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The 2013 stock assessment of paua (*Haliotis iris*) for PAU 3

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Contents

EXECUTIVE SUMMARY

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This report summarises the stock assessment for PAU 3 which includes fishery data up to the 2012–13 fishing year. The report describes the model structure and output, including current and projected stock status. The stock assessment is implemented as a length-based Bayesian estimation model, with point estimates of parameters based on the mode of the joint posterior distribution, and uncertainty of model estimates investigated using the marginal posterior distributions generated from Markov chain-Monte Carlo simulation.

The data fitted in the assessment model were: (1) a standardised CPUE series based on the early CELR data, (2) a standardised CPUE series based on recent PCELR data, (3) commercial catch sampling length frequency series (CSLF), and (4) maturity-at-length data.

Because growth data were not available from PAU 3, the growth parameters were fixed within the stock assessment model. MPD model runs were carried out with growth parameters and natural mortality (*M*) fixed at a combination of low, medium, and high values. These parameter settings were intended to incorporate the uncertainty in the estimate of stock status associated with key model assumptions. For the MPD models considered, estimated B_0 ranged from 1800 to 2900 t, and $B_{current}$ ranged from 21% to 66% of B_0. Models assuming a lower value of *M* (0.1) fitted most data poorly and models using a higher value of M (0.15 or 0.20) generally fitted data better. The differences in the fits to the observations are very minor between models with low, medium, and high values of growth.

The MCMC was carried out for a model in which the growth parameters were fixed at the medium values and *M* was estimated. This model was considered to be the base case model. The base case model estimated that B_0 was about 2670 t (2470–2960 t) and $B_{current}$ was about 52% (45–60%) of B_0. The base case model may not have encompassed the uncertainty in the estimate of stock status associated with the growth.

The model projection made for three years assuming current catch levels and using recruitments re-sampled from the recent model estimates, suggested that the spawning stock abundance will slightly decrease to about 51% (0.41–0.63) of B_0 over the next three years. The projection indicated that the probability of the spawning stock biomass being above the target (40% B_0) over the next three years is close to 100%.

This assessment considered a plausible range of productivity assumptions for the stock, and the model estimates suggested that that the stock status was relatively healthy and that the stock status is very unlikely to be below the soft (20%) and hard limits (10%). However, one major source of uncertainty of the assessment was that the history of the recreational catch was not well known and anecdotal evidence suggested that the actual recreational catch in recent years could be much higher than that used in the model. Better information on growth and non-commercial catch are needed to improve the estimates of the stock status.

1. INTRODUCTION

1.1 Overview

This report summarises the stock assessment for PAU 3 (Canterbury & Kaikoura, Figure 1) with the inclusion of data to the end of 2012–13 fishing year. The report describes the model structure and output, including current and projected stock status. The stock assessment is conducted with the length-based Bayesian estimation model first used in 1999 for PAU 5B (Breen et al. 2000a) with revisions made for subsequent assessments in PAU 5B (Breen et al. 2000b, Breen & Smith 2008, Fu 2014), PAU 4 (Breen & Kim 2004a), PAU 5A (Breen & Kim 2004b, Breen & Kim 2007, Fu & Mackenzie 2010a, b), PAU 5D (Breen et al. 2000a, Breen & Kim 2007, Fu 2013), PAU 7 (Andrew et al. 2000, Breen et al. 2001, Breen & Kim 2003, 2005, McKenzie & Smith 2009, Fu 2012). The model was published by Breen et al. (2003).

The four sets of data used in the assessment were: (1) a standardised CPUE series covering 1990–2001 based on CELR data (CPUE), (2) a standardised CPUE series covering 2002–2013 based on PCELR data (PCPUE), (3) A commercial catch sampling length frequency series (CSLF), and (4) maturity-at-length data. Catch history was an input to the model, encompassing commercial, recreational, customary, and illegal catch. Another document describes the datasets that are used in the stock assessment and the updates that were made for the previous assessment (Fu et al. 2014).

The growth data available for the PAU 3 assessment were collected from several sites in Banks Peninsula. Because most of the paua at these sites were stunted, incorporating these data in the assessment would under-estimate the growth for the whole stock. There were also some growth data from Cape Campbell (within PAU 7) which is close to the northern boundary of PAU 3, but the sample size was too small to be useful. Therefore no growth data were fitted within the stock assessment model and the growth parameters were assumed to be fixed in all model runs. Because no research diver surveys have been done in this area, survey abundance indices were not used in the assessment.

The assessment was made in several steps. First, the model was fitted to the data with parameters estimated at the mode of their joint posterior distribution (MPD) and sensitivity trials were explored by comparing MPD fits made with alternative model assumptions. Next, from the resulting fit, a base case was chosen and Markov chain-Monte Carlo (MCMC) simulations were made to obtain a large set of samples from the joint posterior distribution.

This document describes the model structure and assumptions, the fits to the data, estimates of parameters and indicators, and projection results. This report fulfils Objective 1 “Undertake a stock assessment for PAU 3, using a length-based Bayesian model” of the Ministry for Primary Industries project PAU201202.

1.2 Description of the fishery

The paua fishery was summarised by Schiel (1992), and in numerous previous assessment documents (e.g., Schiel 1989, McShane et al. 1994, 1996, Breen et al. 2000a, 2000b, 2001, Breen & Kim 2003, 2004a, 2004b, 2007). A summary of the PAU 3 fishery up to the 2012–13 fishing year is presented in Fu et al. (2014).

2. MODEL

This section gives an overview of the model used for the stock assessment of PAU 3 in 2013; for a full description see Breen et al. (2003). The model was developed for use in PAU 5B in 1999 and has been revised each year for subsequent assessments, in many cases echoing changes made to the rock lobster assessment model (Kim et al. 2004), which is a similar but more complex length-based Bayesian model. The last revision made to the model was in 2012 for the assessment of PAU 5D (Fu 2013).

2.1 Changes since the 2003 model

In the 2010 assessment for PAU 5A, Fu & McKenzie (2010a, 2010b) reported B_{init}; the spawning stock biomass at the end of the initialisation phase (the equilibrium biomass assuming that recruitment is equal to base recruitment and with no fishing), and B_0; the equilibrium spawning stock biomass assuming that recruitment is equal to the average recruitment from the period for which recruitment deviations were estimated (B_0 normally differs from B_{init}). In this assessment a constraint was placed on the recruitment deviations so that their average is 1 for the period in which they are estimated, based on the parameterisation of Bull et al (2012). This ensures that the average recruitment for the period in which they are estimated (1980–2008) is close to R_0, and as a result B_{init} will be close to B_0.

2.2 Model description

The model partitioned the paua stock into a single sex population, with length classes from 70 mm to 170 mm, in groups of 2 mm (i.e., from 70 to under 72 mm, 72 mm to under 74 mm, etc.). The largest length bin is well above the maximum size observed. The stock was assumed to reside in a single, homogeneous area. The partition accounted for numbers of paua by length class within an annual cycle, where movement between length classes was determined by the growth parameters. Paua entered the partition following recruitment and were removed by natural mortality and fishing mortality.

The model annual cycle was based on the fishing year. Note that model references to “year” within this paper refer to the fishing year, and are labelled as the most recent calendar year, i.e., the fishing year 1998–99 is referred to as “1999” throughout. References to calendar years are denoted specifically.

The models were run for the years 1965–2013. The model assumes one time step within an annual cycle. Catches were collated for 1974–2013, and were assumed to increase linearly between 1965 and 1973 from 0 to the 1974 catch level. Catches included commercial, recreational, customary, and illegal catch, and all catches occurred at the same time step.

Recruitment was assumed to take place at the beginning of the annual cycle, and length at recruitment was defined by a uniform distribution with a range between 70 and 80 mm. Recruitment deviations were assumed known and equal to 1 for the years up to 1980. This was ten years before the length data were available (loosely based on the approximate time taken for recruited paua to appear at the right hand end of the length distribution). The stock-recruitment relationship is unknown for paua, but is likely to be weak (Shepherd et al. 2001). A relationship may exist on small scales, but may not be apparent when large-scale data are modelled (Breen et al. 2003). No explicit stock-recruitment relationship has been modelled in previous paua assessments (Breen et al. 2000a, 2000b, Breen & Kim 2004a, 2004b, 2007, Breen & Smith 2008). For the more recent paua assessments (Fu 2012, 2013) the Shellfish Working Group suggested using a Beverton-Holt stock-recruitment relationship.

For this assessment, a Beverton-Holt stock-recruitment relationship with a steepness of 0.75 was assumed.

Maturity does not feature in the population partition. The model estimated proportions mature with the inclusion of length-at-maturity data. Growth was fixed in the model but natural mortalities were estimated .

The models used two selectivities: the commercial fishing selectivity and research diver survey selectivity — both assumed to follow a logistic curve (see later) and then remain constant.

The model is implemented in AD Model Builder™ (Otter Research Ltd., http://otter-rsch.com/admodel.htm) version 9.0.65, compiled with the MinGW 4.50 compiler.

The five sets of data fitted in the assessment model were: (1) a standardised CPUE series based on CELR data (2) a standardised CPUE series based on PCELR data (3) a commercial catch sampling length frequency series (4) tag-recapture length increment data and (5) maturity-at-length data (see Fu et al. 2014).

2.2.1 Estimated parameters

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

$\ln(R0)$	natural logarithm of base recruitment
M	instantaneous rate of natural mortality
g_1	expected annual growth increment at length L_1
g_2	expected annual growth increment at length L_2
ϕ	CV of the expected growth increment
α	parameter that defines the variance as a function of growth increment
β	parameter that defines the variance as a function of growth increment
$\Delta_{\max}$	maximum growth increment
l_{50}^{g}	length at which the annual increment is half the maximum
l_{95}^{g}	length at which the annual increment is 95% of the maximum
l_{95-50}^{g}	difference between l_{50}^{g} and l_{95}^{g}
q^{I}	scalar between recruited biomass and CPUE
q^{I_2}	scalar between recruited biomass and PCPUE
L_{50}	length at which maturity is 50%
L_{95-50}	interval between L_{50} and L_{95}
D_{50}	length at which commercial diver selectivity is 50%
D_{95-50}	difference between D_{50} and D_{95}
$\tilde{\sigma}$	common component of error
h	shape of CPUE *vs.* biomass relation
ε	vector of annual recruitment deviations, estimated from 1977 to 2013
H	steepness of the Beverton-Holt stock-recruitment relationship

2.2.2 Constants

l_k	length of a paua 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}	minimum standard deviation of the expected growth increment (assumed to be 1 mm)
σ_{obs}	standard deviation of the observation error around the growth increment (assumed to be 0.25 mm)
MLS_t	minimum legal size in year *t* (assumed to be 125 mm for all years)
$P_{k,t}$	a switch based on 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, taken from Schiel & Breen (1991) (2.592E-08 and 3.322 respectively, giving weight in kilograms)
w_k	the weight of an abalone at length l_k
ϖ^I	relative weight assigned to the CPUE dataset. This and the following relative weights were varied between runs to find a basecase with balanced residuals
ϖ^{I2}	relative weight assigned to the PCPUE dataset.
ϖ^s	relative weight assigned to CSLF dataset
ϖ^{mat}	relative weight assigned to maturity-at-length data
ϖ^{tag}	relative weight assigned to tag-recapture data
κ_t^s	normalised square root of the number of paua 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 of paua measured greater than 89 mm in RDLF records for each year, normalised by the lowest year
$U^{\max}$	exploitation rate above which a limiting function was invoked (0.80 for the base case)
μ_M	mean of the prior distribution for *M*, based on a literature review by Shepherd & Breen (1992)
σ_M	assumed standard deviation of the prior distribution for *M*
σ_ε	assumed standard deviation of recruitment deviations in log space (part of the prior for recruitment deviations)
n_ε	number of recruitment deviations
L_1	length associated with g_1 (75 mm)
L_2	length associated with g_2 (120 mm)

2.2.3 Observations

C_t	observed catch in year *t*
I_t	standardised CPUE in year *t*
$I2_t$	standardised PCPUE in year *t*
σ_t^I	standard deviation of the estimate of observed CPUE in year *t*, obtained from the standardisation model
cv_t^I	CV of the estimate of observed CPUE in year *t*, obtained from the standardisation model

σ_t^{I2}	standard deviation of the estimate of observed PCPUE in year *t*, obtained from the standardisation model
cv_t^{I2}	CV of the estimate of observed PCPUE in year *t*, obtained from the standardisation model
$p_{k,t}^s$	observed proportion in the k^{th} length class in year *t* in CSLF
l_j	initial length for the j^{th} tag-recapture record
d_j	observed length increment of the j^{th} tag-recapture record
Δt_j	time at liberty for the j^{th} tag-recapture record
p_k^{mat}	observed proportion mature in the k^{th} length class in the maturity dataset

2.2.4 Derived variables

$R0$	base number of annual recruits
$N_{k,t}$	number of paua in the k^{th} length class at the start of year *t*
$N_{k,t+0.5}$	number of paua in the k^{th} length class in the mid-season of year *t*
$R_{k,t}$	recruits to the model in the k^{th} length class in year *t*
g_k	expected annual growth increment for paua in the k^{th} length class
σ^{g_k}	standard deviation of the expected growth increment for paua in the k^{th} length class, used in calculating $\mathbf{G}$
$\mathbf{G}$	growth transition matrix
B_t	spawning stock biomass at the beginning of year *t*
$B_{t+0.5}$	spawning stock biomass in the mid-season of year *t*
B_0	equilibrium spawning stock biomass assuming no fishing and average recruitment from the period in which recruitment deviations were estimated.
B_{init}	spawning stock biomass at the end of initialisation phase (or B_{1964})
B_t^r	biomass of paua above the MLS at the beginning of year *t*
$B_{t+0.5}^r$	biomass of paua above the MLS in the mid-season of year *t*
B_0^r	equilibrium biomass of paua above the MLS assuming no fishing and average recruitment from the period in which recruitment deviations were estimated
B_{init}^r	biomass of paua above the MLS at the end of initialisation phase (or B_{1964}^r)
U_t	exploitation rate in year *t*
A_t	the complement of exploitation rate
$SF_{k,t}$	finite rate of survival from fishing for paua in the k^{th} length class in year *t*
V_k^r	relative selectivity of research divers for paua in the k^{th} length class
V_k^s	relative selectivity of commercial divers for paua in the k^{th} length class
$\sigma_{k,t}^s$	error of the predicted proportion in the k^{th} length class in year *t* in CSLF data
n_t^s	relative weight (effective sample size)of the CSLF data in year *t*
σ_j^d	standard deviation of the predicted length increment for the j^{th} tag-recapture record
σ_j^{tag}	total error predicted for the j^{th} tag-recapture record

σ_k^{mat}	error of the proportion mature-at-length for the k^{th} length class
$-\ln(\mathbf{L})$	negative log-likelihood
f	total function value

2.2.5 Predictions

$\hat{I}_t$	predicted CPUE in year t
$\hat{I}2_t$	predicted PCPUE in year t
$\hat{p}_{k,t}^{s}$	predicted proportion in the k^{th} length class in year t in commercial catch sampling
$\hat{d}_j$	predicted length increment of the j^{th} tag-recapture record
$\hat{p}_k^{mat}$	predicted proportion mature in the k^{th} length class

2.2.6 Initial conditions

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

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

(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) $$\Delta l_k = \left(\frac{L_2 g_1 - L_1 g_2}{g_1 - g_2} - l_k \right) \left[1 - \left(1 + \frac{g_1 - g_2}{L_1 - L_2} \right) \right]$$

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 $\left(1 + \frac{g_1 - g_2}{L_1 - L_2} \right)$ to remain positive. If the growth model is exponential (used for the base case), the expected annual growth increment for the k^{th} length class is:

(4) $$\Delta l_k = g_1 \left(g_2 / g_1 \right)^{(l_k - L_1)/(L_2 - L_1)}$$

again using posfun with a dummy penalty to ensure a positive expected increment at all lengths. If the inverse logistic growth model is used), the expected annual growth increment for the k^{th} length class is:

$$\Delta l_k = \frac{\Delta_{\max}}{\left(1+\exp\left(\ln(19)\left(\left(l_k - l_{50}^g\right)/\left(l_{95}^g - l_{50}^g\right)\right)\right)\right)} \tag{5}$$

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

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

Or a more complex functional form between the growth increment and its standard deviation can be defined as:

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

From the expected increment and standard deviation for each length class, the probability distribution of growth increments for a paua 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 $\mathbf{R_t}$:

$$\mathbf{N_t} = \left(\mathbf{N_{t-1}}\,e^{-M}\right) \bullet \mathbf{G} + \mathbf{R_t} \tag{8}$$

where the dot (•) denotes matrix multiplication.

2.2.7 Dynamics

2.2.7.1 Sequence of operations

After initialising, the first model year is 1965 and the model is run through to 2009. In 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.

2.2.7.2 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:

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

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

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

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

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

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

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

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

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

or

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

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

$$(16) \qquad \mathbf{N_t} = \left(\left(\mathbf{SF_{t-1}} \otimes \mathbf{N_{t-1}} \right) e^{-M} \right) \bullet \mathbf{G} + \mathbf{R_t}$$

where $\otimes$ denotes the element-by-element vector product. The vector of recruitment, $\mathbf{R_t}$, is determined from *R0*, estimated recruitment deviations, and the stock-recruitment relationship:

$$(17) \qquad R_{k,t} = 0.2R0e^{\left(\varepsilon_t - 0.5\sigma_t^2\right)} \frac{B_{t-1+0.5}}{B_0} \Bigg/ \left(1 - \frac{5H-1}{4H}\left(1 - \frac{B_{t-1+0.5}}{B_0}\right)\right) \qquad \text{for } 1 \le k \le 5$$

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

The recruitment deviation parameters ε_t were estimated for all years from 1980. The recruitment deviations were constrained to have a mean of 1 in arithmetic space.

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

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

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

$$(20) \qquad N_{k,t+0.5}^{vuln} = N_{k,t}\left(1 - \frac{\left(1-A_t\right)}{2} V_k^s\right).$$

Similarly,

$$(21) \qquad \hat{I}2_t = q^{I2}\left(B_{t+0.5}\right)^h = Xq^I\left(B_{t+0.5}\right)^h$$

The same shape parameter *h* is used for both the early and recent CPUE series: experimentation outside the model showed that this was appropriate despite the different units of measurement for the two series.

The model predicts proportions-at-length for the CSLF from numbers in each length class for lengths greater than 103 mm:

$$(22) \qquad \hat{p}_{k,t}^s = \frac{N_{k,t+0.5}^{vuln}}{\sum_{k=23}^{51} N_{k,t+0.5}^{vuln}} \qquad \text{for } 23 \le k < 51$$

The predicted increment for the *j*th tag-recapture record, using the linear model, is:

$$(23) \qquad \hat{d}_j = \left(\frac{\beta g_\alpha - \alpha g_\beta}{g_\alpha - g_\beta} - L_j\right)\left[1 - \left(1 + \frac{g_\alpha - g_\beta}{\alpha - \beta}\right)^{\Delta t_j}\right]$$

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

$$(24) \qquad \hat{d}_j = \Delta t_j g_\alpha \left(g_\beta / g_\alpha\right)^{\left(L_j - \alpha\right)/\left(\beta - \alpha\right)}$$

The error around an expected increment is:

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

Predicted maturity-at-length is:

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

2.2.8 Fitting

2.2.8.1 Likelihoods

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

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

Where

(28) $$\sigma_t^I = \sqrt{\log((cv_t^I)^2 + 1)}$$

and similarly for PCPUE:

(29) $$-\ln(\mathbf{L})\left(\hat{I}2_t \mid \theta\right) = \frac{\left(\ln\left(I2_t\right) - \ln\left(\hat{I}2_t\right)\right)^2}{2\left(\sigma_t^{I2} \tilde{\sigma} / \varpi^{I2}\right)^2} + \ln\left(\sigma_t^{I2} \tilde{\sigma} / \varpi^{I2}\right) + 0.5\ln\left(2\pi\right)$$

Where

(30) $$\sigma_t^{I2} = \sqrt{\log((cv_t^{I2})^2 + 1)}$$

The proportions-at-length from CSLF data are assumed to follow a multinomial distribution, with a standard deviation that depends on the effective sample size (see Section 2.2.9.3) and the weight assigned to the data:

(31) $$\sigma_{k,t}^s = \frac{\tilde{\sigma}}{\varpi^s n_t^s}$$

The negative log-likelihood is:

(32) $$-\ln(\mathrm{L})\left(\hat{p}_{k,t}^s \mid \theta\right) = \frac{p_{s,t}^s}{\sigma_{k,t}^s}\left(\ln\left(p_{k,t}^s + 0.01\right) - \ln\left(\hat{p}_{k,t}^s + 0.01\right)\right)$$

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 (25)), observation error, and weight assigned to the data:

(33) $$\sigma_j^{tag} = \tilde{\sigma} / \varpi^{tag} \sqrt{\sigma_{obs}{}^2 + \left(\sigma_j{}^d\right)^2}$$

and the negative log-likelihood is:

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

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

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

The negative log-likelihood is:

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

2.2.8.2 Normalised residuals

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

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

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

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

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:

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

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

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

2.2.8.3 Priors and bounds

Bayesian priors were established for all estimated parameters (Table 1). Most were incorporated simply as uniform distributions with upper and lower bounds set arbitrarily 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:

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

The prior probability density for the vector of estimated recruitment deviations ε , was assumed to be normal with a mean of zero and a standard deviation of 0.4. The contribution to the objective function for the whole vector is:

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

Constant parameters are given in Table 2**Error! Reference source not found.**

2.2.8.4 Penalty

A penalty is applied to exploitation rates higher than the assumed maximum (equation 12); it is added to the objective function after being multiplied by an arbitrary weight (1E6) determined by experiment.

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

2.2.8.5 Dataset weights

Proportions at length (CSLF) were included in the model with a multinomial likelihood. The length frequencies for individual years were assigned relative weights (effective sample size), based on a sample size that represented the best least squares fit of log(cv_i)~log(P_i), where cv_i was the bootstrap CV for the *i*th proportion, P_i.. The weights for individual years (n_t^s for CSLF) were multiplied by the weight assigned to the dataset (ϖ_s for CSLF) to obtain the model weights for the observations.

In previous assessments, the weight of the dataset was determined iteratively so that the standardised deviation of the normalised residuals was close to one. In this assessment, we used an alternative weighting scheme following Francis (2011), where the weight for the CSLF dataset was determined as

(43) $$\varpi^s = 1/\operatorname{var}_t\left[\left(\overline{O}_t^s - \overline{E}_t^s\right)/\left(v_t^s / n_t^s\right)^{0.5}\right]$$ (Method TA1.8, table A1 in Francis 2011)

Where

(44) $\overline{O}_t^s = \sum_k p_{k,t}^s l_k$

(45) $\overline{E}_t^s = \sum_k \hat{p}_{k,t}^s l_k$

(46) $v_t^s = \sum_k (l_k)^2 \hat{p}_{k,t}^s - \left(\overline{E}_t^s\right)^2$

This weighting method allows for the possibility of substantial correlations within a dataset, and generally produces relatively smaller sample size, thus down-weighting the composition data (Francis 2011). The actual and estimated sample sizes for the commercial catch proportions at length are given in Table 3.

The relative abundance indices (CPUE) were included in the model with a lognormal likelihood. The weights for individual years were determined from associated CVs (usually calculated from the standardisation model) and were scaled by the weight assigned to the dataset to obtain the model weights for the observations. The most recent stock assessment of PAU 5B (2014) used a weighting scheme recommended by Francis (2011) in which a series of lowess lines of various degrees of smoothing were fitted to the abundance indices, and CV of the residuals from the lowess line which is considered to have the "appropriate" smoothness is used. However, this method cannot be applied here because both the early and recent CPUE indices in PAU 3 have shown a smooth and flat trend and fitting a lowess line to these indices gives a very small CV (less than 0.01) for the residuals. For this assessment it was decided to fix the CVs of both CPUE series at 0.1.

2.2.9 Fishery indicators

The assessment calculates the following quantities from their posterior distributions: the model's mid-season spawning and recruited biomass for 2013 ($B_{current}$ and $B^r_{current}$) and for the projection period (B_{proj} and B^r_{proj}).

Simulations were carried out to calculate deterministic MSY: maximum constant annual catch that can be sustained under deterministic recruitment. A single simulation run was done by starting from an unfished equilibrium state, and running under a constant exploitation rate until the catch and spawning stock biomass stabilised. For each simulation run with exploitation rate *U*, the equilibrium total annual catch and spawning stock biomass were calculated. The exploitation rate *U* that maximizes the annual catch is U_{msy}. The corresponding catch is MSY, and the corresponding SSB is B_{msy}. Together with B_o, B_{msy}, $U_{current}$, $U_{\%40B0}$ and U_{msy} the current and projected stock status is reported in relation to the following indicators:

$\%B_0$	current and projected spawning biomass as a percent of B_0
$\%B_{msy}$	current and projected spawning biomass as a percent of B_{msy}
$\Pr(> B_{current})$	Probability that projected spawning biomass is greater than $B_{current}$
$\Pr(> B_{msy})$	Probability that current and projected spawning biomass is greater than B_{msy}
$\%B^r_0$	current and projected recruited biomass as a percent of B^r_0
$\%B^r_{msy}$	current and projected recruited biomass as a percent of B^r_{msy}

$\Pr(> B^r_{msy})$ Probability that current and projected recruit-sized biomass is greater than B^r_{msy}

$\Pr(> B^r_{current})$ Probability that projected recruit-sized biomass is greater than $B^r_{current}$

$\Pr(B_{proj} > 40\% B_0)$ Probability that current and projected spawning biomass is greater than 40% B_0

$\Pr(B_{proj} < 20\% B_{msy})$ Probability that current and projected spawning biomass less than 20% B_0

$\Pr(B_{proj} < 10\% B_{msy})$ Probability that current and projected spawning biomass less than 10% B_0

$\Pr(U_{proj} > U_{40\%B0})$ Probability that current and projected exploitation rate greater than $U_{40\%B0}$

2.2.10 Markov chain-Monte Carlo (MCMC) procedures

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

For the MCMCs in this assessment single long chains were run, starting at the MPD estimate. The base case was 5 million simulations long and samples were saved, regularly spaced by 5000. The value of $\tilde{\sigma}$ was fixed to that used in the MPD run because it may be inappropriate to let a variance component change during the MCMC.

2.2.11 Development of model runs

After initial discussions of input data and exploratory analyses, the Shellfish WG decided on a set of model runs in which growth and natural mortality were fixed at a combination of values. The fixed growth parameters considered were low (g_1=*15* mm, g_2=*4.5 mm*), medium (g_1=*20 mm*, g_2=*6 mm*), and high (g_1=*25* mm, g_2=*7.5 mm*). The medium values were based on the estimates of growth using the tag-recapture data from Cape Campbell (see Fu 2014). The low and high values were loosely based on the range of growth estimates from assessments of other paua stocks. An exponential growth curve with a CV of 0.45 was used to generate the growth transition matrix (see Section 2.1.6.3). Natural mortality was fixed at three levels: 0.1, 0.15, and 0.2. These values were considered to have covered the plausible range of natural mortality for paua. Nine model runs were carried out, each corresponding to a combination of low, medium, or high values of growth and natural mortality rates (Table 4).

These parameter settings were selected to evaluate the sensitivity of model results to key productivity assumptions and to incorporate uncertainty into the estimates of stock status. Each parameter setting was considered as an equally likely scenario and each model run was assessed through the fits to the observational data.

All models were fitted to the two CPUE series, CSLF, and maturity data. The CPUE shape parameter was fixed at 1 assuming a linear relationship between CPUE and abundance. The sample sizes of the CSLF data were determined using the TA1.8 method (Francis 2011) and were generally less than 1% of the actual number of fish measured in the sample (Table 3). This was expected as this method accounted for the potential correlations in the proportion-at-length data. The CV for both the early and recent CPUE was fixed at 0.1.

The recruitment deviations were estimated for the years 1980–2008. In assessments of other paua stocks, the recruitment deviation was usually estimated up to 10 years before the first length frequency data were available (based on the growth rates of paua). For PAU 3, the commercial catch length frequency series started in 2000, suggesting that an appropriate period for estimating recruitment deviation is from 1990 onwards. However, preliminary model runs showed that the model was unable to fit the CPUE indices unless the recruitment deviations were estimated a few years before the inception of the early CPUE series. It was therefore decided that recruitment deviations should be estimated for the years 1980–2008.

An MCMC model run was also specified by the SFWG and was subsequently chosen to be the base case (model 6.3). The base case estimated M within the model (with a lognormal prior with a mean of 0.1) but fixed the growth parameters at the medium value (g_1=20 mm, g_2=6 mm). Initially, we attempted to estimate growth within the model, but the posterior samples from the MCMC did not converge. Therefore the MCMC run has only incorporated uncertainty associated with natural mortality.

3. RESULTS

3.1 MPD results

Model estimates of objective function values (negative log-likelihood), parameters, and indicators for the nine MPD model runs are given in Table 5, and fits to the CSLF and CPUE data are shown in Figure 2–Figure **7**.

When *M* was fixed at 0.1, the three models (low, medium, or high growth) fitted the CSLF data poorly (Figure 2). These models tended to underestimate the mode of the distribution and predicted many more large-sized paua than were observed. The fits to the early CPUE were not ideal: all three models predicted a decreasing trend as opposed to an overall flat trend in the observed CPUE (Figure 3–left). The fits to the recent CPUE were reasonable and all models predicted a slight decreasing trend similar to that in observed indices (Figure 3–right).

When M was fixed at 0.15, the fits to the CSLF data improved markedly (Figure 4), although they missed the mode of the distribution for the first few years. It was difficult to compare models with high, medium, or low growth as they appeared to have fitted the CSLF data equally well. These models also fitted the early CPUE much better (Figure 5– left) than the models with a lower M*,* but the fits to the recent CPUE were similar (Figure 5– right).

When *M* was fixed at 0.2, the fits to the CSLF data appeared to have improved further compared to models with *M* fixed at 0.15, but the difference was minor (Figure 6). There is also some small improvement in the fits to the early CPUE (Figure 7–left). The fits to the recent CPUE are similar to the other models with lower M (Figure 7–right). Again it was difficult to distinguish models with high, medium, or low growth.

The (negative log) likelihood from fits to the CSLF and the early CPUE improved (decreased) markedly when *M* increased from 0.1 to 0.15 and improved marginally when *M* increased from 0.15 to 0.2 (see Table 5). This was true for models with high, medium, or low growth. There were only very minor changes in likelihood values for the recent CPUE. The differences in likelihood between models with high, medium or low growth were very small, although it appeared that models with slow growth were generally preferred.

The profile likelihood on *M* suggested that the model has a strong preference on higher values of *M* when *M* is less than 0.15, and the likelihood function values were sensitive to *M* within this range, particularly for the CSLF and the early CPUE data (Figure 8). When *M* is greater than 0.15, the improvement in fits as *M* increases is very small. Further investigation using profile likelihood on the two growth parameters showed that model results are more sensitive to parameter g_2 than g_1. However, for the range of values of g2 considered in the assessment, the difference was not obvious although smaller values (slower growth) tend to lead to better objective function values.

The estimates of recruitment deviations showed similar patterns among all the model runs: the recruitment was much lower than the long term average before 1990, and was higher between 1990 and 2008 (Figure 9). The estimates of the recruitment deviations were strongly influenced by the early CPUE series.

For the nine model runs, B_0 ranged from 1500 t to 2900 t, and $B_{current}$ ranged from 21% to 66% of B_0. All model runs showed an overall deceasing trend in spawning stock biomass and the decrease has become much slower in recent years (Figures 10 & 11). In general, a combination of higher M and faster growth resulted in lower estimates of initial and current biomass (as indicative of a more productive stock), and a combination of lower M and slower growth led to higher estimates of initial and current biomass (Table 5).

3.2 MCMC results

A base case model was chosen for MCMC simulations. The base case fixed growth at the medium (g_1=*20 mm*, g_2=*6 mm*) but estimated M with a lognormal prior with a mean of 0.1 (the same prior adopted in assessments of other paua stocks). The main diagnostic used for the MCMC was the trace plots of the posterior samples for estimated parameters. The traces show good mixing and there is no evidence of non-convergence (Figure 12).

The posterior distributions for estimated parameters and biomass indicators are summarised in Table 6 for the base case. The posterior of M has a medium of 0.14 with a 90% credible interval between 0.12 and 0.15. The posterior medium was higher than that of the prior but the breadth of both distributions were very similar (Figure 13). This suggested that the estimate of M was influenced by both the observations and the prior.

The estimates of recruitment deviations showed a period of relatively low recruitment between 1980 the 1990 and recruitment in recent years (after 2002) was above the long term average (Figure 14–left). Exploitation rates showed a gradual upward trend since the 2000s (Figure 14–right), and the estimated exploitation rate in 2013 was about 0.16 (0.09–0.14).

The posterior distributions of spawning stock biomass showed a gradual declining trend (Figure 15), and estimated B_0 was about 2670 t (2470–2960t) and $B_{current}$ was about 52% (45–60%) of B_0 (Table 6). However, the base case model was most likely to have underestimated the uncertainly in biomass because the growth parameters were fixed.

The model projection made for three years assuming current catch levels and using recruitments re-sampled from the recent model estimates, suggested that the spawning stock abundance will slightly decrease to about 51% (0.41–0.63) of B_0 over the next three years (Table 7). The projection indicated that the probability of the spawning stock biomass being above the target (40% B_0) over the next three years is close to 100%.

4. DISCUSSION

This report assesses PAU 3 and includes fishery data up until the 2012–13 fishing year. The base model fitted the two CPUE series and the CSLF data, and estimated that the current stock status was about 52% B_0 and that it was very unlikely that the stock will fall below the soft or hard limits. However, the base case model was most likely to have underestimated the uncertainly in biomass because growth was fixed. Uncertainly in stock status is perhaps better captured by the sets of MPD model runs in which parameter settings corresponding to various levels of stock productivity have been assumed. Estimated $B_{current}$ from the sets of MPD model runs ranged from 21% to 66% of B_0 .

Because there is lack of information on growth and natural mortality, growth rates and *M* were fixed at a combination of high, medium, and low values. When *M* was fixed at 0.1, the models fitted the CSLF and CPUE data poorly. Model fits improved markedly when *M* was increased to 0.15 or 0.20, suggesting that a higher *M* was better supported by the data. The SFWG believed that an *M* of 0.2 is probably too high for paua, and an *M* of 0.15 is more credible. Model fits to the observations did not provide a clear distinction among possibilities of low, medium, or high growth rates, although models assuming slower growth had slightly better objective function values. The estimate of stock depletion was rather sensitive to the assumed value of growth parameters, therefore collection of reliable growth information will be important for future assessment of the stock.

The assessment used CPUE as an index of abundance. The assumption that CPUE indexes abundance is questionable. The literature on abalone suggests that CPUE is difficult to use in abalone stock assessments because of serial depletion. This can happen when fishers can deplete unfished or lightly fished beds and maintain their catch rates by moving to new areas, thus CPUE stays high while the biomass is actually decreasing. In PAU 3, both the early and recent CPUE indices have shown a relatively flat trend (the recent CPUE decreased slightly). It was unknown that to what extent the CPUE series tracked stock abundance in PAU 3. Information from commercial fishers indicated that the stock is in relatively good shape, suggesting that the trend in CPUE series may be credible.

Even if the CPUE indices are credible, they are not very useful in informing estimates of B_0 in this case because they have shown a relatively flat trend. Therefore the catch sampling length frequencies are the most important observations that provide information on the initial size of the stock. The catch sampling coverage in PAU 3 is considered to be reasonably adequate and the CSLF data are likely to have been representative of the stock.

Another source of uncertainty is the catch data. The commercial catch is known with accuracy since 1985, but is probably not well estimated before that. In addition, non-commercial catch estimates are poorly determined. The estimate of illegal catch is uncertain. Anecdotal evidence suggests that the recreational catch in PAU 3 is very likely to have increased substantially in recent years and could be much higher than was assumed in the model. However, the increase in non-commercial catch (if it is true) was not reflected in the recent CPUE indices, which showed an almost flat trend. One possible reason is that the commercial divers may have fished deeper than recreational fishers, and could be fishing on different sectors of the population. If there is substantial bias in estimates of catches, the model could significantly under-estimate the level of stock depletion. Therefore better information on the scale and trend in recreational catch needs to be collated for more accurate assessment of the stock status.

Another source of uncertainty is that fishing may cause spatial contraction of populations (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..

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Table 1: Base case model specifications: for estimated parameters, the phase of estimation, type of prior, (U, uniform; N, normal; LN, lognormal), mean and CV of the prior, lower bound and upper bound. The three growth parameters g_1, g_2, and φ were fixed in this assessment (phase = -1).

Parameter	Phase	Prior	μ	CV	Bounds	
					Lower	Upper
ln($R0$)	1	U	–	–	5	50
M	3	LN	0.1	0.35	0.01	0.5
g_1	-1	U	–	–	1	50
g_2	-1	U	–	–	0.01	50
φ	-1	U	–	–	0.001	1
$Ln(q^I)$	1	U	–	–	-30	0
$Ln(q^J)$	1	U	–	–	-30	0
L_{50}	1	U	–	–	70	145
$L_{95\text{-}50}$	1	U	–	–	1	50
D_{50}	2	U	–	–	70	145
$D_{95\text{-}50}$	2	U	–	–	0.01	50
ε	1	N	0	0.4	-2.3	2.3

Table 2: Values for fixed quantities for base case model.

Variable	Value
L_1	75
L_2	120
A	2.99E-08
B	3.303
U^{max}	0.80
σ_{min}	1
σ_{obs}	0.25
$\tilde{\sigma}$	0.2
H	0.75

Table 3: Actual sample sizes, initial sample sizes determined for the multinomial likelihood, and model weighted sample sizes for the PAU 3 commercial catch sampling length frequencies from base case model.

Fishing year	Actual sample size	Initial sample size	Model 6.1 sample size
2000	6 532	1 443	361
2002	6 892	1 351	338
2003	7 480	1 532	383
2004	4 787	864	216
2005	4 386	987	247
2006	4 268	1 186	297
2007	2 029	342	86
2008	5 306	1 347	337
2009	6 368	1 706	427
2010	8 021	2 021	505
2011	8 234	1 888	472
2012	9 617	2 117	529

Table 4: Summary descriptions for MPD (3.1, 3.2, 3.3, 4.1, 4.2, 4.3, 4.4, 5.1, 5.2, and 5.3) and MCMC (6.1, base case) model runs.

Model	Description
3.1	M fixed at 0.10 (low), g_1 fixed at 25 mm and g_2 fixed at 7.5 mm
3.2	M fixed at 0.10, g_1 fixed at 20 mm and g_2 fixed at 6 mm
3.3	M fixed at 0.10, g_1 fixed at 15 mm and g_2 fixed at 4.5 mm
4.1	M fixed at 0.15, g_1 fixed at 25 mm and g_2 fixed at 7.5 mm
4.2	M fixed at 0.15, g_1 fixed at 20 mm and g_2 fixed at 6 mm
4.3	M fixed at 0.15, g_1 fixed at 15 mm and g_2 fixed at 4.5 mm
5.1	M fixed at 0.20, g_1 fixed at 25 mm and g_2 fixed at 7.5 mm
5.2	M fixed at 0.20, g_1 fixed at 20 mm and g_2 fixed at 6 mm
5.3	M fixed at 0.20, g_1 fixed at 15 mm and g_2 fixed at 4.5 mm
6.1	Estimated M, g_1 fixed at 20 mm and g_2 fixed at 6 mm

Table 5: MPD estimates for models 3.1–3.3, 4.1–4.3, and 5.1–5.3. Red indicates parameter fixed and likelihood contributions not used when datasets were removed.

Model runs	3.1	3.2	3.1	4.4	4.2	4.3	5.1	5.2	5.3
Likelihoods									
CPUE	2.4	-0.9	-7.5	-12.5	-13.3	-14.0	-15.9	-15.9	-15.9
PCPUE	-20.4	-21.2	-22.0	-22.0	-22.7	-22.8	-22.6	-23.0	-23.0
CSLF	36.0	26.8	15.2	12.6	10.4	8.9	8.5	7.9	7.5
Tags	26.4	24.3	26.4	26.4	24.3	25.6	26.4	24.3	25.6
Maturity	-30.1	-30.1	-30.1	-30.1	-30.1	-30.1	-30.1	-30.1	-30.1
Prior on M	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Prior on ε	22.7	16.2	7.3	12.9	8.3	4.3	6.0	3.6	1.8
U penalty	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ε penalty	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	37.1	15.3	-10.7	-12.6	-23.0	-28.2	-27.6	-33.2	-34.2
Parameters									
ln(R0)	13.2	13.4	13.8	13.6	13.8	14.2	13.8	14.2	14.8
M	0.10	0.10	0.10	0.15	0.15	0.15	0.20	0.20	0.20
T50	82.0	82.0	82.1	82.0	82.1	82.1	82.1	82.1	82.1
T95-50	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2	20.2
D50	123.1	123.3	123.7	124.0	124.3	124.5	124.4	124.7	124.879
D95-50	3.8	4.0	4.4	4.7	4.9	5.1	5.2	5.4	5.4
ln(qI)	-13.3	-13.4	-13.8	-12.9	-13.1	-13.5	-12.7	-13.0	-13.5
ln(qI2)	-12.9	-13.1	-13.6	-12.6	-12.9	-13.3	-12.5	-12.9	-13.4
gα	25.0	20.0	15.0	25.0	20.0	15.0	25.0	20.0	15.0
gβ	7.50	6.00	4.00	7.50	6.00	4.50	7.50	6.00	4.5
φ	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Indicators	3.1	3.2	3.3	4.4	4.2	4.3	5.1	5.2	5.3
B_0	2344	2460	2916	1795	1965	2452	1497	1767	2594
$B_{current}$	488	672	1231	474	718	1262	520	848	1708
$B_{current}/B_0$	0.21	0.27	0.42	0.26	0.37	0.51	0.35	0.48	0.66
$rB0$	2118	2119	2215	1514	1523	1632	1168	1215	1423
$rB_{current}$	310	384	628	242	327	509	235	340	592
$rB_{current}/rB_0$	0.15	0.18	0.28	0.16	0.21	0.31	0.20	0.28	0.42
$U_{current}$	0.32	0.26	0.17	0.39	0.30	0.21	0.40	0.30	0.18

Table 6: Summary of the marginal posterior distributions from the MCMC chain from the base case (6.1). The columns show the minimum values observed in the 1000 samples, the maxima, the 5th and 95th percentiles, and the mediums. Biomass is in tonnes.

	Min	5%	Medium	95%	Max
Parameters					
f	-20.8	-15.0	-8.8	-1.1	12.0
ln($R0$)	13.8	14.0	14.1	14.3	14.6
M	0.109	0.120	0.135	0.153	0.172
D_{50}	121.9	123.1	124.0	125.1	126.1
D_{95-50}	2.3	3.3	5.1	6.8	10.3
L_{50}	78.3	79.9	81.9	83.6	84.6
L_{95-50}	14.1	16.8	20.8	25.3	30.4
ln(q^I)	-14.2	-14.0	-13.7	-13.5	-13.3
ln(q^{II})	-14.1	-13.9	-13.6	-13.3	-13.1
Indicators					
B_0	2 289	2 470	2 666	2 957	3 311
$B_{current}$	984	1 133	1 390	1 727	2 277
$B_{current}/B_0$	0.40	0.45	0.52	0.60	0.72
B_0^r	1 518	1 700	1 880	2 100	2 431
$B_{current}^r$	393	502	657	874	1130
$B_{current}^r/B_0^r$	0.22	0.28	0.35	0.43	0.54
$U_{current}$	0.10	0.12	0.16	0.21	0.26

Table 7: Summary of current and projected indicators for the base case with future commercial catch set to current TACC: biomass as a percentage of the virgin and current stock status, for spawning stock and recruit-sized biomass. $B_{()}$ **(current or projected biomass),** $U_{()}$ **(current or projected exploitation rate).**

	2013	2014	2015	2016
B_t	1408 (1116–1848)	1390 (1088–1858)	1379 (1067–1855)	1371 (1041–1847)
B_t%B_0	0.525 (0.445–0.623)	0.520 (0.439–0.620)	0.515 (0.429–0.620)	0.513 (0.412–0.631)
B_t%B_{msy}	1.88 (1.61–2.19)	1.87 (1.58–2.18)	1.85 (1.55–2.20)	1.84 (1.49–2.24)
Pr(>B_{msy})	1.00	1.00	1.00	1.00
Pr(>$B_{current}$)	–	0.35	0.32	0.32
Pr(>40%B_0)	1.00	1.00	0.99	0.99
Pr(<20%B_0)	0.00	0.00	0.00	0.00
Pr(<10%B_0)	0.00	0.00	0.00	0.00
rB_t	675 (500–970)	657 (481–946)	643 (462–926)	626 (443–915)
%rB_0	0.359 (0.281–0.462)	0.349 (0.267–0.455)	0.341 (0.252–0.446)	0.332 (0.241–0.439)
%rB_{msy}	5.31 (3.08–10.42)	5.17 (2.95–10.45)	5.04 (2.83–10.35)	4.91 (2.73–10.19)
Pr(>rB_{msy})	1.00	1.00	1.00	1.00
Pr(>r$B_{current}$)	–	0.12	0.09	0.05
Pr(U_{proj}>$U_{40\%B0}$)	0.02	0.03	0.04	0.05

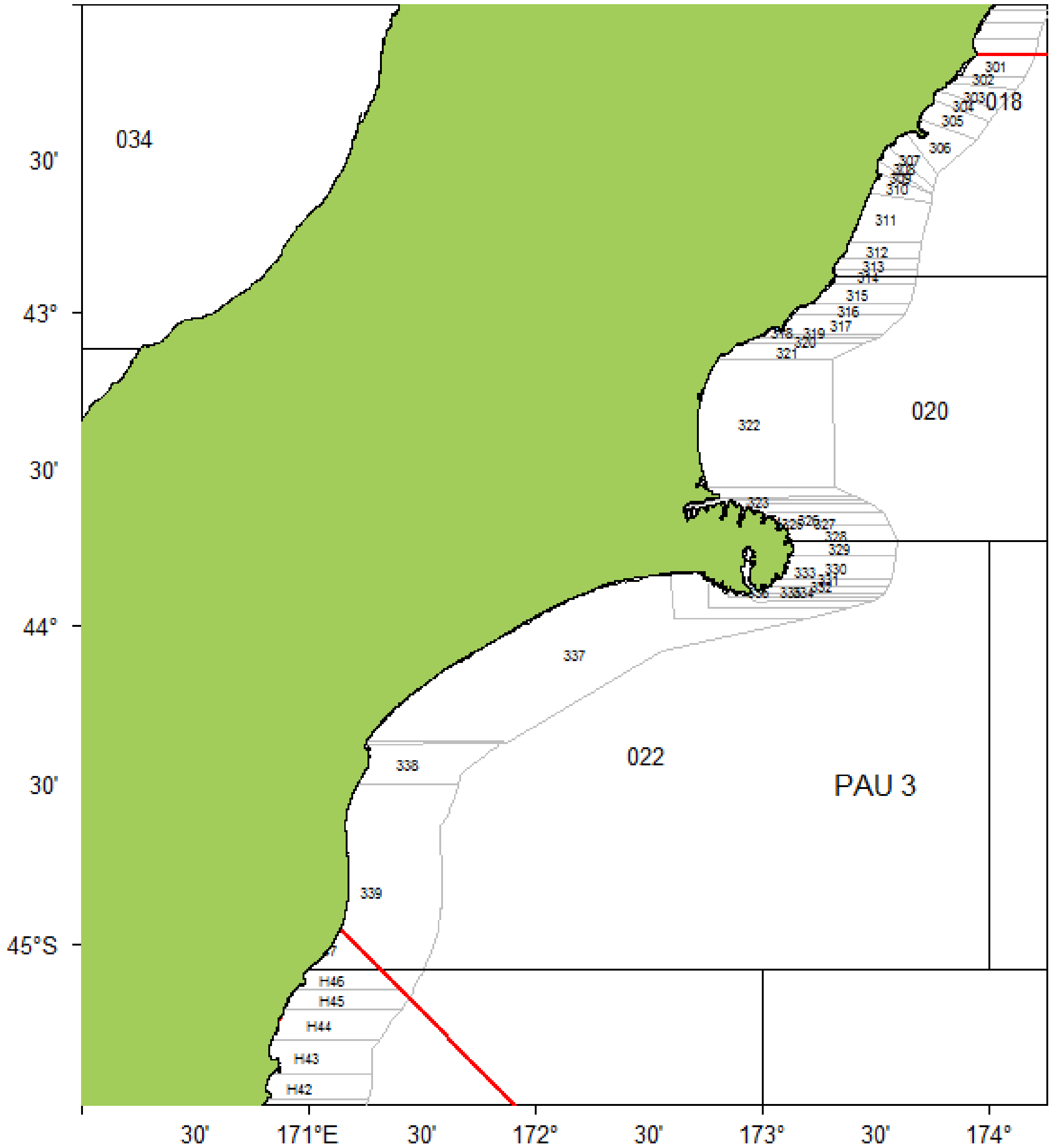

Figure 1: Map of PAU 3 showing the boundaries of the general statistical areas.

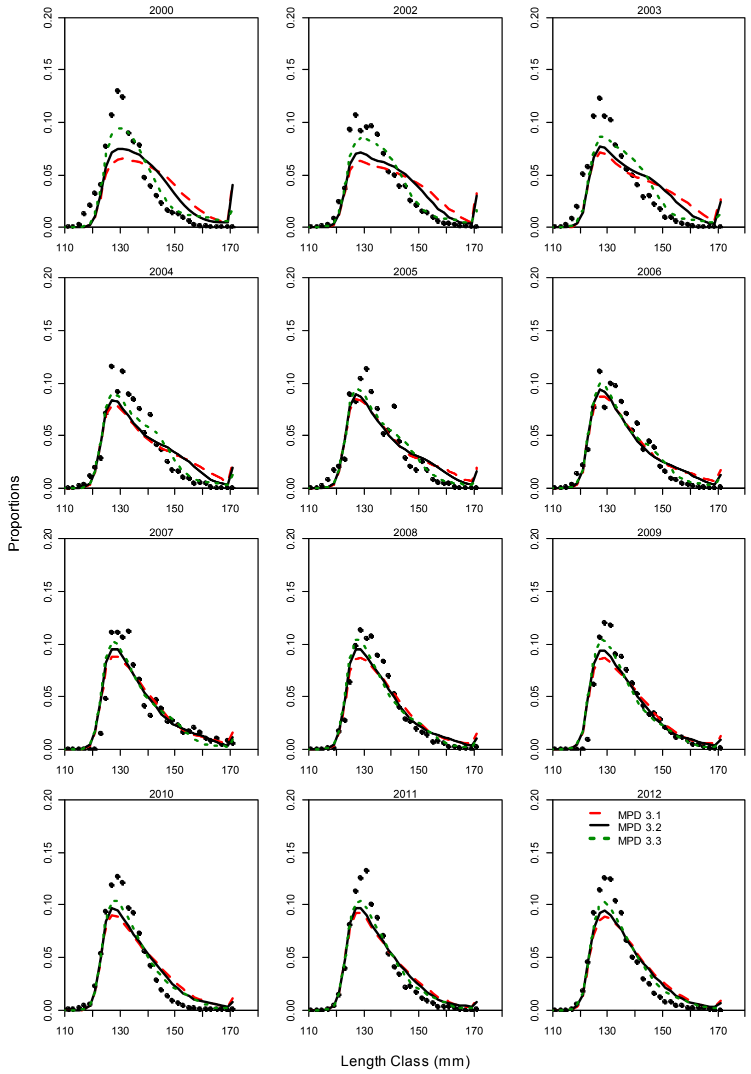

Figure 2: MPD fits to the CSLF data for models 3.1, 3.2, and 3.3.

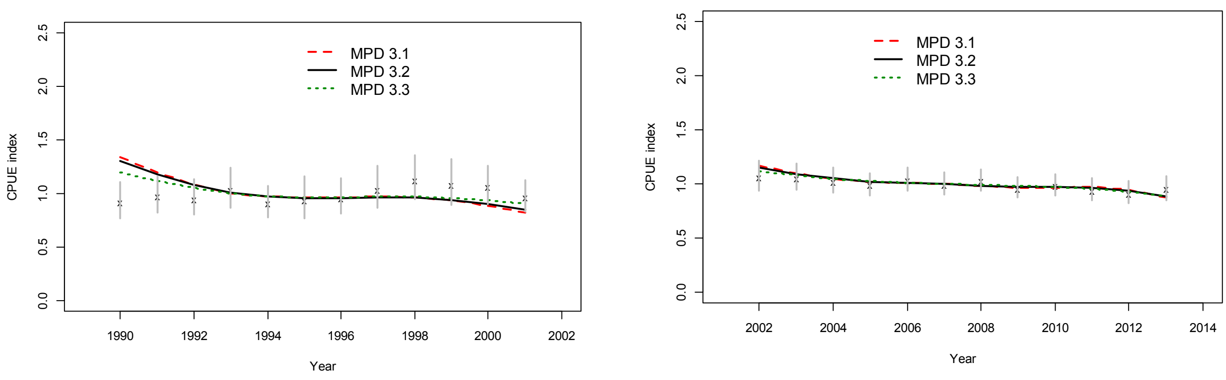

Figure 3: MPD fits to the CPUE indices (left) and PCPUE indices (right), for the models 3.1, 3.2, and 3.3.

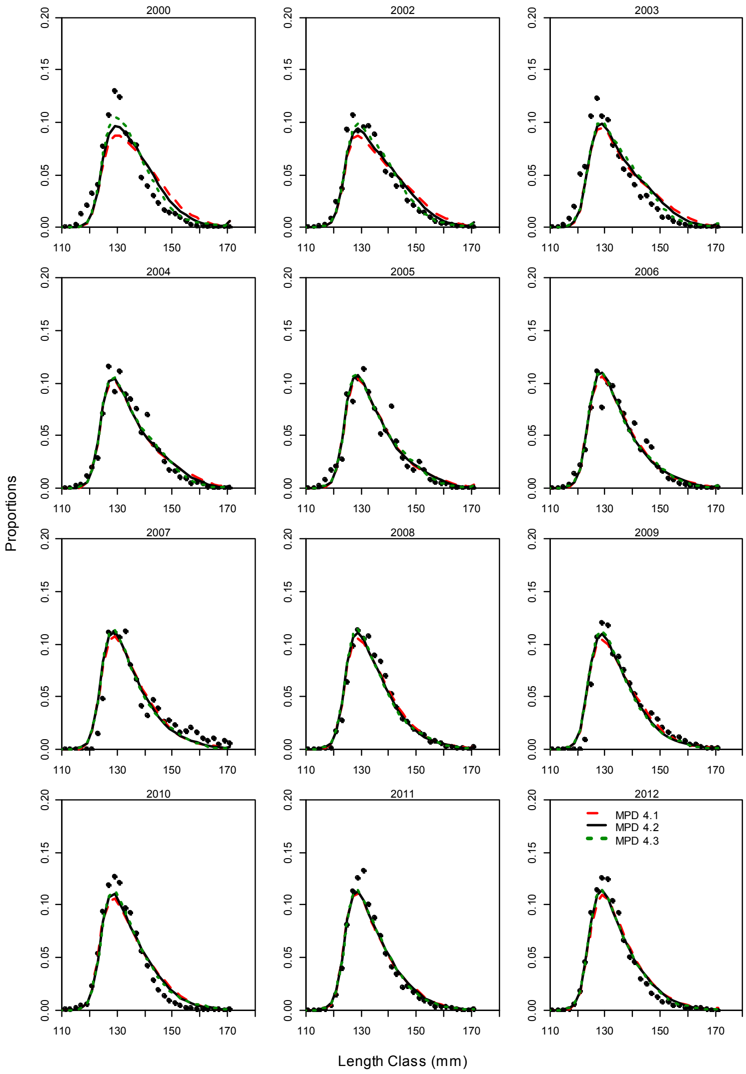

Figure 4: MPD fits to the CSLF data for models 4.1, 4.2, and 4.3.

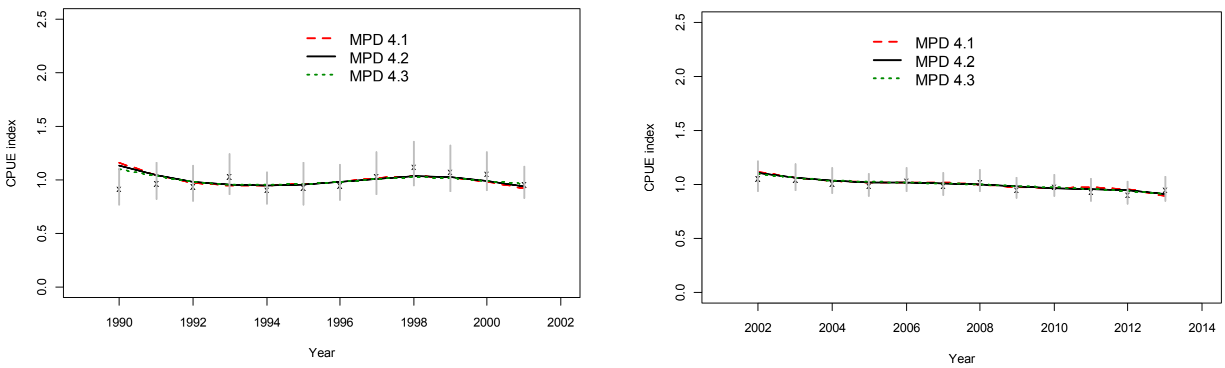

Figure 5: MPD fits to the CPUE indices (left) and PCPUE indices (right), for the models 4.1, 4.2, and 4.3.

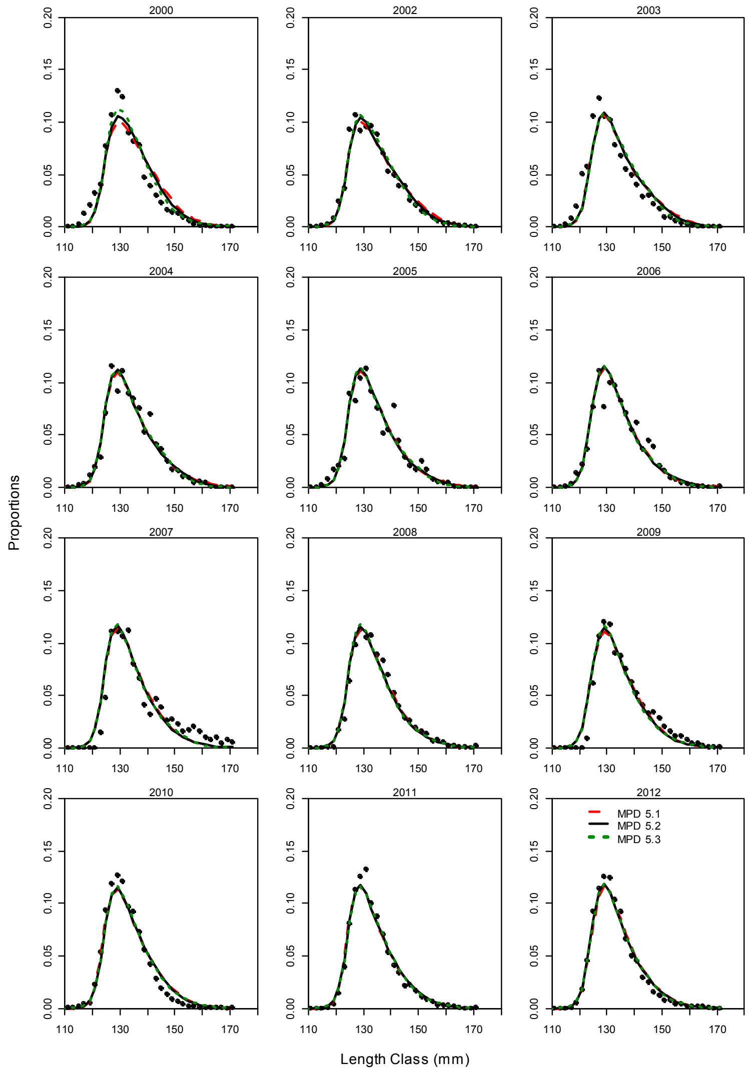

Figure 6: MPD fits to the CSLF data for models 5.1, 5.2, and 5.3.

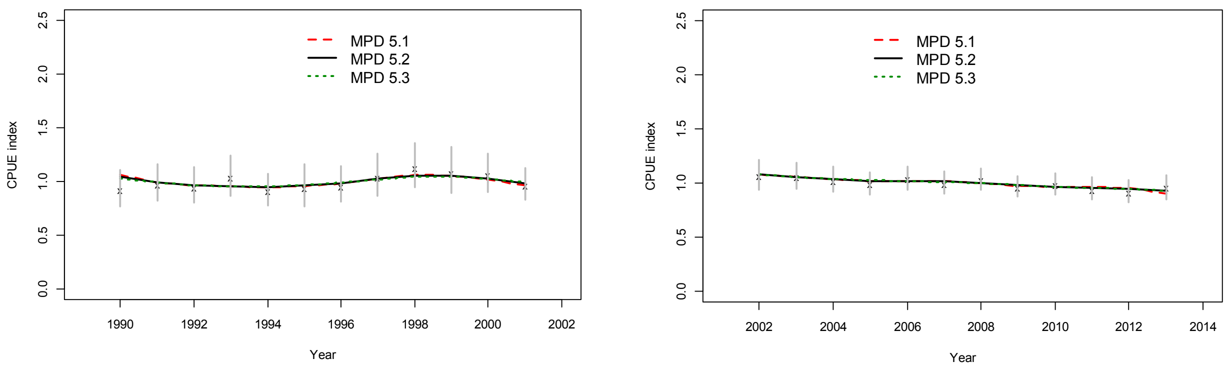

Figure 7: MPD fits to the CPUE indices (left) and PCPUE indices (right), for the models 5.1, 5.2, and 5.3.

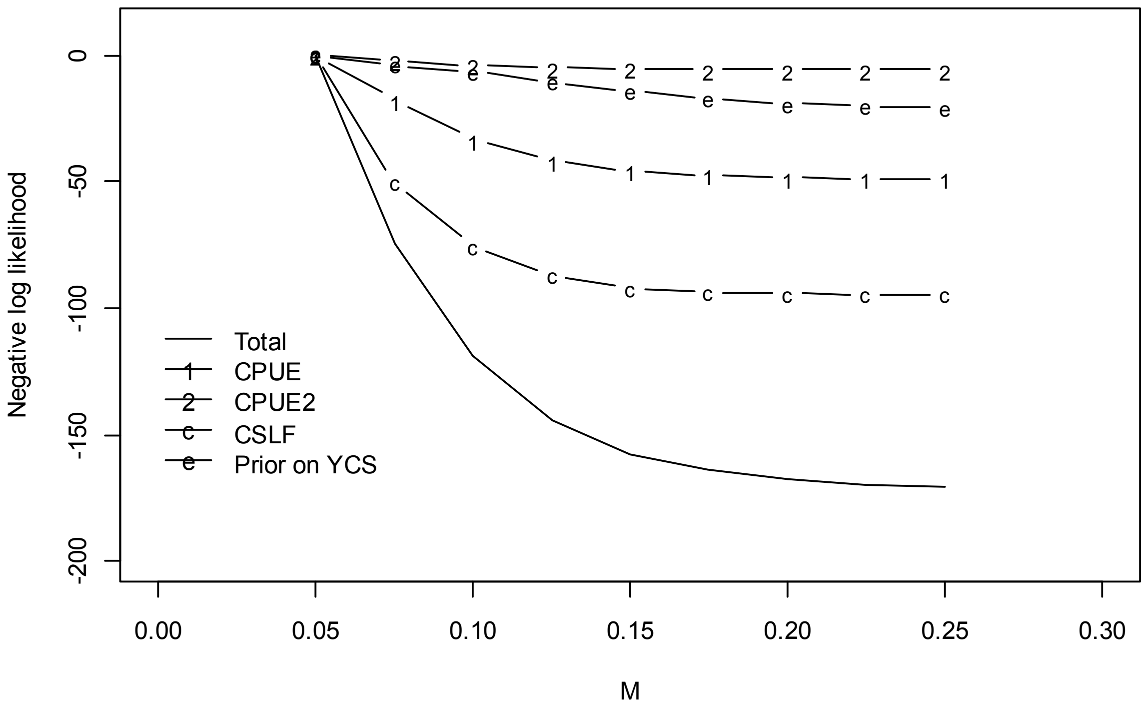

Figure 8: Profile likelihood for parameter *M* based on the MPD model run in which growth was fixed at medium value. The profile likelihood is shown for the total objective function value (top left), component likelihood (CPUE, PCPUE, and CSLF), and for the prior on recruitment deviation.

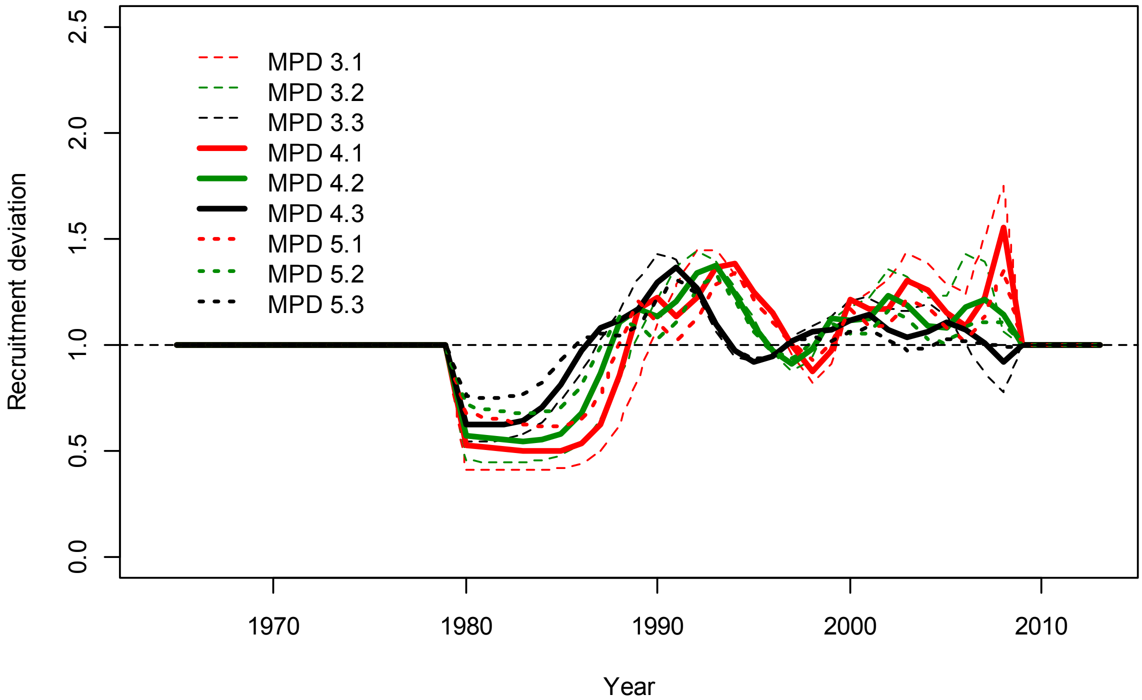

Figure 9: Estimates of recruitment deviations for MPD models 3.1, 3.2, 3.3, 4.1, 4.2, 4.3, 5.1, 5.2, 5.3.

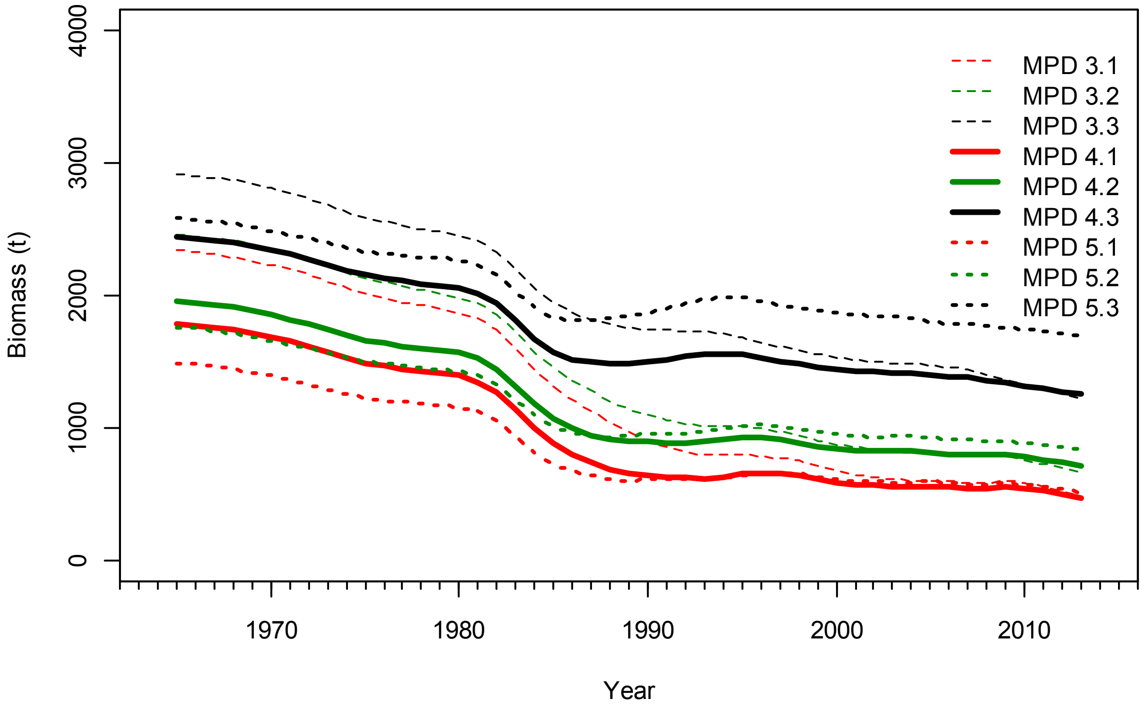

Figure 10: Estimates of spawning stock biomass for MPD models 3.1, 3.2, 3.3, 4.1, 4.2, 4.3, 5.1, 5.2, and 5.3.

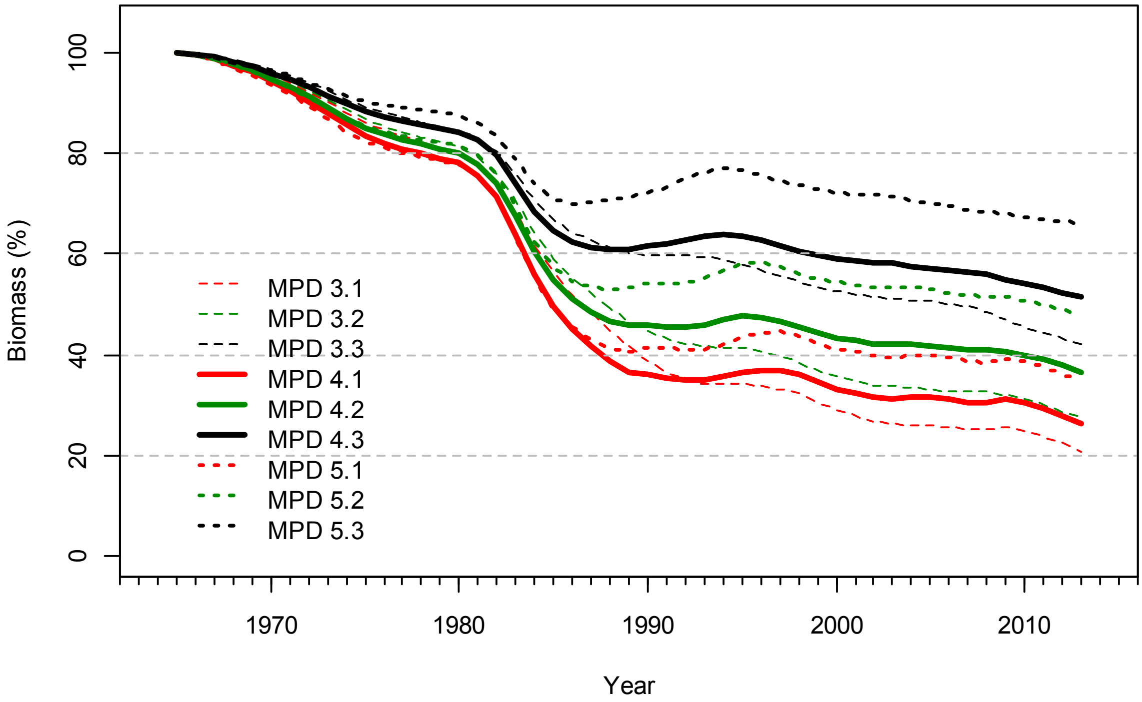

Figure 11: Estimates of spawning stock biomass as a ration of B_0 for MPD models 3.1, 3.2, 3.3, 4.1, 4.2, 4.3, 5.1, 5.2, and 5.3.

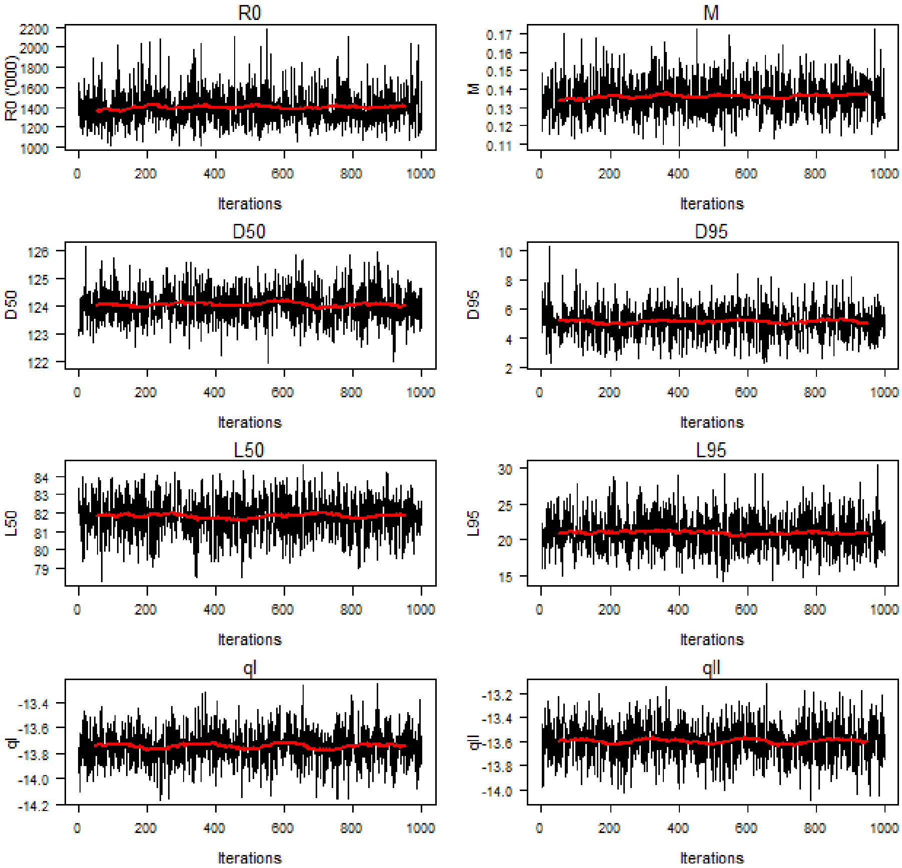

Figure 12: Traces of estimated parameters (left) and biomass indicators (right) for base case MCMC 6.1.

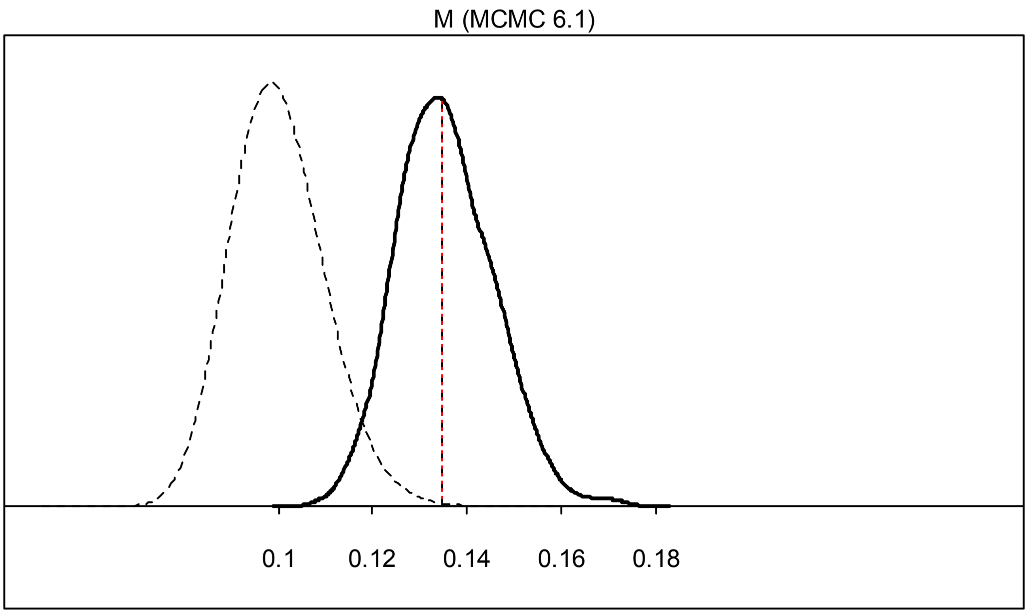

Figure 13: Posterior and prior distributions of estimated natural mortality (*M*) for MCMC 6.1, and posterior distribution of *M* for MCMC 0.4. The black dashed lines are the posterior medium and red line and the red dashed lines are the MPD estimates.

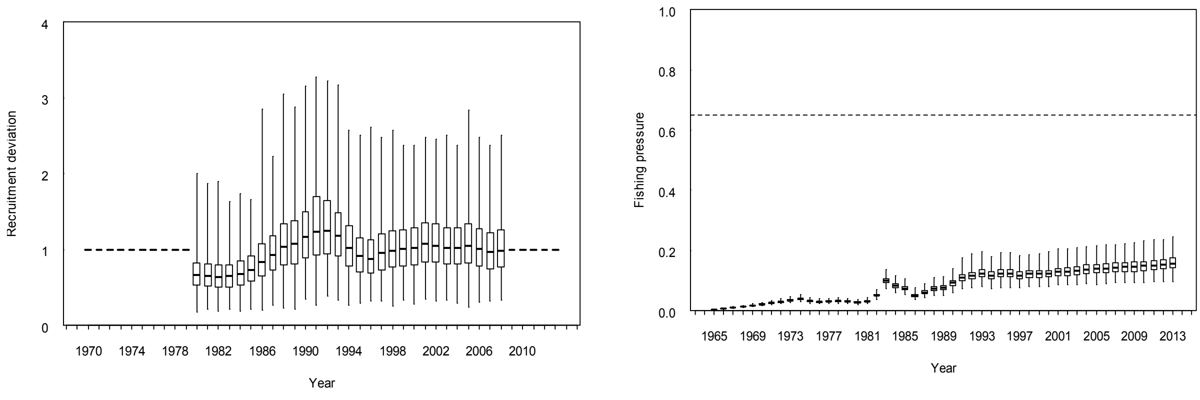

Figure 14: Posterior distributions of recruitment deviations (left), and exploitation rates (right) for the MCMC 6.1. The box shows the medium of the posterior distribution (horizontal bar), the 25th and 75th percentiles (box), with the whiskers representing the full range of the distribution. Recruitment deviations were estimated for 1980–2008, and fixed at 1 for other years.

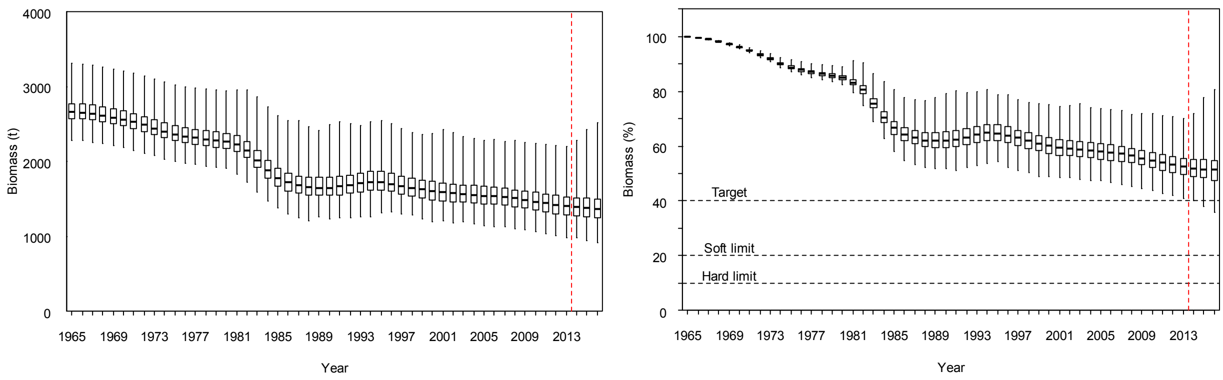

Figure 15: Posterior distributions of spawning stock biomass and spawning stock biomass as a percentage of virgin level from MCMC 6.1 (including projections). The box shows the medium of the posterior distribution (horizontal bar), the 25th and 75th percentiles (box), with the whiskers representing the full range of the distribution.