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The 2016 stock assessment and management procedure review for rock lobsters (*Jasus edwardsii*) in CRA 4

New Zealand Fisheries Assessment Report 2017/29

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This document describes a new stock assessment of red rock lobsters (*Jasus edwardsii*) in CRA 4 and describes a review of operational management procedures. The work was conducted by a stock assessment team contracted by the New Zealand Rock Lobster Industry Council Ltd.

The stock assessment was made using the length-based multi-stock model MSLM. The Rock Lobster Fishery Assessment Working Group oversaw this work: data files and all technical decisions were agreed beforehand or subsequently approved (and sometimes changed) by that group. The model was fit to CPUE indices, size frequency data, tag-recapture and puerulus settlement data. This document describes the procedures used to find acceptable base cases and shows the model fits. The assessments were based on Markov chain – Monte Carlo (McMC) simulations; the document describes the diagnostics for these and shows the results of McMC sensitivity trials. Short-term projections were made at the current estimated levels of catch.

At the same time, a new single stock CRA 4 model, written in STAN and developed by Webber (unpublished), was verified against the MSLM results. An experimental multi-area assessment for CRA 4 was conducted with both the MSLM and new models; results were compared with those presented here. Only the MSLM single-stock assessment is discussed here.

The assessment showed that current vulnerable biomass is below the reference level *Bref*, the average biomass in 1979–88. Because of high estimated *M*, *Bmsy* is not a useful reference point, with *Bref* being both more conservative and more credible. Spawning stock biomass in CRA 4 is about 50% of the unfished level. MPD and McMC sensitivity trials explored the possible effects of modelling choices.

The assessment model was used as the basis for an operating model to evaluate the performance of alternative management procedures for CRA 4, which has had management procedures to determine catch levels since 2007. Each management procedure candidate was tested with 1000 20-year simulations, based on the McMC posteriors, to address parameter uncertainty, and with stochastic variation in CPUE observation error and in recruitment to address environmental uncertainty. The operating model productivity was lower than recent fishery performance in terms of catch and CPUE: reasons for this are discussed.

The base case operating model predicted strong short-term decline in the stock followed by strong rebuilding to near *Bref* in 5 years. This behaviour is discussed in the report and an alternative model (robustness trial) tested the possible reason for this behaviour.

An interactive user interface was developed and deployed online so that stakeholders could explore these rules; this was supplanted when a new rule set was run and time was too limited to update the online viewer. Based on a more primitive spreadsheet viewer, the National Rock Lobster Management Group chose two rules on which to solicit submissions in a formal consultation process.

To make it accessible to the non-specialist, this document also provides a glossary of terms used in the stock assessment and management procedure evaluations.

1. INTRODUCTION

This work addressed Objectives 4 and 5 of the Ministry for Primary Industries (MPI) contract CRA2015-01A. This three-year contract, which began in April 2016, was awarded to the NZ Rock Lobster Industry Council Ltd. (NZ RLIC Ltd.), who sub-contracted Objectives 4 and 5 to the authors of this report.

Objective 4 - Stock assessment: To estimate biomass and sustainable yields for rock lobster stocks

Objective 5 - Decision rules: To evaluate new management procedures for rock lobster fisheries

The National Rock Lobster Management Group (NRLMG) determined that the CRA 4 stock should be assessed in 2016. Data were compiled by a team comprising Paul Starr (Starrfish), D'Arcy Webber (Quantifish) and Paul Breen (Breen Consulting; see Starr et al. 2017). CRA 4 was assessed in the usual way, assuming a single homogeneous stock, using the purpose-built multi-stock length-based model (MSLM) of Haist et al. (2009); this work was done by Paul Breen, Paul Starr and Vivian Haist (Haist Consultancy) with input from D'Arcy Webber and Charles Edwards (NIWA).

A new model with the same dynamics as MSLM, written in STAN by D'Arcy Webber, was fit to the same data as MSLM and comparative results were verified by D'Arcy Webber and Charles Edwards. At the same time, an experimental multi-stock assessment of CRA 4 was conducted by Vivian Haist, using the multi-stock capability of MSLM, and also by D'Arcy Webber and Charles Edwards, using the new STAN model. These results will be described elsewhere and only the single-stock MSLM results are presented here. New graphic routines in R were developed by D'Arcy Webber and Charles Edwards.

Decisions on data and modelling choices were discussed and approved by the Rock Lobster Fishery Assessment Working Group (RLFAWG).

The CRA 4 (Figure 1) fishery extends from the Wairoa River on the east coast southwards along the Hawkes Bay, Wairarapa and Wellington coasts, through Cook Strait and north to the Manawatu River in the South Taranaki Bight. The CRA 4 total allowable catch (TAC) for 2016–17 was 592 t. Allowances set by the Minister for Primary Industries were 35 t for customary catch, 85 t for recreational catch, 75 t for illegal unreported removals and a 397 t total allowable commercial catch (TACC). The CRA 4 commercial fishery is open all year. The minimum legal size (MLS) is 54 mm tail width (TW) for males and 60 mm TW for females for both the commercial and recreational fisheries.

The CRA 4 commercial fleet comprised 51 vessels in the 2015–16 fishing year[1]. Most vessels in the fleet operate from coastal bases in isolated rural areas on the Hawkes Bay and Wairarapa coastlines. The CRA 4 commercial catch supports several processing and export operations in Napier, Wellington and Auckland.

Potting and hand gathering are the preferred methods for recreational fishers in this area. As in most CRA areas, most recreational catch is taken in the summer months. The region also sustains a recreational fishing and dive charter industry during summer. Lobsters are very important to Maori in this area, and the customary allowance allows lobsters to be taken under permit for use by the marae.

This is a trap or pot fishery, conducted by small boats on day trips, fishing in relatively shallow waters. The stock assessment and data preparation separate the autumn-winter (AW, April through September) and spring-summer (SS) seasons. The stock is managed with an operational management procedure (MP) that determines the TACC, the primary management tool. Allowances are added by the Minister for the non-commercial fisheries to produce a TAC. Other management measures include protection of ovigerous (berried) females, sex-specific MLS and escape gaps in pots.

[1] The fishing year runs from 1 April through 31 March; the fishing year is named by the April–December portion; *viz.* 2015–16 is called "2015".

In the previous stock assessment of CRA 4 in 2011, Starr et al. (2012) described the data and Breen et al. (2012) described the stock assessment and management procedure evaluations (MPEs), which used the MSLM model. The model was fit to tag-recapture data, standardised CPUE from 1979–2010, historical catch rate data from 1963–1973, length frequency data from voluntary logbooks and observer catch sampling, and puerulus settlement data. Changes in MLS and changes in selectivity caused by escape gap regulations were taken into account.

After the 2011 stock assessment, MPs were evaluated using an operating model based on the stock assessment base case model. MPs are extensively simulation-tested decision rules (Butterworth & Punt 1999): see Johnston & Butterworth (2005) and Johnston et al. (2014) for discussion of MPs used to manage rock lobsters in South Africa. MPs are now a major part of New Zealand rock lobster management (Breen 2016; Breen et al. 2016a, 2016b). They were used to rebuild the depleted CRA 8 stock in New Zealand and to manage the volatile CRA 7 stock (Starr et al. 1997; Bentley et al. 2003); a voluntary management procedure was used to govern ACE shelving in CRA 4 to rebuild a badly depleted stock (Breen et al. 2009a); a management procedure was adopted for CRA 5 for the 2012–13 season, after using a voluntary management procedure designed to maintain high abundance (Breen 2009); a management procedure was adopted for CRA 3 in 2010 (see Breen et al. 2009b); MPs were also developed for CRA 2 in 2013 (Starr et al. 2014) and CRA 1 in 2014 (Webber & Starr 2015).

The present document describes a new stock assessment and MPEs for CRA 4. The existing MP was explored and new MPs were developed and evaluated. Evaluation results were presented to the NRLMG, who chose two final candidates and engaged in formal consultation on them.

Data for this work are described by Starr et al. (2017). This document describes the base case stock assessments, modes of the joint posteriors (MPD) and Markov chain – Monte Carlo (McMC) sensitivity trials, the projection model, MPE design and results and an interactive user interface provided to stakeholders for their choice of suitable rules. The stock assessment was done in a workshop in Wellington from 19 September through to 20 October; it was presented to the Mid-year Plenary on 1 November. The MPE work was begun in the workshop and continued through mid-November.

Technical terms used here are defined in the Glossary.

2. BASE CASE MPD AND SENSITIVITY TRIALS

2.1 Model

The Bayesian multi-stock length-based model MSLM was described by Haist et al. (2009). The model is implemented in AD Model Builder (ADMB, Fournier et al. 2012). It is an integrated model (see Maunder & Punt 2013; Punt et al. 2013) that estimates most structural parameters by fitting to several data sets simultaneously. CPUE is an exception to this: it is standardised outside the model and the model fits to the standardised indices. It might be preferable to estimate the explanatory variables for CPUE along with the other parameters (Maunder 2011) but this is not done for logistic and other reasons.

The model time step is specified and can vary during the period being simulated. The model's number and width of size bins is specified. Fishing is modelled by taking into account the observed catch, MLS that can change during the period simulated, estimated seasonal vulnerability and estimated size-selectivity of the fishing gear that can vary over time. The model fits the catch (SL catch) that is limited by MLS and a restriction on landing ovigerous females, comprising the commercial and recreational catches, and separately fits the catch (NSL catch) not limited by these regulations, comprising the illegal and customary catches, which are assumed to take all the lobsters caught by a pot.

In each time step, the number of male, immature female and mature female lobsters in each size class is updated as a result of annual recruitment to the model, which occurs to a specified mean size with specified size variation. Recruitment can vary over time. Natural mortality is estimated but assumed to be constant over time, sizes and sexes. Handling mortality of returned lobsters (undersized and berried females) is assumed.

A growth transition matrix, based on estimated sex-specific growth parameters, specifies the probability of an individual lobster remaining in the same size bin or growing into each of the other size bins, including smaller ones. Maturation of females is described by a two-parameter logistic curve.

The model calculates biomass vulnerable to the fishery at each time step from numbers-at-size for each sex, the size-weight relations, female maturity (for the SL fishery, mature females are assumed to be berried and thus not legal in the AW season), MLS (for the SL fishery only), sex-specific trap selectivity-at-size and sex-specific seasonal vulnerability. MLS has changed over time and is input as data for each year.

The model is fit to abundance indices, size data, tag-recapture data and puerulus settlement data. A maximum-likelihood-based goodness of fit is calculated for each data set and added to penalties (from the comparison of predicted and observed catch, for instance) and contributions from the Bayesian priors to form a total function value.

After a suitable base case is found, the stock assessment estimates and their uncertainty are made with Markov chain – Monte Carlo simulations (McMC). Although Bayesian procedures are time-consuming, they are recommended as the default method for estimating uncertainty in stock assessments (Magnusson et al. 2012).

Changes to the model for the 2016 stock assessment from the 2015 version (Haist et al. 2016) were minor. Before 2015, most lobster stock assessments had used robust normal likelihood when fitting the tag-recapture data. In 2015, Webber (unpublished data), using the tag-recapture data from all stocks, showed that this likelihood did not perform as well as other choices, so the 2015 stock assessments (Haist et al. 2016; Starr & Webber 2016) used normal likelihood. In 2016 we reverted to the robust normal likelihood after explorations of possible base cases and examination of test McMC chains. We retained the 2015 Webber (unpublished) priors for observation error (*Gobs*, see below) and sex-specific shape and variance parameters (*Gshape* and *GCV*).

For stocks where a substantial weight of legal fish is returned to the sea, such as CRA 8, the model's *MSY* and *Bmsy* calculations take the estimated weight of returned fish into account. For CRA 4 the retention was assumed, based on analyses of observer catch sampling data, to be negligible.

2.2 Model parameters

Estimated model parameters listed in the tables below and discussed in the text are defined by Haist et al. (2009). Because these definitions are often Greek letters and often superscripted or subscripted, this document uses the set of simplified notations described in Table 1.

The growth density-dependence parameter (*GrowthDD*) can take values between 0 and 1. When it is active, the predicted growth increment is multiplied by the factor

$$1 - GrowthDD\left(B_t / B0\right)$$

where B_t is the total biomass in period *t* and *B0 i*s the initial total biomass.

2.3 Model options and fitting

The model was fit to two CPUE indices (the older one is referred to as CR) using lognormal likelihood, to length frequency distributions (LFs) using multinomial likelihood, to tag-recapture data using robust normal likelihood and the puerulus settlement index using normal-log likelihood.

Most model options followed recent usage.

The model was started at 1945, where the catch data series began, with *Uinit* fixed at 0. Experiments (not reported) used 1960 and 1974 starts and estimated *Uinit*; the 1945 start was considered a better reconstruction. The model used a 1-year time step until 1979, when the Fisheries Statistic Unit (FSU) data began, and from then used a 6-month time step (AW and SS). The model used data to the end of the 2015 fishing year (i.e. the end of March 2016).

The model's size structure was 31 bins, each 2 mm wide, starting at 30 mm as in most recent assessments. Recruitment to the model was the same at the beginning of both time steps in a year and had a mean of 32 mm TW and standard deviation of 2 mm. When the model was fit to the Puerulus index, *Rdev*s were estimated for 1945–2017; when the model not fit to the puerulus index, *Rdev*s were estimated for 1945–2013. The model used size vectors for males, immature females and mature females as in all recent assessments.

Because CRA 4 was assessed as a single stock the movement parameters were not estimated.

The fishing dynamics used instantaneous rates for each fishery, SL and NSL, estimated from catch and model biomass and *M* with 3 Newton-Raphson iterations. The selectivity was double-normal, with the right-hand limb fixed to a high value to prevent large numbers of estimated cryptic large fish. Selectivity was estimated for two epochs: 1945–1992 and 1993–2015, the change in epochs being coincident with changes in escape gap regulations. Stock-recruitment was not estimated and density-dependent growth was not estimated after exploratory fits determined that the density-dependence effect was very small. CPUE was assumed to be linear with vulnerable biomass (*CPUEpow* fixed to 1).

Data weighting was determined iteratively to obtain standard deviations of normalised residuals (sdnrs) close to 1 or median absolute residuals (MARs) close to 0.67. For LFs, we used the approach suggested by Francis (2011); weighting of the individual records is described by Starr et al. (2017). For tag-recaptures we set the relative weight to 1, so that the *GCV* prior would remain correct, and we iteratively re-weighted the CPUE, CR and LF data sets to obtain an sdnr close to 1 and a MAR close to 0.67.

Growth was estimated with the Schnute-Francis model as in recent stock assessments. The *Gmin* parameter was fixed to a small value. Observation error *Gobs* and sex-specific shape *Gshape* and variance *GCV* parameters were estimated using priors based on those developed by Webber (unpublished) in fits to the entire New Zealand tag-recapture data set. This was a major change from assessments before 2015.

Handling mortality had been assumed to be 10% in previous lobster stock assessments. After doing a literature review we revised this to 5% for 1990 onwards. The downward change from 10% to 5% seemed likely because at about that time live exports began and fish were both sorted more quickly and handled more carefully.

Priors: for *M*, recent assessments have used a lognormal prior with a mean of 0.12 and CV of 0.4. Priors for three growth parameters are described above. *Rdev*s were given a normal prior in log space, with a mean of zero and *SigmaR* of 0.4 as in recent previous assessments. Remaining parameters were given uniform priors with wide bounds.

2.4 Base case MPD

2.4.1 Initial explorations

More than 100 minimisations were made in the process of choosing a base case. Some early explorations were simple tests of modelling choices: for instance, to see whether three Newton-Raphson iterations were sufficient (they were), whether the data showed any signal for growth density-dependence (they didn't), whether a later start than 1945 gave better results (it didn't), etc. We experimented to see which sex- and seasonal vulnerability should be fixed to 1 so that all others were estimated as less than 1. We adjusted the dataset weights to try to achieve either a standard deviation of normalised residuals (sdnr) close to 1 or a median of absolute residuals (MAR) close to 0.67.

Some problems were obvious in the LF data. First, we rejected records with fewer than 100 fish measured. Some remaining records contained large immature females and a high proportion of immature females relative to other records. This suggested some misclassification of female maturity, which proved to be the case, as described by Starr et al. (2017). To address this, a data set was made with no immature females in the LF data, instead with all females contained in the mature females. The immature female fitting was given very low weight and the maturation parameters were fixed. This *ad hoc* approach seemed to work well and was used along with a second approach in searching for a base case.

The problem with misclassified females in the LF data was explored and localised to SS samples from two samplers in two or three years (Starr et al. 2017). Fourteen affected samples were removed and the affected records were re-weighted accordingly; then the conventional approach (fitting to immature females and mature females) was used. The model fits only to a specified range of size bins, so that bins with very few observed fish are aggregated into plus and minus groups specified separately for each sex class. The initial specifications were made by inspecting the distributions of observations among bins and final specifications were confirmed by inspecting the normalised residuals by sex and size bin to ensure that none was greater than 10.

Usually a preliminary base is found without fitting to puerulus data and then a set of randomisation trials explores whether there is a signal in the puerulus data at different lags between settlement and recruitment to the model. Because we were sanguine (based on the previous CRA 4 stock assessment) that the puerulus data would have a signal, and because various problems had caused time constraints, we eliminated this step and fit to puerulus in the search for a suitable base case. We used an assumed lag of 2 years between settlement and recruitment to the model.

Problems encountered in searching for a base case were:

- lack of fit to the last year of CPUE in both seasons
- high *M* estimates
- estimates of *Gshape* that were close to the mean of the prior, calling into question the tight standard deviations on the priors for *Gshape*, *Gobs* and *GCV*
- dubious estimates of *mat95Add* because of the scarcity of immature females in the LF data
- Hessian matrices that were not positive definite (pdH); which is required for running McMCs in ADMB

These were addressed as follows:

- the fit to the most recent two years of CPUE was improved by arbitrarily decreasing the assumed CPUE process error term in the last two years from 0.25 to 0.075
- high estimated *M* was difficult to address, but the value of *M* was a factor in considering alternative model fits and the *Gshape* prior was adjusted in explorations
- we considered that the priors on *Gshape* and *GCV*, based on an analysis of all the tag-recapture data (D'Arcy Webber, unpublished study) were too tight and we tried to relax them to make them have a value that was 30% of the prior mean. This approach tended to deliver non-pdH

results, so the prior standard deviation for *Gshape* was then decreased until a pdH fit was obtained

- we fixed *mat95Add* to its MPD value
- we experimented with many approaches to obtain pdH fits, of which the most effective seemed to be the width of the prior on *Gshape*

2.4.2 Base case

The final base case was chosen from a short list of four, which here will be termed “2-sex fit”, “3-sex fit”, “fixedG1” and “fixedG2”.

The 2-sex fit used the original LF dataset (except for those records with fewer than 100 fish measured) but with the immature and mature females combined in the mature class. Maturity parameters were fixed at MPD values obtained from the 3-sex fit and the fit between predicted immature female LFs and observed (all the observed were zero) was given a very low weight. This approach was not too unrealistic because of the small size at maturation and the low numbers of immature females seen in the data. We developed this approach before we had diagnosed and repaired the problem with some LF records described above; it allowed us to fit to all the data despite the obvious misclassification of females in some records.

The other three fits used the revised LF dataset with the suspect samples (where females were mis-classified in the SS season) removed. Remaining samples contributing to the record were retained (see Starr et al. 2017). The 3-sex fit estimated all relevant parameters except *CPUEpow*, *mat95add* and *Gmin*. In the fixedG1 fit, *Gshape*, *GCV* and *Gobs* were fixed to their non-pdH MPD values, but *mat95add* was estimated. The fixedG2 fit was the same except that *mat95add* was fixed at its MPD value from the fixedG1 fit. The fixedG1 and fixedG2 fits explored the effect of allowing *Gshape* to be larger, which in turn allowed *M* to be smaller.

Priors were the same or very similar among these four fits: priors for the 3-sex fit are shown in Table 2. Fixed quantities differed somewhat among the four runs (Table 3). Fixed quantities that did not vary are shown in Table 4. The sex-season vulnerabilities were varied among the four fits so as to prevent estimated values from reaching the upper bound of 1 (Table 5).

MPD results from the four base case candidates were generally similar (Table 6), with the 2-sex and 3-sex fits tending to be more similar to each other than to the fixedG1 and fixedG2 fits, which had faster growth, lower *M* and current biomass only slightly above *Bmsy*.

From these four fits, the 3-sex fit was chosen as the base case. The 2-sex fit, with similar results, might have been preferable because it used all the data, whereas the other three fits used the revised LF data with some samples removed. However, a trial McMC had very poor traces in the 2-sex fit compared with the 3-sex fit (see next section). The fixedG1 and fixedG2 fits were rejected as the base case because the fixed growth parameters arbitrarily reduced the assessment uncertainty.

The base case fit the CPUE data reasonably well (Figure 2) with some minor problems, including a tendency to underestimate AW CPUE and overestimate SS CPUE in the early years and some large residuals in recent years (Figure 3). The q-q plot was generally acceptable (Figure 4). There was a good fit to the historical CR series (Figure 5 and Figure 6).

Fits to early, late and most recent LF data are shown in Figure 7–9 and residuals in Figure 10. Except for immature females (few data), the model picked up the signal in mean lengths from the LF data (Figure 11). The predicted size distribution of the unfished stock is shown in Figure 12.

The fit to the puerulus index was far from exact but caught the main upward and downward trends (Figure 13 and Figure 14). The fit to proportions-at-sex (Figure 15 and Figure 16; residuals in Figure 17) tended to be better for the observer catch sampling records than for the logbook sampling, probably because of poor representativeness of the logbook programme in the 1990s and early 2000s (see Starr et al. 2017).

Predicted increments-at-size by sex are shown in Figure 18. Much of the signal for growth comes from the tag-recapture data; predicted sizes at recapture are compared with observed in Figure 19. Residuals from northern statistical areas tended to be negative and vice-versa (Figure 20), suggesting faster growth in the north. There was no relation between the residuals and the number of re-releases (Figure 21) or initial size (Figure 22). There was some suggestion in the residuals that growth rate had decreased over the time series (Figure 23), but the effect was relatively weak and we did not invoke the model's option to estimate growth in separate time periods. Figure 24 shows the q-q plot of tag residuals, most of which lay between -2 and 2 but had extreme residuals at the tails. This plot is potentially misleading because a robust normal likelihood was used.

Estimated selectivity by sex is shown in Figure 25. Estimated recruitment by year is shown in Figure 26, where it is compared with the recruitment estimated when puerulus data were not fit in a sensitivity trial reported below. Estimated exploitation rates for the two fisheries by season are shown in Figure 27, which suggests that SS exploitation rate exceeded 1 in the SL fishery in SS in the 1990s while the NSL rates were comparatively low throughout.

The MPD trajectory of vulnerable biomass (Figure 28; note that the annual time step is plotted as AW before 1979) shows considerable fluctuation. The MPD trajectory suggested that start of 2016 vulnerable biomass was only 75% of *Bref* but was about 40% above *Bmsy*, which is not a useful target given its small size because of the high estimate of *M*.

2.4.3 Puerulus randomisation trials

After the base case had been chosen and while it was being described for the RLFAWG, we conducted randomisation trials to see whether the puerulus data have a signal. The null hypothesis is that there is no signal; the research hypothesis is that there is a signal that allows the model to find a better function value than it would with randomised data. The base case used a lag of two years between settlement and recruitment to the model at 32 mm TW. We explored using lags of 0–4 years. For each lag, we fit the model to the data using the specified lag. Then we randomised the puerulus series, fit the model again, noted the function value and repeated this 500 times. The null hypothesis could be rejected if the function value obtained with the actual data lay in the tail of the distribution of function vales.

These trials (Table 7) indicated that the null hypothesis could be rejected for lags of 0 and 1 year, almost rejected for lag of 2 years and was acceptable for larger lags. A lag of zero is not plausible in the real world, but is plausible as a model result because the model has no way to estimate growth rate of small lobsters. A lag of zero implies that growth rate of small lobsters after recruitment to the model has been underestimated.

With more time we could have changed the base case to one with a lag of 1 year; by the time we had done these trials there was no time in which to do this. An earlier MPD sensitivity trial suggested that doing this would have had little effect on the stock assessment results; see an McMC sensitivity trial below.

2.5 MPD sensitivity trials

We ran a variety of sensitivity trials to various modelling choices: each was run from the 3-sex base case control and data files except for the change indicated. A large set of trials was run with a preliminary base case that was later abandoned and some trials showed no effect of the change. These were:

- density-dependent growth: the parameter was estimated near zero and there was only a trifling change to results

- using five Newton-Raphson iterations instead of three: little change to results, suggesting that three iterations were adequate
- changing the puerulus lag from 2 years to 1
- estimating *CPUEpow* (slight hyperstability only)
- not fitting to LFs (no convergence)

These five trials were not repeated. Sensitivity trials made with the actual base case were:

- half illegal: as suggested by the RLFAWG, with the assumed illegal catch reduced by half
- tightG: with the original tight default CVs on the priors for *Gshape*, *GCV* and *Gobs*; in the base case these had been relaxed
- handling 10%: with a constant 10% mortality from 1990; in the base case this was 5%
- *M* 0.12: with *M* fixed to 0.12 instead of being estimated
- *mat95*: with *mat95Add* fixed to 10; in the base case it was 2.92
- normal: with normal likelihood for the tag fit instead of robust normal in the base case
- noCPUE: not fit to the CPUE
- noCR: not fit to the CR
- notags: not fit to the tag-recapture data
- noPoo: not fit to the puerulus index

All were run with the single change indicated, with no change to data weights. The noCR trial was run as a restart from the base case parameters to get convergence. In the noPoo, noCPUE and noCR trials the relevant *q* was not estimated. All these trials were pdH except (perversely) tightG.

Estimates are shown in Table 8. The biggest effects were caused by M12 and notags. When *M* was fixed to 0.12, about half the base case estimate, estimated growth was considerably less and biomass was only 20% of *Bmsy*. In the notags fit, estimated growth was faster and its variability was higher; again the ratio of current biomass to *Bmsy* was substantially lower. The growth estimates were not implausible, suggesting strong signals in the LF data. Although biomass was not well scaled in the noCPUE trial, the model picked the major fluctuations seen in the CPUE (Figure 29).

3. BASE CASE MCMC

The base case for the stock assessment was the “3-sex fit” described in the previous section. An McMC of 5 million iterations, with 1000 samples saved, was made, starting from the MPD. Posterior distributions of parameter estimates for this base case are summarised in Table 9.

Traces are shown for estimated and derived parameters in Figure 30–33; diagnostic plots are shown in Figure 34–. Histograms of the posterior distributions of estimated and derived parameters are shown in Figure 38–41.

Traces for important estimated leading parameters such as *M* and ln(*R0*) and important derived parameters such as *Bmin* and *Bref* show reasonable stability, although there is a downward drift in the first parts of ln(*R0*) and *M*. Most parameter estimates stayed away from the bounds with the exception of some of the *vuln* parameters (Figure 39).

The posterior distributions of the fits to CPUE (Figure 42) and CR (Figure 43) were similar to the MPD fits. The posterior distributions of the fit to the puerulus index (Figure 44) was also similar to the MPD. The fit to the proportions-at-sex showed good agreement with the observations (Figure 45).

Estimated recruitment was variable with an apparent declining trend after the early 1990s (Figure 46). Estimated vulnerable biomass (Figure 47) showed large-scale variations, with peaks in the 1980s, late 1990s and late 2000s; each successive low abundance appeared slightly lower than the previous low. Maturation was estimated to be early (Figure 48) with most females maturing by 50 mm TW. Estimated selectivity appeared consistent with the shift in regulations between epochs (Figure 49).

The assessment indicators *B2016/Bref* and *B2016/Bmsy* showed good stability (Figure 33).

4. STOCK ASSESSMENT

4.1 Assessment indicators

Stock assessment indicators requested by MPI and the RLFAWG are summarised in Table 10. These included several based on vulnerable biomass such as current biomass *B2016*, projected biomass *B2019* and the minimum of the vulnerable biomass trajectory after 1979, *Bmin*. These were all start-of-season AW biomass, which does not include mature females. Vulnerable biomass takes MLS, selectivity and sex/seasonal vulnerability into account and is the biomass available to the fishery. Vulnerable biomass was calculated with the appropriate MLS: 54 mm TW for males and 60 mm TW for females.

The most important indicator was *Bref*, the mean of AW vulnerable biomass in 1979–88. This is a *Bmsy* proxy reference point (see MFish 2011). Estimated *Bmsy* is sensitive to growth and mortality estimates and also to the assumptions under which it is estimated. *Bref* is based on a period when the stock was in a relatively good position and above a lower level from which the stock subsequently recovered.

Bmsy and *MSY* were estimated in deterministic 50-year simulations that started at the 2016 biomass estimates. The NSL catch was assumed to remain constant at the 2015 value and the simulations used the 2015 SL catch split between AW and SS. Recruitment was based on *R0*. A series of multipliers on *F* was applied: *MSY* was the maximum SL catch; *Bmsy* was the biomass from which *MSY* was taken; *Fmult* was the multiplier on 2015 *F* that gave *MSY*; *CPUEmsy* was the CPUE associated with *MSY*.

Spawning stock biomass *SSB* was the biomass of all mature females at the start of AW; *SSBmsy* was the biomass associated with *MSY*. *SSB0* was the spawning stock biomass at unfished equilibrium with *R0*.

For the short-term stock projections, biomass and spawning stock biomass were projected for three years using recruitment based on the most recent 10 years of estimates, constant fishing patterns and constant catches at the 2015 levels.

USL was the exploitation rate on the size-limited (SL) stock and *UNSL* was the exploitation rate on the non-size-limited (NSL) stock.

Btot and *Ntot* were the biomass and numbers of all fish without regard to MLS, selectivity or vulnerability.

As well as the simple indicators, the RLFAWG requested the posterior distribution of ratios, for instance the ratio of current biomass to *Bmsy*, and the probabilities that various propositions were true in the McMCs.

Three new indicators requested for 2016 were MinHandMort, the minimum handling mortality tonnage for 1979–2016, HandMort2015 and HandMort2019. Handling mortality was assumed to be 5% for all lobsters returned to the sea from 1990 and 10% before 1990. Lobsters in the model subject to this were caught in the SL fishery: undersized of both sexes and mature females in AW.

4.2 CRA 4 stock assessment

The posteriors of assessment indicators are summarised in Table 11. The median stock was estimated to be 30% above *Bmin* (5th and 95th quantiles 18% to 41%), 47% above *Bmsy* (27% to 71%) but only 75% of *Bref* (69% to 81%). There was zero probability that 2016 biomass was above *Bref*. At 2015 levels of catch, projected biomass decreased with 65% probability by a median of 6% and remained below *Bref* with 98% probability.

Spawning stock biomass was 51% of *SSB0* (44% to 62%) and there was no probability that it was below 20% *SSB0.* At 2015 levels of catch, projected *SSB* increased slightly.

MSY was more than twice *Bmsy* (this is misleading, because MSY is taken from both the AW and SS biomass, while *Bmsy* is the AW biomass only) and was achieved with an *F* 3 times the current *F* levels. The proxy *Bref* was twice *Bmsy* and therefore a more conservative reference point.

Surplus production (Figure 50) shows a strongly declining trend from the mid-1990s, with some increasing phases that align with trends in CPUE.

The phase diagram of fishing intensity vs. biomass is shown in Figure 51. This “snail trail” is a plot developed by the Stock Assessment Methods Working Group, showing the median spawning biomass on the x-axis and median fishing intensity on the y-axis; thus high biomass/low fishing intensity is in the lower right-hand corner, where a stock would be when fishing first began, and low biomass/high intensity is in the upper left-hand corner, where an uncontrolled fishery would be likely to go. Specifically, the x-axis is spawning stock biomass *SSB* as a proportion of the unfished spawning stock *SSB0*. Estimated *SSB* changes every year; *SSB0* is constant for all years of a simulation, but varies among the 1000 samples from the posterior distribution.

The y-axis is fishing intensity as a proportion of the fishing intensity that would have given *MSY* (*Fmsy*) under the fishing patterns in year *y*; fishing patterns include MLS, selectivity, the seasonal catch split and the balance between SL and NSL catches. *Fmsy* varies among years because the fishing patterns change. It was calculated with a 50-year projection for each year in each simulation, with the NSL catch held constant at that year’s value, deterministic recruitment at *R0* and a range of multipliers on the SL catch *F*s estimated for year *y*. The *F* (actually *F*s for two seasons) that gave *MSY* was *Fmsy* and the multiplier was *Fmult*.

Each point on the figure was plotted as the median of the posterior distributions of biomass ratio and fishing intensity ratio. The vertical line in the figure is the median (line) and 90% interval (shading) of the posterior distribution of *SSBmsy* as a proportion of *SSB0*; this ratio was calculated using the fishing pattern in 2015. The horizontal line in the figure is drawn at 1, the fishing intensity associated with *Fmsy*. The bars at the final year of the plot show the 90% intervals of the posterior distributions of biomass ratio and fishing intensity ratio.

This plot suggests that spawning stock biomass has rarely been below *SSBmsy* (although it was in 2016) and also that fishing intensity has rarely been above *Fmsy*. *SSBmsy/SSB0* is about 60% because of the small size at maturation, allowing much breeding before females reach the MLS. Because of the high fishing intensity associated with *Bmsy*, this plot should be interpreted cautiously; the Plenary did not accept the plot for the Plenary Report.

4.3 McMC sensitivity trials

Five sensitivity trials were run with McMC. For each, only the change specified was made to the base case; five million simulations were started from the MPD and 1000 samples were saved. The trials were:

- lag1: with the puerulus lag set to 1 year instead of 2
- 2-sex: from the 2-sex fit described above as a base case MPD candidate
- normal: with normal tag likelihood instead of robust normal
- fixedG1: from the fixedG1 fit described above as a base case MPD candidate
- fixedG2: from the fixedG2 fit described above as a base case MPD candidate

Traces for important estimated parameters are compared in Figure 52–Figure 56 and diagnostic plots are shown in Figure 57–Figure 61. Traces and diagnostics for the lag1, normal and fixedG2 trials were not as good as in the base case (see Figure 30 and Figure 34) and were poor in the 2-sex and fixedG1 trials. All five trials showed some drift in the key parameters of ln(*R0*) and *M*, as seen in the base case, but the drift was more pronounced in the sensitivity trials.

Estimated parameters are compared among these trials in Table 12. Differences were not large. In the fixedG1 and fixedG2 trials, *M* decreased by about 9%. The assessment indicators are compared in Table 13. The major important differences involved the trials fixedG1 and fixedG2:

- *B2016/Bmsy* was much lower than in the base case, although still greater than 1
- *B2019/Bmsy* was much higher than in the base case
- *B2016/Bref* was slightly lower than in the base case
- projected biomass increased by nearly 50% whereas it decreased in the base case
  - probably because of the high fixed value for *Gshape*
- projected biomass increased to more than *Bref*
- current and projected spawning biomass were higher than *Bref* and *Bmsy*

The probability indicators are compared in Table 14. The fixedG1 and fixedG2 trials differ again from the base case in ways consistent with those just noted. The lag1 trial has a much higher probability of increasing biomass at current catch levels and higher probability that *B2019* would be greater than reference values; these results occur because the high recent recruitment estimates reach the stock sooner.

Recruitment is compared among the base case and these five sensitivity trials in Figure 62. Note the lower recruitment, consistent with lower *M*, in the fixedG1 and fixedG2 trials. The form of the trajectories is similar among all trials, which show generally low recent recruitment. Vulnerable biomass trajectories (Figure 63) are also similar in form, but the 2-sex, fixedG1 and fixedG2 trials showed much less variability, which reflects the effect of fixing maturity or growth parameters.

5. MANAGEMENT PROCEDURE EVALUATIONS

MPs have been in place for CRA 4 since 2007 (Breen 2016) and the current MP has been the basis of TAC and TACC changes since 2012.

5.1 The 2012 CRA 4 management procedure

The CRA 4 MP used from 2012–16 was based on work conducted in 2011 by Breen et al. (2012), who used an operating model based on the CRA 4 stock assessment done in that same year. Rules evaluated were all generalised plateau step rules (see Breen 2016). From the options recommended by the NRLMG 2012, the Minister adopted rule 28a. This was a generalised plateau step rule and is illustrated in Figure 64.

The output variable was TACC (tonnes) and the input variable was standardised CPUE (kg/potlift) based on the offset year (1 October through 30 September) collated with the B4-L algorithm (see Starr 2016). When CPUE was below 0.5 kg/potlift the specified TACC was zero; between CPUE values of 0.5 and 0.9 kg/potlift the TACC increased linearly with CPUE to a plateau of 467 tonnes, which extended to a CPUE of 1.3 kg/potlift. As CPUE increased above 1.3 kg/potlift, TACC increased in steps with a width of 0.1 kg/potlift and a height of 7% of the preceding TACC. There was no latent year (TACC could be changed every year if necessary) and the rule had no thresholds for minimum and maximum change, except a maximum 25% increase when CPUE was below the plateau.

The history of operation of this rule is given in Table 15. In November 2015, standardised B4-L offset-year CPUE had decreased and was to the left of the plateau. The rule gave a TACC of 446.219 t. Although this was a change of only 4.5%, the CRA 4 MP had no minimum change threshold, so the result was a TACC of 446.219 t. CRA 4 industry decided that a bigger cut was required; they made representations to the NRLMG and conducted a vote, resulting in a TACC reduced by 15% to 397 t. In the history of MP management of New Zealand lobsters, this was the third instance (after CRA 5 and CRA 9 for 2015–16) where a management procedure result was not followed.

5.2 Operating model

The base case stock assessment model was extended to make 20-year projections with the TACC being set each year by the harvest control rule being tested. Recreational catch was projected using an estimated exploitation rate from 1979–2015. Non-commercial catches were held at their 2015 estimates.

Projected recruitment was based on the mean and standard deviation of estimated *Rdev*s from 2008–2017. Fishing took place every six months. Recreational and customary catches were assumed to be taken 90% in SS; illegal catch was assumed to have the same seasonal catch split as the commercial catch in each year. The proportion of commercial catch taken in AW was predicted from a regression based on AW CPUE (Figure 65) using the model's predicted AW CPUE for each year.

Real-life MPs are driven by offset-year CPUE, which is calculated from AW data from the year in which the MP is operated and from SS in the preceding fishing year. The model estimated projected offset-year CPUE for year x by taking the mean of CPUE from AW in fishing year x and from the SS season in fishing year x-1. This procedure appears to be reliable: the relation between the result and the observed CPUE was linear (Figure 66). Observation error was added to the model's predicted offset-year CPUE based on the residuals in CPUE seen in the minimisation for each sample of the joint posterior.

The operating model comprised all the samples of the joint posterior obtained in the base case stock assessment McMC: each rule was evaluated with each of the 1000 samples of the joint posterior and also with robustness trials as described below.

5.3 Performance indicators

Performance was evaluated over 5 or 20 years in each of the 1000 runs for each rule evaluated. Indicators were identified for each of the four important performance classes:

- abundance, reflected in biomass and CPUE indicators
- yield, reflected in recreational and commercial catch indicators
- safety, reflected in the chance that biomass would be less than reference points
- stability, reflected in the frequency and size of annual changes to the TACC.

For biomass, catch and CPUE indicators, the mean, over 5 or 20 years, was calculated for each simulation and the indicators were reported as the medians and the 5th and 95th quantiles of the posterior distributions of the 1000 means. Average annual change in TACC was treated similarly, where the percentage of changes was calculated as the change divided by the mean TACC (shown for the 20-year indicator; similarly for the 5-year indicator):

$$AAVH = \frac{\sum_{y=2017}^{y=2036} 100 \frac{\left|TACC_y - TACC_{y-1}\right|}{0.5\left(TACC_y + TACC_{y-1}\right)}}{20}$$

Terminal biomass was reported as the median of the posterior distribution of biomass in the last projection year. Minimum commercial and recreational catches were reported as the posterior distribution of the minimum catches during each simulation; similarly for minimum CPUE. The 5-year commercial catch was reported as the median of the posterior distribution of commercial catch in the 5th projection year. Indicators related to total biomass and numbers were added at MPI request in 2014.

Probabilities (i.e., the proportion of 20 000 projected years in which the proposition was true) were calculated for biomass being less than a reference level, for CPUE being to the left or right of the plateau and for the TACC being changed.

Indicators were added in 2016 to address the need to evaluate the first five years of the projection; this need became obvious after inspection of sample trajectories. Some worthless indicators from 2015 were omitted. The complete list of indicators that were calculated was:

- average biomass over 20 years, scaled by *Bref*: 5%, median and 95%
- average biomass over 5 years, scaled by *Bref*: 5%, median and 95%
- average biomass over 20 years scaled by *Bmsy*: 5%, median and 95%
- terminal biomass (scaled by *Bref*): 5%, median and 95%
- minimum commercial catch over 20 years: 5%, median and 95%
- average commercial catch over 20 years: 5%, median and 95%
- average commercial catch over 5 years: 5%, median and 95%
- commercial catch in the 5th year of the projection: 5%, median and 95%
- minimum recreational catch over 20 years: 5%, median and 95%
- average recreational catch over 20 years: 5%, median and 95%
- minimum CPUE over 20 years: 5%, median and 95%
- minimum CPUE over 5 years: 5%, median and 95%
- average CPUE over 20 years: 5%, median and 95%
- average CPUE over 5 years: 5%, median and 95%
- CPUE in the 5th year of the projection: 5%, median and 95%
- AAVH, the average percentage change in TACC, over 20 years: 5%, median and 95%
- AAVH over 5 years: 5%, median and 95%
- proportion of years with a change in TACC over 20 years
- probability that biomass after 5 years was less than biomass at the start
- probability that biomass was less than *Bref* after 20 years
- probability that biomass was less than *Bref* after 5 years
- probability that biomass was less than *Bmin* after 20 years
- probability that biomass was less than *Bmsy* after 20 years
- probability that *SSB* was less than 20% *SSB0* after 20 years
- probability that *SSB* was less than 10% *SSB0* after 20 years
- proportion of years with biomass less than 50% *Bref* over 20 years
- proportion of years with biomass less than 25% *Bref* over 20 years
- proportion of years with CPUE below the left of the plateau over 20 years
- proportion of years with CPUE above the right of the plateau over 20 years
- proportion of years with CPUE above the right of the plateau over 20 years
- proportion of years with CPUE greater than 0.5 over 20 years
- proportion of years with CPUE greater than 0.8 over 20 years
- proportion of years with CPUE greater than 0.914 over 20 years
- proportion of runs in which TACC was set at less than 200 t in the first 5 years
- proportion of runs in which TACC was set at less than 250 t in the first 5 years
- total biomass in 20th projection year: 5%, median and 95%
- total biomass in 20th projection year divided by *B0*: 5%, median and 95%
- total numbers in 20th projection year: 5%, median and 95%
- total biomass in 20th projection year divided by *N0*: 5%, median and 95%

The total output from each rule was 74 indicator values. Not all of these were considered useful; for instance, 5th and 95th quantiles were discussed only for minimum CPUE over 5 years (5th quantile only). A subset of indicators is provided in tables; the NRLMG agreed on a much smaller list of key indicators to be shown to stakeholders and MPI presented an even shorter list in consultation documents.

In what follows, the "average" of indicators such as catch or biomass is the median of the mean results from 1000 runs.

5.4 Productivity of the operating model

Productivity of the operating model was explored in constant-TACC runs with a wide range of TACCs and in constant-rate runs where the TACC was a constant times the projected previous year's offset-year CPUE. Average CPUE vs. average commercial catch (Figure 67) was similar for the two types of rule. The maximum commercial catch averaged over 20-year projections was 446 t at a constant TACC of 450 t; this was associated with average CPUE of 0.46 kg/pot with biomass less than *Bref* in 93% of years. For the constant-rate rules, the maximum commercial catch was 445 t, obtained with a multiplier on CPUE of 1160 and associated with average CPUE of 0.37 kg/pot and with biomass less than *Bref* 99% of the time. Average recreational catch followed the same relation with CPUE, because recreational catch is assumed to be proportional to SS CPUE, with an average catch of 19 to 22 t when commercial catch was maximised.

Figure 68 shows the proportion of years with biomass less than *Bref* vs. average commercial catch. The maximum catch that could be taken with a proportion less than 50% was 330 t, obtained with a constant TACC of 330 t, at an average CPUE of 0.89 kg/pot; very similar results were obtained with a constant rate multiplier of 370.

The average commercial catch associated with a CPUE of 1 kg/potlift would be near 200 t over 5 years and near 300 t over 20 years (Figure 67). Such productivity is well below the recent history of the fishery (Table 16), where the average catch has been 400 t or more associated with average CPUE of 1 kg/potlift or more. The reduced productivity was also seen in the trajectory of surplus production (Figure 50).

Although there was some suggestion of decreasing growth rate over time (Figure 23), the main cause of decreased productivity in the operating model lay in recruitment. Recent recruitment was estimated as low for 2008–2014 (Figure 46). This 10-year average, used by the operating model to make its projections, was the lowest in the time series (Figure 69), which explains the low productivity of the operating model.

The first comparison of an operating model result with an actual observation was possible when offset-year CPUE was calculated in November 2016 after MPEs were complete (Figure 70). The 2016 value was 0.685 kg/potlift. The distribution of predictions from the operating model ranged from 0.608 to 0.929 kg/potlift; the observed value was at the 11th quantile of this distribution . For what it was worth, this comparison suggested that the operating model's predicted productivity was not unduly pessimistic.

5.5 Performance of the 2012 CRA 4 management procedure

Predicted performance of the 2012 CRA 4 MP for a very small set of indicators (Table 17) was consistent with the low productivity discussed above: mean commercial catch was 336 t associated with mean CPUE of 0.83 kg/potlift in 20-year runs, but only 306 t in 5-year runs (with a slightly higher average CPUE). Years with biomass less than *Bref* were 60%, which would likely be unacceptable.

The better performance in 20-year runs vs. 5-year runs is partly explained by the depleted state of the 2016 stock. However, when we examined the TACC and CPUE trajectories of 20 representative runs (saving every 50th run) under this rule, the results were striking (Figure 71): TACC was decreased in 18 of the 20 runs from 2017 to 2018, with some runs decreasing TACC to very low values. In most runs, TACC then increased from 2018 to 2019 and in all runs from 2019 to 2020. By 2022, most runs (83%) had biomass at or above *Bref* despite the depleted stock in 2018.

This behaviour was not unique to the 2012 management procedure: the pattern of initial strong decrease in abundance followed by strong and rapid increase was also seen in preliminary rule experiments and in the final set of rules described below. The pattern of recent recruitment estimates is key to understanding it. Estimated recruitment (Figure 72) was low for 2008–14 as discussed above, then increased strongly for 2015–17. The time between recruitment to the model and growing to MLS (Table 6) is 4.5 years for males and 7.5 years for females, thus recruitment to the stock during 2017 and 2018 is driven by the estimated recruitment to the model for 2009–13. After the first two years of projections, the strong recruitment to the model in 2015 begins to recruit to the stock, explaining the very strong rebuild of the stock to 2022. In the early projection years, recruitments to the model are not projected; they are model estimates, in turn based for the most recent years on the fit to puerulus indices.

Examining these trajectories suggested that 5-year indicators were very important, with much of the differences among rules being expressed most strongly in the first 5 years; we expanded the number of 5-year indicators and presented these to the NRLMG and stakeholders. Second, it quickly became obvious that the minimum level of TACC, usually occurring in 2018 or 2019, was of major interest and we programmed additional indicators to address this.

5.6 Robustness trials

The RLFAWG suggested that four robustness trials should be run:

- fixedG2: the McMC sensitivity trial described above
- normal: the McMC sensitivity trial described above
- high observation: the standard deviation of CPUE observation error was doubled
- high recruitment: this trial used projected recruitment based on 1992–2001, which had recruitment 50% higher than in the base case

With a preliminary set of rules, we ran the rules with both the base case and robustness models and presented results to the RLFAWG. The problems described above – strong decreases and increases in abundance in the first 5 years, and the tendency for rules to produce very low TACC values in 2018 despite later rebuilds – were discovered after this and the initial set of rules was discarded in favour of the rule set described below. Time became limited and this set of four robustness trials was not retained.

At the Plenary, the major issue identified for consideration of alternative candidate rules was the strong increase after 2018 or 2019, which as described above is driven by the strong puerulus indices seen in 2015–17 (Figure 44). The Plenary noted that the model's uncertainty around recruitment estimates for 2015–17 was low, because the model was fitting only to the puerulus indices for these years and there was no influence of CPUE or LFs because these fish had not yet grown to appear in the data. It was argued that the model's projected strong stock increase to 2022 was too certain and that the strong puerulus settlement might not actually produce strong recruitment to the stock.

A further robustness trial addressed this concern. This trial was not fit to puerulus data and hence was called "noPoo". *Rdev*s could be estimated only for 1945–2013, so projections were based on the 10 years from 2004–13. The McMC was 5 million simulations with 1000 samples saved as in the base case.

5.7 Development of a new CRA 4 MP

Stakeholders were canvassed for their views about the form of a new CRA 4 management procedure. A CRA 4 stakeholder meeting was convened by MPI in Masterton on 20 July 2016. The purpose of the workshop was (paraphrased from Alicia McKinnon, unpublished document to the NRLMG): for people to learn about rock lobster stock assessment, management procedure evaluations and catch limit setting; and to share and discuss future aspirations for the CRA 4 fishery.

Stakeholders broke into sub-groups to discuss how they would like the CRA 4 fishery to perform in the future. Some assessment-related concerns were identified:

- assessments should be annual and perhaps the methodology should be changed
- best available information should be used
- finer-scale management should be explored
- environmental effects on the stock should be studied
- concerns with inaccuracy of the CPUE data should be addressed
- all sectors should be reporting their catches

Desiderata for the new management procedure were loosely summarised as sustainability, good abundance and fish for the next generation. These were useful but only of limited help in designing a new management procedure. A CRAMAC4 executive meeting also identified a range of concerns, including:

- the 2012 rule plateau might be too high
- the 2012 plateau might extend too far to the left
- any new rule should be responsive to declining CPUE

Industry's dissatisfaction with the 2012 rule was obvious in early 2016, when CRAMAC4 rejected the rule's suggested 5% TACC reduction and voted to ask the Minister for a 15% TACC reduction. Clearly, they were not comfortable with the rule's suggested TACC at the 2015 level of CPUE.

At MPI's request, we evaluated rules that used standardised CPUE as input, collated with the F2-LFX procedure (see Starr 2016), to set a TACC. This was a change: the 2012 MP used CPUE collated with the older B4-L procedure as an input. As a result, all lobster MPs now use the F2-LFX procedure except CRA 8, which uses F2-LF.

After preliminary explorations that were reported to the RLFAWG, we explored the set of 96 rules summarised in Table 18. Choices are explained below.
***par1*:** we used only rule type 4, plateau step rules; we believe this rule type to be sufficiently flexible to accommodate stakeholder aspirations
par2: we experimented with shifting the intercept to the left to reduce the severe effects of low CPUE on TACC. The 2012 rule shut the fishery when CPUE was 0.5 kg/potlift or lower; we experimented with values down to zero
***par3*:** we used the 2012 rule's value of 0.9 kg/potlift for the left plateau; we also used the larger value of 1.0 kg/potlift
***par4*:** because the important rule performance occurred in the first few years, we did not experiment with alternative values for the right-hand edge of the plateau, using only the 2012 rule's value of 1.3 kg/potlift
***par5*:** we experimented with 8 values of plateau height after preliminary analyses showed that this was by far the most important variable: we used 8 values from 320 t to 440 t, just under the 2012 rule's height
***par6*:** we did not experiment with the 2012 rule's step width of 0.1 kg/potlift
***par7*:** we used a step height of 0.053, except that we increased this for low plateau heights such that rules would deliver similar TACCs if CPUE reached 1.4 kg/potlift
***par8*:** based on the history of operation of this rule and experience with rules in other stocks, we specified a 5% minimum TACC change threshold
***par9*:** based on preliminary evaluations of rules, we specified that there should not be a maximum change threshold, because this decreased the rule's ability to increase TACC as CPUE increased after 2018
***par10*:** based on preliminary evaluations of rules, we specified that there should not be a latent year (latent years decreased safety)

Of the parameters that varied, the effects were reasonably simple. Higher plateau heights tended to have a larger average catch over 5 years and a lower average abundance over 5 years. Larger intercepts tended to have much higher probability that TACC would fall below 200 or 250 t in the first

5 years. Using the higher value for plateau left tended to have a lower average catch and higher average CPUE over the first 5 years.

Looking at the distributions of indicators across the whole set of 96 rules, averages are compared for some major indicators in Table 19 between the base case and the noPoo trial. Because the 10 years that formed the basis for recruitment were different, the noPoo trial had higher average recruitment than the base case (Figure 69), which was reflected in higher mean commercial catch and CPUE. The variability of some indicators was considerably greater in the noPoo trial (illustrated for one rule in Figure 73). Although the median 5th year biomass was near *Bref* for both models, the probability of 5th year biomass being less than *Bref* was only 3% in the base case and was 43% in the noPoo trial.

Median biomass after 5 years as a proportion of *Bref* showed the same pattern for both models (Figure 74). The probability that the TACC would be less than 250 t at some stage during the first 5 years (Figure 75) was least in the rules that gave high catches, but showed much variation at each level of average catch. The base case had higher probabilities than the noPoo trial from rules that gave low average catches but the converse was true for rules that gave high average catches. The noPoo trial had consistently higher minimum 5-year CPUE for the same average catch (Figure 76). The probability that 5th year biomass was less than *Bref* increased as average catch increased for both models but was consistently much higher for the noPoo trial (Figure 77).

Before the changes to indicators, changes from the preliminary set of rules and the change to the new robustness trial, a web-based viewer had been constructed and demonstrated to the RLFAWG. There was unfortunately no time available to revise this after the changes were made, so that viewer was not used in showing rule results to stakeholders. Instead, a much more primitive spreadsheet viewer was constructed, as shown in Figure 78, and distributed to the NRLMG, who then made it available to stakeholders.

Screening procedures to reduce the number of rules from 96 to something more tractable were discussed with stakeholders. It proved difficult to find rules that kept TACC above 200 or 250 t with an acceptable probability and at the same time had acceptable CPUE indicators and an acceptable probability of rebuild. The NRLMG went to consultation on two rules after much discussion.

6. DISCUSSION

The MSLM model fit the CRA 4 data with some difficulty. Maturation parameters were a problem because CRA 4 females mature at small sizes and, because of low trap selectivity for small lobsters, are not well represented in the data. It was necessary to fix the shape parameter for the maturation ogive. High estimated *M* (well outside the prior distribution) appeared to be related to the low proportions of larger lobsters in the LF data: when the growth shape parameter was estimated with a relaxed prior it increased to higher values, allowing fast growth in smaller lobsters and slow growth in larger lobsters, accompanied by lower *M*. Because of high estimated *M*, *Bmsy* was small and *Fmsy* was very high. *Bref* was both a more conservative and a more credible reference point.

A possible approach would be to use the MSLM model for the seven stocks where it has been used, estimate *M* with a wide uniform prior, then use the posterior distribution of results as an informative prior. For CRA 4 the high estimated *M* may reflect a mis-specification of some kind.

Apart from *M* and maturity, we had few problems with parameter estimates, except that it was necessary to reduce the assumed CPUE process error for recent years to force a good fit to recent CPUE. The treatment of catchability was somewhat simplistic: we assumed a linear relation between abundance and CPUE and (probably more importantly) we assumed that catchability has been unchanged throughout the time series. The second assumption is likely to be violated by changes in pot construction and improvements in technology. This issue is scheduled for exploration.

The MPD sensitivity trials that involved removing datasets one at a time suggested that stock assessment results were not strongly dependent on any one data set, except that the model did not converge when the LF data were removed. When tag-recapture data were removed, growth parameters were reasonably estimated; trends in abundance were reasonably estimated even with CPUE removed.

Both MPD and McMC sensitivity trials suggested that the stock assessment results were robust to modelling choices. However, the base case showed much better traces than the alternatives. As always, the RLFAWG identified the lack of information on non-commercial catches and their trends as being a substantial source of uncertainty.

A major concern must be the declining productivity of the CRA 4 stock, reflected in both the declining surplus production estimates and the low operating model productivity compared with recent fishery results. There was a weak time trend in the tag-recapture residuals that suggested declining growth rates, but this seems unlikely to be the main cause. A declining recruitment trend was estimated by the model and may be a cause of the low productivity. Climate changes are an obvious possible direct or indirect cause, along with inshore ecological changes such as increased siltation.

The stock assessment showed a stock depleted below *Bref*, but spawning stock biomass was a high proportion of the unfished stock level *SSB0* because of the small size at maturity. Depletion of the stock was recognised even before the stock assessment by all stakeholders. The multi-stock assessment, not discussed here, confirmed strong sub-area differences in population rates within the CRA 4 stock. Future stock assessments will explore this further with the intent of moving on from simplistic single-stock assumptions and models.

The base case operating model predicts further decline in the stock at all reasonable TACC levels, leading to further decreased TACCs for 2018 and then followed in some runs by even further declines. It then predicts a very strong stock increase to levels near *Bref* by 2022. The decline and increase are both driven by the estimated recruitment to the model with the strong increase partly driven by high puerulus settlement levels in 2015–17. The noPoo robustness trial, not fit to settlement indices, shows much more uncertainty in the projected rebuild because it ignores the settlement data.

Some lessons were learned during the rule development and MPE phase of this work. First, more time should be allowed for this phase of the work. This assessment fell behind schedule during the process of finding a base case, largely because of problems with the LF data. All the substantial work that led to the information provided to stakeholders took place after the assessment workshop, much of this after the Plenary.

Second, it is imperative always to examine the trajectories of abundance and TACC from representative runs for each rule. This was not done in the work presented to the last RLFAWG meeting and the dramatic decline/increase behaviour could easily have been missed.

Third, because rules are put into place for 5 years and then reviewed, 5-year indicators are important, although longer run results must also be used to ensure that the rule is basically stable.

Fourth, it was obvious in the final stages of the NRLMG's explorations of rules that few stakeholders had much understanding of the results. They were unsure how to interpret robustness trial results and showed confusion about how rule parameter changes affected the results. These basic problems suggest that the information presented to the average stakeholder is far too complex and the set of rules offered for inspection is far too high. Although stakeholders should be making the decisions about risk and trades-off, the assessment team could assist by screening rules, reducing the set of indicators shown and providing summaries of the tradeoffs for a small set of final rule candidates.

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Table 1: Definitions of parameters discussed in the text.

ln(*R0*)	natural log of initial numbers recruiting
Uinit	initial exploitation rate (first year in equilibrium with this)
M	instantaneous rate of natural mortality
Rdevs	annual recruitment deviations
SigmaR	standard deviation of *Rdevs*
ln(*qCPUE)*	natural log of relation between *Bvuln* and CPUE
CPUEpow	*shape of* relation between *Bvuln* and CPUE (1 implies linear)
ln(*qCR*)	natural log of relation between *Bvuln* and CR index
Mat50	size where 50% of immature females become mature
Mat95Add	difference between *Mat50* and *Mat95*
Galpha	annual growth increment at 50 mm TW
Gbeta	annual growth increment at 80 mm TW (calculated)
Gdiff	the ratio of *Gbeta* to *Galpha*
Gshape	parameter for shape of growth curve: 1 implies vonB straight line; >1 implies concave upwards
GCV	standard deviation of growth-at-size divided by growth-at-size
Gobs	standard deviation of observation error for tag-recaptures
Gmin	minimum standard deviation of growth
Growthd-d	strength of growth density-dependence
SelLH	shape of the LH of selectivity curve (as if it were a standard deviation)
SelMax	size at maximum selectivity
SelRH	shape of the RH of selectivity curve (as if it were a standard deviation)
vuln	relative vulnerability by sex and season
movements	proportion of fish that move from CRA 7 to CRA 8 by season (estimated by year)
Bvuln	start-of-season AW biomass available to be caught legally
B2016	vulnerable biomass at start of AW 2016
B2020	similarly
Bref	mean of AW *Bvuln* for 1979–88
Bmsy	biomass at *MSY*

Table 2: Priors used in the CRA 4 3-sex fit for estimated parameters: the estimation phase, upper and lower bounds, prior type (0: uniform, 1: lognormal, 2: normal), prior mean and standard deviation or CV and the initial values.

Season	Sex	Parameter	Phase	lower bound	upper bound	prior type	prior mean	prior std/CV	initial value
		ln(*R0*)	1	1	25				18
		M	4	0.01	0.35	2	0.12	0.4	0.12
		*Rdev*s	2	-2.3	2.3	1	0	*sigmaR*	0
		ln(*qCPUE*)	1	-25	0	0			-6
		ln(*qCR*)	1	-25	2	0			-3
		ln(*qpoo*)	1	-25	0	0			-6
		mat50	4	30	80				41.82
	male	*Galpha*	2	1	20	0			3.5
	male	*Gdiff*	2	0.001	1	0			0.8
	female	*Galpha*	2	1	20	0			3.5
	female	*Gdiff*	2	0.001	1	0			0.5
	male	*Gshape*	3	0.1	15	1	4.81	0.48	4.8
	male	*GCV*	5	0.01	2	1	0.59	0.18	0.59
		Gshape	3	0.1	15	1	4.51	0.45	4.5
		GCV	5	0.01	2	1	0.82	0.25	0.82
		Gobs	5	0.00001	10	1	1.48	0.074	1.5
	male	*SelLH*	4	1	50	0			4.1
	female	*SelLH*	4	1	50	0			9.2
	male	*SelMax*	5	30	90	0			55
	female	*SelMax*	5	30	90	0			64
		vulns (all)	3	0.01	1	0			0.8

Table 3: Dataset weights used for the four final base case candidates described in the text.

	2-sex	3-sex	fixedG1	fixedG2
tags	1	1	1	1
CPUE	3	2.8	2.8	2.8
CR	4	4	4	4
sex ratio	4.06	3.45	3.45	3.45
male LFs	4.06	3.45	3.45	3.45
immature	0.001	0.167	0.167	0.167
mature	1.84	1.814	1.814	1.814
puerulus	0.683	0.683	0.683	0.683

Table 4: Fixed quantities used in searching for a CRA 4 base case.

Quantity	Value	Quantity	Value
multiplier on maximum *U*	1.00E+06	*UInit*	0
process error CPUE 1979-2013	0.25	*GDD*	0
process error CPUE 2014-2015	0.075	*Gmin*	0.0001
relative sigma for CR	0.3	*SelRH*	200
Newton-Raphson iterations	3	male length-weight *a*	4.16E-06
lag for puerulus	2	male length-weight *b*	2.9354
last year of estimated *Rdevs*	2017	female length-weight *a*	1.30E-05
years for *Rdev* projections	2008–2017	female length-weight *b*	2.5452
CRA 4 reference years	1979–88	handling mortality, 1945-89	0.1
projected SL catch	434	handling mortality, 1990-2015	0.05
projected NSL catch	60	min survival proportion	0.02
marine reserve proportion	0	CRA 4 reference years	1979–88
male bins	6 to 26	projected SL catch	434
immature bins	1 to 20	projected NSL catch	60
mature bins	7 to 28	marine reserve proportion	0
sigmaR	0.4	male bins	6 to 26
CPUEpow	1	immature bins	1 to 20
Mat95Add	2.92	mature bins	7 to 28

Table 5: Map of *vuln* parameters in the four fits described in the text.

Sex	Season	2-sex	3-sex	fixedG1	fixedG2
male	AW	1	*vuln1*	*1*	*1*
male	SS	*vuln1*	*vuln2*	*vuln1*	*vuln1*
immature female	AW	*vuln2*	*1*	*vuln2*	*vuln2*
immature female	SS	*vuln2*	*vuln3*	*vuln3*	*vuln3*
mature female	AW	*vuln3*	*vuln4*	*vuln4*	*vuln4*
mature female	SS	*vuln4*	*vuln3*	*vuln3*	*vuln3*

Table 6: Comparing MPD results from the four base case finalists.

	2-sex	3-sex	estMat95	fixMat95
LFs-weight-female	1.84	1.814	1.814	1.814
LFs-sdnr	0.877	0.971	0.644	0.644
LFs-MAR	0.062	0.175	0.164	0.164
LFs-LL	7256.2	6470.2	6437.1	6437.1
Tags-sdnr	1.573	1.578	1.827	1.827
Tags-MAR	0.700	0.694	0.717	0.717
Tags-LL	2382.3	2376.2	2338.7	2338.7
CPUE-sdnr	1.228	1.187	1.228	1.228
CPUE-MAR	0.810	0.718	0.805	0.805
CPUE-LL	-131.4	-129.9	-126.3	-126.3
CR-sdnr	0.857	0.894	0.354	0.354
CR-MAR	0.650	0.696	0.093	0.093
CR-LL	-24.4	-24.1	-27.8	-27.8
SexRatio-sdnr	1.005	0.953	0.928	0.928
SexRatio-MAR	0.252	0.417	0.491	0.491
Priors	-39.6	-40.6	-43.6	-43.6
Function value	9481.7	8691.0	8567.6	8567.6

	2-sex	3-sex	estMat95	fixMat95
ln(*R0*)	15.06	14.99	14.32	14.32
M	0.253	0.259	0.236	0.236
ln(*qCPUE*)	-6.435	-6.123	-5.900	-5.900
ln(*qCR*)	-2.338	-2.012	-1.677	-1.677
ln(*qpoo*)	-14.86	-14.81	-14.18	-14.18
mat50	42.27*	42.27	44.81	44.81
mat95Add	2.92*	2.92*	4.9	4.9*
GalphaM	2.999	3.034	3.033	3.033
GbetaM	2.467	2.317	2.211	2.211
GalphaF	2.378	2.434	2.431	2.431
GbetaF	1.329	1.287	1.451	1.451
GshapeM	5.49	5.73	10.01*	10.01*
GCVM	0.633	0.634	0.693*	0.693*
GshapeF	4.60	5.05	7.09*	7.09*
GCVF	1.05	1.08	1.09*	1.09*
StdObs	0.611	0.609	0.397*	0.397*
SelLH1M	0.792	0.714	0.872	0.872
SelMax1M	0.010	0.553	0.388	0.388
SelLH1F	0.667	0.649	0.636	0.636
SelMax1F	0.875	0.488	0.492	0.492
SelLH2M	5.9	6.1	6.8	6.8
SelMax2M	55.4	55.4	53.2	53.2
SelLH2F	15.5	13.3	15.0	15.0
SelMax2F	74.9	73.0	72.2	72.2
SelLH1M	4.4	4.4	5.5	5.5
SelMax1M	56.1	56.0	56.8	56.8
SelLH1F	6.7	7.9	9.3	9.3
SelMax1F	65.8	67.9	69.1	69.1
B2016/Bref	0.732	0.745	0.699	0.699
Bref	637.9	461.0	452.9	452.9
Bmsy	356.7	246.9	292.5	292.5
B2016/Bmsy	1.310	1.392	1.082	1.082
MSY	635.7	640.4	636.1	636.1
Fmult	2.69	2.94	2.22	2.22
yrstoMLSM	4.5	4.5	2.5	2.5
yrstoMLSF	8.5	7.5	6.5	6.5

Table 7: Position of the functional value when fitting to puerulus data, using the lag shown, in the distribution of values obtained from fitting to 500 randomised data sets.

Lag	Quantile
0	0.050
1	0.046
2	0.060
3	0.074
4	0.124

Table 8: CRA 4 base case MPD: MPD sensitivity trial results. An asterisk denotes a fixed quantity and grey indicates that quantities were not fit. Growth increment values in mm TW, biomass in tonnes.

	Base	half illegal	tight Gpriors	hand 10%	M12	mat95	normal tag LL	no CPUE	no CR	no tags	no poo
LFs-sdnr	0.971	1.002	1.046	0.974	1.065	0.983	1.079	0.694	0.959	1.136	0.958
LFs-MAR	0.175	0.177	0.181	0.175	0.171	0.176	0.168	0.156	0.173	0.168	0.174
LFs-LL	6470.2	6493.5	6484.2	6471.2	6473.0	6472.0	6456.1	6414.1	6468.9	6448.7	6468.6
Tags-sdnr	1.578	1.596	1.149	1.578	1.488	1.578	1.002	1.701	1.578		1.579
Tags-MAR	0.694	0.708	0.545	0.693	0.662	0.695	0.487	0.686	0.695		0.695
Tags-LL	2376.2	2379.4	2577.2	2375.8	2669.1	2376.1	3025.2	2373.2	2374.5		2374.9
CPUE-sdnr	1.187	1.466	1.209	1.183	1.106	1.187	1.162		1.199	1.020	1.116
CPUE-MAR	0.718	0.918	0.827	0.750	0.601	0.718	0.696		0.731	0.721	0.679
CPUE-LL	-129.9	-101.7	-128.0	-130.3	-136.8	-130.0	-132.2		-128.9	-143.6	-136.0
CR-sdnr	0.894	0.937	0.817	0.923	0.563	0.893	0.817	0.616		0.391	0.914
CR-MAR	0.696	0.702	0.592	0.728	0.200	0.694	0.600	0.393		0.166	0.724
CR-LL	-24.1	-23.7	-24.8	-23.8	-26.7	-24.1	-24.8	-26.4		-27.6	-23.9
Poo-sdnr	1.057	1.080	1.057	1.054	1.212	1.057	1.045	0.789	1.062	1.135	
Poo-MAR	0.839	0.837	0.743	0.818	0.813	0.837	0.716	0.393	0.790	0.939	
Poo-LL	-25.9	-25.0	-25.9	-26.0	-19.0	-25.9	-26.3	-35.2	-25.7	-22.7	
Sex-sdnr	0.953	0.987	0.977	0.954	1.030	0.953	0.961	0.934	0.953	0.976	0.953
Sex-MAR	0.417	0.455	0.419	0.425	0.471	0.421	0.453	0.433	0.420	0.494	0.424
Priors	-40.6	-41.9	-41.8	-40.8	-35.6	-40.6	-41.0	-50.3	-46.2	-47.3	-40.9
Function value	8691.0	8738.6	8846.8	8691.6	8944.5	8692.6	9255.2	8758.8	8709.1	6202.2	8708.8
ln(*R0*)	14.99	15.28	15.22	14.96	14.51	15.00	15.10	14.25	14.97	15.20	14.94
M	0.259	0.293	0.280	0.251	0.12*	0.260	0.256	0.190	0.250	0.334	0.251
ln(*qCPUE*)	-6.12	-7.34	-6.21	-6.12	-5.99	-6.10	-5.67	-6.12*	-6.10	-5.49	-6.13
ln(*qCR*)	-2.01	-2.55	-2.05	-2.05	-2.19	-1.99	-1.66	-1.84	-2.01*	-1.60	-2.03
ln(*qpoo*)	-14.81	-15.10	-15.03	-14.79	-14.20	-14.82	-14.91	-14.08	-14.75	-14.99	-6*
mat50	42.3	42.0	41.8	42.3	42.0	40.3	42.8	42.0	42.3	42.0	42.3
GalphaM	3.034	2.909	2.902	3.037	2.347	3.034	3.032	3.291	3.023	4.557	3.032
GbetaM	2.317	2.145	2.213	2.310	2.347	2.317	2.786	0.609	2.311	4.557	2.311
GalphaF	2.434	2.621	2.724	2.447	1.515	2.444	2.053	2.656	2.403	3.312	2.428
GbetaF	1.287	1.149	1.232	1.295	0.852	1.283	1.662	1.266	1.280	2.833	1.279
GshapeM	5.728	5.162	5.579	5.767	2.366	5.730	5.722	7.731	5.876	4.809	5.816
GCVM	0.634	0.638	0.578	0.634	0.010	0.634	0.587	0.669	0.639	0.263	0.638
GshapeF	5.045	4.837	4.947	5.049	5.848	5.029	4.989	5.243	5.074	4.165	5.068
GCVF	1.082	1.013	0.826	1.078	1.457	1.080	1.438	1.040	1.097	0.748	1.085
StdObs	0.609	0.641	1.394	0.608	1.335	0.609	1.477	0.603	0.605	1.480	0.606
vuln1	0.714	1.000	0.713	0.719	1.000	0.697	0.466	1.000	0.698	0.539	0.723
vuln2	0.553	0.762	0.528	0.555	0.787	0.540	0.377	0.195	0.541	0.444	0.558
vuln3	0.649	0.624	0.588	0.647	0.252	0.632	0.563	0.140	0.636	0.540	0.646
vuln4	0.488	0.491	0.438	0.484	0.198	0.475	0.423	0.416	0.480	0.412	0.483
SelLH1M	6.08	5.36	5.88	6.09	5.62	6.08	5.81	6.96	6.12	5.44	6.17
SelMax1M	55.42	53.89	55.51	55.50	55.52	55.42	55.43	54.64	55.29	54.69	55.37
SelLH1F	13.34	8.12	13.89	13.44	11.10	13.42	10.95	13.42	12.93	9.17	13.77
SelMax1F	72.98	60.57	74.10	73.32	66.62	73.10	70.22	73.17	72.07	65.80	73.54
SelLH2M	4.42	4.32	4.34	4.42	4.25	4.42	4.35	5.66	4.44	4.22	4.41
SelMax2M	56.03	56.00	56.03	56.04	55.79	56.03	56.17	56.88	56.00	55.93	55.95
SelLH2F	7.88	7.51	7.61	7.90	7.43	7.91	7.38	8.31	7.89	6.97	7.89
SelMax2F	67.92	66.27	67.34	67.99	65.53	67.96	67.74	67.72	67.90	66.28	67.86
B2016/Bref	0.745	0.606	0.769	0.741	0.642	0.746	0.752	0.413	0.746	0.768	0.715
Bref	461.0	762.5	492.9	458.9	482.6	449.9	292.8	901.1	451.4	283.6	464.9
Bmsy	246.9	324.0	244.6	307.2	1516.0	240.6	168.7	324.5	256.9	188.7	253.6
B2016/Bmsy	1.392	1.426	1.548	1.108	0.204	1.394	1.305	1.148	1.311	1.153	1.312
MSY	640.4	685.1	673.8	603.3	653.3	640.9	627.6	643.5	664.0	659.2	637.3
Fmult	2.94	3.06	3.53	1.94	0.33	2.95	2.56	1.97	2.83	2.21	2.78
yrstoMLSM	4.5	4.5	4.5	4.5	5.5	4.5	4.5	2.5	4.0	3.5	4.5
yrstoMLSF	7.5	7.0	7.0	7.5	11.5	7.5	9.5	7.0	8.0	7.0	7.5

Table 9: Summaries of estimated parameter posteriors from the base case MCMC. Grey cells indicate fixed parameter values.

epoch	sex	quantity	min	0.05	median	0.95	max	MPD
		function	8722.2	8730.6	8741.1	8753.3	8764.4	8691.0
		ln(*R0*)	14.58	14.77	14.99	15.21	15.38	15.00
		M	0.211	0.236	0.262	0.292	0.327	0.259
		ln(*qCPUE*)	-6.683	-6.53	-6.321	-5.911	-5.475	-6.123
		ln(*qCR*)	-3.269	-2.896	-2.468	-1.849	-1.176	-2.012
		ln(*qpoo*)	-15.21	-15.03	-14.80	-14.60	-14.42	-14.81
		mat50	32.57	38.876	42.016	44.181	45.545	42.269
		mat95Add	2.92	2.92	2.92	2.92	2.92	2.92
	male	*Galpha*	2.80	2.89	3.00	3.11	3.18	3.03
	male	*Gbeta*	1.67	2.00	2.27	2.56	2.70	2.32
	male	*Gdiff*	0.564	0.656	0.756	0.854	0.923	0.764
	male	*Gshape*	4.64	5.23	5.92	6.56	7.37	5.73
	male	*GCV*	0.571	0.608	0.644	0.68	0.72	0.634
	female	*Galpha*	2.08	2.26	2.47	2.65	2.90	2.43
	female	*Gbeta*	0.99	1.11	1.27	1.44	1.60	1.29
	female	*Gdiff*	0.371	0.439	0.517	0.61	0.695	0.529
	female	*Gshape*	4.07	4.55	5.07	5.55	6.16	5.05
	female	*GCV*	0.915	0.977	1.075	1.192	1.304	1.082
		Gobs	0.471	0.542	0.611	0.689	0.767	0.609
		vuln1	0.350	0.533	0.820	0.978	0.999	0.714
		vuln2	0.269	0.424	0.636	0.766	0.817	0.553
		vuln3	0.364	0.513	0.775	0.972	1.000	0.649
		vuln4	0.257	0.390	0.579	0.757	0.897	0.488
1	male	*SelLH*	4.1	5.1	6.2	7.6	10.1	6.1
1	male	*SelRH*	200	200	200	200	200	200
1	male	*SelMax*	51.5	53.3	55.3	57.4	60.4	55.4
1	female	*SelLH*	6.7	10.9	14.1	18.6	22.4	13.3
1	female	*SelRH*	200	200	200	200	200	200
1	female	*SelMax*	60.3	68.1	74.4	81.8	89.8	73.0
2	male	*SelLH*	3.9	4.1	4.4	4.8	5.1	4.4
2	male	*SelRH*	200	200	200	200	200	200
2	male	*SelMax*	55.0	55.4	55.9	56.5	57.0	56.0
2	female	*SelLH*	6.8	7.4	8.0	8.8	9.6	7.9
2	female	*SelRH*	200	200	200	200	200	200
2	female	*SelMax*	65.5	66.5	68.1	69.8	71.5	67.9

Table 10: Stock assessment indicators.

Indicator	Median
Bmin	the lowest estimated vulnerable biomass at the start of the AW season
B2016	estimated vulnerable biomass at the start of the 2016 AW season
Bref	mean vulnerable biomass from the start of the 1979–81 seasons
B2019	estimated vulnerable biomass at the start of the 2019 AW season
Bmsy	vulnerable AW biomass associated with *MSY*
MSY	maximum sustainable yield at current fishing patterns
Fmult	the multiplier on current *F* required to attain *MSY*
SSB2015	biomass of mature females in AW 2015
SSB2019	biomass of mature females in AW 2019
SSBmsy	biomass of mature females associated with *MSY*
CPUE2015	predicted AW CPUE in 2015
CPUE2019	predicted AW CPUE in 2019
CPUEmsy	AW CPUE associated with *MSY*
SSB0	estimated AW biomass of mature females with no fishing
USL2015	exploitation rate in the size-limited fishery in 2015
USL2019	exploitation rate in the size-limited fishery in 2019
Btot2015	total AW biomass at the start of AW 2015
Ntot2015	total numbers at the start of AW 2015
Ntot0	total numbers in the absence of fishing
MinHandMort	the minimum estimated handling mortality tonnage, 1945–2015
HandMort2015	the estimated handling mortality tonnage for 2015
HandMort2019	the estimated handling mortality tonnage for 2019

Table 11: Summary of stock assessment indicators from the base case McMC.

Quantity	5%	Median	95%
Bmin	213.5	324.2	394.8
B2016	276.9	416	517.6
Bref	370.6	560.9	682.9
B2019	236.7	384.3	563.3
Bmsy	188.4	283.6	352.4
MSY	578.2	638.8	713.1
Fmult	2.645	3.11	3.68
SSB2016	1436.2	1601.2	1809.7
SSB2019	1333.1	1649.3	1990.8
SSBmsy	1608.4	1889.9	2201.9
CPUE2015	0.71	0.737	0.764
CPUE2019	0.403	0.584	0.798
CPUEmsy	0.288	0.339	0.397
B2016/Bmin	1.178	1.295	1.413
B2016/Bref	0.687	0.749	0.809
B2016/Bmsy	1.265	1.471	1.712
B2019/B2016	0.721	0.942	1.217
B2019/Bref	0.516	0.708	0.927
B2019/Bmsy	1.021	1.385	1.839
SSB2016/SSB0	0.458	0.508	0.566
SSB2019/SSB0	0.435	0.518	0.621
SSB2016/SSBmsy	0.769	0.85	0.946
SSB2019/SSBmsy	0.741	0.867	1.013
SSB2019/SSB2016	0.885	1.021	1.183
USL2015	0.188	0.229	0.346
USL2019	0.182	0.267	0.434
USL2019/USL2015	0.857	1.134	1.544
Btot2016	3452.4	4056.8	4731.2
Btot2016/Btot0	0.353	0.406	0.469
Ntot2016	1.139E+07	1.415E+07	1.756E+07
Ntot2016/Ntot0	0.435	0.5	0.589
minHandMort	13.02	14.25	15.65
HandMort2016	16.71	18.14	19.76
HandMort2019	21	25.88	33.88
P(*B2016*>*Bmin*)		1	
P(*B2016*>*Bref*)		0	

Quantity	5%	Median	95%
P(*B2016*>*Bmsy*)		1	
P(*B2019*>*Bmin*)		0.859	
P(*B2019*>*Bref*)		0.02	
P(*B2019*>*Bmsy*)		0.96	
P(B2019>B2016)		0.35	
P(*SSB2016*>*SSBmsy*)		0.004	
P(*SSB2019*>*SSBmsy*)		0.073	
P(*USL2019*>*USL2015*)		0.774	
P(*SSB2016*<*0.2SSB0*)		0	
P(*SSB2019*<*0.2SSB0*)		0	

Table 12: Comparison of median estimated parameters between the base case McMC and the five McMC sensitivity trials.

epoch	sex	parameter	base	lag1	2-sex	normal	fixedG1	fixedG2
		function	8741.1	8743.4	9528.7	9306.7	8618.5	8616.9
		ln(*R0*)	14.99	15.04	15.10	15.10	14.36	14.37
		M	0.262	0.269	0.263	0.259	0.237	0.239
		ln(*qCPUE*)	-6.321	-6.286	-6.493	-6.039	-6.026	-6.025
		ln(*qCR*)	-2.468	-2.396	-2.649	-2.246	-2.414	-2.369
		ln(*qpoo*)	-14.80	-14.88	-14.91	-14.91	-14.21	-14.22
		mat50	42.02	42.06	42.27	42.96	44.11	44.54
		mat95Add	2.92	2.92	2.92	2.92	6.75	4.90
	male	*Galpha*	3.00	2.97	2.96	2.99	2.98	2.98
	male	*Gbeta*	2.27	2.27	2.43	2.70	2.31	2.33
	male	*Gdiff*	0.756	0.762	0.822	0.904	0.778	0.779
	male	*Gshape*	5.92	5.79	5.57	5.80	10.01	10.01
	male	*GCV*	0.644	0.647	0.642	0.601	0.693	0.693
	female	*Galpha*	2.47	2.46	2.42	2.07	2.39	2.40
	female	*Gbeta*	1.27	1.28	1.31	1.64	1.48	1.49
	female	*Gdiff*	0.517	0.519	0.540	0.792	0.618	0.619
	female	*Gshape*	5.07	5.04	4.69	4.96	7.09	7.09
	female	*GCV*	1.075	1.069	1.046	1.429	1.09	1.09
		Gobs	0.611	0.61	0.611	1.479	0.397	0.397
		vuln1	0.820	0.777	0.787	0.633	0.864	0.865
		vuln2	0.636	0.600	0.011	0.512	0.507	0.517
		vuln3	0.775	0.747	0.656	0.799	0.786	0.777
		vuln4	0.579	0.556	0.866	0.595	0.610	0.604
1	male	*SelLH*	6.2	6.2	6.0	6.0	7.3	7.2
1	male	*SelRH*	200	200	200	200	200	200
1	male	*SelMax*	55.3	55.5	55.5	55.4	53.8	53.7
1	female	*SelLH*	14.1	14.4	18.3	11.6	16.8	16.9
1	female	*SelRH*	200	200	200	200	200	200
1	female	*SelMax*	74.4	75.2	78.8	71.4	76.4	76.5
2	male	*SelLH*	4.4	4.4	4.4	4.4	5.4	5.4
2	male	*SelRH*	200	200	200	200	200	200
2	male	*SelMax*	55.9	55.9	56.1	56.1	56.5	56.5
2	female	*SelLH*	8.0	8.0	6.7	7.4	9.5	9.4
2	female	*SelRH*	200	200	200	200	200	200
2	female	*SelMax*	68.1	68.1	65.7	67.7	69.9	69.8

Table 13: Comparison of median indicators values between the base case McMC and the five McMC sensitivity trials.

Indicator	base	lag1	2-sex	normal	fixedG1	fixedG2
Bmin	324.2	307.1	391.4	248.8	270.2	270.2
B2016	416.0	399.3	493.9	316.8	347.1	346.8
Bref	560.9	542.6	672.4	423.1	494	493.1
B2019	384.3	412.6	449.5	272.9	509.3	509.6
Bmsy	283.6	269.3	351.1	227.1	305.4	304.8
MSY	638.8	642.2	643	620.9	634.8	635
Fmult	3.11	3.23	2.97	2.72	2.31	2.33
SSB2016	1601.2	1635.8	1669.2	1526.4	1081.1	1072.8
SSB2019	1649.3	1750.3	1691.1	1514.4	1040.5	1020.7
SSBmsy	1889.9	1940.1	2018.5	1815	1101.4	1088.6
CPUE2015	0.737	0.741	0.733	0.742	0.747	0.747
CPUE2019	0.584	0.646	0.555	0.544	1.028	1.017
CPUEmsy	0.339	0.327	0.353	0.375	0.461	0.459
B2016/Bmin	1.295	1.309	1.263	1.279	1.279	1.28
B2016/Bref	0.749	0.741	0.735	0.751	0.701	0.7
B2016/Bmsy	1.471	1.497	1.414	1.389	1.131	1.137
B2019/B2016	0.942	1.043	0.914	0.884	1.483	1.473
B2019/Bref	0.708	0.773	0.669	0.664	1.035	1.03
B2019/Bmsy	1.385	1.568	1.282	1.239	1.666	1.668
SSB2016/SSB0	0.508	0.51	0.508	0.509	0.473	0.475
SSB2019/SSB0	0.518	0.545	0.512	0.503	0.454	0.452
SSB2016/SSBmsy	0.850	0.841	0.827	0.835	0.981	0.985
SSB2019/SSBmsy	0.867	0.901	0.833	0.827	0.941	0.944
SSB2019/SSB2016	1.021	1.065	1.014	0.989	0.964	0.957
USL2015	0.229	0.236	0.193	0.302	0.285	0.285
USL2019	0.267	0.249	0.229	0.376	0.202	0.202
USL2019/USL2015	1.134	1.045	1.181	1.209	0.707	0.709
Btot2016	4056.8	4465	4415.5	4429.6	2162.9	2154.7
Btot2016/Btot0	0.406	0.441	0.415	0.418	0.291	0.293
Ntot2016	1.4E+07	1.7E+07	1.6E+07	1.7E+07	6.5E+06	6.4E+06
Ntot2016/Ntot0	0.500	0.584	0.512	0.531	0.393	0.394
minHandMort	14.25	14.42	14.44	14.62	10.99	11
HandMort2015	18.14	17.9	18.54	18.95	19.18	19.23
HandMort2019	25.88	24.22	26.78	26.87	16.65	16.7

Table 14: Comparison of probability indicators between the base case McMC and the five McMC sensitivity trials.

Indicator	base	lag1	2-sex	normal	fixedG1	fixedG2
P(*B2016*>*Bmin*)	1.000	1.000	1.000	1.000	1.000	1.000
P(*B2016*>*Bref*)	0.000	0.000	0.000	0.000	0.000	0.000
P(*B2016*>*Bmsy*)	1.000	1.000	1.000	1.000	0.930	0.920
P(*B2019*>*Bmin*)	0.859	0.952	0.753	0.743	0.991	0.995
P(*B2019*>*Bref*)	0.020	0.073	0.006	0.005	0.566	0.546
P(*B2019*>*Bmsy*)	0.960	0.990	0.879	0.839	0.980	0.973
P(*B2019*>*B2016*)	0.350	0.601	0.245	0.218	0.965	0.962
P(*SSB2016*>*SSBmsy*)	0.004	0.001	0.000	0.002	0.372	0.398
P(*SSB2019*>*SSBmsy*)	0.073	0.149	0.030	0.026	0.295	0.298
P(*USL2019*>*USL2015*)	0.774	0.599	0.841	0.868	0.079	0.089
P(*SSB2016*<*0.2SSB0*)	0.000	0.000	0.000	0.000	0.000	0.000
P(*SSB2019*<*0.2SSB0*)	0.000	0.000	0.000	0.000	0.000	0.000

Table 15: History of the CRA 4 management procedure. "Rule result" is the result of the management procedure after operation of all its components including thresholds. TACC and TAC values are shown with the precision used by MPI.

Year	Applied to fishing year	Offset CPUE (kg/potlift)	Rule result: TACC (t)	Applied TACC (t)	Applied TAC (t)
2011	2012–13	1.194	466.9	466.9	661.9
2012	2013–14	1.374	499.69	499.7	694.7
2013	2014–15	1.293	467	467	662
2014	2015–16	1.168	467	467	662
2015	2016–17	0.882	446.219	397	592

Table 16: Average commercial catch and CPUE in the CRA 4 fishery over the past 5, 10 and 20 years compared with 5 and 10 year projections from the operating model.

			Actual		Projected
	5 years	**10 years**	**20 years**	**5 years**	**20 years**
commercial catch (t)	438	402	472	199	300
CPUE (kg/potlift	1.2	1.0	1.1	1.0	1.0

Table 17: Predicted performance of the 2012 CRA 4 management procedure.
Predicted performance of the current CRA 4 management procedure under the base case operating model.

Indicator	Value
mean commercial catch (20 year)	346
mean commercial catch (5 year)	306
mean CPUE (20 year)	0.828
mean CPUE (5 year)	0.842
mean recreational catch (20 year)	37.1
%AAVH (20 year)	24.7
%AAVH (5 year)	16.30
P(*B*<*Bref*) (20 year)	60%
plateau left (20 year)	60.5%

Table 18: Rule parameters used to define a set of 96 rules for management procedure evaluations. The values for *par7* were depended on the value for *par5*; otherwise these parameters were independent and all 96 combinations were run.

Parameter	Role	Values							
par1	**rule type**	4							
par2	**intercept**	0	0.1	0.2	0.3	0.4	0.5		
par3	**plateau left**	0.9	1						
par4	**plateau right**	1.3							
par5	**plateau height**	320	340	360	380	400	420	440	460
par6	**step width**	0.1							
par7	**step height**	0.120	0.095	0.075	0.053	0.053	0.053	0.053	0.053
par 8	**minimum change**	5%							
par 9	**maximum change**	0							
par 10	**latent year**	0							

Table 19: Comparison of some major MPE indicators between the base case and noPoo operating models.

			base			noPoo
Indicator	**5%**	**median**	**95%**	**5%**	**median**	**95%**
median *B/Bref* 5-yr	0.97	1.11	1.24	0.87	1.02	1.17
median avCatch 5-yr	238	286	333	270	314	352
median Catch 5th-yr	320	380	441	320	380	441
P(TACC<200)	0.00	0.36	0.96	0.05	0.32	0.64
P(TACC<250)	0.17	0.91	1.00	0.28	0.59	0.80
5% minCPUE 5-yr	0.51	0.55	0.57	0.44	0.49	0.52
median minCPUE 5-yr	0.60	0.64	0.66	0.61	0.68	0.72
median avCPUE 5-yr	0.75	0.85	0.93	0.77	0.89	1.02
median CPUE 5th-yr	0.92	1.04	1.17	0.85	0.99	1.18
P(*B2022*<*Bref*)	0.00	0.03	0.18	0.24	0.43	0.63

Figure 1: CRA 4 and its statistical areas (light blue).

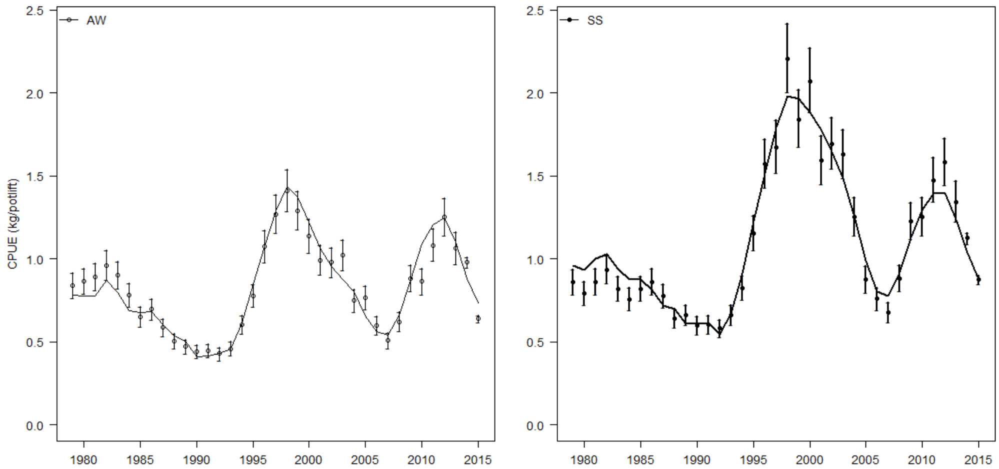


Figure 2: CRA 4 base case MPD: Fit to CPUE: AW on left.

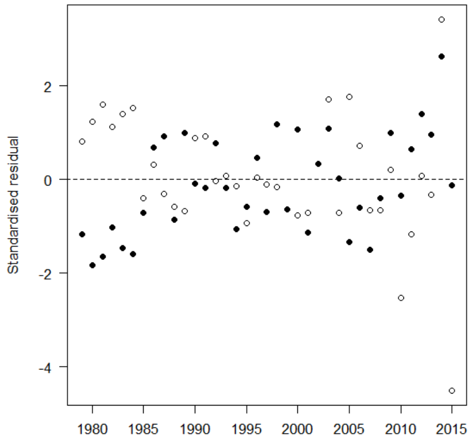


Figure 3: CRA 4 base case MPD: CPUE residuals: AW open circles.

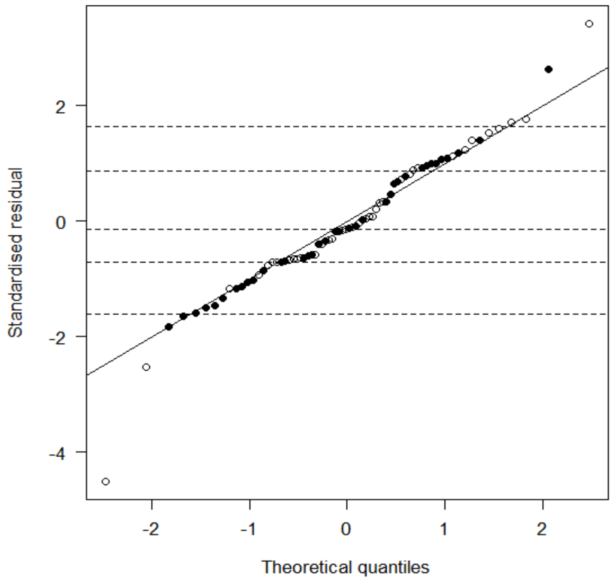


Figure 4: CRA 4 base case MPD: Q-Q plot of CPUE residuals: closed circles are SS and open circles AW.

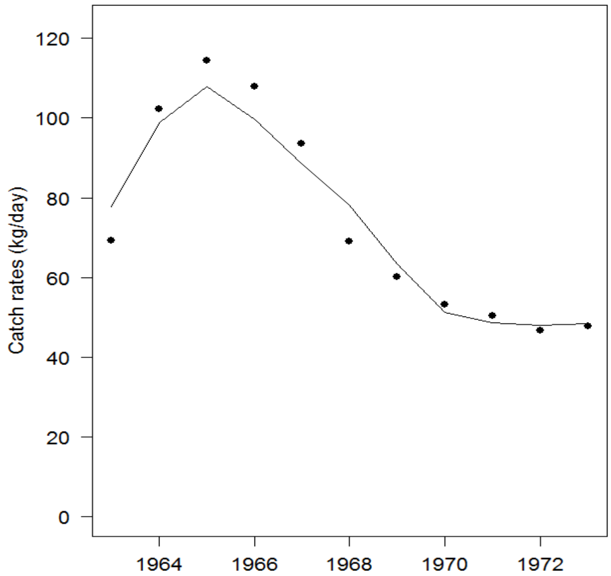


Figure 5: CRA 4 base case MPD: Model fit to the CR series.

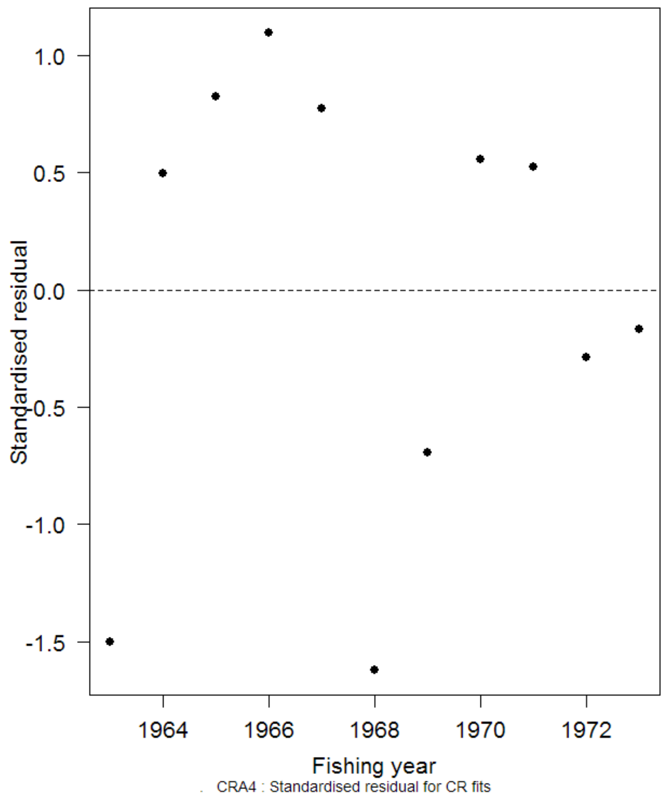


Figure 6: Residuals from the base case MPD fit to CR.

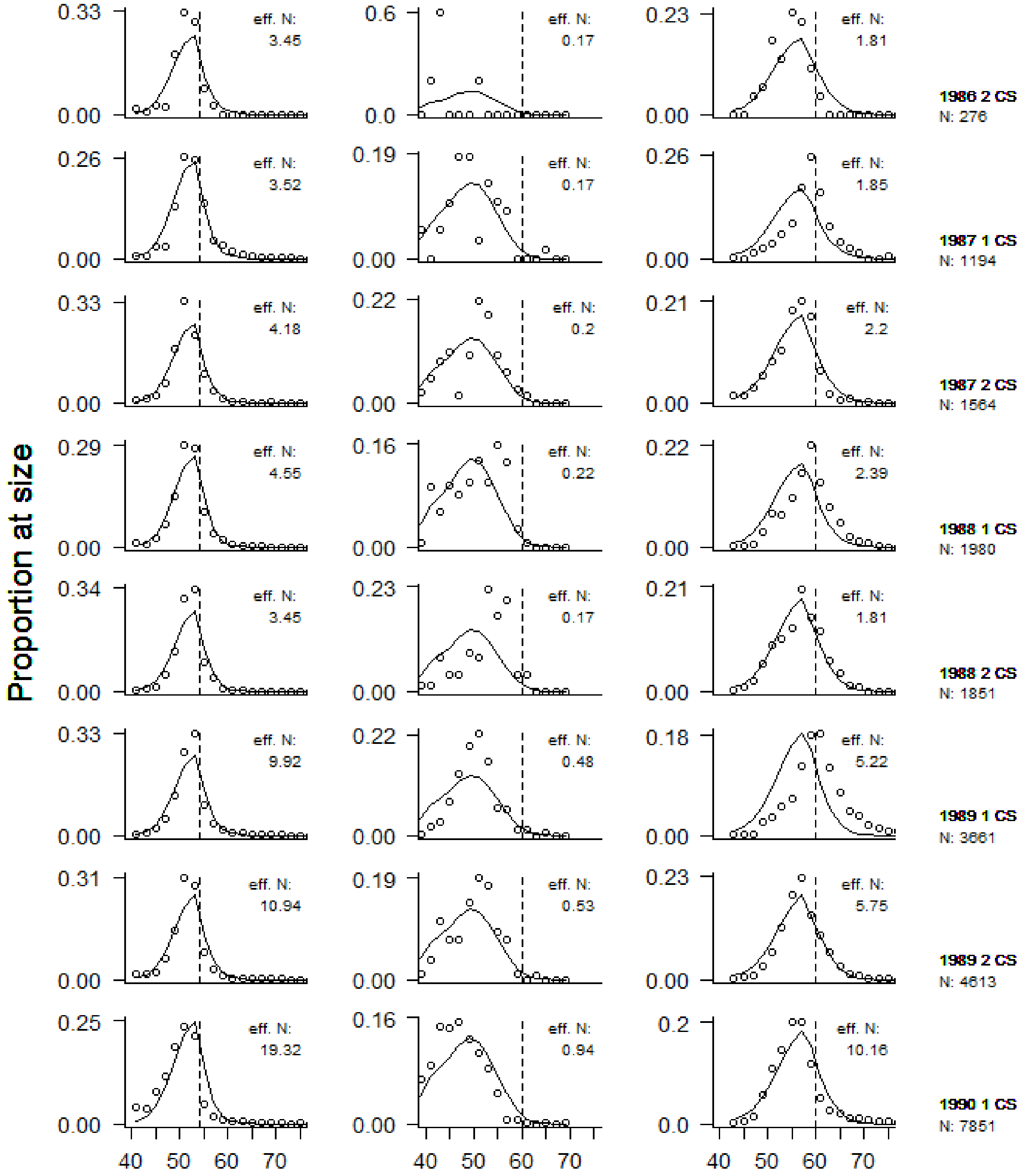


Figure 7: CRA 4 base case MPD: Model fits to LFs from 1986 through AW 1990.

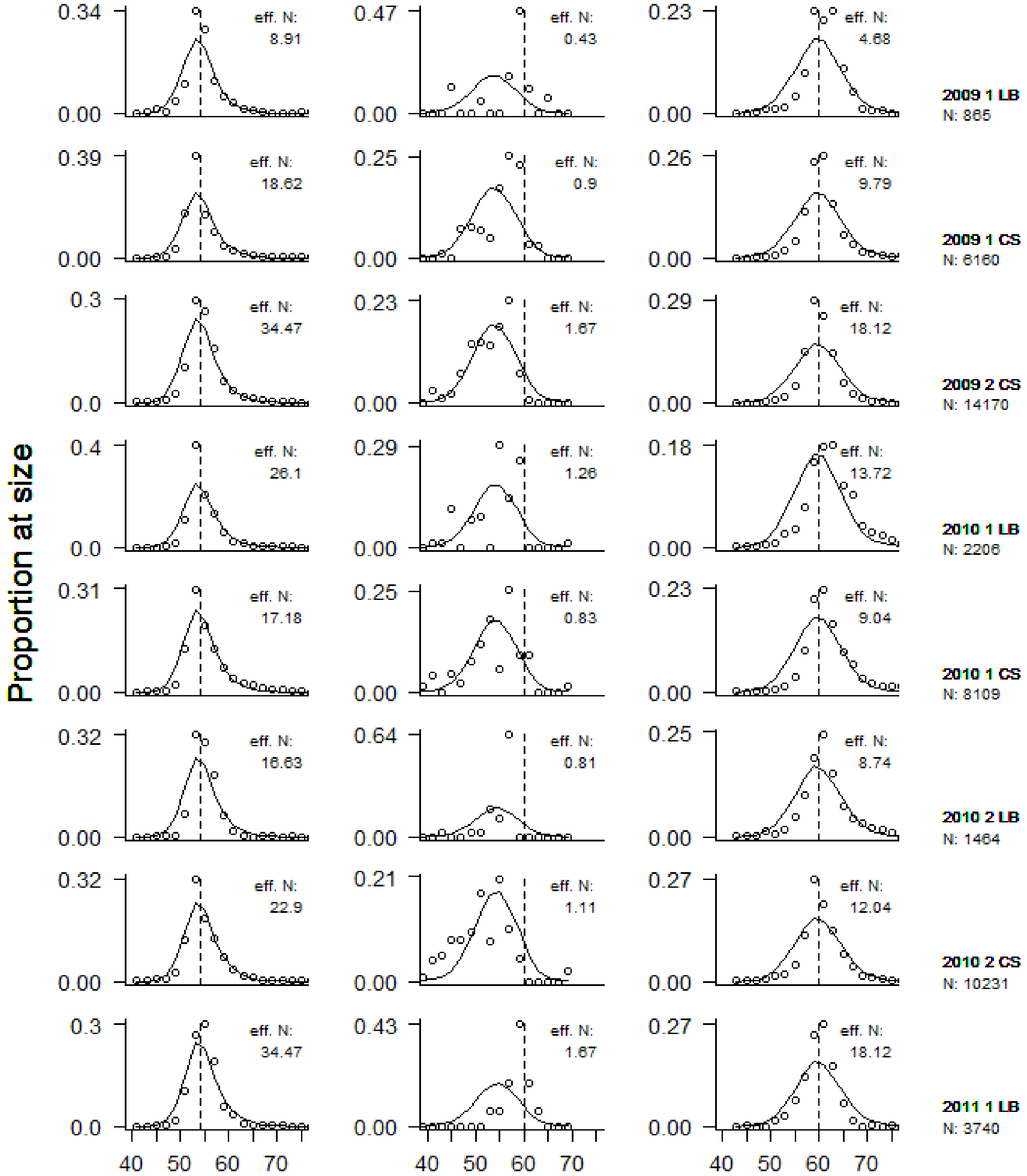


Figure 8: CRA 4 base case MPD: Model fits to LFs from AW 2009 through AW 2011.

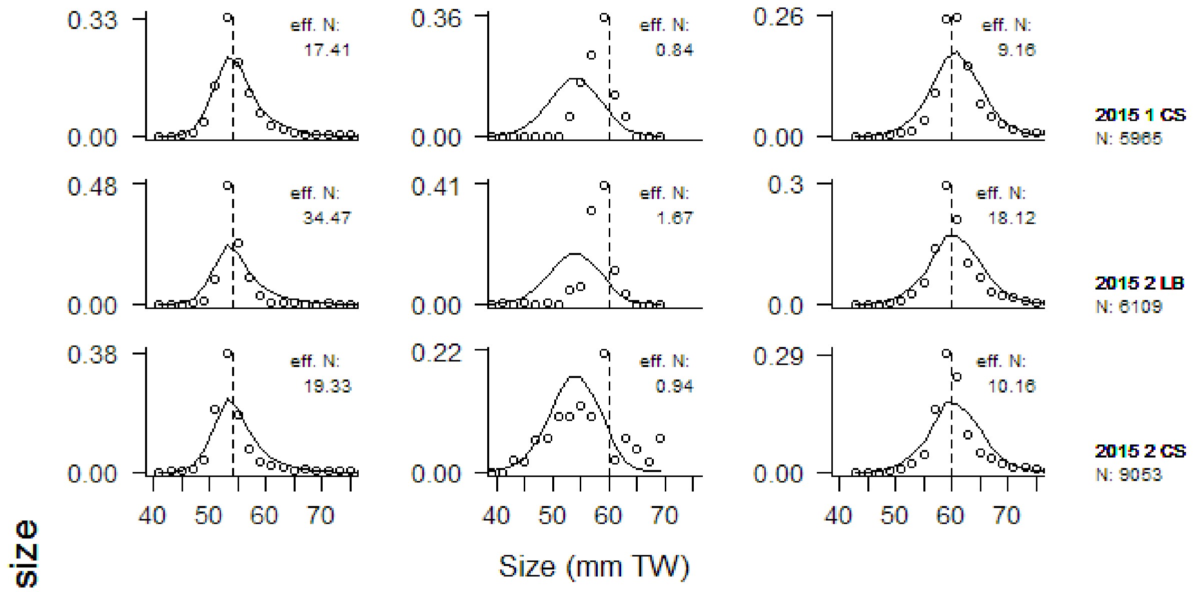


Figure 9: CRA 4 base case MPD: Model fits to LFs from the 2015–16 fishing year.

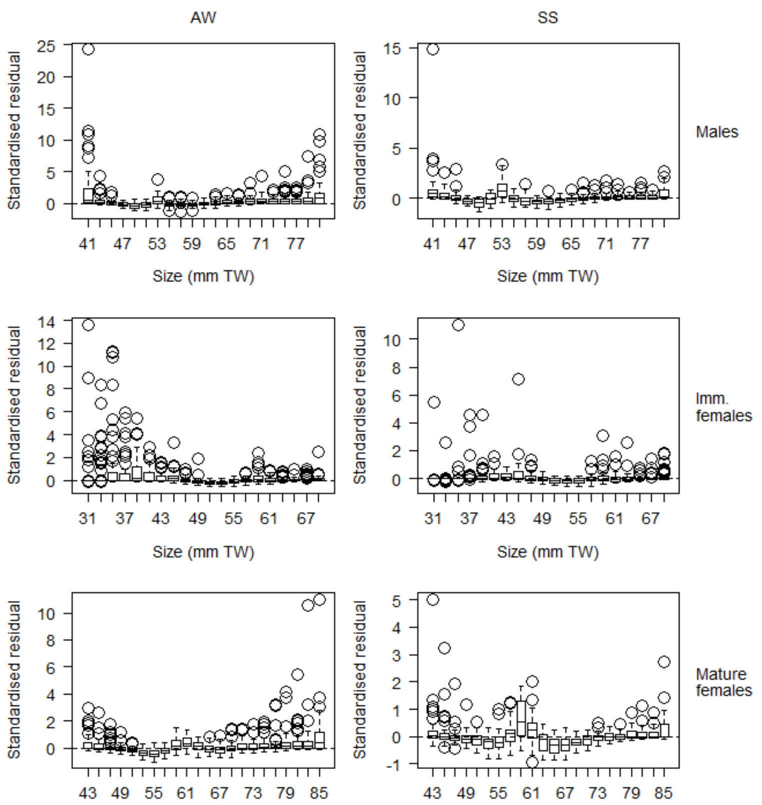


Figure 10: CRA 4 base case MPD: LF residuals by sex and season.

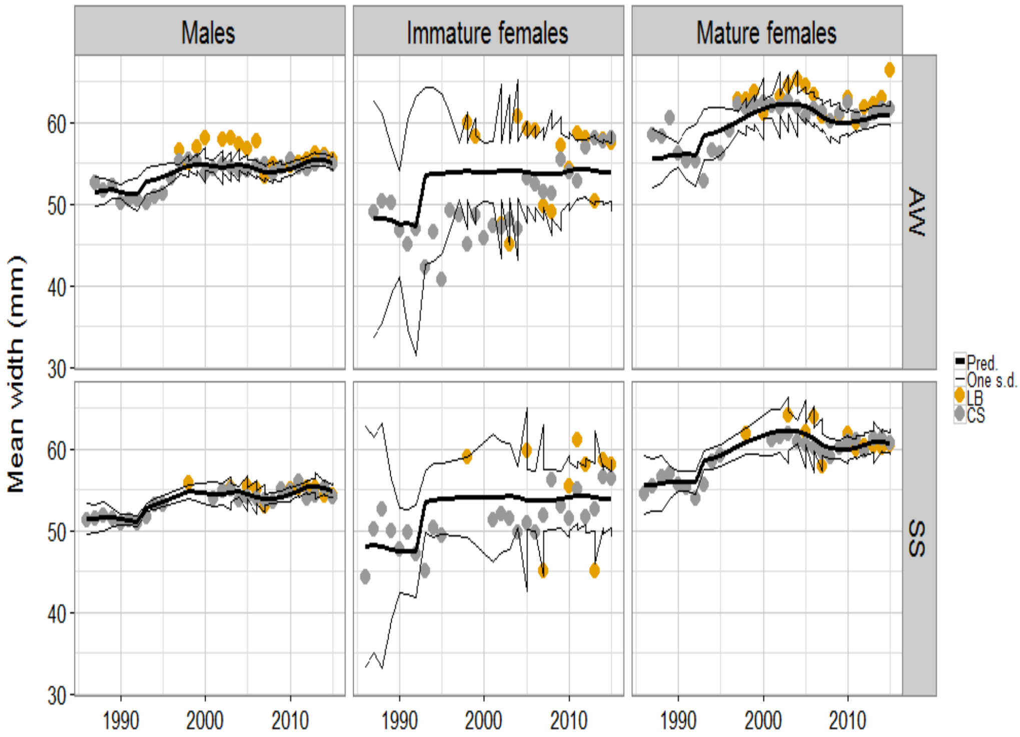


Figure 11: CRA 4 base case MPD: Model fit to mean lengths by sex and season. Logbook data are grey and observer sampling is orange).

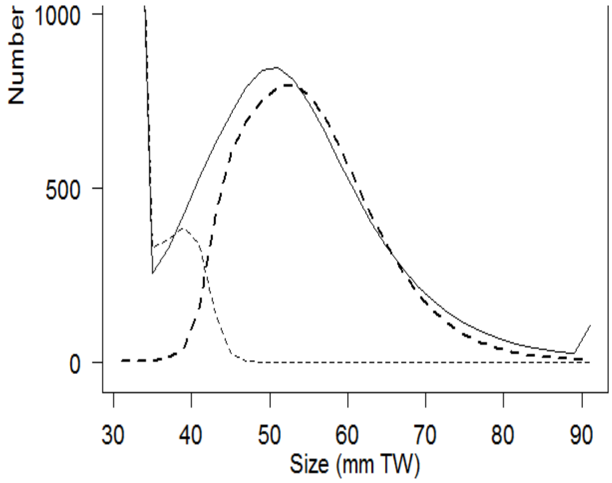


Figure 12: CRA 4 base case MPD: Size distributions of the unfished stock; solid line: males, lightly dotted line: immature females, heavy dotted line: mature females.

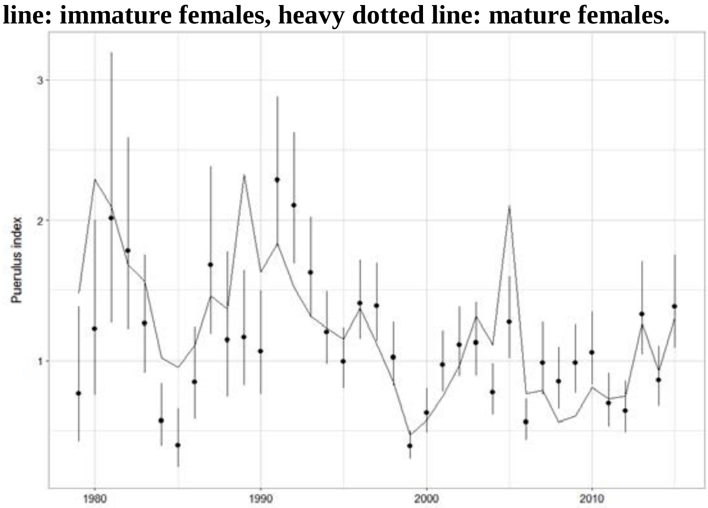


Figure 13: CRA 4 base case MPD: Fit to the puerulus index.

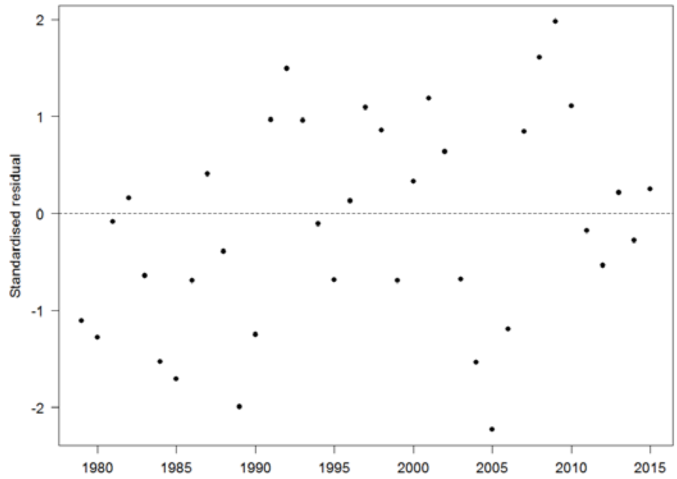


Figure 14: CRA 4 base case MPD: Residuals from the puerulus index.

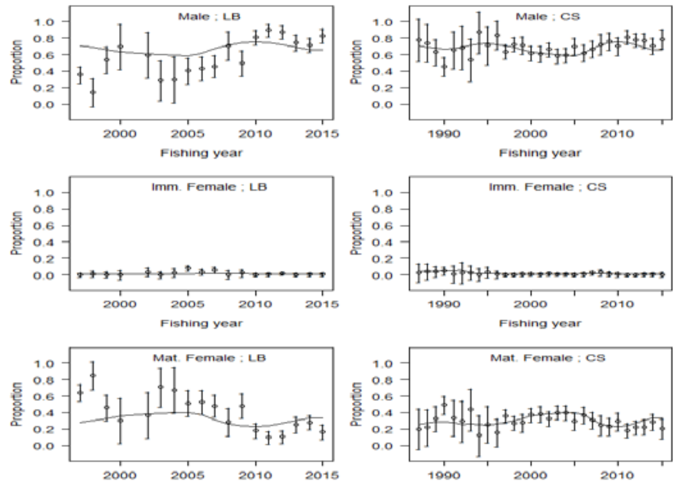


Figure 15: CRA 4 base case MPD: Model predictions to proportion-at-sex in AW by sampling source: LB – logbooks, CS – observer catch sampling.

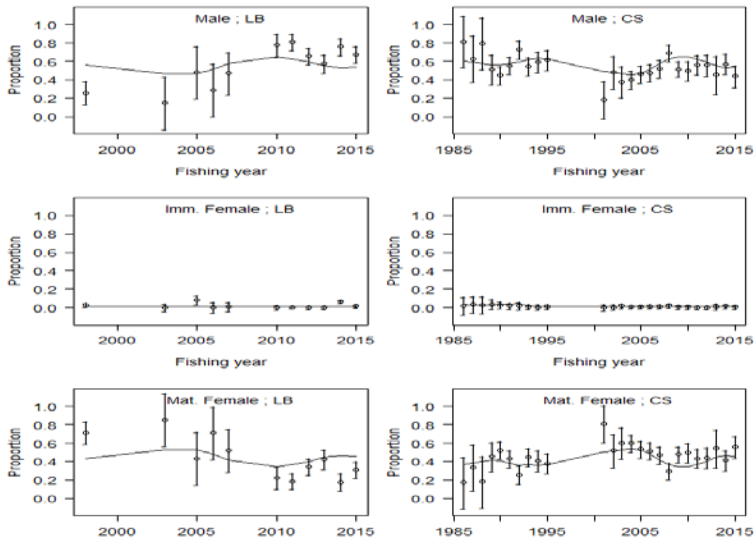


Figure 16: CRA 4 base case MPD: Model predictions to proportion-at-sex in SS by sampling source: LB – logbooks, CS – observer catch sampling.

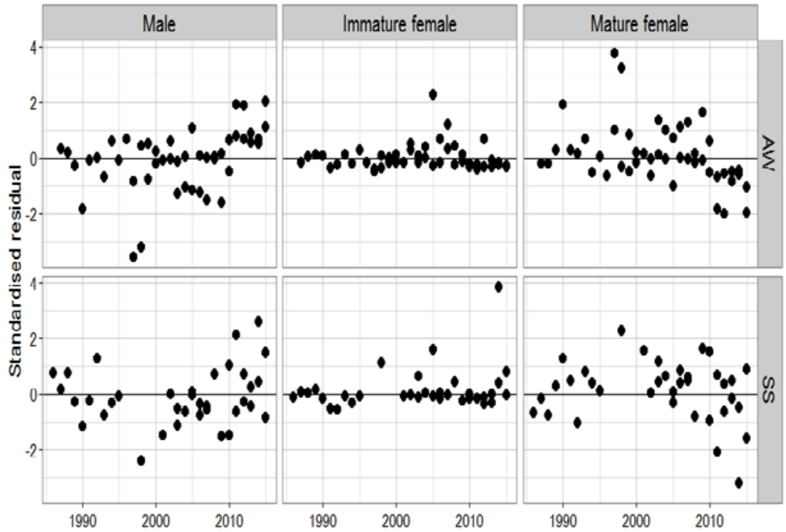


Figure 17: CRA 4 base case MPD: Residuals from the fit to proportions-at-sex; open circles are AW.

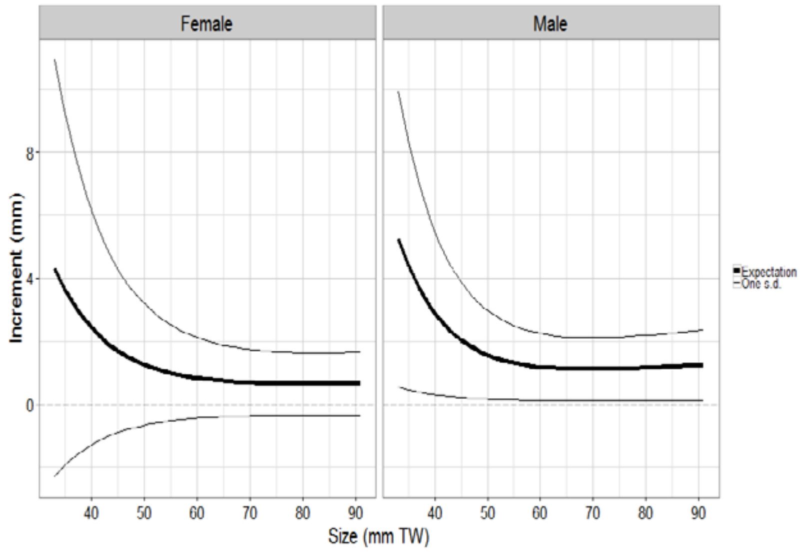


Figure 18: CRA 4 base case MPD: Predicted increments-at-length and their standard deviations.

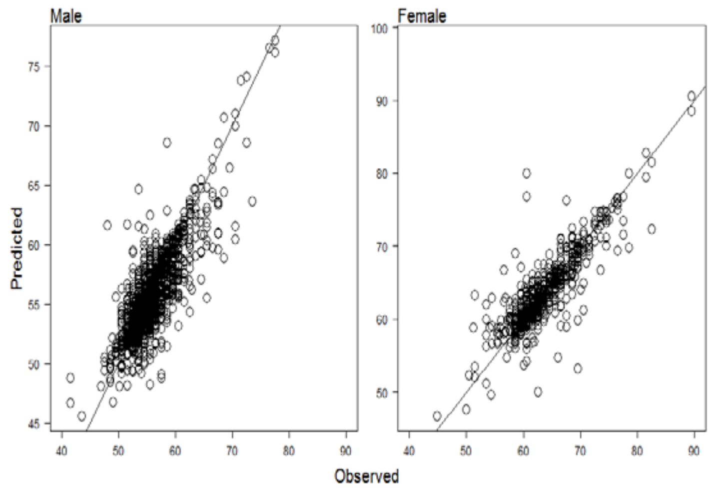


Figure 19: CRA 4 base case MPD: Predicted vs. observed growth increments.

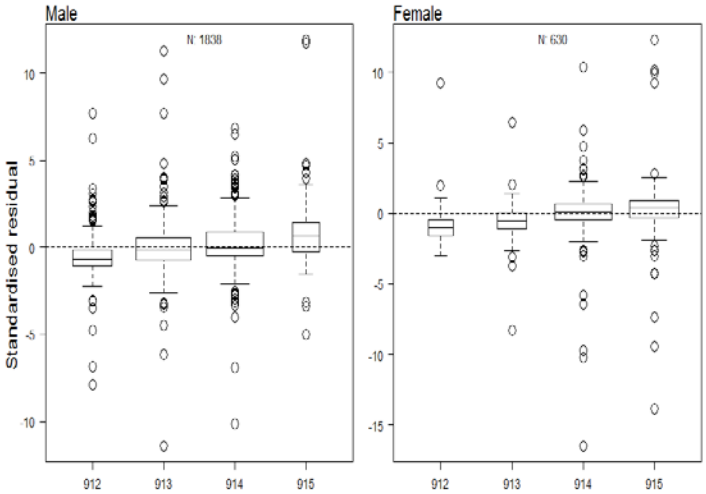


Figure 20: CRA 4 base case MPD: Residuals from the fit to tag data by area, males on the left.

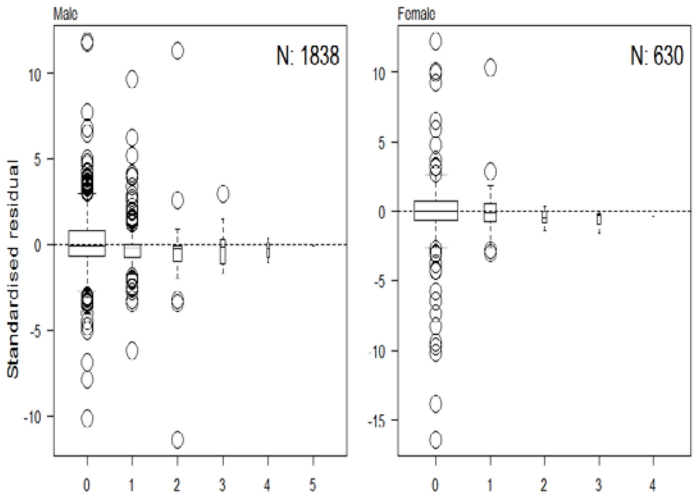


Figure 21: CRA 4 base case MPD: Residuals from the fit to tag data by number of re-releases, males on the left.

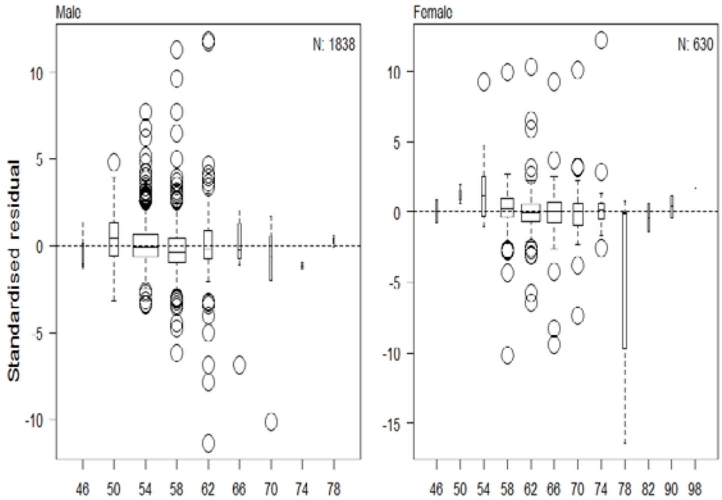


Figure 22: CRA 4 base case MPD: Residuals from the fit to tags by size class.

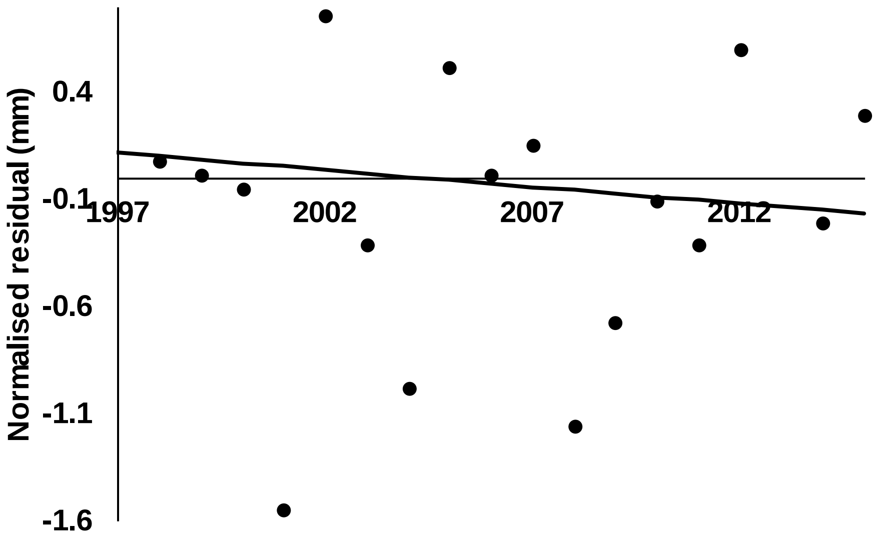


Figure 23: Average standardised residuals by year (circles) from the fit to the tag-recapture data, both sexes combined, and the regression of standardised residuals vs. year, using all the data (line; intercept = 31.35, slope = -0.0156).

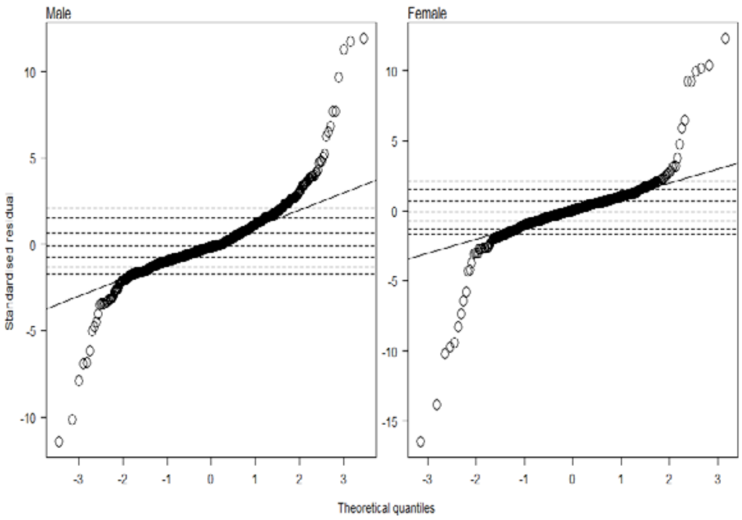


Figure 24: CRA 4 base case MPD: QQ plot of the tag residuals.

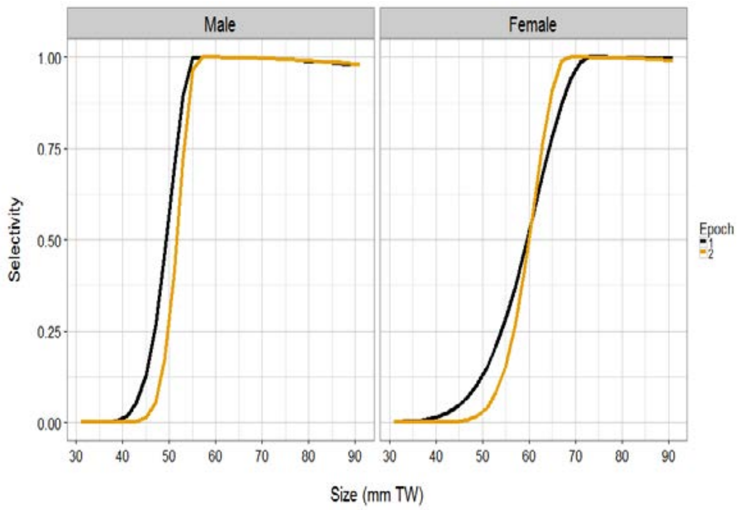


Figure 25: CRA 4 base case MPD: selectivity in two epochs.

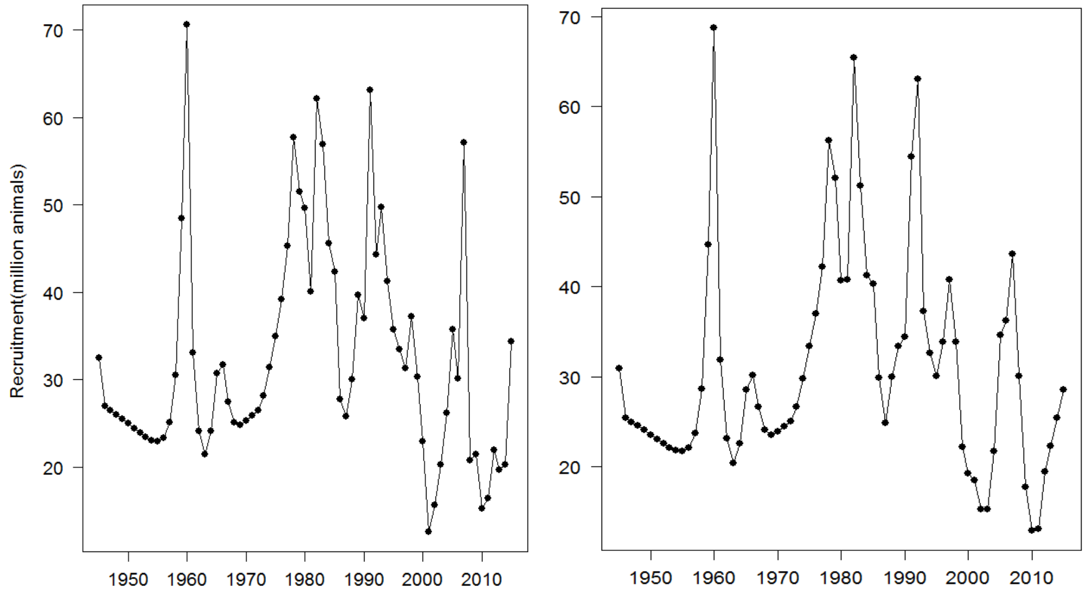


Figure 26: Left: CRA 4 base case MPD: recruitment; right: recruitment in the no puerulus sensitivity trial (noPoo) reported below.

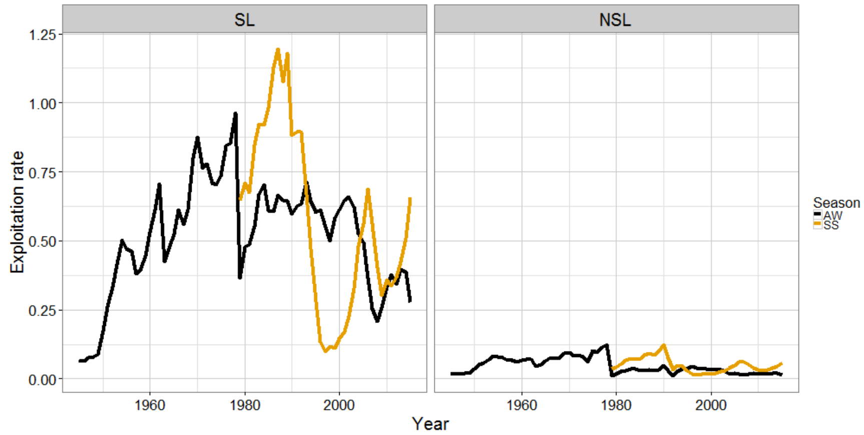


Figure 27: CRA 4 base case MPD: exploitation rate.

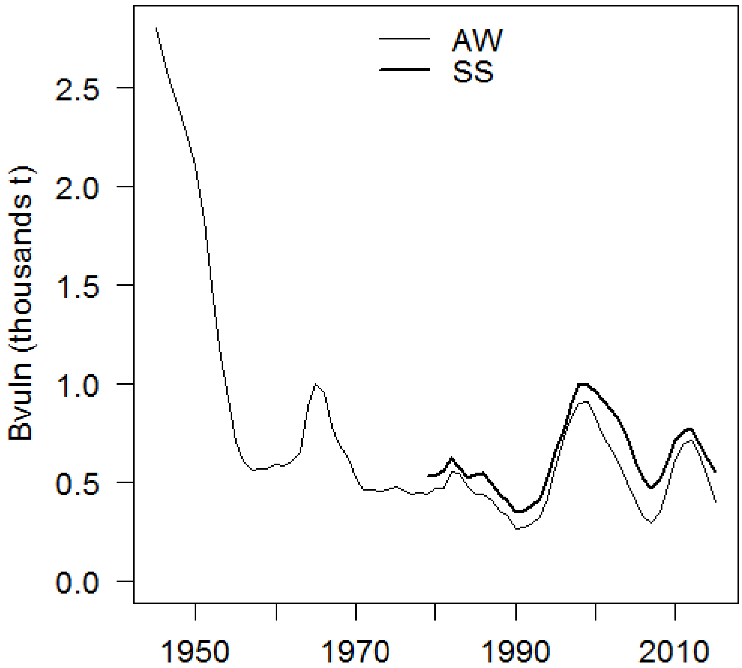


Figure 28: CRA 4 base case MPD: vulnerable biomass.

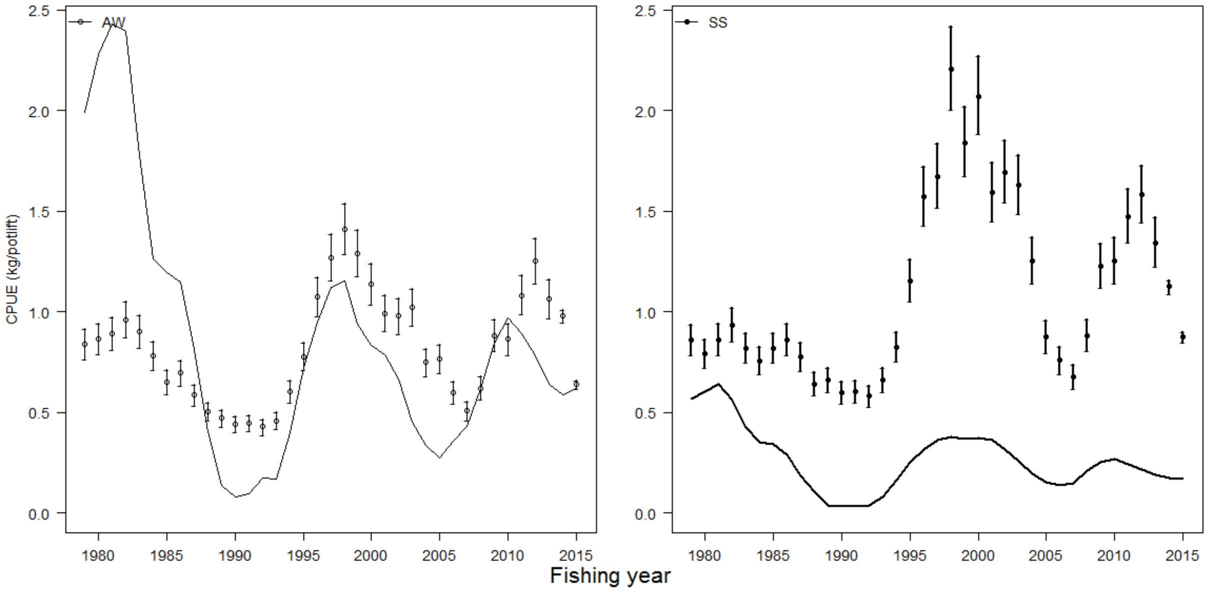


Figure 29: CRA 4 MPD sensitivity trial with CPUE not fit: Predicted and observed CPUE.

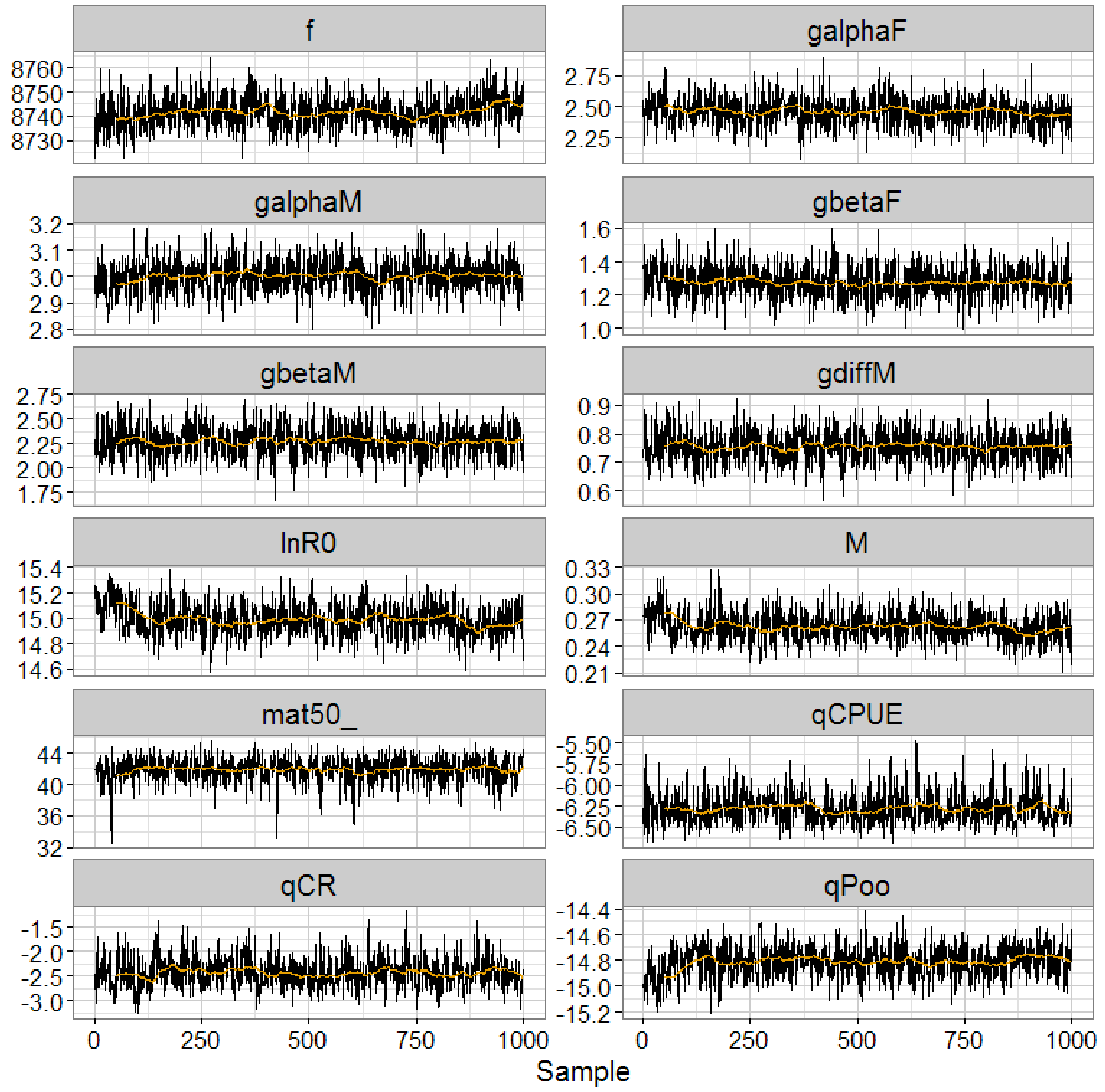


Figure 30:Traces for estimated parameters from the base case McMC. The gold line is a moving mean over 50 samples.

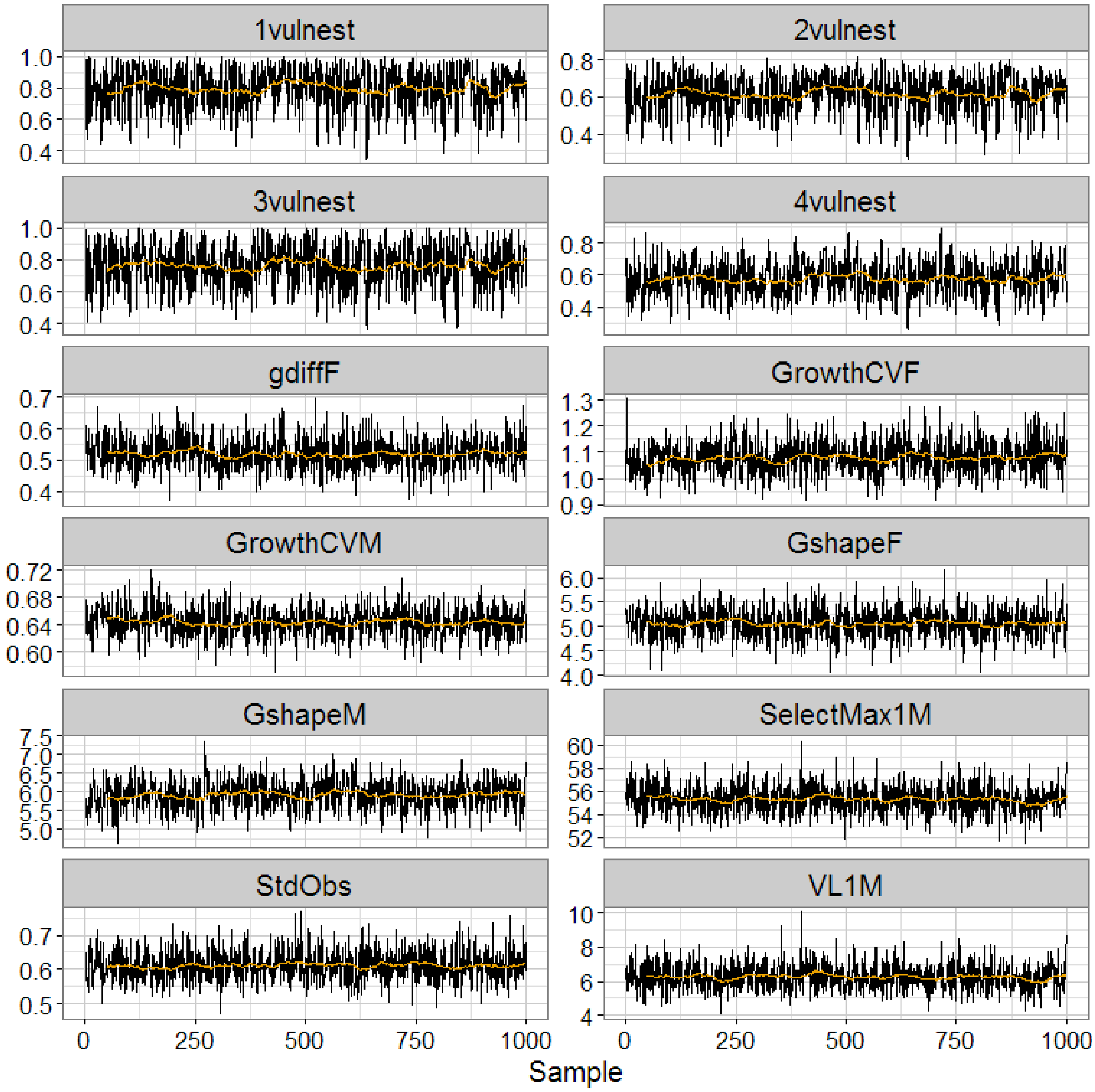


Figure 31: Traces for estimated parameters from the base case McMC. The gold line is a moving mean over 50 samples.

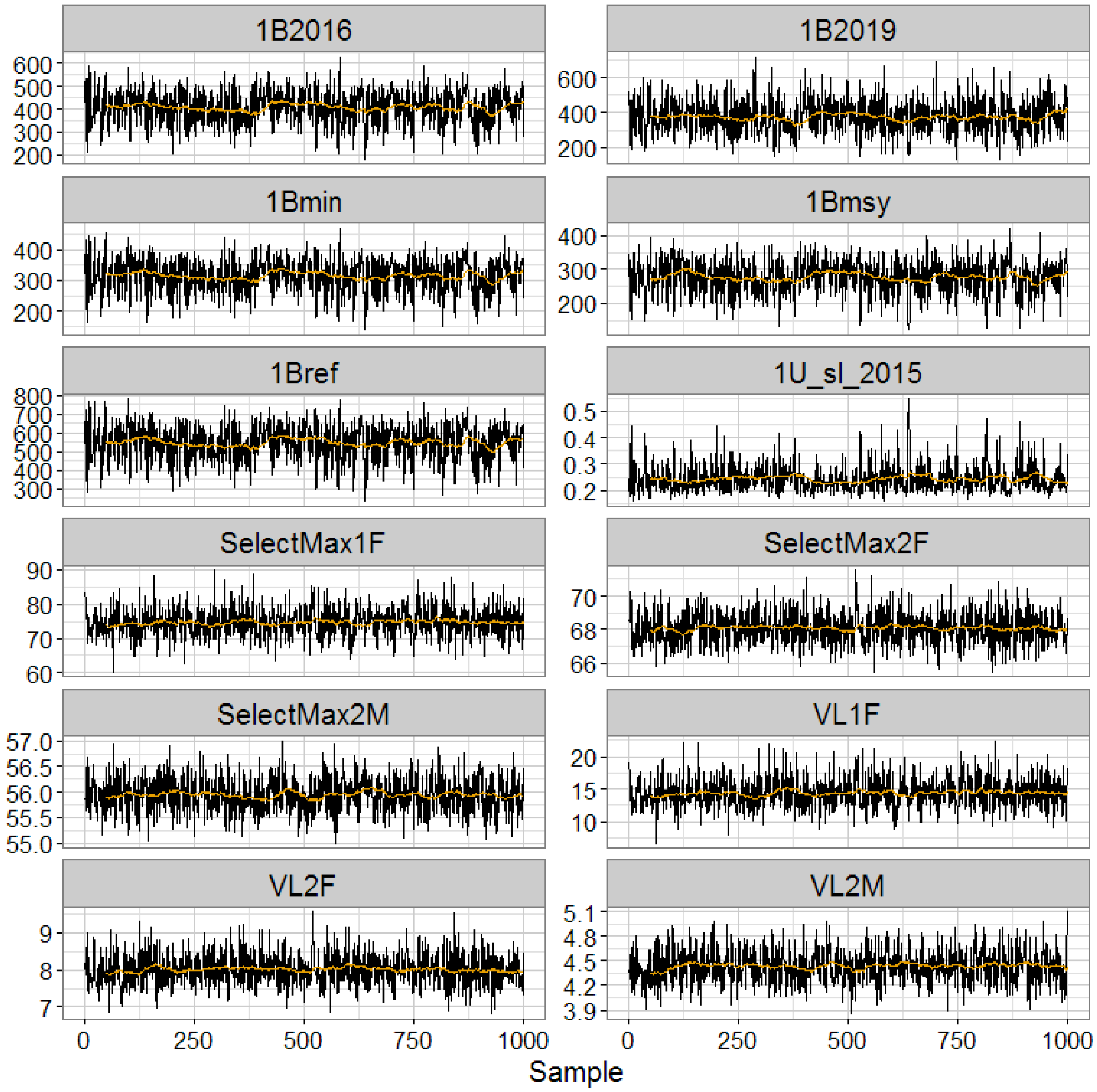


Figure 32: Traces for estimated and derived parameters from the base case McMC. The gold line is a moving mean over 50 samples.

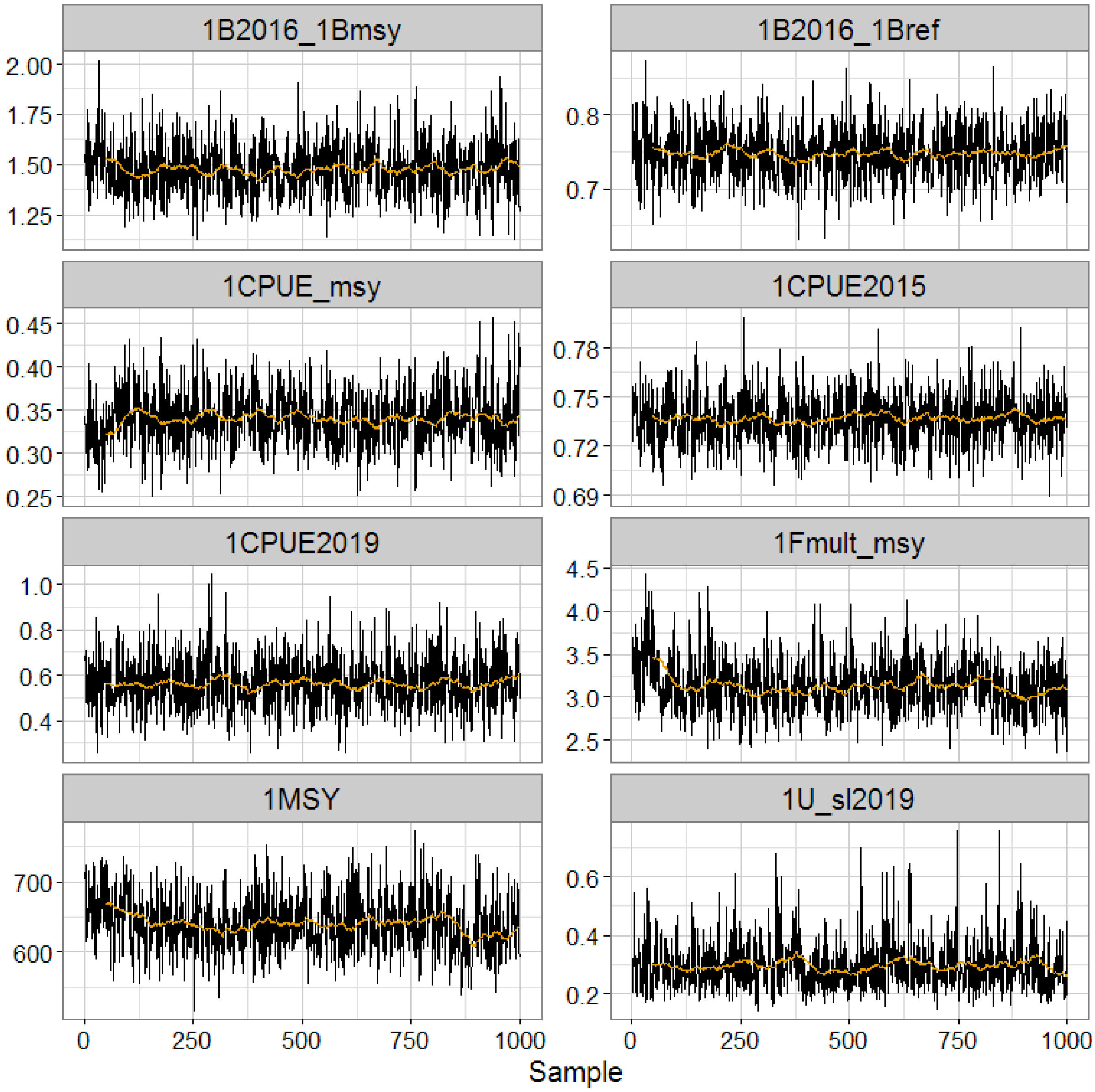


Figure 33: Traces for estimated and derived parameters from the base case McMC. The gold line is a moving mean over 50 samples.

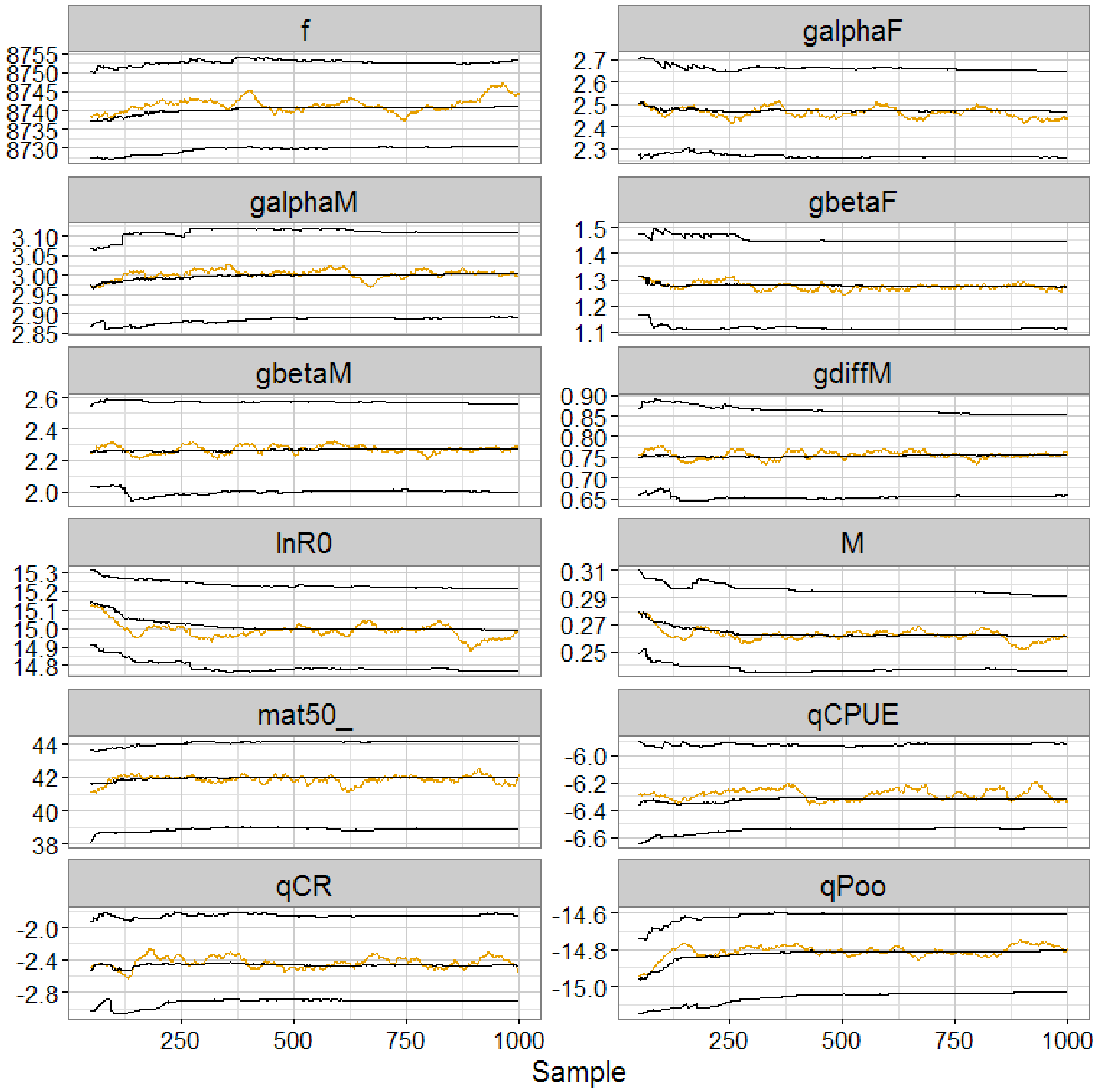


Figure 34: Diagnostic plots for the traces seen in Figure 30 from the base case McMC; solid black lines are the running median and 5th and 95th quantiles; the gold line is a moving mean over 50 samples.

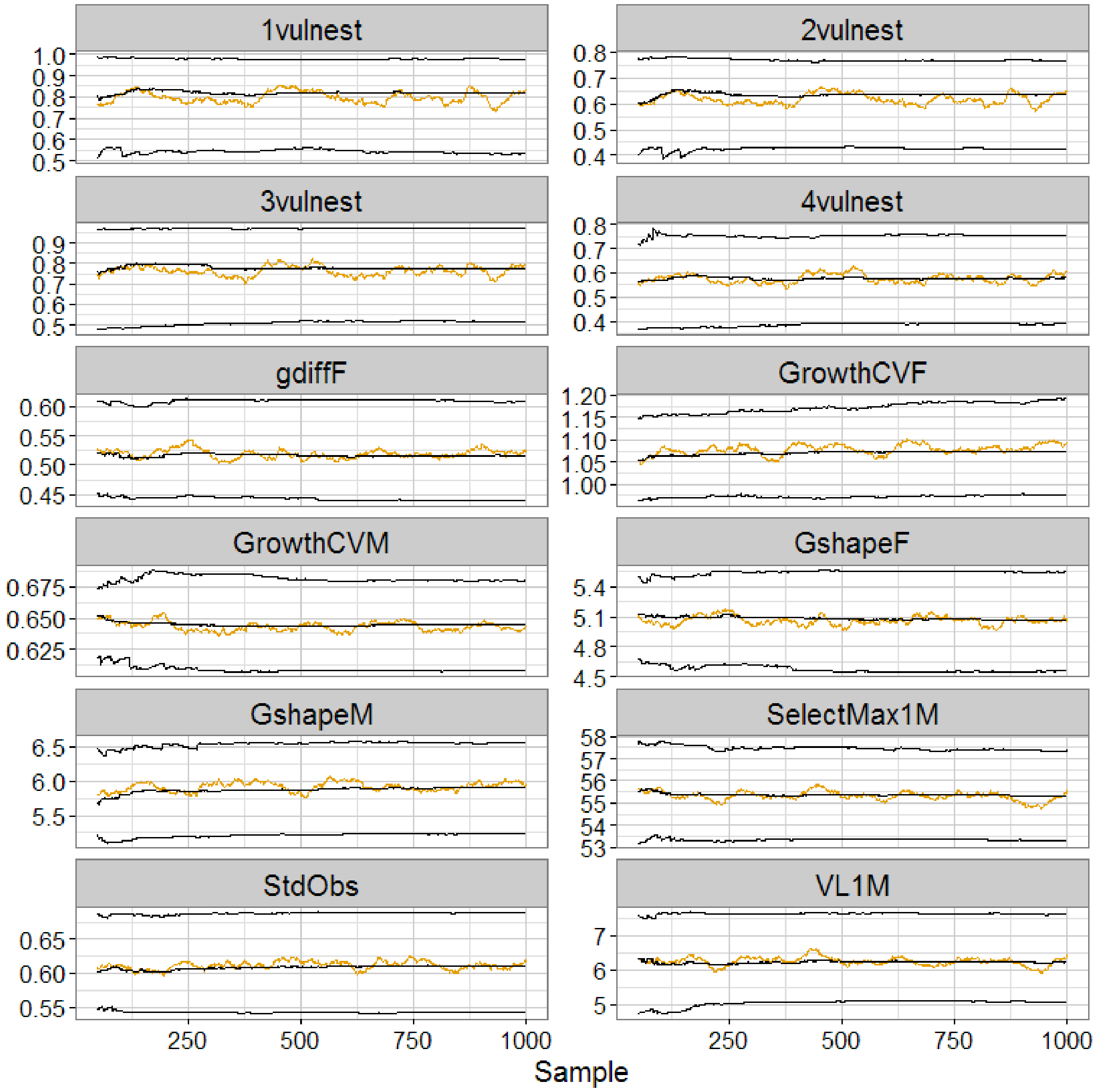


Figure 35: Diagnostic plots for the traces seen in Figure 30 from the base case McMC; solid black lines are the running median and 5th and 95th quantiles; the gold line is a moving mean over 50 samples.

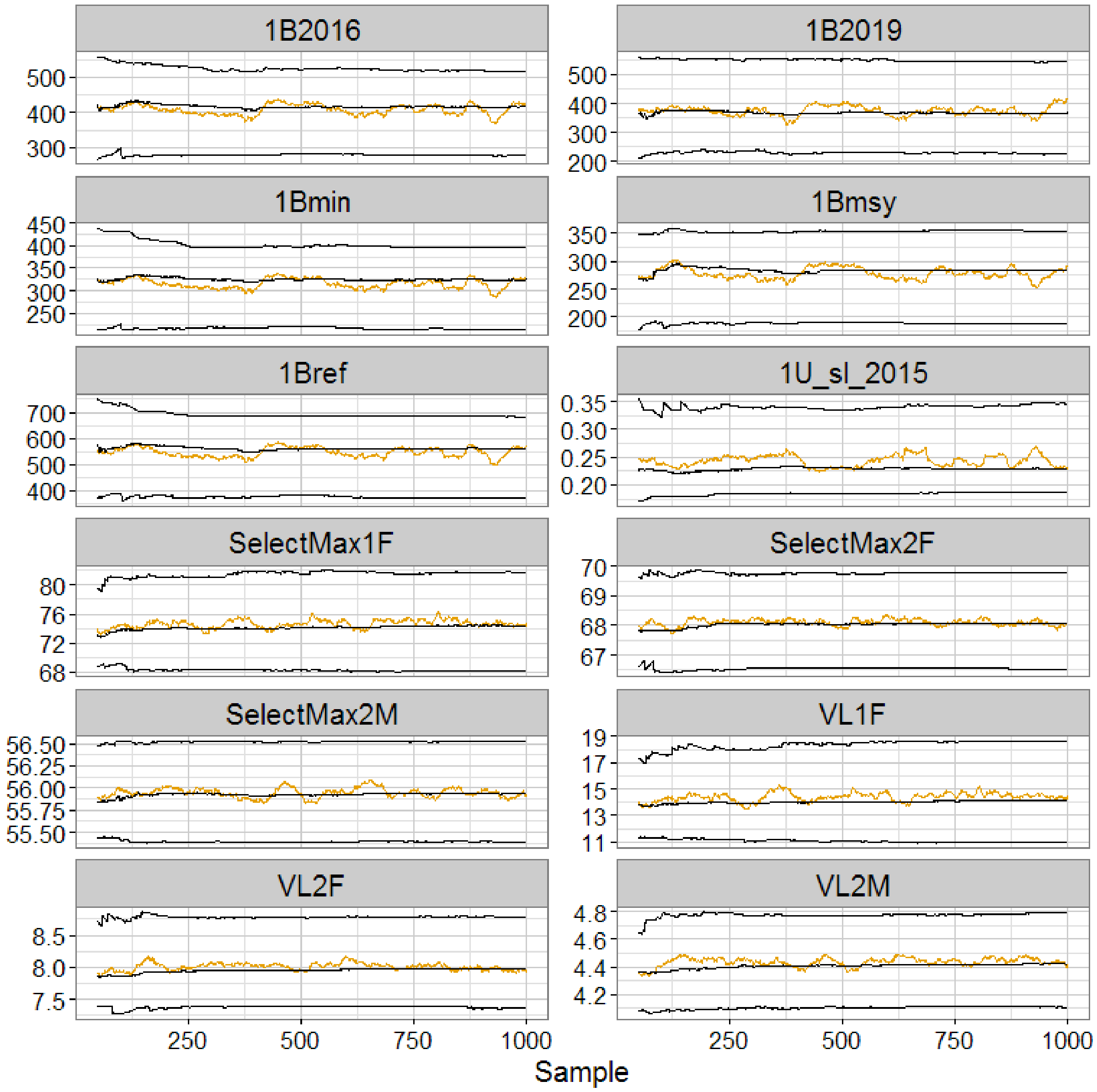


Figure 36: Diagnostic plots for the traces seen in Figure 32 from the base case McMC; solid black lines are the running median and 5th and 95th quantiles; the gold line is a moving mean over 50 samples.

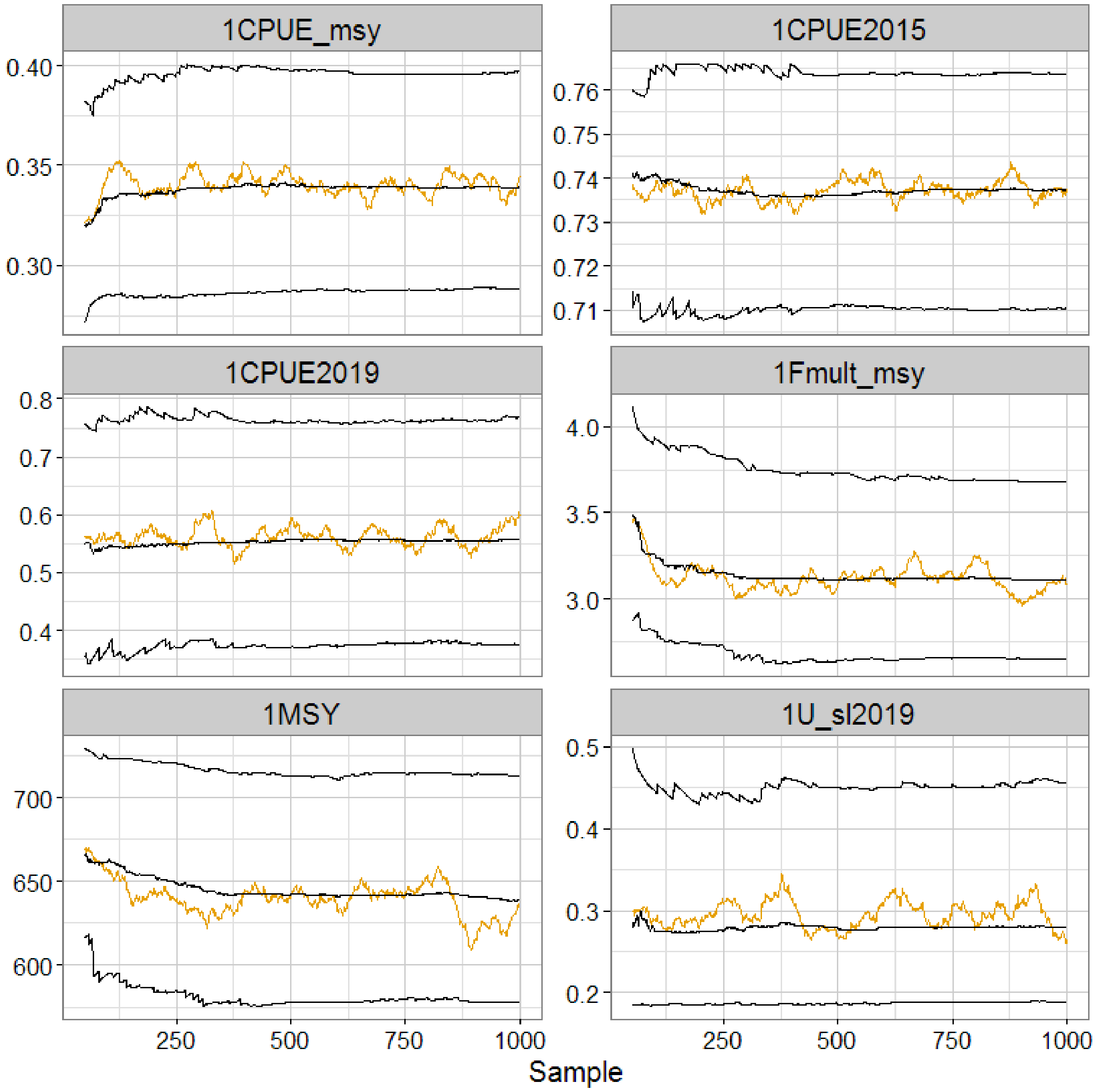


Figure 37: Diagnostic plots for the traces seen in Figure 33 from the base case McMC; solid black lines are the running median and 5th and 95th quantiles; the gold line is a moving mean over 50 samples.

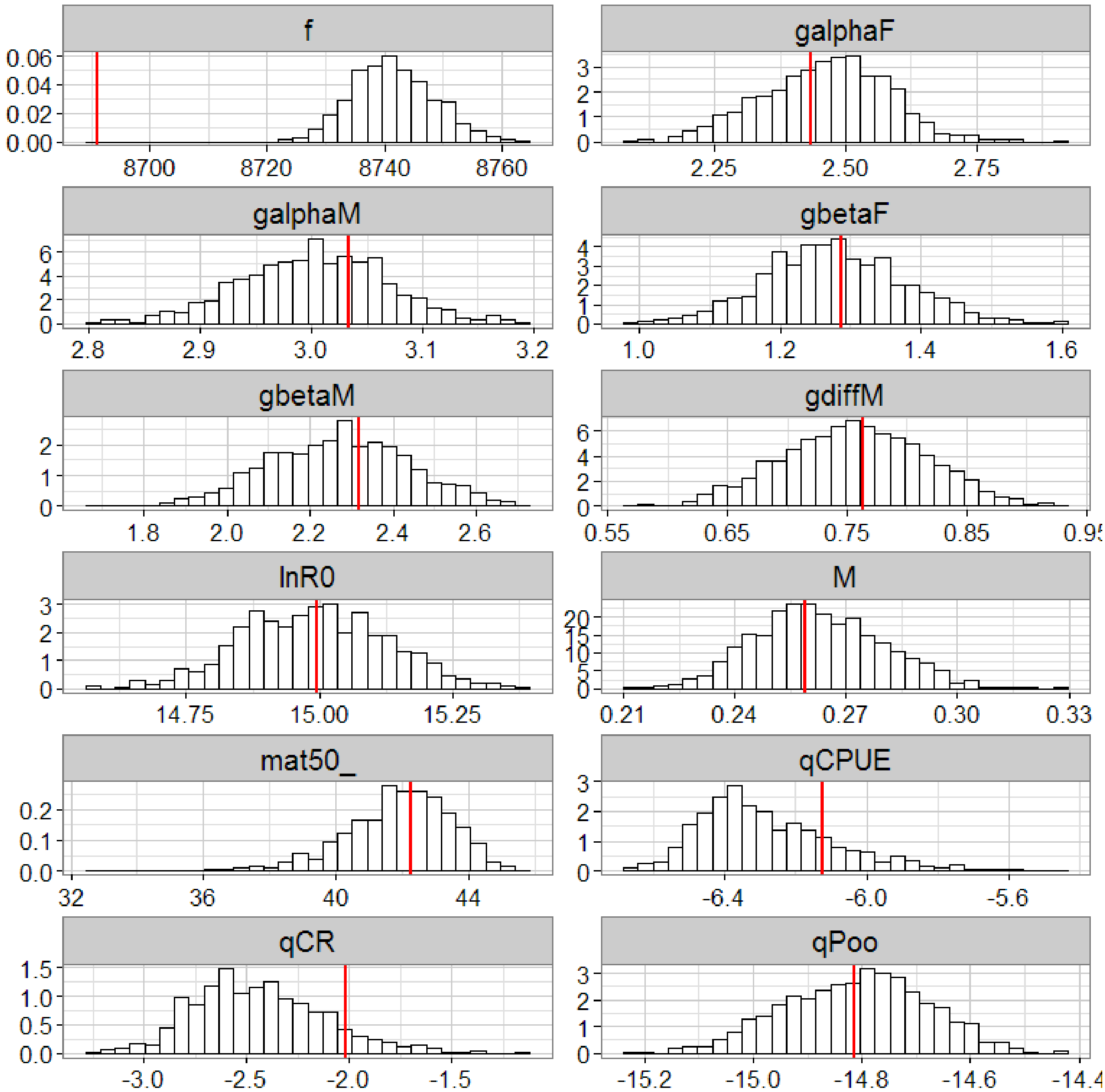


Figure 38: Posterior distributions of estimated parameters from the base case McMC.

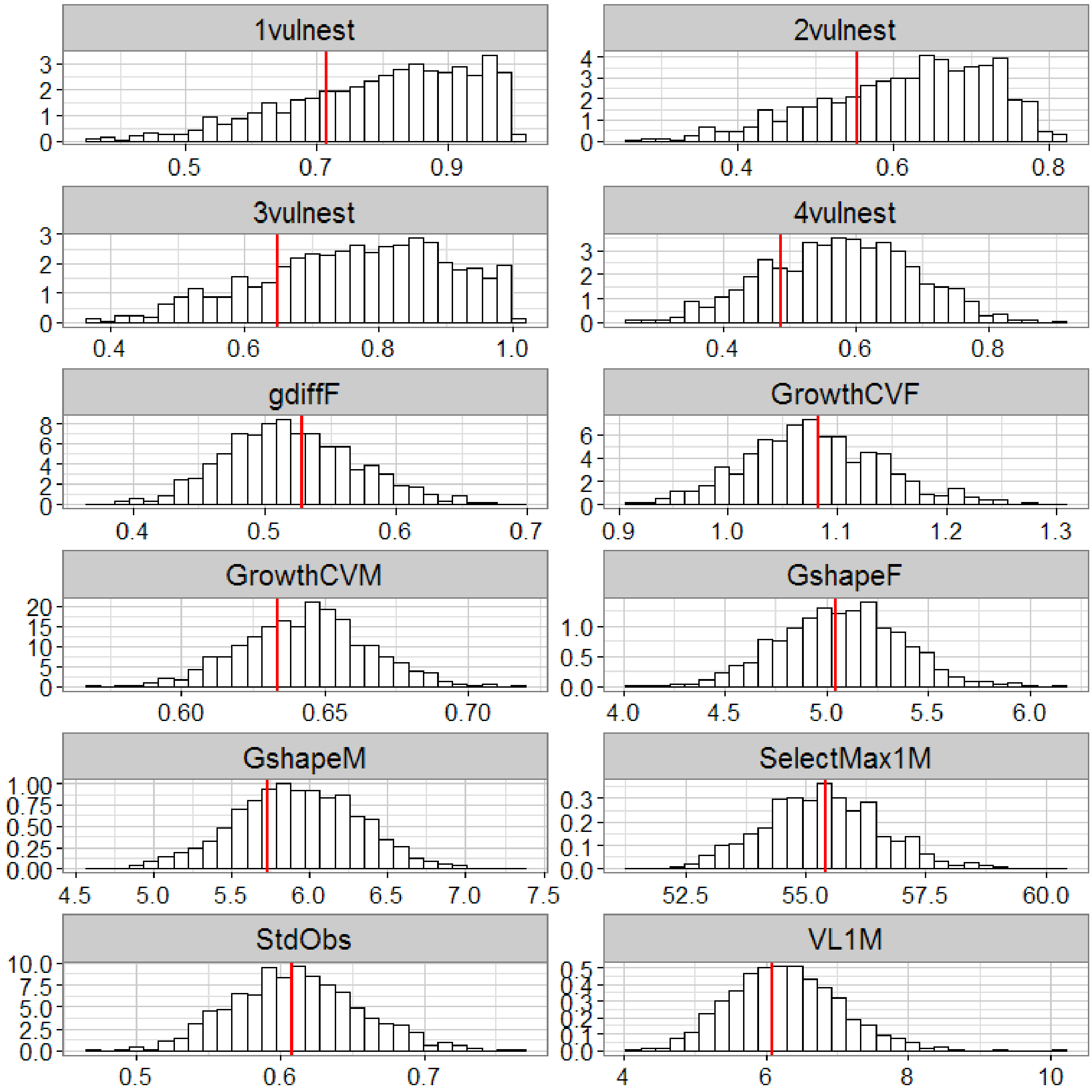


Figure 39: Posterior distributions of estimated parameters from the base case McMC.

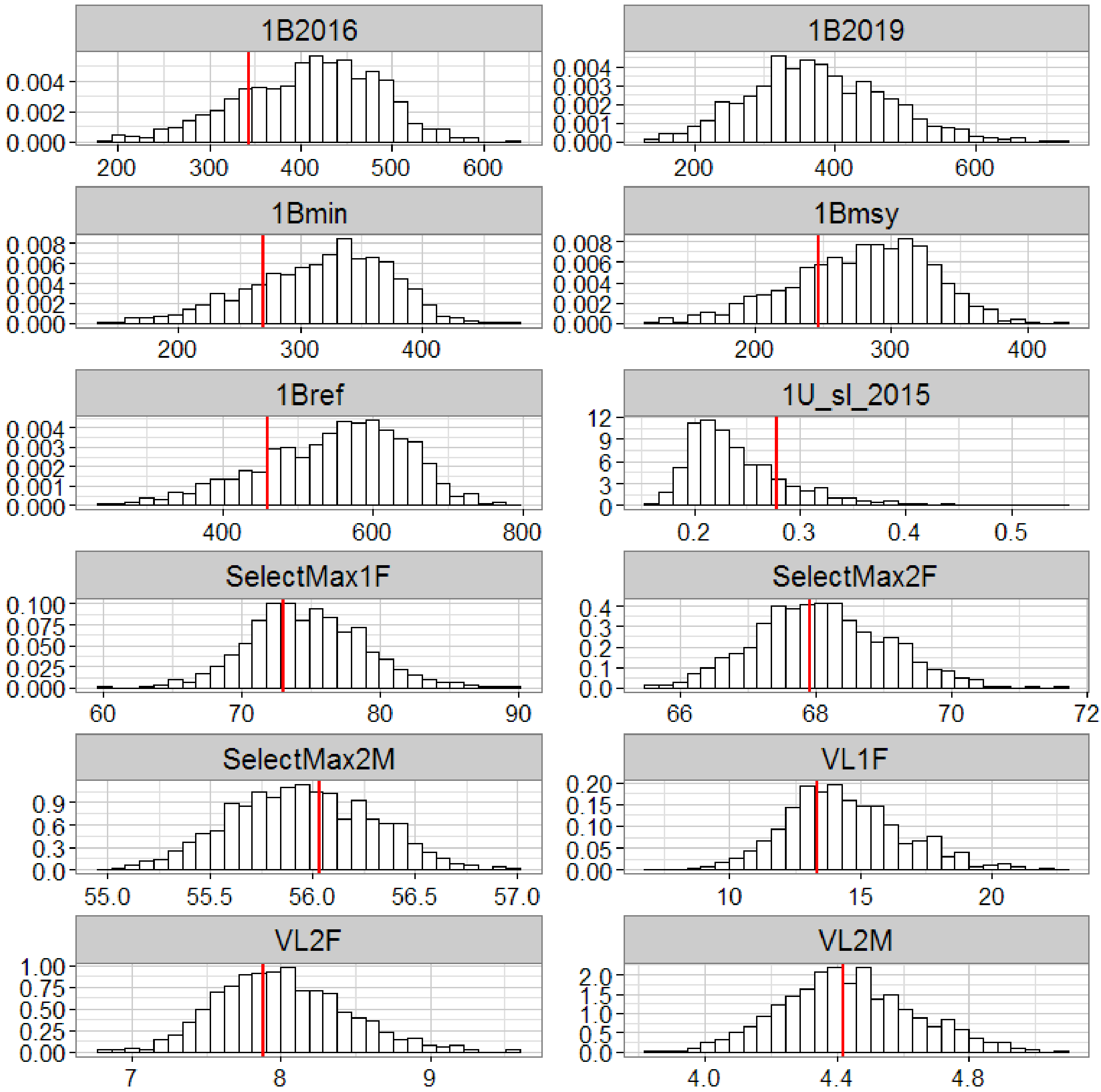


Figure 40: Posterior distributions of estimated and derived parameters from the base case McMC.

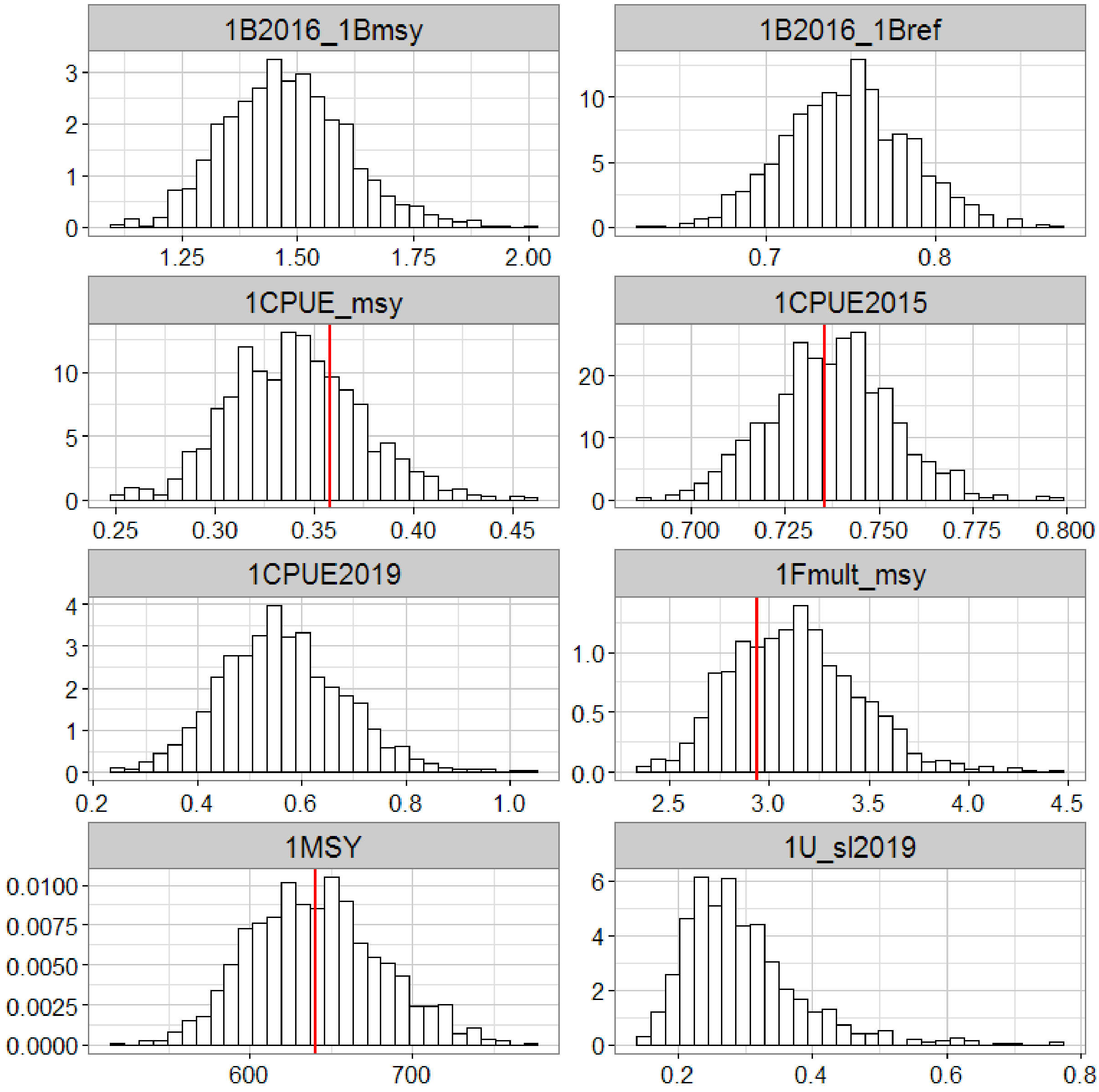


Figure 41: Posterior distributions of estimated and derived parameters from the base case McMC.

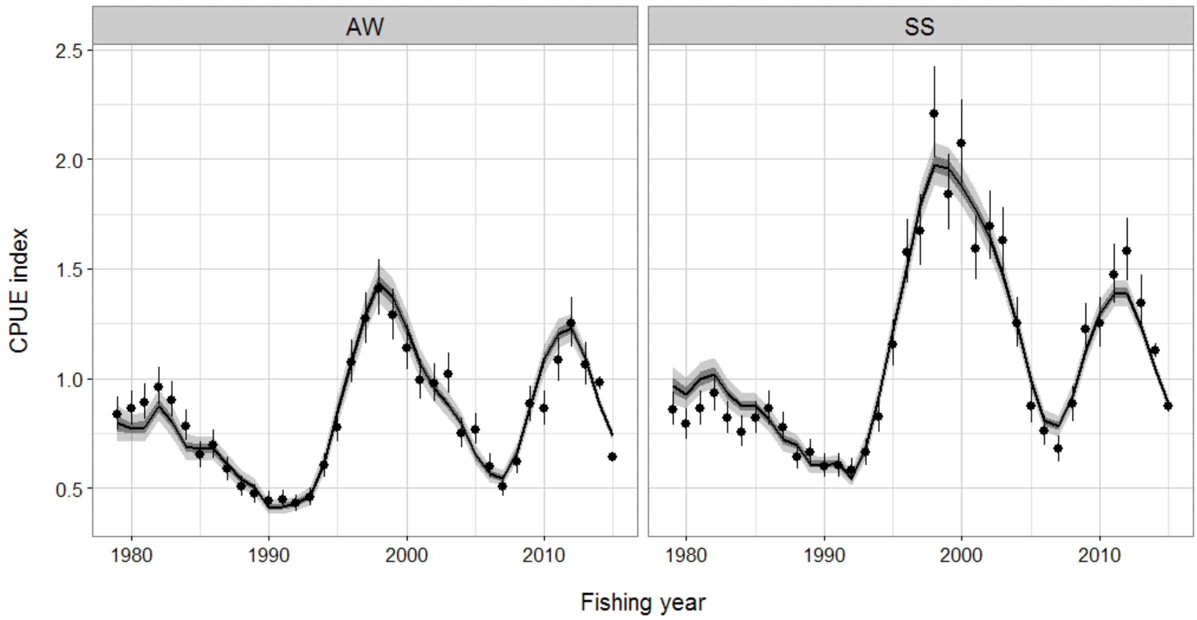


Figure 42: Posterior of the fit to CPUE from the base case McMC; shaded areas show the 5%, 25%, 75% and 95% quantiles of the posterior; the heavy solid line is the median of the posterior distribution; error bars on the CPUE values are one standard deviation.

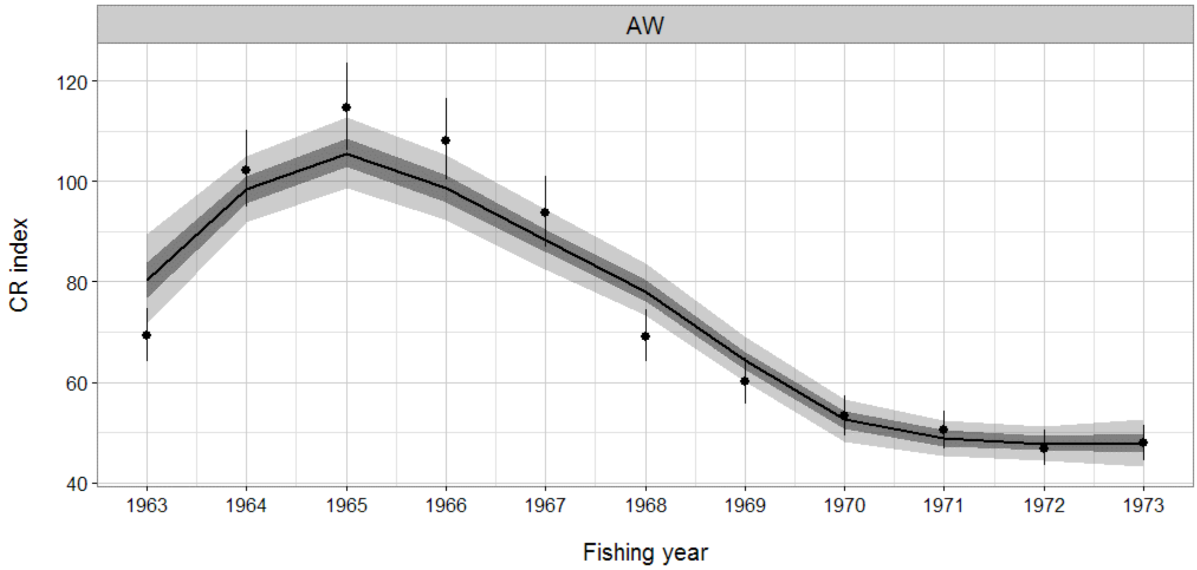


Figure 43: Posterior of the fit to the CR index from the base case McMC; shaded areas show the 5%, 25%, 75% and 95% quantiles of the posterior; the heavy solid line is the median of the posterior distribution; error bars on the CR values are one standard deviation.

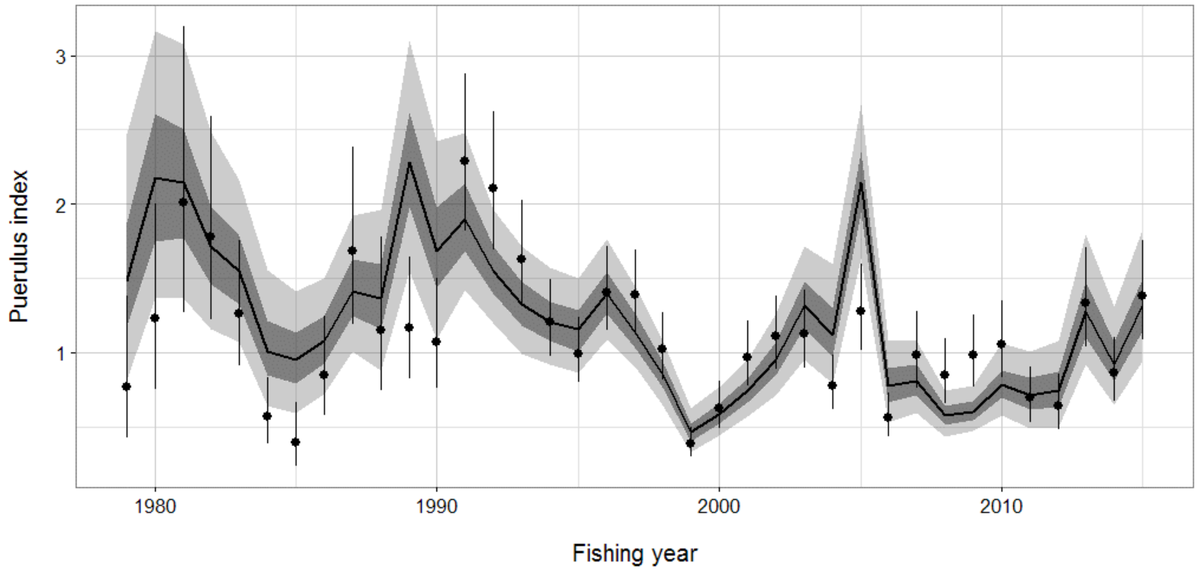


Figure 44: Posterior of the fit to the puerulus index from the base case McMC; shaded areas show the 5%, 25%, 75% and 95% quantiles of the posterior; the heavy solid line is the median of the posterior distribution; error bars on the puerulus values are one standard deviation.

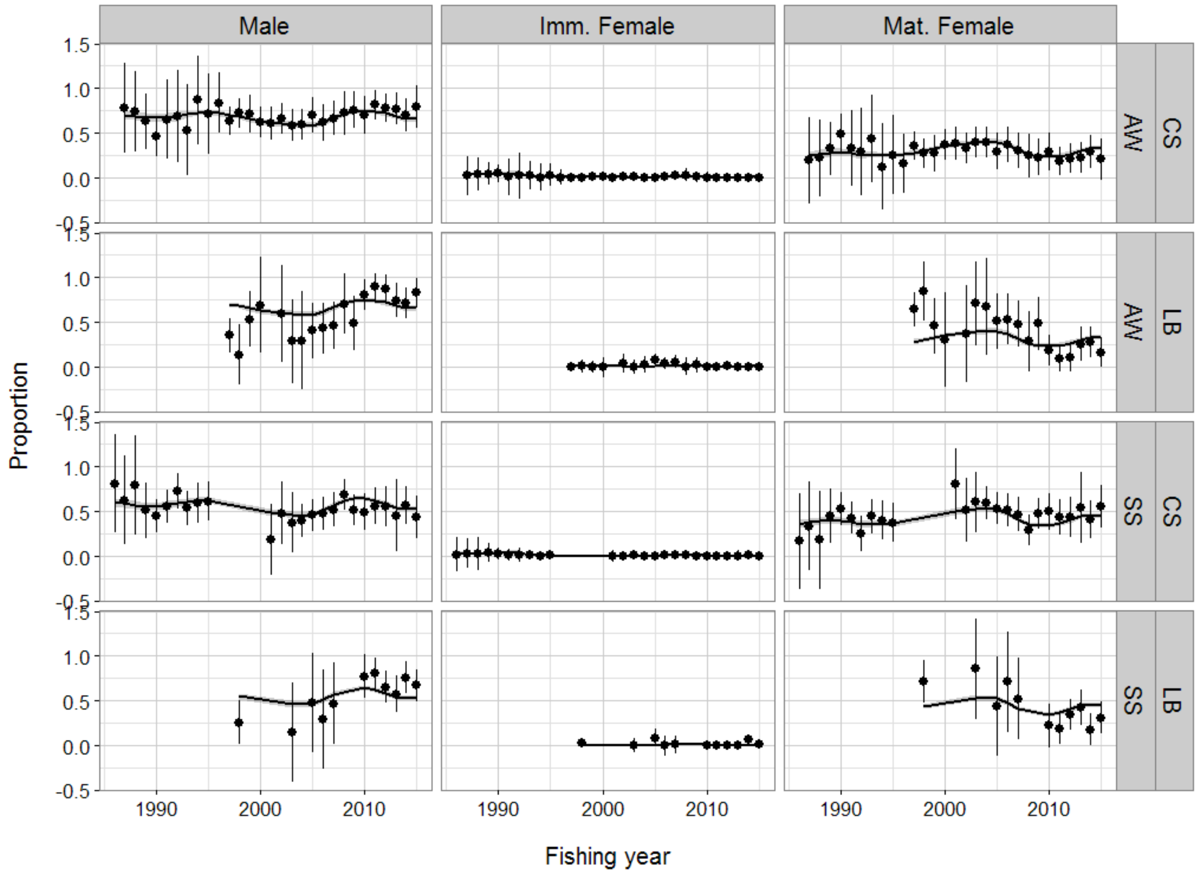


Figure 45: Posterior of the fit to the proportions-at-sex in the LF data from the base case McMC by season, sex and data source; shaded areas show the 5%, 25%, 75% and 95% quantiles of the posterior and the heavy solid line is the median of the posterior distribution. Error bars show one standard deviation.

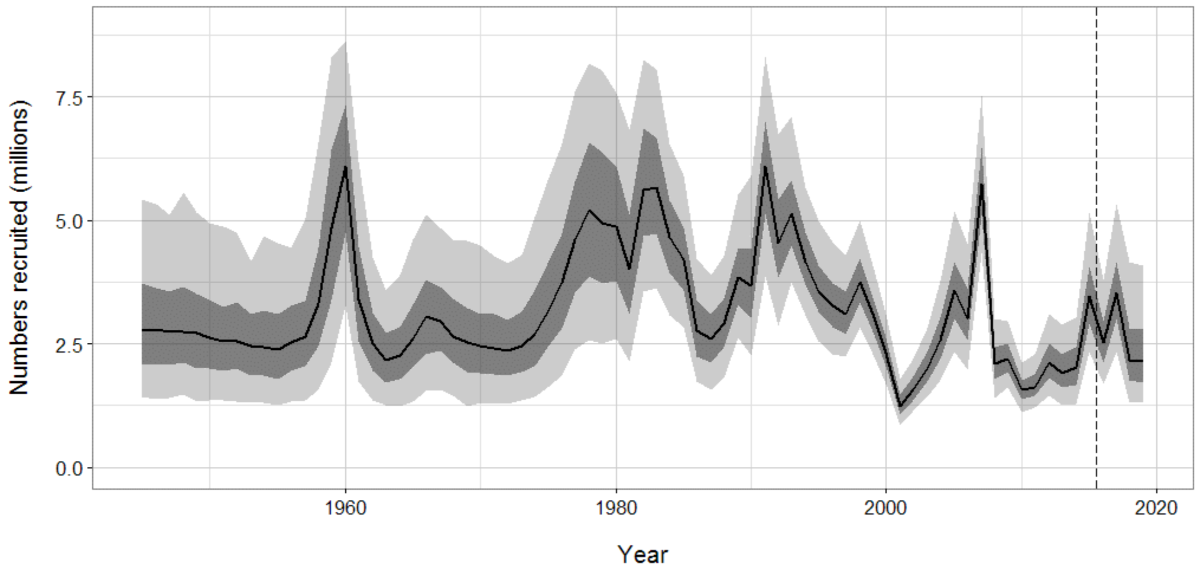


Figure 46: Posterior trajectory of recruitment to the model, 1945–2015, and projected recruits from 2016–2019 from the base case McMC; shaded areas show the 5%, 25%, 75% and 95% quantiles of the posterior; the heavy solid line is the median of the posterior distribution; the vertical line shows 2015, the final fishing year of the model reconstruction.

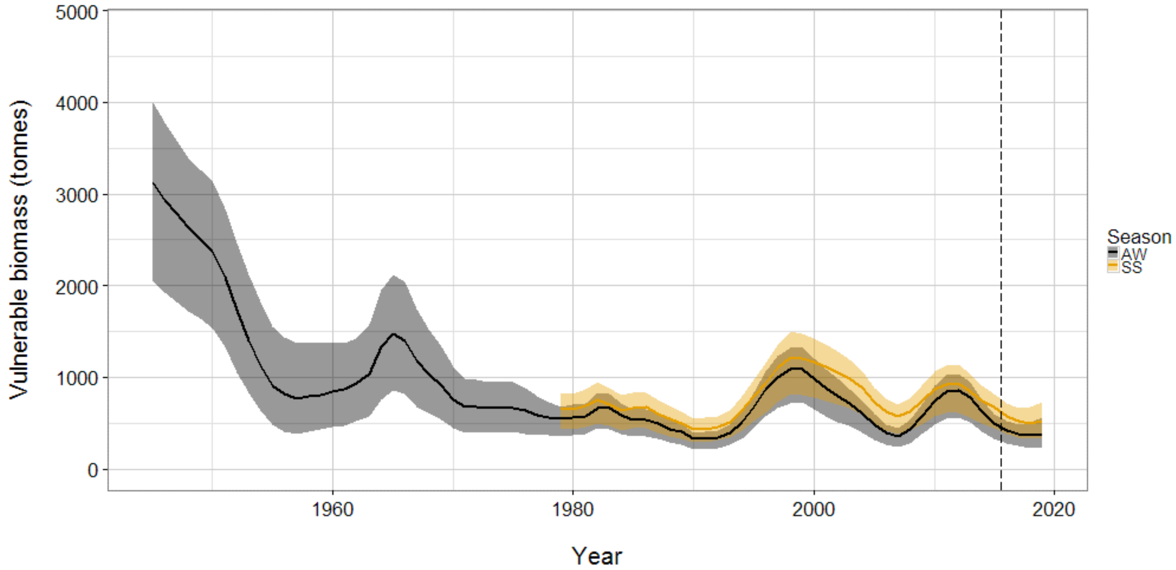


Figure 47: From the base case McMC, vulnerable biomass from 1945–2019 by season from the base case McMC; shaded areas show the 90% credibility intervals; the heavy solid line is the median of the posterior distributions; the vertical line shows 2015, the final fishing year of the model reconstruction. Biomass before 1979 is annual but plotted using the AW coding.

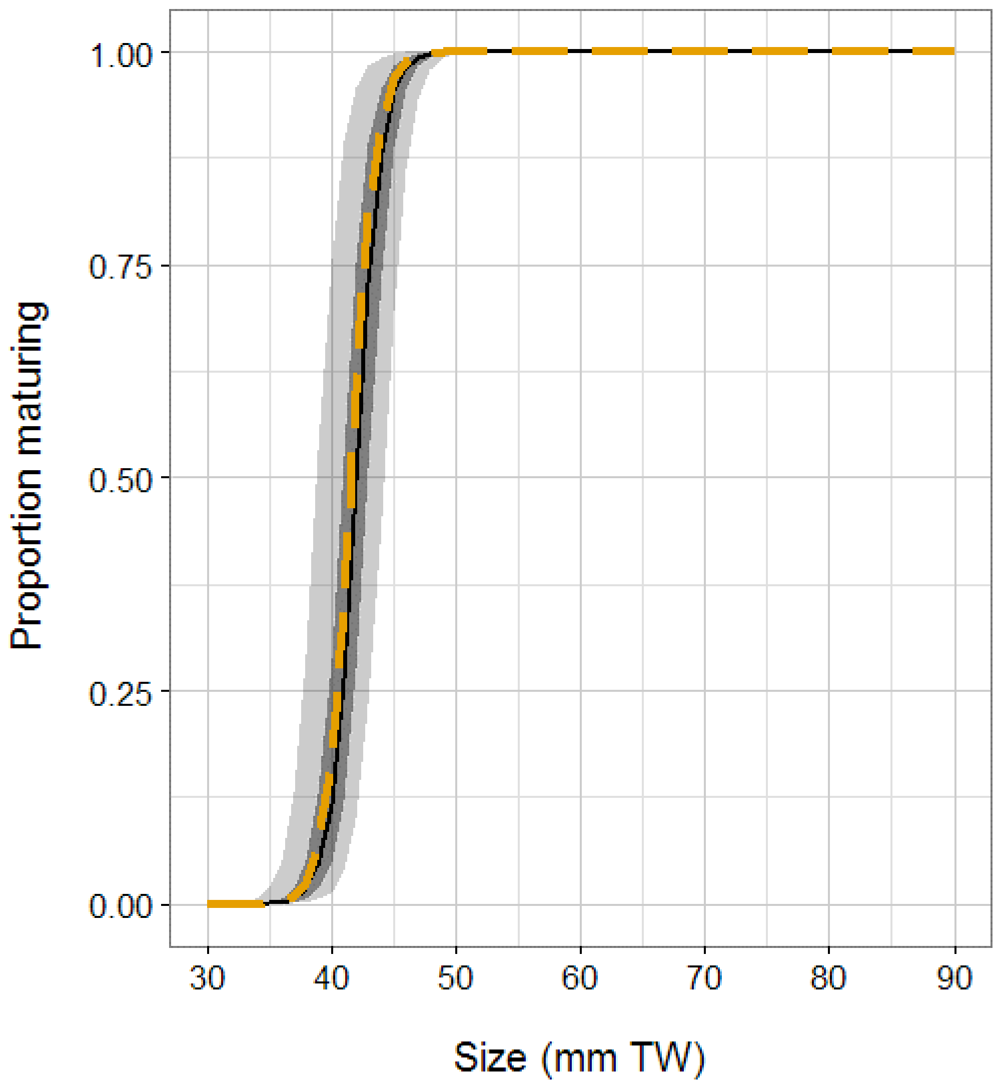


Figure 48: From the base case McMC, the posterior distribution of maturation-at-size.

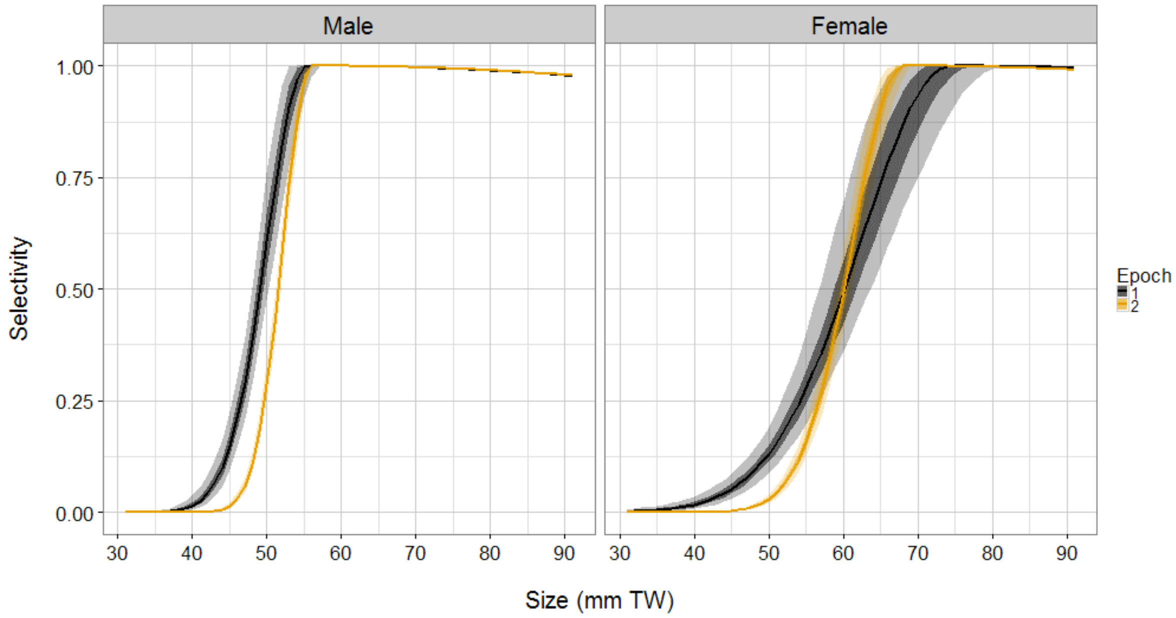


Figure 49: From the base case McMC, the posterior distribution of selectivity by sex and epoch.

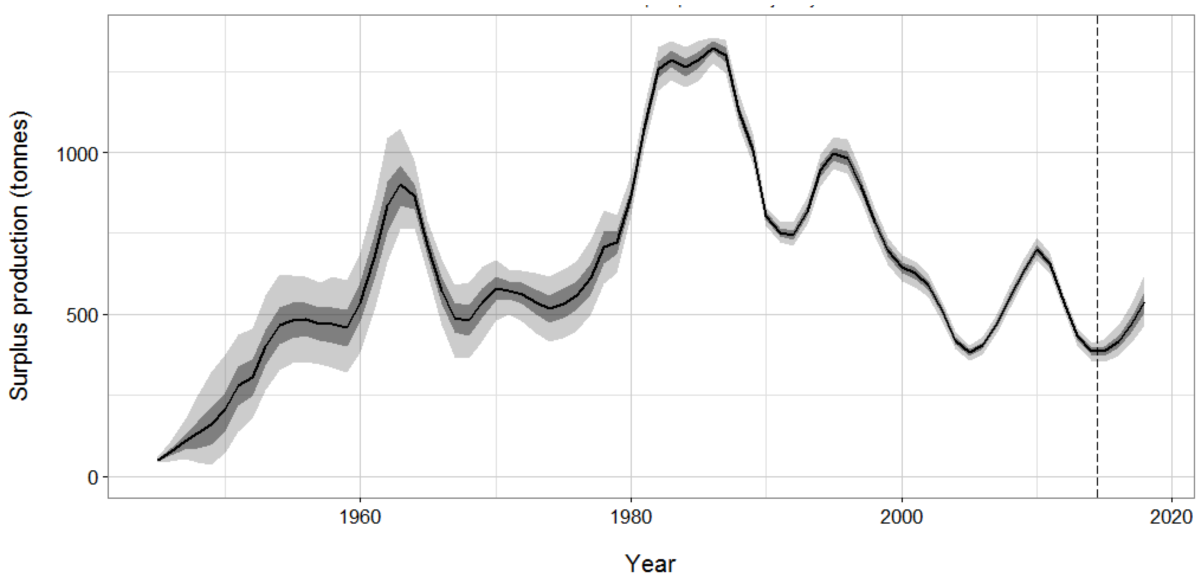


Figure 50: Surplus production trajectory from the base case McMC.

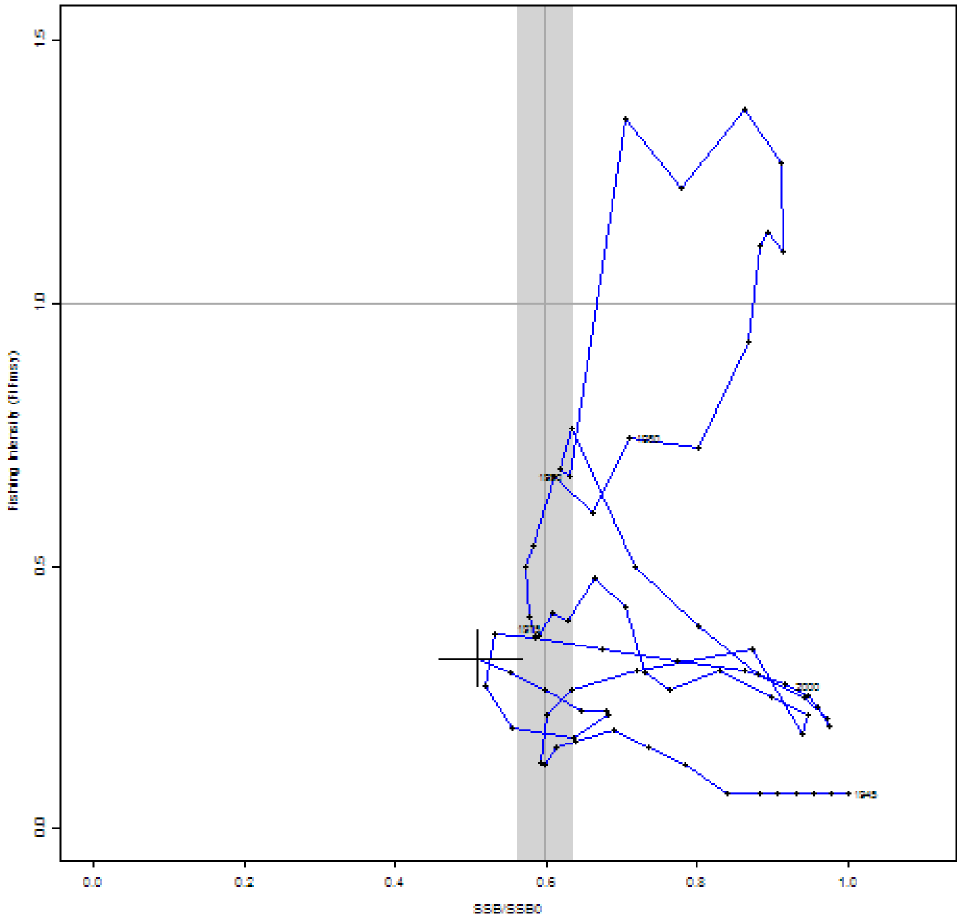


Figure 51: Phase diagram of the median spawning biomass on the x-axis and median fishing intensity on the y-axis. Specifically, the x-axis is spawning stock biomass *SSB* as a proportion of the unfished spawning stock *SSB0*. Estimated *SSB* changes every year while *SSB0* is constant for all years of a simulation and both vary among the 1000 samples from the posterior distribution. The y-axis is fishing intensity as a proportion of the fishing intensity that would have given *MSY* (*Fmsy*) under the fishing patterns in year y; fishing patterns include MLS, selectivity, the seasonal catch split and the balance between SL and NSL catches. *Fmsy* varies among years because the fishing patterns change. It was calculated with a 50-year projection for each year in each simulation, with the NSL catch held constant at that year's value, deterministic recruitment at *R0* and a range of multipliers on the SL catch *F*s estimated for year y. The *F* (actually *F*s for two seasons) that gave *MSY* was *Fmsy*, and the multiplier was *Fmult*. Each point on the figure was plotted as the median of the posterior distributions of biomass ratio and fishing intensity ratio. The vertical line in the figure is the median (line) and 90% interval (shading) of the posterior distribution of *SSBmsy* as a proportion of *SSB0*; this ratio was calculated using the fishing pattern in 2015. The horizontal line in the figure is drawn at 1, the fishing intensity associated with *Fmsy*. The bars at the final year of the plot show the 90% intervals of the posterior distributions of biomass ratio and fishing intensity ratio.

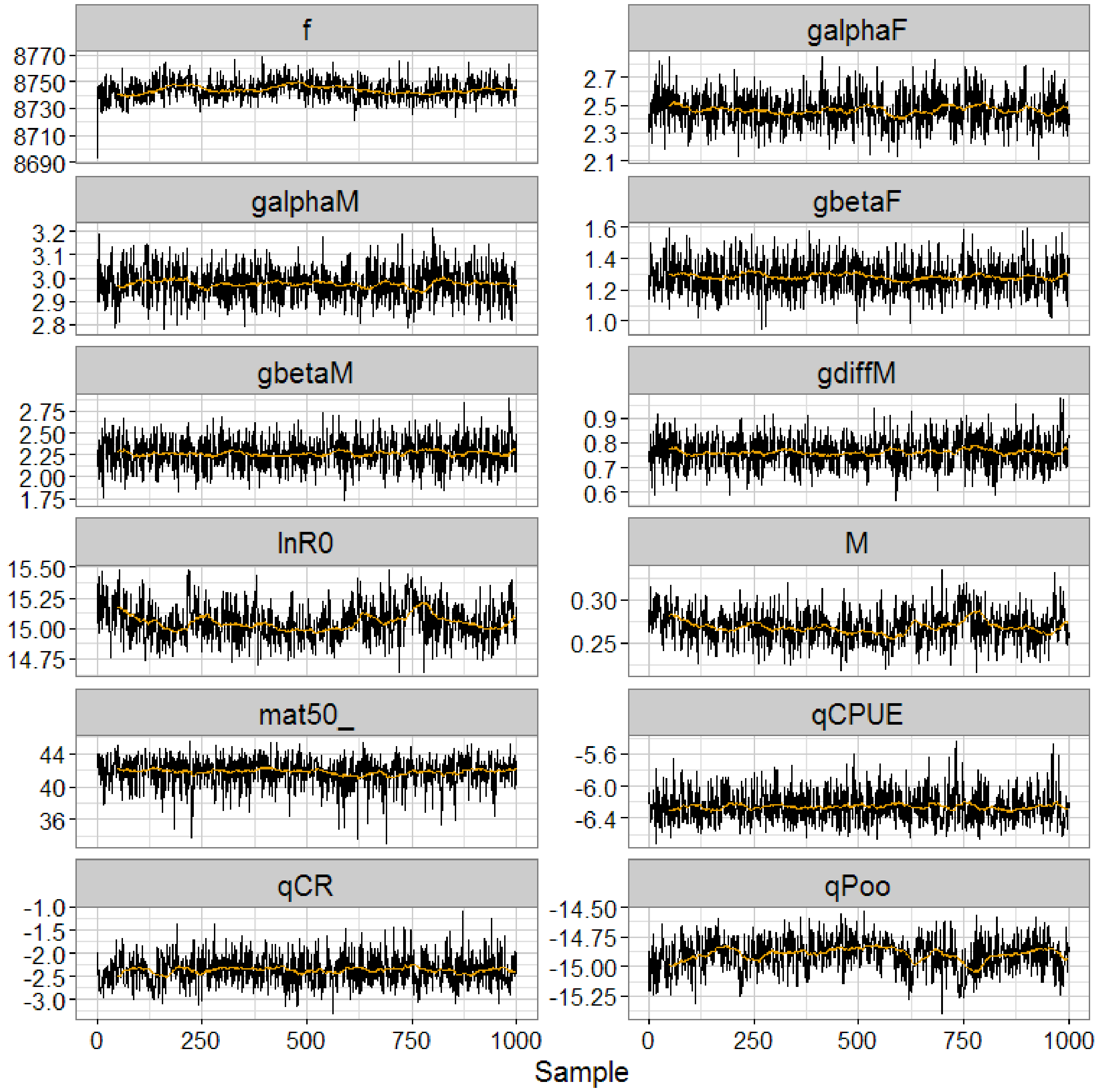


Figure 52: Traces from the lag1 McMC sensitivity trial.

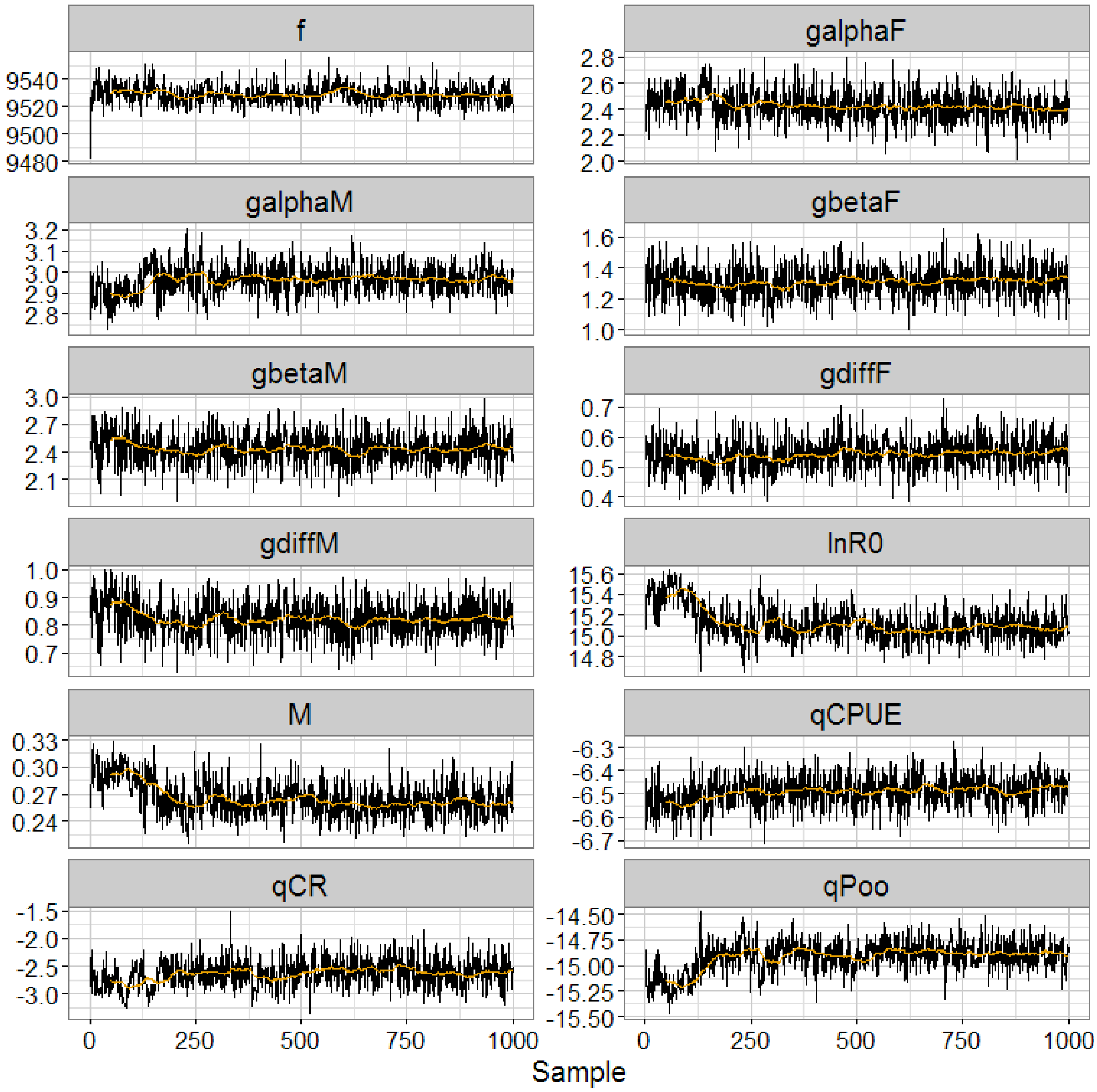


Figure 53: Traces from the 2-sex McMC sensitivity trial.

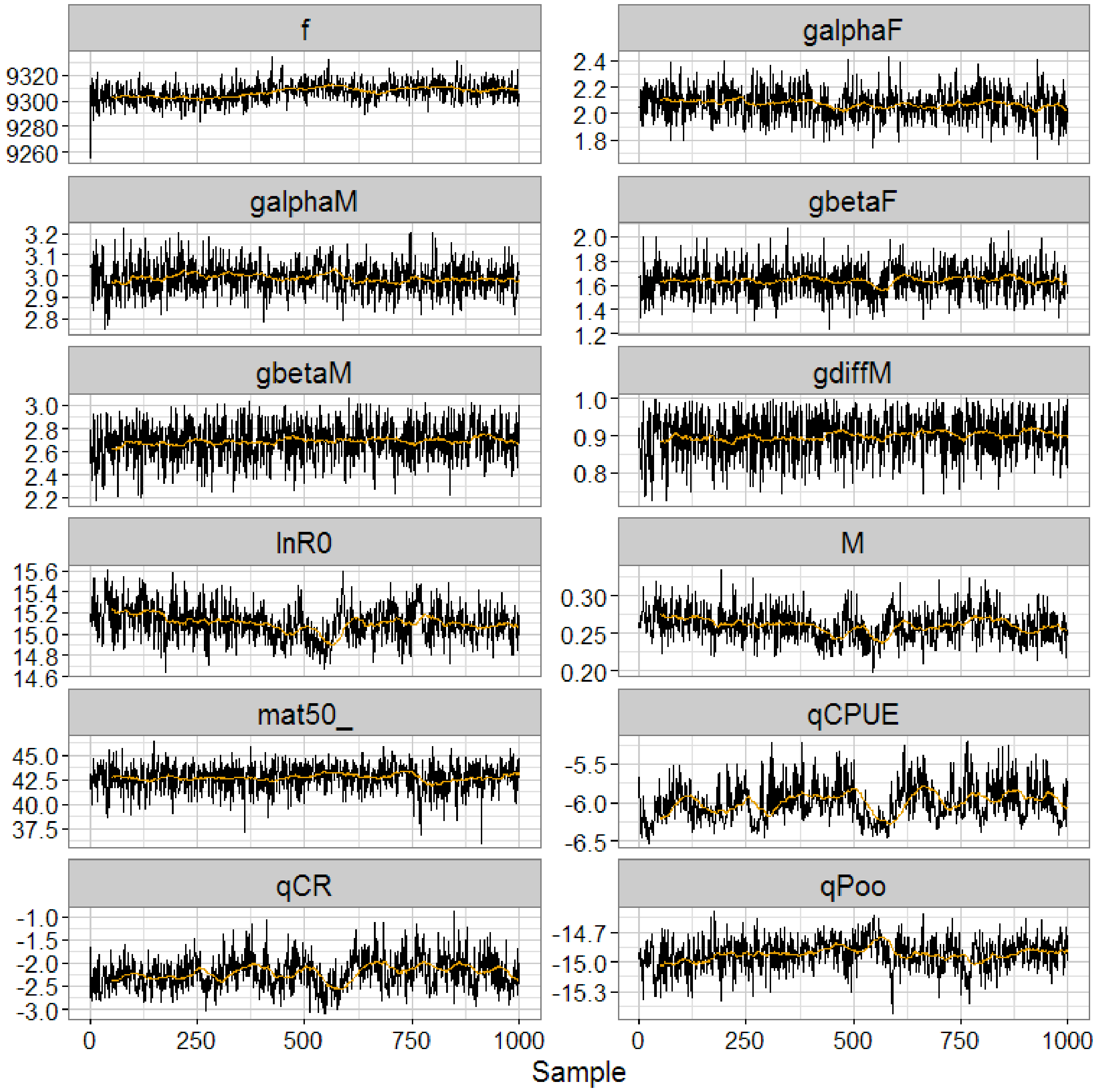


Figure 54: Traces from the normal McMC sensitivity trial.

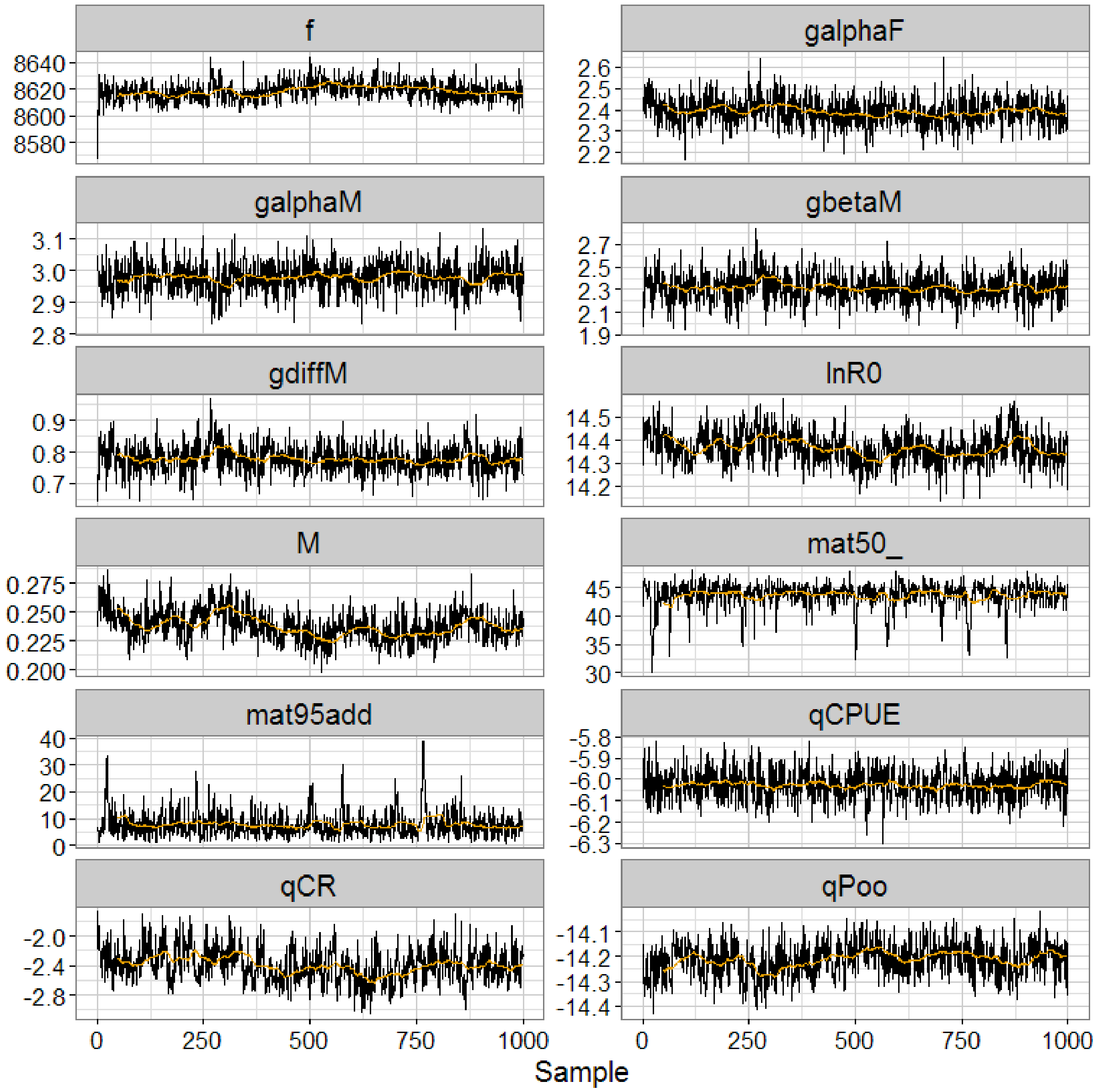


Figure 55: Traces from the fixedG1 McMC sensitivity trial.

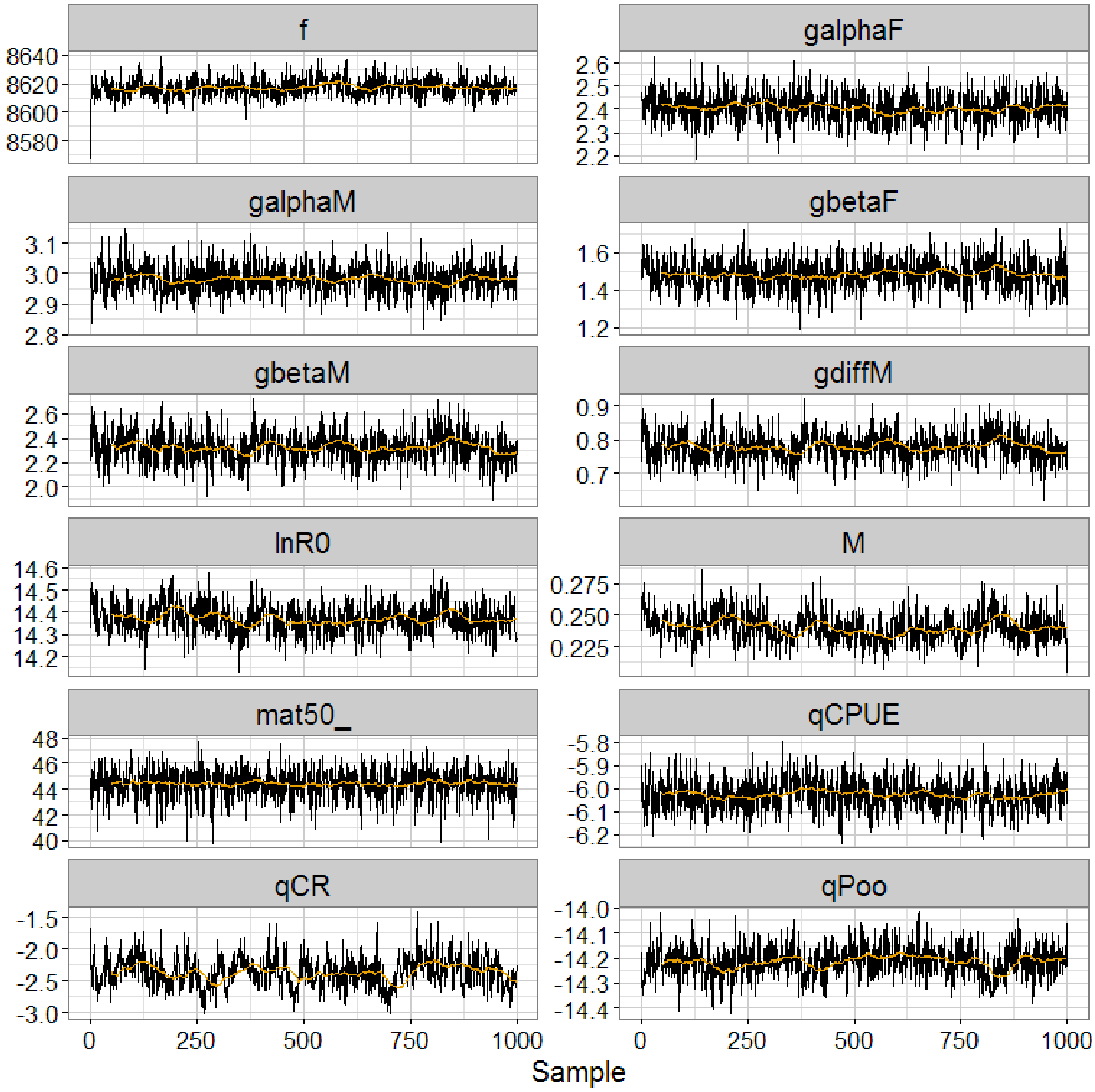


Figure 56: Traces from the fixedG2 McMC sensitivity trial.

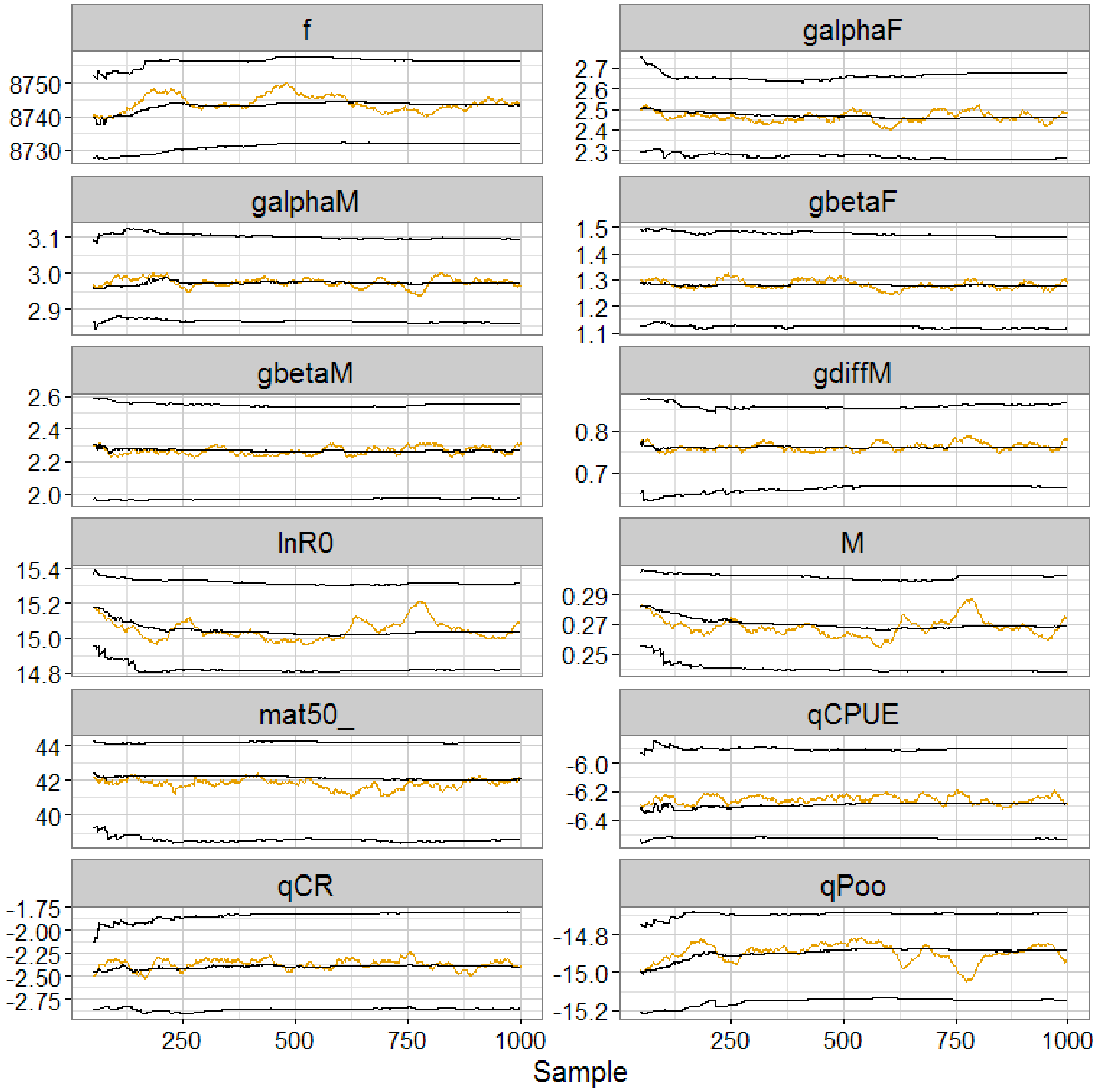


Figure 57: Diagnostic plots for the lag1 McMC sensitivity trial.

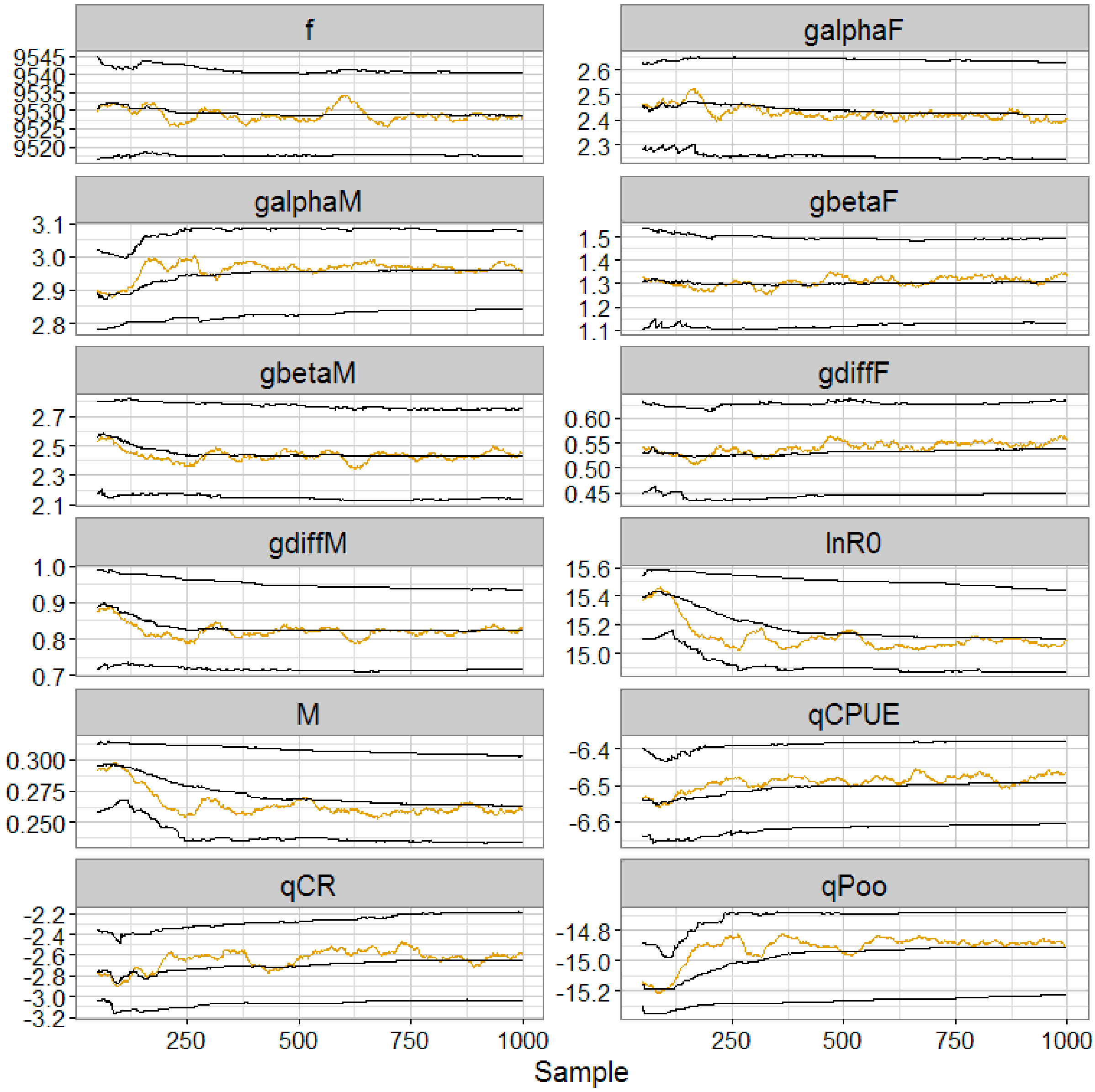


Figure 58: Diagnostic plots for the 2-sex McMC sensitivity trial.

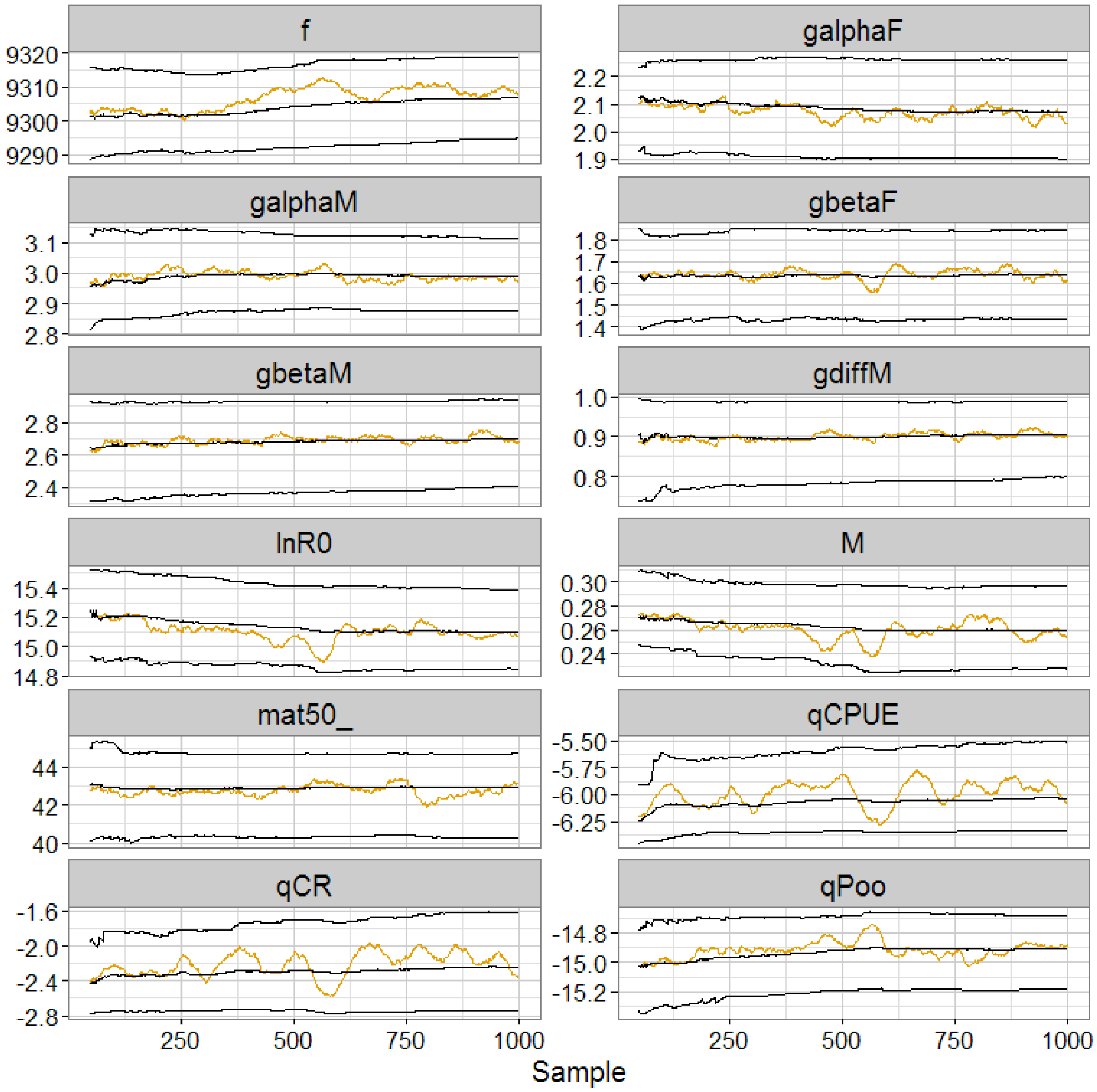


Figure 59: Diagnostic plots for the normal McMC sensitivity trial.

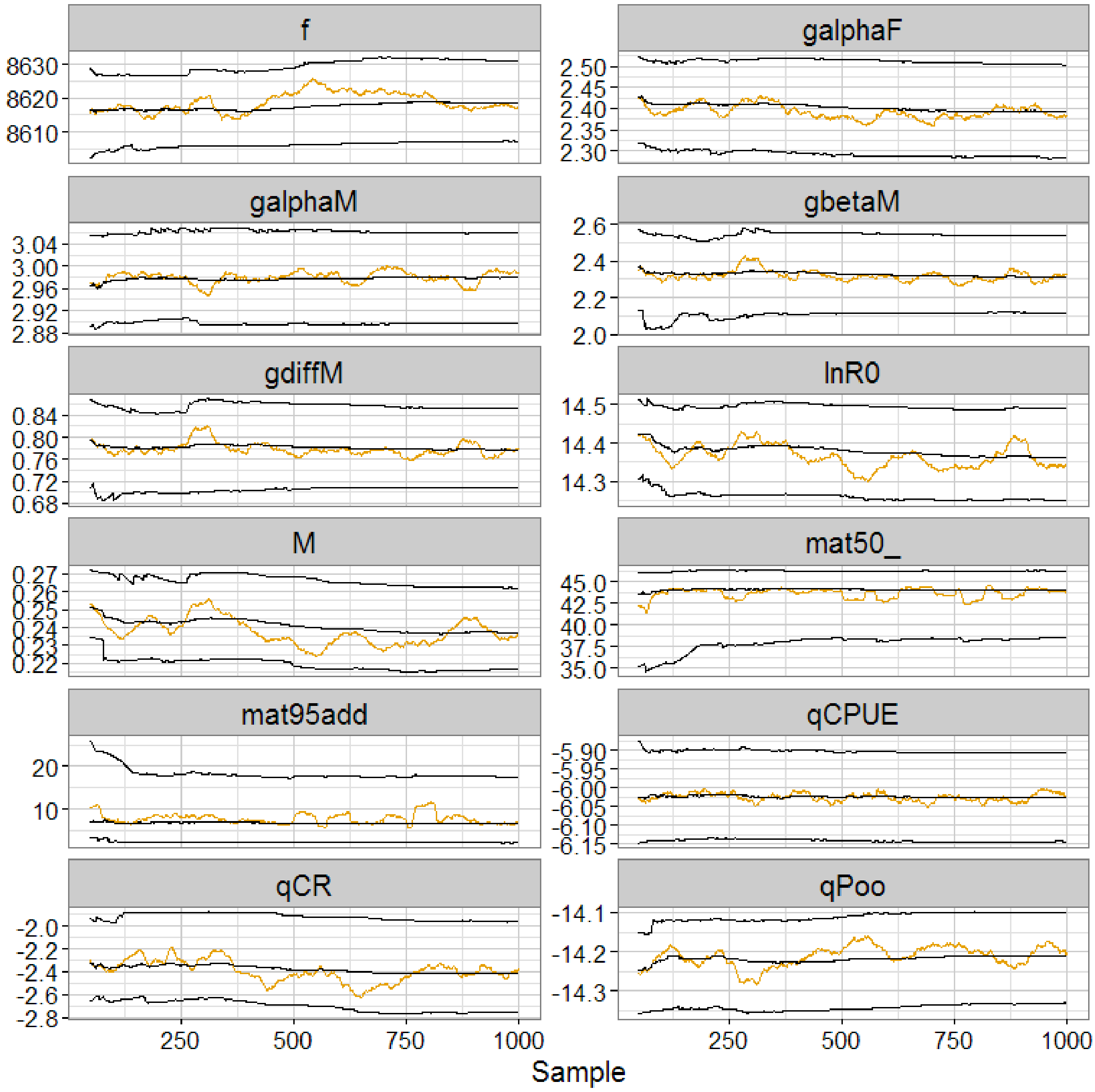


Figure 60: Diagnostic plots for the fixedG1 McMC sensitivity trial.

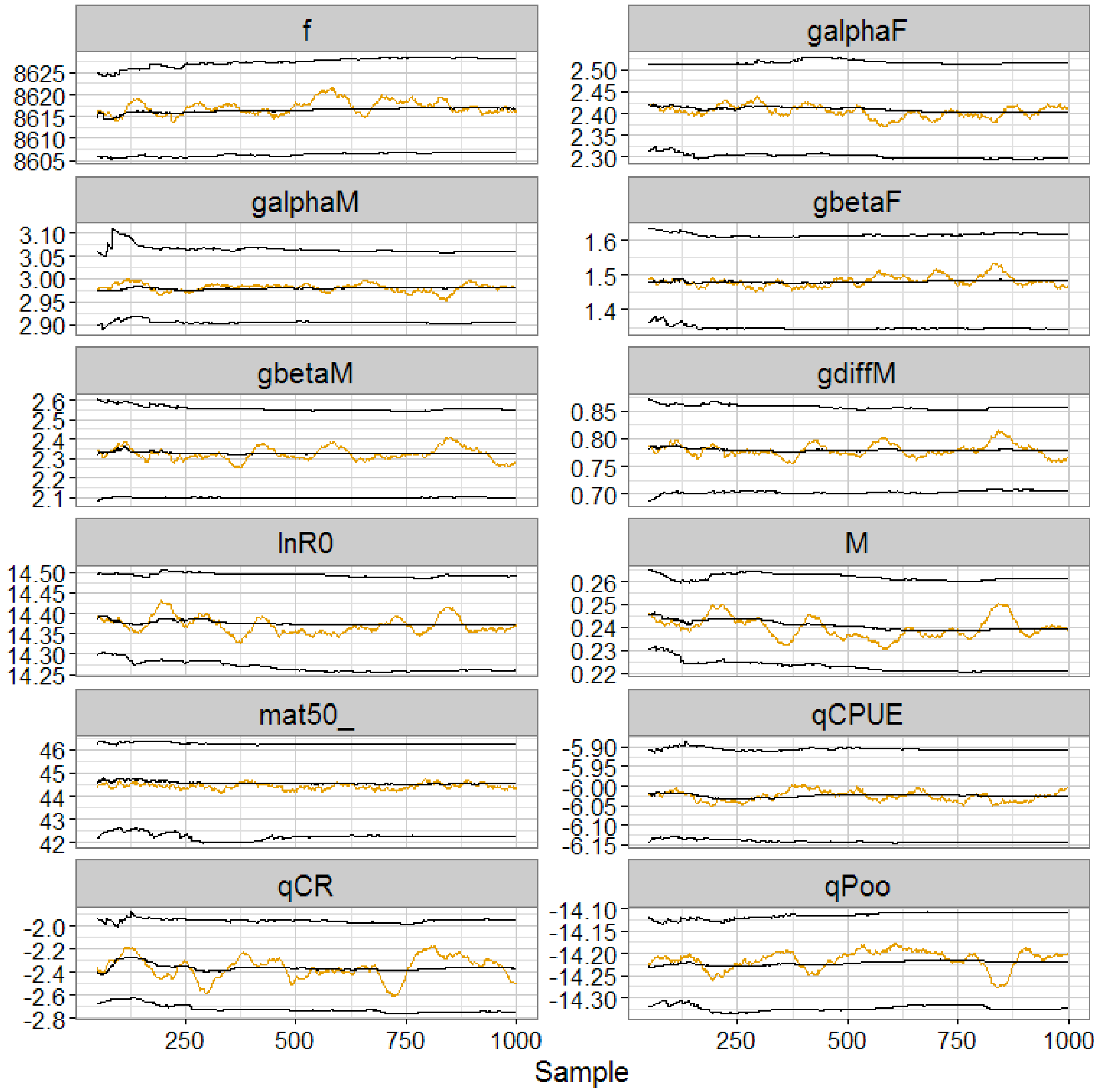


Figure 61: Diagnostic plots for the fixedG2 McMC sensitivity trial.

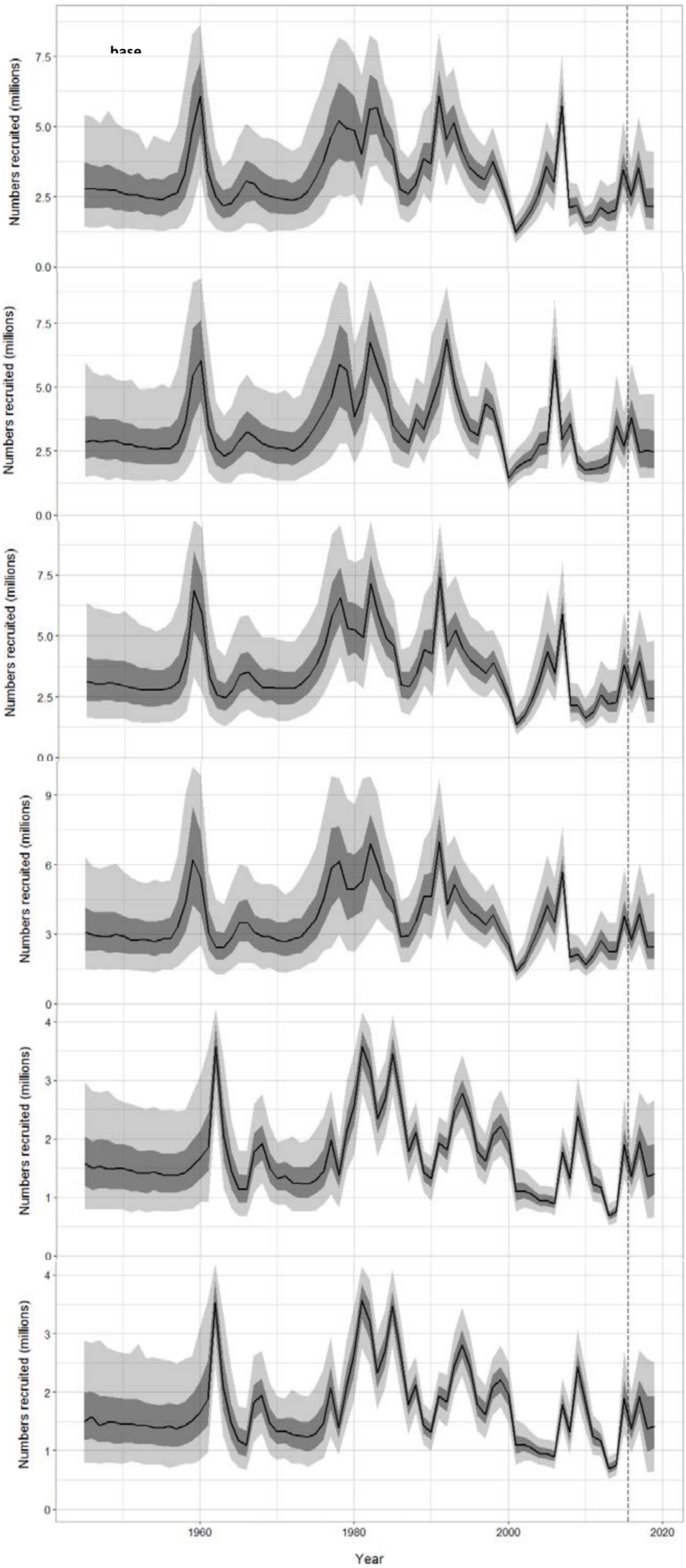


Figure 62: Recruitment trajectories from the base case McMC and the five McMC sensitivity trials.

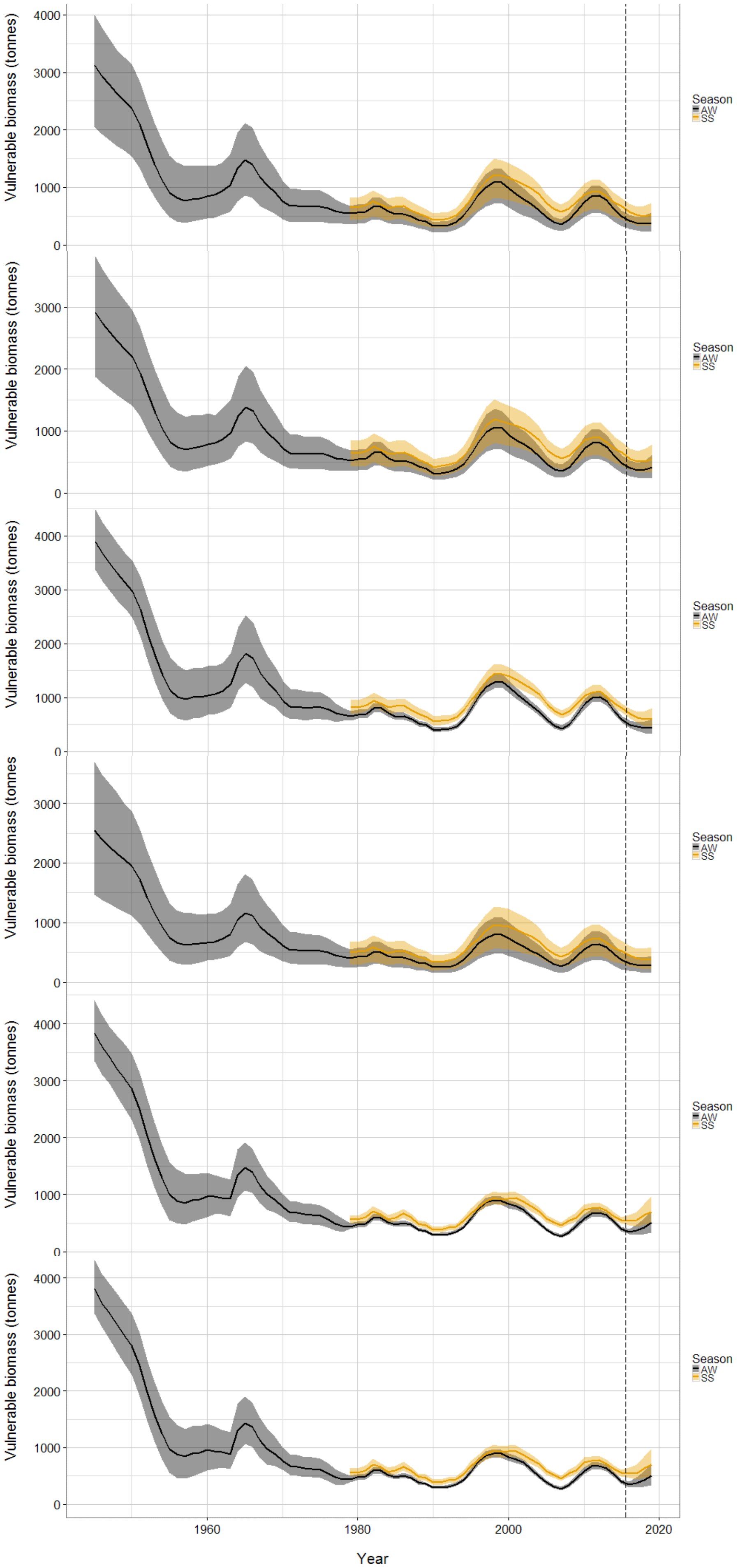


Figure 63: Vulnerable biomass trajectories from the base case McMC and the five McMC sensitivity trials.

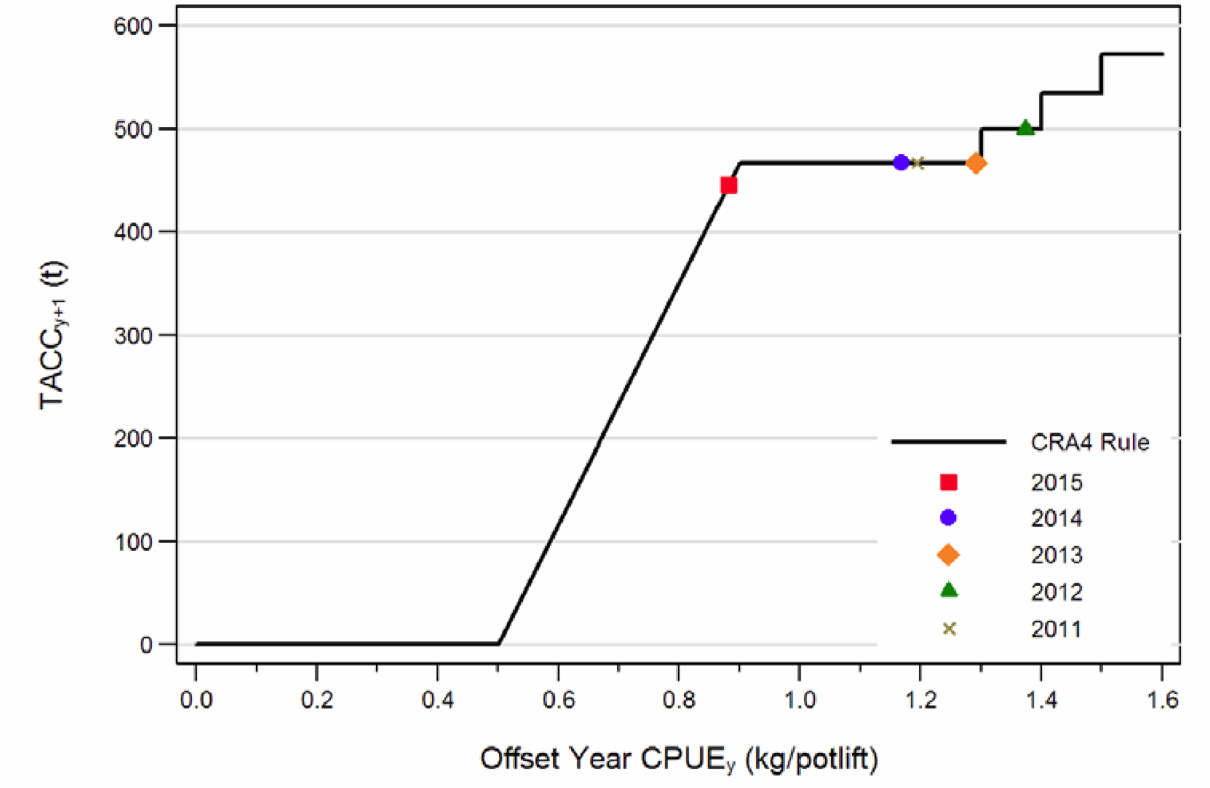


Figure 64: History of the current CRA 4 management procedure. The 2016 TACC is that specified by the rule, not the lower TACC that was adopted.

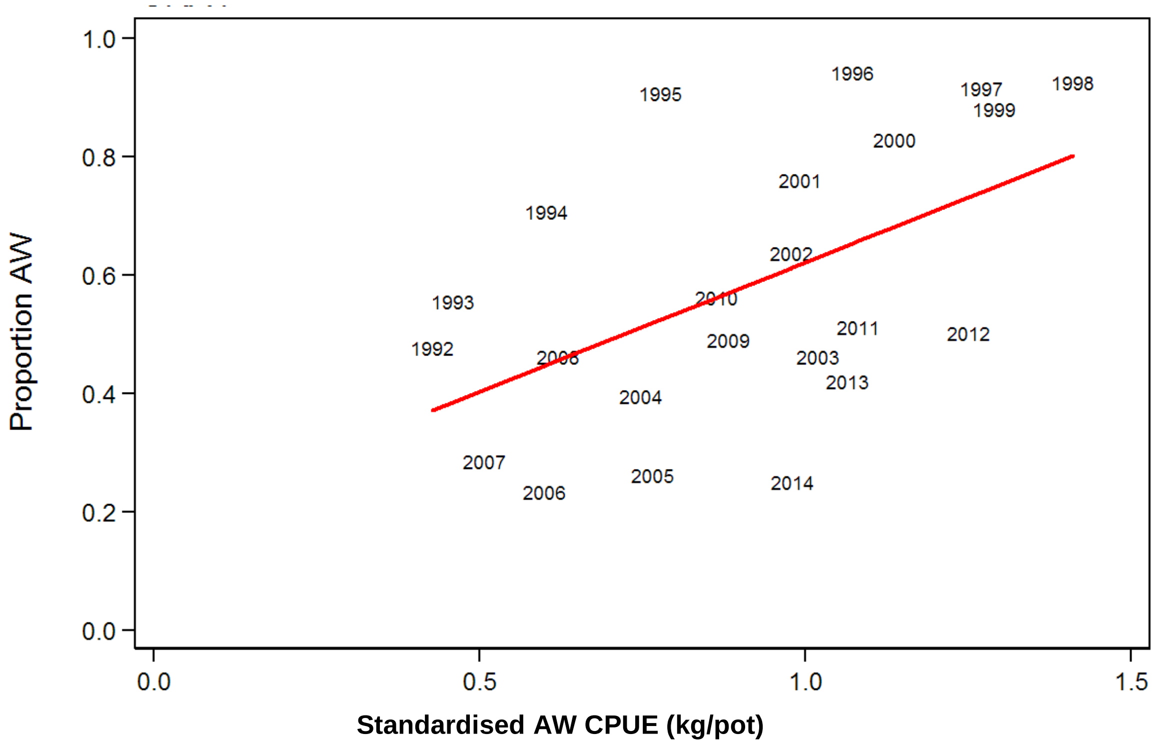


Figure 65: Observed proportion of catch taken in AW vs. the standardised AW CPUE; the line shows a predictive regression with parameters intercept = 0.184 and slope = 0.4372.

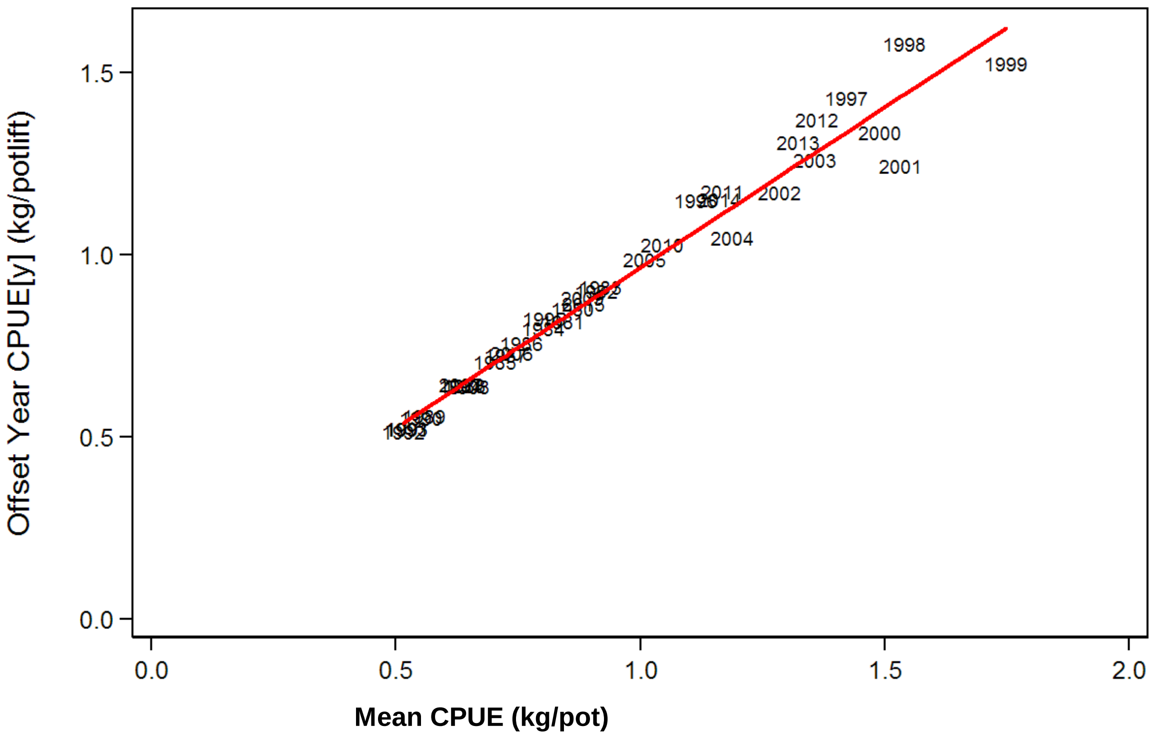


Figure 66: Observed standardised offset-year CPUE vs. the average of AW CPUE in the same year and SS CPUE from the previous year; the line shows a predictive regression with parameters intercept = 0.0844 and slope = 0.8803.

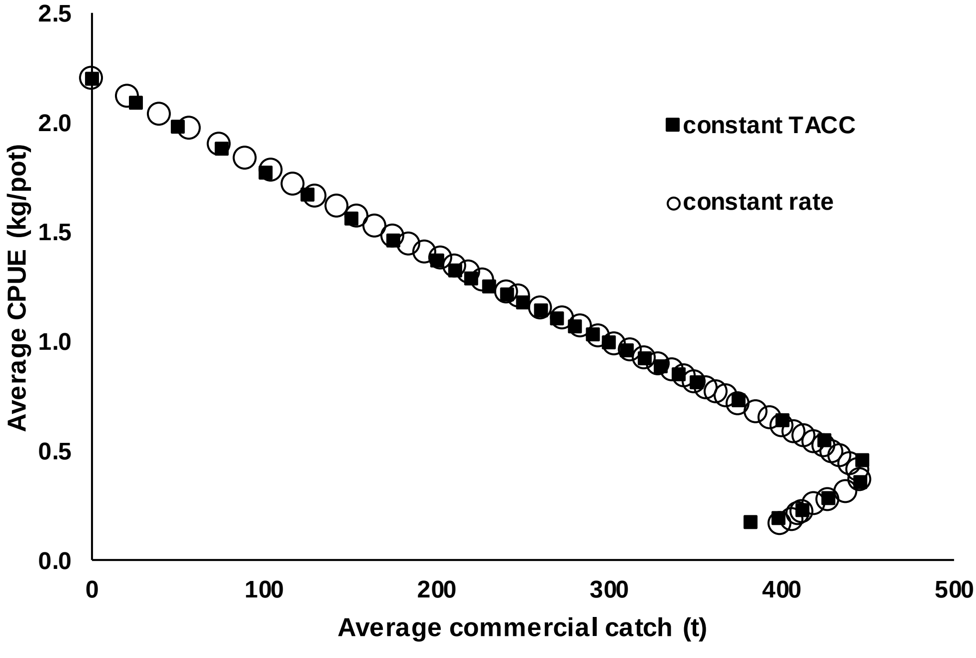


Figure 67: Productivity of the base case CRA 4 operating model: average CPUE vs. average commercial catch from constant TACC (black squares) and constant rate (open circles) rules.

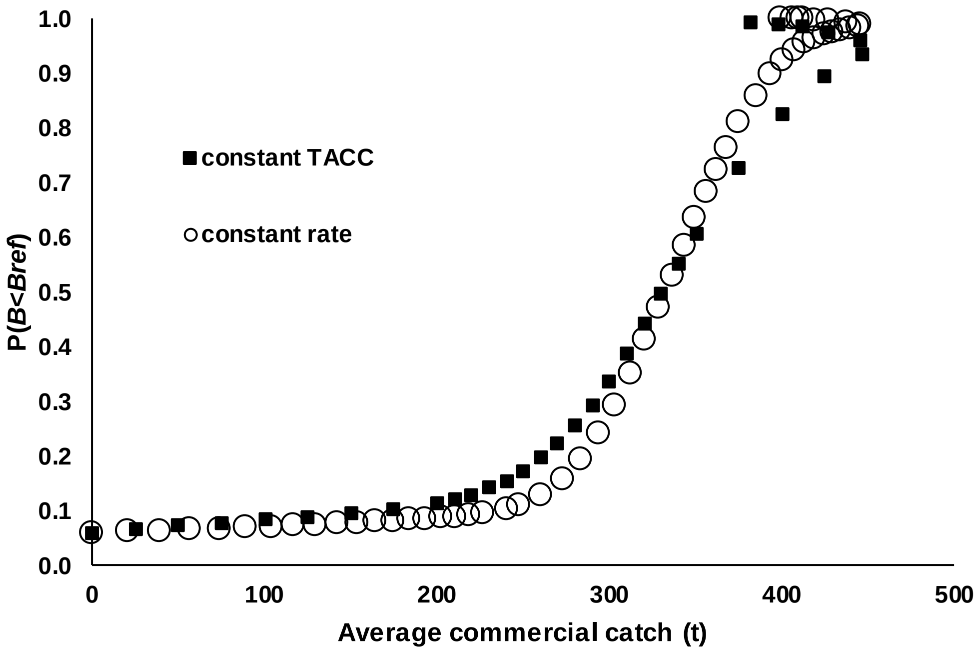


Figure 68: Productivity of the CRA operating model: proportion of years where biomass was less than *Bref* vs. average commercial catch from constant TACC (black squares) and constant rate (open circles) rules.

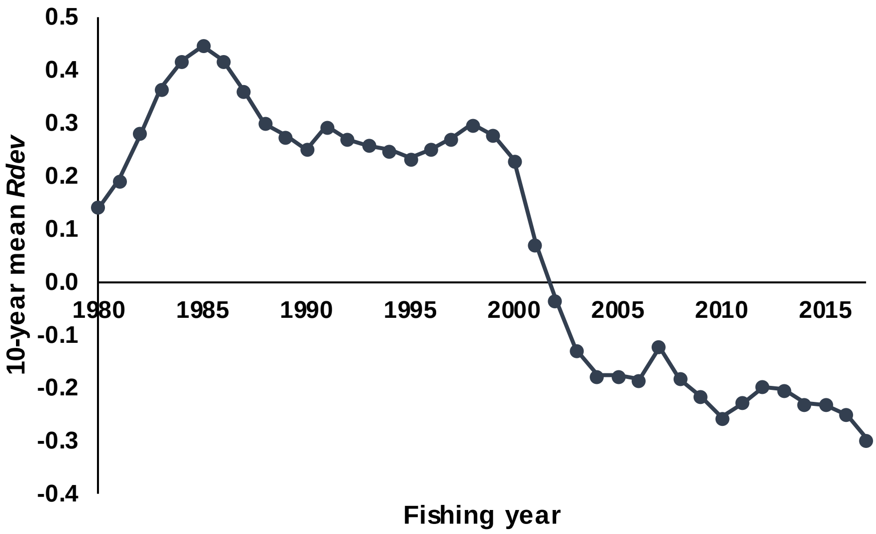


Figure 69: Ten-year average *Rdevs*, 1980–2017; plotted against the final year.

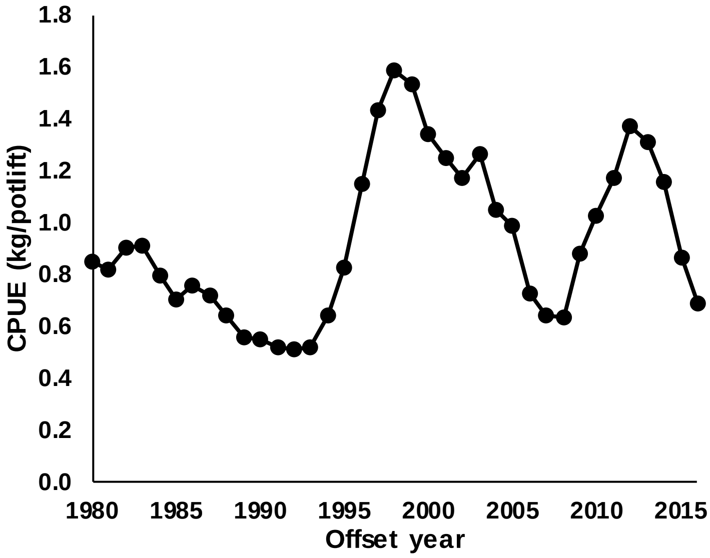


Figure 70: CRA 4 offset-year CPUE (Starr 2017).

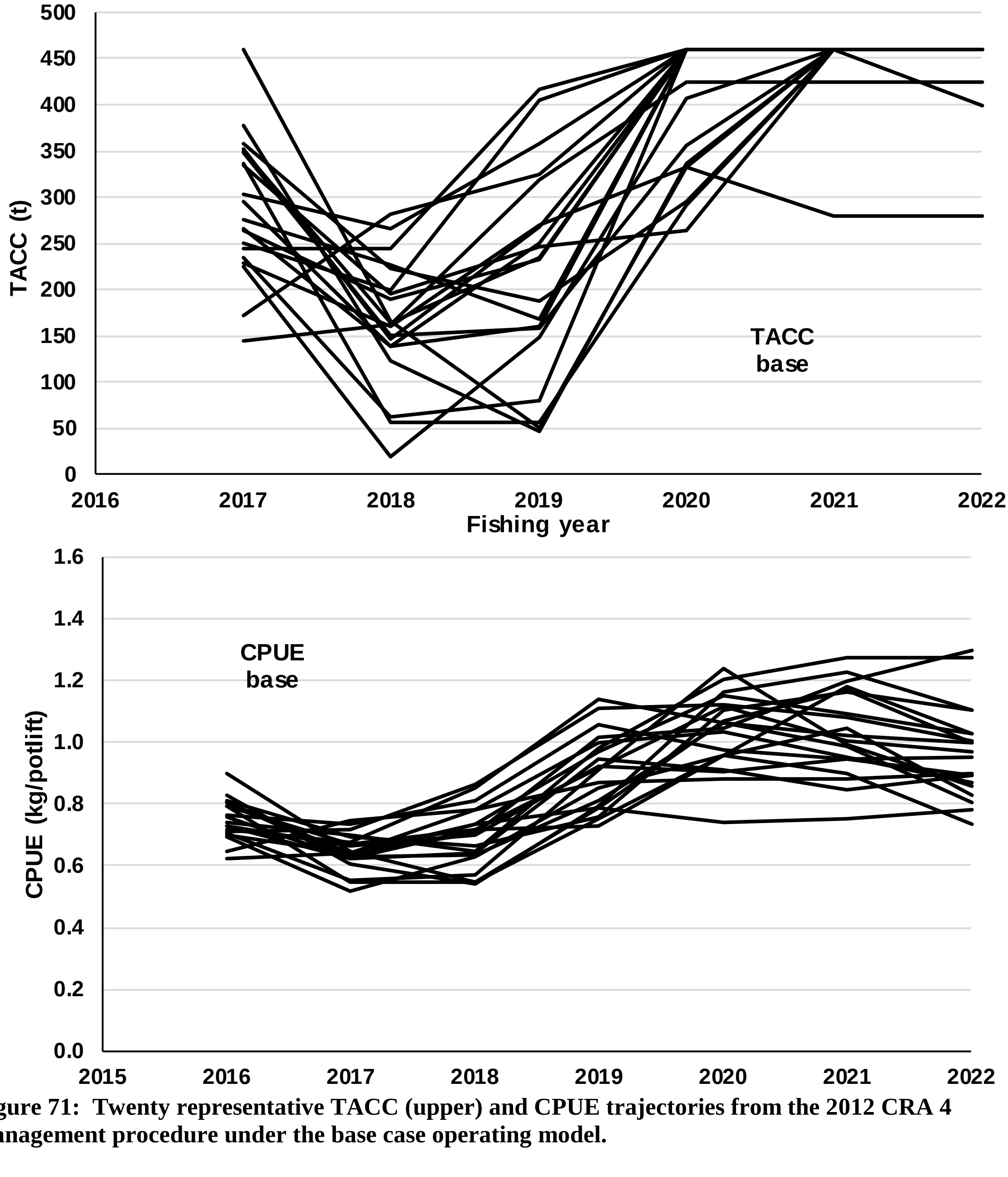


Figure 71: Twenty representative TACC (upper) and CPUE trajectories from the 2012 CRA 4 management procedure under the base case operating model.

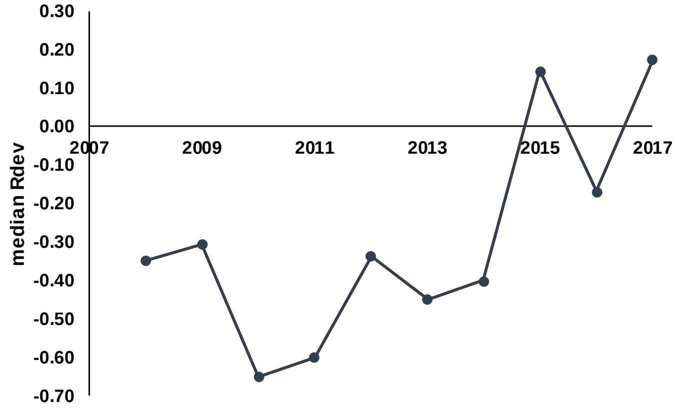


Figure 72: From the base case McMC, median *Rdevs* from 2008 through 2017.

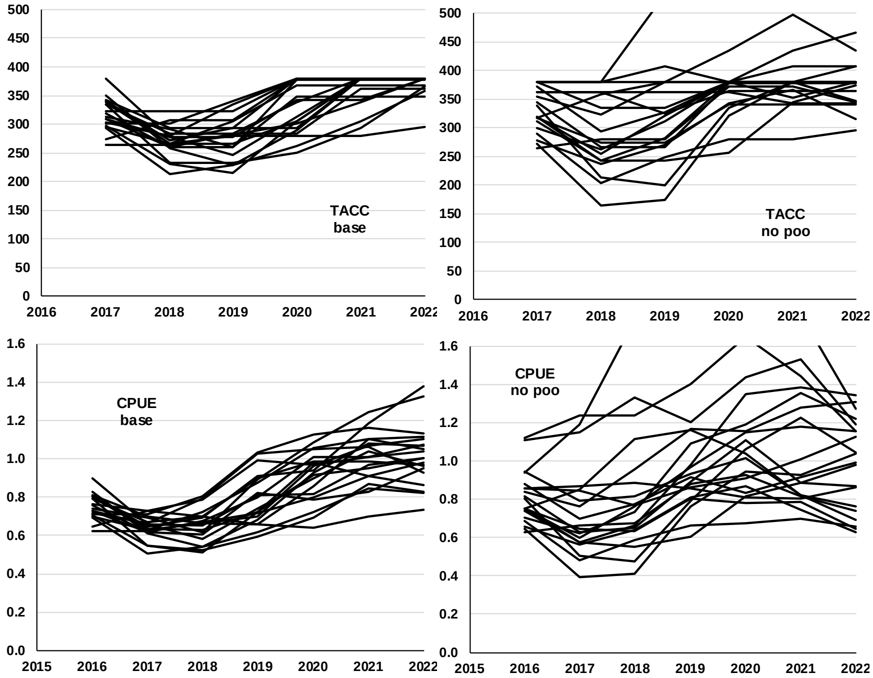


Figure 73: Comparison of 20 TACC (upper) and CPUE trajectories from the same rule (rule 6) made from the base case (left) and noPoo operating models.

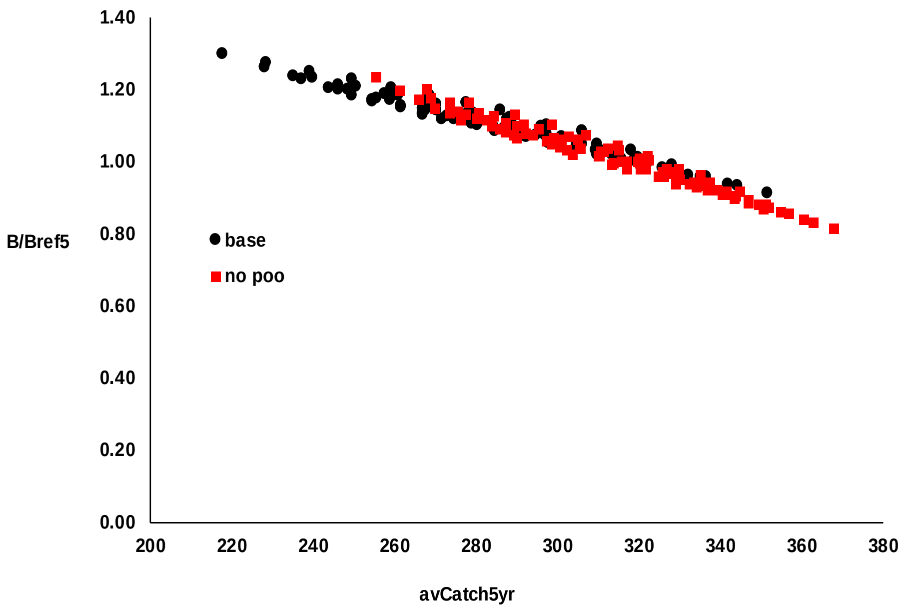


Figure 74: From the set of 96 rules, median biomass in year 5 as a proportion of *Bref* vs. average 5-year catch: base case black circles, noPoo trial red squares.

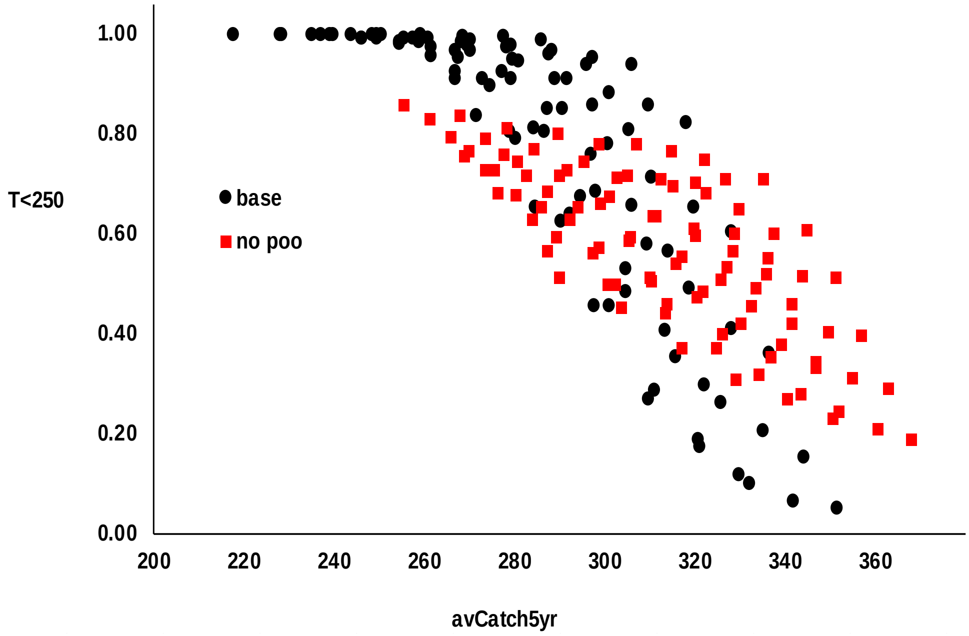


Figure 75: From the set of 96 rules, probability that TACC would be set below 250 t at some time during the 5 years vs. average 5-year catch: base case black circles, noPoo trial red squares.

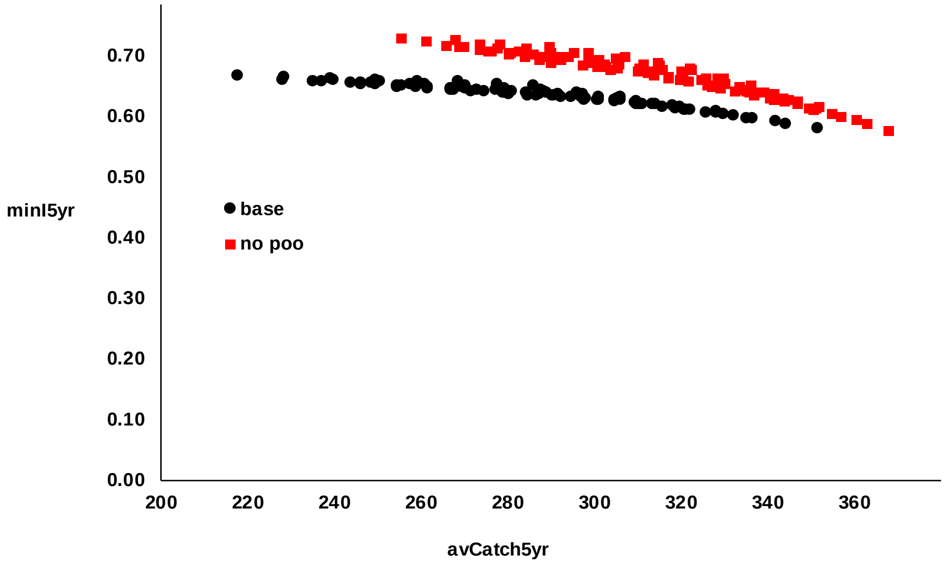


Figure 76: From the set of 96 rules, minimum CPUE over 5 years vs. average 5-year catch: base case black circles, noPoo trial red squares.

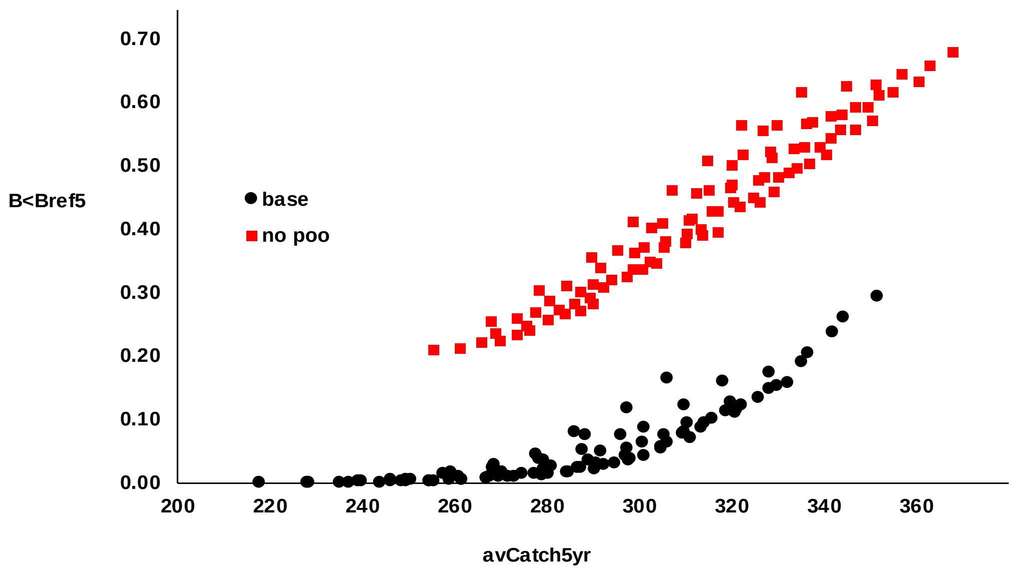
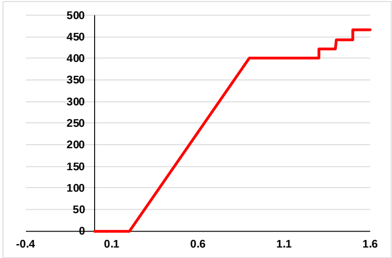


Figure 77: From the set of 96 rules, probability that 5th year biomass would be less than *Bref* vs. average 5-year catch: base case black circles, noPoo trial red squares.

rule	39	
intercept	0.2	
plateau left	0.9	
plateau right	1.3	
plateau height	400	
step width	0.1	abundance
step height	0.053	catch
2017 TACC	277	

20 years indicator	value
median *B/Bref*	0.96
median minCatch	234
median avCatch	344
median RecCatch	36
median minCPUE	0.61
median avCPUE	0.835
median AAVH	9.05
P(B<Bref)	0.58
nchanges	58.5%
left of plateau	64.7%
right of plateau	2.6%
P(AW CPUE I>0.8)	39.3%
P(AW CPUE I>0.914)	20.6%

5 years indicator	base value	nopoo value
median *B/Bref* 5-yr	1.03	0.94
median avCatch 5-yr	309	332
median Catch 5th-yr	397	400
P(TACC<200)	9.0%	20.4%
P(TACC<250)	58.2%	45.8%
5% minCPUE 5-yr	0.54	0.47
median minCPUE 5-yr	0.62	0.64
median avCPUE 5-yr	0.796	0.83
median CPUE 5th-yr	0.98	0.93
P(*B2021<Bref*)	7.9%	49.0%



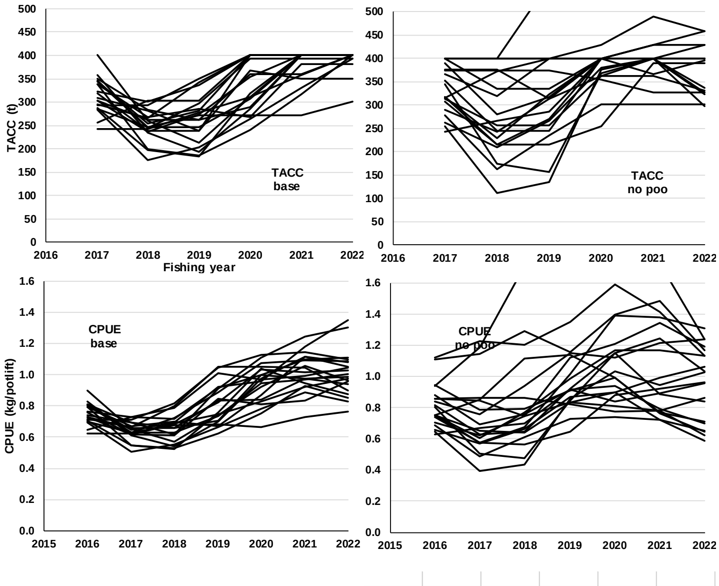


Figure 78: Example of the spreadsheet viewer given to stakeholders to explore rule results. Results are shown from both 5 and 20 year runs and from both the base case and noPoo models.

GLOSSARY

This glossary is intended to make the rock lobster stock assessment and MP development processes more accessible to non-technical readers. A knowledge of statistical terms is assumed and such terms are not explained here. Technical terms are defined with specific reference to rock lobster stock assessment and the multi-stock length-based model (MSLM) and may not be applicable in other contexts.

Underlining indicates a cross-reference to a separate entry.

abundance index: usually a time-series of estimates of abundance in numbers or weight (biomass).

AD Model Builder: a modelling package widely used in fisheries work; it uses auto-differentiation to calculate the derivatives of the function value with respect to model parameters and passes these to an efficient minimiser; the user has to write only the model and calculate the function value.

allowance: the Minister must make Allowances for catch from various sectors within the TAC; the TACC and other allowances must sum to the TAC.

AW: autumn-winter season, 1 April through 30 September; see SS.

***B0*:** the biomass that would be attained if there were no fishing and recruitment were constant at its average level; in the MSLM the initial biomass is *B0*.

Bayesian stock assessment: a method that allows prior independent information to be used formally in addition to the data; the equivalent of the least-squares or maximum likelihood estimate is called the MPD (mode of the joint posterior distribution); often uncertainty is estimated using Markov chain Monte Carlo simulations (McMC) which give the posterior distributions of estimated and derived parameters.

***Bcurrent*:** the MSLM estimate of vulnerable biomass in the last year with data.

biomass: the weight of fish in part of the stock.

biological reference points: a target for the fishery or a limit to be avoided, or that invokes management action; expressed quantitatively, usually in units of fishing intensity or stock size.

***Bmin*:** the minimum of estimated vulnerable biomass in the years for which MSLM estimates biomass.

***Bmsy*:** in the *MSY* paradigm, the biomass that allows the stock to generate its maximum productivity; this biomass is usually less than half the unfished biomass.

bounds: model parameters can be restricted so that parameter estimates cannot be less than a lower bound or higher than an upper bound; these are sometimes necessary to prevent mathematical impossibility (e.g. a proportion must be between 0 and 1 inclusive) or to ensure biologically realistic model results.

***Bproj*:** vulnerable biomass in the last projection year, determined by running the model dynamics forward with specified catches and resampled recruitment.

***Bvuln*:** see vulnerable biomass.

catch: the numbers or weight (yield) of fish removed from the stock by fishing in a season or a year; considered in components such as commercial and illegal catches, or together as total catch; does not include fish returned alive to the sea.

catchability: a proportionality constant that relates an abundance index such as CPUE or CR to biomass, or that relates the puerulus settlement index to numbers; has the symbol *q*.

catch sampling: see logbooks and observer catch sampling.

cohort: a group of lobsters that settled in the same year.

converged chain: refers to McMC results; the "chain" is the sequence of parameter estimates; convergence means that the average and the variability of the parameter estimates are not changing as the chain gets longer.

CPUE: catch per unit of effort; has the units kg of catch per potlift; assumed to be an abundance index such that CPUE = catchability times vulnerable biomass; can be estimated in several ways (see standardisation).

CPUEpow: a parameter that determines the shape of the relation between CPUE and biomass; when equal to 1, the relation is linear; when less than 1, CPUE decreases less quickly than biomass (known as hyperstability); when greater than 1, CPUE decreases faster than biomass (known as hyperdepletion).

CR: an historical CPUE abundance index in kilograms per day from 1963–73.

customary fishing: fishing under permit by Maori for purposes associated with a marae; there is more than one legal basis for this.

density-dependence: populations are thought to self-regulate: as population biomass increases, growth might slow down, mortality increase, recruitment decrease or maturity occur later; growth is density-dependent if it slows down as the biomass increases.

derived parameter: any quantity that depends on the model's estimated parameters; e.g. average recruitment *R0* is an estimated parameter but initial biomass is a derived parameter that is determined by model parameters for growth, natural mortality and recruitment.

diagnostic plots: plots of running or moving statistics based on the McMC chains to check for convergence.

epoch: a period when selectivity was constant; different epochs have different estimated selectivity; epoch boundaries are associated with changes that affect selectivity, e.g. changes in escape gaps or MLS.

escape gaps: openings in the pot that allow small lobsters an opportunity to escape.

equilibrium: in models, a stable state that is reached when catch, fishing patterns, recruitment and other biological processes are constant; does not occur in nature.

exploitation rate: a measure of fishing intensity; catch in a year or period divided by initial biomass; symbol *U*.

explanatory variable: information associated with catch and effort data (e.g., month, vessel, statistical area or fishing year) that might affect CPUE; the standardisation procedure can identify patterns associated with explanatory variables and can relate changes in CPUE to the various causes.

***F*:** instantaneous rate of fishing mortality.

fishing intensity: informal term with no specific definition; higher fishing intensity involves higher fishing mortality or higher exploitation rate, or (as in the snail trial) a higher ratio of *F* to *Fmsy*.

fishing mortality: (symbol *F*) the instantaneous rate of mortality caused by fishing; if there were no natural mortality or handling mortality, survival from fishing would be e^{-F}; with fishing and natural mortality, survival is $e^{-(F+M)}$.

fishing pattern: the combination of selectivity and the seasonal distribution of catch.

fishing year: for rock lobsters, the year from 1 April through 30 March; often referred to by the April to December portion, *i.e.* 2009–10 is called "2009".

fixed parameter: a parameter that could be estimated by the model but that is forced to remain at the specified initial value.

Fmsy: the instantaneous fishing mortality rate *F* that gives *MSY* under some simplistic constant conditions.

function value: given a set of parameters, how well the model fits the data and prior information; determined by the sum of negative log likelihood contributions from each data point and the sum of contributions from the priors; a smaller value reflects a better fit.

growth: lobsters grow when they moult; smaller lobsters do this more often than larger lobsters; the model assumes a continuous growth process described by a flexible growth sub-model that predicts mean growth increment for a time step based on sex and initial size and predicts the variability of growth around this mean.

growthCV **:** determines the expected variability in growth around the mean increment for a given initial size.

harvest control rule: defines what the agreed management response will be at each observed level of the stock; often a mathematical relation between an observed index such as CPUE and the allowable catch.

Hessian matrix: a matrix of numbers calculated by the model using formulae based on calculus, then used to estimate variances and covariances of estimated parameters; if the matrix is well-formed it is "positive definite" and the model run is said to be "pdH".

hyperdepletion: see *CPUEpow.*

hyperstability: see *CPUEpow.*

indicators: generic term for agreed formal outputs that act as the basis for the stock assessment or MPE comparisons.

initial value: when the model minimises, it has to start with a parameter set and the initial values comprise this set; the final estimates should be robust to the arbitrary selection of the initial values.

length frequency (LF) (also called size frequency)**:** The distribution of numbers-at-size (TW) from catch samples; based either on observer catch sampling or voluntary logbooks; the raw data are compiled with a complex weighting procedure.

length-based: a stock assessment using a model that keeps track of numbers-at-size over time.

likelihood contribution: for the model's fit to a data set, there is a calculated negative log likelihood for each data point; the contribution to the function value for a dataset is the sum of all these; this approach to fitting data is based on maximum likelihood theory.

logbooks: in some areas, fishers tag four or five pots and when they lift one of these they measure all the lobsters and determine sex and female maturity; these data are a source of LFs for stock assessment; see also observer catch sampling.

M**:** instantaneous rate of natural mortality.

management procedure: more properly "operational management procedure"; a set of rules that specify an input and how it will be determined, a harvest control rule and the conditions under which it will operate; a special form of decision rule because it has been extensively simulation tested.

MAR: median of the absolute values of residuals for a dataset. In a good estimation with multiple data sets, this should be close to 0.7; a common procedure is to weight datasets to try to obtain MAR close to 0.7.

maturity: the ability to reproduce; it is determined in catch sampling (for females only), by observing whether the abdominal pleopods have long setae.

maturation ogive: the relation between female size and the probability that an immature female will become mature in the next specified time step.

McMC: Markov chain – Monte Carlo simulations. In the minimisations, the model uses a mathematical procedure to find the set of parameters that give the best (smallest) function value. McMC simulations randomly explore the combinations of parameters in the region near the "best" set of parameters, using a sort of random walk, and from this the uncertainty in estimated and derived parameters can be measured. In one "simulation", the algorithm generates a new parameter set, calculates the function value and chooses whether to accept or reject the new point.

MFish: the New Zealand Ministry of Fisheries (now part of the Ministry for Primary Industries, MPI).

mid-season biomass: biomass after half the catch has been taken and half the natural mortality has acted in the time step.

minimising: the model fits to data are determined by estimated parameters and the goodness of fit can be measured in terms of the model's function value, where a lower value reflects a better fit; when minimising, the model adjusts parameter values to try to reduce the function value, using a mathematical approach based on calculus.

MLS: minimum legal size; currently 54 mm TW for males and 60 mm TW for females for most of New Zealand, but some QMAs have different MLS regimes.

mortality: processes that kill lobsters; see natural mortality *M* and fishing mortality *F*; handling mortality of 10% is assumed for lobsters returned to the sea by fishing.

MPD: when the model is minimising, the result is the set of parameter estimates that give the lowest function value; these "point estimates" comprise the mode of the joint posterior distribution or MPD; also sometimes called maximum posterior density.

MPEs: management procedure evaluations; for each proposed harvest control rule, a run is made from each sample of the joint posterior distribution, indicators are calculated and collated and a set of indicators for that rule with that operating model (which might be the base case or one of the robustness trials) is generated.

MPI: Ministry for Primary Industries (formerly Ministry of Fisheries or MFish).

MSY: under the MSY paradigm, the maximum average catch that can be taken sustainably from the stock under constant environmental conditions; usually calculated under simplistic assumptions.

MSY paradigm: a simplistic interpretation that predicts surplus production as a function of biomass: with zero surplus production at zero biomass, zero surplus production at carrying capacity (symbol *K*) and a maximum production at some intermediate biomass in between; this ignores the effects of age and size structure, lags in recruitment and variability in production that is unrelated to biomass.

MSLM: multi-stock length-based model; current version of the stock assessment model: length-based, Bayesian, with capacity for assessing multiple stocks simultaneously.

natural mortality: (symbol *M*) the instantaneous rate of mortality from natural causes. If there were no fishing mortality *F*, survival would be e^{-M}. With both fishing and natural mortality, survival is $e^{-(F+M)}$.

Newton-Raphson iteration: the model dynamics need a value for fishing mortality rate *F* in each time step; MSLM has information about catch, biomass and *M*, but there is no equation that can give *F* directly from these; Newton-Raphson iteration begins with an arbitrary value for *F* and calculates catch, then refines the value for *F* using a repeated mathematical approach based on calculus to obtain the *F* value that is correct.

normalised residual: the residual divided by the standard deviation of observation error that is assumed or estimated in the minimising procedure.

NRLMG: National Rock Lobster Management Group, a stakeholder group comprising representatives from MPI, commercial, customary and recreational sectors, that provides rock lobster management advice to the Minister for Primary Industries.

NSL catch: catch taken without regard to the MLS and prohibition on egg-bearing females; assumed by the model to be the illegal and customary catches; note that NSL catch includes fish above the MLS.

observer catch sampling: catch sampling in which an observer on a vessel measures all the fish in as many pots as possible on one trip.

offset year: the year from 1 October through 30 September, six months out of phase with the rock lobster fishing year.

operating model: a simulation model that represents the stock and that can be projected forward to test the results of using alternative harvest control rules.

parameters: in a simulation model, numbers that determine how the model works (they define mortality and growth rates, for instance) and that can be estimated during fitting to data or minimising.

pdH: see Hessian matrix.

period: sequential time steps (years or seasons or a mixture of both) in the stock assessment model.

population: in nature, a group of fish that shares common ecological and genetic features; in models, the numbers of fish contained in a stock unit within the model.

posterior distribution: the distribution of parameter estimates resulting from McMC simulation; is a Bayesian concept; the posterior distribution is a function of the prior probability distribution and the likelihood of the model given the data.

potlift: a unit of fishing effort; the commercial fishery uses traps or pots baited to attract lobsters and equipped with escape gaps; pots are sometimes lifted daily, often less frequently because of weather or markets; pots are often moved around during the fishing year.

pre-recruit: a fish that has not grown large enough (to or past the MLS) to become vulnerable to the fishery.

priors: short for prior probability distribution; these allow the modeller to estimate parameter values using Bayes's theorem and (if desired) to incorporate prior belief (based on data that are not being used by the model) about any likely parameter values.

productivity: stock productivity is a function of fish growth and recruitment, natural mortality and fishing mortality.

projections: given a set of parameters, assumed catches and recruitments, the stock assessment model or operating model dynamics can be run into the future and any indicators calculated that are wished; this is called projecting the model; projections are sometimes thought of as predictions but, more properly, projections determine the range of values in which parameters about the future stock may lie.

puerulus: settling lobster larvae; this stage is transitional between the planktonic phyllosoma larva and the benthic juvenile lobster; in reality the puerulus settlement index includes juveniles of the first instars. The puerulus settlement index for a stock is calculated from monthly observations of settlement on sets of collectors within the QMA, using a standardisation method.

QMA: A management unit in the Quota Management System, which in most cases is assumed to represent the extent of the biological stock; the unit of management in the quota management system; QMAs contain smaller statistical areas.

QQ plots: in an estimation where the data fit the model's assumptions about them, the normalised residuals would follow a normal distribution with mean zero and standard deviation of one; a QQ plot allows a comparison of the actual and theoretical distributions of normalised residuals by plotting the observed quantiles in a way that gives a straight line if they follow the theoretical expectations.

***R0* :** the base recruitment value in numbers of fish.

randomisation: in the puerulus randomisation trials, a new index is generated by randomly rearranging the yearly values data in a new order.

***Rdev*s**: estimated model parameters that determine whether recruitment in a given year is above or below average; they modify the base recruitment parameter *R0.*

recreational: refers to catch taken legally under the recreational regulations; includes s. 111 catch taken by commercial fishers; includes Maori fishing that is not governed by a customary permit.

recruited biomass: the weight of all fish above the MLS, including egg-bearing females, whether or not they can be caught by the fishery.

recruitment: can mean recruitment to the population (as in puerulus settlement), recruitment to the model at a specified size, or recruitment to the stock (by growing above MLS); when used with no qualification in documentation here it means "recruitment to the model".

resampling: in projections, recruitment for a projection year is equal to estimated recruitment in a randomly chosen year that lies within the range of years being resampled.

residual: the observed data value minus the model's predicted value, for instance for CPUE in a given time step it would be the difference between the observed CPUE in that year and the model's predicted value.

RLFAWG (Rock Lobster Fishery Assessment Working Group): a group convened by MPI to discuss stock assessment alternatives and to act as peer-reviewers; comprises MPI, stakeholders and contracted peer-reviewers.

robustness trial: in making MPEs, the sensitivity of results to critical assumptions in the operating model is tested by making runs in robustness trials using a different operating model.

sdnr: the standard deviation of normalised residuals; in a good estimation with multiple data sets, this should be close to 1; a common procedure is to weight datasets to try to obtain sdnrs close to 1.

season: refers to the AW or SS seasons; for early years the MSLM model can be run with an annual time step.

selectivity: lobster pots do not catch very small lobsters; selectivity describes the relative chance of a lobster being caught, given its sex and size, hence "selectivity ogive".

sensitivity trials: a base case stock assessment model is the result of inevitable choices made by the modeller; sensitivity trials examine whether results are seriously dependent on ("sensitive to") these choices.

sex: in the model can be male, immature female or mature female; this set of three possibilities is referred to as "sex" (see maturity).

snail trail: a plot of historical fishing intensity against historical biomass.

SL catch: the catch that is taken respecting the MLS and prohibition on egg-bearing females; assumed by the model to be the commercial and recreational catches.

spawning stock biomass: *SSB***,** the weight of all mature females in the AW, without regard to MLS, selectivity or vulnerability; three specific forms are *SSBcurrent*, the estimated *SSB* in the last year with data; *SSBO*, the *SSB* in the first model year; *SSBmsy*, the *SSB* at equilibrium *Bmsy*.

SS: spring-summer season, 1 October– through 30 March; see AW.

standardisation: a statistical procedure that extracts patterns in catch and effort data associated with explanatory variables; the pattern in the time variable (e.g. period or year) is interpreted as an abundance index.

statistical area: sub-area of a QMA that is identified in catch and effort data; the most detailed area information currently available from catch and effort data for rock lobster.

stock: by definition, a group of fish inhabiting a quota management area QMA; may often not coincide with biological population definitions.

stock assessment: an evaluation of the past, present and future status of the stock; a computer modelling exercise using a model such as MSLM that is minimised by fitting to observed fishery data; the results include estimated biomass and other trajectories; a comparison of the current stock size and fishing intensity with biological reference points ("stock status"); this often involves short-term projections with various catch levels.

stock-recruit relation: a relation between biomass and recruitment, with low recruitment at lower biomass; an optional component of MSLM.

surplus production: surplus production is growth plus recruitment minus mortality; if production would cause the stock biomass to increase it is "surplus" and can be taken as catch without decreasing the stock size; a concept central to the MSY paradigm.

sustainable yield: a catch that can be removed from a stock indefinitely without reducing the stock biomass; usually estimated with simplistic assumptions.

TAC/TACC: Total Allowable Catch and Total Allowable Commercial Catch limits set by the Minister for Primary Industries for a stock.

trace: refers to a plot of a parameter's values in the McMC simulation, plotted in the sequence they were obtained, taking every *n*th value of the simulation chain.

TW: tail width measured between the second abdominal spines.

vulnerability: outside the phrase vulnerable biomass (for which see below), means sex- and season-specific vulnerability; the relative chance of a lobster being caught, given its sex and the season; this allows males and females in the model to have different availabilities to fishing and for these to change with season.

vulnerable biomass: the biomass that is available to be caught legally: above the MLS, not egg-bearing if female, modified by selectivity and vulnerability; in the model this is called *Bvuln*; for comparing biomass with *Bref* and for reporting historical trajectories, the model calculates *Bvulref* using the last year's selectivity and MLS for consistency of comparison.

weights for datasets: weights are used to balance the importance of the different datasets to minimisation; higher weights decrease the sigma term in the likelihood and increase the contribution to the function value from that dataset; usually adjusted iteratively to achieve sdnr or MAR targets.

Z: total instantaneous mortality rate; $Z = F + M$.