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using an improved Bayesian length-based model**

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EXECUTIVE SUMMARY

A revised length-based model was used to assess the status of the PAU 5B stock of paua (abalone) (*Haliotis iris*). The assessment used Bayesian techniques to estimate model parameters, the state of the stock, future states of the stock, and their uncertainties. Point estimates from the mode of the joint posterior distribution were used to explore sensitivity of the results to model assumptions and the input data; the assessment itself was based on posterior distributions generated from Monte Carlo - Markov chain simulation.

The model was revised from the 1999 model by eliminating the stock-recruit relation and an estimated relation between CPUE and biomass, by eliminating catchabilities as parameters and calculating them instead, by introducing "fat-tailed" distributions for specifying likelihoods and prior probability distributions, and by estimating growth parameters within the model from both length frequency and tag-recapture data. The model was applied to five data sets from PAU 5B: standardised CPUE, an independent survey index of relative abundance, length frequencies from catch sampling and population surveys, and tag-recapture data.

Model results for PAU 5B suggested a stock well below B_{MSY} which is likely to decrease further at the current level of catch. Results were not sensitive to individual data sets, nor to the exclusion of both population indices or both length frequency data sets, and were robust to the catch series used and other modelling choices. Thus qualitative conclusions about the state of the stock appear to be robust. The abundance index and length frequency data sets appeared to contain the same information about the stock.

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

1. INTRODUCTION

1.1 Overview

This document presents a Bayesian stock assessment of paua (abalone) (*Haliotis iris*) in PAU 5B (Stewart Island). The assessment is made with a revised length-based model first used in 1999 (Breen *et al.* 2000), results of which were summarised by Annala *et al.* (1999). This model is driven by reported commercial catches from 1974 through 1999 and is fitted to five sets of data: standardised CPUE (Kendrick & Andrew 2000), a diver survey index (Andrew *et al.* 2000a), length frequency data from catch sampling and from diver surveys (Breen *et al.* 2000), and a set of tagged paua growth increment data described here for the first time.

Paua supports a valuable fishery in New Zealand, with total annual landings of about 1200 t. Legislation requires that New Zealand fisheries be managed so that stocks are maintained at or above B_{MSY} , the biomass associated with the maximum sustainable yield (MSY). The Ministry of Fisheries (MFish) advises the Minister of Fisheries whether stocks are at or above B_{MSY} and whether current TACCs are sustainable and likely to move stocks toward B_{MSY} .

Quantitative assessments of abalone remain comparatively rare. This document describes a revised assessment model improved in several ways from the model used in 1999. Only in New South Wales (Worthington *et al.* 1998) is a similar model used to assess abalone populations. This document describes the data sets used in the assessment and assumptions made in fitting the model. It describes the basic fit of the model to the data, and describes how the point estimates of model and derived parameters respond to a variety of changes to data sets and other modelling choices in sensitivity trials. The posterior distributions of model and derived parameters are shown and summarised. Results of a series of forward projections, requested by the Ministry to evaluate alternative management options, are described and summarised.

1.2 Description of the fishery

The fishery was summarised by Annala *et al.* (1999) and in numerous previous assessment documents (e.g., Schiel 1989, and *see* McShane *et al.* 1994, 1996 for recent summaries).

In 1995, the southern stock of paua, PAU 5, was divided into three sub-areas, 5A, 5B and 5D (Figure 1a), each with a TACC of 147.66 t. From 1 November 1997 these areas were further subdivided into 17, 16 and 11 statistical areas respectively (Figure 1b). Subdivision of the commercial catch and effort data from PAU 5 into these new areas was described by Kendrick & Andrew (2000).

2. DATA

2.1 Catch data

2.1.1 Commercial catch data

For the paua fishery throughout New Zealand, recent commercial quotas and reported landings were summarised by Annala *et al.* (1999). These authors also discussed illegal, recreational and traditional catches.

Fishery data from PAU 5 were described by Kendrick & Andrew (2000). The division of PAU 5 into three new stocks created some difficulty in dividing the reported catches into the new stocks.

Catches have been reported for each of the new stocks since 1996. From 1984 through 1995, catches from each stock can be estimated from the proportion of catches reported by statistical area. However, some statistical areas used during that period overlap the new stock boundaries, so this division is not straightforward. Before 1984, catches must be estimated from the total PAU 5 catch under some assumption about proportionality.

Procedures used to estimate 5B catches were described fully by Kendrick & Andrew (2000). The results of two alternative procedures were presented in the previous assessment (Breen *et al.* 2000) and were illustrated by Annala *et al.* (1999). For the base case in this assessment, we used the "Series 2" catch vector, in which 75% of reported catch in statistical areas 25 and 30 was assumed to have come from PAU 5B. As a sensitivity trial, we used the "1999 base case" catch vector, in which 67% of reported catch from area 25 and 32% from area 30 were assumed to have come from PAU 5B. These two catch series are given in Table 1 and illustrated in Figure 2. In 1999 the Working Group agreed that 1986 catches appeared to be unrealistically low, perhaps because of reporting problems. A sensitivity to this was explored (Breen *et al.* 2000). For this assessment, 1986 catch was taken as the average of the 1985 and 1987 reported catches.

The 1999-2000 TACC for PAU 5B was 119 t, and this level of catch was assumed for the model year 2000.

2.1.2 Other catch data

Illegal catch was estimated by the Ministry of Fisheries to be 3 t. No historical estimates are available. We added this estimate to the commercial catches used to drive the model (Table 1).

Although recreational catch estimates are available for PAU 5 (Teirney *et al.* 1997, Bradford 1998), no estimate was available for PAU 5B, and no estimated historical trend was available. No estimates of customary catches were available for PAU 5B. These catches were thus not addressed by the assessment.

2.1.3 Other sources of fishing mortality

Sub-legal paua may be subject to handling mortality when removed from the substrate to be measured. Mortality may result from wounds, desiccation, osmotic and temperature stresses, replacement onto unsuitable substrate, and predators. Taylor *et al.* (1994) reported that 14% of paua removed from the reef by commercial divers are undersized and are returned to the reef. Pirker (1992) reported that 13% of undersized animals captured by a diver in PAU 4 were damaged in some way.

Handling mortality was not addressed by the model.

2.2 CPUE

Although catch rate (CPUE) has problems as an index of abundance, we used standardised catch rates (Kendrick & Andrew 2000), which show a declining trend. We consider that declines in an index likely to be hyperstable reflect real declines in abundance, which may be steeper than the index.

Catch and effort data reported to the Catch and Effort Landing Return (CELR) system were standardised with the method of Vignaux (1993) as described by Kendrick & Andrew (2000).

This was done for all data through the end of the 1998-99 fishing year. As a sensitivity, the CPUE series was also standardised using the incomplete data (about 30% of the TACC was represented) available at the time from 1999-2000. These two CPUE series are given in Table 1 and illustrated in Figure 3.

2.3 Diver survey index

Fishery-independent diver survey estimates of relative abundance are described by Andrew, Naylor & Gerring (2000). These indices are shown in Table 1.

2.4 Length frequency data

Length frequencies were measured in samples of shells during 1992, 1993, 1994, 1998, 1999 and 2000. Proportions-at-length from this catch sampling will be described in discussion of the model fits below.

Length frequencies from diver surveys of paua populations, described by Andrew *et al.* (2000a), were available for the years 1994, 1995 and 1998. Length frequencies from a survey by Schiel (1991) were available for 1989. Proportions-at-length from population surveys will be described in discussion of the model fits below.

2.5 Growth increment data

About 800 paua were tagged at Waituna, on the west coast of Stewart Island, on two occasions - 1 May 1995 and 14 July 1996. Paua were collected by divers and taken to the surface, where they were measured to the nearest 1 mm shell length and marked with individually numbered plastic tags glued to the shell with cyanoacrylate glue. Paua were then taken back to the bottom and individually replaced on the substrate by divers. Divers recovered 132 tagged paua after 289 and 214 days from the two episodes, respectively, and measured their shell lengths again. The growth observed in these animals is shown plotted against the initial shell length in Figure 4.

3. DESCRIPTION OF THE MODEL

3.1 Overview

Abalone populations are difficult to assess (Breen 1992) because:

- abalones are essentially sedentary after settlement, so the effects of fishing are highly localised;
- differences in population dynamics, particularly recruitment, growth and mortality, may also be highly localised;
- the behaviour of fishers may lead to stability in catch rate as overall abundance decreases, thus catch rate is difficult to interpret as an index of abundance;
- the behaviour of fishers may lead to stability in catch length frequencies as the overall population length distribution changes; thus length distribution is difficult to interpret as an index of population change;

- abalones, including paua, generally cannot be reliably aged.

In this report we describe the revised length-based assessment model. The model is similar to length-based models developed for abalone by Worthington (1997, *see Andrew et al. 1996 for application the NSW abalone fishery*), and for lobsters by Punt & Kennedy (1997), Starr *et al.* (1999), and Breen & Kendrick (1999).

The model is fitted to data using robust techniques to specify likelihoods and to describe prior distributions. Chen *et al.* (in press) showed, using an earlier version of this model, that robust techniques perform slightly less well than normal distributions in the absence of outliers in the data or mis-specifications of prior distributions. However, they are much less subject to the effects of outliers and prior mis-specification. Because fishery data are likely to contain outliers and priors are likely to be mis-specified in some way, robust techniques are more likely to give reliable estimates than standard techniques.

The model population is initialised and then driven by observed catches. The model is fitted with Bayesian techniques to vectors of standardised CPUE, relative abundance indices from diver surveys, and observed length frequencies from research surveys and catch sampling. Outputs are the present and projected future states of the stock, estimated using Bayesian methods. The assessment is based on the marginal posterior distributions of the parameters and derived parameters of interest, in turn based on Monte Carlo - Markov chain (mcmc) simulations. Males and females are not modelled separately.

3.2 Model parameters

Parameters estimated by the model are:

$\ln(R0)$	the natural logarithm of average recruitment,
M	the instantaneous rate of natural mortality, assumed to be constant over time and paua sizes,
L_{∞}	asymptotic length,
K	the instantaneous rate of approach to L_{∞} ,
$Rdev$	a vector of recruitment deviations modifying the actual model recruitment in a given year,
$S90$	relative selectivity of research divers for paua of 90 mm shell length, and
$Sfull$	the size at full selectivity by research divers.

The parameters L_{∞} and K were added to the model this year - growth was previously estimated outside the model and assumed within the model. Results were found to be very sensitive to the growth assumption (Breen *et al.* 2000), so growth is now estimated within the model from the tagging data set and from patterns in length frequencies.

The 1999 model estimated the catchability coefficients, which in this model are calculated as described below. It estimated a parameter describing "hyperstability" - the shape of the relation between CPUE and abundance - but there was no information about this parameter in the data (Breen *et al.* 2000) and it was dropped. The 1999 model also estimated a parameter describing a stock-recruit relation; this was also dropped after consideration of international modelling usage.

3.3 Initial conditions

The model contains 50 length 'bins', each encompassing 2 mm paua shell length. The smallest is 70.0 through 71.9 mm; the largest is 168.0 through 169.9 mm. Recruitment is evenly divided among the first five bins and added to any animals remaining there after growth from the previous year. The last bin acts as a "plus group".

The model is 'burnt in' for 60 years by running it with no fishing to allow numbers-at-length to approach equilibrium. In each year t , for length bins $k = 1$ through 5 (shell lengths 70 through 79 mm):

$$(1) \quad N_{k,t} = R0 / 5$$

A growth transition matrix is determined inside the model. From the von Bertalanffy growth parameters L_∞ and K , an annual growth increment, Δl_k , is calculated for each length class:

$$(2) \quad \Delta l_k = (L_\infty - l_k) (1 - \exp(-K))$$

where l_k is the mid-point shell length of paua in bin k . The standard deviation of this increment is assumed to be the greater of 1 and 0.35 of the expected increment:

$$(3) \quad \sigma_k^{\Delta l} = \max(1, 0.35 \Delta l_k)$$

This relation is based on patterns seen in increments from tag-recapture data in PAU 7 (Andrew *et al.* 2000b). Using the expected increment and standard deviation, the distribution of increments for length bin k is calculated from the normal distribution. This distribution is then translated into the vector of probabilities of transition from length bin k to other length bins, and repeated for all initial length bins to form the growth transition matrix G . Negative increments are not permitted, but zero growth is permitted.

In the initialisation calculations, the vector N_t of numbers-at-length for year t is determined from $R0$ (equation 1), numbers in the previous year, survival, and the growth transition matrix G :

$$(4) \quad N_t = N_{t-1}' \bullet G \exp(-M)$$

where the prime (') denotes vector transposition and the dot (\bullet) denotes matrix multiplication. At any plausible growth rate, all individuals move out of all the first five length bins between years.

After the burn-in period, the model population is nearly in equilibrium - only the last few length bins are slowly increasing.

3.4 Model dynamics

For each year t , the model calculates biomass available to the fishery:

$$(5) \quad B_t^{\text{legal}} = \sum_k N_{k,t} P_{k,t} w_k$$

where w_k is the weight of paua in length bin k and $P_{k,t}$ is a switch (1 = on, 0 = off) that determines whether length bin k is above the minimum legal size (MLS) in year t .

Exploitation rate, U_t , is then calculated from the model biomass and observed catch, C_t , in two steps. Catch is compared with biomass:

$$(6) \quad \varphi_t = C_t / B_t^{legal}$$

This is used as U_t unless it exceeds an arbitrary limit of 0.8, in which case exploitation rate is reduced to just above 0.8 and a penalty Y is added to the likelihood function:

$$(7a) \quad U_t = \varphi_t \quad \text{for } \varphi_t < 0.8$$

$$(7b) \quad U_t = 0.8 + \exp(-3) - \exp(-5\varphi_t) \quad \text{for } \varphi_t > 0.8$$

$$(8a) \quad Y = 0 \quad \text{for } \varphi_t < 0.8$$

$$(8b) \quad Y = \sum_t \left(U_t - \left(\frac{C_t}{B_t^{legal}} \right) \right) \quad \text{for } \varphi_t > 0.8$$

This prevents the model from generating unrealistically high exploitation rates during the minimisations; in the final results most exploitation rates come nowhere near this limit. Survival from fishing, $S_{k,t}^{fishing}$, is calculated as:

$$(9) \quad S_{k,t}^{fishing} = 1 - U_t P_{k,t}$$

The vector of numbers-at-length in the following year is then calculated from the current vector of numbers-at-length, the vector of survival from fishing, the growth transition matrix, and natural mortality:

$$(10) \quad N_t = (S_{k,t}^{fishing} N_{t-1})' G \cdot \exp(-M)$$

Recruitment in year $t + 1$ is calculated for the first five bins, $k = 1$ through 5, from mean recruitment and the parameter $Rdev_t$:

$$(11) \quad N_{k,t} = 0.2 R_0 \exp(Rdev_t - 0.5 \sigma_{Rdev}^2)$$

where $Rdev_t$ is the recruitment deviation for year t and σ_{Rdev} is the assumed standard deviation of the recruitment deviations.

3.5 Model predictions

The model predicts CPUE, F_t^{pred} , from the model biomass B_t^{legal} :

$$(12) \quad F_t^{pred} = qI B_t^{legal}$$

The scaling coefficient qI is calculated from the observed CPUE and the model biomass:

$$(13) \quad qI = \exp \left[\left(\frac{1}{nI} \right) \sum_t \ln \left(\frac{I_t^{obs}}{B_t^{legal}} \right) \right]$$

where nI is the number of CPUE observations. The predicted diver survey index, IS_t^{pred} , is calculated from the number of paua in the model 90 mm and greater:

$$(14) \quad IS_t^{pred} = q2 \sum_{k=11}^{k=50} N_{k,t} V_k$$

where V_k is the relative selectivity for paua in length bin k . This allows the model to account for possible reduced diver selectivity of small paua. Selectivity is calculated from the model parameters $S90$ and $Sfull$:

$$(15) \quad V_k = \min(1, \alpha + \beta l_k)$$

where

$$(16) \quad \beta = (1 - S90) / (Sfull - 90)$$

$$(17) \quad \alpha = S90 - (90 \beta)$$

The scaling coefficient $q2$ is calculated from

$$(18) \quad q2 = \exp \left[\left(\frac{1}{nIS} \right) \sum_t \ln \left(\frac{IS_t^{obs}}{\sum_{k=11}^{k=50} V_k N_{k,t}} \right) \right]$$

where nIS is the number of diver survey estimates. The calculated $q1$ and $q2$ values are thus the geometric means of the ratios of observed index and model quantity.

The model predicts numbers-at-length from the numbers of paua in each length class:

$$(19) \quad N_{k,t}^{pred} \propto V_k N_{k,t}$$

Predicted numbers-at-length are normalised to predicted proportions-at-length, $p_{k,t}^{pred}$, in two sets: one beginning at 126 mm shell length, for comparison with lengths observed in catch sampling, and one beginning at 90 mm shell length, for comparison with lengths observed in the population surveys. Predicted numbers-at-length are zero for lengths below 126 and 90 mm respectively. For each set:

$$(20) \quad p_{k,t}^{pred} = N_{k,t}^{pred} / \sum_k V_k N_{k,t}^{pred}$$

Predicted increments in the tag data set are calculated from the length-based von Bertalanffy equation (2).

3.6 Model fitting

Predictions are fitted to observed CPUE and population survey indices, I^{obs} , and IS^{obs} , respectively, with robust likelihood. Likelihood of these indices is estimated assuming that the residuals have with a Student's t distribution with 4 degrees of freedom. The likelihood is:

$$(21) \quad p(x | \theta) = \prod_t \frac{1.329}{\sqrt{4\pi}} \left[\left(1 + \frac{[\ln(I_t) - \ln(q1B_t^{legal})]^2}{4(\sigma_I)^2} \right) \right]^{-2.5}$$

where θ is the parameter vector and σ_I is the assumed standard deviation. Similarly for the diver survey index:

$$(22) \quad p(x | \theta) = \prod_t \frac{1.329}{\sqrt{4\pi}} \left[\left(1 + \frac{[\ln(IS_t) - \ln(q2N_{k,t})]^2}{4(\sigma_{IS})^2} \right) \right]^{-2.5}$$

where σ_{IS} is the standard deviation. These are summed for all years with observations. Values for σ_I and σ_{IS} were assumed - these act as relative weights (weight is inversely proportional to the value). The populations surveys were thought to have more accuracy than CPUE, so σ_I was set to 0.50 and σ_{IS} to 0.25.

The robust multinomial likelihood proposed by Fournier *et al.* (1990) is used to fit model predictions to observed length compositions, $p_{k,t}^{obs}$. The variance is assumed to be multinomial and is weighted by the effective sample size, τ_t :

$$(23) \quad p(x | \theta) = \prod_t \prod_k \frac{1}{\sqrt{2\pi p_{k,t}^{obs}(1-p_{k,t}^{obs}) + 0.1/\Omega}} \exp \left[\frac{-\tau_t (p_{k,t}^{obs} - p_{k,t}^{pred})^2}{2[p_{k,t}^{obs}(1-p_{k,t}^{obs}) + 0.1/\Omega]} + 0.01 \right]$$

where Ω is the number of size bins. The 0.01 term reduces the influence of outliers. The 0.1/ Ω term prevents the variance from tending to zero as the predicted value tends to zero, reducing the influence of observed outliers with small predicted probability (Fournier *et al.* 1990).

To obtain τ_t , observed proportions-at-length were weighted by the square root of the number measured for catch samples, and by twice the square root of number measured for population samples. This reflected greater confidence in the sampling procedures for population sampling than for catch sampling.

The tag data set was fitted with normal likelihood. For the j th increment:

$$(24) \quad p(x | \theta) = \prod_j \left[\frac{1}{\sqrt{2\pi \sigma_j^{\Delta l}}} \exp \left(-\frac{[\Delta l_j^{obs} - \Delta l_j^{pred}]^2}{2(\sigma_j^{\Delta l})^2} \right) \right]$$

where the standard deviation $\sigma_j^{\Delta l}$ is calculated from (3).

3.7 Priors, bounds and assumptions

Bayesian priors were established for all parameters. Most were uninformative, incorporated simply as uniform distributions with upper and lower bounds. Except for the selectivity parameters, these bounds were arbitrarily set so wide as not to restrict the estimation.

The prior probability density for M was taken as a Cauchy distribution:

$$(25) \quad f(x_M) = \left[0.675\pi \sigma_M \left[1 + \left(\frac{x_M - \mu_M}{0.675\sigma_M} \right)^2 \right] \right]^{-1}$$

where μ_M and σ_M are the mean and standard deviation of the prior distribution for M and x_M is the current value of M .

The prior probability density for the $Rdev$ vector was calculated from the normal distribution:

$$(26) \quad f(Rdev) = \prod_i \frac{1}{\sigma_{Rdev} \sqrt{2\pi}} \exp\left(-\frac{Rdev^2}{2\sigma_{Rdev}^2}\right)$$

where σ_{Rdev} is the assumed standard deviation of $Rdevs$.

Table 2 shows the prior distribution and bounds used for each parameter.

Table 2. PAU 5B model parameters and their priors and bounds.

Model parameters	Definition	Priors and bounds
$\ln(R0)$ prior	Natural log(average recruitment)	uniform, 5, 50
M prior	Natural mortality	Cauchy with mean 0.1, CV 0.5, bounds 0.01, 0.50
L_∞ prior	asymptotic length	uniform, 100, 250
K prior	Brody's coefficient	uniform, 0.01, 0.80
$S90$ prior	90 mm selectivity	uniform, 0.0, 1.0
$Sfull$ prior	size at full selectivity	uniform, 92, 125
$Rdev$ prior	A vector of recruitment deviations	normal, mean 0 bounds -2.3 and 2.3
σ_I	Std. dev. of the error in CPUE	Assumed 0.50
σ_{IS}	Std. dev. of the error in the timed-swim survey	Assumed 0.25
σ_{Rdev}	Std. dev. of the recruitment deviations	Assumed 0.60

The prior for M was based on a consideration of published natural mortality rate discussions for temperate species of abalone (Shepherd & Breen 1992). The CV was set to specify a distribution lying mostly between 0.05 and 0.20, believed to be the reasonable range. McAllister & Kirkwood (2000) suggest setting prior CVs no less than 0.5 to avoid biased estimates.

3.8 Biological assumptions

The length-weight relation was taken from Schiel & Breen (1991) and was

$$(27) \quad w_k = 2.99 \cdot 10^{-8} l_k^{3.03}$$

where l_k is in mm and w_k is in kg.

In calculating spawning biomass, it was assumed that maturity was knife-edged at 90 mm shell length. McShane & Naylor (1995) suggested that 50% maturity is attained at 75-95 mm shell length. Recruitment to the fishery was assumed to be knife-edged at 126 mm shell length. The model excluded observations below 126 mm in catch samples.

3.9 Forward projections

The model makes forward projections by using parameter estimates obtained from fitting or mcmc simulation, and using the dynamics equations in conjunction with specified catch and MLS for the period of projection. Projections were made to the beginning of 2010 with outputs based on 2004 and 2010. Projections were made, at the request of the Ministry of Fisheries, using the 1999-2000 catch levels (122 t total), and from 40 to 110 t in 10 t increments; and with the current MLS of 125 mm and an increased MLS of 135 mm.

In the absence of a stock-recruit relation, projections required some assumption about future recruitment levels. To assume future recruitments at R_0 is too optimistic if recent recruitments have been substantially below this level. To assume a functional relationship is unwarranted. We assumed future recruitments with a mean of the most recent 10 years estimated by the model.

For the sensitivity tests, which were based on the mode of the joint posterior distribution (MPD), the projections were deterministic based on this mean. In the mcmc simulations, recruitment was stochastic, based on this mean modified by

$$(28) \quad \exp(\delta_i \sigma_{Rdev} - 0.5 \sigma_{Rdev}^2)$$

where δ_i is a normally distributed random number with mean 0 and standard deviation of unity.

3.10 Model indicators

In addition to model parameters, derived parameters such as population size and exploitation rate were calculated and their posterior distributions summarised. These indicators were as follows.

Virgin biomass, B_0 , was estimated as the recruited biomass at the end of the burn-in period:

$$(29) \quad B_0 = B_{1974}^{legal}$$

B_{MSY} was estimated with deterministic simulations, with no recruitment variability, to determine $F_{0.1}$. The model did this for each MPD estimate and each mcmc simulation. B_{MSY} was then the equilibrium biomass associated with the $F_{0.1}$ estimate.

The indicators for current and projected biomass, B_{2000} , B_{2004} and B_{2010} , were the values for recruited biomass in those years. Spawning biomass indicators for the virgin, current and projected populations were called S_0 , S_{2000} , S_{2004} and S_{2010} , and were calculated as

$$(30) \quad S_t = \sum_{k=11}^{k=50} N_{k,t} \omega_k$$

Ratios of the population indices were used to estimate how depleted the current and projected population was, where it stood relative to B_{MSY} , and whether it would increase or decrease by 2004 and 2010.

Exploitation rates in 2000, 2004 and 2010 were taken from U_{2000} , U_{2004} and U_{2010} .

For the sets of mcmc simulations, three additional indicators were the percentages of runs in which projected exploitation rate in 2004 was greater than 0.8, in which biomass in 2004 was greater than 2000 biomass, and in which spawning biomass in 2004 was greater than the 2000 spawning biomass.

3.11 Data fitted by the model

The model was driven by a vector of observed catches C from 1974 through 1998 (Table 1). This includes an estimated illegal harvest of 3 t annually. The model was fitted to five data sets: standardised CPUE from 1984 through 1999 (Table 1); independent survey estimates for 1994, 1995, 1996 and 1998 (Table 1); length frequencies from catch samples in 1992, 1993, 1994, 1998, 1999 and 2000; length frequencies from population samples for 1989, 1994, 1995 and 1998; and the tagging data set described above.

Recreational and customary catch estimates were unavailable and were not estimated.

3.12 Assessment procedure

The MPD estimate served as the starting point for Monte Carlo - Markov chain (mcmc) simulations. One million simulations were made, using the mcmc capability of ADModelBuilder™. Of these, 5000 (every 200th) were saved. Posterior distributions of parameters and indicators formed the basis of the assessment. These were summarised by the minimum and maximum, mean and median, and 5th and 95th percentiles of the distributions.

The MPD estimates were also used as the basis of comparisons in sensitivity tests. Sensitivity tests were used to explore sources of uncertainty not incorporated into the assessment procedure described above, such as uncertainty about the observed catch vector and the effect of using robust estimators. Sensitivity to the five data sets was examined by removing the data sets from the estimation procedure one at a time, and then removing both population indices and both length frequency data sets.

4. MODEL RESULTS

4.1 MPD

The MPD fits of the model to CPUE and the survey index are shown in Figure 5; fits to length frequency data are shown in Figure 6; estimated parameter and indicator values are shown in Table 3 under "base case".

In the MPD fit, the model's recruited biomass index reproduces the general downward trend seen in CPUE (Figure 5a) but does not reproduce year-to-year variation very well. The model's population survey index captures some, but not all, of the observed downward trend (Figure 5c). The model clearly cannot fit both the CPUE and survey indices because of their different shapes. The fit to tagging data (Figure 5f) fits the observed increments well, but has a much higher L_{∞} (150 mm) than would be estimated from the tag increment data alone (129 mm), and consequently a lower Brody coefficient (0.205 vs 0.303).

Recruitment in the model was estimated to be higher than average for the first few years for which recruitment deviations were estimated (Figure 5d). This was followed by declining recruitment: the mean of the last 10 years is substantially less than $R0$ (compare the value in Figure 5d for 1998-2000, which is the mean of the previous 10 years, with the value on the lefthand side of Figure D, which is $R0$). When model recruitment is plotted against model spawning biomass with a 3-year lag (Figure 5e), the relation suggests that recruitment has declined concurrently with spawning biomass. Exploitation rate in the model rose steadily to reach a plateau in 1987.

The model population fits the catch sampling length frequency data reasonably well (Figure 6) except for under-estimating the proportion of larger paua observed in the most recent sample. The fit to the population samples is similar.

Current exploitation rate is estimated by the MPD fit to be about 23%; $F_{0.1}$ is estimated to be 0.15 and M 0.10, together implying an optimal rate for a simple $F_{0.1}$ strategy of 13%. MSY was estimated at 147 t, greater than the current catch level of 122 t.

The MPD fit suggests that recruited biomass in 2000 was 18% of $B0$ and about half of B_{MSY} . The spawning biomass is estimated as 23% of the virgin level $S0$. Deterministic projections with current catch levels suggested that recruited biomass would decline by 16% and spawning biomass would stay about the same over 4 years (Table 3).

4.2 Sensitivity

Sensitivity trials on the MPD results are shown in Table 3. Only the MPD results are compared; these must be treated with some caution because the shape of posterior distributions could differ between cases despite the MPDs being similar, and conversely.

Results from the MPD fit described above are termed the "base case". In the next three columns, sensitivity to the fitting procedure is explored. In the first, the fat-tailed t distribution was replaced with "robust normal likelihood" (Chen *et al.* in press) for fitting CPUE and the survey index. In the second, the Cauchy distribution for specifying prior probabilities was replaced with the normal distribution. In the third, these changes were made together. The first change made very little difference; the second and third gave slightly more optimistic MPD fits, suggesting that the Cauchy had a greater effect on fitting than the fat-tailed likelihood.

The next seven columns explore the effects of eliminating one or more data sets. These are followed by tests in which: the most recent year of CPUE was added, although data are incomplete; the 1999 base case catch series was used; selectivity of research divers was fixed to 1 for all sizes above 90 mm; the prior on M was changed to have a mean of 0.12; and L_{∞} was fixed at 170 mm. MPD point estimates were generally robust to all these changes. Estimated current biomass remained below 22% of $B0$ and below 61% of B_{MSY} .

When tagging increments were not fitted, the model estimated a high L_∞ (171 mm); conversely when length frequency data were not fitted and the model's main information about growth was the tag data, L_∞ was 154 mm and K was much higher. Thus the tag data imply a smaller final size than do the length frequency data. Despite that difference, current biomass as a percentage of B_0 and B_{MSY} did not change appreciably.

These results suggest that no single data set is driving the MPD fit in conflict with the other four data sets, and that other modelling choices such as the fitting procedure, catch data series, etc. do not have a great impact on conclusions drawn from the assessment. These results are in contrast to the previous assessment (Breen *et al.* 2000), in which assumptions made about L_∞ and 'steepness' had major impacts on conclusions about the state of the stock.

4.3 Posterior distributions and assessment results

The sequential trends of the 5000 parameter values for estimated and derived model parameters (Figure 7) showed variation without much pattern over the ranges observed. No parameter except S_{90} and S_{full} was near its bounds, and the 'wandering behaviour' seen in the previous assessment (Breen *et al.* 2000), in which the value wandered with a long-period tendency through the simulations, was absent.

Posterior distributions for the major parameters and indicators are shown in Figure 8. The posterior for M was centred on the mean of the prior distribution, 0.10.

Posterior distributions are summarised in Table 4. Most of the base case MDP point estimates of model parameters were reasonably close to the median of the posterior distribution. The medians of posterior distributions for derived parameters were generally more optimistic than the MPD estimates; for instance, current biomass was 51% of B_{MSY} in the MPD, but 63% as the median of the posterior.

Current biomass, B_{2000} , was 22% of B_0 (5th and 95th percentiles 13-32%) and 63% of B_{MSY} (40-95%). The qualitative conclusion is that this stock is almost certainly below B_{MSY} as defined by the simplistic $F_{0.1}$ strategy. Spawning biomass was estimated to be 28% (20-39%) of the virgin level, S_0 .

Projections at the current catch and MLS (Table 4) indicated median expectations for both recruited and spawning biomass to remain near their current levels for the next 4 or 10 years, and for recruited biomass to remain near 60% of B_{MSY} . The 5th to 95th percentile ranges on these projections were large, reflecting uncertainty about future population behaviour; the uncertainty increases for longer projections. For instance, the posterior for B_{2004}/B_{2000} suggests that recruited biomass could decrease with 64% or increase with 36% probability (Table 4) in the next 4 years. The 5th to 95th percentile range is for B_{2004} to be 67-134% of B_{2000} , and for B_{2010} to be 39-207% of B_{2000} .

4.4 Model projections

Stochastic projections made from 18 combinations of catch and MLS levels were summarised by plotting the median and 5th and 95th percentiles for each indicator against catch level, doing this for each level of MLS. These are shown in Figures 9 through 11.

When spawning biomass in 2010 is compared with S_0 (Figure 9), the median expectation is that it would rebuild to 40% of S_0 (an arbitrary reference point suggested for abalones by Shepherd &

Partington (1995)) only if catch were reduced to 90 t or less; this conclusion is about the same for both MLS levels. However, to be 95% certain of rebuilding the spawning stock to 40% S_0 in 10 years would require a catch level of less than 30 t.

The chance of increasing the spawning biomass in 4 years is similarly illustrated in Figure 9. The median expectation is that spawning biomass would increase slightly at either level of MLS. To be 95% certain of increasing spawning biomass would require a catch level of 60 t; this is the same for both MLS levels.

Projected levels of rebuilding in recruited biomass over 4 years are shown in Figure 10. At the current catch and MLS, the median expectation is that recruited biomass will remain the same. A 95% certainty of increasing recruited biomass requires a catch level of 70 t at the current MLS of 125 mm. If MLS were increased, this would create an immediate and substantial reduction in recruited biomass, and no catch level above 30 t would ensure that this biomass recovered to its current level. A catch level as low as 50 t is required before the recruited biomass has more than a 5% chance of recovering.

To ensure a 95% certainty of rebuilding recruited biomass over 10 years (Figure 10) would require a catch level of 70 t at MLS 125 or 50 t at MLS 135 mm.

The percentages of runs in which exploitation rate exceeded 80% after 4 years are shown in Figure 11. This is negligible for MLS 125 mm, but approaches 10% at MLS 135 mm at the current catch level. This risk of the fishery not being able to catch the quota is greatly reduced as the catch level is decreased.

The percentages of runs in which recruited biomass increased over 4 years are also shown in Figure 11. The percentage rises steeply from 36% at the current catch to 100% at 40 t for MLS 125 mm. The percentage is zero for MLS 135 mm until the catch is reduced to 70 t or less.

The percentages of runs in which spawning biomass increased over 4 years are also shown in Figure 11. The percentage is similar for both MLS levels, and rises from 60% at the current catch to 100% at 40 t catch.

5. DISCUSSION

For PAU 5B, the current model provided an apparently robust assessment of the stock. The assessment and sensitivity trials suggest a depleted stock below B_{MSY} , with a median expectation of remaining depleted at current catch and MLS levels. The TACC appears to be sustainable, in that recruited biomass is about equally likely to increase or decrease at this level. The TACC has no tendency to return the stock towards B_{MSY} .

The spawning biomass is probably less than 40% of S_0 . Some abalone biologists suggest that 40-50% of virgin egg production should be considered a limit reference point (e.g., Shepherd & Partington 1995, Shepherd *et al.* 1995, Shepherd & Baker 1998). The only stock-recruit relation for abalone has been suggested by Shepherd & Partington (1995) - their data suggested a Ricker-type curve with a very steep left-hand portion, in turn suggesting populations vulnerable to rapid recruitment overfishing at low spawning stock sizes. The potential of Allee effects to become important at low densities of abalone and similar sedentary species (*see* discussion in Babcock & Keesing (1999)) suggests that spawning biomass should be maintained at a relatively high level compared with other taxonomic groups.

The quantitative conclusions appear to be robust, when MPD estimates are compared, to inclusion or exclusion of each of the five data sets used, to the fitting procedure, and to other modelling choices. The data on proportion-at-length are also reasonably consistent with each other and with the abundance index data (see Table 3). Results are much more robust than in the 1999 assessment. This may have been brought about by simplification of the model, by estimating growth within the model and including the tagging data set, or by improving the model fit by adding relative selectivity of the research divers to small paua, or the combination of these.

Specific fishery indicators were projected over 4 and 10 years under 18 combinations of catch and MLS. These are described and discussed above. These should provide managers with the information they require to make decisions about which management options to choose, once they decide on criteria for required future population performance. In all situations, lower catch levels increase the chance of rebuilding and the median expectation of the level of rebuild. Increasing the MLS produces small gains, when compared with the catch level at 125 mm MLS, in terms of spawning biomass. However, the decrease in recruited biomass caused by increased MLS is immediate, substantial, and unlikely to be recovered except with severe decreases in catch levels.

The model assumes that PAU 5B is a unit stock, that paua have the same growth and mortality characteristics in all parts of the stock, and that CPUE responds to abundance as if abundance were homogeneous within statistical areas. These are obviously over-simplifications. Growth, for instance, is likely to vary over small distances (Day & Fleming 1992). Differences in growth over small scales may explain why the model fits the "plus group" poorly when many large paua are observed in the population length frequency samples. An alternative explanation might be that some large paua are left behind when paua density in an area has been reduced to non-commercial levels. Such paua could be vulnerable to research divers but functionally protected from the commercial fishery by reason of their low density. Karpov *et al.* (1998) described a refuge in depth for red abalone in California that is effectively a similar mechanism.

The effect of small-scale variability on model results, apart from degrading the fits, is unknown. Any attempt to reduce the assumed model stock size and to include more biological realism will encounter problems with fishery data, which have been collected at larger scales. Quantitative assessments must always balance these competing scales.

It is possible that the model results are over-optimistic. This could arise from several sources. Hyperstability in CPUE is likely - this is widely recognised as a problem by abalone scientists (see Breen 1992). The diver survey index declines at a much higher rate than the CPUE index (see Figures 5a and 5c). If the decline in abundance is steeper than the decline in CPUE, then model results are too optimistic.

Serial depletion, the main cause of hyperstability in CPUE, could also have caused catch sample length frequencies to show less change than was actually present in the population. If this happened, then model results are too optimistic. Serial depletion can also cause local recruitment failure through Allee effects, again causing the model results to be too optimistic.

Finally, we chose to use a deterministic equilibrium $F_{0.1}$ calculation to estimate B_{MSY} . This is overly simplistic, and is likely to under-estimate the true B_{MSY} . Because real populations and population processes fluctuate, equilibria are non-existent and information about stock size is imperfect and comes with a lag. However, in the absence of specifications from the Ministry about levels of risk or other reference points, this approach to B_{MSY} was considered most appropriate. If the model under-estimates B_{MSY} for the reasons described, then comparisons of the model's current and future biomass with B_{MSY} are too optimistic. A better reference point for paua might be based on a comparison of spawning biomass with S_0 , as discussed above.

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Table 1. Input data used in the PAU 5B assessment. Years are named after the second part of the fishing year, viz “1986” refers to the fishing year 1985-86. Two catch series are shown as described in the text: the “base case” catch used in 2000, and “series 1”, which was the base case used in 1999. Two CPUE series are shown as described in the text: the “base case” and a series in which the incomplete data for 2000 were included.

year	comm. catch base case (kg)	comm. catch series 1 (kg)	illegal catch (kg)	CPUE base case	CPUE 2000	diver survey index
1974	110 588	114 000	3 000	-	-	-
1975	104 614	108 000	3 000	-	-	-
1976	83 257	86 000	3 000	-	-	-
1977	115 128	118 000	3 000	-	-	-
1978	173 399	176 000	3 000	-	-	-
1979	181 979	185 000	3 000	-	-	-
1980	225 212	228 000	3 000	-	-	-
1981	272 657	276 000	3 000	-	-	-
1982	180 211	183 000	3 000	-	-	-
1983	230 350	233 000	3 000	-	-	-
1984	356 898	290 000	3 000	2.623	2.598	-
1985	190 884	182 000	3 000	2.598	2.574	-
1986	226 982	192 500	3 000	2.673	2.651	-
1987	263 080	203 000	3 000	2.893	2.869	-
1988	305 902	218 000	3 000	1.910	1.895	-
1989	285 099	194 000	3 000	1.772	1.761	-
1990	268 166	202 000	3 000	1.715	1.706	-
1991	272 344	224 000	3 000	1.497	1.490	-
1992	255 918	199 000	3 000	1.418	1.406	-
1993	211 137	174 000	3 000	1.299	1.289	-
1994	222 900	167 000	3 000	1.139	1.132	50.1
1995	222 593	159 000	3 000	1.051	1.044	36.9
1996	131 462	134 000	3 000	0.990	0.984	28.7
1997	142 357	144 000	3 000	1.117	1.111	-
1998	145 337	146 000	3 000	1.080	1.074	17.6
1999	148 255	148 255	3 000	1.000	1.000	-
2000	119 000	119 000	3 000	-	1.219	-

Table 3. MPD results from the base case (column 2) and from sensitivity trials described in the text. The bottom portion of the table shows the negative log-likelihood contributions from the five data sets, the priors and the penalty on exploitation rate.

Parameter	base case	no fattail	no Cauchy	no neither	no CPUE	no IS	no catch sample LFs	no popn LFs	no tags	no popn. indices	no LFs	plus 2000 CPUE	1999 base catch	no select'y	mean of M prior 0.12	L_{∞} fixed at 170
$ln(R0)$	13.92	13.91	14.20	14.18	13.91	13.95	13.98	13.98	13.99	13.94	14.06	14.08	13.81	13.90	14.18	13.87
M	0.101	0.100	0.122	0.121	0.100	0.101	0.100	0.100	0.101	0.101	0.100	0.100	0.100	0.099	0.120	0.101
L_{∞}	166.6	166.8	168.8	169.0	166.9	166.2	164.3	165.2	170.7	166.4	154.1	154.0	154.0	164.7	168.7	170.0
K	0.182	0.181	0.175	0.175	0.181	0.183	0.190	0.188	0.154	0.182	0.243	0.243	0.243	0.189	0.176	0.170
$S90$	0.048	0.049	0.005	0.007	0.046	0.042	0.079	0.995	0.028	0.042	0.001	0.002	0.000	1.000	0.008	0.039
$Sfull$	125	125	125	125	125	125	122	93	125	125	109	103	105	110	125	125
$max(Rdev)$	0.56	0.57	0.46	0.48	0.57	0.55	0.56	0.65	0.61	0.56	0.11	0.12	0.15	0.70	0.47	0.62
$B0$	3077	3060	2993	2970	3042	3133	3199	3256	3124	3111	3196	3265	2470	3041	2998	2997
B_{2000}	540	519	669	635	497	615	647	670	592	591	607	687	314	586	659	469
$B_{2000}/B0$	17.6%	17.0%	22.4%	21.4%	16.3%	19.6%	20.2%	20.6%	19.0%	19.0%	19.0%	21.1%	12.7%	19.3%	22.0%	15.7%
B_{2004}	455	434	665	625	414	530	572	667	486	505	711	786	314	463	650	354
B_{2004}/B_{2000}	84.3%	83.7%	99.4%	98.5%	83.2%	86.2%	88.4%	99.5%	82.1%	85.5%	117.2%	114.3%	100.0%	79.1%	98.5%	75.4%
$S0$	3604	3582	3639	3603	3559	3674	3759	3815	3723	3647	3810	3893	2945	3559	3634	3496
S_{2000}	842	817	1076	1030	794	930	972	1043	935	901	1070	1158	666	848	1058	741
$S_{2000}/S0$	23.4%	22.8%	29.6%	28.6%	22.3%	25.3%	25.9%	27.3%	25.1%	24.7%	28.1%	29.7%	22.6%	23.8%	29.1%	21.2%
S_{2004}	820	796	1146	1095	772	902	958	1100	902	872	1200	1291	695	870	1122	684
S_{2004}/S_{2000}	97.3%	97.4%	106.5%	106.3%	97.3%	97.0%	98.6%	105.5%	96.4%	96.8%	112.2%	111.5%	104.3%	102.6%	106.0%	92.3%
U_{2000}	22.6%	23.5%	18.2%	19.2%	24.5%	19.8%	18.9%	18.2%	20.6%	20.6%	20.1%	17.7%	38.8%	20.8%	18.5%	26.0%
U_{2004}	26.8%	28.1%	18.3%	19.5%	29.5%	23.0%	21.3%	18.3%	25.1%	24.2%	17.2%	15.5%	38.8%	26.3%	18.8%	34.5%
B_{msy}	1053	1046	1012	998	1039	1075	1084	1120	1054	1067	1102	1126	852	1040	1041	1009
B_{2000}/B_{msy}	51.3%	49.6%	66.1%	63.6%	47.8%	57.2%	59.7%	59.8%	56.2%	55.4%	55.1%	61.1%	36.9%	56.4%	63.3%	46.5%
MSY	147	146	171	169	145	150	156	156	142	149	168	171	130	145	167	141
$F_{0.1}$	0.150	0.150	0.185	0.185	0.150	0.150	0.155	0.150	0.145	0.150	0.165	0.165	0.165	0.150	0.175	0.150
CPUE	16.37	4.03	16.41	4.05	0.00	16.29	16.26	16.13	16.42	0.00	15.96	17.00	16.00	16.45	16.40	16.52
catch LFs	-626.6	-626.6	-626.8	-626.8	-626.7	-626.6	0.0	-626.7	-627.0	-626.6	0.0	0.0	0.0	-622.3	-626.8	-627.3
IS	6.44	0.49	6.81	0.91	6.30	0.00	6.38	6.80	6.40	0.00	6.84	6.98	6.62	5.55	6.79	6.18
priors	-2.22	-2.22	0.30	0.30	-2.22	-2.21	-2.23	-2.24	-2.21	-2.21	-2.24	-2.24	-2.24	-2.13	-2.06	-2.19
$Rdev$	12.72	12.89	11.96	12.20	13.03	12.28	11.57	11.37	13.22	12.45	9.06	8.95	9.09	17.23	12.00	13.65
popn. LFs	-284.59	-284.70	-285.56	-285.69	-284.76	-284.14	-284.48	0.00	-285.31	-284.30	0.00	0.00	0.00	-273.74	-285.51	-285.22
U penalty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
tags	352.55	352.59	353.20	353.26	352.64	352.44	351.92	352.16	0.00	352.49	350.09	350.09	350.09	352.02	353.15	353.55
f	-525.32	-543.54	-523.68	-541.82	-541.73	-531.91	99.43	-242.46	-878.53	-548.22	379.70	380.78	379.55	-506.98	-526.03	-524.81

Table 4. Summary of the marginal posterior distributions derived from the base case. The columns show the minimum value observed in 5000 samples from 1 million mcmc simulations, the maximum, the 5th and 95th percentiles, the mean and the median. The MPD estimates from the base case are shown for comparison.

	Min	Max	5%	95%	Mean	Median	MPD
$\ln(R0)$	13.30	14.79	13.73	14.16	13.92	13.91	13.92
M	0.071	0.165	0.093	0.117	0.102	0.101	0.101
$Linf$	158.7	177.6	163.0	172.3	167.4	167.2	166.6
K	0.144	0.221	0.162	0.198	0.180	0.179	0.182
$S90$	0.000	0.449	0.006	0.226	0.091	0.076	0.048
$Sfull$	116.17	125.00	118.69	124.83	122.18	122.49	125
$\max(Rdev)$	0.399	2.174	0.804	1.518	1.133	1.115	0.56
$B0$	2327	3871	2729	3309	3015	3012	3077
B_{2000}	222	1654	386	1038	672	647	540
$S0$	2850	4647	3190	3930	3543	3534	3604
S_{2000}	425	2340	660	1504	1030	1000	842
U_{2000}	7.4%	54.8%	11.8%	31.6%	19.9%	18.9%	22.6%
$F_{0.1}$	0.110	0.245	0.145	0.175	0.153	0.150	0.150
B_{msy}	803	1314	930	1129	1027	1025	1053
MSY	100	241	127	170	146	144	147
f	-525.3	-493.0	-517.7	-506.1	-512.5	-512.8	-525.32
$B_{2000}/B0$	7.1%	47.0%	13.6%	32.3%	22.1%	21.5%	17.6%
B_{2000}/B_{msy}	21.5%	136.9%	40.0%	95.1%	64.8%	63.2%	51.3%
$S_{2000}/S0$	12.5%	54.4%	20.2%	39.2%	28.8%	28.3%	23.4%
B_{2004}	85	1844	297	1075	649	623	455
B_{2010}	42	3546	187	1442	741	696	
S_{2004}	218	3275	606	1717	1099	1056	820
S_{2010}	199	5003	476	2045	1158	1097	
B_{2004}/B_{2000}	28.8%	370.3%	66.7%	134.1%	96.1%	93.5%	84.3%
B_{2010}/B_{2000}	8.1%	716.2%	38.5%	206.7%	110.5%	102.6%	
B_{2004}/B_{msy}	9.2%	154.2%	31.1%	98.0%	62.3%	61.0%	
B_{2010}/B_{msy}	4.4%	285.8%	19.6%	133.6%	71.0%	67.4%	
$S_{2004}/S0$	7.5%	83.7%	18.6%	45.1%	30.7%	29.8%	
$S_{2010}/S0$	6.3%	119.9%	14.5%	54.2%	32.3%	31.0%	
S_{2004}/S_{2000}	47.8%	230.3%	81.1%	140.8%	106.3%	103.5%	97.3%
S_{2010}/S_{2000}	30.0%	315.1%	61.1%	174.3%	111.3%	107.1%	
U_{2004}	6.6%	80.0%	11.3%	41.1%	22.0%	19.6%	26.8%
U_{2010}	3.4%	80.0%	8.5%	65.1%	22.9%	17.5%	
% $U_{2004} \geq 0.8$	0.5%						
% $B_{2004} > B_{2000}$	35.8%						
% $S_{2004} > S_{2000}$	59.4%						

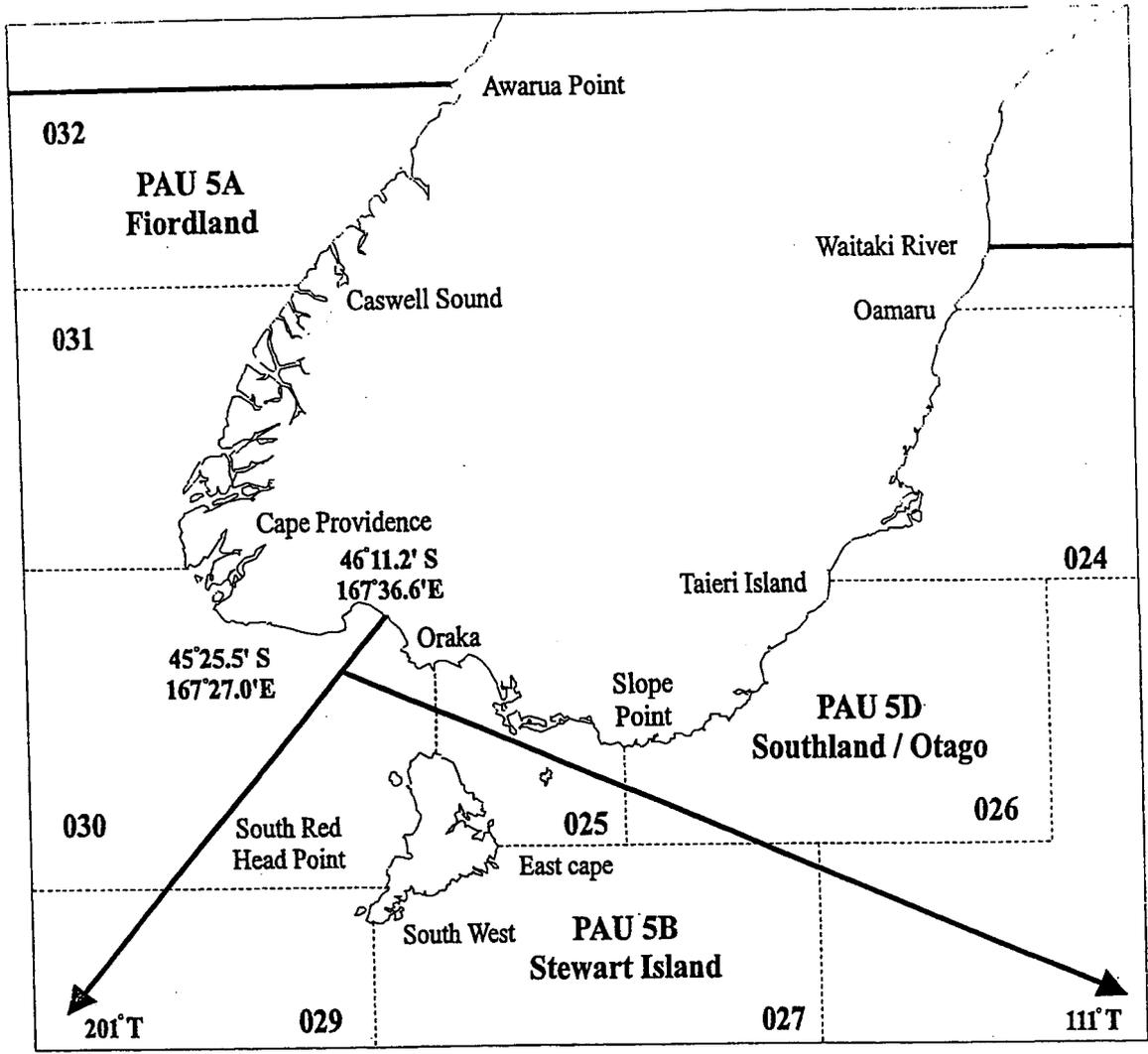


Figure 1a: Area PAU 5 and the new subdivision boundaries creating three areas - PAU 5A, PAU 5B and PAU 5D.

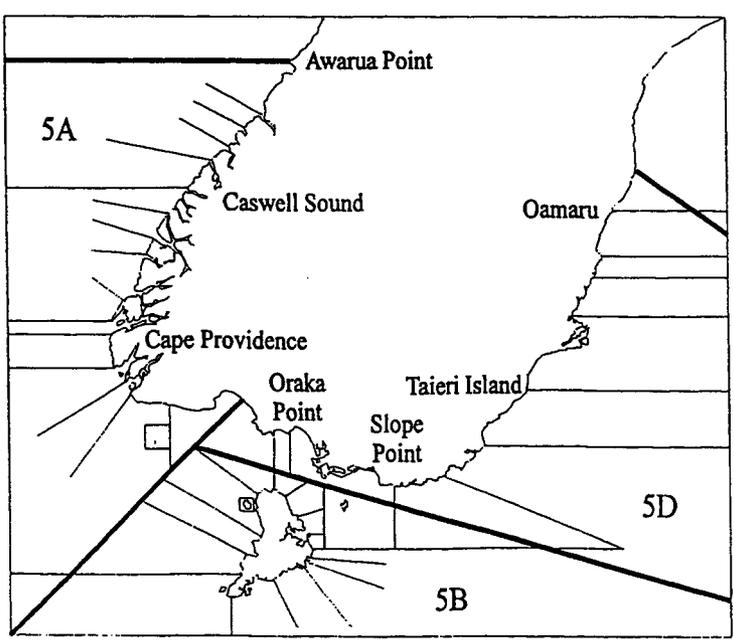


Figure 1b: The locations of new statistical reporting areas within PAU 5.

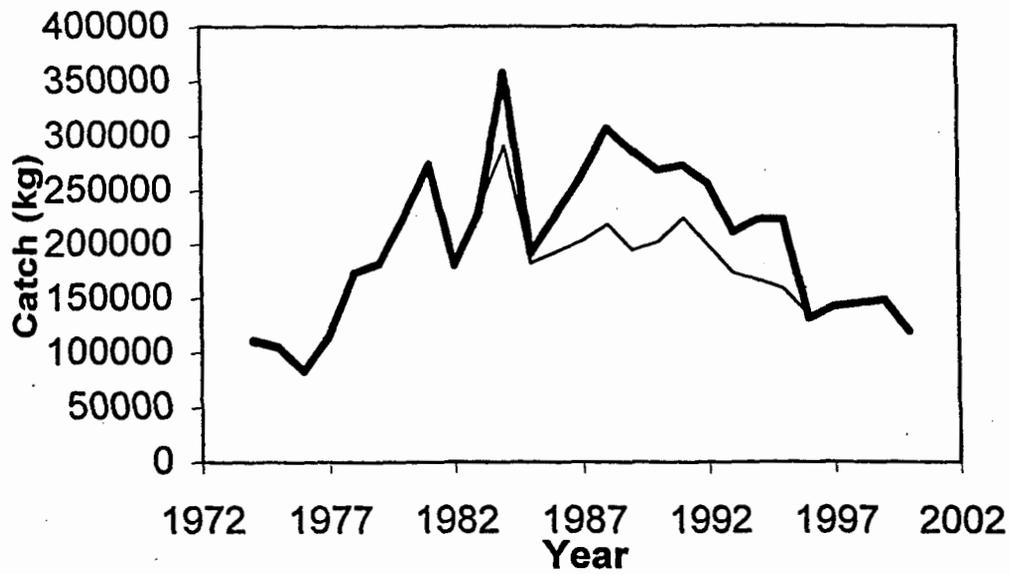


Figure 2. The two catch series (Table 1) used in the assessment. The base case is the heavy line; the series used in 1999 as the base case is the lighter line.

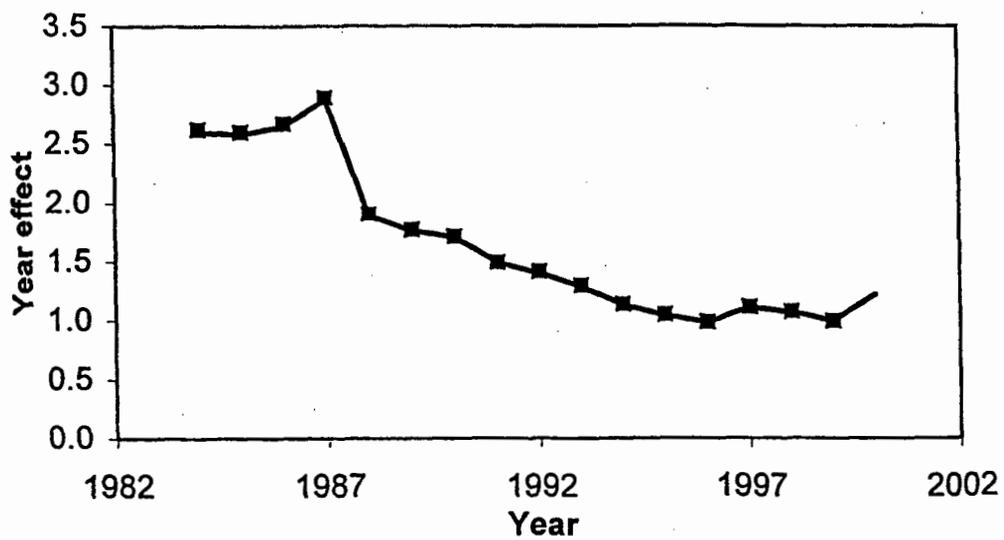


Figure 3. The two CPUE series (Table 1) used in the assessment. The base case values are shown as solid squares; the line shows the series calculated when incomplete data from 2000 were used.

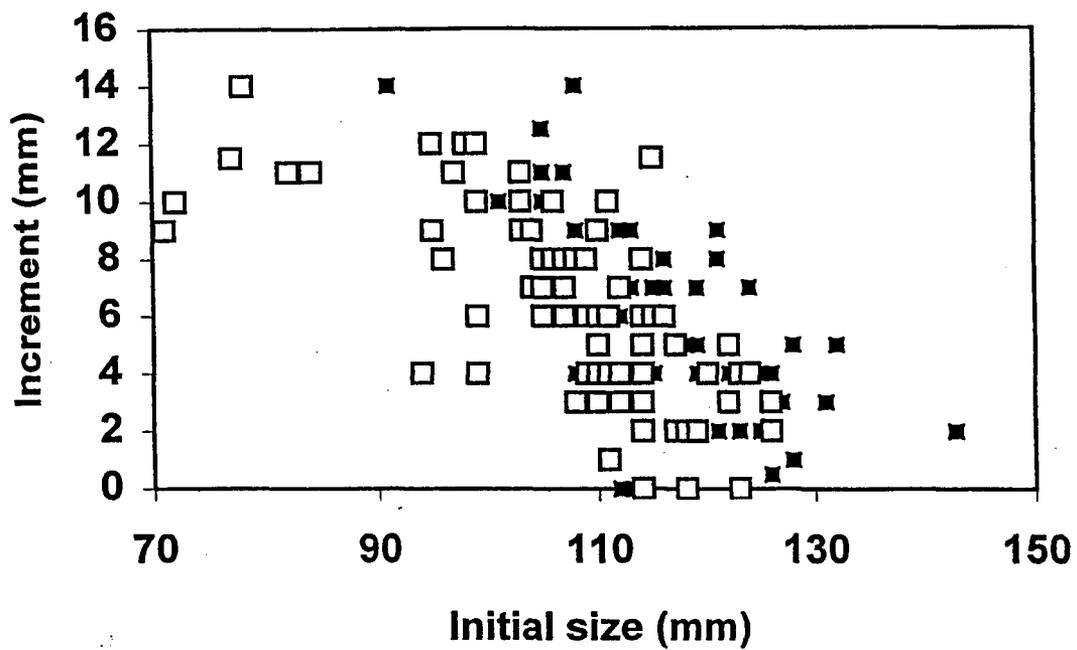


Figure 4. Length increments from paua tagged and recaptured at Waituna. The solid squares show increments of paua recaptured after 214 days; the open squares show increments of paua recaptured after 289 days.

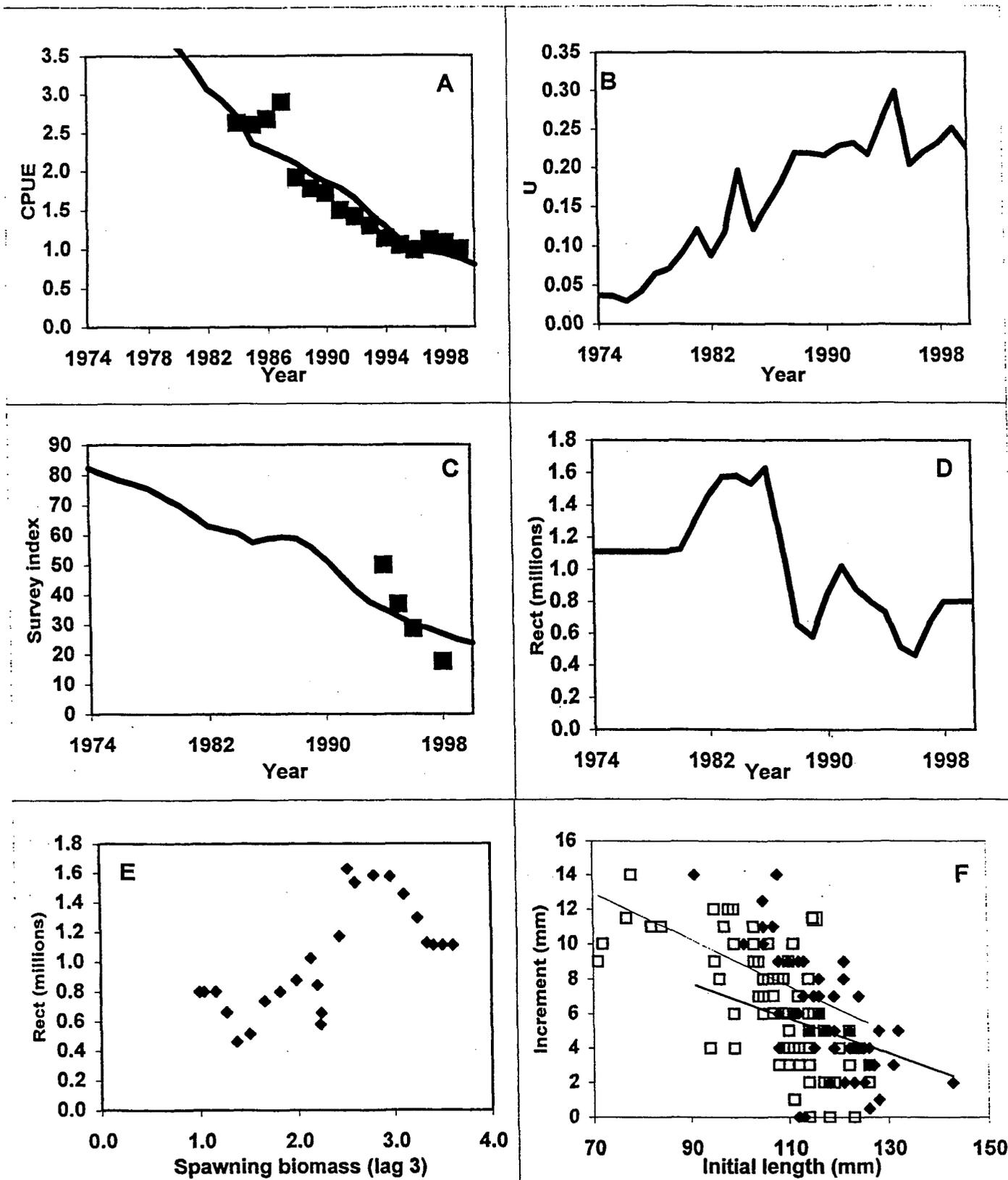


Figure 5. Results from the base case MPD fit for PAU 5. A: Observed (squares) and predicted (solid line) CPUE; B: the model's exploitation rate; C: Observed (squares) and predicted (solid line) diver survey index; D: the model's annual recruitment; E: recruitment plotted against spawning biomass three years earlier; F: Observed length increments from paua tagged at Waituna and recovered 214 days (solid squares) or 289 days (open squares) later, and predicted length increments - the lower line is for 214-day recoveries; the upper for 289-day recoveries.

PAU 5B sensitivity :
511501 BASE

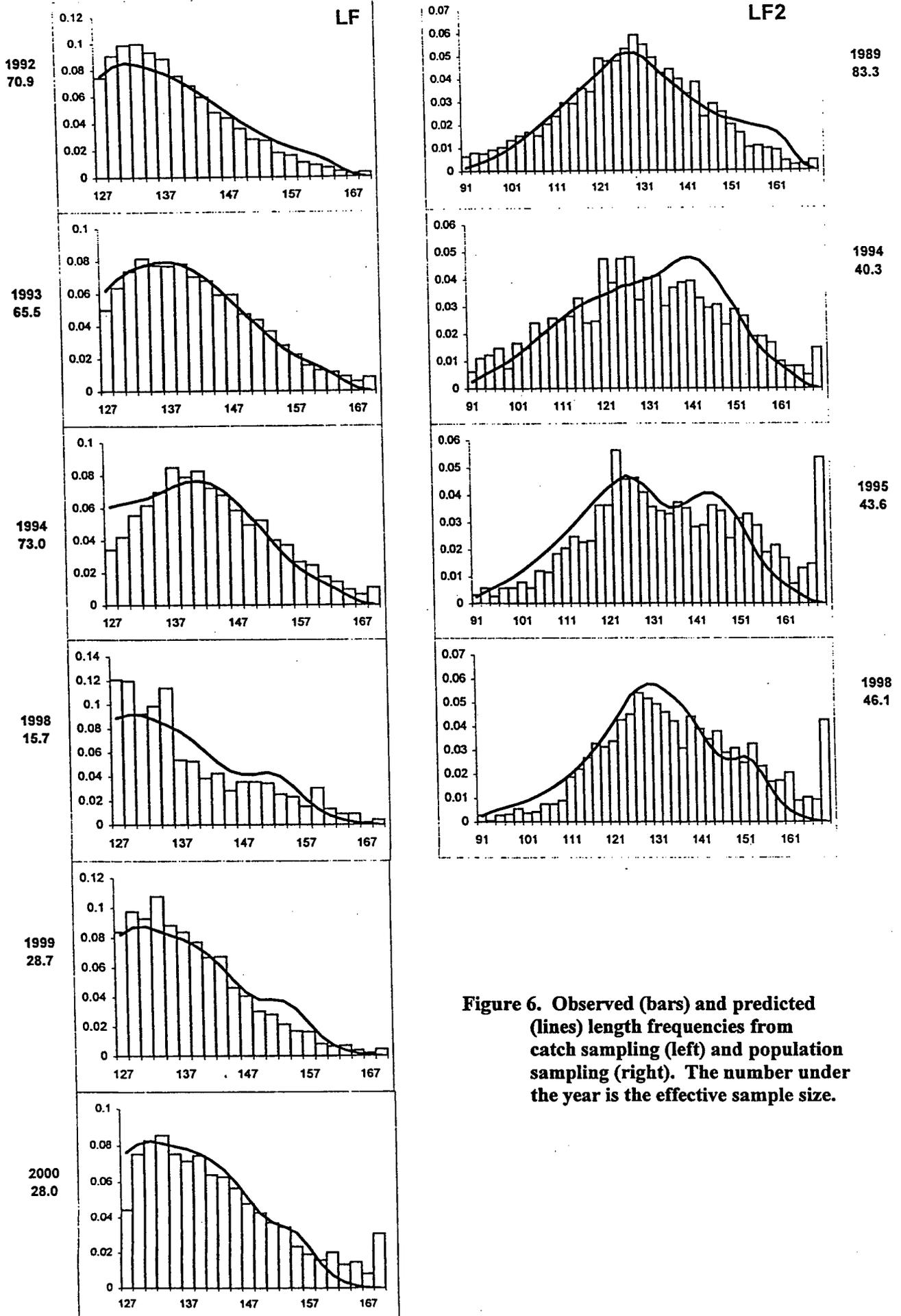


Figure 6. Observed (bars) and predicted (lines) length frequencies from catch sampling (left) and population sampling (right). The number under the year is the effective sample size.

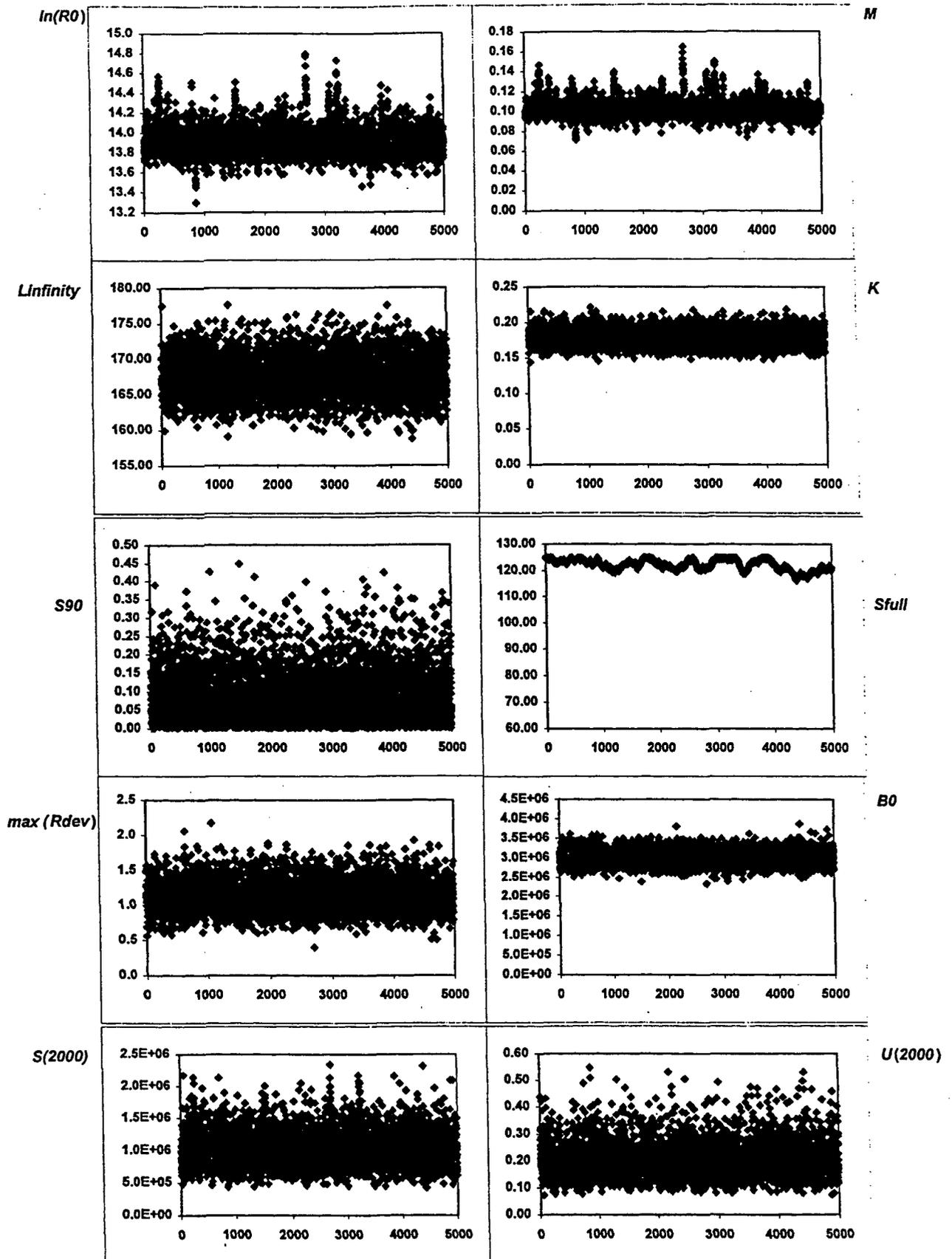


Figure 7. Values of the parameters indicated during mcmc simulations. Each plot shows the values plotted in the order that samples were taken: one sample was taken every 200 simulations from a run of 1 million.

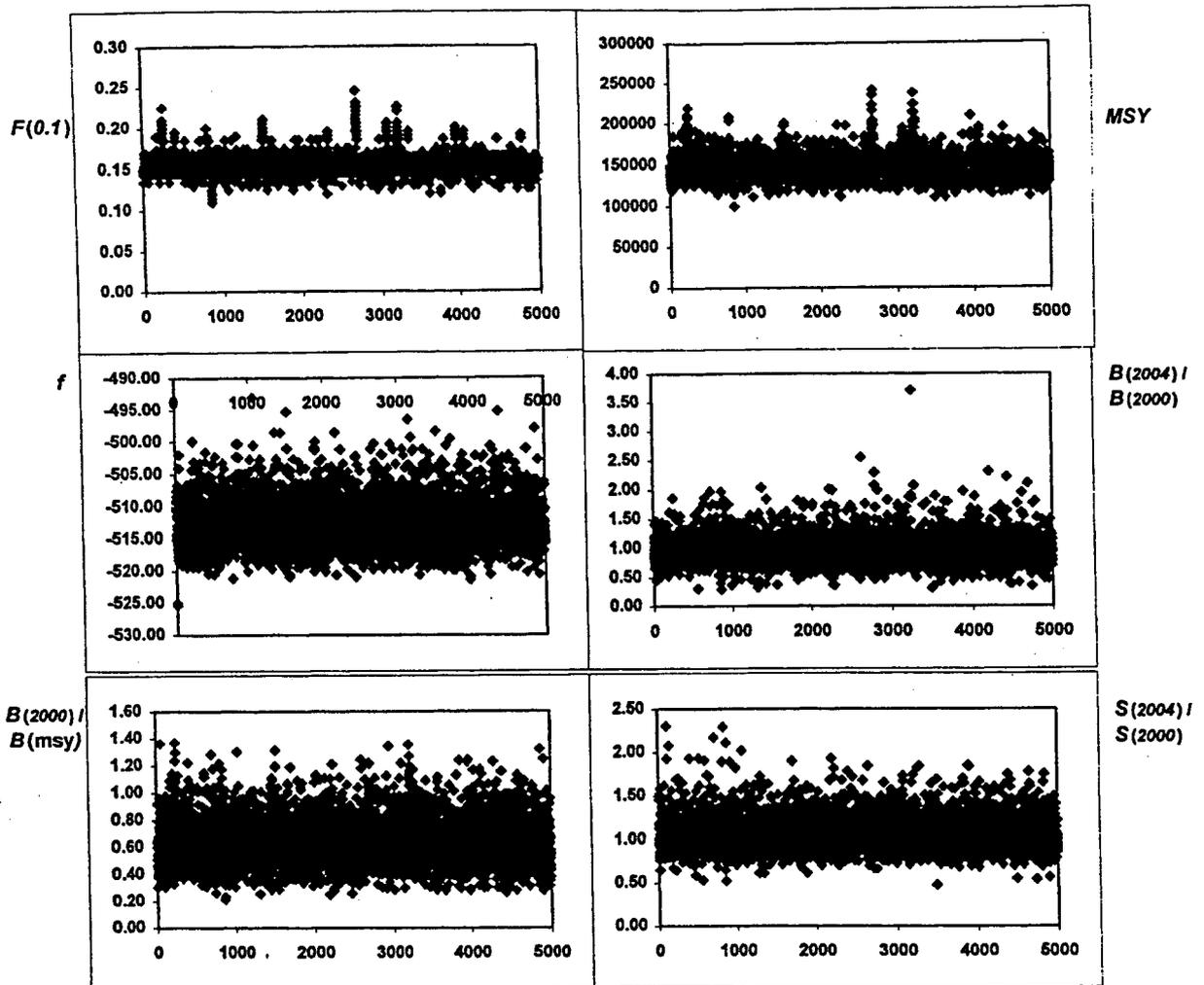


Figure 7 continued.

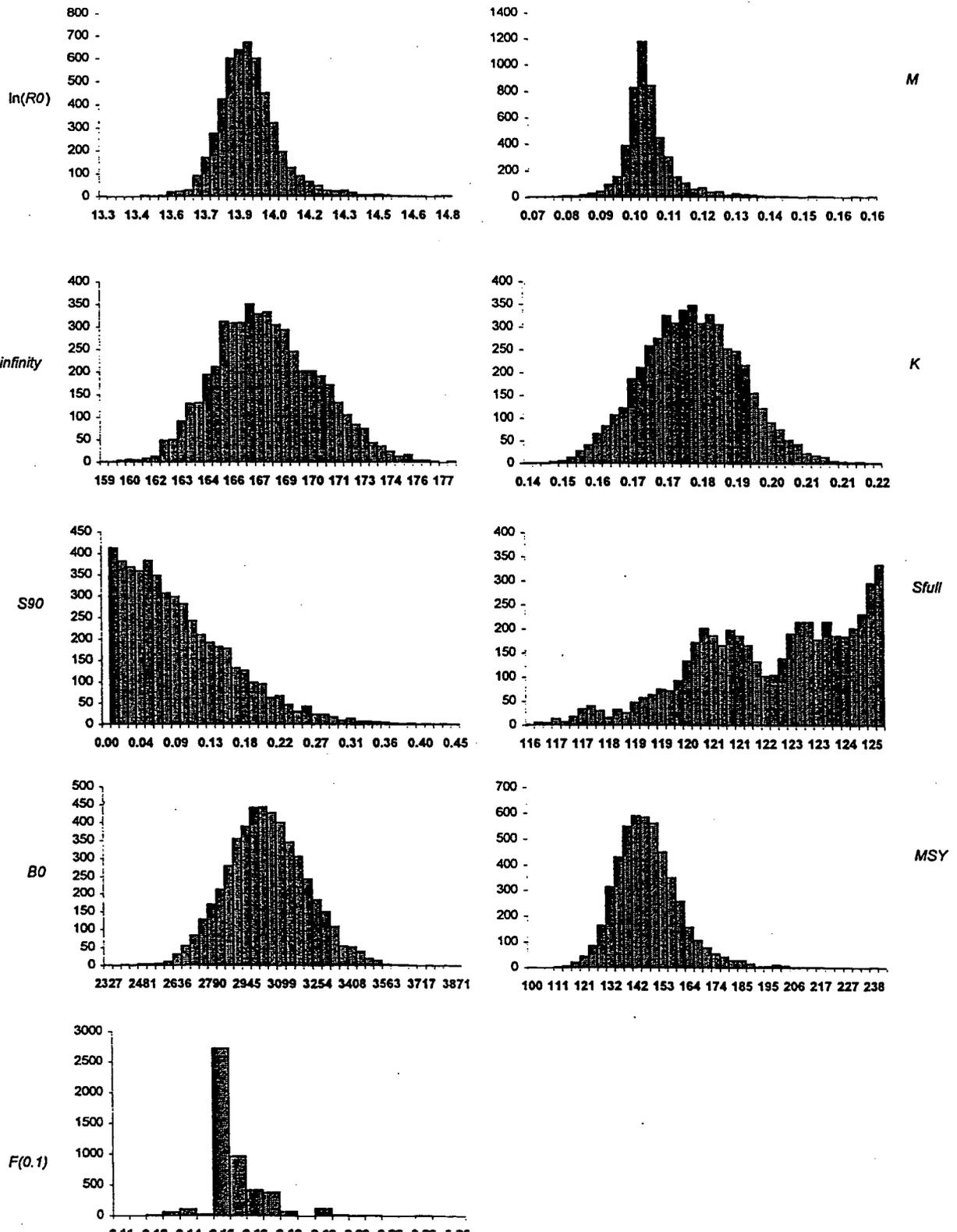


Figure 8. Posterior distributions from the 5000 samples shown in Figure 7.

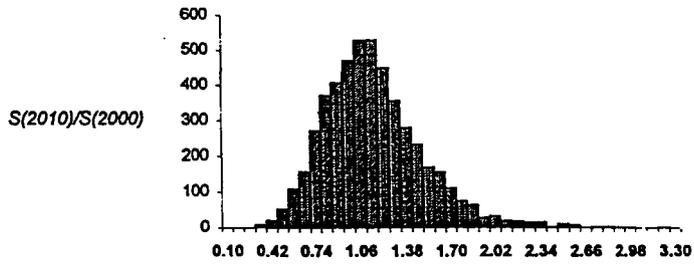
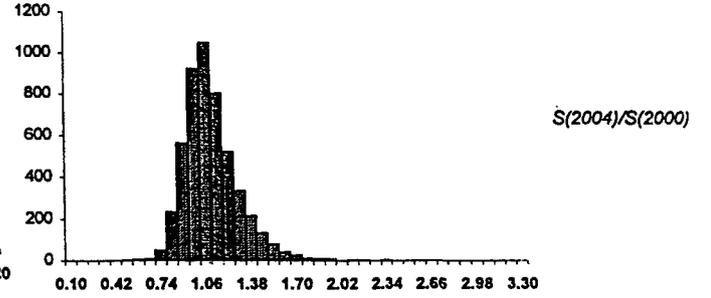
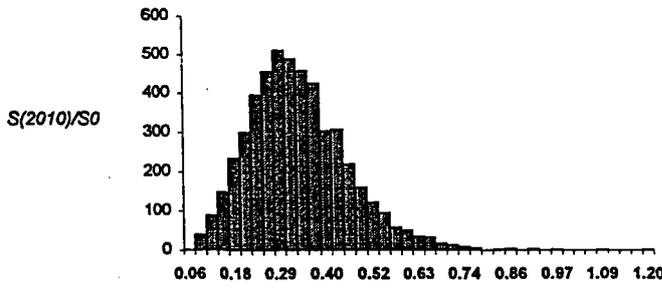
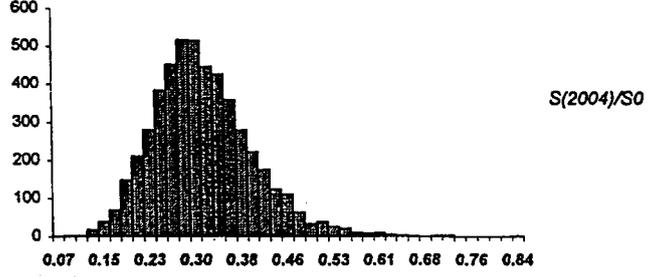
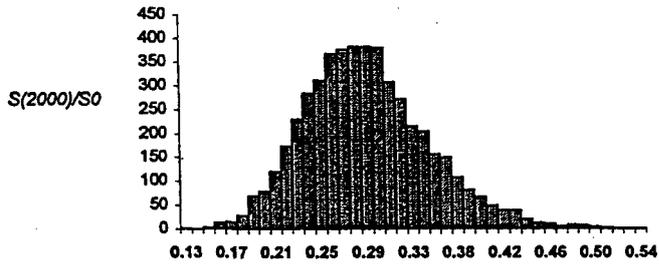
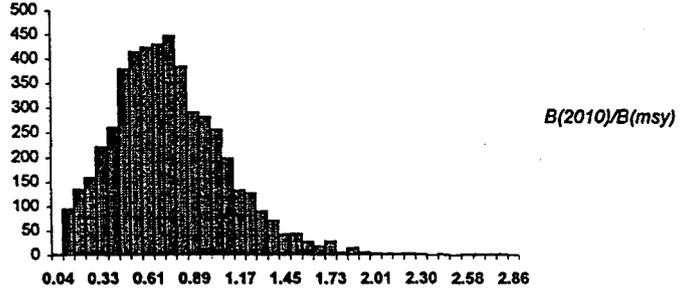
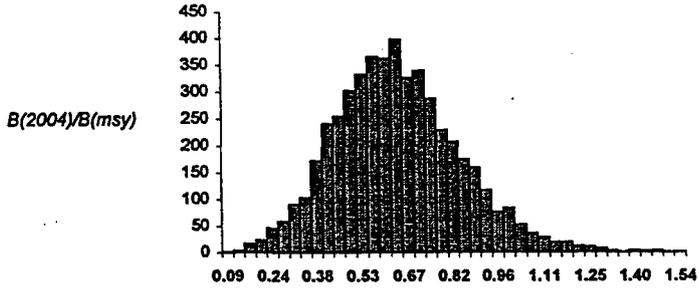
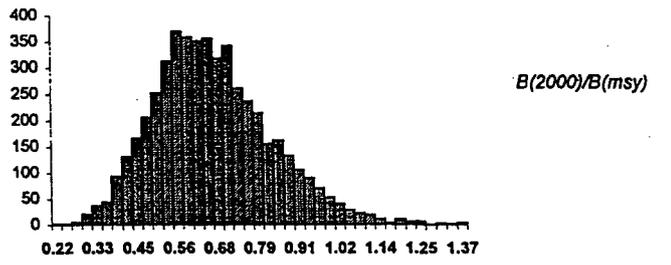
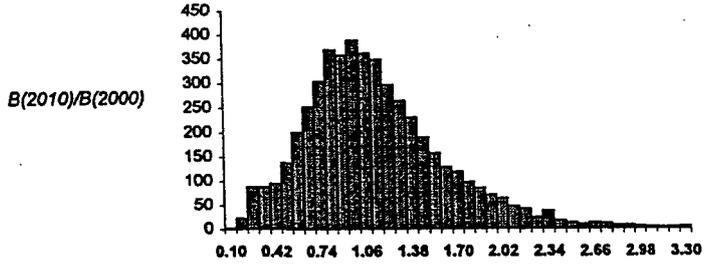
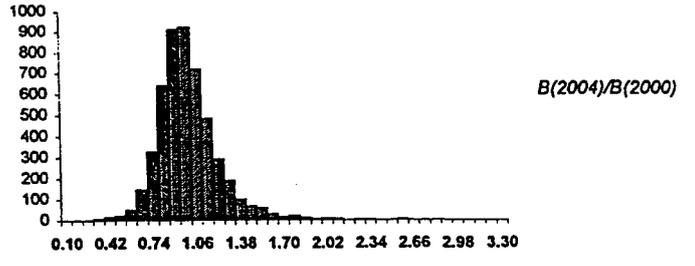
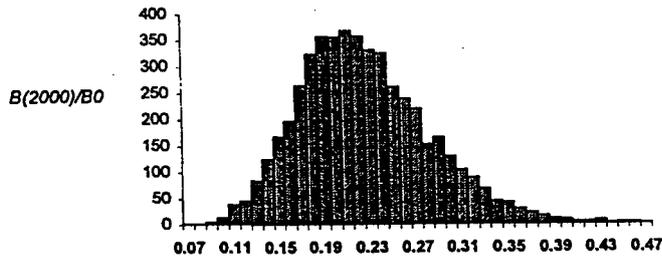


Figure 8 continued.

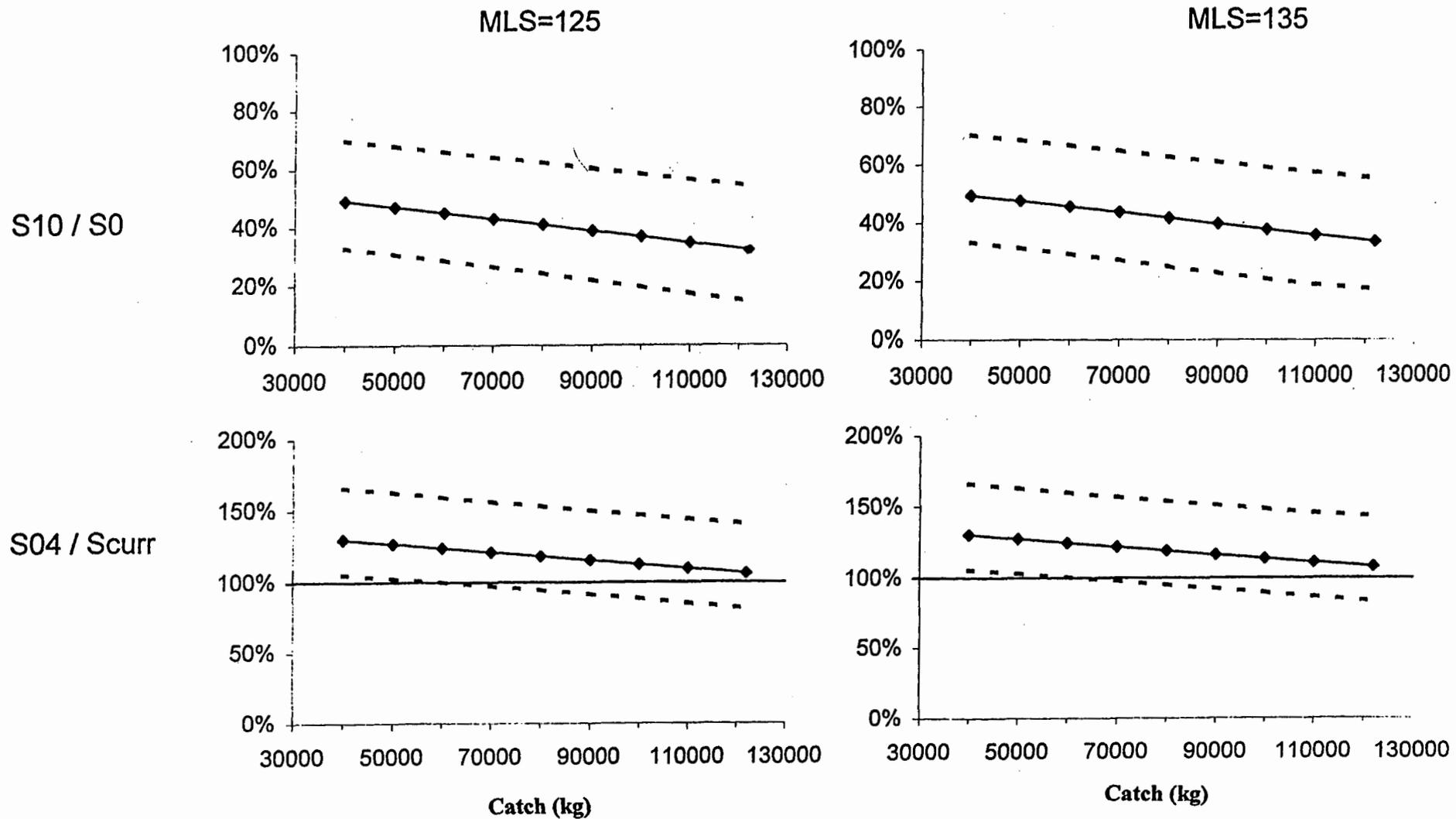


Figure 9. A graphic summary of the posterior distributions for two indicators. The upper figures show the ratio of spawning biomass in 2010 to that in 1974; the lower figures show the ratio of spawning biomass in 2004 to that in 2000. Figures on the left are from runs with $MLS = 125$ mm; on the right with $MLS = 135$ mm. Each figure shows the median (solid line) and the 5th and 95th percentiles (dotted lines) of the posterior distribution at each of nine commercial catch levels (kg) shown on the x-axis. Projections were stochastic.

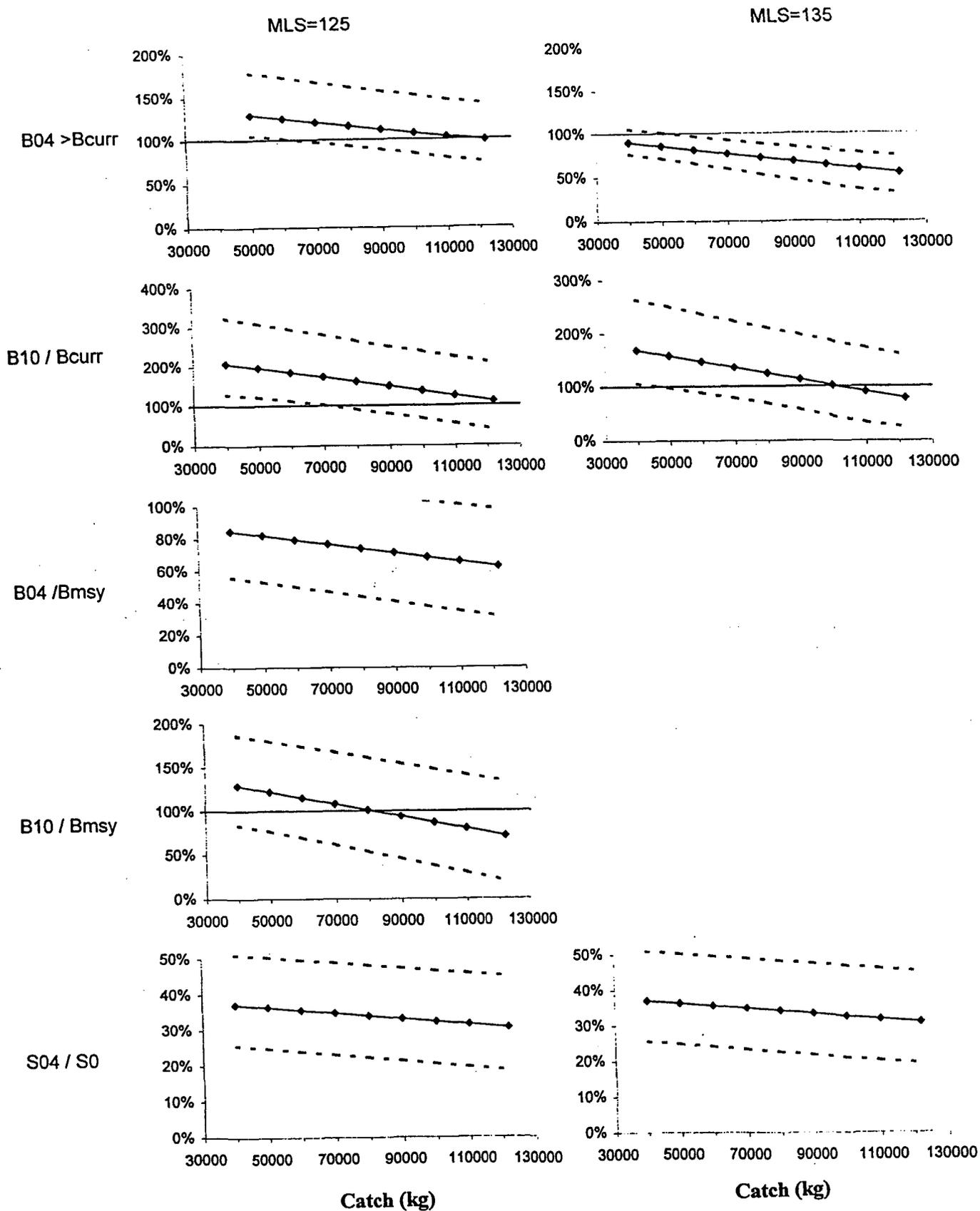


Figure 10. Summaries of the posterior distributions for population indicators as labelled. Figures on the left are from runs with $MLS = 125$ mm; on the right with $MLS = 135$ mm. Each figure shows the median (solid line) and the 5th and 95th percentiles (dotted lines) of the posterior distribution at each of nine commercial catch levels (kg) shown on the x-axis. Projections were stochastic. The current recruited biomass was calculated with $MLS = 125$ mm. B_{MSY} was not calculated for $MLS = 135$ mm.

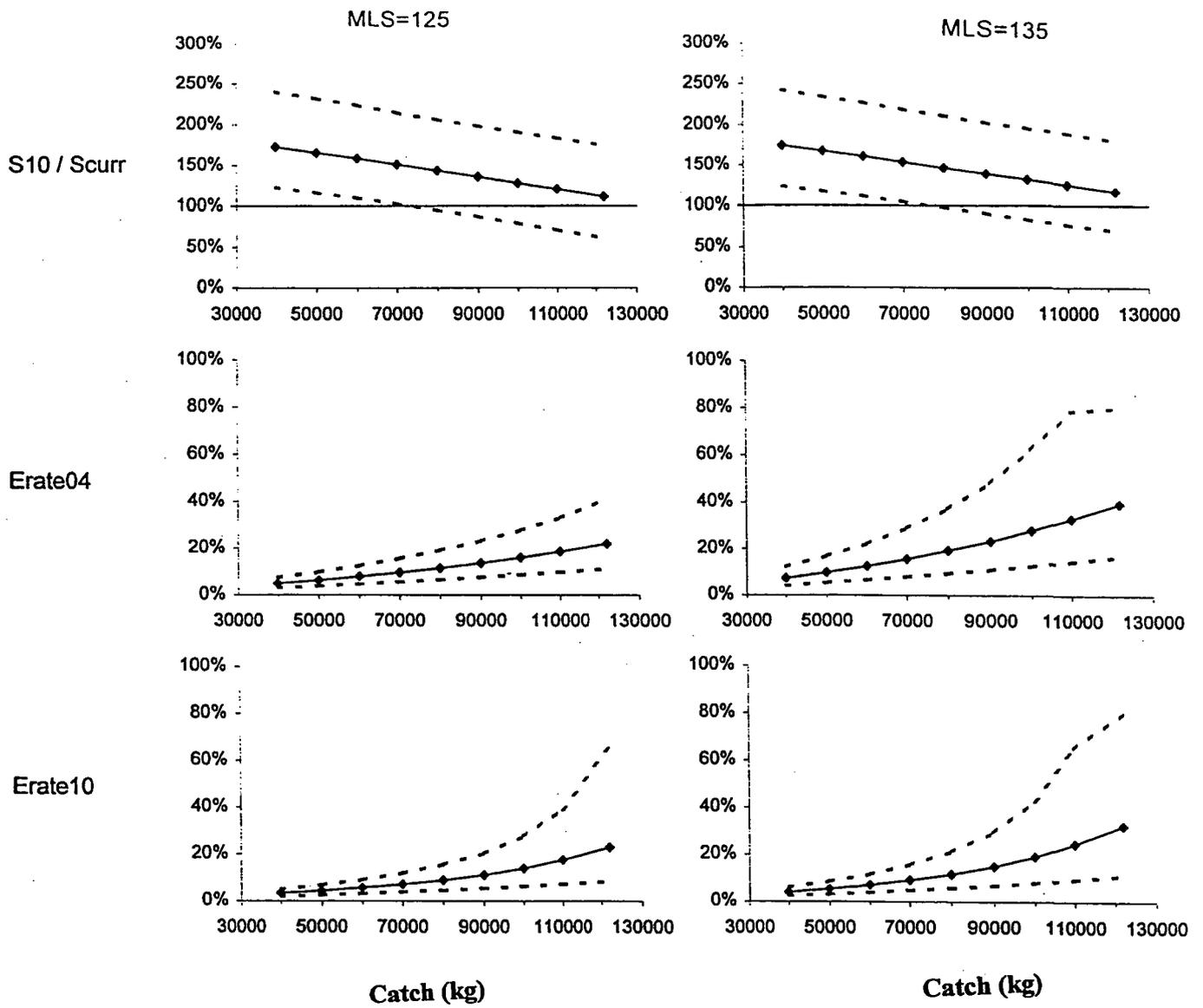


Figure 10 continued.

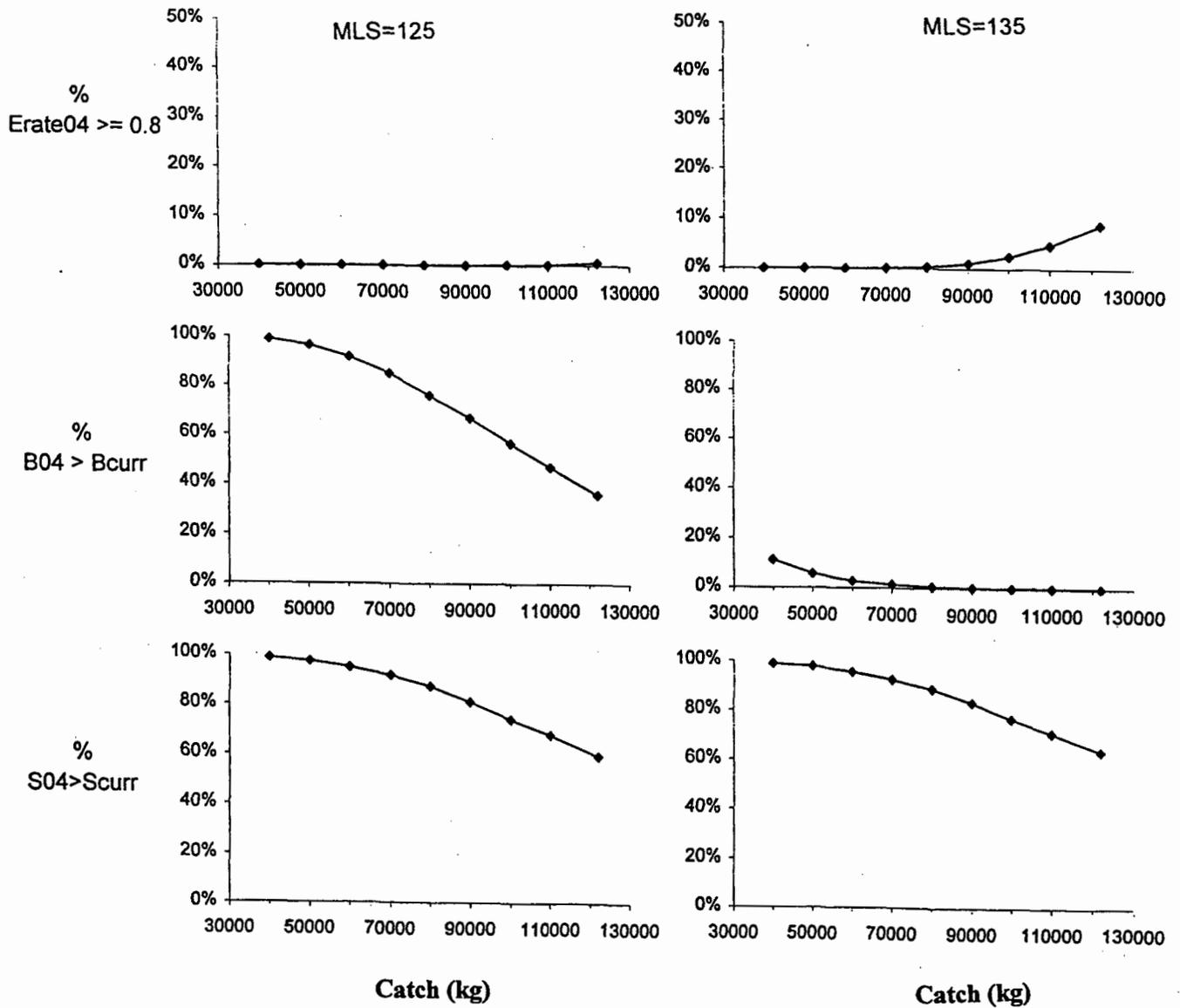


Figure 11. The percentage of 5000 runs in which exploitation rate in 2004 equalled or exceeded 80% (top row), in which recruited biomass increased from 2000 to 2004 (middle row), and in which spawning biomass increased between 2004 and 2004 (bottom row). Figures on the left are from runs with $MLS = 125$ mm; on the right with $MLS = 135$ mm.