56	5.65	4.77	6.06	8.44	1.67	1.91	2.19	5.21	16.60	24.83
$\tilde{\sigma}$	0.170	0.183	0.197	0.164	0.176	0.190	0.149	0.160	0.172	0.098	0.105	0.112	0.210	0.220	0.232
M	0.228	0.273	0.318	0.237	0.280	0.322	0.285	0.322	0.354	0.115	0.130	0.147	0.253	0.256	0.261
g_α	11.39	12.40	13.44	11.86	12.84	13.84	13.15	14.14	15.15	12.86	13.87	14.84	12.58	12.89	13.34
g_β	4.67	5.04	5.42	4.78	5.13	5.50	4.93	5.25	5.61	5.12	5.54	5.96	4.64	4.75	4.99
δ	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
D_{95-50}	5.1	6.0	7.1	5.1	6.0	7.0	5.2	6.0	6.9	5.1	5.6	6.2	0.2	1.9	5.2
φ	0.70	0.78	0.87	0.70	0.77	0.85	0.71	0.78	0.87	0.68	0.74	0.82	0.71	0.76	0.78
$\ln\left(q^I\right)$	-3.29	-2.38	-1.96	-3.20	-2.48	-2.04	-5.38	-3.55	-2.63	-28.34	-14.84	-1.52	-19.11	-12.53	-3.43
$\ln\left(q^J\right)$	-5.96	-4.84	-4.31	-5.85	-4.95	-4.41	-8.54	-6.25	-5.12	-3.72	-3.59	-3.47	-25.45	-17.22	-5.86
h	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800
sdnrCPUE	2.309	2.544	2.779	2.298	2.530	2.765	2.215	2.423	2.650	27.664	360.073	734.631	1.795	1.916	2.077
sdnrRDSI	3.269	4.152	5.020	2.408	3.288	4.196	9.349	11.100	13.019	0.050	0.511	1.446	3.708	4.099	4.476
sdnrCSLF	0.826	0.889	0.951	0.852	0.914	0.977	0.900	0.966	1.031	1.047	1.114	1.188	0.872	0.929	0.994
sdnrRDLF	0.432	0.487	0.552	0.441	0.497	0.559	0.486	0.551	0.626	0.612	0.693	0.777	0.432	0.454	0.484
sdnrTags	0.919	0.985	1.053	0.911	0.978	1.043	0.865	0.937	1.006	0.878	0.936	0.998	1.046	1.065	1.081
LikeCPUE	10.7	21.6	33.9	9.2	20.1	32.6	2.6	12.3	23.9	2.8E+04	7.1E+06	2.9E+07	-7.8	-4.3	1.3
LikeRDSI	5.9	12.4	20.4	0.9	5.9	12.7	82.4	118.2	164.4	-5.9	-5.6	-3.8	9.3	12.4	15.6
LikeCSLF	-669.1	-655.0	-640.1	-671.8	-658.8	-644.5	-681.3	-671.4	-659.1	-752.8	-740.7	-727.0	-608.5	-595.6	-584.2
LikeRDLF	-325.9	-319.3	-312.3	-329.9	-323.4	-316.4	-338.7	-331.7	-324.4	-380.4	-372.3	-365.5	-302.6	-299.1	-291.9
LikeTags	847.4	849.9	853.7	847.0	848.9	852.5	846.6	848.4	852.9	847.5	850.9	856.7	847.4	849.1	851.1
Prior on M	31.3	47.7	64.3	34.3	50.4	65.7	52.1	65.7	77.5	-2.6	0.0	4.1	40.4	41.3	43.4
Prior on ε	24.1	31.2	40.0	22.9	29.5	37.8	21.1	27.0	34.3	35.1	44.6	55.0	34.6	42.1	45.9
Total	-17	-10	-2	-32	-26	-18	-55	-49	-41	-228	-222	-214	633	644	648

Table 21 continued.

	Base case			less decline in RDSI			no RDSI data			no CPUE data			no CSLF data		
	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95
U04	4.2%	12.7%	21.1%	4.6%	11.0%	18.6%	0.3%	2.6%	8.1%	44.4%	52.7%	61.4%	0.0%	0.0%	3.6%
U07	5.4%	17.6%	32.2%	5.8%	14.3%	26.0%	0.3%	2.7%	8.5%	80.0%	80.0%	80.0%	0.0%	0.0%	4.6%
PCatIndex	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	60.6%	72.7%	86.5%	100.0%	100.0%	100.0%
Sav	1331	2384	7690	1460	2629	6798	3004	9721	98693	568	703	890	7603	6.4E+08	2.4E+12
S04	1357	2360	7497	1578	2790	6855	4119	13298	130866	399	483	593	7205	6.3E+08	2.3E+12
S05	1289	2326	7571	1527	2754	6939	4121	13381	131391	308	395	517	7026	6.4E+08	2.3E+12
S06	1238	2345	7810	1480	2776	7095	4161	13510	133311	255	346	480	6949	6.5E+08	2.3E+12
S07	1212	2393	7949	1456	2806	7249	4148	13648	132979	241	339	489	6918	6.6E+08	2.5E+12
Bav	740	1265	3972	818	1423	3501	1721	5420	53550	173	237	326	4767	4.0E+08	1.5E+12
B04	713	1230	3871	820	1432	3537	1999	6299	61519	196	241	300	4492	4.1E+08	1.5E+12
B05	611	1087	3519	724	1295	3229	1946	6238	60363	120	157	216	4106	3.8E+08	1.4E+12
B06	517	959	3186	631	1163	2962	1898	6134	59319	72	96	135	3758	3.6E+08	1.3E+12
B07	439	863	2971	562	1082	2782	1871	6113	58896	58	73	95	3515	3.3E+08	1.2E+12
S04/Sav	89.5%	99.2%	110.8%	95.5%	105.5%	117.9%	120.3%	136.5%	159.6%	59.6%	68.4%	79.8%	93.3%	98.0%	101.9%
S07/Sav	76.3%	98.0%	129.4%	83.2%	105.8%	135.0%	114.2%	139.0%	170.9%	35.1%	47.7%	69.3%	82.4%	93.4%	133.5%
S07/S04	79.3%	98.3%	128.6%	81.5%	99.8%	125.4%	88.8%	101.3%	117.3%	53.6%	69.0%	97.8%	85.4%	94.9%	135.5%
B04/Bav	92.2%	97.2%	102.3%	95.9%	100.7%	105.9%	109.7%	116.0%	122.4%	78.9%	102.0%	132.5%	93.7%	99.2%	103.0%
B07/Bav	56.0%	68.2%	79.0%	64.3%	75.7%	86.0%	97.4%	111.3%	130.7%	22.9%	31.0%	42.3%	73.4%	81.1%	84.7%
B07/B04	59.1%	70.1%	79.6%	65.2%	74.9%	84.1%	85.9%	95.8%	109.9%	24.4%	30.1%	39.2%	77.8%	81.3%	84.2%
S07<S04		54.5%			50.6%			44.0%			95.9%			64.8%	
S07<Sav		54.7%			34.9%			0.4%			99.9%			67.4%	
B07<B04		100.0%			100.0%			71.3%			100.0%			100.0%	
B07<Bav		100.0%			100.0%			9.7%			100.0%			100.0%	

Table 21 continued.

	no RDLF data			no tagging data			estimate δ			estimate h			estimate h and δ		
	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95
z	16.33	17.45	18.65	57.18	89.93	97.05	14.35	15.63	18.40	17.21	19.06	21.52	16.46	19.58	22.38
ln($R0$)	1.92	2.10	2.31	20.36	30.85	34.37	3.64	4.42	5.86	4.32	5.00	6.06	4.38	5.12	6.33
$\tilde{\sigma}$	0.235	0.253	0.273	0.161	0.172	0.178	0.170	0.183	0.197	0.146	0.155	0.166	0.146	0.156	0.167
M	0.104	0.113	0.122	0.319	0.340	0.351	0.229	0.273	0.320	0.227	0.253	0.281	0.229	0.255	0.283
g_α	12.22	13.31	14.47	12.40	12.74	13.23	10.52	12.82	15.37	10.77	11.65	12.64	11.07	13.27	16.06
g_β	4.80	5.17	5.56	5.16	5.35	5.59	4.62	5.02	5.43	4.18	4.49	4.85	4.10	4.40	4.95
δ	2.50	2.50	2.50	2.50	2.50	2.50	1.52	2.73	3.88	2.50	2.50	2.50	2.33	3.33	4.31
$D_{95\sim50}$	6.0	7.6	9.5	4.7	5.3	6.1	5.0	6.0	7.0	4.7	5.5	6.3	4.7	5.4	6.3
φ	0.70	0.78	0.87	0.02	0.16	0.24	0.70	0.77	0.86	0.75	0.83	0.92	0.72	0.82	0.92
$\ln\left(q^I\right)$	-1.68	-1.52	-1.38	-25.90	-23.14	-14.70	-3.42	-2.40	-1.96	-9.11	-7.23	-6.14	-9.82	-7.64	-6.30
$\ln\left(q^J\right)$	-3.84	-3.70	-3.57	-34.27	-30.80	-20.24	-6.10	-4.85	-4.32	-6.45	-5.51	-4.96	-6.78	-5.68	-5.03
h	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	0.800	1.984	1.996	2.000	1.982	1.988	1.999
sdnrCPUE	1.992	2.238	2.491	2.437	2.589	2.871	2.313	2.552	2.797	1.999	2.189	2.398	1.998	2.190	2.399
sdnrRDSI	2.516	3.257	4.022	2.261	2.952	3.825	3.277	4.186	5.096	4.268	5.038	5.846	4.396	5.291	6.169
sdnrCSLF	0.709	0.770	0.836	0.834	0.886	0.932	0.824	0.886	0.952	0.864	0.922	0.981	0.858	0.915	0.973
sdnrRDLF	0.319	0.351	0.386	0.535	0.570	0.636	0.424	0.481	0.550	0.477	0.532	0.593	0.442	0.505	0.574
sdnrTags	0.890	0.959	1.029	2.916	3.994	4.510	0.923	0.987	1.057	0.964	1.027	1.093	0.971	1.037	1.102
LikeCPUE	4.6	14.3	25.4	14.1	22.1	36.3	10.9	22.2	35.5	-8.0	-0.7	8.3	-7.9	-0.5	8.6
LikeRDSI	2.2	6.5	12.0	0.2	3.8	9.7	5.9	12.7	21.2	13.2	20.3	29.0	14.2	22.9	33.0
LikeCSLF	-606.0	-595.7	-584.0	-683.9	-673.4	-665.3	-669.3	-654.8	-639.8	-698.8	-689.3	-678.8	-699.1	-690.3	-680.1
LikeRDLF	-294.3	-286.5	-277.9	-327.7	-322.2	-317.9	-326.2	-319.5	-312.2	-342.1	-336.4	-330.4	-343.9	-337.6	-331.4
LikeTags	846.7	848.2	851.8	1651.4	2695.8	3327.6	846.0	849.5	854.9	848.4	852.4	857.8	845.9	851.1	856.9
Prior on M	-4.1	-1.5	3.9	64.8	72.5	76.4	31.4	47.7	65.2	30.8	40.4	50.6	31.3	41.1	51.4
Prior on ε	29.7	35.6	43.0	25.8	32.4	39.8	24.4	31.4	39.9	18.8	25.2	33.3	18.0	24.6	32.4
Total	303	309	317	-874	-864	-858	-16	-9	-1	-93	-87	-79	-94	-88	-80

Table 21 continued.

	no RDLF data			no tagging data			estimate δ			estimate h			estimate h and δ		
	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95	0.05	median	0.95
U04	28.5%	34.7%	41.4%	0.0%	0.0%	0.0%	3.6%	12.5%	21.1%	2.4%	6.0%	10.3%	1.6%	4.9%	9.5%
U07	44.7%	65.8%	80.0%	0.0%	0.0%	0.0%	4.5%	17.0%	32.5%	3.0%	7.6%	13.4%	2.0%	6.0%	12.3%
PCatIndex	91.3%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Sav	566	660	784	1.3E+10	5.3E+14	1.7E+16	1335	2397	8890	3021	5436	14477	3236	6475	20191
S04	577	702	864	1.2E+10	4.6E+14	1.5E+16	1348	2408	8734	2766	4844	12530	2979	5885	17843
S05	488	630	823	1.2E+10	4.8E+14	1.6E+16	1298	2396	8762	2695	4781	12428	2914	5847	18001
S06	402	571	840	1.3E+10	4.9E+14	1.6E+16	1249	2410	8999	2650	4772	12414	2862	5852	18209
S07	333	526	871	1.4E+10	5.0E+14	1.6E+16	1213	2443	9130	2619	4799	12650	2855	5894	18493
Bav	359	431	522	6.2E+09	2.4E+14	7.4E+15	746	1288	4597	1529	2648	6783	1659	3280	9880
B04	332	409	510	6.3E+09	2.4E+14	7.7E+15	715	1254	4563	1542	2680	6878	1680	3328	9992
B05	256	337	441	5.6E+09	2.1E+14	6.7E+15	613	1115	4155	1408	2474	6370	1538	3090	9303
B06	170	258	369	4.8E+09	1.8E+14	5.7E+15	513	983	3827	1269	2260	5837	1382	2849	8693
B07	103	181	298	4.3E+09	1.6E+14	5.2E+15	435	893	3571	1151	2084	5474	1269	2681	8306
S04/Sav	94.9%	106.1%	118.5%	83.7%	87.9%	96.3%	89.9%	99.8%	112.3%	81.8%	88.7%	97.0%	82.7%	90.2%	99.4%
S07/Sav	53.7%	78.1%	127.8%	76.0%	94.3%	112.4%	76.2%	99.7%	131.6%	71.6%	87.4%	107.5%	73.3%	90.0%	111.3%
S07/S04	54.2%	72.3%	118.2%	87.0%	106.1%	125.2%	78.8%	98.8%	130.0%	83.2%	97.7%	119.2%	83.8%	99.2%	120.7%
B04/Bav	86.9%	95.0%	103.5%	98.9%	102.2%	106.2%	92.4%	97.2%	102.4%	98.6%	101.0%	103.6%	98.7%	101.1%	103.6%
B07/Bav	26.7%	41.9%	60.7%	65.4%	68.8%	74.8%	56.0%	69.1%	80.9%	72.2%	78.5%	84.9%	73.4%	80.8%	88.3%
B07/B04	29.8%	44.2%	60.7%	64.4%	66.6%	74.9%	58.9%	71.1%	81.8%	72.2%	77.7%	83.1%	73.3%	79.9%	86.6%
S07<S04		85.1%			30.2%			52.8%			57.4%			52.9%	
S07<Sav		80.3%			68.7%			50.9%			85.5%			79.1%	
B07<B04		100.0%			100.0%			100.0%			100.0%			100.0%	
B07<Bav		100.0%			100.0%			100.0%			100.0%			100.0%	

Table 21 continued.

	basecase 0.05	basecase median	basecase 0.95	retro03 0.05	retro03 median	retro03 0.95	retro02 0.05	retro02 median	retro02 0.95	retro01 0.05	retro01 median	retro01 0.95
z	14.31	15.56	17.24	14.45	15.69	17.27	13.08	14.08	15.16	14.32	15.37	16.39
$\ln(R0)$	3.62	4.33	5.32	3.48	4.19	5.08	3.08	3.63	4.22	1.75	1.90	2.04
$\tilde{\sigma}$	0.171	0.184	0.198	0.177	0.191	0.206	0.161	0.174	0.190	0.447	0.483	0.522
M	0.227	0.269	0.310	0.214	0.258	0.298	0.204	0.249	0.288	0.103	0.115	0.129
g_α	11.45	12.43	13.39	11.62	12.56	13.60	12.59	13.61	14.70	16.39	17.57	18.80
g_β	4.71	5.06	5.43	4.74	5.09	5.45	4.92	5.28	5.66	5.72	6.09	6.48
D_{95-50}	5.1	6.0	7.1	5.1	6.1	7.2	5.5	6.6	7.7	46.8	47.8	49.7
φ	0.70	0.77	0.86	0.70	0.77	0.85	0.69	0.76	0.84	0.66	0.72	0.80
$\ln\left(q^I\right)$	-2.97	-2.33	-1.95	-2.85	-2.30	-1.93	-2.19	-1.87	-1.60	-1.05	-0.92	-0.84
$\ln\left(q^J\right)$	-5.55	-4.77	-4.31	-5.40	-4.71	-4.25	-4.60	-4.20	-3.87	-1.31	-1.26	-1.21
sdnrCPUE	2.309	2.545	2.794	2.261	2.498	2.736	2.080	2.313	2.566	1.237	1.443	1.668
sdnrRDSI	3.245	4.119	5.018	3.192	4.043	4.902	1.676	2.611	3.535	–	–	–
sdnrCSLF	0.828	0.888	0.950	0.833	0.897	0.965	0.903	0.977	1.053	0.553	0.608	0.663
sdnrRDLF	0.430	0.483	0.543	0.409	0.457	0.514	0.446	0.498	0.555	0.115	0.136	0.159
sdnrTags	0.922	0.984	1.051	0.922	0.986	1.050	0.890	0.955	1.024	0.834	0.903	0.971
LikeCPUE	10.6	21.8	34.7	9.3	20.4	32.7	0.2	10.0	21.6	-7.1	-2.9	2.8
LikeRDSI	5.8	12.2	20.3	5.5	11.7	19.3	-2.1	1.9	7.6	71.2	83.3	96.7
LikeCSLF	-666.9	-653.7	-639.5	-594.2	-581.7	-568.0	-507.7	-496.2	-484.0	-294.2	-283.7	-272.9
LikeRDLF	-325.6	-318.9	-311.9	-322.8	-315.6	-308.0	-331.5	-324.6	-316.6	-129.7	-123.5	-117.2
LikeTags	847.5	849.9	853.7	847.3	849.6	852.9	846.6	848.4	852.1	854.4	861.1	869.9
Prior on M	30.9	46.1	61.5	26.0	42.0	57.0	22.5	38.7	53.3	-3.6	-2.5	-0.1
Prior on ε	24.0	30.8	39.5	23.5	29.9	38.1	23.6	29.9	37.5	26.7	31.9	39.0
Total	-17	-11	-3	51	57	65	103	109	116	559	565	572

Table 21 continued.

	basecase 0.05	basecase median	basecase 0.95	retro03 0.05	retro03 median	retro03 0.95	retro02 0.05	retro02 median	retro02 0.95	retro01 0.05	retro01 median	retro01 0.95
U04	6.3%	13.5%	21.3%	7.4%	14.5%	22.4%	20.0%	30.4%	43.7%	48.2%	80.0%	80.0%
U07	8.2%	18.8%	32.6%	9.5%	19.5%	34.1%	24.5%	43.2%	80.0%	36.8%	80.0%	80.0%
PCatIndex	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	98.8%	100.0%	100.0%	59.3%	75.5%	100.0%
Sav	1316	2220	5064	1210	2008	4154	803	1169	1825	320	355	407
S04	1343	2217	4944	1352	2157	4302	891	1254	1892	383	437	510
S05	1278	2171	4913	1270	2092	4249	816	1192	1848	299	362	589
S06	1247	2180	4999	1211	2087	4306	752	1163	1902	231	295	662
S07	1202	2204	5140	1154	2119	4569	645	1183	2098	152	256	898
Bav	733	1185	2606	697	1108	2211	443	621	932	203	234	282
B04	705	1153	2566	747	1177	2336	455	636	955	178	209	252
B05	603	1017	2324	668	1073	2152	391	565	866	151	182	232
B06	506	894	2089	572	948	1937	309	473	758	111	139	209
B07	433	802	1921	412	771	1657	134	318	612	48	71	364
S04/Sav	89.8%	99.4%	110.9%	98.7%	107.1%	116.6%	99.5%	107.0%	115.2%	110.0%	122.2%	136.9%
S07/Sav	76.0%	97.9%	129.2%	77.7%	105.0%	140.2%	66.0%	100.7%	142.3%	41.3%	73.4%	253.7%
S07/S04	78.7%	97.6%	128.2%	73.1%	97.6%	129.8%	62.1%	93.7%	133.0%	34.3%	58.6%	204.1%
B04/Bav	91.9%	97.0%	102.2%	101.7%	106.1%	110.8%	98.1%	102.3%	106.9%	79.2%	89.2%	99.6%
B07/Bav	56.0%	67.3%	77.9%	56.0%	69.3%	81.0%	28.0%	50.2%	75.0%	19.6%	30.6%	150.3%
B07/B04	59.1%	69.3%	78.8%	53.0%	65.3%	76.0%	27.2%	49.3%	73.2%	22.2%	34.2%	169.2%
S07<S04		56.1%			55.1%			60.9%			67.9%	
S07<Sav		54.8%			40.0%			48.8%			55.6%	
B07<B04		100.0%			100.0%			100.0%			82.5%	
B07<Bav		100.0%			100.0%			99.9%			86.0%	

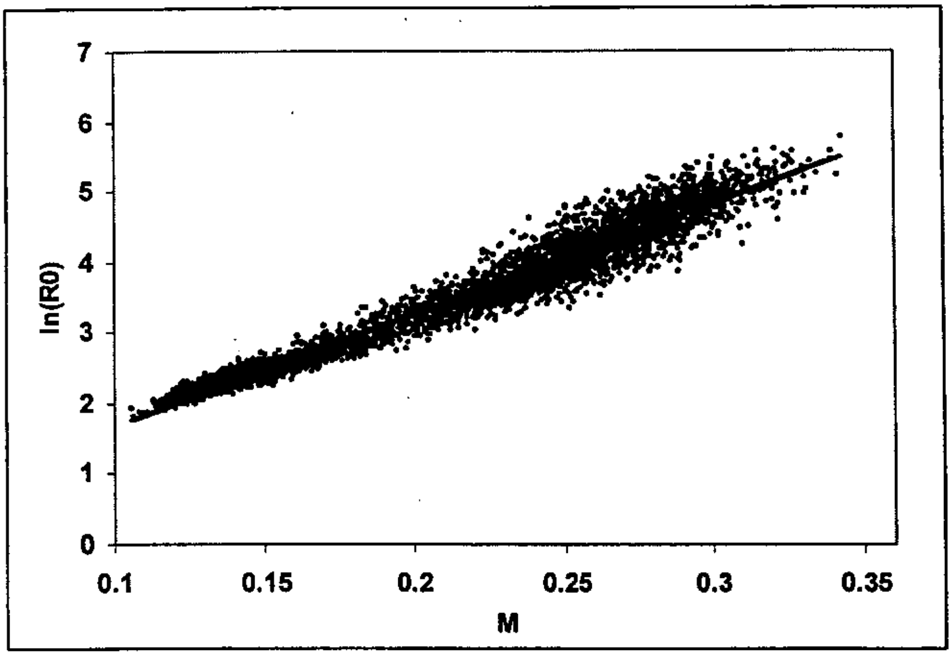


Figure 1: Observed (dots) and predicted (line) relation between ln(*R0*) and *M* from the posteriors in an early McMC rejected by the Working Group.

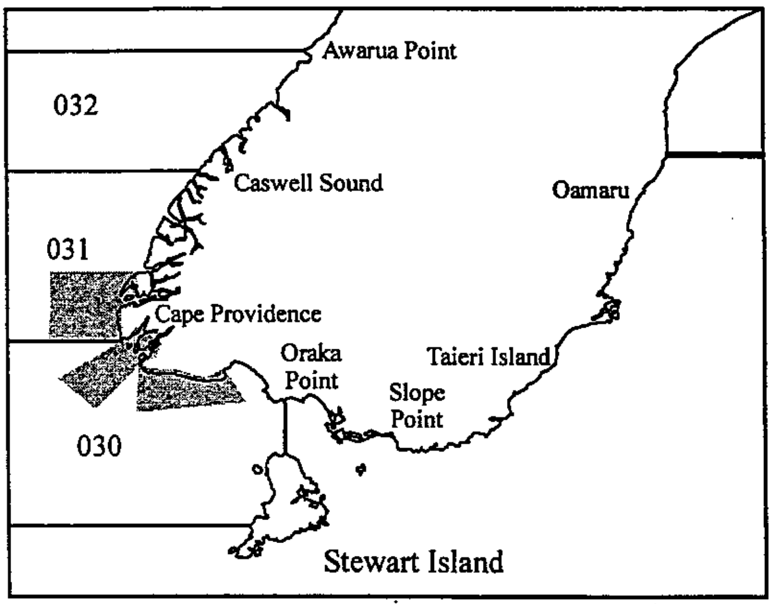


Figure 2: Boundaries of PAU 5A and its three statistical areas. Shaded areas are research strata: South Coast (lower, Chalky (middle) and Dusky. The line just north of Oamaru is the northern boundary of PAU 5D, the boundary of the old PAU 5.

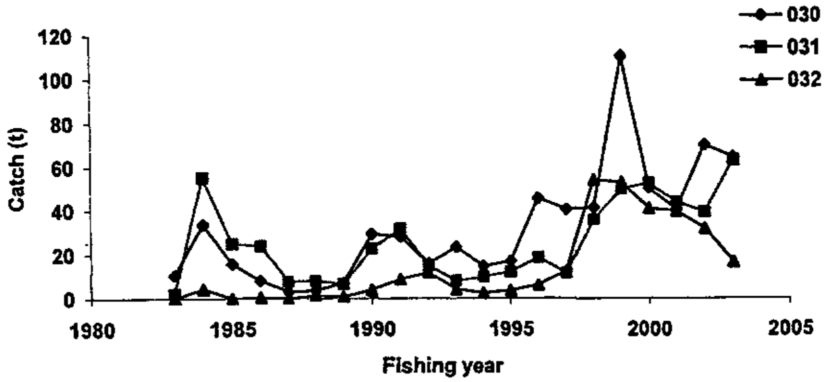


Figure 3: Estimated commercial catch in PAU 5 statistical areas.

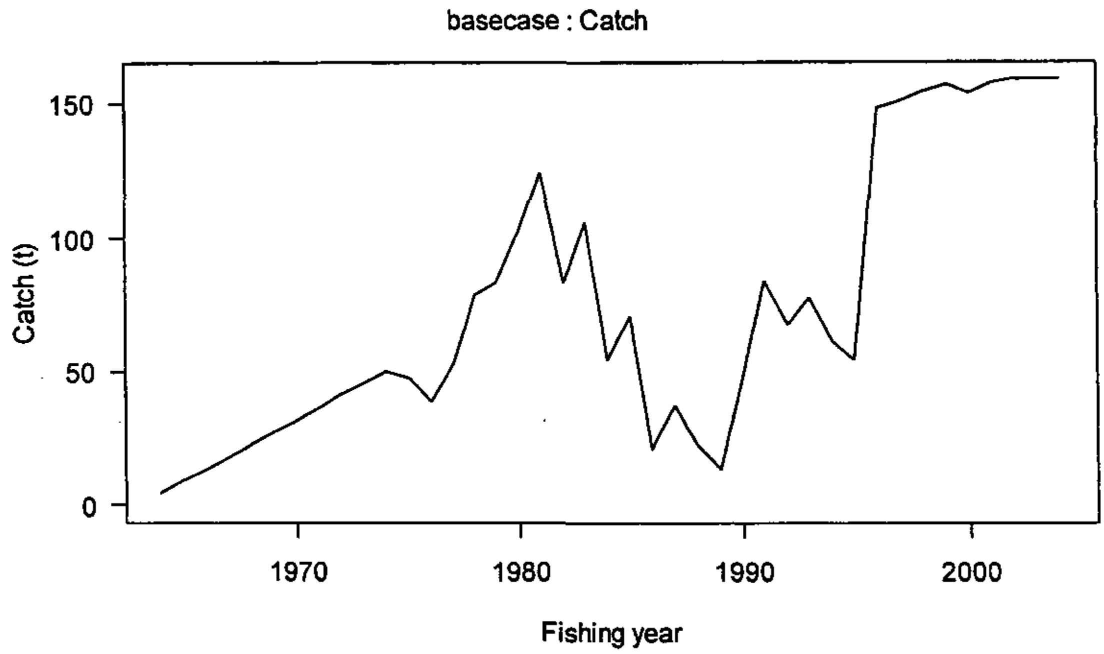


Figure 4: Estimated total catch for PAU 5A.

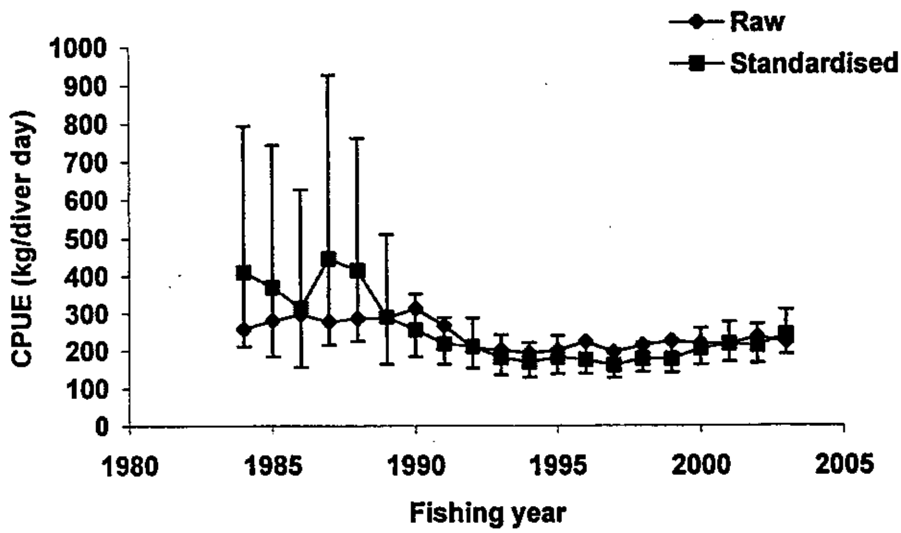


Figure 5: **Raw and standardised CPUE from all PAU 5A statistical areas using Option 1.**

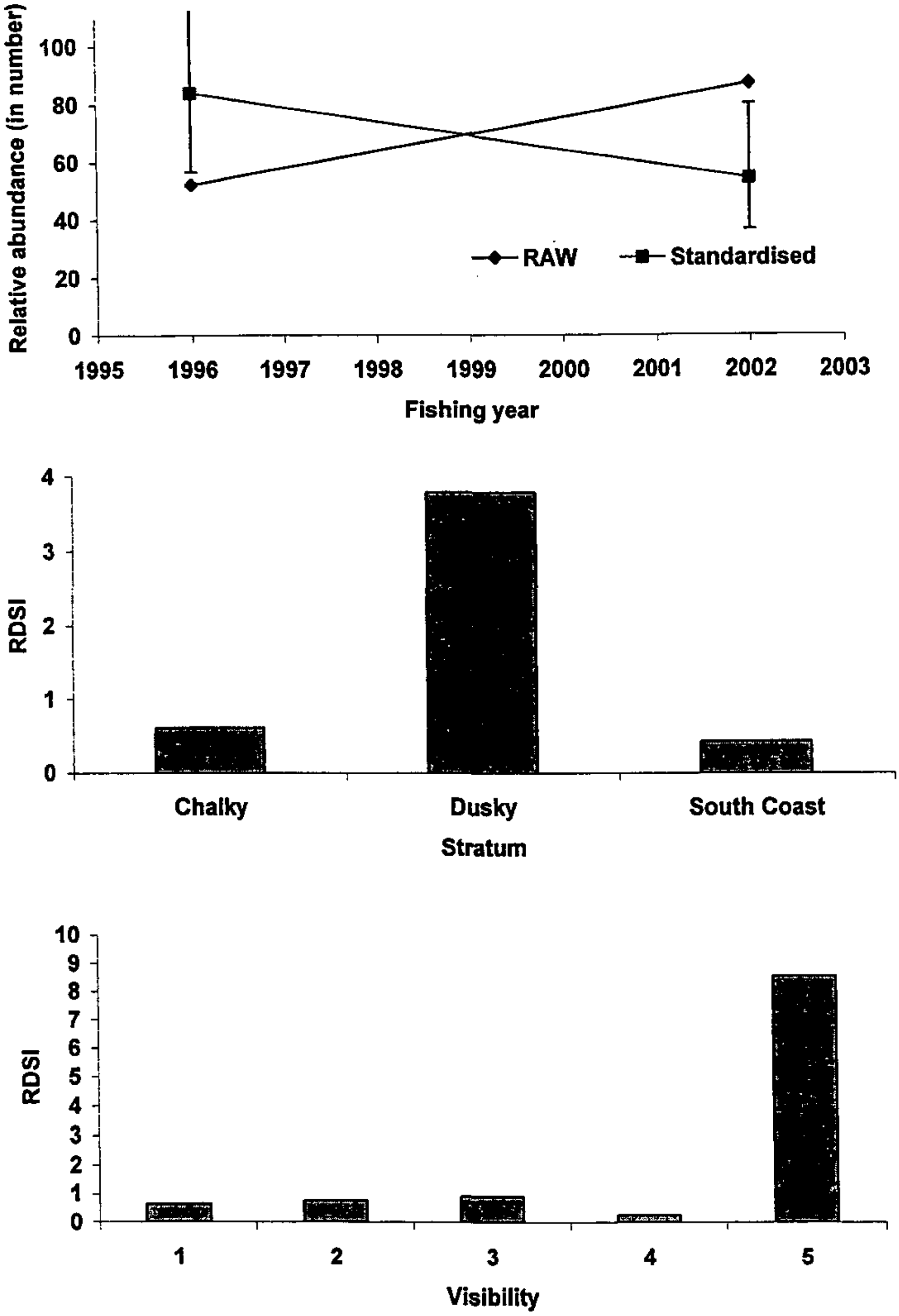


Figure 6: Raw and standardised RDSI for PAU 5A (top), stratum effects (middle) and visibility effects (bottom).

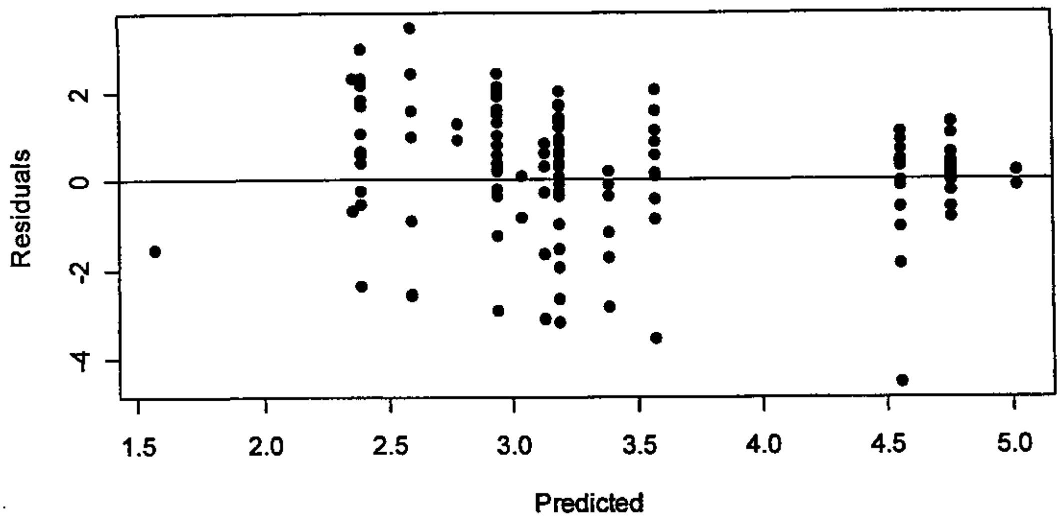
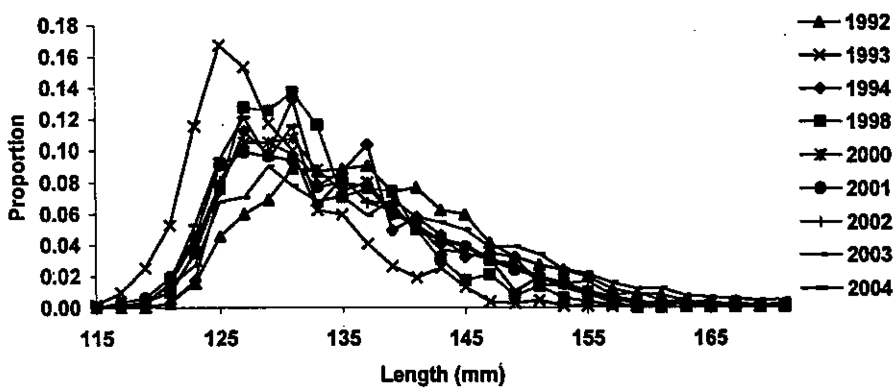


Figure 7: Residuals for the fits to the PAU 5A research diver survey data fitted with searching time incorporated. The x-axis shows the predicted timed-swim index in log space.



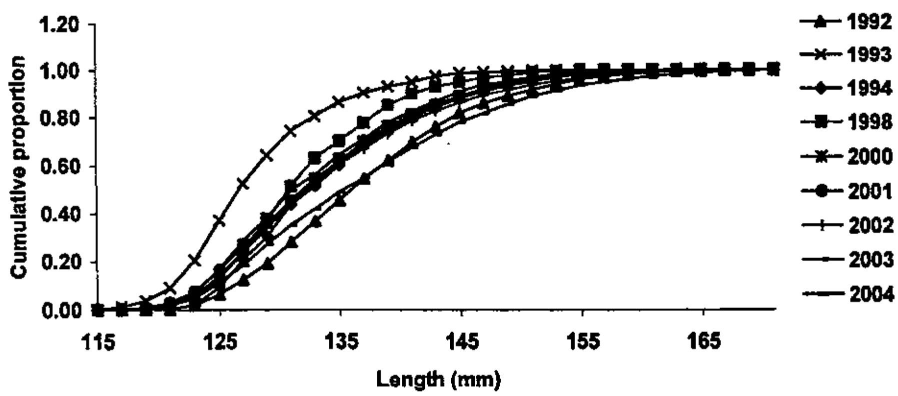


Figure 8: CSLF data from PAU 5A from each year, aggregated across strata, plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom).

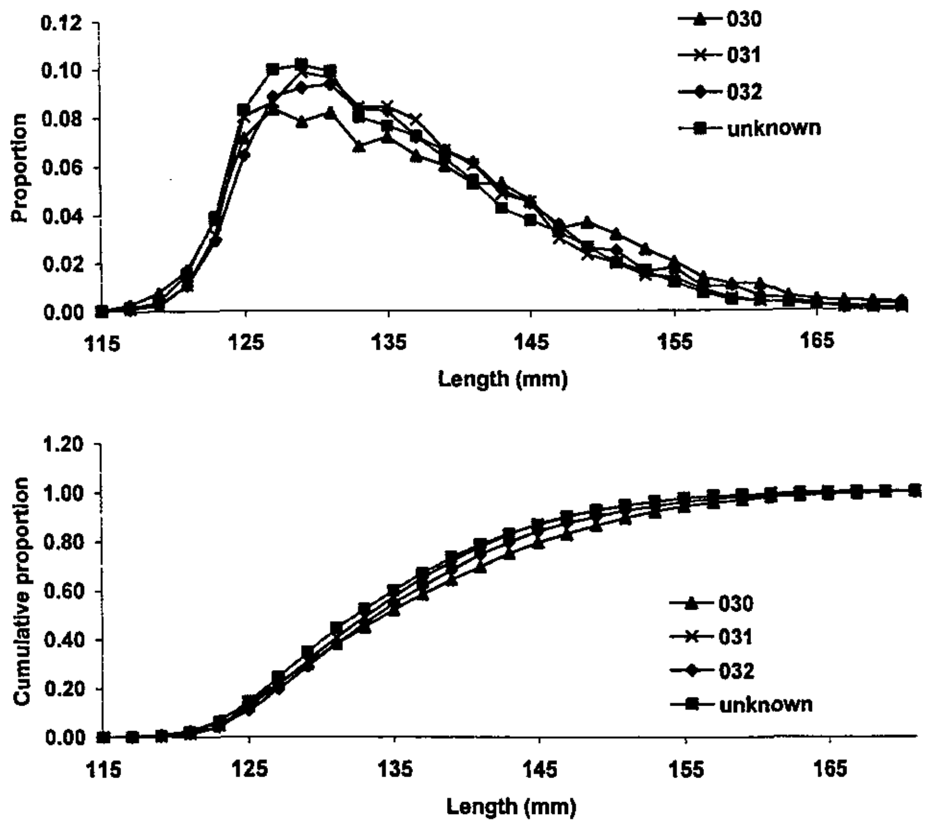


Figure 9: CSLF from each PAU 5A statistical area, summed across all years, plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom).

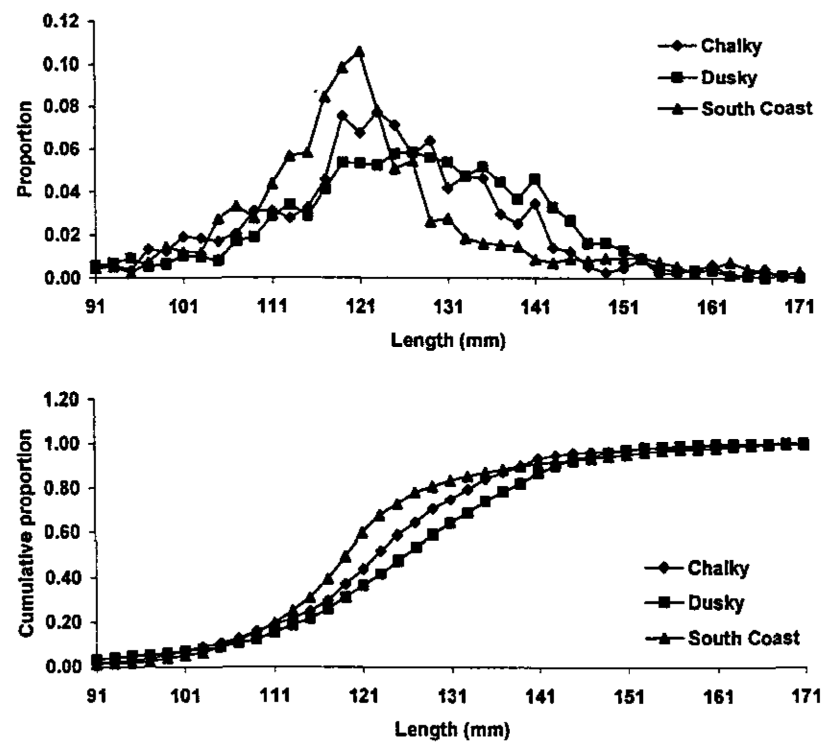


Figure 10: RDLF data from each PAU 5A stratum, plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom).

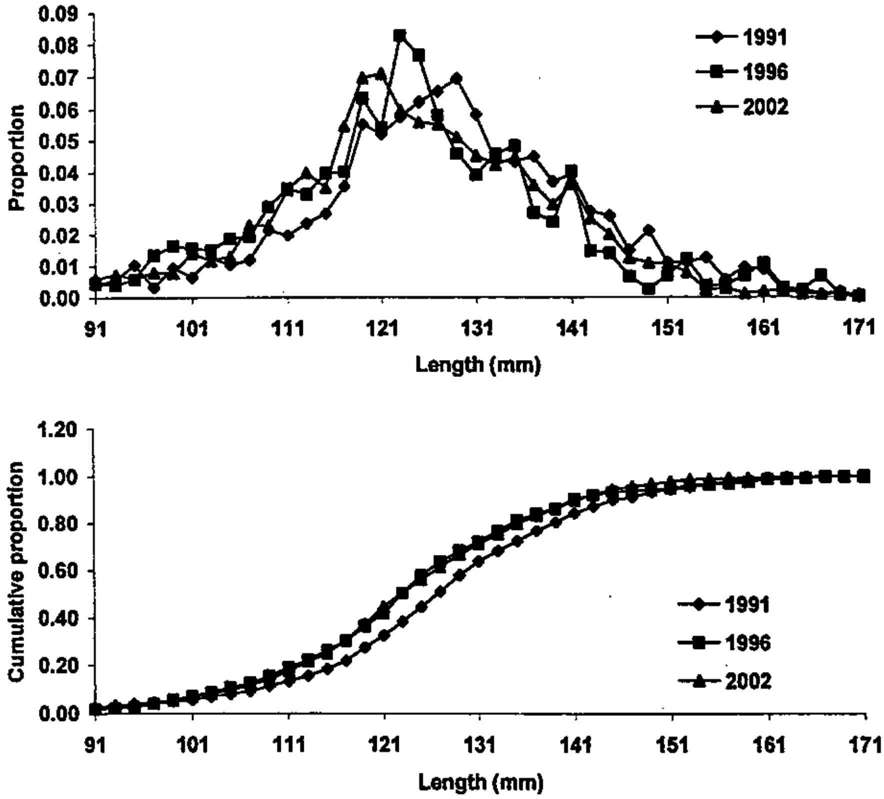


Figure 11: RDLF data from each year in PAU 5A, plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom).

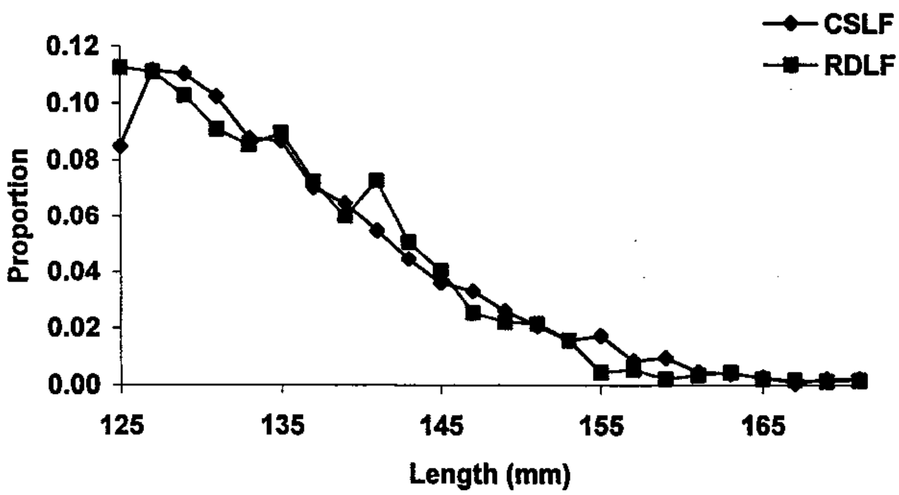


Figure 12: A comparison of CSLF and RDLF proportions-at-length, for lengths above the MLS for the 2002 fishing year, the only year of overlap.

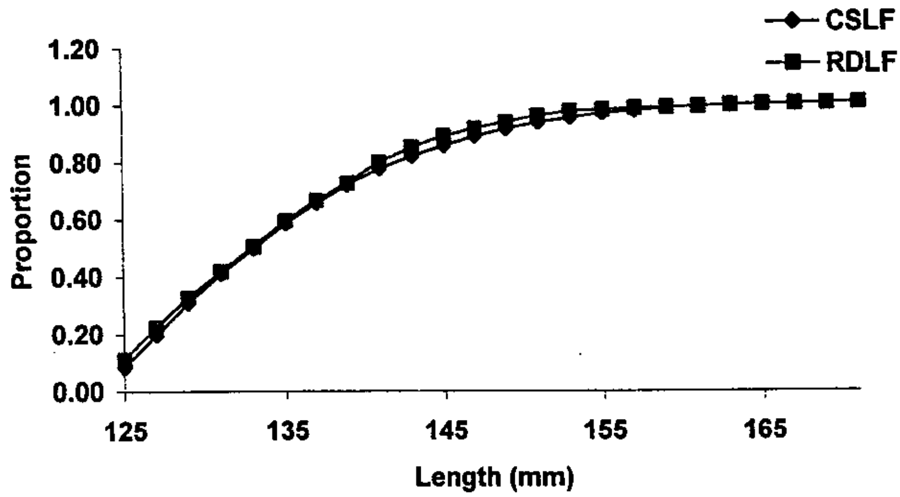


Figure 13: A comparison of cumulative proportions-at-length from CSLF and RDLF data for the 2002 fishing year.

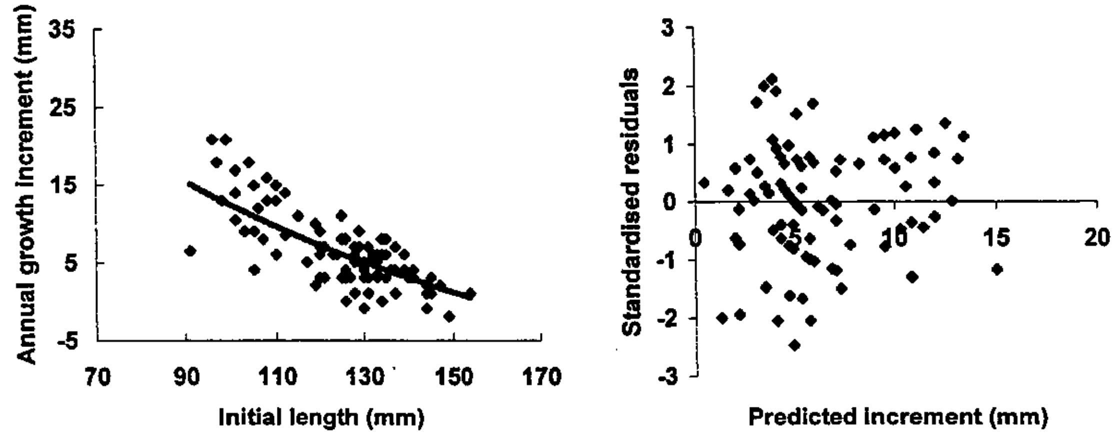


Figure 14: Observed (dots) and predicted (line) annual growth increments from tagging data from Red Head (left), and standardised residuals from the fit (right).

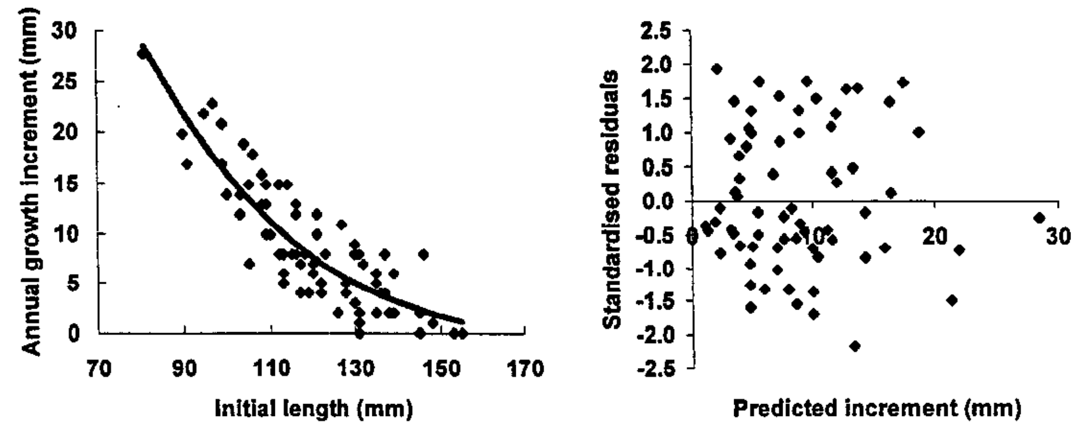


Figure 15: Observed (dots) and predicted (line) annual growth increments from tagging data from Landing Bay (left), and standardised residuals from the fit (right).

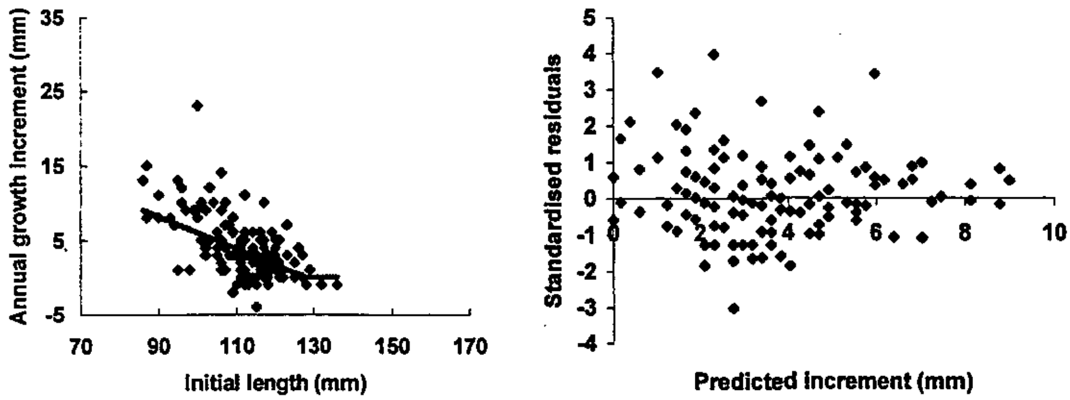


Figure 16: Observed (dots) and predicted (line) annual growth increments from tagging data from Poison Bay (left), and standardised residuals from the fit (right).

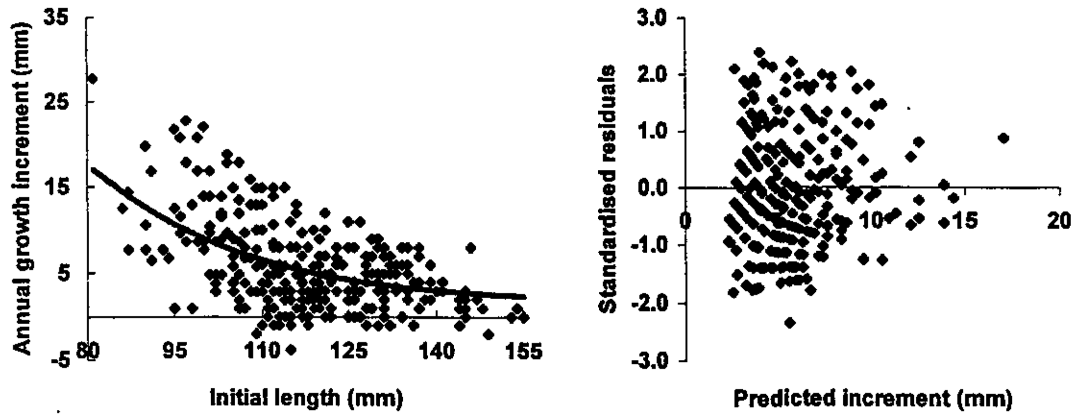


Figure 17: Observed (dots) and predicted (line) annual growth increments from tagging data from all PAU 5A areas (left), and standardised residuals from the fit (right).

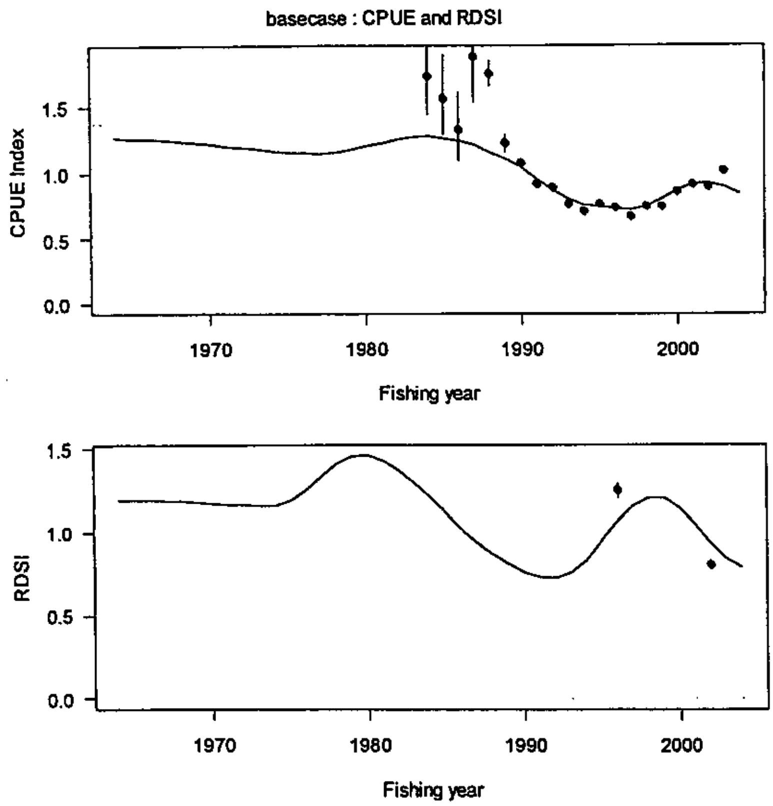


Figure 18: Observed (dots) and predicted (solid line) CPUE (top) and RDSI (bottom) for the base case MPD fit for PAU 5A. Error bars show the standard error term used by the model in fitting.

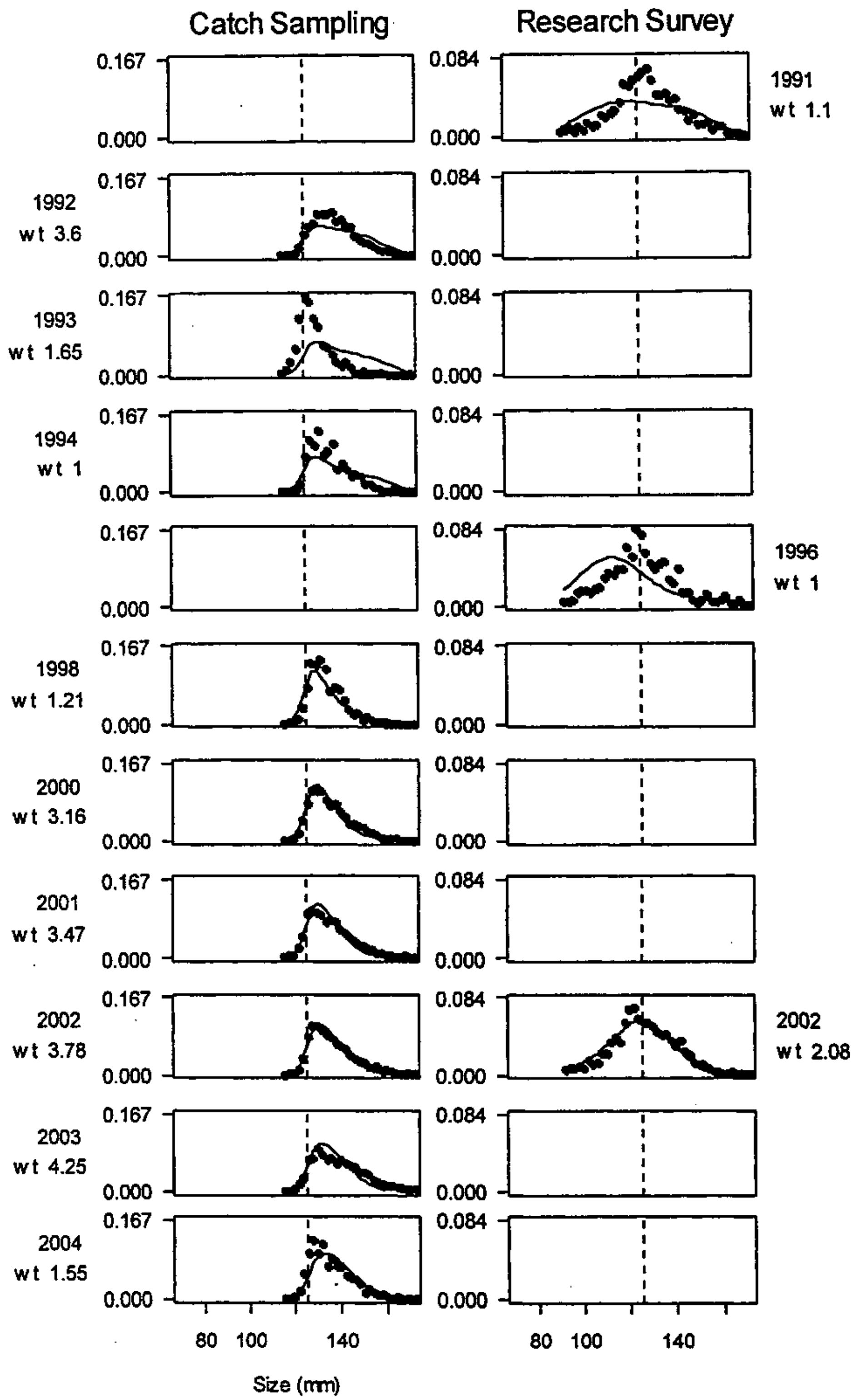


Figure 19: The base case MPD fits for PAU 5A to CSLF data (left) and RDSI data. The number under each year is κ_t.

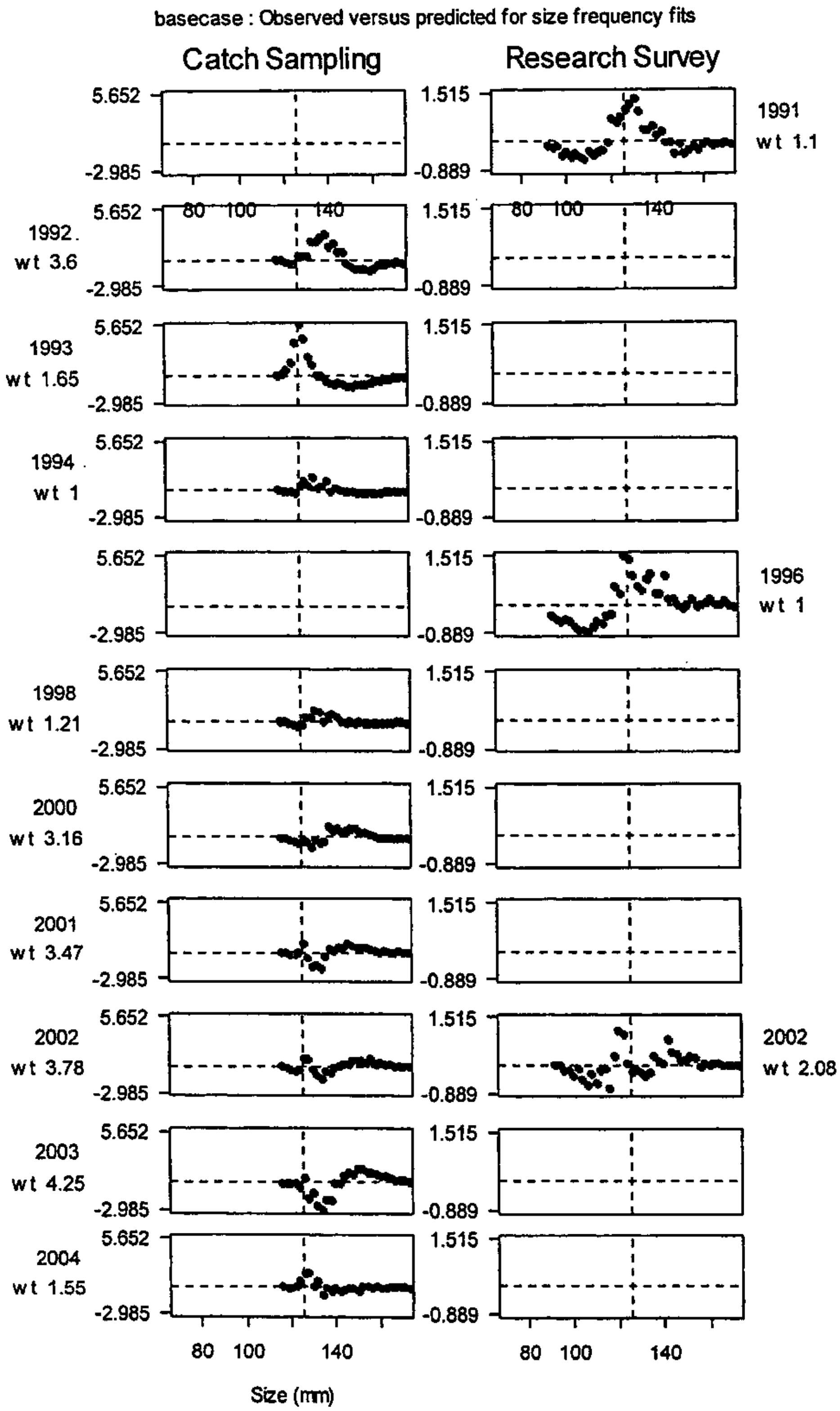


Figure 20: Residuals from the fits to proportions-at-length data seen in Figure 19 from the base case MPD fit for PAU 5A.

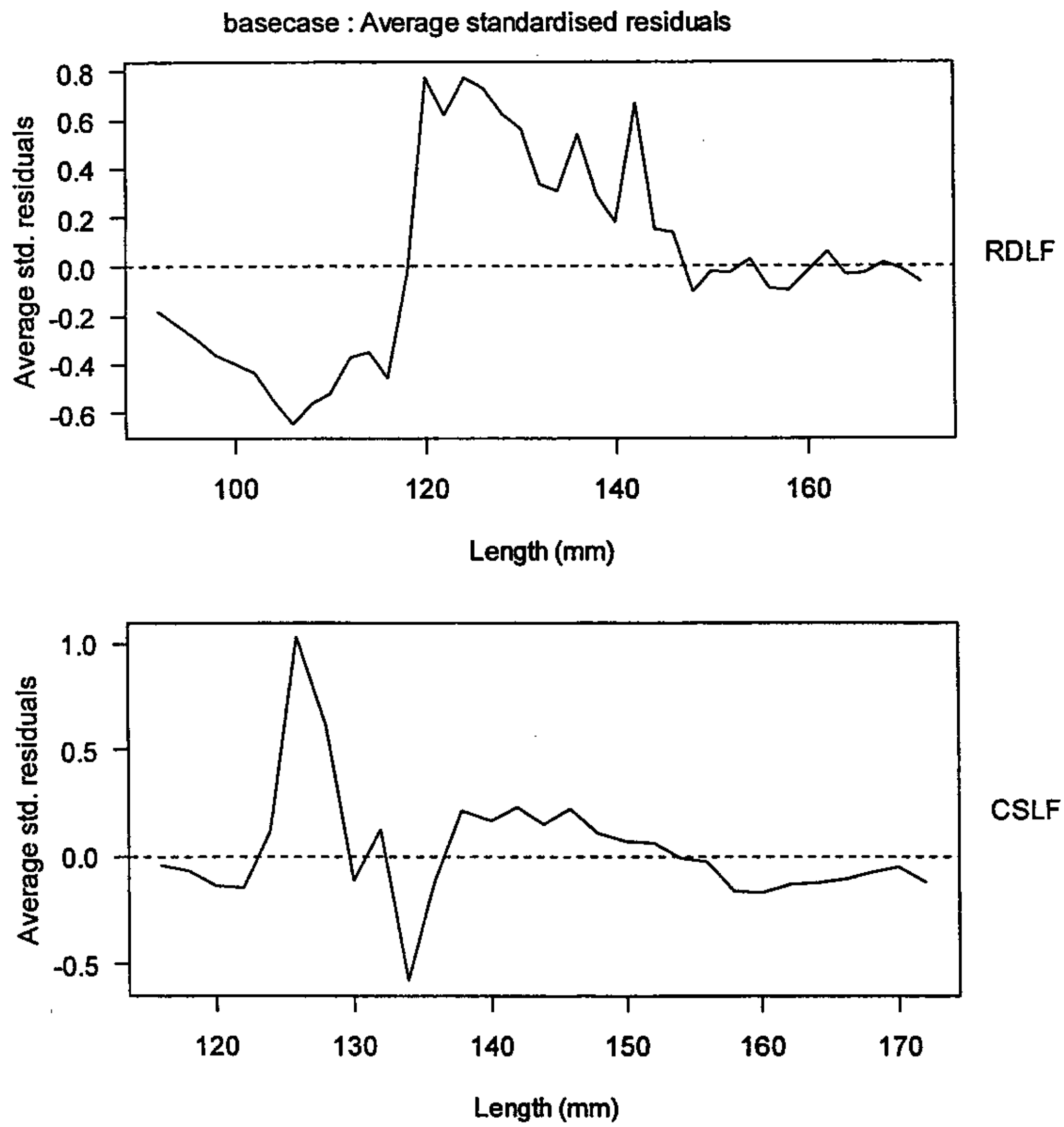


Figure 21: Means of the normalised residuals from proportions-at-length, plotted against length for RDLFs (upper) and CSLFs from the base case MPD fit for PAU 5A.

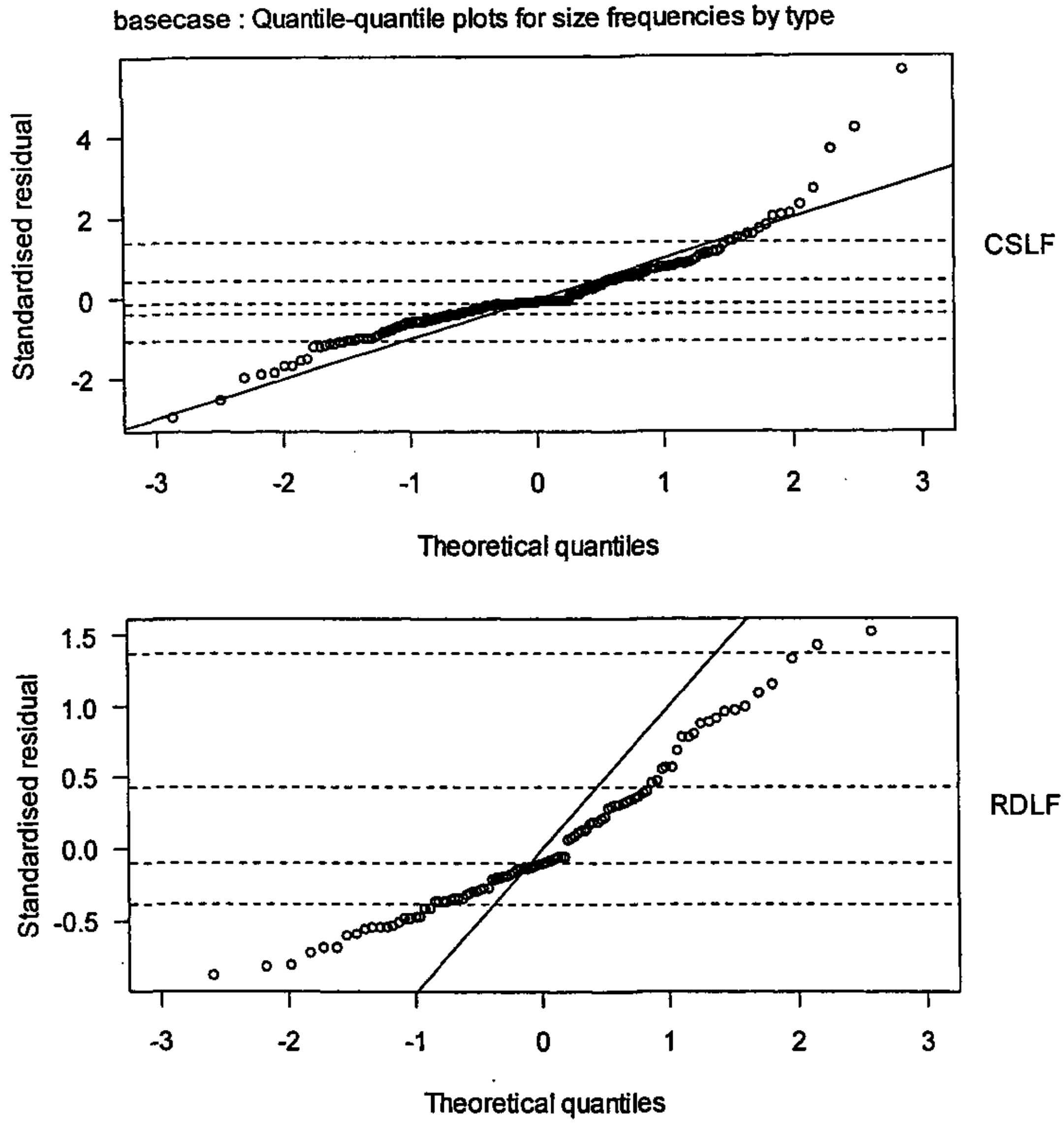


Figure 22: Q-Q plot of residuals for the fits to proportions-at-length from CSLF (top) and RDLF data (bottom) from the base case MPD fit for PAU 5A.

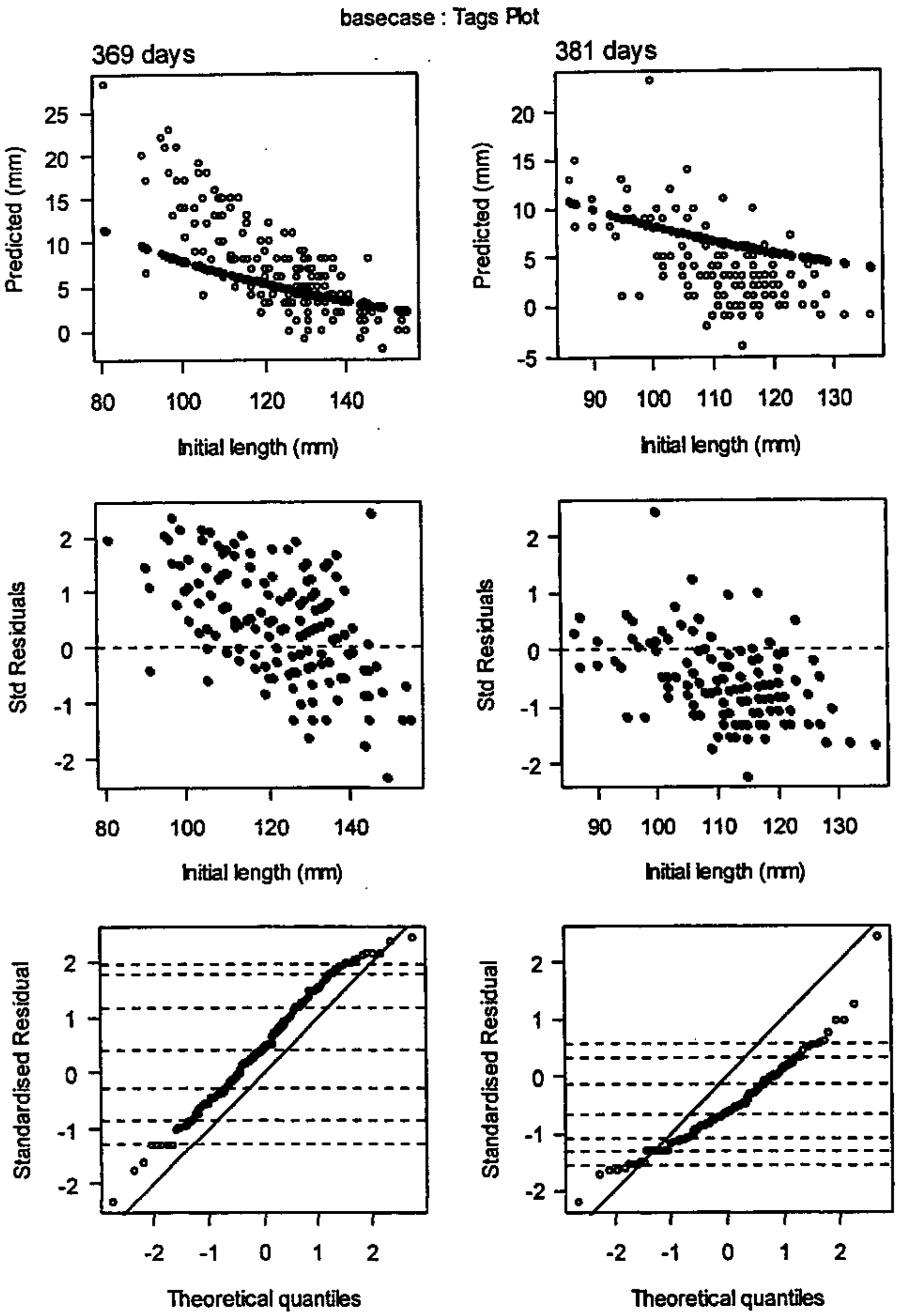


Figure 23: Top: Observed (open circles) and predicted (closed circles) growth increments from Landing Bay and Red Head (left) and Poison Bay (right); middle: normalised residuals; bottom: Q-Q plots of the normalised residuals. Numbers at the top indicate days-at-liberty.

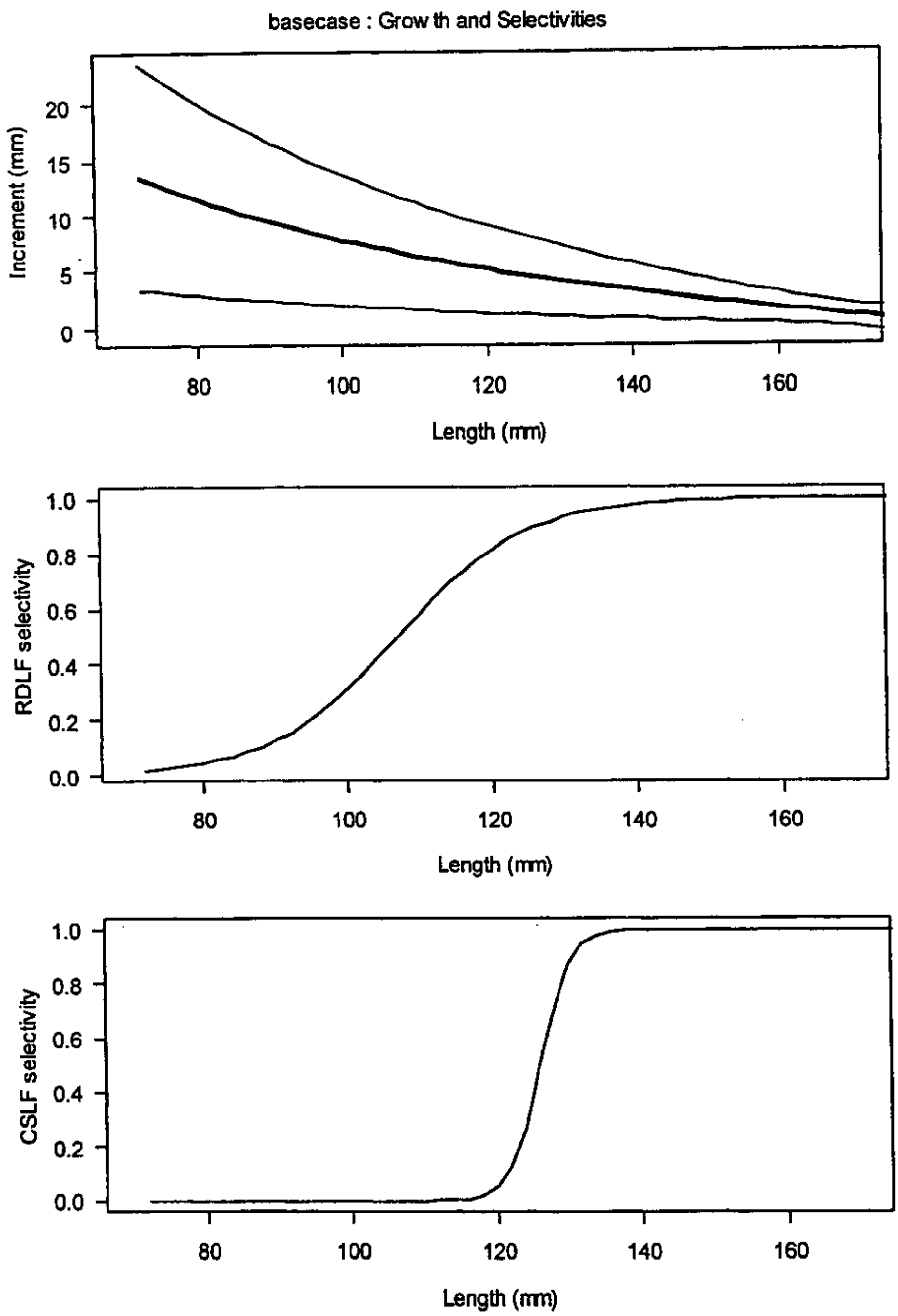


Figure 24: Top: predicted annual growth increment (thick line) *vs* initial length of paua, shown with one standard deviation around the increment (thin line); middle: research diver survey selectivity; bottom: commercial catch sampling selectivity.

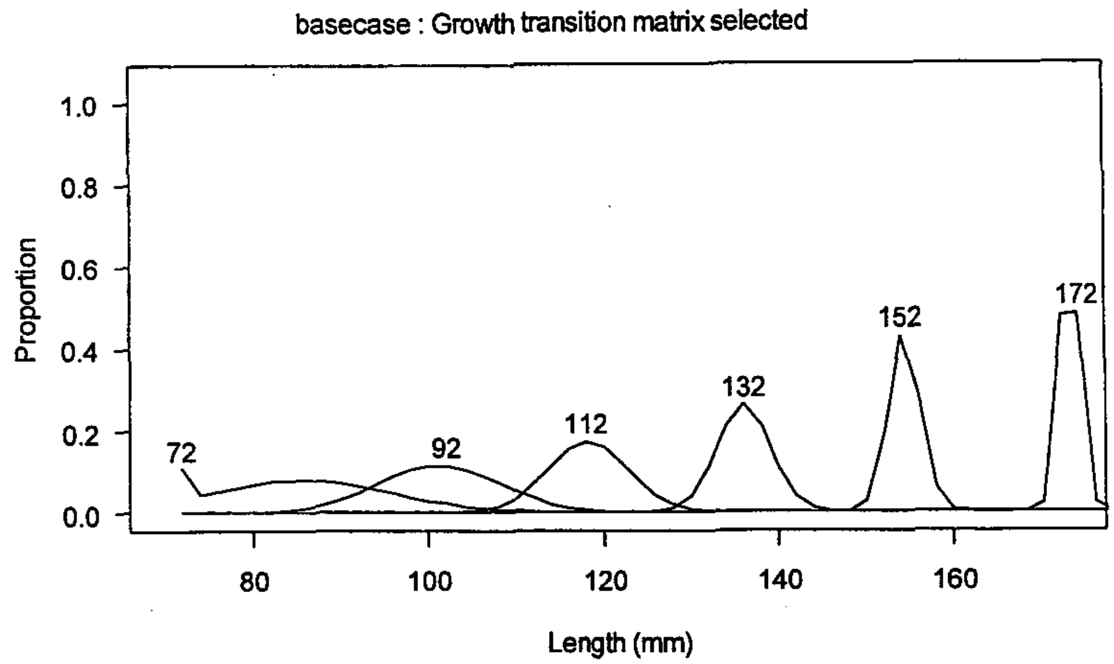


Figure 25: Sections from the growth transition matrix for the base case MPD fit for PAU 5A, showing the distribution of probabilities of growing from the size indicated to the various new sizes.

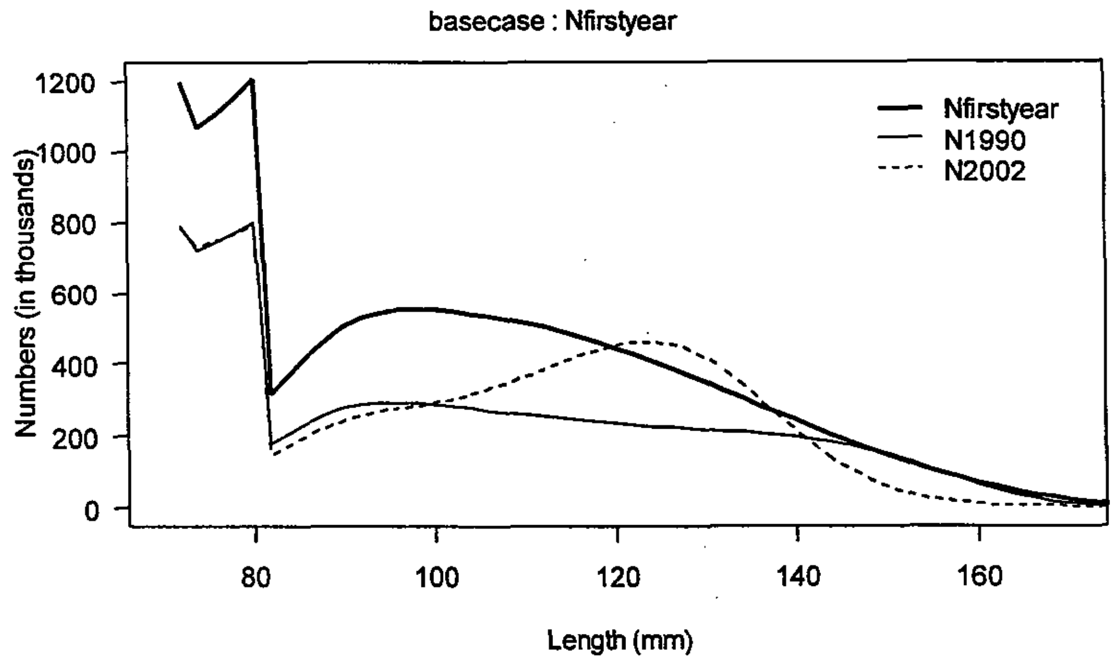


Figure 26: Numbers-at-length predicted by the model for 1964 (heavy line), 1990 and 2002 from the MPD fit for the PAU 5A base case.

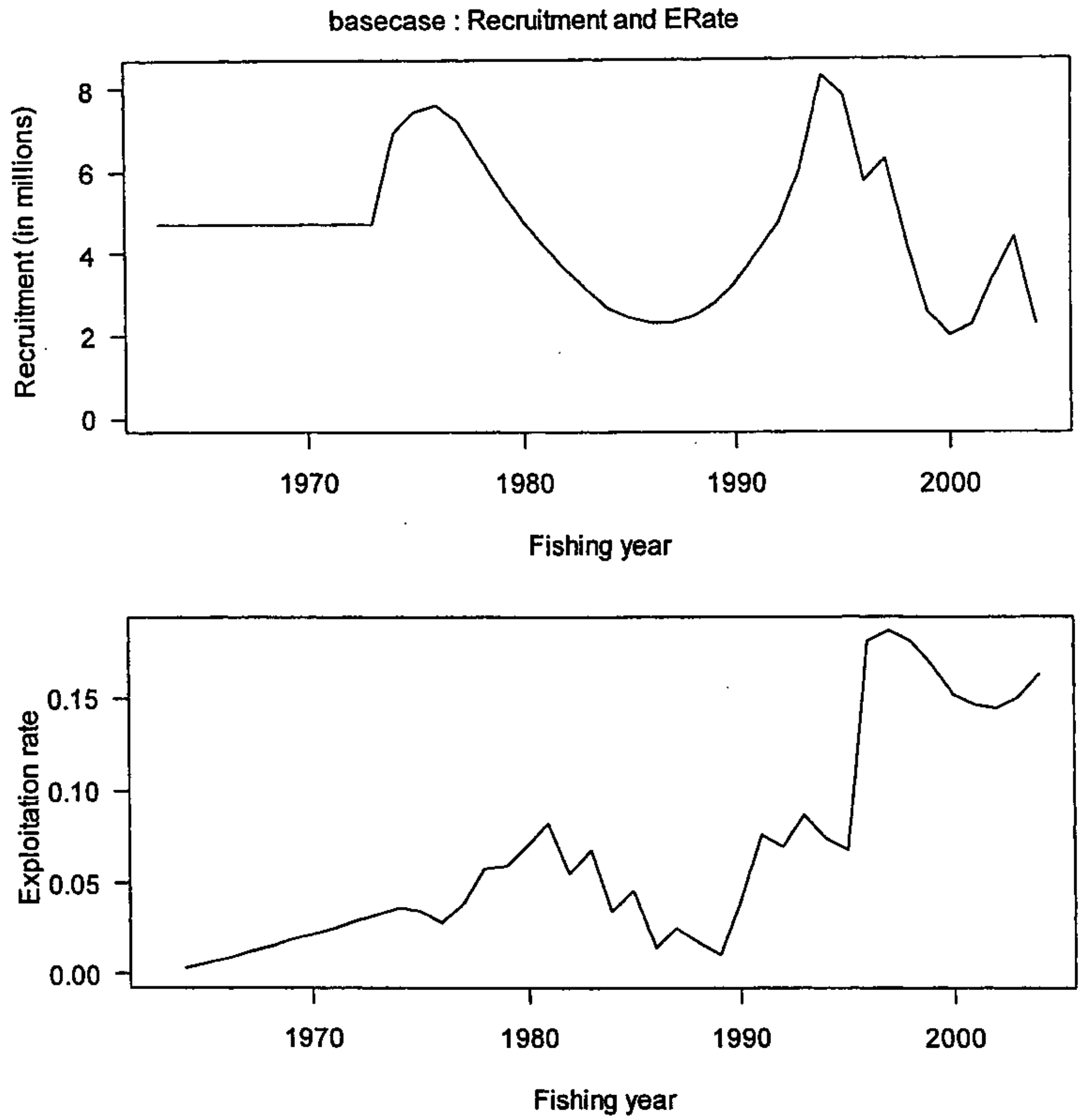


Figure 27: Recruitment in millions of animals (top) and exploitation rate (bottom) from the base case MPD fit in PAU 5A.

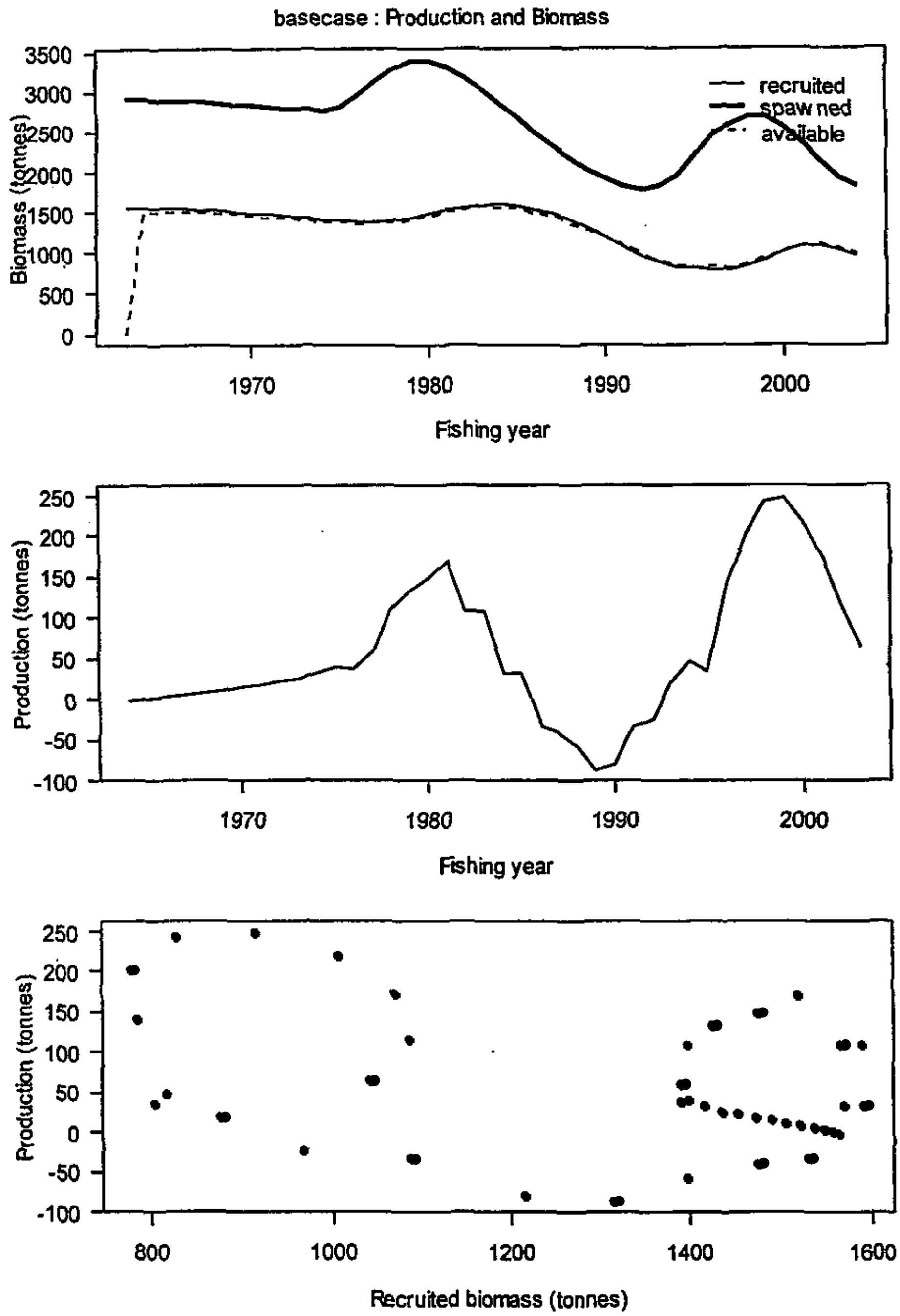


Figure 28: Top: biomass trajectories from the base case MPD fit for PAU 5A; middle: the surplus production trajectory; bottom: surplus production plotted against recruited biomass.

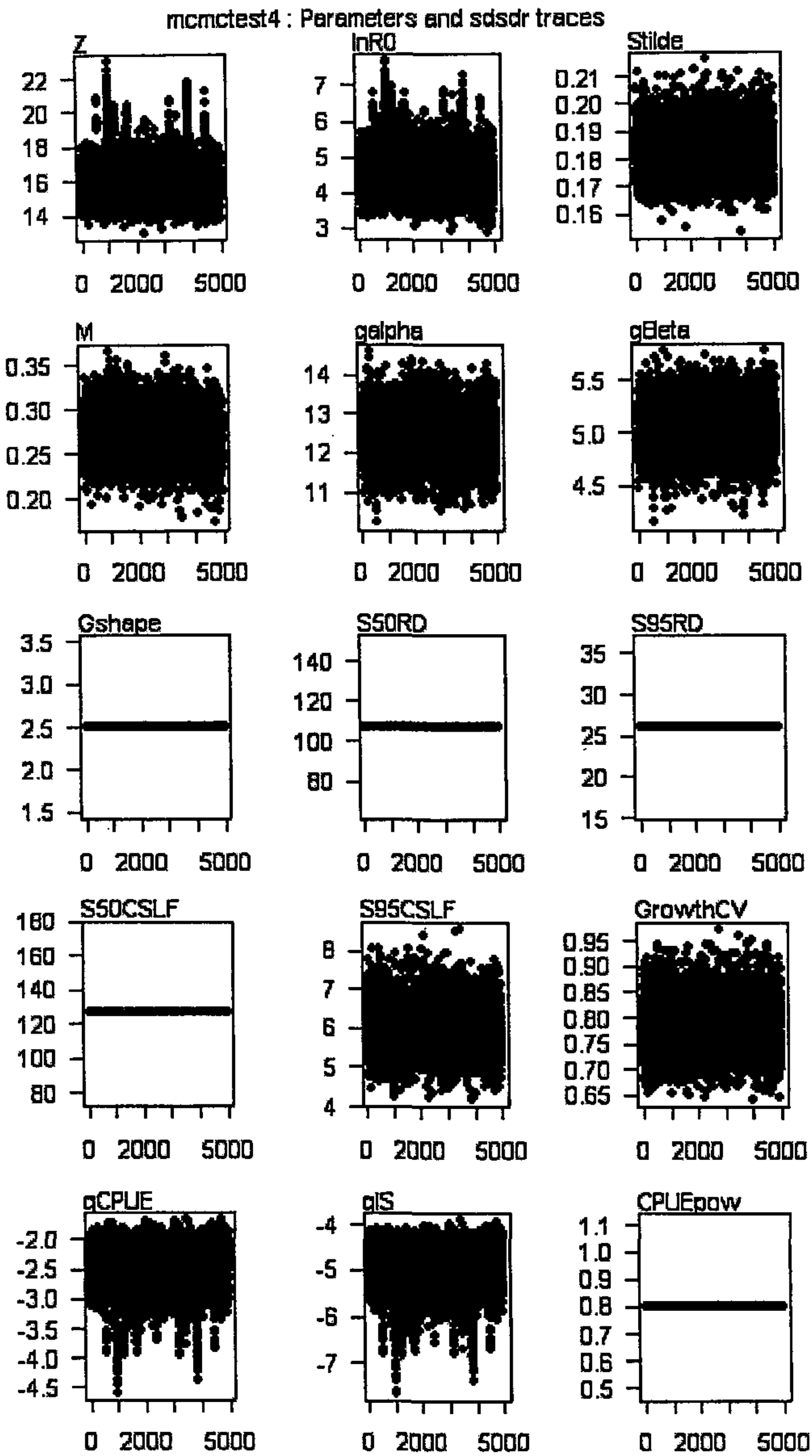


Figure 29: Traces of the posteriors indicated from the base case McMC for PAU 5A. "qIS" is the scalar for RDSI. "CPUEpow" is *h*.

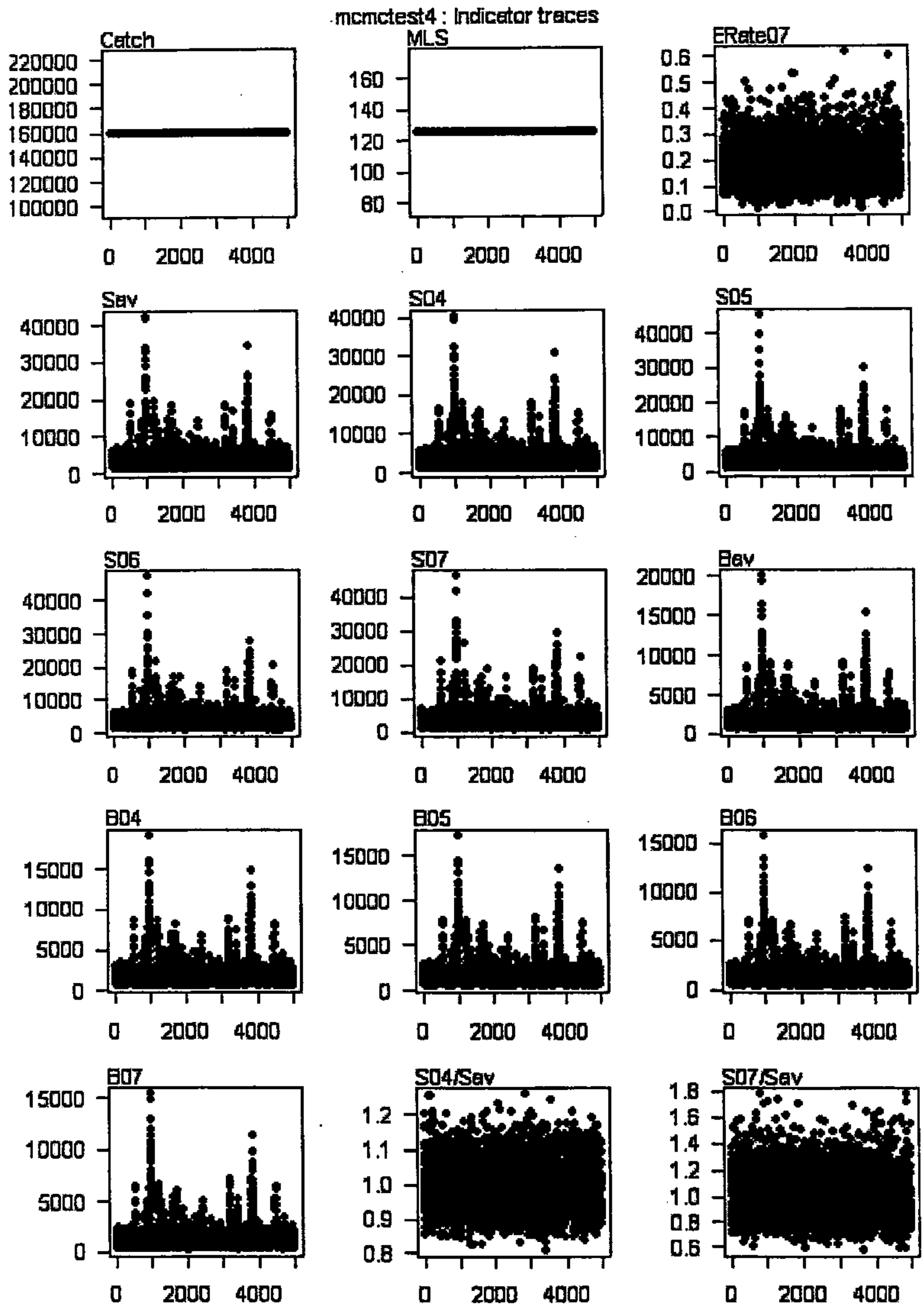


Figure 29 continued.

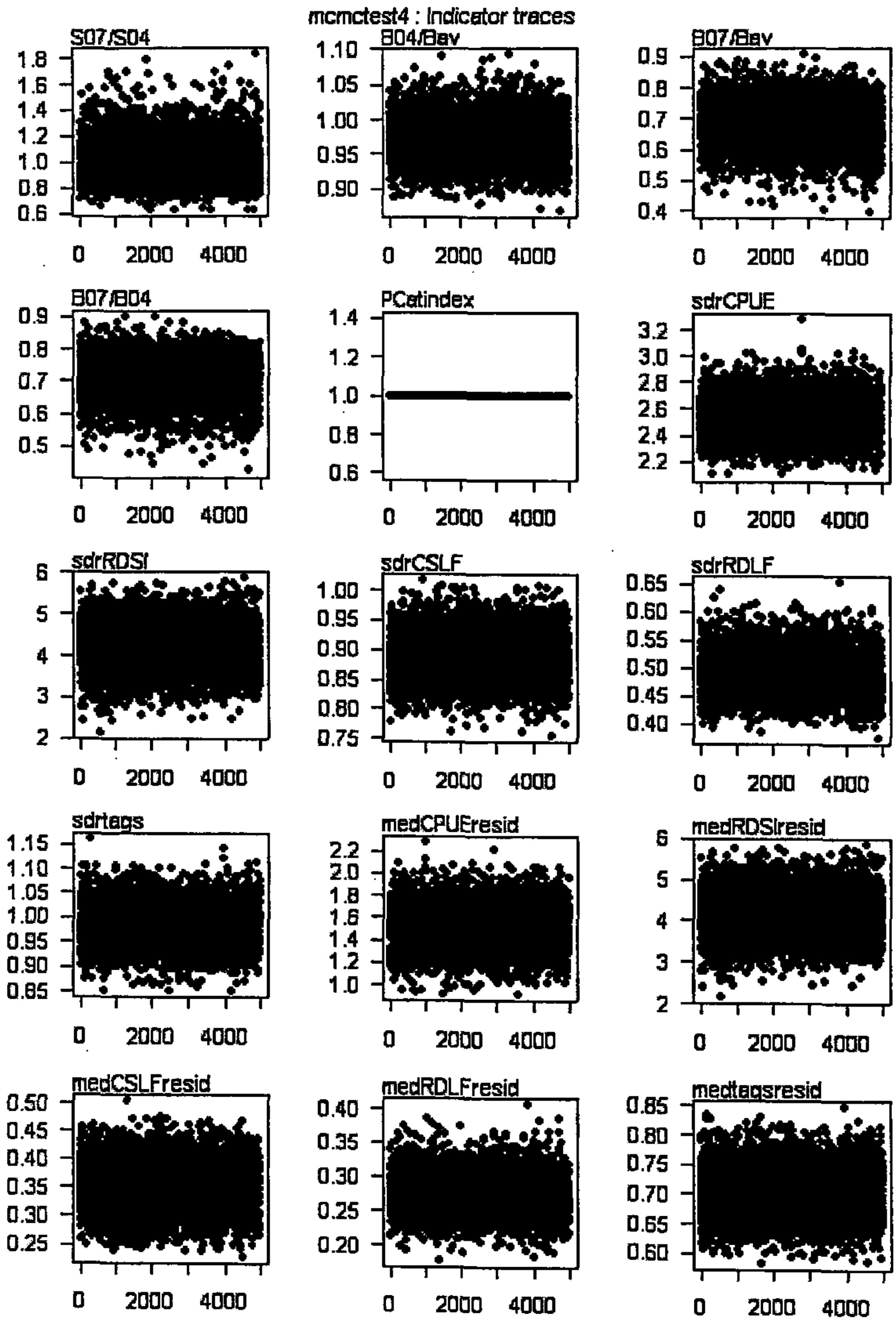


Figure 29 continued.

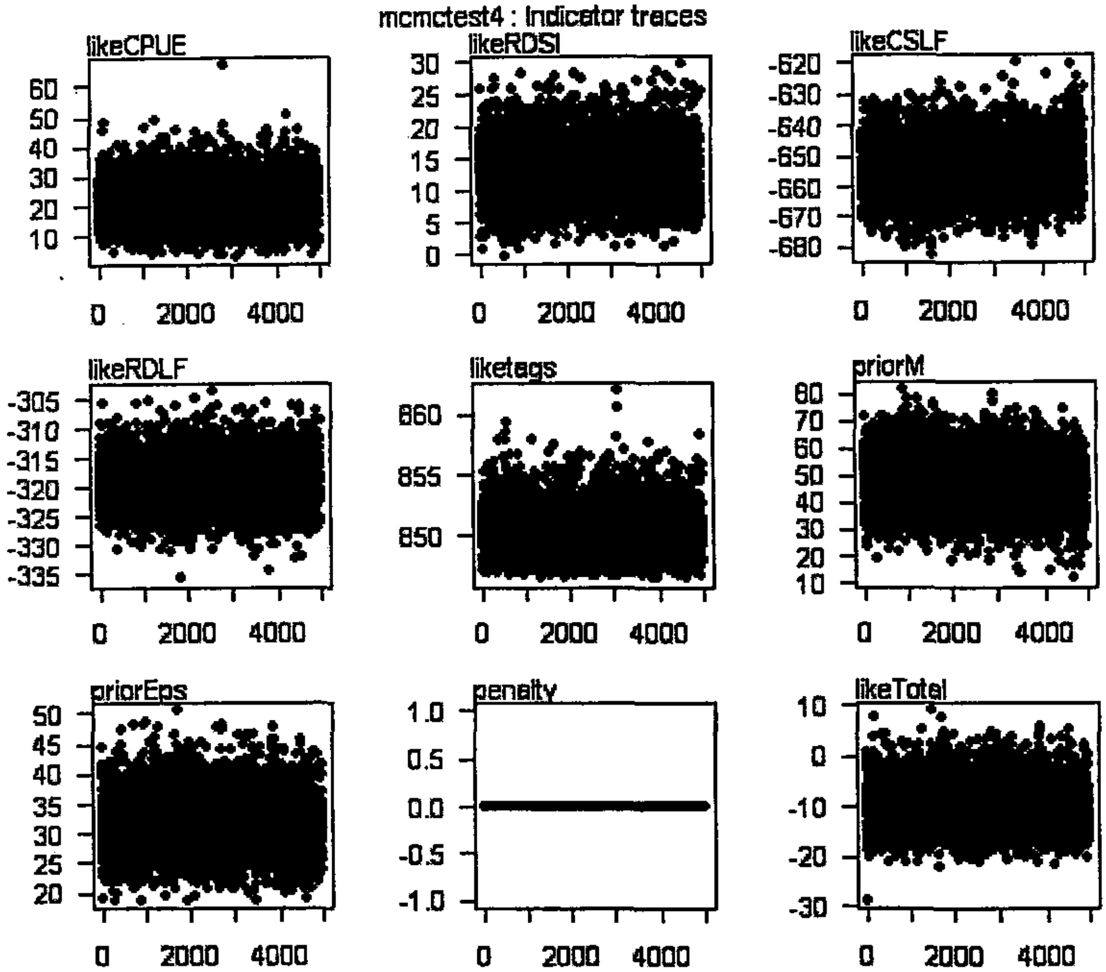


Figure 29 concluded.

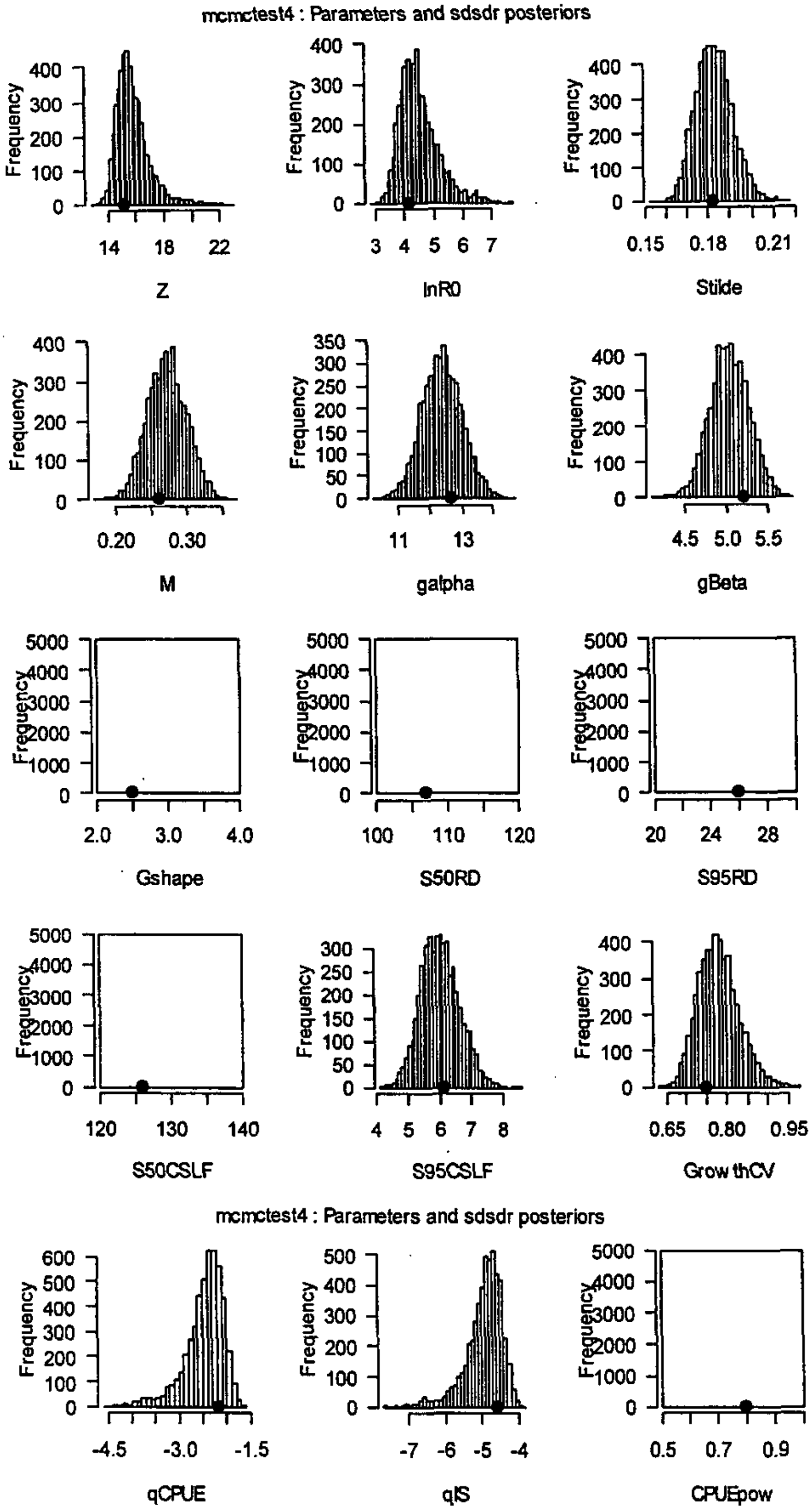


Figure 30: Posterior distributions of parameters and indicators from the McMC chain for the base case for PAU 5A. The dark point shows the MPD estimate, where available.

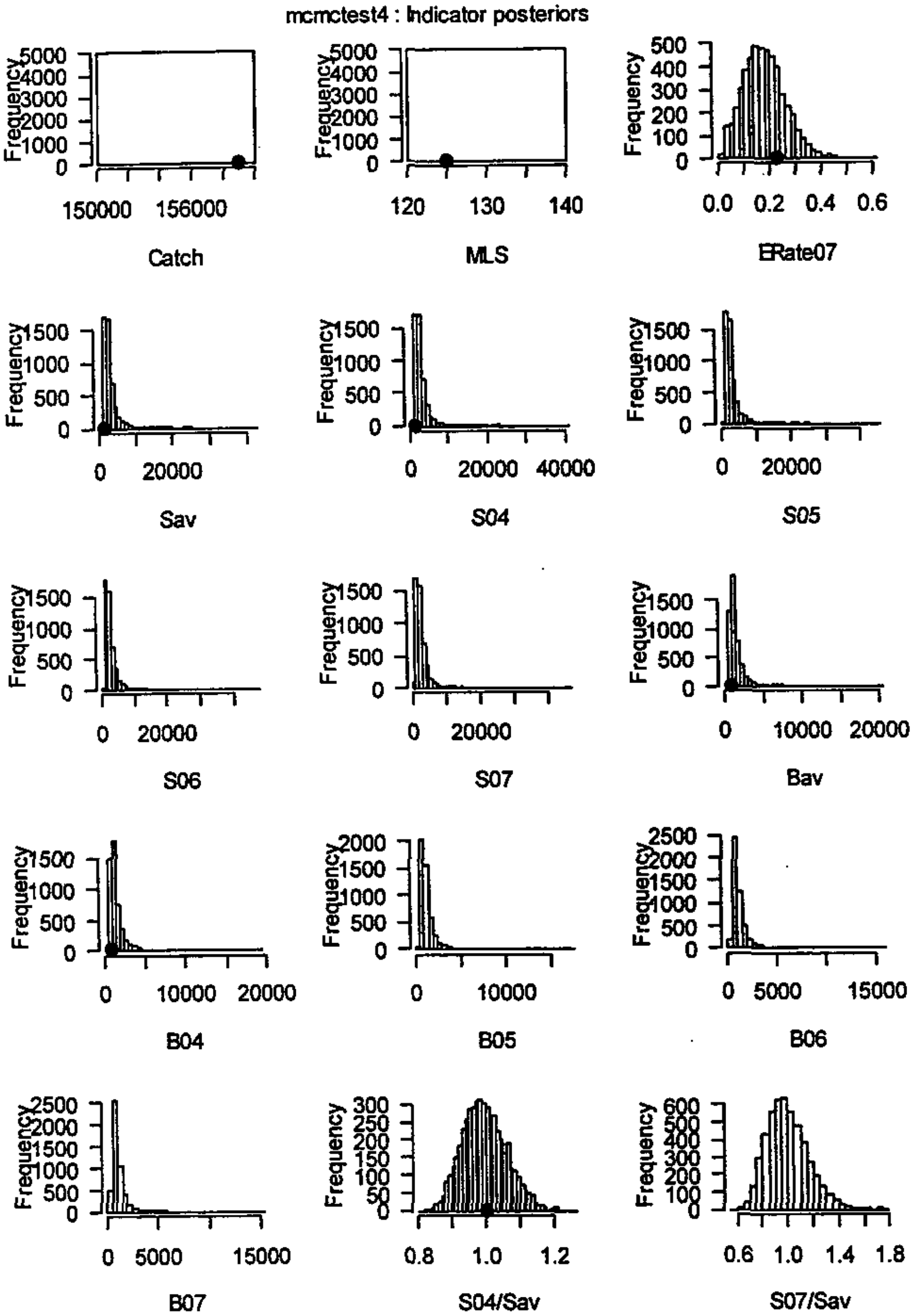


Figure 30 continued.

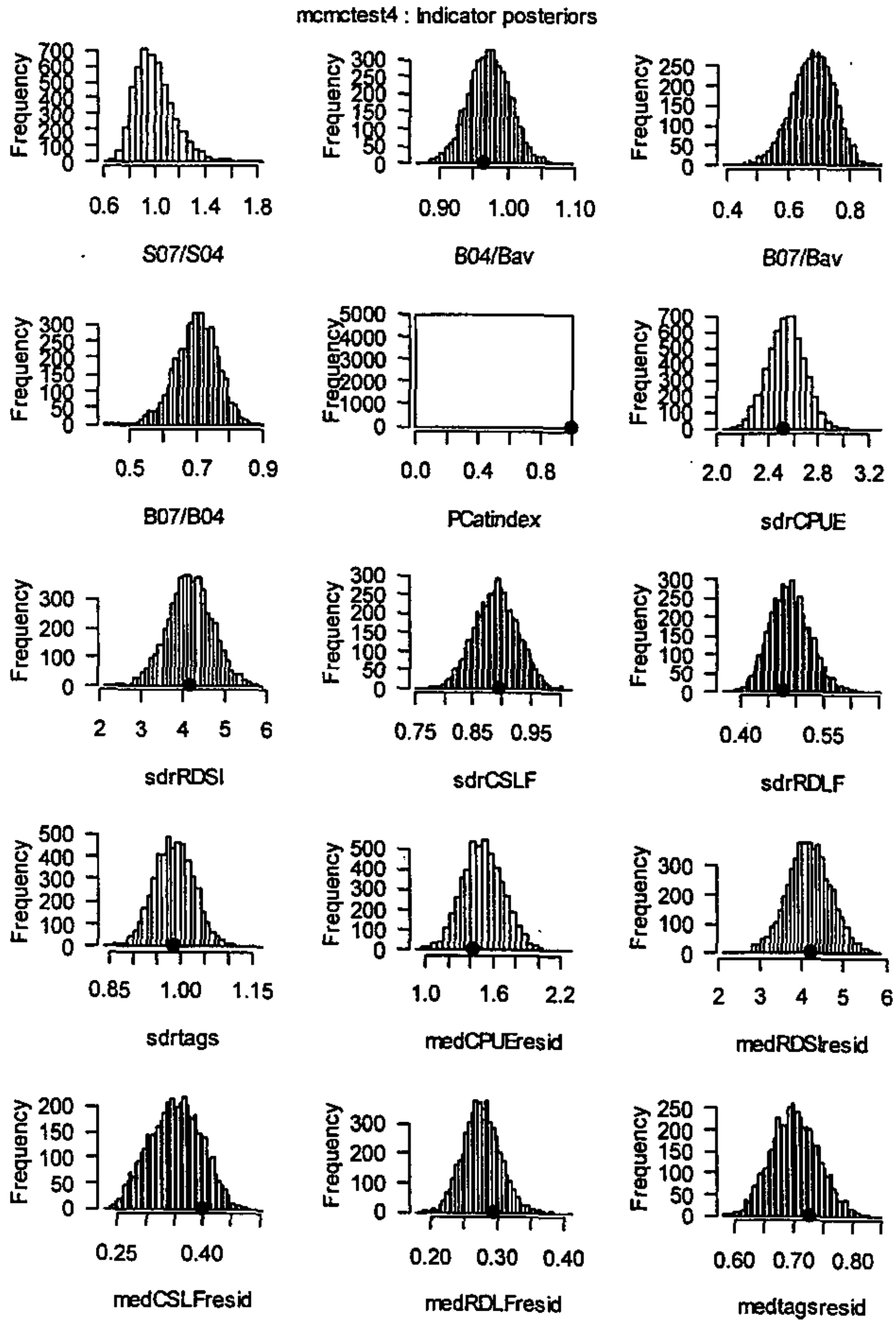


Figure 30 continued.

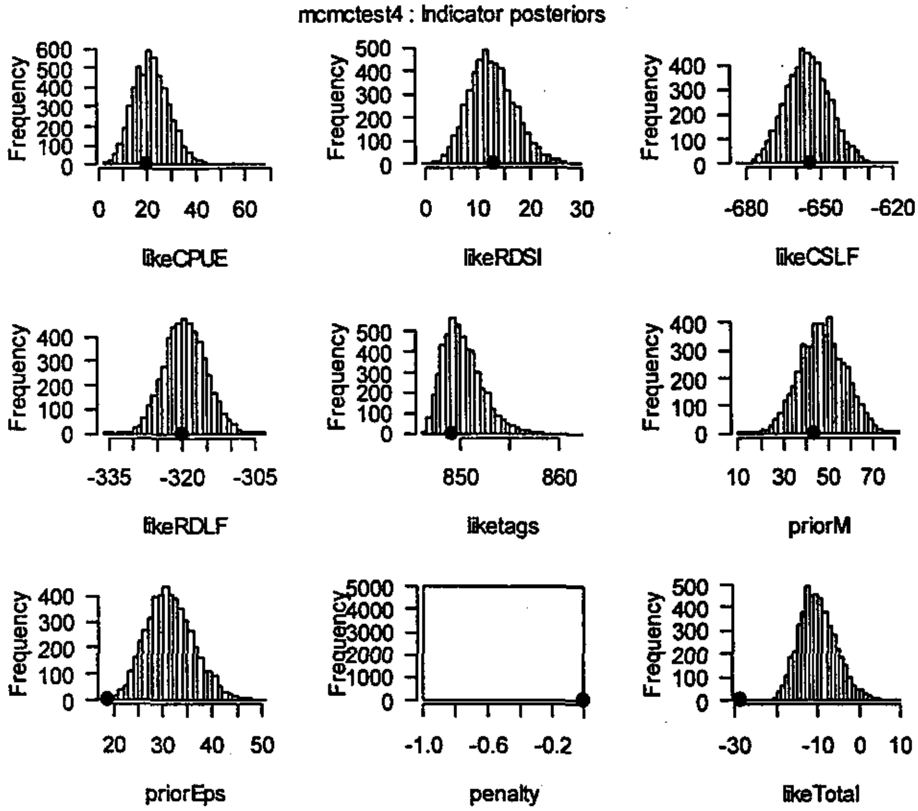
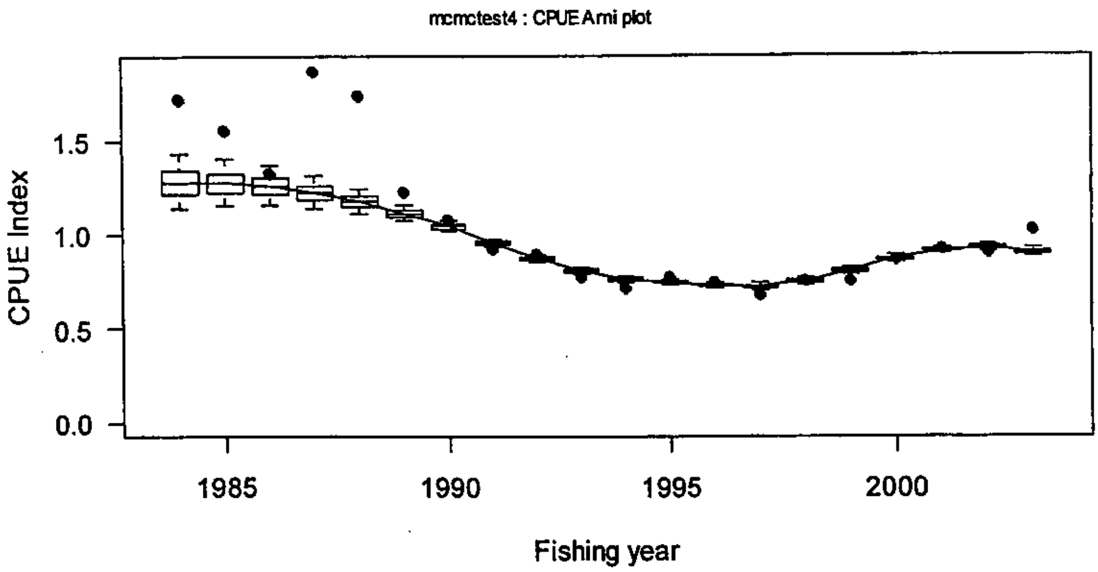


Figure 30 concluded.



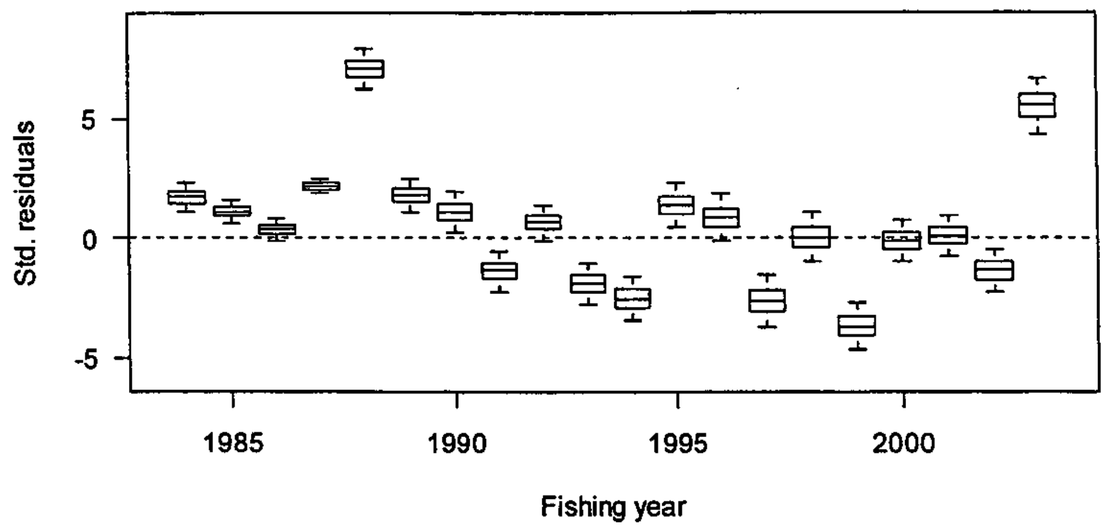


Figure 31: The posterior distributions of the fits to CPUE data (top) and the posterior distributions of the normalised residuals. For each year, the figure shows the median of the posterior (horizontal bar), the 25th and 75th percentiles (box) and 5th and 95th percentiles of the posterior.

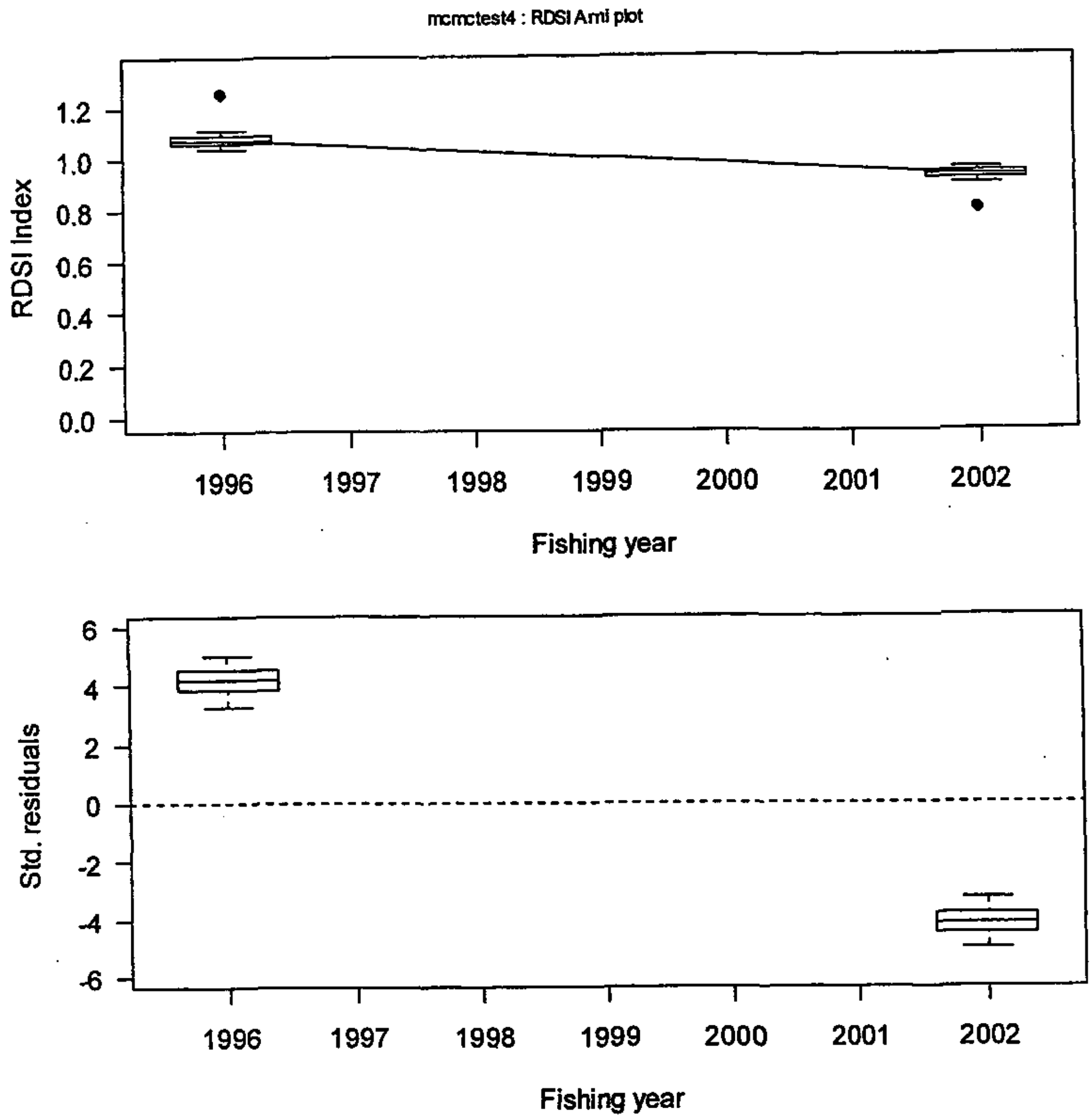


Figure 32: The posterior distributions of the fits to RDSI data (top) and the posterior distributions of the normalised residuals.

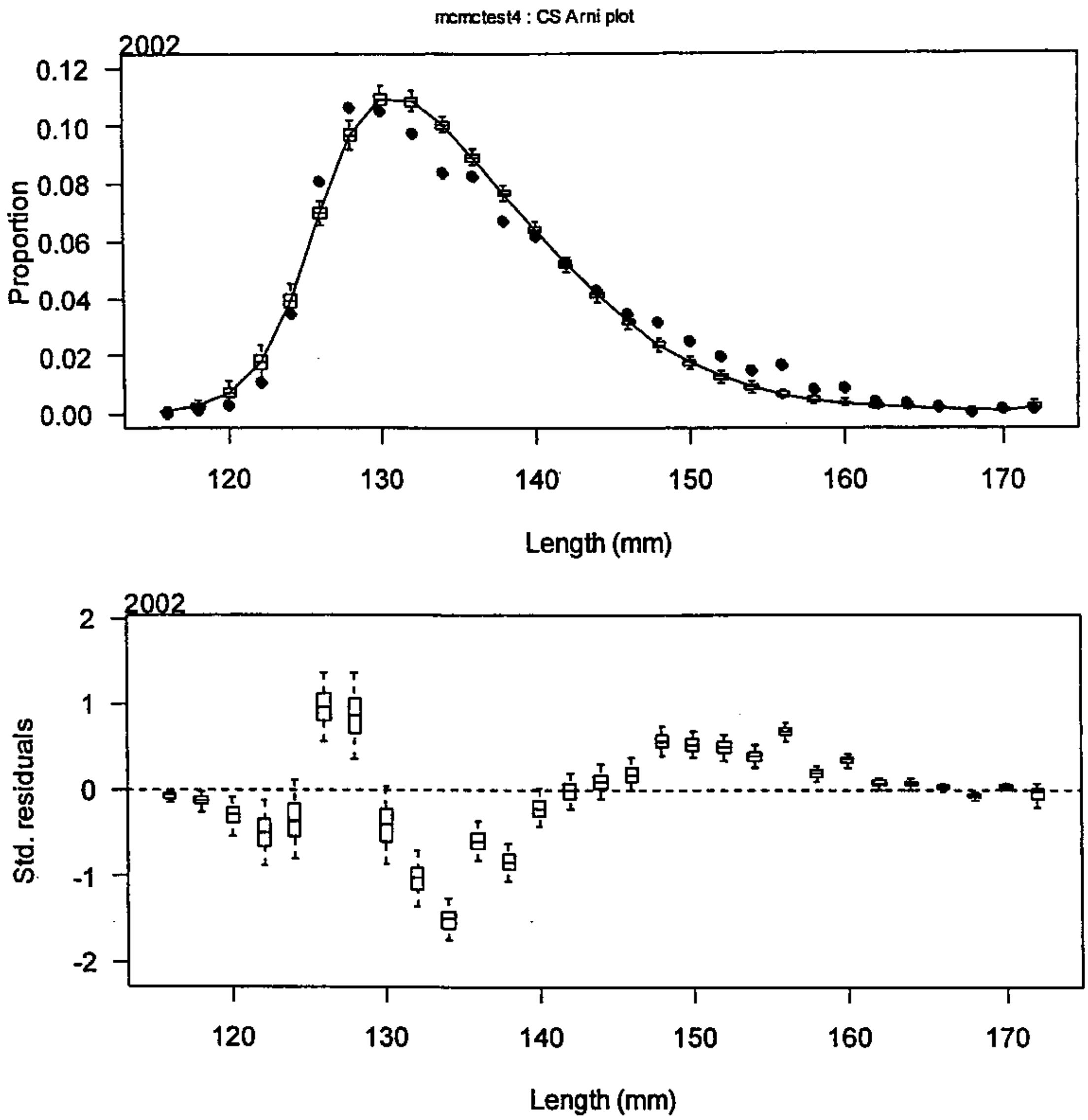


Figure 33: The posterior distributions of the fits to CSLF from 2002 (top) and the posterior distributions of the normalised residuals.

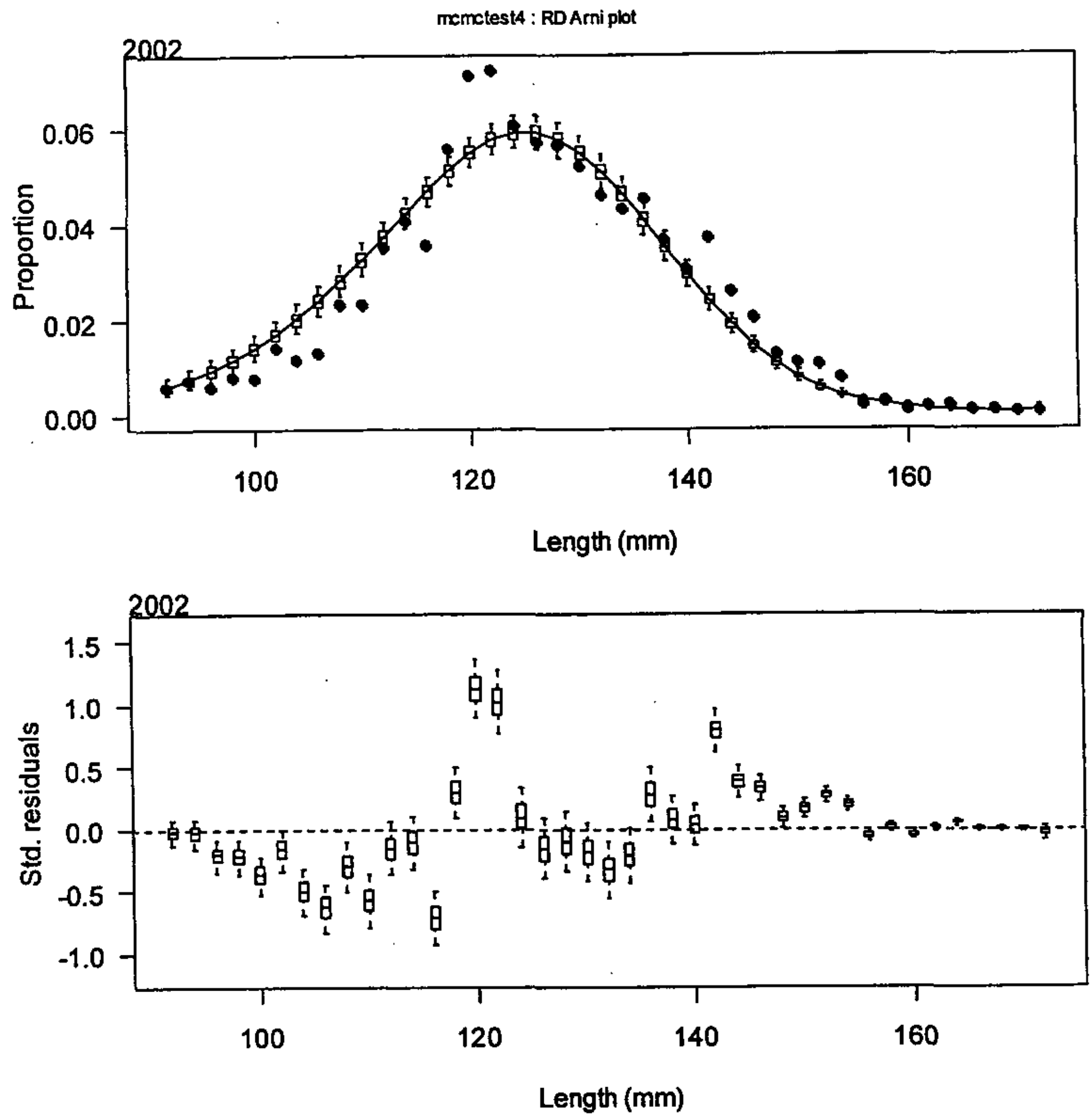


Figure 34: The posterior distributions of the fits to RDLF from 2002 (top) and the posterior distributions of the normalised residuals.

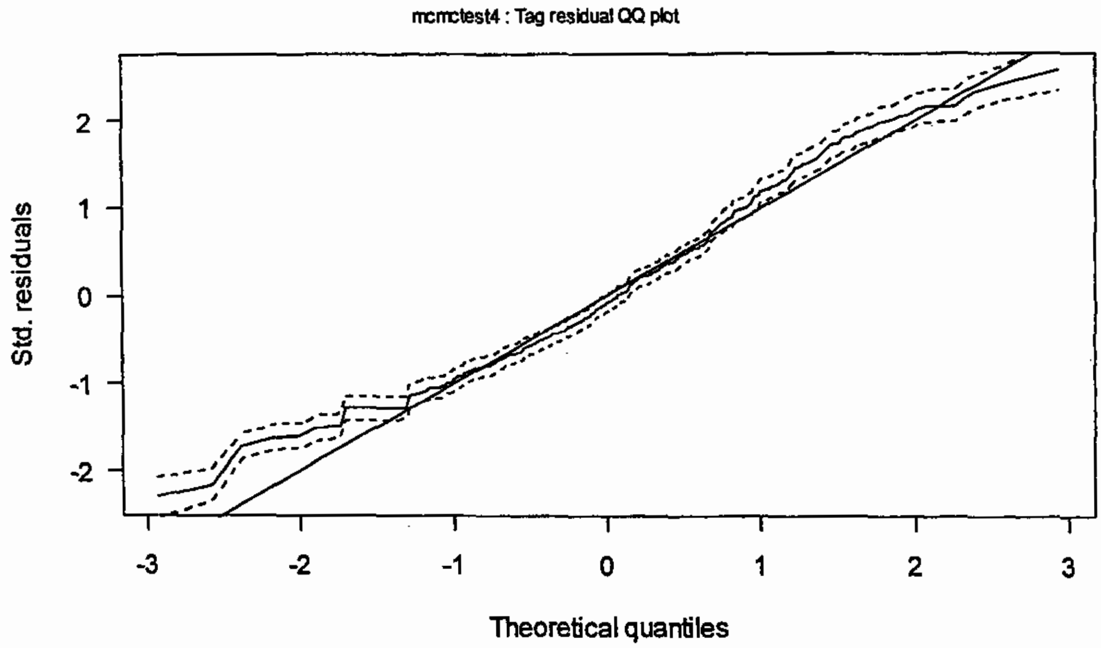


Figure 35: Q-Q plot of the normalised residuals from the posterior distributions of fits to the tag-recapture data.

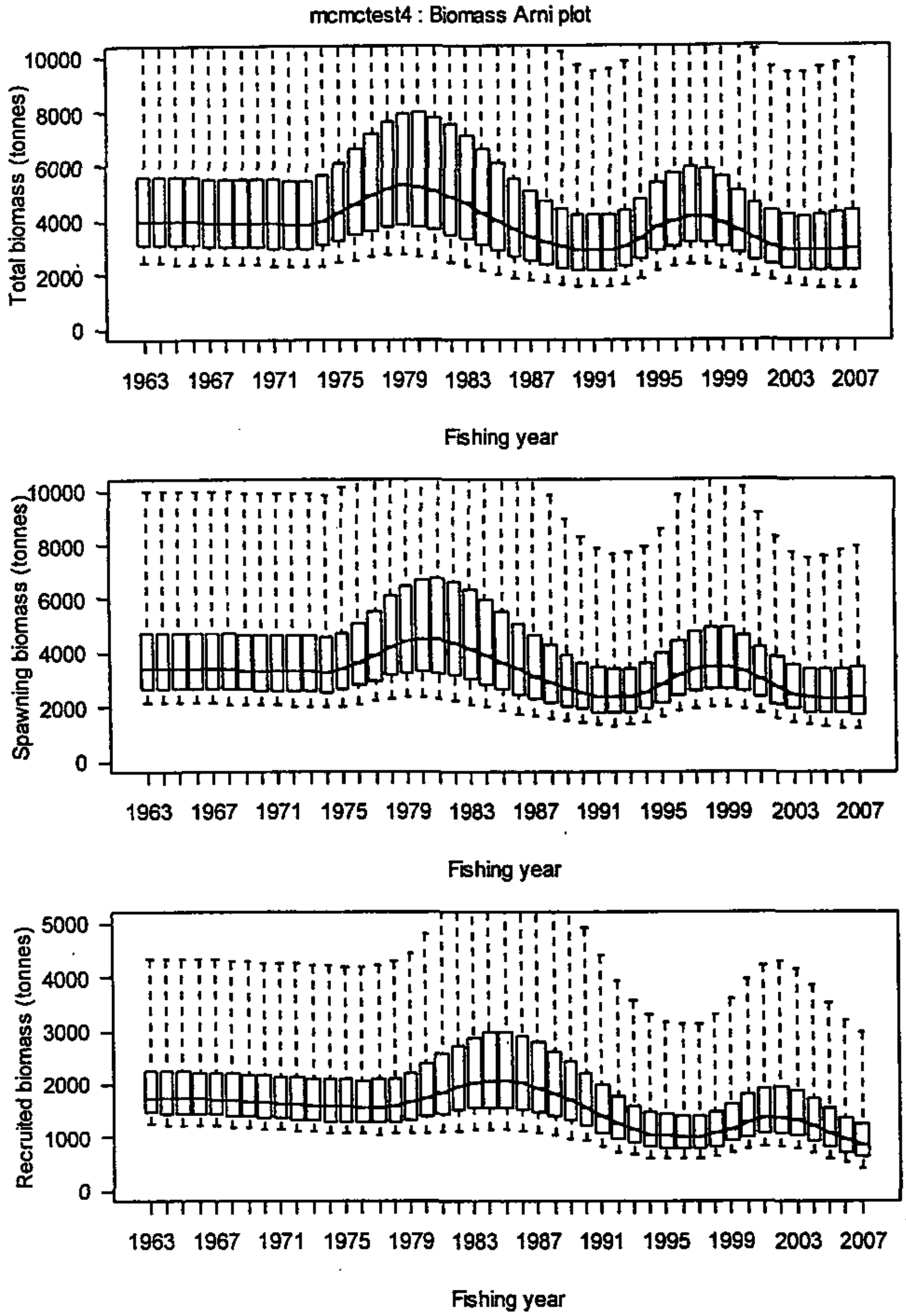


Figure 36: The posterior biomass trajectories for total (top), spawning (middle) and recruited (bottom) biomass for the base case for PAU 5A.

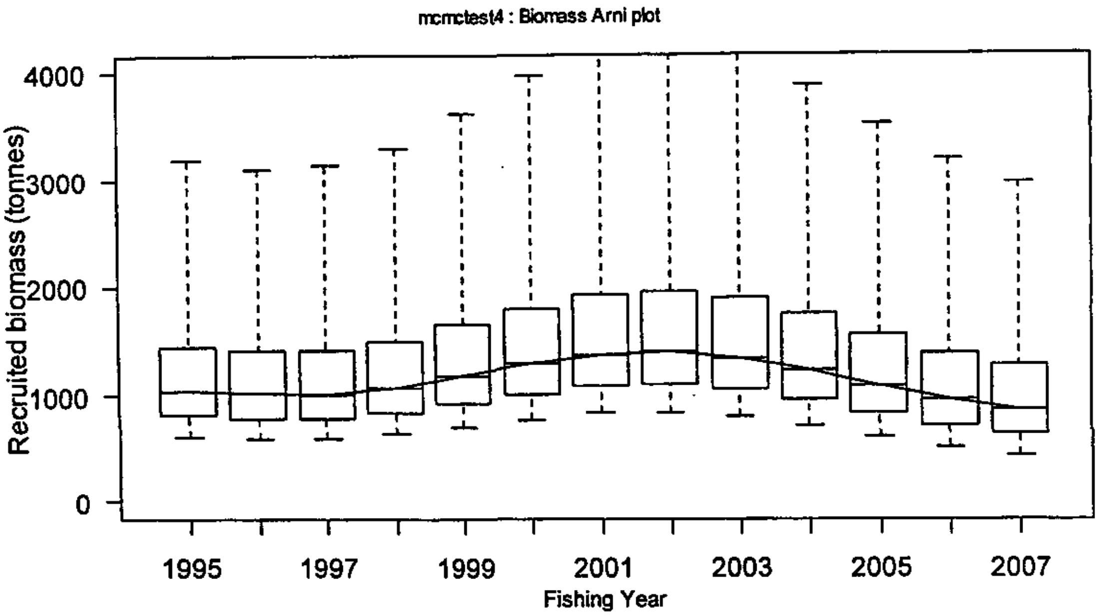
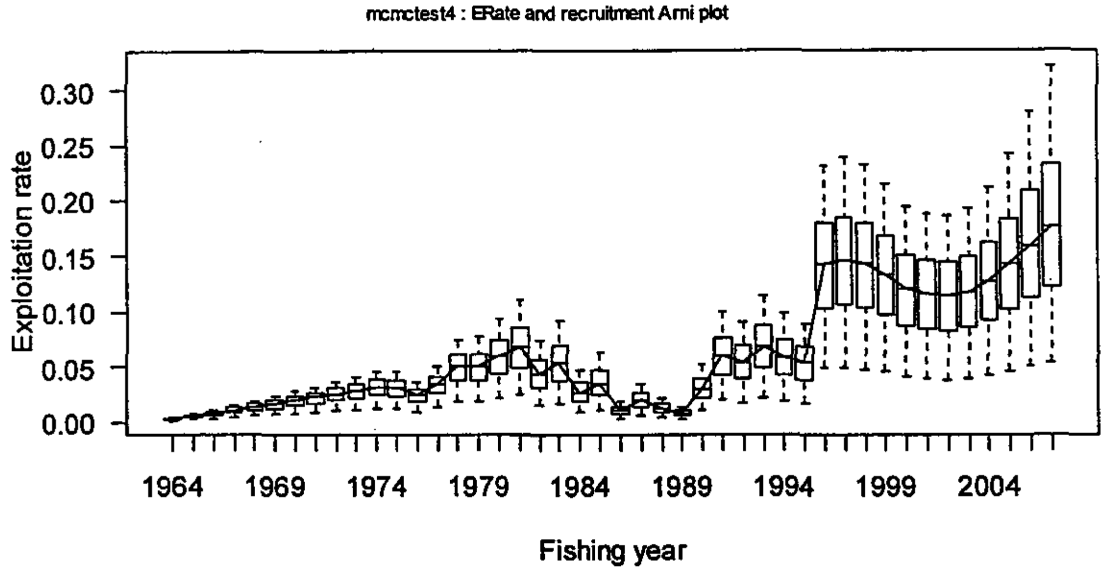


Figure 37: Posterior distribution of the biomass trajectory for recruited biomass from 1995 onwards.



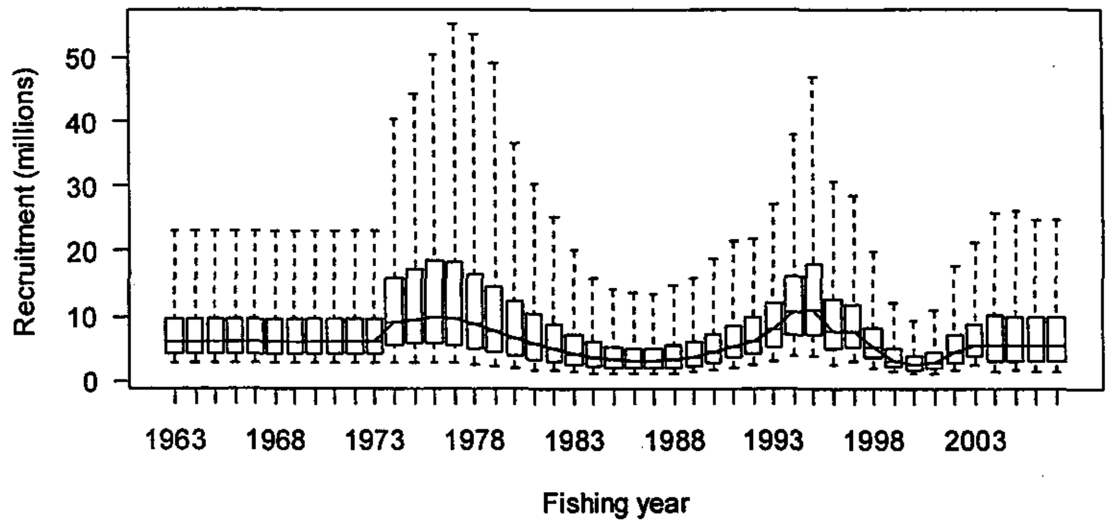


Figure 38: The posterior trajectories of exploitation rate (upper) and recruitment (lower) for the base case for PAU 5A.

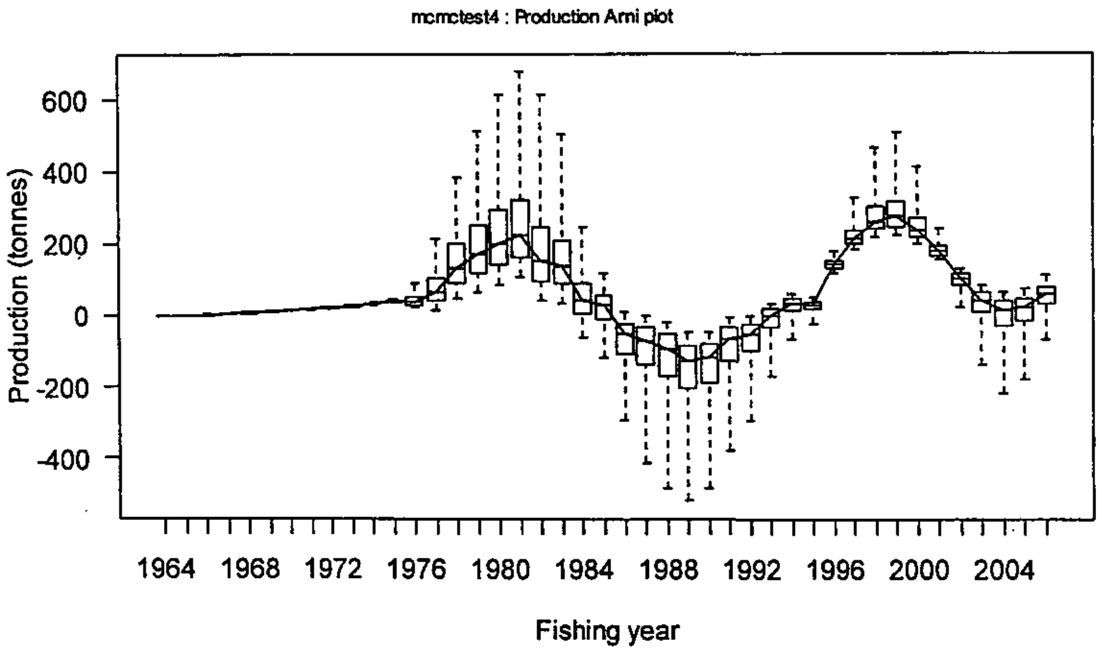


Figure 39: The posterior trajectory of surplus production for the base case for PAU 7.

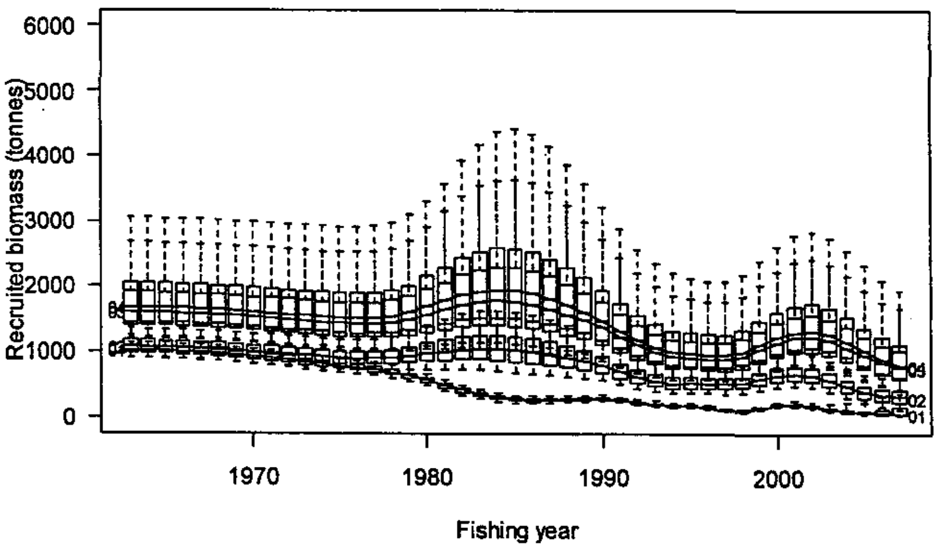


Figure 40: Posteriors of recruited biomass trajectories in four retrospective trials: lines are named (right hand edge) for the last year of data included.

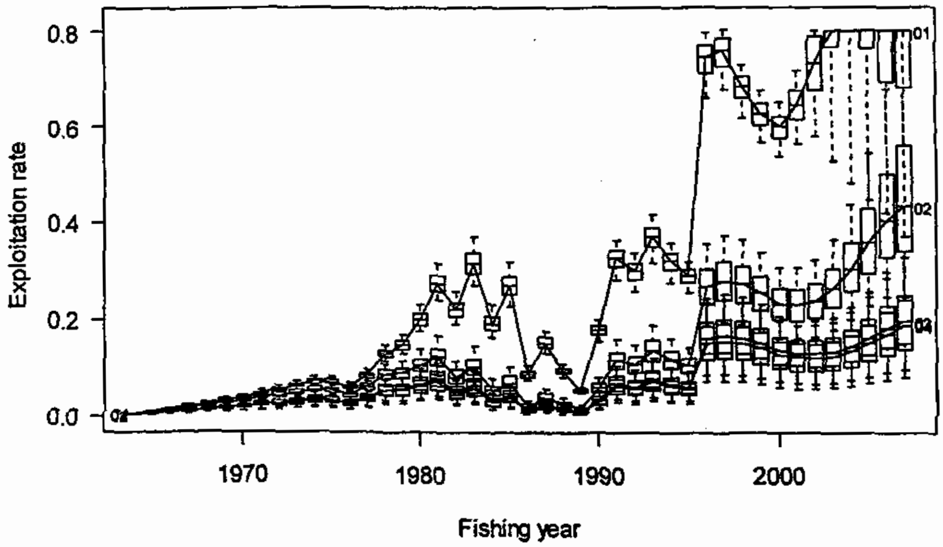


Figure 41: Posteriors of exploitation rate trajectories in four retrospective trials: lines are named (right hand edge) for the last year of data included.