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EXECUTIVE SUMMARY

Breen, P.A.; Kim, S.W. (2004). The 2004 stock assessment of paua (*Haliotis iris*) in PAU 4.

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A revised length-based model was used to assess the PAU 4 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. Point estimates from the mode of the joint posterior distribution were used to explore sensitivity of the results to model assumptions and the input data; the assessment itself was based on marginal posterior distributions generated from Markov chain-Monte Carlo simulation.

The model was revised from the 2003 assessment model by re-parameterising the growth model. Other minor changes were made for various reasons, and a full description of the revised model is provided.

The model was applied to five datasets from PAU 4: 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.

Iterative re-weighting of the datasets produced a base case result in which the standard deviations of the normalised residuals were close to unity for all datasets. Model results for PAU 4 suggest a stock currently exploited at a rate of about 20%, and with recruited and spawning biomass above those in an arbitrary reference period, 1991–93, during which the stock was moderately stable. Results were not unduly sensitive to the exclusion of single datasets, and were robust to other modelling choices. Retrospective analyses were reasonably favourable except for when we had data up until 2002.

At the current catch levels and minimum legal size, recruited biomass has a low likelihood (4.1%) of decreasing over the next 3 years. Spawning biomass has a 64% chance of decreasing. There is small chance that either could reach the reference levels in the next three years.

The assessment may be too optimistic – possible mechanisms causing such a result are discussed.

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1. INTRODUCTION

1.1 Overview

This document presents a Bayesian stock assessment of blackfoot paua (abalone) (*Haliotis iris*) in PAU 4 (Chatham Islands, Figure 1) 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, Breen et al. 2001, Breen & Kim 2003). This model is driven by reported commercial catches from 1983 to 2004 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) and 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.

This document describes the model, the datasets used in the assessment, assumptions made in fitting, the basic fit of the model to the data, and how the point estimates of model parameters respond to a variety of changes to datasets and other modelling choices in sensitivity trials. The assessment is based on posterior distributions of model and derived parameters, which are obtained from Markov chain-Monte Carlo (McMC) simulations. Diagnostics from these are discussed and results are summarised.

1.2 Description of the fishery

The paua fishery was summarised by Schiel (1992), Annala et al. (2003), and in numerous previous assessment documents (e.g., Schiel 1989, McShane et al. 1994, 1996, Breen et al. 2000a, 2000b, 2001, and Breen & Kim 2003). A further summary is not presented here.

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

2. MODEL

This section describes the model used for stock assessment of PAU 4 in 2004. The model was 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 (Breen et al. 2002), 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 Catch and biomass units

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

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

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:

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

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 $\boldsymbol{\theta}$.

$\ln(R0)$	natural logarithm of base recruitment
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
q^J	scalar between numbers and the RDSI
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, estimated from 1983 to 2004

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 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, 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 *k*th length class in year *t* in RDLF
$p_{k,t}^s$	observed proportion in the *k*th length class in year *t* in CSLF
l_j	initial length for the *j*th tag-recapture record
d_j	observed length increment of the *j*th tag-recapture record
Δt_j	time at liberty for the *j*th tag-recapture record
p_k^{mat}	observed proportion mature in the *k*th length class in the maturity dataset

2.2.4 Derived variables

$R0$	base number of annual recruits
$N_{k,t}$	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) $R_{k,t} = 0.2R0$ for $1 \le k \le 5$

(2) $R_{k,t} = 0$ 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:

(3) $$x = \left(\beta^\delta - \alpha^\delta\right) \Big/ \left(\left(\beta + g_\beta\right)^\delta - \left(\alpha + g_\alpha\right)^\delta\right)$$ and

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

and then the expected increment g_k for the kth length is

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

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}:

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

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 *k*th 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 $\mathbf{R}_t$:

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

where the dot (•) denotes matrix multiplication.

2.2.7 Dynamics

2.2.7.1 Sequence of operations

After initialising, the first model year is 1973, 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 1983. The assumed catch vector rises linearly from zero to the 1983 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.
- 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:

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

or, if the commercial selectivity is used instead of the MLS, to derive biomass vulnerable to commercial fishing:

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

where

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

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 $1-U_t$:

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

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

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

(13) $$1000000\left(A_{\min} - \left(1 - \frac{C_t}{B_t}\right)\right)^2$$

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:

(14) $$SF_{k,t} = 1 - (1 - A_t) P_{k,t}$$

or

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

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

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

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:

(17) $$R_{k,t} = 0.2 R0 e^{\left(\varepsilon_t - 0.5\sigma_\varepsilon^2\right)} \qquad \text{for } 1 \le k \le 5$$

(18) $R_{k,t} = 0$ for $k > 5$

The recruitment deviation parameters ε_t were estimated for all years after 1982 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:

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

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 (8) or (9), but using the mid-year numbers, $N_{k,t+0.5}$:

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

or if commercial selectivity is used instead of MLS:

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

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:

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

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

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

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

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

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

and

(26) **Error! Objects cannot be created from editing field codes.** for the plus group.

Predicted proportions-at-length for CSLF are similar:

(27) **Error! Objects cannot be created from editing field codes.** for $11 \le k < 51$

and

(28) **Error! Objects cannot be created from editing field codes.** for the plus group.

The predicted increment for the *j*th tag-recapture record is

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

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

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

Predicted maturity-at-length is

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

2.2.9 Fitting

2.2.9.1 Likelihoods

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

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

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

$$(33)\quad -\ln(\mathrm{L})\left(\hat{J}_t \mid \theta\right) = \frac{\left(\ln(J_t) - \ln\left(\hat{J}_t\right) + 0.5\left(\sigma_t^J \tilde{\sigma} / \varpi^J\right)^2\right)^2}{2\left(\sigma_t^J \tilde{\sigma} / \varpi^J\right)^2} + \ln(J_t) + \ln\left(\sigma_t^J \tilde{\sigma} / \varpi^J\right) + 0.5\ln(2\pi)$$

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:

$$(34)\quad \sigma_{k,t}^s = \frac{\tilde{\sigma}}{\kappa_t^s \varpi^s \sqrt{p_{k,t}^s + 0.1}}$$

The negative log-likelihood is:

$$(35)\quad -\ln(\mathrm{L})\left(\hat{p}_{k,t}^s \mid \theta\right) = \frac{\left(p_{k,t}^s - \hat{p}_{k,t}^s\right)^2}{2\sigma_{k,t}^{s\,2}} + \ln\left(\sigma_{k,t}^s\right) + 0.5\ln(2\pi)$$

The likelihood for research diver sampling is analogous. The model was revised to accept alternative likelihoods for proportions-at-age, but these, after experimentation, were not used in the PAU 4 assessment and need not be described.

Errors in the tag-recapture dataset were also assumed to be normal. For the jth record, the total error is a function of the predicted standard deviation (equation (30)), and the observation error:

$$(36)\quad \sigma_j^{tag} = \sqrt{\sigma_{obs}^{\ 2} + \left(\sigma_j^d\right)^2}$$

and the negative log-likelihood is:

$$(37)\quad -\ln(\mathrm{L})\left(\hat{d}_j \mid \theta\right) = \frac{\left(d_j - \hat{d}_j\right)^2}{2\sigma_j^{tag\,2}} + \ln\left(\sigma_j^{tag}\right) + 0.5\ln(2\pi)$$

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

$$(38)\quad \sigma_k^{mat} = \frac{\tilde{\sigma}}{\varpi^{mat} \sqrt{p_k^{mat} + 0.1}}$$

The negative log-likelihood is:

$$(39)\quad -\ln(\mathrm{L})\left(\hat{p}_k^{mat} \mid \theta\right) = \frac{\left(p_k^{mat} - \hat{p}_k^{mat}\right)^2}{2\left(\sigma_k^{mat}\right)^2} + \ln\left(\sigma_k^{mat}\right) + 0.5\ln(2\pi)$$

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

$$(40) \qquad \frac{\ln(I_t)-\ln(\hat{I}_t)}{\left(\sigma_t^I \tilde{\sigma} / \varpi^I\right)}$$

and similarly for the RDSI. For the commercial sampling proportions-at-length, the residual is

$$(41) \qquad \frac{p_{k,t}^s - \hat{p}_{k,t}^s}{\sigma_{k,t}^s}$$

and similarly for proportions-at-length from the research diver surveys. 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, and these 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

$$(42) \qquad \frac{d_j - \hat{d}_j}{\sigma_j^{tag}}$$

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

$$(43) \qquad \frac{p_k^{mat} - \hat{p}_k^{mat}}{\sigma_k^{mat}}$$

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, iteratively changing them to obtain standard deviations of the normalised residuals (*sdnr*) close to unity for each dataset.

2.2.9.4 Priors and bounds

Bayesian priors were established for all estimated parameters. Most were incorporated simply as uniform distributions with upper and lower bounds arbitrarily set wide so as not to constrain the estimation. 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:

$$(44) \qquad -\ln(\mathrm{L})(x \mid \mu_M, \sigma_M) = \frac{\left(\ln(M)-\ln(\mu_M)\right)^2}{2\sigma_M{}^2} + \ln\left(\sigma_M \sqrt{2\pi}\right)$$

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:

$$(45) \quad -\ln(\mathrm{L})(\varepsilon \mid \mu_\varepsilon, \sigma_\varepsilon) = \frac{\sum_{i=1}^{n_\varepsilon} (\varepsilon_i)^2}{2\sigma_\varepsilon^{\ 2}} + \ln(\sigma_\varepsilon) + 0.5\ln(2\pi).$$

2.2.9.5 Penalty

A penalty is applied to exploitation rates higher than the assumed maximum (equation 13); 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 mid-season recruited and spawning biomass from 2004 (current biomass) and from a reference period, 1991–93. This was a period when the biomass was stable, production was good and there was a long subsequent period when the fishery flourished. The means of values from the three years were called *Sav* and *Bav* for spawning and recruited biomass respectively. We also used annual exploitation rate in 2004, *U04*, and in 2007, *U07*. Ratios of these reference points 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 MPD estimate. The base case was 6 million simulations long and we saved 5000 regularly spaced samples.

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.

Recruitment was stochastic in projections, obtained by re-sampling the estimated recruitment from 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 value is inappropriate for projections and we overwrite 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. An indicator is calculated to show, for each projection, the mean of actual catches (exploitation rate times available biomass) as a percentage of the specified catch. In this assessment the actual catch was never less than specified catch and we do not show this indicator.

3. DATA

3.1 Catch data

3.1.1 Commercial catch

The commercial catch history from 1983 to 1989 is from the FSU (Fisheries Statistics Unit) data. Catches from 1989 onwards were captured on QMR forms and reported in Plenary documents (e.g., Annala et. al. 2003). Data for 2002 and 2003 were supplied by MFish on 28 January 2004 (Figure 2). For the 2004 catch we assumed the TACC.

It may be unrealistic to start the model in 1983 under an assumption of unfished equilibrium, as in previous assessments. There may have been some fishing before 1983 from which the catches were unknown, although they are likely to have been small. We assume that catches increased linearly from zero in 1973 to the average of observed 1983 and 1984 catches in the 1983 fishing year (Table 1, Figure 3).

3.1.1.1 TACC

The TACC was set at 261 t when paua entered the QMS in 1987. This steadily increased and the TACC has been 326.54 t since the 1996 fishing year (Table 1).

3.1.2 Recreational catch

No recreational catch estimates are available for PAU 4. We assumed 0 t of recreational catch for the 2004 assessment.

3.1.3 Illegal catch

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

3.1.4 Customary catches

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

3.2 CPUE

Standardisation used the natural logarithm of catch per diver day. 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 4 is shown in Table 2.

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 4, FSU data were extracted from the NIWA-managed database for the period January 1983 through September 1988. There is a gap for the 1989 fishing year (transition period from FSU data to CELR data), and 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 reliable 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 CELR data (possibly because the species code PAU was used for both yellowfoot and blackfoot paua), but it was not possible to sort them out reliably and they were left in place.

PAU4 CELR data and PCELR from 1 October 1989 to 30 September 2003 were extracted from MFish, and PAU FSU data were extracted from the NIWA database in December 2003.

There were 10955 (same as the number of effort data extracted) records. Of these, 437 records were deleted because the number of divers in the CELR form was missing, 9 records because the number of divers was greater than 8, 11 records because diving hours per diver was greater than 10, and 25 records because CPUE (estimated catch per diver in one day) was greater than or equal to 2000 kg. This grooming process left 10473 records; this became 10123 after collapsing PCELR data by form number and statistical area so that the data were in the same form as CELR data.

Of these 10123 records, there were 31 records with zero or "NULL" estimated catches (0.3 % of data). "NULL" indicates there was no catch reported (estimate of catch column was empty in the form). Since there were 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 10092 records. Historically, for the paua CPUE standardisation, vessel was one of the important variables; hence we calculated the number of years the vessel has been operated in PAU 4, then removed all data recorded by vessels that operated less than 5 fishing years. This process left 6475 records. This includes 527 records (8%) with vessel code as "NULL". These data were not included in the analysis even if there are possibilities that some of these data are gathered using no vessel. MFish advised:

NULL value for the vessel means no value has been entered. On the PCELR forms the fisher is supposed to enter NONE to declare that he didn't use a vessel (this would still show up in the database as NULL): if he leaves it blank (it will also show up as NULL) the validators would send the permit holder a letter asking him to correct his data by either entering the vessel or declaring NONE. This relies on the permit holder correcting the data and is one of the reasons why the database changes as the time this takes varies from individual to individual.

Hence the final number of records used for the standardization of CPUE is 5927 records.

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.

For PAU 4 the interaction between area and month was significant ($\alpha<0.0001$). Variables offered to the model were vessel, fishing year, month, and statistical area. The fishing year was 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. Because the statistical area effect is not included in the model, we adapted Andre Punt's suggestion to look at the interaction between area and month. The model explained 27.4% of the variation in CPUE for PAU 4 (and 28.7% with interaction).

Raw and standardised CPUE for PAU 4 (with interaction) are shown in Figure 4 (raw CPUE is the sum of catch divided by the sum of diver days). The standardised CPUE generally follows the pattern of the raw CPUE. Raw CPUE underestimates the standardised CPUE for pre-1993 fishing years and overestimates it for post-1993 fishing years. CPUE reached its highest point in 1987 then decreased until the mid 1990s when it started to increase again. There is a slight drop in standardised CPUE from 2002 to 2003.

The raw CPUE and standardised CPUE indices with the interaction term for PAU 4 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 5A.

3.3 Research diver survey index (RDSI)

The timed-swim survey index method was described by Andrew et al. (2002). Divers make a timed swim of 10 minutes after sighting the first paua, and they record the patch size by grade (in 1994 data) or by actual count (in 2002 data). The timed-swim index for a swim is the product of numbers of patches and numbers per patch, for patch types. Surveys were conducted in PAU 4 in 1994 and 2002.

In calculating the RDSI 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 1994 data (Table 5). For the 2002 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 now count patches, 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 ath 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 approach was adopted.

The definition of the visibility code is shown in Table 6. Code 1 is for very clear water and code 5 is for murky water. The summary of the research diver survey data is shown in Table 7.

There were four strata in PAU 4 research diver surveys, which were the same as the old statistical areas (see Figure 1). Some timed-swim data come from a marine reserve in PAU 4. These were not included in the standardisation analysis for the abundance index.

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 4. The model with searching time explains 20.6% of the variation in RDSI and the model without searching time explains 17.5% of the variation in RDSI.

Raw and standardised diver survey indices with confidence intervals are shown in Figure 5 (the raw index is the arithmetic mean of the indices from each swim). There is only a small difference in raw and standardised research diver survey indices and the confidence intervals are wide. The visibility effect and the stratum effect are similar both with and without searching time (Figure 5).

The standardised RDSI for each year are shown in Table 9.

3.4 Commercial catch sampling length frequency data (CSLF)

The number of days sampled from the commercial fishing in each statistical area in each fishing year is shown in Table 10. The number of paua measured in each area for each fishing year is shown in Table 11. Only one day was sampled and a very small number of paua were measured in 1999.

As for the CSLF data used for the 2003 PAU 7 assessment (Breen & Kim. 2003), the sample length frequencies were simply added together for each year (Table 11). It is not possible to stratify the data by catch, because the statistical area for some paua measured is unknown because some divers (or quota owners) were reluctant to give out this information.

Data from the four strata aggregated over all years are generally consistent (Figure 6), and all have median distributions within a few millimetres of the MLS, although stratum 52 appears to have higher abundance of smaller paua.

The data are shown aggregated across strata for each year as cumulative frequencies in Figure 7. The 1999 fishing year showed the smallest abundance of large paua.

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

$$K_t^s = \frac{\sqrt{n_t^{paua \geq MLS}}}{\min_t\left(\sqrt{n_t^{paua \geq MLS}}\right)}.$$

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.

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, 6 978 paua were measured. The number of paua measured in each stratum in each year is shown in Table 12.

The RDLF data by fishing year (Figure 8) show a difference, with fewer large paua in 2002. The weighted length frequencies and cumulative frequencies by stratum (Figure 9) show similarity among strata, but stratum 2 (with the smallest sample size) has more small and fewer large paua.

For 2002, which has both RDLF and CSLF data, we compare the proportions-at-length for the paua above the MLS (Figure 10 and Figure 11). There is an obvious difference between the patterns seen in the two types of data: the research diver surveys tended to find more small paua and fewer large paua (this is the opposite of the pattern seen elsewhere).

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 population model. We describe the raw data, grooming, and experimental fitting.

3.6.1 Raw data

Paua were tagged (Reyn Naylor, NIWA, pers. comm.) to measure paua growth in various locations. In early November 2000, 2488 paua were tagged in The Horns (Stratum 4 on Figure 1), Waitangi West (Stratum 4), and Wharekauri (Stratum 1). No sex or maturity information were recorded for these data. A year later, 187 tagged paua were recovered by research divers (Table 13).

Because the model does not represent paua less than 70 mm in length, we removed all records for paua tagged at smaller sizes (4 records, all from Waitangi West).

3.6.2 Growth models

Tagging data were fitted using Schnute's growth model (Schnute 1981). First we fitted to tag data for each area separately, then to all data pooled, with α and β fixed at 75 and 120 respectively. The growth shape parameter, δ, was fixed at 1, which represents a linear decline in increment at length; when the shape parameter was estimated, the growth curve was dome shaped (Figure 12). This is in contrast to the result from PAU 5A (Breen & Kim 2004).

The Horns and Wharekauri, where relatively smaller numbers of tagged paua were recaptured, showed slowest and fastest growth respectively for small paua (Table 14). For all PAU 4 tag data, the growth estimation was dominated by Waitangi West tags. Fits are shown in Figure 13 to Figure 16.

3.7 Maturity data

In June 1994, 92 paua were measured and observed in a study of maturity-at-size (Reyn Naylor, pers. comm.). The number of paua measured and number of paua mature among them are shown in Table 15. For some length classes, only a small number were available. The proportion of mature paua in PAU 4 and a simple logistic curve fitted to the data are shown in Figure 17. This fit uses a simple likelihood based on the same formula used in the assessment. The fit is not weighted by the number of paua measured, which might be a better way to fit this type of data. Consequently, the effect of observations in length bins 103 and 105 where half happened to be immature is to decrease the slope of the curve. No paua over 108 mm were measured.

Because of the small sample sizes, the population model was not fitted to these data. The maturity parameters affect only the model estimates of spawning biomass. In the assessment we used assumed values.

4. MODEL RESULTS

This section first shows the MPD results from the base case, which was chosen by adjusting the relative weight parameters for each dataset until the standard deviations of standardised residuals were close to 1.0 for each dataset. Sensitivities to the influence of datasets and modelling options were explored by comparing MPD runs.

Second, we show diagnostics from one long McMC chain for the base case model. Third, we show the Bayesian fits and residuals from these fits. The assessment is obtained from the posterior distributions of a set of indicators based on biomass and exploitation rate at three times: the present, at the end of three-year projections, and a reference period, 1991–93. Values are given in a table showing, for each relevant indicator, the minimum and maximum, the 5th and 95th percentiles, and the mean and median.

4.1 Finding a base case

As for the 2003 assessment of PAU 7 (Breen & Kim. 2003), the base case was chosen by altering the relative weight of each dataset until the standard deviations of the normalised residuals were close to 1.0 for each dataset. In these runs, the shape parameter δ was fixed at 1 and the shape parameter h was fixed at 0.62, the latter taken from the PAU 7 assessment.

The CPUE time series shows a slight decline after a steep increase in the early years. It was difficult for the model to fit the early years with an increase and the model tended to estimate M on its upper bound with very high recruitment and trifling exploitation rates, producing a predicted CPUE that was almost flat. It seemed reasonable to assume a three-fold increase in the standard error for the first four years of data (from 1983 through 1986).

In sensitivity trials, we tested for the effect of estimating δ and h. This case was subsequently chosen as the final base case for the PAU 4 stock assessment (Table 16).

4.2 MPD results

Parameter estimates and some indicators are shown in Table 17. The initial base case is denoted model run "001" and the final base case is run "017". The MPD estimate of M was 0.199, slightly larger than the assumed mean of the prior distribution, 0.10 (Table 17).

The final base case model fits the observed CPUE reasonably well for the recent years and fits the two RDSI data well (Figure 18). Having two years of RDSI data leads to a pattern in the residuals (Figure 19), both over time and against the predicted value.

The model estimated h as 0.72, giving a relation between CPUE and biomass with some hyperstability (Table 17). This is what one would expect from abalone populations, where divers can maintain high catch rates as the stock is fished down.

Fits to proportions-at-length were reasonably good (Figure 20), and there was no consistent relation between the residuals and length (Figure 21), although there are some patterns near

MLS for the commercial catch sampling data. The q-q plot is generally better from the commercial catch sampling data (Figure 22).

The fit to growth increment data (Figure 23) is generally good: using the proportions-at-length data enables the estimation of shape parameter δ. There is one large negative residual (near -6, Figure 23) and one large positive one (near 4) from 363 days tagging data, but no large positive or negative residuals from the 362 days tagging data. The q-q plot is generally good.

The q-q plot from all model residuals from all data (Figure 24) is generally good and the *sdnr* for each data set is close to 1 (Table 17).

The expected annual growth increment is shown in Figure 25 (top). The midpoint of the research diver selectivity ogive (Figure 25, middle) was 110.6 mm, and the ogive was broad. The midpoint of the commercial selectivity (Figure 25, bottom) was 124.1 mm, just under the MLS, and this ogive was very narrow.

The model's MPD estimates of recruitment (Figure 26, top) were lower than average in the late 1980s, and a higher than average in the late 1990s.

Exploitation rate (Figure 26, bottom) increased steadily over the history of the fishery, reached 30% in 1994, decreased slightly, and then increased to near 30% again in 2004.

The virgin length frequency (Figure 27) has a mode at 80 mm and has substantial numbers of large paua. Recent proportions-at-length still have many small paua and fewer large paua.

The model recruitment plotted against the model's spawning biomass two years earlier (Figure 28) shows no obvious relation.

The biomass trajectories, the surplus production trajectories and surplus production plotted against the recruited biomass are shown in Figure 29. Biomass has decreased since the beginning of the model until the mid 1990s, and then increased slightly in the last 10 years. The surplus production has increased as biomass decreased and is relatively high in recent years, most likely in response to recent high recruitments (see Figure 26).

4.3 MPD sensitivity trials

The base case MPD was chosen from the sensitivity trials made with an earlier base case candidate; these sensitivities were not re-run. The sensitivity trials with an earlier base case candidate are shown in Table 17.

In these sensitivities, the calculation for *Bav* was based on years 1985–87. After these were run, the definition of *Bav* was changed to 1991–93, so these results are for examining sensitivities only and cannot be compared with the McMC results.

In these trials, the likelihood used for fitting length frequencies (runs 001 through 004) had a large effect on biomass estimates, but this was mainly through weighting the data sets differently, as shown by the *sdnr*s and *manr*s (Table 17). These could have been pursued further with iterative re-weighting trials, but there was insufficient time for this.

When the model was fitted to one data set at a time, runs 005 through 009, reasonable results were obtained only when CPUE was used. Conversely, however, when all data sets were fitted **except** CPUE (and maturity, which was never fitted), the results were not grossly different from the base case except for lower biomass.

Using a Cauchy prior allowed *M* to reach its upper bound.

Estimating h led the model to estimate moderate hyperstability in CPUE, although h increased again when δ was estimated also. Estimating the shape of the growth curve improved the fit overall (although not to CSLFs) and led to a more plausible estimate of exploitation rate. We chose this run as the new base case.

4.4 McMC results

We examined the chain for each parameter from the long McMC run. Five tests – Raftery & Lewis (1992), Geweke (1992), Stationary and Half width test by Heidelberger & Welch (1983), and the single chain Gelman – were used to test the single chains for stationarity and convergence (see Brooks & Roberts 1998). Diagnostics on the chain (Table 18) were poor for two tests and generally good for the others, not an unusual situation.

Traces (Figure 30) appeared to be reasonable, but δ reached the upper bound in many samples. The correlation matrix shows several high correlations among the parameter posteriors, the highest being between h and $\ln(q^I)$, M and $\ln(R0)$ and among the growth parameters (Table 19).

4.5 Marginal posterior distributions and the Bayesian fit

Posteriors (Figure 31) were generally well formed and MPDs were mostly near the centres (but they tended to be in the lower part for biomass posteriors); δ and h went against their upper bound. Posteriors of the *sdnrs* were mostly in the range from 0.8 to 1.2 except for RDSI (two data points only).

The posteriors are summarised in Table 20. Some parameter posteriors (selectivity) were tight, others (M and h) were loose. Biomass indicators tended to be loosely estimated: for instance *Bav* had a 90% range from 820 to 2107 t; *B04* from 769 to 2338. The ratio indicators were tighter, for instance *B07/B04* had a 90% range from 101% to 138%.

The posteriors of fits to CPUE (Figure 32) show that variation was greatest for the early years, where data are weakest, and was low for the recent years. Some years have predictions that do not encompass the observed values but there is no pattern in the residuals. The posteriors for predicted RDSI data (Figure 33) fit the data well.

The posteriors of predicted CSLFs for 2002, when both CSLF and RDLF data were available, (Figure 34) were very tight and often did not match the observed values. Proportions near the MLS tended to be overestimated, and proportions near 150 mm tended to be underestimated. The residual pattern was worse for RDLFs in the same year (Figure 35), although the overall fit was acceptable. The selectivity curve may be mis-specified in some parts of the size range.

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 36). This is well formed between -2 and 2 quartiles.

The biomass trajectory posteriors (Figure 37) were generally wide, reflecting high variability in these absolute abundance estimates. Variability was least for recruited biomass and greatest for total biomass. Variability for spawning biomass would have been much greater if the maturity parameters had been estimated: assuming fixed values greatly reduced the uncertainty.

In all three biomass measures, the stock declined from 1972 to the early 1990s. Recruited biomass then increased slightly and decreased again. The projections at current assumed catch levels show an increase, but uncertainty in projections was high and we projected only three years ahead. The recruited biomass trajectory is shown in more detail in Figure 38.

Exploitation rate (Figure 39, top) also had least uncertainty in the early years, when it was low, and greatest in the most recent years. It increased steadily until the millennium, and although highly variable it tends to decrease in projections. The estimates were lower in the McMC than they were in the MPD (Table 20).

Recruitment (Figure 39, bottom) had a trajectory with the median showing less annual variability than in the MPD. The posteriors are very broad, showing limited information about the absolute value of recruitment.

The surplus production trajectory followed catch (Figure 40) and was least variable in the early years and most variable in the recent years.

4.6 Assessment of PAU 4

The assessment results (summarised in Table 20) suggest that current recruited biomass is 1450 t (5% to 95% range 770 to 2340 t), and that the current exploitation rate is 19% (12–33%). This is a relatively wide range of uncertainty. Optimum exploitation rate is unknown.

The reference period, 1991–93, 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 just above *Bav*, but with high uncertainty (83–125%) reflected in Figure 37. Current spawning biomass appears more certainly high than *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 with a high priority.

Projections suggest an increasing recruited biomass, with a median of 20% increase (1.4–38%) and a more uncertain spawning biomass (median 4% decrease, 90% range of 18% decrease to 16% increase). The 2007 recruited biomass could be above *Bav* (median 26% increase), but is uncertain (12% decrease to 60% increase). The 2007 spawning biomass is similar.

In this assessment the overall chance of recruited biomass decreasing is only 4%, but for spawning biomass is 64%. The chance of falling below reference levels in 2007 is 13% and 10% for recruited and spawning biomass respectively.

4.7 Retrospective analysis

In MPD retrospectives, tagging data were not removed, and the dataset weights were left at the base case values (not iteratively adjusted). We compared four retrospective analyses: the first used the full dataset, the next eliminated data from 2003, and so on. Table 21 shows a summary of data used for this analysis.

Retrospectives for the fit to the CPUE data (Figure 41) show that removing two years of data (i.e., the 2002 retrospective) made a slight difference from other retrospectives. Recruited biomass retrospectives (Figure 42, top) show that removing two years of data causes biomass estimates to change considerably, although the shape was roughly the same, then removing one more year (2001) returned model biomass to the base case. The 2002 retrospective had very high *M* and ln(*R0*). The retrospectives for recruitment also show that the 2002 retrospective is quite different from others (Figure 42, bottom). Exploitation rates (not shown) are stable except for 2002, which was much lower as a result of the high biomass.

Except that absolute biomass estimates change somewhat in these retrospectives (Table 22), and apart from the 2002 run, these trials show a roughly stable pattern.

5. DISCUSSION

5.1 PAU 4 assessment

The diagnostics for this assessment were favourable. The base case obtained from iterative re-weighting appeared to be a good fit to the various data, and the standard deviation of the normalised residuals remained near 1 during the McMCs. The posteriors of fits to proportions-at-length suggest that these data may have been over-weighted, and in future it would be preferable to choose the base case relative weightings from trial McMCs rather than from MPDs.

Sensitivity trials with the MPD indicated no single data set upon which the assessment results depended strongly and showed general consistency between the data sets. The tagging data set was the major basis for the growth parameter estimates, as shown by different estimates when it was removed, and the indicators changed slightly when this dataset was removed. McMC runs appeared to be converged.

The assessment is an optimistic one, and indicates that the current level of catch is sustainable. The current exploitation rate is low (18.8%); consequently the estimated current biomass is high. In model projections the current catch is likely to be fully caught in the near future, recruited biomass is likely to increase with a high probability, and spawning biomass has a 96% chance of increasing further.

Retrospective analysis shows that excluding data after 2002 causes a big change to biomass, exploitation rate trajectories, and parameter estimates, but it also shows adding the 2003 data brings the patterns of biomass, exploitation trajectories, and parameter estimates back to the 2001 level and they stayed at that level with the addition of the 2004 data. There is no pattern whether the addition of each successive year of data causes projections to be more optimistic or more pessimistic. The major features of the data, possibly accounting for this behaviour, are: an increase in CPUE between 2001 and 2002, an increase in the RDSI between 1994 and 2002, and shifts in both sets of proportion-at-length data towards relatively smaller paua and relatively fewer large paua.

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, although the choice of a base case was reasonably objective. Sensitivity trials (see Table 17) 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. The commercial catch data show large fluctuations in 1983 to 1986 that suggest anomalies in data capture. The period before 1983 is unknown, and although we think the effect is minor, major differences may exist between the catches we assume and what was taken. In addition, non-commercial catch estimates are unavailable but could be substantial.

The tagging data are from only three locations, which may not reflect fully the average growth and range of growth in this population. Similarly, length frequency data collected from the commercial catch may not represent the commercial catch with much precision: only 110 days have been sampled in five years and only 1000 paua were measured in total from some areas.

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 148 sites may not be fully representative of Chatham Islands paua habitat, and thus length frequencies may not be representative.

5.2.3 The model is homogeneous

The model treats the whole of PAU 4 as if it were a single stock with homogeneous biology, habitat and fishing pressures. This mean the model assumes homogeneity in recruitment, natural mortality, which does not vary by size or year and growth has the same mean and variance (we know this is violated because we know some that areas are stunted and some are fast-growing).

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

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

5.2.4 The model assumptions may be violated

The most suspect assumption made by the model 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 this assessment, the degree of hyperstability was poorly determined.

In fully developed fisheries such as PAU 7 this is not such a serious problem. The difference is illustrated by CPUE itself: for PAU 7 it was 64 kg per diver day in 2002; for PAU 4 it was 335 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 4 length frequencies show only small changes among the years sampled if the suspect 1999 is excluded, although the 2004 frequency does show fewer large paua and more small paua.

If serial depletion occurs in the current PAU 4 fishery, then these assessment results may be misleading. Biomass may be declining much faster than CPUE indicates, and the size structure may be changing to smaller paua much faster than the CSLFs indicate. The fishery-independent research diver data are too sparse to indicate if serial depetion is occuring.

Whether serial depletion is a problem cannot be determined with the current data. Statistical area catches show no obvious pattern (see Figure 2).

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 catch (kg) for the PAU 4 assessment and TACC (t). Catches before 1983 are assumed.

Fishing year	Catch	TACC (t)
1973	23 214	
1974	46 428	
1975	69 641	
1976	92 855	
1977	116 069	
1978	139 283	
1979	162 497	
1980	185 710	
1981	208 924	
1982	232 138	
1983	101 703	–
1984	409 000	–
1985	278 000	–
1986	221 000	–
1987	267 370	261.00
1988	279 570	269.08
1989	284 780	270.69
1990	287 380	287.25
1991	253 610	287.25
1992	281 590	287.25
1993	266 380	287.25
1994	297 760	287.25
1995	282 100	287.25
1996	220 170	326.54
1997	251 710	326.54
1998	301 690	326.54
1999	281 760	326.54
2000	321 560	326.54
2001	326 890	326.54
2002	321 640	326.54
2003	325 620	326.54
2004	326 543	326.54

Table 2: Data sources, periods and number of records for data used for the CPUE standardisation for the PAU 4 assessment.

Data source	Data periods	Extracted in	Raw records
FSU	2 January 1983 – 18 September 1988	December 2003	5 657
CELR	1 October 1989 – 28 February 2002	December 2003	3 892
PCELR	1 October 2001 – 30 September 2003	December 2003	1 406
Total			10 955

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 4.

Variable	Model r^2(%)
Fyear	9.3
Vessel	25.9
Month	27.4
Area*Month	28.7

Table 4: Standardised CPUE indices for PAU 4. Standard errors for the first four years were arbitrarily tripled.

Year	Year effect	SE
1983	0.583	0.216
1984	0.901	0.155
1985	1.047	0.174
1986	1.055	0.176
1987	1.546	0.061
1988	1.434	0.065
1990	1.253	0.063
1991	1.225	0.061
1992	1.201	0.060
1993	0.773	0.052
1994	0.686	0.046
1995	0.848	0.047
1996	0.994	0.054
1997	1.030	0.052
1998	0.789	0.049
1999	1.057	0.051
2000	0.933	0.053
2001	0.957	0.056
2002	1.187	0.062
2003	1.038	0.067

Table 5: Definition of research diver survey patch type by number of paua; the old definition assumed mean number and the new definition uses actual mean number for PAU 4.

		Average patch size	
Patch type	Patch size	Old	New
1	1–4	1.28	1.58
2	5–10	7.5	6.88
3	11–20	15.5	14.48
4	21–40	30.5	28.07
5	41–80	60.5	52.58
6	>80	120.5	150.51

Table 6: Definition of visibility code.

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

Table 7: Summary of research diver survey data - 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 of abundance involving time searching is shown by stratum in (c) and by visibility in (d).

(a)

Count				Stratum
Fishing year	1	2	3	4
1994	22	2	10	
2002	30	22	30	28

(b)

Count					Visibility
Fishing year	1	2	3	4	5
1994	14	4	14		2
2002	2	46	56	6	

(c)

Average				Stratum
Fishing year	1	2	3	4
1994	126.34	116.92	174.33	
2002	225.41	303.35	221.68	194.03

(d)

Average					Visibility
Fishing year	1	2	3	4	5
1994	64.50	109.06	238.44		39.64
2002	206.09	238.06	227.57	235.41	

Table 8: The order in which variables were selected into the GLM model of RDSI incorporating searching time and their cumulative effect on the model r^2 for PAU 4.

Variable	Model r^2(%)
Fyear	8.3
Visibility	17.9
Stratum	20.6

Table 9: Standardised RDSI for PAU 4.

Fishing year	Index	SE
1994	0.862	0.126
2002	1.160	0.126

Table 10: Number of commercial catch sampling days in each area in each fishing year for PAU 4.

Fyear	049	050	051	052	unknown	Total
1999	1					1
2000	9	1	4	2	5	17
2001	10	3	10	2	7	27
2002	9		13	3		20
2003	11	3	11	8	1	29
2004	8		7	3		16
Total	48	7	45	18	13	110

Table 11: Numbers of paua measured in commercial catch sampling by year and stratum in PAU 4.

Fyear	049	050	051	052	blank	Total
1999	101					101
2000	914	114	438	217	650	2 333
2001	1 362	532	1 305	224	987	4 410
2002	1 559		1 776	446		3 781
2003	1 396	361	1 683	958	111	4 509
2004	1 025		886	348		2 259
Total	6 357	1 007	6 088	2 193	1 748	17 393

Table 12: Numbers of paua measured in research diver surveys by year and stratum in PAU 4.

Fyear	1	2	3	4	Total
1994	602	92	427		1 121
2002	1 650	1 111	1 285	1 811	5 857
Total	2 252	1 203	1 712	1 811	6 978

Table 13: Summary of tag-recapture datasets discussed in this report.

Area	Release	Recovery	Recovered	Tagged	% recovery
The Horns	27 Nov 2001	25 Nov 2002	36	820	4.4
Waitangi West	25 Nov 2001	23 Nov 2002	120	826	14.5
Wharekauri	26 Nov 2001	23 Nov 2002	31	842	3.7
Total			187	2 488	7.5

Table 14: Estimated value for each parameter with tag data in each area. g_α is the expected growth increment for a 75 mm initial length, g_β for a 120 mm initial length, φ is estimated, and σmin is the minimum standard deviation. -ln(L) is the negative log-likelihood function.

	The Horns	Waitangi West	Wharekauri	All PAU 4
g_α	16.13	17.80	22.57	18.22
g_β	3.64	2.44	3.59	2.70
φ	0.14	0.35	0.17	0.31
σ_{min}	2.91	4.32	2.82	4.00
-ln(L)	89.5	340.2	76.8	520.9

Table 15: Numbers of paua and number mature-at-length in the maturity-at-size study in PAU 4.

Length	Number	Mature
73	2	0
75	3	0
77	2	0
79	0	0
81	3	0
83	1	0
85	1	0
87	1	0
89	10	1
91	6	2
93	6	2
95	9	4
97	12	8
99	16	12
101	10	6
103	7	3
105	2	1
107	1	1
Total	92	

Table 16: PAU 4 base case: for estimated parameters, the phase of estimation (-1 indicates fixed), lower bound, upper bound, type of prior, (0 uniform, 1 normal, 2 lognormal), mean of the prior, stdandard deviation of the prior, and initial values; for other variables, values assumed for the base case. "Varied" means fixed in the base case, but varied between runs to find a base case.

Variable	Source	Phase	LB	UB	Prior	Mean	StdDev	Initial
$\ln(R0)$	est	1	0.01	50	0	0	0	1
M	est	1	0.01	0.5	2	0.1	0.35	0.14
g_α	est	2	1	50	0	0	0	15
g_β	est	2	0.01	50	0	0	0	8
ϕ	est	2	0.001	1	0	0	0	0.5
q^I	est	1	-30	0	0	0	0	-13
q^I	est	1	-30	0	0	0	0	-13
δ	est	1	0.001	5	0	0	0	1
L_{50}	fixed	-1	70	145	0	0	0	95
L_{95-50}	fixed	-1	1	50	0	0	0	7
T_{50}	est	2	70	125	0	0	0	100
T_{95-50}	est	2	0.001	50	0	0	0	25
D_{50}	est	2	70	145	0	0	0	124
D_{95-50}	est	2	0.01	50	0	0	0	2
$\ln(\tilde{\sigma})$	est	1	-10	10	0	0	0	-1
h	est	1	0.01	2	0	0	0	0.62
ε	est	3	-2.3	2.3	1	0	0.4	0
σ_{MIN}	fixed	-2	0.001	5	0	0	0	1
σ_{obs}	fixed	-1	0.001	5	0	0	0	0.25
MLS								125
ϖ^I	varied							0.1
ϖ^J	varied							0.75
ϖ^r	varied							65
ϖ^s	varied							23
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: MPD sensitivity trials for PAU 4. The full caption follows the table.

run index	"001	"002	"003	("004)	"005	"006	("007)	("008)	"009	"010	"011	"012	"013	("014)	"015	"016	"017
LFlike	1	2	3	4	1	1	1	1	1	1	1	1	1	1	1	1	1
wtCPUE	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
wtRDSI	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
wtCSLF	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
wtRDLF	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65	65
sdnrCPUE	0.933	0.890	1.522	3.572	**0.967**	2.838	2.344	16.588	0.503	26.25	1.044	1.633	0.932	0.991	0.916	0.934	0.909
sdnrRDSI	0.871	0.228	0.205	0.242	10.038	**1.000**	2.107	6.791	1.028	1.012	3.725	0.114	0.217	1.264	0.083	0.908	0.839
sdnrCSLF	1.078	1.159	1.407	2.831	50.688	8.957	**0.999**	21.043	2.505	1.073	1.071	10.84	1.009	1.106	1.110	1.077	1.095
sdnrRDLF	0.820	1.042	1.084	2.835	20.662	6.583	3.187	**1.000**	1.911	0.822	0.803	0.769	3.225	0.709	0.750	0.825	0.779
sdnrTags	1.025	1.003	1.040	0.914	4.736	0.513	3.882	5.273	**1.000**	1.012	1.043	1.029	1.028	41.35	0.942	1.017	1.042
manrCPUE	0.721	0.806	1.156	2.355	**0.267**	10.322	7.999	56.044	0.457	81.76	0.639	1.143	0.672	0.658	0.720	0.730	0.551
manrRDSI	0.871	0.228	0.205	0.242	719.021	**1.000**	215.676	296.305	67.238	1.012	240.05	0.114	0.217	1.264	0.083	0.908	0.839
manrCSLF	0.360	0.513	0.728	3.066	10.477	0.666	**0.350**	5.325	0.353	0.361	0.341	12.863	0.370	0.423	0.368	0.371	0.348
manrRDLF	0.297	0.544	0.583	3.066	8.200	0.661	1.597	**0.557**	0.558	0.307	0.329	0.421	0.707	0.419	0.296	0.296	0.301
manrTags	0.567	0.564	0.559	0.462	13.850	1.252	3.183	5.039	**0.492**	0.547	0.599	0.501	0.536	3.190	0.482	0.553	0.487
$\tilde{\sigma}$	0.298	3.351	0.177	0.046	0.098	0.726	0.298	0.102	0.910	0.296	0.299	0.154	0.307	0.273	0.287	0.296	0.299
$\ln(R0)$	2.802	2.568	3.152	5.063	2.572	15.458	26.393	21.523	22.357	2.624	2.450	2.931	2.536	3.212	4.823	2.618	2.822
M	0.218	0.208	0.258	0.496	0.351	0.094	0.400	0.253	0.088	0.208	0.179	0.227	0.190	0.197	0.500	0.202	0.199
T_{50}	110.9	105.8	109.5	95.0	97.6	70.9	98.3	118.2	99.2	110.0	107.8	125.0	95.0	113.3	113.7	110.3	110.6
T_{95-50}	16.7	19.2	17.3	38.1	25.0	0.3	25.0	18.8	25.0	16.6	18.1	33.9	0.2	20.4	14.7	16.7	19.8
D_{50}	124.0	124.4	123.9	124.0	143.1	111.5	125.3	106.0	120.0	124.0	123.9	122.0	123.6	124.7	124.4	124.0	124.1
D_{95-50}	7.9	8.1	8.2	1.9	0.1	25.0	7.7	24.6	17.0	8.0	8.1	0.3	7.6	8.5	7.7	8.0	8.1
$\ln(q^I)$	-0.6075	0.0000	-0.7079	-1.5673	-0.3394	-14.9290	-15.4659	-15.5156	-14.2434	-15.0000	-0.6058	-0.6267	-0.6659	-0.9155	-0.9920	-0.3717	-1.0251
$\ln(q^J)$	-2.9375	-2.7421	-3.1843	-5.3758	-15.0000	-17.8043	-15.4659	-15.5156	-14.2434	-2.7944	-15.0000	-2.5795	-3.4820	-3.4993	-3.5979	-2.8192	-3.3816
g_α	12.1	11.8	12.2	14.0	36.5	24.1	7.8	5.5	14.0	12.1	12.0	13.7	13.1	8.8	13.0	12.1	15.9
g_β	6.6	7.2	6.6	7.0	14.8	24.4	4.4	2.3	4.4	6.8	6.4	5.3	6.7	5.2	7.1	6.8	5.3
δ	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3.504
φ	0.597	0.604	0.581	0.591	0.026	0.501	0.235	0.183	0.635	0.597	0.593	0.583	0.558	0.192	0.602	0.596	0.590
h	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.432	0.720

run index	"001	"002	"003	("004)	"005	"006	("007)	("008)	"009	"010	"011	"012	"013	("014)	"015	"016	"017
Likelihoods																	
CPUE	-4	56	0	77	-26	1946	517	27364	12	64628	-2	1	-4	-5	-5	-4	-4
RDSI	-3	1	-5	-8	517086	-1	46516	87837	4520	-3	57634	-5	-4	-3	-4	-3	-3
CSLF	-575	-664	-612	-846	228349	6480	-590	37731	64	-578	-576	9442	-583	-586	-576	-577	-572
RDLF	-291	-331	-321	-408	17110	1535	98	-365	77	-292	-292	-349	1110	-305	-299	-291	-294
Tags	564	569	565	568	20680	791	1956	5204	549	566	564	553	565	1971	567	566	558
Prior on *M*	1	1	2	10	5	-2	7	2	-2	0	0	1	0	0	4	0	0
Prior on ε	6	7	11	37	8	0	3	7	0	6	4	9	6	7	9	6	6
U^{max} penalty	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	-303.4	-361.1	-360.1	-569.1	-12.2	-3.5	-579.9	-356.0	547.0	-299.9	-302.9	210.1	-19.7	-891.8	-304.5	-303.9	-308.0
Indicators																	
maxRdev	1.977	2.953	3.071	5.984	2.324	1.048	1.989	2.020	1.000	2.028	1.785	2.462	2.616	2.050	2.531	1.933	1.814
minRdev	0.676	0.552	0.589	0.242	0.487	0.868	0.688	0.603	0.923	0.705	0.718	0.552	0.676	0.659	0.591	0.699	0.674
U04	44.4%	73.4%	34.9%	8.7%	67.9%	0.0%	0.0%	0.0%	0.0%	56.0%	65.0%	34.1%	43.5%	28.2%	20.3%	52.3%	28.4%
Bav	1195	1102	1238	3481	1800	8.0E+09	2.0E+12	2.0E+10	2.8E+12	1122	1227	990	1307	1691	1531	1215	1639
B04	533	283	699	3390	1090	7.8E+09	2.2E+12	2.0E+10	2.7E+12	398	324	579	533	976	1316	434	915
B04/Bav	44.6%	25.6%	56.4%	97.4%	60.5%	97.0%	106.1%	99.3%	94.7%	35.4%	26.4%	58.5%	40.8%	57.7%	85.9%	35.7%	55.8%
B07	579	196	1162	3039	996	7.9E+09	2.1E+12	2.1E+10	2.7E+12	322	171	811	510	1270	1879	399	1103
B07/Bav	48.5%	17.8%	93.9%	87.3%	55.3%	98.0%	103.0%	104.3%	94.2%	28.7%	13.9%	81.9%	39.1%	75.1%	122.7%	32.9%	67.3%
S04	1772	1053	2683	8933	1438	8.0E+09	9.8E+12	1.5E+11	3.3E+12	1361	1077	2352	1560	3535	5804	1456	2648
S07	1533	950	3148	9308	1345	8.1E+09	1.0E+13	1.4E+11	3.2E+12	1091	838	2444	1196	3283	6132	1202	2516

Caption for Table 17: MPD sensitivity trials for PAU 4. Run indices are explained below; parentheses indicate that the Hessian was not positive definite. Variables are defined in Table 1. "LFlike" denotes the type of likelihood used for fitting length frequencies: 1 Bentley, 2 Fournier, 3 robust Bentley, 4 robust Fournier. "sdnr" is the standard deviation of normalised residuals for the data set shown; "manr" is the median of the absolute normalised residuals. Bold for these values indicates that only one data set was fitted; grey for these indicates that this data set alone was not fitted. Grey for parameters indicates a fixed value. The initial base case is 001 and the actual base case is run 017. Run index:

001 initial base case
002 likelihood for length frequencies changed to Fournier
003 likelihood for length frequencies changed to robust Bentley
004 likelihood for length frequencies changed to robust Fournier
005 fitting to CPUE only
006 fitting to RDSI only
007 fitting to RDLF only
008 fitting to CSLF only
009 fitting to Tags only
010 fitting to all data except CPUE and maturity
011 fitting to all data except RDSI and maturity
012 fitting to all data except RDLF and maturity
013 fitting to all data except CSLF and maturity
014 fitting to all data except Tags and maturity
015 prior for M changed to Cauchy
016 h estimated
017 h and δ estimated (base case)

Table 18: Convergence diagnostics from the base case McMC chains. An asterisk indicates that the test statistic was significantly different (P=0.05) from that indicating convergence. RL: Raftery & Lewis; HW: Heidelberger & Welsh.

	RL	Geweke	HW Stationarity	HW Halfwidth	Gelman
Parameters					
$\ln(R0)$		*	*		
$\tilde{\sigma}$					
M	*	*	*		
g_{α}			*		
g_{β}	*	*	*		
δ		*	*		
T_{50}	*	*	*		
T_{95-50}	*		*		
D_{50}			*		
D_{95-50}					
φ					
$\ln\left(q^{I}\right)$	*	*	*		
$\ln\left(q^{J}\right)$	*	*	*		
h		*	*		
Indicators					
U07	*	*	*		
Sav		*	*		*
S04		*	*		*
S05		*	*		
S06		*	*		
S07		*	*		
Bav		*	*		*
B04		*	*		*
B05		*	*		
B06		*	*		
B07		*	*		
S04/Sav		*	*		
S07/Sav		*	*		
S07/S04					
B04/Bav		*	*		
B07/Bav		*	*		
B07/B04		*	*		
sdnrCPUE			*		
sdnrRDSI		*	*		
sdnrCSLF					
sdnrRDLF					
sdnrTags					

Table 19: Correlations among parameters in the PAU 4 McMC. Boxes indicate absolute values grater than 0.50

	ln(*RO*)	$\tilde{\sigma}$	M	g_α	g_β	δ	T_{50}	T_{95-50}	D_{50}	D_{95-50}	φ	$\ln(q^I)$	$\ln(q^J)$	h
ln(*RO*)	1.00													
$\tilde{\sigma}$	-0.03	1.00	1.00											
M	0.90	-0.06	1.00											
g_α	-0.19	0.00	-0.26	1.00										
g_β	0.10	-0.07	0.48	-0.39	1.00									
δ	-0.17	-0.01	-0.35	0.85	-0.67	1.00								
T_{50}	0.56	-0.07	0.66	-0.43	0.48	-0.39	1.00							
T_{95-50}	-0.28	0.04	-0.46	0.39	-0.59	0.51	-0.40	1.00						
D_{50}	0.34	-0.07	0.39	-0.16	0.16	0.01	0.51	-0.08	1.00					
D_{95-50}	-0.21	0.00	-0.23	0.19	-0.18	0.25	-0.15	0.30	0.50	1.00				
φ	0.03	0.07	-0.16	-0.20	-0.51	0.15	-0.09	0.17	0.00	0.01	1.00			
$\ln(q^I)$	-0.51	-0.03	-0.29	-0.13	0.40	-0.21	-0.07	-0.12	0.00	0.11	-0.19	1.00		
$\ln(q^J)$	-0.53	-0.05	-0.18	-0.29	0.71	-0.42	0.19	-0.28	0.07	0.05	-0.30	0.71	1.00	
h	0.42	0.03	0.28	0.08	-0.27	0.14	0.11	0.06	0.02	-0.10	0.13	-0.96	-0.54	1.00

Table 20: Summary of the marginal posterior distributions from the MCMC chain from the base case for PAU 4. The columns show the minimum values observed in the 5000 samples, the maxima, the 5th and 95th percentiles, and the means and medians. The last four rows show the percentage of runs for which the indicator was true. %MPD is the position that the MPD estimate would occupy in the posterior. Biomass is in tonnes.

Quantity	min	0.05	median	mean	0.95	max	%MPD
$\ln(R0)$	1.78	2.34	2.99	3.04	3.90	5.23	34.9
$\tilde{\sigma}$	0.267	0.288	0.310	0.310	0.334	0.364	22.2
M	0.096	0.134	0.192	0.200	0.289	0.441	55.0
g_α	11.69	14.36	16.80	16.71	18.73	20.15	25.4
g_β	3.36	3.88	4.56	4.61	5.54	6.76	89.5
δ	1.20	2.95	4.24	4.15	4.93	5.00	15.8
T_{50}	83.8	102.4	109.9	109.2	113.8	118.5	61.4
T_{95-50}	8.0	17.7	22.9	24.1	34.9	49.8	19.2
D_{50}	123.0	123.6	124.1	124.1	124.6	125.3	48.0
D_{95-50}	6.9	7.6	8.2	8.2	8.8	9.8	42.1
φ	0.50	0.57	0.63	0.64	0.71	0.87	15.0
$\ln\left(q^I\right)$	-5.19	-3.76	-1.78	-1.93	-0.64	-0.03	82.1
$\ln\left(q^J\right)$	-4.76	-4.27	-3.83	-3.80	-3.26	-2.80	90.4
h	0.015	0.437	0.985	1.033	1.794	1.999	24.7
sdnrCPUE	0.698	0.815	0.932	0.936	1.065	1.250	36.6
sdnrRDSI	0.000	0.073	0.756	0.823	1.825	3.756	55.3
sdnrCSLF	0.934	1.012	1.091	1.092	1.176	1.278	53.4
sdnrRDLF	0.555	0.658	0.755	0.756	0.863	1.018	64.8
sdnrTags	0.857	0.953	1.037	1.037	1.122	1.229	54.1
U04	6.7%	12.1%	18.8%	20.2%	33.4%	67.1%	88.9
U07	5.3%	10.3%	16.6%	18.3%	31.8%	80.0%	88.2
Sav	1265	1858	3006	3116	4743	9510	9.7
S04	1008	2184	3875	4085	6675	13961	12.7
S05	953	2106	3820	4036	6667	12796	12.7
S06	961	2043	3789	4005	6662	12474	11.5
S07	940	1989	3760	3985	6726	13029	9.4
Bav	488	820	1393	1420	2107	3632	10.1
B04	324	769	1457	1494	2338	4302	10.8
B05	236	831	1617	1656	2613	4918	11.5
B06	176	861	1714	1764	2817	5484	11.9
B07	170	836	1741	1794	2901	5831	11.9
S04/Sav	78.4%	106.0%	129.6%	129.9%	155.7%	191.7%	48.0
S07/Sav	56.1%	93.2%	124.5%	126.5%	165.4%	247.8%	25.6
S07/S04	63.6%	81.7%	96.2%	97.1%	115.7%	152.8%	15.9
B04/Bav	57.8%	82.5%	105.0%	104.5%	124.9%	156.3%	32.1
B07/Bav	30.9%	88.4%	125.8%	125.0%	160.5%	204.8%	35.3
B07/B04	46.6%	101.4%	119.1%	119.2%	138.1%	175.0%	49.7
S07 < S04				64.0%			
S07 < Sav				10.1%			
B07 < B04				4.1%			
B07 < Bav				12.5%			

Table 21: Number of data in each dataset for each retrospective analysis. Each column heading represents the last year of data included.

	2004	2003	2002	2001
CPUE	20	20	19	18
RDSI	2	2	2	1
CSLF	6	5	4	3
RDLF	2	2	2	1

Table 22: MPD retrospectives for PAU 4. Note that *Bav* is not the same as that used for McMC results.

Quantity	base	2003	2002	2001
sdnrCPUE	0.909	1.018	1.061	1.421
sdnrRDSI	0.839	0.236	0.113	n.a.
sdnrCSLF	1.095	1.098	1.125	1.015
sdnrRDLF	0.779	0.793	0.776	0.680
sdnrTags	1.042	1.065	1.079	1.078
$\tilde{\sigma}$	0.299	0.260	0.246	0.191
ln(*R0*)	2.822	3.278	4.833	2.355
M	0.199	0.249	0.408	0.156
T_{50}	110.6	108.773	109.38	112.267
$T_{95\text{-}50}$	19.8	17.5	16.2	16.8
D_{50}	124.1	124.2	125.1	122.3
$D_{95\text{-}50}$	8.1	9.0	9.6	7.5
$\ln(q^I)$	-1.025	-1.297	-2.954	-0.775
$\ln(q^J)$	-3.382	-3.585	-4.388	-3.102
g_α	15.9	14.9	14.3	15.8
g_β	5.3	5.6	5.8	5.3
δ	3.504	3.122	2.920	3.515
φ	0.590	0.579	0.572	0.574
h	0.720	0.855	1.351	0.575
likeCPUE	-4.44	-5.11	-5.11	-1.20
likeRDSI	-3.44	-4.37	-4.52	-2.67
likeCSLF	-571.51	-490.92	-382.66	-304.05
likeRDLF	-293.61	-304.18	-310.00	-148.72
likeTags	558.40	559.62	561.01	559.07
Prior on *M*	0.18	1.86	7.06	-1.19
Prior on ε	6.41	7.79	8.69	7.85
Total	-308.02	-235.30	-125.53	109.09
maxRdev	1.81	2.30	1.94	2.93
minRdev	0.67	0.62	0.51	0.52
U04	28.4%	26.4%	13.9%	38.4%
Bav	923	985	2009	746
B04	915	1009	2107	607
B04/Bav	99.1%	102.4%	104.9%	81.4%
B07	1103	1295	2718	538
B07/Bav	119.6%	131.4%	135.3%	72.1%
S04	2648	3281	7155	1524
S07	2516	2810	9035	1774

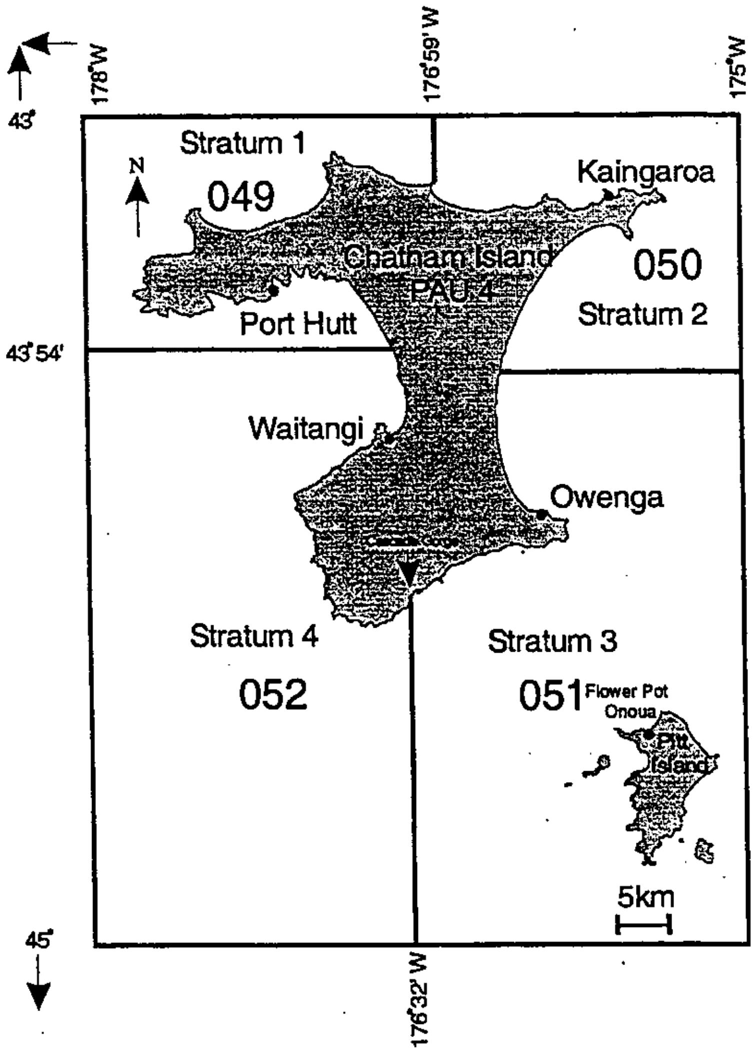


Figure 1: Boundaries of PAU 4 with its statistical areas (numbers 049 to 051) and research strata (stratum 1 to stratum 4).

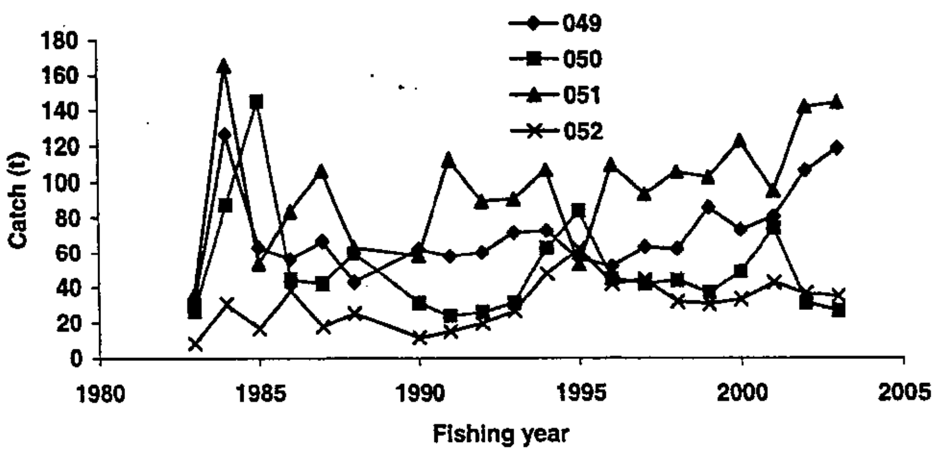


Figure 2: Estimated commercial catch (t) by PAU 4 statistical area.

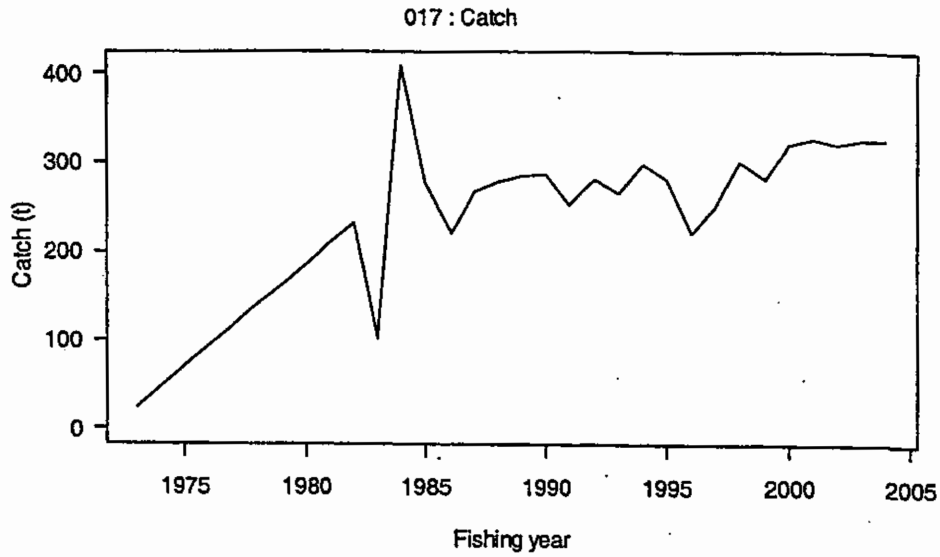


Figure 3: Assumed total catch trajectory for PAU 4.

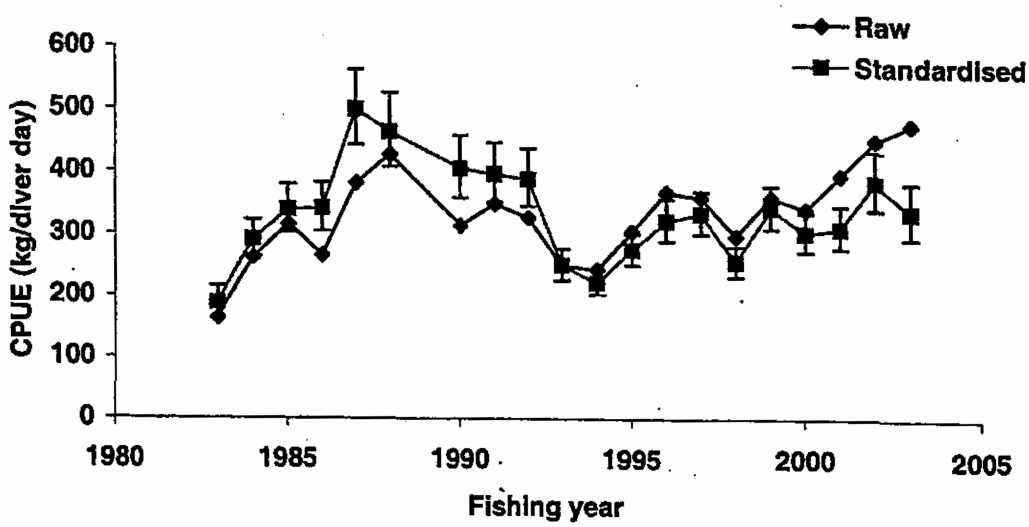


Figure 4: Raw and standardised CPUE from all statistical areas for 5-year vessels.

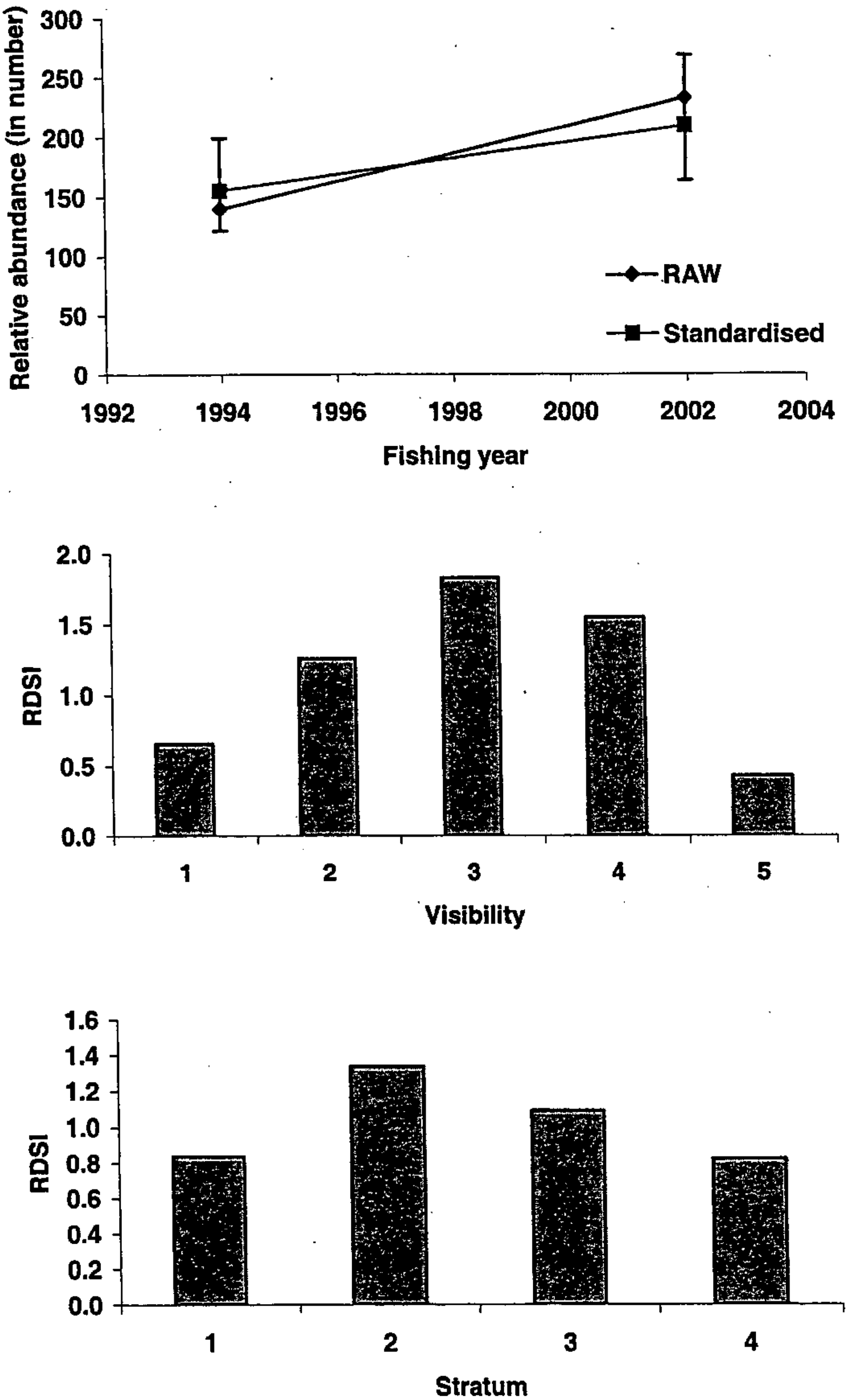


Figure 5: Raw and standardised RDSI for PAU 4: (top), visibility effects (middle) and stratum effects (bottom).

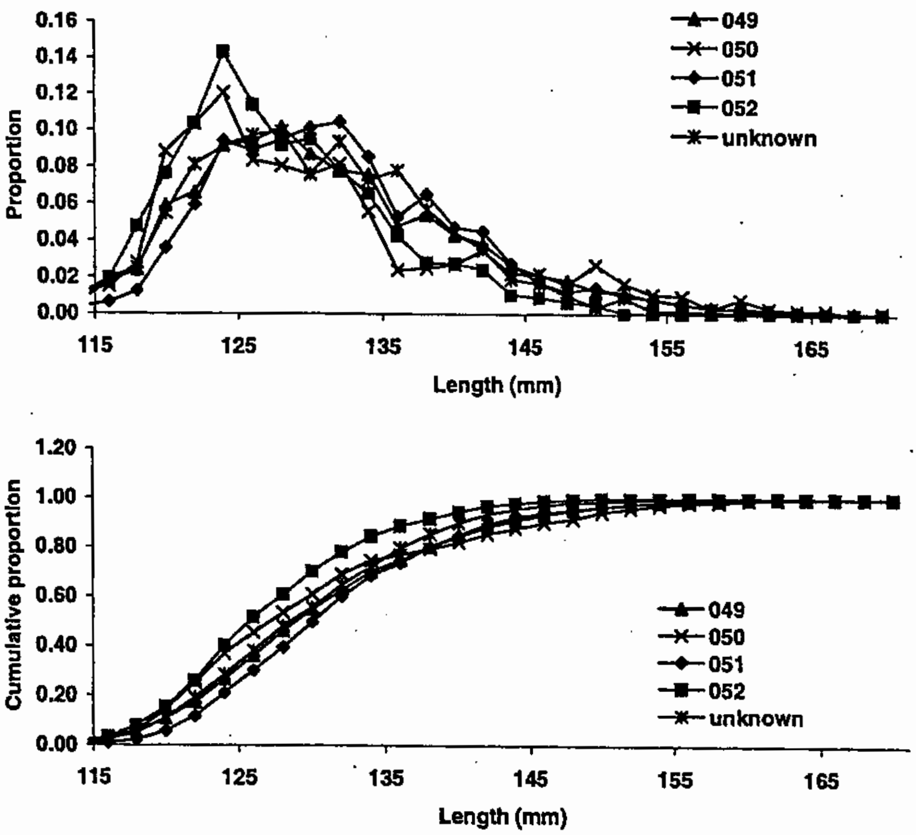


Figure 6: CSLFs from all years, plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom) for each statistical area.

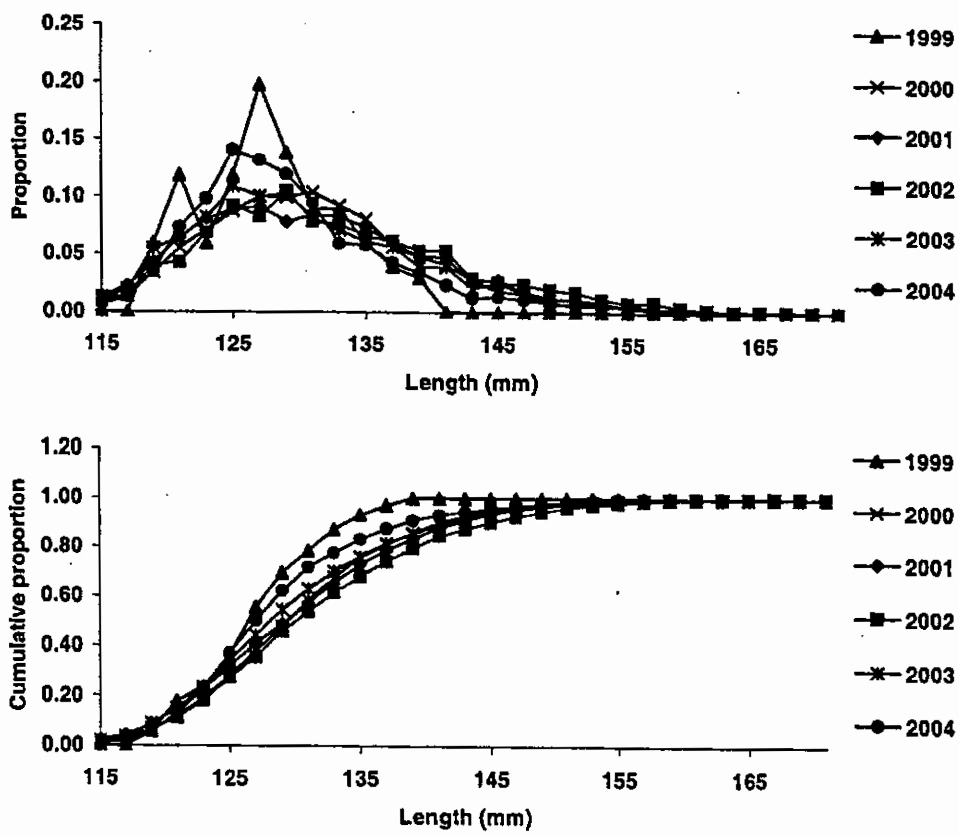


Figure 7: CSLFs from all survey strata aggregated, plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom) for each year.

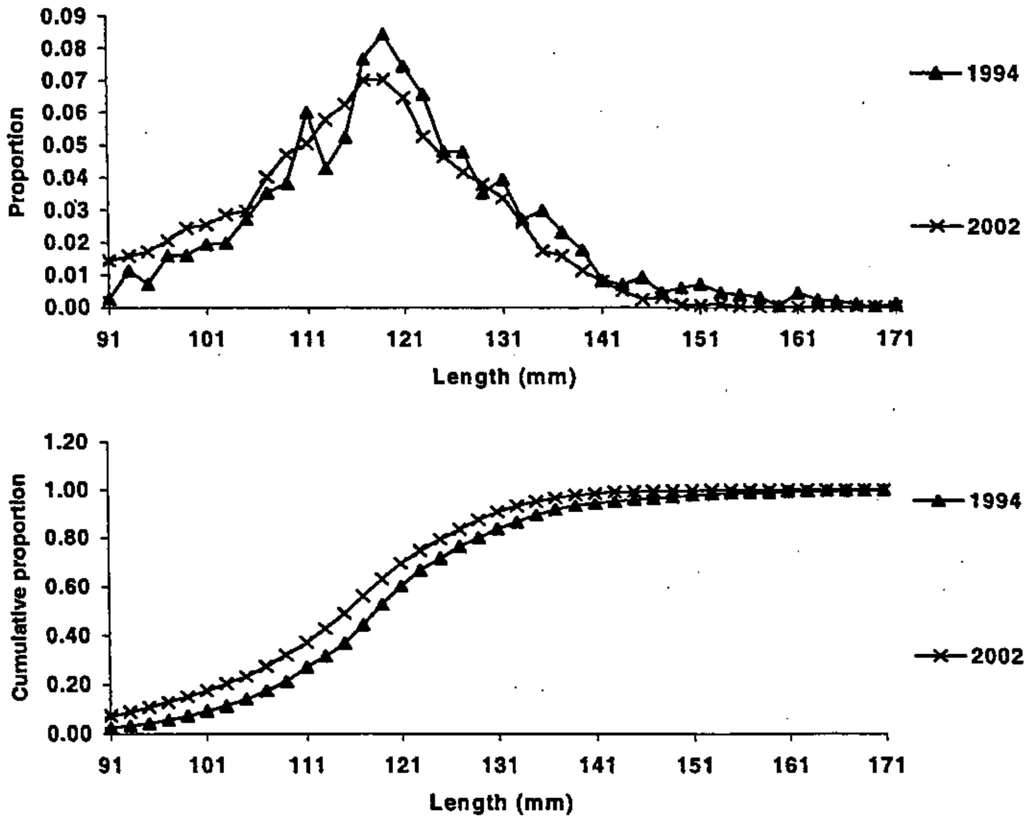


Figure 8: RDLFs from all survey strata aggregated for each year and plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom) for each year.

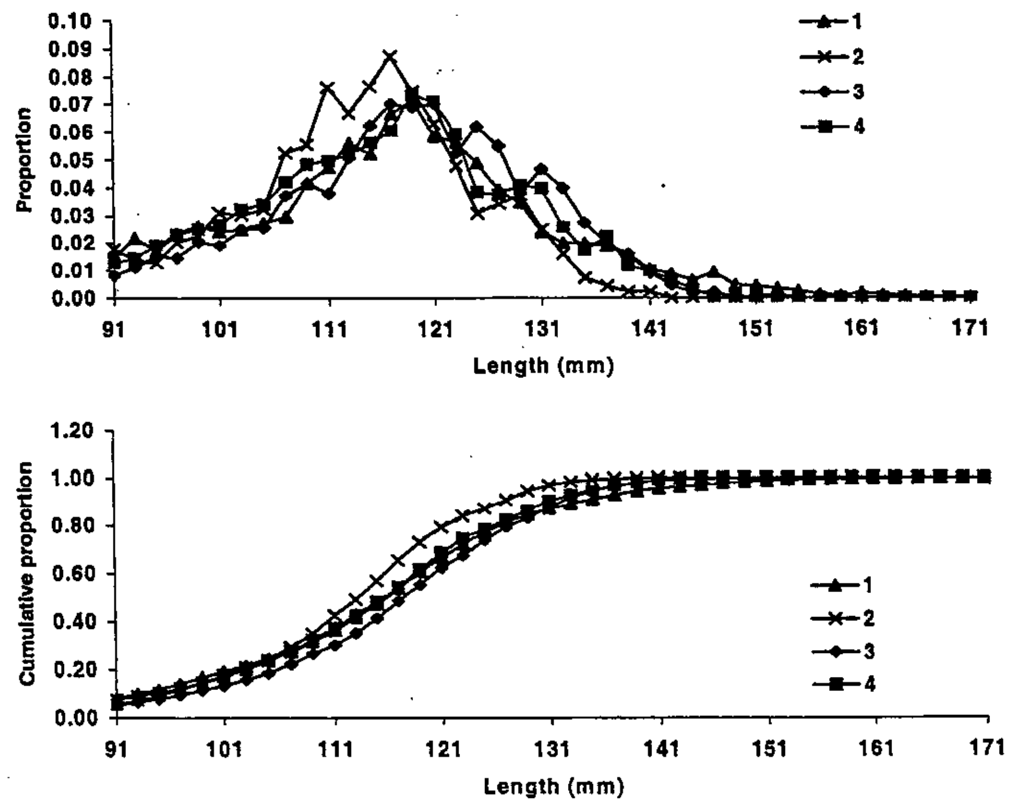


Figure 9: RDLFs from all years, plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom) for each survey stratum.

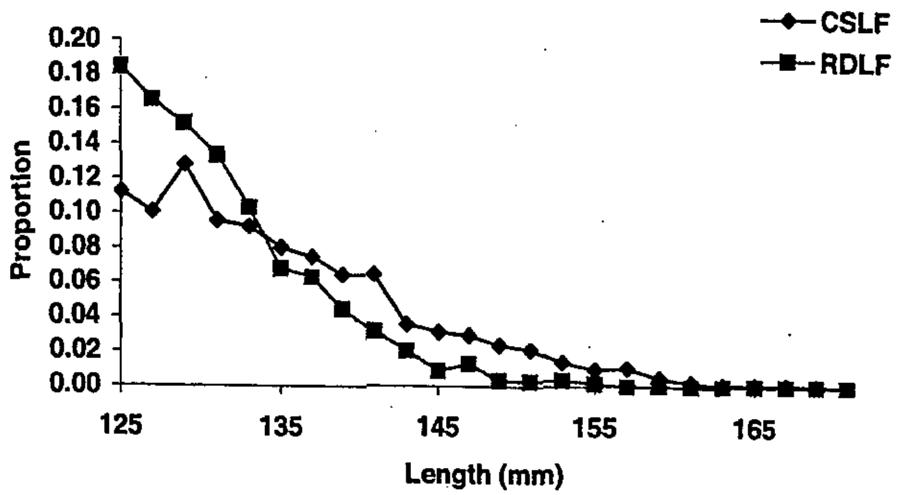


Figure 10: Comparison of CSLF and RDLF for the 2002 fishing year for sizes above the MLS.

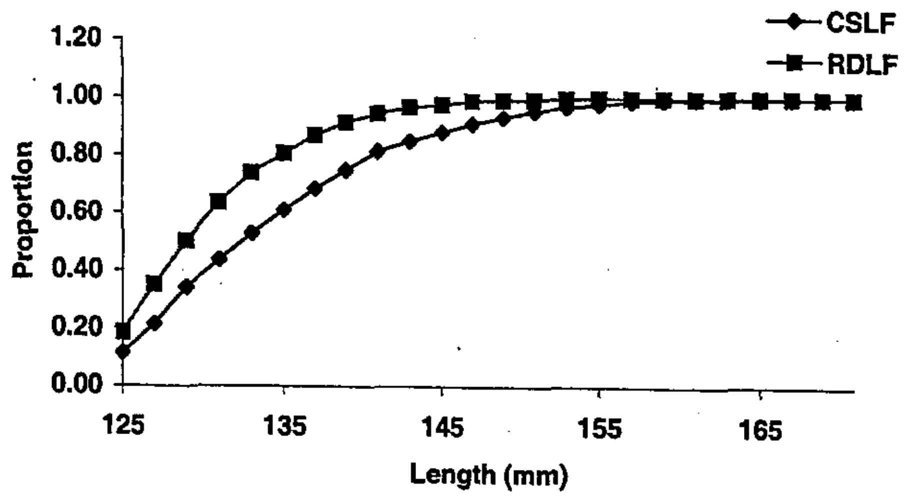


Figure 11: Comparison of cumulative proportions-at-length from CSLF and RDLF for the 2002 fishing year.

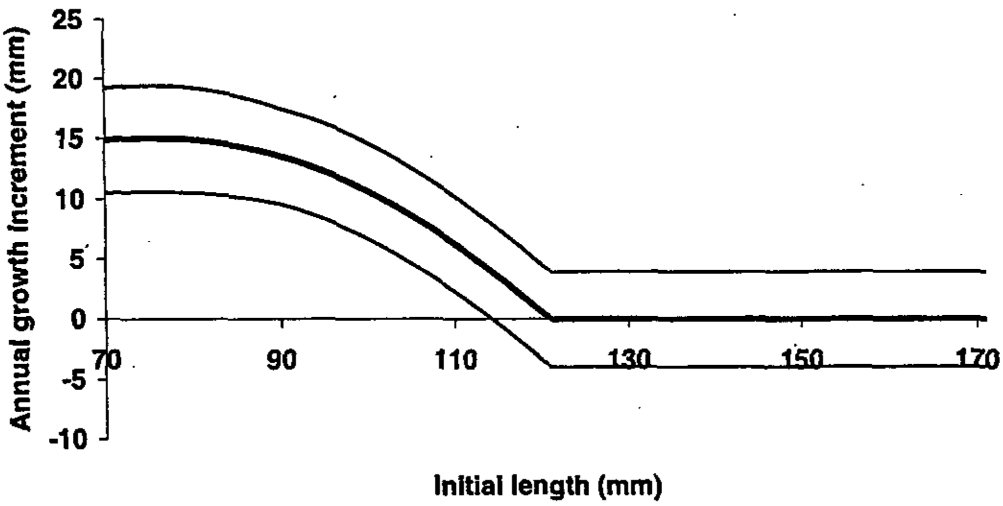


Figure 12: Growth increment curve when the shape parameter was estimated for PAU 4 tagging data. The central solid line is the expected annual increment as a function of initial length; the lighter lines are the predicted standard deviation of the increment.

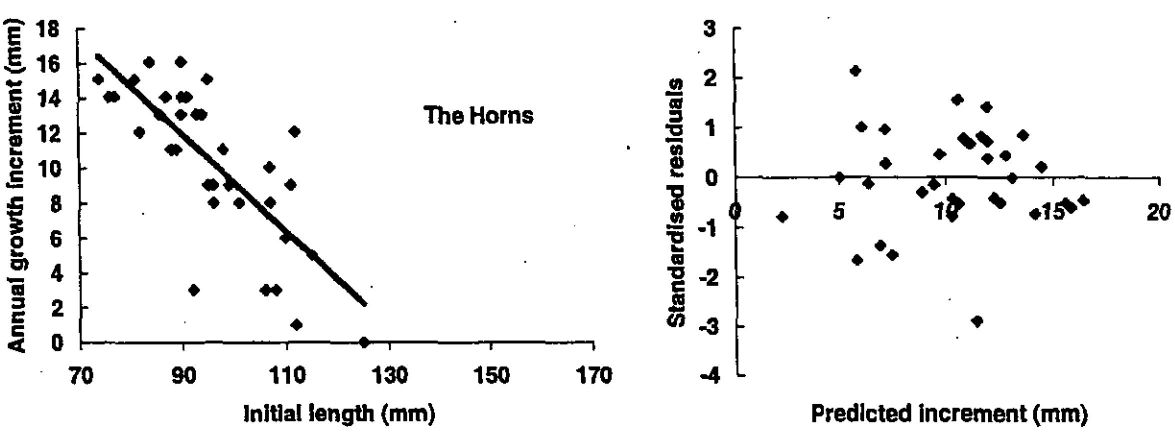


Figure 13: Observed (dots) and predicted (line) annual growth increment from tagging data from the Horns (left) and standardised residuals from the fit (right).

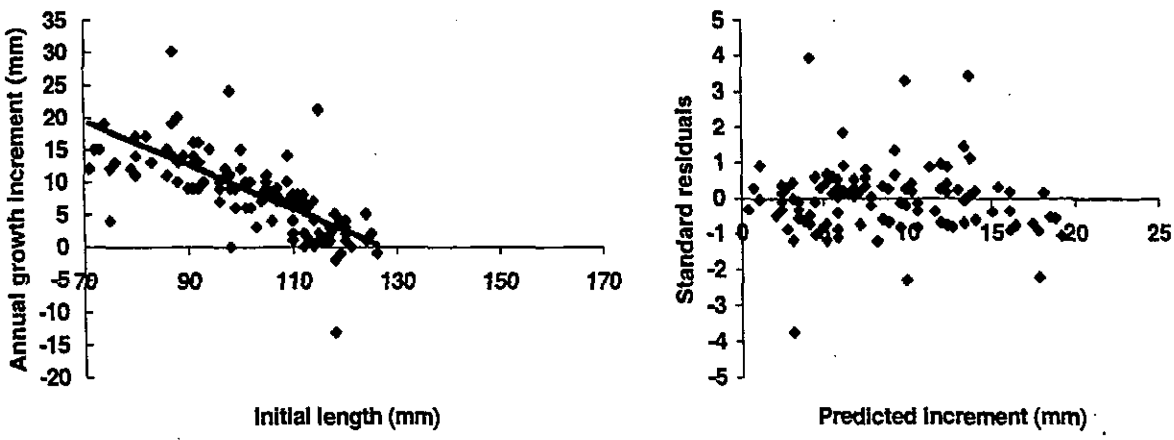


Figure 14: Observed (dots) and predicted (line) annual growth increment from tagging data from Waitangi West (left) and standardised residuals from the fit (right).

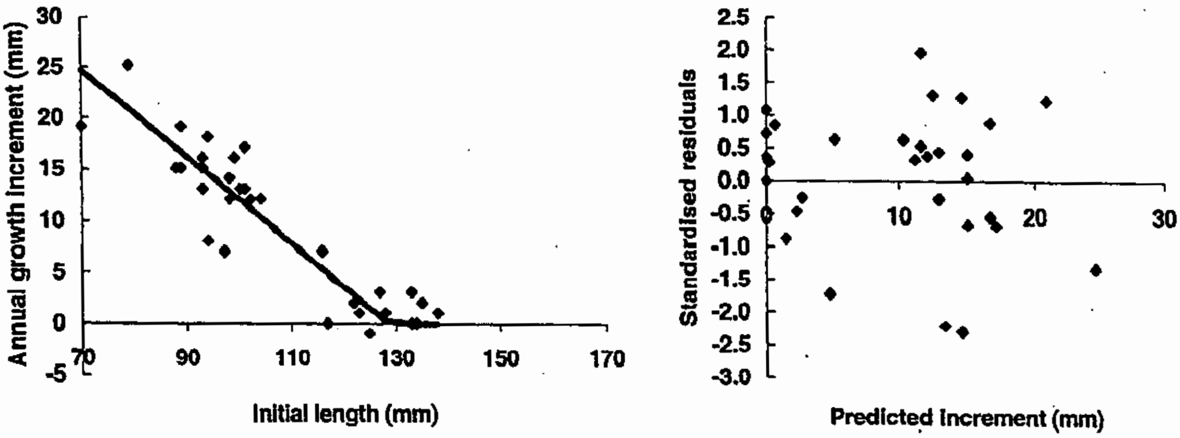


Figure 15: Observed (dots) and predicted (line) annual growth increment from tagging data from Wharekauri (left) and standardised residuals from the fit (right).

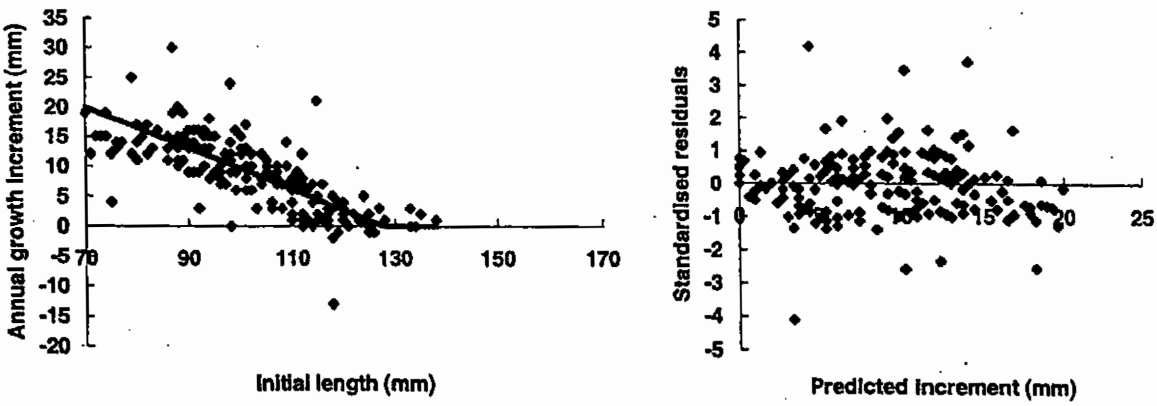


Figure 16: Observed (dots) and predicted (line) annual growth increment from tagging data from all PAU 4 areas (left) and standardised residuals from the fit (right).

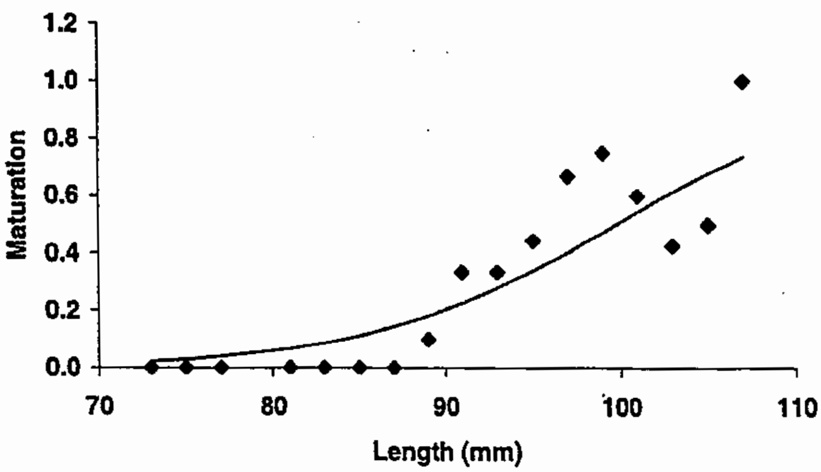


Figure 17: Fit of the model to observed proportion mature-at-length data.

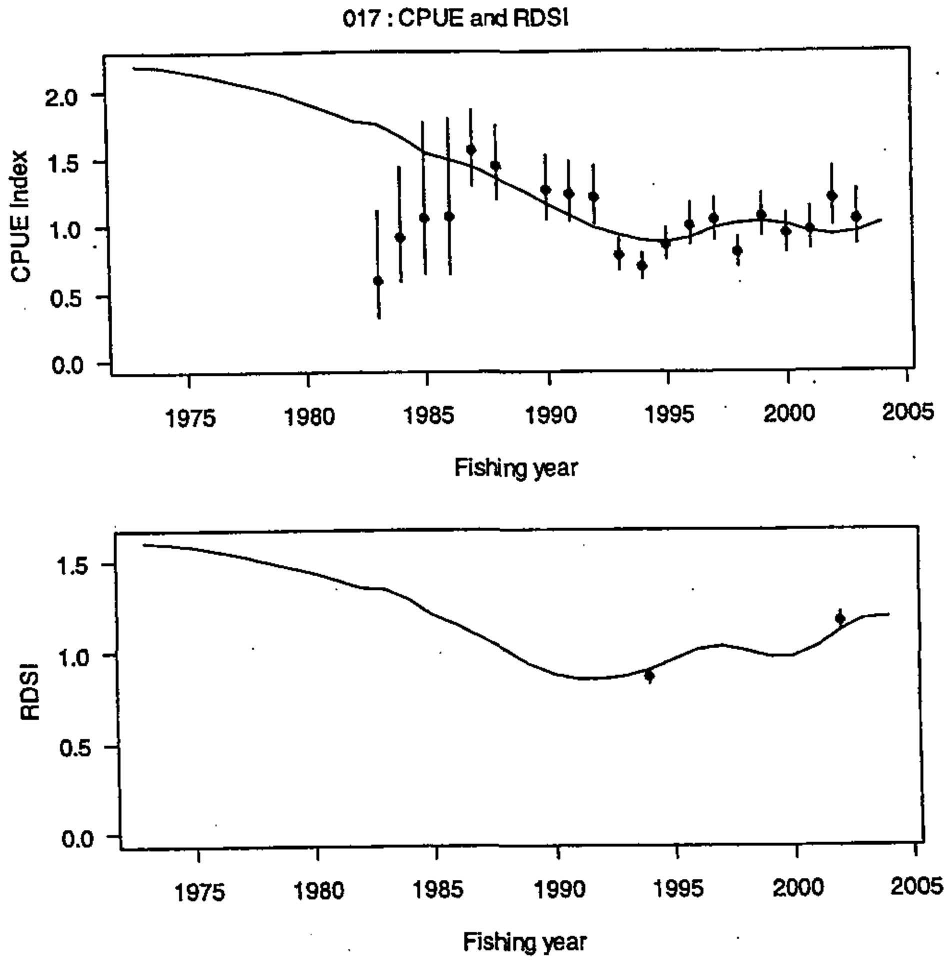


Figure 18: Observed (dots) and predicted (solid line) CPUE (top) and research diver survey indices (RDSI) (bottom) for the base case MPD fit for PAU 4. Error bars show the standard error term used by the model in fitting.

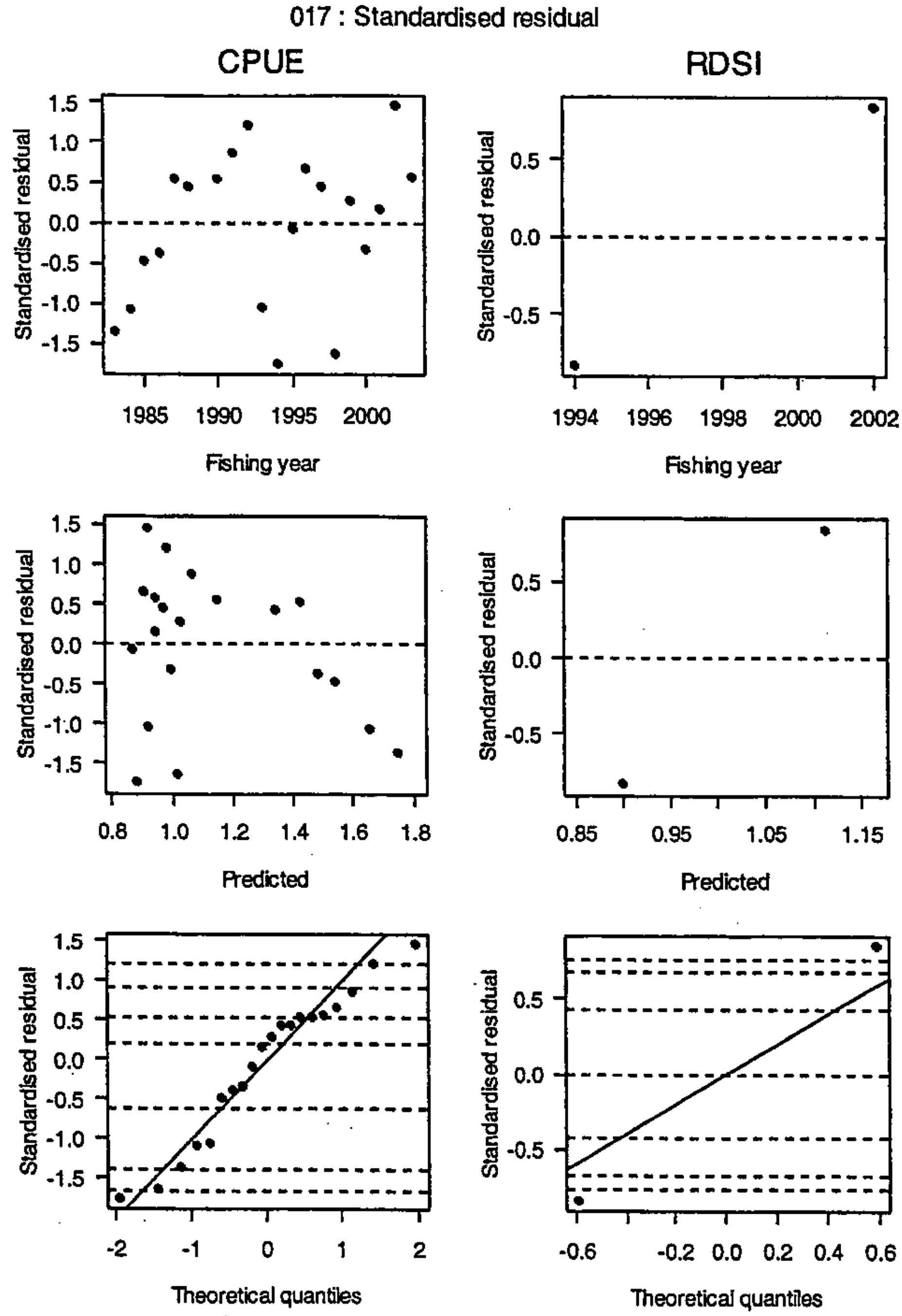


Figure 19: Standardised residuals for CPUE (left) and RDSI (right) for the base case MPD fit for PAU 4.

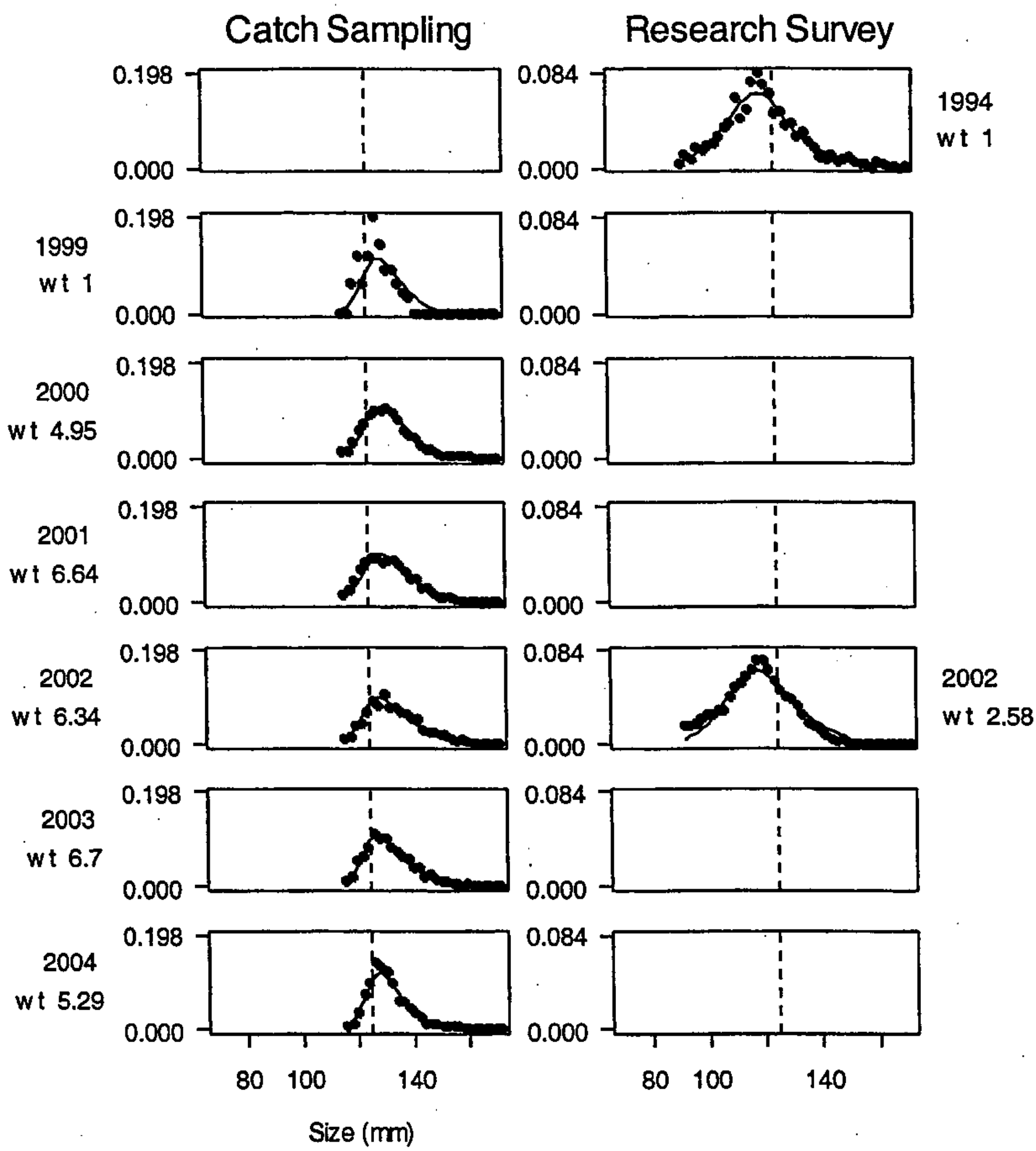


Figure 20: Observed (dots) and predicted (lines) proportions-at-length from commercial catch sampling (left) and research diver surveys (right) for the base case MPD fit for PAU 4. The number under each year is the relative weight given to the dataset, based on the number of paua measured and (for the research diver surveys) the number of strata sampled.

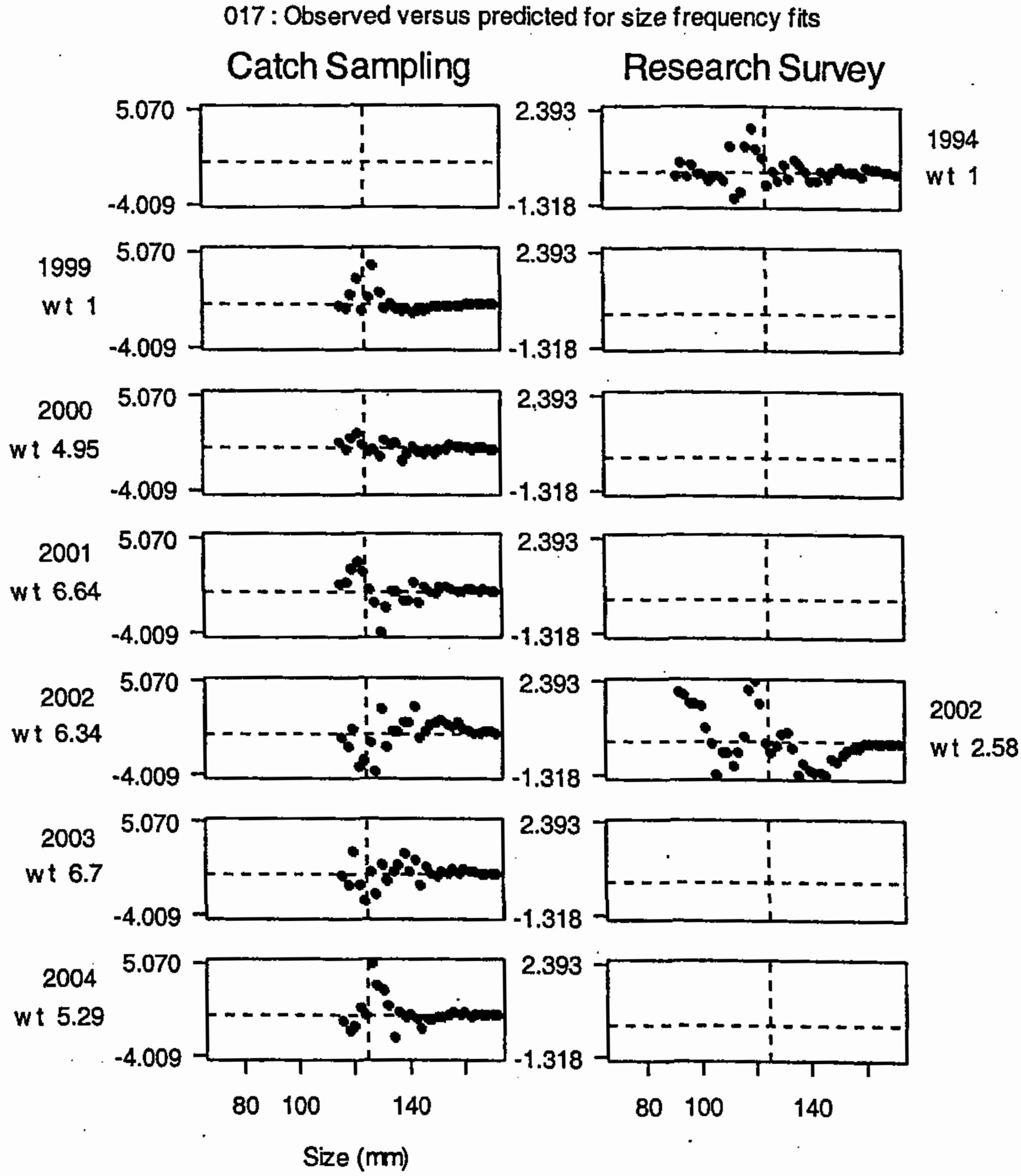


Figure 21: Residuals from the fits to proportions-at-length data seen in Figure 20 from the base case MPD fit for PAU 4.

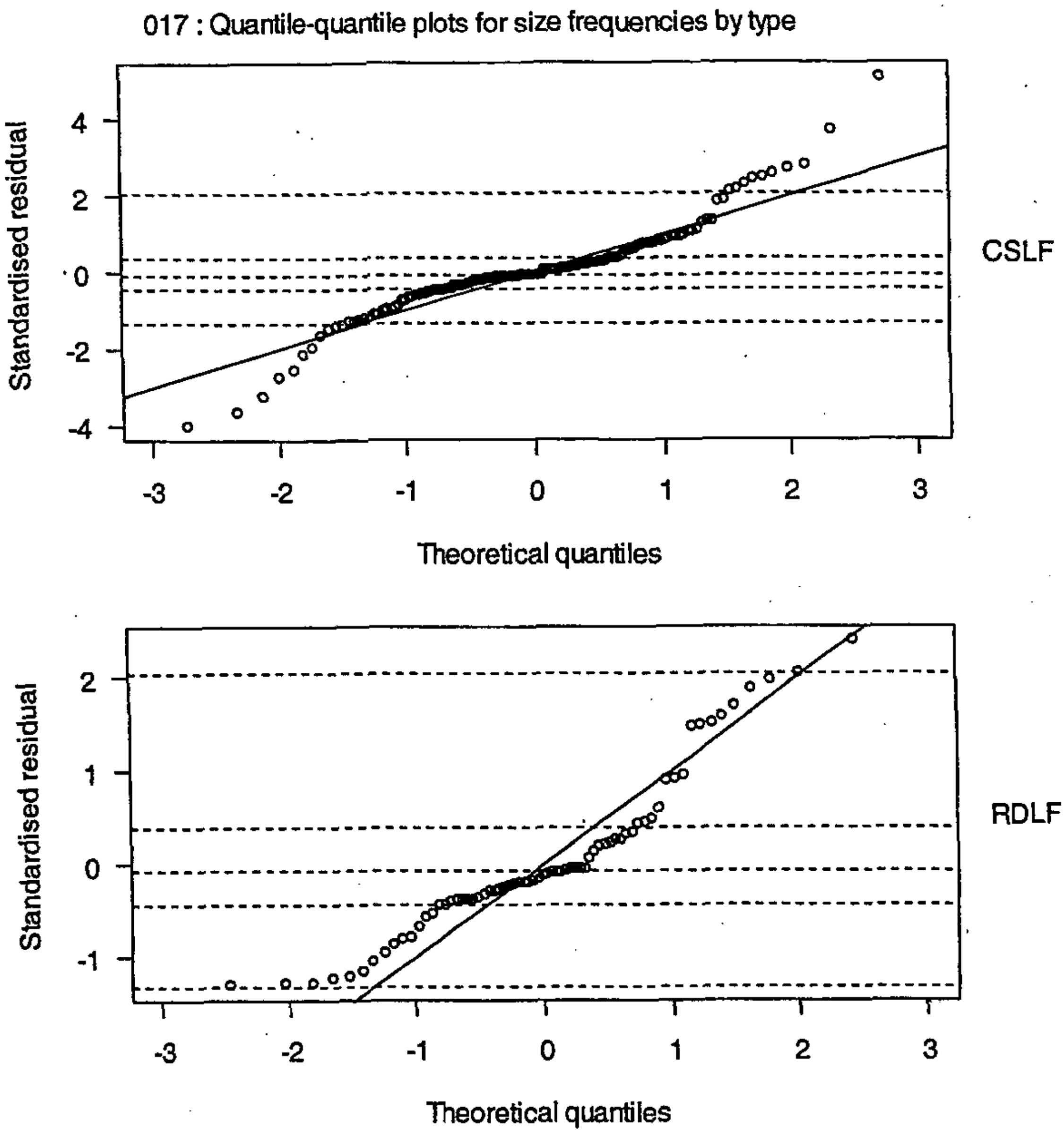


Figure 22: Q-Q plot of residuals for the fits to proportions-at-length from commercial catch sampling (top) and research diver surveys (bottom) from the base case MPD fit for PAU 4.

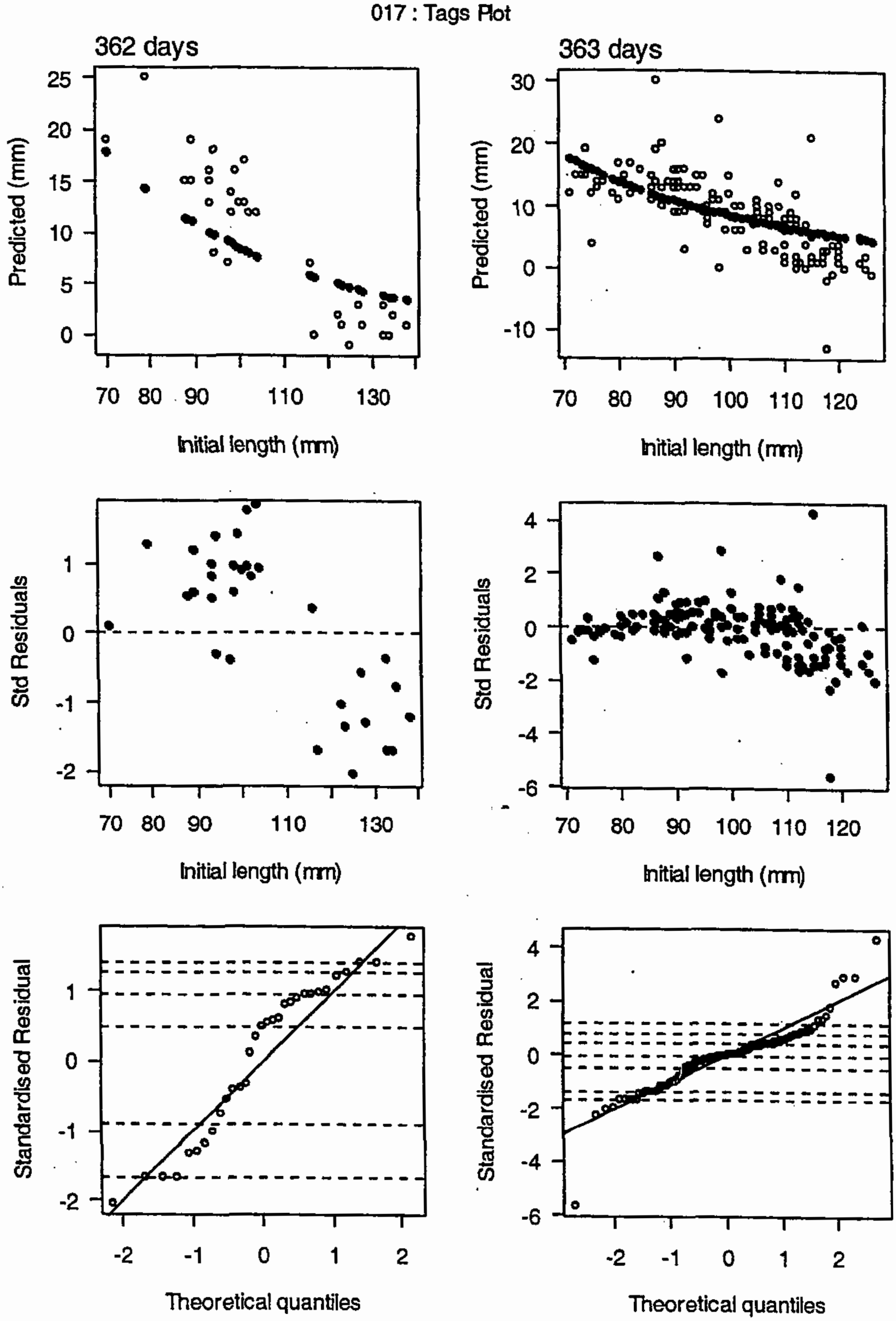


Figure 23: Top: predicted (closed circles) and observed (open circles) increments vs initial length of tagged paua from the base case MPD fit for PAU 4; middle: standardised residuals plotted against initial length; bottom: Q-Q plot of standardised residuals. For each length, there can be more than one predicted increment because different animals were at liberty for different periods. Numbers at the top denote days-at-liberty.

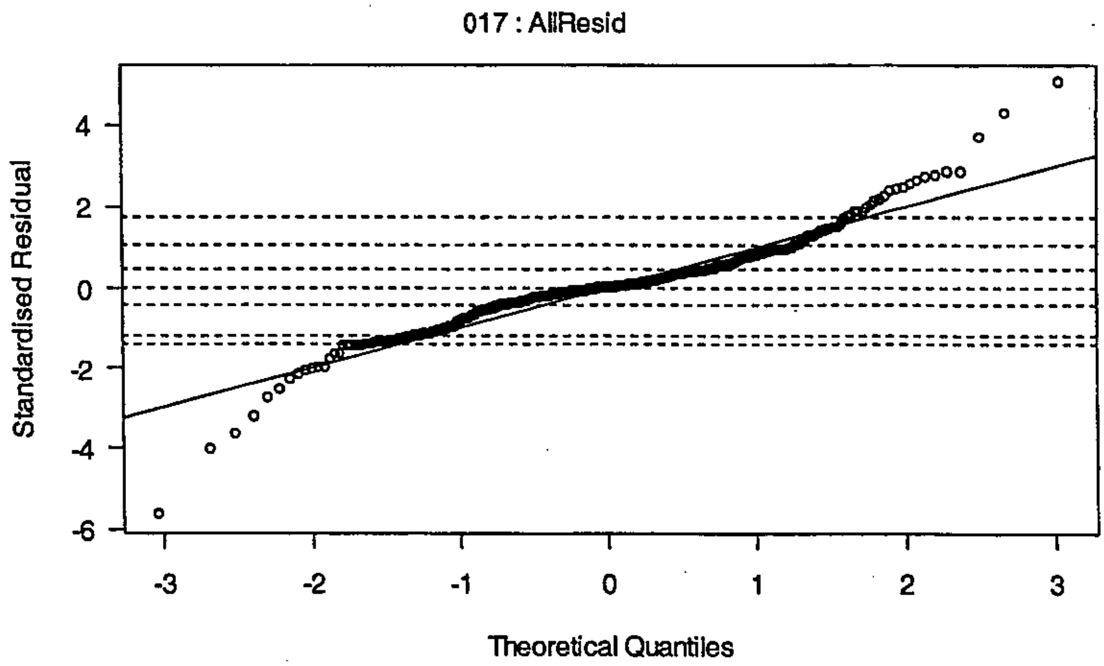


Figure 24: Q-Q plot of the normalised standard residuals from all datasets used by the model in the base case MPD fit.

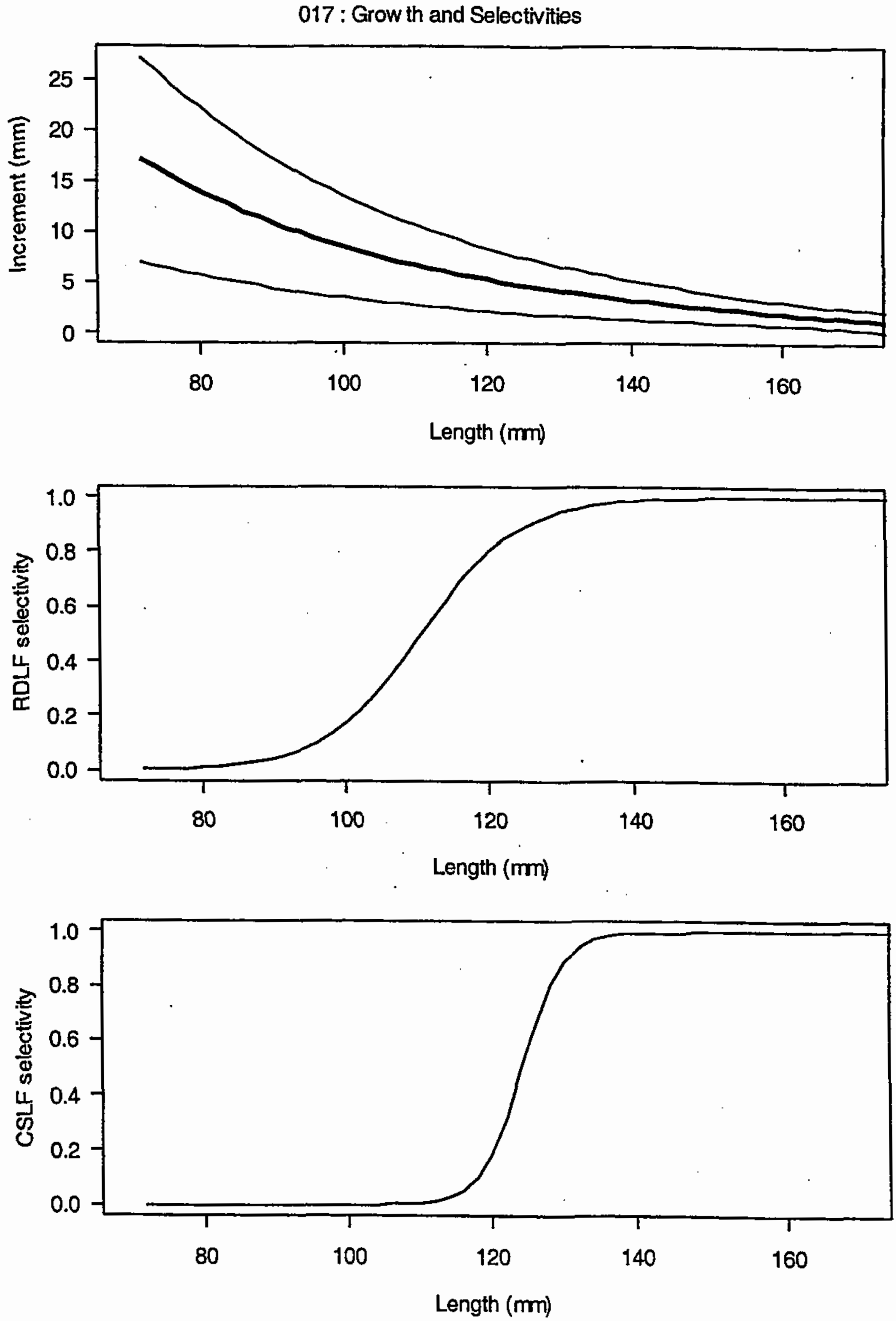


Figure 25: Top: predicted annual growth increment (thick line) *vs* initial length of paua, shown with one standard deviation around the increment (thin line); middle: research diver survey selectivity; bottom: commercial catch sampling selectivity.

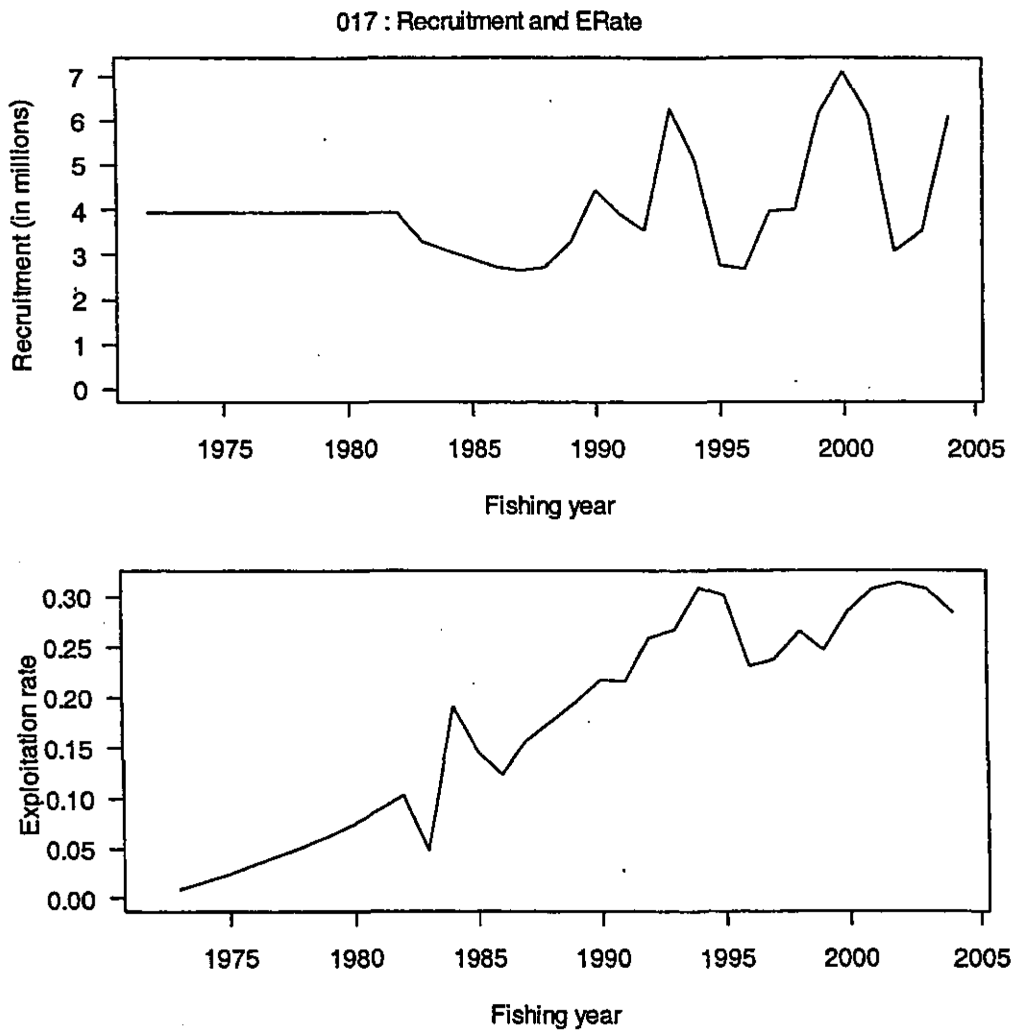


Figure 26: Recruitment in millions of animals (top) and exploitation rate (bottom) from the base case MPD fit in PAU 4.

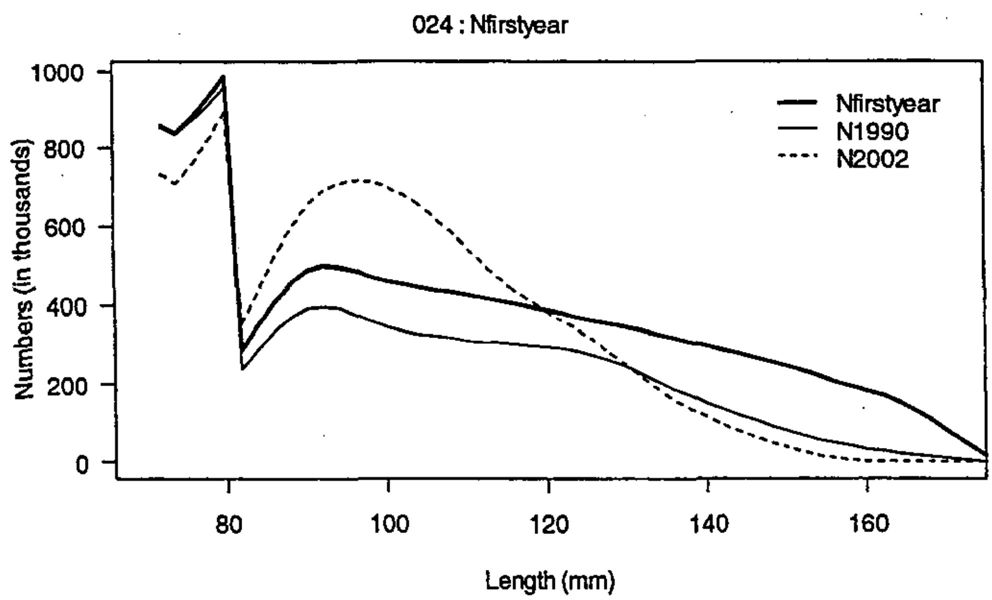


Figure 27: Comparison of the virgin population (heavy line) to the population in 1990 (thin line) and 2002 (dashed line) from the base case MPD fit in PAU 4.

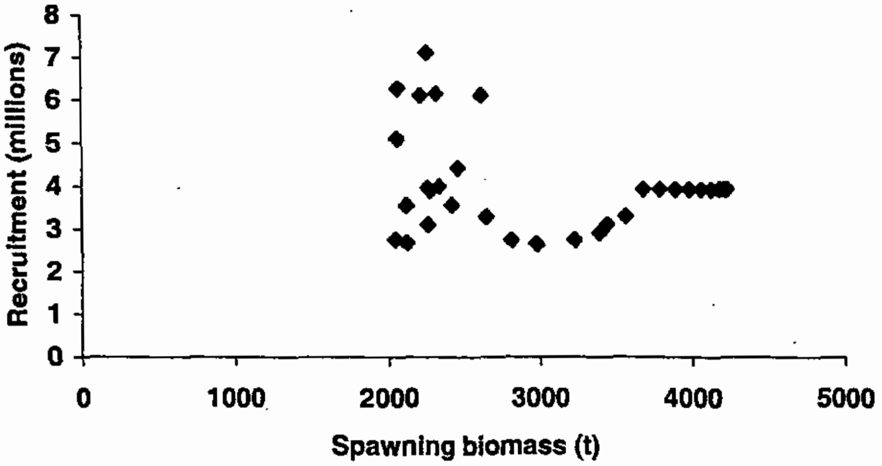


Figure 28: Recruitment plotted against spawning biomass two years earlier from the base case MPD fit in PAU 4.

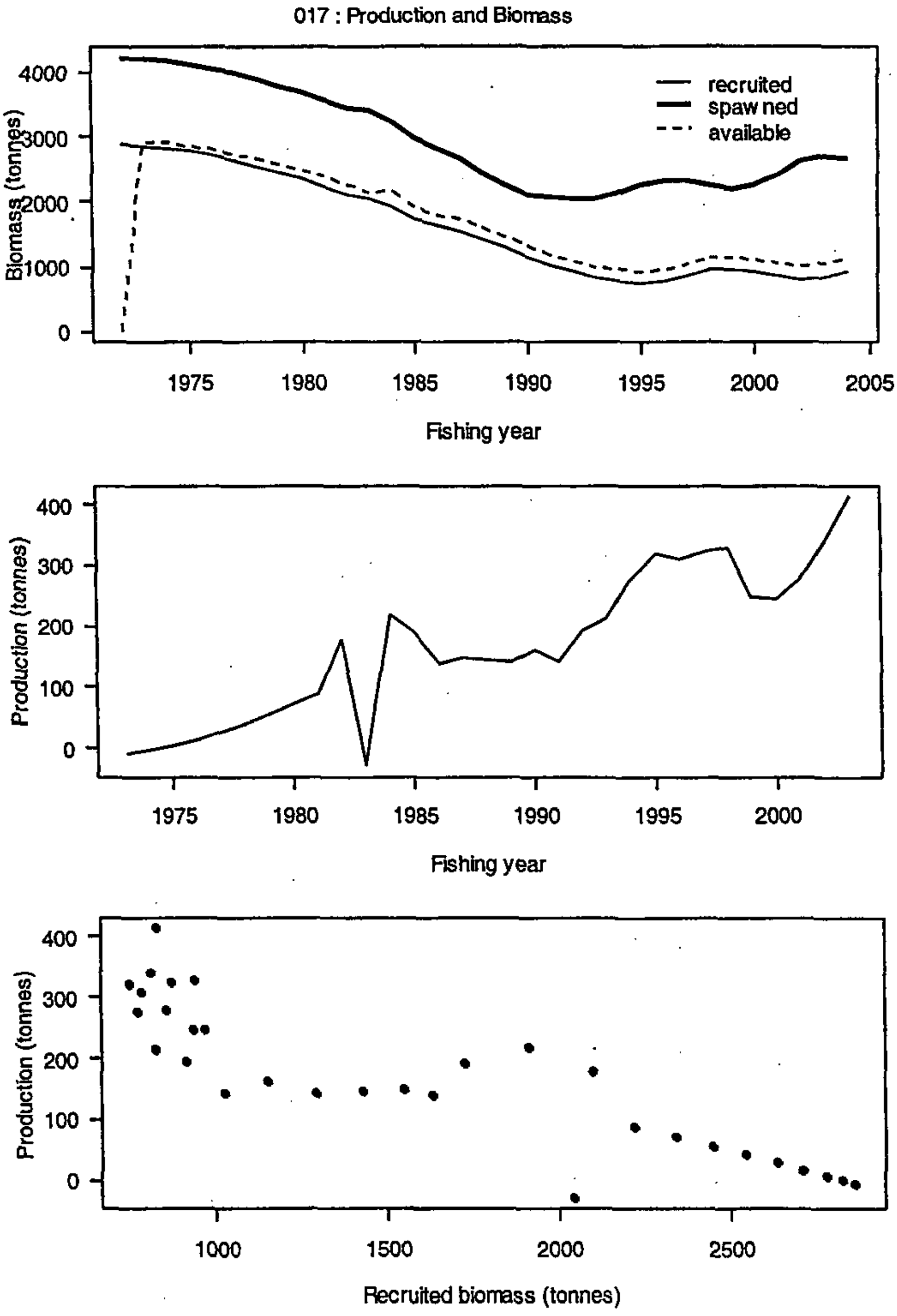


Figure 29: Recruited, spawned and available biomass trajectories (top), surplus production trajectories (middle), and surplus production against recruited biomass (bottom) in tonnes from the base case MPD fit in PAU 4.

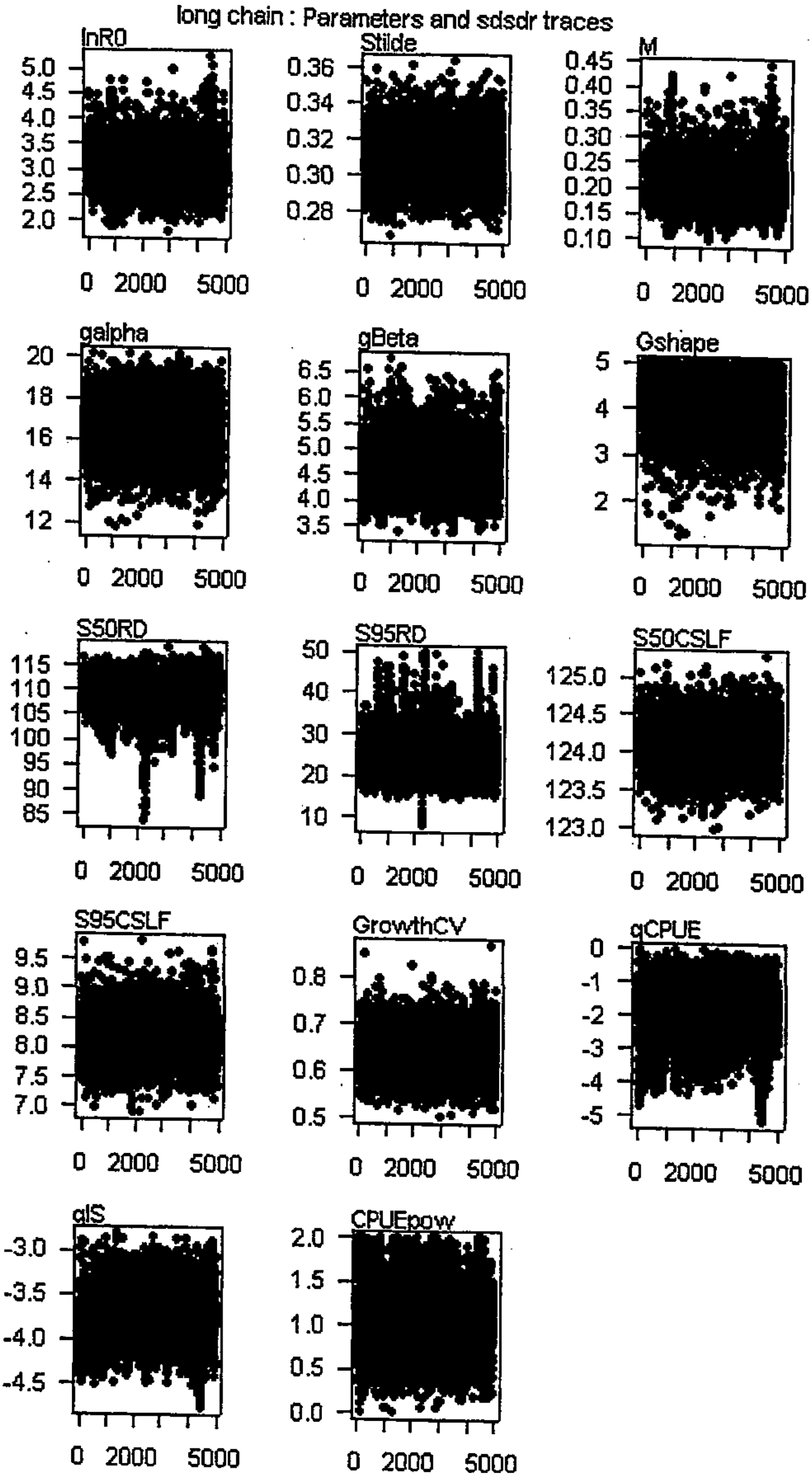


Figure 30: Traces from the PAU 4 McMC.

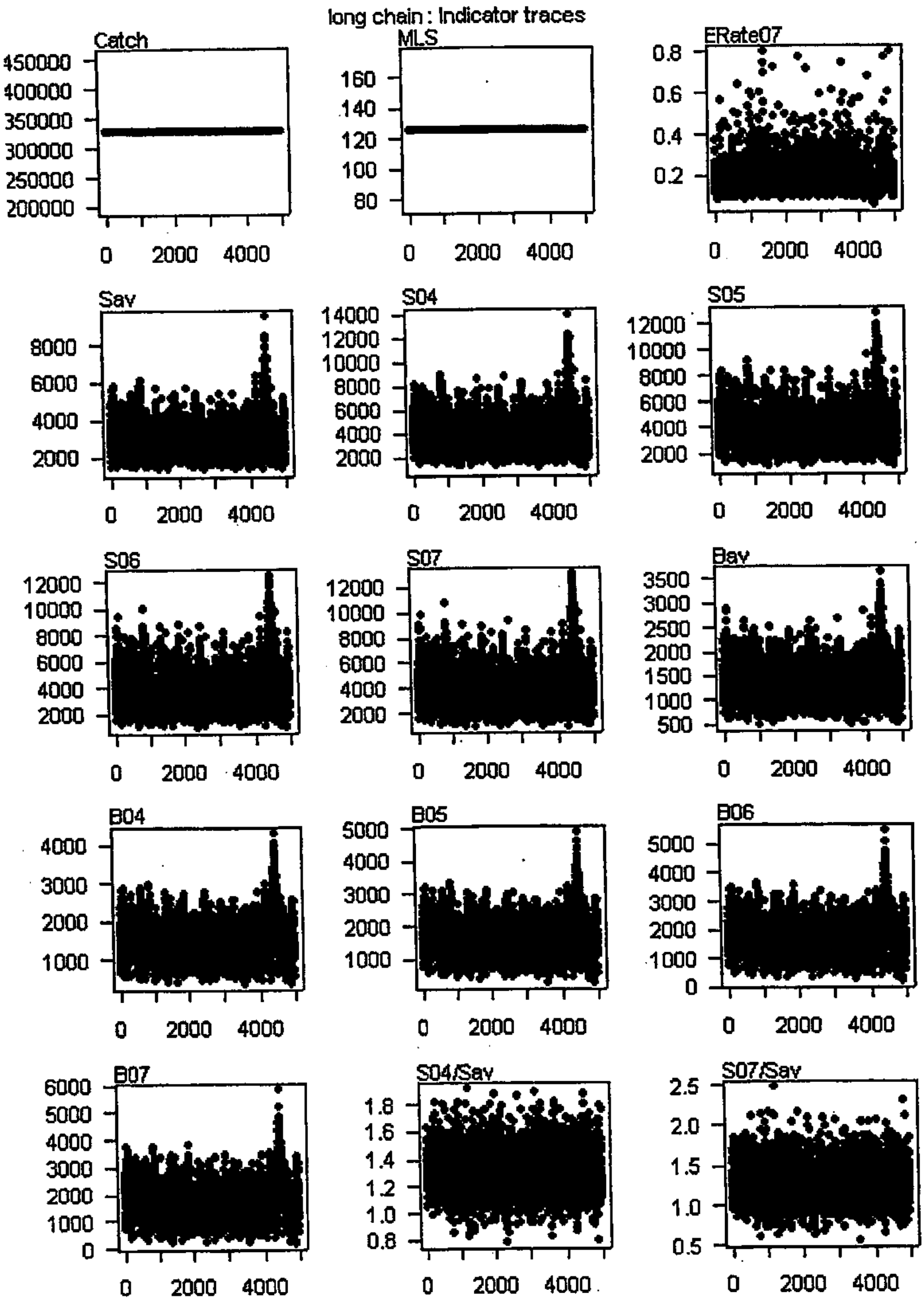


Figure 30 continued.

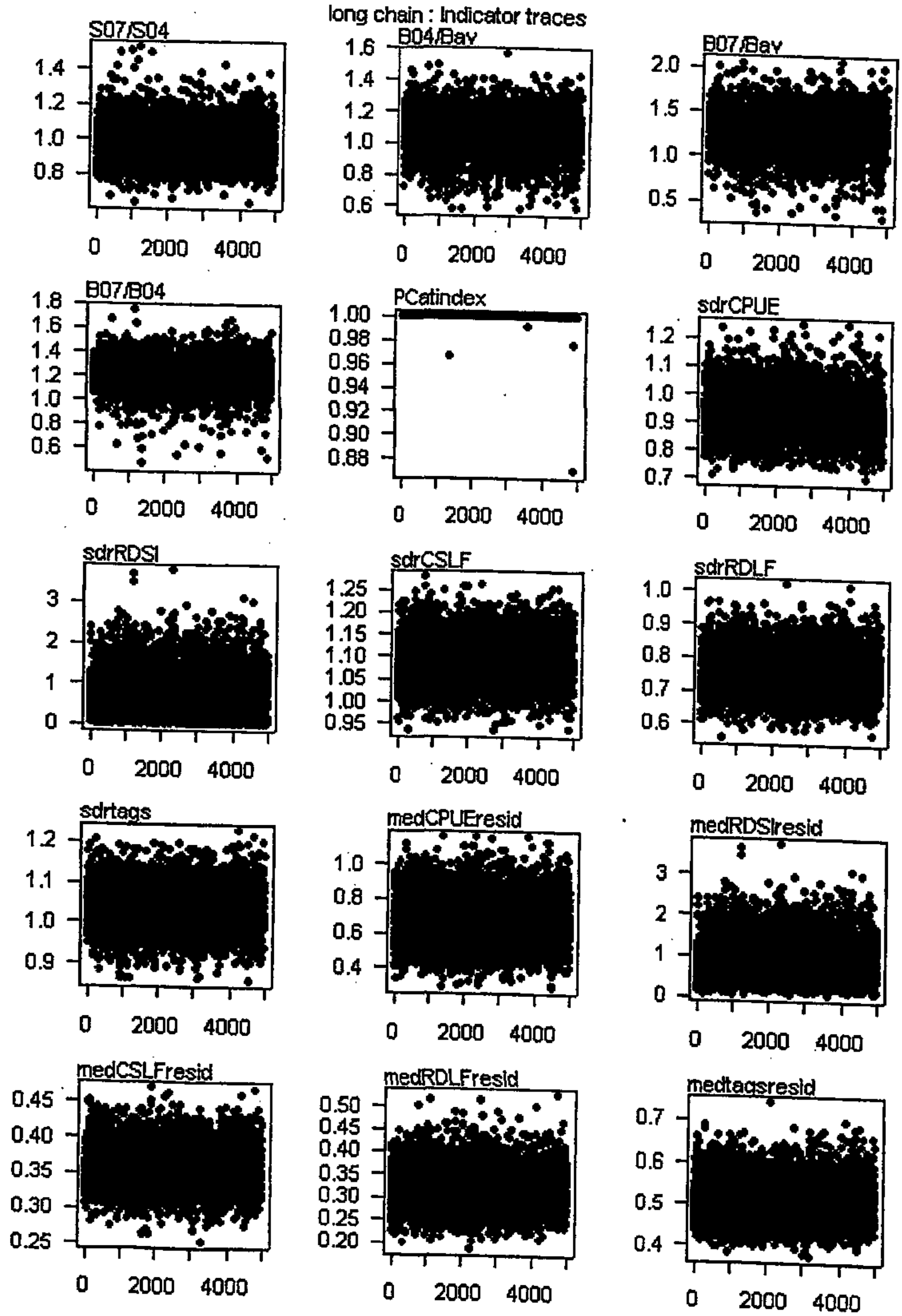


Figure 30 continued.

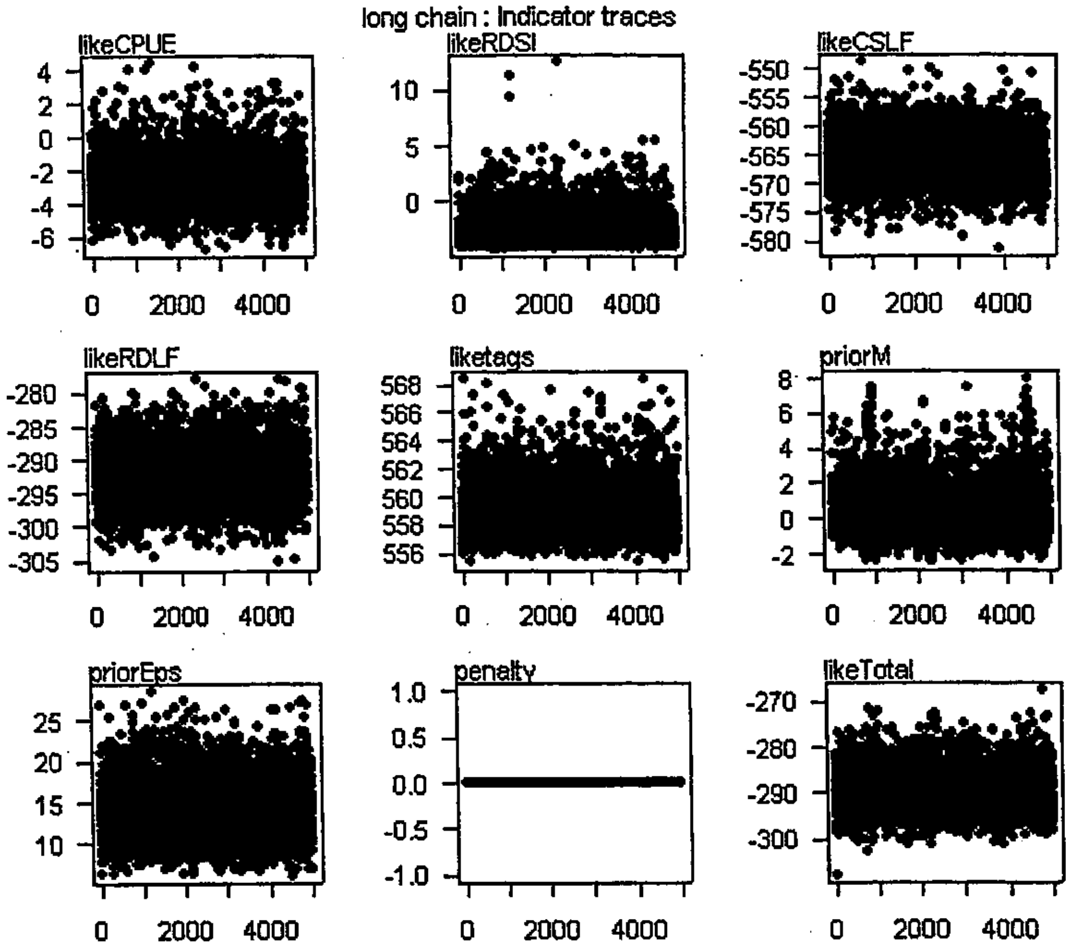


Figure 30 concluded.

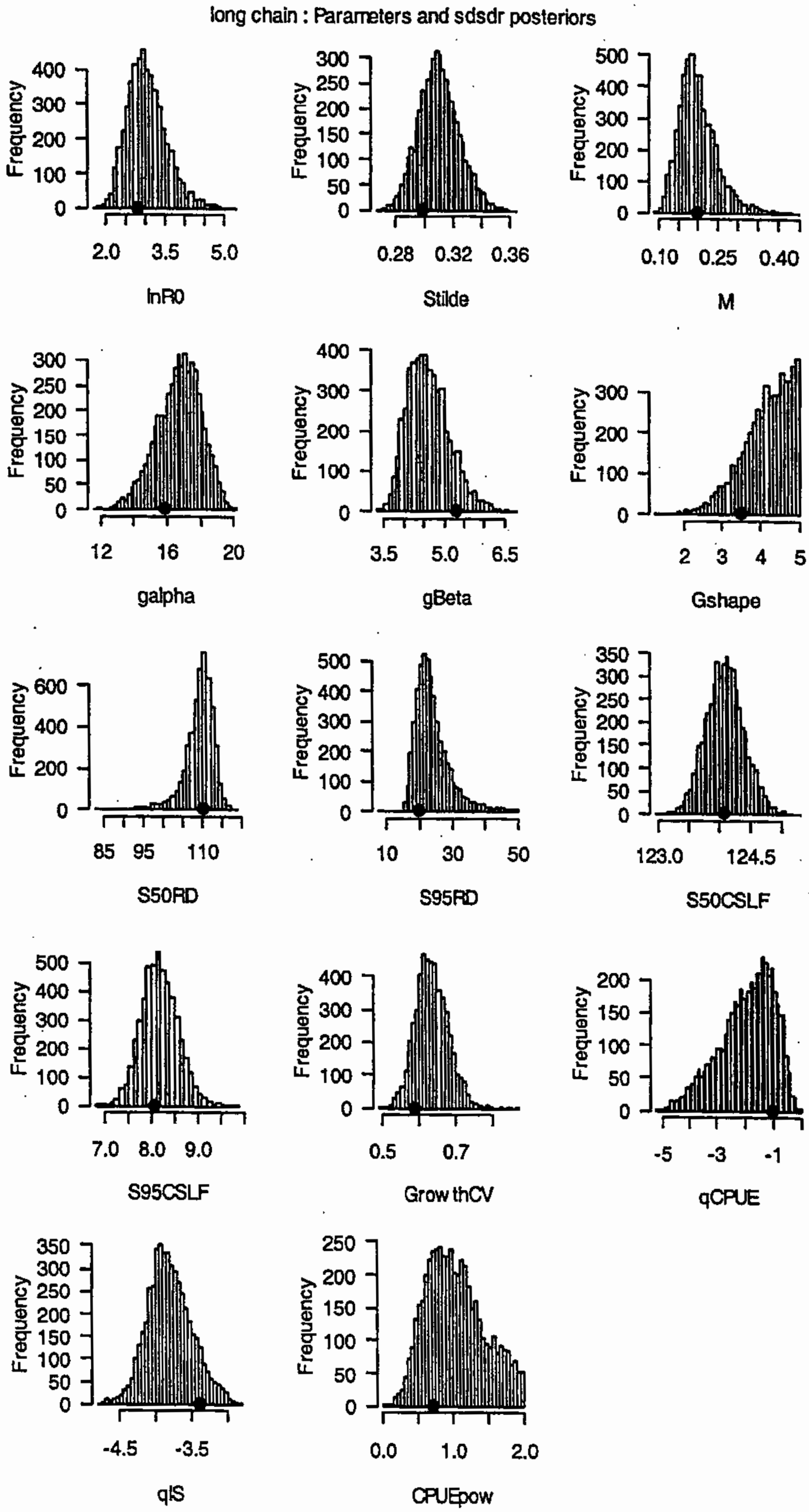


Figure 31: Posterior distributions of parameters and indicators from the combined chain for the base case for PAU4. The dark point shows the MPD estimate.

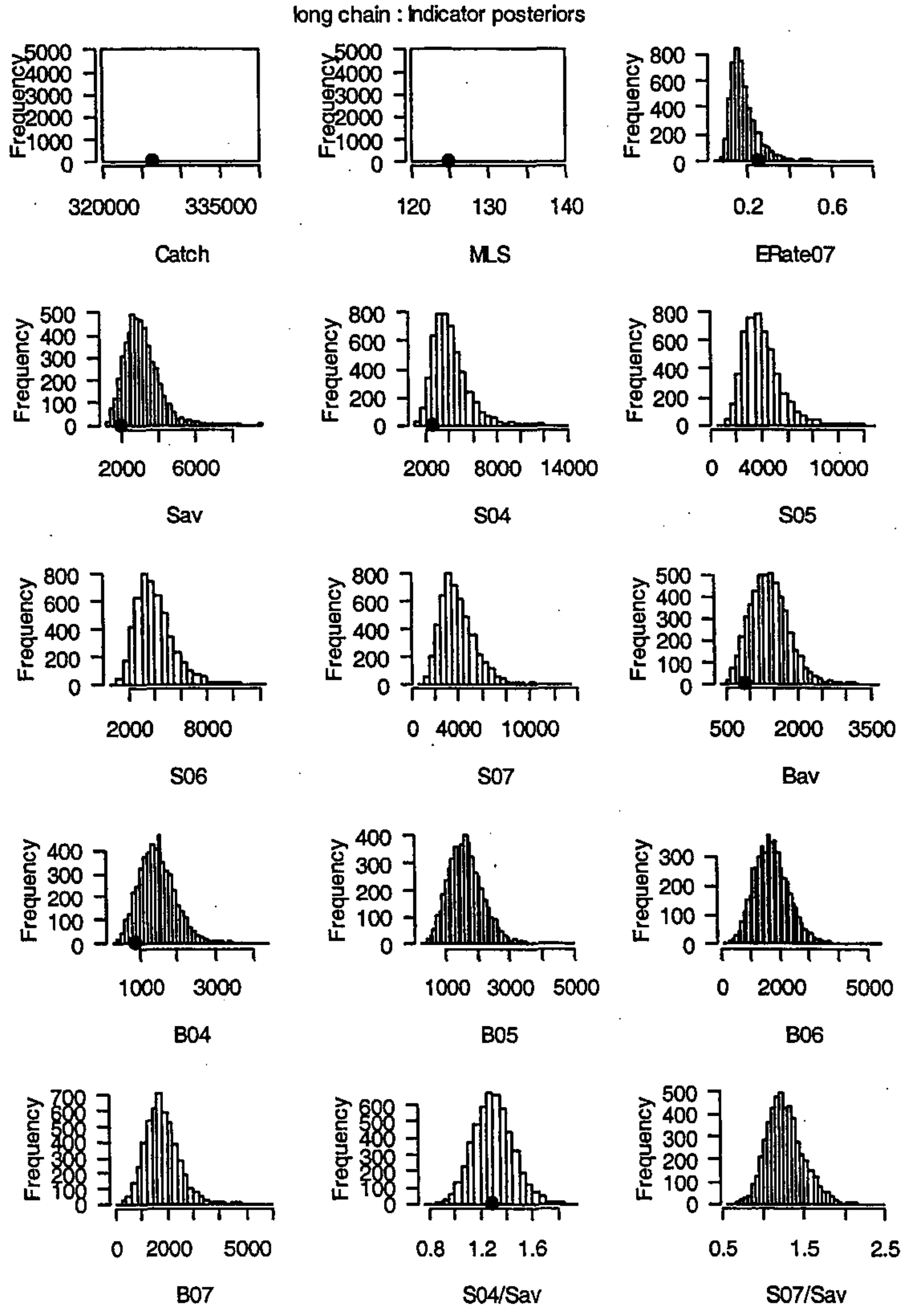


Figure 31: continued.

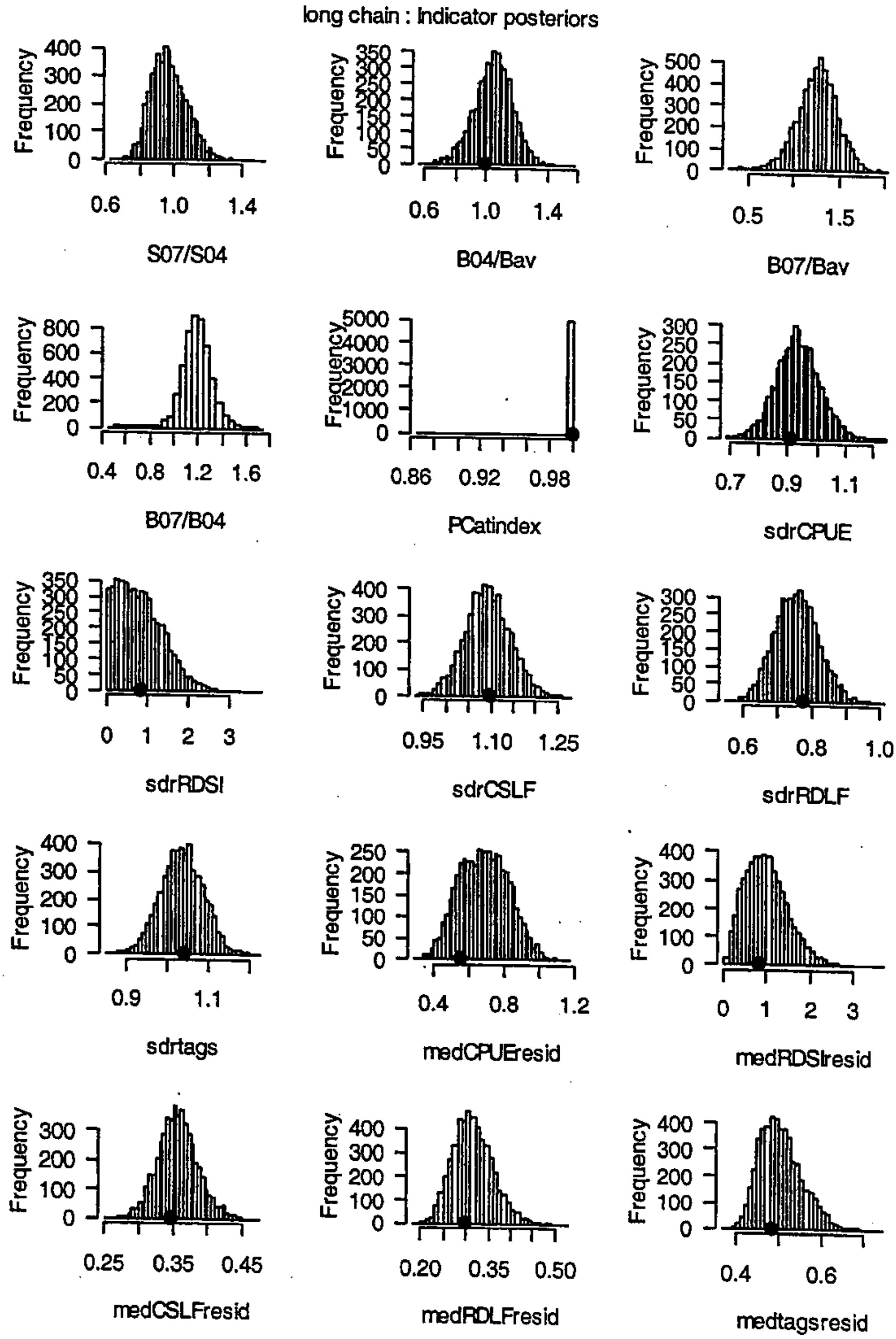


Figure 31: continued.

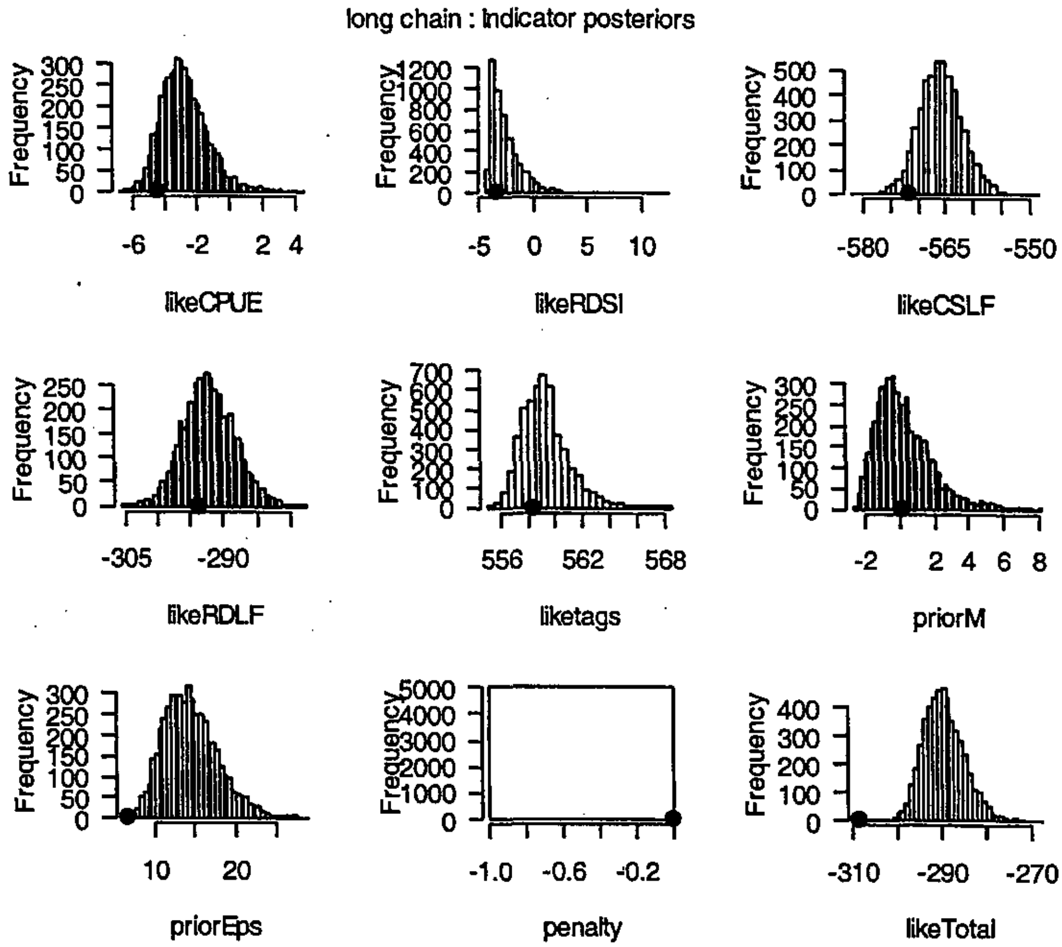


Figure 31: continued.

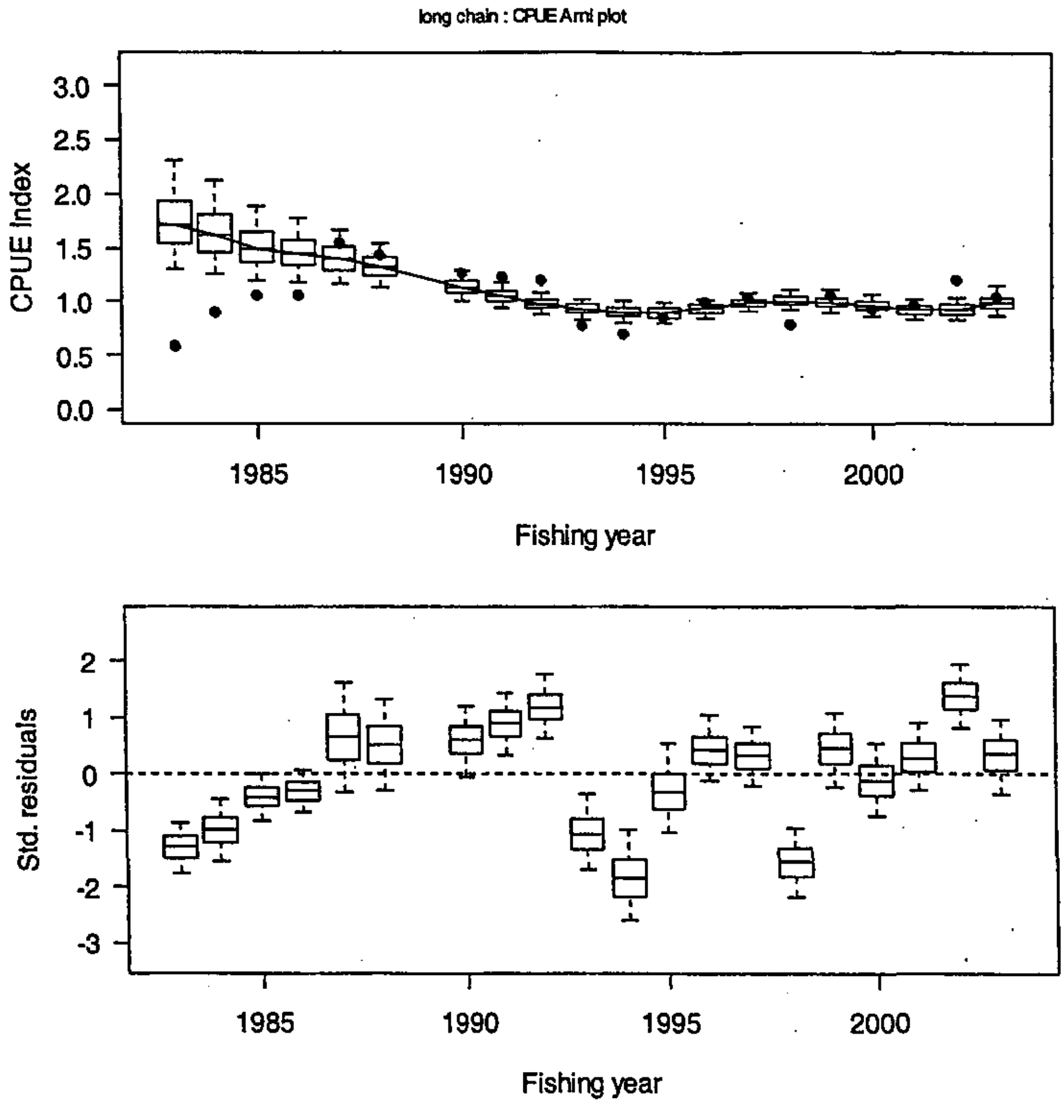


Figure 32: The posterior distributions of the fits to CPUE data (top) and the posterior distributions of the normalised residuals. For each year, the figure shows the median of the posterior (horizontal bar), the 25th and 75th percentiles (box) and 5th and 95th percentiles of the posterior.

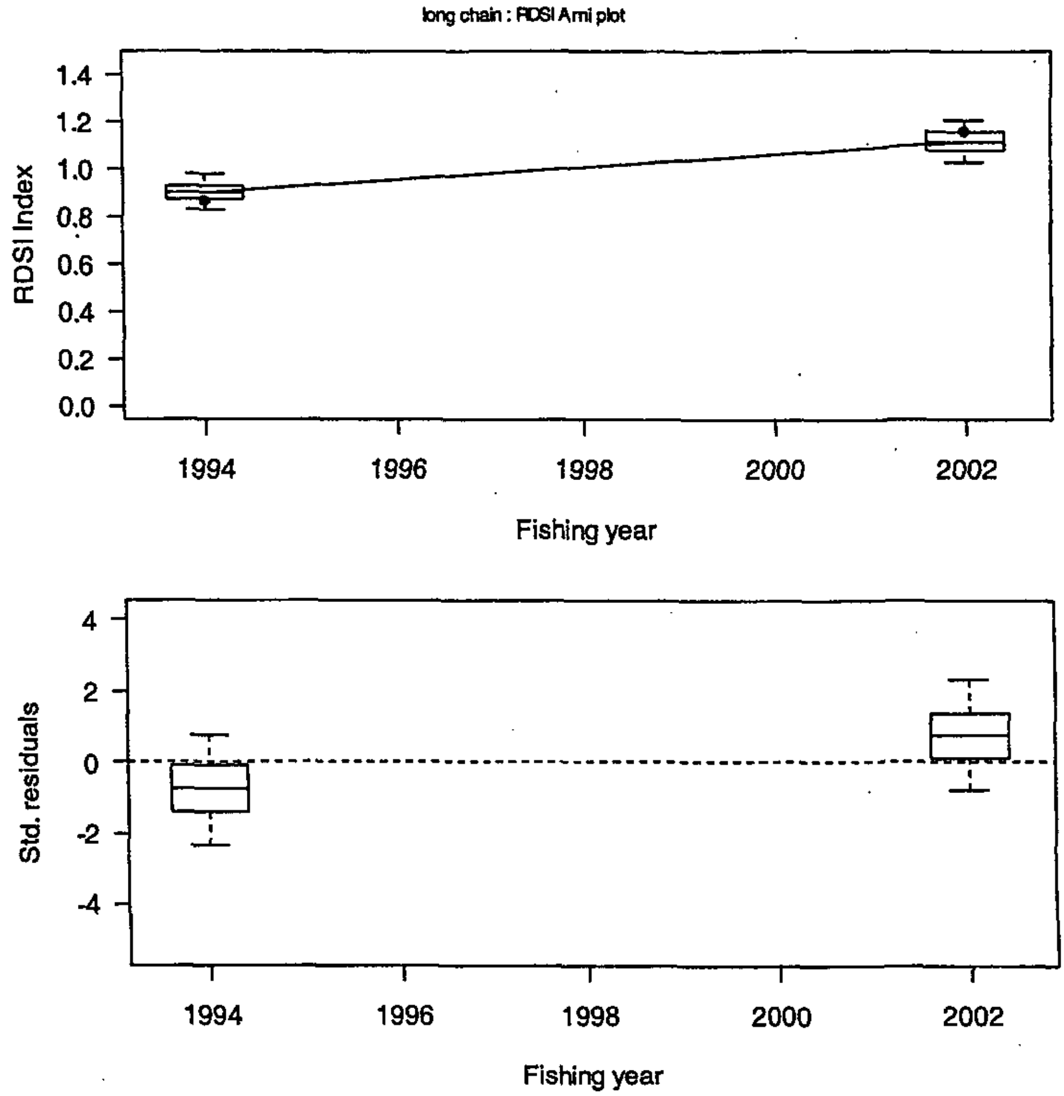


Figure 33: The posterior distributions of the fits to RDSI data (top) and the posterior distributions of the normalised residuals.

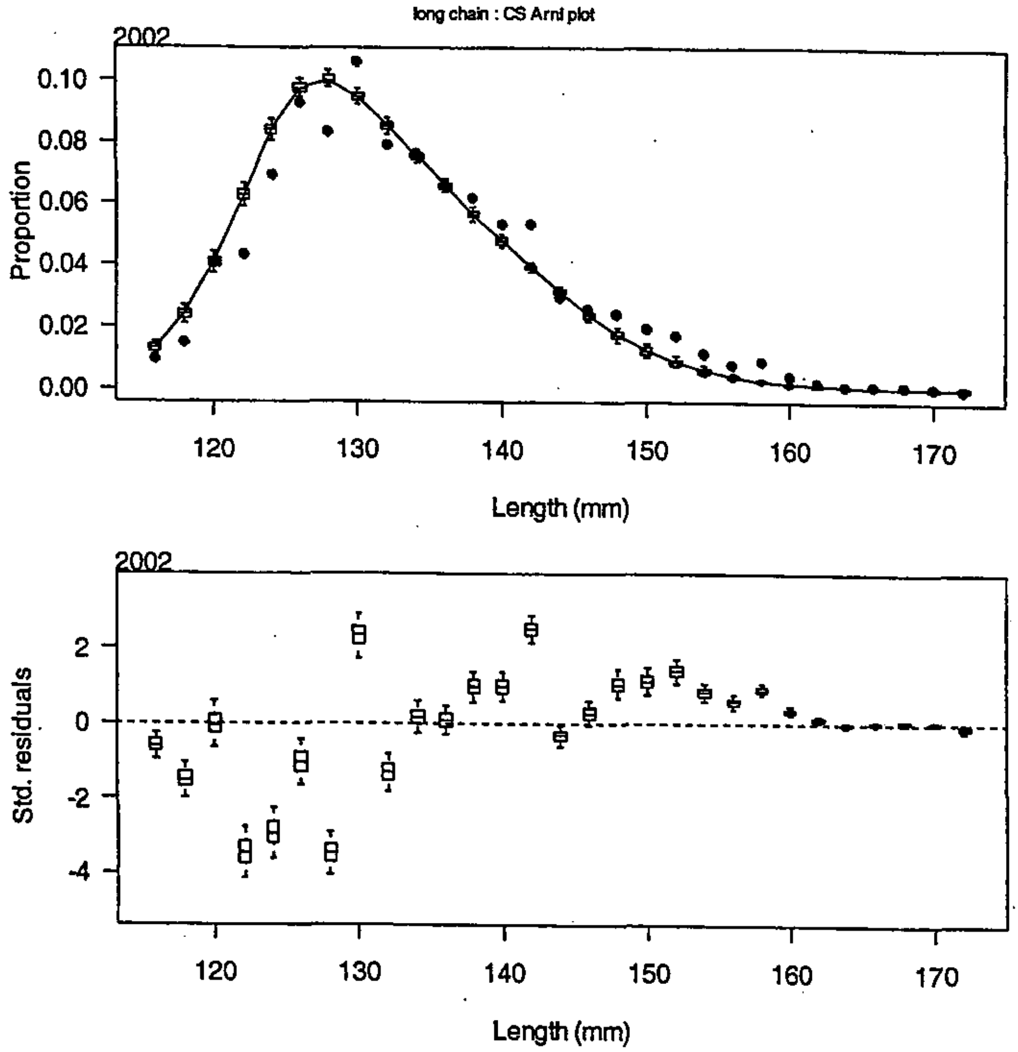


Figure 34: The posterior distributions of the fits to commercial catch sampling proportions-at-length from 2002 (top) and the posterior distributions of the normalised residuals.

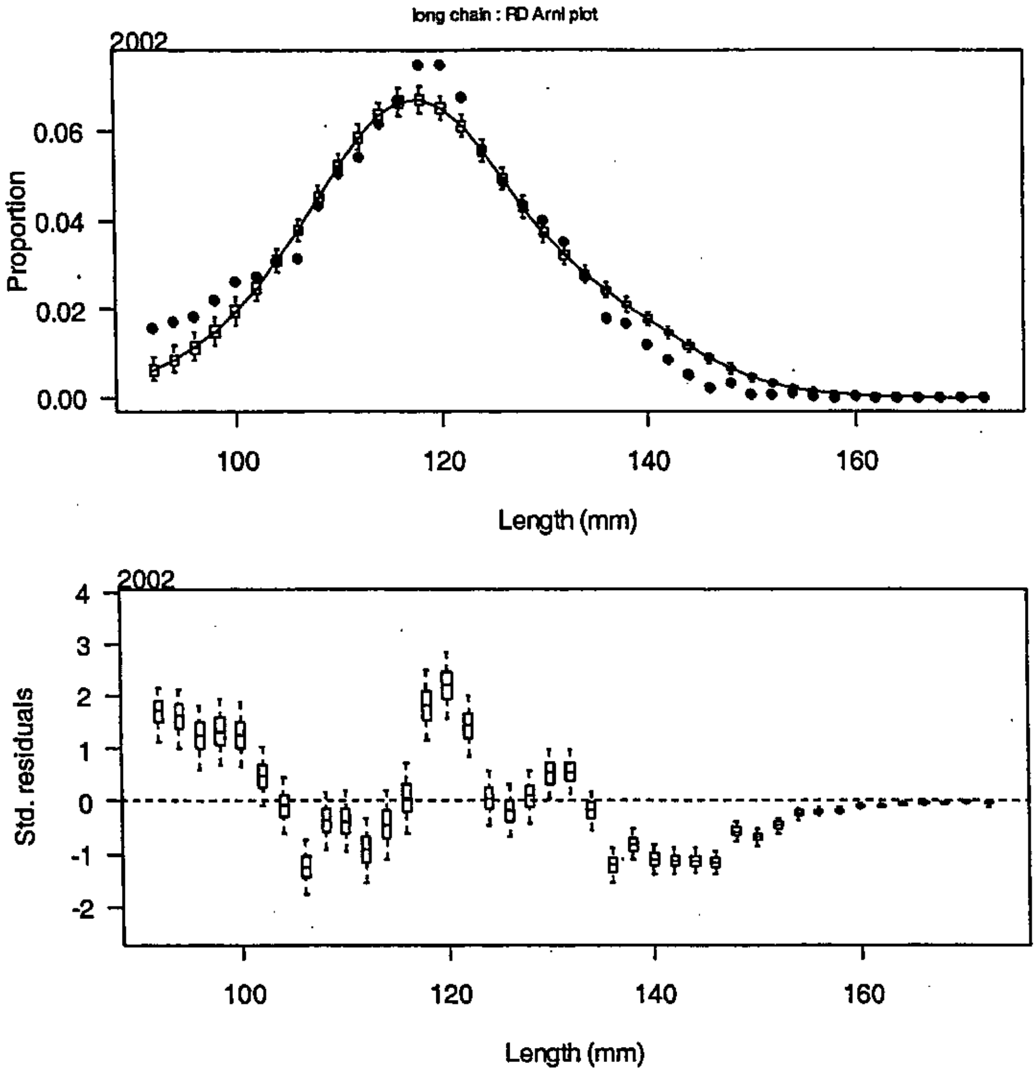


Figure 35: The posterior distributions of the fits to research diver survey proportions-at-length from 2002 (top) and the posterior distributions of the normalised residuals.

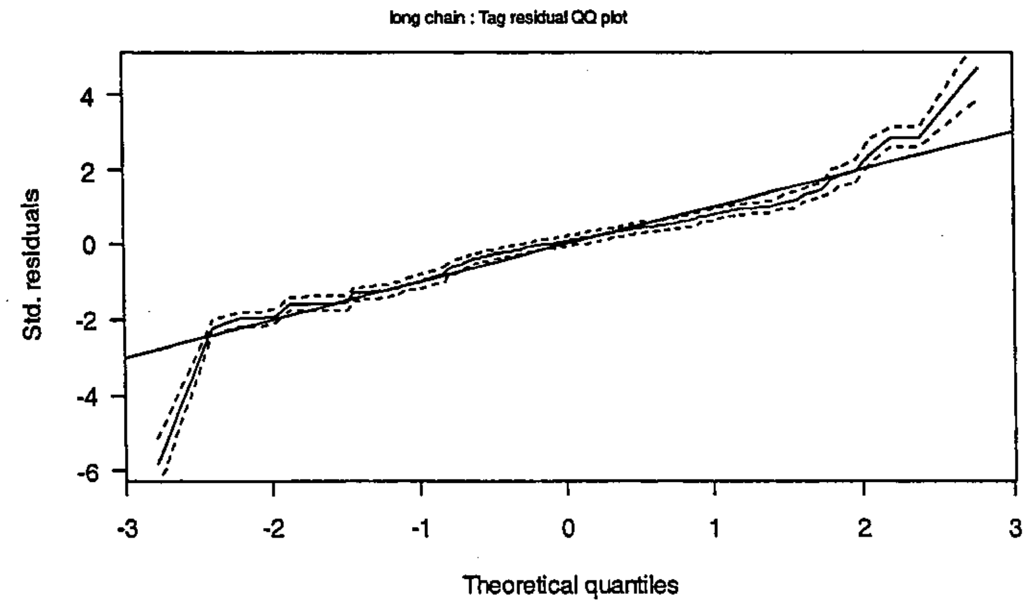


Figure 36: Q-Q plot of the normalised residuals from the posterior distributions of fits to the tag-recapture data.

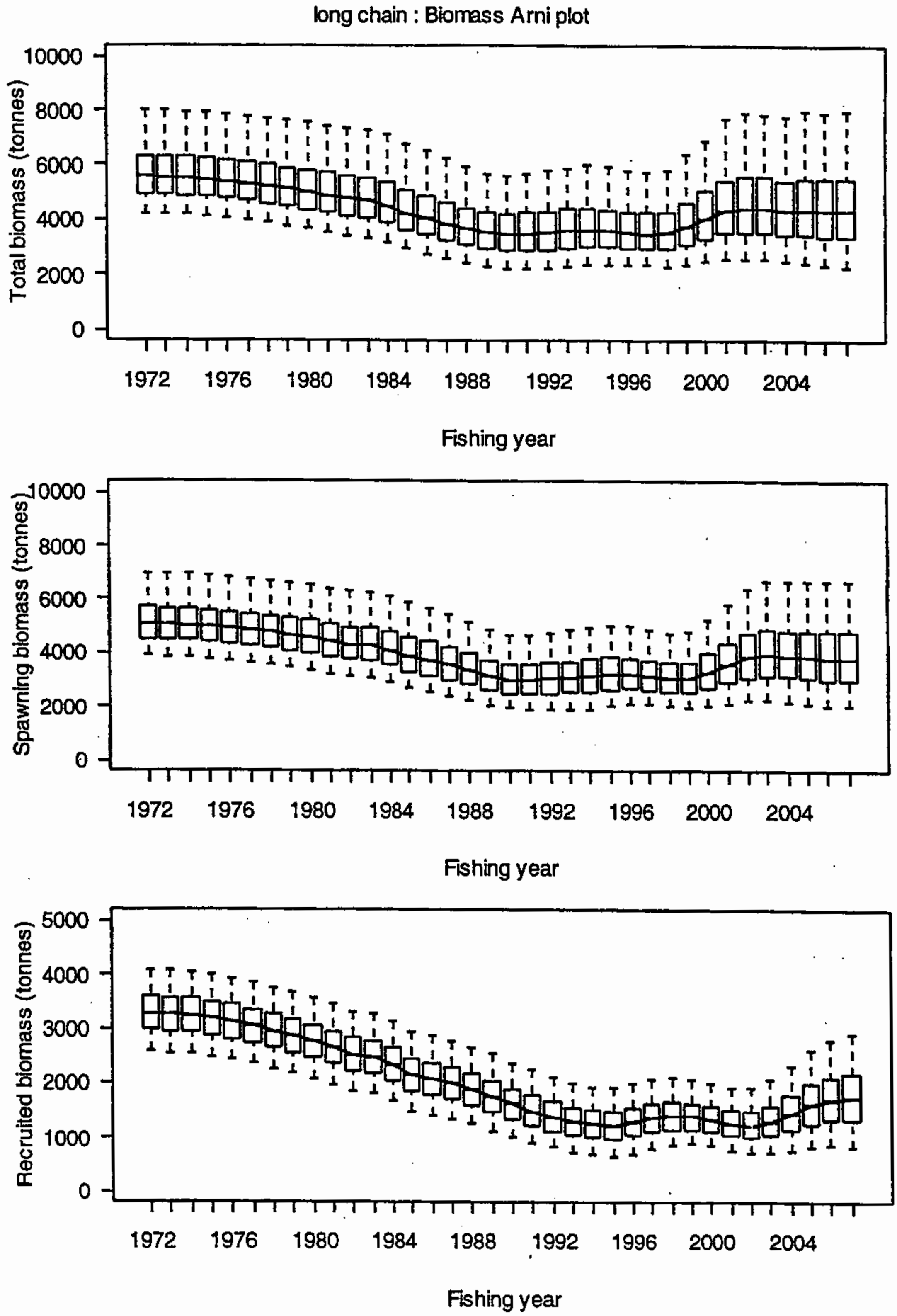


Figure 37: The posterior biomass trajectories for total (top), spawning (middle) and recruited (bottom) biomass for the base case for PAU 4.

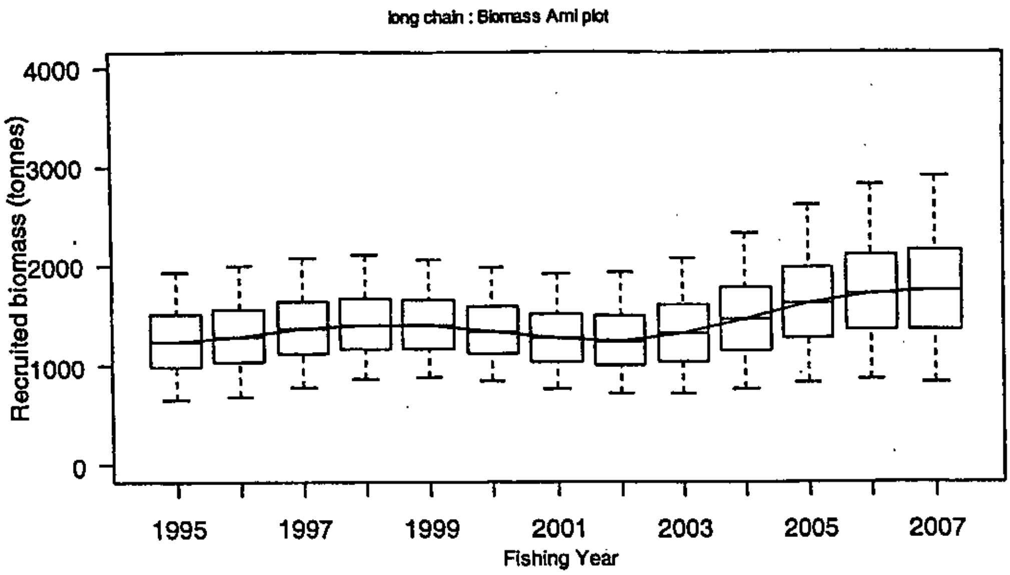
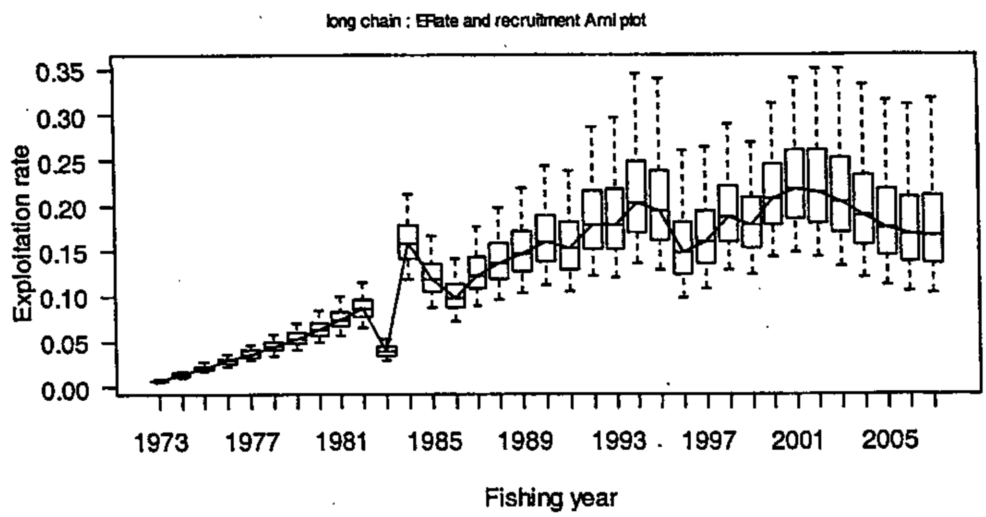


Figure 38: Posterior distribution of the biomass trajectory for recruited biomass from 1995 onwards.



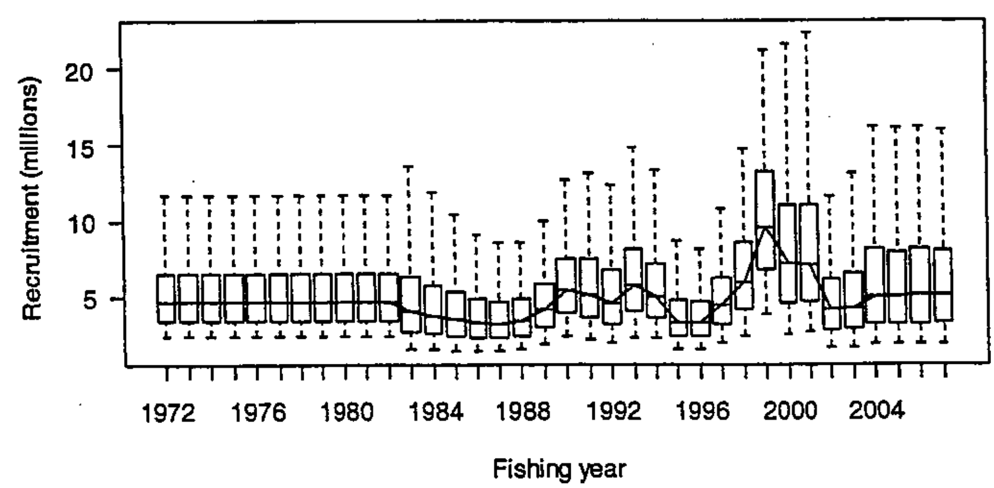


Figure 39: The posterior trajectories of exploitation rate (upper) and recruitment (lower) for the base case for PAU 4.

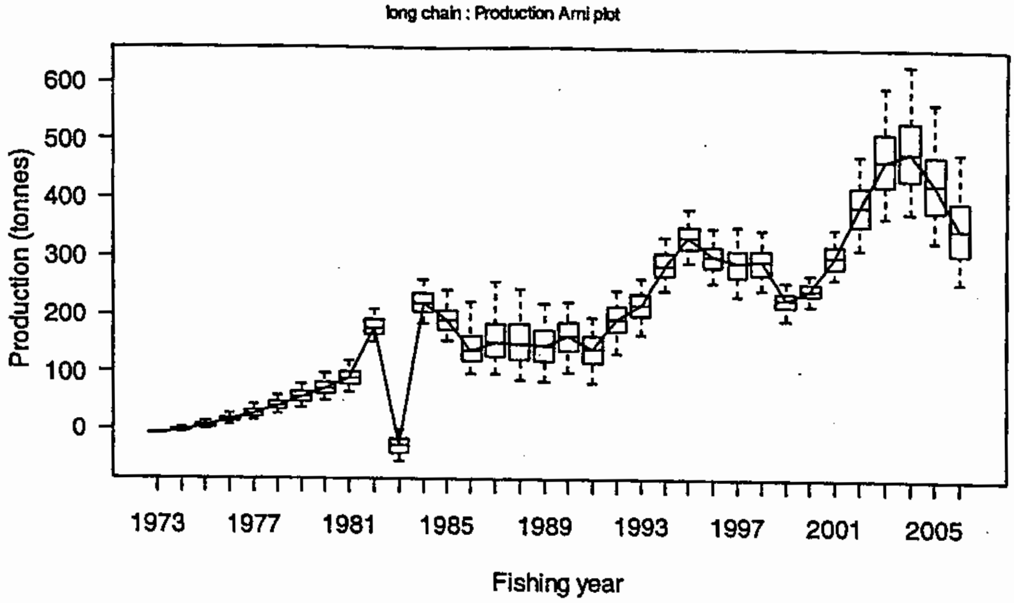


Figure 40: The posterior trajectory of estimated surplus production for the base case for PAU 4.

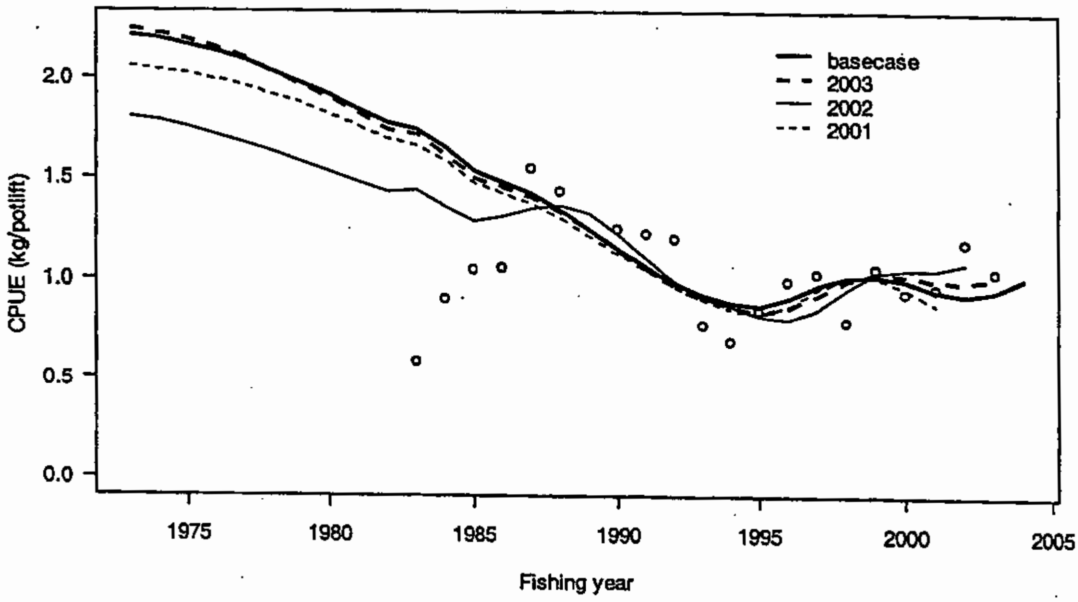
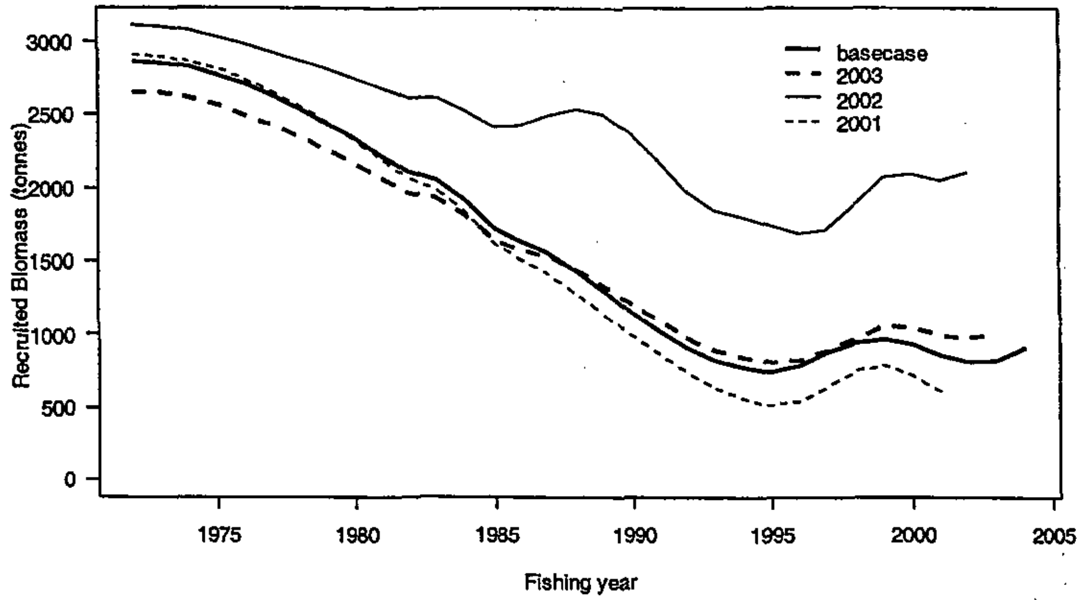


Figure 41: MPD retrospectives: open circles are the observed CPUE; lines are the model's predicted CPUE; lines are named for the last year of data included.



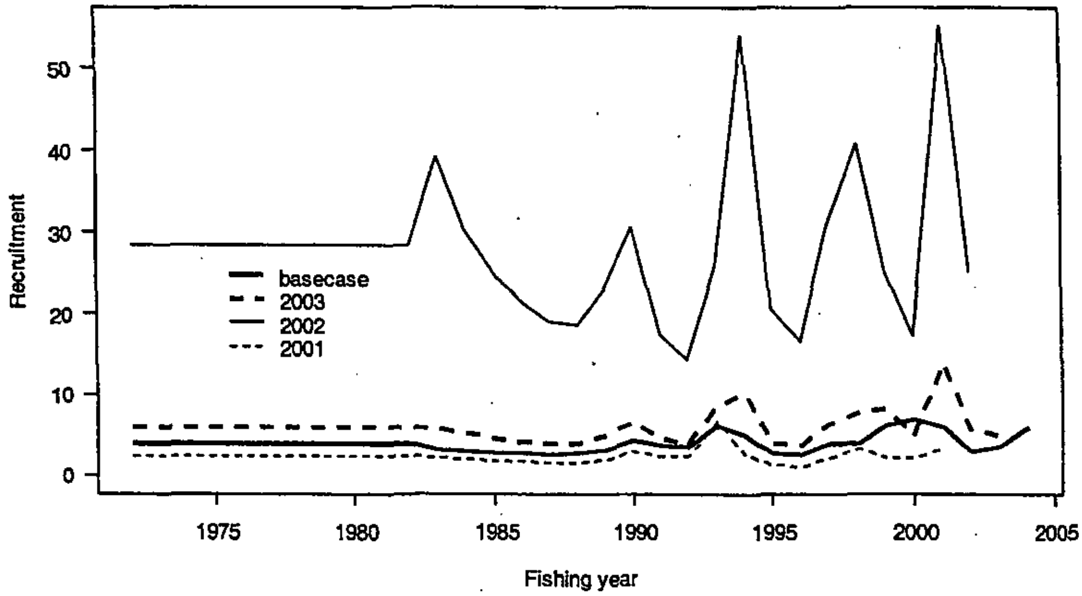


Figure 42: Recruited biomass (upper) and recruitment (lower) trajectories from the MPD estimates in a retrospective analysis. The key refers to datasets labelled by the last year of data they include. The "base case" includes all data to 2004.