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The 2006 stock assessment for paua (*Haliotis iris*) stocks PAU 5A (Fiordland) and PAU 5D (Otago)

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EXECUTIVE SUMMARY

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A length-based paua stock assessment model was used to assess stocks of paua (abalone) (*Haliotis iris*) in PAU 5A and PAU 5D. The assessment used Bayesian techniques to estimate model parameters, the state of the stock, future states of the stock and their uncertainties. The assessment was based on marginal posterior distributions generated from Markov chain – Monte Carlo simulation (McMC). Various sensitivity trials are described.

The model was nearly unchanged from the model used in 2005 to assess PAU 7. A full description of the model is provided. The model was fitted to six datasets for each stock: a standardised CPUE series, a standardised index of relative abundance from research diver surveys, proportions-at-length from commercial catch sampling and research diver surveys, tag-recapture data and maturity-at-length data. The model, data and some modelling choices were discussed and agreed by the Shellfish Fishery Assessment Working Group before the assessment work began.

The PAU 5A assessment faced a contradiction between the catch-per-unit-effort (CPUE) and research diver survey index (RDSI) datasets. Runs were made based on a compromise fit to both datasets, a fit that excluded CPUE and a fit that excluded RDSI. Although these runs differed in many ways, projections made from all three suggested that recruited and spawning biomass are both very likely to decline under the current level of catch. Alternative catch projections are provided.

A major uncertainty for the PAU 5A assessment is the extent to which the RDSI index is representative of the PAU 5A stock as a whole, given that one stratum was surveyed only once. A separate analysis of the southern three strata indicated that abundance declined by 50–75% over a few years while CPUE declined only slightly. This decline was in an area that has produced 60% of the catch in recent years. The assessment suggests that the current catch is not sustainable in PAU 5A.

The PAU 5D assessment was sensitive to the length frequency data obtained by research divers. The selectivity parameters could not be estimated reasonably, so they were fixed to values obtained in the 2005 assessment for PAU 7. There was not great sensitivity to other datasets. A high sensitivity to the choice of growth model was also noted. The base case has estimated M values that are congruent with expectation, whereas sensitivity trials tended to have higher values.

The base case assessment suggests that the PAU 5D stock is depleted, has a high exploitation rate, is near the historical minimum and is much less than the target reference value. Five-year projections from this run suggest that the current catch is not sustainable. However, these conclusions are sensitive to data and modelling choices. Projections become very favourable when the research length frequency dataset is excluded or when a different growth model is used. The PAU 5D assessment was considered inconclusive by the Shellfish Working Group.

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1. INTRODUCTION

This document presents Bayesian stock assessments of blackfoot paua (abalone) (*Haliotis iris*) in PAU 5A (Fiordland) and PAU 5D (Otago), conducted in 2006. This work was conducted under Ministry of Fisheries (MFish) contracts PAU200503, Objective 2, and PAU200502, Objective 1, for the two stocks respectively.

The assessments were made with a version of the length-based model first used in 1999 for PAU 5B (Stewart Island) (Breen et al. 2000a) and revised for subsequent assessments in PAU 5B and PAU 7 (Marlborough) (Andrew et al. 2000a, Breen et al. 2000b, 2001, 2003, Breen & Kim 2004a, 2004b, 2005). The model is described fully below.

The model is conditioned on or "driven by" observed or estimated commercial and non-commercial catches from 1974 through 2005 and an assumed catch series from 1965 through 1973. The model can be fitted to six sets of fishery and research data for each stock. A catch per unit of effort (CPUE) index comes from standardising catch and effort data obtained from paua fishers by MFish, and is assumed to be proportional (not necessarily linearly) to abundance. A second abundance index, the research diver survey index (RDSI), is obtained from research diver surveys based on stratified random 10-minute swims (Andrew et al. 2000b). Two sets of length frequency data from various years are available from market sampling of commercial catches (CSLF) and the research diver surveys (RDLF). Tag-recapture and maturity data are also used.

The model and data (except for the 2006 research survey in PAU 5A) were discussed by the Shellfish Fishery Assessment Working Group before the assessment itself began. Some key decisions, some of which are elaborated upon below, were made:

- non-commercial catch assumptions were agreed;
- it was agreed that handling mortality would not be incorporated, mostly because of lack of data;
- several choices for handling CPUE data were agreed;
- it was agreed to discard some early and some one-off survey length frequency data,
- it was agreed to weight the CSLF data by the statistical area catch, and to discard samples for which no area data were available;
- it was agreed to ignore spatial alienations;
- a set of fishery indicators was agreed;
- several constants were agreed;
- projection procedures were agreed;
- a list of sensitivity trials was agreed.

The assessment generally followed procedures established in previous years. First, the model was fitted to the data with arbitrary weights on the various datasets. Dataset weights were then iteratively adjusted to produce balanced residuals among the datasets. The fit obtained is the mode of the joint posterior distribution of parameters (MPD), which would be the same as the maximum likelihood estimate (MLE) except for the operation of Bayesian priors.

Further adjustments, discussed further below, were made to obtain credible base cases for each stock. Next, from the resulting fit or fits, Markov chain-Monte Carlo (McMC) simulations were made to obtain a set of samples from the joint posterior distribution. From this set of samples, forward projections were made with the 2005 catch levels and a set of agreed indicators was obtained. Sensitivities of the results were explored by comparing MPD fits made with datasets removed one at a time, other MPD sensitivity trials were made to explore modelling choices, some trials were made with McMC simulations and for PAU 5D we compared MPD retrospective analyses. Procedures were not identical for PAU 5A and 5D because of the late arrival of PAU 5A data, which meant that the PAU 5A assessment was done in a much shorter time than had been available for PAU 5D.

The New Zealand paua fishery has been summarised by Schiel (1992) and in numerous previous assessment documents, e.g., Schiel (1989), Schiel & Breen (1991), McShane et al. (1994, 1996), Breen et al. (2000a, 2000b, 2001, 2003), Breen & Kim (2004a, 2004b, 2005). A further summary is not presented here.

The paua fishing year is from October through September. The convention used here is to use the second year as the short name; *viz.* the 2002-03 fishing year may be referred to as "2003".

2. MODEL

The model was developed for use in PAU 5B in 1999 and has usually been revised each year for subsequent assessments, in many cases echoing changes made to the rock lobster assessment model (Breen et al. 2006), which is a similar but more complex length-based Bayesian model. Only minor changes for maintenance were made in 2005 (Breen & Kim 2005) to the 2003 assessment model (Breen & Kim 2004a).

The length-based paua stock assessment model SALAL (Stock Assessment Laboratory for Abalone using Length) does not use age; instead it uses a number of length bins (51 in this assessment), each of width 2 mm shell length. The left-hand edge of the first bin is 70 mm and few, if any, paua are observed in the largest bin. Sexes are not distinguished. The time step is one year for the main dynamics. There is no spatial structure within the area modelled. The model is implemented in AD Model Builder™ (Otter Research Ltd., http://otter-rsch.com/admodel.htm) version 6.2.1.

2.1 Estimated parameters

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

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

M instantaneous rate of natural mortality

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

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

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

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

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

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

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

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

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

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

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

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

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

ε (*Eps*) vector of annual recruitment deviations, estimated from 1974 to 2004

2.2 Constants

l_k length of an abalone at the midpoint of the *k*th length class (l_k for class 1 is 71 mm, for class 2 is 73 mm and so on)

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

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

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

$P_{k,t}$ a switch based whether abalone in the *k*th length class in year *t* are above the minimum legal size (MLS) ($P_{k,t} = 1$) or below ($P_{k,t} = 0$)

a, b constants for the length-weight relation

w_k the weight of an abalone at length l_k

ϖ^I (*CPUEwt*) relative weight assigned to the CPUE dataset. This and the following relative weights were varied between runs to find a base case with balanced residuals

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

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

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

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

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

κ_t^s normalised square root of the number measured greater than 113 mm in CSLF records for each year, normalised by the lowest year

κ_t^r normalised square root of the number measured greater than 89 mm in RDLF records for each year, normalised by the lowest year

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

μ_M (*meanMprior)* mean of the prior distribution for *M*, based on a literature review by Shepherd & Breen (1992)

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

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

n_ε number of recruitment deviations

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

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

2.3 Observations

C_t observed or assumed total catch in year *t*

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

$p^{r}_{k,t}$ observed proportion in the kth length class in year t in RDLF

$p^{s}_{k,t}$ observed proportion in the kth length class in year t in CSLF

l_j initial length for the jth tag-recapture record

d_j observed length increment of the jth tag-recapture record

Δt_j time at liberty for the jth tag-recapture record

p^{mat}_{k} observed proportion mature in the kth length class in the maturity dataset

2.4 Derived variables

$R0$ base number of annual recruits

$N_{k,t}$ number of abalone in the kth length class at the start of year t

$N_{k,t+0.5}$ number of abalone in the kth length class in the mid-season of year t

$R_{k,t}$ recruits to the model in the kth length class in year t

g_k expected annual growth increment for abalone in the kth length class

σ^{g_k} standard deviation of the expected growth increment for abalone in the kth length class, used in calculating $\mathbf{G}$

$\mathbf{G}$ 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 kth length class in year t

V^{r}_{k} relative selectivity of research divers for abalone in the kth length class

V^{s}_{k} relative selectivity of commercial divers for abalone in the kth length class

$\sigma^{r}_{k,t}$ error of the predicted proportion in the kth length class in year t in RDLF data

$\sigma^{s}_{k,t}$ error of the predicted proportion in the kth length class in year t in CSLF data

σ^{d}_{j} standard deviation of the predicted length increment for the jth tag-recapture record

σ^{tag}_{j} total error predicted for the jth tag-recapture record

σ^{mat}_{k} error of the proportion mature-at-length for the kth length class

$-\ln(\mathbf{L})$ negative log-likelihood

f (LikeTotal) total function value

2.5 Predictions

$\hat{I}_t$ predicted CPUE in year t

$\hat{J}_t$ predicted RDSI in year t

$\hat{p}^{r}_{k,t}$ predicted proportion in the kth length class in year t in research diver surveys

$\hat{p}^s_{k,t}$ 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

$\hat{p}^{mat}_k$ predicted proportion mature in the *k*th length class

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

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

A growth transition matrix is calculated inside the model from the estimated growth parameters. If the growth model is linear, the expected annual growth increment for the *k*th length class is

(3) $$\Delta l_k = \left(\frac{\beta g_\alpha - \alpha g_\beta}{g_\alpha - g_\beta} - l_k\right)\left[1 - \left(1 + \frac{g_\alpha - g_\beta}{\alpha - \beta}\right)\right]$$

The model uses the AD Model Builder™ function *posfun*, with a dummy penalty, to ensure a positive expected increment at all lengths, using a smooth differentiable function. The *posfun* function is also used with a real penalty to force the quantity $\left(1 + \frac{g_\alpha - g_\beta}{\alpha - \beta}\right)$ to remain positive. If the growth model is exponential, the expected annual growth increment for the *k*th length class is

(4) $$\Delta l_k = g_\alpha \left(g_\beta / g_\alpha\right)^{(l_k - \alpha)/(\beta - \alpha)}$$

again using *posfun* with a dummy penalty to ensure a positive expected increment at all lengths.

The standard deviation of g_k is assumed proportional to g_k with minimum σ_{MIN}:

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

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 $\mathbf{R}_t$:

(6) $$\mathbf{N_t} = \left(\mathbf{N_{t-1}}\,e^{-M}\right) \bullet \mathbf{G} + \mathbf{R_t}$$

where the dot (•) denotes matrix multiplication.

2.7 Dynamics

2.7.1 Sequence of operations

After initialising, the first model year is 1965 and the model is run through 2005. For the first nine years the model is run with an assumed catch vector, because it is unrealistic to assume that the fishery was in a virgin state when the first catch data became available in 1974. The assumed catch vector rises linearly from zero to the 1974 catch. These years can be thought of as an additional part of the initialisation, but they use the dynamics described in this section.

Model dynamics are sequenced as follows:

- numbers at the beginning of year t-1 are subjected to fishing, then natural mortality, then growth to produce the numbers at the beginning of year t.
- recruitment is added to the numbers at the beginning of year t.
- biomass available to the fishery is calculated and, with catch, is used 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.

2.7.2 Main dynamics

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

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

where

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

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:

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

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

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

(11) $$1E6\left(A_{\min}-\left(1-\frac{C_t}{B_t}\right)\right)^2$$

This prevents the model from exploring parameter combinations that give unrealistically high exploitation rates. Survival from fishing is calculated as:

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

or

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

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

(14) $$\mathbf{N_t} = \left((\mathbf{SF_{t-1}} \otimes \mathbf{N_{t-1}})\mathrm{e}^{-M}\right) \bullet \mathbf{G} + \mathbf{R_t}$$

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:

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

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

The recruitment deviation parameters ε_t were estimated for all years from 1977; there was no constraint for deviations to have a mean of one in arithmetic space except for the constraint of the prior, which had a mean of zero in log space; and we assumed no stock recruitment relationship.

2.8 Model predictions

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

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

Available biomass $B_{t+0.5}$ is the mid-season vulnerable biomass after half the catch has been removed (no natural mortality is applied, because the time over which half the catch is removed might be short). It is calculated as in equation 0, but using the mid-year numbers, $N_{k,t+0.5}$:

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

The predicted research diver survey index is calculated from mid-season model numbers in bins greater than 89 mm length, taking into account research diver selectivity-at-length:

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

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

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

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

The model predicts proportions-at-length for the RDLF from numbers in each length class for lengths greater than 89 mm:

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

Predicted proportions-at-length for CSLF are similar:

(23) $$\hat{p}^s_{k,t} = \frac{N^{vuln}_{k,t+0.5}}{\sum_{k=23}^{51} N^{vuln}_{k,t+0.5}} \qquad \text{for } 23 \le k < 51$$

The predicted increment for the jth tag-recapture record, using the linear model, is

(24) $$\hat{d}_j = \left(\frac{\beta g_\alpha - \alpha g_\beta}{g_\alpha - g_\beta} - L_j\right)\left[1-\left(1+\frac{g_\alpha - g_\beta}{\alpha-\beta}\right)^{\Delta t_j}\right]$$

where Δt_j is in years. For the exponential model (used in the base case) the expected increment is

(25) $$\hat{d}_j = \Delta t_j g_\alpha \left(g_\beta / g_\alpha\right)^{(L_j-\alpha)/(\beta-\alpha)}$$

The error around an expected increment is

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

Predicted maturity-at-length is

$$(27)\qquad \hat{p}_k^{mat} = \frac{1}{1+19^{-\left((l_k - L_{50})/L_{95-50}\right)}}$$

2.9 Model fitting

2.9.1 Likelihoods

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

$$(28)\qquad -\ln(\mathbf{L})\left(\hat{I}_t \mid \theta\right) = \frac{\left(\ln(I_t) - \ln\left(\hat{I}_t\right)\right)^2}{2\left(\sigma_t^I \tilde{\sigma} / \varpi^I\right)^2} + \ln\left(\sigma_t^I \tilde{\sigma} / \varpi^I\right) + 0.5\ln(2\pi)$$

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

$$(29)\qquad -\ln(\mathbf{L})\left(\hat{J}_t \mid \theta\right) = \frac{\left(\ln(J_t) - \ln\left(\hat{J}_t\right)\right)^2}{2\left(\sigma_t^J \tilde{\sigma} / \varpi^J\right)^2} + \ln\left(\sigma_t^J \tilde{\sigma} / \varpi^J\right) + 0.5\ln(2\pi)$$

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:

$$(30)\qquad \sigma_{k,t}^s = \frac{\tilde{\sigma}}{\kappa_t^s \varpi^s \sqrt{p_{k,t}^s + 0.1}}$$

The negative log-likelihood is:

$$(31)\qquad -\ln(\mathbf{L})\left(\hat{p}_{k,t}^s \mid \theta\right) = \frac{\left(p_{k,t}^s - \hat{p}_{k,t}^s\right)^2}{2\left(\sigma_{k,t}^s\right)^2} + \ln\left(\sigma_{k,t}^s\right) + 0.5\ln(2\pi)$$

The likelihood for research diver sampling is analogous. Errors in the tag-recapture dataset were also assumed to be normal. For the *j*th record, the total error is a function of the predicted standard deviation (equation 0) and the observation error:

$$(32)\qquad \sigma_j^{tag} = \frac{\tilde{\sigma}\sqrt{\sigma_{obs}^{\,2} + \left(\sigma_j^{\,d}\right)^2}}{\omega^{tag}}$$

and the negative log-likelihood is:

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

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

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

The negative log-likelihood is:

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

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

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

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

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

and similarly for proportions-at-length from the RDLFs. Because the vectors of observed proportions contain many empty bins, the residuals for proportions-at-length include large numbers of small residuals, which 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

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

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

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

2.9.3 Priors and bounds

Bayesian priors were established for all estimated parameters. Most were uniformed, 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:

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

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:

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

Breen & Kim (2005) described testing the effects of model structure and priors with an "implicit prior" sensitivity trial that downweighted the data to extremely small function value contributions.

2.9.4 Penalty

A penalty is applied to exploitation rates higher than the assumed maximum (equations 10 and 11); this operates only when the model reaches the upper bound.

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

3. DATA

3.1 Catch

The assessment uses four catch estimates that are combined into a total catch vector: commercial, recreational, customary and illegal.

3.1.1 Commercial catch

Commercial catch is recorded now on Monthly Harvest Returns (MHRs), which were previously called Quota Management Reports (QMRs). Before the Quota Management System, catches were reported to the Fisheries Statistics Unit (FSU).

Before 1995, there was only one PAU 5. This was split into PAU 5A, 5B and 5D for the 1995–96 season (Figure 1). After the split, catches have been reported to the new stocks. Before the split, the proportions of PAU 5 catch coming from the three new stocks was estimated by Kendrick & Andrew (2000). For statistical areas lying wholly within one of the new stocks, catch reported on the catch and effort forms could be used to estimate the proportion, but two statistical areas straddled the new stocks. For these two statistical areas, a proportion of the total catch from each area was assigned to the new stocks. The 2006 assessment uses those results.

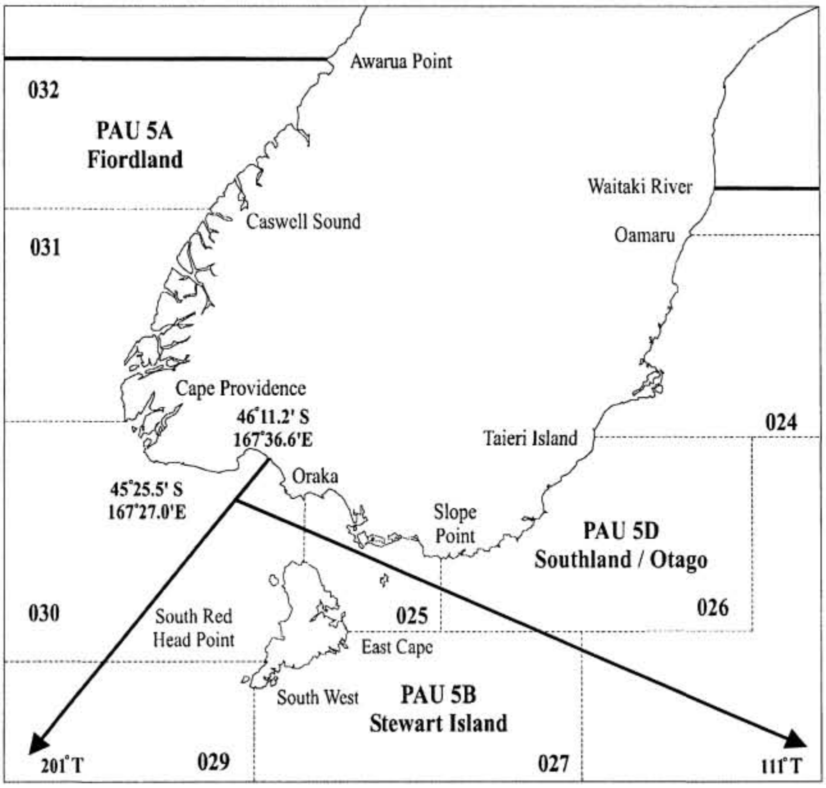


Figure 1: PAU 5 and the split into three new stocks, also showing statistical areas: note how areas 025 and 030 straddle the new stock boundaries.

Commercial catch estimates by stock are shown in Figure 2.

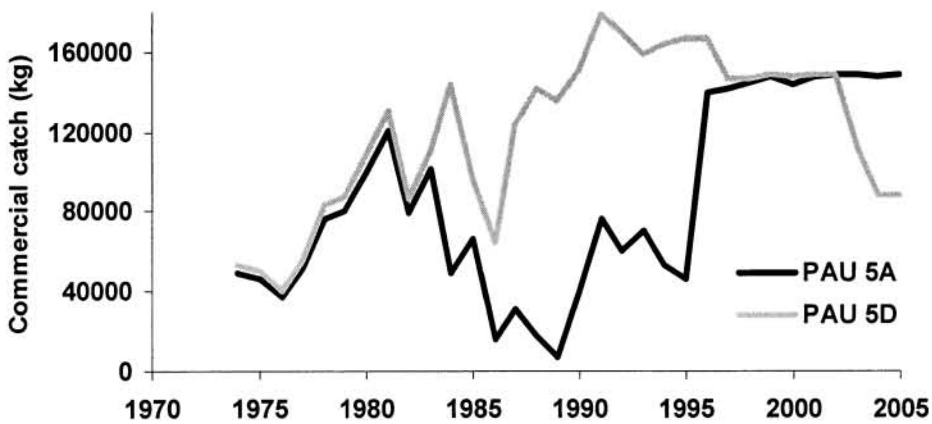


Figure 2: Commercial catch for PAU 5A and PAU 5D.

3.1.2 Recreational catch

The previous stock assessment for PAU 5A (Breen & Kim 2004a) used 10 t, which increased linearly from 1 t in 1974. The two previous assessments for PAU 5D (Breen et al. 2000a, 2003) did not document the estimate used and provide only the total non-commercial catch estimate (42.8 t).

The SFWG considered harvest estimates from the 1996 telephone diary survey and the 1999–2000 and 2000–2001 National Recreational Fishing Survey estimates (Kingett-Mitchell, unpublished data). The 1996 estimates are considered unreliable because of a methodological error; the later estimates are considered unbelievably high for some stocks, although they do not have the same methodological error as in the 1996 survey. The Marine Recreational Fisheries Technical Working Group considered that there are inherent potential sources of bias in the method, including having an unrepresentative sample of diarists and a small number of diarists in some areas. Paua in general suffer from low sample sizes in these surveys.

After discussion, the SFWG agreed to assume that 1974 recreational catches were 1 t and 2 t for PAU 5A and PAU 5D respectively and that these increased linearly to 2 t and 10 t in 2005.

On the catch and effort forms used since 2002, fishers can report paua they land as part of a recreational catch entitlement (destination code "F"). These landings are very small: the sums for years 2002 through the partial data for 2006 are 124 kg and 173 kg for PAU 5A and PAU 5D respectively.

3.1.3 Customary catch

There are no published estimates of customary catch. The previous stock assessment for PAU 5A (Breen & Kim 2004a) used zero in the absence of information. The SFWG agreed to assume that customary catches have been constant at 1 t and 2 t for PAU 5A and PAU 5D respectively.

3.1.4 Illegal catch

There are no published estimates of illegal catch. MFish (unpublished data) has estimated the illegal catch from all of New Zealand to be 1000 t annually. The previous stock assessment for PAU 5A (Breen & Kim 2004a) used zero in the absence of information. The SFWG agreed to assume that illegal catches have been constant at 5 t and 10 t for PAU 5A and PAU 5D respectively.

3.2 CPUE

Catch and effort data are held in the Catch and Effort Landing Return (CELR) system and its predecessor, the Fisheries Statistics Unit (FSU) system. The FSU system involved reporting catch for each month, with effort reported in both days and hours. The CELR system, operating after July 1987, captured estimated catch each day, with effort by days and hours until 1 October 2001, when the generalised CELR forms were replaced for paua with a specific paua form (PCELR). This change involved finer statistical reporting areas (Figure 3 and Figure 4) and reporting estimated daily catch and effort from individual divers.

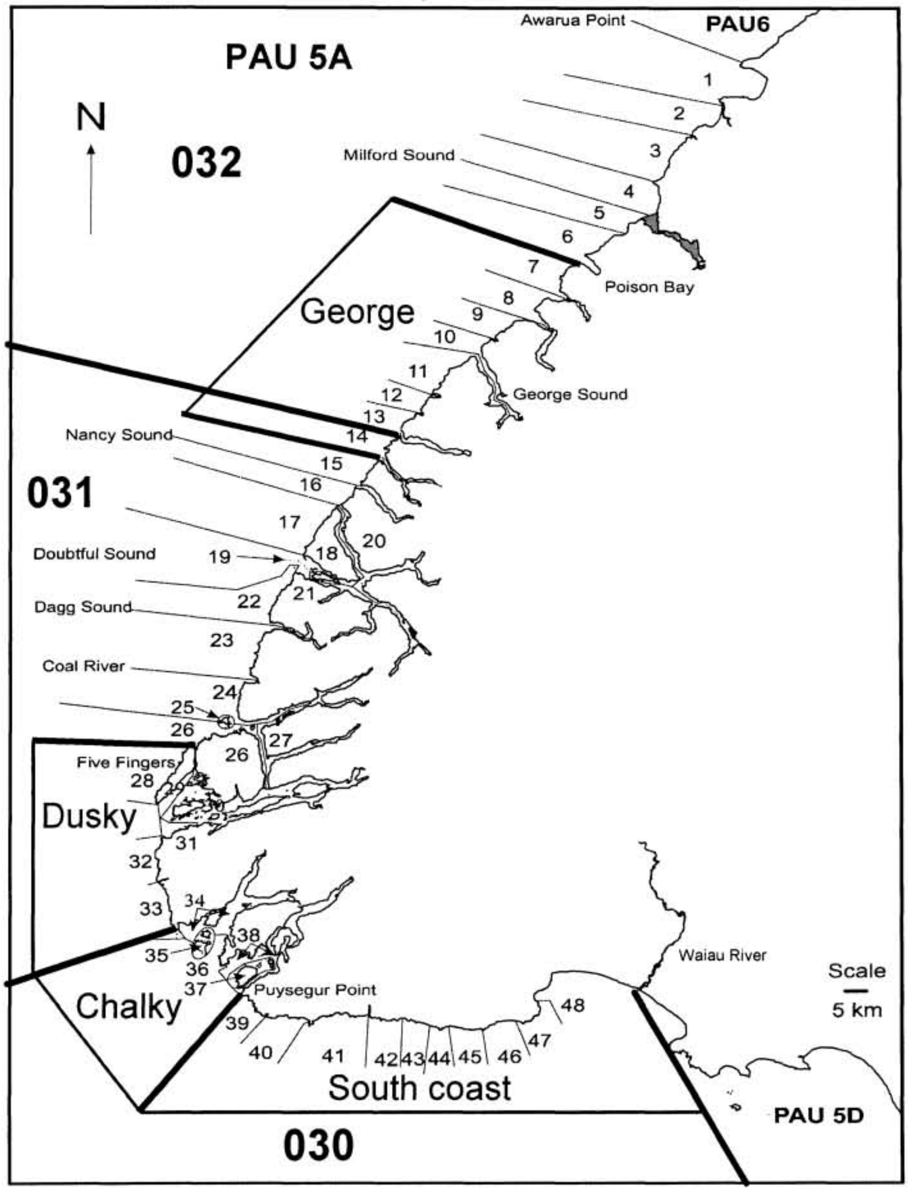


Figure 3: Map of statistical areas, fine-scale statistical areas and research strata for PAU 5A.

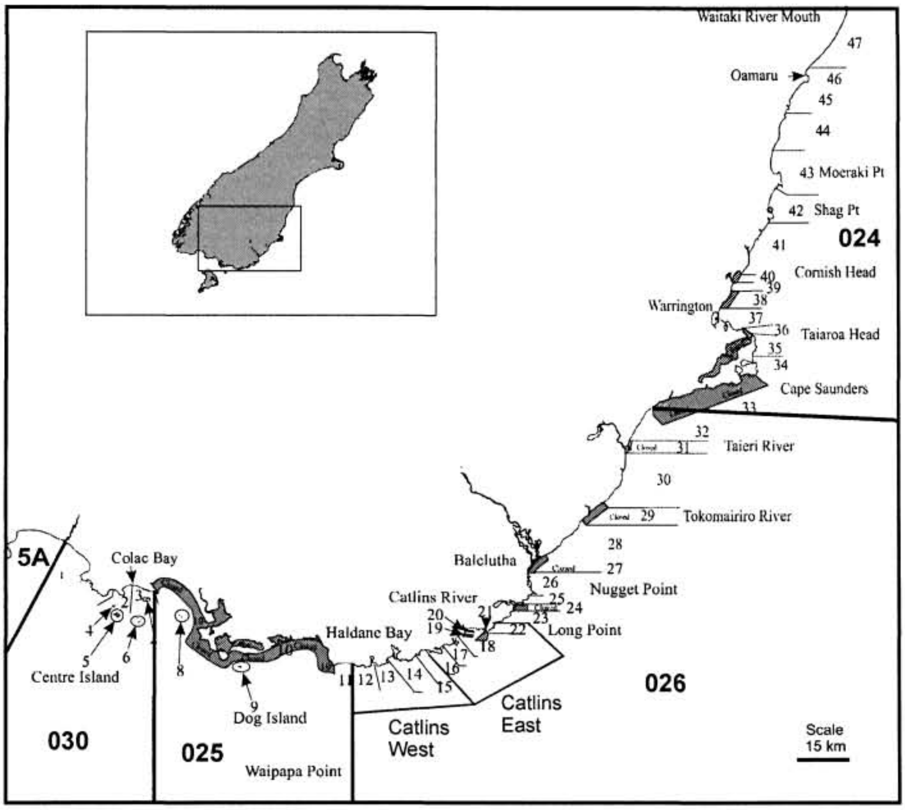


Figure 4: Map of statistical areas, fine-scale statistical areas and research strata for PAU 5D.

Before 1995 there was only one southern paua stock, PAU 5. In 1995, this was divided into three new stocks: PAU 5A, PAU 5B and PAU 5D, which comprise Fiordland, Stewart Island and Otago respectively (see Figure 1). Catches and CPUE from the years before this division were estimated by Kendrick & Andrew (2000).

FSU/CELR data that had been extracted in 2003 for the 2004 stock assessment were used again. PCELR data were extracted from the MFish database from 1 October 2001 (the start of the 2002 fishing year) to 16 December 2005, including partial data from the 2005–06 fishing year.

The CELR and PCELR forms are separated into two parts: a catch and effort part and a landing part, and both parts were extracted. In the catch and effort part, the CELR form includes 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, estimated catch, species caught (recorded as PAU for most records), vessel key and client key.

The PCELR form includes 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 part, both the CELR and PCELR forms include 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.

3.2.1 Descriptive summaries

3.2.1.1 Numbers of records

Numbers of records from each system are shown in Table 1, counted after records had been removed that were missing data in critical fields. The PCELR dataset may have several records for a vessel-day event – one for each diver – whereas the older dataset has only one record for the comparable event.

Numbers of vessel codes over-represent the true numbers of vessels, because new codes were assigned when operators changed their vessels. Diver codes may not fairly represent the true number of individual divers because the same diver may be coded differently on different days, and conversely because a code such as "diver1" may be used for different divers. Most vessels in PAU 5A are associated with 10 or fewer divers, while a few vessels are associated with up to 64 divers. Many divers catch less than 1 t.

Table 1: For each stock, the numbers of useable records in each dataset, the numbers of unique vessel codes vessels in the FSU/CELR dataset and in the PCELR dataset, and the number of unique diver codes in the PCELR dataset.

	PAU 5A	PAU 5D
FSU	302	1336
CELR	1600	5342
vessels	182	268
PCELR	2531	3820
vessels	42	61
divers	292	409

3.2.1.2 Estimated catch

On the CELR and PCELR forms, catch is available as both estimated and landed. For the PCELR forms, the estimated catch is divided among divers. It is challenging to match the actual landed weight from the fish receiver against the estimated weights, so we use estimated weights. The annual sum of estimated weights from the catch and effort forms against the estimated actual catches is compared in Figure 5 and Figure 6. For years before 1995, when PAU 5 was split up into three stocks, actual catches were estimated as described by Kendrick & Andrew (2000). After 1995, actual catches come from the Quota Management Reports (QMRs) and their successor, the Monthly Harvest Returns (MHRs).

For the most recent five years, the estimated catches are 90% or more of the actual catches. Before 2000, the comparisons are not as close. In both stocks, the two data sources show roughly similar trends. The patterns suggest considering a scale of weights on CPUE, with increasing weight after 1995 (when the stock is first known accurately) and again after 2001 (when the comparison between estimated and actual catch becomes close).

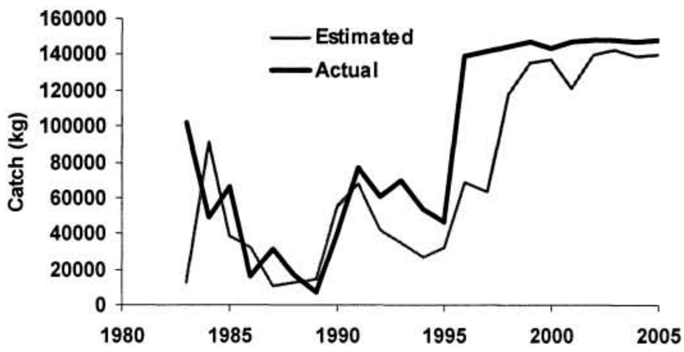


Figure 5: Comparison for PAU 5A of the annual catches estimated from the catch and effort forms ("Estimated") and the catches from the catch reporting forms ("Actual").

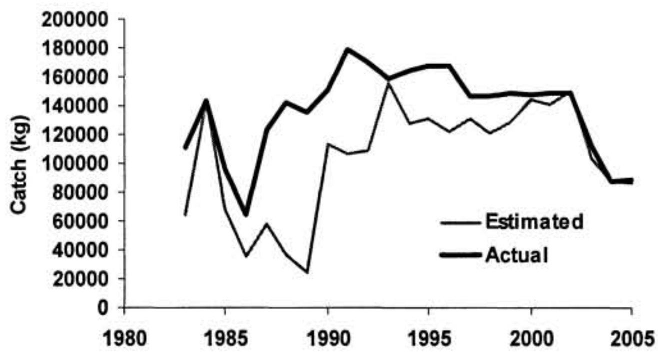


Figure 6: Comparison for PAU 5D of the annual catches estimated from the catch and effort forms ("Estimated") and the catches from the catch reporting forms ("Actual").

3.2.1.3 Catch by area

The annual percentages of catch from the large-scale statistical areas are shown for each stock in Figure 7 and Figure 8. In PAU 5A, area 030 has always provided a relatively low percentage of the catch, except in the late 1990s, and the other two areas have been roughly equal over the history of the fishery, remembering that catches were low before the PAU 5 split in 1995.

In PAU 5D, about half the catch has come from area 026. Area 032 contributed relatively little until 2002 and the remainder was evenly divided between 024 and 025, except that the percentage from 025 fell off sharply from 2002.

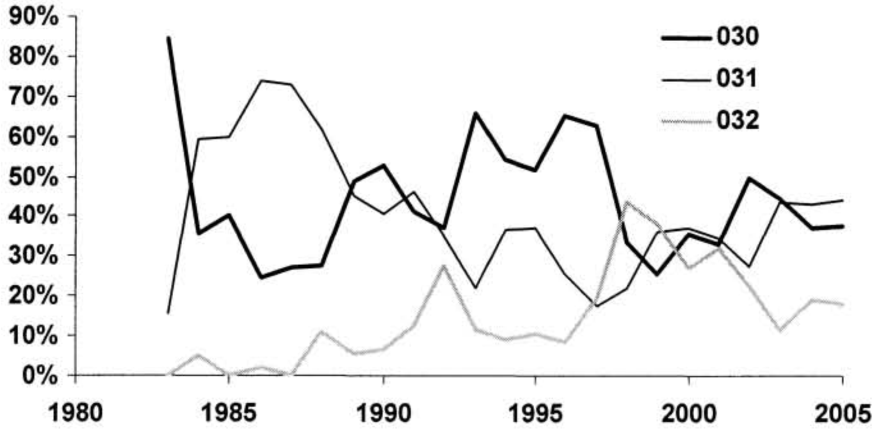


Figure 7: The annual percentage of catch estimated on the catch and effort forms from each statistical area in PAU 5A.

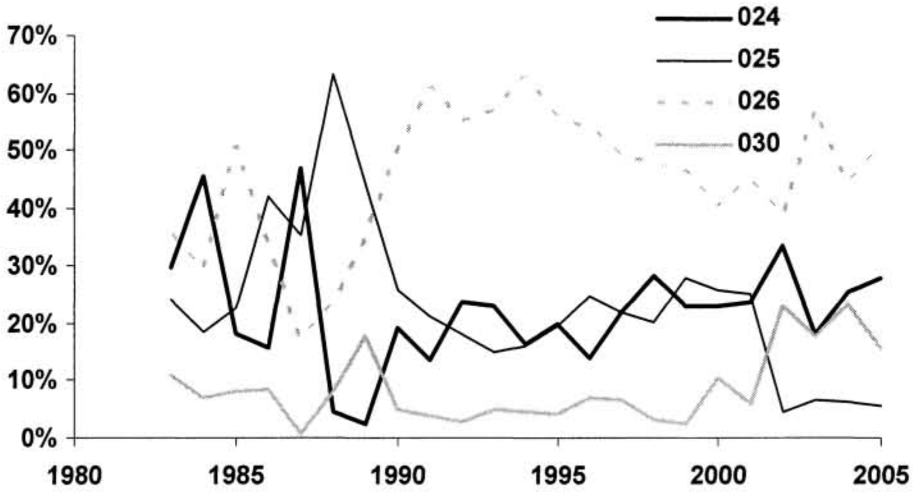


Figure 8: The annual percentage of catch estimated on the catch and effort forms from each statistical area in PAU 5D.

3.2.1.4 Divers and diver-hours

In the FSU/CELR datasets, the number of divers was given for each vessel/day/area record. Almost half the vessels carried two divers (Table 2). Vessels in PAU 5D tended to carry fewer divers than in PAU 5A and comparatively few records had more than four divers.

There is very high ambiguity in the CELR dataset: for records with more than one diver, do the hours represent the total diving hours or the hours per diver? The mean numbers of hours per record, for records with various numbers of divers, are shown in Figure 10. If the total number of hours for all divers were reported, one would expect mean hours to increase linearly with increasing numbers of divers, whereas if hours per diver were reported, one would expect the curve to be reasonably flat.

Table 2: Percentage frequencies of the numbers of records with different numbers of divers in the FSU/CELR datasets.

No. divers	PAU 5A (%)	PAU 5B (%)
1	15	34
2	47	44
3	23	16
4	6	3
5	3	1
6	3	1
7	3	0

In the FSU/CELR datasets, the number of hours for each record ranged from 0.02 to 360. Hours reported on the FSU forms appeared to have been multiplied by 10 (Figure 9). Hours on the CELR forms range as high as 36.

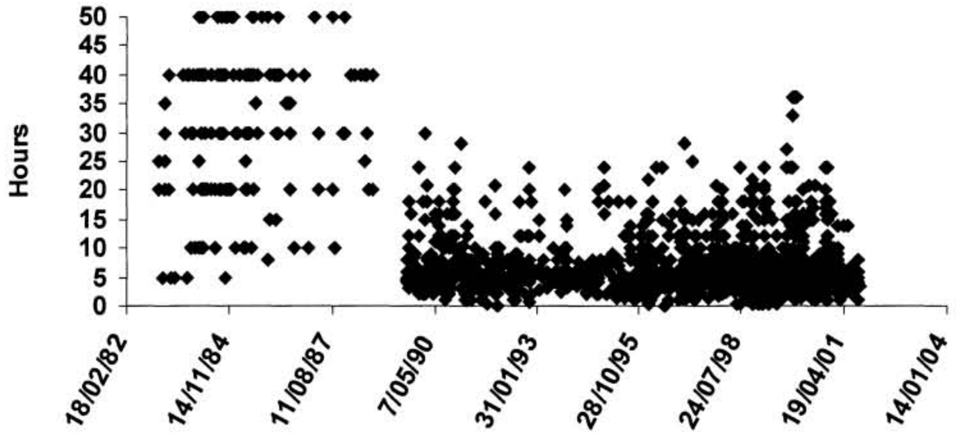


Figure 9: From PAU 5A, the date and the number of hours reported on each record from the FSU/CELR datasets. The y-axis is truncated and early data go to 360 hours.

Figure 10 is ambiguous: there is an increase in mean hours from one to three divers, but the increase is not proportional. There is a decline after three divers. These patterns suggest that sometimes hours were recorded as total hours and sometimes (especially for larger numbers of divers) as hours per diver. The hours per diver data are unusable from the CELR dataset because of this ambiguity, and are unusable from the FSU dataset because their scale is clearly wrong.

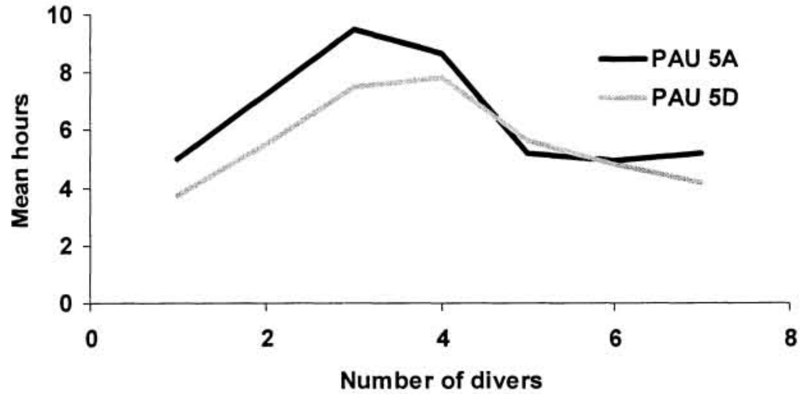


Figure 10: Mean number of hours for records with various numbers of divers in the CELR dataset.

The distribution of hours among diver-days in the PCELR datasets (Figure 11) shows that most days fishing involve 3 or more hours, few exceed 7 hours and very few exceed 8 hours. Dive times tend to be slightly longer in PAU 5D than PAU 5A.

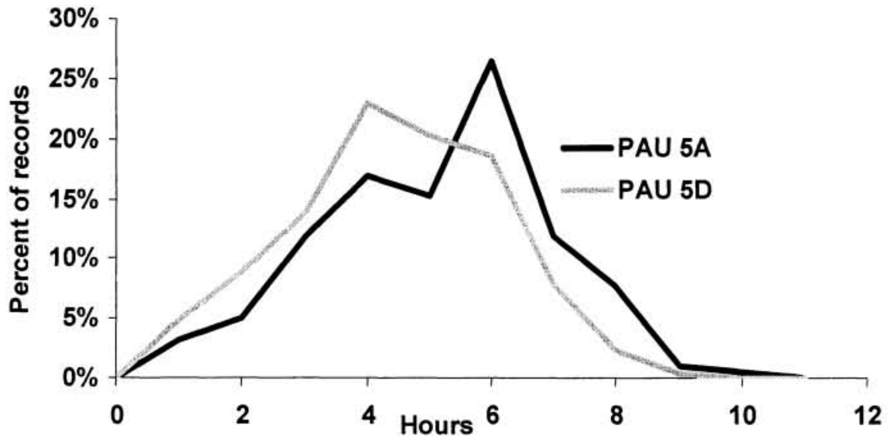


Figure 11: Percentage distributions of the numbers of records with different hours recorded for a diver-day in the PCELR dataset.

3.2.1.5 Grain size of the data

We examined precision of the reporting by looking at the percentage of records with estimated catch recorded as a multiple of 50 or 100 kg, and the percentage of "hours" recorded as an exact multiple of one hour. For the PCELR data, where a separate record is provided for each diver, we collated the records that were from more than one diver on the same vessel and same day in the same area, and we compared the estimated catch with the preceding record.

Results (Table 3) suggest that resolution in the data is low. In PAU 5A, almost two-thirds of the estimated catches for a diver are multiples of 50 kg; in PAU 5D (where CPUE is lower) the resolution is somewhat higher. For both stocks, time is estimated to the nearest hour in 80% of records.

Where more than one diver fishes, Table 3 suggests that most operators apportion the total day's catch among the divers on the PCELR forms, without attempting to estimate the true diver catches: 75% of the records available to be compared are the same as the preceding record from the same fishing event. The even division of catches among divers was previously described to the SFWG for PAU 7 by David Middleton (SeaFIC, unpublished data).

Table 3: The percentages of records from each stock in which the estimated catch is a multiple of 50 and 100 kg, the time is a multiple of 1 hour, or, for the PCELR data only, where a record from the same vessel, day and area has the same estimated catch as the preceding record.

		PAU 5A (%)	PAU 5D (%)
FSU/CELR	50 kg	62	33
	100 kg	45	22
	1 hour	86	84
PCELR	50 kg	62	36
	100 kg	37	20
	1 hour	79	80
	Est. catch	76	74

3.2.1.6 CPUE distributions

The distribution of CPUE in the FSU/CELR dataset (Figure 12) reflects a higher overall mean CPUE in PAU 5A (237 kg/diver-day) than in PAU 5D (155 kg/diver-day). Although there are records as high as 9 t/diver-day, the distributions suggest that anything above 1000 kg/diver-day can be treated as an outlier.

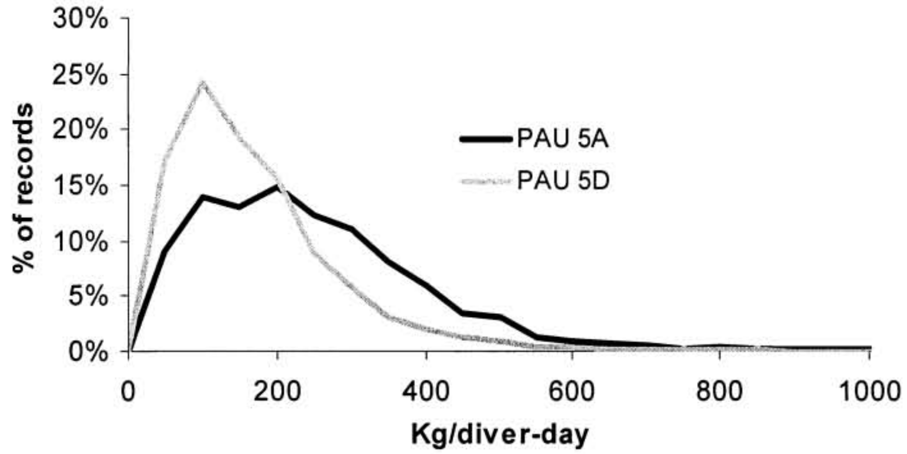


Figure 12: The percentage frequency of records in various CPUE bins from the FSU and CELR datasets. The x-axis is truncated at 1000 kg/diver-day.

The distribution of CPUE in the PCELR dataset (Figure 13) also reflects a higher overall mean CPUE in PAU 5A (46.4 kg/diver-hour) than in PAU 5D (27.3 kg/diver-hour). Although there are records as high as 1.2 t/diver-hour, the distributions suggest that anything above 200 kg/diver-hour can be treated as an outlier.

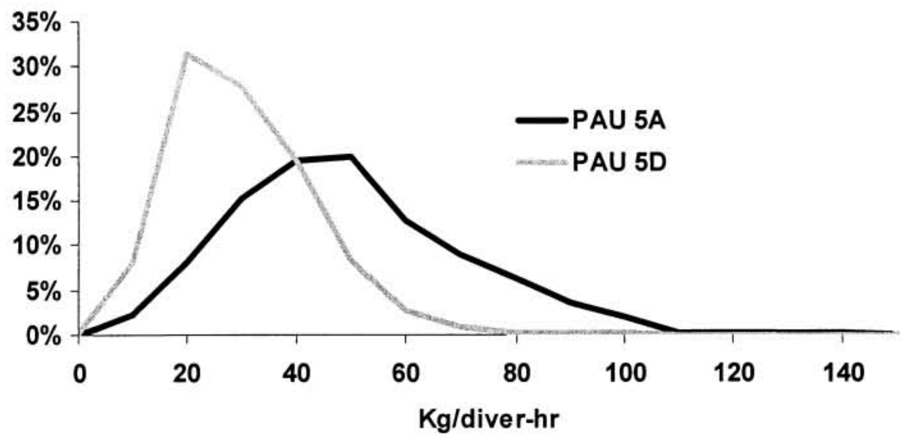


Figure 13: The percentage frequency of records in various CPUE bins from the PCELR datasets. The x-axis is truncated at 150 kg/diver-hour.

3.2.1.7 Mean CPUE by area

The pattern of CPUE by year and area is shown in Figure 14 through Figure 17. In PAU 5A, CPUE is roughly similar in the three statistical areas, with area 032 showing much fluctuation. CPUE declined to 1994 and then shows a shallow rise. In PAU 5D, the area differences after 1995 are minor. CPUE shows a general decline to 1998, is flat until 2003 and shows a shallow increase in the past two years.

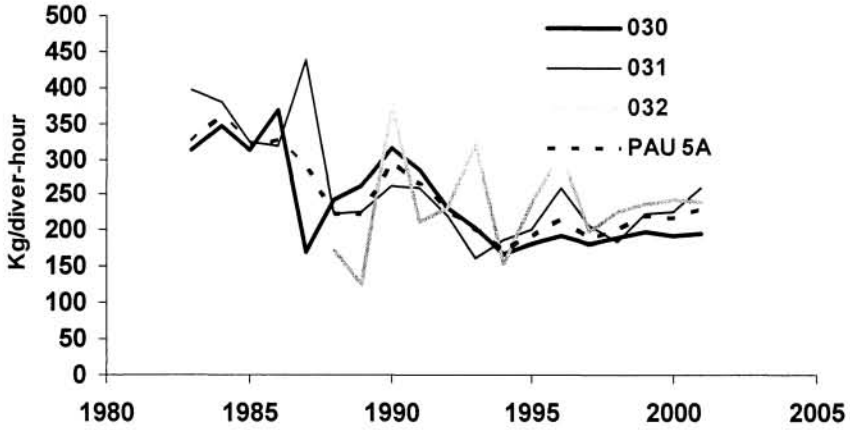


Figure 14: Raw CPUE by area in PAU 5A from the FSU/CELR forms. For this analysis, records with CPUE>1000 kg/diver-day were truncated to 1000 kg/diver-day.

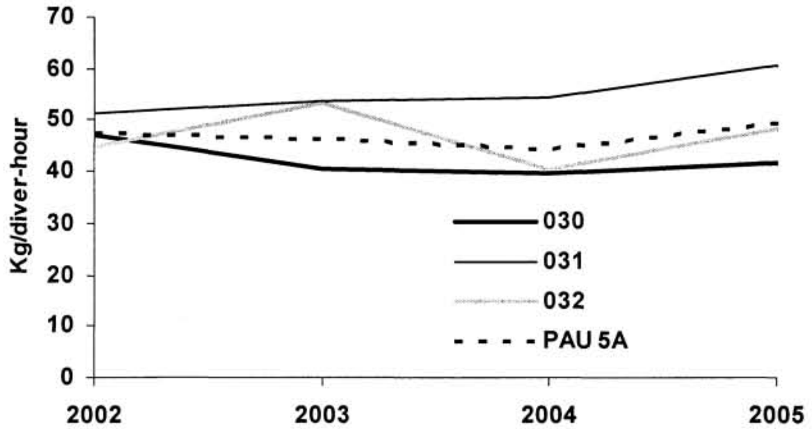


Figure 15: CPUE by area in PAU 5A from the PCELR forms. For this analysis, records with CPUE>200 kg/diver-hour were truncated to 200 kg/diver- hour.

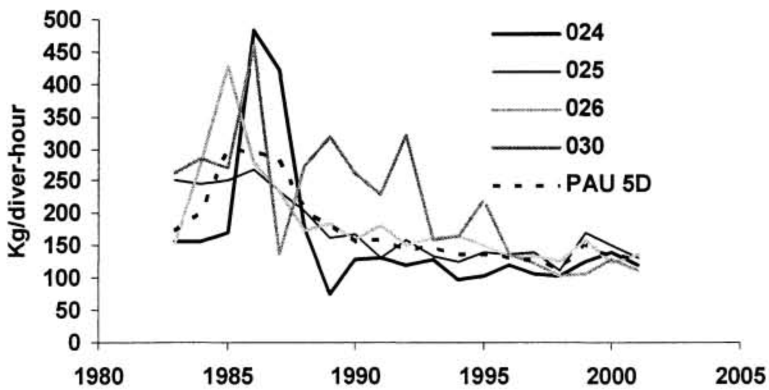


Figure 16: CPUE by area in PAU 5D from the FSU/CELR forms. For this analysis, records with CPUE>1000 kg/diver-day were truncated to 1000 kg/diver-day.

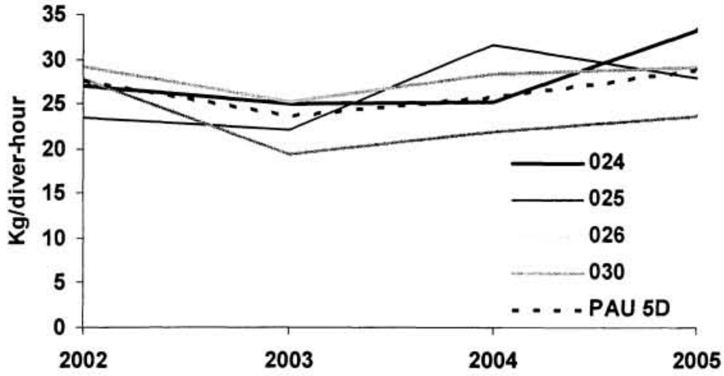


Figure 17: CPUE by area in PAU 5D from the PCELR forms. For this analysis, records with CPUE>200 kg/diver-hour were truncated to 200 kg/diver- hour.

On the PCELR forms, the fine-scale reporting areas (see Figure 3 and Figure 4) are much smaller than the old statistical areas. For these data it is possible to compare catch and CPUE. In PAU 5A (Figure 18), when the fine-scale areas are ranked by catch, 75% of the catch comes from the 20 top areas, or 45% of the available areas. Mean CPUE by area, when plotted against the ranked areas, shows a shallow decline. The relation between CPUE and catch from each area (Figure 18, lower) shows a weak relation with a shallow slope.

The patterns seen in PAU 5A are also seen in PAU 5D (Figure 19). The top 13 areas (30%) produce 75% of the catch. There is not much relation between catch and mean CPUE by area.

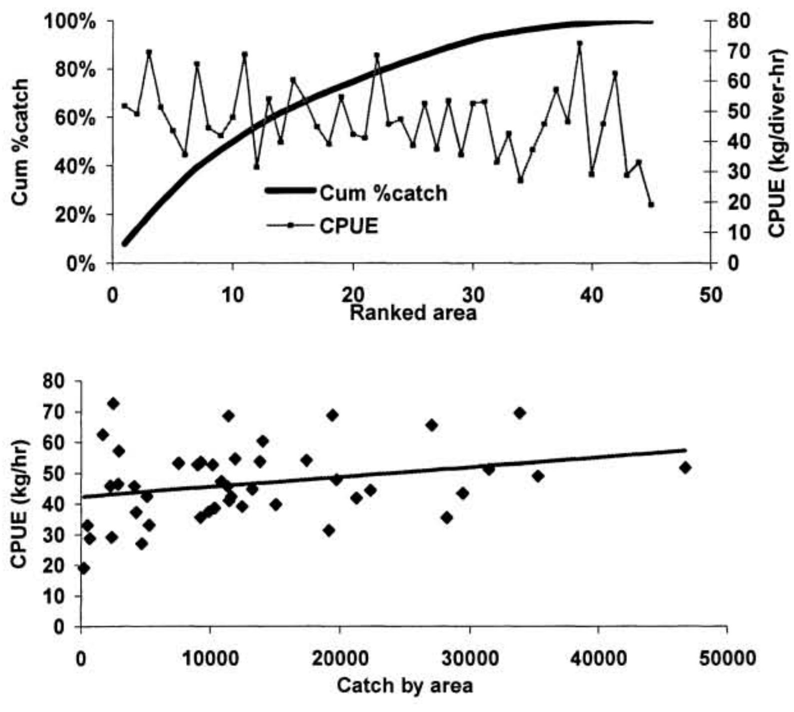


Figure 18: Upper: cumulative percentage of catch plotted against ranked small-scale reporting area from the PCELR dataset for PAU 5A and mean CPUE for the ranked areas. Lower: mean CPUE by area plotted against the catch by area, with a fitted line: CPUE=42.3+0.000319(catch).

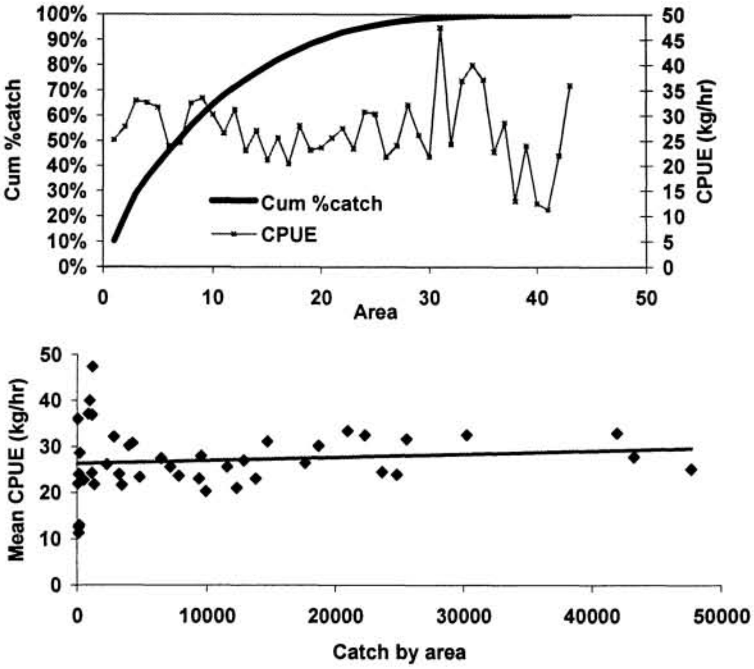


Figure 19: Upper: cumulative percentage of catch plotted against ranked small-scale reporting area from the PCELR dataset for PAU 5d and mean CPUE for the ranked areas. Lower: mean CPUE by area plotted against the catch by area, with a fitted line: CPUE=26.3+0.000069(catch).

3.2.1.8 Catch against fishing unit

The fishing units in these datasets are very skewed in their catches. The top fishing unit typically takes 8–10% of the total catch. The cumulative catch, when plotted against the ranked vessel or diver (Figure 20 through Figure 22) rises steeply (a few units take much of the catch) and has a long shallow plateau (many units take very little catch). Table 4 shows that 20–25% of vessels take 75% of the catch from both stocks in both types of dataset.

The divers are even more skewed: the top 75% of the catch from both stocks is caught by the top 12% of the divers (Table 4 and Figure 22).

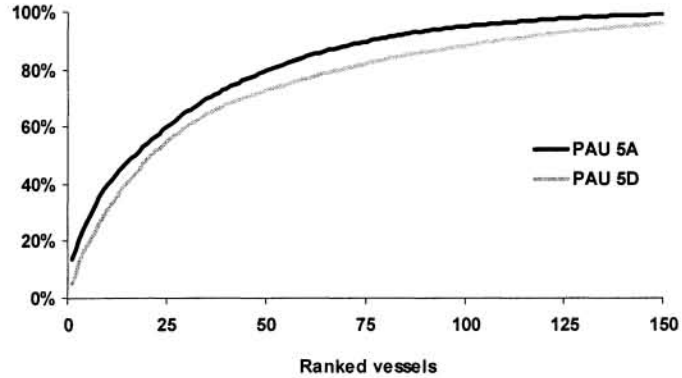


Figure 20: Cumulative percentage of catch from the FSU/CELR datasets, plotted against the ranked vessel after sorting by total catch.

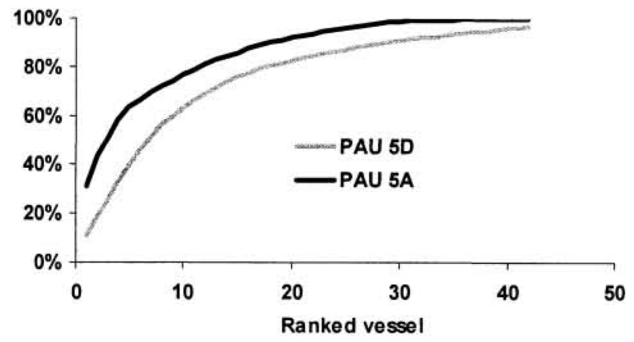


Figure 21: Cumulative percentage of catch from the PCELR datasets, plotted against the ranked vessel after sorting by total catch.

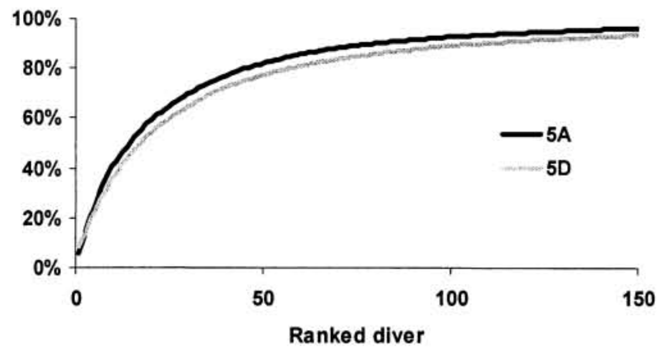


Figure 22: Cumulative percentage of catch from the PCELR datasets, plotted against the ranked diver after sorting by total catch.

Table 4: The position of the ranked fishing unit that takes 75% of the cumulative catch. For instance, in PAU 5A, the top 23% of vessels take 75% of the catch.

		PAU 5A	PAU 5D
FSU/CELR	Vessel	23.1%	20.1%
PCELR	Vessel	23.8%	24.6%
	Diver	12.3%	11.0%

3.2.1.9 Exploratory analysis summary

Quality of the catch and effort data is not high, although it does improve with time. Data before mid 1987 (FSU data) appear to contain incorrect hours: although this is not a large problem because the hour data are not used, it may reflect other problems. Further problems were identified when the data were standardised (see below); in future assessments the FSU data should probably not be used. In the CELR data, hours were recorded but the meaning is ambiguous for records with more than one diver.

It is difficult to mate the actual landings, as weighed by fish receivers, and the estimated landings. Estimated catches agree well with catches reported on the QMR/MHR systems, especially in recent years, so we use the estimated catches.

The newer PCELRs have data by diver, but the quality of the data by diver may be low: there are suspiciously high numbers of diver codes for the number of vessels, and most operators appear to be assigning a day's catch evenly among the divers on the forms. Because of the low resolution of the catch by diver data, catch per diver-day may be a good unit of CPUE, eliminating the need to calculate two abundance index series and to have two catchability parameters in the model.

A few vessels, roughly 25%, take 75% of the catch. The 2005 PAU 7 assessment (Breen & Kim 2005) restricted the CPUE standardisation to data from vessels landing the top 75% of catch in each year, and the analysis above suggests that is a defensible procedure.

3.2.2 CPUE standardisation

In the 2005 assessment for PAU 7, the PCELR data were treated as a second series, with units of kg/day-hour, and the model fitted them separately from the CELR series. Doing this allowed a diver effect to be estimated, used the finer-scale effort unit and used fine-scale reporting areas.

However, the exploratory analyses above suggest that a day's catch is usually not recorded by individual diver, that resolution of the data is low and that mean CPUE does not relate strongly to catch among the fine-scale areas. After considering exploratory standardisations that are not fully reported here, the SFWG agreed to use CPUE as a single series with units of kg/diver-day, and to restrict each year's data to records from those vessels that caught the top 75% of the catch.

Based on the results shown below, the SFWG agreed to omit CPUE indices before 1989 because of their large uncertainty. Data from these years were used in the standardisation model but the indices were not used in the assessment.

3.2.2.1 FSU/CELR Data

The same grooming process was done as in the 2005 analysis (Breen & Kim 2005). Numbers of records removed are shown and explained in Table 5. After grooming there were 1656 and 5494 records from these datasets for PAU 5A and PAU 5D, respectively.

Table 5: Number of FSU/CELR records removed in grooming for PAU 5A and PAU 5D.

	No. of records removed	
Reason	PAU 5A	PAU 5D
Diver No.=0	0	0
Diver No. not recorded	17	20
Diver No.>9	1	1
Dive hrs not recorded	31	94
Diver hrs per diver >10	241	1151
Vessel key=NA	0	66
Est. Catch not recorded	8	1
Est. Catch=0	0	10
FY> 2001	0	1
FY< 1984	5	33
CPUE>2000kg/diver-day	1	0
No. statistical areas	1	0

3.2.2.2 PCELR data

The PCELR extracts included yellowfoot paua (*Haliotis australis*) with a separate species code (PAA). The estimated catches of *H. australis* averaged only 1.2 t and 1.0 t for PAU 5A and PAU 5D respectively for 2002 to the present. Only catches of *H. iris* were included in the analyses reported here.

There were 2577 PCELR records from PAU 5A in the December 2005 extract, of which 2462 records were from before the 2006 fishing year. Of these, 46 records were removed because the *H. iris* catch was recorded as "NULL" (15 of these were "NULL" catch in total). Records without a vessel key were not removed at this stage because only vessels that fished the top 75% of total catch in any year were used in the analysis (see below) and vessels with no vessel key tend to have small catches.

For the assessment standardisations, we extracted information from the PCELR dataset to be compatible with the CELR data. On the PCELR form, for one day's fishing in one area from one vessel, estimated catch is recorded for each diver with a record of hours for that diver. These data were collapsed by form number and statistical area so that the data have the same format as the CELR data. Specifically, for one vessel for one day in one area, PCELR estimated catch was summed for all divers and the divers were counted. Numbers of records involved in this combined dataset are shown in Table 6.

Table 6: Numbers of records from each data source for the combined dataset.

	CELR	PCELR	Total
PAU 5A	1656	859	2515
PAU 5D	5494	1708	7202

Records from vessels that fished the top 75% of catch in any given year were chosen for the analysis. Records from 71 vessels for PAU 5A and 97 vessels for PAU 5D were used for the CPUE analysis; numbers of vessels chosen in each year are shown in Table 7.

Table 7: Number of vessels in the groomed datasets and the number of vessels chosen (because they caught the top 75% of catch) in each fishing year.

	PAU 5A		PAU 5D	
Fishing year	No. vessels in data	No. vessels used	No. vessels in data	No. vessels used
1984	10	5	18	8
1985	9	5	8	5
1986	5	2	5	3
1987	3	2	7	3
1988	1	1	7	2
1989	11	8	22	12
1990	23	15	54	26
1991	38	22	50	28
1992	27	17	52	27
1993	28	20	61	29
1994	29	20	56	31
1995	24	15	65	33
1996	28	18	44	28
1997	28	14	49	34
1998	23	17	40	27
1999	28	18	42	25
2000	33	19	42	29
2001	32	15	46	25
2002	22	15	40	24
2003	24	14	45	25
2004	25	15	33	17
2005	25	13	28	14

This resulted in 2003 and 5733 records chosen for PAU 5A and PAU 5D, respectively, and the number of years these vessels fished varied from 1 to 14 years for PAU 5A and 1 to 13 years for

PAU 5D (Table 8). CPUE ranged from 1 to 1000 kg/diver-day in PAU 5A and from 1 to 764 kg/diver-day for PAU 5D.

Table 8: Number of vessels in the final datasets that fished for each number of fishing years.

No. years	PAU 5A	PAU 5D
1	12	13
2	12	23
3	16	18
4	6	6
>4	25	37

3.2.3 CPUE standardisation results

3.2.3.1 PAU 5A

The standardisation was done on the natural logarithm of catch per diver-day. Variables offered to the model were vessel, fishing year, month and statistical area, with fishing year forced to be in the model as 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 9. All variables were included in the final model, and the model explained 15.2% of the variation in CPUE for PAU 5A.

Table 9: The order in which variables were selected into the GLM model of CPUE for PAU 5A and their cumulative effect on the model r^2.

Variable	r^2 (%)
Fishing year	2.7
Vessel	13.2
Month	15.2
Area	16.1
Area: Month	17.1

Raw and standardised CPUE for PAU 5A are shown in Figure 23 and Table 10. Standardised CPUE loosely follows the pattern of the raw CPUE after 1987 and shows a very shallow rising trend since 1990.

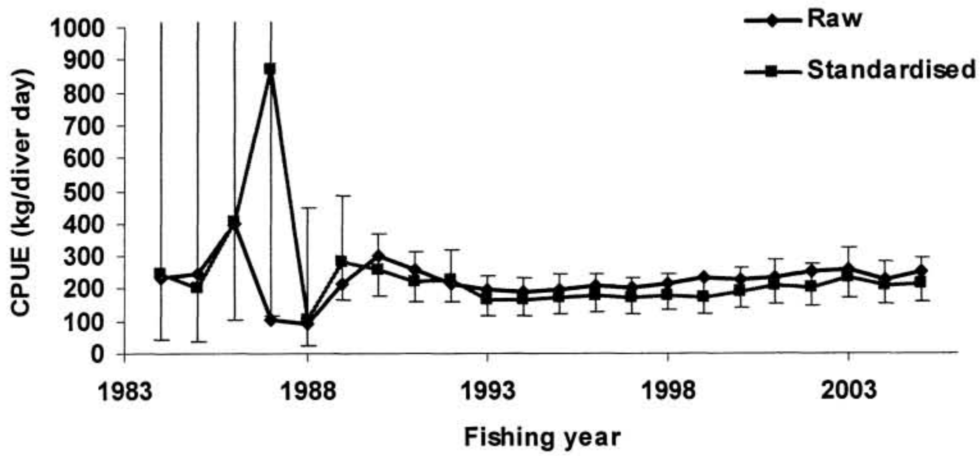


Figure 23: Standardised and raw CPUE (kg/diver day) for PAU 5A.

Table 10: Raw and standardised CPUE index for PAU 5A.

Fishing year	No. records	Raw	Std	LB	UB
1984	30	232.1	245.4	44.8	1345.0
1985	9	247.3	199.7	34.2	1165.5
1986	3	399.7	403.3	106.0	1535.0
1987	2	105.8	869.9	118.2	6400.8
1988	1	90.6	103.0	23.7	447.4
1989	19	217.0	284.9	167.3	485.2
1990	79	303.1	254.9	177.9	365.4
1991	89	259.5	223.8	161.7	309.9
1992	54	212.5	224.0	156.8	320.2
1993	52	198.0	168.0	117.7	239.8
1994	45	187.6	163.9	115.7	232.0
1995	52	195.3	173.0	121.7	246.0
1996	112	211.3	177.9	129.3	244.8
1997	96	199.9	170.5	123.6	235.0
1998	204	216.6	179.8	132.1	244.9
1999	191	232.7	171.0	125.5	233.1
2000	165	228.5	192.4	140.1	264.2
2001	137	234.2	209.3	151.9	288.3
2002	165	252.0	202.0	147.3	277.1
2003	169	255.3	234.8	171.1	322.3
2004	170	228.0	206.4	150.5	283.0
2005	158	251.9	215.8	156.9	296.7

The effect of using data from the vessels that caught the top 75% of catch is shown in Figure 24. CPUE using data from all vessels is slightly higher after 1988.

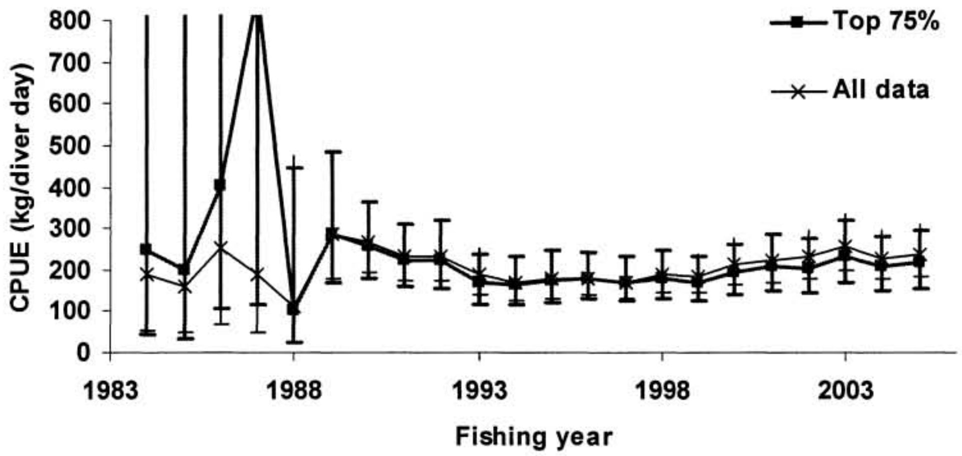


Figure 24: Raw and standardised PAU 5A CPUE with data from all vessels and vessels that caught the top 75% of catch.

We compared this CPUE series with the previous (Breen & Kim 2004a) series, calculated from records from vessels that operated for 5 years or longer: the two series are similar after 1988 (Figure 25). Choices made during these standardisations do not have a large effect on the indices.

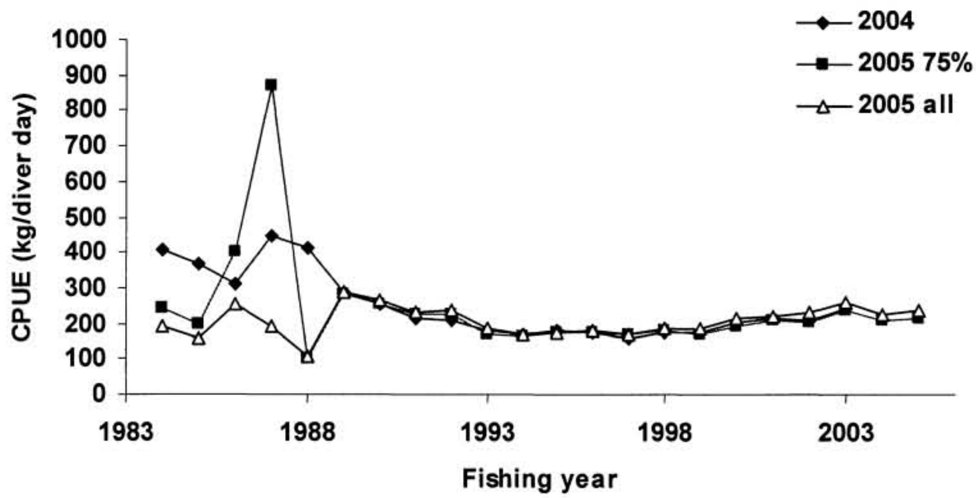


Figure 25: Comparison of standardised PAU 5A CPUE from 2004 and 2006.

3.2.3.2 PAU 5D

The method was the same as for PAU 5A. The order in which variables were selected into the model and their effect on the model r^2 are shown in Table 11. All variables were included in the final model, and the model explained 19.1% of the variation in CPUE for PAU 5D.

Table 11: The order in which variables were selected into the GLM model of PAU 5D CPUE and their cumulative effect on the model r^2.

Variable	r^2 (%)
Fishing year	2.1
Vessel	16.2
Month	19.1
Area	19.4
Area:Month	21.0

Raw and standardised CPUE for PAU 5D are shown in Figure 26 and Table 12. Standardised CPUE generally follows the pattern of the raw CPUE after 1988. There is a general decreasing trend in CPUE from 1989 to 2001.

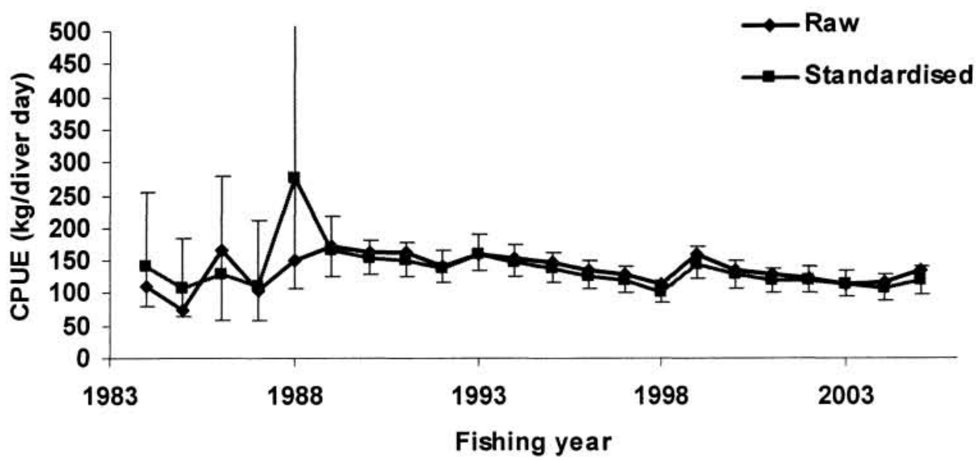


Figure 26: Standardised and raw CPUE (kg/diver-day) for PAU 5D.

Table 12: Raw and standardised CPUE index for PAU 5D.

Fishing year	No. records	Raw	Std	LB	UB
1984	58	108.9	141.2	78.3	254.6
1985	17	74.5	107.5	63.2	182.8
1986	4	167.1	128.8	59.2	280.0
1987	9	103.8	110.3	57.5	211.8
1988	12	150.3	275.6	106.4	714.3
1989	40	171.5	166.5	127.2	218.0
1990	304	162.3	153.4	129.6	181.7
1991	285	161.5	149.9	125.6	179.0
1992	324	141.1	138.9	117.3	164.5
1993	387	160.6	160.2	135.4	189.4
1994	337	153.9	147.3	124.5	174.3
1995	317	147.5	136.7	115.5	161.7
1996	379	134.7	127.0	107.7	149.9
1997	397	128.1	120.3	102.1	141.8
1998	414	114.7	101.2	85.9	119.1
1999	312	160.7	145.0	122.5	171.6
2000	447	135.0	128.2	108.8	151.1
2001	386	129.9	118.2	100.0	139.5
2002	461	122.1	119.9	101.7	141.3
2003	368	113.5	112.7	95.2	133.5
2004	255	116.6	107.6	90.2	128.4
2005	220	135.4	118.4	98.4	142.3

The effect of using data from vessels that caught the top 75% of catch is shown in Figure 27: as for PAU 5A there is very little difference after 1988.

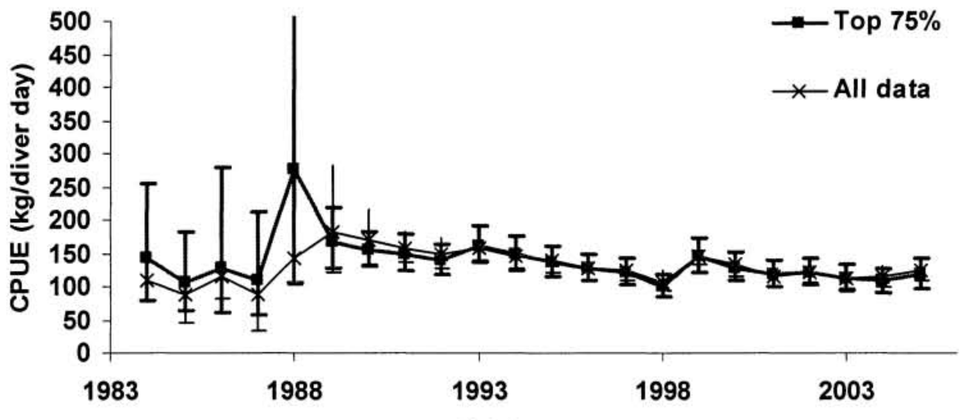


Figure 27: Raw and standardised CPUE with data from all vessels and vessels caught the top 75% of catch for PAU 5D.

3.3 Research diver survey index (RDSI)

Andrew et al. (2000b, 2002) described the timed survey index method. Divers make a timed swim of 10 minutes after sighting the first paua and record the patch size by grade (in the older data) or by actual count (in the new data). The timed-swim index for a swim is the sum of products, by patch type, of numbers of patches and numbers per patch.

Because research divers now count the numbers in all patches, we used the mean numbers per patch for calculating the index for the older data (Table 13) and used the actual number counted for each patch where available.

Table 13: Definition of patch type by number of paua, the old assumed average number and the actual mean number per patch for PAU 5A and PAU 5D.

		Number per patch		
Patch type	Patch size	Old	PAU 5A actual	PAU 5D actual
1	1-4	1.28	1.6	1.5
2	5-10	7.5	6.9	7.0
3	11-20	15.5	14.4	14.5
4	21-40	30.5	27.4	28.7
5	41-80	60.5	51.5	52.3
6	>80	120.5	129.9	105.0

We use searching time to refine the estimated abundance. When divers are underwater it takes some time to count the number of paua in a patch, collect a sample of four paua from that patch and record the patch size. McShane et al. (1996) found "handling time" to be 7.8 seconds per patch. Divers now count paua in each patch, but this does not increase patch handling time much, and divers stop the watch when the patch size looks larger than 20. Total time spent searching in a 10-minute swim can be estimated the swim time minus handling time:

time searching = 600 – 7.8 (number of patches found).

The timed swim index is then modified by rescaling:

index (IS_t') = 600(relative abundance (IS_t) /time searching)

Divers record visibility in a code (Table 14) that ranges from very clear water to very murky water.

Table 14: 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

For each stock, the coverage by stratum is compared with recent catch in Table 15. The diver survey strata in PAU 5A (see Figure 3) cover the area that has produced 84% of the catch in the past four years; diver survey strata in PAU 5D (see Figure 4) cover about 25% of the areas producing the recent catches. The four statistical areas immediately to the east of the Catlins East stratum, P5DH23 through P5DH26, produced another 21% of the recent catches.

Table 15: For each stock, the percentage of estimated catch from PCELR forms, 2002–2005, in each of the research diver survey strata and in areas not included in survey strata.

	Area	Percent	
PAU 5A	northern non-stratum	1.7%	
	George	18.8%	
	middle non-stratum	14.9%	
	Dusky	21.0%	
	Chalky	12.7%	
	South Coast	30.9%	100.0%
PAU 5D	western non-stratum	25.7%	
	Catlins West	14.2%	
	Catlins East	10.3%	
	eastern non-stratum	49.9%	100.0%

3.3.1 PAU 5A

Data included in the analysis are summarised in Table 16. Four strata were surveyed in 2006, three in 2002 and only two in 1996. One swim, for only 5 minutes in 2006, was removed from the analysis. The percentage of swims with zero abundance increased over time (Table 16) to more than 20% in 2006. There was a steady increase in the prevalence of zero swims in the Chalky stratum, surveyed in all 3 years, and a large increase in Dusky between 2002 and 2006. In previous analyses we removed the few zero-abundance swims, but this is not a reasonable approach in this situation.

We used the Tweedie model (Tweedie 1984) with a log link for the standardisation, with results changed into canonical form as described by Francis (1999), giving estimates that are independent of the reference year. The standardisation was based on the natural logarithm of the number of paua per 10-minute search, after correcting for search time. Variables offered to the model were fishing year, diver, stratum and visibility, with fishing year forced to be in the model as an explanatory variable.

Table 16: Number of swims by fishing year and stratum in PAU 5A, and numbers and percentages of zero-abundance swims.

Fishing year	Stratum	Swims	Zero swims	%Zero	%Zero (yearly)
1996	South Coast	2	0	0	
	Chalky	42	2	4.8	4.5
2002	South Coast	29	7	24.1	
	Chalky	32	6	18.8	
	Dusky	30	1	3.3	15.4
2006	South Coast	24	3	12.5	
	Chalky	22	10	45.5	
	Dusky	24	7	29.2	
	George	28	1	3.6	20.4

Not many data have visibility code 4 and only two records have code 5 (Table 17).

Table 17: Number of timed swims with each visibility code in each survey for PAU 5A.

Fishing year	1	2	3	4	5
1996	24	8	10	2	
2002	28	52	8	1	2
2006		54	44		

The order in which variables were selected into the model and their effect on the model r^2 for PAU 5A are shown in Table 18. All variables were important for the relative abundance index for PAU 5A, with stratum being the most important. The model explains 17.9% of the variation in RDSI.

Table 18: Variables selected into the RDSI model for PAU 5A, with their corresponding r^2.

Variable	r^2 (%)
Fishing year	5.0
Stratum	14.7
Visibility	16.5
Diver	17.9

The standardised RDSI index is generally similar to the raw mean number of paua per 10-minute search for 2002 and 2006; the standardised index is substantially higher than the raw value for 1996 (Figure 28, Table 19). Uncertainty in 1996 is wider than in other years because only two strata were surveyed (with only two sites in one of them). The standardised index shows a 65% decrease from 1996 to 2006.

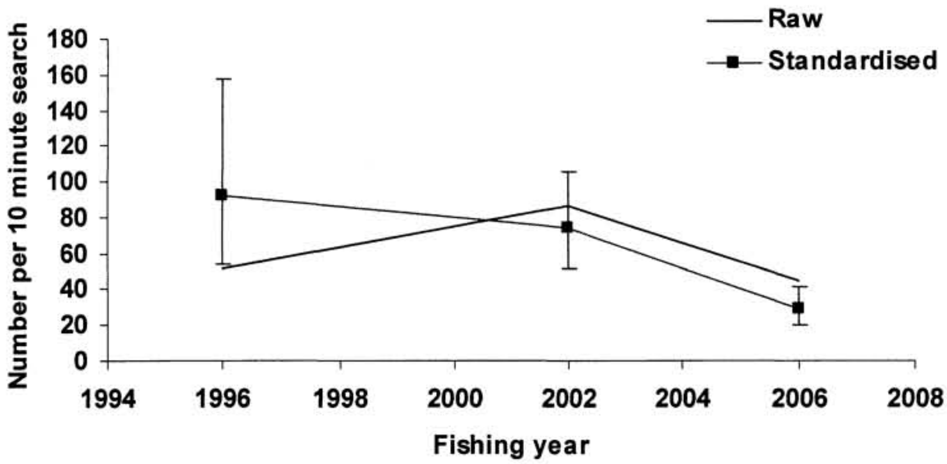


Figure 28: Raw and standardised RDSI indices for PAU 5A (number of paua per 10-minute search). The error bars indicate two standard errors of the standardised index.

Table 19: Raw and standardised RDSI indices for PAU 5A and the standard error for standardised indices.

Fishing year	Raw	Standardised	Index	SE
1996	51.6	91.8	1.573	0.275
2002	86.2	74.4	1.275	0.181
2006	44.6	29.1	0.499	0.183

The Q-Q plot of randomised quantile residuals (Dunn & Smyth 1996) from the Tweedie model (Figure 29) reflects a good fit.

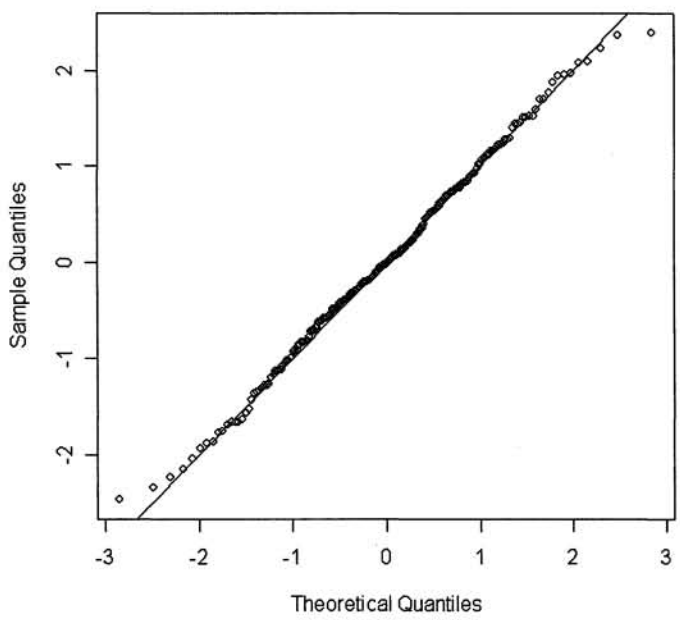


Figure 29: Q-Q plot of the fit to PAU 5A RDSI data using the Tweedie model.

More paua were seen in Dusky and George strata than in Chalky and South Coast (Figure 30). More paua were seen in better visibility conditions, except that the two swims with visibility code 5 (low visibility) showed large numbers of paua (Figure 31) and swims with visibility code 1 showed smaller numbers of paua than visibility codes 2 or 3. Diver effects (Figure 32) varied substantially, with diver 5 having a much larger effect.

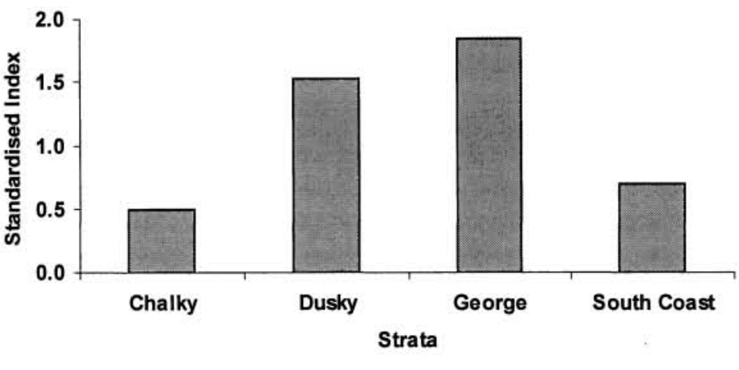


Figure 30: Standardised stratum index from the PAU 5A RDSI model.

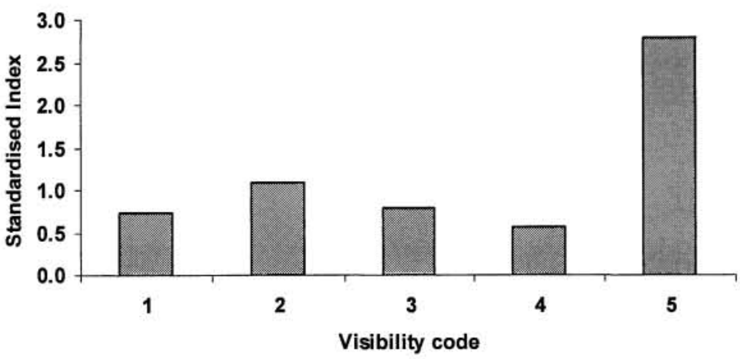


Figure 31: Standardised visibility index from the PAU 5A RDSI model.

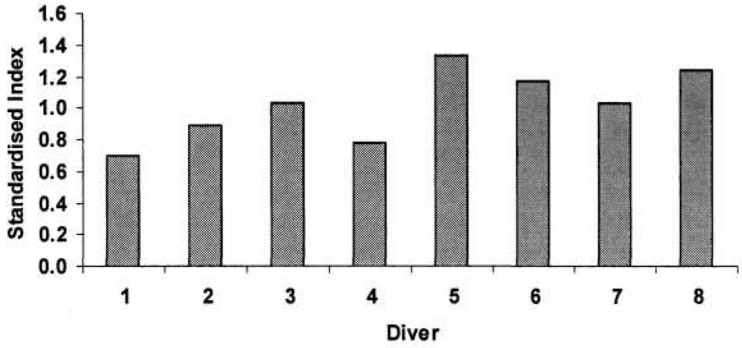


Figure 32: Standardised diver index from the PAU 5A RDSI model.

3.3.2 PAU 5D

The standardisation used the method of Vignaux (1993) as described by Kendrick & Andrew (2000), with results changed into canonical form as described by Francis (1999), giving estimates that are independent of the reference year.

Few swims (4.8%) had zero abundance and four swims had unknown visibility. Because the percentage of zero abundance data is low and we use visibility as an explanatory variable, these were removed from the analysis. In the 1997 fishing year, only the Catlins West stratum was surveyed, but these data were included in the analysis (Table 20).

Table 20: Number of data in each stratum in each fishing year after removing zero-abundance swims and four swims with no visibility code.

Fishing year	Catlins East	Catlins West
1994	18	20
1997	0	18
1999	28	29
2001	18	30
2004	27	30

There are not many data with visibility code 4 and only two records with code 5 (Table 21).

Table 21: Number of timed swims with each visibility code in each fishing year for PAU 5D.

				Visibility
Fishing year	2	3	4	5
1994	6	30	2	0
1997	2	13	3	0
1999	28	27	0	2
2001	23	19	4	0
2004	24	27	4	0

The order in which variables were selected into the model and their effect on the model r^2 for PAU 5D are shown in Table 22. All variables except for stratum were important for the relative abundance index for PAU 5D. The model explains 11.5% variation in RDSI.

Table 22: Variables selected into the RDSI model for PAU 5D, with their corresponding r^2.

Variable	r^2 (%)
Fishing year	6.7
Visibility	8.9
Diver	11.5

The standardised RDSI index is generally similar to the raw mean number of paua per 10-minute search (Figure 33 and Table 23). Uncertainty in 1997 is wider than in other years because only one stratum was surveyed. The index shows a decrease from 1997 to 1999 and a partial increase since then.

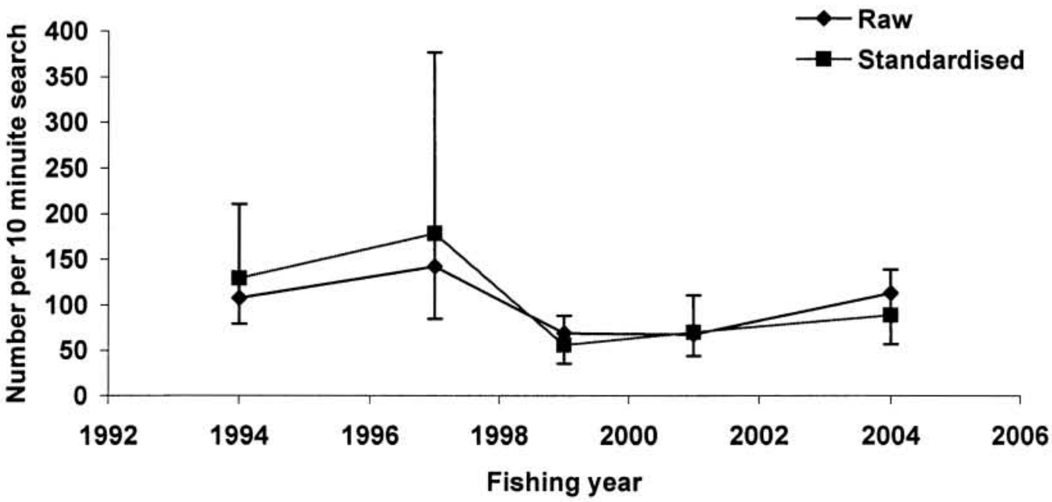


Figure 33: Raw and standardised RDSI indices for PAU 5D (number of paua per 10-minute search). The error bars indicate 2 standard errors of the standardised index.

Table 23: Raw and standardised RDSI indices for PAU 5D and the standard error for standardised indices.

	Raw	Standardised	Index	SE
1994	107.7	129.3	1.349	0.249
1997	142.5	178.6	1.864	0.381
1999	68.9	56.2	0.586	0.232
2001	67.5	70.0	0.730	0.234
2004	113.2	89.1	0.930	0.228

The visibility effect shows that more paua were counted with better visibility conditions, except that the two swims with visibility code 5 showed large numbers of paua (Figure 34). Diver effects (Figure 35) varied substantially, with diver 4 having a larger effect than other divers.

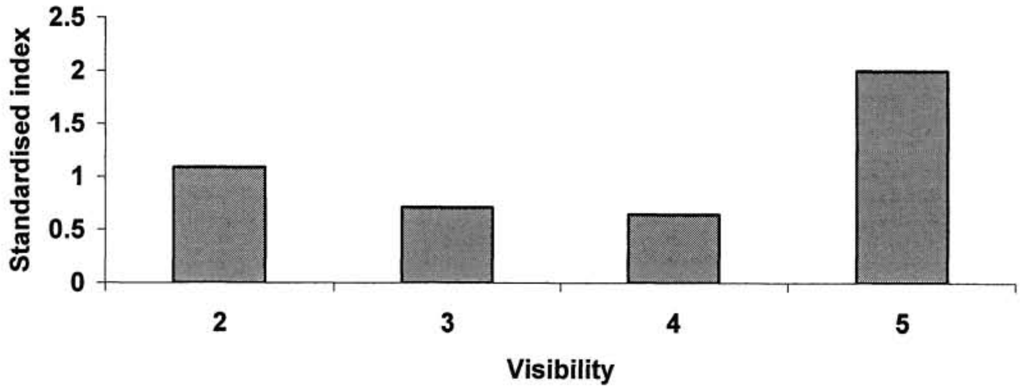


Figure 34: Standardised visibility index from the PAU 5D RDSI model.

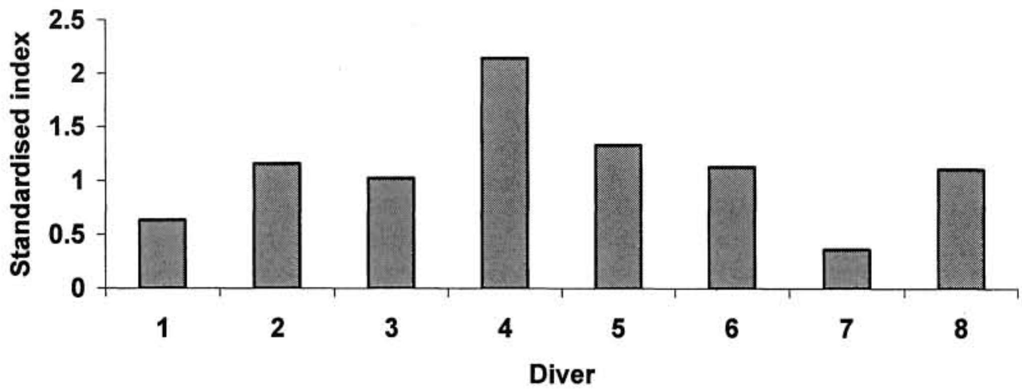


Figure 35: Standardised diver index from the PAU 5D RDSI model.

3.4 Research diver length frequency data (RDLFs)

During the research diver surveys, divers collect four paua from each patch, or the whole patch if it is less than five, for later measurement at the surface, and these paua are then returned to the water.

Earlier data are available from diver surveys made before the timed-swim system was begun. These are discussed below and used where possible. The model begins at 70 mm shell length, so the few paua less than 70 mm are not used.

The research diver length frequency from each swim was weighted by the ratio of the abundance estimate for that swim to the mean abundance estimate:

$$(42) \qquad L_{s,j} = L'_{s,j} \; \frac{IS_j}{\sum_j IS_j \big/ n_j}$$

where $L'_{s,j}$ is the raw frequency at size s from the jth sample and IS_j is the time scaled abundance of the jth sample. For each year's dataset, we weight the record by the normalised square root of the weighted number of fish measured.

3.4.1 PAU 5A

Data from the four surveys (Table 24), including 1991 (Schiel unpublished data), contain 6125 paua at or above 70 mm.

Table 24: Number of paua sampled in each stratum in each year. Research strata are shown in Figure 3.

Fishing year	South Coast	Chalky	Dusky	George	Total
1991			1272		1272
1996	13	798			811
2002	663	657	1174		2494
2006	330	230	376	612	1548
Total	1006	1685	2822	612	6125

The raw and weighted (by the abundance estimate in each swim) length frequencies are compared in Figure 36: they are quite similar, but both in 2002 and 2006, there are slightly more large fish in weighted length frequency.

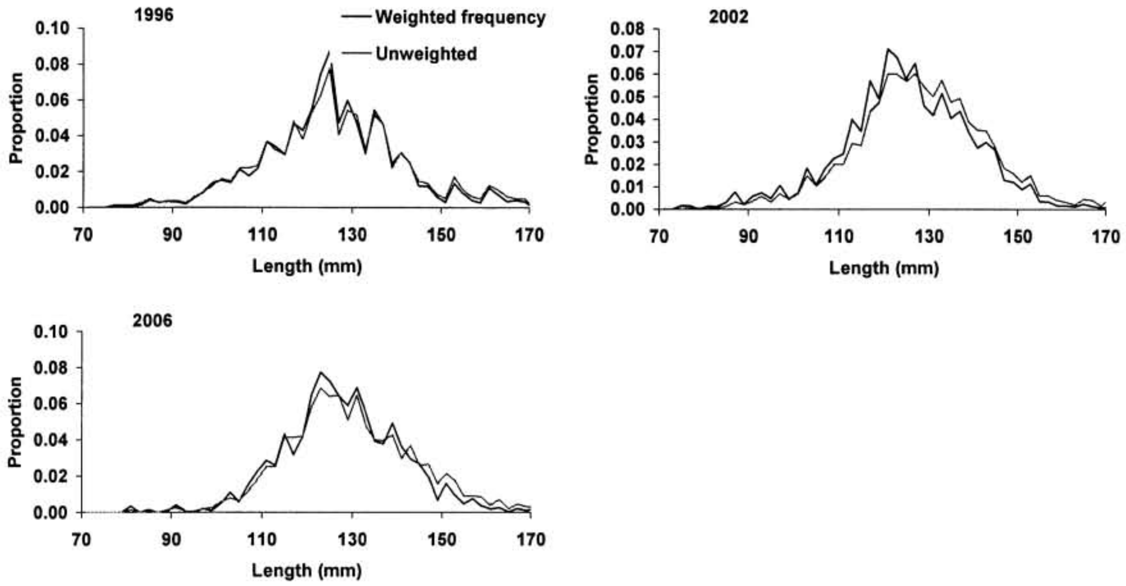


Figure 36: Comparison of weighted and unweighted length frequencies for PAU 5A.

The RDLF data by fishing year for PAU 5A show similar patterns over time (Figure 37). The length frequencies plotted by research strata show that George has a slightly larger paua distribution and South Coast has a slightly smaller paua distribution than other strata (Figure 38).

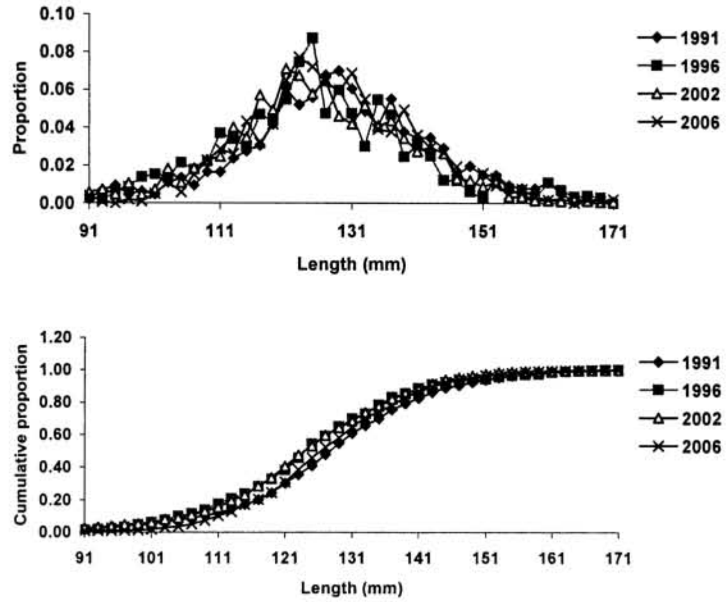


Figure 37: RDLFs from all survey strata in PAU 5A aggregated for each year and plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom) for each year.

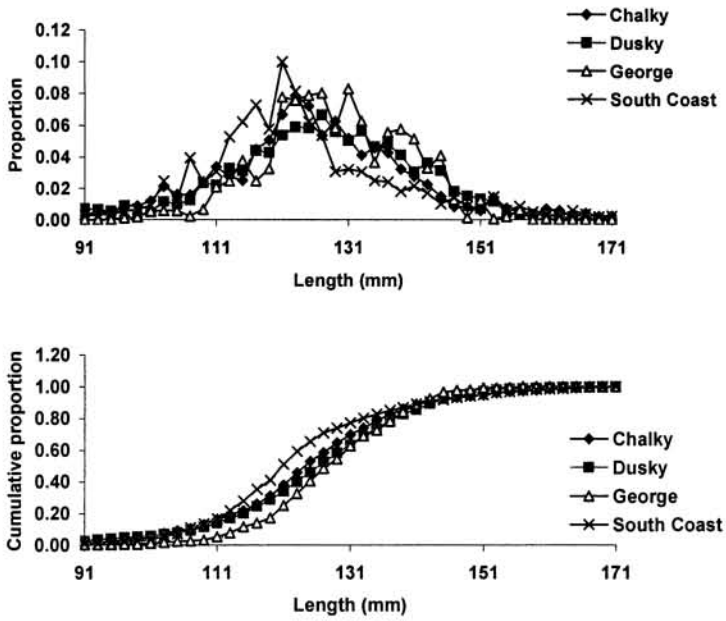


Figure 38: RDLFs from all survey years for PAU 5A, aggregated by stratum and plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom).

3.4.2 PAU 5D

Data are available from seven surveys (Table 25). There were 8916 paua were measured over 70 mm. Data from regions called "Otago North, Otago South and Nuggets North" were not used because these areas were surveyed only once. The 1982 data were also not used because only 54 paua were measured.

Table 25: Number of paua sampled in each stratum in each year. Research strata are shown in Figure 4. Grey indicates data that were not used.

Fishing year	Catlins East	Catlins West	Nuggets North	Otago North	Otago South
1982	54			111	
1992	930	537			
1994	430	604	317	748	85
1997		691			
1999	694	524			
2001	524	794			
2004	705	1166			

The raw and weighted (by the abundance estimate in each swim) length frequencies are compared in Figure 39: they are quite similar.

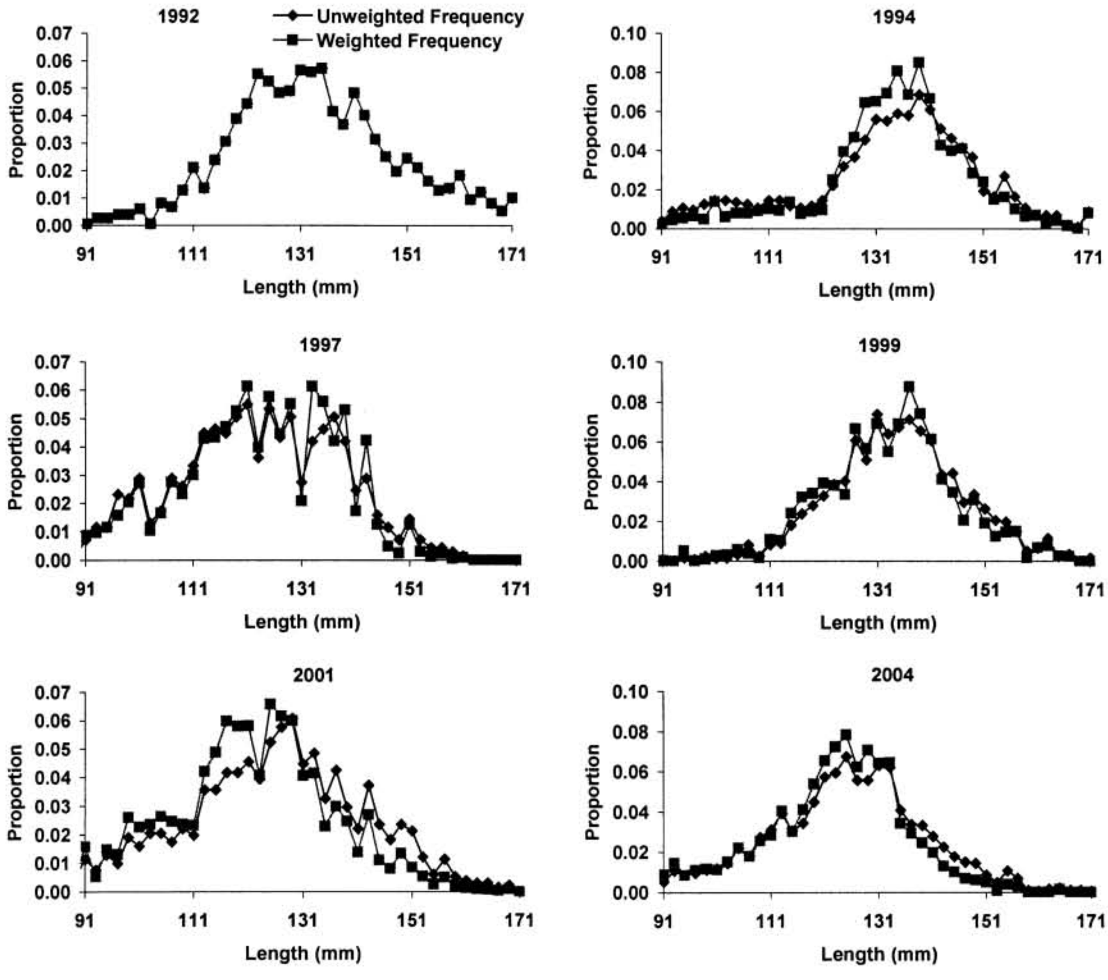


Figure 39: Comparison of weighted (grey lines and squares) and unweighted length frequencies for PAU 5D.

The RDLF data by fishing year for PAU 5D show a difference in pre- and post-1999 data (Figure 40) except for 1997, which has a length distribution similar to more recent data. There were many large paua in the early years but not in the recent years or 1997. The length frequencies plotted by research strata show that Catlins East has a slightly larger paua distribution than Catlins West (Figure 41).

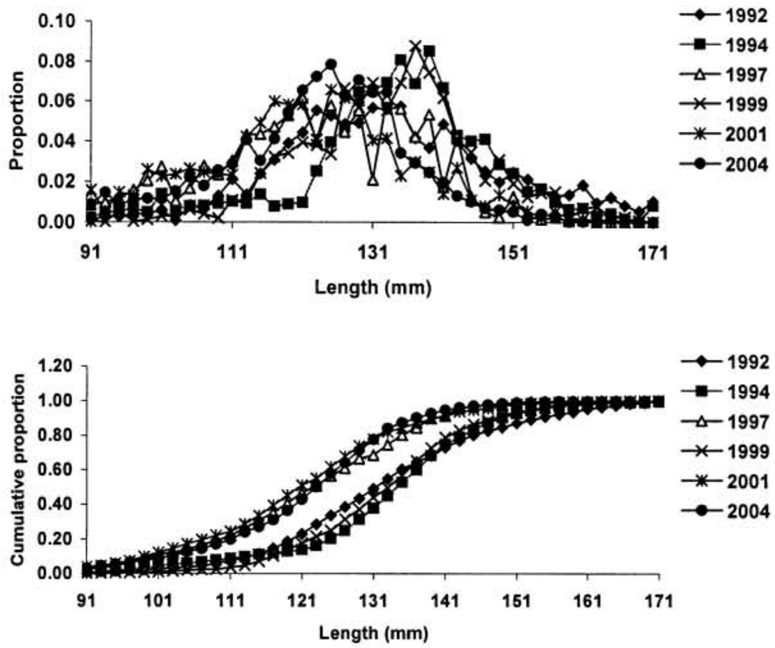


Figure 40: RDLFs from both survey strata in PAU 5D aggregated for each year and plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom) for each year.

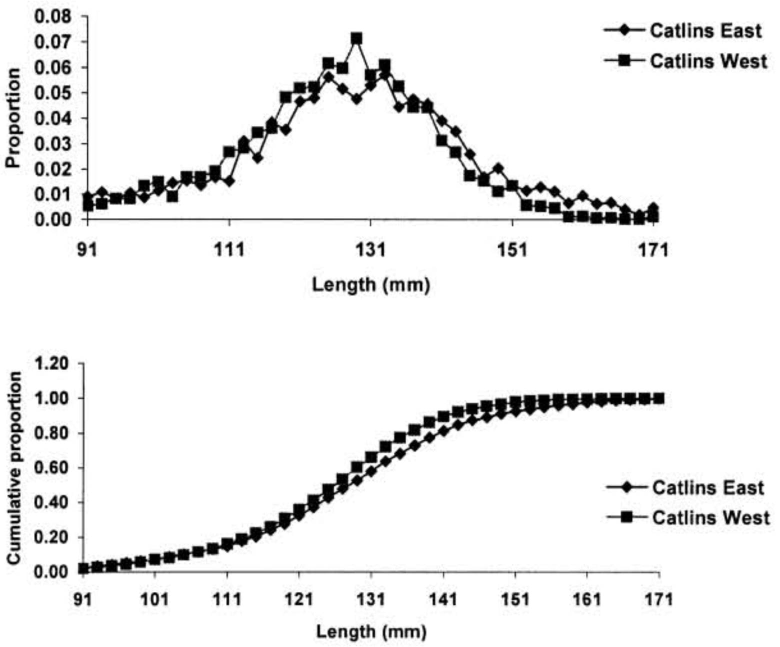


Figure 41: RDLFs from all survey years for PAU 5D, aggregated by stratum and plotted as proportion-at-length (top) and cumulative proportion-at-length (bottom).

3.5 Catch sampling length frequencies (CSLFs)

Length frequency data from paua catch sampling (actually market sampling, sometimes called shed sampling) were extracted from the MFish market sampling database (*market*) in January 2006. Only paua with lengths of 108 mm or greater are summarised here and used for the stock assessment; there are few such small paua because the MLS is 125 mm.

Some paua less than 125 mm are found in this sampling because the catch samplers measure slightly differently from fishers. For the fishery, the MLS applies to total length, which may include a barnacle on the posterior shell margin, or parts of the shell that overhang the aperture. The samplers measure the length between shell edges at the aperture. Some small paua may also slip through the system into processing sheds.

Within each year, we weighted the length frequency by the ratio of area catch to the mean area catch. Data without area information were not added to the weighted length frequency distribution. We obtained the sum of estimated catch for each statistical area from the CELR and PCELR data.

Weighted length frequency $L_{s,a,y}^{CSLF}$ in length bin s, statistical area a and year y is calculated as:

$$(43) \qquad L_{s,a,y}^{CSLF} = L_{s,a,y}^{CSLF} \frac{c_{a,y}}{\sum_{a} c_{a,y} / n_y}$$

where $L_{s,a,y}^{CSLF'}$ is raw length frequency in length bin s, statistical area a and year y, $c_{a,y}$ is catch in statistical area a in year y, and n_y is the number of statistical areas that have been fished in year y. Each year's record is weighted by the normalised square root of the weighted number of fish measured.

3.5.1 PAU 5A

The number of catch sampled landings for each year is shown in Table 26. Some samples of paua shells come with area information, but some operators refuse to supply the information. For a few samples with missing information, the landing can be matched with a landing in the PCELR database when only one landing was made on that date, but about one-third of the measurements have no associated area information.

Table 26: Number of catch sampled landings and number of paua measured with areas known or unknown for PAU 5A.

	No. Landings			No. paua measured		
Fishing year	Area unknown	Area known	Total	Area unknown	Area known	Total
1992		9	9		4 515	4 515
1993		3	3		1 162	1 162
1994		1	1		348	348
1998		4	4		527	527
2000	23	2	25	3 420	201	3 621
2001	32	3	35	4 069	365	4 434
2002	13	31	44	1 532	3 598	5 130
2003	14	40	54	1 634	4 830	6 464
2004	15	46	61	1 713	5 620	7 333
2005	4	29	33	477	2 965	3 442
Total	101	168	269	12 845	24 131	36 976

The distribution of length frequencies for PAU 5A is shown in Figure 42 for all data and Figure 43 for weighted data with areas known. The length frequency distribution in 1993 is different from all others, having smaller paua. The distributions are largely the same when the data with no area information are excluded, which affects mainly 2000 and 2001 (Table 26 and Figure 44).

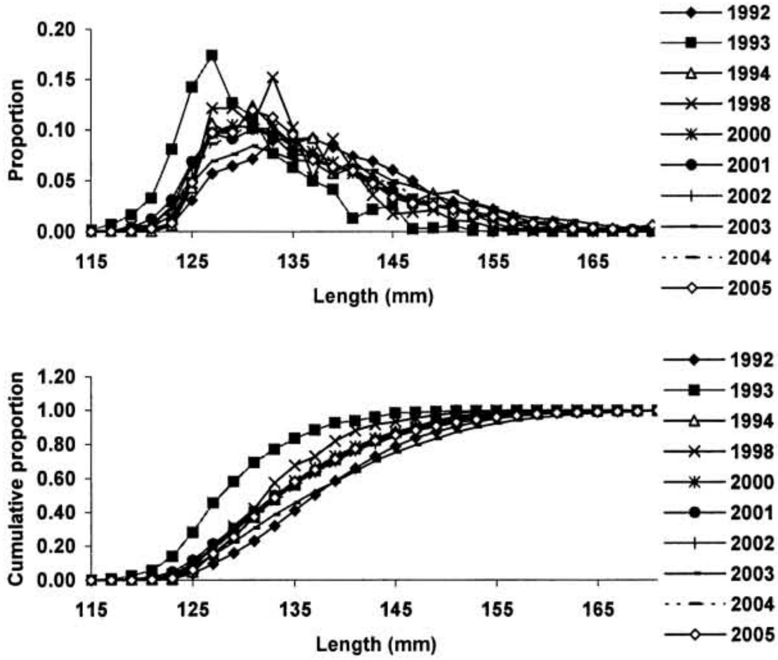


Figure 42: Distribution of catch sampled length frequency from all data for PAU 5A.

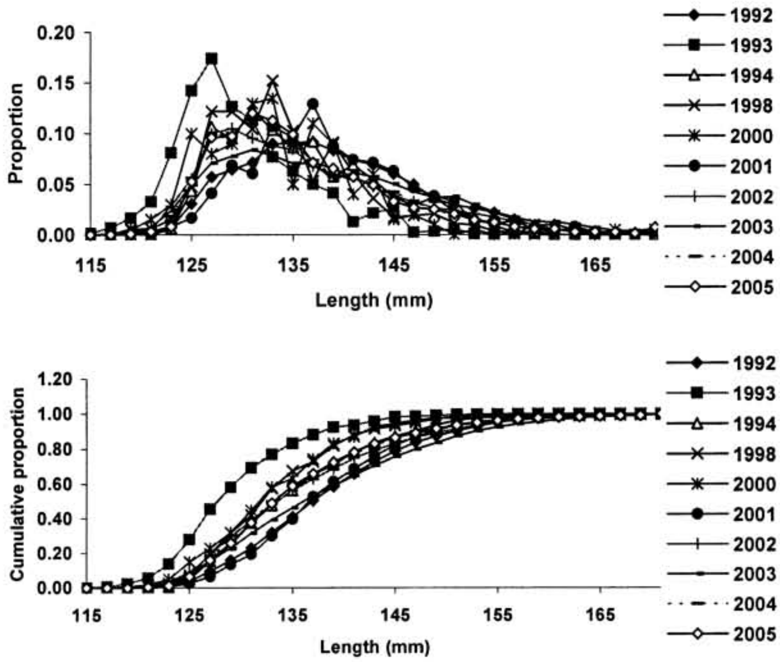


Figure 43: Distribution of weighted catch sampled length frequency from data with area information only for PAU 5A.

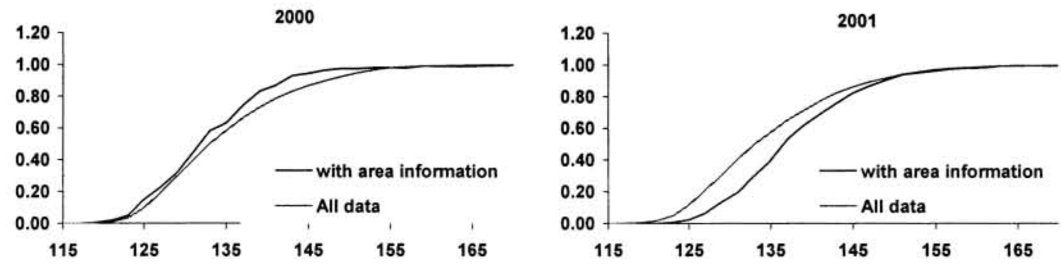


Figure 44: Cumulated proportions of CSLF data with area information only and with all data in PAU 5A.

The representativeness of this dataset is addressed in Table 27, where numbers measured are compared with percentage of catch and mean size in the old statistical areas, 1992 through 2001. Similar data are available from the PCELR forms, but the number of vessels is frequently below three and so these data cannot be shown.

Table 27: Number of paua measured, percentage of catch and mean size by old statistical area from 1992 to 2001 in PAU 5A.

	Area	1992	1993	1994	1998	2000	2001
No. measured	030	967	831	348	157		120
	031	3222	331		121	201	
	032	326			249		245
%Catch	030	35.8	66.1	54.5	33.8	34.5	33.2
	031	35.7	22.3	36.5	22.3	37.9	34.8
	032	28.4	11.6	8.9	43.9	27.7	32.0
Mean size	030	138.7	129.8	135.5	133.9		136.4
	031	138.8	128.8		133.6	133.4	
	032	137.3			133.2		139.2

3.5.2 PAU 5D

The number of catch sampled landings for each year from PAU 5D is shown in Table 28. The years where most sampling had no area information were 1999 through 2001. Of 26 landings without information, only one could be matched with the PCELR.

Table 28: Number of catch sampled landings with areas known or unknown for PAU 5D.

	No. landings			No. paua measured		
Fishing year	Area unknown	Area known	Total	Area unknown	Area known	Total
1992		15	15		4 806	4 806
1993		33	33		10 409	10 409
1994		16	16		5 292	5 292
1998	1	17	18	136	2 206	2 342
1999	1		1	187		187
2000	18	14	32	2 279	1 424	3703
2001	38	6	44	4 850	763	5 613
2002	5	43	48	659	5 245	5 904
2003	8	51	59	906	5 907	6 813
2004	6	30	36	685	3 277	3 962
2005	7	12	19	734	1 278	2 012
Total	84	237	321	10 436	40 607	51 043

The PAU 5D length frequency data were also weighted by catch within that year and area in a similar way to PAU 5A.

The distribution of length frequency for PAU 5D is shown in Figure 45 for all data and Figure 46 for data with areas known only. The length distribution in 1999, all from data without area information, is different from that in other years, having larger paua. Apart from 1999, the distributions are similar from data with and without area information. Contrast among years is not great except the years 2000 and 2001 (Figure 47).

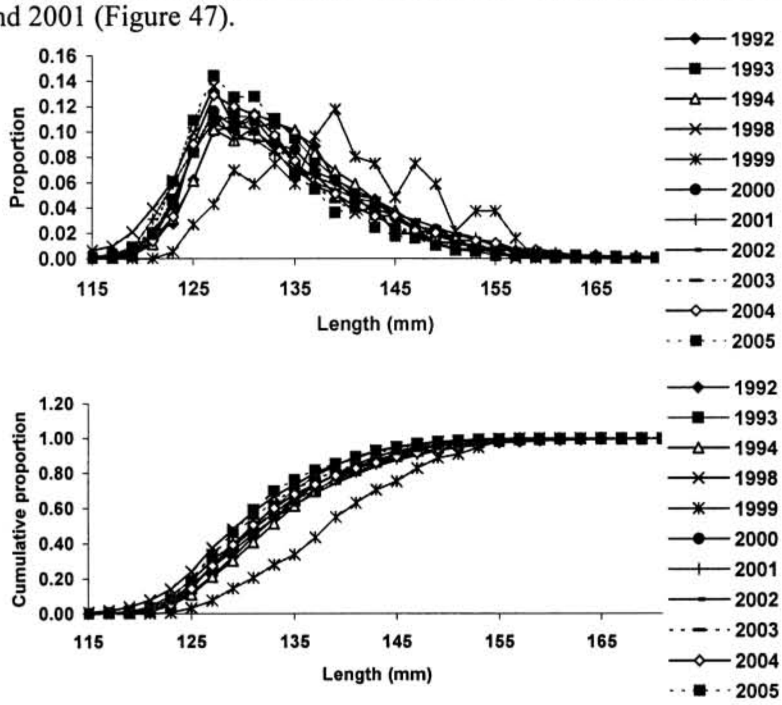


Figure 45: Distribution of catch sampled length frequency from all data with or without area information for PAU 5D.

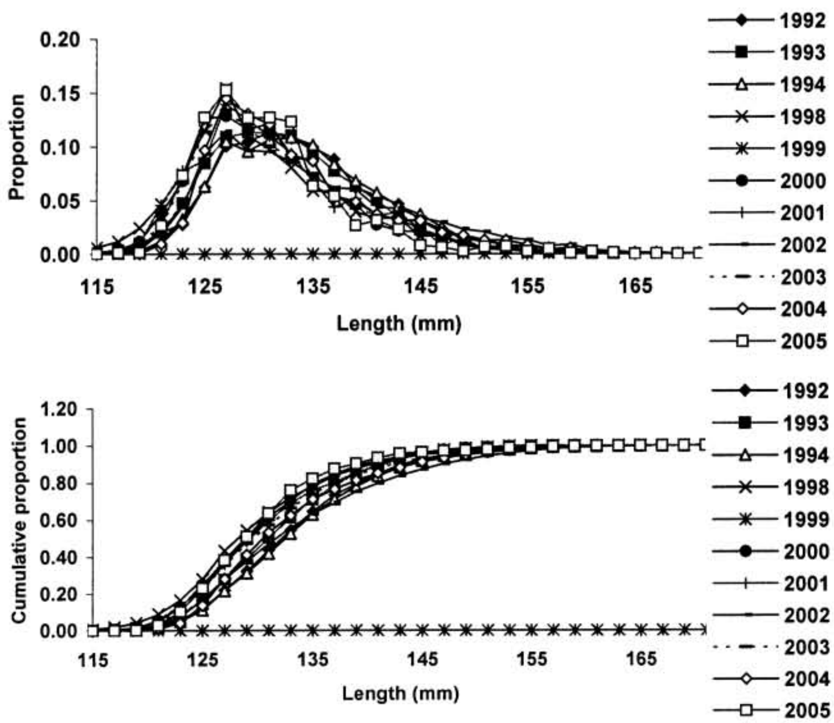


Figure 46: Distribution of catch sampled length frequency from data with area information only for PAU 5D.

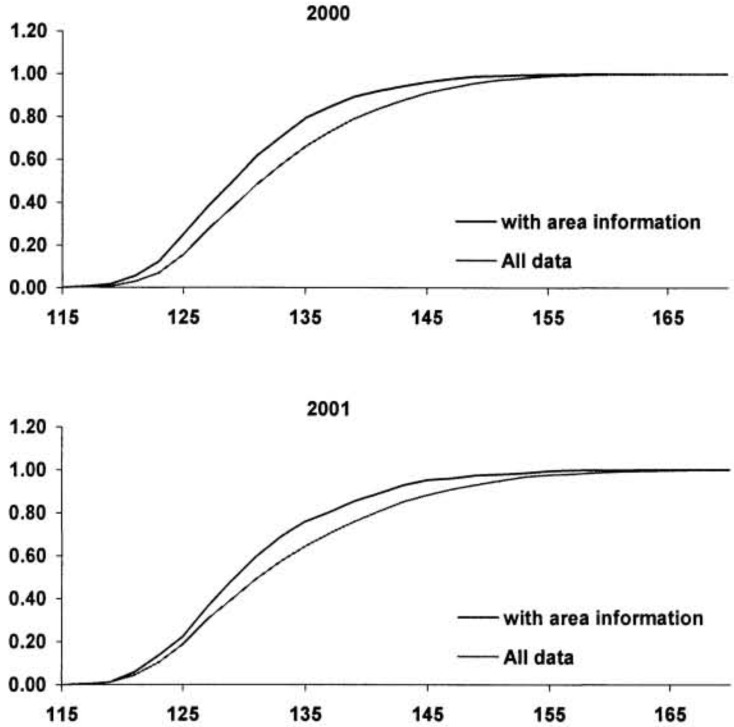


Figure 47: Cumulated proportions of CSLF data with area information only and with all data in PAU 5D.

The representativeness of this dataset is addressed in Table 29, where numbers measured are compared with percentage of catch and mean size in the old statistical areas, 1992 through 2001. Using data from the newer forms, Figure 48 shows the proportions of catch by fine-scale area compared with the number of shells measured in each year from 2002 through 2005. These data are also shown in Table 30.

Table 29: Number of paua measured, percentage of catch and mean size by old statistical area from 1992 to 2001 in PAU 5D.

	Area	1992	1993	1994	1998	2000	2001
No. measured	024				859	218	
	025		308	307	259		
	026	4 806	10 101	4 985	803	1 206	364
	030				285		399
%Catch	024	23.8	23.1	16.5	28.5	23.2	23.6
	025	18.3	15.0	16.0	20.2	25.9	25.0
	026	55.1	57.2	63.0	48.2	40.4	45.3
	030	2.8	4.8	4.4	3.1	10.5	6.0
Mean size	024				128.5	128.9	
	025		137.3	140.5	133.5		
	026	133.7	132.1	133.9	130.5	130.8	130.5
	030				136.9		136.4

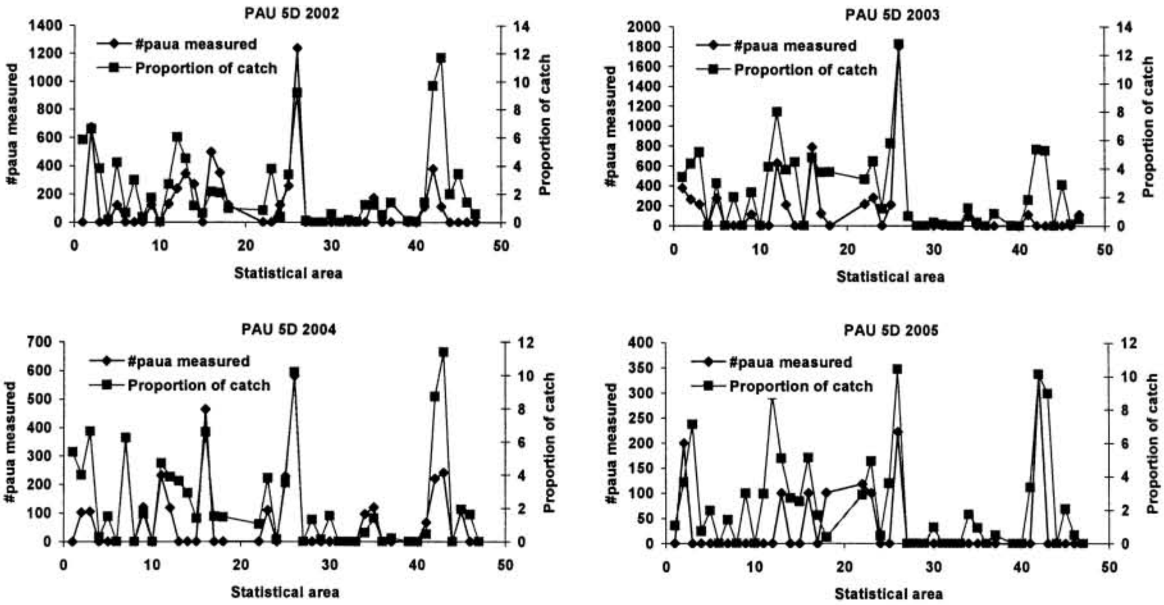


Figure 48: Number of paua measured and proportion of catch in PCELR form by fine-statistical area from 2002 to 2005 in PAU 5D.

Table 30: Number of paua measured, proportion of catch and mean size by fine-statistical area from 2002 to 2005 in PAU 5D.

	No. measured				%Catch				Mean size			
Area	2002	2003	2004	2005	2002	2003	2004	2005	2002	2003	2004	2005
1	0	377	0	0	5.8	3.4	5.4	1.1		128.1		
2	673	262	102	200	6.6	4.4	4.0	3.7	138.7	128.3	131.1	129.9
3	0	214	105	0	3.8	5.2	6.6	7.1		134.8	139.5	
4	0	0	0	0	0.2	0.0	0.3	0.7				
5	121	275	0	0	4.2	3.0	1.5	2.0	132.7	128.9		
6	0	0	0	0	0.7	0.0	0.0	0.0				
7	0	0	362	0	3.0	2.0	6.2	1.4			141.1	
8	0	0	0	0	0.4	0.0	0.0	0.0				
9	122	110	120	0	1.7	2.4	1.7	3.0	132.8	131.2	131.7	
10	0	0	0	0	0.0	0.0	0.0	0.0				
11	129	0	232	0	2.7	4.1	4.7	3.0	130.1		129.2	
12	237	625	119	0	6.0	8.0	3.9	8.9	139.4	131.1	129.7	
13	343	210	0	100	4.5	3.9	3.6	5.1	135.2	136.4		131.2
14	269	0	0	0	1.2	4.5	2.9	2.7	129.9			
15	0	0	0	0	0.6	0.0	1.4	2.5				
16	496	785	464	100	2.2	4.8	6.6	5.1	133.4	136.1	134.0	130.5
17	350	123	0	0	2.1	3.7	1.5	1.7	136.6	135.2		
18	119	0	0	101	1.0	3.8	1.5	0.4	133.5			131.9
22	0	217	0	118	0.8	3.3	1.1	2.9		137.2		127.4
23	0	282	110	100	3.8	4.5	3.8	4.9		132.6	131.3	135.4
24	121	0	0	0	0.4	1.2	0.1	0.5	137.2			
25	257	212	229	0	3.4	5.8	3.5	3.6	137.8	135.1	134.1	
26	1 238	1 801	581	222	9.2	12.8	10.2	10.4	131.7	130.7	132.5	129.5
27	0	100	0	0	0.1	0.7	0.0	0.0		127.7		
28	0	0	0	0	0.0	0.0	1.3	0.0				
29	0	0	0	0	0.0	0.0	0.1	0.0				
30	0	0	0	0	0.6	0.3	1.6	1.0				

	No. measured				%Catch				Mean size			
Area	2002	2003	2004	2005	2002	2003	2004	2005	2002	2003	2004	2005
31	0	0	0	0	0.0	0.1	0.0	0.0				
32	0	0	0	0	0.1	0.0	0.0	0.0				
33	0	0	0	0	0.0	0.0	0.0	0.0				
34	0	94	96	0	1.2	1.2	0.5	1.7		147.4	125.9	
35	172	0	120	0	1.2	0.3	1.4	0.9	138.4		133.0	
36	0	0	0	0	0.5	0.0	0.0	0.0				
37	0	0	0	0	1.4	0.9	0.2	0.5				
39	0	0	0	0	0.1	0.0	0.0	0.0				
40	0	0	0	0	0.1	0.0	0.0	0.0				
41	111	110	67	0	1.4	1.8	0.5	3.4	130.6	138.2	157.9	
42	378	0	220	337	9.7	5.4	8.7	10.1	134.6		129.6	130.7
43	109	0	241	0	11.7	5.3	11.4	9.0	128.6		128.9	
44	0	0	0	0	2.0	0.0	0.0	0.0				
45	0	0	109	0	3.4	2.9	1.9	2.1			138.2	
46	0	0	0	0	1.4	0.1	1.6	0.5				
47	0	110	0	0	0.6	0.5	0.0	0.0		133.1		

3.6 Tag-recapture data

Paua were tagged (Reyn Naylor, NIWA, pers. comm.) to measure growth in various locations. In NIWA tagging, paua were collected carefully by divers, then taken to the surface and measured; a small numbered plastic tag was glued to the shell with cyano-acrylate glue and the paua were replaced; tagged paua were recovered as close to one year after tagging as possible. In other tagging datasets used here, other forms of tags may have been used and the times at liberty sometimes differed from one year.

3.6.1 PAU 5A

In May 2000, 2307 tagged paua were released in Poison Bay, statistical area 032. In early November 2000, 1463 paua were tagged in Landing Bay and Red Head, both in research stratum Chalky, statistical area 030 (Figure 3). No sex and maturity information were recorded for these data. About a year later, tagged paua were recovered by research divers.

The dataset, groomed by Breen & Kim (2004a), comprises 299 records, with initial lengths ranging from 81 to 155 mm. Time at large ranges from 369 to 381 days and increments range from -4 to 28 mm.

The pattern of growth (Figure 49) shows a decreasing increment with increasing length, as expected, and shows a suggestion of some curvature in the relation. The plot suggests zero mean growth at about 150 mm. This is somewhat inconsistent with the length frequencies, which show paua at lengths up to 170 mm.

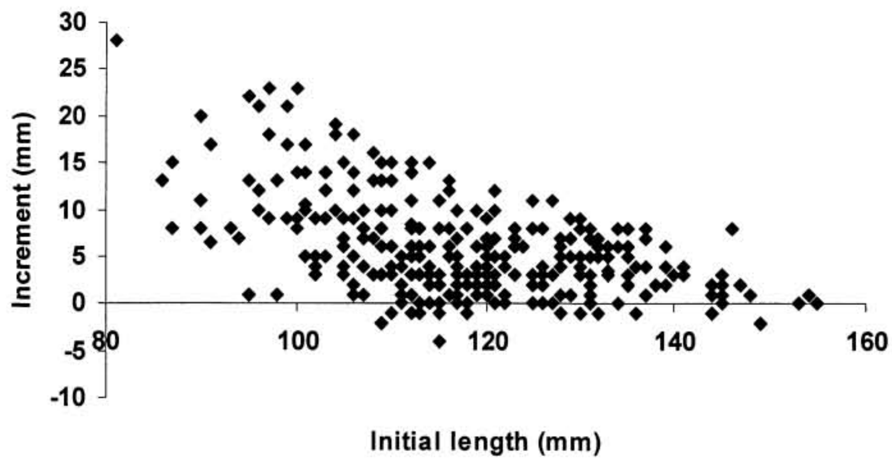


Figure 49: Increments plotted against initial length for tagged paua in PAU 5A.

3.6.2 PAU 5D

Paua were tagged at a variety of locations in Otago, including Boat Harbour (two sites near Nugget Point), Roaring Bay and Saddle (Reyn Naylor, NIWA, pers. comm.; John Pirker, University of Canterbury, pers. comm.; R.J. Street, Dunedin, pers. comm.). Dates ranged from March 1976 to March 2001. Times at liberty ranged from 243 days to 473 days (29 records with longer times at liberty were removed).

After grooming, the dataset comprised 233 records, with initial lengths ranging from 70 to 168 mm and increments from -1 to 27 mm.

The pattern of growth (Figure 50) shows a decreasing increment with increasing length, as expected, and shows no suggestion of curvature in the relation. The plot suggests zero mean growth at about 150 mm. This is somewhat inconsistent with the length frequencies, which show paua at lengths up to 170 mm.

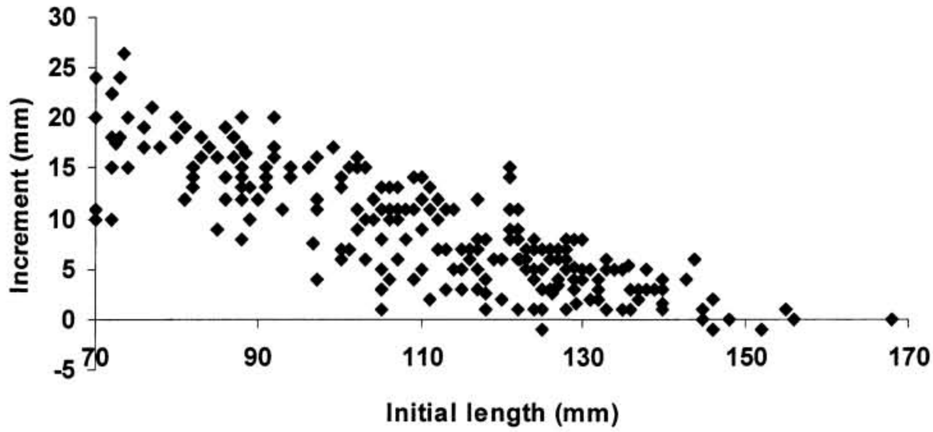


Figure 50: Increments plotted against initial length for tagged paua in PAU 5D.

3.7 Maturity

Maturity can be estimated by the model from proportion-at-age data. The model has no stock-recruit function, but "spawning biomass" is calculated as the sum of the element products of the vectors of numbers- and maturity-at-length for each year.

Because small paua cannot be sexed, and because the sample sizes are too small to permit of sex-specific analysis in any case, maturity is determined collectively for both sexes combined. The implicit assumption is that males and females mature at approximately the same rates with increasing length.

3.7.1 PAU 5A

Data were collected during February 2006 (Reyn Naylor, NIWA, unpublished data), at sites in the Dusky stratum. Two hundred and seventeen paua of various sizes were examined visually for sex and maturity. Immature animals cannot be sexed. Animals were scored for sex as "indeterminate", "just male", "just female", "male" and "female" and for maturity as "mature" or "immature".

Eleven animals below 70 mm were discarded from the dataset. The proportion mature in 5-mm bins is shown in Table 31 and Figure 51. The sample size is very small, but most animals are mature by 110 mm and 50% maturity probably lies between 95 and 105 mm. The curve in Figure 51 is based on same logistic curve estimated by the model, but was estimated for illustration here with weighted non-linear least squares.

Table 31: Numbers of paua observed, number mature and proportion mature in sampling in the Dusky stratum. The bin size is the mid-point.

Bin (mm)	No. obs.	No. mature	Proportion
72.5	3	0	0.000
77.5	12	0	0.000
82.5	16	0	0.000
87.5	17	2	0.118
92.5	6	2	0.333
97.5	9	4	0.444
102.5	21	17	0.810
107.5	32	32	1.000
112.5	24	24	1.000
117.5	19	19	1.000
122.5	24	24	1.000
127.5	8	8	1.000
>132.5	15	15	1.000
Total	206	147	

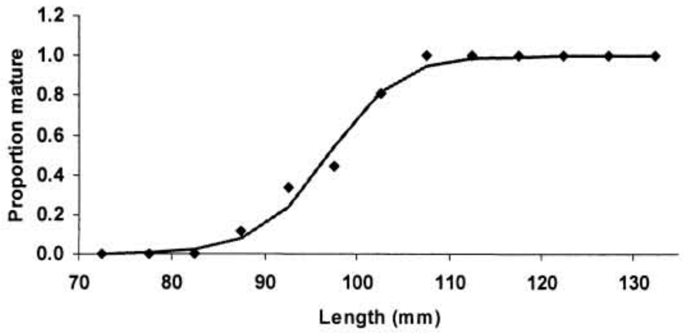


Figure 51: Data from Table 31, also showing a logistic equation with parameters *mat50* = 96.8, *mat95-50* = 109.6.

3.7.2 PAU 5D

Data were collected during research surveys in November 1996 and March 2001 (Reyn Naylor, unpublished data) at sites in the Catlins West research stratum. Seventy-nine paua of various sizes were examined visually for sex and maturity as described for PAU 5A.

One animal below 70 mm was discarded from the dataset. The proportion of animals mature in 5-mm bins is shown in Table 32 and Figure 52. The sample size is very small, but most animals are mature by 100 mm and 50% maturity probably lies between 77 and 87 mm.

Table 32: Numbers of paua observed, number mature and proportion mature in sampling in Catlins West. The bin size is the mid-point.

Bin (mm)	No. obs.	No. mature	Proportion
72.5	6	1	0.167
77.5	5	1	0.200
82.5	4	3	0.750
87.5	10	8	0.800
92.5	14	13	0.929
97.5	24	22	0.917
102.5	2	2	1.000
>105	13	13	1.000
Total	78	63	

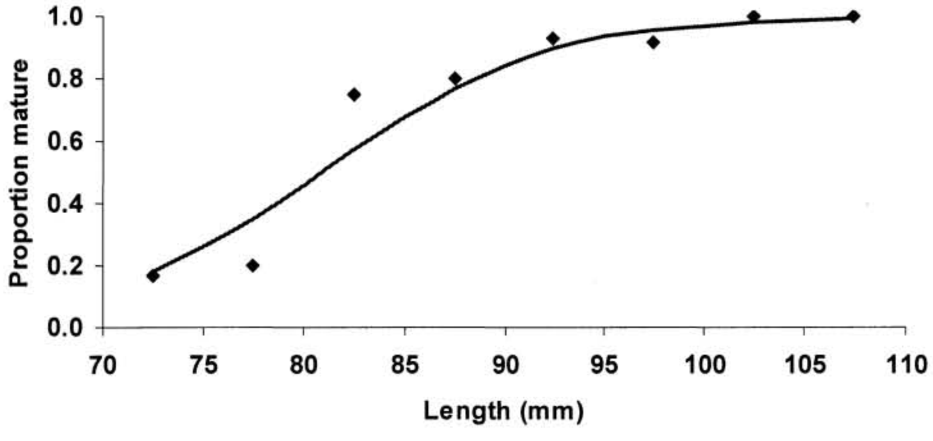


Figure 52: Data from Table 32, also showing a logistic equation with parameters *mat50* = 80.7, *mat95-50* = 97.0.

4. EXPLORATORY ANALYSES FOR PAU 5A

An immediate problem for the PAU 5A assessment is that CPUE and RDSI indices behave in opposite ways: CPUE increased while RDSI decreased (Figure 53). We made some further analyses to explore this. In the first, we re-standardised RDSI so that the decline in the southern three research strata could be analysed and we tested the significance of the decline with a bootstrap analysis. Second, we estimated the catch that had been taken from the survey area between the 2002 and 2006 surveys, so that we could estimate the 2002 biomass. Third, we plotted standardised CPUE, RDSI and catch for the southern three areas on the same plot so that we could compare comparable indices for that region. Finally, we plotted catch by fine-scale area to look for evidence of serial depletion.

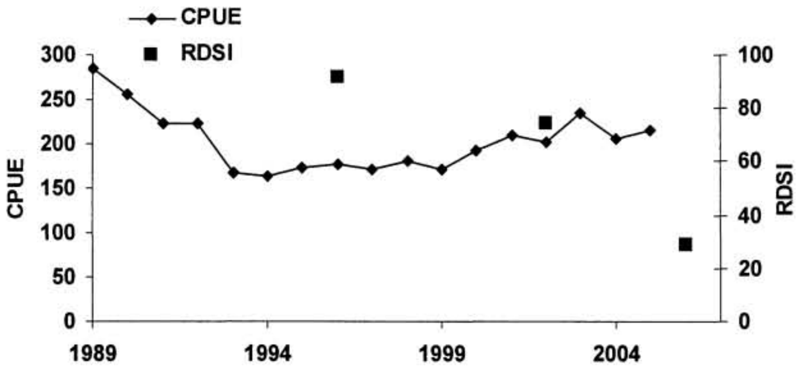


Figure 53: Standardised CPUE (kg/diver-day) and RDSI (number per 10-minute swim) indices for PAU 5A.

4.1 RDSI for the South coast, Chalky and Dusky strata

Not all strata were surveyed in each research diver survey (see Figure 3, Table 16): only two were surveyed in 1996, three in 2002 and all four in 2006. The 1996 survey had greatly limited representation, although it may contain useful information about visibility and diver effects. The second and third surveys are fully representative of the southern three strata, but the George stratum was surveyed only in the 2006 survey.

However, the three southern strata (all but George) were all surveyed in 2002 and 2006. We re-standardised the survey data with the method described above, but excluding the George stratum data from 2006. Stratum had the largest effect (Table 33), but all variables had significant effects. The raw indices and year effects (Figure 54) were similar to those obtained from the full dataset (cf. Figure 28).

Table 33: Variables offered to the three-stratum PAU 5A standardisation model and the cumulative r^2.

Variable	r^2 (%)
Fishing year	7.6
Stratum	15.9
Visibility	17.4
Diver	18.7

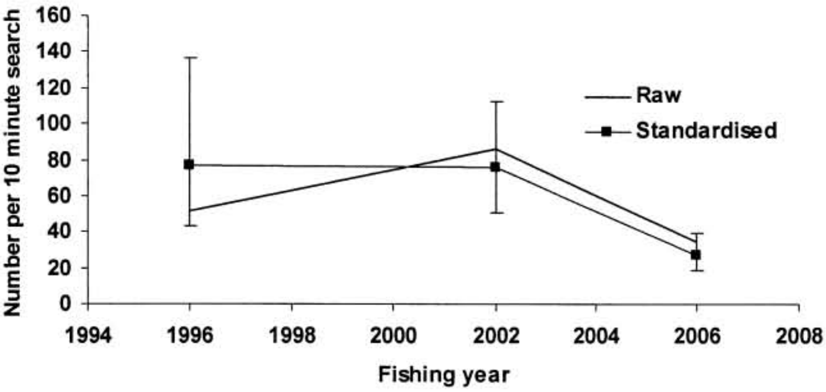


Figure 54: Raw and standardised RDSI for PAU 5A from the three-stratum PAU 5A standardisation.

The point estimates of the indices suggest that abundance in 2006 was only 36% of the abundance in 2002, thus that abundance in the three southern strata decreased by 64% between the two surveys. We explored this estimate further by bootstrapping the data: in each of 1000 trials, for each stratum and each survey we randomly chose the same number of swims from the data, with replacement, as were in the original dataset. For each trial we then standardised the bootstrap dataset and calculated the ratio of the abundance index in 2006 to that in 2002.

The resulting distribution of ratios (Table 34) has a wide range, with its centre near the point estimate and a 90% confidence interval of 22 to 50%, corresponding to a decrease of 50 to 78% in the three southern strata between 2002 and 2006.

Table 34: For the three-stratum PAU 5A standardised RDSI index, summary of the bootstrapped distribution of the ratio of the 2006 to 2002 indices. Rows show the minimum and maximum, 5th and 95th quantiles, median and mean.

Quantity	2006/2002
Minimum	0.1429
5%	0.2205
Median	0.3419
Mean	0.3480
95%	0.5010
Maximum	0.7518

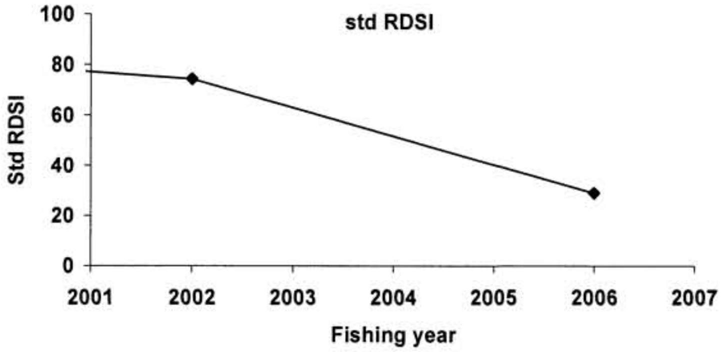
4.2 CPUE and catch in the southern three strata

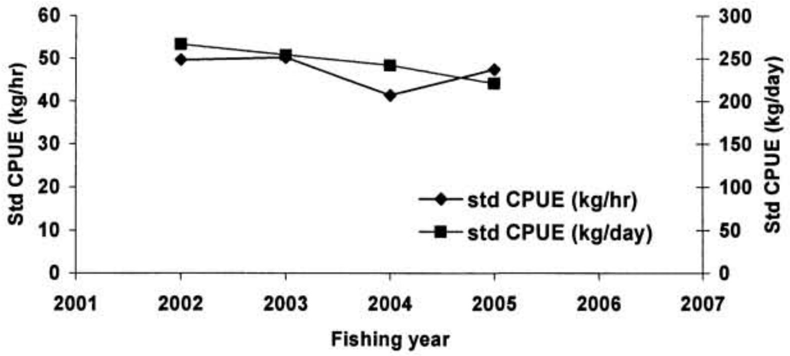
We also re-standardised CPUE from the PCELR data, restricting it to data from fine-scale areas P5A028 through P5A049, comprising the South Coast, Chalky and Dusky research strata. For this, we followed the same procedures used for the main CPUE standardisation. Catch from these data was collated by year.

Standardised CPUE for this area shows only a slight decline from 2002 to 2005 if units of kg/diver-hour are used (Figure 55, Table 35), and a 17% decline if units of kg/diver-day are used. This pattern differs from that for the whole of PAU 5A, which increases (Figure 53). Catch has been about 90 t, with reasonable stability (see Figure 55).

Table 35: Raw and standardised CPUE from the southern three research strata in PAU 5A.

		Kg/diver-hour		Kg/diver-day
Year	Raw	Standardised	Raw	Standardised
2002	46.43	49.67	246.9	266.7
2003	44.79	50.20	244.7	254.1
2004	47.84	41.33	237.0	242.0
2005	49.15	47.45	252.9	220.8





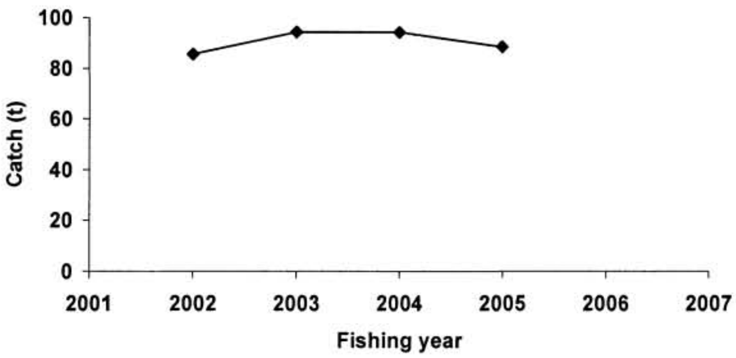


Figure 55: RDSI (top), CPUE (middle) and catch from the southern three research strata in PAU 5A, comprising statistical areas P5A028 through P5A049, from 2002 to 2006.

4.3 Catch by fine-scale reporting area

To explore the question of serial depletion, the possibility of which is suggested by the increasing percentage of zero-abundance swims in PAU 5A (Table 16 and Figure 56), we examined trends in catch by area in the PCELR data, which is reported by fine-scale statistical area for 2002 and later.

These catches do not support any gross generalisation about catch among areas. Some areas have increased and others have decreased, but there is little geographical pattern to the changes.

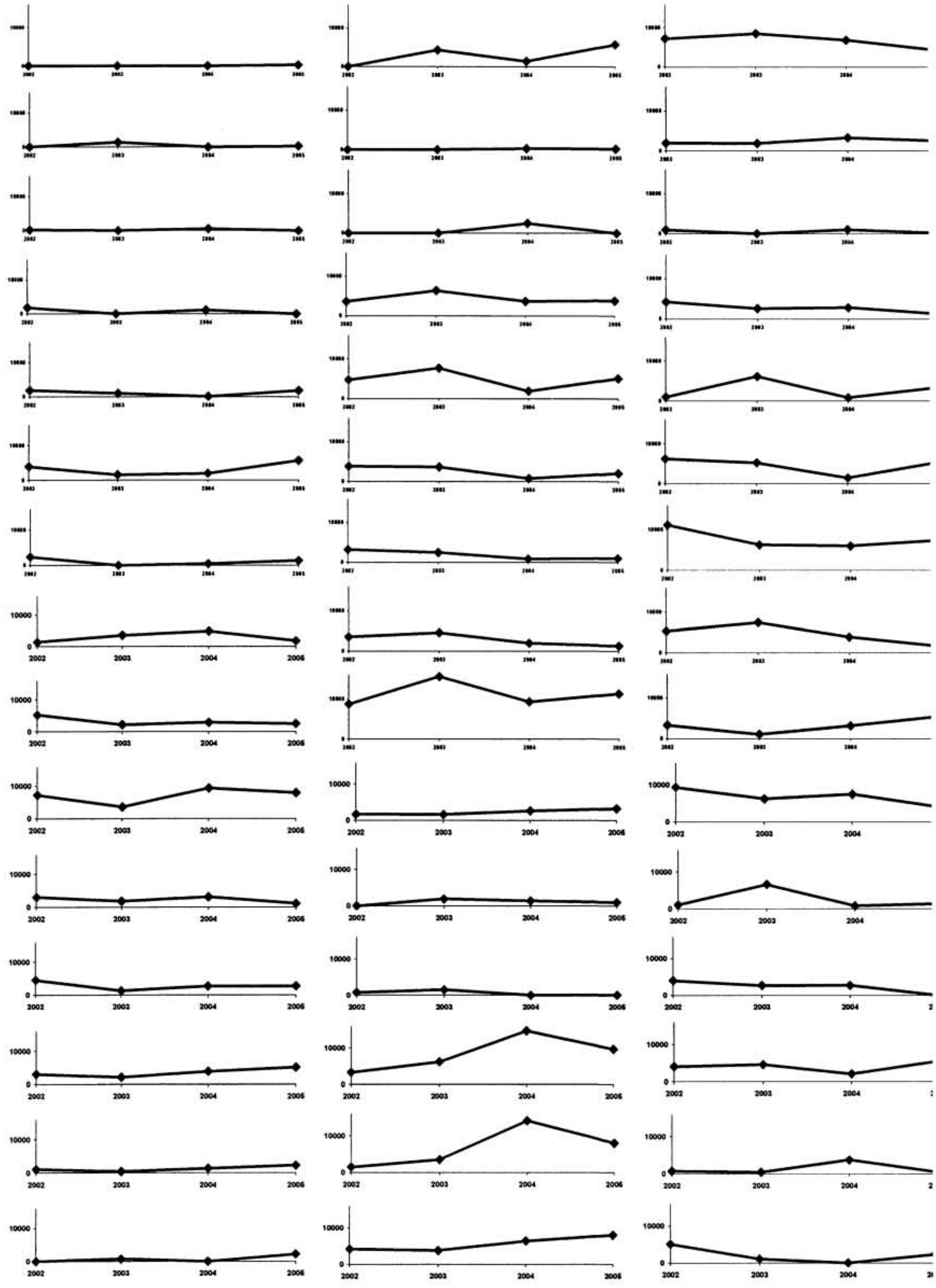


Figure 56: Catch by year by fine-scale statistical area. The areas are the northernmost area in the top left (P5AF01) and the southeasternmost (P5AF49) in the bottom right, reading down each column.

5. INDICATORS

The SFWG requested both three- and five-year projections. The indicators that comprise the assessment are based on exploitation rates and biomass in 2005 and in the two projected years 2008 and 2010.

Exploitation rate indicators were for 2005 (*U2005*) and for the two projected years (*U2008* and *U2010*). The historical minimum spawning biomass (*Smin*) and recruited biomass (*Bmin*) were determined from the trajectories between 1974 and 2005. Spawning biomass is the product of numbers-, weight- and maturity-at-size. Recruited biomass is the product of numbers- and weight-at-size for sizes greater than or equal to the MLS. Spawning and recruited biomass were output for 2005, 2008 and 2010, thus *S2005*, *B2008* etc. All reference biomass indicators are mid-season biomass (the pre-season biomass minus half the year's catch).

Recent practice has been to define a reference period in which biomass was stable, catches were good and the exploitation rate was sustainable. The references are called *Sav* and *Bav*. For PAU 5D, the period chosen was 1989–96, described further below. However, for PAU 5A different biomass trajectories in sensitivity runs suggested this approach was inappropriate for this assessment. Therefore *Sav* and *Bav* were not used as indicators for PAU 5A.

Additional indicators were calculated as the probability that, or percentage of runs in which:

- projected spawning biomass had decreased from 2005: P(*S08*<*S05*), P(*S10*<*S05*),
- projected spawning biomass was less than the nadir: P(*S08*<*Smin*), P(*S10*<*Smin*)
- projected recruited biomass had decreased from 2005: P(*B08*<*B05*), P(*B10*<*B05*)
- projected recruited biomass was less than the nadir: P(*B08*<*Bmin*), P(*B10*<*Bmin*)

6. PAU 5A ASSESSMENT

At the outset of the assessment, we compared results obtained from using the 2006 datasets and 2006 model with those from the only previous assessment for PAU 5A, done in 2004 (Breen & Kim 2004a). Both the model and data were reasonably consistent with the 2004 assessment when minimisations were made in the same way: details were shown to the SFWG but are not reported here.

6.1 Finding a base case

To find a base case, our basic approach was to adjust the dataset weights iteratively to balance the standard deviations of the normalised residuals (sdnrs). New weights are determined by dividing the trial weight by the sdnr for each dataset. This proved to be a frustrating exercise, in which the realised sdnrs and visual fits behaved somewhat unpredictably, especially for CPUE and RDSI. More than 130 exploratory trials were made. Estimated *M* tended to be large, and we reduced the c.v. of the prior for *M* from 0.35 to 0.10 for many of the exploratory runs. In nearly all exploratory runs, *CPUEpow* was fixed to 1 to prevent estimated hyperdepletion: this parameter went to its upper bound of 2 when estimated. In all these runs, the exponential growth model was used because of obvious curvature in the tag-recapture data.

One suitable candidate was finally developed, fitting to all the data, by fixing the research diver selectivity parameters to *RD50* = 110 and *RD95* = 19, values obtained from other runs in which these parameters were estimated. Specifications for this run, 073SK, are shown in Table 36 and Table 37.

The two abundance indices are contradictory: CPUE increases while RDSI decreases. We believed that this conflict was the source of much of the trouble encountered in balancing residuals in exploratory runs. Further explorations were therefore made to develop otherwise credible base case candidates that excluded CPUE (run 041PAB) or excluded the RDSI (059PAB). Specifications for these runs are also shown in Table 36 and Table 37. There will be no ambiguity if we refer to these runs as run 073, run 041 and run 059; also termed the compromise fit, RDSI fit and CPUE fit respectively.

Reasonable estimates for *M* could not be obtained in run 059 except by making the c.v. of the prior so small that it was tantamount to fixing *M*, so *M* was fixed in this run. An acceptable fit to the CPUE in this run could not be obtained without increasing the weight for CPUE and accepting an sdnr greater than 1. Run 041 experienced a high *M* under the original prior, but was satisfactory with the tightened prior and otherwise showed no problems requiring intervention.

The SFWG suggested that run 041 be treated as the base case and that runs 073 and 059 should be considered sensitivities.

Table 36: Values of constants used in the base case and two other candidate runs for PAU 5A discussed in the text. Run 041 is considered the base case. Run 073 was fitted to all data, run 041 excluded CPUE and run 059 excluded RDSI. Run 073 was fitted to all data, run 041 excluded CPUE and run 059 excluded RDSI.

Parameter	Run 073	Run 041	Run 059
CPUEwt	2.00	n.a.	3.00
RDSIwt	2.00	0.36	n.a.
CSLFwt	20.00	22.69	11.69
RDLFwt	40.00	118.77	50.77
tagwt	0.35	0.50	0.50
matwt	12.00	11.52	11.52
Umax	0.65	0.65	0.65
a	2.99E-08	2.99E-08	2.99E-08
b	3.303	3.303	3.303
alpha	75	75	75
Beta	120	120	120

Table 37: Parameter specifications for the three runs discussed in the text. Run 073 was fitted to all data, run 041 excluded CPUE and run 059 excluded RDSI. Prior types 0: uniform; 1: normal; 2: normal-log.

Parameter	Run	Phase	Lower bound	Upper bound	Type	Mean	Prior Std. dev.
sigmatilde	All	1	0.01	2	0	-	-
ln(*R0*)	All	1	5	50	0	-	-
M	073, 041	1 or 3	0.01	0.5	2	0.1	0.1
M	059	Fixed at 0.10					
RD50	073	Fixed to 110					
RD50	041, 059	2	70	125	0	-	-
RD95	073	Fixed to 19	0.001	50	0	-	-
RD95	041, 059	2	0.001	50	0	-	-
CS50	All	2	70	145	0	-	-
CS95	All	2	0.01	50	0	-	-
Mat50	All	3	70	145	0	-	-
Mat95	All	3	1	50	0	-	-
Eps	All	3	-2.3	2.3	1	0	0.4
ln(qCPUE)	073, 059	1	-30	10	0	-	-
ln(qCPUE)	041	Not estimated					
ln(qRDSI)	All	1	-30	0	0	-	-

Parameter	Run	Phase	Lower bound	Upper bound	Type	Mean	Prior Std. dev.
ln(qRDSI)	059	Not estimated					
galpha	All	2, 3 or 4	1	50	0	-	-
gBeta	All	2, 3 or 4	0.01	50	0	-	-
GrowthCV	All	2	0.001	10	0	-	-
SigmaMin	All	Fixed to 1	0.001	5	0	-	-
SigmaObs	All	Fixed to 0.25	0.001	5	0	-	-
CPUEpow	All	Fixed to 1	0.01	2	0	-	-

6.2 MPD results

MPD estimation results from these three runs are shown in Table 38. The sdnrs are all near 1 for run 041, but both RDSI and CPUE are over-weighted in run 073, reducing the effective weight of the length frequencies, and CPUE is over-weighted in run 059. Except that we had to fix the *RD50* and *RD95* parameters in run 073, there is little change among research selectivity, commercial selectivity and maturity parameter estimates among the runs.

The best fits to length frequencies were obtained in run 041. Fits to tag-recapture and maturity data varied little among these three runs.

Table 38: MPD results from the three runs described in the text. Grey indicates quantities not estimated or not based on estimated parameters. Run 041 is considered the base case.

			Run
Quantity	073	041	059
sdnr CPUE	2.33	18.52	2.21
sdnr RDSI	5.38	0.97	3.20
sdnr CSLF	0.92	0.95	0.99
sdnr RDLF	0.42	0.98	0.81
sdnr tags	1.03	1.05	0.97
sdnr maturity	0.82	0.97	1.38
sigmatilde	0.45	0.37	0.26
ln(R0)	14.23	13.10	12.65
M	0.193	0.127	0.10
RD50	110	111.0	112.3
RD95	19	19.6	19.4
CS50	125.9	125.9	126.1
CS95	6.07	5.44	5.68
Mat50	97.0	97.0	97.0
Mat95	11.3	11.3	11.3
ln(*qCPUE*)	-8.00	1.00	-6.82
ln(*qRDSI*)	-11.08	-10.52	-13.00
galpha	15.34	17.17	18.95
gBeta	5.37	5.20	4.57
GrowthCV	0.52	0.92	1.61
LikeCPUE	6.5	159763	-14.2
LikeRDSI	37.6	-0.5	693.5
LikeCSLF	-718.8	-808.9	-707.3
LikeRDLF	-443.3	-591.4	-535.4
LikeTags	847.3	845.5	847.9
LikeMat	-21.3	-21.7	-19.7
contribution from prior on *M*	20.1	1.6	0.0
contribution from prior on *Eps*	25.3	36.9	44.4
penalty on maximum *U*	0.0	0.0	0.3
LikeTotal	-246.6	-538.5	-384.0

MPD indicator estimates are shown in Table 39. The compromise run 073, fitted to both abundance indices, had higher biomass and lower exploitation rate than either of the runs fit to only one abundance index, illustrating the non-linear character of the problem. For Table 39,the indicators *Sav* and *Bav* were based on a completely arbitrary period: 1992-98. Because of differences in results among the three runs, this period was not chosen to represent a reference or a target, but was chosen only to permit of comparisons being made among runs.

Although run 073 showed highest biomass, it also showed the lowest ratios of current biomass to minimum references *Smin* and *Bmin*. Of the three, run 041 was generally intermediate with respect to indicators.

Table 39: MPD values of indicators from the three base case candidate runs for PAU 5A described in the text.

			Run
Quantity	073	041	059
Maximum *U*	0.253	0.474	0.655
U2006	0.248	0.474	0.569
Smin	834	317	231
Sav	1252	887	284
S05	834	453	402
Bmin	510	166	153
Bav	541	417	167
B05	565	258	204
S05/Sav	67%	51%	141%
B05/Bav	104%	62%	122%
S05/Smin	100%	143%	174%
B05/Bmin	111%	155%	134%

Fits to CPUE and RDSI are shown for run 073 in Figure 57, the fit to RDSI for run 041 in Figure 58 and the fit to CPUE in run 059 in Figure 59. There is no fit to CPUE in run 041 nor to RDSI in run 059. In the compromise fit, the model fits the 2002–2006 decline in RDSI, but does not fit the 1996 research survey point. The run 073 fit to CPUE has trouble with the first two data, 1989 and 1990, then fits acceptably but decreases in 2005, whereas the data increased. As one would expect, the other two runs show very good fits to the indices they fit to.

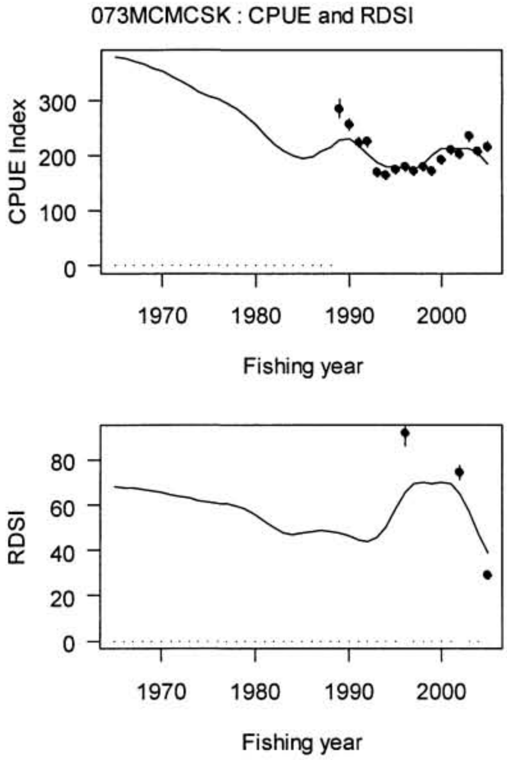


Figure 57: Observed (dots) and predicted (solid lines) CPUE (top) and RDSI (bottom) for the compromise MPD fit for PAU 5A, run 073. Error bars show the standard error term used by the model in fitting, including the effect of the common error term and dataset weights.

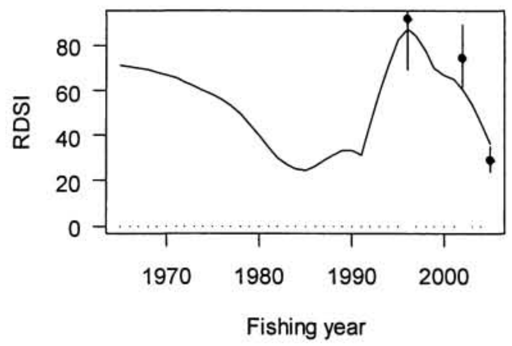


Figure 58: Observed (dots) and predicted (solid line) RDSI from the MPD RDSI fit for PAU 5A, run 041.

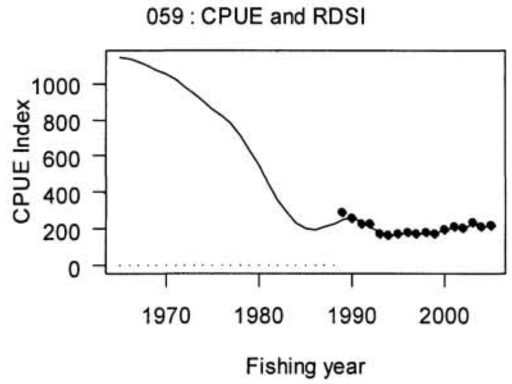


Figure 59: Observed (dots) and predicted (solid line) CPUE from the MPD CPUE fit for PAU 5A, run 059.

Base case fits to the length frequencies are shown in Figure 60. Base case fit to the tagging data (Figure 61) was good, also to maturity (Figure 62), and both showed little difference among the runs. Slices of the growth transition matrix are shown in Figure 63, and the initial length structure in Figure 64.

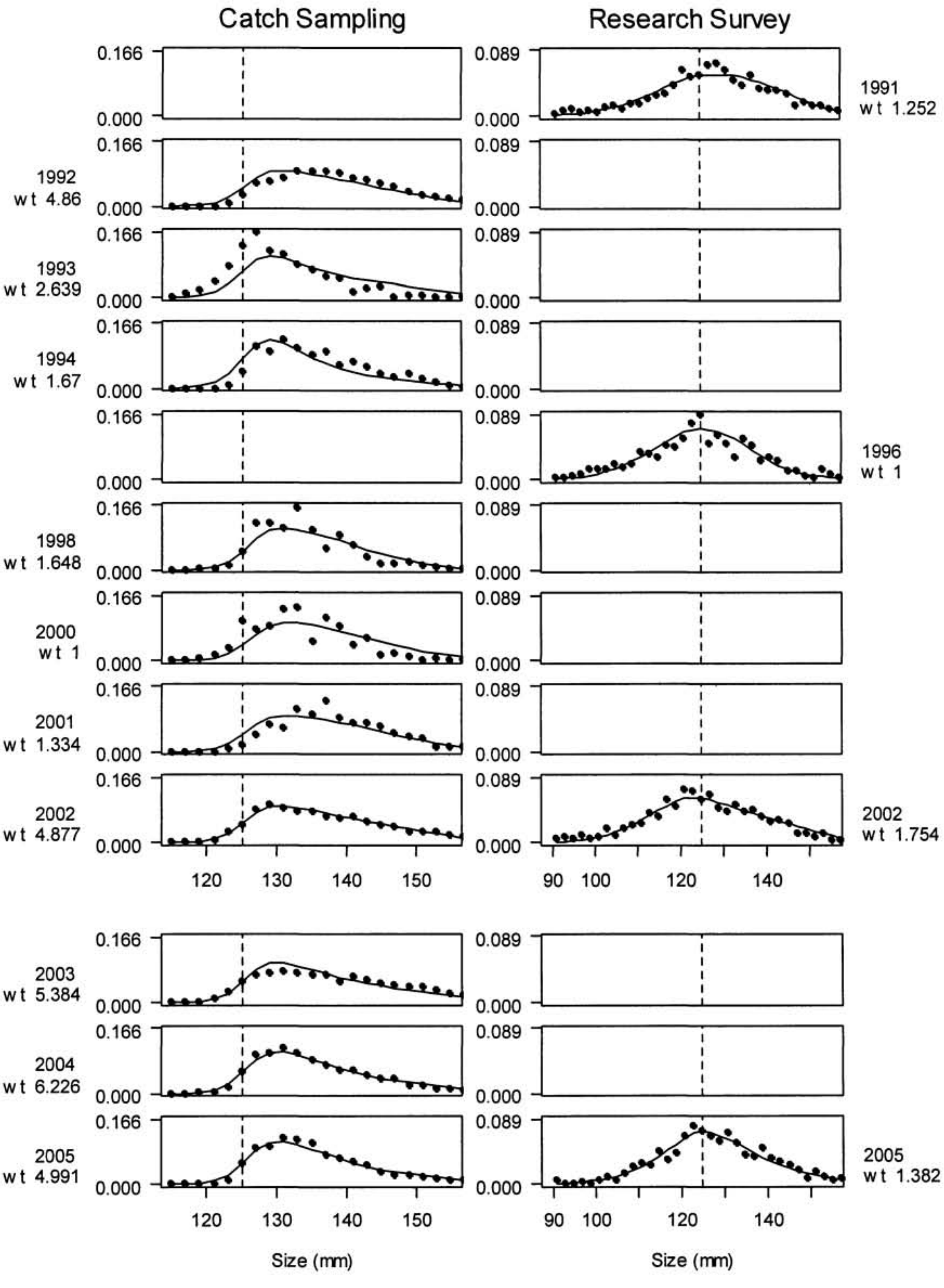


Figure 60: Observed (dots) and predicted (lines) proportion-at-length from commercial catch sampling (left) (CSLF) and research diver surveys (right) (RDLF) for the RDSI MPD fit, run 041, for PAU 5A. The number under each year is the relative weight given to the dataset (see text).

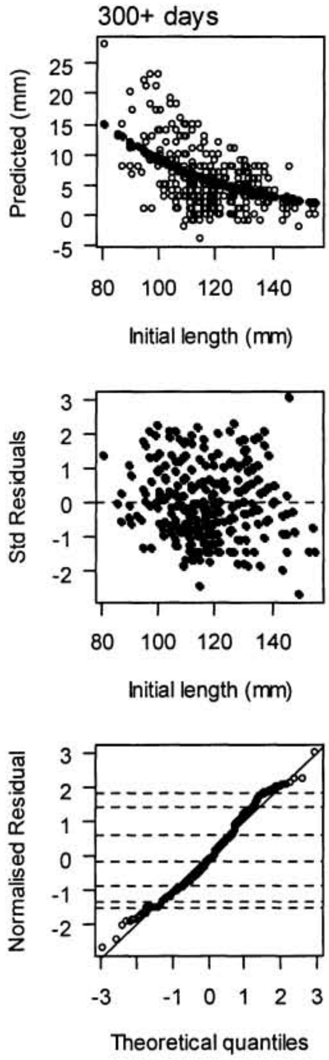


Figure 61: Top: predicted (closed circles) and observed (open circles) increments plotted against initial length of tagged paua from the base case MPD, run 041 for PAU 5A; middle: standardised residuals plotted against initial length; bottom: Q-Q plot of standardised residuals.

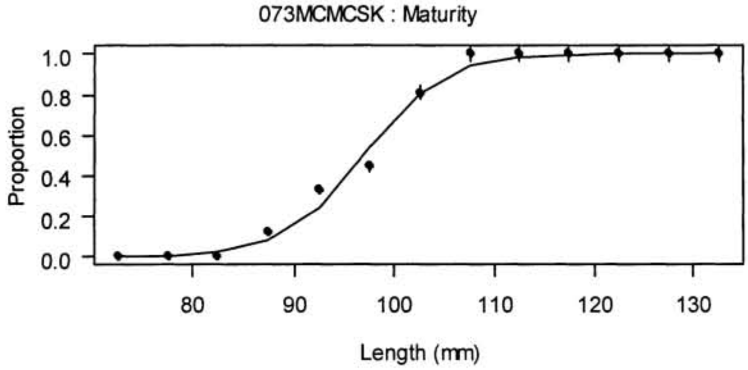


Figure 62: Observed (dots) and predicted (solid lines) maturation-at-length for the base case MPD fit for PAU 5A. Error bars show the standard error term used by the model in fitting, including the effect of the common error term and dataset weights.

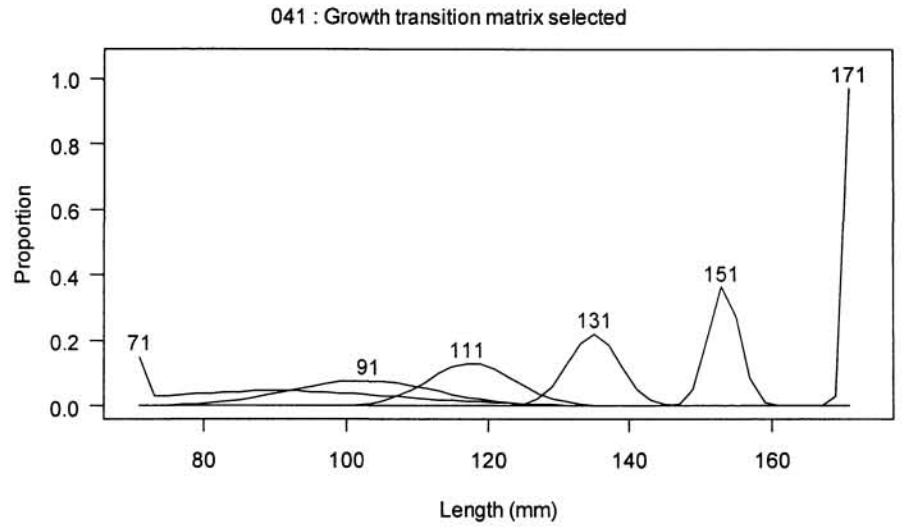


Figure 63: Sections from the MPD growth transition matrices from the base case MPD, run 041, for PAU 5A, showing the distribution of probabilities of growing from the size indicated to the various new sizes.

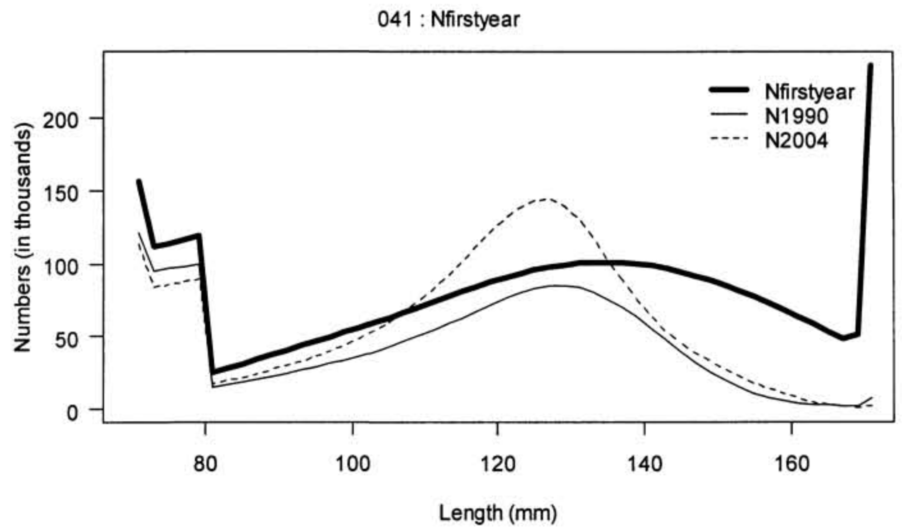


Figure 64: Numbers-at-length predicted by the model for 1965 (heavy line), 1990 and 2004 from the base case MPD, run 041, for PAU 5A.

Estimated recruitment (Figure 65) is average or below average until 1990, then shows a very strong spike, followed later by two lesser spikes; Exploitation rate (Figure 65) shows a steeply increasing trend in the past two years, but does not approach the upper bound of 65%.

Spawning biomass (Figure 66) shows a decline from the start to the mid 1990s, with a bump in the late 1980s, then increases to a peak in the mid 1990s and declines. Recruited biomass shows a strong increase and strong decline.

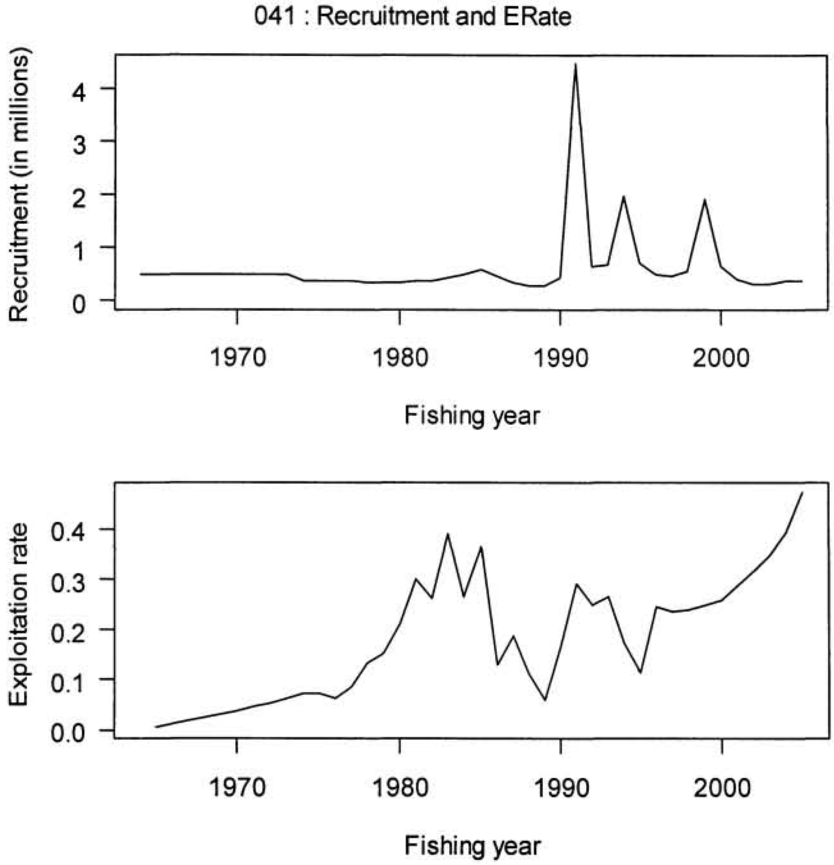


Figure 65: Recruitment to the model and exploitation rate from the base case MPD fit (run 041) for PAU 5A.

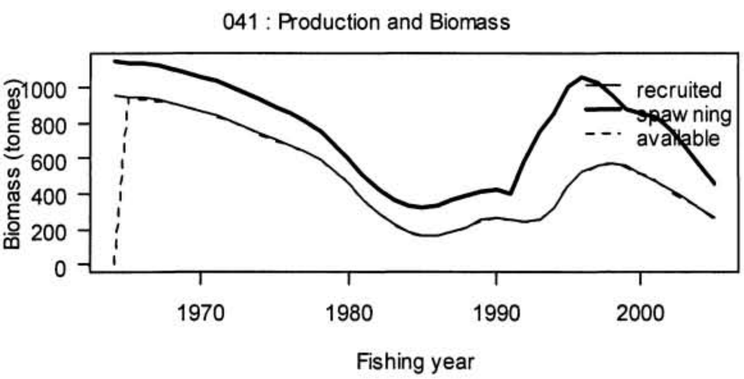


Figure 66: Recruited, spawning and available biomass trajectories, from the base case MPD (run 041) fits for PAU 5A. Recruited biomass includes all individuals above the MLS; spawning biomass includes all mature individuals; available biomass includes all recruited individuals that are selected by the commercial fishery.

6.3 MPD sensitivities

For each of the three runs described above, we made a set of sensitivity trials: we used the linear growth model instead of the exponential, we estimated *CPUEpow* (not for run 041, which was not fitted to CPUE), and we removed the CSLF data, the RDLF data, both LF datasets, and the tag dataset. Dataset weights were left unchanged. When a length frequency dataset was excluded, the selectivity parameters for that dataset were also fixed.

Results are shown in Table 40 through Table 42. Some common features were: *CPUEpow* went to its upper bound when estimated; the maturity parameters were affected by nothing; commercial selectivity parameters were little changed in the trials when estimated; *gBeta* showed little change; removal of a length frequency dataset caused the fit to deteriorate, but many of the resulting "fits" were still visually credible.

The linear growth model gave somewhat worse total negative log-likelihood values and worse tag contributions for all runs, although one or other of the length frequencies was fitted slightly better. The effect was not very large, but the exponential growth model appears to be the correct choice for these data.

Removal of the tag dataset caused large changes in *galpha*, and for run 073 gave slightly better fits to length frequencies, while in the other two runs the fits to length frequencies deteriorated. For run 041, removal of the tag dataset increased all biomass estimates substantially.

The only dramatic change was caused by removing both length frequency datasets from run 059. Exploitation rate went to zero and biomass became very high: the model essentially put a flat line through the only dataset fitted, CPUE.

Other trials produced changes, but removal of datasets showed no consistent pattern. The robustness of visual fits to the data suggests a high redundancy of information among the various datasets.

Table 40: Results of PAU 5A sensitivity trials based on run 073. Grey indicates parameters not estimated or quantities not based on estimated parameters.

Quantity	Base 062	Linear growth 068	Estimated *CPUEpow* 067	No CSLF 063	No RDLF 064	No CSLF No RDLF 065	No tags 066
sdnr CPUE	2.33	2.27	1.74	1.76	1.98	0.81	2.42
sdnr RDSI	5.38	5.25	6.54	4.58	4.49	2.18	4.31
sdnr CSLF	0.92	0.94	0.90	1.50	0.77	0.99	0.96
sdnr RDLF	0.42	0.42	0.41	0.54	0.37	0.34	0.56
sdnr tags	1.03	1.03	1.05	1.03	1.02	1.01	3.91
sdnr maturity	0.82	0.81	0.85	0.86	0.67	0.41	0.90
sigmatilde	0.453	0.456	0.439	0.431	0.551	0.910	0.415
ln(*R0*)	14.231	14.035	14.705	13.314	13.902	13.321	14.195
M	0.193	0.175	0.213	0.130	0.160	0.126	0.209
RD50	110.00	110.00	110.00	110.00	110.00	110.00	110.00
RD95	19.00	19.00	19.00	19.00	19.00	19.00	19.00
CS50	125.85	125.72	125.70	126.00	125.88	126.00	126.40
CS95	6.07	5.98	5.63	6.12	6.46	6.12	6.66
mat50	96.97	96.97	96.97	96.97	96.97	96.97	96.97
mat95	11.28	11.28	11.28	11.28	11.28	11.28	11.28
ln(*qCPUE*)	-8.00	-7.73	-22.22	-7.25	-7.92	-7.16	-7.57
ln(*qRDSI*)	-11.08	-10.84	-11.50	-10.54	-10.98	-10.59	-10.77
galpha	15.3	11.3	16.0	16.5	15.8	20.0	11.3
gBeta	5.4	5.9	5.1	5.3	5.3	4.9	6.4
GrowthCV	0.520	0.511	0.547	0.550	0.436	0.262	0.084
CPUEpow	1	1	2	1	1	1	1
LikeCPUE	6.5	4.6	-14.2	-13.9	-2.6	-22.0	8.7
LikeRDSI	37.6	35.5	58.4	25.5	24.8	3.0	21.7
LikeCSLF	-718.8	-712.9	-733.1	-531.2	-697.8	-496.3	-733.6
LikeRDLF	-443.3	-442.3	-448.9	-441.4	-414.0	-333.5	-446.1
LikeTags	847.3	855.6	845.3	845.6	845.9	842.5	2695.6
LikeMat	-21.3	-21.3	-21.5	-21.5	-20.3	-15.7	-21.6
contribution from *M* prior	20.1	14.3	27.2	2.0	9.7	1.3	25.7
contribution from *Eps* prior	25.3	27.0	23.2	33.4	23.5	24.6	26.8
U penalty	0.0	0.0	0.0	0.0	0.0	0.0	0.0
LikeTotal	-246.6	-239.6	-263.5	429.7	183.2	833.5	-1118.4
Maximum *U*	0.25	0.32	0.16	0.47	0.27	0.51	0.37
U2005	0.248	0.315	0.156	0.470	0.265	0.500	0.358
Smin	834	648	1342	432	761	449	567
Sav	1252	987	1872	688	1130	728	994
S2005	834	648	1342	432	761	449	567
Bmin	510	389	862	231	469	216	334
Bav	541	411	884	253	502	233	356
B2005	565	427	934	268	529	253	382
S2005/Sav	66.6%	65.7%	71.7%	62.7%	67.3%	61.6%	57.0%
B2005/Bav	104.4%	103.9%	105.6%	105.9%	105.2%	108.5%	107.4%
S2005/Smin	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
B2005/Bmin	110.8%	109.7%	108.2%	116.1%	112.6%	117.0%	114.4%

Table 41: Results of PAU 5A sensitivity trials based on run 041. Grey indicates parameters not estimated or quantities not based on estimated parameters.

	Base "069	Linear growth "075	No CSLF "070	No RDLF "071	No CSLF No RDLF "072	No tags "073
sdnr CPUE	18.52	18.52	15.54	18.55	15.53	16.67
sdnr RDSI	0.97	1.31	1.15	1.01	1.16	1.66
sdnr CSLF	0.95	0.92	1.48	0.94	1.94	1.02
sdnr RDLF	0.98	1.01	0.90	1.51	2.32	0.95
sdnr tags	1.05	1.06	1.05	1.06	1.00	4.33
sdnr maturity	0.97	0.97	0.91	0.97	0.96	0.96
sigmatilde	0.367	0.369	0.390	0.367	0.371	0.372
ln(*R0*)	13.096	13.227	13.452	13.173	13.248	13.861
M	0.127	0.130	0.138	0.131	0.098	0.134
RD50	110.97	114.59	113.91	100.00	100.00	107.94
RD95	19.65	16.24	22.29	19.00	19.00	18.58
CS50	125.92	125.99	123.30	126.00	123.30	125.51
CS95	5.44	5.41	3.30	5.36	3.30	5.27
mat50	96.97	96.97	96.97	96.97	96.97	96.97
mat95	11.28	11.28	11.28	11.28	11.28	11.28
ln(*qCPUE*)	1.00	1.00	1.00	1.00	1.00	1.00
ln(*qRDSI*)	-10.52	-10.43	-10.53	-10.74	-10.46	-11.33
galpha	17.2	11.4	17.4	17.3	17.2	27.0
gBeta	5.2	5.8	4.9	5.1	5.0	4.6
GrowthCV	0.917	0.898	0.923	0.933	0.997	0.190
LikeCPUE	159763.0	152144.0	150689.0	160871.0	174325.0	192036.0
LikeRDSI	-0.5	0.7	0.3	-0.4	0.2	2.3
LikeCSLF	-808.9	-814.5	-602.2	-812.1	-389.0	-784.3
LikeRDLF	-591.4	-585.8	-593.8	-483.4	-226.4	-594.9
LikeTags	845.5	853.9	845.0	845.1	844.0	3064.2
LikeMat	-21.7	-21.7	-21.6	-21.7	-21.7	-21.7
contribution from *M* prior	1.6	2.0	3.8	2.2	-1.4	3.0
contribution from *Eps* prior	36.9	39.9	18.1	32.6	0.4	6.9
U penalty	0.0	0.0	0.0	0.0	0.0	0.0
LikeTotal	-538.5	-525.5	251.8	45.7	821.6	-1388.6
Maximum *U*	0.47	0.48	0.39	0.52	0.65	0.20
U2005	0.474	0.476	0.392	0.517	0.650	0.198
Smin	317	274	520	368	330	1156
Sav	887	826	933	946	1095	1798
S2005	453	504	532	439	330	1156
Bmin	166	121	284	192	142	705
Bav	417	340	508	449	861	1106
B2005	258	258	284	231	142	705
S2005/Sav	51.1%	61.1%	57.0%	46.4%	30.1%	64.3%
B2005/Bav	62.0%	75.7%	55.9%	51.5%	16.5%	63.8%
S2005/Smin	143.1%	184.1%	102.2%	119.4%	100.0%	100.0%
B2005/Bmin	155.4%	212.5%	100.0%	120.5%	100.0%	100.0%

Table 42: Results of PAU 5A sensitivity trials based on run 059. Grey indicates parameters not estimated or quantities not based on estimated parameters.

	Base	Linear growth	*CPUEpow*	No CSLF	No RDLF	No CSLF No RDLF	No tags
	"076	"082	"081	"077	"078	"079	"080
sdnr CPUE	2.21	3.12	1.63	1.85	1.87	1.35	1.23
sdnr RDSI	3.20	3.10	3.52	3.07	3.00	2.88	3.20
sdnr CSLF	0.99	0.99	1.01	1.20	0.95	0.39	1.01
sdnr RDLF	0.81	0.76	0.86	0.82	0.81	0.40	0.90
sdnr tags	0.97	0.85	0.98	1.00	0.96	1.00	3.45
sdnr maturity	1.38	1.35	1.47	1.28	1.30	0.26	1.35
sigmatilde	0.258	0.263	0.243	0.279	0.275	1.370	0.264
ln(*R0*)	12.649	12.905	12.627	12.656	12.633	25.543	12.525
M	0.10	0.10	0.10	0.10	0.10	0.10	0.10
RD50	112.27	117.83	113.25	114.03	110	110	87.21
RD95	19.42	19.29	19.30	19.75	19	19	0.58
CS50	126.10	126.54	126.24	123.30	125.94	123.30	125.80
CS95	5.68	6.41	5.75	3.30	5.46	3.30	8.68
mat50	96.97	96.97	96.97	96.97	96.97	96.97	96.97
mat95	11.28	11.28	11.28	11.28	11.28	11.28	11.28
ln(*qCPUE*)	-6.82	-6.81	-18.82	-6.84	-6.83	-21.17	-6.83
ln(*qRDSI*)	-13.00	-13	-13	-13	-13	-13	-13
galpha	18.9	10.3	18.4	21.6	21.1	19.8	50.0
gBeta	4.6	5.2	4.7	4.8	4.8	4.9	5.7
GrowthCV	1.610	1.746	1.661	1.376	1.453	0.250	0.366
CPUEpow	1	1	2	1	1	1	1
LikeCPUE	-14.2	27.2	-34.2	-25.4	-25.0	-12.1	-42.6
LikeRDSI	693.5	640.5	824.3	654.2	600.1	285.4	670.6
LikeCSLF	-707.3	-702.1	-717.7	-615.7	-699.3	-342.5	-693.8
LikeRDLF	-535.4	-538.0	-539.0	-520.6	-524.9	-301.7	-518.5
LikeTags	847.9	858.8	846.3	849.1	848.6	842.6	2236.6
LikeMat	-19.7	-19.9	-18.7	-20.5	-20.4	-10.6	-19.9
contribution from *M* prior	0.0	0.0	0.0	0.0	0.0	0.0	0.0
contribution from *Eps* prior	44.4	40.2	49.9	41.8	42.7	4.2	38.8
U penalty	0.3	0.0	0.1	0.0	0.1	0.0	0.1
LikeTotal	-384.0	-333.8	-413.3	324.4	146.7	824.1	-1236.0
Maximum *U*	0.66	0.65	0.65	0.65	0.65	0.00	0.65
U2005	0.569	0.583	0.609	0.561	0.567	0.000	0.563
Smin	231	283	230	216	226	3.43E+08	196
Sav	284	391	289	261	276	3.48E+08	234
S2005	402	483	383	363	388	3.79E+08	314
Bmin	153	152	160	140	153	2.80E+08	157
Bav	167	169	168	154	167	2.90E+08	173
B2005	204	204	188	178	203	3.16E+08	213
S2005/Sav	141.3%	123.7%	132.4%	139.0%	140.5%	108.8%	134.2%
B2005/Bav	121.9%	121.0%	111.9%	115.9%	121.5%	109.0%	123.1%
S2005/Smin	173.8%	170.6%	166.5%	167.9%	171.4%	110.5%	160.8%
B2005/Bmin	133.6%	134.2%	117.6%	126.9%	132.9%	112.7%	135.8%

6.4 McMC results

An McMC was run for each of runs 073, 041 and 059. McMCs were run as single chains, started at the MPD, for 5 million simulations with 5000 samples saved. In contrast to the runs for PAU 5D, *sigmatilde* was not fixed during McMCs.

Traces were acceptable and appeared to be well mixed. Representative plots of these are shown from each of the three runs in Figure 67 through Figure 69. In run 073, ln(*R0*) and *M* showed an excursion in the centre of the run; this affected biomass indicators but was brief and transient. Run 059 showed a similar brief excursion in *galpha* that affected biomass indicators.

As well as traces, our main diagnostics were plots of running and moving statistics: representative plots are shown in Figure 70 through Figure 72. We saw no reason to suspect that the chains were not converged, with one single exception: the MPD estimate for *Eps* for 1991 in run 041 was on its upper bound, and this caused poor mixing in the McMC.

The excursions discussed earlier are reflected in the moving means and, for run 059, in the running statistics, which follow the excursion early on, but they are not serious. Marginal posteriors appeared to be well formed, with the MPD mostly near the centre of the distribution (Figure 73 through Figure 75).

Runs 041 and 059 showed comparatively few substantial correlations among parameters (Table 43). Outside the recruitment deviations, these involved correlations between natural mortality and base recruitment, and among the growth parameters or between growth and selectivity. Run 073 had many more substantial correlations: the additional ones involved the catchabilities for the two abundance indices, underscoring the compromise nature of this fit.

Table 43: Correlations among estimated parameters in PAU 5A McMCs from the three runs. Correlations with absolute values less than 0.50 are not shown.

Par1	Par2	Run 073	Run 041	Run 059
ln(*R0*)	*M*	0.92	0.85	(Fixed *M*)
ln(*R0*)	ln(*qCPUE*)	-0.87		
ln(*R0*)	ln(*qRDSI*)	-0.92		
M	ln(*qCPUE*)	-0.73		
M	ln(*qRDSI*)	-0.80		
sigmatilde	*GrowthCV*	-0.52		
galpha	*RD50*		-0.68	
galpha	*GrowthCV*		-0.57	-0.94
galpha	*Eps 1998*	-0.55		
galpha	*Eps 1999*	0.68		
gBeta	*GrowthCV*		-0.66	-0.88
gBeta	ln(*qRDSI*)	0.51		
ln(*qCPUE*)	ln(*qRDSI*)	0.96		
CS50	*CS95*	0.65	0.61	
Eps1993	*Eps1994*	-0.52		-0.56
Eps1994	*Eps1995*	-0.53		
Eps1998	*Eps1999*	-0.73	-0.56	-0.51
Eps1999	*Eps2000*		-0.60	-0.51

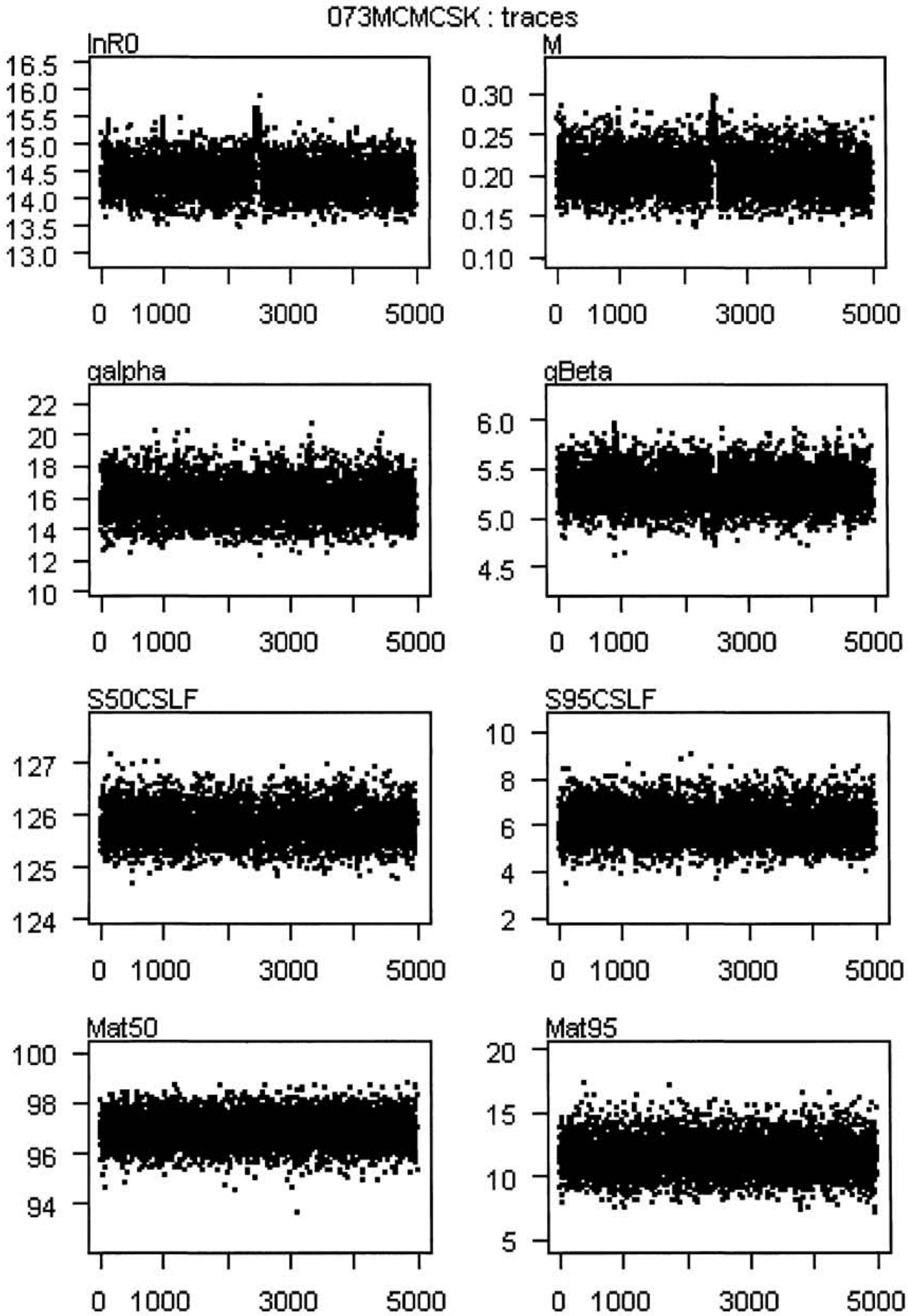


Figure 67: Traces for the first eight estimated parameters from the McMC of run 073 for PAU 5A.

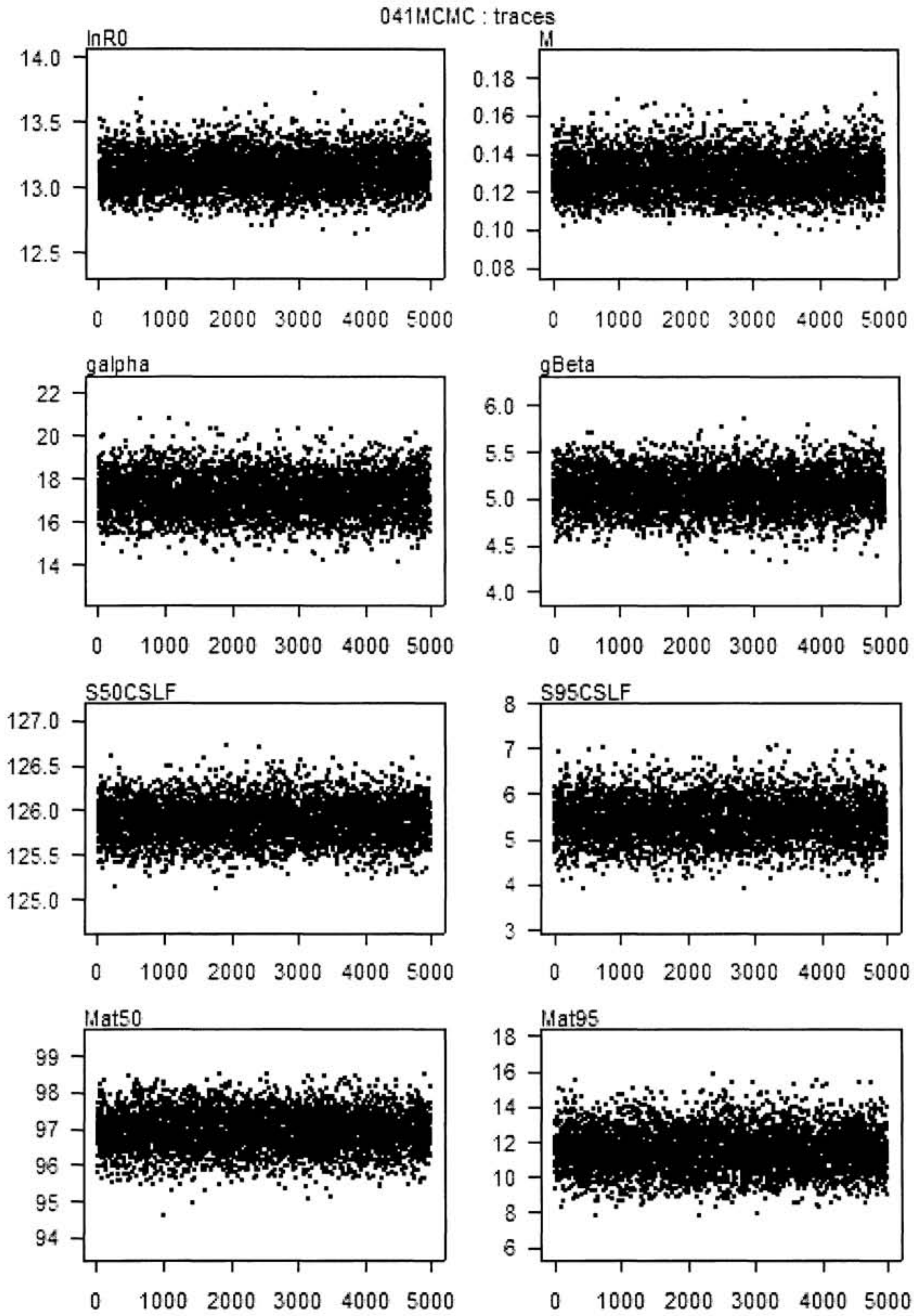


Figure 68: Traces for the first eight estimated parameters from the McMC of run 041 for PAU 5A.

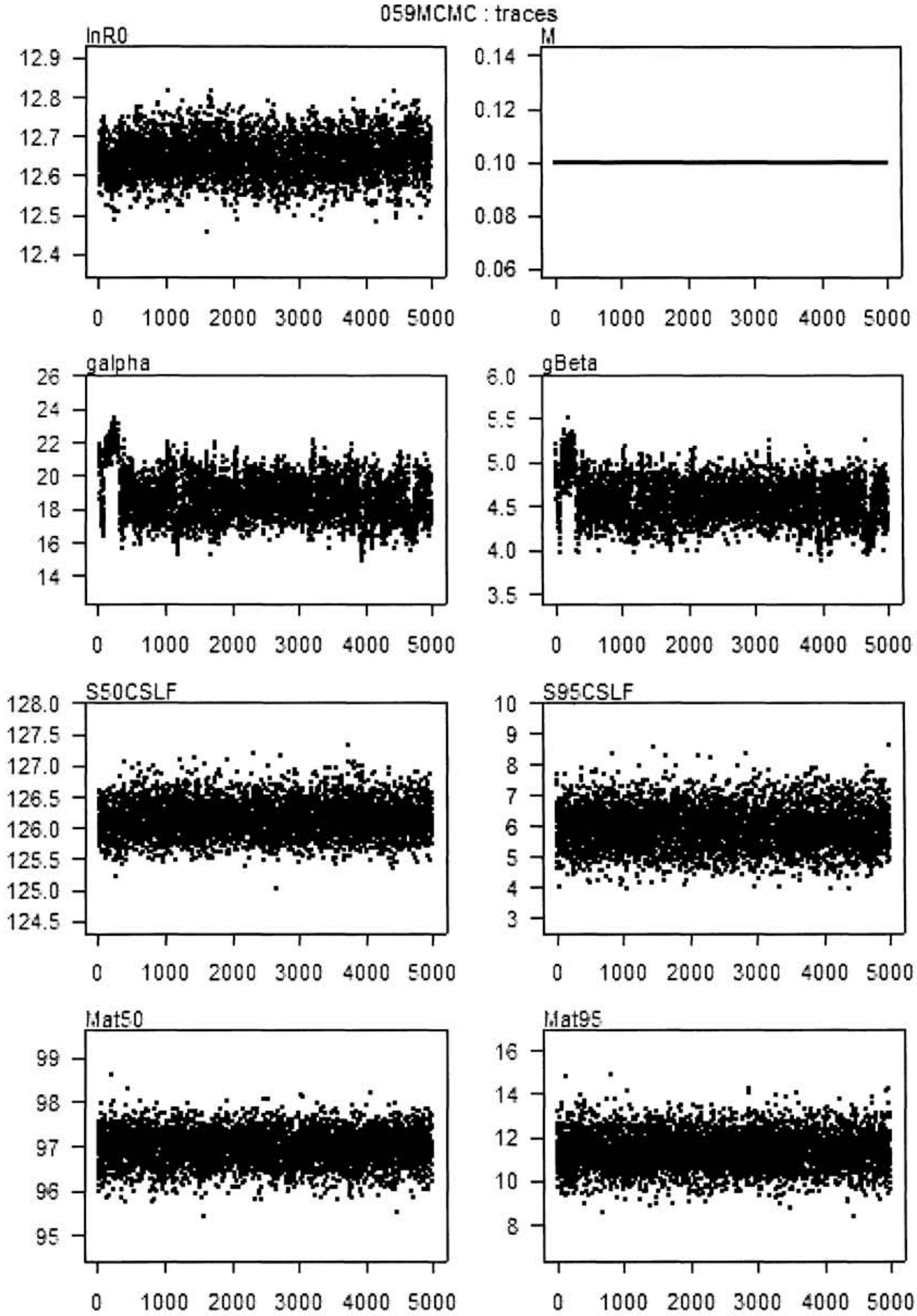


Figure 69: Traces for the first eight estimated parameters from the McMC of run 059 for PAU 5A.

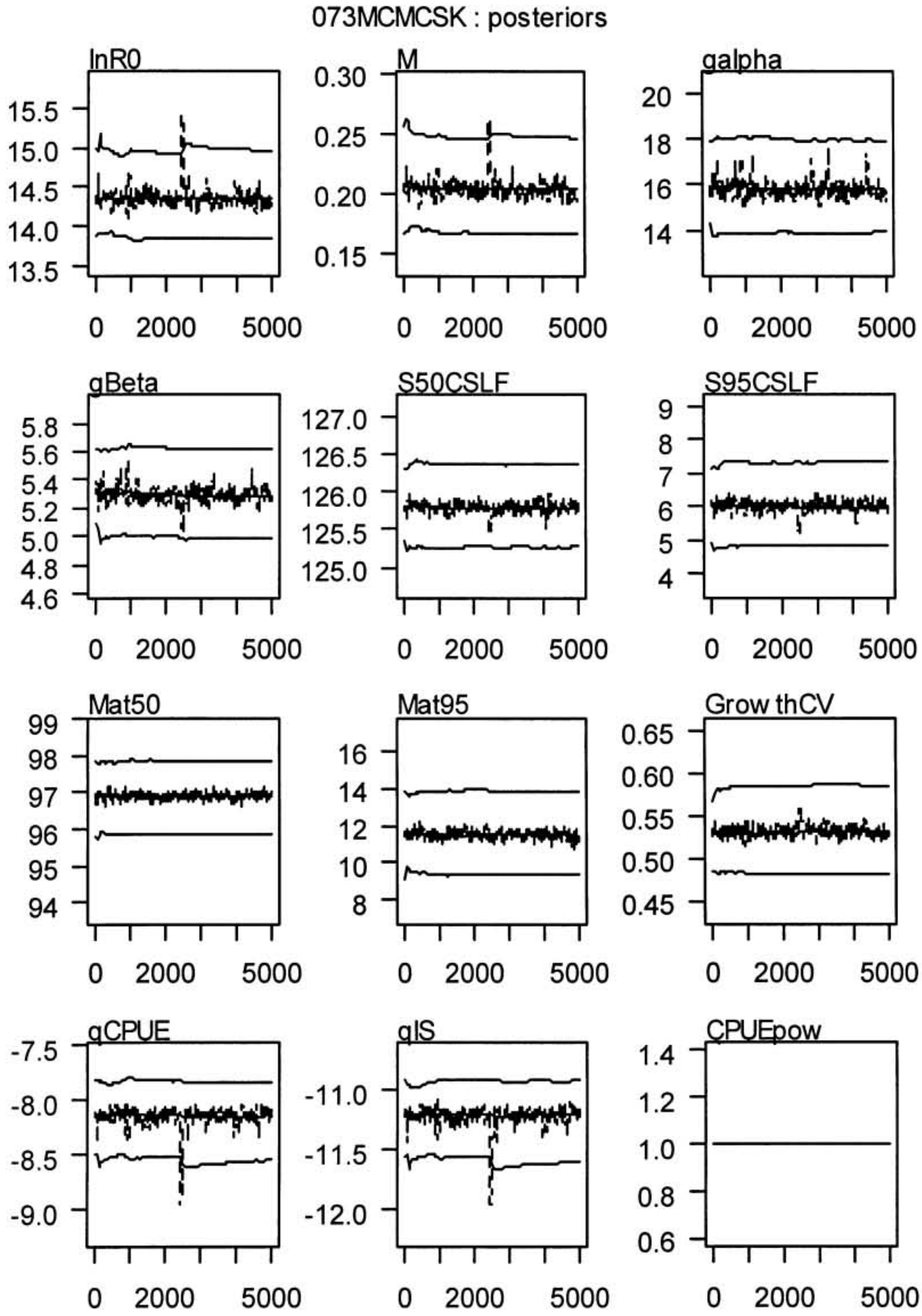


Figure 70: Diagnostic plots on the traces for the first 12 estimated parameters from the McMC for run 073 for PAU 5A. The central line is the running median; the upper and lower lines are the running 5th and 95th quantiles; the central dots show a moving average over 40 samples.

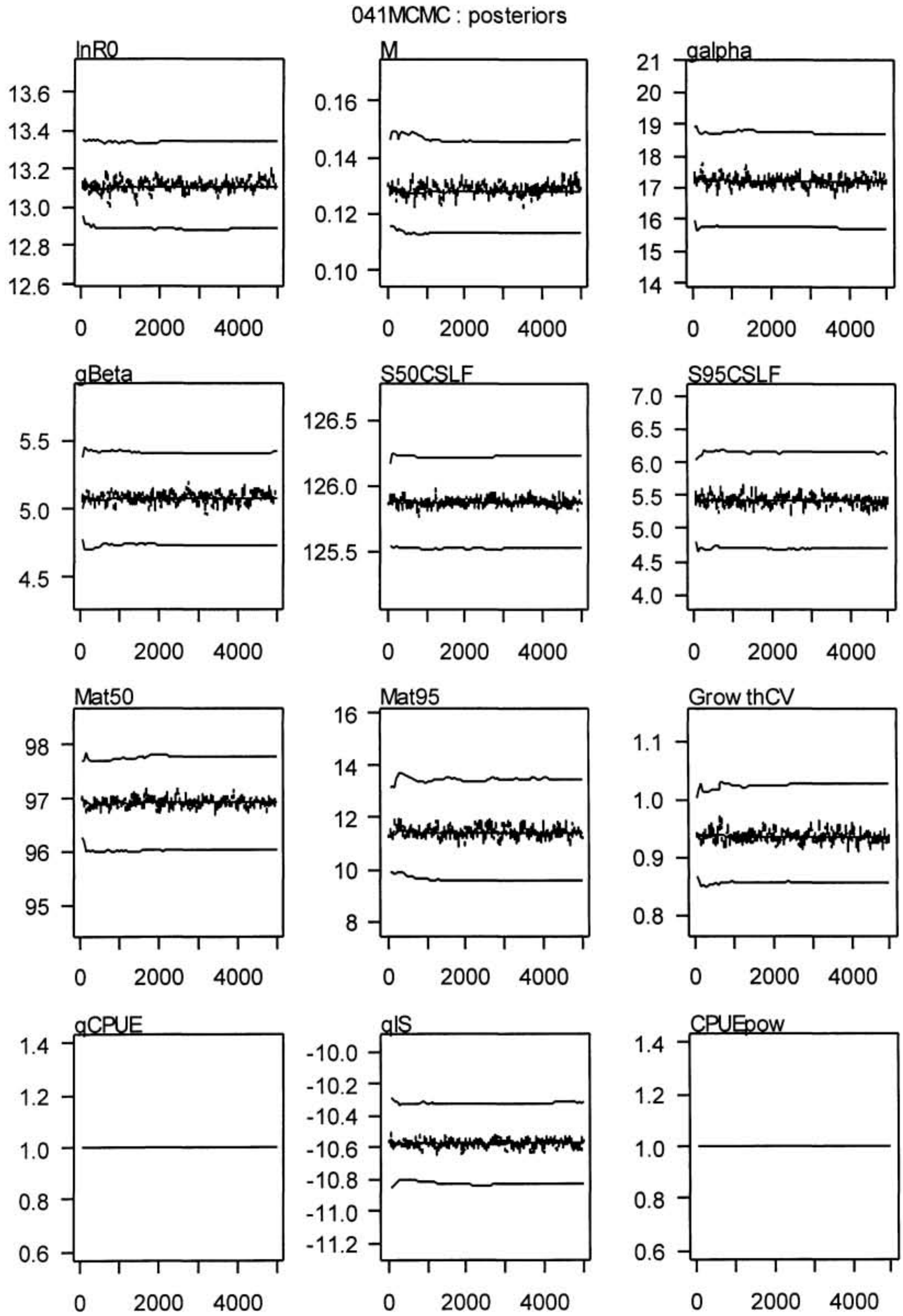


Figure 71: Diagnostic plots on the traces for the first 12 estimated parameters from the McMC for run 041 for PAU 5A.

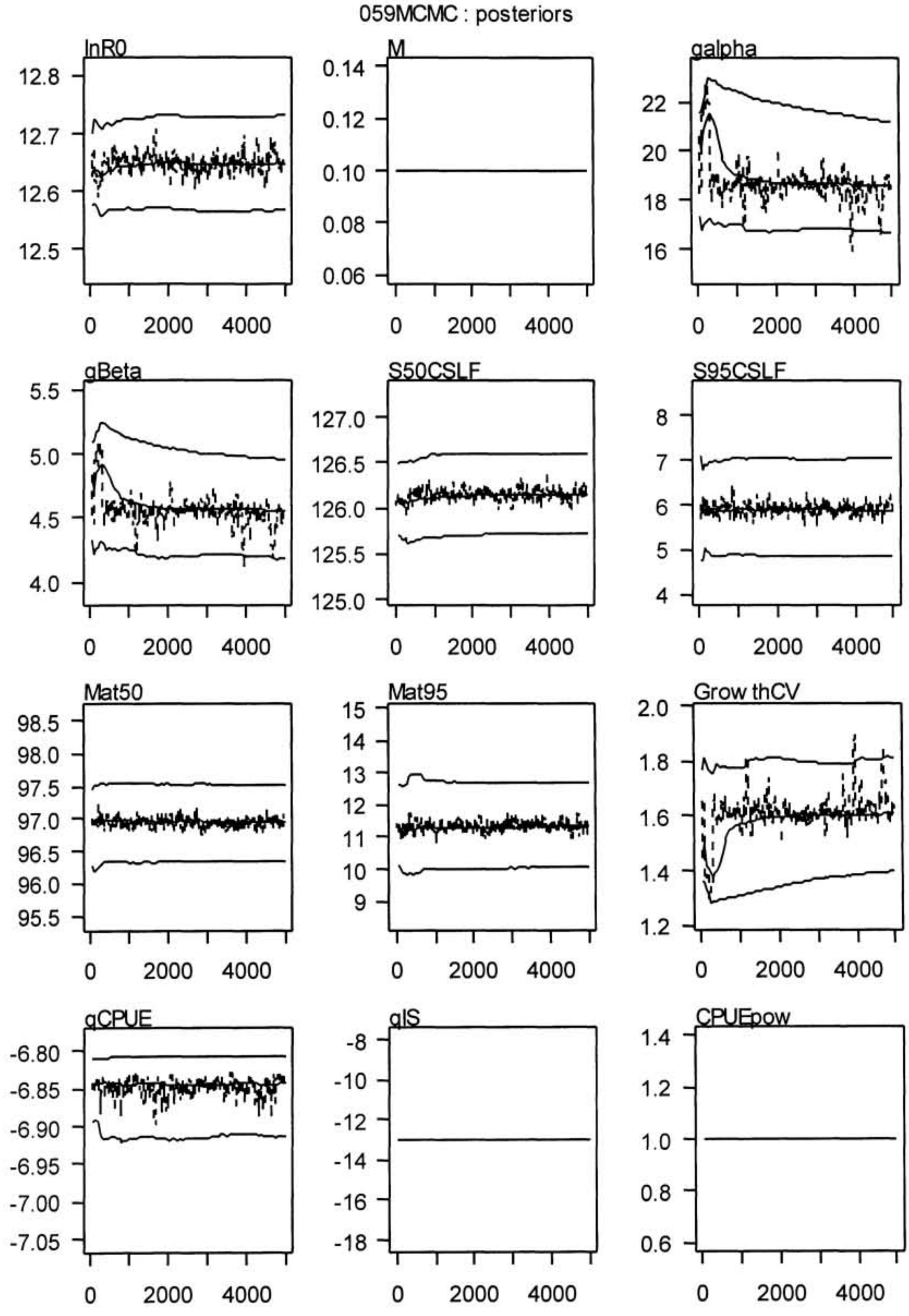


Figure 72: Diagnostic plots on the traces for the first 12 estimated parameters from the McMC for run 059 for PAU 5A.

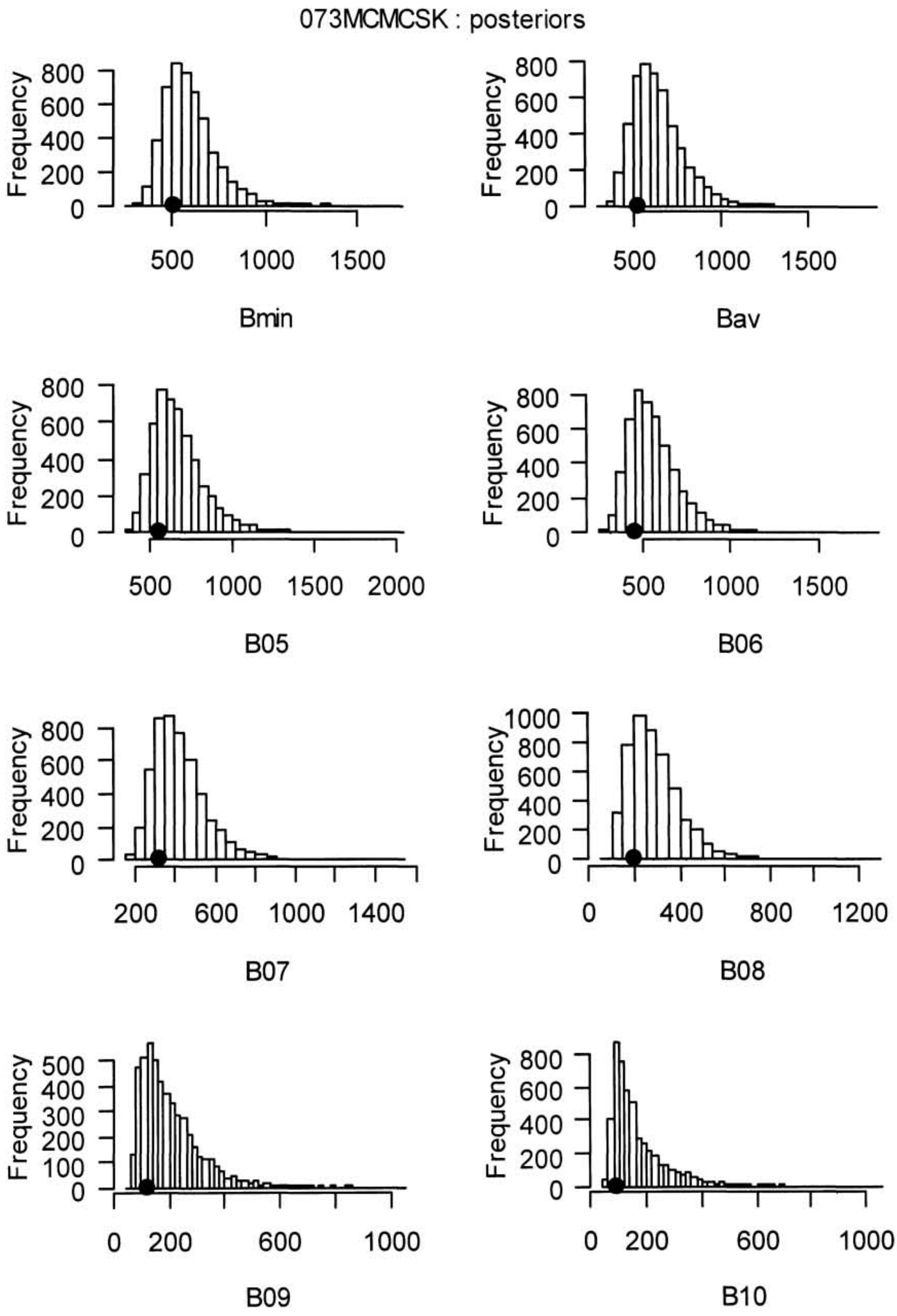


Figure 73: Marginal posterior distributions of some indicators from the McMC for run 073 for PAU 5A. Dots show the location of the MPD estimate.

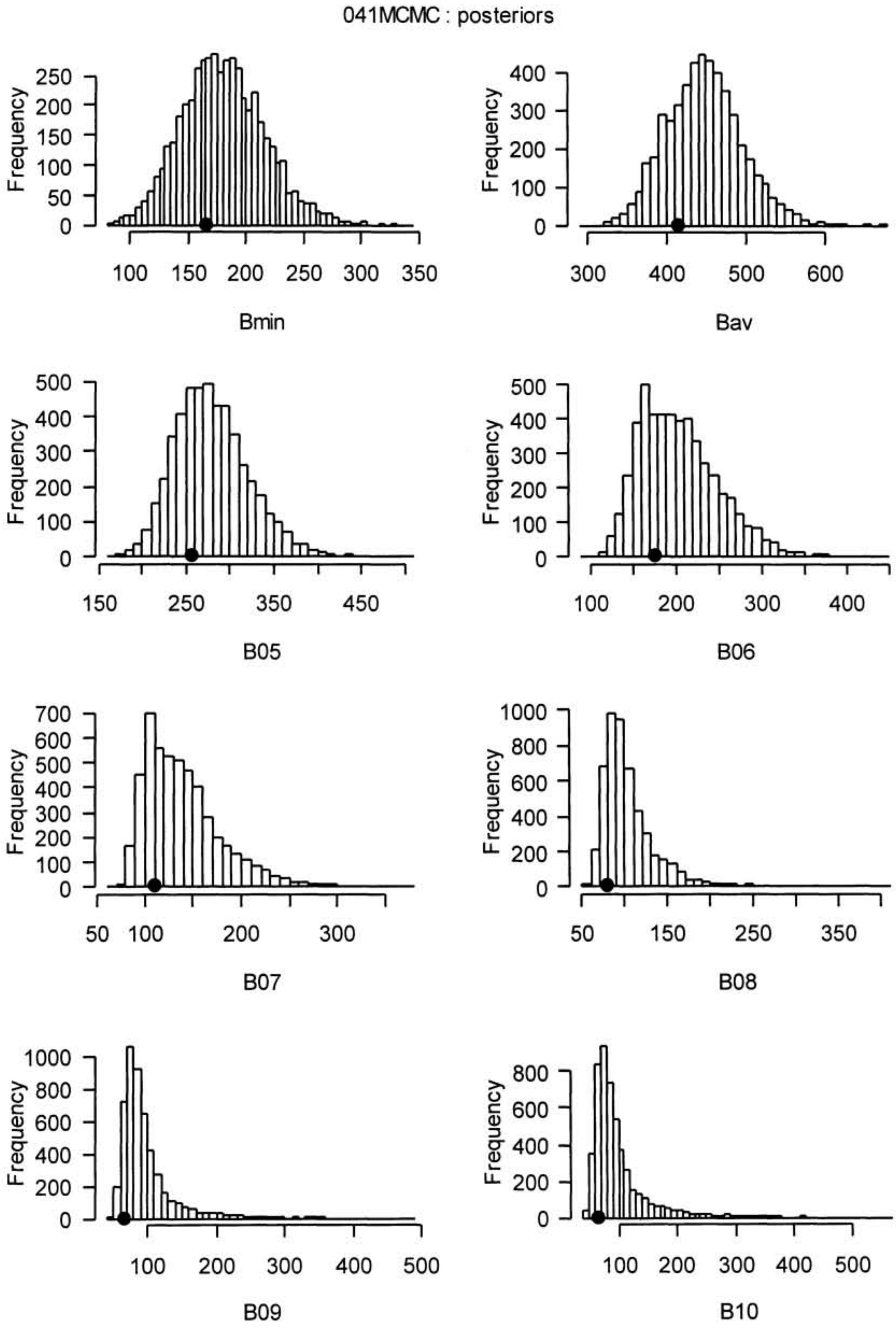


Figure 74: Marginal posterior distributions of some indicators from the McMC for run 041 for PAU 5A. Dots show the location of the MPD estimate.

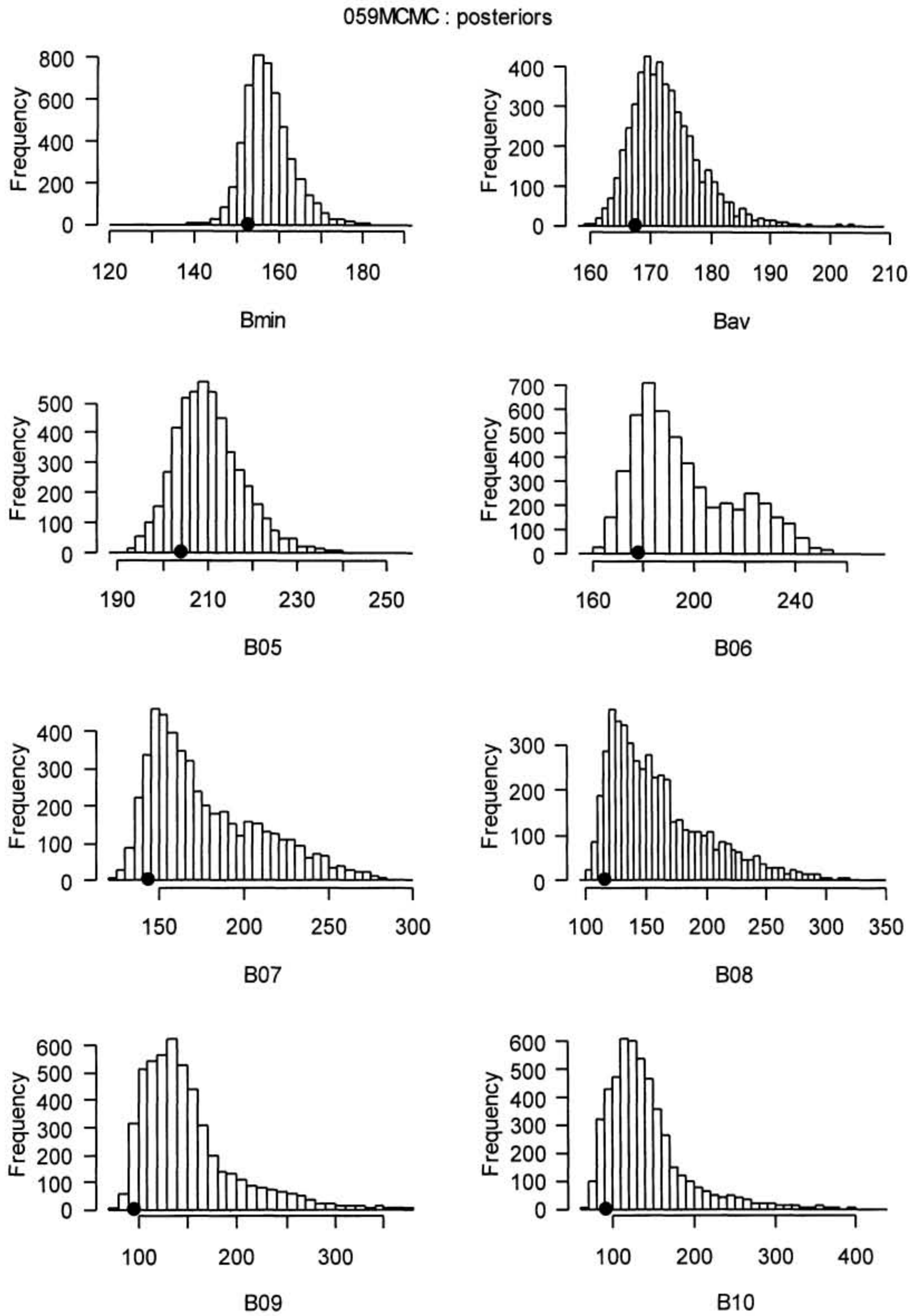


Figure 75: Marginal posterior distributions of some indicators from the McMC for run 059 for PAU 5A. Dots show the location of the MPD estimate.

Marginal posterior distributions of estimated parameters are summarised from the three runs in Table 44. The MPD estimates for most parameters are near the centre of the posterior. As noted for the MPDs, there is not much difference among the selectivity and maturity parameters among the three runs, variability of growth increases from 073 to 059, *M* is higher in run 073 than in run 041.

Table 44: Summaries of the marginal posterior distributions of estimated parameters from the three PAU 5A runs described in the text. Columns show the minimum and maximum, 5th and 95th quantiles and median of each distribution, and the position of the MPD estimate in the marginal posterior. Grey indicates fixed parameters.

Run						073						041						059
Parameter	Min	0.05	Median	0.95	Max	MPD	Min	0.05	Median	0.95	Max	MPD	Min	0.05	Median	0.95	Max	MPD
LikeTotal	-246.6	-232.0	-225.0	-216.4	-206.9		-538.5	-523.7	-517.0	-508.4	-498.1		-384.0	-368.7	-361.4	-352.8	-340.1	
ln(*R0*)	13.48	13.85	14.35	14.96	15.86	0.344	12.63	12.89	13.11	13.35	13.73	0.454	12.45	12.57	12.65	12.73	12.82	0.504
sigmatilde	0.392	0.429	0.455	0.485	0.514	0.435	0.337	0.355	0.373	0.392	0.416	0.295	0.237	0.252	0.264	0.278	0.298	0.228
M	0.137	0.166	0.203	0.246	0.295	0.325	0.097	0.113	0.128	0.146	0.172	0.468	0.100	0.100	0.100	0.100	0.100	
galpha	12.3	13.9	15.8	17.9	20.6	0.369	14.1	15.7	17.2	18.7	20.8	0.493	14.9	16.7	18.6	21.2	23.5	0.602
gBeta	4.6	5.0	5.3	5.6	5.9	0.660	4.3	4.7	5.1	5.4	5.8	0.725	3.9	4.2	4.6	5.0	5.5	0.531
RD50	110	110	110	110	110		103.5	108.3	110.7	112.9	115.0	0.569	105.6	109.8	112.3	114.5	117.4	0.491
RD95	19	19	19	19	19		13.8	16.5	19.6	23.6	30.3	0.509	11.6	16.2	20.1	25.2	34.2	0.390
CS50	124.7	125.3	125.8	126.4	127.2	0.595	125.1	125.5	125.9	126.2	126.7	0.586	125.0	125.7	126.1	126.6	127.3	0.434
CS95	3.5	4.8	6.0	7.3	9.1	0.553	3.9	4.7	5.4	6.1	7.0	0.525	3.9	4.9	5.9	7.0	8.6	0.374
mat50	93.6	95.9	96.9	97.9	98.8	0.530	94.6	96.0	96.9	97.8	98.5	0.523	95.4	96.3	97.0	97.5	98.6	0.516
mat95	7.1	9.4	11.5	13.9	17.4	0.450	7.8	9.6	11.4	13.5	15.9	0.461	8.4	10.1	11.3	12.7	14.9	0.481
GrowthCV	0.433	0.481	0.531	0.585	0.655	0.375	0.779	0.857	0.934	1.027	1.143	0.369	1.215	1.401	1.609	1.816	1.980	0.503
ln(*qCPUE*)	-9.26	-8.54	-8.14	-7.83	-7.54	0.752	1.00	1.00	1.00	1.00	1.00		-7.06	-6.91	-6.84	-6.81	-6.78	0.800
ln(*qRDSI*)	-12.25	-11.60	-11.21	-10.92	-10.66	0.745	-11.25	-10.83	-10.58	-10.32	-9.94	0.631	-13.00	-13.00	-13.00	-13.00	-13.00	

The posterior trajectories of spawning biomass (Figure 76 through Figure 78) show greatest uncertainty in run 073, least in run 059. The shapes of the curves are roughly similar among the three runs, but vary in scale and timing. All three runs show a strong decrease after 2005, although runs 073 and 041 both show stabilisation or increase in the medians by 2010 (this is caused by the exploitation rate being bounded).

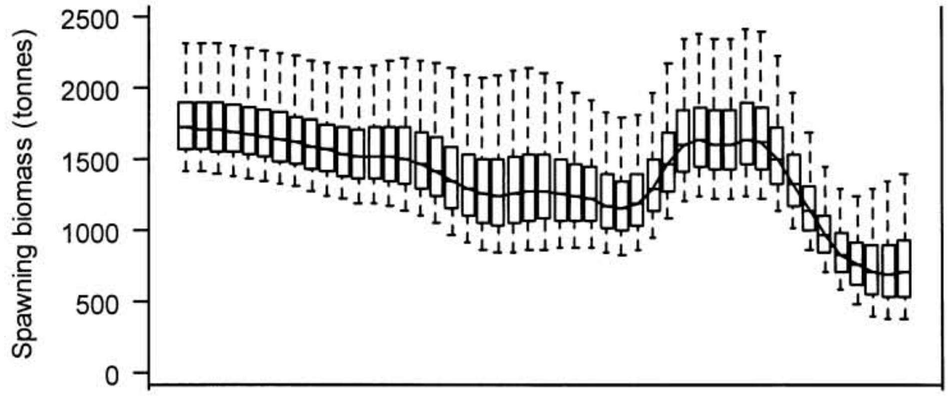


Figure 76: Posterior distribution of the spawning biomass trajectory from run 073 for PAU 5A. The box plots show, for the distribution for each year, the median, 25th-75% range and the 5%-95% range.

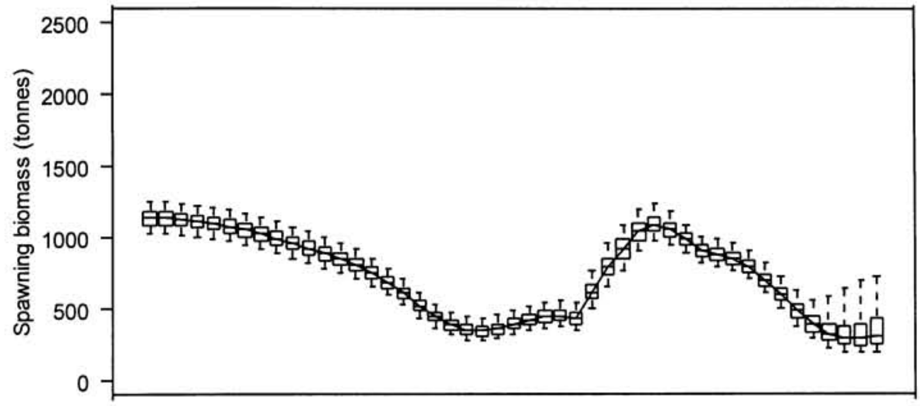


Figure 77: Posterior distribution of the spawning biomass trajectory from run 041 for PAU 5A.

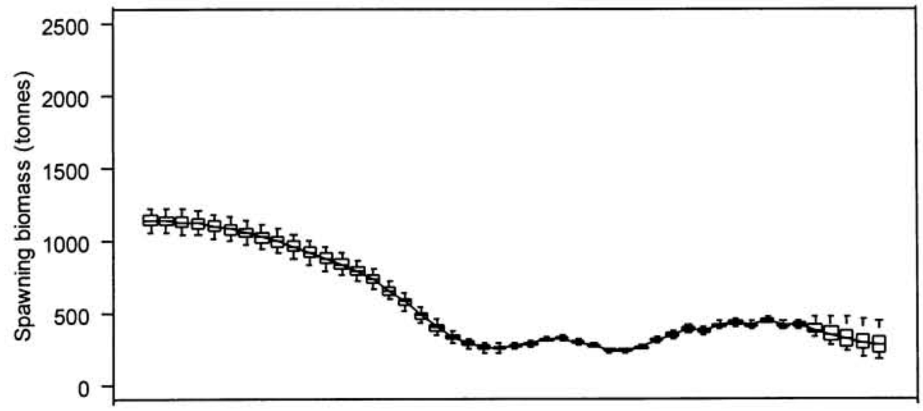


Figure 78: Posterior distribution of the spawning biomass trajectory from run 059 for PAU 5A.

Recruited biomass posterior trajectories (Figure 79 through Figure 81) show the same differences in uncertainty as for spawning biomass, with run 073 having the widest posteriors and run 059 the narrowest. Shapes of these trajectories differ after the early 1990s, but all decrease after 2005.

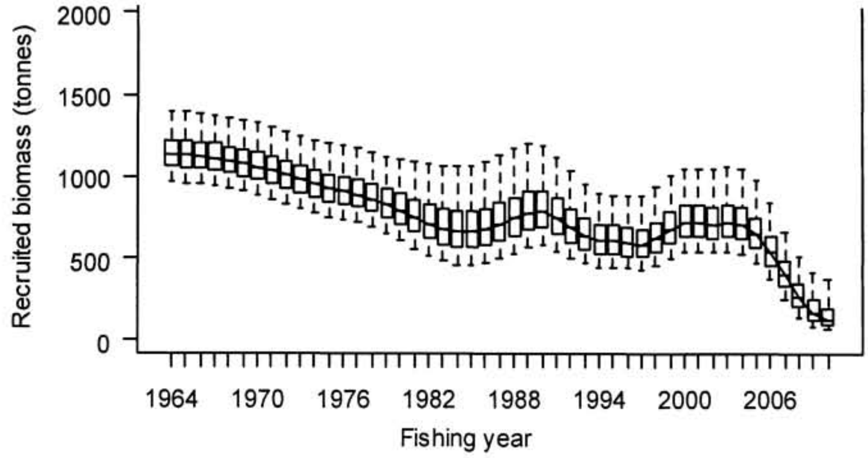


Figure 79: Posterior distribution of the recruited biomass trajectory from run 073 for PAU 5A.

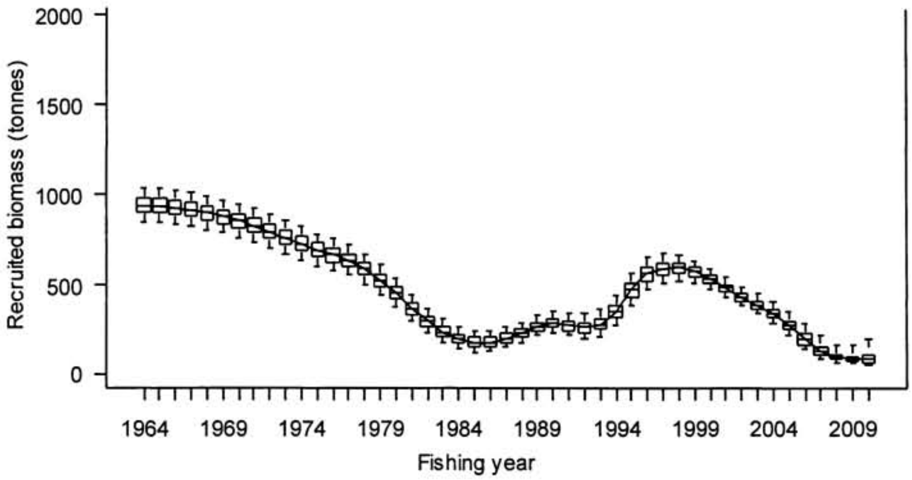


Figure 80: Posterior distribution of the recruited biomass trajectory from run 041 for PAU 5A.

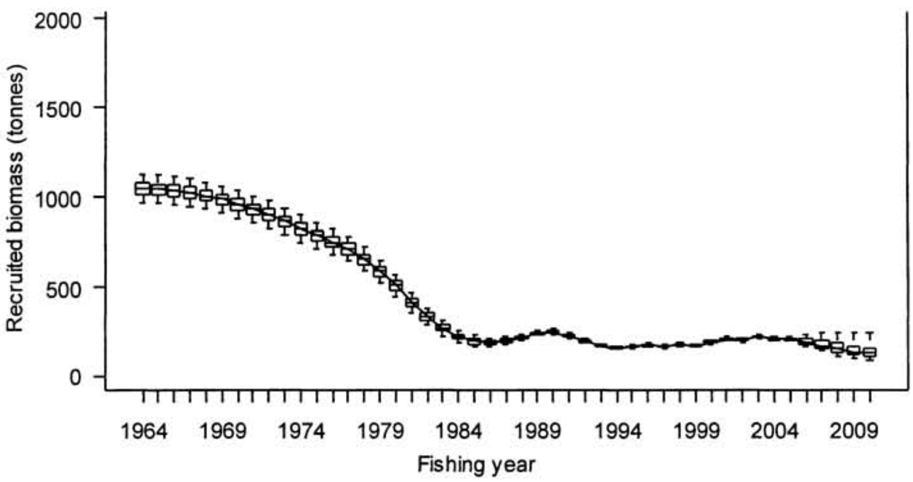


Figure 81: Posterior distribution of the recruited biomass trajectory from run 059 for PAU 5A.

The most recent years of recruited biomass posterior trajectories are shown in Figure 82 through Figure 84. Run 073 shows the strongest biomass decline after 2005, run 059 the shallowest; run 041 is intermediate as it is in many aspects of these three runs.

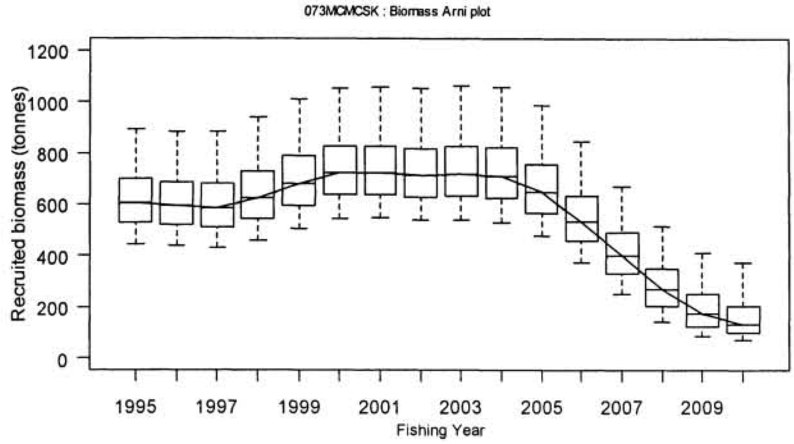


Figure 82: Posterior distribution of the recruited biomass trajectory from run 073 for PAU 5A, 1995 to 2010.

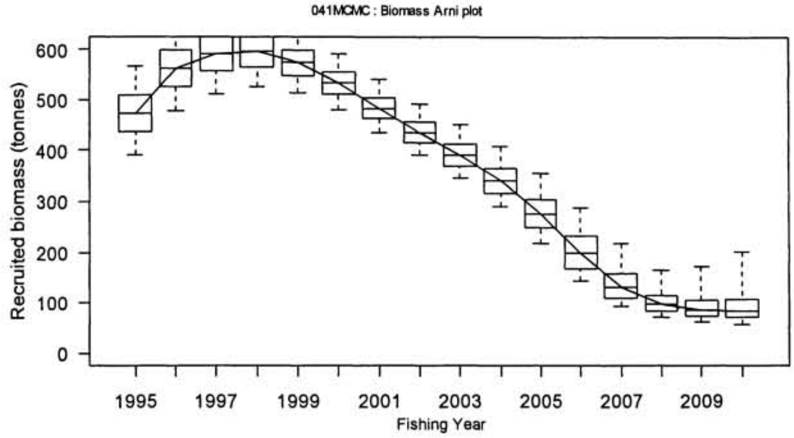


Figure 83: Posterior distribution of the recruited biomass trajectory from run 041 for PAU 5A, 1995 to 2010.

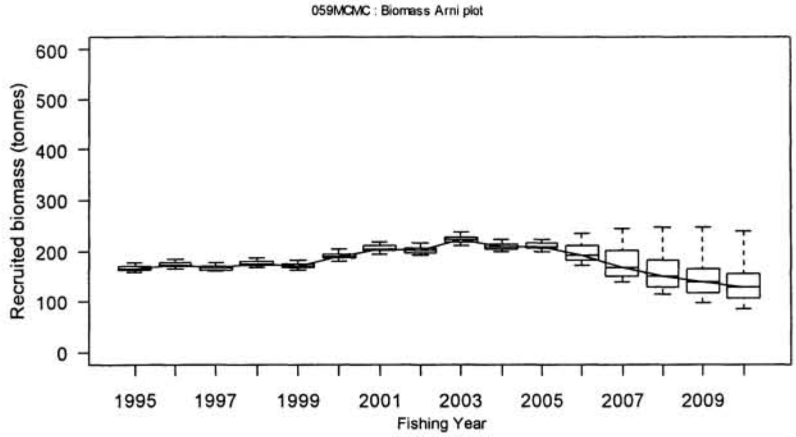


Figure 84: Posterior distribution of the recruited biomass trajectory from run 059 for PAU 5A, 1995 to 2010.

Exploitation rate trajectories (Figure 85 through Figure 87) show the differences already discussed in the MPDs (Figure 65): run 073 had the lowest rate in 2005, but the rate increases sharply after 2005, and by 2010 the median is on the upper bound of 65%. Run 041 also shows a steep increase, one that began earlier, and nearly all runs are on the upper bound after 2006. The shape is different for run 059, but nearly all runs are also on the upper bound after 2006.

Recruitment trajectories (Figure 85 through Figure 87) show patterns similar to those seen in the MPDs (Figure 65).

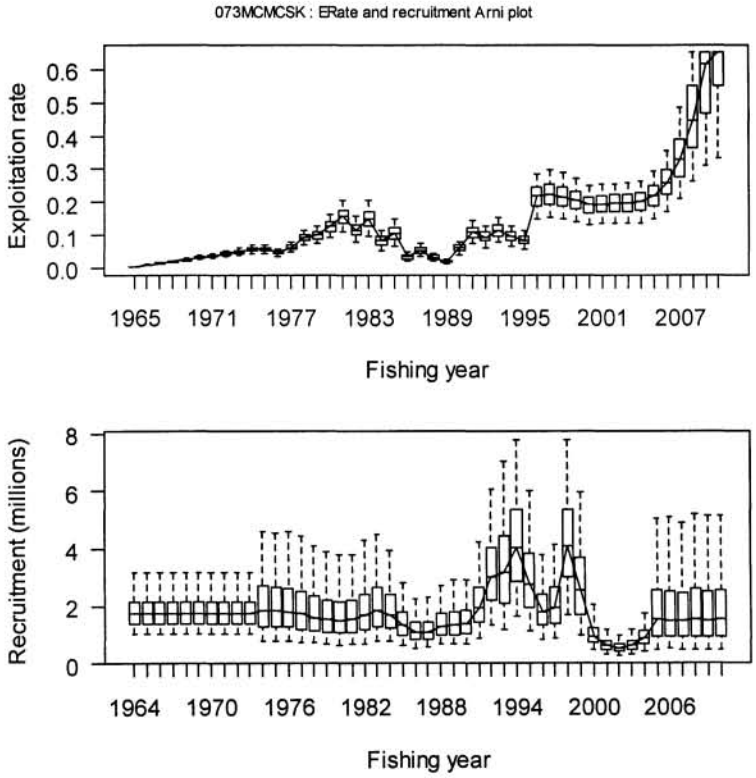


Figure 85: Posteriors of the exploitation rate (upper) and recruitment trajectories from run 073 for PAU 5A.

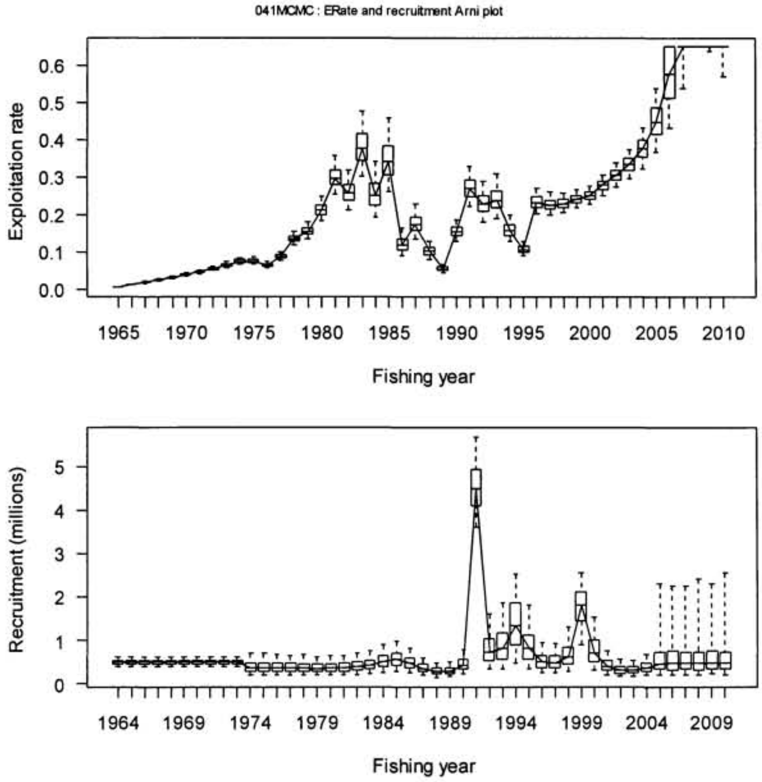


Figure 86: Posteriors of the exploitation rate (upper) and recruitment trajectories from run 041 for PAU 5A.

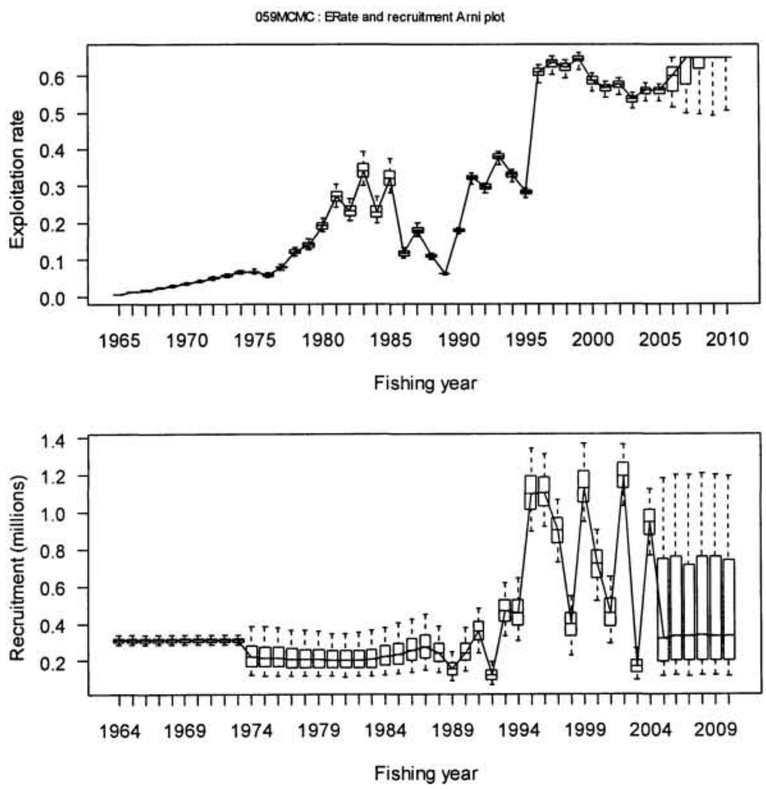


Figure 87: Posteriors of the exploitation rate (upper) and recruitment trajectories from run 059 for PAU 5A.

6.5 PAU 5A assessment results

Indicators are summarised in Table 45, which shows substantial difference among the three runs in current biomass and exploitation rate. *U2005* hardly overlaps among the three runs: the 90% confidence interval is 15–30% in run 073, 37–54% in run 041 and 53–60% in run 059. Current biomass patterns are the inverse of this: largest in run 073 and least in run 059; reference biomass is also greatest in run 073 and least in run 059.

Projections reflect the strong tendencies for exploitation rates to increase to the upper bound (Figure 85 through Figure 87) and for recruited biomass to decrease (Figure 82 through Figure 84).

Three-year projected indicators (Table 45) are most optimistic for run 073, but there is a strong trend in that run for both spawning and recruited biomass to decrease compared with 2005 biomass. In run 041, nearly all runs had *U2008* on the upper bound of 65%; in run 059 more than half the runs were on this bound. The trend for biomass to decrease, seen in run 073, was also present in these runs.

Five-year projections also showed high proportions of runs on the upper bound for *U2010*, and showed decreasing biomass. The probabilities of biomass decrease, measured in various ways (Table 46), were mostly greater than 50%; many were greater than 90%.

Despite the substantial differences among the three runs, all three runs suggest that current catches are unsustainable.

Table 45: Summaries of the marginal posterior distributions of indicators from the three PAU 5A runs described in the text. Columns show the minimum and maximum, 5th and 95th quantiles and median of each distribution, and the position of the MPD estimate in the marginal posterior. Biomass in tonnes.

Run						073						041						059
Indicator	Min	0.05	Median	0.95	Max	MPD	Min	0.05	Median	0.95	Max	MPD	Min	0.05	Median	0.95	Max	MPD
U2005	0.073	0.149	0.219	0.291	0.376	0.748	0.272	0.366	0.449	0.538	0.651	0.673	0.478	0.532	0.561	0.579	0.595	0.753
Smin	544	702	954	1440	2940	0.249	201	270	340	430	634	0.318	182	222	236	251	288	0.283
Sav	824	1051	1412	2110	4130	0.265	684	810	928	1069	1407	0.302	265	278	294	313	356	0.156
S2005	544	702	954	1440	2940	0.249	290	382	482	619	861	0.334	362	389	414	442	502	0.212
Bmin	294	419	578	870	1726	0.275	81	125	179	242	343	0.363	121	149	157	168	192	0.199
Bav	348	457	621	927	1855	0.250	291	373	446	529	676	0.260	159	165	172	183	208	0.169
B2005	362	476	649	985	2028	0.245	168	218	276	355	503	0.328	189	199	209	224	255	0.213
S2005/Sav	0.587	0.630	0.674	0.723	0.794	0.378	0.337	0.433	0.520	0.630	0.791	0.436	1.330	1.369	1.407	1.444	1.489	0.593
S2005/Smin	1.000	1.000	1.000	1.000	1.036	0.000	1.000	1.140	1.421	1.782	2.393	0.522	1.632	1.686	1.753	1.837	2.153	0.350
B2005/Bav	0.930	0.995	1.047	1.100	1.162	0.463	0.392	0.504	0.620	0.770	0.956	0.500	1.152	1.187	1.218	1.250	1.298	0.518
B2005/Bmin	1.000	1.057	1.121	1.219	1.611	0.374	1.000	1.165	1.550	2.155	3.259	0.506	1.251	1.290	1.335	1.386	1.700	0.510
U2008	0.114	0.261	0.447	0.650	0.650		0.334	0.650	0.650	0.650	0.650		0.371	0.494	0.650	0.650	0.650	
S2008	544	398	706	1289	2696		143	200	294	645	1289		187	230	315	474	668	
S2008/Sav	0.254	0.347	0.486	0.701	1.063		0.158	0.225	0.314	0.696	1.196		0.660	0.792	1.076	1.603	2.208	
S2008/S2005	0.368	0.527	0.722	1.034	1.564		0.363	0.455	0.593	1.356	2.654		0.480	0.565	0.762	1.141	1.544	
B2008	544	143	271	517	1277		52	71	96	165	408		96	114	151	247	348	
B2008/Bav	0.216	0.305	0.437	0.569	0.692		0.115	0.160	0.217	0.369	0.821		0.546	0.661	0.875	1.426	2.004	
B2008/B2005	0.216	0.297	0.418	0.535	0.649		0.247	0.293	0.349	0.552	1.036		0.461	0.546	0.718	1.168	1.632	
U2010	0.135	0.334	0.650	0.650	0.650		0.245	0.572	0.650	0.650	0.650		0.311	0.506	0.650	0.650	0.650	
S2010	544	375	700	1388	2878		136	191	312	726	1609		121	176	276	452	740	
S2010/Sav	0.179	0.304	0.491	0.768	1.235		0.153	0.210	0.330	0.768	1.857		0.432	0.601	0.938	1.536	2.448	
S2010/S2005	0.262	0.455	0.727	1.135	1.763		0.296	0.406	0.634	1.482	3.218		0.317	0.429	0.667	1.088	1.731	
B2010	544	73	133	372	1050		40	58	84	200	569		63	85	129	239	430	
B2010/B2005	0.093	0.135	0.208	0.412	0.765		0.162	0.212	0.299	0.742	2.000		0.306	0.406	0.615	1.134	2.018	

Table 46: For three-year (upper portion) and five-year projections (both with MLS = 125 mm), the probabilities that spawning or recruited biomass will be less than the other indicators shown, based on the McMC results from the runs shown.

			Run
Probability	073	041	059
S2008<S2005	0.932	0.890	0.860
S2008<Sav	1.000	0.997	0.403
B2008<B2005	1.000	1.000	0.865
B2008<Bav	1.000	1.000	0.692
S2008<Smin	0.932	0.687	0.067
B08<Bmin	1.000	0.959	0.568
S2010<S2005	0.870	0.804	0.921
S2010<Sav	0.997	0.989	0.588
B2010<B2005	1.000	0.988	0.922
B2010<Bav	1.000	0.999	0.840
S2010<Smin	0.870	0.591	0.285
B2010<Bmin	1.000	0.920	0.758

6.6 Projections with alternative catches

The SFWG requested additional projections with reduced commercial catches for PAU 5A. They specified that total catch should be reduced from the current value of 156.7 t (this included non-commercial estimates) in 30 t increments. We added some intermediate values at the low end, where indicators changed very quickly. The catches used were 36.7 t, 46.7 t, 56.7 t, 66.7 t, 96.7 t, 126.7 t and 156.7 t (the current catch).

Projections were made for five years at the current MLS of 125 mm. Summaries of five-year spawning and recruited biomass indicator posteriors are shown in Figure 88 and more indicators are shown in Table 47 and Table 48.

The median of *U2010* is on the upper bound even when catch is reduced to 127 t, and is still 56% at 97 t catch, then declines rapidly as catch is reduced further.

The probability of *S2010* being less than *S2005* is 80% in the base case; this decreases with decreasing catch and becomes less than 50% somewhere between 57 and 67 t catch. The analogous probability for recruited biomass is 98% in the base case, and this decreases to just over 50% at 57 t catch. That exploitation rate is on its bound at the current catch leads to indicators changing little as catch is reduced, then changing quickly as catch is reduced below about 100 t.

The probability of *S2010* being less than *Smin* is 60% in the base case, reducing very steeply once catch is below 100 t, to 8% at a catch of 57 t. The probability that *B2010* will be less than *Bmin* is 92% in the base case, again declining very steeply after catch is reduced below 100 t, and is also 8% at a catch of 57 t. These probabilities diminish to near zero at 37 t catch.

The SFWG discussed the pattern of estimated recruitments, which for some runs showed lower than average recruitments until the time at which data began; then a set of spikes or pulses. Base case projections were made by re-sampling 25 years of recruitment, and it was possible that the projected recruitment was artificially small. To explore this, we made an alternative set of projections in which recruitment was resampled from 14 years; 14 years being chosen to include a substantial spike of recruitment.

These results are also shown in Table 47 and Table 48 and Figure 89. The results are slightly more optimistic, but the differences are not large.

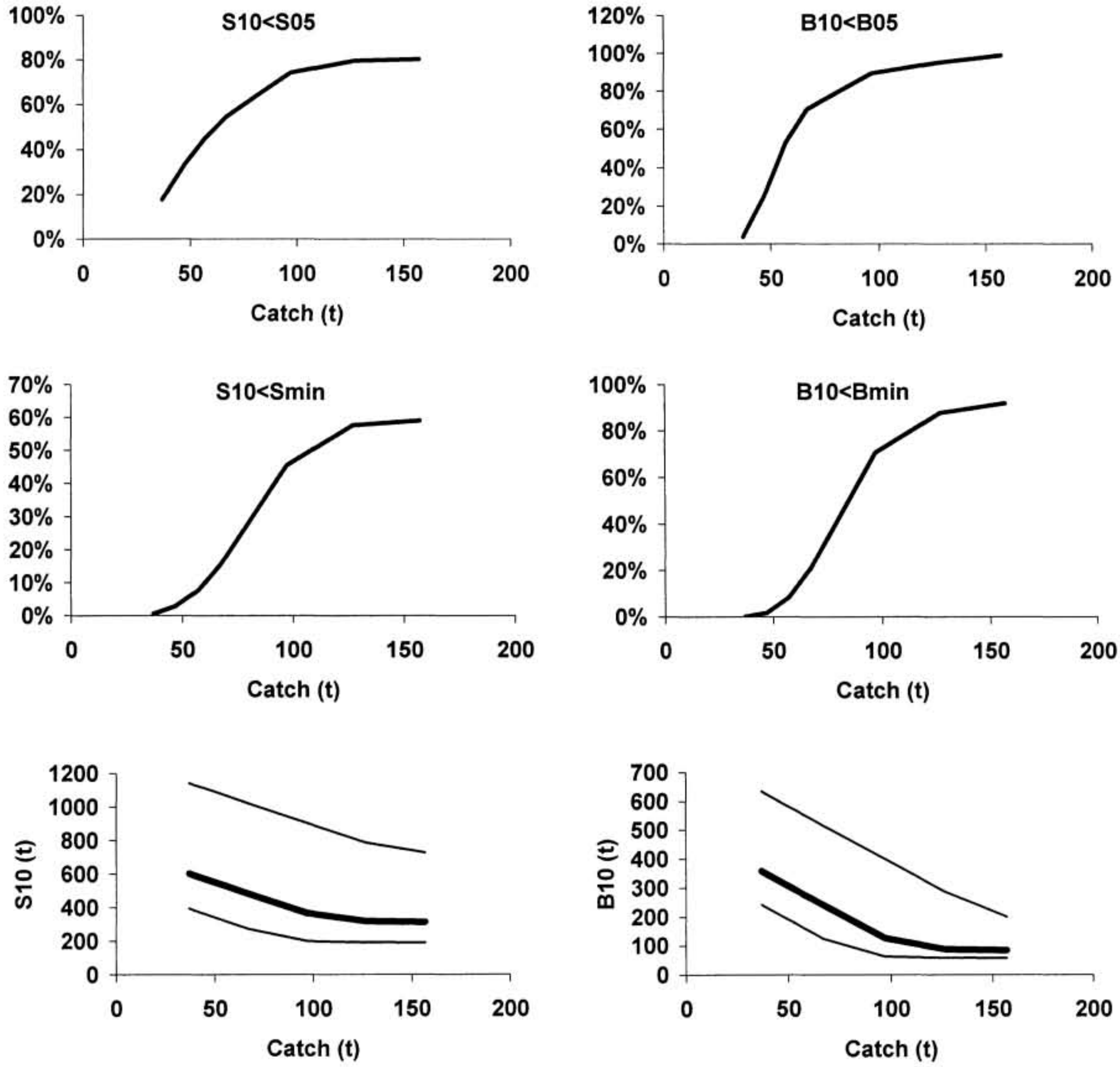


Figure 88: Summary of various indicators with different projected catch levels for PAU 5A.

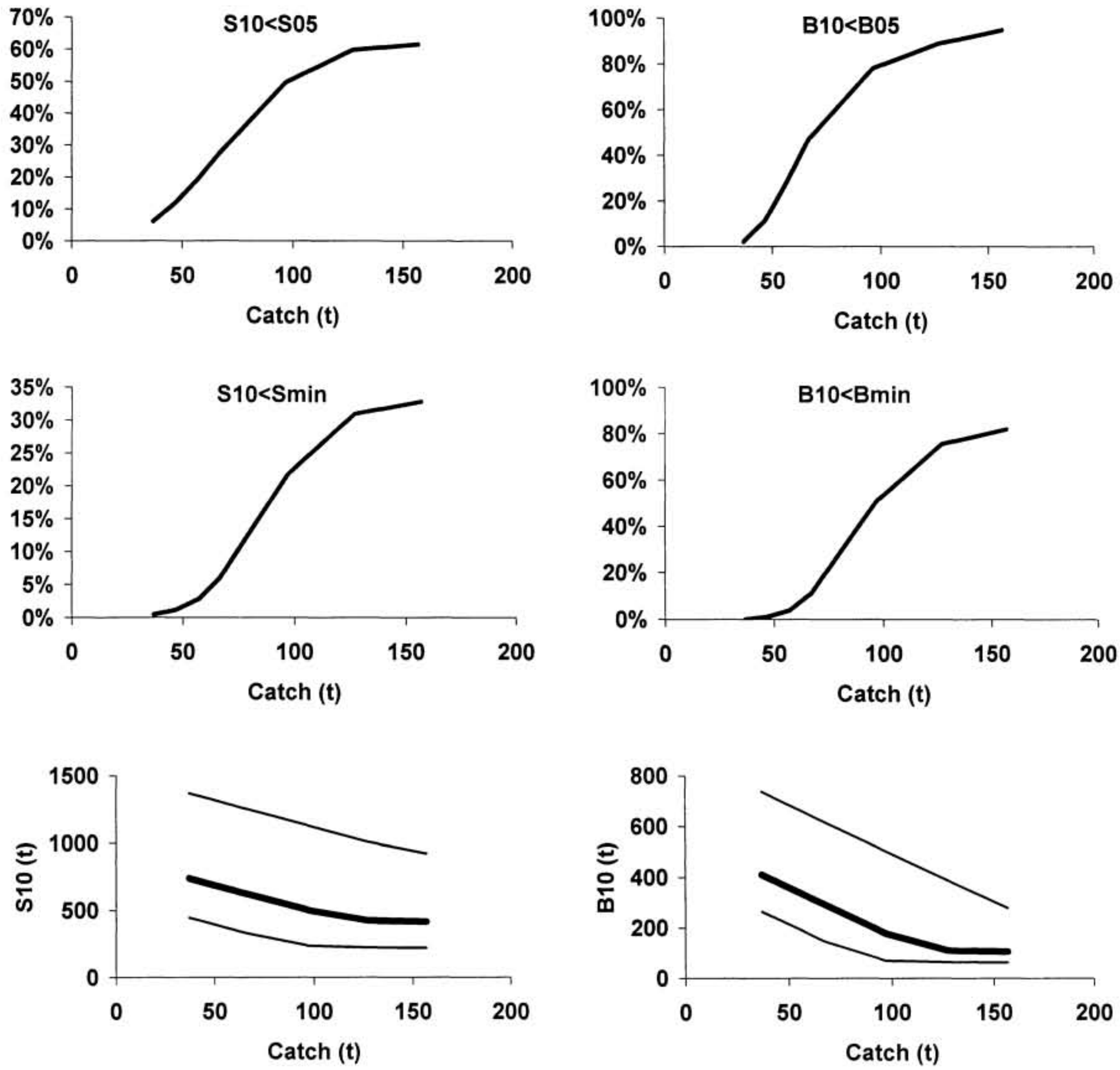


Figure 89: Summary of various indicators from PAU 5A projections with different projected catch levels when recruitment was resampled only from the last 14 years.

Table 47: Summary of exploitation rates and biomass with different projected catch levels from the base case (upper half) and projections made with recruitment resampled from the last 14 years.

Catch	0.05	Median	Basecase 157t 0.95	0.05	Median	127t 0.95	0.05	Median	97t 0.95	0.05	Median	67t 0.95	0.05	Median	57t 0.95
25-yr sampling															
U2008	65.0%	65.0%	65.0%	43.4%	65.0%	65.0%	28.0%	44.7%	65.0%	16.7%	24.7%	36.5%	13.6%	19.7%	28.2%
U2010	57.2%	65.0%	65.0%	36.6%	65.0%	65.0%	21.7%	56.2%	65.0%	12.2%	24.4%	42.5%	9.7%	18.4%	29.6%
S2006	287	387	560	292	402	575	307	417	590	322	432	605	327	437	610
S2007	225	320	590	235	348	624	263	391	667	307	435	711	321	449	725
S2008	200	294	645	205	315	696	228	374	767	294	445	838	317	469	862
S2009	191	296	690	194	307	748	206	364	841	281	459	938	314	492	971
S2010	191	312	726	191	317	785	198	365	903	273	482	1022	312	521	1063
B2006	143	198	288	146	212	303	160	226	317	174	240	331	179	245	336
B2007	93	132	217	98	157	259	123	199	300	165	241	342	179	254	356
B2008	71	96	165	74	113	229	89	171	296	152	239	364	174	261	387
B2009	61	85	172	63	92	242	70	145	334	138	238	426	169	268	458
B2010	58	84	200	58	88	285	63	126	400	125	241	517	164	280	556
14-yr sampling															
U2008	57.9%	65.0%	65.0%	39.3%	65.0%	65.0%	25.7%	41.7%	65.0%	15.5%	23.4%	34.8%	12.7%	18.7%	27.0%
U2010	43.9%	65.0%	65.0%	28.2%	65.0%	65.0%	17.5%	43.1%	65.0%	10.2%	20.4%	37.1%	8.3%	15.7%	26.5%
S2006	290	401	593	297	416	608	312	431	623	327	446	638	332	451	643
S2007	235	354	680	247	384	722	277	427	765	320	470	809	335	485	823
S2008	217	355	767	223	379	829	252	440	900	320	510	970	344	534	993
S2009	213	385	841	218	399	920	236	467	1014	318	563	1110	350	595	1141
S2010	221	415	923	223	425	1012	236	501	1131	326	619	1252	365	659	1290
B2006	144	200	290	147	214	304	161	228	319	175	242	333	180	247	337
B2007	95	136	226	101	163	268	127	205	309	169	247	350	183	260	364
B2008	74	104	195	77	124	260	96	185	327	160	253	395	183	276	417
B2009	65	99	221	67	108	307	77	175	399	153	267	491	184	298	522
B2010	63	106	279	65	110	389	70	177	504	148	293	620	187	332	659

Table 47 continued.

	0.05	Median	47t 0.95	0.05	Median	37t 0.95
25-yr sampling						
U2008	10.8%	15.3%	21.3%	8.1%	11.3%	15.5%
U2010	7.6%	13.6%	20.7%	5.6%	9.8%	14.1%
S2006	332	442	615	337	447	620
S2007	336	464	740	351	478	754
S2008	341	492	886	364	515	909
S2009	346	524	1003	378	555	1036
S2010	353	561	1102	394	601	1141
B2006	184	250	340	188	255	345
B2007	193	268	369	207	282	383
B2008	197	284	409	220	307	432
B2009	200	300	489	232	331	520
B2010	203	319	595	242	358	634
14-yr sampling						
U2008	10.0%	14.5%	20.5%	7.6%	10.8%	14.9%
U2010	6.5%	11.8%	18.8%	4.9%	8.6%	13.0%
S2006	337	456	648	342	461	653
S2007	349	499	838	364	514	852
S2008	368	557	1016	391	581	1040
S2009	383	627	1172	416	659	1204
S2010	406	698	1331	446	738	1371
B2006	184	252	342	189	256	347
B2007	197	274	378	211	288	392
B2008	206	299	440	229	322	463
B2009	215	329	553	246	360	584
B2010	226	371	698	264	410	738

Table 48: Summary of rates and probability indicators with different projected catch levels from the base case and projections made with recruitment resampled from the last 14 years. The first four rows show the biomass ratios indicated; following rows show the probabilities of the event indicated.

			Basecase 157t			127t			97t			67t			57t
	0.05	Median	0.95	0.05	Median	0.95	0.05	Median	0.95	0.05	Median	0.95	0.05	Median	0.95
25-yr sample															
S2008/S2005	45.5%	59.3%	135.6%	48.2%	63.6%	143.1%	55.6%	74.5%	156.6%	71.5%	88.4%	170.8%	76.9%	93.2%	175.4%
S2010/S2005	40.6%	63.4%	148.2%	41.4%	64.5%	158.6%	45.1%	73.2%	179.8%	64.2%	95.6%	205.5%	73.0%	103.7%	214.4%
B2008/B2005	29.3%	34.9%	55.2%	31.6%	40.9%	71.3%	39.8%	60.8%	92.5%	67.0%	85.0%	114.5%	76.9%	93.1%	123.0%
B2010/B2005	21.2%	29.9%	74.2%	22.3%	31.4%	100.0%	25.8%	44.9%	141.1%	53.4%	84.9%	183.0%	69.7%	98.4%	196.8%
P(S2008<S2005)	89.0%			87.0%			81.1%			70.5%			64.0%		
P(B2008<B2005)	100.0%			99.5%			96.1%			86.4%			73.2%		
P(S2008<Smin)	68.7%			60.1%			38.3%			13.0%			7.4%		
P(B2008<Bmin)	95.9%			86.2%			55.9%			14.2%			6.2%		
P(S2010<S05)	80.4%			79.7%			74.2%			54.6%			45.3%		
P(B2010<B05)	98.8%			95.0%			89.5%			70.5%			52.8%		
P(S2010<Smin)	59.1%			57.7%			45.4%			15.3%			7.5%		
P(B2010<Bmin)	92.0%			87.9%			70.5%			20.8%			8.3%		
14-yr sample															
S2008/S2005	48.0%	71.3%	155.1%	51.1%	76.4%	165.2%	59.5%	87.4%	179.5%	75.0%	102.0%	194.1%	80.1%	106.7%	199.3%
S2010/S2005	46.8%	85.2%	189.3%	47.4%	87.6%	202.5%	52.2%	100.2%	227.1%	72.3%	124.4%	253.6%	81.1%	132.5%	262.8%
B2008/B2005	30.0%	37.6%	66.2%	32.6%	44.5%	86.1%	41.8%	65.8%	110.3%	69.8%	89.7%	134.7%	79.6%	97.7%	142.9%
B2010/B2005	23.3%	37.7%	100.8%	24.2%	39.9%	135.0%	28.7%	62.5%	176.5%	60.6%	102.5%	218.6%	76.5%	116.0%	232.5%
P(S2008<S2005)	77.5%			74.5%			65.2%			47.1%			39.3%		
P(B2008<B2005)	99.8%			98.3%			92.4%			75.6%			57.3%		
P(S2008<Smin)	46.7%			39.2%			23.3%			6.9%			4.1%		
P(B2008<Bmin)	92.3%			79.1%			46.2%			10.5%			4.5%		
P(S2010<S05)	61.5%			59.8%			49.7%			27.5%			19.2%		
P(B2010<B05)	94.9%			89.0%			78.3%			47.2%			28.9%		
P(S2010<Smin)	32.8%			30.9%			21.7%			6.1%			2.7%		
P(B2010<Bmin)	82.0%			75.7%			51.0%			11.1%			3.8%		

Table 48 continued.

	0.05	Median	47t 0.95	0.05	Median	37t 0.95
25-yr sample						
S2008/S2005	82.2%	97.9%	180.8%	87.4%	102.7%	186.1%
S2010/S2005	81.7%	111.7%	222.8%	90.4%	119.7%	231.7%
B2008/B2005	86.8%	101.2%	131.5%	96.3%	109.3%	140.1%
B2010/B2005	85.8%	112.0%	210.4%	101.6%	125.7%	223.3%
P(S2008<S2005)	54.9%			42.3%		
P(B2008<B2005)	45.2%			12.3%		
P(S2008<Smin)	3.4%			1.5%		
P(B2008<Bmin)	2.3%			0.6%		
P(S2010<S05)	32.8%			17.7%		
P(B2010<B05)	24.8%			3.8%		
P(S2010<Smin)	2.8%			0.5%		
P(B2010<Bmin)	1.7%			0.1%		
14-yr sample						
S2008/S2005	85.3%	111.5%	203.9%	90.4%	116.3%	209.2%
S2010/S2005	89.5%	140.9%	271.6%	98.1%	149.0%	280.6%
B2008/B2005	89.1%	105.8%	150.9%	98.5%	113.8%	158.9%
B2010/B2005	92.0%	129.8%	246.8%	107.2%	144.0%	261.3%
P(S2008<S2005)	30.8%			21.6%		
P(B2008<B2005)	30.6%			7.1%		
P(S2008<Smin)	2.3%			1.1%		
P(B2008<Bmin)	1.5%			0.3%		
P(S2010<S05)	12.1%			6.1%		
P(B2010<B05)	11.6%			2.1%		
P(S2010<Smin)	1.1%			0.4%		
P(B2010<Bmin)	1.1%			0.0%		

7. PAU 5D ASSESSMENT

7.1 Comparison with 2002 assessment

We first used the 2006 dataset in combination with the model used to assess PAU 7 in 2002, and conversely the PAU 5D 2002 dataset and the 2006 model, to assess whether model changes or additional data produced substantially different estimates. These trials required a set of consistent protocols, determined by the 2002 assessment (Breen et al. 2003):

- using Cauchy priors (Chen et al. 2001) and the linear growth model,
- fixing *CPUEpow* to 1,
- fixing maturity parameters to *mat50* = 91, *mat95* = 14,
- modelling the commercial fishery with knife-edged selectivity rather than an estimated selectivity curve,
- fixing *sigmaMin* and *sigmaObs*,
- fixing the research diver selectivity parameters *RD50* and *RD95* to 108 and 23 mm and
- fitting to CSLF data from 126 mm and above.

Results are summarised, for quantities that can be compared (the two models were programmed to produce different indicators), in Table 49. When using the same data with different models, results are reasonably similar; when comparing the same model used with the old and new datasets, results are less similar. Thus, differences seen are more due to new and different data than to model changes.

Table 49: Results from trials with old and new models and data combinations. Results from the 2002 model and data combination are from Breen et al. (2003).

Model	2006	2006	2002	2002
Data	2006	2002	2006	2002
CPUEwt	0.118	0.25	0.14	0.24
RDSIwt	0.142	0.67	0.16	0.5
CSLFwt	17.5	21.4	20	20
RDLFwt	30.1	28.5	36	30
sdnrs CPUE	1.21	1.00	1.04	1.18
sdnrs RDSI	0.98	0.96	1.02	0.98
sdnrs CSLF	1.03	0.97	1.02	0.96
sdnrs RDLF	0.96	1.02	0.98	1.01
sdnrs tags	1.09	1.08		
sigmatilde	0.172	0.320	0.192	0.273
ln(*R0*)	13.82	13.65	13.92	13.56
M	0.154	0.140	0.172	0.131
galpha	19.4	21.2	19.22	23.20
gBeta	8.4	9.4	8.53	10.13
GrowthCV	0.403	0.368	0.411	0.273
sigmaMin	1	1	1	3.32
Like CPUE	-6.61	-19.97	-7.3	-18.4
Like RDSI	1.24	-2.68	1.4	-2.0
Like CSLF	-572.64	-513.19	-578.9	-529.5
Like RDLF	-740.74	-577.60	-754.4	-622.6
Like Tags	617.42	531.06	618.9	534.8
M prior contribution	1.18	0.82	3.3	1.9
Eps prior contribution	10.63	10.62	10.0	12.0
Like Total	-689.52	-570.93	-707.0	-623.7
Maximum *ERate*	52.9%	51.7%	53.0%	57.5%
ERate[LastYear]	24.8%	51.2%	23.6%	57.5%

In addition to the new data not available in 2002, changes in the data include:

- varying the assumptions made about non-commercial catches (Figure 90),
- standardising CPUE differently,
- excluding CPUE before 1989 (Figure 91),
- standardising RDSI differently (Figure 92) by including a visibility code, using the new mean patch size estimates and correcting for searching time,
- weighting the RDLF data by abundance from each swim (Figure 93 shows one typical record),
- weighting the CSLF data by catch (Figure 94),
- discarding data without area information,
- discarding 2000 and 2001 data and
- including 32 additional records of tag-recapture data.

Of these changes, the new standardisation of RDSI had the largest apparent effect on the dataset.

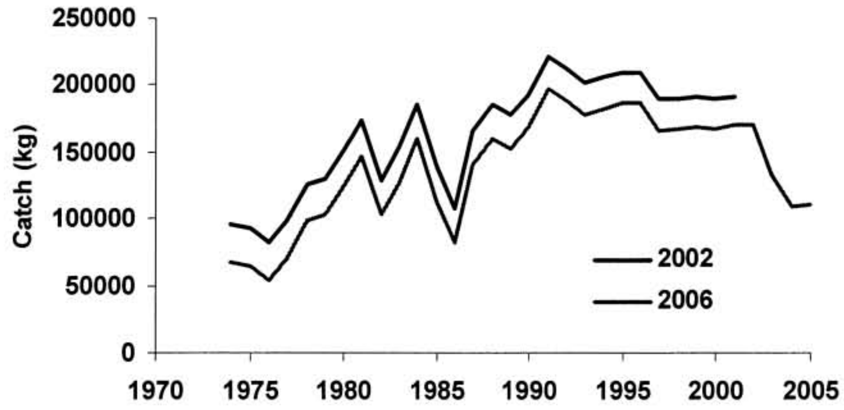


Figure 90: Total catch used in the 2002 and 2006 assessments for PAU 5D.

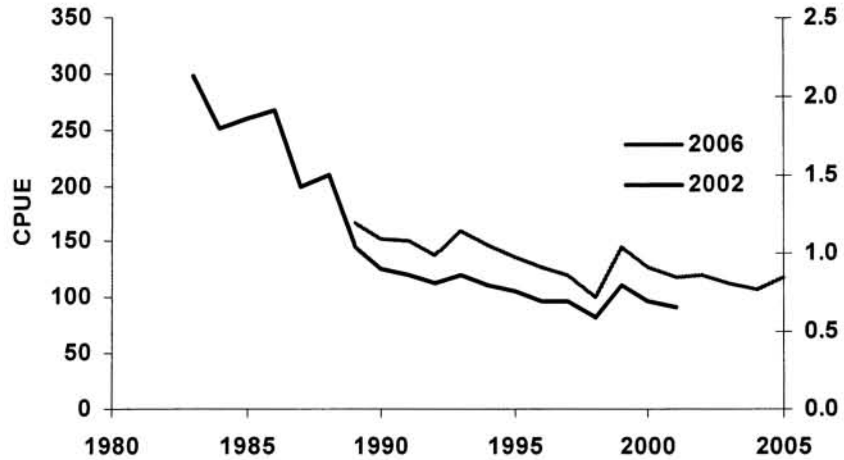


Figure 91: Standardised CPUE (kg/diver-day) used in the 2002 and 2006 assessments for PAU 5D.

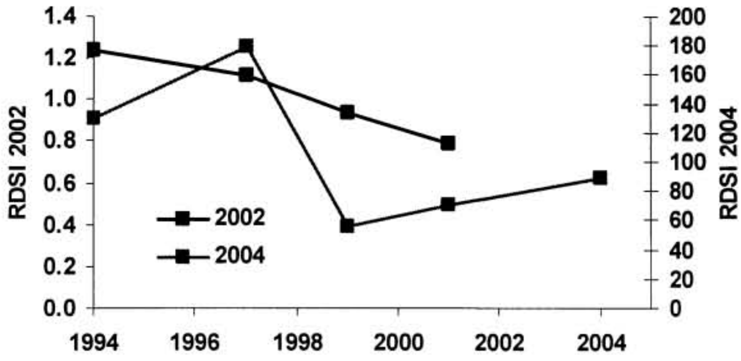


Figure 92: Standardised RDSI used in the 2002 assessment (dimensionless index) and from 2004, used in the 2006 assessment (number per swim).

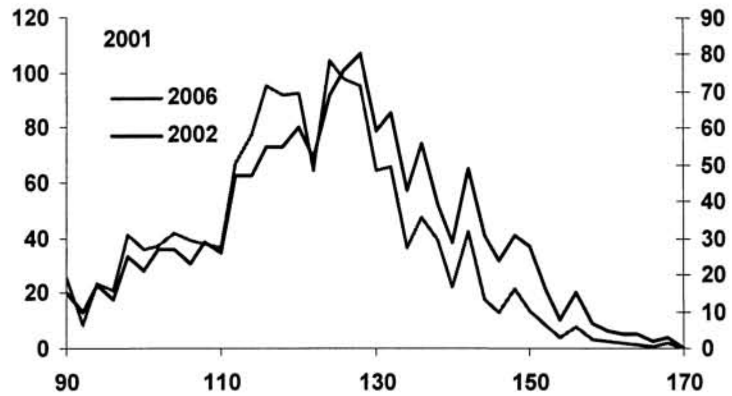


Figure 93: Comparison of the RDLF record for 2001 as used in the 2002 and 2006 assessments.

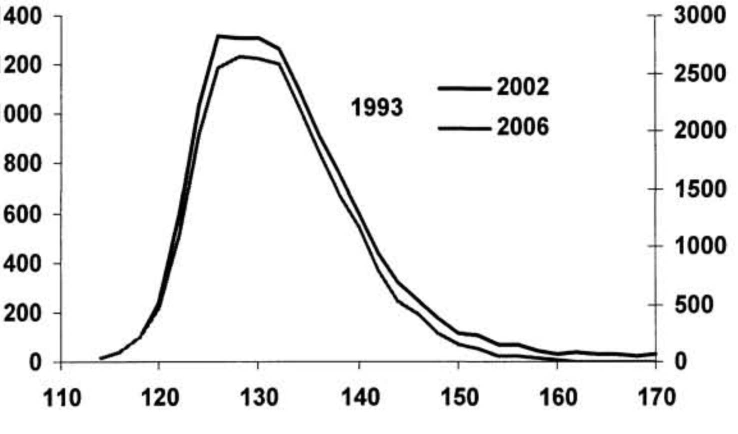


Figure 94: Comparison of the CSLF record for 1993 as used in the 2002 and 2006 assessments.

7.2 Finding a base case

More than 65 exploratory runs were made before choosing a base case. Our approach was to adjust the relative weights for each dataset until the sdnrs were close to one. Some associated choices were as follows.

- Experimentation showed that using Cauchy priors had almost no effect on the MPD estimate and we chose to use conventional priors.
- Fixing *CPUEpow* to 1 gave lower exploitation rates and a more optimistic result whereas estimating this parameter produced substantial hyper-stability and less optimistic estimates, so we chose to estimate *CPUEpow*.
- Using knife-edged selectivity for the commercial fishery instead of estimating selectivity gave a much worse objective function value, so we estimated the commercial fishery selectivity.
- In early trials, using the exponential growth model gave a slightly worse fit than the linear model, a higher *M* estimate and more optimistic results, so we used the linear model for the base case.

With free research diver selectivity parameters, *RD50* went to its upper bound of 125. This bound was set in early assessments because it was thought likely that research divers would be sampling legal-sized paua at 100% efficiency.

This issue was explored further, using an experimental version of the model in which separate selectivity parameters, bounded from 0 to 1, were estimated for each size bin above 90 mm, the smallest data included in the dataset. The model obtained its best fit by estimating low selectivity for smaller sizes, including the MLS (Figure 95). The specific shape seen in Figure 95 could be mimicked with the two-parameter logistic curve when *RD50* was given wider bounds.

However, this result runs against belief: research divers select paua randomly from aggregations and legal-sized paua should be fully emerged from the cryptic habitat used by small individuals. In the PAU 7 assessment (Breen & Kim 2005), the model estimated *RD50* at 100 mm. Further, when *RD50* was estimated, *M* went to its upper bound of 0.50, whereas *M* is believed to be near 0.10 (Shepherd & Breen 1992).

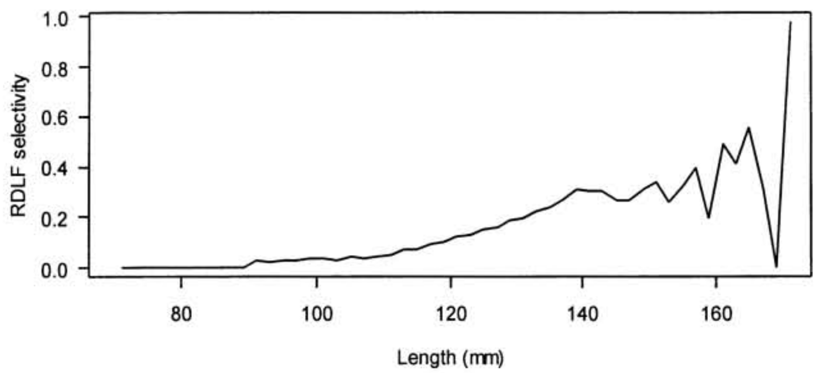


Figure 95: PAU 5D research diver selectivity from an experimental version of the model, estimating a separate parameter for each size bin.

For these reasons we considered it unrealistic and inappropriate to estimate *RD50* and we chose to fix it. It was necessary to fix the *RD95* also, because when *RD50* was fixed *RD95* went to its upper bound. We next explored the effect of using various values for *RD50* (Figure 96) from 100 to 140. The model estimates were very sensitive to this value: with increased *RD50*, estimated *M* went quickly from near 0.10 to its upper bound of 0.50, current exploitation rate decreased from near 50 to 10–15% and *B05/Bmin* increased from 1 to nearly 2.

This sensitivity is surprising, and obviously the choice of *RD50* will determine the outcome of the assessment. The most recent and reliable assessment in which we estimated the research diver selectivity was the 2005 assessment of PAU 7 (Breen & Kim 2005): *RD50* was 100 mm and *RD95* was 19 mm (this is the difference between the sizes at 50% and 95% selectivity). Discussion with the research divers confirmed that their selectivity was expected to be the same in PAU 5D as in PAU 7. An objective approach is thus to fix these two parameters at their PAU 7 values, based on an assessment where there is no reason to suspect the estimates. We chose this course.

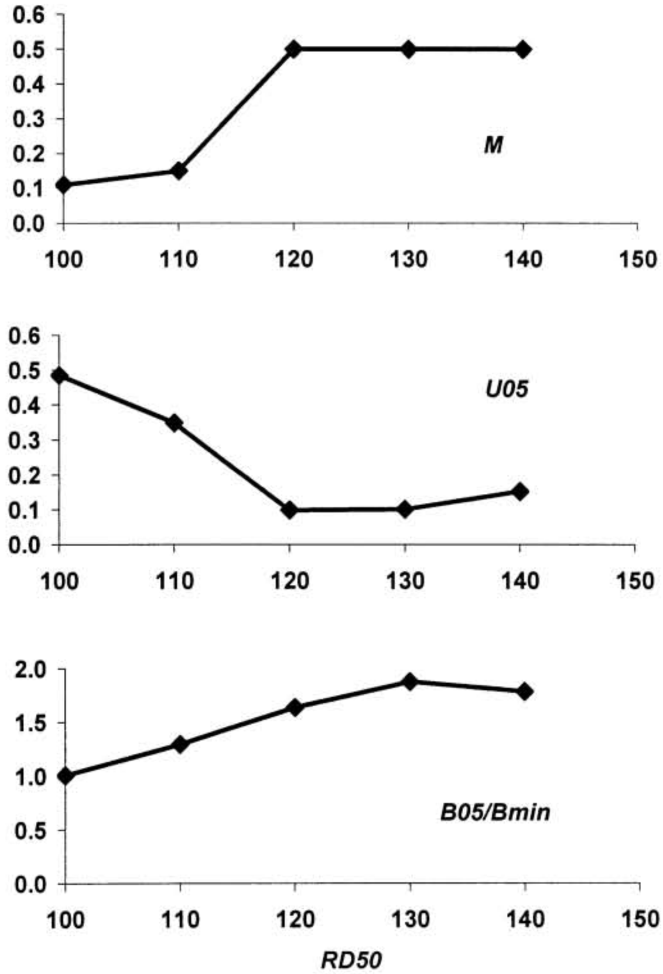


Figure 96: The model's PAU 5D estimates of *M*, 2005 exploitation rate and the ratio of 2005 recruited biomass to *Bmin* at various assumed values for *RD50*.

7.3 Base case results

The values of constants assumed for the base case are shown in Table 50 and the specifications for estimated parameters in Table 51. The base case estimates at the mode of the joint posterior distribution (MPD estimates) are also shown in Table 51.

Table 50: Values of constants used in the base case fit for PAU 5D. The length-weight constants *a* and *b* give weight in kg.

Parameter	Value
CPUEwt	0.142
RDSIwt	0.113
CSLFwt	18.525
RDLFwt	27.626
tagwt	0.1
matwt	3.02
Umax	0.65
a	2.99E-08
b	3.303
alpha	75
Beta	120
RD50	100
RD95	19
sigmaMin	1
sigmaObs	0.25

Table 51: For each estimated parameter, the estimation phase, bounds, prior type (0 uniform, 1 normal, 2 normal-log) and specification and initial value for PAU 5D.

Parameter	Phase	Lower bound	Upper bound	Prior type	Prior mean	Prior c.v.	Initial value
sigmatilde	1	0.01	2	0			0.37
ln(*R0*)	1	5	50	0			15
M	3	0.01	0.5	2	0.10	0.35	0.25
CS50	2	70	145	0			124
CS95	2	0.01	50	0			2
mat50	3	70	145	0			91
mat95	3	1	50	0			14
Eps	3	-2.3	2.3	1	0.0	0.4	0
ln(*qCPUE*)	1	-30	10	0			1
ln(*qRDSI*)	1	-30	0	0			-13
galpha	2	1	50	0			20
gBeta	2	0.01	50	0			10
GrowthCV	2	0.001	1	0			0.5
CPUEpow	3	0.01	2	0			1

With the weights adjusted as shown above, the sdnrs are all close to 1 (Table 52). Estimated *M* is close to the mean of its prior and *CPUEpow* indicates considerable hyperstability in CPUE (Figure 97).

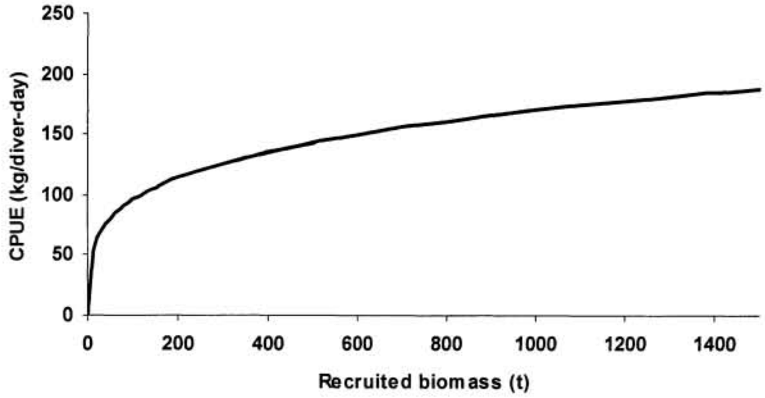


Figure 97: Predicted CPUE for PAU 5D as a function of biomass from the base case MPD fit, based on the estimated *CPUEpow* and ln(*qCPUE*).

The fit to CPUE (Figure 98) is good for the recent years, 2000 through 2005, but is sketchy for the years before the turn of the millennium. The fit to the RDSI index (Figure 98) catches the downward trend between 1994 and 1999, but is otherwise loose. The fit to the CSLF data is good (Figure 99) but the fit to RDLFs is not as good because selectivity parameters are fixed. When the mean of residuals is determined for each size bin (Figure 100), there is considerable structure for the RDLF dataset.

The fit to the tagging data shows that the model tends to under-estimate the growth of small fish and over-estimate the growth of larger fish (Figure 101). Data from animals at liberty for more than 300 days were not as good as fits to the main body of the data, where animals were at liberty for 265 days.

The fit to maturity is tight despite the low sample size (Figure 102). Estimated growth and selectivity patterns (assumed for the research divers) are shown in Figure 103. Recruitment (Figure 104) shows high variability, with strong pulses in the late 1980s and mid 1990s. The autocorrelation in estimated *Eps* from 1984 to 2004 was 0.56. Exploitation rate (Figure 104) showed a steady increase to peak of 0.576 in 2002, then a decrease to 0.485. Recruitment is plotted against spawning biomass with a two-year lag (Figure 105); no obvious relation is seen.

Mid-season recruited biomass reaches its nadir near 2003 (Figure 106). Surplus production estimates reflect the strong recruitment pulses discussed above. Production plotted against recruited biomass suggests that production was higher when recruited biomass was near 400 t (the current estimate is 160 t, Table 52), but this may be an artefact of the recruitment patterns.

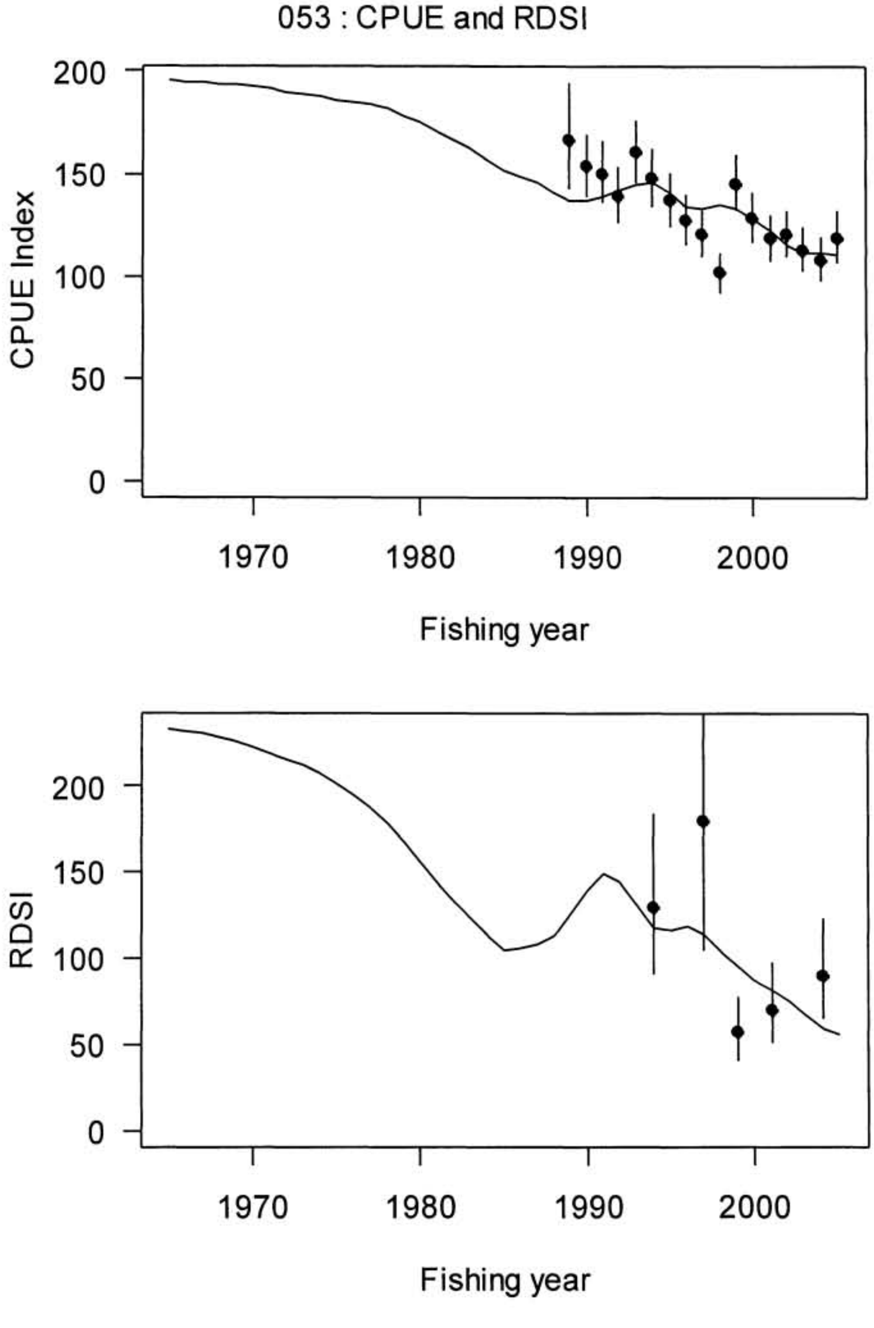


Figure 98: Observed (dots) and predicted (solid lines) CPUE (top) and RDSI (bottom) for the base case MPD fit for PAU 5D. Error bars show the standard error term used by the model in fitting, including the effect of the common error term and dataset weights.

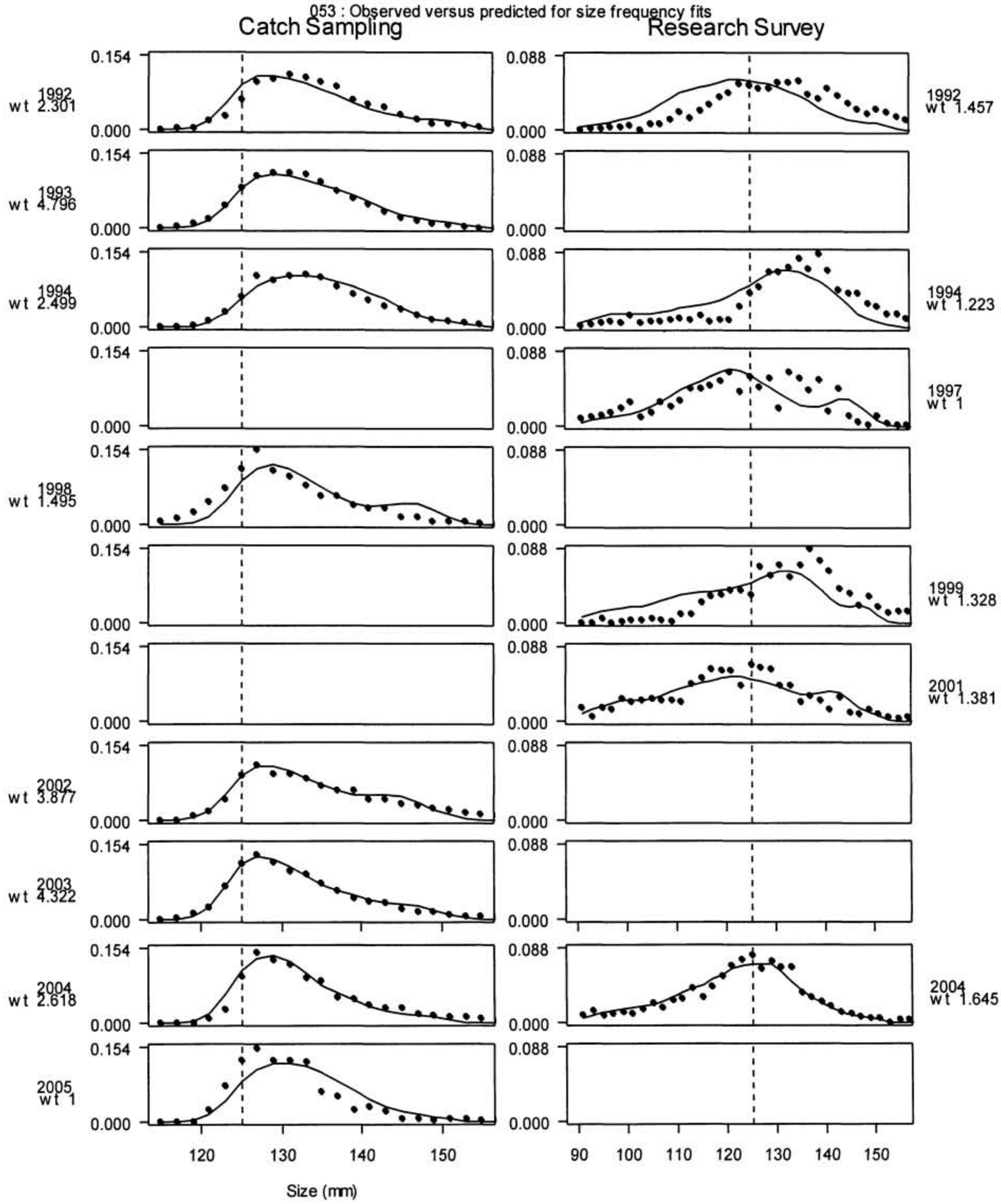


Figure 99: Observed (dots) and predicted (lines) proportion-at-length from commercial catch sampling (left) (CSLF) and research diver surveys (right) (RDLF) for the base case MPD fits for PAU 5D. The number under each year is the relative weight given to the dataset (see text).

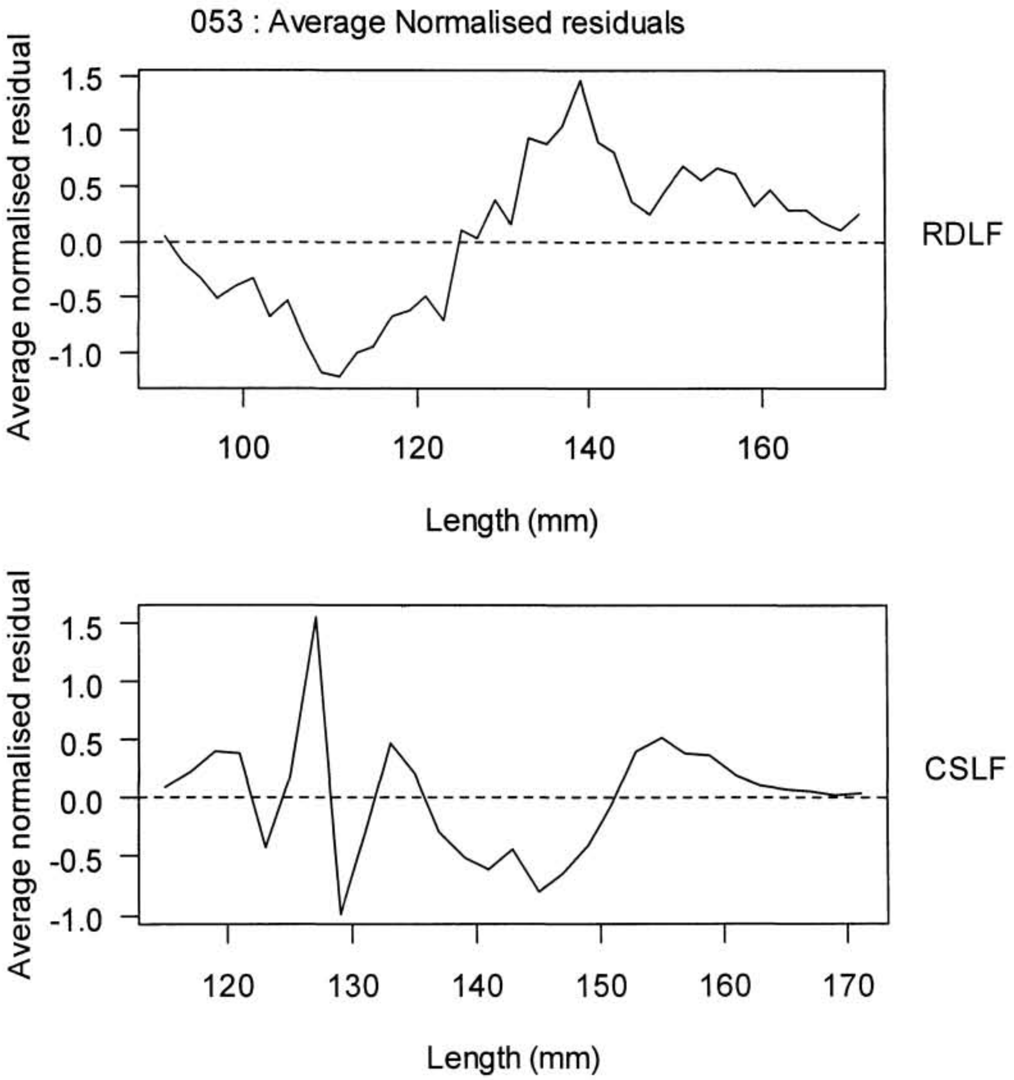


Figure 100: Means of normalised residuals at each length for the PAU 5D MPD base case fits to the RDLF (upper) and CSLF datasets.

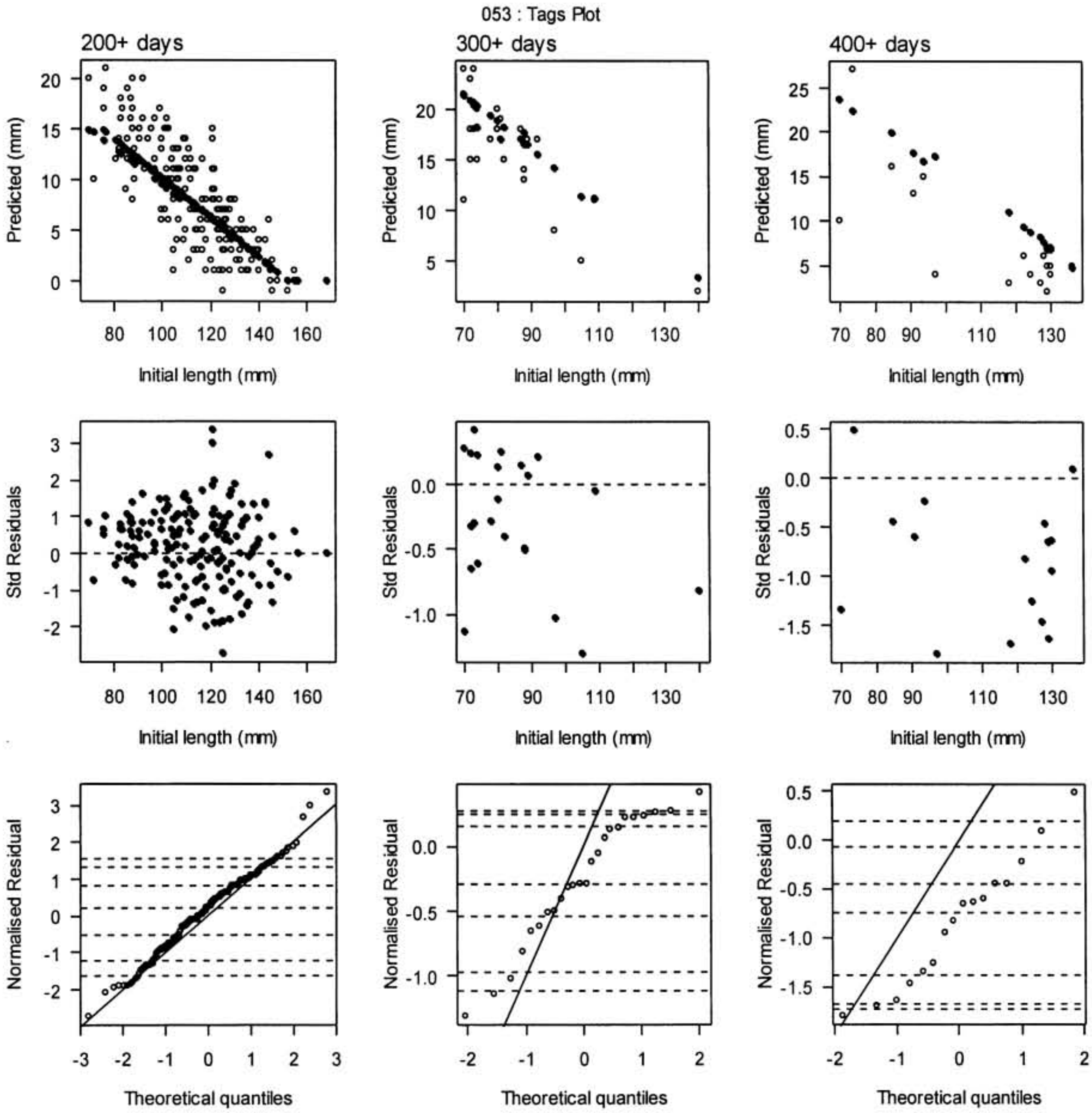


Figure 101: Top: predicted (closed circles) and observed (open circles) increments plotted against initial length of tagged paua from the base case MPD fit for PAU 5D; middle: standardised residuals plotted against initial length; bottom: Q-Q plot of standardised residuals. Among the columns, the data have been divided based on the approximate time-at-liberty, which varied among experiments, animals within each experiment having almost the same time-at-liberty.

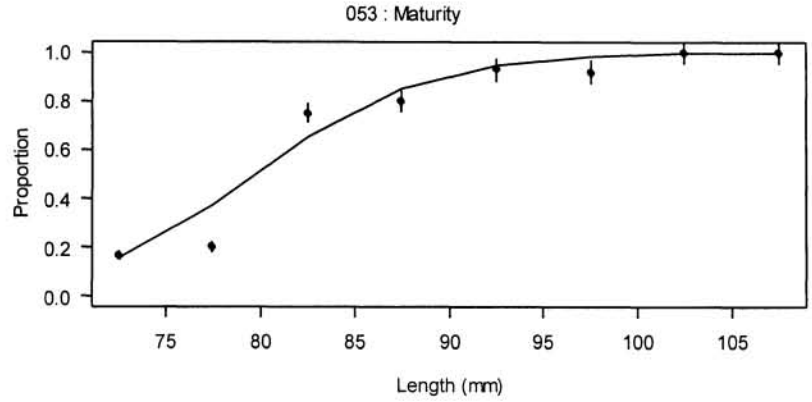


Figure 102: Observed (dots) and predicted (solid lines) maturation-at-length for the base case MPD fit for PAU 5D. Error bars show the standard error term used by the model in fitting, including the effect of the common error term and dataset weights.

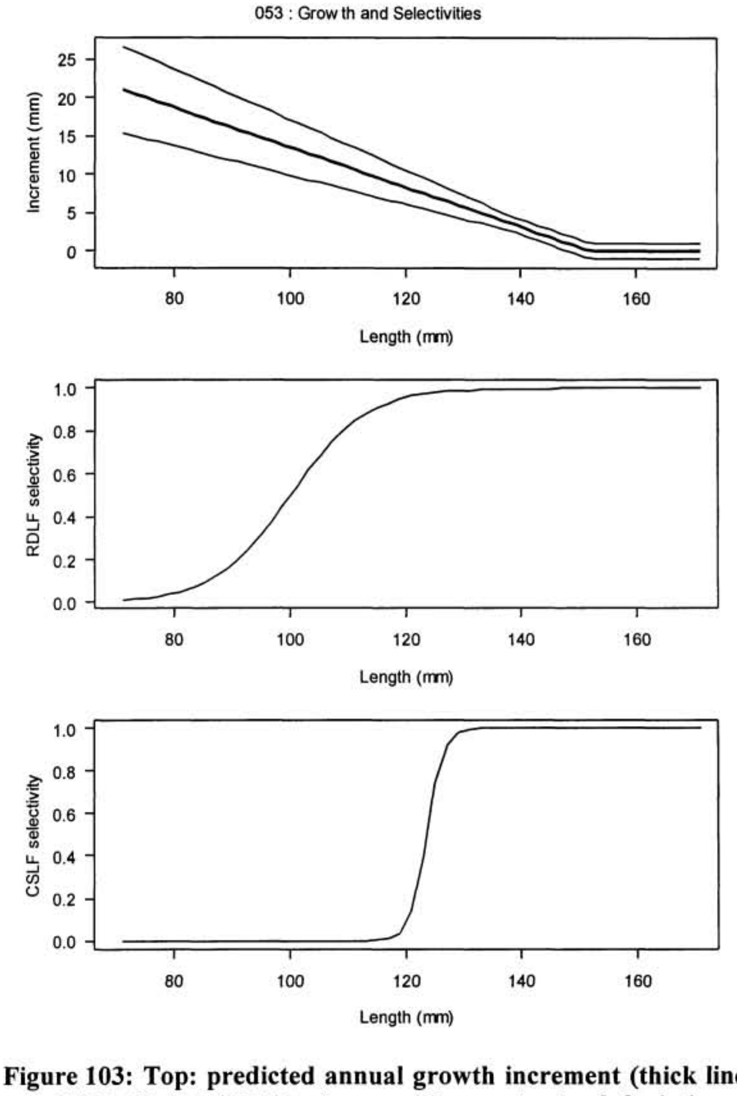


Figure 103: Top: predicted annual growth increment (thick line) vs. initial length of paua from the base case MPD fit to PAU 5D, shown with one standard deviation around the increment (thin line); middle: estimated research diver survey selectivity; bottom: estimated commercial fishery selectivity.

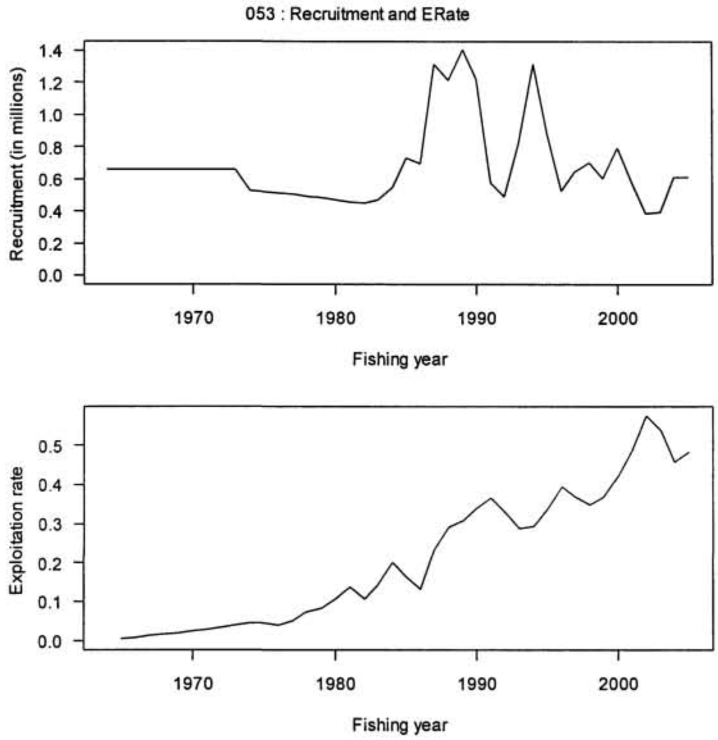


Figure 104: Recruitment to the model (top) and exploitation rate (bottom) from the base case MPD fit in PAU 5D.

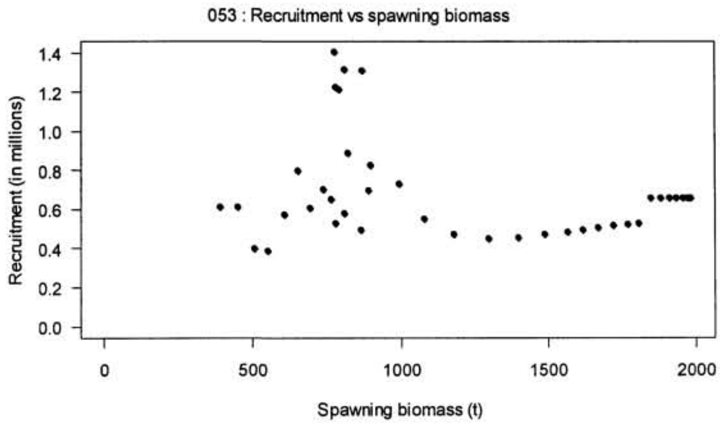


Figure 105: Recruitment plotted against spawning biomass two years earlier from the base case MPD fit in PAU 5D.

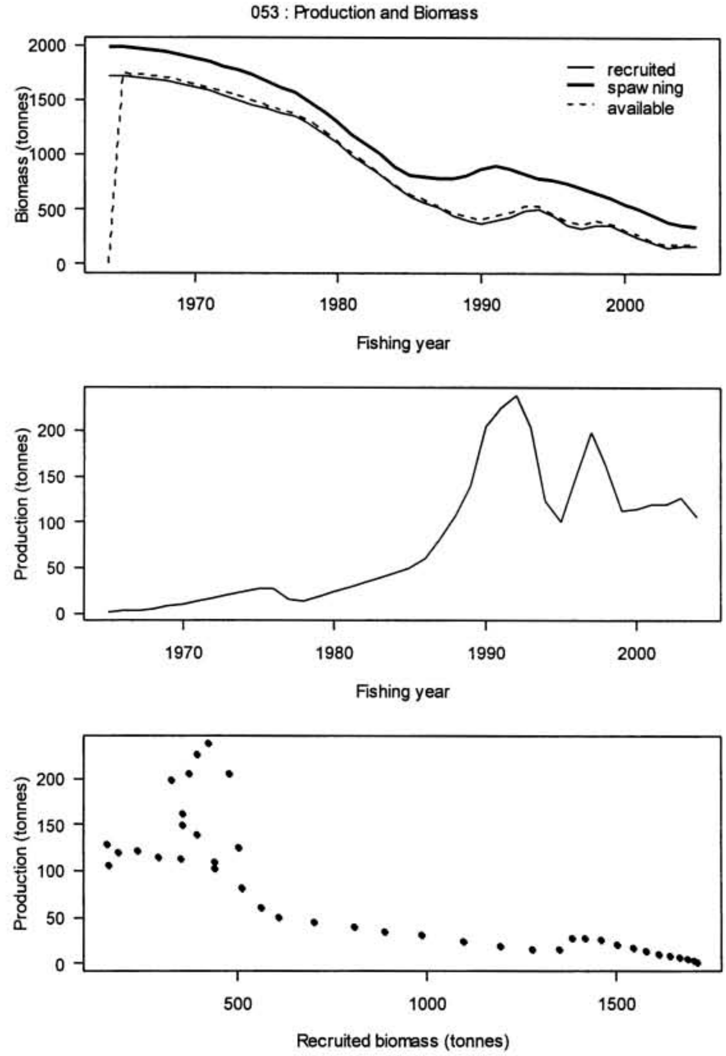


Figure 106: Recruited, spawning and available biomass trajectories (top), the surplus production trajectory (middle) and surplus production plotted against recruited biomass (bottom), all from the base case MPD fit for PAU 5D. Recruited biomass includes all individuals above the MLS; spawning biomass includes all mature individuals; available biomass includes all recruited individuals that are selected by the commercial fishery.

7.4 MPD sensitivity trials

In these trials we explored the effects of some choices we made in finding the base case, and we examined the relative influence of each dataset by removing each dataset (except for maturity, which would affect only the estimates of spawning biomass) one at a time.

No trial produced sdnrs very different from 1, except of course where the dataset was not used in fitting, and except that sdnr increased for maturity data when length frequency datasets were omitted: the maturity parameter estimates were unchanged but *sigmatilde* changes, changing the sdnrs. No trial hit the upper bound on exploitation rate.

As described above, using Cauchy priors (trial 2) had almost no effect on the MPD estimate. The exponential growth (Gilbert) model (trial 3) gave a slightly better fit to the data (unlike the early experimental trial), much higher *M*, lower exploitation rate and higher biomass. When *CPUEpow* was fixed (trial 4), the fit deteriorated (the objective function value *LikeTotal* became larger), biomass increased and exploitation rates decreased. When a knife-edged selectivity was used for the commercial fishery (trial 5), the fit was much worse and this trial had the highest biomass and lowest exploitation rate estimates.

When the two growth parameters *sigmaMin* and *sigmaObs* were estimated (trials 6 and 7), the fit improved, especially for *sigmaMin*, but other estimates were little changed.

Removal of the CPUE dataset (trial 8) had only a small pessimistic effect, increasing exploitation rate and decreasing biomass estimates. Likelihoods for other datasets did not improve much. Removal of the RDSI dataset (trial 9) caused estimated exploitation rate to increase and biomass to decrease somewhat.

Removal of the CSLF data (trial 10) caused slightly more optimistic results – higher biomass and lower exploitation rates – and current recruited biomass was estimated at well above the minimum (i.e., the nadir occurred at some point in the past instead of recently). Removal of the RDLF data caused the most dramatic differences seen in these trials: estimated *M* became very large, biomass increased while exploitation rates decreased and the current biomass was 30–45% larger than minimum biomass levels.

When both the research datasets (RDSI and RDLF) were removed in trial 12, the effect was similar to that seen in trial 11, where just the RDLF data were excluded. Conversely, when both commercial datasets (CPUE and CSLF) were removed in trial 13, the assessment became slightly more optimistic. Removal of the tag-recapture data (trial 14) led to an improvement in the fit to CSLF (but not to other) data, increased growth rates but decreased *GrowthCV*, and a more pessimistic assessment.

Table 52: Results from the PAU 5D MPD sensitivity trials. Grey shading for sdnrs and negative log-likelihood values indicates where the relevant dataset was not used in fitting; grey shading for parameters indicates where they were fixed at their initial values.

	Base case	Cauchy priors	Exp. growth	Fixed *CPUEpow*	Knife-edged CSS	Est. *sigmaMin*	Est. *sigmaObs*	No CPUE	No RDSI	No CSLF	No RDLF	neither RDSI RDLF	neither CPUE CSLF	No tag
Trial number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Reference	"053	"067	"068	"070	"071	"072	"073	"074	"075	"076	"077	"079	"080	"078
sdnr CPUE	1.01	1.01	1.12	1.44	0.96	1.07	1.02	9.61	1.04	1.10	0.97	0.97	11.07	1.04
sdnr RDSI	1.02	1.02	0.89	0.82	0.74	1.06	1.02	1.08	1.54	1.02	1.00	1.00	1.03	1.10
sdnr CSLF	1.00	1.00	0.96	0.97	1.07	1.03	1.01	1.00	1.00	2.79	0.96	0.96	2.80	0.97
sdnr RDLF	1.02	1.02	1.02	1.02	0.97	1.05	1.03	1.02	1.02	0.94	2.10	2.10	0.94	1.02
sdnr tags	0.97	0.97	1.01	0.97	0.95	0.90	0.95	0.97	0.97	1.04	1.03	1.03	1.04	1.12
sdnr maturity	1.01	1.01	1.10	0.97	0.90	1.08	1.02	1.01	1.02	1.23	1.21	1.21	1.24	1.01
sigmatilde	0.160	0.160	0.147	0.166	0.179	0.150	0.158	0.159	0.159	0.132	0.134	0.134	0.131	0.161
ln(*R0*)	13.40	13.37	13.78	13.49	13.80	13.39	13.40	13.38	13.36	13.30	14.70	14.66	13.29	13.32
M	0.109	0.107	0.185	0.116	0.161	0.106	0.109	0.108	0.107	0.091	0.295	0.288	0.091	0.110
CS50	123.5	123.5	123.5	123.6	124.0	123.4	123.5	123.5	123.5	124.0	124.2	124.2	124.0	123.4
CS95	4.1	4.1	4.0	4.1	2.0	3.9	4.1	4.1	4.1	2.0	4.8	4.8	2.0	4.7
mat50	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8	79.8
mat95	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8
ln(*qCPUE*)	1.71	1.73	1.33	-7.92	-0.21	1.71	1.69	1.00	2.18	1.90	-1.47	-1.58	1.00	2.13
ln(*qRDSI*)	-10.00	-10.00	-10.03	-10.15	-10.21	-10.02	-10.01	-9.98	-13.00	-9.95	-10.55	-13.00	-9.95	-9.83
galpha	20.0	20.0	36.1	20.6	22.2	20.3	19.9	20.0	20.0	22.0	18.7	18.7	22.0	22.8
gBeta	8.3	8.3	7.4	8.6	9.4	8.2	8.3	8.4	8.4	8.9	8.6	8.6	8.9	9.5
GrowthCV	0.268	0.268	0.336	0.248	0.213	0.277	0.262	0.269	0.269	0.290	0.310	0.310	0.292	0.197
CPUEpow	0.248	0.247	0.273	1.000	0.399	0.246	0.250	1.000	0.212	0.231	0.496	0.505	1.000	0.218
sigmaMin	1.00	1.00	1.00	1.00	1.00	1.78	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
sigmaObs	0.25	0.25	0.25	0.25	0.25	0.25	0.60	0.25	0.25	0.25	0.25	0.25	0.25	0.25
LikeCPUE	-14.9	-14.9	-14.3	-5.3	-13.7	-14.9	-14.9	68848	-14.5	-16.6	-18.6	-18.6	105312	-14.3
LikeRDSI	2.2	2.2	1.1	1.5	1.6	2.1	2.1	2.5	188.3	1.2	1.2	173.6	1.3	2.6
LikeCSLF	-753.6	-753.6	-782.7	-751.6	-568.5	-761.5	-753.0	-754.1	-754.4	-11.6	-805.1	-804.9	-4.7	-759.6
LikeRDLF	-723.7	-724.1	-746.3	-714.4	-707.3	-731.9	-723.6	-724.3	-724.8	-791.9	-350.9	-353.2	-792.4	-721.8
LikeTags	611.7	611.7	659.3	611.5	618.5	617.0	610.8	611.7	611.7	615.4	615.6	615.7	615.5	626.4
LikeMat	-10.4	-10.4	-10.3	-10.5	-10.4	-10.4	-10.4	-10.4	-10.4	-9.9	-10.0	-10.0	-9.9	-10.5

	Base case	Cauchy priors	Exp. growth	Fixed *CPUEpow*	Knife-edged CSS	Est. *sigmaMin*	Est. *sigmaObs*	No CPUE	No RDSI	No CSLF	No RDLF	neither RDSI RDLF	neither CPUE CSLF	No tag
Trial number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Reference	"053	"067	"068	"070	"071	"072	"073	"074	"075	"076	"077	"079	"080	"078
M prior	-0.1	-0.2	1.4	0.0	0.8	-0.1	-0.1	-0.1	-0.1	-0.1	4.6	4.4	-0.1	-0.1
Eps prior	13.3	13.6	11.5	11.5	8.4	13.2	13.2	14.0	14.6	11.4	5.6	5.6	11.5	13.4
LikeTotal	-875.6	-875.6	-880.3	-857.3	-670.8	-886.4	-876.1	-860.8	-878.0	-190.5	-206.6	-207.9	-174.0	-1490.3
Umax	0.576	0.577	0.486	0.515	0.541	0.558	0.572	0.585	0.591	0.595	0.514	0.517	0.602	0.639
U(2005)	0.485	0.490	0.319	0.267	0.241	0.463	0.478	0.541	0.591	0.390	0.282	0.282	0.401	0.623
Smin	341	336	435	564	588	352	345	308	282	392	758	748	383	256
S2005	341	336	562	577	701	352	345	308	282	392	975	969	383	256
Bmin	157	155	211	214	228	164	158	135	120	164	205	204	160	112
B2005	157	155	258	330	405	166	160	135	120	213	294	295	205	112
S2005/Smin	1.00	1.00	1.29	1.02	1.19	1.00	1.00	1.00	1.00	1.00	1.29	1.30	1.00	1.00
B2005/Bmin	1.01	1.00	1.22	1.54	1.78	1.01	1.01	1.00	1.00	1.30	1.44	1.45	1.28	1.00

These trials are summarised in Table 53. The RDSI and tag-recapture datasets produce optimistic effects (i.e., when they are omitted the results are more pessimistic); other datasets and combinations produce more pessimistic results; CPUE has little effect. The RDLF dataset is the one to which the model is most sensitive.

Table 53: Summary of the effects of PAU 5D datasets as deduced from sensitivity trials.

Dataset	Direction of effect	Magnitude of effect
CPUE	nil	nil
RDSI	optimistic	moderate
CSLF	pessimistic	slight
RDLF	pessimistic	very strong
RDSI+RDLF	pessimistic	very strong
CPUE+CSLF	pessimistic	slight
Tag-recapture	optimistic	slight

7.5 Reference period and recruitment re-sampling

We chose the reference period based on the MPD trajectory of recruited biomass (Figure 106 and Figure 107). We looked for a period in which exploitation was moderate, recruitment was near average and biomass was stable. There is no such place. Around the early 1990s, recruited biomass and exploitation rates showed rough plateaux, although recruitment shows a strong pulse beforehand. We chose 1989–96 as the reference period.

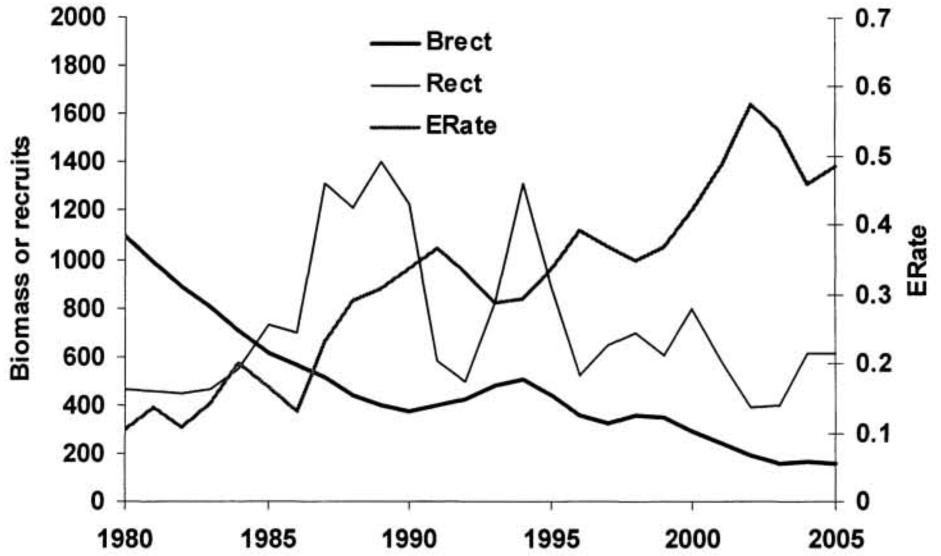


Figure 107: Recruited biomass, recruitment and exploitation rate trajectories from the MPD base case fit to PAU 5D.

The performance of forward projection may depend on the period chosen from which to resample recruitments (see Figure 104). We explored this by looking at average recruitment in the MPD fit, calculated from 2004 back to different years (Figure 108). As more years are included in the mean, working backwards from 2002, mean recruitment increases to a peak for 1988–2004, then decreases again. We chose to re-sample from 1992–2004: this is a compromise between the highest possible mean recruitment and the low mean recruitment that would be obtained by resampling a short period.

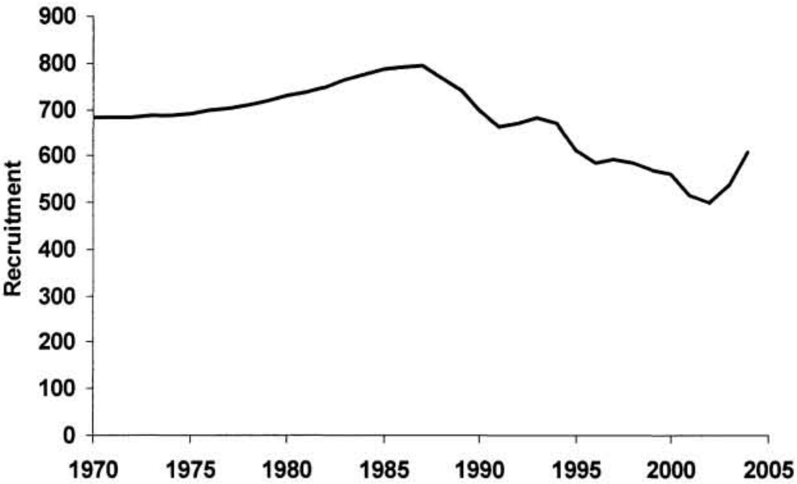


Figure 108: Backwards-running mean recruitment from the base case MPD fit for PAU 5D. The point shown at each year is mean recruitment from that year to 2004.

7.6 Base case McMC results

We made a single long chain, starting at the MPD, of 5 million simulations, saving every thousandth for a sample size of 5000. In the runs shown first, projections were made for five years, using the 2006 catches with an MLS of 125 mm. In all runs, *sigmatilde* was fixed at the MPD value (in a comparison not reported here this made some, but not very much, difference in the marginal posterior distributions of parameters).

Traces (Figure 109) show good mixing. The trace for the penalty on exploitation rate shows that a few runs reached the upper bound (65%). We used running and moving average diagnostics (Figure 110): they show little evidence of non-convergence. *M* estimates take some excursions late in the run, seen in both the traces and diagnostics, but they didn't go very far and they returned to the long-term mean. Related but less dramatic excursions are seen in other estimated parameters.

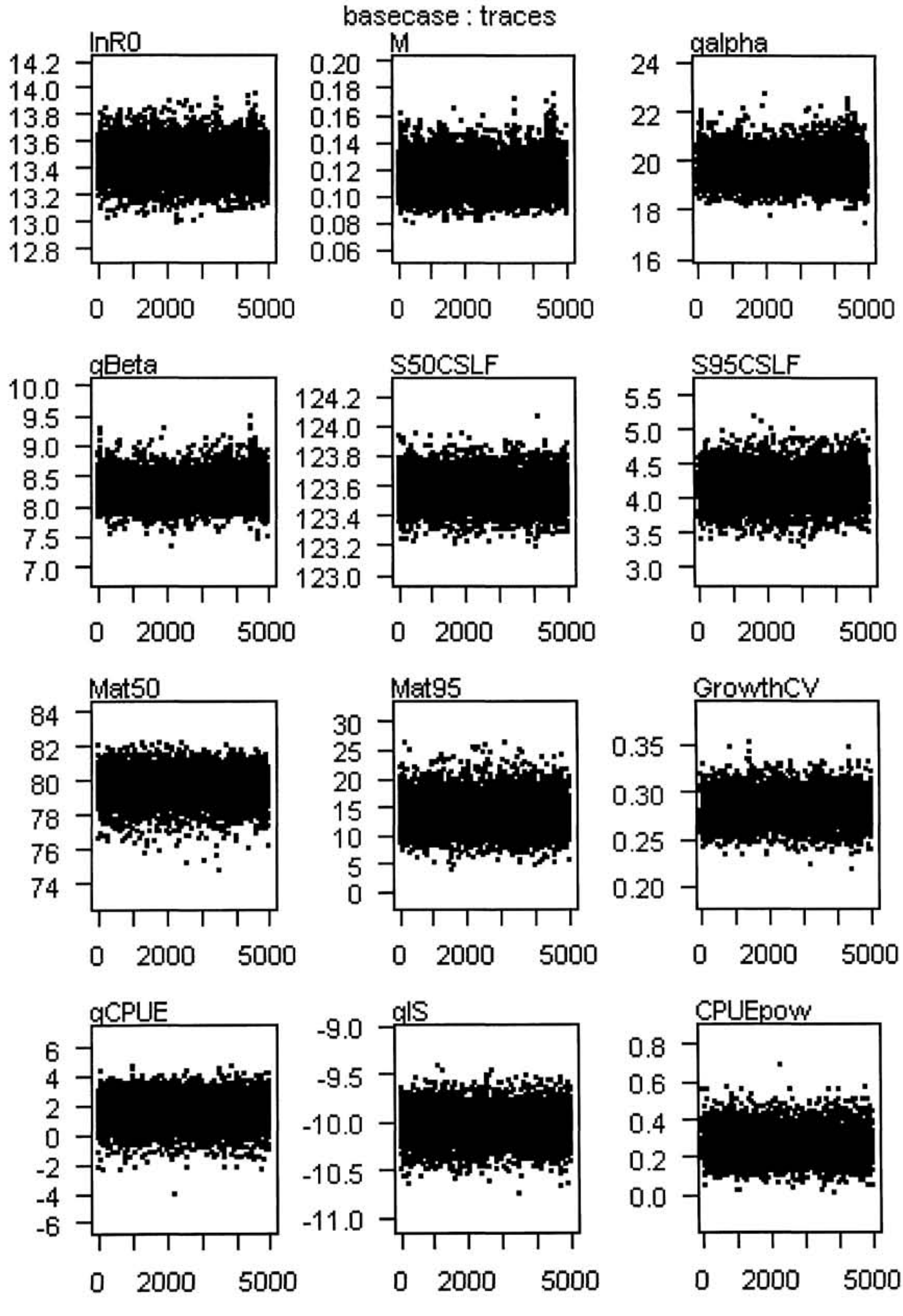


Figure 109: Traces from the PAU 5D base case McMC.

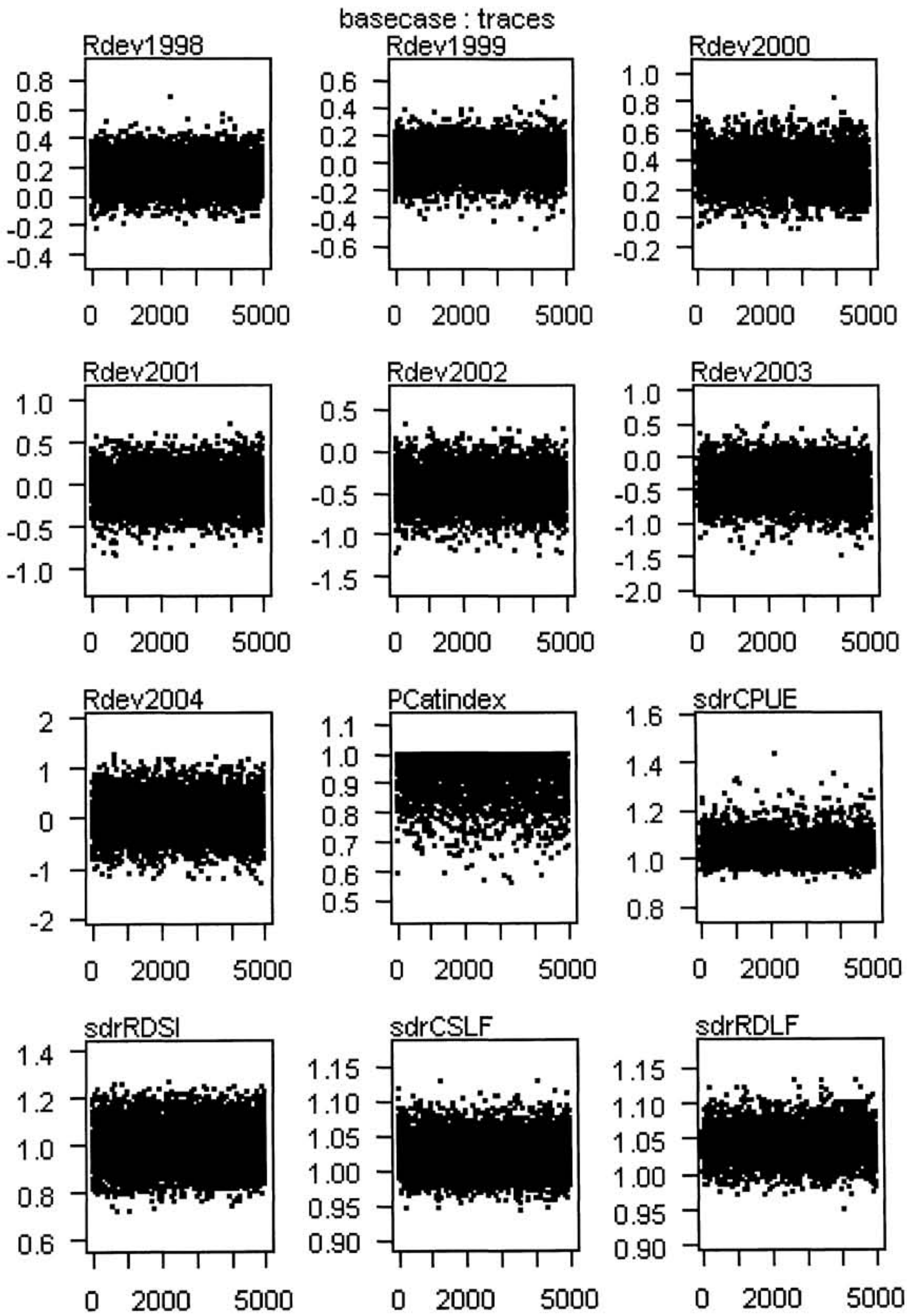


Figure 109 continued.

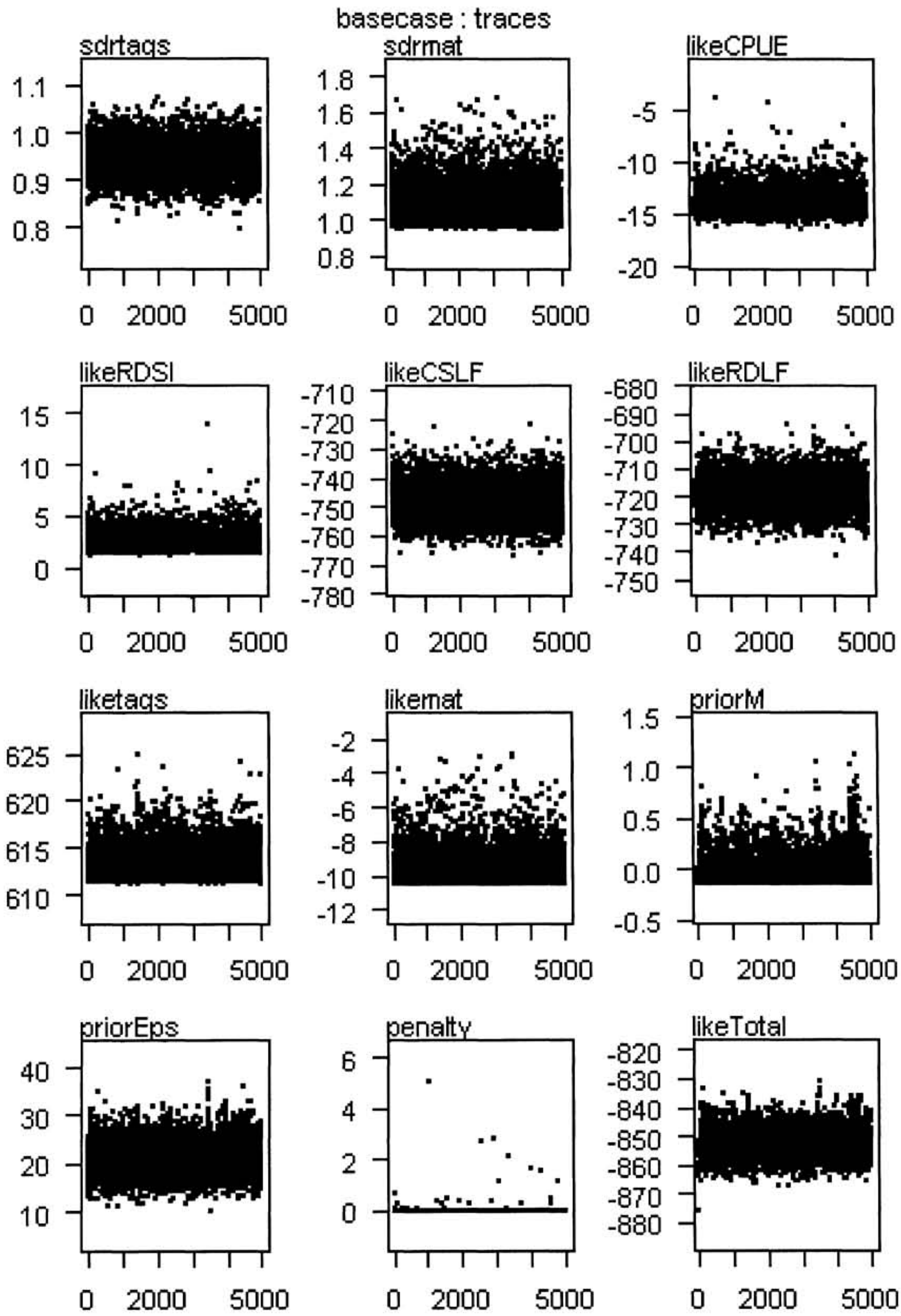


Figure 109 continued.

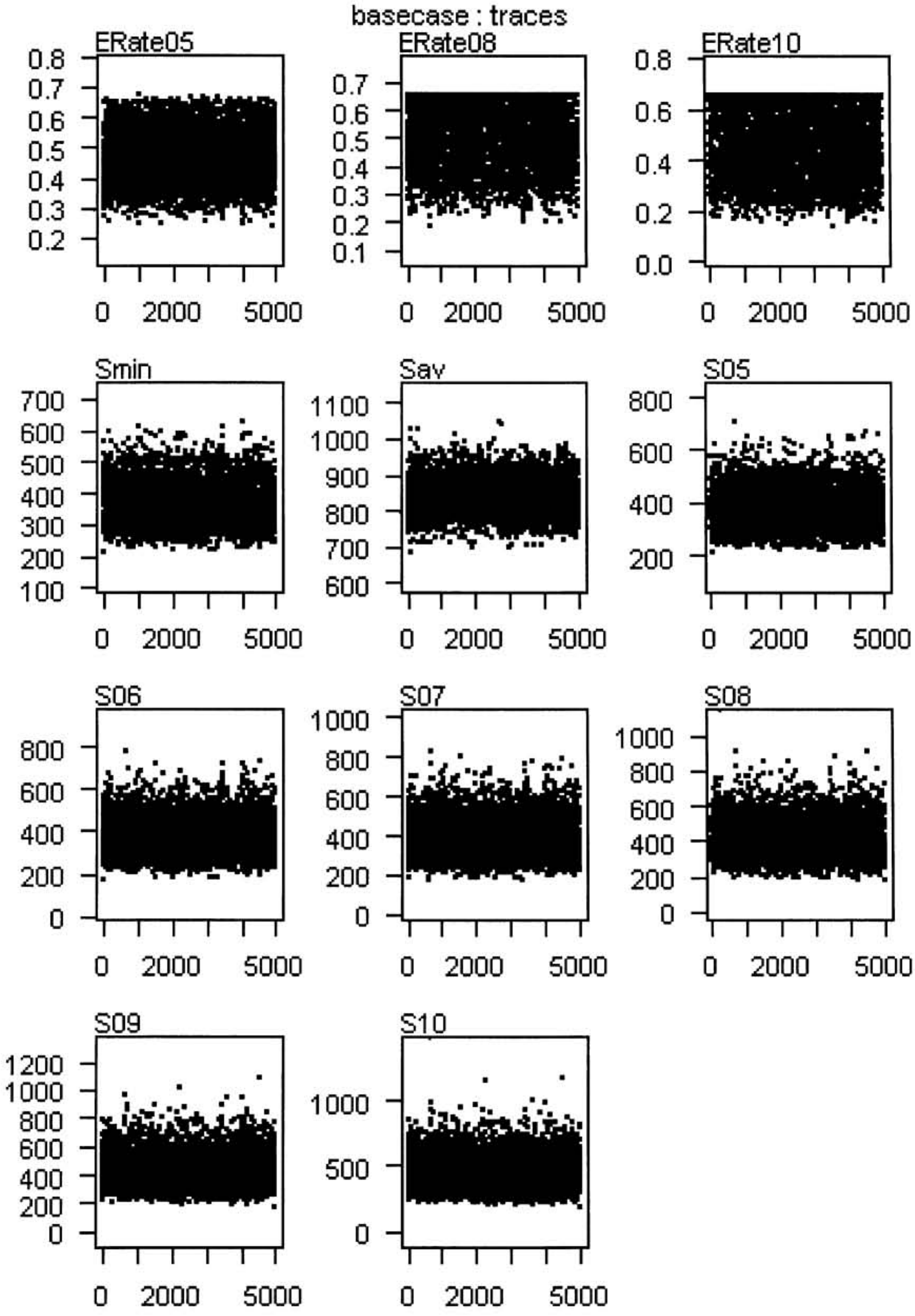


Figure 109 continued.

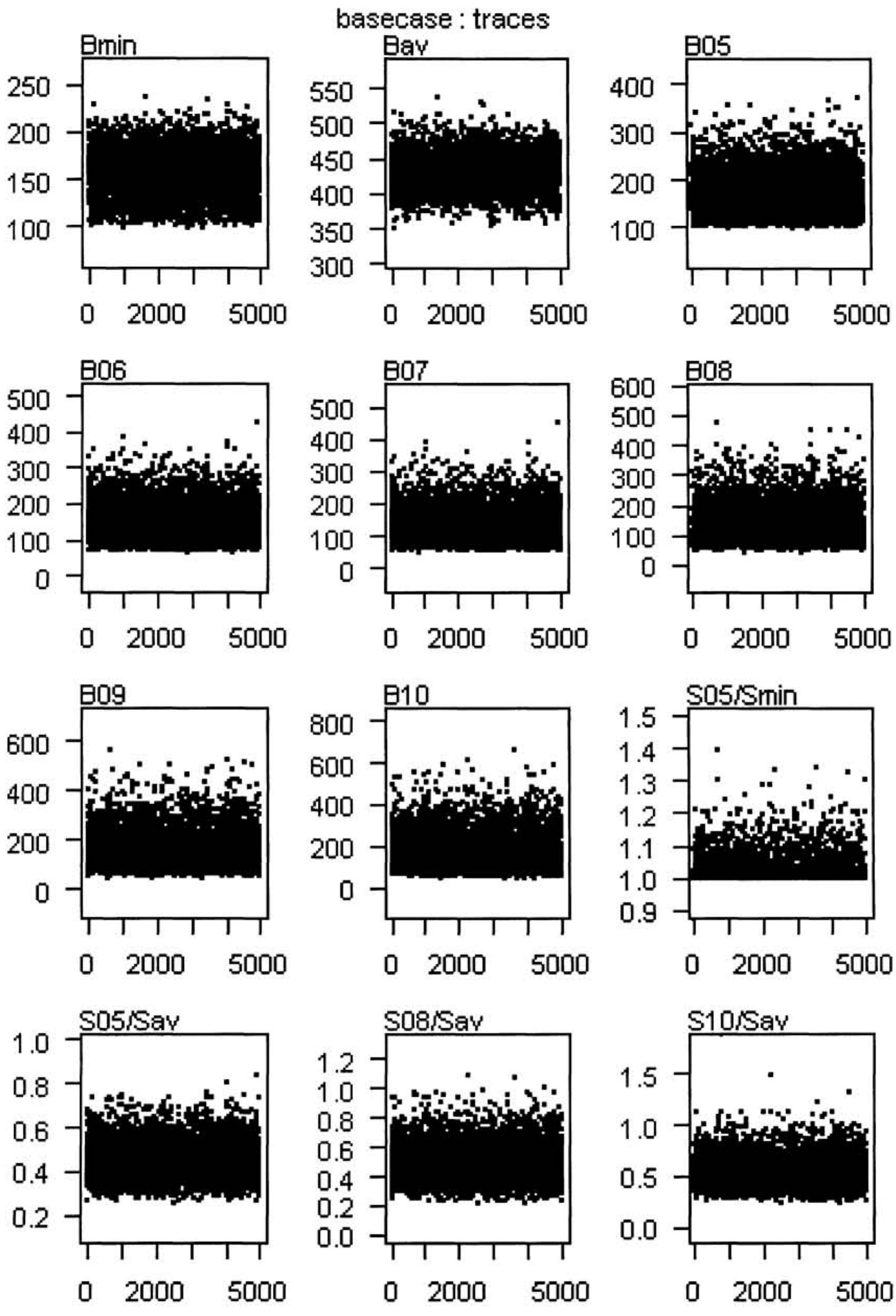


Figure 109 continued.

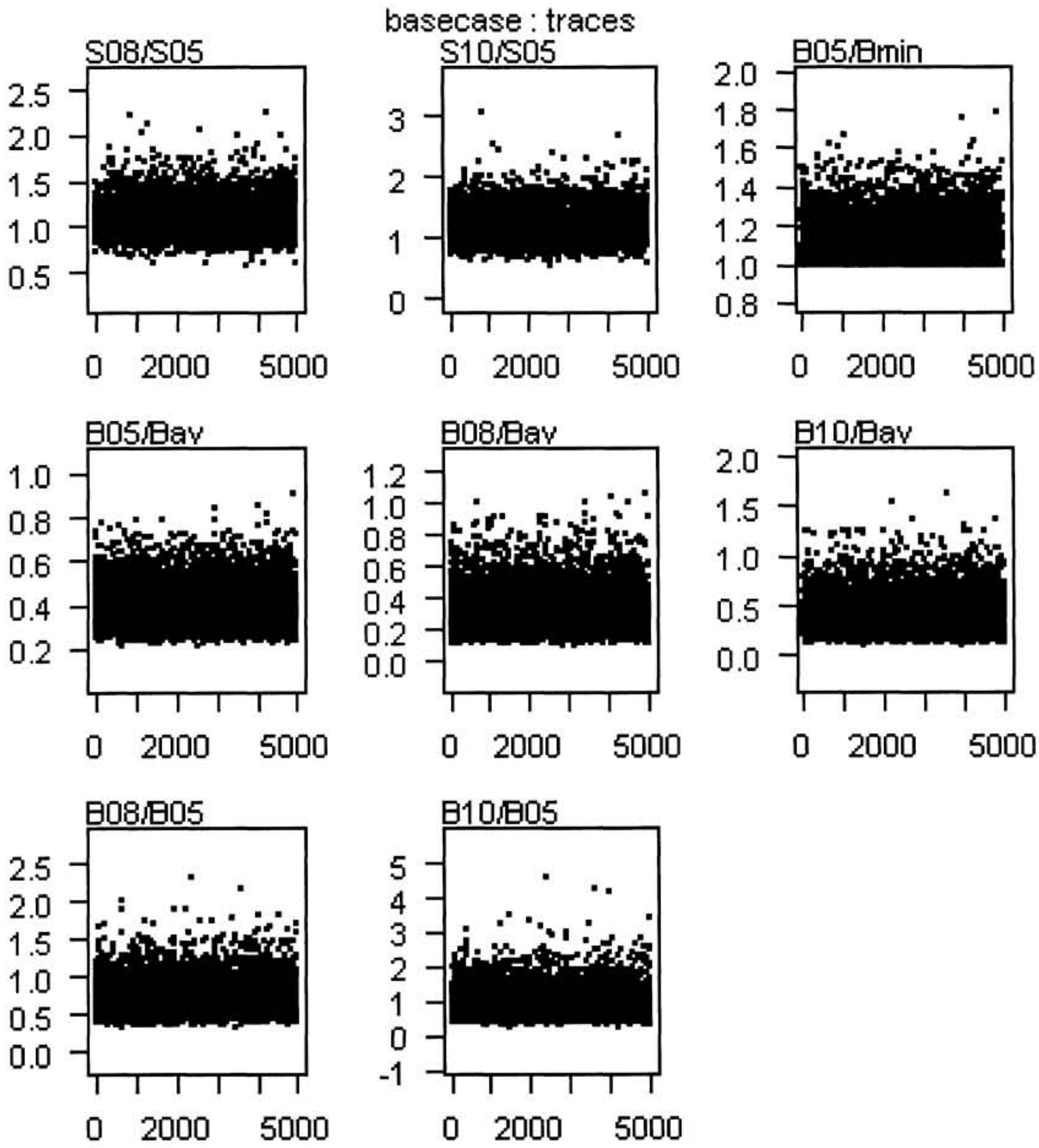


Figure 109 continued.

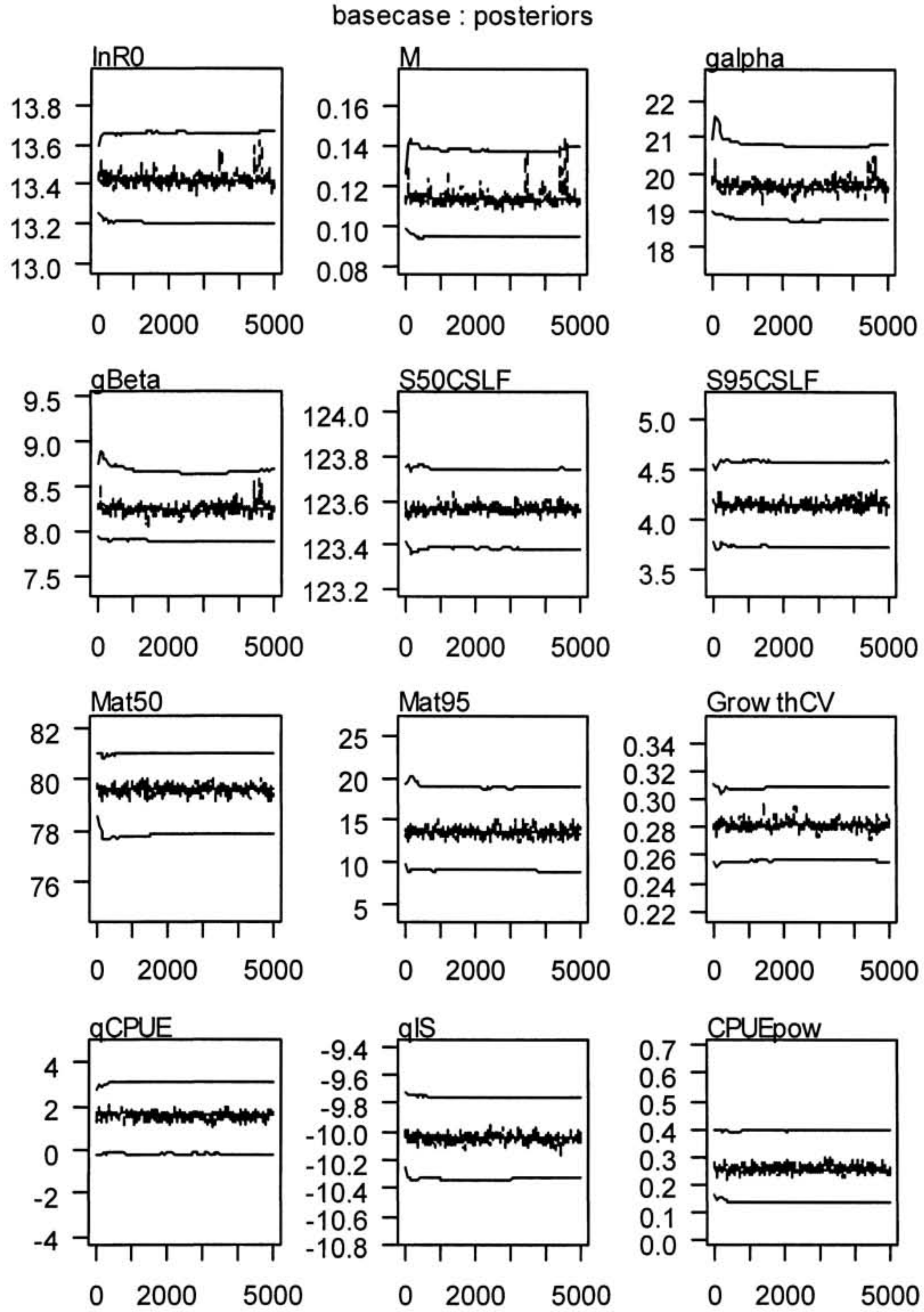


Figure 110: Diagnostic plots on the traces from the base case PAU 5D McMC simulations. The central line is the running median; the upper and lower lines are the running 5th and 95th quantiles; the central dots show a moving average over 40 samples Some recruitment deviations are not shown.

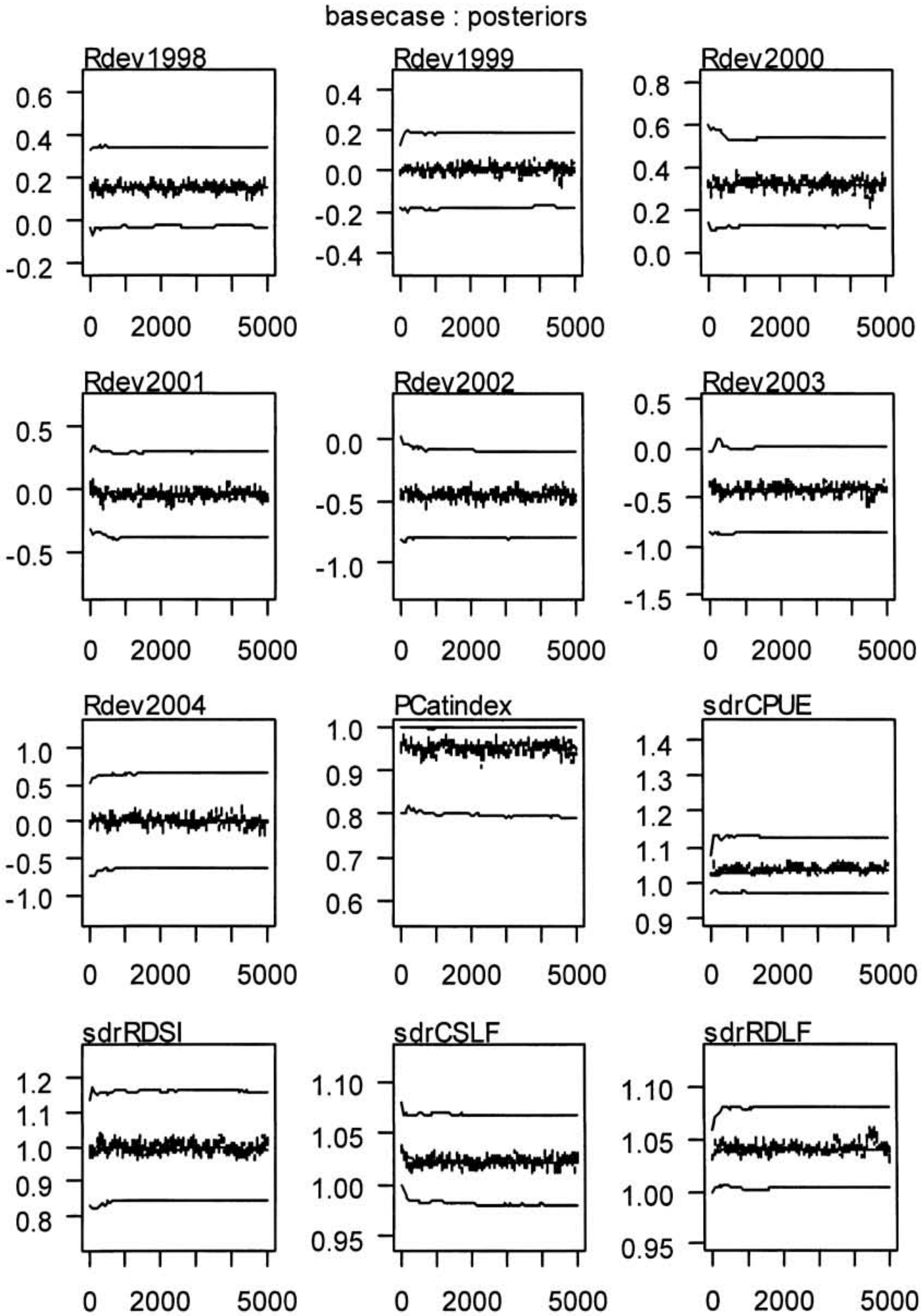


Figure 110 continued.

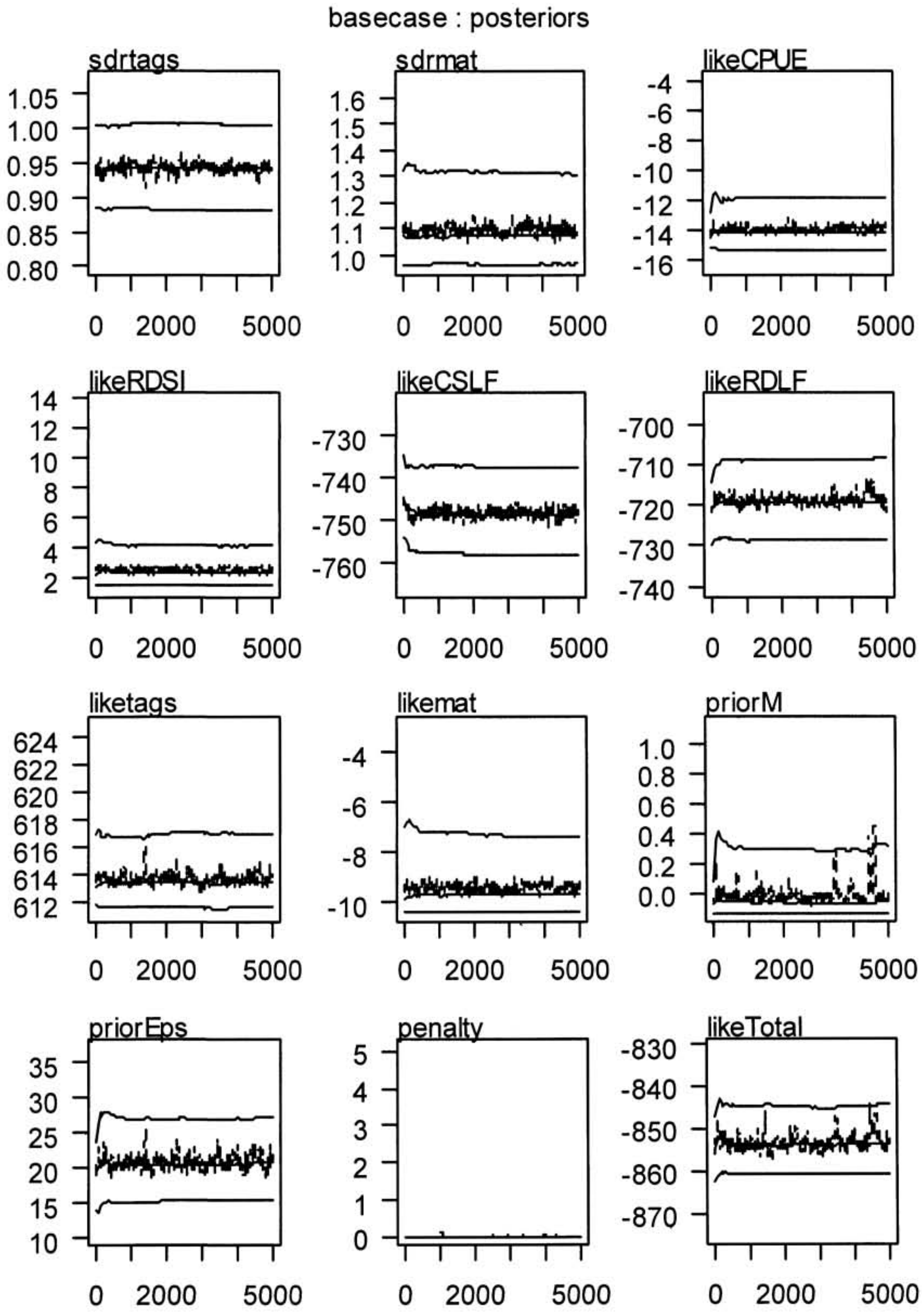


Figure 110 continued.

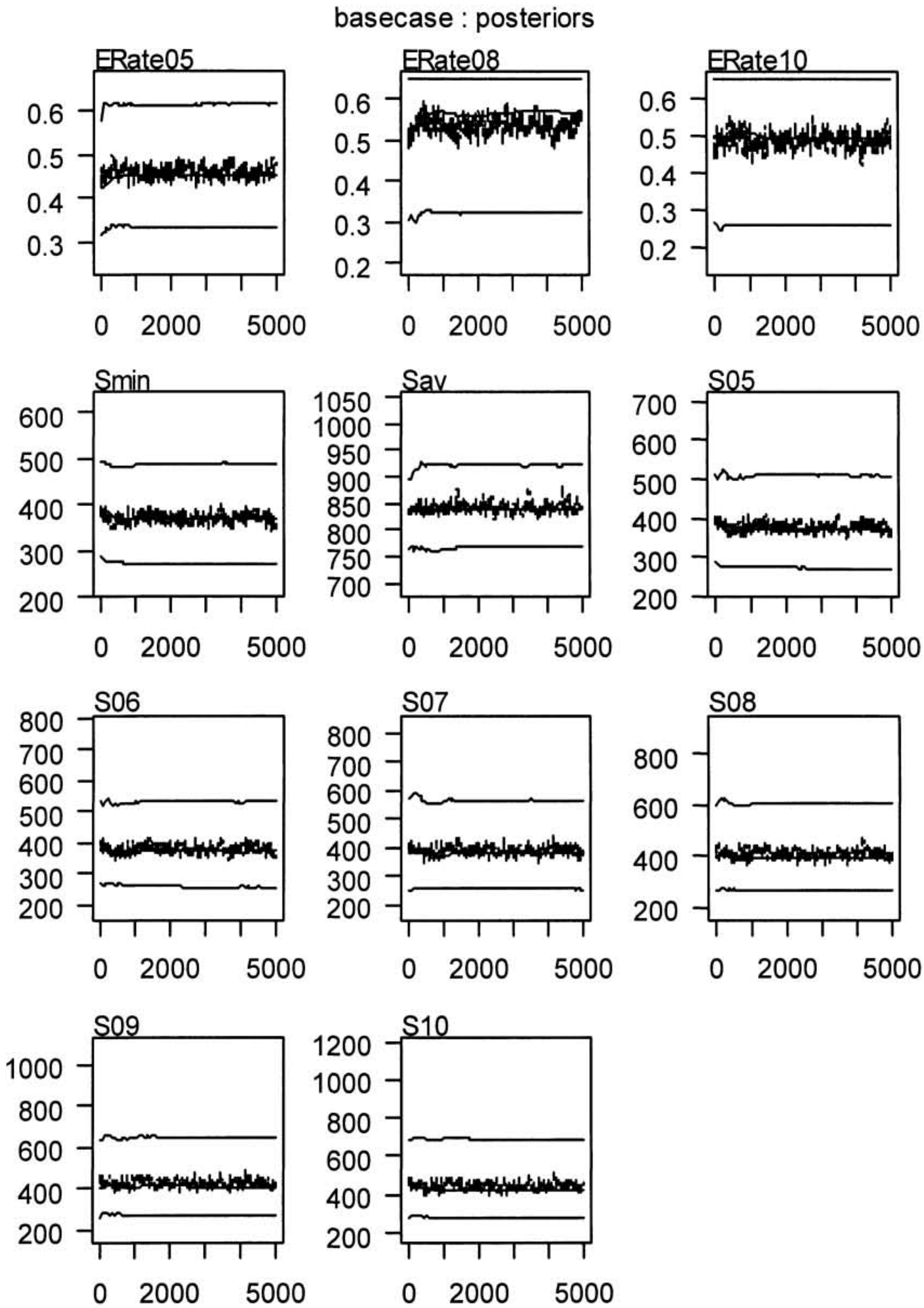


Figure 110 continued.

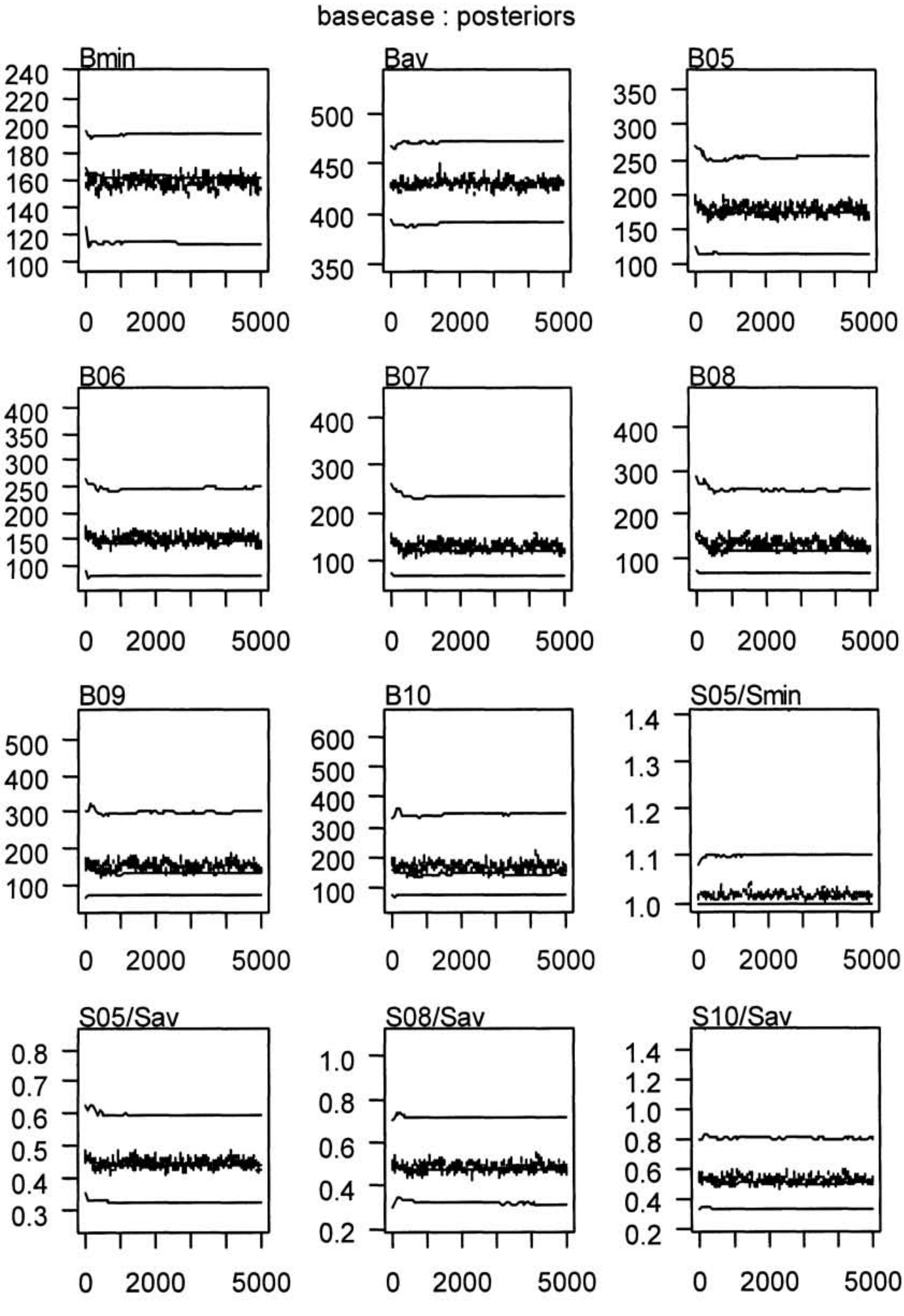


Figure 110 continued.

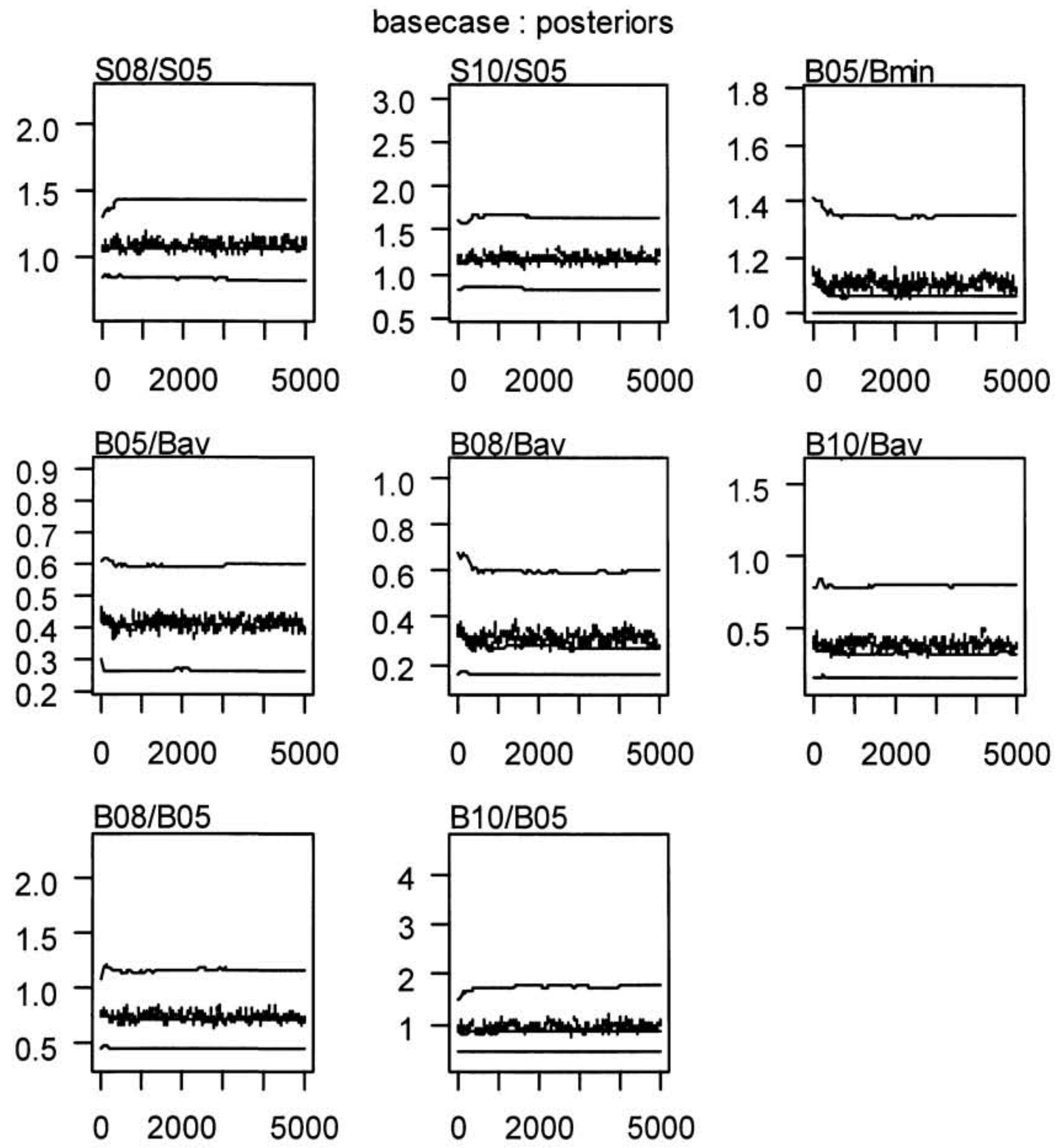


Figure 110 continued.

Marginal posteriors (Figure 111) are well formed and most estimated parameter posteriors are centred on the MPD estimate. The *PCatindex* has about half its distribution at 1, indicating that the specified catch was taken in projections, while the other half ranges down to about 0.8, when the maximum exploitation rate was reached and the catch could not be taken. Projected exploitation rates have similar distributions, with many runs at 65% and a long tail ranging down to 20–30%.

Ratios of current biomass to minimum biomass – *B05/Bmin* and *S05/Smin* – show many or most runs at 1, reflecting the minimum biomass occurring in 2005.

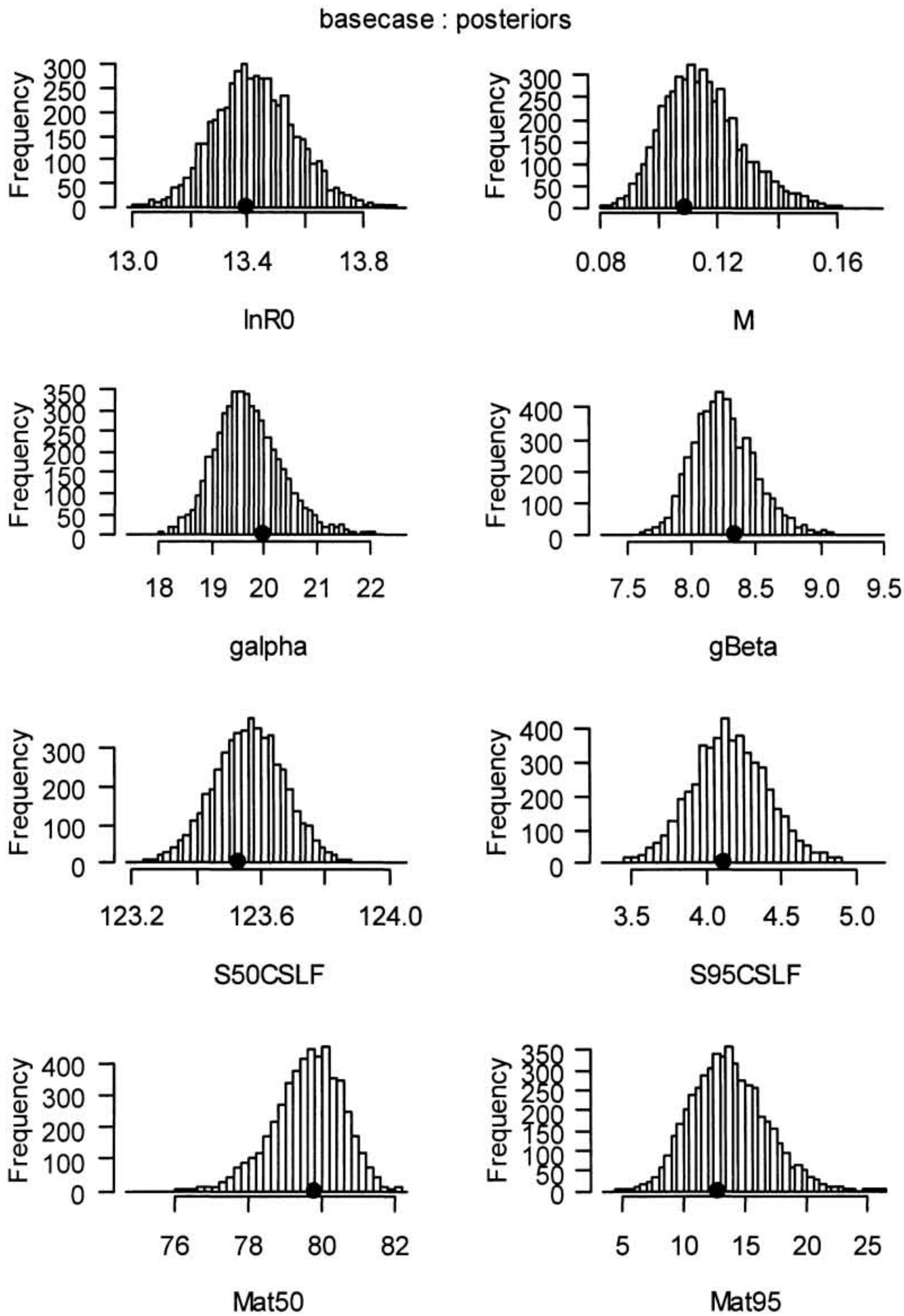


Figure 111: Posterior distributions of parameters and indicators from the base case PAU 5D McMC. Dots on the x-axis show the MPD estimate.

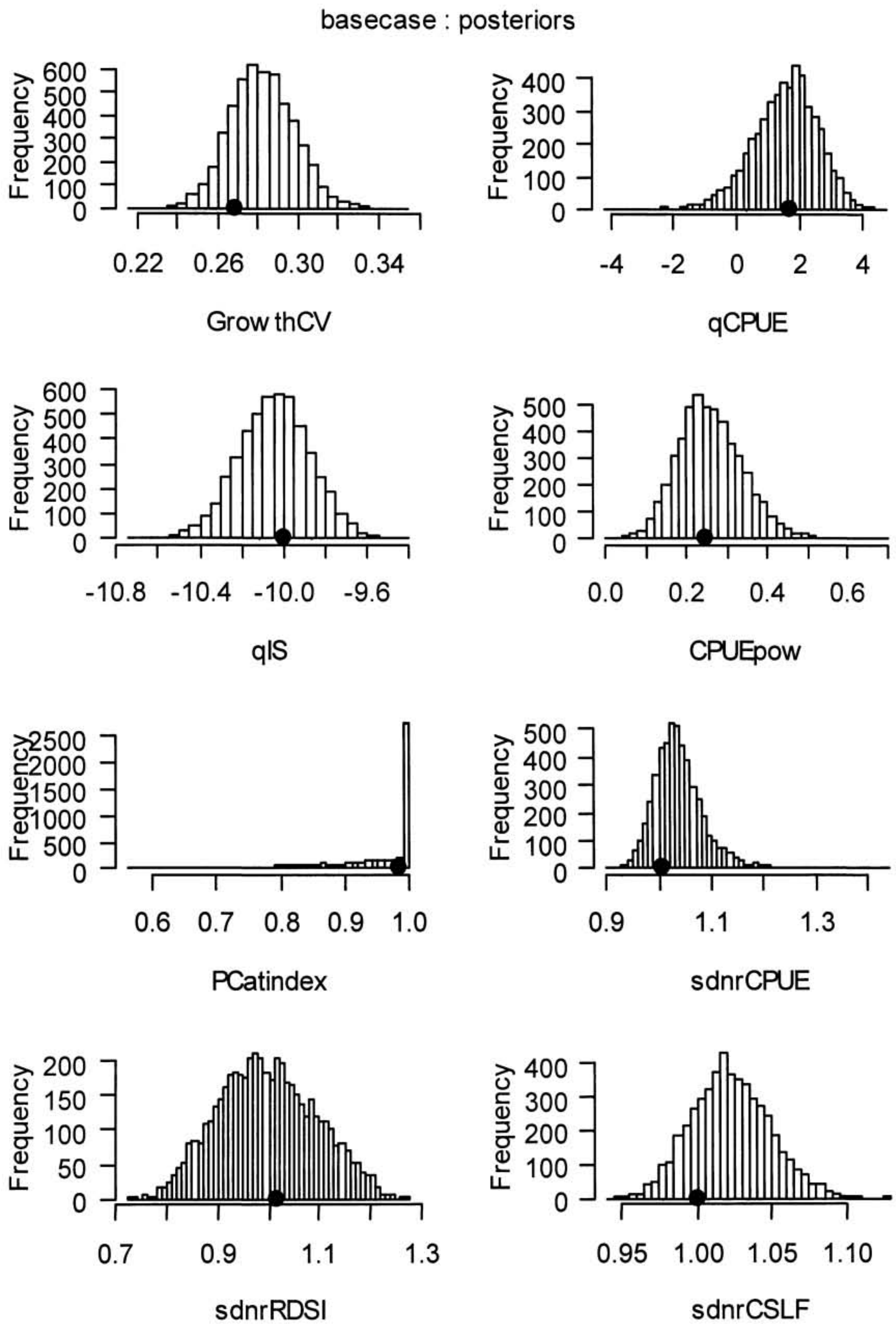


Figure 111 continued.

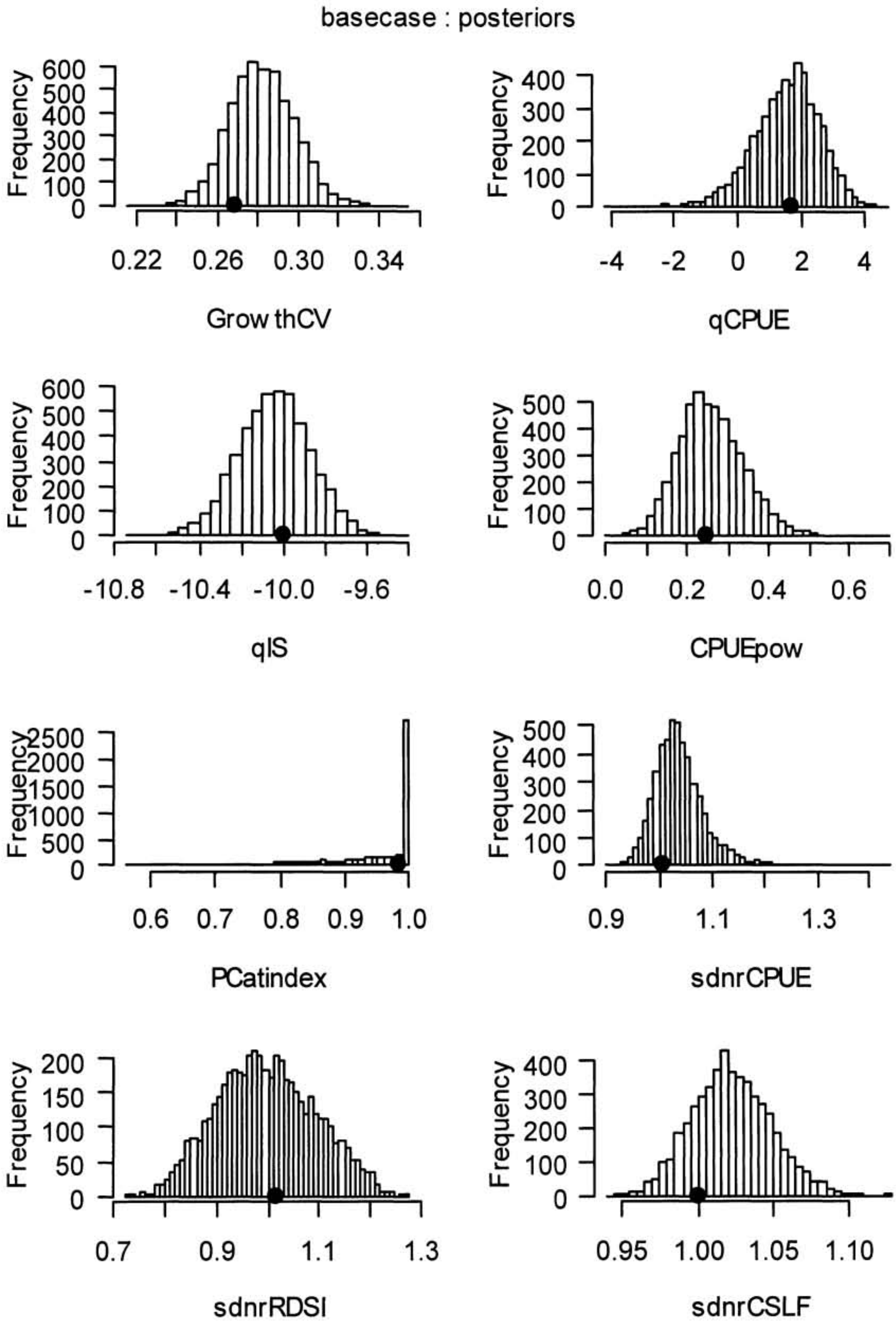


Figure 111 continued.

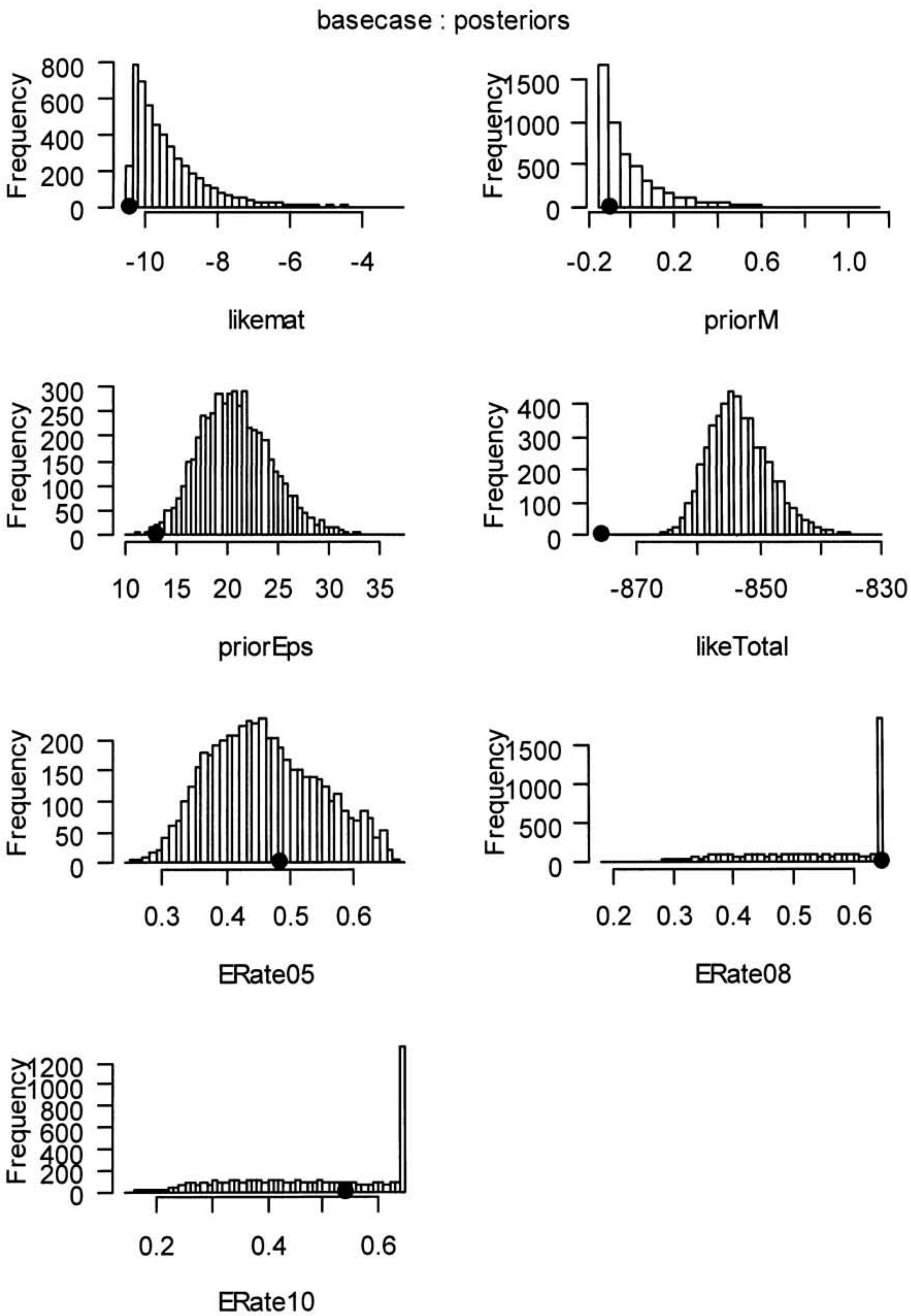


Figure 111 continued.

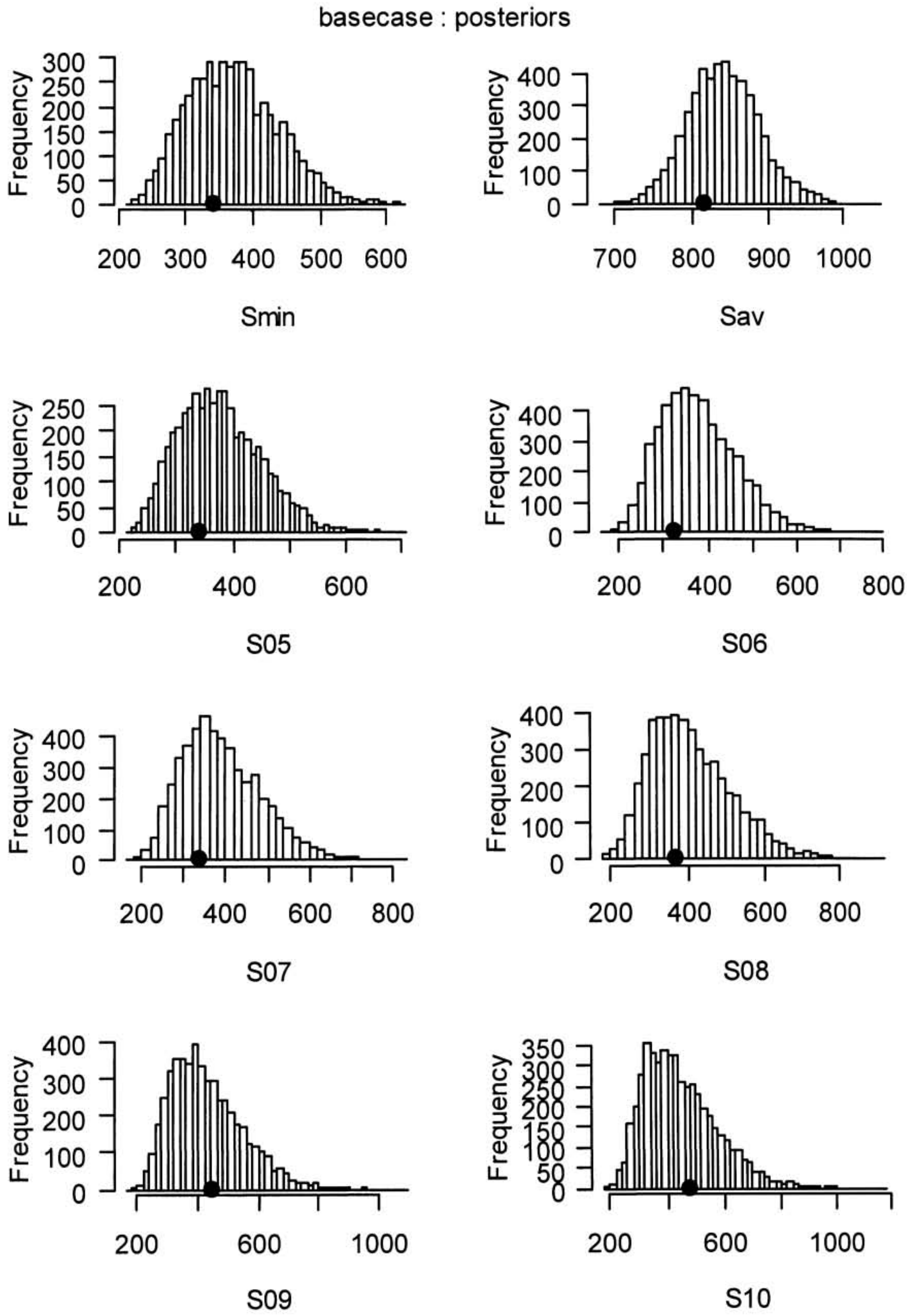


Figure 111 continued.

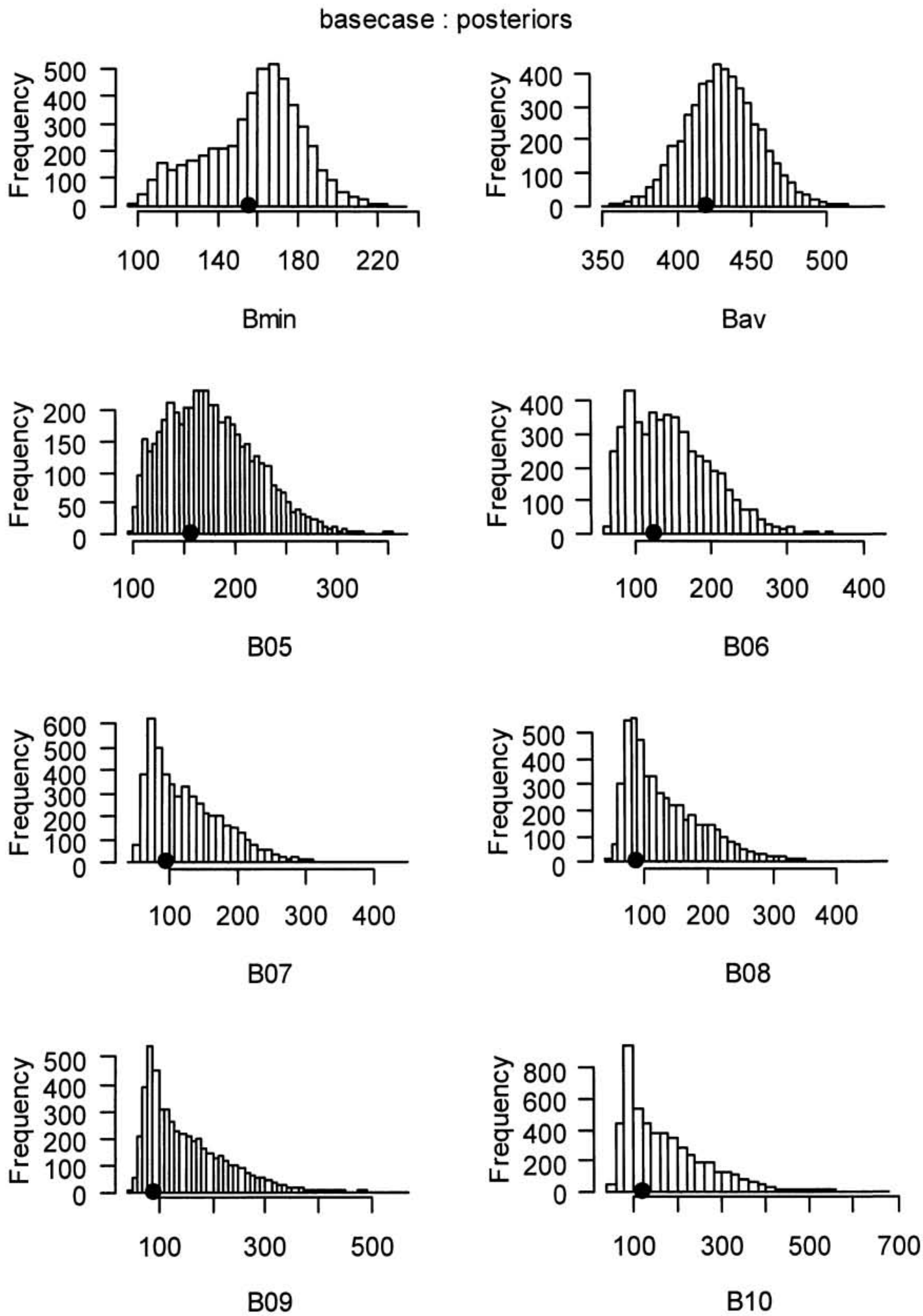


Figure 111 continued.

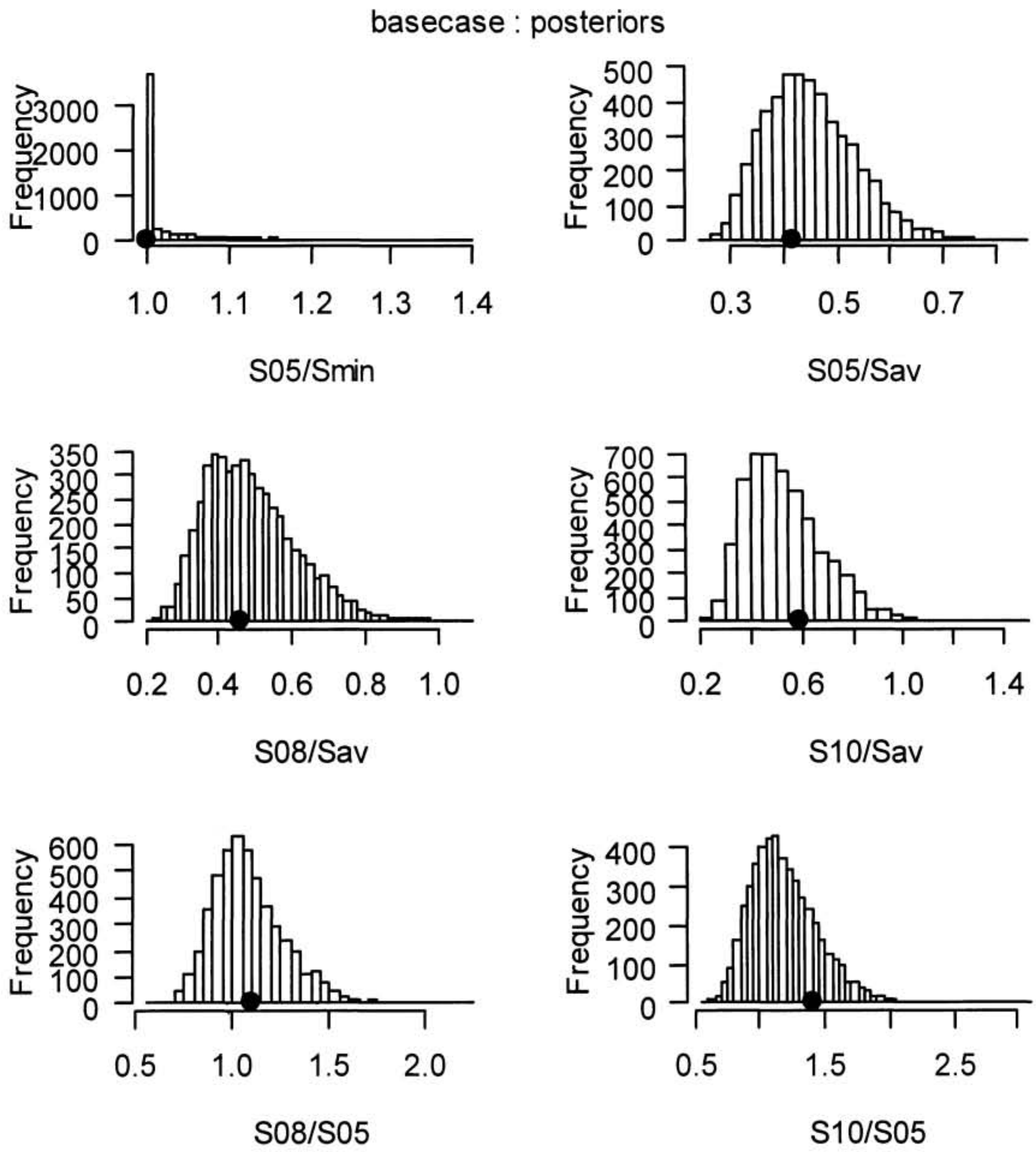


Figure 111 continued.

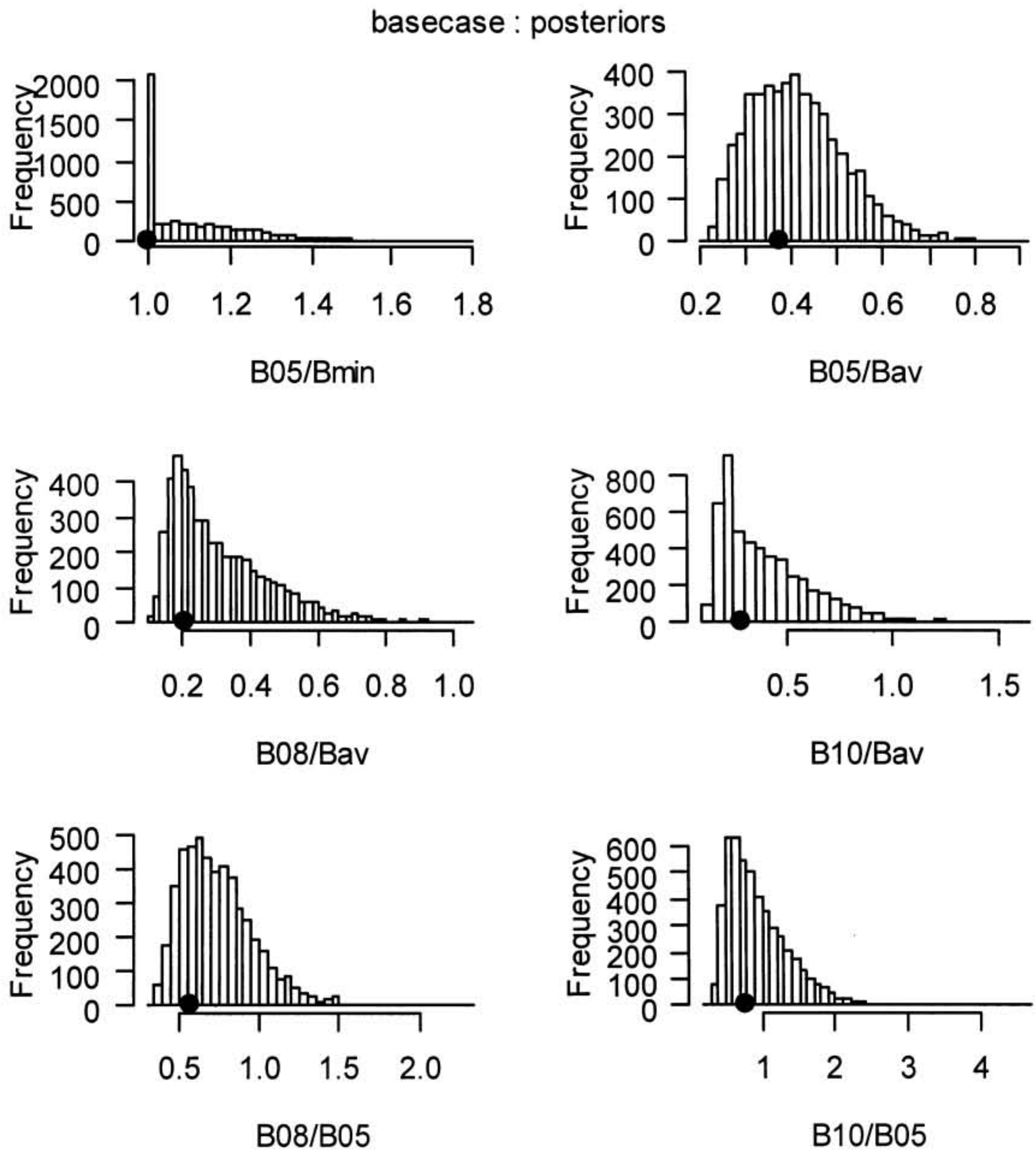


Figure 111 continued.

The marginal posterior distributions of predicted CPUE, or the posterior of model fit to CPUE (Figure 112), show some difficulty with years 1989, 1998 and 1999, but not bad fits otherwise. The fit to RDSI (Figure 113) also shows difficulties: the model does not reproduce the 1997 increase or the 1999 decrease. The fit to a selected example of the CSLF data (Figure 114) is good, but the fit to a selected example of the RDLF data (Figure 115) is not good, as seen in the MPD fits.

The posterior distribution of the Q-Q plot of residuals to the tag-recapture dataset (Figure 116) shows a good pattern. The fit to maturity data (Figure 117) is generally good.

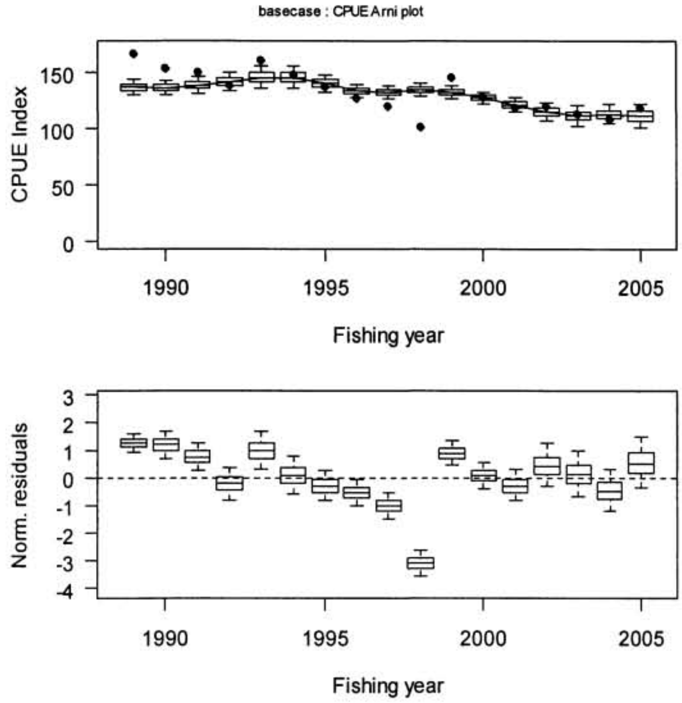


Figure 112: The posterior distributions of the fits to CPUE data (top) and the posterior distributions of the normalised residuals from the base case McMC for PAU 5D. In the upper plot, black dots show the observations. For each year, the box plot shows the median of the posterior distribution (horizontal bar), the 25th and 75th percentiles (box) and 5th and 95th percentiles of the posterior.

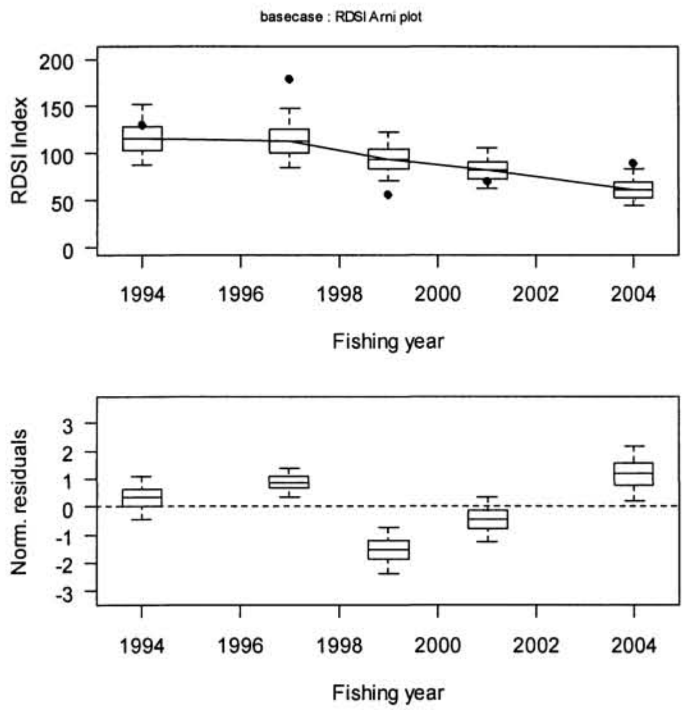


Figure 113: The posterior distributions of the fits to RDSI data (top) and the posterior distributions of the normalised residuals from the base case McMC for PAU 5D. In the upper plot, black dots show the observations. For each year, the Figure shows the median of the posterior distribution (horizontal bar), the 25th and 75th percentiles (box) and 5th and 95th percentiles of the posterior.

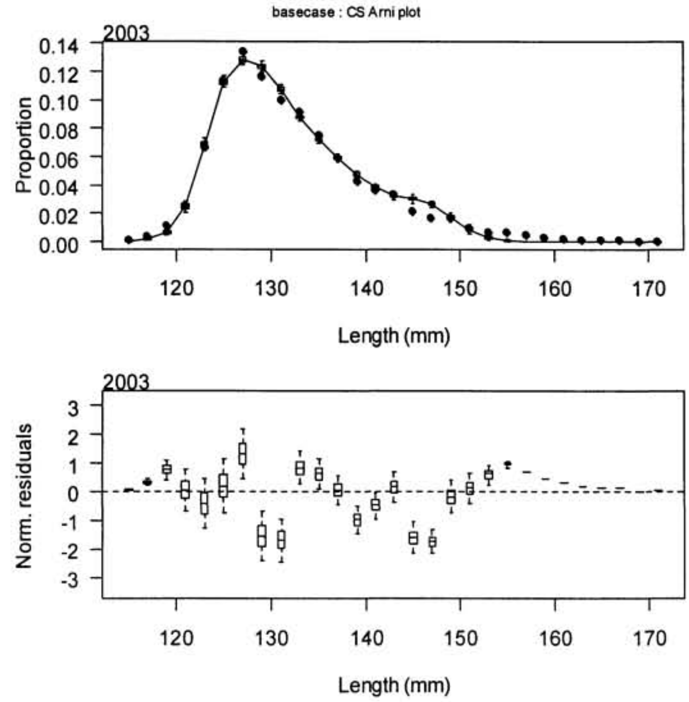


Figure 114: The posterior distributions of the base case McMC fit to the CSLF data from 2003 (top) and the posterior distributions of the normalised residuals.

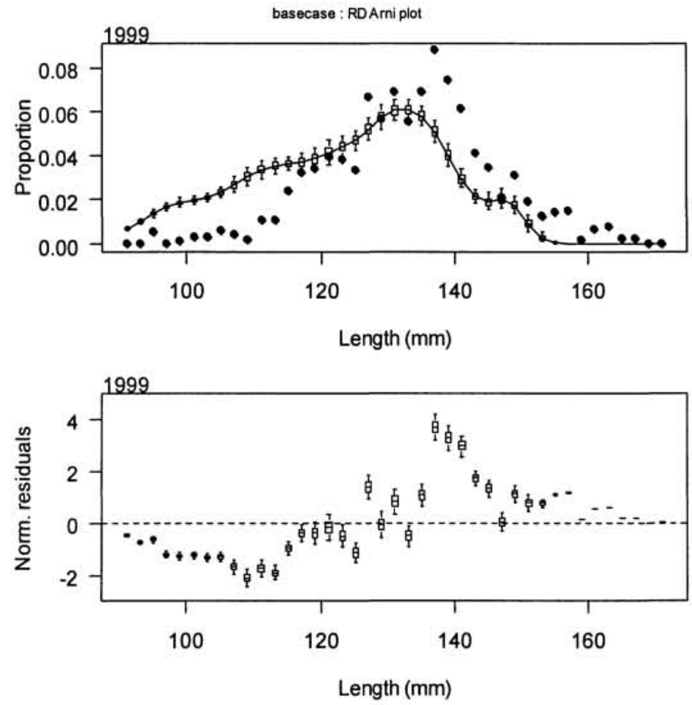


Figure 115: The posterior distributions of the base case McMC fit to the RDLF data from 1999 (top) and the posterior distributions of the normalised residuals.

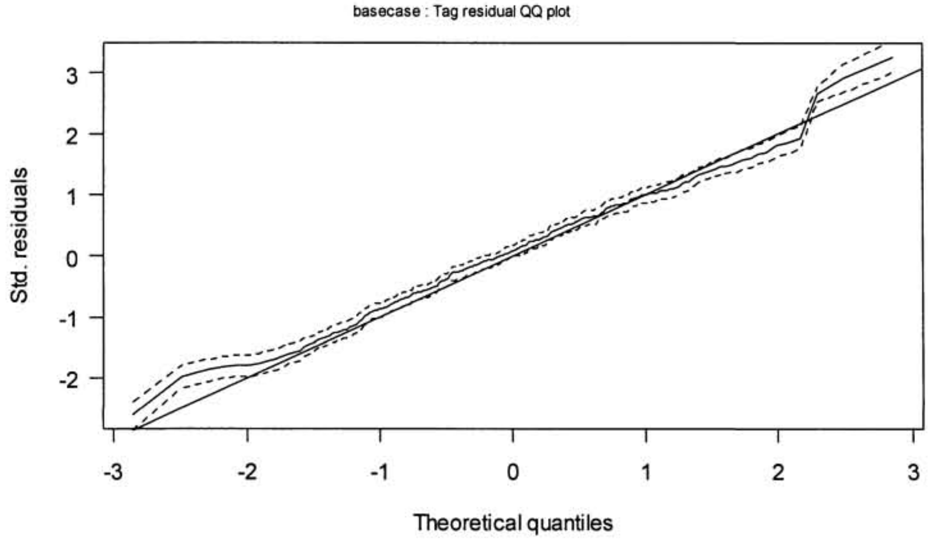


Figure 116: The posterior distribution of the Q-Q plot of the normalised residuals from the base case McMC fits to the tag-recapture data.

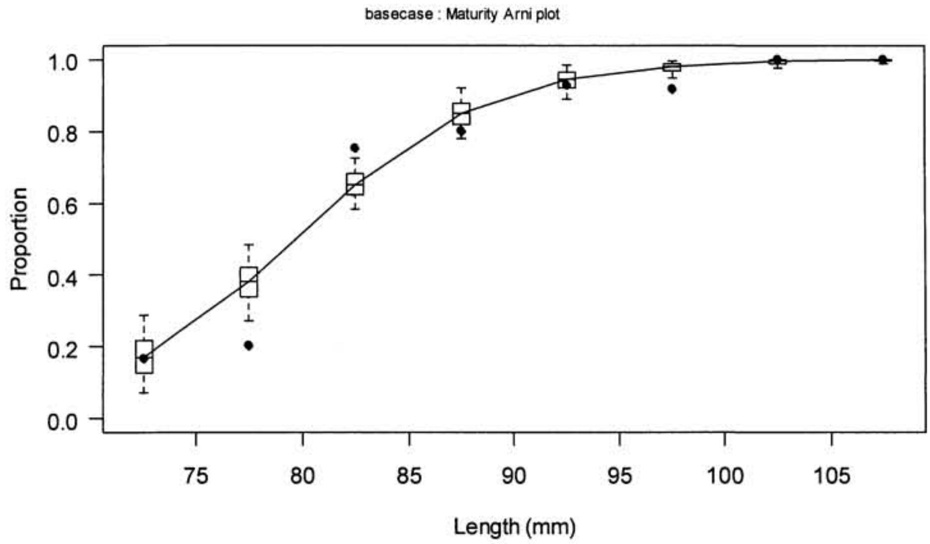


Figure 117: The posterior distributions of the base case McMC fit to maturity-at-length for PAU 5D. Dots show the observations and the box plots summarise the posterior as in previous captions.

Biomass trajectories (Figure 118) are similar to those seen in the MPD (Figure 106), with least uncertainty and minimum biomass close to the present. The recent trajectory for recruited biomass (Figure 119) has increasing uncertainty after 2002 and uncertainty increases through the projections; there is a tendency for biomass to decrease initially in projections and then increase. Exploitation rate (Figure 120) is the complement of the trend just described; in projections it sometimes hits the upper bound.

The posterior of the recruitment trajectory shows a median pattern similar to that seen in the MPD (Figure 104). Uncertainty about the recruitment pulses and troughs is generally low: recruitment is always high in the pulses and low in the troughs.

The posterior surplus production trajectory (Figure 121) shows a peak in the early 1990s, following the strong recruitment pulse, is low in 2004 and 2005 and increases in projections. Figure 122 shows the posterior distribution of production vs. recruited biomass, suggesting that the point of maximum productivity is around 200–500 t recruited biomass and maximum production is 150–250 t, but is very poorly determined.

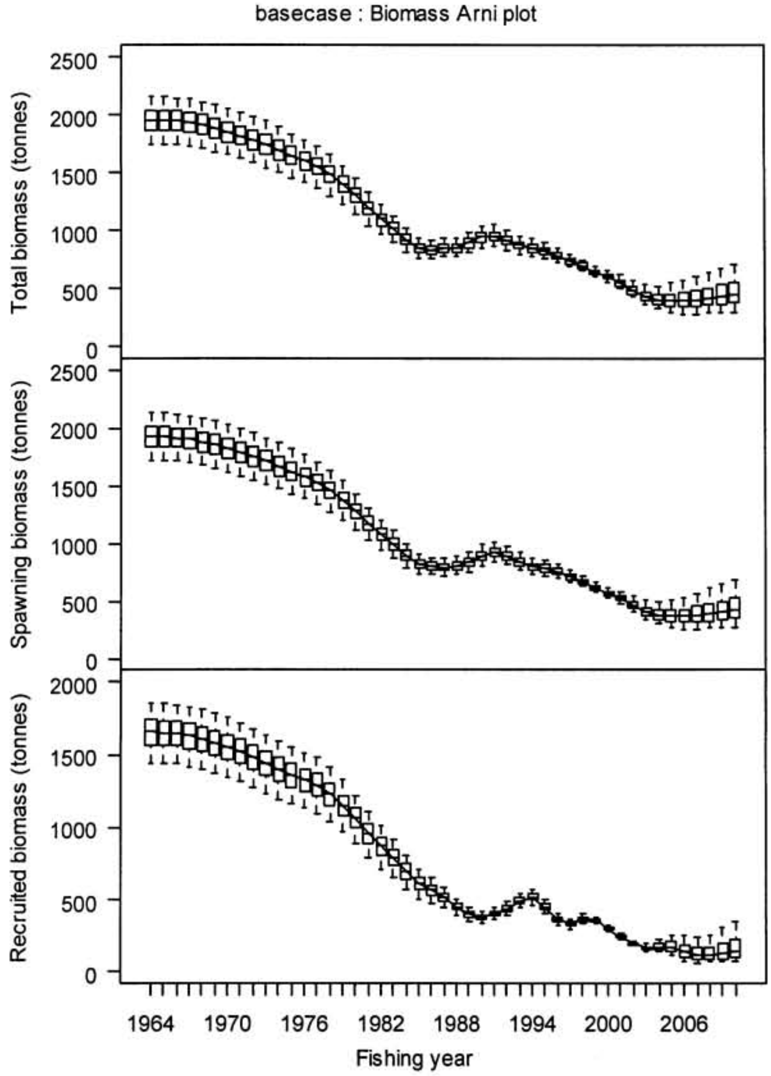


Figure 118: The posterior biomass trajectories from the base case McMC for PAU 5D: total biomass (top), spawning biomass (middle) and recruited biomass (bottom). Box plots summarise the posterior distribution for each year as described in previous captions.

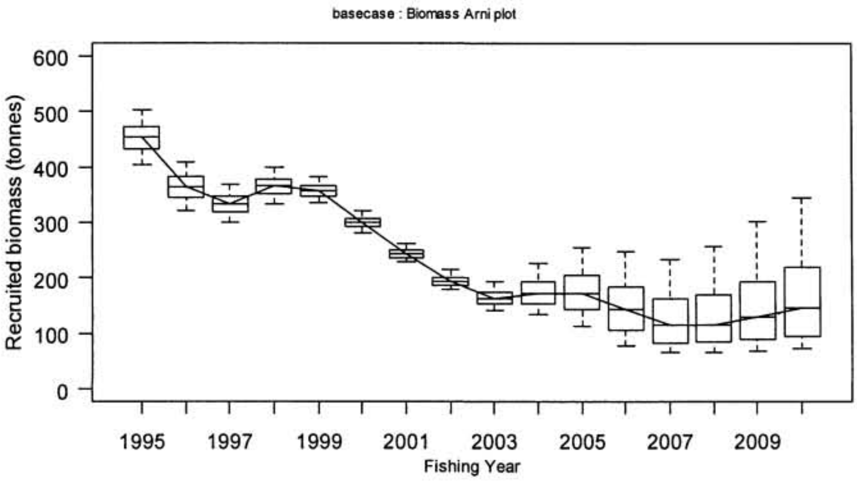


Figure 119: The posterior distributions of the base case McMC recruited biomass trajectory from 1995 onwards.

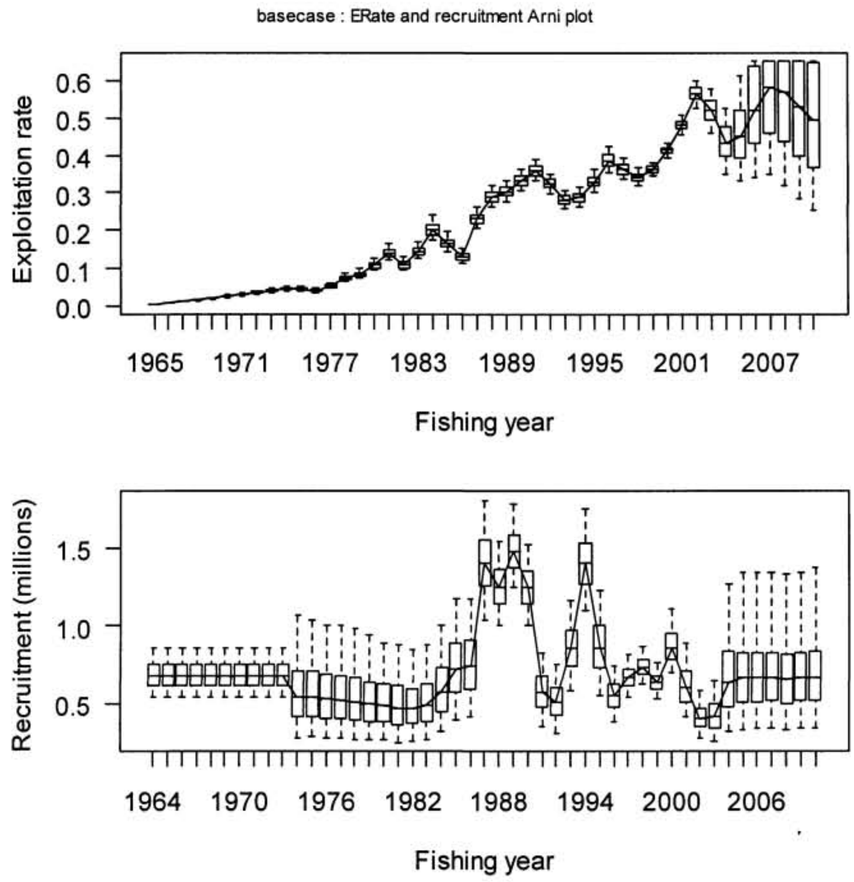


Figure 120: The posterior trajectories of exploitation rate (upper) and recruitment (lower) for the base case McMC for PAU 5D.

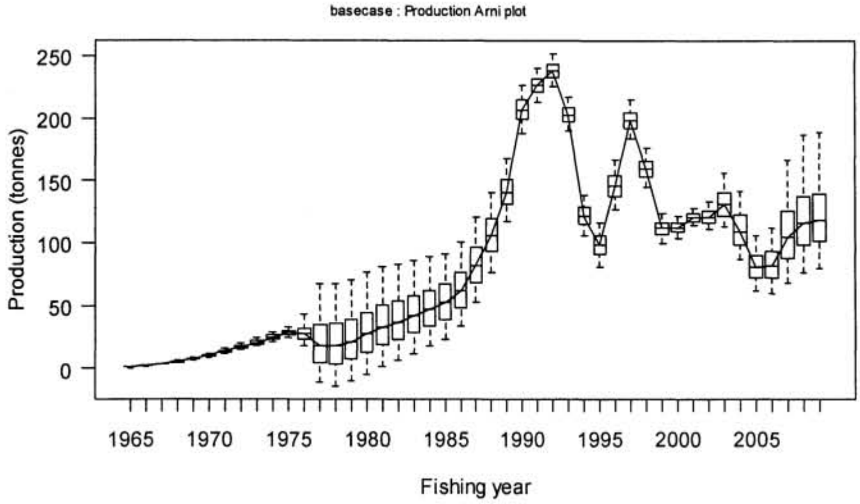


Figure 121: The posterior trajectory of estimated surplus production from the base case McMC for PAU 5D.

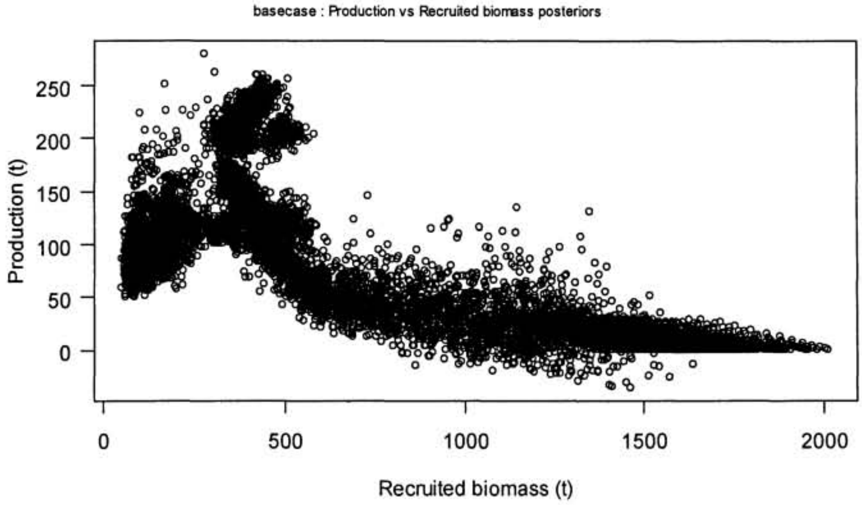


Figure 122: Surplus production plotted against mid-year recruited biomass from the base case McMC for PAU 5D. Each point represents one year in one sample from the joint posterior distribution. For this plot, samples were uniformly thinned to 4% of the total sample.

Marginal posteriors for estimated parameters and associated quantities are summarised in Table 54. The 5 to 95% range of sdnrs was 0.85 to 1.30, showing that the functional weightings of datasets did not change much during the McMC.

For estimated parameters, the 5 to 95% range of *M* was 0.095 to 0.134, reasonably tight. Growth and selectivity parameters also had quite tight ranges; *mat50* was tight but *mat95* varied from 9 to 19 mm. Catchability for the RDSI did not vary much, but catchability for CPUE varied greatly, in turn because *CPUEpow* varied from 0.14 to 0.70.

In some of the runs, exploitation rate reached the upper bound (Figure 120), reflected in the penalty contribution.

Table 54: Summary of the marginal posterior distributions of parameter estimates from the McMC chain from the base case for PAU 5D. The columns show the minimum values observed in the 5000 samples, the maxima, the 5th and 95th percentiles and the medians. %MPD shows the position that the MPD estimate occupies in the marginal posterior distribution.

	Min	0.05	Median	0.95	Max	%MPD
ln(*R0*)	13.0	13.2	13.4	13.7	13.9	42.7
M	0.0803	0.0951	0.1136	0.1395	0.1746	36.9
galpha	17.5	18.8	19.6	20.8	22.7	69.4
gBeta	7.34	7.89	8.24	8.68	9.47	67.9
CS50	123.2	123.4	123.6	123.7	124.1	38.5
CS95	3.31	3.74	4.15	4.58	5.18	44.1
Mat50	74.8	77.9	79.7	81.0	82.2	55.7
Mat95	3.97	9.03	13.48	18.96	26.45	41.4
GrowthCV	0.219	0.256	0.281	0.308	0.354	19.6
ln(*qCPUE*)	-4.043	-0.222	1.628	3.110	4.723	52.8
ln(*qRDSI*)	-10.75	-10.33	-10.04	-9.76	-9.40	59.0
CPUEpow	0.011	0.138	0.254	0.398	0.692	47.3
sdnrCPUE	0.903	0.973	1.033	1.126	1.437	26.7
sdnrRDSI	0.722	0.846	0.994	1.160	1.272	57.9
sdnrCSLF	0.943	0.981	1.021	1.067	1.128	20.6
sdnrRDLF	0.951	1.004	1.041	1.081	1.133	20.7
sdnrtags	0.798	0.881	0.942	1.004	1.071	77
sdnrmat	0.954	0.967	1.076	1.308	1.671	24.6
Like CPUE	-16.4	-15.3	-14.1	-11.8	-3.9	14
Like RDSI	1.21	1.60	2.42	4.17	13.72	34.3
Like CSLF	-766.6	-758.2	-748.8	-737.7	-722.1	20.5
Like RDLF	-741.1	-728.4	-719.1	-708.5	-694.4	20.7
Like tags	611.2	611.6	613.4	617.0	625.0	7.9
Like mat	-10.4	-10.4	-9.7	-7.4	-2.9	0.0
prior on *M*	-0.131	-0.130	-0.062	0.322	1.137	34.9
prior on *Eps*	10.1	15.5	20.7	27.1	37.1	0.7
Umax penalty	0.000	0.000	0.000	0.000	5.106	0.0
LikeTotal	-875.6	-860.6	-853.7	-844.4	-830.6	0.0

Correlations among estimated parameters, based on the samples from the joint posterior (Table 55) show a high correlation between ln(*R0*) and *M*, and between ln(*qCPUE*) and *CPUEpow*, but few other strong relations.

Table 55: Correlations among estimated parameters in the PAU 5D McMC. Boxes indicate absolute values greater than 0.50. The *Eps*, commercial selectivity and maturity parameters are not shown.

	ln(*R0*)	*M*	*galpha*	*gBeta*	*GrowthCV*	ln(*qCPUE*)	ln(*qRDSI*)	*CPUEpow*
ln(*R0*)	1.00							
M	0.90	1.00						
galpha	0.00	0.09	1.00					
gBeta	-0.04	0.11	0.87	1.00				
CS50	0.12	0.10	-0.29	-0.14				
CS95	-0.01	-0.01	0.00	-0.02				
mat50	0.02	0.01	0.01	0.00				
mat95	0.00	0.00	0.01	0.01				
GrowthCV	-0.04	-0.09	-0.55	-0.55	1.00			
ln(*qCPUE*)	-0.10	-0.05	-0.06	-0.04	0.04	1.00		
ln(*qRDSI*)	-0.21	-0.19	0.13	0.18	-0.07	0.11	1.00	
CPUEpow	0.09	0.04	0.06	0.05	-0.04	-1.00	-0.10	1.00

7.7 PAU 5D base case results

The marginal posterior distributions for indicators are summarised in Table 56. At the request of the SFWG, projections were made with MLS of both 125 and 127 mm and indicators are summarised for three- and five-year projections.

The current state of the stock is reflected in the first group of indicators. The marginal posterior distribution of mid-2005 recruited biomass has a median of 106% *Bmin* (5 to 95% range 100 to 135%); for nearly half the runs the model's *Bmin* occurred in 2005. The relation of current recruited biomass to the reference level has a median of 40% (27 to 60%), indicating that the stock is well below the reference level. The median of current exploitation rate is 45% (33 to 61%). Spawning biomass is similar: a majority of runs have the minimum (*Smin*) occurring in 2005 and the current level is 33 to 60% of the reference level.

In three-year projections with the current level of catch and current MLS (the second group of indicators in Table 56), the median expectation is that recruited biomass will be only 70% of that in 2005, with a 5–95% range from 45 to 118%. Only 13% of the runs increased in recruited biomass; almost all remained less than the reference level; 75% fell below *Bmin*. The spawning biomass had a slight median increase (range 83 to 144% of 2005 levels); 65% of runs increased but almost all remained below the reference level; 34% of runs had spawning biomass falling below *Smin*.

With the current MLS, five-year projections were somewhat more optimistic than the three-year projections. All the median and probability indicators were more favourable, indicating a shift in the distributions; the lower 5% and minimum for many indicators tended to be worse, reflecting a widening of the distribution. Some of the main conclusions from three-year projections remained valid: recruited biomass was more likely to decrease than increase; it was almost certain to remain below the reference level; there was a substantial chance of falling below *Bmin*.

For three-year projections, increasing the MLS led to increases in spawning and recruited biomass. In these comparisons, "recruited biomass" was calculated with MLS = 125 mm for both 2005 and 2008 (or 2010) so that like quantities were compared. More often than not, exploitation rate hit the upper bound of 65% and the catch specified could be taken: the median of *U08* is 65%. Thus, the main effect of increased MLS for these projections is a *de facto* decrease in TACC for most runs.

For five-year projections the effect of increased MLS is not as dramatic: median *U10* is 56%, which is less than the bound but still higher than the comparable *U10* with MLS = 125.

Thus, five-year projections are more favourable than three-year projections, whatever the MLS, and the larger MLS gives more favourable projections than MLS = 125, although much of this result is caused by reduced catches. In the most favourable combination, MLS = 127 with five-year projections, the chance of decreased recruited biomass is almost 50%, of remaining below the reference level 98%, of falling below *Bmin* 37%. Spawning biomass is only 12% likely to decrease and 11% likely to fall below *Smin*, although highly likely to remain below the reference level.

Table 56: Summary of indicators from the base case MCMC with 125 mm MLS and 127 mm MLS in projections. Biomass indicators are in tonnes. Recruited biomass calculations for indicators (but not dynamics) are based on MLS = 125 mm.

					125mm					127mm
Indicator	Min	0.05	Median	0.95	Max	Min	0.05	Median	0.95	Max
2005										
Smin	216	271	366	489	625					
Sav	687	768	841	922	1043					
S2005	216	271	371	508	702					
Bmin	99	114	162	194	235					
Bav	351	392	430	472	535					
B2005	99	114	173	256	369					
U2005 (%)	24.4	33.1	45.2	61.3	67.1					
S2005/Sav (%)	25.7	32.5	44.0	59.5	84.1					
S2005/Smin (%)	100.0	100.0	100.0	110.2	139.6					
B2005/Bav (%)	21.5	26.6	40.3	59.6	90.1					
B2005/Bmin (%)	100.0	100.0	105.8	135.2	178.0					
2008										
S2008	183	264	394	608	919	204	299	420	620	925
B2008	43	67	117	257	471	62	92	137	255	468
U2008 (%)	18.8	32.0	56.9	65.0	65.0	24.0	40.8	65.0	65.0	65.0
S2008/S2005 (%)	57.6	82.6	105.8	143.8	223.9	61.0	88.9	113.0	155.2	241.2
S2008/Sav (%)	22.0	31.7	47.0	71.8	109.6	25.1	35.8	50.2	73.1	110.4
B2008/B05 (%)	32.7	45.1	70.7	117.5	233.4	40.2	56.6	82.3	127.9	270.9
B2008/Bav (%)	10.4	15.4	27.0	60.0	104.7	14.8	21.5	31.8	59.7	104.8
P(S2008<S05)	35.4					20.8				
P(S2008<Sav)	99.9					99.9				
P(S2008<Smin)	33.7					20.0				
P(B2008<B05)	87.0					78.0				
P(B2008<Bav)	99.9					99.9				
P(B2008<Bmin)	74.3					65.2				
2010										
S2010	189	278	426	684	1179	216	325	466	703	1190
B2010	47	73	146	345	666	66	109	175	358	685
U2010 (%)	14.4	25.4	49.2	65.0	65.0	16.4	29.7	55.8	65.0	65.0
S2010/S2005 (%)	56.1	83.2	115.0	164.8	305.1	66.1	92.3	125.8	180.7	334.0
S2010/Sav (%)	23.5	33.2	50.7	80.6	149.1	27.1	38.7	55.5	83.0	150.9
B2010/B2005 (%)	24.8	45.4	84.6	178.0	462.6	34.8	62.4	103.5	201.2	514.6
B2010/Bav (%)	10.6	16.8	33.9	81.0	161.1	15.4	25.1	40.8	84.0	165.6
P(S2010<S2005)	24.9					11.9				
P(S2010<Sav)	99.5					99.4				
P(S2010<Smin)	23.9					11.3				
P(B2010<B2005)	63.3					46.2				
P(B2010<Bav)	98.7					98.5				
P(B2010<Bmin)	54.9					36.8				

7.8 McMC sensitivity trials

We used full McMC trials to explore the sensitivity of the assessment to three modelling choices. We removed the RDLF dataset (trial 2), we used the exponential growth model rather than linear growth (Trial 3) and we omitted the tag-recapture data (trial 4). In a final trial, we forced the model to fit to recent CPUE and RDSI points by decreasing their c.v.s and increasing the dataset weights (trial 5). In each trial, only the one change was made from the base case. McMC procedures were the same as those described for the base case. In these trials we used MLS = 125 mm, and we compare results from three-year projections only.

Recruitment patterns and resulting biomass trajectories varied among these runs. Biomass (the base case is shown in Figure 119 and sensitivity trials in Figure 123 through Figure 126) shows a more or less steady decline to 2003 in all trials. In the base case, it then stabilises for two years, decreases for the first two years of projections and increases weakly. Trial 4 is similar. In trials 2, 3 and 5, biomass increases strongly after 2003.

Recruitment and exploitation rate are shown in Figure 120 for the base case and Figure 127 through Figure 130 for the sensitivity trials. Base case recruitment shows a strong pulse in 1987 through 1990, another in 1993 through 1995 and a weak pulse in 2000. Recruitment in trial 4 is similar. Recruitment in trial 2 shows a much weaker pulse in 1987–90, only a single year pulse in 1995 and quite a strong pulse in 2002. Trial 3 is similar to the base case until the recent years: it has a weak pulse in 2001 and a very strong pulse in 2004.

Exploitation rate peaks in 2002 in all trials. In the base case and in trial 4, a two-year decline is then followed by increases. In trials 2, 3 and 5, the decline continues after 2002 through the projections.

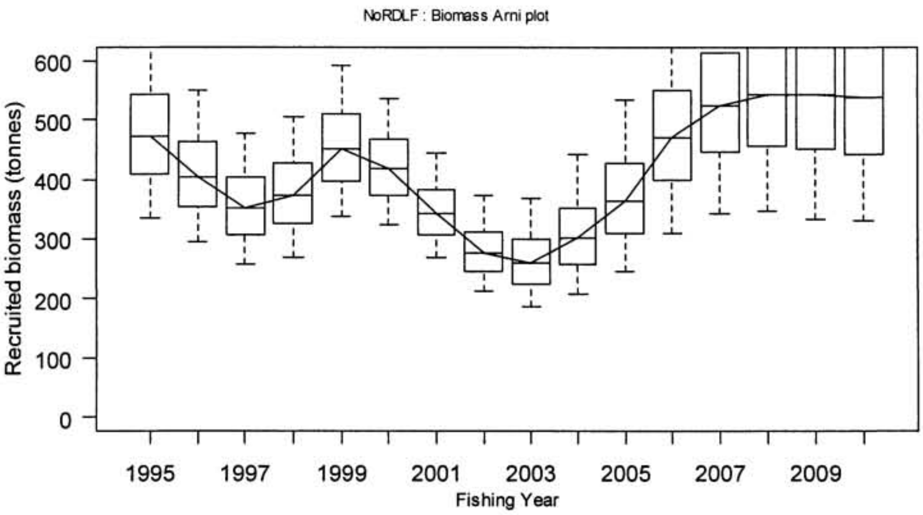


Figure 123: The posterior trajectory for recruited biomass from 1995 onwards in the McMC sensitivity trial 2 (no RDLF) for PAU 5D.

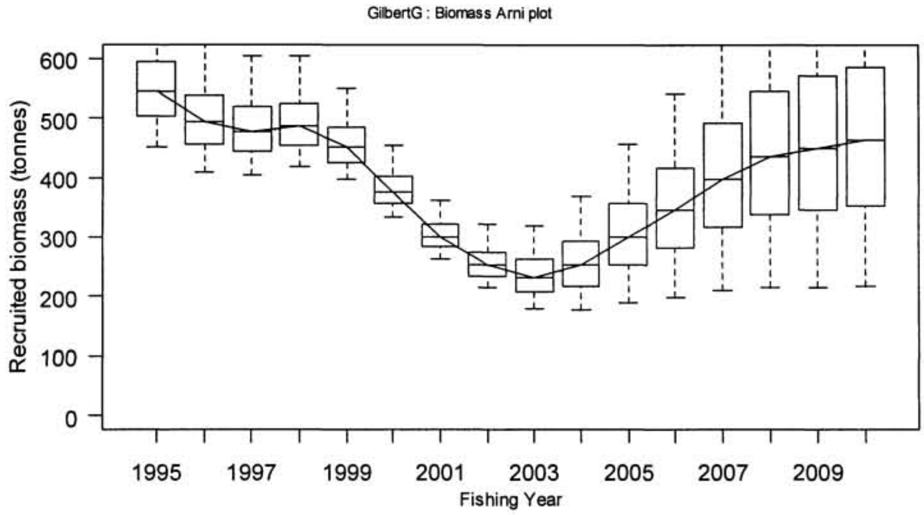


Figure 124: The posterior trajectory for recruited biomass from 1995 onwards in the McMC sensitivity trial 3 (exponential growth) for PAU 5D.

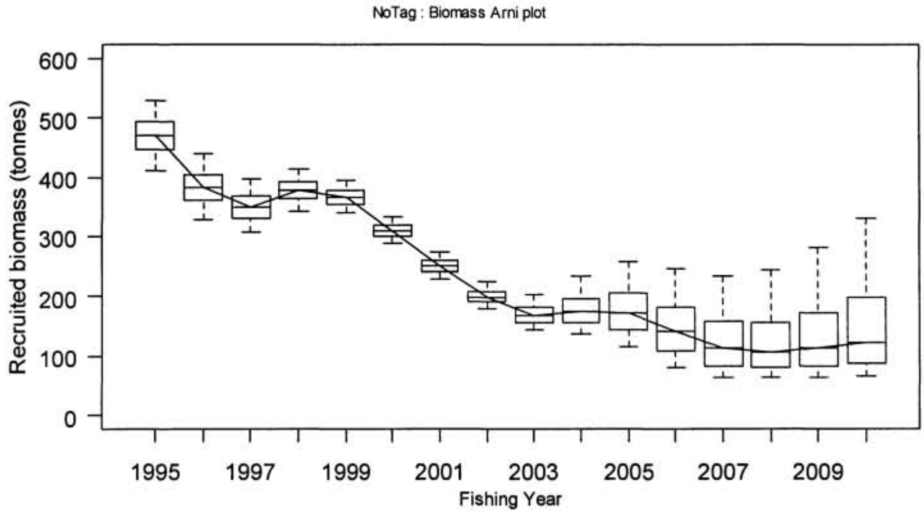


Figure 125: The posterior trajectory for recruited biomass from 1995 onwards in the McMC sensitivity trial 4 (no tag-recapture) for PAU 5D.

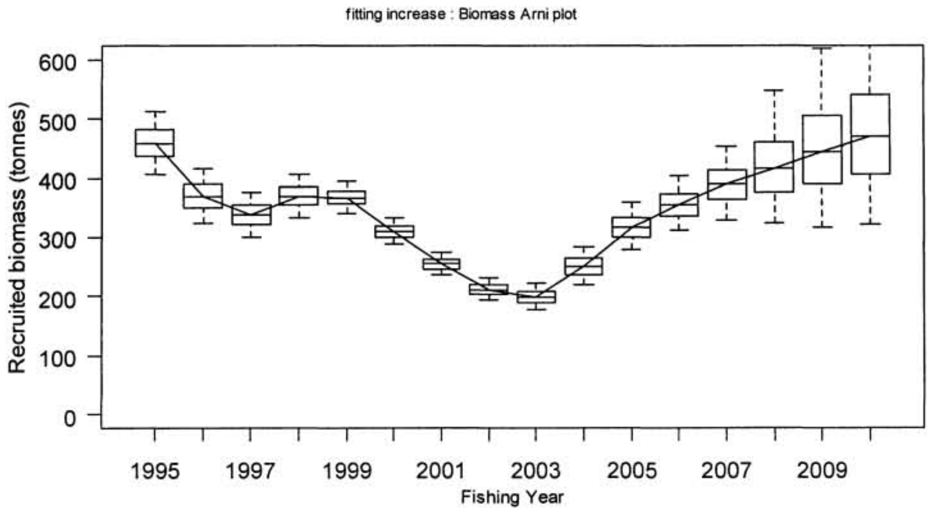


Figure 126: The posterior trajectory for recruited biomass from 1995 onwards in the McMC sensitivity trial 5 (extra weight on abundance indices) for PAU 5D.

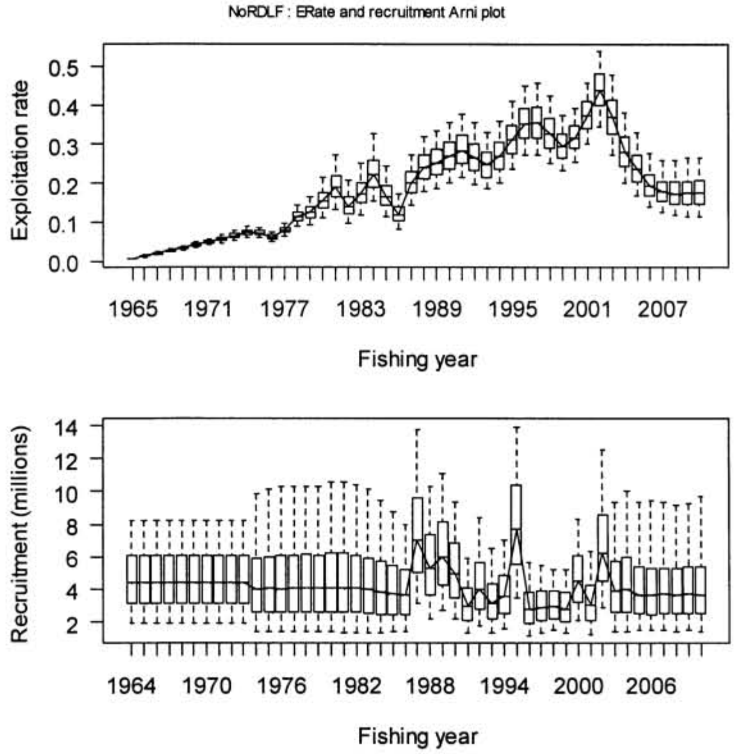


Figure 127: The posterior trajectories of exploitation rate (upper) and recruitment (lower) from the McMC sensitivity trial 2 (no RDLF) for PAU 5D.

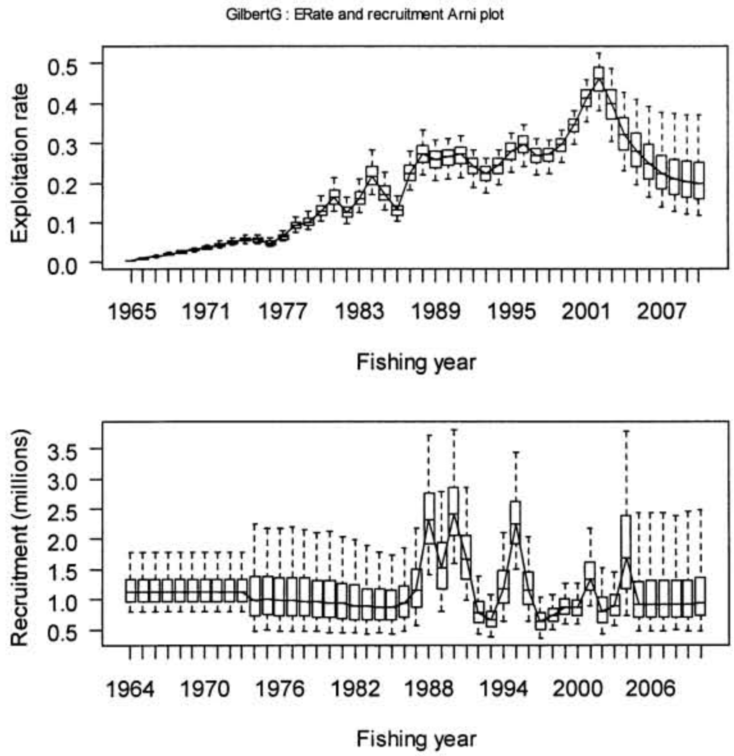


Figure 128: The posterior trajectories of exploitation rate (upper) and recruitment (lower) from the McMC sensitivity trial 3 (exponential growth) for PAU 5D.

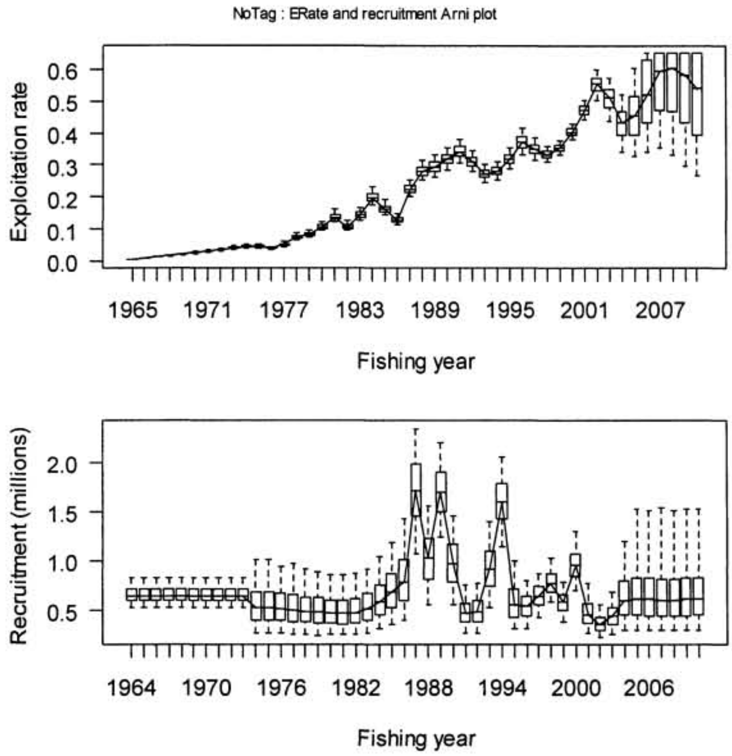


Figure 129: The posterior trajectories of exploitation rate (upper) and recruitment (lower) from the McMC sensitivity trial 4 (no tag-recapture) for PAU 5D.

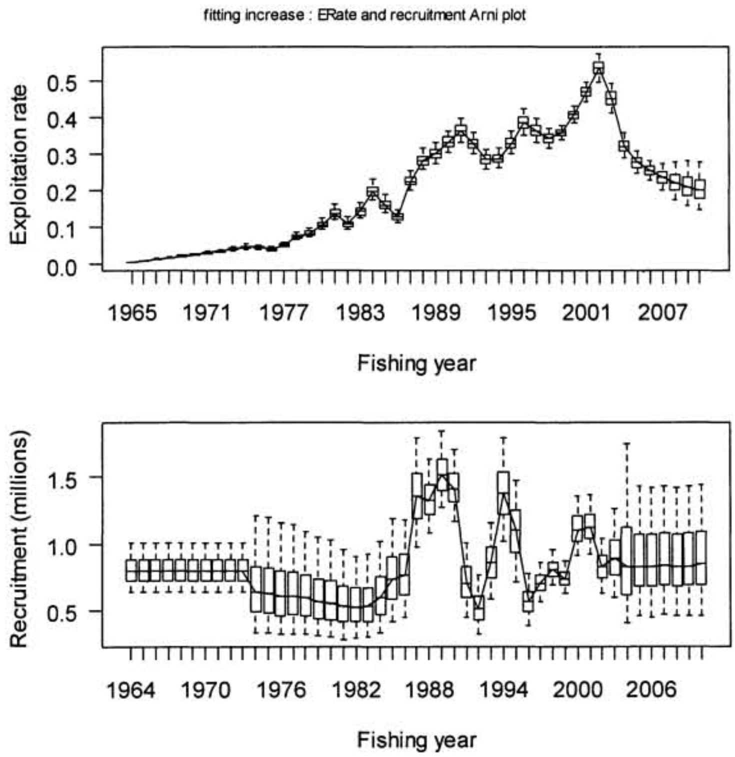


Figure 130: The posterior trajectories of exploitation rate (upper) and recruitment (lower) from the McMC sensitivity trial 5 (increased weight on abundance indices) for PAU 5D.

These comparisons show generally similar patterns in recruitment and resulting biomass until about 2000, but after that, estimated recruitment patterns and their consequences are sensitive to modelling choices.

Medians of marginal posterior distributions of parameter estimates (Table 57) show the same differences as seen in the analogous MPD trials (Table 52). *M* increased substantially for trials 1 and 2, as did *GrowthCV*, and *CPUEpow* doubled in trial 2, indicating less hyperstability. In trial 4, the main changes were decreased growth increment parameters but increased *GrowthCV*.

Indicators are summarised in Table 58. As in the MPD trials, omitting the RDLF data led to much higher biomass estimates and lower exploitation rates, and comparisons of current biomass with reference levels were much more favourable. Using exponential growth had a similar but smaller effect. In these trials, the posteriors of biomass estimates were narrowest in the base case.

In three-year projections, omitting the RDLF data gave more optimistic results. Most runs showed increased biomass, the chance of falling below *Smin* or *Bmin* became less than 5% and more runs attained the reference biomass levels. Again, using exponential growth had a similar effect compared with the base case, less pronounced but with low chances of falling below *Smin* or *Bmin*. Omitting the tag-recapture data had a small pessimistic effect in both the current state and projected states of the stock.

Increased weight on the recent abundance indices (trial 5) led to slightly increased *M* and slightly less hyperstability, but not much change in other estimated parameters. The estimated state of the stock is much much higher than in the base case (much higher biomass and lower exploitation rate) with much more chance of increase. This trial underscores the sensitivity of the assessment to recent patterns in the data.

Table 57: Summary of parameter estimates from sensitivity trials.

Trial	1	1	Base case 1	2	2	No RDLF 2	3	3	Exp. growth 3	4	4	No Tags 4	5	5	Fit to recent Increase 5
Parameter	0.05	Median	0.95	0.05	Median	0.95	0.05	Median	0.95	0.05	Median	0.95	0.05	Median	0.95
ln(*R0*)	13.2	13.4	13.7	14.5	15.3	15.9	13.6	13.9	14.4	13.2	13.4	13.6	13.4	13.6	13.8
$\tilde{\sigma}$	0.160	0.160	0.160	0.134	0.134	0.134	0.147	0.147	0.147	0.157	0.166	0.175	0.160	0.160	0.160
M	0.095	0.114	0.140	0.262	0.393	0.486	0.1623	0.214	0.296	0.090	0.106	0.129	0.106	0.126	0.153
galpha	18.8	19.6	20.8	17.6	18.4	19.2	34.4	36.2	38.2	17.1	18.4	19.8	19.2	20.3	21.6
gBeta	7.89	8.24	8.68	8.15	8.48	8.79	6.88	7.27	7.67	7.12	7.67	8.26	8.04	8.45	8.96
CS50	123.4	123.6	123.7	124.1	124.3	124.5	123.4	123.6	123.7	123.4	123.6	123.8	123.5	123.7	123.8
CS95	3.74	4.15	4.58	4.48	4.84	5.22	3.60	3.99	4.40	3.74	4.18	4.64	3.83	4.23	4.68
mat50	77.9	79.7	81.0	78.3	79.7	80.9	78.2	79.7	80.9	77.8	79.7	81.1	77.9	79.7	81.0
mat95	9.03	13.48	18.96	9.47	13.34	17.60	9.24	13.31	17.98	8.72	13.52	19.33	8.98	13.49	18.88
GrowthCV	0.256	0.281	0.308	0.297	0.327	0.361	0.321	0.351	0.385	0.307	0.374	0.429	0.246	0.272	0.301
ln(*qCPUE*)	-0.222	1.628	3.110	-3.185	-0.848	1.126	-0.483	1.411	2.907	-0.145	1.675	3.177	-2.211	-0.292	1.616
ln(*qRDSI*)	-10.33	-10.04	-9.76	-11.30	-10.87	-10.41	-10.45	-10.12	-9.81	-10.40	-10.09	-9.79	-10.33	-10.22	-10.10
CPUEpow	0.138	0.254	0.398	0.288	0.439	0.619	0.150	0.265	0.410	0.132	0.249	0.391	0.249	0.398	0.549

Table 58: Summary of indicators from PAU 5D McMC sensitivity trials. The MLS was 125 and projections were made for three years only.

			Base case			No RDLF			Exp. growth			No Tags			Fit to recent increase
Trial	1	1	1	2	2	2	3	3	3	4	4	4	5	5	5
Parameter	0.05	Median	0.95	0.05	Median	0.95	0.05	Median	0.95	0.05	Median	0.95	0.05	Median	0.95
2005															
Smin	271	366	489	687	1056	1526	348	479	633	276	374	503	509	568	632
Sav	768	841	922	998	1545	2253	782	941	1240	793	886	992	765	846	938
S2005	271	371	508	845	1390	2218	395	636	1026	276	378	520	560	652	770
Bmin	114	162	194	187	259	365	175	232	315	116	165	204	177	198	223
Bav	392	430	472	371	513	700	464	554	717	398	449	505	392	434	480
B2005	114	173	256	245	365	533	190	300	456	116	172	257	278	316	359
U2005 (%)	33.1	45.2	61.3	16.7	23.5	33.0	19.4	28.0	41.0	33.0	45.3	60.5	24.6	27.5	30.5
S2005/Sav (%)	32.5	44.0	59.5	69.3	90.6	117.6	45.0	66.8	97.3	31.7	42.7	58.0	68.8	76.9	88.1
S2005/Smin (%)	100.0	100.0	110.2	106.0	131.5	168.5	100.7	132.2	186.6	100.0	100.0	108.2	103.9	114.4	130.2
B2005/Bav (%)	26.6	40.3	59.6	53.7	71.7	90.3	36.6	53.6	74.6	25.9	38.4	56.8	65.2	72.9	81.7
B2005/Bmin (%)	100.0	105.8	135.2	120.7	140.2	160.9	103.0	128.3	157.0	100.0	102.4	131.1	148.7	159.1	170.9
2008															
S2008	264	394	608	888	1427	2261	406	705	1174	256	390	613	584	749	964
B2008	67	117	257	347	543	813	216	434	747	63	107	244	323	416	547
U2008 (%)	32.0	56.9	65.0	11.9	17.3	25.8	12.8	20.9	37.3	33.4	60.5	65.0	17.1	22.0	27.6
S2008/S2005 (%)	82.6	105.8	143.8	82.5	102.4	132.0	82.1	107.8	157.3	76.8	102.7	147.7	98.3	114.8	133.8
S2008/Sav (%)	31.7	47.0	71.8	67.3	92.2	131.1	44.9	73.6	116.2	29.1	44.1	69.0	70.4	88.6	112.3
B2008/B2005 (%)	45.1	70.7	117.5	105.2	147.2	213.9	96.2	140.9	209.7	43.3	64.4	107.0	104.6	131.3	172.0
B2008/Bav (%)	15.4	27.0	60.0	69.8	106.1	156.2	40.8	76.5	127.5	13.9	23.8	54.5	75.1	95.8	126.1
P(S2008<S2005)(%)	35.4			43.8			35.4			44.5			7.3		
P(S2008<Sav) (%)	99.9			64.6			86.2			99.9			80.9		
P(S08<Smin) (%)	33.7			4.3			5.6			42.8			1.9		
P(B2008<B2005) (%)	87.0			3.0			7.0			91.7			2.4		
P(B2008<Bav) (%)	99.9			40.3			80.0			99.9			62.1		
P(B08<Bmin)	74.3			0.1			3.0			82.8			0.0		

7.9 PAU 5D assessment

Although results are presented above as a "base case", which was the least manipulated trial, and four McMC sensitivity trials, the SFWG did not consider that the "base case" should form the basis of the assessment in isolation from the sensitivity trials. They considered that all five runs should be presented as the basis for the assessment. The runs are all presented in the two preceding sections.

The assessment is extraordinarily sensitive to the RDLF dataset. When all data are fitted, current exploitation rate has median 45%; when RDLF data are left out from fitting, it is only 23% and biomass is correspondingly higher. With all data, the chance of a recruited biomass decrease over three years is 87%; without the RDLFs data is only 3%.

High sensitivity is also seen to the choice of growth model. When the exponential model is used, current exploitation rate has median 28%, and the chance of a recruited biomass decrease over three years is only 7%.

These two trials had high *M* values (medians of 0.40 and 0.21 respectively) compared with 0.11 in the base case. These reduce the credibility of the no-RDLF and exponential growth runs, but the high sensitivity translates to high uncertainty about sustainability of the current catches and the likely future of the stock. The base case suggests (so does the no-tags trial) that current catches are not sustainable, but other trials suggest a high probability of stock increase. The probability of spawning stock increase over three was greater than 50% in all trials.

7.10 Retrospective trials

The SFWG agreed that retrospective trials should be given a lower priority than McMC sensitivity trials, so we restricted these to MPD trials. We removed data (except for tag-recapture data) one year at a time and obtained MPD estimates without iteratively re-weighting. In these runs, *sigmatilde* was fixed at the base case MPD value.

Recruitment (Figure 131) is similar until the late 1990s and then each year of data from 2003 onwards modifies the model's pattern. This is reflected in the exploitation rate trajectories (Figure 132): they are very similar until 2002 and then each successive year of data modifies the pattern. Biomass (Figure 133) is quite similar throughout, although quite a strong increase in biomass after 2003 is seen when the 2005 data are omitted.

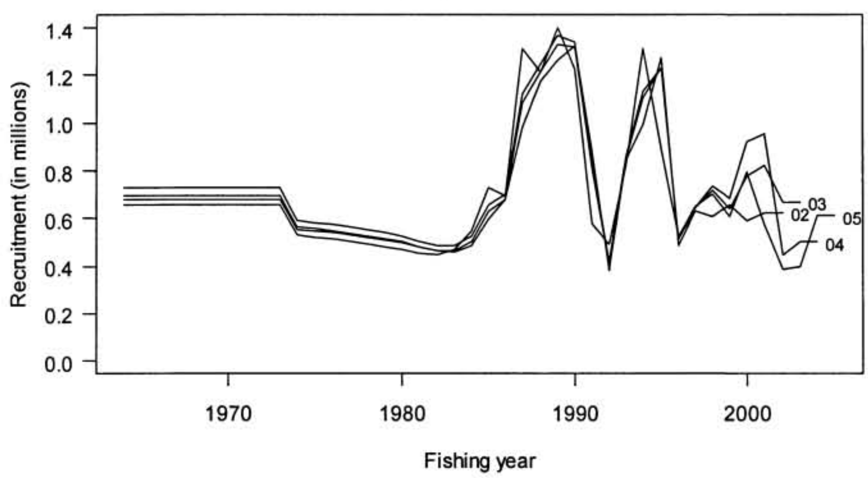


Figure 131: MPD retrospectives for recruitment in PAU 5D.

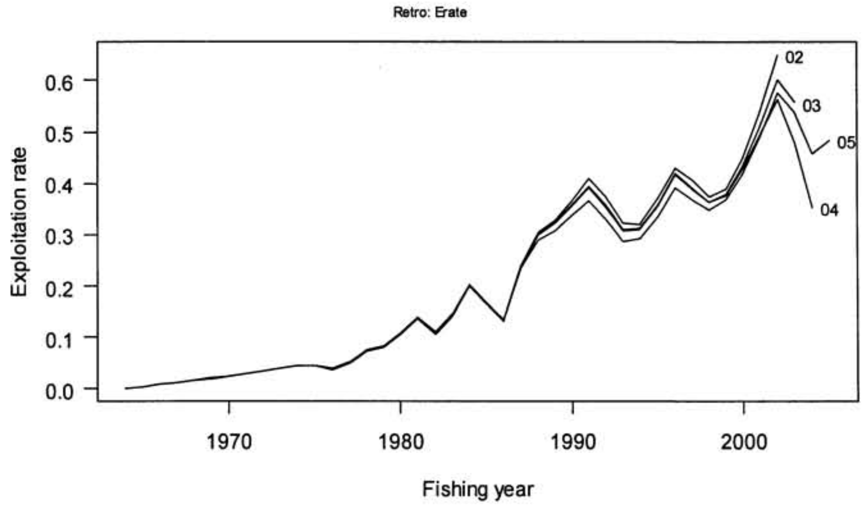


Figure 132: MPD retrospectives for exploitation rate in PAU 5D.

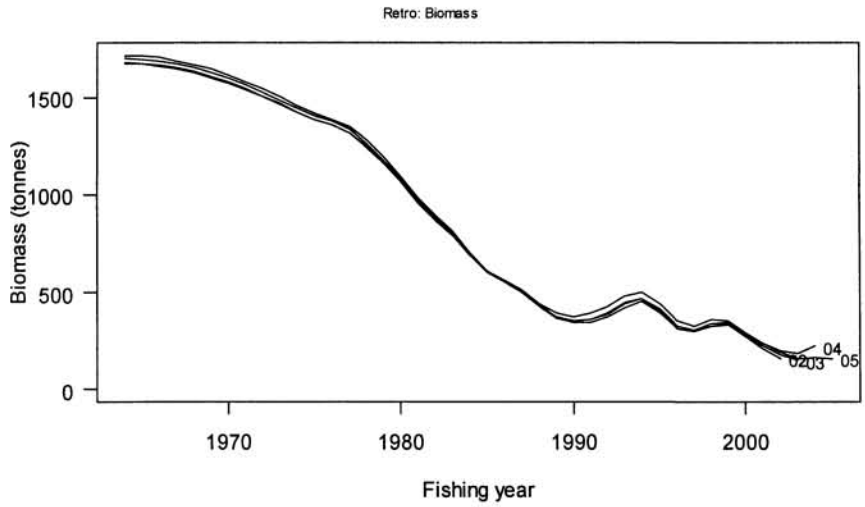


Figure 133: MPD retrospectives for recruited biomass in PAU 5D. Trials are named for the last year of data included.

The estimates are shown in Table 59, where the trials are listed by the last year of data included; *viz.* the base case is "2005". The sdnrs generally changed little (the sdnr for RDSI changed most, by 16%). Most parameters changed little: an exception was for the 2004 retrospective, where *CPUEpow* increased and the catchability changed commensurately.

The maximum exploitation rate and 2002 exploitation rate increased in the 2002 and 2003 trials, both reaching the upper bound in the 2002 trial. Biomass indicators change through the trials without much pattern, although the 2002 trial is generally the most pessimistic.

Table 59: Results from retrospective sensitivity trials.

	2005	2004	2003	2002
sdnr CPUE	1.009	1.035	1.057	1.099
sdnr RDSI	1.015	0.866	0.862	0.847
sdnr CSLF	1.001	0.997	1.013	1.005
sdnr RDLF	1.023	1.022	1.094	1.096
sdnr tags	0.970	0.984	0.984	0.989
sdnr maturity	1.012	1.012	1.012	1.012
ln(*R0*)	13.400	13.46	13.500	13.43
M	0.109	0.118	0.122	0.117
CS50	123.5	123.6	123.5	123.7
CS95	4.1	4.3	4.4	4.7
Mat50	79.8	79.8	79.8	79.8
Mat95	12.8	12.8	12.8	12.8
ln(*qCPUE*)	1.710	0.361	1.475	1.465
ln(*qRDSI*)	-10.005	-10.040	-10.084	-10.025
galpha	20.0	21.5	21.5	22.1
gBeta	8.3	8.9	8.9	9.1
GrowthCV	0.268	0.245	0.246	0.239
CPUEpow	0.248	0.354	0.267	0.269
Umax	0.576	0.563	0.602	0.650
U2002	0.576	0.563	0.602	0.650
Smin	341	454	420	378
Sav	816	753	762	727
S02	449	498	444	378
Bmin	157	183	149	160
Bav	421	389	392	377
B2002	189	196	178	160
S2002/Sav (%)	0.550	0.661	0.582	0.520
B2002/Bav (%)	0.450	0.503	0.455	0.425
S2002/Smin (%)	1.317	1.097	1.056	1.000
B2002/Bmin (%)	1.209	1.071	1.193	1.000

8. DISCUSSION

8.1 Model

The model used for these two assessments was the same as that used in 2005 for PAU 7 (Breen & Kim 2005) and apparently performed well. Experiments with the model and data used in the previous PAU 5A and PAU 5D assessments showed reasonable agreement, despite model and data changes. For PAU 5D these trials suggested (see Table 49) that new and differently handled data had a greater effect on results than did any model differences.

Basic diagnostics for the assessments were favourable. During exploratory searches for base case MPD fits, the main problems were caused by contradictory datasets (CPUE and RDSI) in PAU 5A, and problems with the research diver selectivity in PAU 5D. When these were addressed – by excluding the CPUE data in PAU 5A and fixing selectivity parameters in PAU 5D – subsequent problems were relatively minor, although the fits to RDSI and RDLF datasets in PAU 5D were never excellent, and the residuals were balanced easily. Causal diagnostics were encouraging: there were few badly formed Hessians, numbers of function evaluations were not excessive and we did not see undue sensitivity to phasing or initial values. The model did not often go near the upper bound on exploitation rate, and (in runs that we considered the base cases) estimated M was near the mean of its prior.

Diagnostics for McMC simulations were acceptable. Traces appeared to be well mixed and diagnostic plots of the running-median type gave no suggestion of non-convergence. The related parameters $\ln(R0)$ and M both went on small excursions, but these were short, the estimates did not stray very far from the rest of the population, and then the parameters returned. The McMC chain of 5 million should be long enough to ensure that the shapes of the marginal posteriors were sufficiently precise.

8.2 PAU 5A

A major uncertainty encountered by the PAU 5A assessment is the contradiction in abundance indices: CPUE shows an increasing trend while RDSI shows a decreasing trend. For the three southern research strata between 2002 and 2006, RDSI shows a statistically significant decline of 50–78%. The two indices of abundance are different: CPUE is based on recruited fish, and RDSI is based on fish available to research divers; thus in theory one could increase while the other decreased, but in practice, given the large proportion of legal-sized fish in the population, this seems unlikely.

When datasets are contradictory, one may be likely and the other misleading, so the likely parameter values may occur at one of the apparent extremes (Schnute & Hilborn 1993). Our approach – to make runs fitting to only one of the two abundance indices – was consistent with that philosophy. The compromise fit, using both CPUE and RDSI, is unlikely, and one of the two extremes is likely.

Between the two abundance indices, RDSI seems more likely than CPUE. In developing fisheries, CPUE can be maintained at high levels despite substantial stock declines in abalone (Breen 1986; 1992). In PAU 5A, relatively high catches have been supported for only about a decade, after the PAU 5 subdivision, so this may still be a developing fishery. That notion is supported by the relatively small change in population length frequency (Figure 37): the fishery has probably not shifted yet from one based on natural accumulations to one based on continuing production. Taken to extremes, serial depletion can reduce reproductive success to the point where population viability is threatened (Hobday et al. 2000), but serial depletion is a problem even before this.

The RDSI is an index independent of fisher behaviour. The increasing proportion of zero-abundance swims (see Table 16) suggests that serial depletion has occurred between 1996 and 2006 in the Chalky stratum, and the bootstrap analysis suggests that a substantial decline in the southern three research strata is real.

[In retrospect, when we excluded the CPUE data from the "RDSI fit" because of suspected serial depletion, we should also have excluded the CSLF data, because these are equally subject to distortion through serial depletion.]

The character of the three runs was different: the ranges of 2005 exploitation rates did not overlap; variability of growth varied and the shapes of biomass trajectories varied among them. Despite that, the runs were similar in their forward projections: they all suggest a high probability of declines for both spawning and recruited biomass.

Another uncertainty is generated by the uneven coverage of the research diver surveys. The RDSI is treated by the model as an index of abundance in PAU 5A as a whole, but surveys were made in the George stratum only in the most recent year. It is thus unknown whether abundance in that stratum has changed over time. However, it is certain that abundance in the southern three strata, an area from which about 60% of the recent catch has been taken, declined by 50–75% in the past few years. It seems unlikely that the PAU 5A catch is sustainable.

Another uncertainty is created by estimating the research diver selectivity parameters. Low selectivity for fish smaller than 110 mm (the estimated *RD50*) allows the model to create many sub-legal fish that are not seen by the divers. In PAU 7, the estimated *RD50* is near 100 mm, in an area where the proportion of sub-legal fish is high. The estimate of 110 mm for *RD50* for PAU 5A is not unreasonable, but it may mask a real scarcity of small paua. The productivity of PAU 7 is due in large part to the abundance of juveniles; the apparent difference on juvenile abundance in PAU 5A is another cause for concern.

Sensitivity trials explored the effects of datasets other than the abundance indices. No single dataset appeared to be having an inordinately strong effect on the model results. The stability of visual fits, especially to length frequencies, suggests a high redundancy of information among the various data.

8.3 PAU 5D

The assessment cannot address the stock in PAU 5D as a whole. Some areas are closed to the commercial fishery, and the assessment can be taken to apply only to those areas that are or were in the past open to commercial fishing.

The assessment for PAU 5D displayed an early problem: the *RD50* parameter for research diver selectivity went to its upper bound, and it went very high (140 mm) when the upper bound was moved out of range. When an experimental selectivity curve was estimated, using a parameter for each length bin, results were similar (see Figure 95). These results are not credible for two reasons: they are accompanied by unrealistically high estimates of *M*, and it defies belief that research divers could have reduced selectivity for paua as large as 125 mm.

Our approach was to fix *RD50* and *RD95* and accept considerable degradation in the fit to the RDLF dataset. We discovered large sensitivity to the value to which *RD50* was fixed: larger values lead to higher *M*, greatly reduced exploitation rate estimates and favourable states of the current stock. Our approach to handling this problem was to use the research diver selectivity estimates from the most recent PAU 7 assessment. This approach is objective and defensible. Although the length structures of paua in PAU 5D and PAU 7 are different, and habitats and diving conditions are different, the same divers would be expected to choose paua from a patch in the same way in these two areas.

Looking past that difficulty, sensitivity trials were highly unstable. The MPD trials confirmed some modelling choices (for instance, the choices to estimate commercial fishery selectivity and to estimate *CPUEpow* were good choices) but identified a sensitivity to the choice of growth model. They showed that estimates were reasonably robust to removal of some datasets – CPUE and tag-recapture data – reflecting some redundancy of information among the various datasets, but they also showed a high sensitivity to the RDLF dataset. Without the RDLF data, the assessment results are much more optimistic and *M* estimates are very high. These are the data implicated in the *RD50* problem discussed above, so problems with fitting to this dataset are a major source of uncertainty for the assessment.

McMC trials to explore further the growth model and removal of RDLF and tag-recapture data (separately) give similar general results as the MPD trials. Exploration of these trials shows that recent recruitment patterns vary among the trials, with strong consequences: biomass tends to decline in base case projections but increases strongly in some of the McMC sensitivity trials. Although it can be argued that the base case is defensible and that these trials have unlikely *M* estimates, these results show that considerable uncertainty attaches to the model's assessment of the current state of the stock and the likely direction of future change under the current catch.

The retrospective trials underscore this. Trajectories are similar until 2000, then the recent recruitment patterns are sensitive to the data: adding a year of data causes considerable change to MPD estimates of recruitment and exploitation rate.

The base case runs suggest a stock near its lowest point ever, with a high exploitation rate and with very high probability of further decline at the current catch levels. However, other runs, less credible because of the higher estimated M values, suggest lower current exploitation rates and high chances of increase in the recruited biomass. Much of this uncertainty among runs stems from the RDLF dataset: the assessment becomes much more optimistic when the data are omitted. Major problems with the research diver selectivity parameters must also reflect something amiss with these data.

Thus the PAU 5D assessment is inconclusive.

8.4 Cautionary notes

8.4.1 The McMC process underestimates uncertainty

The two assessments described above both illustrate that the variation in results among the various McMC trials can be much higher than variability within an McMC trial.

8.4.2 The data are not completely accurate

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

The tagging data may not reflect fully the average growth and range of growth in this population. Length frequency data collected from the commercial catch may not represent the commercial catch with high precision.

The research diver data comprise only a few surveys, for some of which the standard errors are quite large, and length frequencies may not be fully representative of the population. Problems with fitting to the RDLF dataset in PAU 5D reflect an unknown problem, and the relevance of the RDSI to PAU 5A as a whole is suspect because of the uneven coverage of surveys.

8.4.3 The model is homogeneous

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

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

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

8.4.4 The model assumptions may be violated

One suspect assumption made by the model is that CPUE is an index of abundance. There is a large literature for abalone that suggests CPUE is difficult to use in abalone stock assessments because of serial depletion, and the problem is illustrated in PAU 5A, where the RDSI declined substantially and CPUE declined slightly in the same area over four years. This can happen when fishers can deplete unfished or lightly fished beds and maintain their catch rates: CPUE stays high while the biomass is actually decreasing.

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

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

9. ACKNOWLEDGEMENTS

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