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A 2018 stock assessment of smooth oreo in OEO 4

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P.L. Cordue

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Table of Contents

EXECUTIVE SUMMARY

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***New Zealand Fisheries Assessment Report 2019/28*. 46 p.**

This report describes the 2018 assessment of smooth oreo in OEO 4. It is an update of the 2014 assessment which assumed a fixed value of natural mortality. The assessment results are sensitive to the value of natural mortality and this report focusses on the analyses that support the base model assessment in which natural mortality was estimated. The assessment was conducted using NIWA's Bayesian stock assessment package CASAL.

The base model, selected by the Deepwater Fishery Assessment Working Group (DWFAWG) and accepted by the Plenary, was used in the estimation of reference points for the smooth oreo stock. The methods and results of this work are also described.

The 2014 assessment of smooth oreo in OEO 4 found that the stock was being overfished and that catches would have to be substantially reduced. The assessment, when updated to the end of 2017–18 with the inclusion of new data and minor changes in parameterisation, was more optimistic with 2013 stock status estimated at 33% B_0 rather than 29% B_0. However, the stock trajectory was still heading downwards with the 2018 stock status estimated at 30% B_0.

The shift to an assessment in which M was estimated created a big shift in estimated stock status with 2018 stock status in the Reference model estimated at 42% B_0 compared to 30% B_0 in the fixed-M model. The increased estimate of M (0.0835 compared to the fixed value of 0.063) was responsible for the large increase in estimated stock status. The strongest signal from the data for a larger value of M was from the commercial length frequencies. This is not an ideal source of information with regard to M and so the DWFAWG decided to move from the Reference model to a base model which excluded the commercial length frequencies. In the base model, M is estimated at 0.079 (95% CI: 0.057–0.10) and current stock status at 40% B_0 (95% CI: 23–59% B_0).

The principle that the "best available information" should always be used as the basis for stock assessment advice is very relevant to the issue of whether to move from a model where M is externally estimated to one in which it is internally estimated. The externally estimated value of M was the best available information in 1997 but since then much relevant data have become available. The information from the early estimate of M was captured in the prior distribution for M used in the model. Five age frequencies contributed alternative information on the value of M and it is appropriate that the information from those data were given some weight in the latest stock assessment.

The projections from the base model show that annual catches in the range 2300–3300 t will maintain median stock status at about 40% B_0. Risks are all very low. An annual catch of 2900 t gives a 50% chance that stock status in 2023 is above (or below) 40% B_0.

The target biomass for this stock is currently set at the default level of 40% B_0 with default limit reference points of 20% B_0 (the soft limit) and 10% B_0 (the hard limit). The formal estimation of a Limit Reference Point (LRP), using extensions of the base model, produced a point estimate of 20% B_0 (95% CI: 20–24% B_0). For the purposes of Marine Stewardship Council (MSC) Principle 1 it is recommended that a LRP of 20% B_0 be adopted.

The formal estimation of B_{MSY} produced differing results for Beverton-Holt and Ricker stock recruitment relationships with respective point estimates of 27% B_0 and 41% B_0. The combined median estimate was 35% B_0 which suggested a target biomass range of 25–45% B_0. However, the lower bound of the target biomass range would then be uncomfortably close to the recommended LRP (20% B_0). The more conservative target biomass range of 30–50% B_0 is recommended for the smooth oreo stock in OEO 4.

1. INTRODUCTION

This report describes the methods and results of a 2018 assessment of smooth oreo in OEO 4. It is an update of the 2014 assessment which assumed a fixed value of natural mortality (*M*) (Fu & Doonan, 2015). The assessment results are sensitive to the value of *M* and this report focusses on the analyses that support the base model assessment in which *M* was estimated.

The base model, selected by the Deepwater Fishery Assessment Working Group (DWFAWG) and accepted by the Plenary (Fisheries New Zealand 2018), was used in the estimation of reference points for the smooth oreo stock. The methods and results of this work are also described.

The assessment and the estimation of reference points used very similar methods to those used in the four orange roughy stock assessments in 2014 (Cordue 2014a) and the subsequent management strategy evaluation (Cordue 2014b). The assessment was conducted using NIWA's Bayesian stock assessment package CASAL (Bull et al. 2012).

2. METHODS

A Bayesian stock assessment was performed for the smooth oreo stock in OEO 4 using very similar methods to those used in the 2014 orange roughy stock assessments (Cordue 2014a). An age-structured population model was fitted to a time series of acoustic survey estimates of smooth oreo biomass with an informed prior on the proportionality constant (the "acoustic *q*"). For three of the acoustic surveys, age frequencies were also fitted as were an early trawl survey age frequency (1991) and a commercial catch age frequency (2009). Some length frequencies from the commercial fishery were also available but these were not used in the base model.

A limit reference point and a target biomass range aimed at being compliant with the Marine Stewardship Council's Principle 1 (MSC 2014) and New Zealand's Harvest Strategy Standard (Ministry of Fisheries 2008) were also estimated.

2.1 Catch history

A catch history for smooth oreo in OEO 4 was constructed by multiplying the annual QMS totals (MHR) for OEO 4 by the proportion of smooth oreo in the estimated catches (Table 1, Figure 1). A catch of 2500 t was assumed for 2017–18.

Table 1: Catch history for smooth oreo in OEO 4.

Year	Catch (t)	Year	Catch (t)
1978–79	1 321	1999–00	6 357
1979–80	112	2000–01	6 491
1980–81	1 435	2001–02	4 291
1981–82	3 461	2002–03	4 462
1982–83	3 764	2003–04	5 656
1983–84	5 759	2004–05	6 473
1984–85	4 741	2005–06	5 955
1985–86	4 895	2006–07	6 363
1986–87	5 672	2007–08	6 422
1987–88	7 764	2008–09	6 090
1988–89	7 223	2009–10	6 118
1989–90	6 789	2010–11	6 518
1990–91	6 019	2011–12	6 357
1991–92	5 508	2012–13	5 964
1992–93	5 911	2013–14	6 016
1933–94	6 283	2014–15	6 318
1994–95	6 936	2015–16	1 992
1995–96	6 378	2016–17	2 279
1996–97	6 359	2017–18	2 500
1997–98	6 248		
1998–99	6 030		

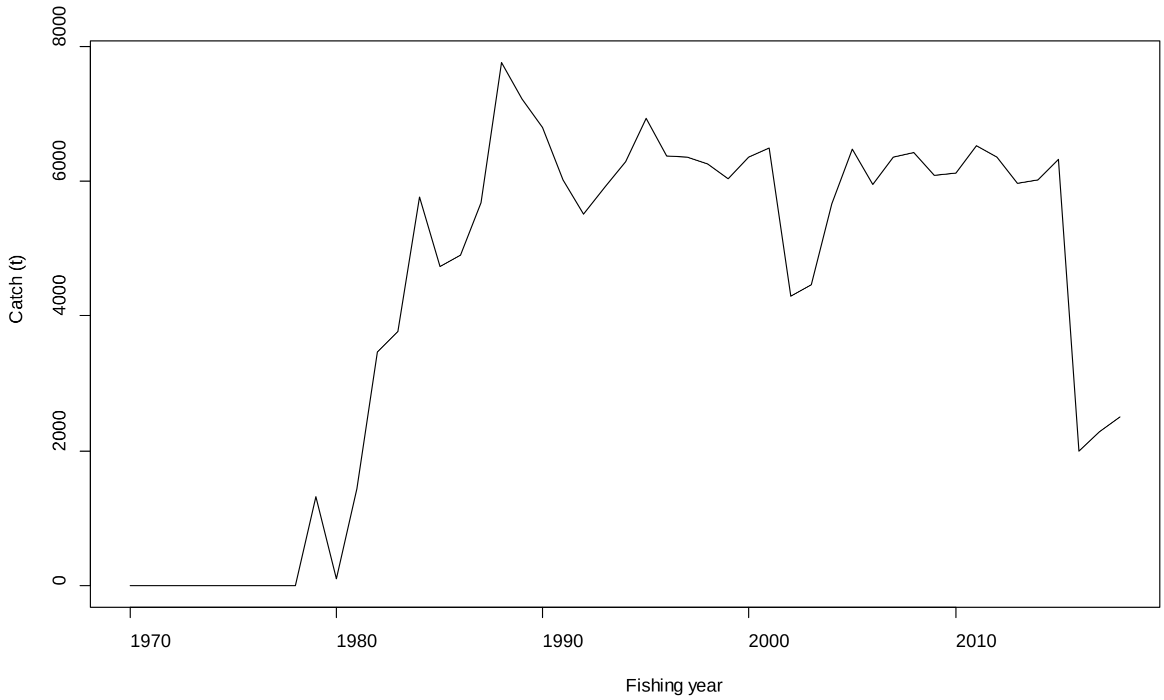

Figure 1: The catch history used in the assessment of smooth oreo in OEO 4.

2.2 Input data and statistical assumptions

Acoustic estimates

Estimates of biomass were available from six acoustic surveys:

(i) 26 September to 30 October 1998 on *Tangaroa* (voyage TAN9812);
(ii) 16 October to 14 November 2001 using *Tangaroa* for acoustic work (voyage TAN0117) and *Amaltal Explorer* (voyage AEX0101) for trawling;
(iii) 3–22 November 2005 using *Tangaroa* for acoustic work (voyage TAN0514) and *San Waitaki* (SWA0501) for mark identification trawling;
(iv) 2–18 November 2009 using *Tangaroa* for acoustic work (voyage TAN0910) and *San Waitaki* (SWA0901) for mark identification trawling;
(v) 8–26 November 2012 using *Tangaroa* for acoustic work (voyage TAN01214) and *San Waitaki* (SWA1201) for mark identification trawling;
(vi) 16 October to 17 November 2016 on *Amaltal Explorer* (AEX1602).

Vulnerable smooth oreo biomass was estimated based on the acoustic mark types, where vulnerable biomass was the sum over two flat mark types: DEEP SCHOOLS and SHALLOW SCHOOLS, with the hill biomass added on (Fu & Doonan, 2015). These estimates were made for smooth oreo in the whole of OEO 4 (Table 2). For fitting in the model, a process error of 20% was added to the estimated observation error to account for possible variation in the acoustic *q* (e.g., due to annual changes in availability). The biomass indices were assumed to be lognormally distributed. An informed prior was used for the acoustic *q* (lognormal with mean of 0.83 and CV of 0.3). The prior was based on limited information on target strength, the QMA scaling-factor, and the proportion of vulnerable biomass in the vulnerable acoustic marks (Fu & Doonan 2013).

One major source of uncertainty in the 2012 survey estimates was that about 25% of the total estimate came from one school mark on the flat. The species composition of this mark was not able to be verified by trawling. Excluding this mark (i.e., assuming they were not smooth oreo) reduced the total biomass for smooth oreo to 36 550 t. However, the consensus of skippers consulted about the mark is that it was probably smooth oreo.

Table 2: Estimated smooth oreo vulnerable biomass (t) and CV (%, after the addition of 20% process error) from acoustic surveys in 1998, 2001, 2005, and 2009, 2012, and 2016.

Year	Biomass (t)	CV (%)
1998	65 679	33
2001	81 633	33
2005	63 237	32
2009	26 953	33
2012	58 603	36
2016	34 022	38

Acoustic survey age frequencies

Age frequencies for smooth oreo in OEO 4 were determined by estimating ages from otoliths and data collected on three acoustic surveys carried out in 1998 and 2005 (Doonan et al. 2008) and 2016. All of the sampled otoliths (n = 546) from the 1998 survey and randomly selected otoliths (n = 500) from the 1800 otoliths collected during the 2005 survey were read, with 398 otoliths used from the 2016 survey.

The age frequency distribution was estimated using the aged otoliths from tows in each mark-type weighted by the catch rates and the proportion of abundance in the mark-type. Age frequencies were estimated by sex and combined over sexes. The variance was estimated by bootstrapping the tows within mark-types (e.g., Doonan 2008). The ageing error was estimated by comparing age estimates from two readers and also by using repeated readings from the same reader. The age frequencies had a mean weighted CV of 36% (1998) and 45% (2005). The ageing error was estimated to be about 8.5% which was used in the assessment. The age frequencies (male and female combined) were included in order to estimate year class strengths.

The age frequencies were assumed to be multinomial with effective sample sizes of 50, 50, and 40 for 1998, 2005, and 2016 respectively (being approximately the number of otoliths used divided by 10). These sample sizes follow the spirit of Francis (2011) who argued that composition data were often given far too much weight in stock assessment models.

Other age frequencies

Two additional age frequencies were constructed for the 2018 assessment. The first was for the commercial catch in 2008–2009. The 1284 otoliths available from the SOP were sampled at random (with replacement) until 400 unique otoliths were obtained. The probability of selection was proportional to the tow catch and inversely proportional to the number of otoliths sampled in the tow. The mean weighted CV was 30% (obtained by bootstrapping). The second age frequency was constructed for the 1991 trawl survey of OEO 4 (TAN9104). Otoliths collected during the trawl survey were sampled at random until 400 unique otoliths were obtained. The probability of selection was proportional to the stratum biomass estimate and by tow catch within stratum, divided by the number of otoliths available from the tow. The mean weighted CV was 35% (obtained by bootstrapping).

The age frequencies were assumed to be multinomial with effective sample sizes of 40 (the number of otoliths used divided by 10).

Observer length frequencies

The length frequencies constructed by Fu & Doonan (2013) were available. They were stratified by season (October-March and April-September) and into west and east parts. The length frequencies were combined over strata by the proportion of catch in each stratum (Fu & Doonan 2013).

Five scaled length frequencies from 1996 to 2008 were used in various model runs but not used in the base model. They were assumed to be multinomial with an effective sample size equal to half the number of sampled trawls (in the spirit of Francis 2011).

2.3 Model structure and survey timing

The model was single-area, two-sex, and age-structured (1–70 years with a plus group). Fish were not categorised by maturity state and, as in the 2014 model, proportions mature at age and sex were estimated externally and fixed in the model (Fu & Doonan 2015). Two time steps were used with the first step instantaneous with no mortality, incorporating the ageing event (fish become 1 year older) and the recruitment event (juveniles recruit at age 1 year). The second time step contained all of the natural and fishing mortality with spawning at the end of the time step (i.e., the end of the fishing year). This approximates the real spawning season which is reported to be from late October to at least December (Fisheries New Zealand 2018).

In the 2014 model, spawning was specified to be at the beginning of the year and stock status was calculated as mid-year mature biomass divided by virgin spawning biomass (B_0) (Fu & Doonan 2015). This was an unusual choice as it causes virgin stock status to be less than 100% B_0. In the current model, the usual definition of stock status was used (spawning biomass divided by virgin spawning biomass) and spawning time was moved to the end of the year to ensure that stock status was dependent on the catch taken that year (if spawning was at the beginning of the year then stock status would be independent of the catch).

The acoustic surveys were typically in October-November and they were specified to be at the end of time step 2 after all of the mortality has occurred (i.e., the end of the fishing year). The 1991 trawl survey was also in October-November and was given the same timing.

A Beverton-Holt stock recruitment relationship was specified with steepness at the New Zealand default value of 0.75. Growth, length-weight, and maturity parameters were separate by sex and fixed at the values used in the 2014 assessment (Fu & Doonan 2015). Values are given in the population.csl file for the base model (see Appendix 2).

2.4 Estimation methods and model runs

The estimation methods were very similar to those used in the 2014 orange roughy assessments (Cordue 2014a). The stock assessments were done using the general Bayesian estimation package CASAL (Bull et al. 2012). The CASAL input files for the base model are given in Appendix 2. The final assessments were based on the marginal posterior distributions of parameters and derived parameters of interest (e.g., virgin biomass (B_0), current biomass (B_{2018}), and current stock status (B_{2018}/B_0)). The marginal posterior distributions were produced using Markov chain Monte Carlo methods (hence termed "MCMC" runs). Preliminary analysis and some sensitivity runs were performed using just the Mode of the Posterior Distribution (MPD) which can be obtained much more quickly than the full posterior distribution (hence "MPD" runs). The MPD estimate is associated with the "best fit" that can be obtained – it is useful to check that the "best fit" is not too bad otherwise there would be concerns about the appropriateness of the model.

The general approach taken to data weighting within the stock assessments was to down-weight composition data (length and age frequencies) relative to biomass indices to allow any scale and trend information in the biomass indices to drive the assessment results. This is in the spirit of Francis (2011) who argued that composition data were generally given far too much weight in stock assessment models and were often allowed to dominate the signals from biomass indices.

As this assessment was an update of the 2014 assessment a detailed "audit trail" was produced from the base model in the 2014 assessment (which had *M* fixed at 0.063) to a similar fixed-*M* model in 2018 (Table 3). A "reference model" was also produced in 2018 where *M* was estimated (with a normal prior, mean = 0.063 and CV=25% based on Doonan et al. 1997) and it was compared with fixed-*M* models where *M* was fixed at values from 0.04 up to 0.11. The comparisons between the reference model and the fixed-*M* models focussed on MCMC residual patterns and estimated selectivities; the question being where the reference model was getting signals with regard to the value of *M* and which fixed values of *M* gave plausible results.

Table 3: The names and description of the model runs in the detailed audit trail from the 2014 assessment base model to a similar fixed-M model in 2018. AF = age frequency. LF = length frequency.

Name	Incremental changes	Final year	YCS estimated
Begin year	Use SSB for stock status	2013	1954–2000
End year	Spawning at end of year	2013	1954–2000
+ LFs	Fit commercial LFs	2013	1954–2000
Double Nsel	Double normal selectivity for acoustic AFs	2013	1954–2000
Catch 2018	Extend catch history	2018	1954–2000
+ TAN9104	Fit AF from TAN9104	2018	1940–2000
+ AF2009	Fit commercial AF 2009	2018	1940–2000
+ AcoAF2016 (sel)	Fit acoustic AF 2016 with its own selectivity	2018	1940–2005
+ AcoAF2016	Fit acoustic AF 2016 with same selectivity as other years	2018	1940–2005
+ AcoBio2016	Add 2016 index to time series	2018	1940–2005
2018, M=0.063 model	Add 20% process error to acoustic time series	2018	1940–2005
Old no-sex (k=0.057)	No-sex with average parameters	2018	1940–2005
No-sex (k=0.055)	No-sex with almost average parameters	2018	1940–2005

In the reference model, the main parameters estimated were: virgin (unfished, equilibrium) biomass (B_0), *M*, fishery selectivity (logistic), acoustic-survey age frequency selectivity (double normal), trawl-survey selectivity (double normal), acoustic *q* (with an informed prior), CV of length-at-mean-length-at-age for ages 1 and 70 years (linear relationship assumed for intermediate ages), and year class strengths (YCS) from 1940 to 2005 (with the Haist parameterisation and "nearly uniform" priors on the free parameters as used by Cordue 2014a). The acoustic survey biomass selectivity was assumed to be the same as the fishery selectivity (as the fishery targets the school marks that the acoustic estimates were based on).

A number of sensitivity runs, estimating *M*, were done in relationship to the reference model (Table 4).

Table 4: The names and descriptions of sensitivity runs relative to the reference model for the 2018 smooth oreo assessment. LN, lognormal distribution with mean and CV given in the bracket. N, normal distribution with mean and CV in the bracket.

Model run	Description
Reference	Acoustic *q* estimated with a LN(0.83, 0.3) prior, nearly uniform prior on YCS, *M* estimated with a N(0.063, 0.25) prior, adult biomass indices (school marks), commercial LFs included
Est M (unf.)	Reference but with a uniform prior on *M*
LN rsd=0.6	Reference but a lognormal prior on YCS parameters, s.d. of log recruitment = 0.6
LN rsd=0.9	Reference but a lognormal prior on YCS parameters, s.d. of log recruitment = 0.9
Three sels	Reference but separate selectivities for each of the three acoustic age frequencies
No sex	Reference but single sex model (k=0.055)
Est. M, h	Reference but with the Beverton-Holt stock recruitment steepness (*h*) estimated
Est. M, h (R)	Reference but with the Ricker stock recruitment steepness (*h*) estimated

The base model accepted by the DWFAWG was the reference model without the commercial length frequencies. The final set of model runs included the two "standard" sensitivity runs as used by Cordue (2014a) where a 20% shift in *M* and in the mean of the acoustic *q* prior are included (Table 5). The LowM-Highq run is expected to produce a lower current stock status compared to the base model because a lower *M* implies a less productive stock and a higher mean on the acoustic *q* implies that there was less biomass present than in the base model. The HighM-Lowq has the opposite effect with a higher current stock status expected.

Table 5: Descriptions of the final model runs of the 2018 smooth oreo assessment. LN, lognormal distribution with mean and CV given in the bracket. N, normal distribution with mean and CV in the bracket. All use Haist parameterisation for YCS.

Model run	Description
Base	Acoustic *q* estimated with a LN(0.83, 0.3) prior, nearly uniform prior on YCS, *M* estimated with a N(0.063, 0.25) prior, adult biomass indices (school marks)
LowM-Highq	M fixed at 0.0632 (20% less than the base estimate) and the mean of the acoustic q prior 20% higher
HighM-Lowq	M fixed at 0.0948 (20% higher than the base estimate) and the mean of the acoustic q prior 20% lower
Plus LFs	Base but with commercial length frequencies included
Fixed M	Base but with fixed M = 0.063 (as assumed in the 2014 assessment)

MCMC chain diagnostics

Mathematical theory proves that MCMC chains will eventually converge to provide the joint posterior distribution. However, one can never be certain that a chain, or multiple chains, have been run long enough to achieve “sufficient” convergence. There is never proof that a chain has converged but there may be evidence that a chain has not yet converged. Many diagnostics exist to help determine whether a chain has achieved sufficient convergence.

In New Zealand, a common approach to judge convergence is to use multiple chains (each starting at a random jump from the MPD estimate) and compare the marginal posterior distributions for the (derived) parameters of interest. The idea is that the chains are sufficiently converged when all of the chains give the “same” answer. For this assessment, three chains were generally used and they were run up to a maximum of 15 million samples. One in every one thousand samples were stored and the first one thousand stored samples were discarded as a “burn-in” (to allow the chain to settle down to a stochastic equilibrium). The three posterior distributions were judged primarily on the basis of their median values as to whether they were sufficiently similar that the chains could be stopped. “Near identical” median values were required (e.g., two out of three chains being the same to two significant figures with the third almost the same; e.g., stock status medians across the three chains of 48, 49, and 49 %B_0 were considered close enough). For the audit trail, generally just one chain of 15 million was used although for some runs there were also results using three chains of 15 million.

There was also a check to ensure that none of the parameter values were “drifting” (progressively moving from a high value to a low value or vice versa). Each chain was split into three sections: the burn-in period, the first half of the remaining stored samples, and the second half of the remaining stored samples. The mean values in each section were standardised by dividing by the mean value from the non-burn-in part of the chain. For each parameter, the standardised values were plotted for each section and the deviation from 1 was examined.

Fishing intensity

For the base model, fishing intensity was measured by the exploitation rate (catch divided by beginning of year vulnerable biomass). The exploitation rates associated with $U_{30\%B0}$, $U_{40\%B0}$, and $U_{50\%B0}$ were determined by running long-term projections at different levels of (CASAL) exploitation rate with the MCMC point estimates of *M* and the fishing selectivity fixed in the population model. Note, the fishing intensity that forces the stock to deterministic equilibrium at x% B_0 is denoted as $U_{x\%B0}$ (Cordue 2012).

Projections

The projections presented to Plenary were for five years for annual catches of 2300 t or 3000 t from the base model. Additional projections were requested by MPI: 2900 t and 3300 t for the base model; and 2300 t, 3000 t, and 3300 t for the fixed M model.

On advice from the fishing industry, a catch of 2300 t was assumed for 2017–18 (rather than the 2500 t used in the assessment). The last ten estimated YCS (1996 to 2005 inclusive) were empirically sampled to bring in random recruitment from 2006 onwards.

The fishery indicators calculated for the projections were: the mean stock status in 2023 ($E[ss_{23}]$) and the probabilities of 2023 stock status being greater than 40% B_0 ($P[ss_{23} > 40\%]$), less than the soft limit ($P[ss_{23} < 20\%]$), less than the hard limit ($P[ss_{23} < 10\%]$), and greater than 2018 stock status ($P[ss_{23} > ss_{18}]$).

The indicators were calculated using all three chains after the burn-in (so based on 42 000 samples). The plots of projected spawning biomass trajectories used only the first chain.

Estimation of steepness

The base stock assessment model was re-run with steepness (h) and M estimated. Informed priors were used for both parameters and the runs were taken through to full MCMC estimation. Estimation of steepness was made for both the Beverton-Holt and Ricker SR relationships. A random sample of 5000 was taken from the posterior distributions of each run for use in the estimation of B_{MSY} and the limit reference point (LRP) (see below).

Estimation of B_{MSY} and the LRP

Bayesian estimation of B_{MSY} and the LRP was performed to account for uncertainty in h and M. This was achieved by calculating B_{MSY} and the LRP as a function of h and M over a two-dimensional grid of values and then obtaining a posterior distribution by using the given posterior samples of h and M (see above). For each pair of posterior samples (h, M) the value of B_{MSY} or the LRP was calculated by interpolation using the corresponding "grid function". The "spline" and "splinefun" functions in R were used to provide the interpolated values (these are cubic splines). Hence, the 5000 samples from the joint posterior of h and M provided 5000 samples from the posteriors of B_{MSY} and the LRP.

For given values of h and M, B_{MSY} was calculated by running the base model (or the Ricker model) in CASAL with deterministic recruitment and constant U over a range of U values to determine the yield curve. Estimated parameters other than h and M were fixed at the MCMC point estimates. The LRP was defined to be the greater of 20% B_0 and 50% B_{MSY}.

3. RESULTS

3.1 Audit trail results and diagnostics

The purpose of an "audit trail" from one assessment to another is to ensure that when small incremental changes are made to data inputs and/or structural assumptions that the changes in assessment results are plausible. If the results are unexpected then a full investigation of the causes needs to be undertaken.

The structural changes to the 2014 assessment (using spawning biomass rather than mid-year mature in stock status estimation, and then moving spawning to the end of the year) made very little difference to the results (Table 6, contrast "Fu and Doonan" with "End year"). The addition of the commercial length frequencies reduced the estimate of B_0 and stock status slightly and then the change to a double normal selectivity from a logistic selectivity for the acoustic age frequencies increased the estimates to former levels (Table 6). Extending the catch history to the end of 2017–18 made no difference to the results (Table 6).

Table 6: MCMC audit trail results: point estimates and 95% CIs for B_0 and stock status in 2013 (B_{13}/B_0) for the runs in the audit trail before the model was extended to 2018 ("Catch 2018"). *The estimates given in Fu & Doonan (2015) are also shown but they are a 90% CI. For "Catch 2018" the point estimate and 95% CI are also given for stock status in 2018 (B_{18}/B_0).

	B_0 (000 t)		Stock status 2013 (%)		Stock status 2018 (%)	
	Median	95% CI	Median	95% CI	Median	95% CI
Fu and Doonan	131	115–156*	27	16–41*		
Begin year (3 chains)	133	114–167	28	16–44		
Begin year	133	114–167	28	16–44		
End year	132	113–166	28	16–45		
+ LFs	127	112–150	27	17–40		
Double Nsel	131	114–161	29	18–44		
Catch 2018	131	114–162	29	18–44	27	14–43

The largest change in results in the initial set of audit trail runs is caused by the change in the shape of the acoustic age frequency selectivity (Table 6). The change in selectivity makes very little difference to the MPD fit of the data (Figure 2). However, there is a large change in the shape of the selectivity for fish older than about 30 years of age, with the older fish being less vulnerable (Figure 3).

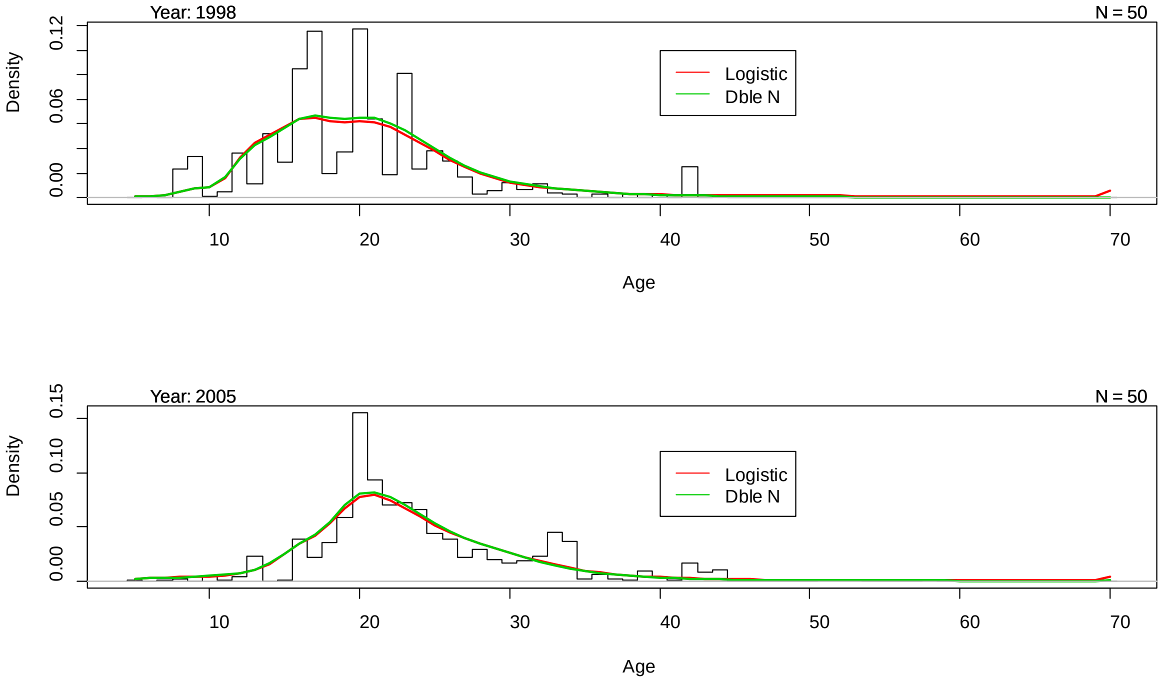

Figure 2: The MPD fits to the acoustic age frequencies in 1998 and 2005 for audit trail runs "+LFS" (which had a logistic selectivity) and "Double Nsel" (which had a double normal selectivity). "N" is the effective sample size used in the model.

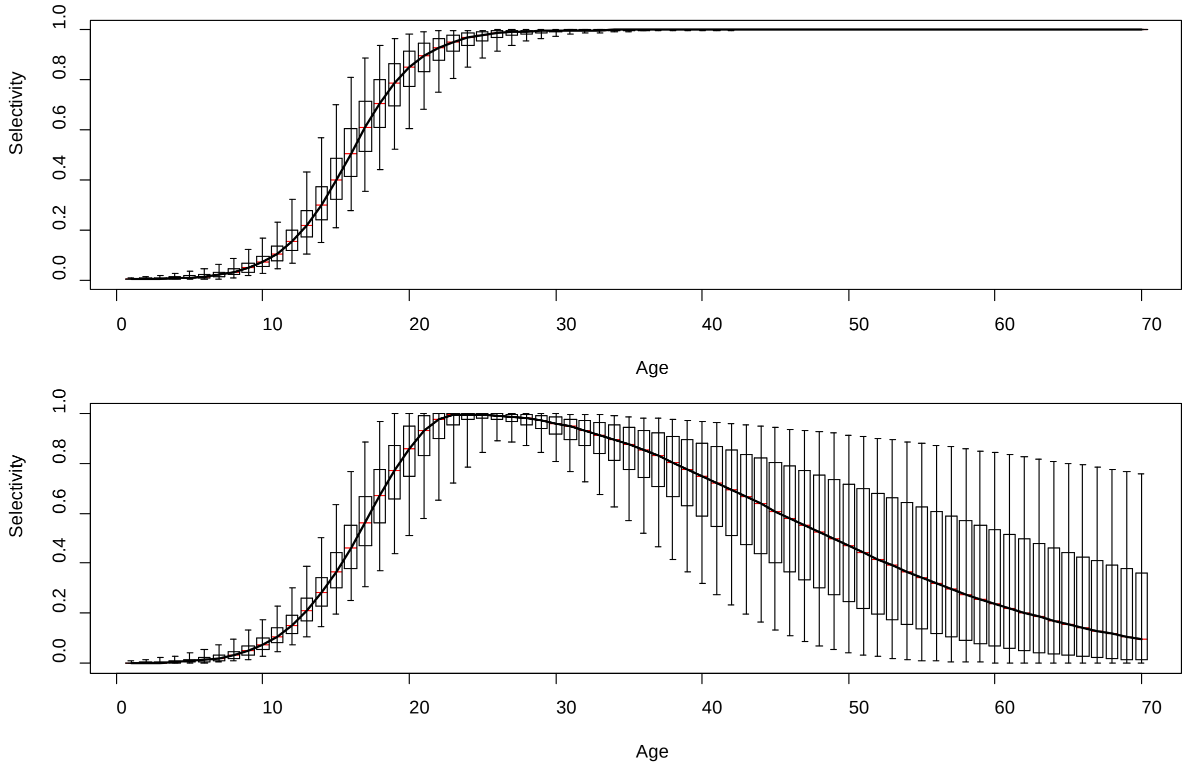

Figure 3: The MCMC estimates of the acoustic age frequency selectivity for audit trail runs "+LFS" (which had a logistic selectivity) and "Double Nsel" (which had a double normal selectivity). At each age the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

The progressive addition of age frequencies to the model changes the results very little until the 2016 acoustic survey age frequency is added (Table 7). The addition of the third acoustic age frequency increases the estimates of B_0, 2013 stock status, and 2018 stock status a little bit (Table 7). It makes very little difference to the results if a separate selectivity is estimated for 2016 ("+ AcoAF2016 (sel)") or if the same selectivity is used for all three acoustic age frequencies ("+ AcoAF2016")(Table 7). The addition of 20% process error to the acoustic survey biomass estimates made almost no difference to the results (contrast "+ AcoBio2016" and "2018, M=0.063 model" in Table 7).

The no-sex model, when average growth parameters were used, gave somewhat lower estimates of B_0, 2013 stock status, and 2018 stock status than the corresponding two-sex model ("2018, M=0.063 model" in Table 7). Using the average growth parameters changed the average weight at age due to non-linear effects. The correct average weight at age for a no-sex model was achieved by using a slightly different value for *k* (0.055 rather than 0.057) and this model gave almost the same result as the corresponding two-sex model (("2018, M=0.063 model" in Table 7).

Table 7: MCMC audit trail results: point estimates and 95% CIs for B_0, stock status in 2013 (B_{13}/B_0), and stock status in 2018 (B_{18}/B_0) for the 2018 audit trail runs. See Table 3 for the description of the runs.

	B_0 (000 t)		Stock status 2013 (%)		Stock status 2018 (%)	
	Median	**95% CI**	**Median**	**95% CI**	**Median**	**95% CI**
Catch 2018	131	114-162	29	18-44	27	14-43
+ TAN9104	130	113-160	29	18-45	27	15-43
+ AF2009	130	114-157	29	18-43	27	15-43
+ AcoAF2016 (sel)	132	116-159	32	21-46	30	18-45
+ AcoAF2016	132	116-160	33	23-46	29	18-43
+ AcoBio2016	132	117-158	33	24-45	29	19-42
2018, M=0.063 model	133	117-160	33	24-46	30	19-44
2018, M=0.063 (3 chains)	133	117-160	33	24-46	30	19-44
No sex (k=0.055)	132	116-158	33	24-46	29	19-43
Old no-sex (k=0.057)	129	114-153	32	23-45	28	18-42
Old no-sex (k=0.057) (3 chains)	129	114-154	32	23-45	28	18-42

There was a substantial difference between the selectivity estimated for the 2016 acoustic age frequency and that estimated for 1998 and 2005 with the 2016 selectivity favouring older fish (Figure 4). However, when just a single selectivity was estimated there was only a small difference between the selectivity estimated for 1998 and 2005 and that estimated for all three years combined (Figure 5). For simplicity it was decided to use just a single selectivity (although a sensitivity run was done using three individual selectivities – see Tables 8 and 9).

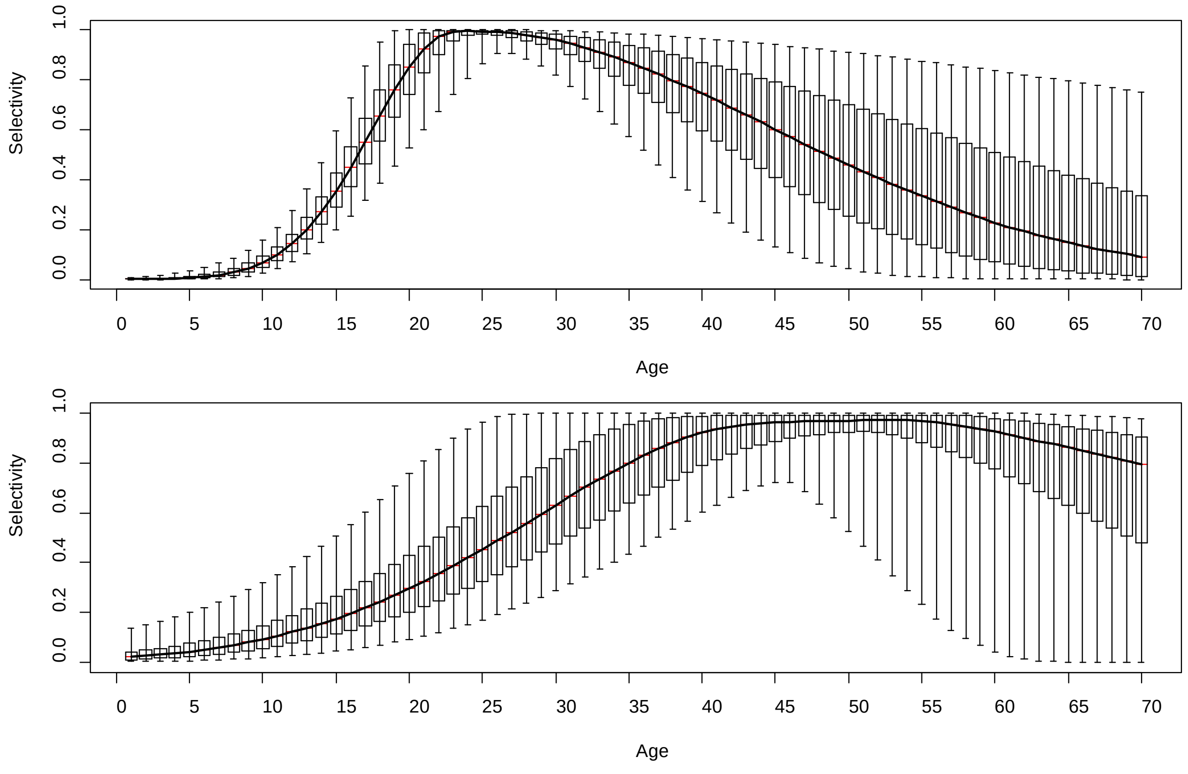

Figure 4: The MCMC estimates of acoustic age frequency selectivities for audit trail runs "+AF2009" (which has a single selectivity for acoustic age frequencies in 1998 and 2005 – top panel) and "+AcoAF2016 (sel)" (which had a separate selectivity for the 2016 acoustic AF – bottom panel). At each age the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

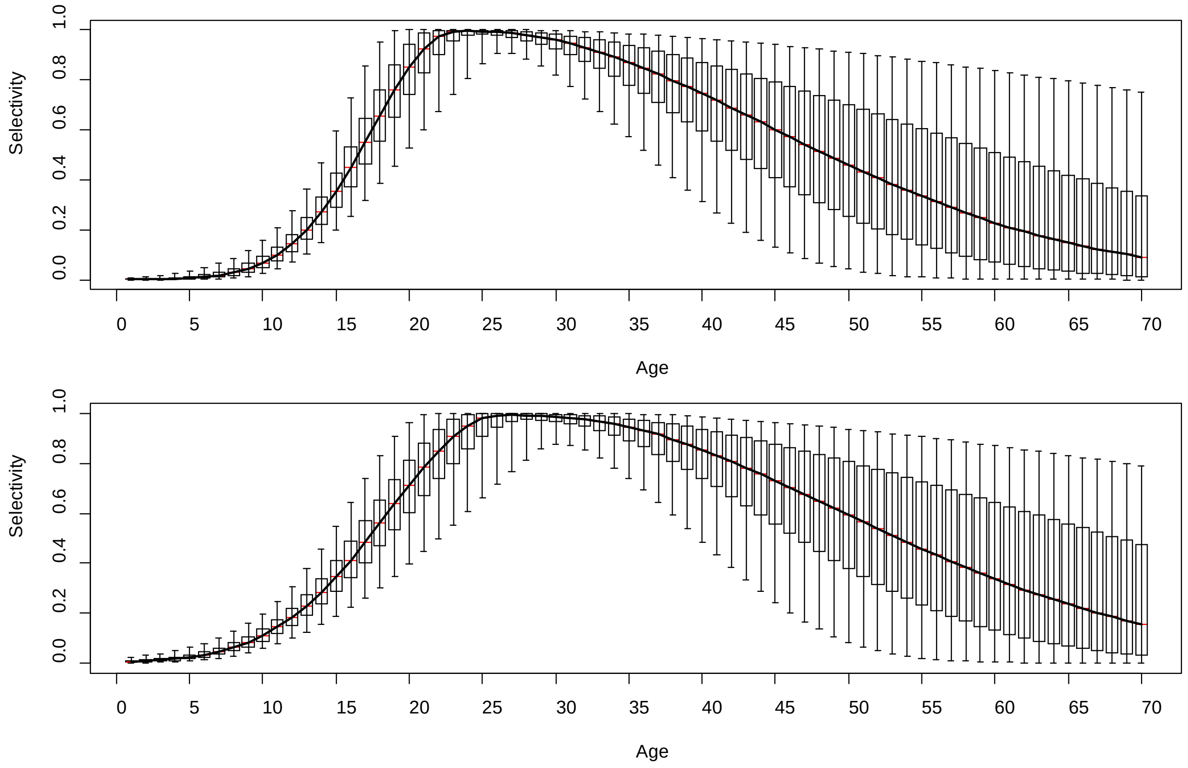

Figure 5: The MCMC estimates of acoustic age frequency selectivities for audit trail runs "+AF2009" (which has a single selectivity for acoustic age frequencies in 1998 and 2005 – top panel) and "+AcoAF2016" (which has a single selectivity for the 1998, 2005, and 2016 acoustic AFs – bottom panel). At each age the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

The reason for the shift in the 2016 selectivity and the estimates of increased stock status when the 2016 acoustic age frequency is added seems clear from the data. The 2016 age frequency has more fish aged 30 years or older than the 1998 and 2005 age frequencies (Figure 6).

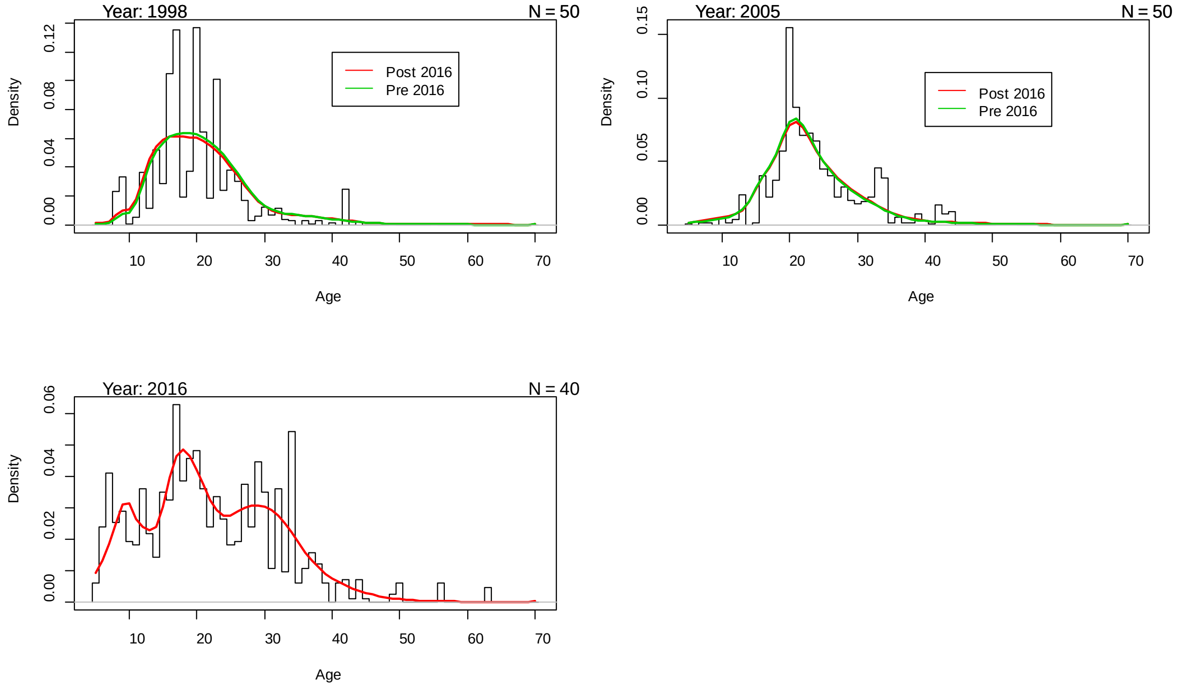

Figure 6: The MPD fits to the acoustic age frequencies in 1998 and 2005 for audit trail runs "+AF2009" ("Pre 2016") and "+AcoAF2016" ("Post 2016"). The MPD fit to the acoustic age frequency for "+AcoAF2016" is also shown. "N" is the effective sample size used in the model.

There is an associated increase in the MPD estimates of the year class strength (YCS) of cohorts associated with the older fish (Figure 7) and this flows through into increased MCMC estimates of YCS (Figure 8) and stock status (Figure 9).

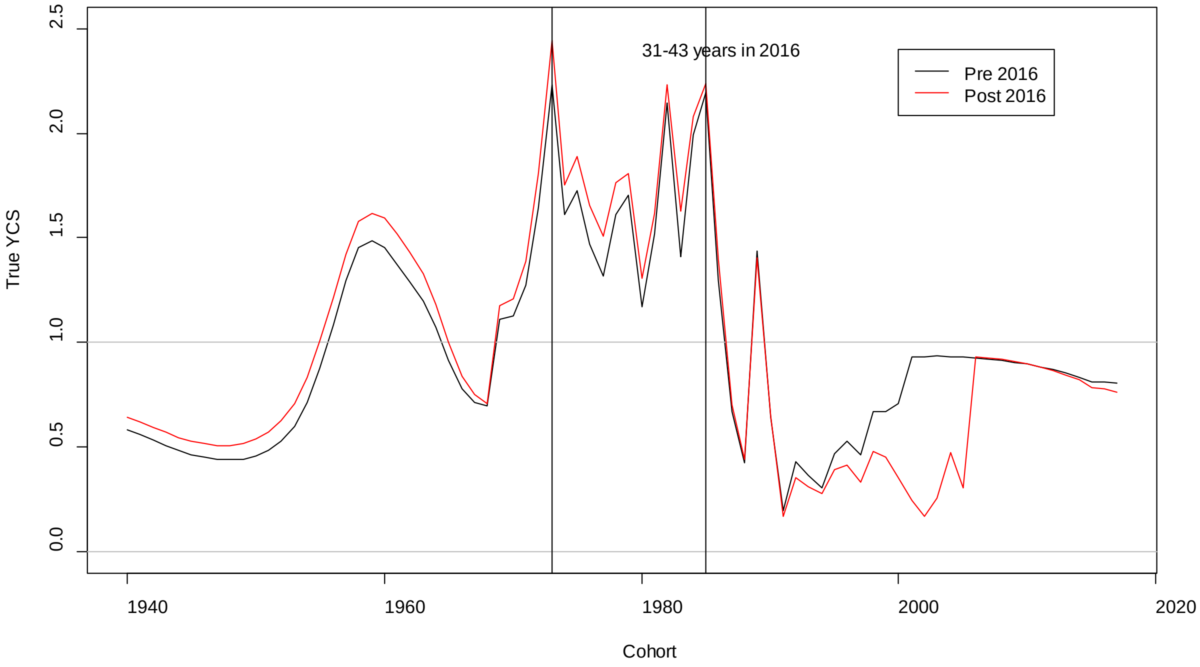

Figure 7: The MPD estimates of true YCS for audit trail runs "+AF2009" ("Pre 2016") and "+AcoAF2016" ("Post 2016").

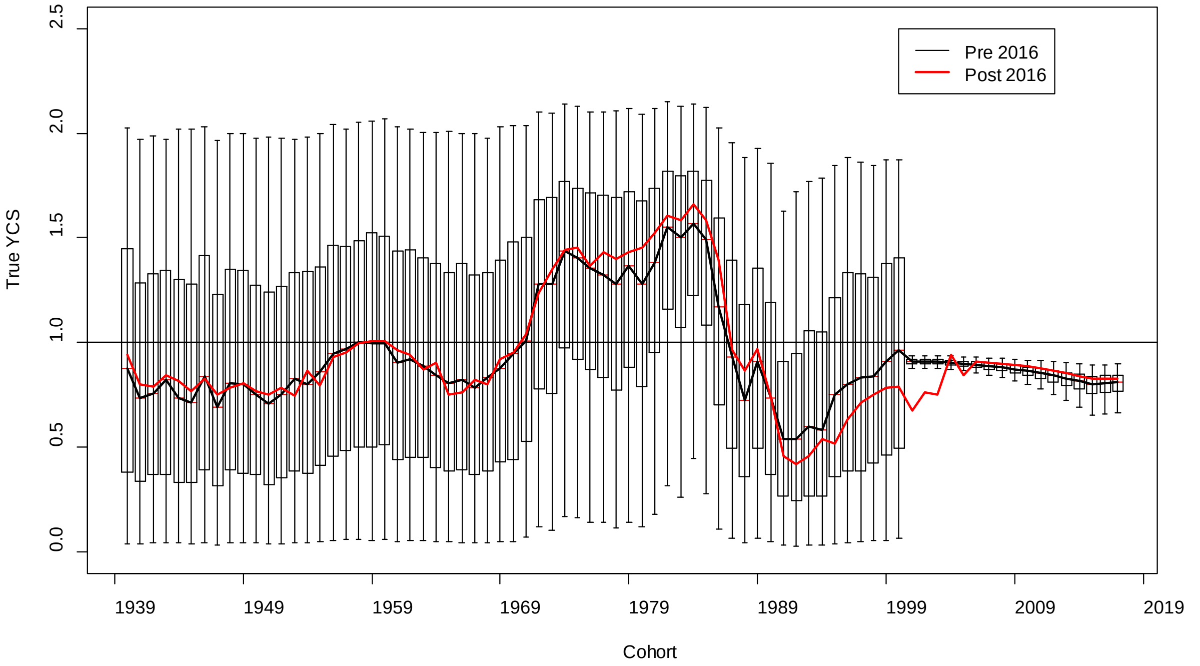

Figure 8: The MCMC estimates of true YCS for audit trail runs "+AF2009" ("Pre 2016", box and whiskers) and "+AcoAF2016" ("Post 2016", medians only). For each cohort the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

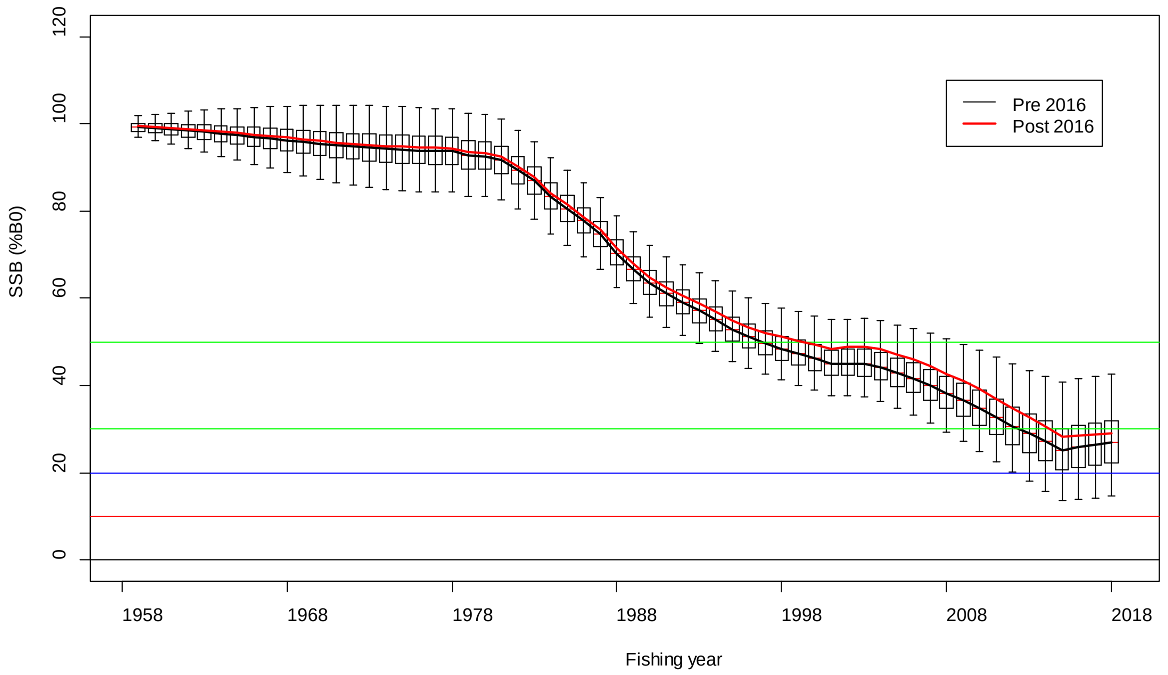

Figure 9: MCMC estimates: spawning stock biomass (SSB) trajectory for audit trail runs "+AF2009" ("Pre 2016", box and whiskers) and "+AcoAF2016" ("Post 2016", medians only). For each year the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

For a given stock assessment model, it is well known that higher values of *M* are associated with higher levels of estimated stock status. There is often some reluctance amongst working groups to accept assessments where *M* is estimated within the model and the estimate is higher than the value of *M* that was estimated externally or previously assumed. This was the case for the DWFAWG and the assessment of smooth oreo in OEO 4. Therefore, there was considerable effort spent investigating why the model was estimating higher values of *M* than the fixed value of 0.063 that was used in the 2014 assessment (Fu & Doonan 2015).

The reference model and every sensitivity run that was performed relative to the reference model had a 95% CI on *M* that was to the right of 0.063 (Table 8). For the reference model, the marginal posterior distribution for *M* essentially excluded the left hand side of the prior distribution (Figure 10). The shift to higher values of *M* is supported by the strong contrast in the distribution of objective function values at fixed values of *M* (Figure 11). There is a drop of 6 likelihood units in the median objective function value from *M* = 0.04 compared to *M* = 0.063 and then a further drop of 3 likelihood units when *M* = 0.11 (Figure 11).

Table 8: Sensitivity runs relative to the reference model: point estimates and 95% CIs for steepness (*h*), *M*, and the acoustic *q*. See Table 4 for the description of the runs.

Run	***h***		***M***		**Acoustic *q***	
	Median	**95% CI**	**Median**	**95% CI**	**Median**	**95% CI**
Reference		0.75	0.085	0.067–0.11	0.83	0.51–1.31
Est. M (unf.)		0.75	0.100	0.076–0.14	0.73	0.43–1.20
LN rsd=0.6		0.75	0.084	0.065–0.10	0.83	0.50–1.31
LN rsd=0.9		0.75	0.082	0.063–0.10	0.84	0.51–1.32
Three sels		0.75	0.085	0.067–0.11	0.92	0.55–1.44
No sex (k=0.055)		0.75	0.086	0.068–0.11	0.84	0.52–1.32
Est. M, h	0.69	0.30–0.95	0.085	0.067–0.11	0.83	0.51–1.31
Est. M, h (R)	0.62	0.24–2.17	0.084	0.066–0.10	0.81	0.48–1.29

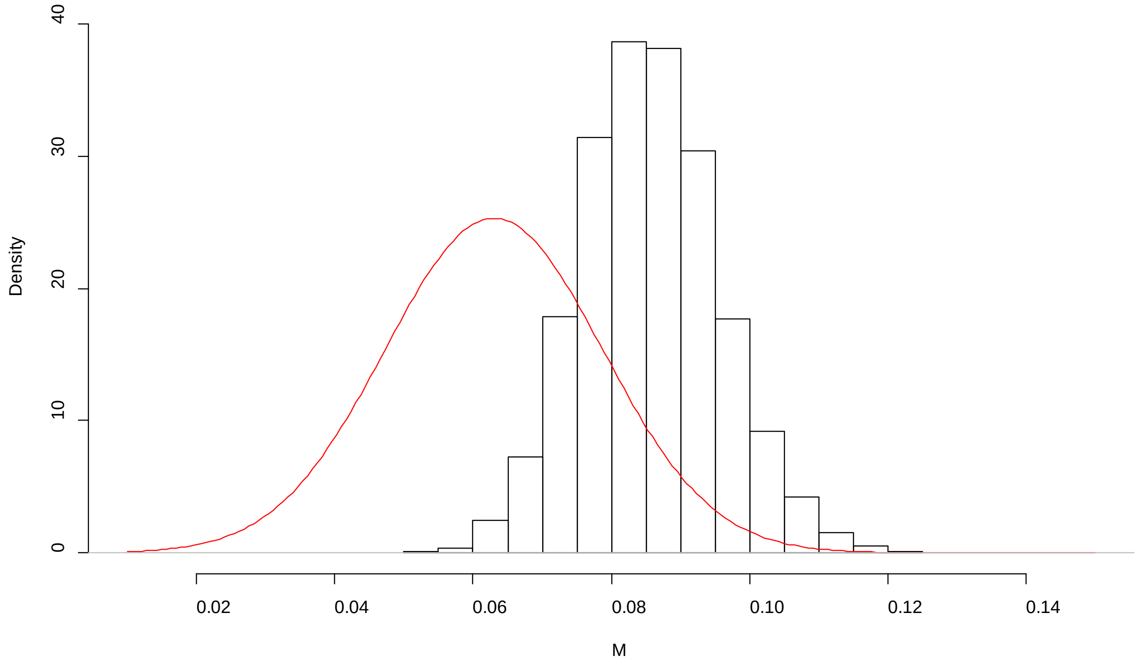

Figure 10: Reference model: the marginal posterior distribution of *M* (histogram) and the prior (red line).

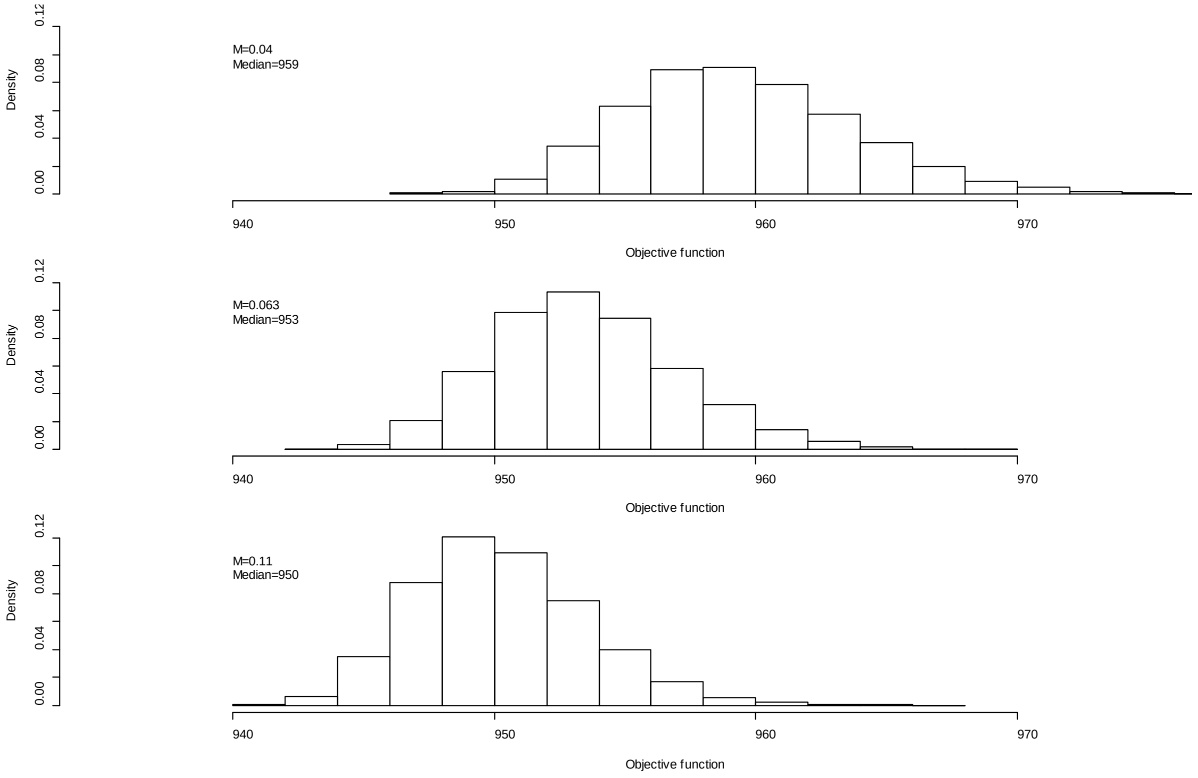

Figure 11: The distributions of the objective function for the Reference model run with fixed values of *M* (0.04, 0.063, and 0.11). The median value of the objective function is given in each legend.

The better fits to the data associated with lower objective function values are not associated with the acoustic biomass indices. The MCMC fit for the Reference model and the runs at the different fixed values of *M* are all adequate (Figure 12). Also, the MCMC residual distributions for the acoustic age frequencies are all very similar for the Reference model and the fixed-M models (Figures 13–15).

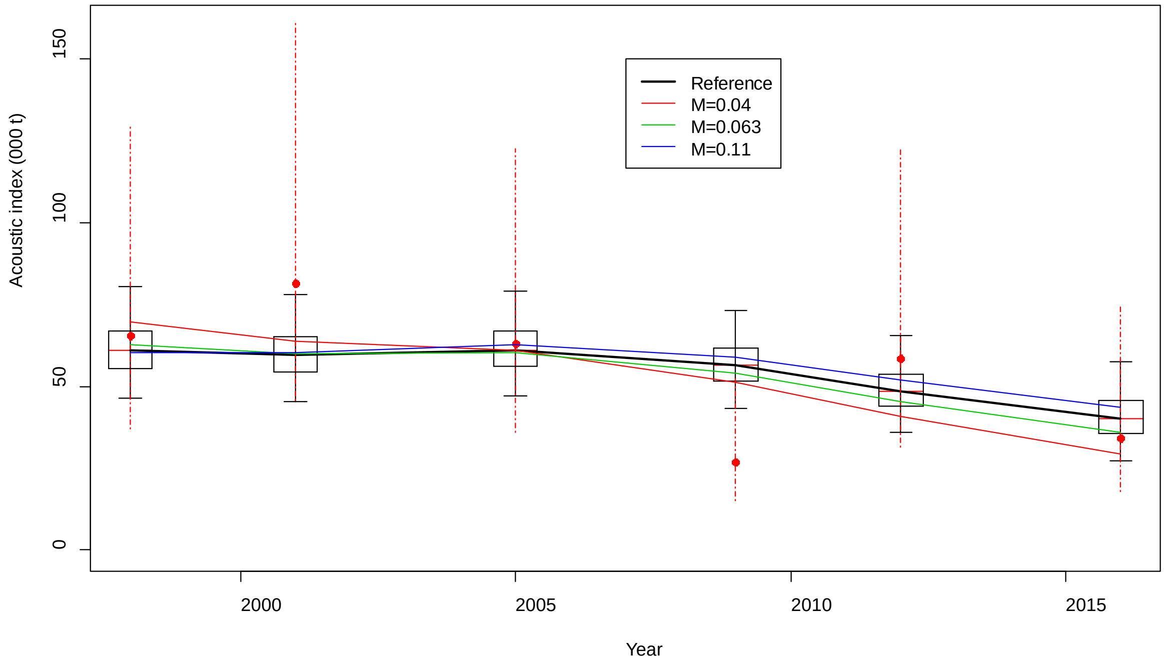

Figure 12: The MCMC fit to the acoustic biomass indices for the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). The acoustic indices are shown with 95% CIs. For each survey year the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

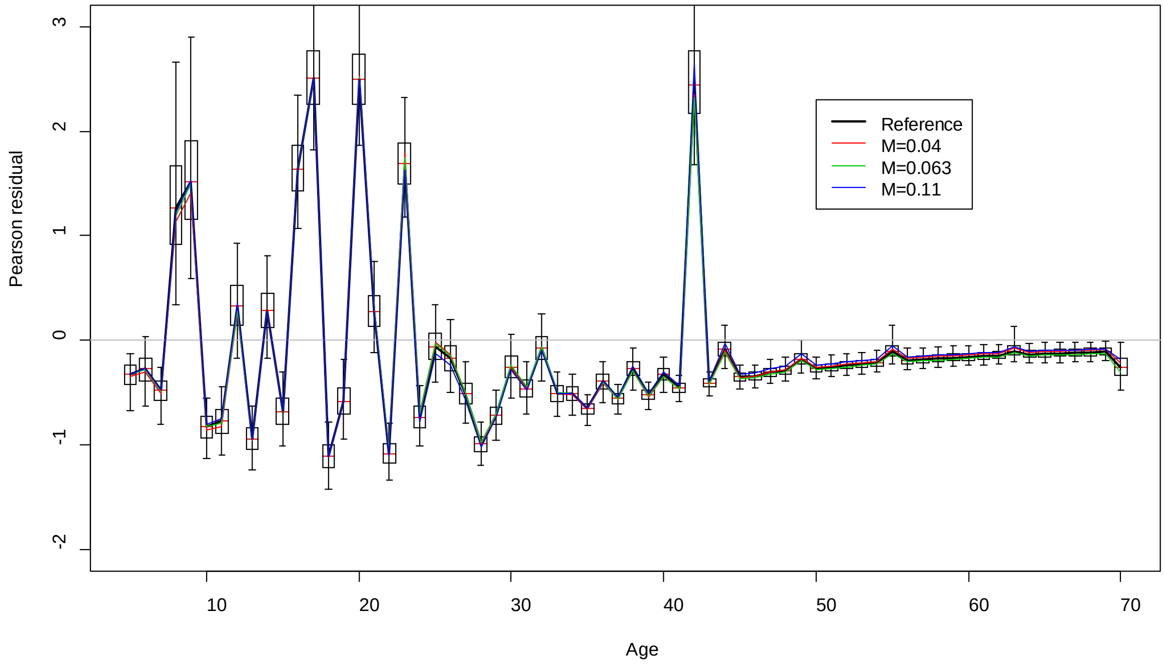

Figure 13: The MCMC Pearson residuals for the 1998 acoustic age frequency for the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). For each age the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

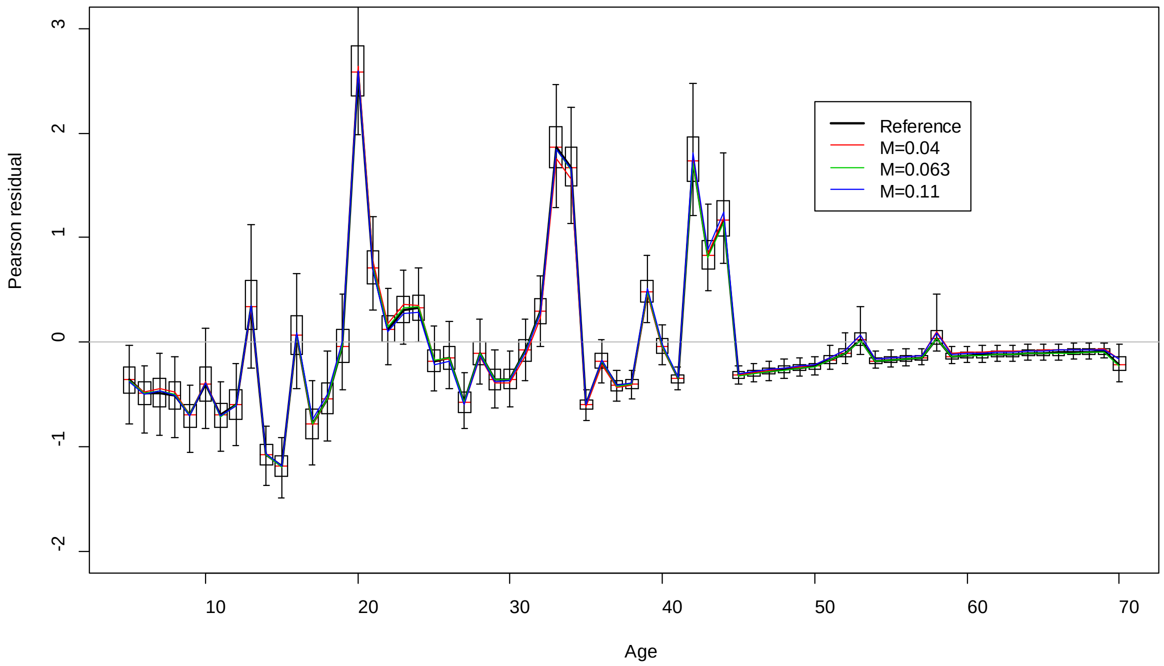

Figure 14: The MCMC Pearson residuals for the 2005 acoustic age frequency and the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). For each age the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

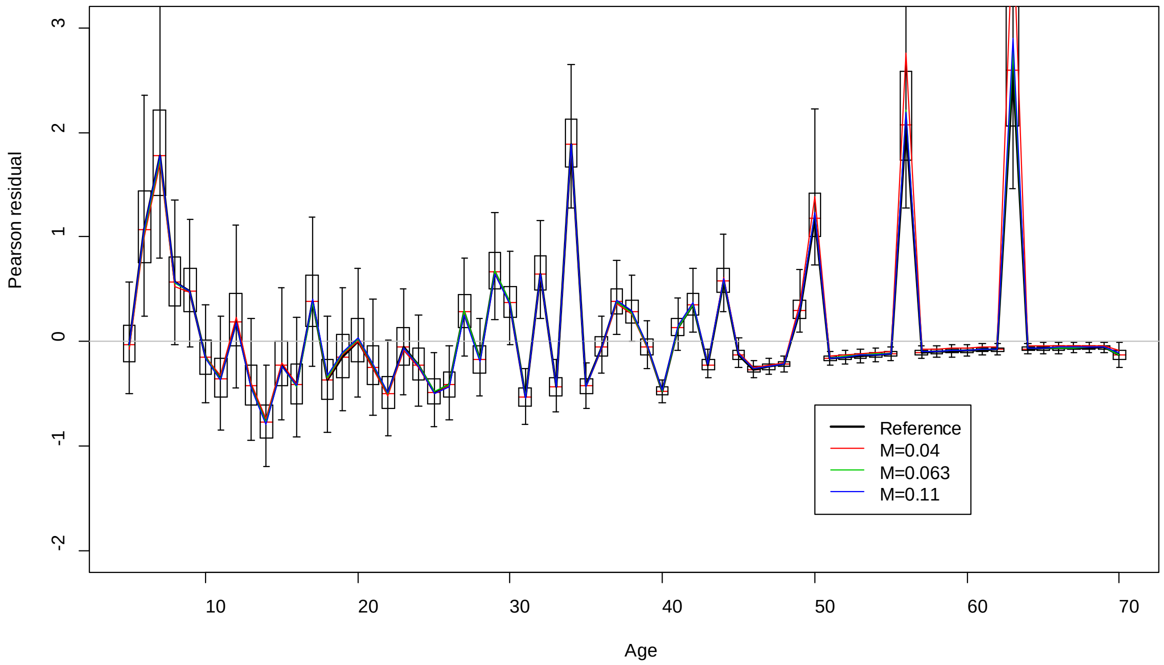

Figure 15: The MCMC Pearson residuals for the 2016 acoustic age frequency and the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). For each age the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

However, the similar fits to the acoustic age frequencies at different values of *M* are only achieved by having very different estimated selectivities. As *M* decreases from 0.11 to 0.04 the selectivity moves from being fairly flat-topped to become very domed and the peak selectivity shifts to the left (Figure 16).

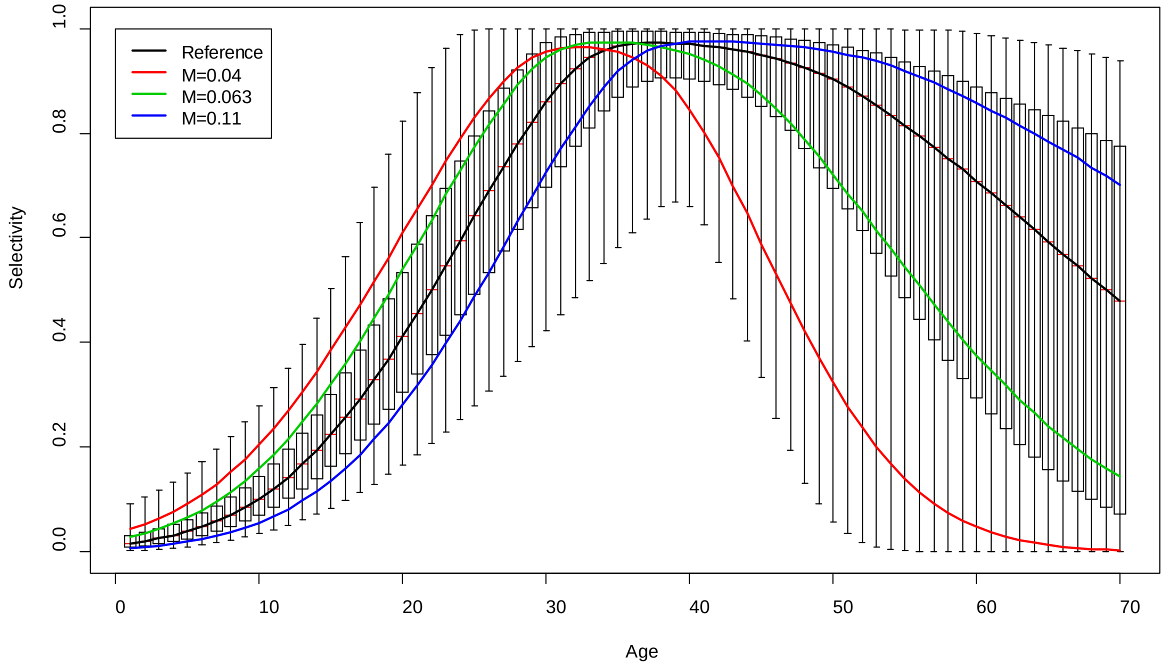

Figure 16: The MCMC estimated acoustic age frequency selectivity for the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). For each age the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

The commercial length frequencies show the strongest contrast in MCMC fits across the different values of *M*. The residual distributions show a similar pattern in each of the five years with *M* = 0.04 associated with the poorest fits to the data (Figures 17–21). There is a pattern indicating not enough large fish observed to be consistent with *M* = 0.04 and the other model assumptions (e.g., the fixed growth parameters).

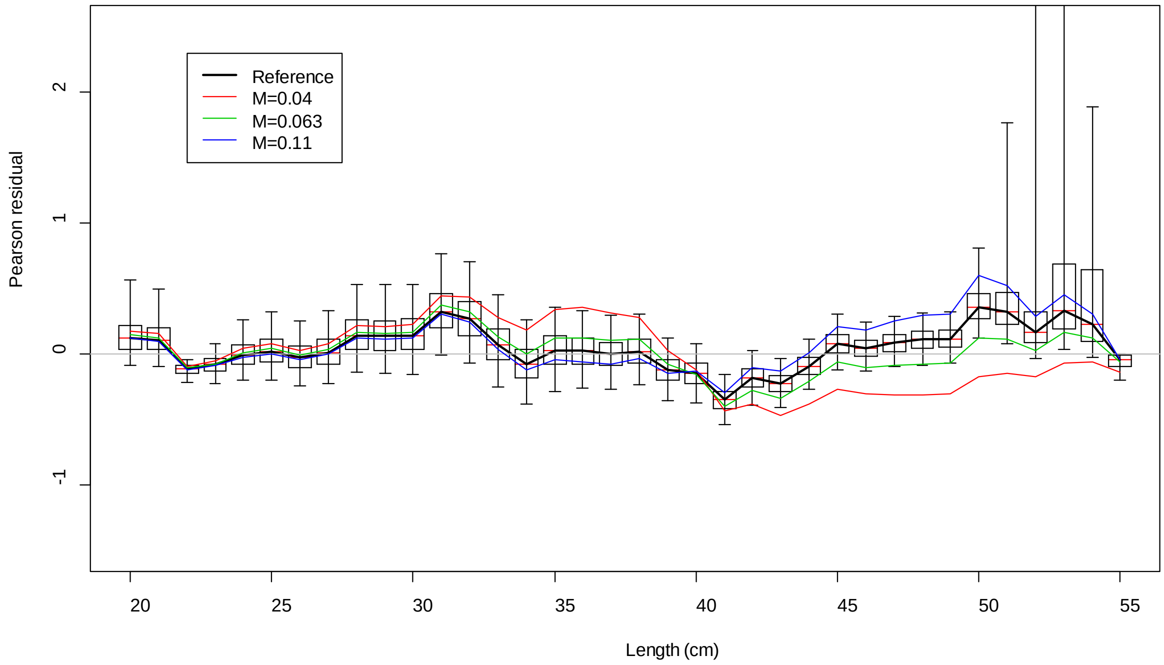

Figure 17: The MCMC Pearson residuals for the 1996 commercial length frequency and the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). For each length the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

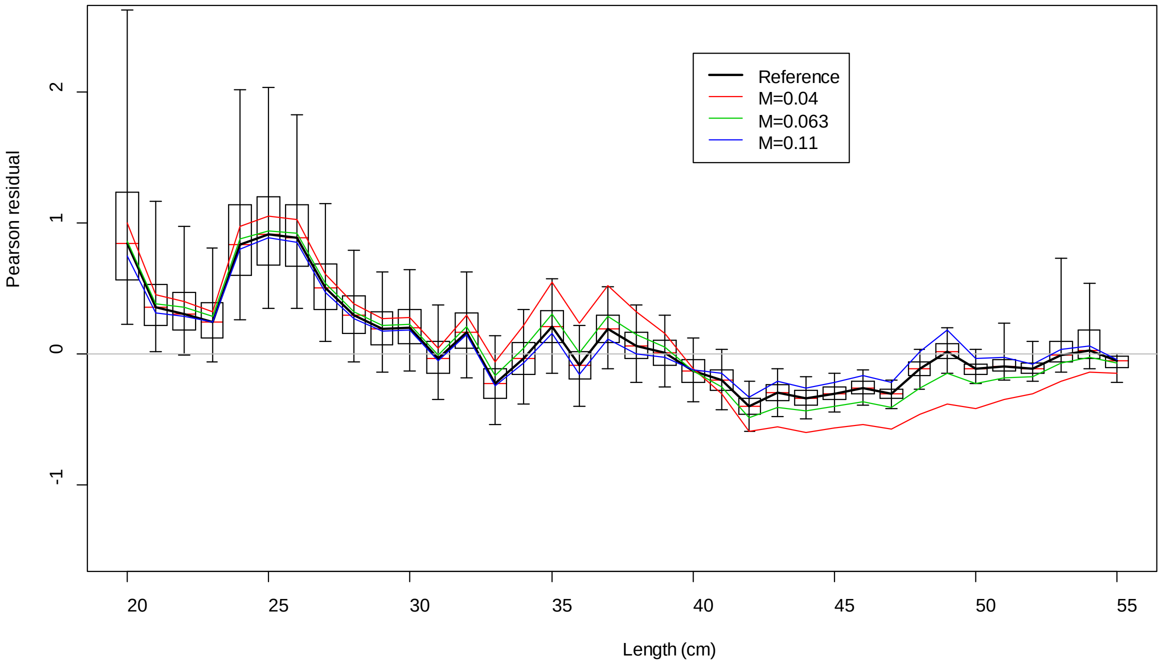

Figure 18: The MCMC Pearson residuals for the 1998 commercial length frequency and the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). For each length the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

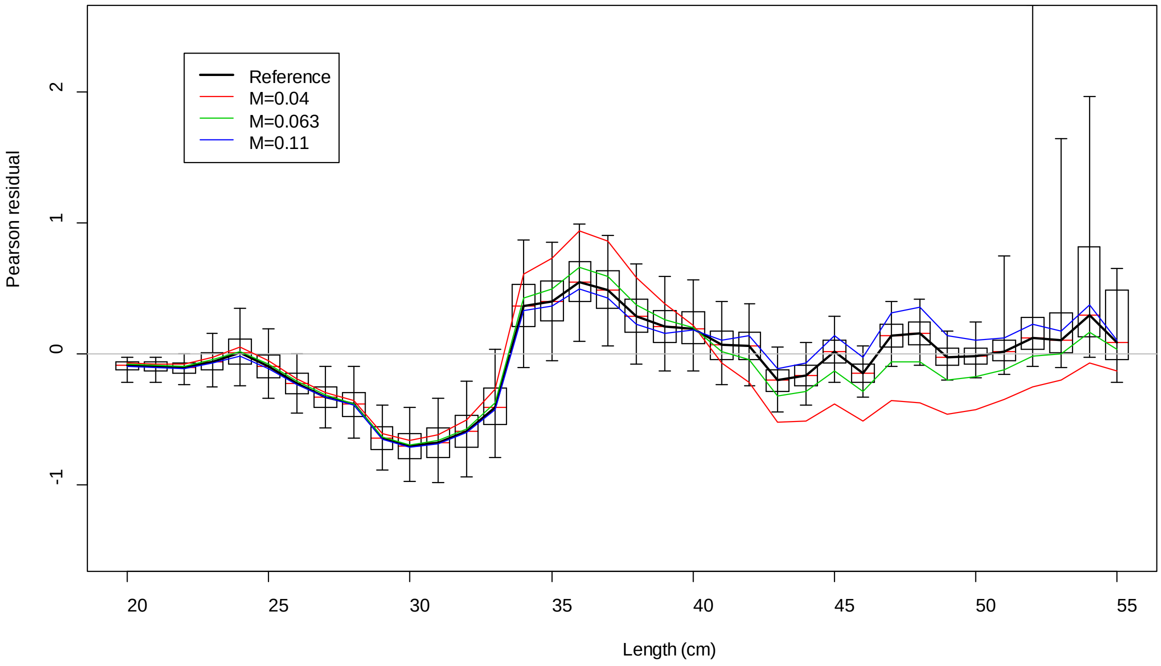

Figure 19: The MCMC Pearson residuals for the 2001 commercial length frequency and the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). For each length the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

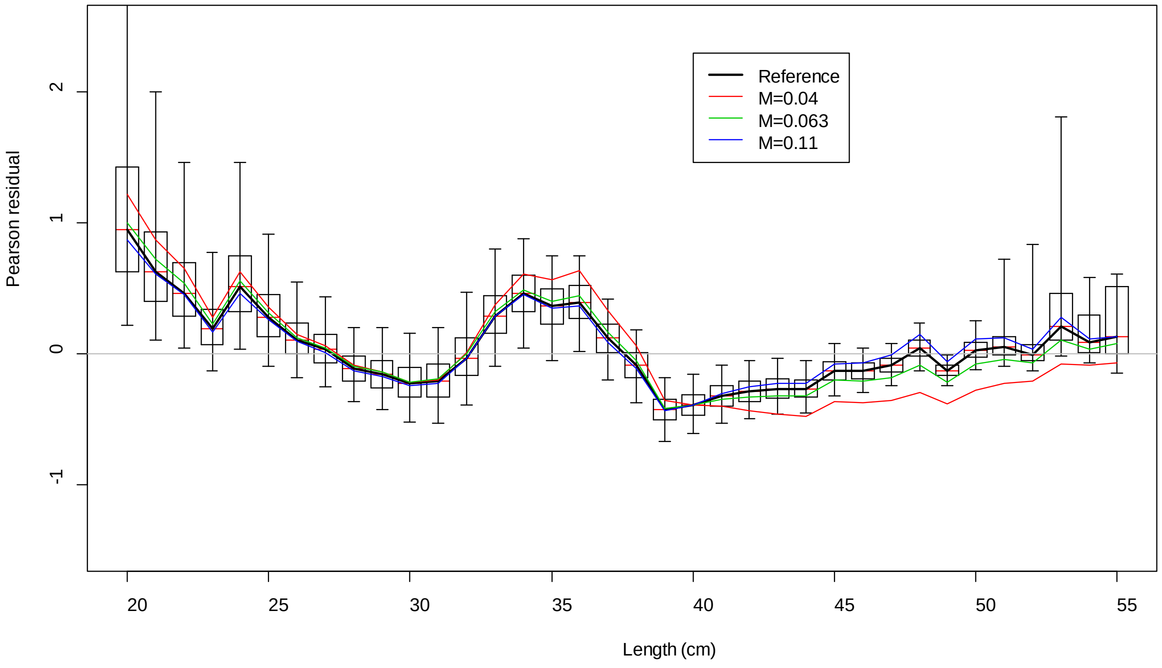

Figure 20: The MCMC Pearson residuals for the 2007 commercial length frequency and the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). For each length the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

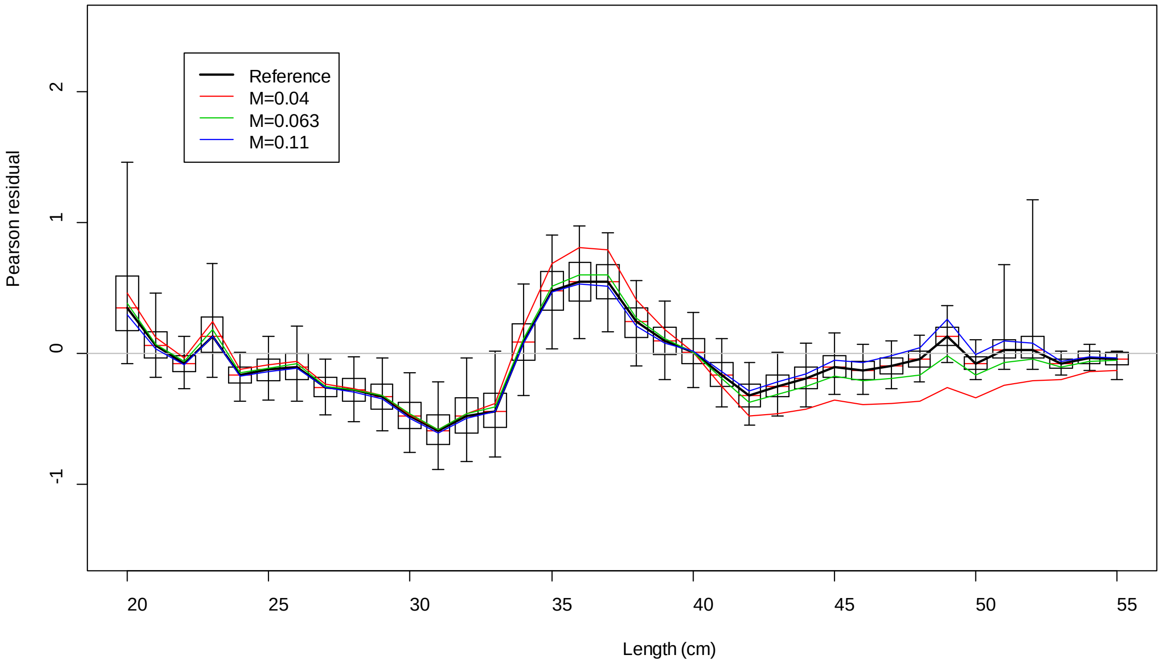

Figure 21: The MCMC Pearson residuals for the 2008 commercial length frequency and the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). For each length the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

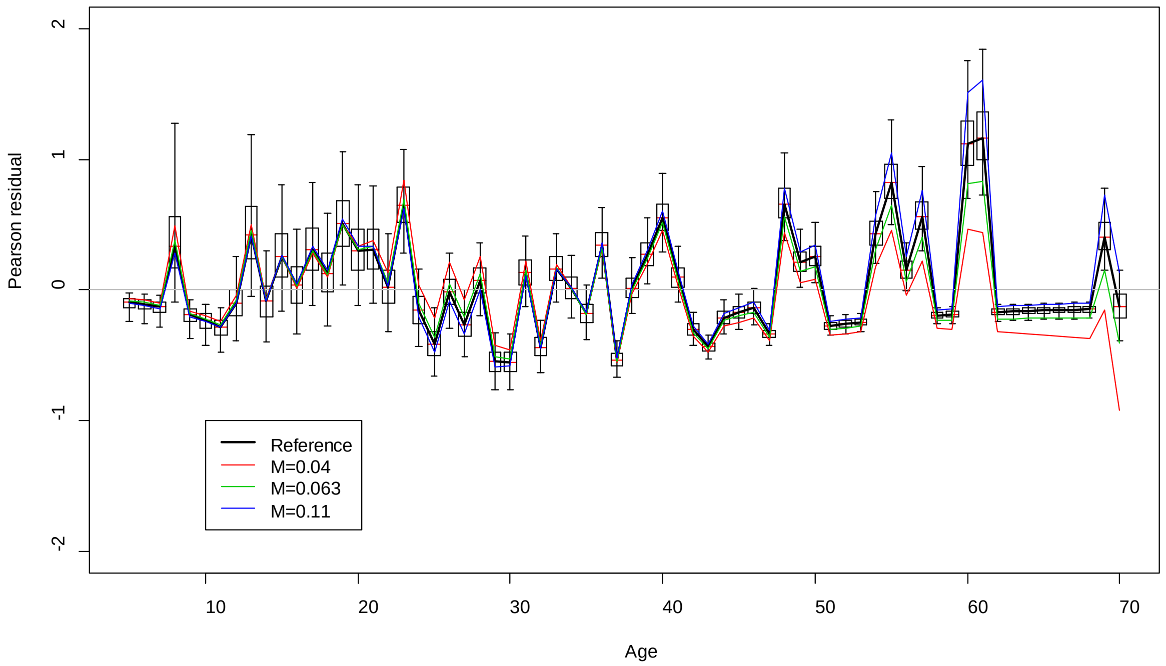

Figure 22: The MCMC Pearson residuals for the 2009 commercial age frequency and the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). For each age the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

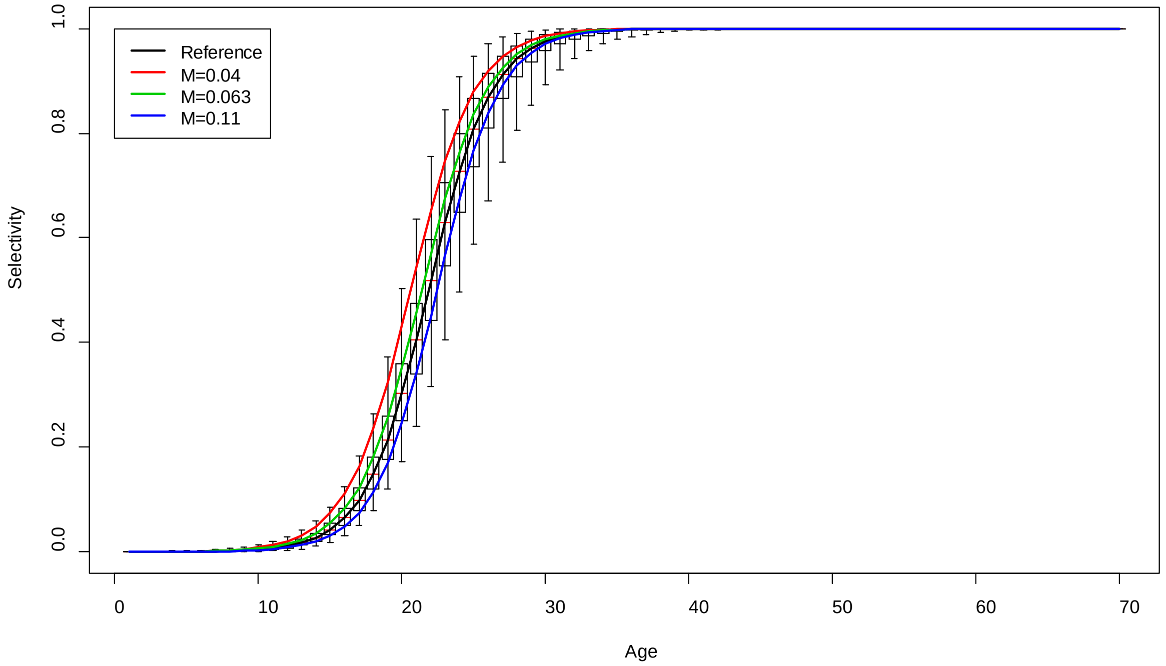

Figure 23: The MCMC estimated commercial selectivity for the Reference model (box and whiskers) and sensitivity runs (medians only) with fixed values of *M* (0.04, 0.063, 0.11). For each age the box covers the middle 50% of the distribution and the whiskers extend to 95% CIs.

The MCMC fit to the commercial age frequency changes with different values of *M* but it is not clear that one fit is better or worse than the others (Figure 22). The commercial selectivity is tightly constrained although there is a shift to the left with decreasing values of *M* (Figure 23).

The Reference run estimated current stock status to be just above the default target biomass of 40% B_0 (Table 9). Although the 95% CI was quite wide (26–60% B_0) there was no probability of being below the soft limit of 20% B_0 (Table 9). The two sensitivity runs that contrasted most with the Reference run were the run with a uniform prior on *M* and the run with high recruitment variability (rsd = 0.9) on the lognormal prior for free YCS parameters. The uniform prior on *M* gave a higher estimate of *M* (see Table 8) and an associated higher stock status (median 51% B_0). The "LN rsd=0.9" run gave a lower stock status of 38% B_0 and a 1% probability of being below the soft limit (Table 9).

Table 9: Reference model and sensitivity runs: MCMC point estimates and 95% CIs for B_0, B_{18}, and ss_{18} (B_{18}/B_0). The probability of current stock status being below 10% or 20% B_0 is also given. See Table 4 for the description of the runs.

Run	B_0 (000 t)		B_{18}(000 t)		ss_{18} (%B_0)		P(ss_{18} < 10%)	P(ss_{18} < 20%)
Reference	133	111–172	55	30–101	42	26–60	0.00	0.00
Est. M (unf.)	141	112–203	72	37–141	51	32–71	0.00	0.00
LN rsd=0.6	133	111–171	56	30–101	42	26–61	0.00	0.00
LN rsd=0.9	127	106–164	48	25–93	38	22–58	0.00	0.01
Three sels	131	111–168	56	30–103	43	26–63	0.00	0.00
No sex (k=0.055)	132	111–170	54	30–100	41	26–60	0.00	0.00

3.2 Final MCMC results

The DWFAWG chose to exclude the commercial length frequencies from the base model because of the influence on the estimate of *M*. They argued that the absence of larger fish than expected could be explained by errors in the growth model or other structural assumptions which were not strictly correct (e.g., constant selectivity at age). The base model is the Reference model with the commercial length frequencies excluded. The Reference model is renamed in this section as the sensitivity run "Incl. LFs".

For the base model, and all of the sensitivity runs, B_0 was estimated at about 140 000 t with 95% CIs ranging from about 110 000 t to 210 000 t (Table 10). Current stock status is estimated (by the median) to be within the biomass range of 30–50% B_0 for all of the runs. However, it is estimated to be just above 30% B_0 for the LowM-Highq and Fixed M runs (Table 10). For all of the runs the estimated probability of current stock status being below the soft limit of 20% B_0 is less than 5% (Table 10). The probability of current stock status being below the hard limit of 10% B_0 was estimated at 0 for all runs (Table 10).

Table 10: Bayesian estimates of *M*, B_0, and current stock status (B_{18}/B_0) for the base model and sensitivity runs (the median and 95% CIs are given). The probability of current stock status being below 10% or 20% B_0 is also given.

	M		B_0 (000 t)		ss_{18} (%B_0)		P(ss_{18} < 10%)	P(ss_{18} < 20%)
Base	0.079	0.057–0.10	138	111–184	40	23–59	0.00	0.01
LowM-Highq		0.0632	138	118–173	31	19–46	0.00	0.04
HighM-Lowq		0.0948	146	111–208	50	33–67	0.00	0.00
Incl. LFs	0.085	0.067–0.11	133	111–172	42	26–60	0.00	0.00
Fixed M		0.063	143	121–184	33	21–50	0.00	0.02

The spawning biomass trajectory for the base model shows a decreasing trend from the start of the fishery in the 1980s with a flattening off in 2015–16 when catches were substantially reduced (Figure 24, see Table 1 for the catches). Current stock status is estimated to be at the default target biomass of 40% B_0 although the 95% CIs are very wide (Figure 24, Table 10).

The estimated year class strengths show a pattern (in the medians) from 1972 to 1987 of above average cohort strength with below average cohort strength from 1990 to 2005 (Figure 25).

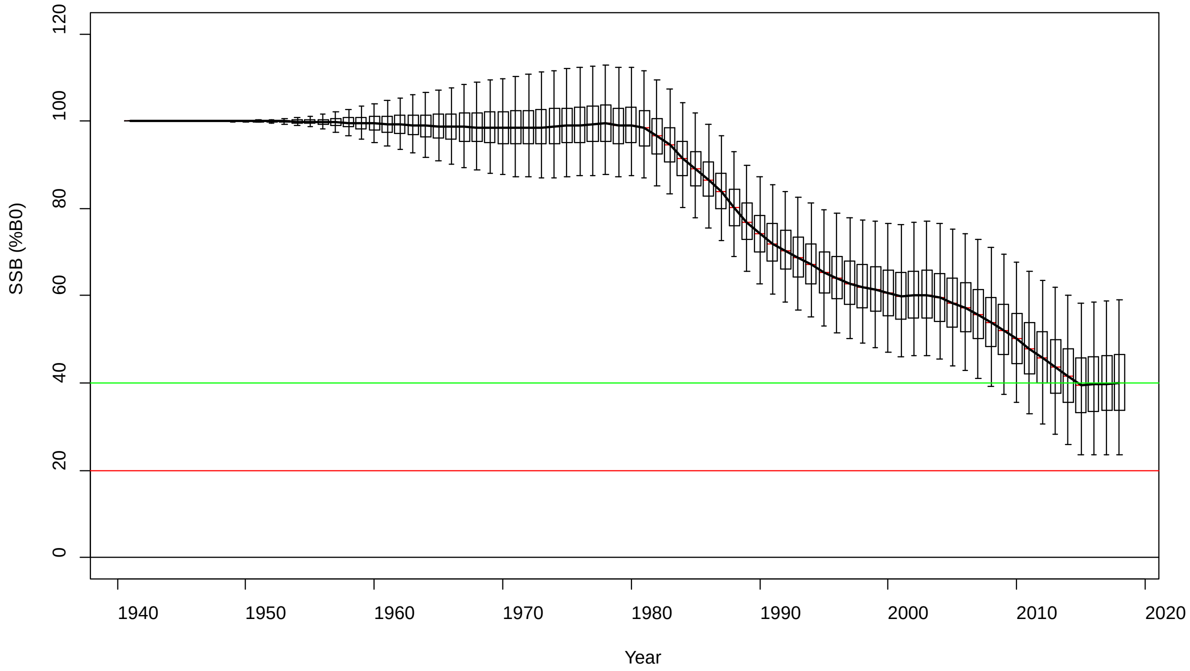

Figure 24: Base model: MCMC estimated spawning-stock biomass trajectory. The box in each year covers 50% of the distribution and the whiskers extend to 95% of the distribution. The soft limit (red) and target biomass (green) are marked by horizontal lines.

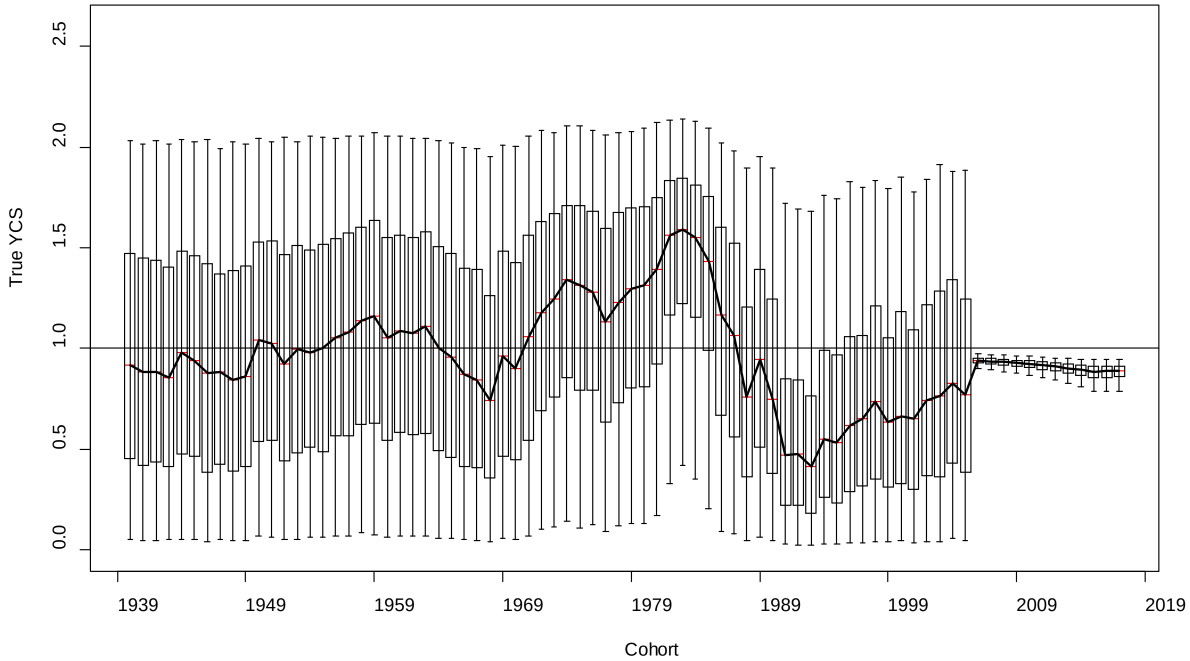

Figure 25: Base model: MCMC estimated "true" YCS (R_y/R_0). The box in each year covers 50% of the distribution and the whiskers extend to 95% of the distribution.

Exploitation rates in the fishery were estimated to be generally increasing from the start of the fishery up until 2014–15 (Figure 26). Catches in the years immediately prior to the TACC reduction in 2015–

16 were at a level increasingly above the default target exploitation rate ($U_{40\%B0}$). With the substantial catch reduction in 2015–16 the estimated exploitation rate (median) dropped to below 5% where it has remained (Figure 26). The historical trajectory of median stock status and median exploitation rate shows a steady increase in exploitation rates (from the start of the fishery) and an associated decrease in spawning biomass which was arrested in the last four years (Figure 27).

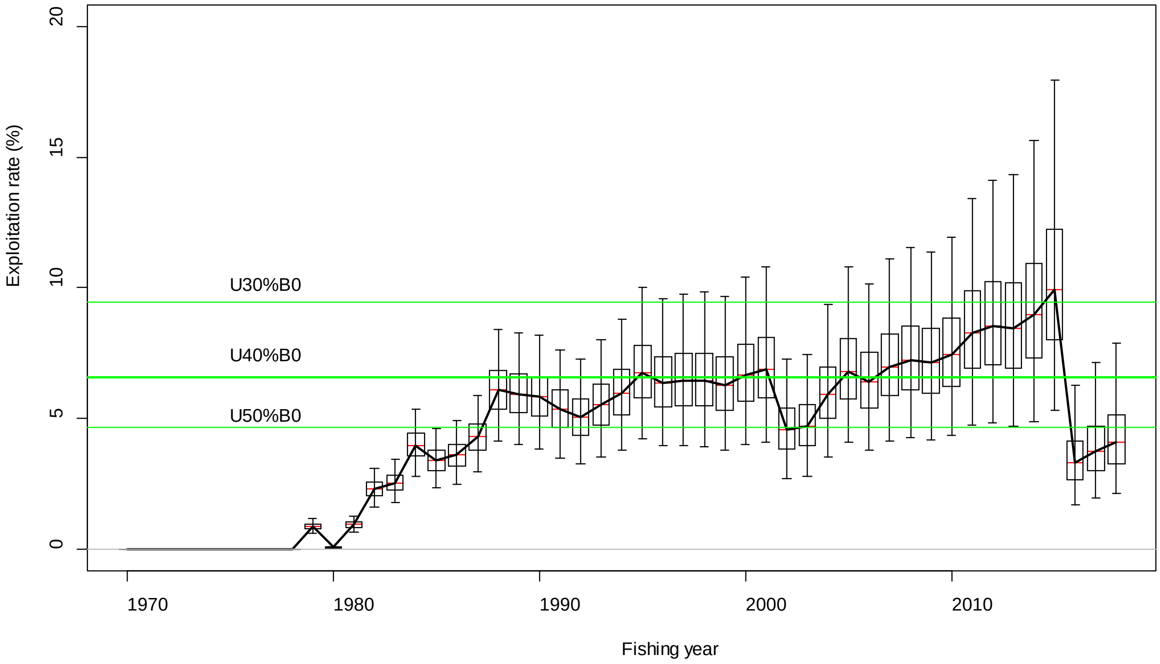

Figure 26: Base model: MCMC estimated exploitation rate trajectory. The box in each year covers 50% of the distribution and the whiskers extend to 95% of the distribution. The exploitation rate limit ($U_{40\%B0}$) associated with the default biomass target of 40% *B_0* is marked by the middle horizontal line ($U_{x\%B0}$ is the exploitation rate that will drive deterministic spawning biomass to x% B_0). $U_{30\%B0}$ and $U_{50\%B0}$ are also marked by horizontal lines.

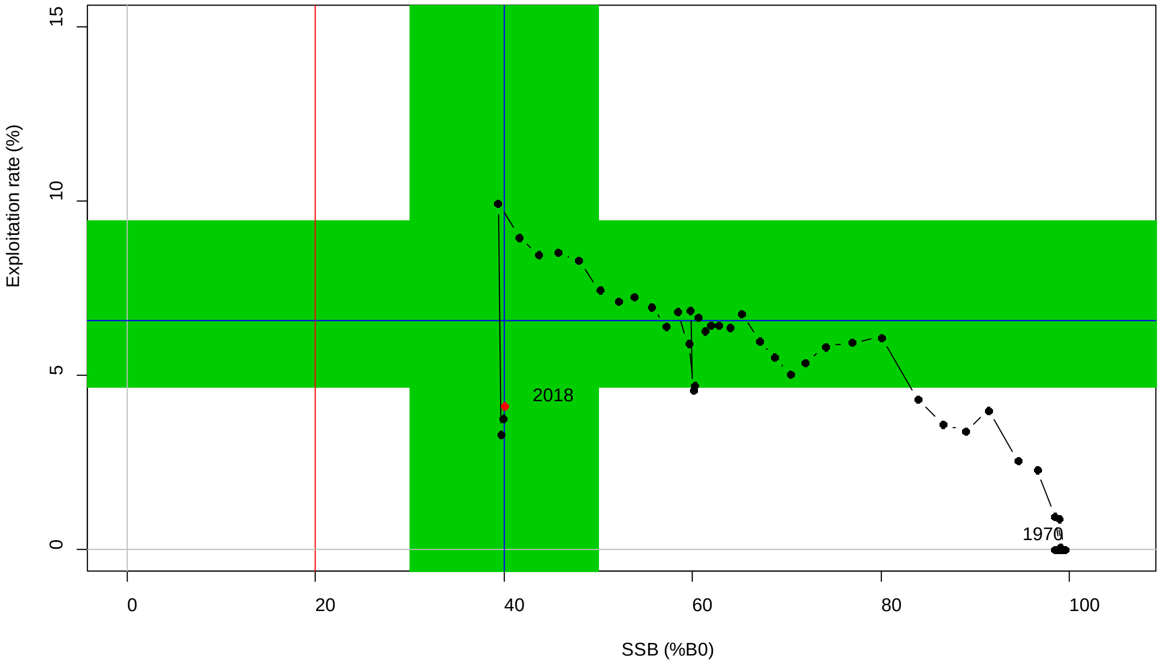

Figure 27: Historical trajectory of spawning biomass (%*B_0*) and exploitation rate (%) (base model, medians of the marginal posteriors). A reference range of 30–50% *B_0* and the corresponding exploitation rate range are coloured in green. The soft limit (20% *B_0*) is marked by a red line and the target biomass (40% *B_0*) and associated exploitation rate limit are marked by blue lines.

3.3 Biological reference points and management targets

For New Zealand stocks, the default target biomass in the absence of a dedicated analysis is 40% B_0 and limit reference points are defined at 20% B_0 ("soft limit") and 10% B_0 ("hard limit") (Ministry of Fisheries 2008). Subsequent to the stock assessment a target biomass *range* and a limit reference point were estimated. The base model was used as a starting point but the stock recruitment relationship was estimated as it is an important driver of reference points.

The priors for steepness for the Beverton-Holt and Ricker relationships (Figure 28) were borrowed from the orange roughy MSE (Cordue 2014b) as smooth oreo are not dissimilar from orange roughy being a deep water species with low natural mortality. The prior on M used in the base model was of course unchanged.

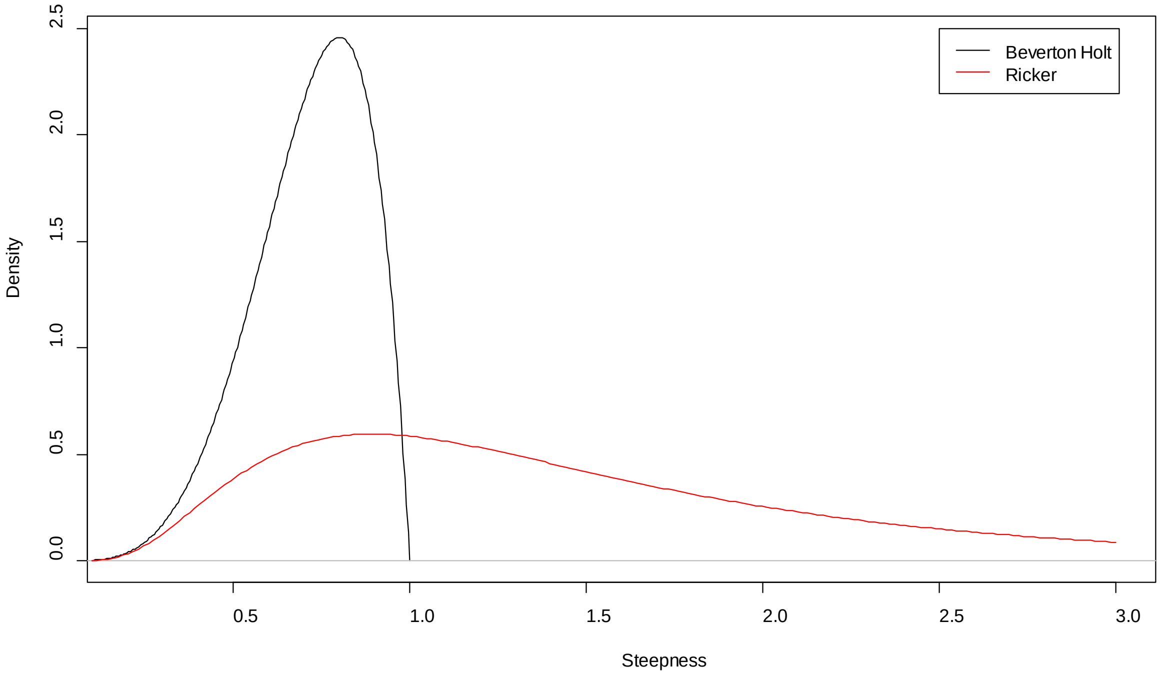

Figure 28: The prior distribution for Beverton-Holt steepness from DFO (2010) and the "equivalent" prior distribution for Ricker steepness (slopes at the origin were equated).

As for all of the estimate-M models, for the Beverton-Holt model the marginal posterior distribution of M was shifted well to the right of the prior (Figure 29). The posterior of steepness (h) was only slightly shifted to the left of the prior (Figure 30). For the Ricker model the posterior of M was very similar to that for the Beverton-Holt model (Figure 31) but the posterior for h was shifted very much to the left with the very high values of steepness in the prior mainly eliminated (Figure 32).

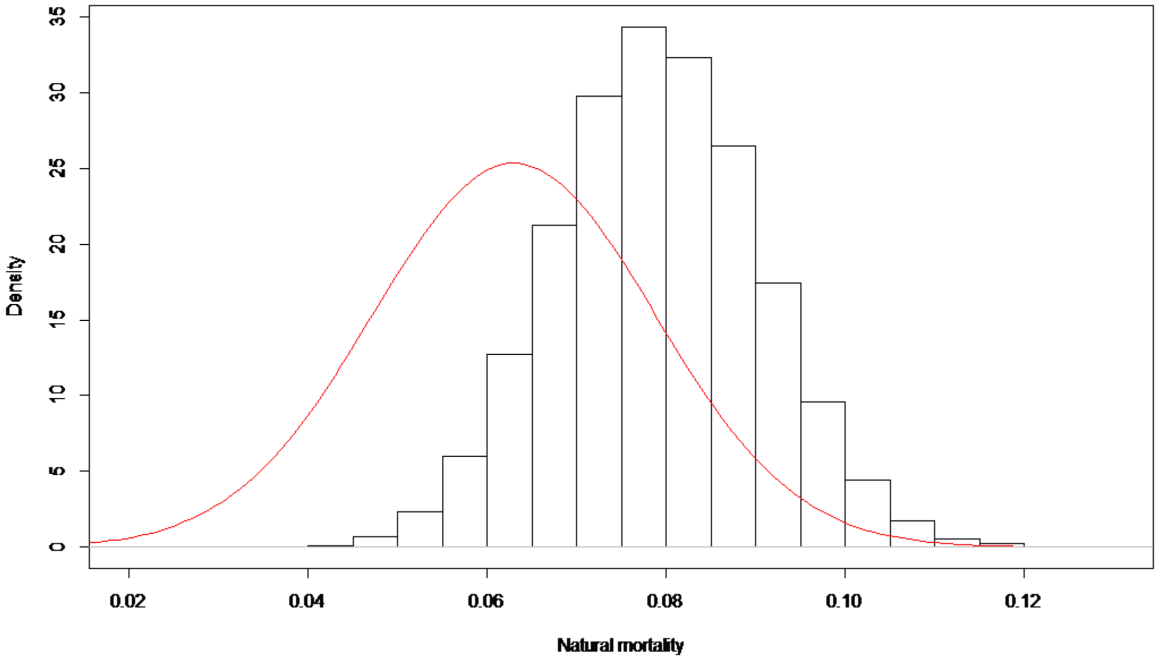

Figure 29: Beverton-Holt, estimate steepness run: marginal posterior distribution of *M* (histogram) and prior (red line).

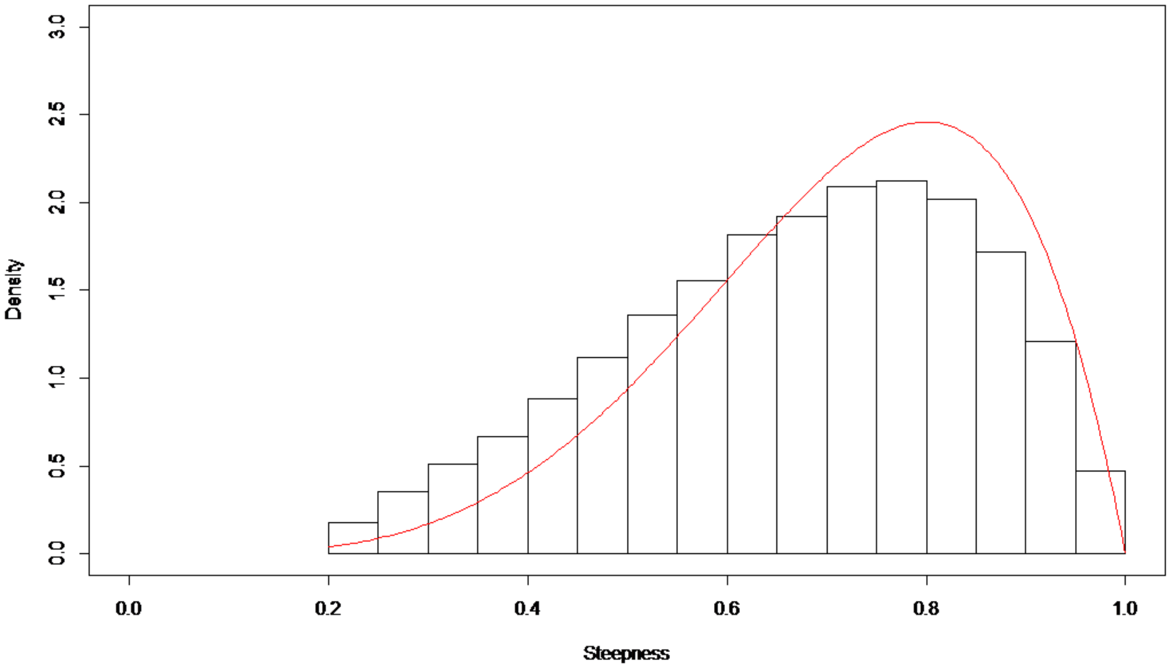

Figure 30: Beverton-Holt, estimate steepness run: marginal posterior distribution of *h* (histogram) and prior (red line).

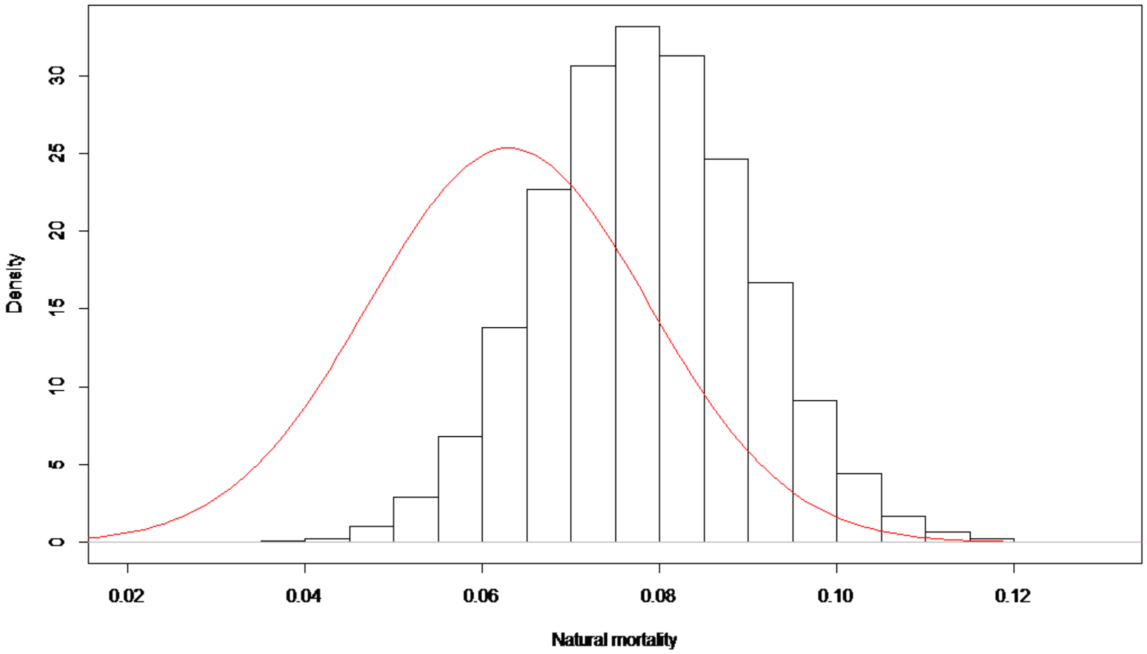

Figure 31: Ricker, estimate steepness run: marginal posterior distribution of *M* (histogram) and prior (red line).

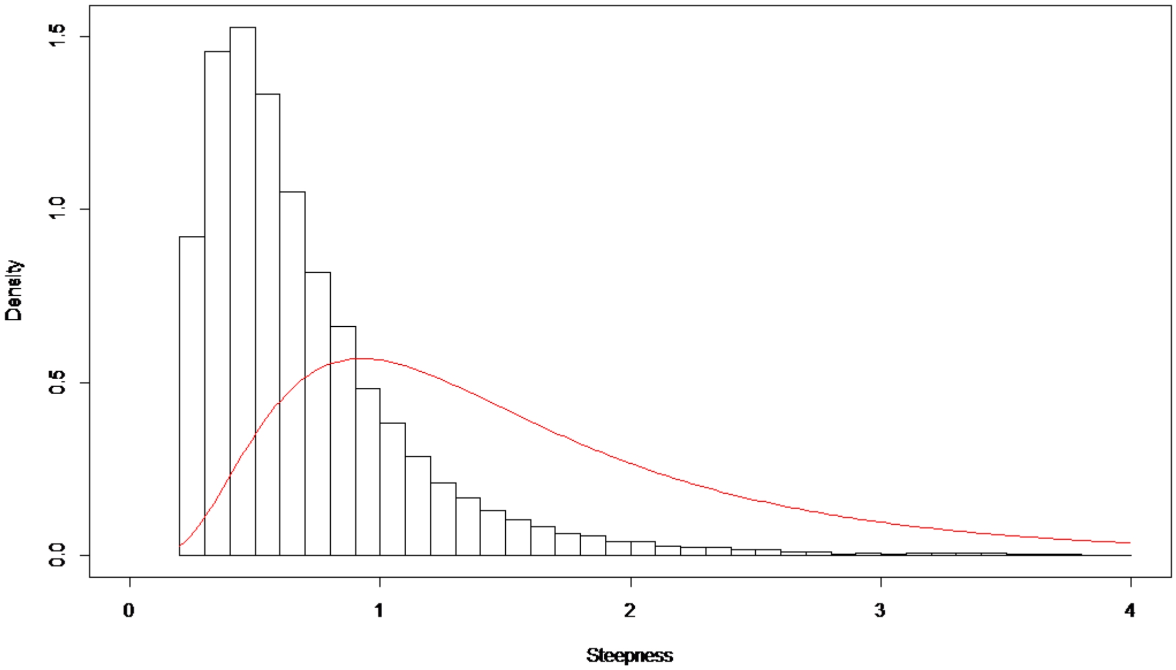

Figure 32: Ricker, estimate steepness run: marginal posterior distribution of *h* (histogram) and prior (red line).

For both Beverton-Holt and Ricker, deterministic B_{MSY}, as a function of *M* and *h*, is primarily driven by *h* with much smaller variation in value with changes in *M* (Tables 11 and 12). For steepness at or above 0.9 the Beverton-Holt B_{MSY} is below the soft limit of 20% B_0 (Table 11). For Ricker, even at the highest values of steepness (found in the posterior distribution), B_{MSY} is never less than 30% B_0 (Table 12).

Table 11: Beverton-Holt: B_{MSY} as a function of M and h. * This was an assumed value as it was not well defined.

				Natural mortality (M)
Steepness (h)	**0.037**	**0.050**	**0.100**	**0.125**
0.21	54	53	52	52
0.25	48	47	47	47
0.30	45	44	44	44
0.50	35	35	34	33
0.60	32	31	29	28
0.75	26	26	23	21
0.90	19	18	14	13
1.00	11	9	9	9^*

Table 12: Ricker: B_{MSY} as a function of M and h. * This was an assumed value as it was not well defined.

				Natural mortality (M)
Steepness (h)	**0.035**	**0.060**	**0.090**	**0.130**
0.21	54	53	52	52
0.25	49	49	49	49
0.40	46	45	44	44
0.80	40	38	36	36
0.90	38	36	35	34
1.50	36	34	33	31
2.00	33	33	32	30
4.00	33	32	30	30
5.80	33	32	30	30^*

The limit reference point (according to the definition of being the maximum of 20% B_0 and half B_{MSY}) was estimated to be close to 20% B_0 (Table 13). The median of the combined distribution for Beverton-Holt and Ricker is exactly 20% B_0 (Table 13). This is the logical choice for a LRP.

The estimate of B_{MSY} for the Beverton-Holt relationship at 27% B_0 was much lower than for the Ricker relationship at 41% B_0 (Table 14). As there is no sensible basis for choosing between the two relationships, the logical midpoint of the target biomass range is the median of the combined distribution which is 35% B_0 (Table 14). However, where then would the lower limit on the target biomass range be put? If it was at 25% B_0 it would be uncomfortably close to the LRP.

The results of a long term projection, when fishing at $U_{35\%B0}$, show that the projected biomass is often below 30% B_0 and the 95% CIs almost extend to the proposed LRP of 20% B_0 (Figure 33). In contrast, when fishing at $U_{40\%B0}$ the projected biomass typically sits comfortably in the 30–50% B_0 range and is comfortably above the proposed LRP (Figure 34). A target biomass range of 30–50% B_0 is consistent with estimates of B_{MSY} and should maintain spawning biomass above the point of recruitment impairment (Table 15).

Table 13: Bayesian estimates of the Limit Reference Point (LRP).

		LRP (%B_0)
	Median	**95% CI**
Beverton-Holt	20	20–22
Ricker	21	20–25
Combined	20	20–24

Table 14: Bayesian estimates of B_{MSY}.

	B_{MSY} (%B$_0$)	
	Median	**95% CI**
Beverton-Holt	27	12–44
Ricker	41	32–50
Combined	35	14–48

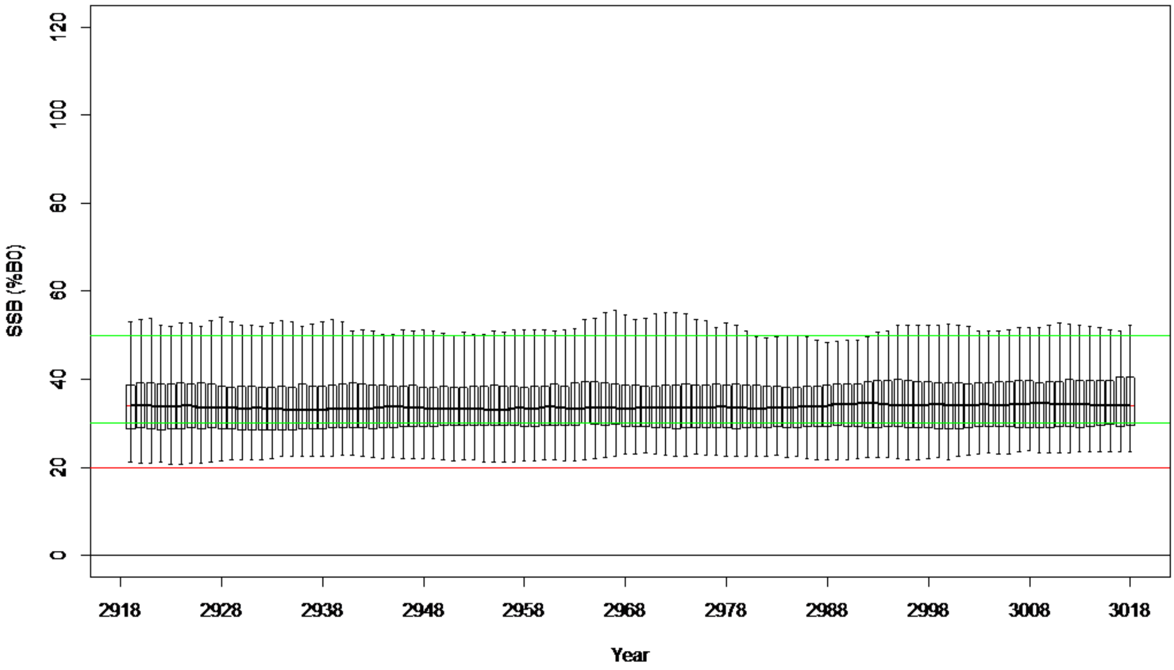

Figure 33: The last 100 years of a 1000 year projection for the base model when fishing at $U_{35\%B0}$. The box in each year covers 50% of the distribution and the whiskers extend to 95% of the distribution. The horizontal green lines are at 30% and 50% B_0.

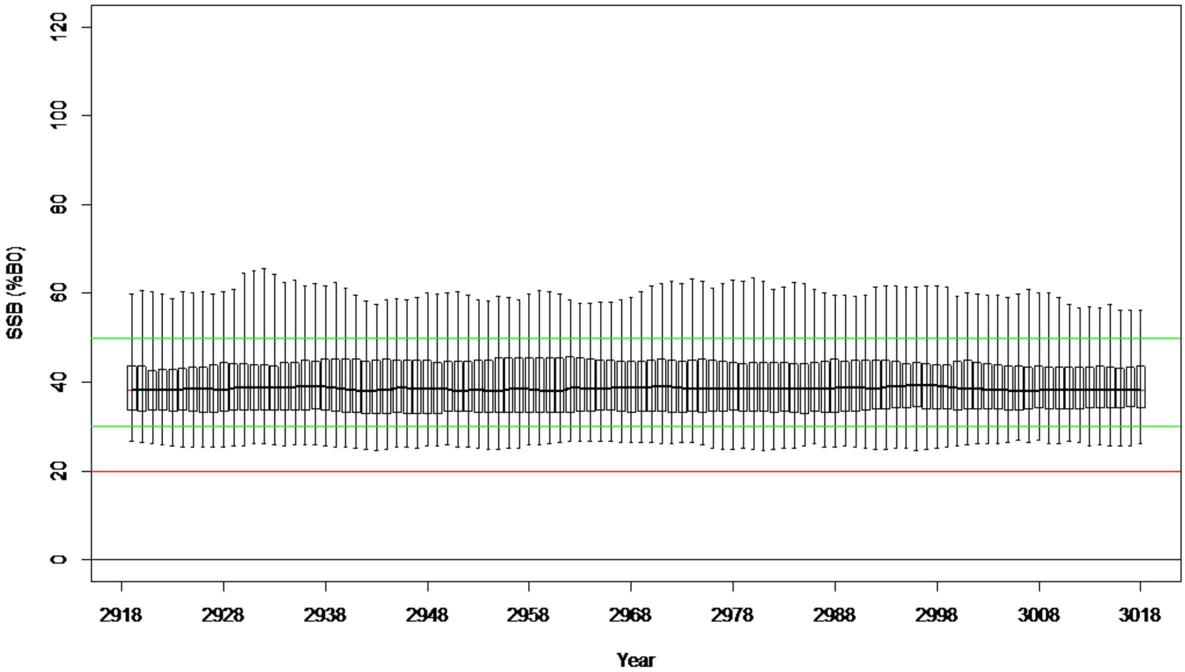

Figure 34: The last 100 years of a 1000 year projection for the base model when fishing at $U_{40\%B0}$. The box in each year covers 50% of the distribution and the whiskers extend to 95% of the distribution. The horizontal green lines are at 30% and 50% B_0.

Table 15: Bayesian estimates of average recruitment at 30% B_0 and 50% B_0 as a percentage of virgin recruitment.

	Av. at 30% B_0 (%)		Av. at 50% B_0 (%)	
	Median	**95% CI**	**Median**	**95% CI**
Beverton-Holt	80	42-97	90	63-99
Ricker	76	35-225	97	56-211

3.4 Projections

The projections from the base model show that annual catches in the range 2300–3300 t will maintain median stock status at about 40% B_0 (Table 16, Figure 35). At 3000 t the median stock status stays at 40% B_0 and there is slightly less than a 50% probability that the biomass in 2023 is greater than the biomass in 2018 (Table 16). Risks are all very low (Table 16). An annual catch of 2900 t gives a 50% chance that stock status in 2023 is above (or below) 40% B_0 (Table 16).

The projections from the fixed M model (M = 0.063) show an identical pattern to the base model for the three projections albeit with stock status starting lower in 2018 at 34% B_0 (Table 16, Figure 36). The stock assessment had 2018 stock status at 33% B_0 for the fixed M model. The small decrease of 200 t in the assumed 2017–18 catch has slightly increased the estimated stock status in 2018 (a shift from 33.4% to 33.9% which was magnified by rounding). Risks are all very low (Table 16)

Table 16: Fishery indicators for five year projections from the base model and the fixed M model at the annual catch limits shown. Indicators are: the mean stock status in 2023 ($E[ss_{23}]$) and the probabilities of 2023 stock status being greater than 40% B_0 ($P[ss_{23} > 40\%]$), less than the soft limit ($P[ss_{23} < 20\%]$), less than the hard limit ($P[ss_{23} < 10\%]$), and greater than 2018 stock status ($P[ss_{23} > ss_{18}]$).

Model	Catch (t)	$E[ss_{23}]$ (%B_0)	$P[ss_{23} > 40\%]$	$P[ss_{23} < 20\%]$	$P[ss_{23} < 10\%]$	$P[ss_{23} > ss_{18}]$
Base	2300	42	0.56	0.01	0.00	0.71
	2900	40	0.50	0.01	0.00	0.51
	3000	40	0.49	0.02	0.00	0.47
	3300	39	0.46	0.02	0.00	0.37
M=0.063	2300	35	0.28	0.02	0.00	0.74
	3000	34	0.21	0.04	0.00	0.44
	3300	33	0.19	0.05	0.00	0.32

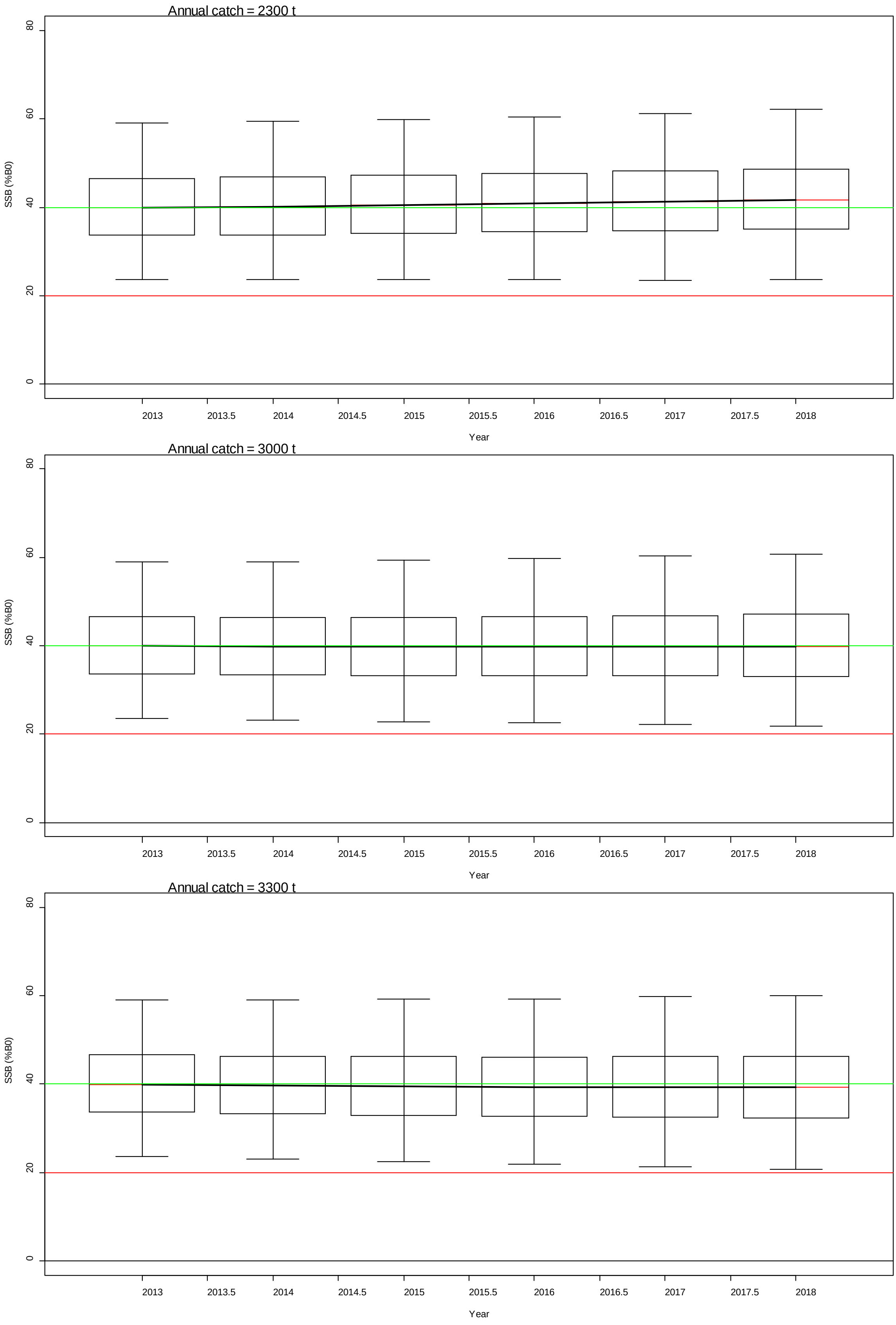

Figure 35: Projections from the base model for five years at annual catches of 2300 t (top), 3000 t (middle), and 3300 t (bottom). Each box covers the middle 50% of the distribution and the whiskers extend to 95% CIs. The soft limit of 20% B_0 and the default target of 40% B_0 are marked by horizontal lines.

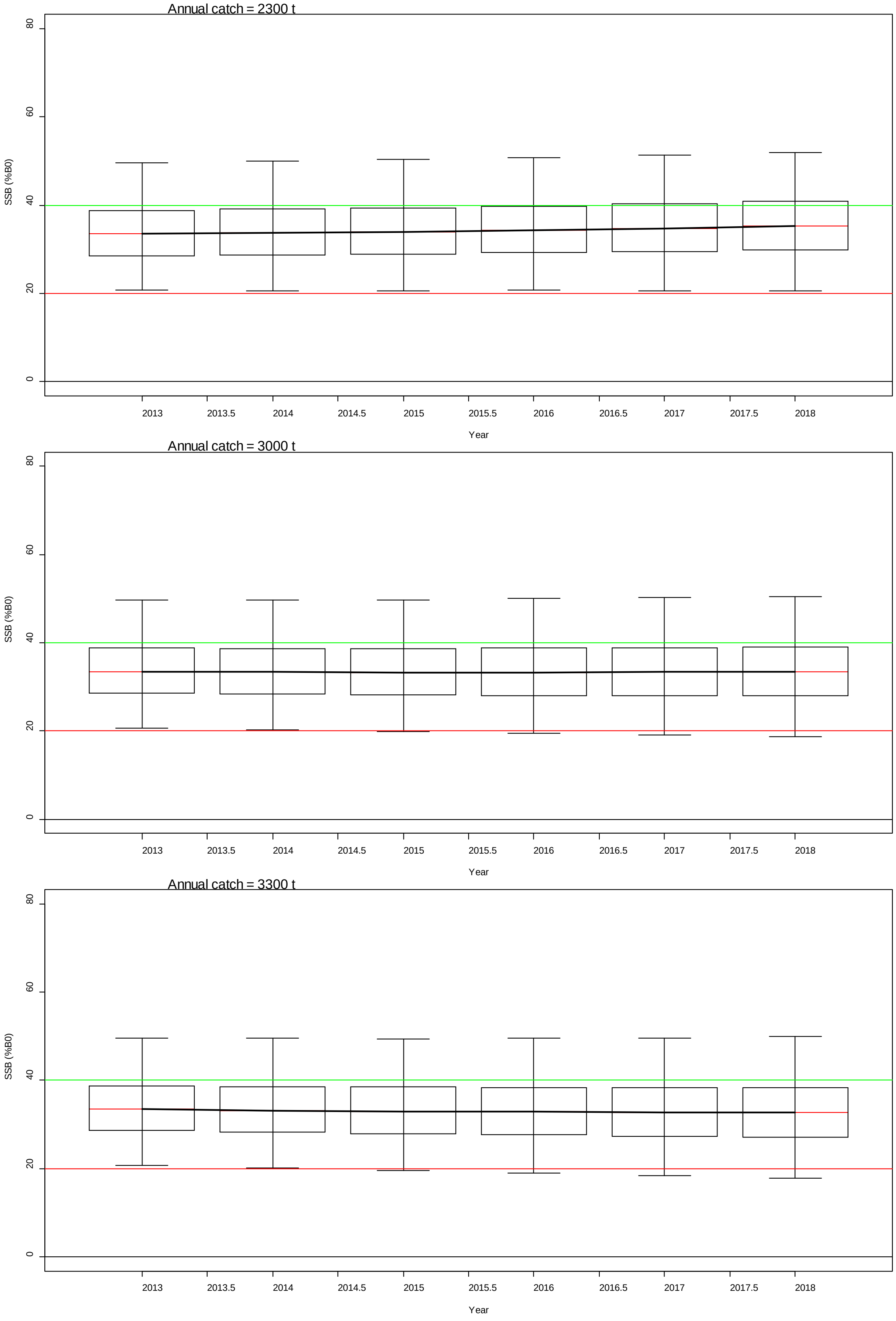

Figure 36: Projections from the fixed M model for five years at annual catches of 2300 t (top), 3000 t (middle), and 3300 t (bottom). Each box covers the middle 50% of the distribution and the whiskers extend to 95% CIs. The soft limit of 20% B_0 and the default target of 40% B_0 are marked by horizontal lines.

4. DISCUSSION AND CONCLUSIONS

The 2014 assessment of smooth oreo in OEO 4 found that the stock was being overfished and that catches would have to be substantially reduced (Fu & Doonan 2015). The review of that assessment, which was conducted as part of the update, detected a small numbers of errors in that analysis, which made almost no difference to the results. The assessment, when updated to the end of 2017–18 with the inclusion of new data and minor changes in parameterisation, was however more optimistic with 2013 stock status estimated at 33% B_0 rather than 29% B_0. However, the stock trajectory was still heading downwards with the 2018 stock status estimated at 30% B_0 (see Table 7).

The shift to an assessment in which *M* was estimated created a big shift in estimated stock status with 2018 stock status in the reference model estimated at 42% B_0 compared to 30% B_0 in the fixed-M model (see Tables 7 and 9). The increased estimate of *M* (0.0835) compared to the fixed value of 0.063 was responsible for the large increase in estimated stock status. The strongest signal from the data for a larger value of *M* was from the commercial length frequencies. This is not an ideal source of information with regard to *M* and so the DWFAWG decided to move from the Reference model to a base model which excluded the commercial length frequencies. In the base model, *M* is estimated at 0.079 (95% CI: 0.057–0.10) and current stock status is therefore a bit lower than the Reference model at 40% B_0 (95% CI: 23–59% B_0).

The principle that the “best available information” should always be used as the basis for stock assessment advice is very relevant to the issue of whether to move from a model where *M* is externally estimated to one in which it is internally estimated. The externally estimated value of *M* was the best available information quite some time ago and since then much relevant data have become available. The information from the early estimate of *M* was captured in the prior distribution for *M* used in the model. Five age frequencies contributed alternative information on the value of *M* and it is appropriate that the information from these data are given some weight in the latest stock assessment.

The projections from the base model show that annual catches in the range 2300–3300 t will maintain median stock status at about 40% B_0 (see Table 16, Figure 35). Risks are all very low (see Table 16). An annual catch of 2900 t gives a 50% chance that stock status in 2023 is above (or below) 40% B_0 (see Table 16).

The target biomass for this stock is currently set at the default level of 40% B_0 with default limit reference points of 20% B_0 (the soft limit) and 10% B_0 (the hard limit). The formal estimation of a LRP, using variations on the base model, produced a point estimate of 20% B_0 (95% CI: 20–24% B_0). For the purposes of MSC Principle 1 it is recommended that a LRP of 20% B_0 be adopted.

The formal estimation of B_{MSY} produced differing results for Beverton-Holt and Ricker stock recruitment relationships with respective point estimates of 27% B_0 and 41% B_0. The combined median estimate was 35% B_0 which suggested a target biomass range of 25–45% B_0. However, the lower bound of the target biomass range would then be uncomfortably close to the recommended LRP (20% B_0). A more conservative target biomass range of 30–50% B_0 is recommended for the smooth oreo stock in OEO 4.

5. ACKNOWLEDGEMENTS

This work was funded by the Deepwater Group Ltd. Thanks to members of MPI’s DWFAWG for providing useful comments and guidance on the assessment. Finally, thanks to NIWA for the use of their excellent stock assessment package CASAL.

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APPENDIX 1: Example MCMC chain diagnostics

Some example chain diagnostics are given below for some of the model runs. All of the diagnostics for all of the runs appeared to be very good.

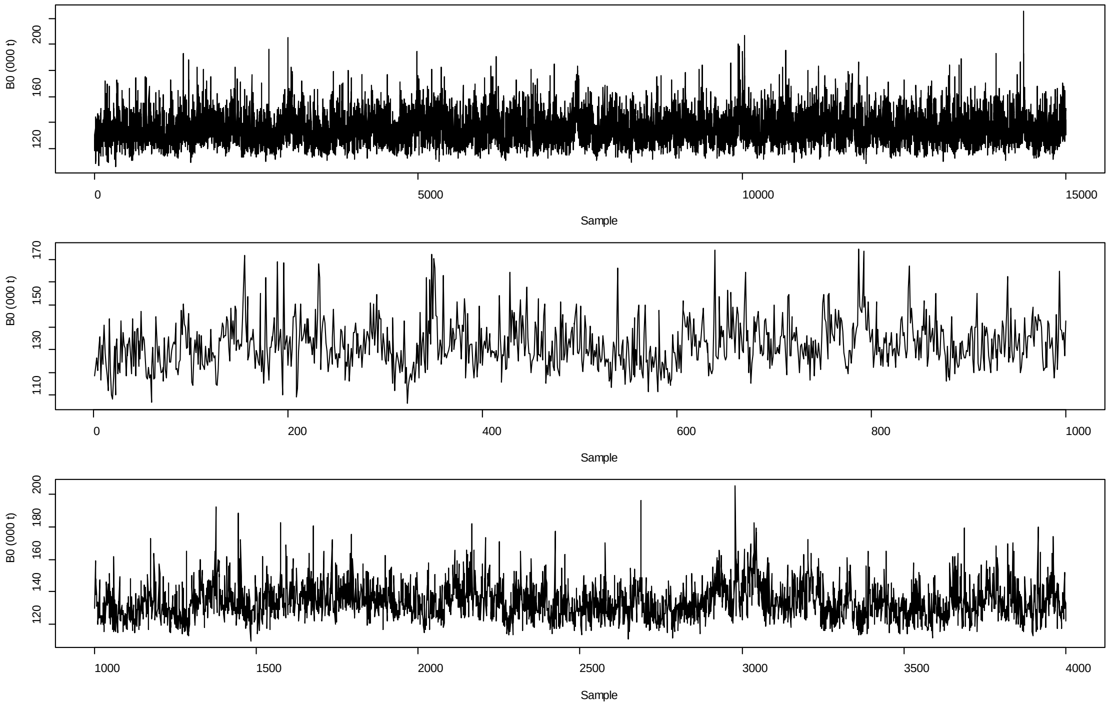

Figure A1: The first MCMC chain for the fixed *M* = 0.063 run in 2018. The top panel shows the full chain, the second panel the burn-in period, and the third panel the first 3000 stored samples after the burn-in period.

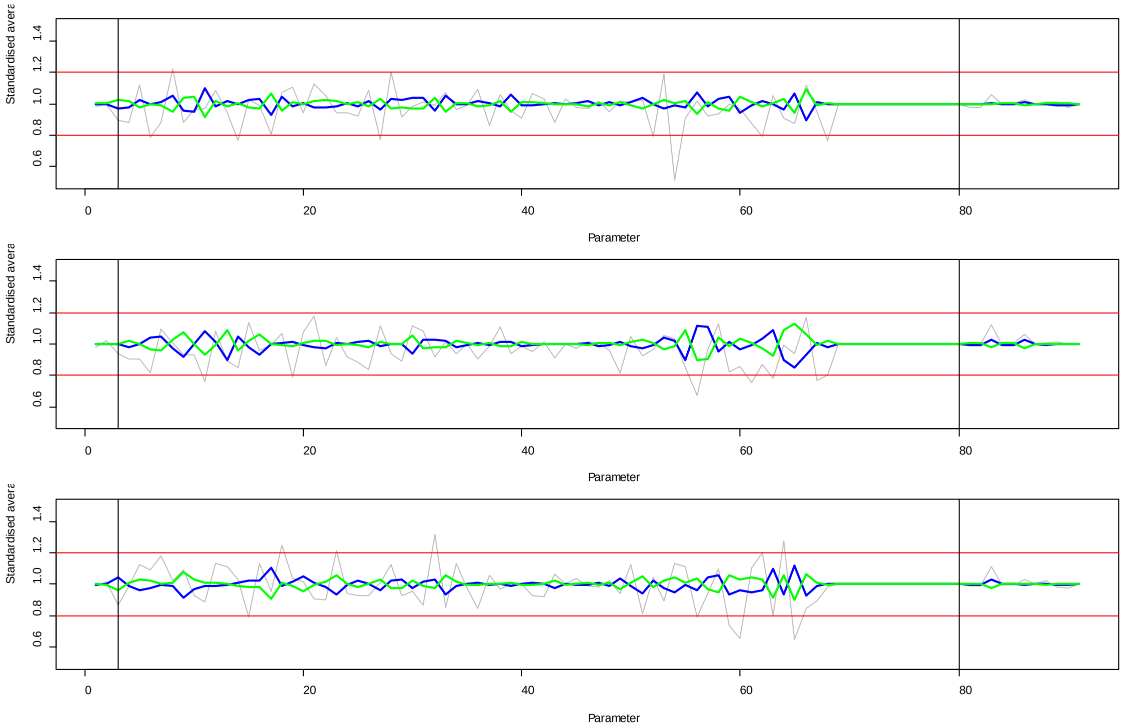

Figure A2: The check for parameter drift in each chain of the fixed *M* = 0.063 run in 2018 (chains 1 to 3 from top to bottom). The parameters are on the x axis with the vertical lines marking the start and end of the free YCS parameters. The grey line is the burn-in period, the blue line the first half of the non burn-in period and the green line the second half of the non burn-in period. The standardised average for each parameter is the average within the period divided by the average of the non burn-in period. Horizontal lines marked at 0.8 and 1.2.

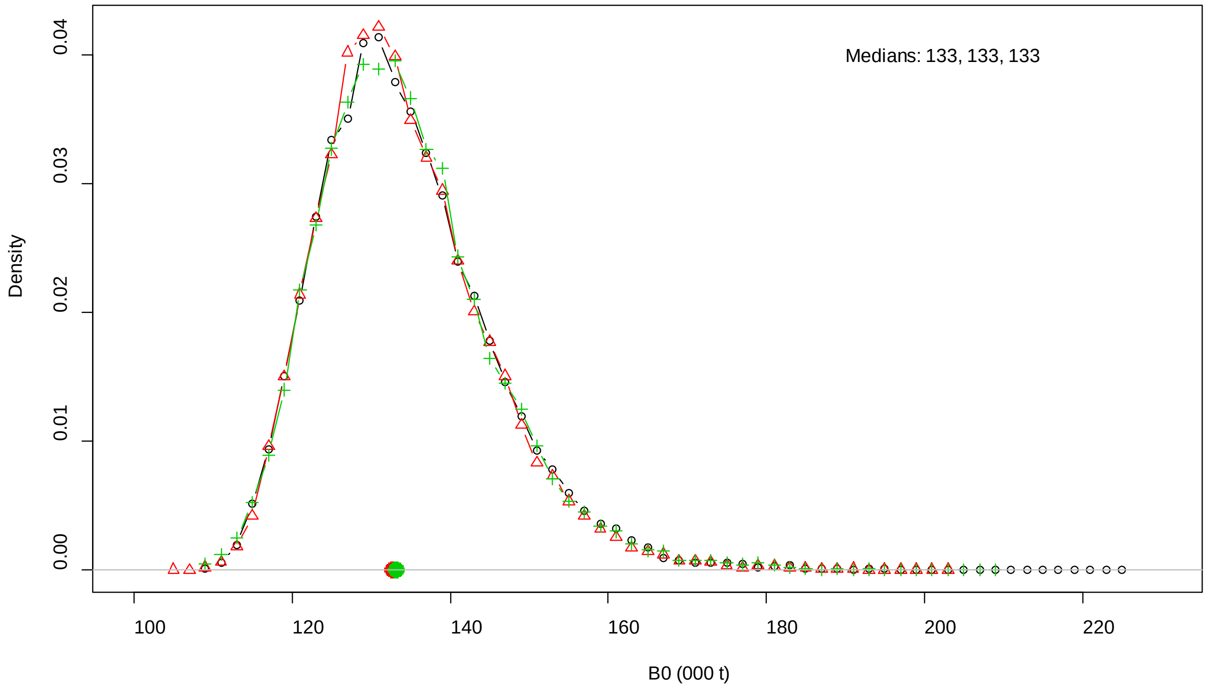

Figure A3: Fixed *M* = 0.063 run in 2018: histograms of B_0 for each of the three chains after burn-in. The medians of each chain are plotted as filled circles on the x axis and the values noted in the legend (each chain had a median B_0 of 133 000 t).

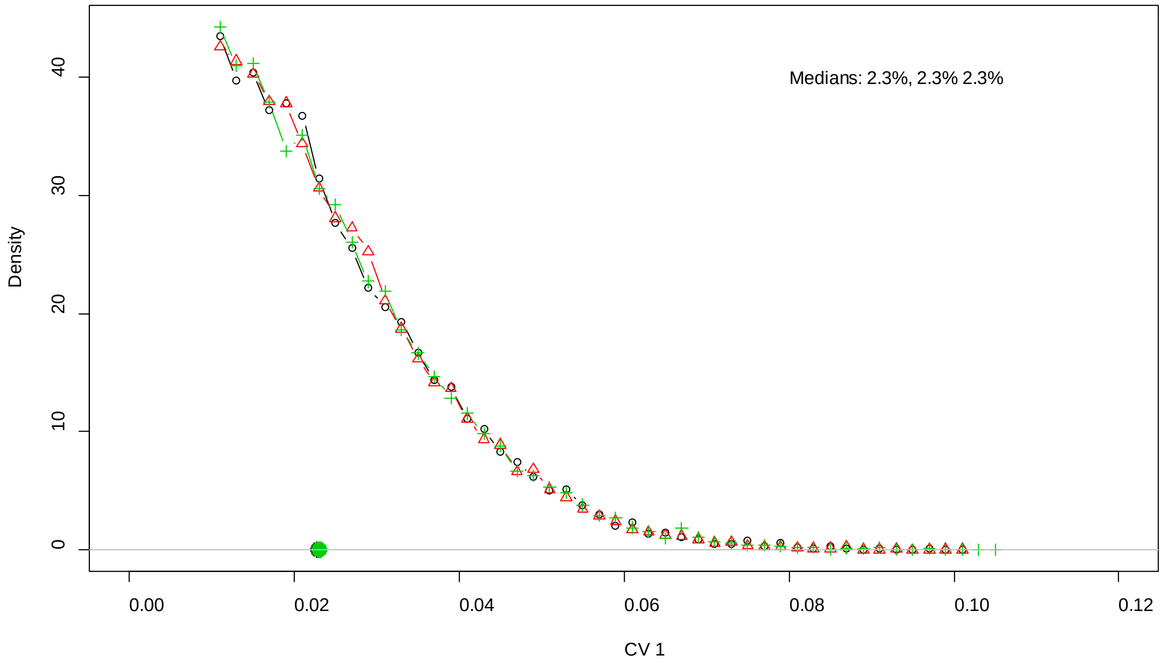

Figure A4: Fixed *M* = 0.063 run in 2018: histograms of CV1 for each of the three chains after burn-in. The medians of each chain are plotted as filled circles on the x axis and the values noted in the legend. CV1 is the CV of length at mean length at age for fish aged 1 year.

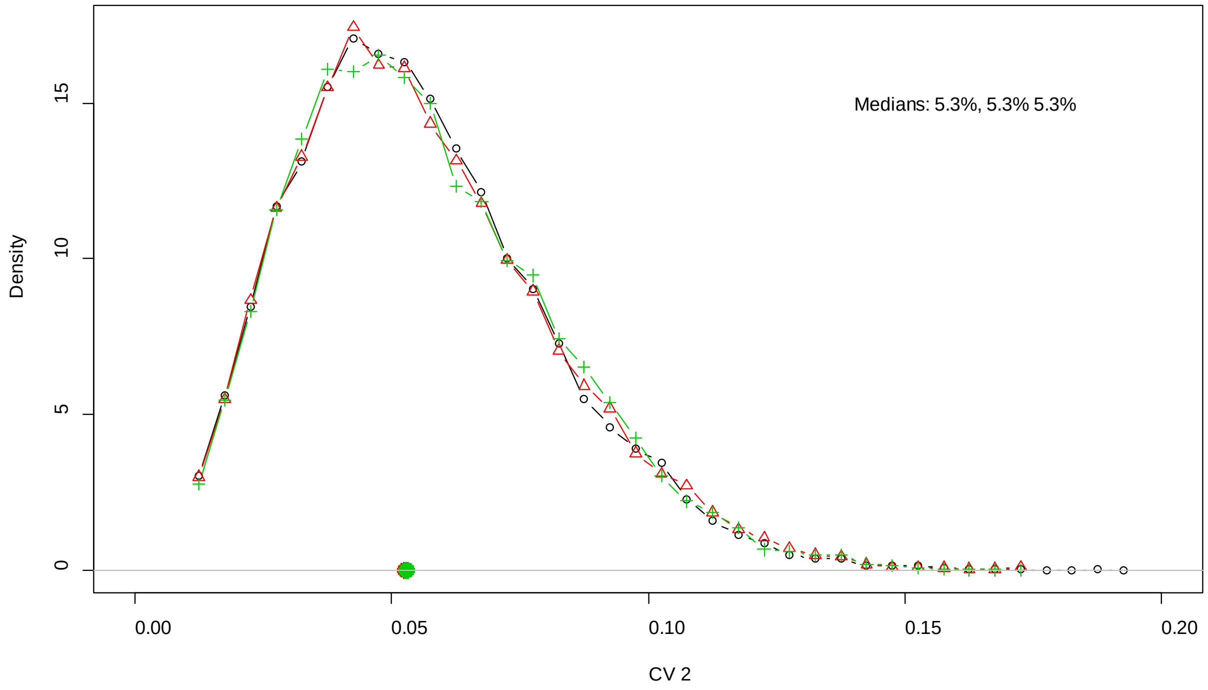

Figure A5: Fixed *M* = 0.063 run in 2018: histograms of CV2 for each of the three chains after burn-in. The medians of each chain are plotted as filled circles on the x axis and the values noted in the legend. CV2 is the CV of length at mean length at age for fish aged 70 years.

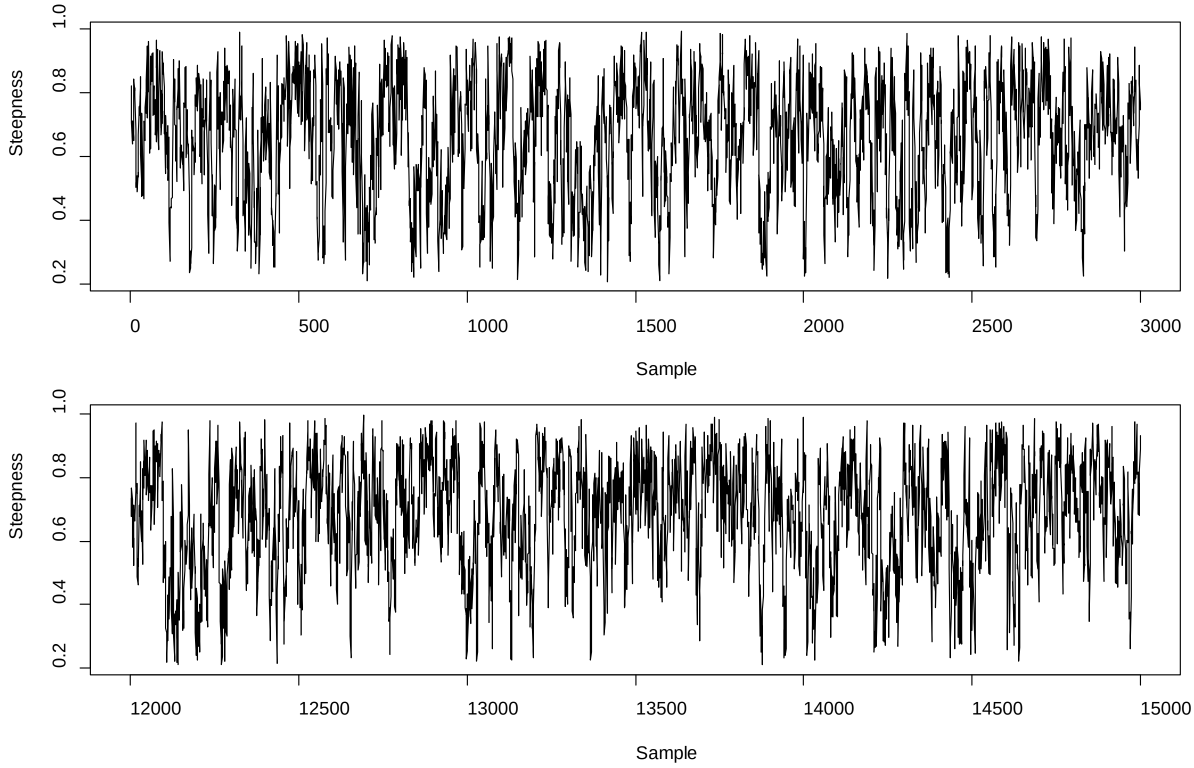

Figure A6: The first MCMC chain for the Beverton-Holt model where steepness (*h*) was estimated. The top panel shows the first 3000 stored samples of *h* and the bottom panel shows the last 3000 stored samples of *h*.

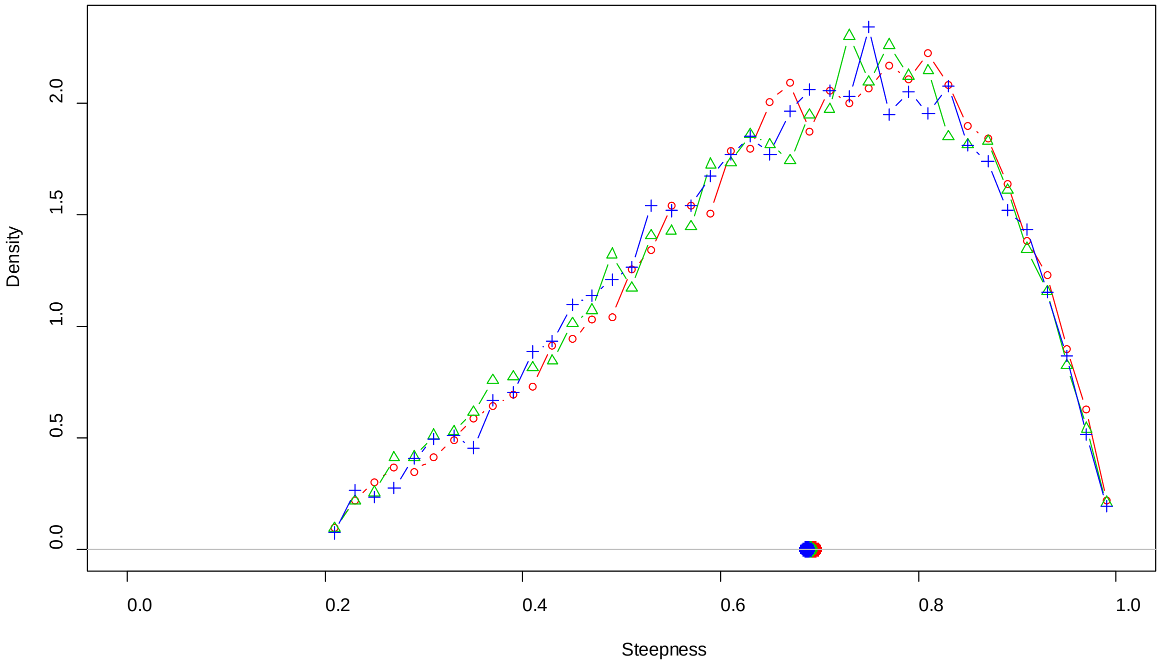

Figure A7: Beverton-Holt, estimate *h* model: histograms of *h* for each of the three chains after burn-in. The medians of each chain are plotted as filled circles on the x axis.

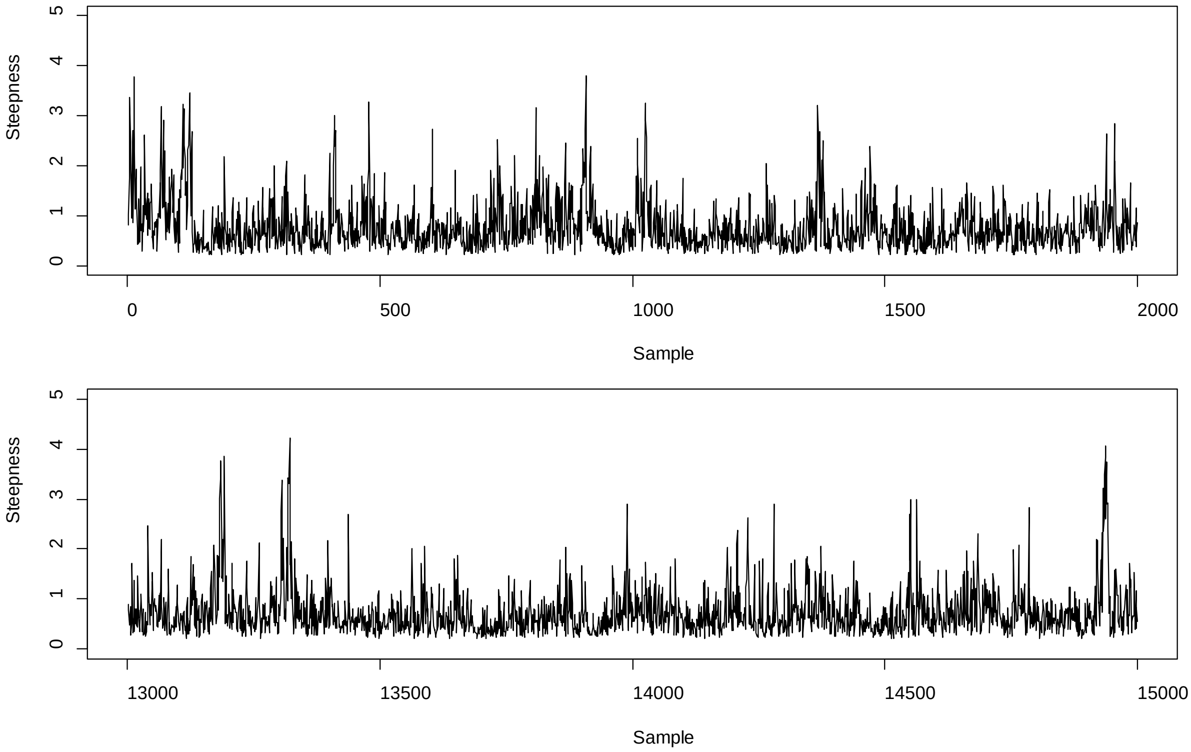

Figure A8: The first MCMC chain for the Ricker model where steepness (*h*) was estimated. The top panel shows the first 2000 stored samples of *h* and the bottom panel shows the last 2000 stored samples of *h*.

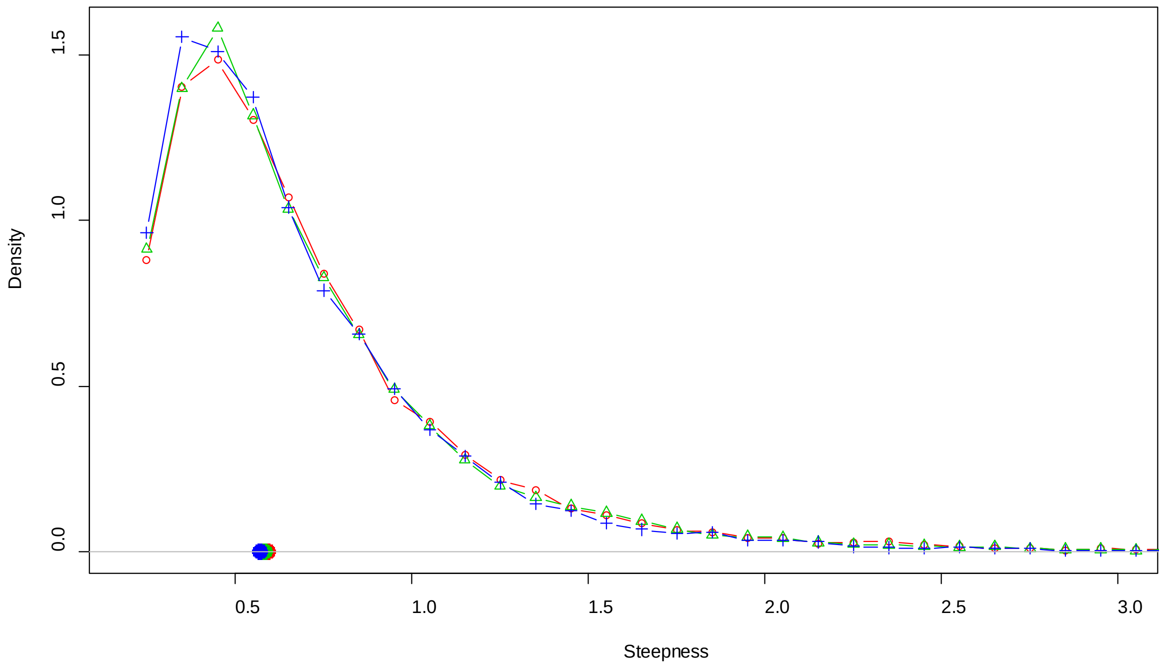

Figure A9: Ricker, estimate *h* model: histograms of *h* for each of the three chains after burn-in. The medians of each chain are plotted as filled circles on the x axis.

APPENDIX 2: CASAL files for the base model

The population and estimation files used in the MCMC base model are given below.

population.csl

```
@size_based false
@min_age 1
@max_age 70
@plus_group true


@n_stocks 1
@sex_partition true
@mature_partition false
@n_areas 1

# TIME SEQUENCE
@initial 1941
@current 2018
@final   2030

@annual_cycle
time_steps 2 # 1:age, recruit 2: mortality then spawning
aging_time 1
growth_props 0 0
M_props 0.0 1.0
recruitment_time 1
spawning_time 2
spawning_part_mort 1
spawning_ps 1
spawning_use_total_B false
baranov false
fishery_names OEO4
fishery_times 2

# RECRUITMENT
@y_enter 1

@standardise_YCS true

@recruitment
SR BH
steepness 0.75
sigma_r 1.1
YCS      1 1 1 1 1 1 1 1 1 1 1 1 1 1 1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   2   2   2
2   2   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
1   1   1   1    1   1  1    1   1   1   1   1         1  1 1 1 1 1
YCS_years  1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950 1951 1952 1953 1954 1955
1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973
1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991
1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
2010 2011 2012 2013 2014 2015 2016 2017
first_free 1940
last_free  2005
```

```
year_range 1940 2005
@randomisation_method empirical
@first_random_year 2006


# NATURAL MORTALITY
@natural_mortality
all    0.063


# FISHING
@fishery OEO4
years   1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971
1972 1973 1974 1975 1976 1977 1978  1979  1980  1981  1982  1983  1984  1985  1986  1987  1988
1989  1990  1991  1992  1993  1994  1995  1996  1997  1998  1999  2000  2001 2002 2003 2004 2005
2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018
catches   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0 0   0   0   0   0   0   0   1321
112  1435  3461  3764  5759  4741  4895  5672  7764  7223  6789  6019  5508  5911  6283  6936  6378
6359  6248  6030  6357  6491 4291 4462 5656 6473 5955 6363 6422 6090 6118 6518 6357 5964 6016
6318 1992 2279 2500
U_max 0.7
selectivity OEO4Sel
future_constant_catches   2500

#Selectivities
@selectivity_names OEO4Sel ACAageSel trawlsel

@selectivity OEO4Sel
all logistic 30 3


@selectivity ACAageSel
all double_normal 20 5 5

@selectivity trawlsel
all double_normal 20 5 5

# INITIALIZING THE PARTITION
@initialization
B0 150000



# SIZE AT AGE
@size_at_age_type von_Bert
@size_at_age_dist normal
@size_at_age
k_female 0.047
t0_female -2.9
Linf_female 50.8
k_male 0.067
t0_male -1.6
Linf_male 43.6
cv1 0.1
cv2 0.05
by_length True
```

```
@size_weight
a_female 0.000000029 # tonnes
b_female 2.90
a_male 0.000000032 # tonnes
b_male 2.87




@maturity_props
male allvalues    0  0  0  0  0 0.01 0.01 0.02 0.03 0.04 0.07 0.10 0.14 0.21 0.28 0.38 0.48 0.59 0.69 0.77
0.84 0.89 0.92 0.95 0.97 0.98 0.99 0.99 0.99   1    1    1    1    1    1    1    1    1   1   1   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
female allvalues 0  0  0  0  0    0    0    0    0    0    0 0.01 0.01 0.01 0.02 0.03 0.04 0.05 0.08 0.11 0.15
0.21 0.28 0.37 0.46 0.56 0.65 0.74  0.8 0.86 0.9 0.93 0.95 0.97 0.98 0.98 0.99 0.99   1   1   1   1   1   1
1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1   1
```

estimation.csl

```
@estimator Bayes
@max_iters 500
@max_evals 1000
@grad_tol 0.001

@MCMC
start 0.2
length 15000000
keep 1000
stepsize 0.1
proposal_t True
df 2
burn_in 1000

@q_method free

@estimate
parameter q[ACAq].q
lower_bound 0.1
upper_bound 3.0
prior lognormal
mu 0.839457
cv 0.3068783

@q ACAq
q 1

@estimate
parameter initialization.B0
lower_bound 10000
upper_bound 500000
prior uniform-log
phase 1

@estimate
parameter recruitment.YCS
#YCS_years   1940 ... 1954  1955  1956  1957  1958  1959  1960  1961  1962  1963  1964  1965  1966
```

```
1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982
1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
2016 2017
lower_bound  0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01
0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01
0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01
0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 1 1 1 1 1 1 1 1 1 1 1 1
upper_bound  10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10 10
10 10 10 10 10 1 1 1 1 1 1 1 1 1 1 1 1
prior lognormal
mu      26489122130   26489122130   26489122130   26489122130   26489122130   26489122130
26489122130  26489122130  26489122130  26489122130  26489122130  26489122130  26489122130
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26489122130 26489122130
cv  2980.958 2980.958 2980.958 2980.958 2980.958 2980.958 2980.958 2980.958 2980.958 2980.958
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@estimate
parameter selectivity[trawlsel].all
lower_bound 10 1 1
upper_bound 60 40 80
prior uniform

@estimate
parameter selectivity[ACAageSel].all
lower_bound 10 1 1
upper_bound 60 40 80
prior uniform

@estimate
parameter selectivity[OEO4Sel].all
lower_bound 10 1
upper_bound 50 10
prior uniform

{ Not estimated in base model because no LFs.
@estimate
parameter size_at_age.cv1
lower_bound     0.01
upper_bound     0.30
prior uniform
```

```
@estimate
parameter size_at_age.cv2
lower_bound     0.01
upper_bound     0.30
prior uniform
}

@estimate
parameter natural_mortality.all
prior normal
mu 0.063
cv 0.25
lower_bound     0.01
upper_bound     0.15

@relative_abundance aco_biomass
years 1998 2001 2005 2009 2012 2016
step 2
q ACAq
proportion_mortality 1
biomass 1
ogive OEO4Sel
1998 65679
2001 81633
2005 63237
2009 26953
2012 58603
2016 34022
cv_1998 0.33
cv_2001 0.33
cv_2005 0.32
cv_2009 0.33
cv_2012 0.36
cv_2016 0.38
dist lognormal

@proportions_at aco_age
years 1998  2005 2016
sexed F
step 2
proportion_mortality 1
ogive ACAageSel
plus_group false
min_class 5
max_class 70
1998 0 8e-04 0 0.023 0.0333 7e-04 0.005 0.0361 0.0117 0.0522 0.0286 0.1049 0.1352 0.0196 0.0371
0.1371 0.0642 0.0187 0.1014 0.0236 0.0382 0.0299 0.0168 0.0026 0.0059 0.0122 0.0067 0.0113 0.0035
0.0026 1e-04 0.0028 4e-04 0.0031 0 0.0016 1e-04 0.0249 0 0.0023 1e-04 0 1e-04 1e-04 6e-04 0 0 0 0
0 4e-04 0 0 0 0 0 0 0 1e-04 0 0 0 0 0 0 0
2005 5e-04 1e-04 0.0012 0.0017 0 0.0051 0.0011 0.0038 0.0233 0 0.0011 0.0387 0.0217 0.0352 0.0586
0.1557 0.0928 0.0703 0.072 0.0662 0.0436 0.0386 0.0219 0.0296 0.0196 0.0162 0.0187 0.0223 0.045
0.0367 0.0013 0.0055 0.0017 0.0012 0.009 0.0035 5e-04 0.016 0.0084 0.01 0 0 0 0 0 0 2e-04 4e-04 8e-
04 0 0 0 0 5e-04 0 0 0 0 0 0 0 0 0 0 0 0
2016  0.006024096  0.02409639  0.04096386  0.0253012  0.02891566  0.01927711  0.01807229
0.03614458  0.02168675  0.01445783  0.03493976  0.03253012  0.0626506  0.03855422  0.04578313
0.04819277  0.03614458  0.02409639  0.03373494  0.02650602  0.01807229  0.01927711  0.0373494
```

```
0.02409639 0.04457831 0.03493976 0.01084337 0.03614458 0.009638554 0.05421687 0.006024096
0.01084337 0.01566265 0.01204819 0.006024096 0 0.006024096 0.007228916 0.001204819
0.007228916 0.001204819 0 0 0 0.002409639 0.006024096 0 0 0 0 0 0.006024096 0 0 0 0 0 0
0.004819277 0 0 0 0 0 0 0
N_1998 50
N_2005 50
N_2016 40
dist multinomial
r 0.00001
ageing_error True

@proportions_at tan9104
years 1991
step 2
proportion_mortality 1
ogive trawlsel
plus_group T
sexed F
sum_to_one T
at_size F
min_class 5
max_class 70
1991 0.006024096 0.02409639 0.04096386 0.0253012 0.02891566 0.01927711 0.01807229
0.03614458 0.02168675 0.01445783 0.03493976 0.03253012 0.0626506 0.03855422 0.04578313
0.04819277 0.03614458 0.02409639 0.03373494 0.02650602 0.01807229 0.01927711 0.0373494
0.02409639 0.04457831 0.03493976 0.01084337 0.03614458 0.009638554 0.05421687 0.006024096
0.01084337 0.01566265 0.01204819 0.006024096 0 0.006024096 0.007228916 0.001204819
0.007228916 0.001204819 0 0 0 0.002409639 0.006024096 0 0 0 0 0 0.006024096 0 0 0 0 0 0
0.004819277 0 0 0 0 0 0 0
N_1991 40
dist multinomial
r 0.00001
ageing_error True

@catch_at obsAF
fishery  OEO4
years 2009
sexed F
sum_to_one True
at_size  F
plus_group True
min_class 5
max_class 70
2009 0 0 0 0.001930502 0 0 0 0.001930502 0.007722008 0.003861004 0.00965251 0.00965251
0.01930502 0.02316602 0.04247104 0.04826255 0.05984556 0.05984556 0.09266409 0.06563707
0.05598456 0.06949807 0.05405405 0.05984556 0.03088803 0.02509653 0.04054054 0.01930502
0.03088803 0.02316602 0.01544402 0.02316602 0.003861004 0.01158301 0.01351351 0.01544402
0.007722008 0.001930502 0 0.001930502 0.001930502 0.001930502 0 0.007722008 0.003861004
0.003861004 0 0 0 0.003861004 0.005791506 0.001930502 0.003861004 0 0 0.005791506
0.005791506 0 0 0 0 0 0 0 0.001930502 0.001930502
N_2009 40
dist multinomial
r 0.00001
ageing_error True

{ Not used in the base model.
@catch_at         LFtrawl
```

```
fishery  OEO4
years 1996 1998 2001 2007 2008
sexed F
sum_to_one True
at_size  True
plus_group True
class_mins      20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47
48 49 50 51 52 53 54 55

1996 0.001006657 0.001243019 3.238563e-05 0.0006787203 0.00224386 0.003803973 0.004581324
0.007696613 0.01452746 0.01990928 0.02881502 0.05071802 0.06682669 0.07500765 0.08187769
0.09821816 0.09667029 0.08719916 0.07890259 0.05953701 0.04887392 0.02884489 0.0293685
0.01957059 0.01812276 0.01835583 0.01300654 0.01094917 0.008763299 0.006440066 0.00762383
0.004993445 0.002211506 0.002288135 0.001091914 0
1998 0.003784018 0.002293884 0.002633837 0.002877871 0.009527894 0.0139847 0.01853233
0.01737153 0.0185072 0.02262811 0.03207932 0.03487445 0.0603283 0.05813507 0.0872537
0.1157849 0.09672082 0.1059584 0.08373412 0.06637149 0.04745248 0.03463823 0.01802865
0.01537026 0.008665516 0.006026017 0.004487049 0.001720117 0.003709586 0.004111775
0.001093322 0.0006211187 5.971299e-05 0.0003652119 0.0002690282 0
2001 0 1.455142e-05 7.364432e-05 0.0004488912 0.001304885 0.001342831 0.001038012
0.001275299 0.003140875 0.00254613 0.007338806 0.01745902 0.03325915 0.05629535 0.1086383
0.1238577 0.1354943 0.1249684 0.09966138 0.07766912 0.06038545 0.04235149 0.03173032
0.01691748 0.01230039 0.01171416 0.006143647 0.007986193 0.006203312 0.002816777
0.001718488 0.001180317 0.001112226 0.0006233264 0.0007430703 0.0002466555
2007 0.003648541 0.003068203 0.002920956 0.001905365 0.00438501 0.003602991 0.002926891
0.003148416 0.003085728 0.005236364 0.009555838 0.01978277 0.04218689 0.08167775 0.1205842
0.1375542 0.1457096 0.1205061 0.09235395 0.05684989 0.04227506 0.03121 0.02127635
0.01349148 0.007843542 0.006799879 0.004418262 0.003398082 0.003573551 0.0009944269
0.001428622 0.0009795297 0.0003705459 0.0007550974 0.0002431823 0.000252674
2008 0.001464125 0.0006716085 0.0003379639 0.001697654 0.0002925361 0.0008551263
0.001561662 0.0007308829 0.00134561 0.002481064 0.003751643 0.008459044 0.02422023
0.04499305 0.09448494 0.1399308 0.1548213 0.1477981 0.1135496 0.08558924 0.06216027
0.03908717 0.02179962 0.01490257 0.009984806 0.007555592 0.004508851 0.003305551
0.002602423 0.002969672 0.0007635089 0.0008110672 0.0004716813 7.104551e-06 2.664181e-05
7.338195e-06
dist multinomial
r 0.00001
N_1996 15
N_1998 20
N_2001 35
N_2007 29
N_2008 35
# tows: 31 40 71 58 71
}

@catch_limit_penalty
label clpOEO4
fishery OEO4
log_scale 1
multiplier 100

@ageing_error
type normal
c 0.085
```