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Tini a Tangaroa

The 2020 stock assessment of red rock lobsters (*Jasus edwardsii*) in CRA 4

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TABLE OF CONTENTS

EXECUTIVE SUMMARY.....	1
1. INTRODUCTION	2
2. STOCK ASSESSMENT.....	3
2.1 Data.....	4
2.2 Model	5
2.3 Parameters and priors.....	5
2.4 Assessment indicators	6
2.5 Maximum <i>a posteriori</i> inference.....	6
2.5.1 MAP base case	6
2.5.2 MAP sensitivity trials.....	9
2.6 Bayesian inference using Markov chain Monte Carlo (MCMC)	10
2.6.1 MCMC base case	10
2.6.2 MCMC sensitivity trials.....	12
2.7 Projections.....	12
2.8 Reference levels.....	13
3. DISCUSSION.....	13
3.1 Future research.....	14
4. ACKNOWLEDGEMENTS.....	15
5. REFERENCES.....	15
6. TABLES	17
7. FIGURES	28

EXECUTIVE SUMMARY

Rudd, M.B.¹; Pons, M.²; Roberts, J.³; Webber, D.N.⁴; Starr, P.J.⁵ (2021). The 2020 stock assessment of red rock lobsters (*Jasus edwardsii*) in CRA 4.

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This document describes the 2020 stock assessment of red rock lobsters (*Jasus edwardsii*) in CRA 4 (Wellington/Hawke Bay). The stock assessment used the lobster stock dynamics (LSD) model. Data inputs and all technical decisions were discussed and agreed upon by the Rock Lobster Working Group, which oversaw this work.

The model was fitted to length frequency data, sex ratio data, tag-recapture data, and standardised catch-per-unit-effort (CPUE) indices. This document describes the procedure used to find an acceptable base case model and shows the model fits. Several sensitivity trials were done to test assumptions in the base case model.

Model inference for this assessment was based on maximum *a posteriori* (MAP) fits and Markov chain Monte Carlo (MCMC) simulations. This document describes the diagnostics for each and presents the results of MAP and MCMC sensitivity trials.

The stock assessment estimated increasing fishing mortality from 1945 to the late 1960s, which remained high during the 1980s, resulting in a decline in red rock lobster biomass in CRA 4. Since the 1990s, CRA 4 has experienced periods of relatively low and high fishing mortality coupled with at least two major recruitment events, leading to oscillations in the estimated population biomass. The stock assessment model estimated that the spawning stock biomass (*SSB*) has generally remained above the soft limit of 20% *SSB*₀ (i.e., 20% of the unfished *SSB*). Although CPUE has been increasing in the past two to three years of the time series, the stock assessment estimated this stock is currently at a low point in the cycle between lower and higher population biomass. Projections suggest that continued harvest at constant current catch levels would likely lead to a decline in the vulnerable biomass and *SSB*, but with no probability of dropping below the soft limit.

A stock-specific vulnerable biomass reference level, based on simulated projections across constant catches and harvest rates and constrained by a probability of no more than 5% of falling below the soft limit, has been developed and accepted for CRA 4. The current median CRA 4 vulnerable biomass was estimated to be slightly above this reference level and was projected to decrease over five years to below this level under present catches and recent (10 year) average recruitment.

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1. INTRODUCTION

This work addresses Objective 4 of the Fisheries New Zealand contract CRA2019-01. This one-year contract, which began in April 2020, was awarded to the New Zealand Rock Lobster Industry Council (NZ RLIC) Ltd, who sub-contracted Objective 4 to the rock lobster stock assessment team.

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

The National Rock Lobster Management Group (NRLMG) decided that CRA 4 and CRA 5 should be assessed in 2020. Data were compiled for both stocks by a team comprising Paul Starr (Starrfish), D'Arcy Webber (Quantifish Ltd), Merrill Rudd (Scaleability), Jim Roberts (independent consultant), and Maite Pons (independent consultant). All team members contributed to the assessments of CRA 4 and CRA 5 concurrently. Decisions on data and modelling choices were discussed and approved by the Rock Lobster Working Group (RLWG, previously named the Rock Lobster Fishery Assessment Working Group).

This document presents an update to the 2016 stock assessment for CRA 4 (Breen et al. 2017), including changes to the catch-per-unit-effort (CPUE) standardisation procedure and improved interpretation of the underlying growth model. All the tables referred to in this document can be found in Section 6 and all the figures except for Figure 1 are in Section 7. Data used in this stock assessment are documented by Starr et al. (2021). CRA 4 was assessed assuming a single homogeneous stock across the five statistical areas (912, 913, 914, 915, and 934), using the lobster stock dynamics (LSD) model (Webber et al. 2018a).

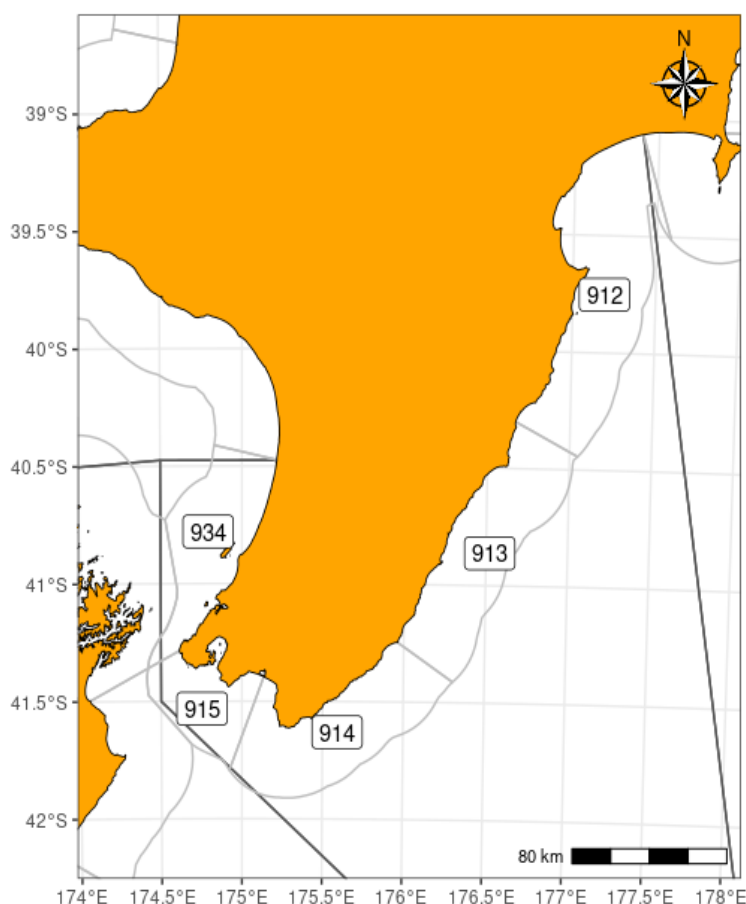


Figure 1: The CRA 4 stock area on the southern coast of the North Island, and its statistical areas. The QMA boundaries are defined by black lines and the statistical area boundaries by grey lines.

The CRA 4 fishery extends from the Wairoa River in northern Hawke's Bay, southwards through Hawke Bay, the Wairarapa and the Wellington coasts, then passing north to the Manawatu River on the Kapiti coast (Figure 1). The CRA 4 commercial fishery is a trap or pot fishery, fished by small boats on day trips and in relatively shallow waters. Most vessels in the fleet operate from coastal bases in isolated rural areas on the Hawke's Bay and Wairarapa coastlines. There is also a fishery along the south coast of the North Island that is largely based in Wellington. 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. Most of the recreational catch is taken in the summer months, which is consistent with all New Zealand rock lobster recreational fisheries. The region also sustains a recreational fishing and dive charter industry during summer. Lobsters are very important to Māori in this area, and the customary allowance allows lobsters to be taken under permit.

The primary management tool is the total allowable catch (TAC) which consists of allowances made to each non-commercial component of the fishery (recreational, customary, and unreported illegal catch) as well as a total allowable commercial catch (TACC), all set by the Minister for Oceans and Fisheries. Each component of the fishery is meant to stay within its allowance. The TACC is set through the operation of the provisions of the Quota Management System (QMS) and the management of the recreational fishery is accomplished by setting a daily bag limit of a maximum of six rock lobster per day. Other management tools include a minimum legal size (MLS) of 54 mm tail width (TW) for males and 60 mm TW for females for both the commercial and recreational fisheries and a general prohibition of the take of berried females and soft-shelled individuals.

The CRA 4 TACC has been managed using a management procedure (MP) since 2007, with the first two years of operation based on the voluntary shelving of Annual Catch Entitlements (ACE) by quota holders. Beginning in 2009, the then Ministry of Fisheries implemented a formal MP based on offset-year (October–September) CPUE, which was operated successfully from 2009 to 2018, resulting in eight TACC changes over the ten-year period from 2009 to 2018 (Starr et al. 2021). The CRA 4 MP was calculated for 2019 and 2020, but the MP-proposed increases were opposed by some stakeholders in each of these years, resulting in the rejection of the proposed increases by the Minister of Fisheries.

The 2019–20 fishing year marked the transition of the collection of rock lobster catch and effort data from a paper-based Catch Effort Landing Return (CELR) system to an electronic reporting (ER) system dependent on a user interface operated from tablets or smart phones. In August 2020, a preliminary analysis of 2019–20 data revealed that data collected electronically are not comparable with data collected on paper forms (see Starr 2021, appendix B, for details). Consequently, the RLWG agreed to temporarily suspend updating CPUE indices beginning with the 2019–20 spring/summer season. MPs based on offset-year CPUE were also temporarily discontinued.

The CRA 4 TAC for 2019–20 was 513.8 tonnes. Allowances set by the Minister for Oceans and Fisheries were 35 tonnes for customary catch, 85 tonnes for recreational catch, 75 tonnes for illegal unreported removals, and a 318.8 tonne TACC. The CRA 4 commercial fishery is open all year.

This stock assessment was completed in a workshop during September and October 2020, based in Wellington but also held remotely due to the COVID-19 pandemic. The stock assessment was presented to and approved by the Fisheries New Zealand mid-year Plenary during November 2020 (Fisheries New Zealand 2020).

2. STOCK ASSESSMENT

The 2020 CRA 4 stock assessment used the LSD model (Webber et al. 2018a). This model is coded in Stan (Stan Development Team 2016, 2017). The transition from the multi-stock length-based model (MSLM, Haist et al. 2009) to the new LSD model is considered complete, the latter having been tested

alongside the MSLM model for the CRA 4 stock assessment in 2016. The LSD model was used as the main assessment model for CRA 2 in 2017 after ascertaining that LSD and MLSM in that year provided equivalent results and was subsequently used as the main assessment model for CRA 6 (2018), CRA 1 (2019), and CRA 3 (2019).

Maximum *a posteriori* (MAP) estimation and Markov chain Monte Carlo (MCMC) were used to make inference about the CRA 4 stock. A series of MAP sensitivity trials were also explored. Three models, including the base case and two sensitivity trials, were extended to a full Bayesian implementation using MCMC.

The suspension of CPUE indices as a result of the shift from paper to electronic monitoring, beginning with the 2019–20 spring/summer (SS) season, prevented the development of a new MP based on the outcome of this stock assessment. Instead, projections explored predicted vulnerable biomass in relation to reference levels based on methods described by Rudd et al. (2021a). The reference levels presented in this document were reviewed and accepted by the RLWG at a meeting in February 2021.

2.1 Data

The data used in this stock assessment are documented by Starr et al. (2021) and the temporal extent of these data is illustrated in Figure 2. Following the procedure adopted by the four most recent stock assessments (CRA 2, Webber et al 2018b; CRA 6, Rudd et al. 2019; CRA 1, Rudd et al. 2021b; and CRA 3, Webber et al. 2020), a vessel explanatory variable was included in the CPUE standardisation model (see Starr et al. 2021) and CPUE was split into three series:

- The catch rate (CR) series is an annual arithmetic daily catch rate from 1963 to 1973. Catchability (q) was assumed constant over this period.
- The Fisheries Statistics Unit (FSU) series is a seasonal standardised index from SS 1979 to autumn-winter (AW) 1989. The standardisation model includes year, month, statistical area, and vessel explanatory variables. The FSU CPUE standardisation included all vessels. Catchability (q) was assumed to be constant over this period.
- The CELR series is a seasonal standardised series from SS 1989 to AW 2019. CPUE for SS 2019 would typically be included, but the RLFAWG agreed to temporarily suspend updating CPUE indices beginning with SS 2019 because data collected electronically are not comparable with data collected on paper forms (Starr 2021, appendix B). The standardisation model included year, month, statistical area, and vessel explanatory variables, filtered for vessels that had fished CRA 4 for at least five years. The catchability coefficient (q) was assumed to improve over time at a constant rate, with the rate of change estimated in the model by the *qdrift* parameter.

This assessment used tag-recapture data from tags released in CRA 4, including statistical areas 912, 913, 914, 915, and 934, identified either by the statistical area of release or project ID. The RLWG did not identify a residual pattern in growth estimates with increasing recapture events, so the stock assessment used all CRA 4 tag-recapture data, including multiple recaptures of the same tag, rather than just the first recapture observation.

The 2016 CRA 4 stock assessment ran an initial exploration of a multi-stock model for CRA 4, primarily as a ‘proof of concept’ for the new LSD model. This exploration confirmed that there were sub-area differences in population characteristics. However, Starr et al. (2021) examined the available CPUE and biological data for differences among the CRA 4 statistical areas in preparation for the 2020 stock assessment and found that CPUE trends were similar across the four primary areas with good agreement among the length frequency (LF) distributions along the east coast of the Wairarapa. The length frequency distributions on the south coast appeared to be larger than the east coast, but the RLWG concluded that assessing this region separately would not result in substantially different management

advice because the south coast region represented only about 15% of the total catch (see appendix C of Starr et al. 2021).

From 1945 to 1949, there was no MLS for red rock lobster in New Zealand. MLS restrictions were initially implemented for New Zealand red rock lobster as measurements of tail length in inches. This measurement standard was subject to some abuse because tails could be stretched but was accepted because a significant fraction of the catch came from Fiordland where it was permissible to tail lobsters at sea. MLS was changed to a width measurement (in mm) across the spines of the second abdominal segment (called tail width or TW) in 1988 for all New Zealand red rock lobsters, requiring the conversion of the pre-1988 regulations into equivalent TW measurements for use in the stock assessment model (Breen et al. 1988). The TW values used for the MLS in the model are given in Table 1.

Although the 2016 CRA 4 stock assessment used the puerulus settlement series in the base case assessment (Breen et al. 2017), the puerulus series was only used in a sensitivity run for this assessment. This was done because the addition of the puerulus data, using the estimate of three years (externally determined using juvenile growth data; Roberts & Webber in prep.) for the lag between settlement and recruitment to the stock assessment model, resulted in non-credible growth parameter estimates and MCMC posterior bimodality. These problems were overcome by dropping the size at which *Galpha* was estimated from 50 mm to 30 mm and constraining the upper bound for *Gshape* to 7.5 (Table 2). However, the RLWG agreed that model behaviour when this data series was included was less satisfactory than for the selected base case and, given the small differences in fits to the data and model parameter estimates, the base case run should not include the puerulus settlement index series.

2.2 Model

This stock assessment treated CRA 4 as a single homogeneous area. The first model year was set to 1945, because this was the first year of available commercial fishery catch data. The last model year was 2019–20 (designated by the first year of the pair, i.e., 2019), because this was the last complete fishing year with data. Fishing years extend from 1 April to 31 March and the first fishing year in the model is 1979–80. The years from 1945 to 1978 are January–December calendar years and January–March 1979 catches were added to 1978 to facilitate the transition from calendar year to fishing year. The model delineates two six-month seasons within a model year: AW (April to September) and SS (October to March). Seasonal data begin with the 1979–80 fishing year. The model tracks the numbers of immature females, mature females, and males in 31 2-mm TW bins (i.e., $\{[30, 32), [32, 34), \dots, [90, \infty)\}$).

2.3 Parameters and priors

Estimated model parameters are listed in Table 2. Priors and parameter bounds are provided in Table 3. Fixed values for some parameters and model settings are provided in Table 4.

Wide uniform priors were specified for q for each CPUE series and recruitment deviates (Table 3). Beta distributions with both shape parameters set to 1 were used for all priors bounded between 0 and 1, including *Gdiff* and all vulnerability parameters (Table 2 and Table 3). An informative lognormal prior was specified for natural mortality (M) and an informative normal prior based on an unpublished meta-analysis was specified for the growth parameters *Gshape* and *GCV* (Table 2 and Table 3). Uninformative normal prior distributions were specified for all other model parameters (Table 3). These uninformative normal priors are basically flat across sensible ranges for each of these parameters and do not influence the outcome of the stock assessment, although they do help the model software (Stan) with MCMC mixing.

The vulnerability of immature females and mature females during the SS season was assumed to be the same. The four vulnerability parameters (i.e., one for each sex category and season) were estimated relative to the vulnerability of immature females during the AW season (which was fixed to 1). The choice of fixing the AW immature female vulnerability parameter to 1 was decided in the 2016

assessment of CRA 4 to aid in model stability and prevent any of the vulnerability parameters from being estimated close to the bound of 1.0 (Breen et al. 2017, Table 5).

Handling mortality was assumed to be 10% for all lobsters returned to sea before 1990 and 5% from 1990 to 2019. This reduction in handling mortality was agreed by the RLWG to coincide with the start of the live export market and the introduction of rock lobsters into the QMS. Handling mortality was applied to undersized lobsters of each sex taken in either season by the size-limited (SL) fishery as well as to mature females taken in the AW SL fishery. It was assumed that there were no discards in the non-size-limited (NSL) fishery. The value H_{2019} is the model estimate of the amount of handling mortality (in tonnes) in the final fishing year (2019).

2.4 Assessment indicators

No additional indicators were considered beyond those included in the 2019 CRA 1 and CRA 3 stock assessments (Webber et al. 2020, Rudd et al. 2021b) for this stock assessment. The main indicators (Table 6) were related to the relative estimates of vulnerable biomass, adjusted vulnerable biomass⁶, spawning stock biomass (SSB), and total biomass, including the probabilities of each of the biomass indicators falling below current levels after projecting the current catch forward for five years.

Vulnerable biomass was defined as 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. Adjusted vulnerable biomass⁶ was calculated by applying the MLS and selectivity from the final model year to all previous years, including those years where alternative regulations were applicable.

The probability of the SSB being below the soft and hard limits was also calculated. SSB is defined as the biomass of all mature females at the start of AW. SSB_0 was the SSB at unfished equilibrium with R_0 . The soft and hard limits are set to the default values from the Harvest Strategy Standard (Ministry of Fisheries 2011) of 20% SSB_0 and 10% SSB_0 , respectively.

The derived values used as assessment indicators are summarised in Table 6. Probabilities were calculated from MCMC posterior distribution samples.

2.5 Maximum *a posteriori* inference

Maximum *a posteriori* (MAP) inference was used for exploring potential model options without committing the computing time required for Bayesian inference. A base case was developed, and sensitivities were used to test the base case assumptions described in Section 2.5.2.

2.5.1 MAP base case

2.5.1.1 Matching previous LSD model to current LSD model

The previous 2016 CRA 4 stock assessment ran the LSD model in tandem with the MLSM program used as the base model. However, there have been several updates to the LSD code from 2016 to present, so the first step to the 2020 assessment involved matching the results from the LSD model to the 2016 LSD results of the base case assessment (Figure 3). The matching process began by including data up to the end of the 2015 fishing year (Model 1_base2016, see Table 7). Following the initial emulation of the previous base case, data updates implemented for the 2020 assessment and changes to the model assumptions were iteratively added until the model held the desired attributes of a new base case but was still based on data that were current up to the end of 2015. This iterative procedure was first used in the 2019 CRA 1 and CRA 3 assessments and has been recommended to be used as the first phase of applying the LSD model for all updated stock assessments (Webber et al. 2020, Rudd et al. 2021b).

⁶ In past stock assessments, this quantity was called 'vulnerable reference biomass' rather than 'adjusted vulnerable biomass'. This change was made to distinguish clearly between rock lobster reference points and this biomass definition.

For CRA 4, this procedure used ten steps, sequentially described in Table 7. The data were re-weighted in a standardised process for each run, aiming for a standard deviation of the normalised residual (SDNR) of 1.0 for all CPUE series and the sex ratio (Breen et al. 2003, Francis 2011). Note that the tag data are self-weighting and the LF weight is derived using the Francis approach (Francis 2011). Table 7 presents the sequential models, where each subsequent model accumulated the modifications from the previous models. The outcomes are shown for each step in Figure 4 to 8. All nine cumulative iterative steps have been superimposed in Figure 9, where step 4.5 in Figure 6 represents a separate check as requested by the RLWG and was not part of the iterative steps.

2.5.1.2 Searching for a 2020 base case

At the end of the procedure described in Table 7, the final model included all data to the end of the 2019 fishing year. In addition to the Table 7 changes from the base model in 2016, model fits and outputs from several additional preliminary models were compared. These models included:

1. CPUE with vessel effect, no *qdrift* parameter, two selectivity epochs, no puerulus index, logbook LF weight truncation;
2. Estimation of a *qdrift* parameter for the CELR series;
3. CPUE series without vessel effect;
4. CPUE series without vessel effects and with the estimation of a *qdrift* parameter for the CELR series;
5. No truncation of LF weights;
6. No logbook LF data;
7. Density-dependent growth;
8. Estimating right-hand limb selectivity;
9. Additional selectivity epoch starting in 2005;
10. Fit to puerulus index with 3-year lag;
11. Fit to puerulus index with 3-year lag and additional selectivity epoch starting in 2005;
12. Fit to puerulus index with 2-year lag;
13. Fit to puerulus index with no lag.

The RLWG reviewed these model explorations and made specific recommendations that the base case be formulated as follows:

- Model years: 1945–2019 (assuming an unfished population in 1945, ending with the 2019–20 fishing year);
- Assume a single-stock model, combining all information from statistical areas 912, 913, 914, 915, and 934, with a shared natural mortality rate and maturation ogive;
- Two seasons: AW and SS during each fishing year starting in 1979;
- Three sex categories: immature females, mature females, males;
- Tail width bins: 31 2-mm wide bins from 30 mm to 90 mm tail width (last bin is a “plus group” or accumulator bin);
- Size at recruitment: mean 33.35 mm with standard deviation 4 mm based on recent studies of juvenile growth (Roberts & Webber in prep.);
- Likelihoods:
 - o Lognormal for three CPUE series (CR, FSU, and CELR)
 - o Robust normal for tags
 - o Multinomial for LFs, fitted to proportions for males, immature females, and mature females, with each sex category normalised separately
 - o Multinomial for sex ratios;
- Data weighting: determined iteratively. No re-weighting of tag data because they are self-weighting through the estimation of an observation error parameter;
- Three CPUE series, each with a separate *q* parameter;
 - o CR: 1963–1973

- o FSU: 1979–1989 AW
- o CELR: 1989 SS–2019 AW
- Standardise the FSU and CELR series by including a vessel explanatory variable. The FSU series used all data and the CELR series was based only on vessels with at least five years in the fishery
- *qdrift* parameter: estimated annual proportional increase of the CPUE *q* for CELR series;
- Selectivity: sex-specific double-normal selectivity, with two epochs split in 1993. The right-hand limb selectivity was fixed at 200 to prevent a descending limb;
- Growth: sex-specific, Schnute-Francis model;
- Four vulnerability parameters: one per sex per season, with immature and mature females during the SS sharing a vulnerability parameter;
- Fishing mortality dynamics: instantaneous using the Newton-Raphson algorithm to iteratively solve the Baranov catch equation (three Newton-Raphson iterations);
- Recruitment deviations (*Rdevs*) estimated: 1945–2017 (final two model years are set to the 2017 estimate, given no real information in data for these recruitments and lack of puerulus index included in the base model);
- Handling mortality: two periods 1945–1989 fixed at 0.1 and 1990–2019 fixed at 0.05;
- Stock-recruitment relationship: off;
- Density-dependent growth: off;
- Catch from 1945 to 2019, with illegal catch from 1945–1989 at 10% of the commercial catch in those years and from 1990 to present set at 5% of the commercial catch, based on the pattern of CPUE;
- Does not fit to the puerulus index;
- Truncate logbook length frequency weights at 10.0 starting in 2010.

All tags and recaptures were included in the models, regardless of time at liberty, to maximise the amount of growth information from the tagging data in this stock assessment. All re-releases were included because preliminary visual analysis of the standardised residuals did not indicate biased estimates of growth after the first recapture event.

To account for technological shifts over time, the vessel explanatory variable on the CPUE series and estimation of the *qdrift* parameter were explored. The *qdrift* parameter was estimated to be very low (*qdrift* = 0.0017) when the model included a vessel effect in the CPUE series. Without the vessel effect on the CPUE series, *qdrift* was estimated to be much larger (*qdrift* = 0.0115, or about 1.2% increase in *q* annually). The RLWG decided that the CPUE vessel effect and *qdrift* parameter were representing two independent processes and decided to include both the CPUE vessel effect and the estimation of the *qdrift* parameter in the base model, even though the MAP estimates of *qdrift* were close to zero.

Based on the LF data weighting methods described by Starr et al. (2021), the post-2009 logbook weights were very high compared with the weights for observer length samples. These very high weights were a consequence of the number of sampling days included in the *ad-hoc* calculation of LF weights. Although the logbook programme samples about half the potlifts compared with the observer samples, the number of days involved was more than an order of magnitude greater than for the observer programme due to the design of the logbook programme which samples fewer pots but involves more fishers. This disparity had not been previously noted for other stock assessments because typically either the logbook or observer programme predominated. This disparity will be resolved once a more objective weighting procedure is developed. In the meantime, logbook weights starting in 2010 were truncated to sum to a maximum of 10 to keep the logbook and observer weights on a similar scale. Removing the logbook programme data altogether as a MAP sensitivity test was also explored. This led to better fits to the sex ratio data in the SS and an overall decrease in *SSB* and adjusted vulnerable biomass across the time series, but no change in relative *SSB* or relative adjusted vulnerable biomass.

A separate study using juvenile growth data estimated a 2.5–3-year lag between puerulus settlement and recruitment to the stock assessment model (Roberts & Webber in prep.). However, initial model runs

with three years lag resulted in non-credible growth parameter estimates. These problems were overcome by dropping the size at which *Galpa* was estimated from 50 mm to 30 mm, informed by the study of juvenile growth, which estimated the size of three-year old juvenile lobsters to be just over 30 mm (Roberts & Webber in prep.). The prior and bounds on *Galpa* were adjusted to match the externally estimated growth rates at 30 mm. A two-year lag was also explored as a MAP sensitivity test because this was the lag time assumed by the previous stock assessment (Breen et al. 2017) and was supported in the puerulus randomisation trials using the current base model. However, all lag options from 0 to 4 years were found to be significant in these puerulus randomisation trials. Consequently, the randomisation trials were not helpful for informing the number of years to set the lag between the puerulus index and recruitment to the model (Figure 10).

Due to poor model fits to the LF data in initial model runs, alternative assumptions about time-varying selectivity were explored. Two models were trialled, one with different *SelM* parameters every year from the first year with LF data, and one with a different *SelM* and *SelLH* parameter every year from the first year with LF data. The likelihoods were examined to determine whether a better model fit could be achieved with an additional selectivity epoch. Adding another selectivity epoch in 2005 improved the overall likelihood and fit to the LFs and sex ratios but made the fit to all three CPUE series and tag data slightly worse. After this exploration, the RLWG decided to discard the additional 2005 selectivity epoch, thus retaining the original two selectivity epochs split in 1993. Poor model fits were attributed to the CELR CPUE series possibly being in conflict with the logbook data⁷, which made it difficult to correctly fit the CPUE indices between seasons.

All other preliminary model runs made little difference to the estimated population trajectories, including estimating the right-limb of the selectivity curve and density-dependent growth.

Diagnostic plots for the base case are presented in Figure 11 to Figure 29, consisting of model predictions relative to observed data, or the standardised residuals of the model fits to the data. Estimated selectivity and maturation ogives are shown in Figure 30 and Figure 31. Annual plots of key estimated quantities for the base case are shown in Figure 32 (recruitment), Figure 33 (fishing mortality), Figure 34 (total biomass by season), and Figure 35 (vulnerable biomass by season). Parameter estimates, likelihoods, and indicators for the base case and sensitivity tests (Table 8) are given in the following tables (Table 9 [likelihoods], Table 10 [parameters], Table 11 [reference points]).

2.5.2 MAP sensitivity trials

The RLWG decided on eight sensitivity trials as single variants relative to the base case (Table 8). These included sensitivities relating to the puerulus index, an alternative prior on *M*, a higher illegal catch trajectory, and removal or down-weighting of different datasets. The results of the sensitivity tests did not have a large impact on the stock trajectories in terms of recruitment, *SSB*, or adjusted vulnerable biomass, with the exception of model runs that drastically down-weighted key datasets such as CPUE or LF data. This is likely due to the high contrast in catch and CPUE over time. A comparison of the vulnerable biomass estimates for the base model and eight sensitivity runs is shown in Figure 36 (upper panel) and as relative *SSB* (lower panel, Figure 36). Figure 37 compares the recruitment trends for all eight sensitivity runs with the base case recruitment trend. Figure 38 compares the male and female selectivity curves by epoch for all eight sensitivity runs with the base case selectivity curve. Individual or smaller groups of sensitivities are compared with the base model from Figure 39 to Figure 50.

A summary of sensitivity tests is provided below.

- *uniformM*: Uniform prior on *M* to explore the impact of the informative prior on *M* used in the base model.
 - The uniform prior on *M* did not have an impact on the MAP estimates but was considered with MCMC inference.
- *lag3*: Fit to puerulus index with a lag of three years.

⁷ The fit to the CELR CPUE series improved in the *noLB* sensitivity model (likelihood increased from -92 (*base*) to -88 (*noLB*); Table 9).

- Negligible changes in *SSB*, adjusted vulnerable biomass, or recruitment estimates from the base model except in the final years of the time series where recruitment was estimated to be slightly higher than the base model.
- *lag2*: Fit to puerulus index with a lag of two years.
 - Negligible changes in *SSB*, adjusted vulnerable biomass, or recruitment estimates from the base model except in the final years of the time series where recruitment was estimated to be slightly higher than the base model.
- *illegalX2*: Double the illegal catch across the time series.
 - Very small increase in spawning biomass across the time series, with a very small decrease (or no change) in adjusted vulnerable biomass.
- *noLB*: Remove logbook LF data.
 - Decrease in *SSB* and adjusted vulnerable biomass across the time series but no change in relative *SSB* or relative adjusted vulnerable biomass.
- *downCPUE*: Down-weighting CPUE by setting the weight to 10% of the base model.
 - Negligible changes to estimates of *SSB*, recruitment, and adjusted vulnerable biomass in the latter years of the time series, but significant deviations to estimates of initial conditions and in the early years of the time series.
- *downSexRatio*: Down-weighting sex ratio by setting the weight to 10% of the base model.
 - Negligible changes to estimates of *SSB*, recruitment, and adjusted vulnerable biomass from the base model.
- *downLF*: Down-weighting LF data by setting the Francis weight to 10% of the base model.
 - Selectivity for females in the early epoch shifted right, resulting in some deviations to the adjusted vulnerable biomass throughout the time series. There was also lower estimated *SSB* throughout the time series compared with the base model but negligible changes to estimates of recruitment. There were negligible deviations to recruitment from the base model with the exception of the final few years of the time series.

2.6 Bayesian inference using Markov chain Monte Carlo

Bayesian inference was used to characterise parameter uncertainty. LSD uses the Stan software to run MCMC simulations using the Hamiltonian Monte Carlo (HMC) algorithm. The MAP values were used as starting values (Table 10). For the base case and two selected sensitivity tests (*uniformM* and *lag3*), the posterior distributions were explored with a total of 1000 samples across four chains, each with a warm-up phase of 500 iterations and length of 500 samples, retaining every second sample.

All CRA 4 models had bimodal posterior distributions for key parameters (e.g., R_0 , M) under the parameter priors and bounds initially specified. Bimodality in the base model stopped when a wide, normal prior was used for R_0 (as opposed to a uniform prior) and a normal prior on $Mat50$ was constrained to a standard deviation of 10 from 30. However, bimodality in the *uniformM* and *lag3* models persisted despite these initial changes. In these cases, at least one chain would jump to a different area of the likelihood surface associated with a high value for *Gshape* (greater than 10). The bimodality stopped when the upper bound on *Gshape* was constrained to 7.5, which the RLWG deemed to represent a reasonable maximum value for this parameter. The RLWG also considered values greater than 10 for the *Gshape* parameter, but these were not credible given associated estimates of juvenile growth compared with external studies of what would be reasonable (Roberts & Webber in prep.).

2.6.1 MCMC base case

MCMC was used to obtain samples from the posterior distribution for the base case model described in Section 2.5.1. Diagnostic traces are shown for estimated parameters in Figure 51 to Figure 53. Density plots of samples from the posterior distributions of estimated parameters and important derived quantities are shown in Figure 54 to Figure 56. Cumulative density diagnostic plots are shown in Figure 57 to Figure 59. Posterior distributions of parameter estimates and derived quantities are summarised in Table 12.

The trace and cumulative density plots indicate that the MCMC chains were well-mixed. The traces for the key estimated biological parameters, such as M and R_0 , showed an acceptable level of stability, with MCMC chains staying away from parameter bounds. The vulnerability parameter for males in the AW season came close to the bound of 1.0 (Figure 53, Figure 56). However, the alternative was to fix the vulnerability of males in the AW to 1.0 and estimate the vulnerability of the combined immature and mature females in the AW. Trial runs estimated this combined vulnerability to be near the bound of 1.0, which did not seem feasible for mature females in the AW, because of the requirement to release ovigerous females. Therefore, the parameterisation of fixing vulnerability of immature females in the AW to 1.0 was retained and vulnerability of males in AW was able to be estimated near the upper bound of 1.0.

A set of base case MCMC diagnostic plots consisting of samples from the posterior distributions of the model predictions relative to the observed data, or the standardised residuals of model fits to the data, are shown from Figure 60 to Figure 75. These are comparable with those provided for the base case MAP results (see Figure 11 to Figure 29).

The model generally fitted the CELR CPUE time series well, although there was some difficulty fitting the SS CPUE series in recent years (Figure 60 and Figure 61). There was also difficulty teasing apart AW from SS CPUE in the early years of the FSU series when the FSU CPUE was relatively flat in both seasons (Figure 60 and Figure 61). These CPUE fits were similar to the equivalent MAP fits (see Figure 11 and Figure 12). The median of the posterior distribution for the *qdrift* parameter on the CELR series was 0.002 (Figure 62). Model fits to the LF and tagging data were also generally acceptable (Figure 63 to Figure 73). Model fits to the observer catch sampling LF data were generally better than fits to the logbook LF data. In some years, the immature female LF fits were skewed to the right compared with other years, likely due to the very low sample sizes/weights for this sex category. The model fitted the observer catch sampling sex ratio data in both seasons very well but was not able to fit the logbook sex ratio data as well, possibly due to a data conflict in the length frequencies from the two sampling programmes (Section 2.5.1.2, Figure 74, Figure 75). Selectivity was estimated to shift to the right for both males and females after 1993 (Figure 76). Length at maturation was estimated to be well below the female MLS (Figure 77), with 50% of females mature at 42 mm TW.

Fits to the tagging data were acceptable, with no strong patterns in the residuals (Figure 78 to Figure 81). The only exceptions were the fits to very small and large individuals, likely due to the small sample sizes in those length classes (Figure 82). The estimated annual growth increment at 30 mm TW was in a reasonable range for recent juvenile growth studies on this species (Roberts & Webber in prep., Figure 82).

The strongest recruitment event was estimated in the early 1990s, with lesser recruitment peaks in the late 1950s, late 1970s and early 1980s, and the mid-2000s (Figure 83). Recruitment was estimated to be lowest in the 1960s and early 2000s, as well as in recent years (late 2000s to present). Recent mean (2009–2017) recruitment is estimated to be below R_0 (Figure 83).

Fishing mortality was estimated to be increasing during the 1970s while catch was generally increasing, reaching its peak in the early 1980s (Figure 84). Estimates of vulnerable biomass and *SSB* decreased rapidly in the early years of the fishery through to the mid-1970s (Figure 85, Figure 86). Vulnerable biomass and *SSB* has generally oscillated over time. *SSB* varied around a stable level after dropping from initial exploitation. This stability was likely due to the small length at maturity relative to the MLS. Length at maturity was smaller than that estimated for other QMAs, with the MCMC estimate of the inflection point at 42 mm. This meant that virtually all females selected by the fishing gear were mature and that a considerable proportion of females below the size limit were also mature. However, there has been a noticeable decline in the *SSB* since the late 2000s. Vulnerable biomass initially decreased rapidly with increasing fishing mortality during the 1970s but has also oscillated around a relatively stable level since the 1970s. The two early CPUE series show decreasing trends as fishing mortality increased along with a decrease in vulnerable biomass during the 1970s; CPUE continued to decrease during the 1980s

(Figure 60). Since the start of the CELR series, CPUE has shown the effects of two large recruitment events climbing and then falling as exploitation rate increased. The pattern of the vulnerable biomass trajectory follows the CPUE series (Figure 60, Figure 85, and Figure 86).

The adjusted vulnerable biomass at the beginning of 2020 was predicted to be at 12.6% of B_0 ($B_{2020}/B_0 = 0.126$ [90% credible interval (CI) = 0.096 – 0.164]; Figure 85). The 2020 SSB was predicted to be at 47.6% of SSB_0 ($SSB_{2020}/SSB_0 = 0.476$ [90% CI = 0.406 – 0.559]; Figure 86). In 2020 there was a negligible probability of being below the soft limit (20% SSB_0) and a probability of 0.995 of being above B_{MIN} (Table 12).

2.6.2 MCMC sensitivity trials

Two sensitivity trials were chosen to be analysed using MCMC: *uniformM* and *lag3*. These runs represented plausible alternative hypotheses that differed in the parameter space investigated (i.e., biomass trajectories) relative to the base case. Both sensitivities had acceptable MCMC diagnostics for the completed chains. Comparisons of these sensitivity trials to the base case are shown in Figure 87 to Figure 93.

The *uniformM* scenario had identical settings to the base case but assumed a uniform prior on the M parameter, with the goal of determining the influence of the normal prior typically assumed for all red rock lobster stock assessments. The base model estimated an M of 0.223 (90% CI = 0.200 – 0.251), and the *uniformM* model estimated an M of 0.231 (90% CI = 0.205 – 0.263). The likelihoods were very similar (base likelihood 13 200 units, *uniformM* likelihood 13 220 units; Table 12). This showed that the prior used for M was not overly informative for CRA 4.

The *lag3* scenario was also very similar to the base model except for recent estimates of recruitment deviations. Although the base model estimated recruitment deviates through to 2017, the *lag3* scenario estimated recruitment deviates through to the last year of the model (2019) due to the assumed lag of three years between puerulus settlement and recruitment to the stock assessment model. The *lag3* model estimated higher recruitment deviations in the two most recent years when compared with the base model, which translated to a minor uptick in SSB compared with the base model (base $SSB_{2020}/SSB_0 = 0.476$ (90% CI = 0.406 – 0.559) compared with *lag3* $SSB_{2020}/SSB_0 = 0.523$ (90% CI = 0.463 – 0.604). This uptick in biomass was predicted to continue through to 2024 for both SSB and vulnerable biomass, given that, with a lag of three years, the puerulus series provided estimates of recruitment up to 2022. For example, the probability that SSB in 2024 is greater than the SSB in 2020 for the base model is 0.281, compared with a probability of 0.901 for the *lag3* model. The probability that adjusted vulnerable biomass in 2024 was greater than adjusted vulnerable biomass in 2020 for the base model was 0.335, compared with 0.970 for the *lag3* model.

2.7 Projections

For each of the models analysed with MCMC, the 2019 recreational and NSL catches were assumed constant when projecting forward for 2020–2024. For the commercial catch, a catch of 350.6 tonnes was assumed for 2020 (this included carryover from 2019 for catches that were forgone due to disruptions to the fishery caused by the COVID-19 pandemic) and a catch of 318.8 tonnes (present TACC) was projected for 2021–2024 (Figure 94 to Figure 96). With these catch assumptions and assuming stochastic recruitment with mean 2008–2017 and standard deviation (σ_R)=0.4⁸, the SSB and adjusted vulnerable biomass were predicted to decrease slightly for the *base* and *uniformM* runs but would increase for the *lag3* run, given the higher average recruitment estimated by this sensitivity run (Figure 87 and Figure 88).

Although current adjusted vulnerable biomass was predicted to be at 12.6% of B_0 ($B_{2020}/B_0 = 0.126$ [90% credible interval (CI) = 0.096 – 0.164]), vulnerable biomass was projected to decrease to 10.9% of B_0

⁸ Projection recruitment deviates were inserted for 2018 and 2019 because recruitment was not estimated in the reconstruction model for these years (Figure 83).

by 2024, at current catch ($B_{2024}/B_0 = 0.109$ [90% CI = 0.042 – 0.205]; Figure 87). Current SSB was predicted to be at 47.6% of SSB_0 ($SSB_{2020}/SSB_0 = 0.476$ [90% CI = 0.406 – 0.559]) and was projected to decline slightly at current levels of catch ($SSB_{2024}/SSB_0 = 0.449$ [90% CI = 0.333 – 0.600]; Figure 86). At current catch levels, there was a probability of 0.335 that the vulnerable biomass in 2024 would be greater than in 2020 and a probability of 0.281 that the 2024 SSB will be greater than in 2020 (Table 12).

2.8 Reference levels

Work has been completed to develop model-based reference levels for red rock lobster stocks (Rudd et al. 2021a). To calculate the reference level, a wide range of fixed catch and fixed F rules were projected forward 30 years, and the performance of each rule was assessed over the final 20 years of the projection period. Evaluated performance indicators included the average annual catch, the CV of catch over time, and the probability of falling below the soft limit. The rule that maximised catch while maintaining less than 5% chance of falling below the soft limit was identified for each rule type (fixed catch or fixed F). Fixed catch rules were further constrained by requiring 99% of the fixed catch amount to be taken for more than 95% of years and simulation replicates. The reference level (B_R) was defined as the average adjusted vulnerable biomass between the maximum constrained fixed catch and fixed F rules.

The reference level projections done during the workshop assumed that projected recruitment deviates and the value for SSB_0 used in the risk constraint would be based on the final ten years of estimated recruitment deviates, in keeping with previous simulations used to evaluate MPs (e.g., Breen et al. 2017). The Fisheries New Zealand mid-year Plenary (November 2020) did not accept these reference levels, arguing that the final ten years may not be adequately representative of productivity over the next 30 years and asked for a longer period over which to estimate mean recruitment. It was agreed that the chosen recruitment reference period would span the full period with adequate length frequency data. Consequently, reference levels were recalculated using the estimated recruitment deviates starting in the first year with reasonable length data, either from the catch sampling or the logbook programmes. For CRA 4, this included 32 years from 1986 to 2017. The reference levels reported in this document (Table 12) and the methods used to estimate them are more thoroughly discussed by Rudd et al. (2021a). Table 12 indicates that the median base case estimate of B_{2020} was slightly above B_R , and the projected median base case estimate of B_{2024} was below B_R , under the assumptions of average recruitment for the most recent 10 years and projected catch. However, the same projection for the *lag3* sensitivity run predicted that the biomass would increase over the same time period and remain well above B_R .

3. DISCUSSION

This assessment describes a stock that was initially heavily fished, resulting in a rapid decline in vulnerable biomass to the end of the 1960s, followed by a long period over which the vulnerable population oscillated at low levels (relative to B_0). Because the length at 50% maturity for females was estimated to be small in CRA 4 relative to the MLS (42 mm compared with 60 mm), the SSB did not decline to the same extent as vulnerable biomass, especially during the early years of the fishery. Similar to the vulnerable biomass, the SSB has oscillated in response to recruitment events around a relatively consistent level (but higher in terms of SSB_0 compared with the vulnerable biomass B_0) up to the end of the late 2000s. Figure 86 suggests that there has been a gradual decline in SSB over the most recent 10–12 years. This estimated decline in spawning and vulnerable biomass in recent years is likely to have been driven by low recent recruitment (Figure 83). Projections show that the population is predicted to decrease slightly over the next five years under current catch levels, assuming base case recruitment levels (Figure 94).

The LSD model fitted all the CRA 4 input data reasonably well, except for the SS CELR series in recent years. The fit to the sex ratio from the observer catch sampling programme was relatively good, but it was more difficult to achieve good fit to the logbook LF data, possibly due to a conflict between the information from the logbook LF data and CPUE series.

The median current CRA 4 vulnerable biomass was estimated to be slightly above the agreed reference level and was projected to decrease over the next five years to below this level under present catches and recent (10 year) average recruitment. However, the sensitivity run including the puerulus series (*lag3*) predicted that the CRA 4 stock will increase over the next five years, because recent levels of recruitment, as indexed by the settlement series, are above the long-term average. Rapid updates of CRA 4 in 2021 will be helpful to determine whether CRA 4 sees an increase in vulnerable biomass due to possible recent higher recruitment as predicted by the settlement series, or whether some form of intervention is needed to ensure CRA 4 remains above the reference level until the next CRA 4 stock assessment is undertaken in about five years.

3.1 Future research

This assessment updated the mean and standard deviation of the length at recruitment in the stock assessment model using recent studies of juvenile growth (Roberts & Webber in prep.). These studies were also used to inform the plausible time lag from puerulus settlement to recruitment to the stock assessment model and plausible growth rate around the size at recruitment for model runs fitting to the puerulus index. However, when the most plausible time lag (three years from settlement to recruitment) was used, it was difficult to fit to the puerulus index, and several adjustments to the growth model parameterisation were required to achieve reasonable growth parameter estimates. Further, key parameter posterior distributions for the CRA 4 stock assessment were bimodal across all models tested and required constraining the bounds of the *Gshape* parameter to avoid this model behaviour. Although there is good representation of tag recoveries across the frequent size bins, more tag observations are needed at the upper and lower extremes of the size distribution to better estimate the growth parameters.

Additionally, alternative methods for estimating growth rate could be explored, such as developing technology for the direct ageing of lobsters from gastric ossicles (e.g., Gnanalingam et al. 2018, Huntsberger et al. 2020, Leland & Bucher 2017). Direct ageing studies could help to better inform growth at small and large sizes. Moreover, such information could be used to identify and correct potential biases in tag-based growth information due to size-based selectivity of fishery-based tag recaptures.

The CRA 4 stock assessment fits the catch sampling data much better than the logbook data. Weighting the logbook data proved problematic due to the high number of sampling days relative to the sample size of lengths measured. Future work on LF standardisation methods would be useful to avoid the weighting issues experienced during the 2020 CRA 4 assessment. CRA 4 would be a useful stock to test such methods once they are developed. A more detailed spatial analysis exploring the reasons for observed differences in TW and sex-ratio from logbook and catch sampling sources may help understand the differences in model fits. Alternative LF weighting procedures should be explored as sensitivities once a replacement procedure has been adopted.

Additional research on priors and parameter bounds would be useful for future CRA 4 assessments. For some models, an adjustment to the upper bound on the *Gshape* parameter from 15.0 to 7.5 was required to prevent bimodality in parameter posterior distributions. This adjustment to the upper bound solved the bimodality issue for the models explored in this study, but further research is required to investigate if this is the best approach to avoid bimodality while allowing the MCMC algorithm to thoroughly explore the parameter space. Although the current prior on *M* is used for all New Zealand red rock lobster stock assessments, the RLWG expressed an interest in reviewing this prior and exploring alternatives. Further, future research should investigate the influence of those priors where the posteriors are substantially different from the prior (e.g., *Gsd*) to determine whether the priors are appropriate and influential or whether the growth meta-analysis needs to be repeated. Other potential future model updates include implementing time-varying vulnerability and alternative weightings for CPUE by statistical area.

There are also uncertainties associated with limited data. Tagging is weak from statistical areas 912 and 915 and additional tagging would better inform lobster growth. Estimates of non-commercial catch are

infrequent and uncertain. These estimates should be improved with more frequent and better designed non-commercial catch surveys and reporting systems.

The 2019–20 fishing year marked the transition of the collection of commercial catch and effort data from a paper-based system to electronic reporting. Previous experience with changes to the collection of catch and effort data in New Zealand demonstrated that it is not always possible to assume that data will be comparable across the two data collection systems. In addition, initial evidence showed poor compliance with data entry instructions by fishers switching to the new electronic system. The RLWG provisionally concluded that the new data collection system was not comparable with the previous system, and that there is consequently a break in the continuity of the CPUE time series (see appendix B of Starr 2021). As a result, it will not be possible to use the new electronic catch and effort data to generate a CPUE series that can be used to drive a stock assessment or an MP until sufficient data accumulate to create a new, reliable series. A procedure for annual, rapid updates of red rock lobster assessments has been developed, which involves running the base model from the last full assessment with updated additional years of catch, length frequency, and tagging data (Webber et al. 2021). CRA 4 will be the subject of a rapid assessment in 2021. Future work is proposed to develop MPs based on the results of the rapid updates and the updated reference levels for each QMA.

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6. TABLES

Table 1: Minimum legal size (MLS) limits for males and females over time. Note that MLS before 1987 were expressed in terms of tail length and have been converted to tail width using the procedure described by Breen et al. (1988).

Period	MLS (tail width, mm)	
	Males	Females
1945–1949	None	None
1950–1951	47	49
1952–1958	51	53
1959–1987	53	58
1988–1991	54	58
1992–2019	54	60

Table 2: Definitions of parameters and derived quantities discussed in the text.

Parameters	Definition
R_0	initial numbers recruiting
M	instantaneous rate of natural mortality
$Rdevs$	annual recruitment deviations
σR	standard deviation of $Rdevs$
q_{CR}	catchability coefficient (relationship between the vulnerable biomass and CR series)
q_{FSU}	catchability coefficient (relationship between the vulnerable biomass and FSU CPUE series)
q_{CELR}	catchability coefficient (relationship between the vulnerable biomass and CELR CPUE series)
$Mat50$	size where 50% of immature females become mature
$Mat95add$	difference between $Mat50$ and the size at which 95% of immature females become mature
$Galpha$	annual growth increment at 50 mm TW
$Gbeta$	annual growth increment at 80 mm TW
$Gdiff$	the ratio of $Gbeta$ to $Galpha$
$Gshape$	parameter for shape of growth curve: 1 implies von Bertalanffy straight line; >1 implies a concave upwards curve
GCV	standard deviation of growth-at-size divided by growth-at-size
$Gobs$	standard deviation of observation error for tag-recaptures
$SelLH$	shape of the left-hand limb of the selectivity curve (as if it were a standard deviation)
$SelM$	size at maximum selectivity
$vuln$	relative vulnerability by sex and season
q_{drift}	additive change in catchability coefficient each year
U_0	initial exploitation rate (first year is in equilibrium using this estimate)
Gdd	density-dependent growth parameter

Table 3: Specifications for estimated parameters in the CRA 4 models including the upper and lower bounds, prior type, and prior parameters (par 1 and par 2).

Season	Sex	Parameter	Lower bound	Upper bound	Prior type	par 1	par 2
		R_0	exp(1)	exp(25)	normal	1e6	1e7
		M	0.01	0.35	lognormal	0.12	0.4
		$Rdevs$	-2.3	2.3	uniform		
		qCR	exp(-25)	1	uniform		
		$qFSU$	exp(-25)	1	uniform		
		$qCELR$	exp(-25)	1	uniform		
		$Mat50$	30	80	normal	50	10
		$Mat95add$	1	60	normal	fixed ¹	fixed ¹
	male	$Galpha$	1	20 ²	normal	2 ³	30 ³
	male	$Gdiff$	0.001	0.99	beta	1	1
	male	$Gshape$	0.1	15 ⁴	normal	4.81	0.48
	male	GCV	0.01	2	normal	0.59	0.18
	female	$Galpha$	1	20 ²	normal	2 ³	30 ³
	female	$Gdiff$	0.001	0.99	beta	1	1
	female	$Gshape$	0.1	15 ⁴	normal	4.51	0.45
	female	GCV	0.01	2	normal	0.82	0.25
		$Gobs$	0.0001	10	normal	1.48	0.074
	male	$SelLH$	1	50	normal	10	10
	female	$SelLH$	1	50	normal	10	10
	male	$SelM$	30	90	normal	50	30
	female	$SelM$	30	90	normal	50	30
SS	male	$vuln1$	0.01	1	beta	1	1
AW	immafem	$vuln2$	0.01	1	beta	1	1
SS	imma & matfem	$vuln3$	0.01	1	beta	1	1
AW	matfem	$vuln4$	0.01	1	beta	1	1
		$qdrift$	-0.08	0.08	normal	0	1

¹ estimated with a uniform prior in the MAP but fixed at the MAP estimate for the MCMC simulation.

² reduced to 10 for the **lag3** sensitivity run.

³ changed to par 1 = 9 and par 2 = 2 for the **lag3** sensitivity run.

⁴ reduced to 7.5 for the **lag3** and **uniformM** sensitivity runs.

Table 4: Fixed quantities used in the CRA 4 models.

Quantity	Value	Quantity	Value
data set weights		fixed parameters	
tags	1.0	σR	0.4
CELR CPUE	1.2	male length-weight a	4.16e-6
FSU CPUE	1.3	male length-weight b	2.935
CR CPUE	2.6	female length-weight a	1.3e-5
sex ratio	14.0	female length-weight b	2.545
LFs	7.12	Gdd	0
catch and handling		U_0	0
handling mortality, 1945–1989	0.10	recruitment	
handling mortality, 1990–2018	0.05	last year of estimated $Rdevs$	2017
projected SL commercial catch	350.6 t	years for estimating $Rdevs$ for projections	2008-2017
projected SL commercial catch	318.8 t	years for estimating autocorrelation	1986-2017
projected SL recreational catch	39.56 t	recruitment size mean	33.35 mm
Projected NSL illegal catch	18.71 t	recruitment size SD	4 mm
Projected NSL customary catch	20 t	recruitment autocorrelation	0.53
growth		other	
length at $Galpha$ ¹	50	Newton-Raphson iterations	3
length at $Gbeta$	80	tail compression: male bins	6 to 26
length at $Gmin$	0.0001	tail compression: female immature bins	1 to 20
$Mat95add$ (mm)	2.58	tail compression: female mature bins	7 to 28

¹ except for the **lag3** sensitivity run where $Galpha$ was fixed at 30 mm.

Table 5: CRA 4 base case: map of vulnerability (*vuln*) parameters. Vulnerability for immature females in AW is fixed at 1 and all other *vuln* parameters are estimated relative to the vulnerability of immature females during the AW.

Sex	Season	<i>Vuln</i>
male	AW	<i>vuln1</i>
male	SS	<i>vuln2</i>
immature female	AW	1
immature female	SS	<i>vuln3</i>
mature female	AW	<i>vuln4</i>
mature female	SS	<i>vuln3</i>

Table 6: Reference points, performance indicators, and stock status probabilities for the CRA 4 stock assessment.

Type	Description
Reference Points	
B_0	beginning of season AW adjusted vulnerable biomass before fishing (1945)
SSB_0	female AW spawning stock biomass before fishing (1945)
B_{0TOT}	equilibrium total biomass
B_{0now}	equilibrium adjusted vulnerable biomass using mean 2008–2017 recruitment
SSB_{0now}	equilibrium female spawning biomass using mean 2008–2017 recruitment
$B_{0TOTNOW}$	equilibrium total biomass using mean 2008–2017 recruitment
B_{MIN}	the lowest beginning AW adjusted vulnerable biomass in the series
B_{2020}	beginning of season AW adjusted vulnerable biomass for 2020
B_{2024}	beginning of season AW adjusted vulnerable biomass for 2024
B_R	reference level in terms of AW adjusted vulnerable biomass (Rudd et al. 2021a)
SSB_{2020}	female spawning stock biomass at beginning of 2020 AW season
SSB_{2024}	female spawning stock biomass at beginning of 2024 AW season
$B_{2020TOT}$	beginning of season AW total biomass for 2020
$B_{2024TOT}$	beginning of season AW total biomass for 2024
$CPUE_{2019}$	AW CPUE at beginning of 2019 (in kg/potlift)
$CPUE_{2024}$	AW CPUE at beginning of 2024 (in kg/potlift)
H_{2019}	total handling mortality for 2019 (tonnes)
H_{2023}	total handling mortality for 2023 (tonnes)
Performance indicators	
B_{2020} / B_0	ratio of B_{2020} to B_0
B_{2024} / B_0	ratio of B_{2024} to B_0
B_{2020} / B_{0now}	ratio of B_{2020} to B_{0now}
B_{2024} / B_{0now}	ratio of B_{2024} to B_{0now}
B_{2024} / B_{2020}	ratio of B_{2024} to B_{2020}
SSB_{2020} / SSB_0	ratio of SSB_{2020} to SSB_0
SSB_{2024} / SSB_0	ratio of SSB_{2024} to SSB_0
SSB_{2020} / SSB_{0now}	ratio of SSB_{2020} to SSB_{0now}
SSB_{2024} / SSB_{0now}	ratio of SSB_{2024} to SSB_{0now}
SSB_{2024} / SSB_{2020}	ratio of SSB_{2024} to SSB_{2020}
$B_{2020TOT} / B_{0TOT}$	ratio of $B_{2020TOT}$ to B_{0TOT}
$B_{2020TOT} / B_{0TOTNOW}$	ratio of $B_{2020TOT}$ to $B_{0TOTNOW}$
$B_{2024TOT} / B_{0TOT}$	ratio of $B_{2024TOT}$ to B_{0TOT}
$B_{2024TOT} / B_{0TOTNOW}$	ratio of $B_{2024TOT}$ to $B_{0TOTNOW}$
$B_{2024TOT} / B_{2020TOT}$	ratio of $B_{2024TOT}$ to $B_{2020TOT}$
Probabilities	
$P(B_{2020} > B_{MIN})$	probability B_{2020} is greater than B_{MIN}
$P(SSB_{2020} < 20\% SSB_0)$	probability SSB_{2020} is less than 20% SSB_0
$P(SSB_{2020} < 10\% SSB_0)$	probability SSB_{2020} is less than 10% SSB_0
$P(SSB_{2020} < 20\% SSB_{0now})$	probability SSB_{2020} is less than 20% SSB_{0now}
$P(SSB_{2020} < 10\% SSB_{0now})$	probability SSB_{2020} is less than 10% SSB_{0now}
$P(SSB_{2024} < 20\% SSB_0)$	probability SSB_{2024} is less than 20% SSB_0
$P(SSB_{2024} < 10\% SSB_0)$	probability SSB_{2024} is less than 10% SSB_0
$P(SSB_{2024} < 20\% SSB_{0now})$	probability SSB_{2024} is less than 20% SSB_{0now}
$P(SSB_{2024} < 10\% SSB_{0now})$	probability SSB_{2024} is less than 10% SSB_{0now}
$P(B_{2024} > B_{2020})$	probability B_{2024} is greater than B_{2020}
$P(SSB_{2024} > SSB_{2020})$	probability SSB_{2024} is greater than SSB_{2020}
$P(B_{2024TOT} > B_{2020TOT})$	probability $B_{2024TOT}$ is greater than $B_{2020TOT}$

Table 7: List of model runs used to iteratively update the base case used in the 2016 assessment of CRA 4.

Model name	Model description	Outcome
<i>1_base2016</i>	Mimics the 2016 assessment model: - Catch and CPUE used in 2016 assessment (up to and including the 2015 fishing year) - LF used in the 2016 assessment (up to and including the 2015 fishing year) - Tag data used in 2016 assessment - FSU and CELR CPUE series linked with single catchability parameter (q). - No density dependence - Included puerulus index with lag of 2 years	MAP estimates of a adjusted vulnerable biomass match well (Figure 3).
<i>2_base2016_noP</i>	Same as <i>1_base2016</i> but does not fit to the puerulus index	Decrease in a adjusted vulnerable biomass across the time series when not fitting to the puerulus index (Figure 4).
<i>3_splitq</i>	Separate q parameters estimated for the FSU and CELR CPUE series	Additional decrease in a adjusted vulnerable biomass during the years of the CELR series when splitting catchability parameters q between the FSU and CELR series (Figure 5).
<i>4_newCELR</i>	Included the updated CELR series to be used in the 2020 assessment, but through 2015 only	Increase in a adjusted vulnerable biomass across the time series with updated CELR series (Figure 5).
<i>4.5_newCELR_novessel</i>	Included the updated CELR series without a vessel effect, through 2015 only	the biomass trajectory of this model lies below the trajectory of <i>4_newCELR</i> , i.e. the average level of biomass is lower if the updated CELR series did not include a vessel effect (Figure 6).
<i>5_newFSU</i>	Included the FSU index run using a Bayesian analysis with a vessel effect to be used in the 2020 assessment, but through 2015 only	Minimal change in a adjusted vulnerable biomass from the updated CELR series after updating the FSU series (Figure 5).
<i>6_newTagging</i>	Replaced old tag extract with new tag extract, through 2015 only	Negligible change in a adjusted vulnerable biomass with new tag extract (Figure 7).
<i>7_newCatch</i>	Replaced old catch data with new catch data (includes updated illegal catch time series), through 2015 only	Negligible change in a adjusted vulnerable biomass with updated catch data that included minor changes in calculation to the illegal and recreational catch time series (Figure 7).
<i>8_newLF</i>	Replaced old length frequency data with updated length frequency data through 2015 only	Additional increase in a adjusted vulnerable biomass with the updated LF data (Figure 7).
<i>9_buildup2019</i>	Carried all updated datasets through to 2019	When extending all data through 2019, a adjusted vulnerable biomass drops back down to levels matched by <i>4_newCELR</i> , <i>5_newFSU</i> , <i>6_newTagging</i> , and <i>7_newCatch</i> (Figures 8 and 9).

Table 8: List of CRA 4 Maximum *a posteriori* (MAP) sensitivity runs. Each model run below the base model run implements a single change to the base model run.

Type	Model name	Model description
Base	<i>base</i>	as defined in Section 2.5.1
Uniform M	<i>uniformM</i>	Base with uniform prior on <i>M</i> (for MCMC, decreased upper bound on <i>Gshape</i> from 15 to 7.5)
Puerulus	<i>lag3</i>	Fits to puerulus index with lag 3 years. Several adjustments made for the estimation of the <i>Galpha</i> parameter based on recent exploration of juvenile growth (Table 3).
	<i>lag2</i>	Fits to puerulus index with lag 2 years
Catch	<i>illegalX2</i>	Double illegal catch
Removing data	<i>noLB</i>	Remove logbook LF data
	<i>downCPUE</i>	Down-weight all CPUE series, by multiplying the weights by 0.1
	<i>downSexRatio</i>	Down-weight the sex ratio information by multiplying the weights by 0.1
	<i>downLF</i>	Down-weight length frequency data information by multiplying the weights by 0.1

Table 9: CRA 4 stock assessment: MAP reference base case and sensitivity trial results for likelihoods, standardised normalised residuals (SDNR), median of absolute residuals (MAR), and weightings.

	<i>base</i>	<i>uniformM</i>	<i>lag3</i>	<i>lag2</i>	<i>illegalX2</i>	<i>noLB</i>	<i>down CPUE</i>	<i>down SexRatio</i>	<i>down LF</i>
Likelihoods									
Total	13 146	13 174	12 975	12 787	13 144	11 457	13 327	11 507	5 349
Prior	98	98	90	97	98	91	92	111	87
tag	2 728	2 729	2 727	2 727	2 729	2 723	2 725	2 731	2 717
sexr	1 835	1 835	1 835	1 834	1 836	2 819	1 837	185	1 833
LF	8 637	8 663	8 499	8 308	8 634	5 971	8 651	8 634	874
CR	-18.63	-18.67	-18.92	-18.49	-19.16	-18.55	1.76	-18.45	-19.79
FSU	-41.21	-41.07	-39.99	-41.11	-40.88	-40.62	-1.63	-42.03	-43.05
CELR	-92.20	-92.12	-91.11	-87.63	-91.98	-87.73	23.13	-93.75	-98.78
puerulus	0.00	0.00	-26.39	-31.19	0.00	0.00	0.00	0.00	0.00
SDNR									
tag	1.455	1.454	1.456	1.457	1.455	1.464	1.457	1.455	1.498
sexr	1.000	1.002	0.995	0.993	1.002	1.018	1.007	0.361	0.969
LF	3.093	3.115	3.138	3.009	3.119	1.228	2.709	3.855	0.636
CR	1.012	1.009	1.004	1.026	0.979	1.021	0.195	1.031	0.890
FSU	1.005	1.012	1.024	1.011	1.016	1.033	0.361	0.961	0.910
CELR	1.025	1.026	1.039	1.010	1.030	1.012	0.514	1.000	0.906
puerulus	0.000	0.000	0.998	0.956	0.000	0.000	0.000	0.000	0.000
MAR									
tag	0.679	0.680	0.653	0.681	0.679	0.676	0.670	0.680	0.679
sexr	0.409	0.414	0.916	0.400	0.419	0.478	0.440	0.166	0.401
LF	0.056	0.057	0.639	0.055	0.056	0.050	0.055	0.055	0.019
CR	0.646	0.640	0.683	0.652	0.646	0.670	0.189	0.654	0.598
FSU	0.888	0.909	0.398	0.856	0.977	0.920	0.204	0.802	0.784
CELR	0.664	0.673	0.055	0.584	0.688	0.659	0.347	0.655	0.520
puerulus	0.000	0.000	0.717	0.793	0.000	0.000	0.000	0.000	0.000
Weightings									
sexr	14	14	14	14	14	31	14	1.4	14
LF	7.12	7.14	7.00	6.84	7.12	7.12	7.14	7.12	0.712
CR	2.6	2.6	2.65	2.6	2.6	2.6	0.26	2.6	2.6
FSU	1.3	1.3	1.25	1.3	1.3	1.3	0.13	1.3	1.3
CELR	1.2	1.2	1.2	1.1	1.2	1.1	0.12	1.2	1.2
puerulus	0.0	0.0	0.4	0.7	0.0	0.0	0.0	0.0	0.0

Table 10: CRA 4 stock assessment: MAP reference base case and sensitivity trial results, parameters. Growth increment values in mm TW and R_0 in numbers.

	<i>base</i>	<i>uniformM</i>	<i>lag3</i>	<i>lag2</i>	<i>illegalX2</i>	<i>noLB</i>	<i>down CPUE</i>	<i>down SexRatio</i>	<i>down LF</i>
R_0	2 983 000	3 047 150	3 027 690	2 950 020	3 116 970	3 036 990	2 948 880	3 008 540	3 381 060
M	0.225	0.226	0.229	0.224	0.224	0.231	0.220	0.219	0.266
q_{drift}	0.0016	0.0015	0.0016	-0.0007	0.0011	-0.0043	-0.0146	0.0027	-0.0153
q_{CELR}	0.0018	0.0018	0.0017	0.0018	0.0017	0.0031	0.0039	0.0018	0.0021
q_{FSU}	0.0014	0.0015	0.0015	0.0014	0.0014	0.0025	0.0017	0.0015	0.0017
q_{CR}	0.0783	0.0790	0.0778	0.0747	0.0837	0.1297	0.1045	0.0754	0.0961
$mat50$	42.099	41.892	42.095	42.201	42.012	41.839	42.065	40.989	41.938
<i>Galpha</i> males	2.685	2.675	9.927	2.702	2.682	2.705	2.663	2.670	2.770
<i>Gbeta</i> males	2.406	2.461	2.379	2.372	2.415	2.122	2.348	2.434	1.577
<i>Gshape</i> males	6.224	6.237	6.185	6.297	6.213	5.909	6.354	6.126	5.646
<i>GCV</i> males	0.707	0.707	0.704	0.704	0.707	0.712	0.718	0.708	0.710
<i>Galpha</i> females	2.056	2.056	8.506	2.067	2.056	2.180	2.109	1.975	2.333
<i>Gbeta</i> females	1.227	1.228	1.234	1.237	1.232	1.248	1.231	1.253	1.061
<i>Gshape</i> females	5.433	5.420	5.430	5.428	5.436	4.896	5.460	5.262	4.979
<i>GCV</i> females	1.270	1.268	1.254	1.260	1.270	1.191	1.244	1.268	1.172
<i>Gobs</i>	0.494	0.494	0.493	0.494	0.495	0.494	0.493	0.495	0.507
<i>vuln1</i>	0.894	0.888	0.920	0.913	0.893	0.495	0.968	0.872	0.905
<i>vuln2</i>	0.730	0.722	0.759	0.747	0.727	0.392	0.995	0.746	0.763
<i>vuln3</i>	0.562	0.551	0.583	0.591	0.558	0.560	0.810	0.552	0.779
<i>vuln4</i>	0.360	0.353	0.374	0.380	0.359	0.320	0.377	0.441	0.482
<i>SelL</i> males > 1993	5.55	5.49	5.56	5.59	5.52	5.56	5.94	5.49	6.68
<i>SelL</i> males ≤ 1993	3.96	3.95	3.96	3.98	3.95	4.56	3.97	3.95	4.06
<i>SelM</i> males > 1993	54.20	54.19	54.20	54.23	54.19	54.09	55.80	54.24	57.88
<i>SelM</i> males ≤ 1993	55.58	55.60	55.58	55.59	55.59	55.98	55.50	55.59	55.58
<i>SelL</i> females > 1993	7.86	7.76	7.93	7.95	7.72	9.68	8.46	7.41	14.50
<i>SelL</i> females ≤ 1993	6.20	6.19	6.19	6.19	6.20	6.62	6.29	6.02	6.63
<i>SelM</i> females > 1993	60.75	60.61	60.83	61.03	60.50	66.10	63.25	60.30	75.49
<i>SelM</i> females ≤ 1993	64.42	64.41	64.40	64.43	64.45	65.52	64.50	64.36	65.37

Table 11: CRA 4 stock assessment: MAP reference base case and sensitivity trial results, Reference points. Biomass values in tonnes.

Reference points	<i>baseuniformM</i>	<i>lag3</i>	<i>lag2</i>	<i>illegalX2</i>	<i>noLB</i>	<i>down CPUE</i>	<i>down SexRatio</i>	<i>down LF</i>	
Adjusted vulnerable biomass									
B_0	3 933	3 885	3 975	4 090	4 121	2 099	4 460	4 027	3 256
B_{0_NOW}	2 426	2 404	2 986	2 688	2 529	1 416	2 582	2 461	2 295
B_{MIN}	360.0	355.7	378.4	376.9	367.0	224.5	257.2	345.4	391.0
B_{2020}	465.7	460.9	499.4	540.1	477.8	322.7	455.5	442.7	699.1
B_{2020}/B_0	0.118	0.119	0.126	0.132	0.116	0.154	0.102	0.110	0.215
Spawning biomass									
SSB_0	3 498	3 543	3 460	3 476	3 682	3 360	3 647	3 545	3 187
SSB_{0_NOW}	2 091	2 123	2 518	2 215	2 190	2 196	2 050	2 101	2 187
SSB_{2020}	1 625	1 665	1 735	1 806	1 693	1 624	1 516	1 663	1 799
SSB_{2020}/SSB_0	0.464	0.470	0.501	0.520	0.460	0.483	0.416	0.469	0.565

Table 12: CRA 4 base case sensitivity runs and combined model MCMC outputs, reporting the 5th, 50th (median; highlighted in yellow), and 95th quantiles of the posterior distributions. Growth increment values in mm TW; biomass values in tonnes; R_0 in numbers; handling mortality (H) in tonnes; CPUE in kg/potlift; ‘-’: not applicable. Most of the projected values in this table differ slightly (i.e., 2–3 decimal places) from tables presented elsewhere (e.g., Fisheries New Zealand 2020) because the projections were repeated after the reference level (B_R) was finalised. The repeated projections were based on a new set of stochastic recruitment deviates which resulted in minor differences in projected values. (Continued on next two pages).

	<i>base</i>			<i>lag3</i>			<i>uniformM</i>		
	5%	50%	95%	5%	50%	95%	5%	50%	95%
Likelihoods									
Total	13 180	13 200	13 210	13 020	13 030	13 040	13 210	13 220	13 240
Prior	113.3	126.2	140.9	97.77	110.7	123.4	111.3	125.5	140.4
Tags	2 717	2 728	2 740	2 720	2 730	2 742	2 718	2 728	2741
Sex ratio	1 835	1 837	1 841	1 835	1 837	1 841	1 835	1 837	1 841
LFs	8 638	8 647	8 658	8 497	8 507	8 518	8 666	8 675	8 686
CPUE[CR]	-19.760	-16.800	-13.020	-19.980	-17.230	-13.470	-19.890	-17.130	-13.240
CPUE[FSU]	-41.850	-38.800	-34.380	-40.780	-37.490	-32.550	-41.730	-38.240	-33.000
CPUE[CELR]	-93.480	-87.630	-80.570	-92.350	-87.240	-80.360	-93.510	-87.910	-81.140
Puerulus	-	-	-	-22.430	-17.080	-11.040	-	-	-
Standard deviation of normalised residuals (SDNR)									
Tag	1.410	1.456	1.499	1.410	1.453	1.500	1.410	1.457	1.501
Sex ratio	0.985	1.015	1.066	0.982	1.013	1.067	0.984	1.017	1.066
LFs	1.674	2.977	6.759	1.789	3.159	7.082	1.735	3.011	7.141
CPUE[CR]	0.860	1.141	1.424	0.850	1.122	1.407	0.850	1.115	1.404
CPUE[FSU]	0.951	1.096	1.272	0.966	1.120	1.322	0.960	1.119	1.323
CPUE[CELR]	0.991	1.090	1.200	1.007	1.094	1.194	0.998	1.084	1.187
Puerulus	-	-	-	1.090	1.235	1.447	-	-	-
Median of absolute residual (MAR)									
Tag	0.650	0.674	0.693	0.650	0.675	0.695	0.650	0.674	0.694
Sex ratio	0.372	0.410	0.469	0.385	0.426	0.482	0.379	0.418	0.473
LFs	0.055	0.057	0.059	0.054	0.056	0.059	0.055	0.057	0.059
CPUE[CR]	0.380	0.732	1.105	0.410	0.737	1.113	0.390	0.735	1.117
CPUE[FSU]	0.654	0.870	1.103	0.636	0.873	1.142	0.670	0.890	1.141
CPUE[CELR]	0.535	0.661	0.798	0.555	0.683	0.809	0.523	0.654	0.811
Puerulus	-	-	-	0.670	0.874	1.096	-	-	-
Parameters									
R_0	2 251 000	2 832 000	3 577 000	2 579 000	3 092 000	3 725 000	2 337 000	2 961 000	3 801 000
M	0.200	0.223	0.251	0.210	0.234	0.261	0.205	0.231	0.263
q_{drift}	-0.010	0.002	0.010	-0.010	0.002	0.010	-0.010	0.002	0.010
q_{CR}	0.05000	0.075000	0.132000	0.050000	0.079140	0.141700	0.050000	0.080000	0.142500
q_{FSU}	0.00100	0.002000	0.002000	0.001180	0.001567	0.002452	0.001147	0.001539	0.002430
q_{CELR}	0.00100	0.002000	0.003000	0.001361	0.001823	0.002811	0.001377	0.001849	0.002957
$q_{Puerulus}$	-	0.000	-	3.405e-7	4.188e-7	5.056e-7	-	0.000	-
$mat50$	37.850	41.730	43.790	37.650	41.710	43.760	38.040	41.680	43.710
$mat95add$	-	2.584	-	-	2.584	-	-	2.584	-
$Galpha\ male$	2.570	2.658	2.759	9.030	9.706	9.970	2.570	2.660	2.759
$Gbeta\ male$	2.136	2.352	2.554				2.120	2.355	2.561
$Gshape\ male$	5.610	6.382	7.111	5.650	6.089	6.505	5.590	6.324	7.050
$GCV\ male$	0.680	0.716	0.751	0.680	0.712	0.750	0.680	0.717	0.754
$Galpha\ female$	1.870	2.042	2.214	7.640	8.416	9.112	1.890	2.070	2.247
$Gbeta\ female$	1.081	1.237	1.393				1.080	1.250	1.415
$Gshape\ female$	5.000	5.468	5.985	4.980	5.459	5.925	4.960	5.455	5.959
$GCV\ female$	1.160	1.270	1.409	1.150	1.256	1.381	1.140	1.259	1.389
$StdObs$	0.450	0.494	0.546	0.450	0.495	0.548	0.450	0.493	0.545

	<i>base</i>			<i>lag3</i>			<i>uniformM</i>		
	5%	50%	95%	5%	50%	95%	5%	50%	95%
<i>vuln1</i>	0.540	0.823	0.979	0.530	0.819	0.985	0.530	0.809	0.979
<i>vuln2</i>	0.443	0.675	0.811	0.441	0.679	0.818	0.432	0.667	0.810
<i>vuln3</i>	0.378	0.545	0.694	0.354	0.537	0.702	0.360	0.535	0.705
<i>vuln4</i>	0.240	0.343	0.452	0.235	0.344	0.450	0.230	0.343	0.463
<i>selL male < 1993</i>	4.760	5.687	6.924	4.660	5.604	6.778	4.710	5.713	6.957
<i>selM male < 1993</i>	52.710	54.230	56.070	52.720	54.290	56.060	52.660	54.300	56.070
<i>selL female < 1993</i>	6.580	8.448	11.150	6.570	8.477	11.160	6.580	8.385	10.800
<i>selM female < 1993</i>	58.400	61.760	66.420	58.410	61.940	66.870	58.480	61.670	65.760
<i>selL male ≥ 1993</i>	3.770	3.981	4.232	3.750	3.931	4.155	3.760	3.972	4.213
<i>selM male ≥ 1993</i>	55.200	55.530	55.920	55.200	55.540	55.950	55.180	55.560	55.940
<i>selL female ≥ 1993</i>	5.850	6.235	6.647	5.790	6.194	6.589	5.830	6.229	6.651
<i>selM female ≥ 1993</i>	63.760	64.540	65.340	63.670	64.540	65.400	63.770	64.560	65.460
Derived parameters: AW adjusted vulnerable biomass									
B_0	2 282	3 441	4 402	2 190	3 341	4 273	2 133	3 271	4 259
B_{0now}	1 448	2 213	2 845	1 648	2 622	3 398	1 381	2 102	2 764
B_{MIN}	216.8	333.8	412.9	220.6	337.8	420.9	215.2	330	409.5
B_R	-	389.1	-	-	389.1	-	-	389.1	-
B_{2020}	283.8	433.6	574.5	281.7	452.3	594.8	273.3	431.3	576.9
B_{2024}	138.5	362.5	713.3	390	690.8	1097	136.9	358.6	715.8
B_{2020} / B_0	0.096	0.126	0.164	0.105	0.134	0.172	0.102	0.132	0.174
B_{2024} / B_0	0.042	0.109	0.205	0.139	0.212	0.318	0.046	0.114	0.211
B_{2020} / B_{0now}	0.156	0.196	0.243	0.136	0.173	0.214	0.165	0.205	0.255
B_{2024} / B_{0now}	0.069	0.169	0.306	0.195	0.273	0.364	0.075	0.176	0.305
B_{2024} / B_{2020}	0.384	0.854	1.537	1.096	1.583	2.214	0.384	0.847	1.444
B_{2020} / B_R	0.730	1.114	1.477	0.724	1.162	1.529	0.702	1.108	1.483
B_{2024} / B_R	0.356	0.932	1.833	1.002	1.775	2.820	0.352	0.922	1.840
Derived parameters: spawning biomass (females only)									
SSB_0	2 970	3 355	3 776	3 105	3 451	3 826	2 969	3 358	3 801
SSB_{0now}	1 851	2 090	2 403	2 233	2 612	3 063	1 849	2 094	2 393
SSB_{2020}	1 331	1 584	1 943	1 575	1 798	2 102	1 345	1 607	1 966
SSB_{2024}	1 085	1 503	2 034	1 641	2 095	2 735	1 103	1 525	2 042
SSB_{2020} / SSB_0	0.406	0.476	0.559	0.463	0.523	0.604	0.409	0.479	0.564
SSB_{2024} / SSB_0	0.333	0.449	0.600	0.487	0.611	0.783	0.334	0.450	0.603
SSB_{2020} / SSB_{0now}	0.695	0.762	0.838	0.614	0.697	0.771	0.702	0.771	0.852
SSB_{2024} / SSB_{0now}	0.558	0.713	0.916	0.704	0.803	0.950	0.562	0.728	0.916
SSB_{2024} / SSB_{2020}	0.768	0.937	1.163	0.967	1.155	1.441	0.761	0.939	1.141
Derived parameters: total biomass									
B_{0tot}	9 515	10 620	11 710	9 925	10 810	11 860	9 487	10 600	11 810
$B_{0totnow}$	6 083	6 829	7 714	7 459	8 438	9 790	6 093	6 801	7 656
$B_{2020tot}$	3 211	4 091	5 330	4 388	5 111	6 075	3 286	4 192	5 404
$B_{2024tot}$	2 715	3 907	5 410	4 156	5 665	7 783	2 747	3 991	5 553
$B_{2020tot} / B_{0tot}$	0.306	0.384	0.489	0.400	0.472	0.568	0.316	0.395	0.501
$B_{2024tot} / B_{0tot}$	0.260	0.367	0.512	0.388	0.528	0.713	0.265	0.373	0.521
$B_{2020tot} / B_{0totnow}$	0.499	0.599	0.724	0.528	0.607	0.687	0.512	0.614	0.740
$B_{2024tot} / B_{0totnow}$	0.416	0.570	0.766	0.541	0.669	0.846	0.427	0.583	0.780
$B_{2024tot} / B_{2020tot}$	0.756	0.941	1.204	0.884	1.105	1.431	0.760	0.948	1.196
Other derived parameters									
$CPUE_{2019}$	0.614	0.683	0.758	0.624	0.685	0.749	0.619	0.686	0.758
$CPUE_{2024}$	0.249	0.626	1.121	0.782	1.099	1.493	0.261	0.636	1.086
H_{2019}	12.75	14.13	15.58	13.25	14.54	15.97	12.81	14.07	15.66
H_{2024}	11.16	16.34	33.91	10.82	13.36	16.78	11.48	16.43	31.38
B_{male} / B_{female}	0.970	1.050	1.115	1.020	1.082	1.137	0.980	1.060	1.129

	<i>base</i>			<i>lag3</i>			<i>uniformM</i>		
	<u>5%</u>	<u>50%</u>	<u>95%</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>	<u>5%</u>	<u>50%</u>	<u>95%</u>
Probabilities									
$P(B_{2020} > B_{MN})$		0.995			1.000			0.994	
$P(SSB_{2020} < 20\%SSB_0)$		0.000			0.000			0.000	
$P(SSB_{2020} < 10\%SSB_0)$		0.000			0.000			0.000	
$P(SSB_{2020} < 20\%SSB_{0now})$		0.000			0.000			0.000	
$P(SSB_{2020} < 10\%SSB_{0now})$		0.000			0.000			0.000	
$P(SSB_{2024} < 20\%SSB_0)$		0.000			0.000			0.002	
$P(SSB_{2024} < 10\%SSB_0)$		0.000			0.000			0.000	
$P(SSB_{2024} < 20\%SSB_{0now})$		0.000			0.000			0.000	
$P(SSB_{2024} < 10\%SSB_{0now})$		0.000			0.000			0.000	
$P(B_{2024} > B_{2020})$		0.335			0.984			0.336	
$P(SSB_{2024} > SSB_{2020})$		0.281			0.901			0.312	
$P(B_{2024tot} > B_{2020tot})$		0.320			0.764			0.336	
$P(B_{2020} > B_R)$		0.691			0.724			0.668	
$P(B_{2024} > B_R)$		0.440			0.952			0.430	

7. FIGURES



Figure 2: Temporal extent of data for each fishing year used in the CRA 4 stock assessment. The sizes of the bubbles represent the relative number of recaptured tags, the effective sample size for length frequency distributions, the standard deviation for CPUE series, or a fixed size for catch. The different bubble colours represent different data sets (e.g., for CPUE, the CR, FSU, and CELR series). See Starr et al. (2021) for a detailed description of these data.

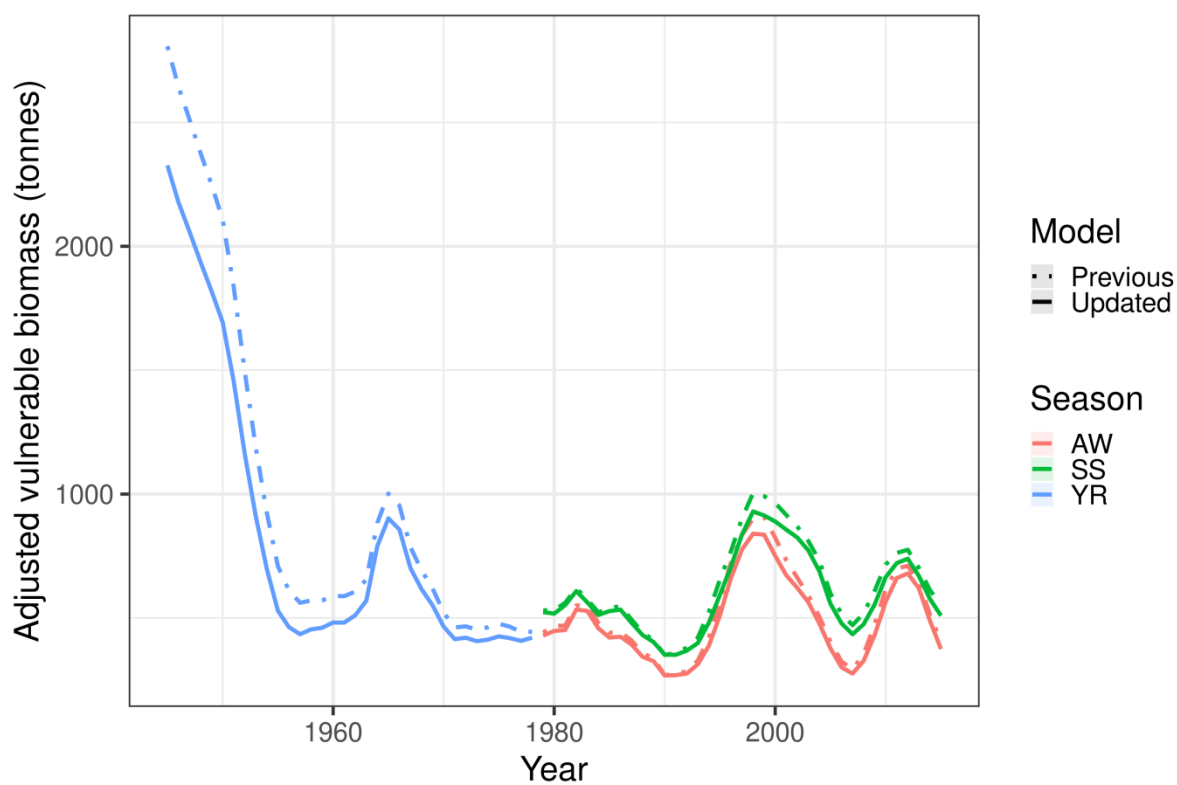


Figure 3: CRA 4 trajectory of adjusted vulnerable biomass by season. Comparison with the 2016 assessment: thick solid line is the MAP for the 2020 model mimic of the 2016 model using LSD. The dashed line is the previous model's MAP using LSD in 2016.

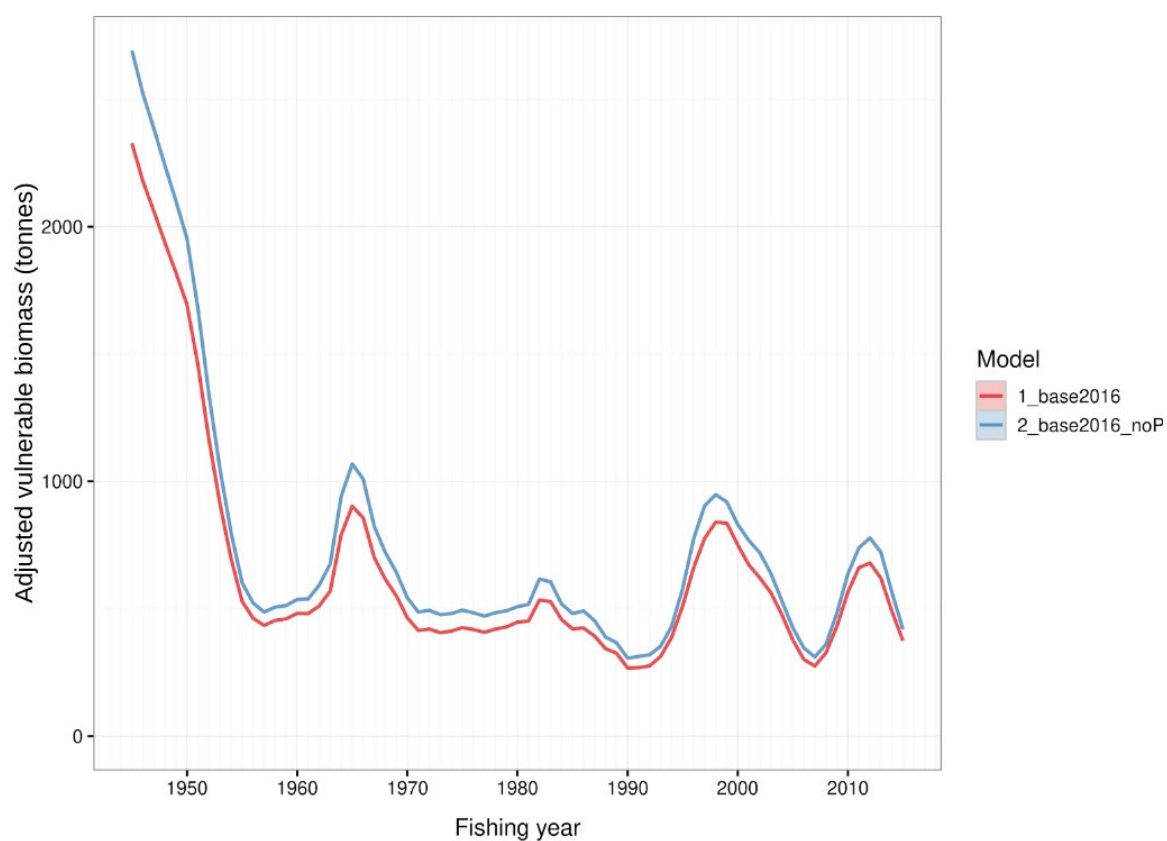


Figure 4: CRA 4 trajectory of adjusted vulnerable biomass. Comparison of mimicked 20166 assessment *1_base2016* with iterative update: *2_base2016_noP* (same as *1_base2016* but does not fit to the puerulus index).

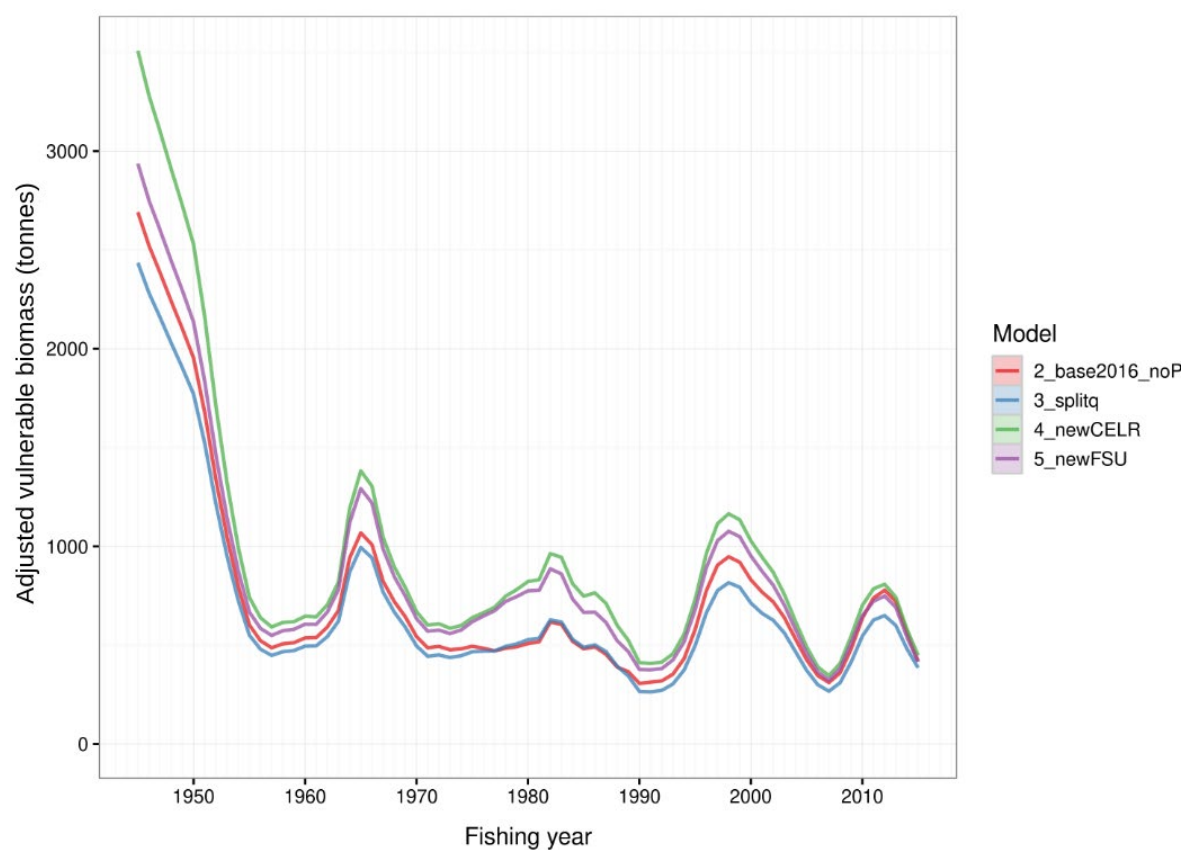


Figure 5: CRA 4 trajectory of adjusted vulnerable biomass. Comparison of mimicked 2016 assessment model without the puerulus index *1_base2016_noP* with iterative updates: Model *3_splitq* and Model *4_newCELR*, and *5_newFSU*.

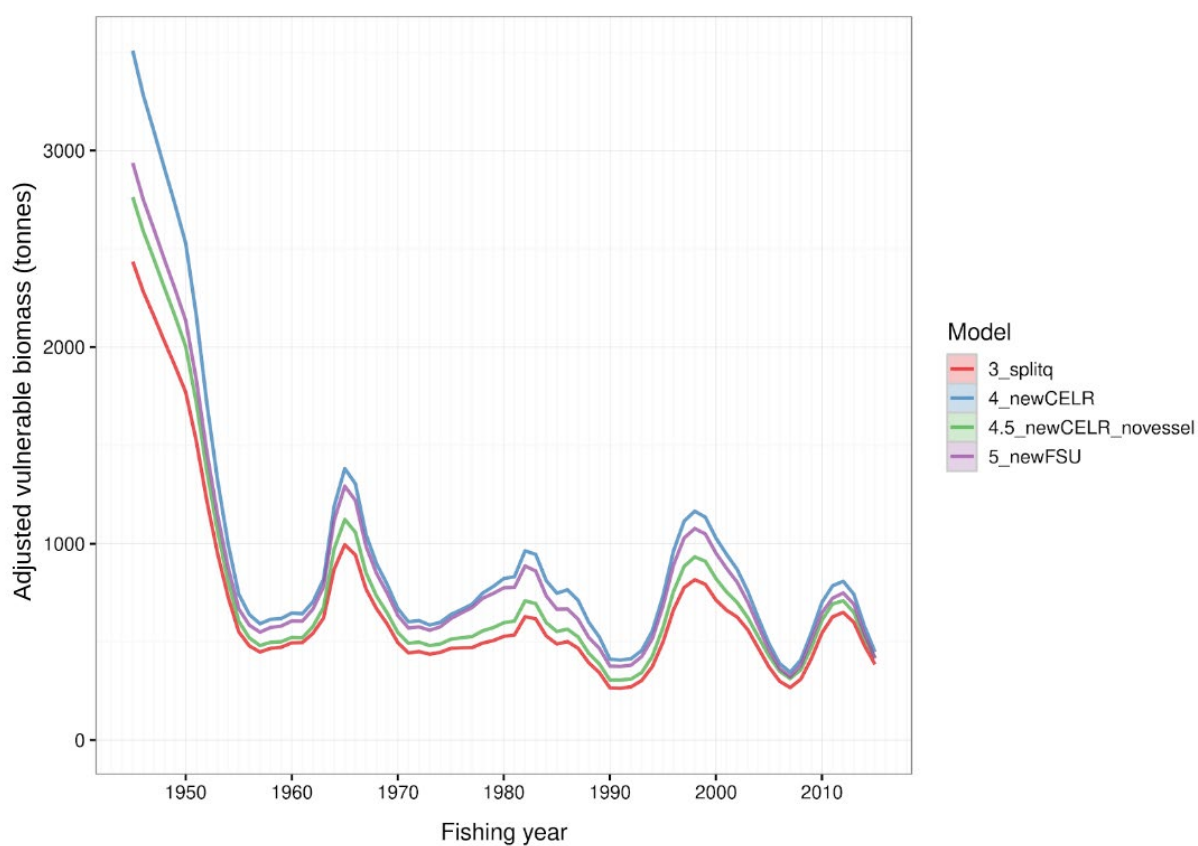


Figure 6: CRA 4 MAP trajectory of adjusted vulnerable biomass. Comparison of mimicked 2016 assessment Model *3_splitq* with the new CPUE series (*4_newCELR* and *5_newFSU*), comparing the impact with and without the vessel effect on the updated CELR series (*4.5_newCELR_novessel*).

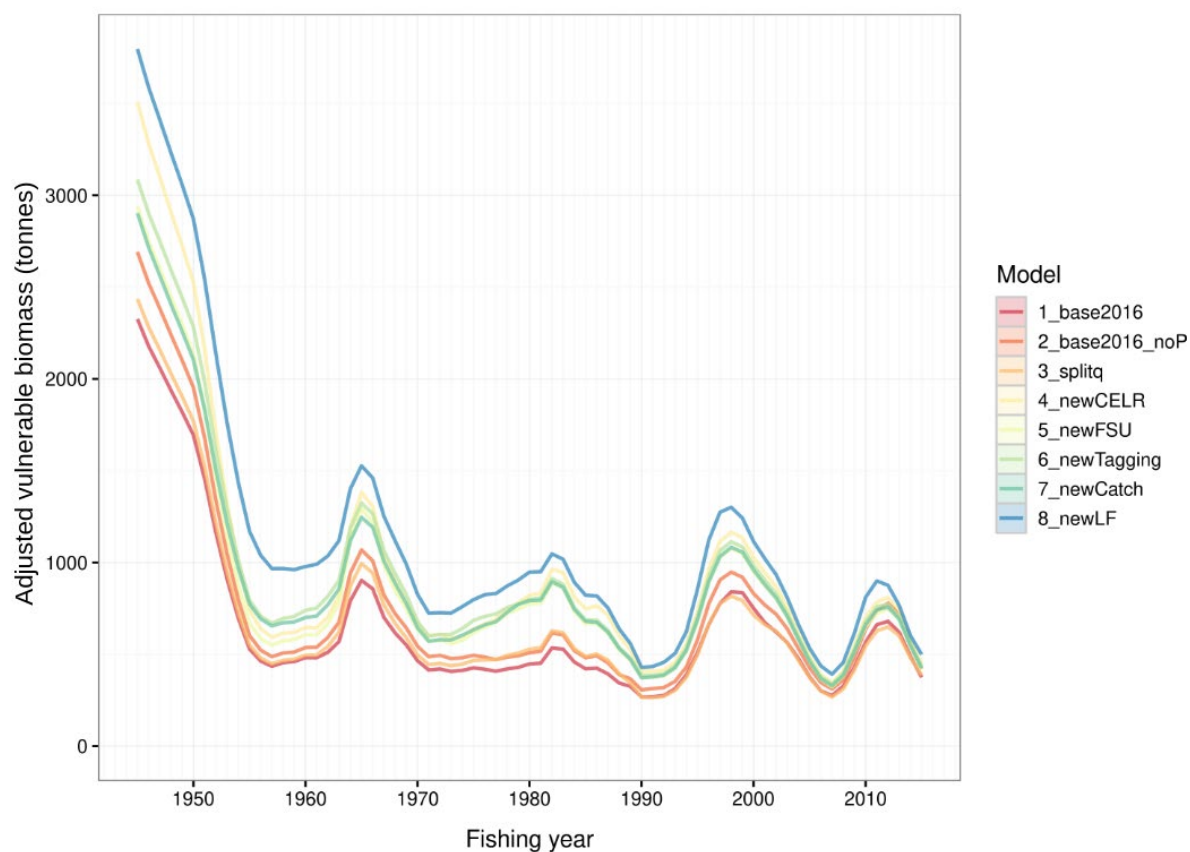


Figure 7: CRA 4 MPA trajectory of adjusted vulnerable biomass. Comparison of mimicked 2016 assessment Model *1_base2016* with iterative updates: Models *2_base2016_noP*, *3_splitq*, *4_newCELR*, *5_newFSU*, *6_newTagging*, *7_newCatch*, *8_newLF*.

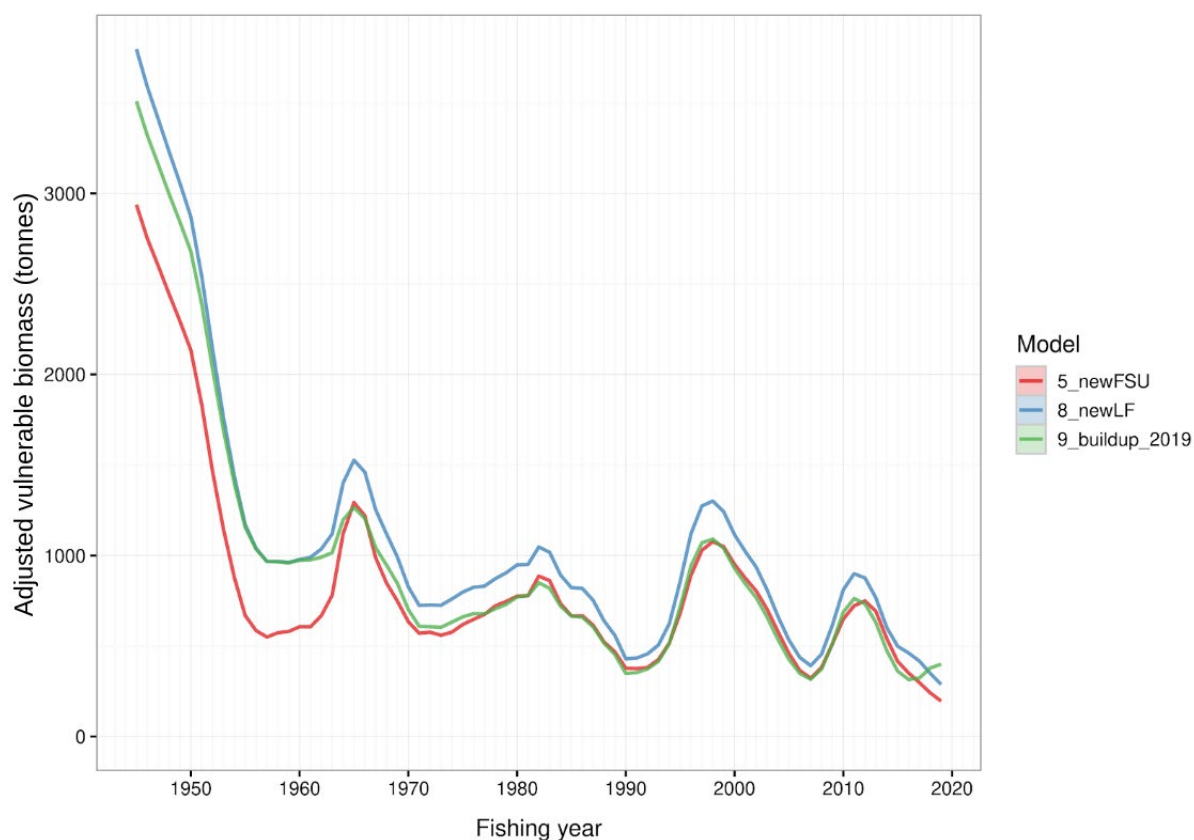


Figure 8: CRA 4 trajectory of adjusted vulnerable biomass. Comparison of mimicked 2016 assessment with updated CPUE series *5_newFSU* with tagging, catch, and LF data through 2015 (*8_newLF*) and all data types extended through 2019 (*9_buildup_2019*). Adjusted vulnerable biomass for models *5_newFSU* and *8_newLF* is derived from the model estimates through 2015, and the values extended to 2019 represent 5-year projections at current catch. Adjusted vulnerable biomass for model *9_buildup_2019* is estimated using data extended through 2019.

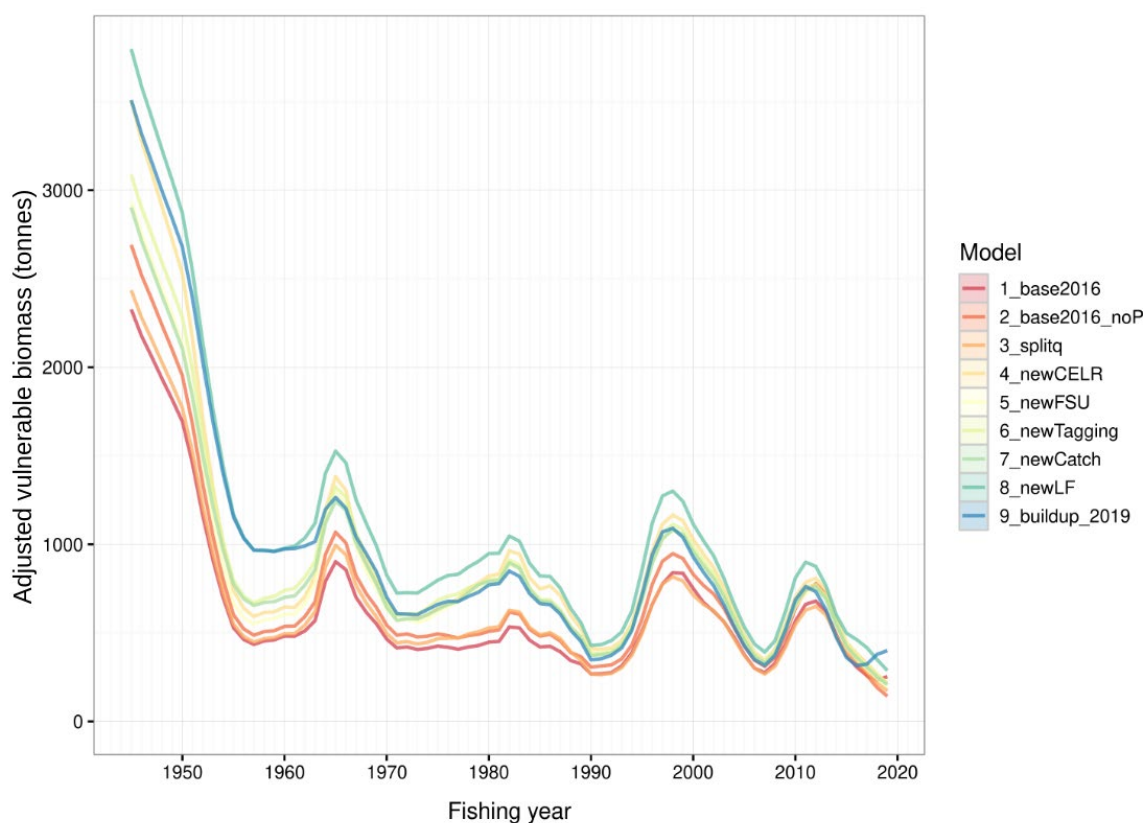


Figure 9: CRA 4 trajectory of adjusted vulnerable biomass. Comparison of mimicked 2016 assessment Model *1_base2016* with all nine additional iterative updates. Adjusted vulnerable biomass for all models except *9_buildup_2019* are estimated through 2015 and then projected forward 5 years to 2019 based on current catch. Adjusted vulnerable biomass for model *9_buildup_2019* is estimated using data extended through 2019.

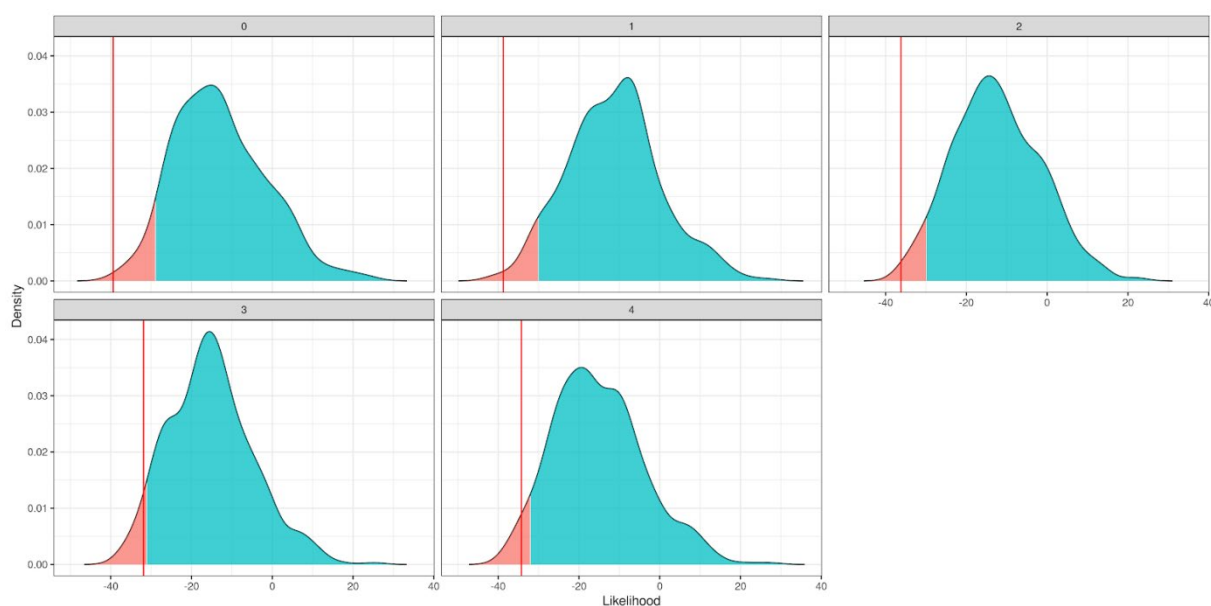


Figure 10: CRA 4 puerulus randomisation trials. Each panel shows the puerulus index likelihood for lags 0–4 years (vertical red lines) and the distribution of likelihoods from 500 puerulus randomisation trials for each lag. The red shaded zone represents the 5% quantile of the distribution. The red line falls within the red zone for all lag options, meaning all lag options are statistically significant.

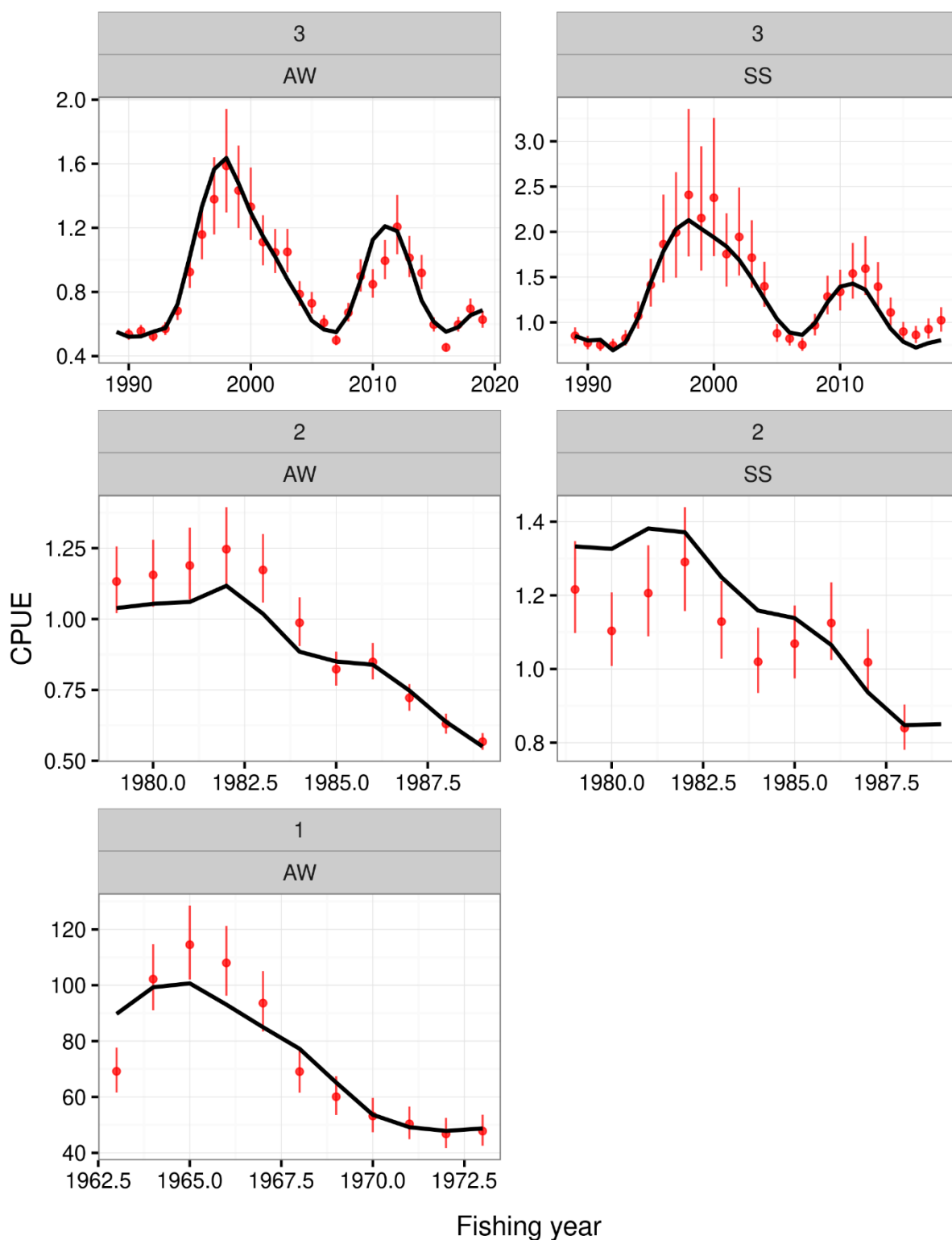


Figure 11: CRA 4 base case: MAP model fit to CPUE by fishing year and season (AW = autumn-winter, SS = spring-summer). Upper panels = CELR fit; middle panels = FSU fit; lower panels = CR fit.

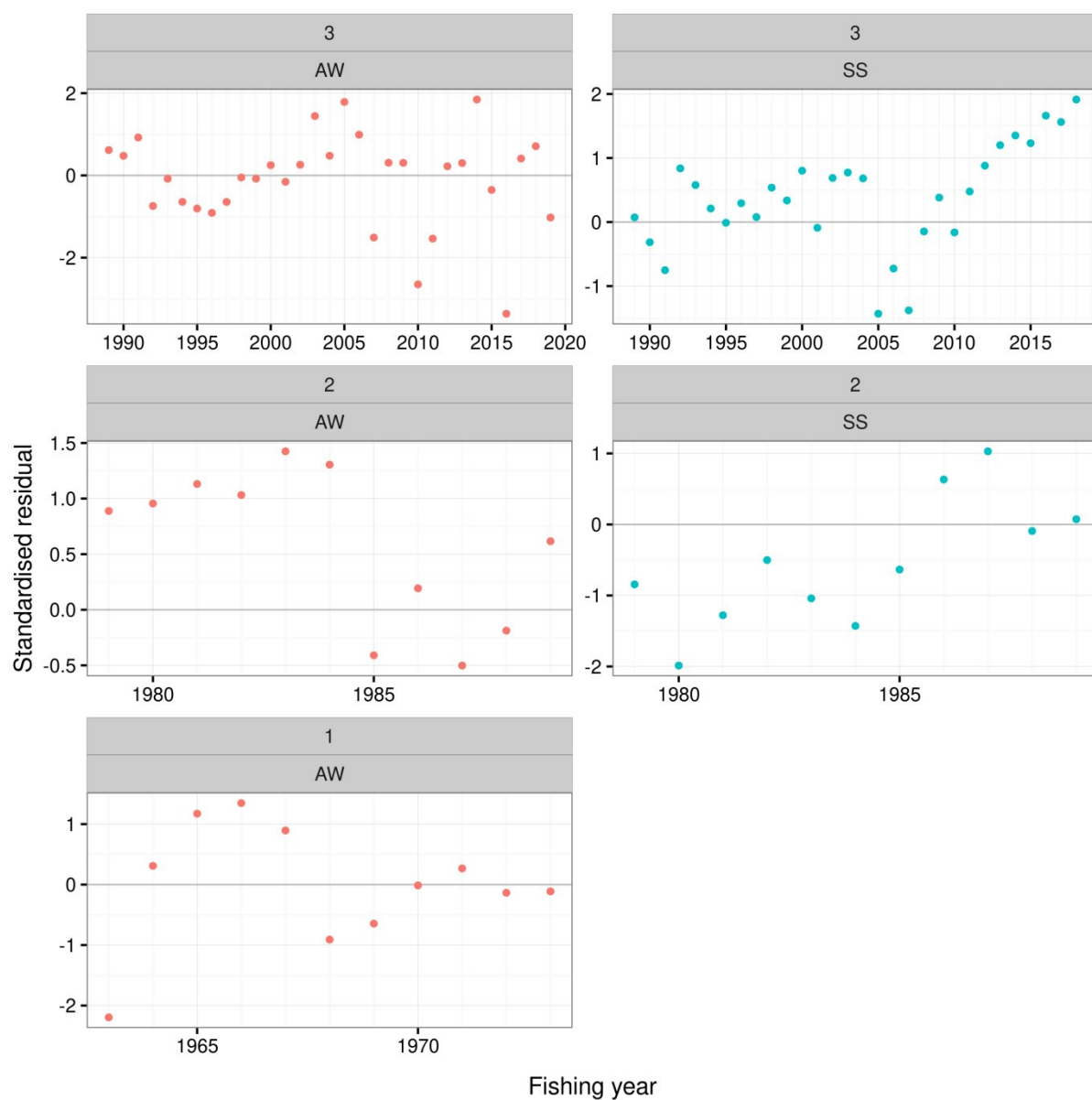


Figure 12: CRA 4 base case: MAP residuals from fit to CPUE. Upper panels = CELR fit; middle panels = FSU fit; lower panels = CR fit.

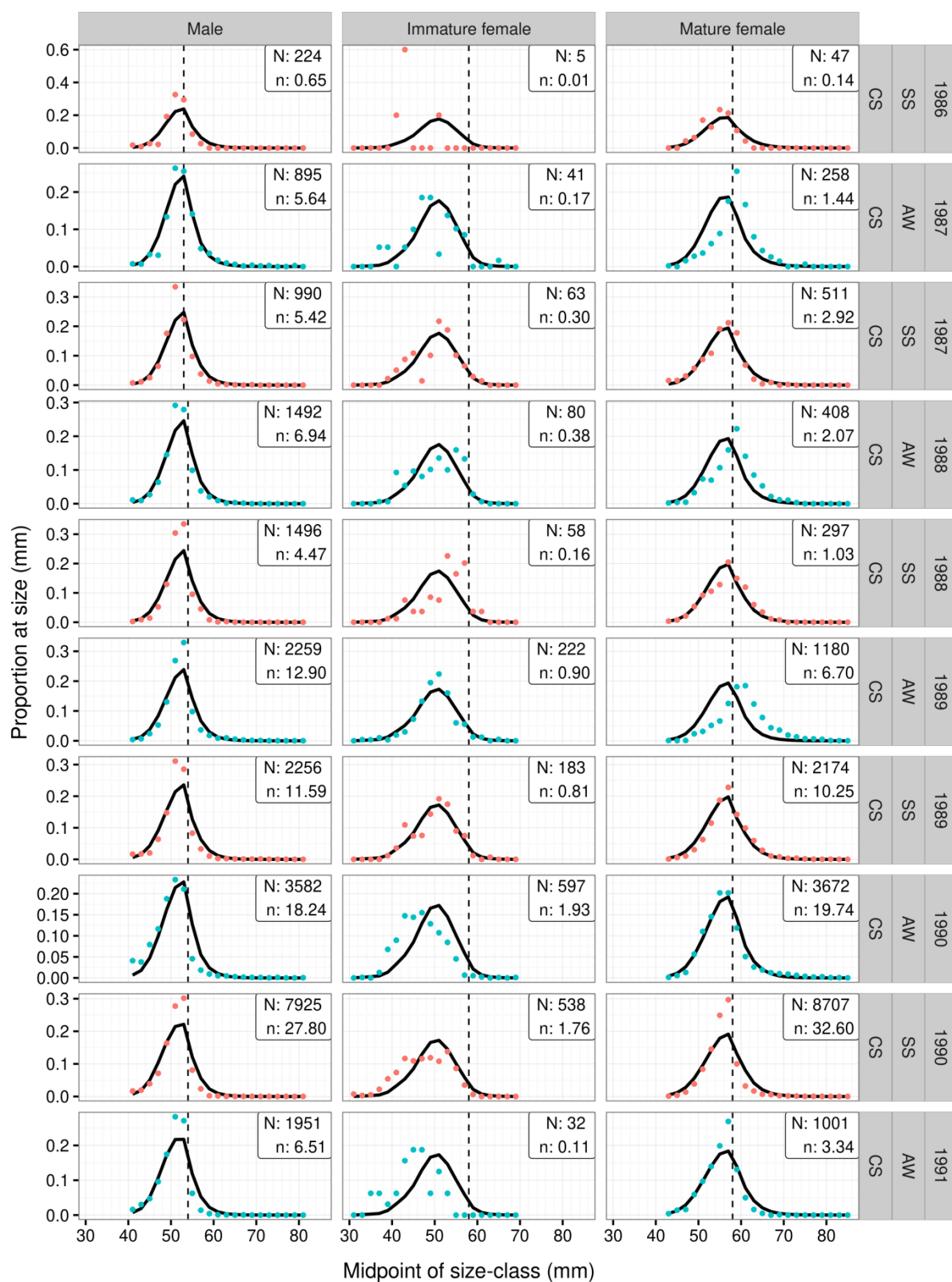


Figure 13: CRA 4 base case MAP: Model fits to LFs from 1986SS CS – 1991 AW CS by sex, fishing year, season, and data source (AW = autumn/winter, SS = spring/summer, LB = logbook, CS = catch sampling).

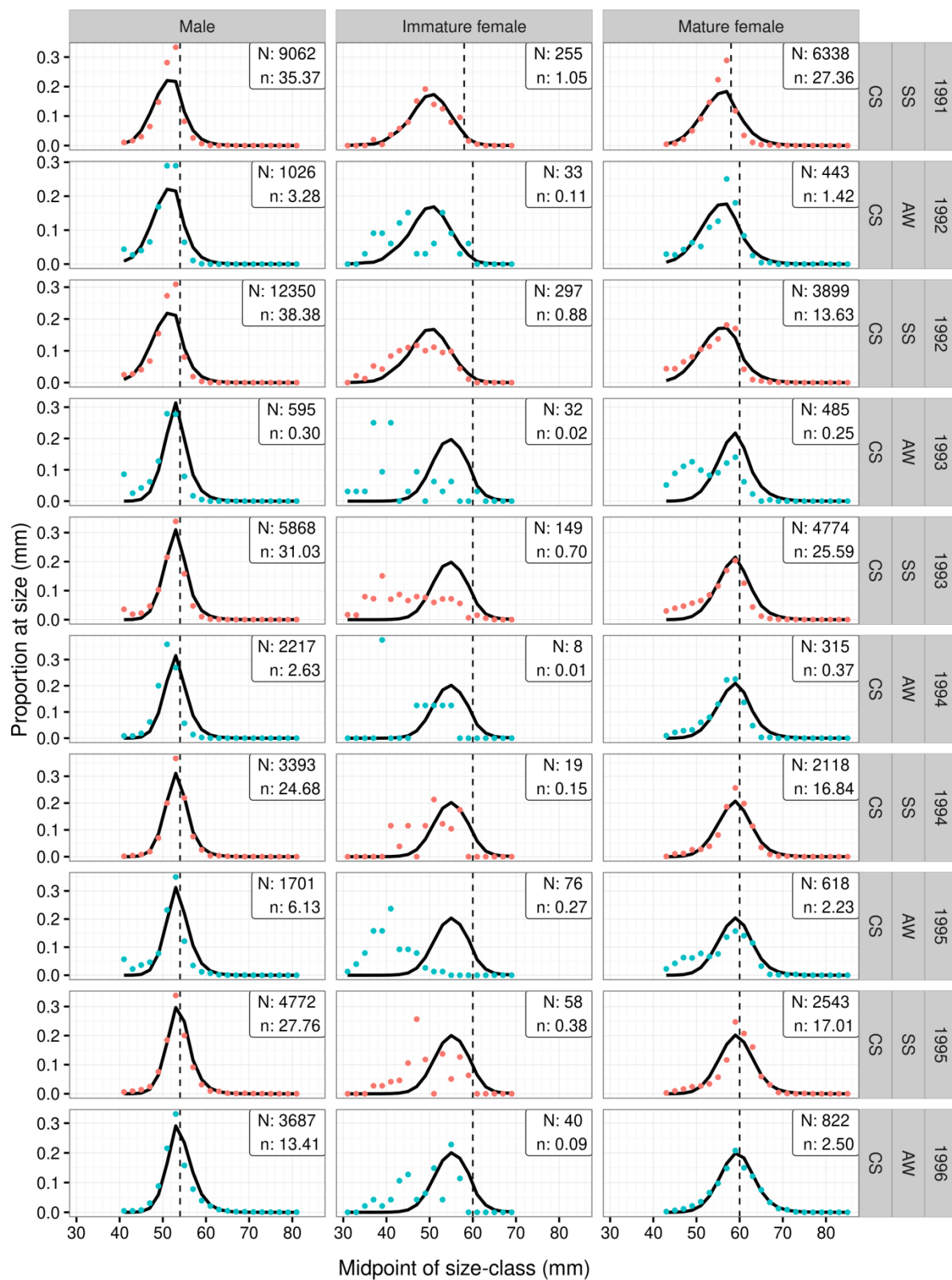


Figure 14: CRA 4 base case MAP: Model fits to LFs from 1991 SS CS – 1996 AW CS by sex, fishing year, season, and data source (AW = autumn/winter, SS = spring/summer, LB = logbook, CS = catch sampling).

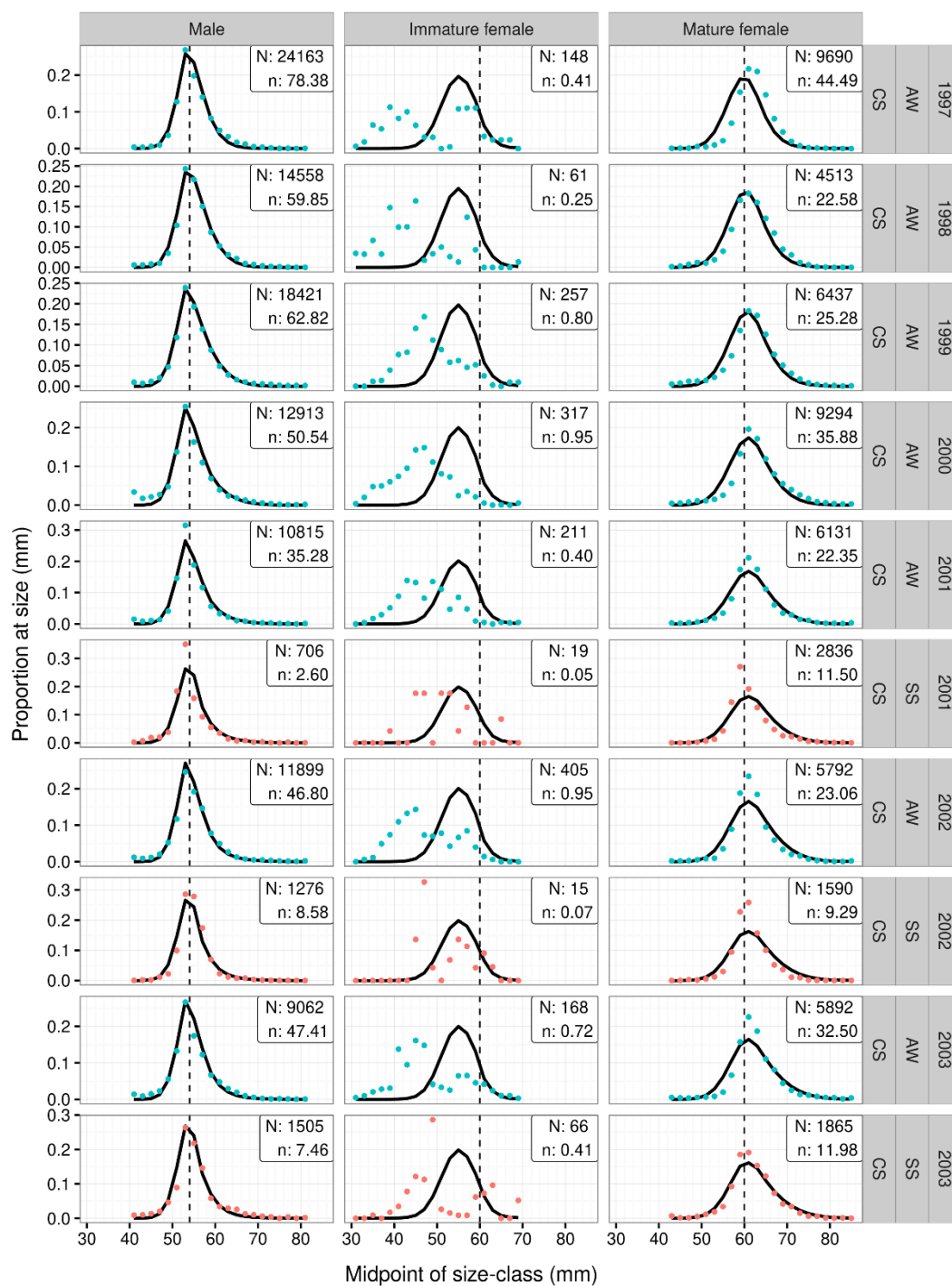


Figure 15: CRA 4 base case MAP: Model fits to LFs from 1997 AW CS – 2003 SS CS by sex, fishing year, season, and data source (AW = autumn/winter, SS = spring/summer, LB = logbook, CS = catch sampling).

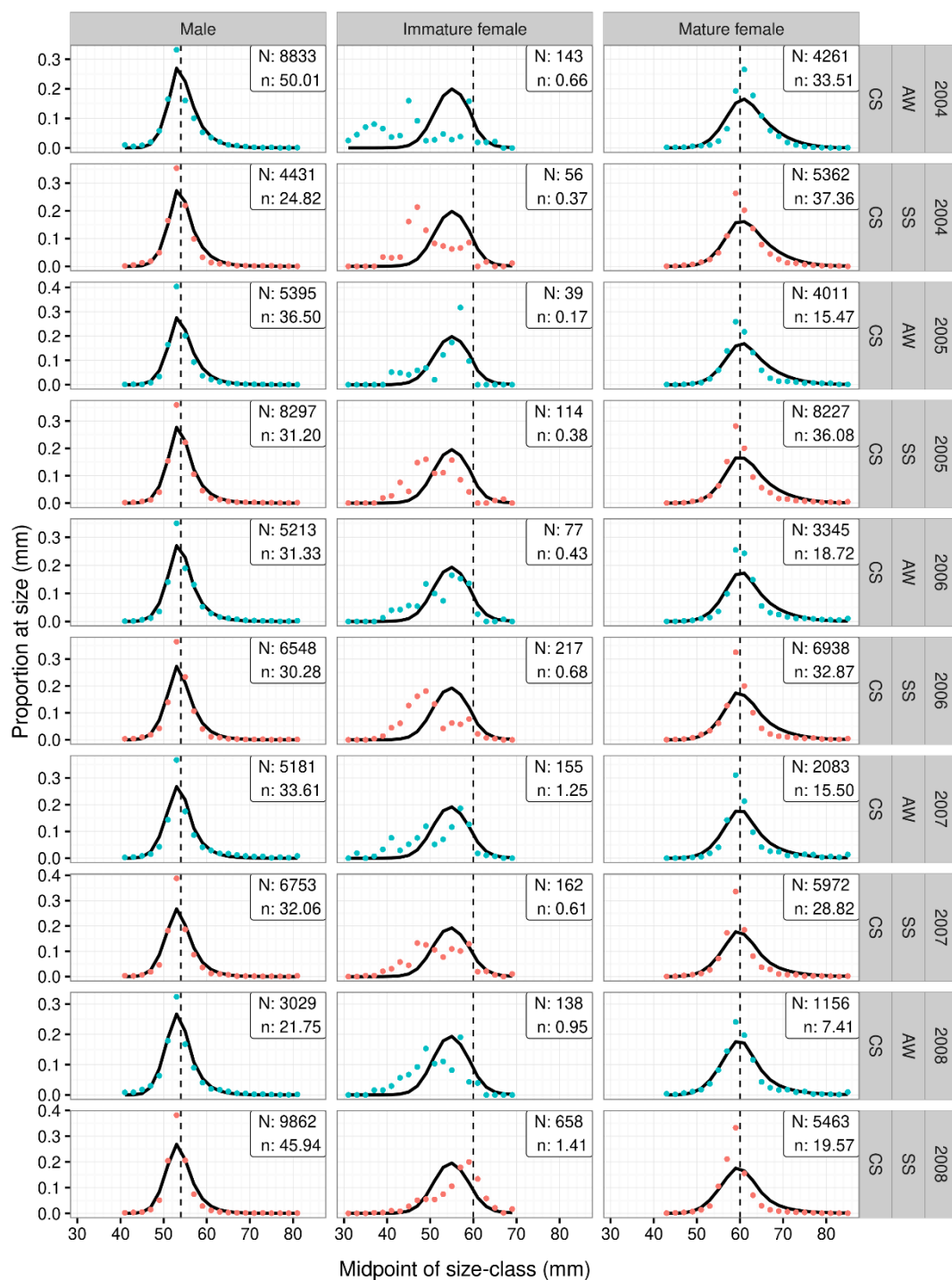


Figure 16: CRA 4 base case MAP: Model fits to LFs from 2004 AW CS – 2008 SS CS by sex, fishing year, season, and data source (AW = autumn/winter, SS = spring/summer, LB = logbook, CS = catch sampling).

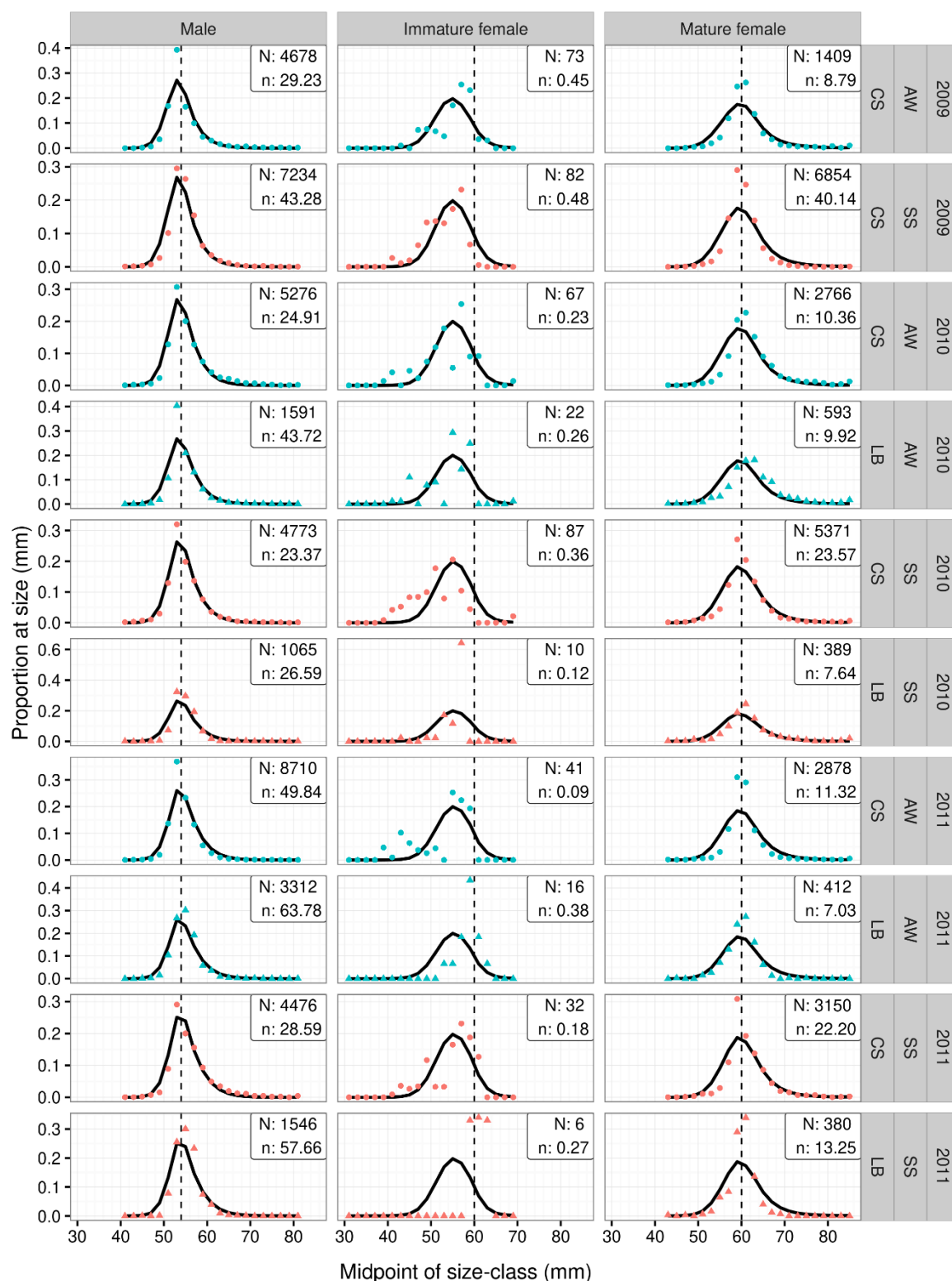


Figure 17: CRA 4 base case MAP: Model fits to LFs from 2009 AW CS – 2011 SS CS by sex, fishing year, season, and data source (AW = autumn/winter, SS = spring/summer, LB = logbook, CS = catch sampling).

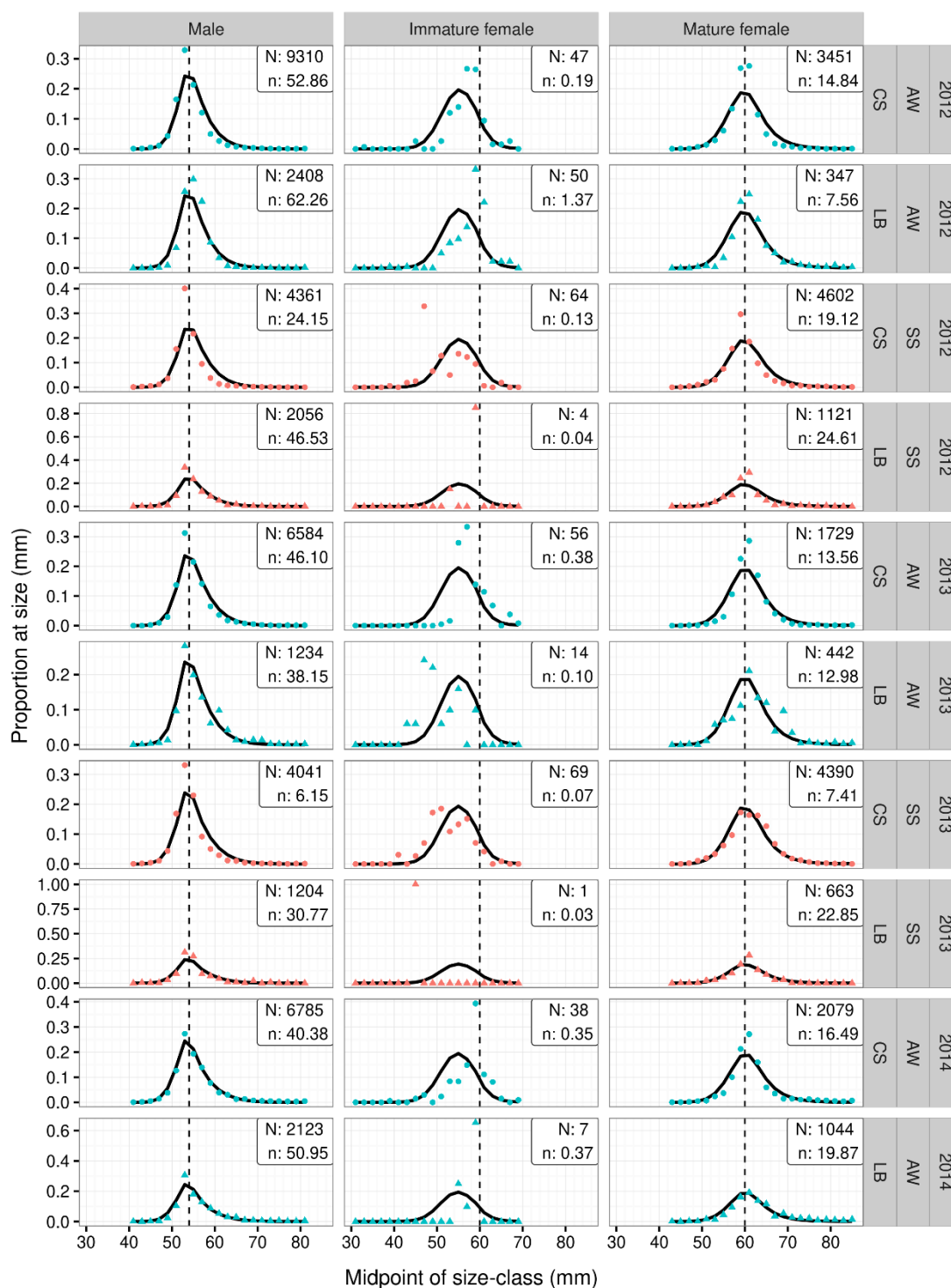


Figure 18: CRA 4 base case MAP: Model fits to LFs from 2012 AW CS – 2014 AW LB by sex, fishing year, season, and data source (AW = autumn/winter, SS = spring/summer, LB = logbook, CS = catch sampling).

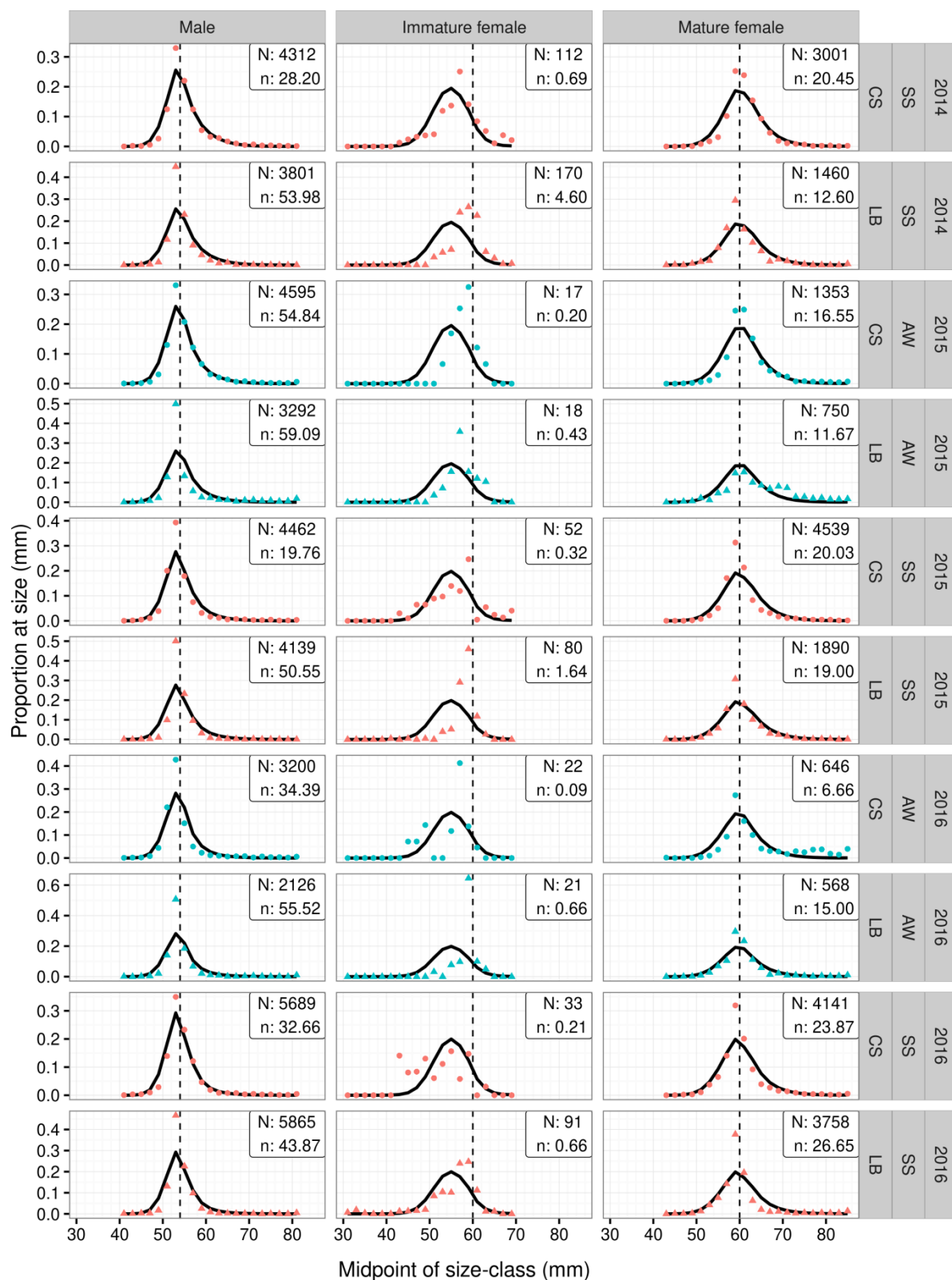


Figure 19: CRA 4 base case MAP: Model fits to LF data from 2014 SS CS – 2016 SS LB by sex, fishing year, season and data source (AW = autumn/winter, SS = spring/summer, LB = logbook, CS = catch sampling).

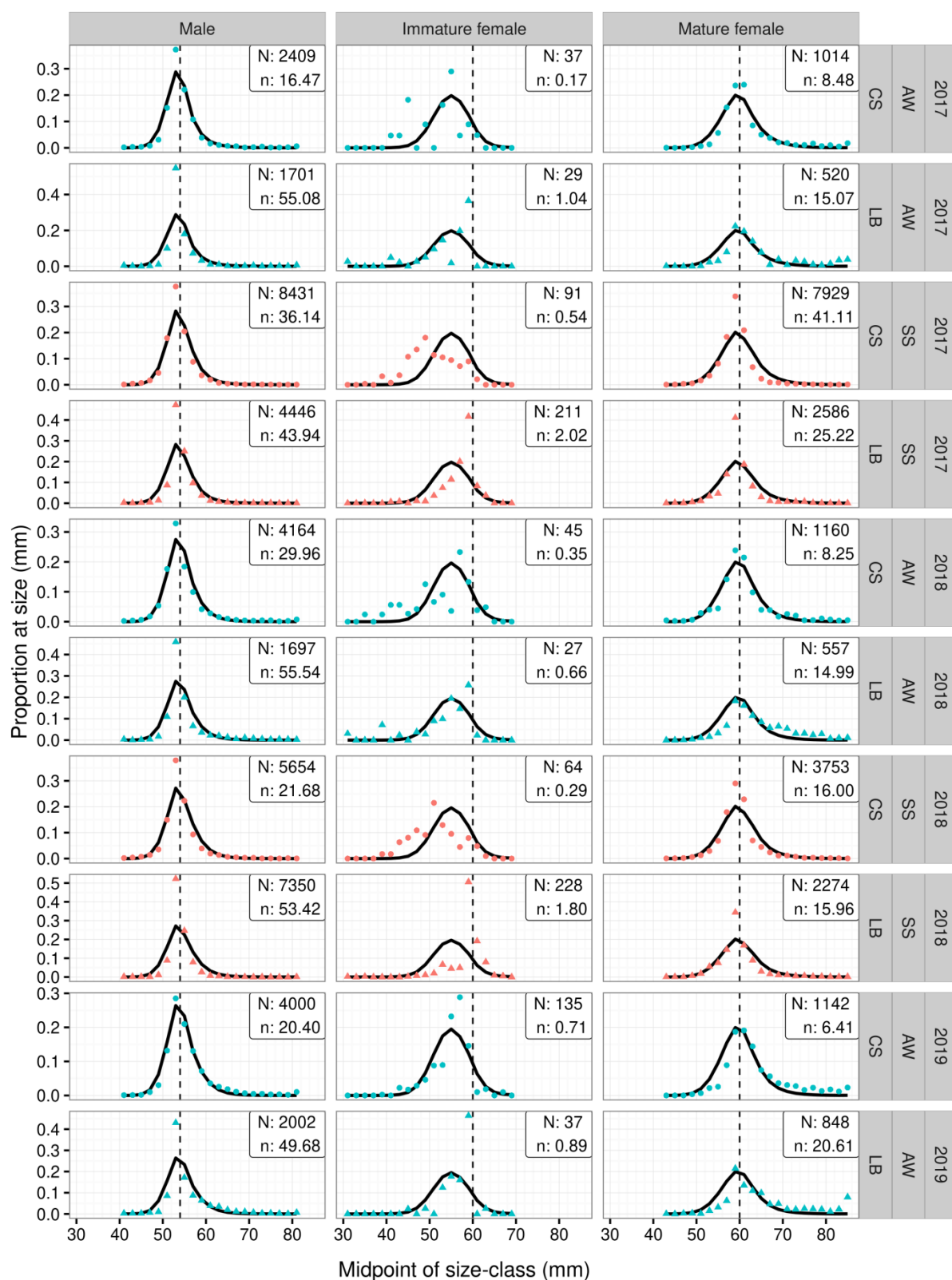


Figure 20: CRA 4 base case MAP: Model fits to LFs from 2017 AW CS – 2019 AW LB by sex, fishing year, season, and data source (AW = autumn/winter, SS = spring/summer, LB = logbook, CS = catch sampling).

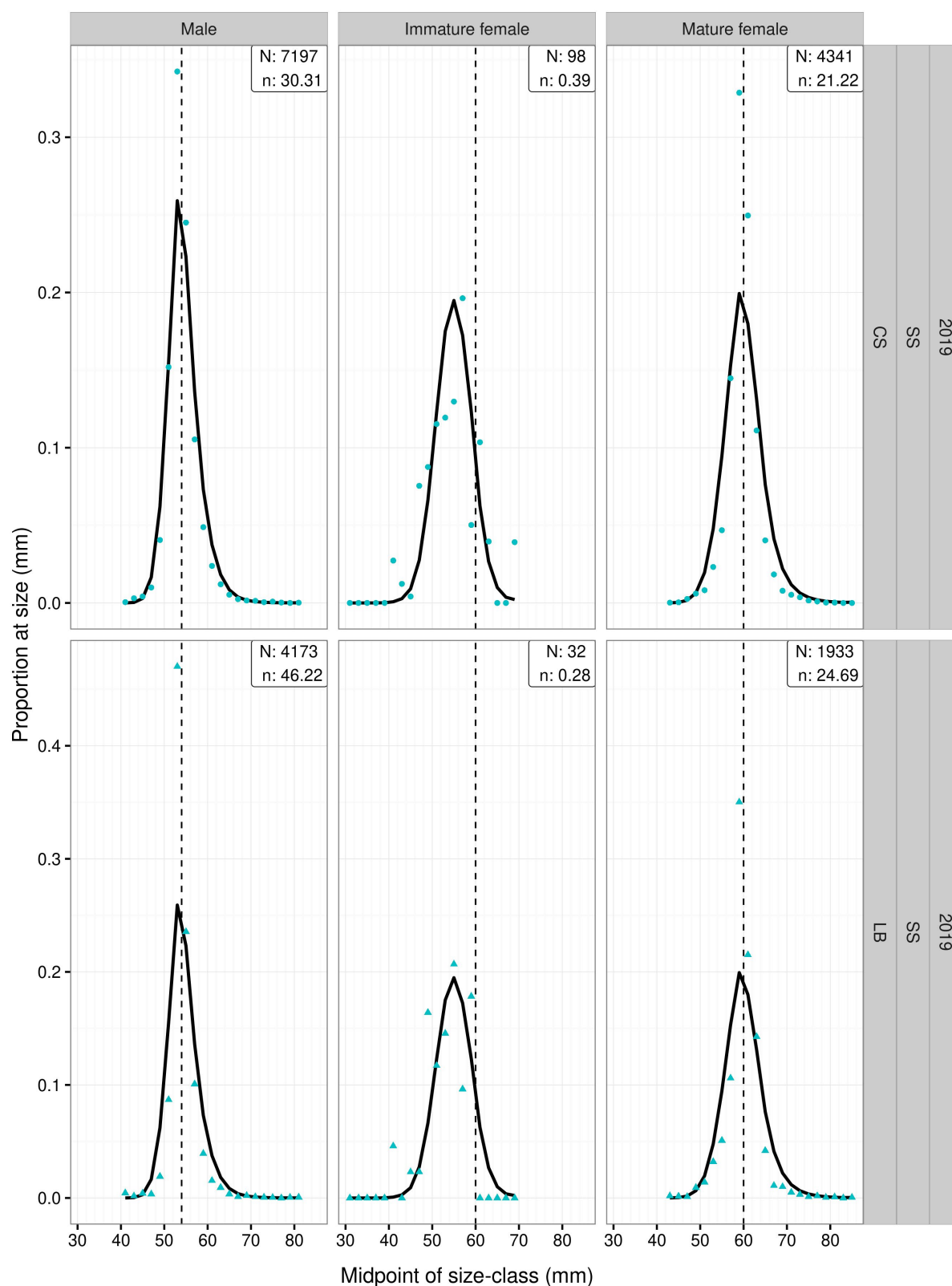


Figure 21: CRA 4 base case MAP: model fits to LFs from 2019 SS CS and LB by sex, fishing year, season, and data source (AW = autumn/winter, SS = spring/summer, LB = logbook, CS = catch sampling).

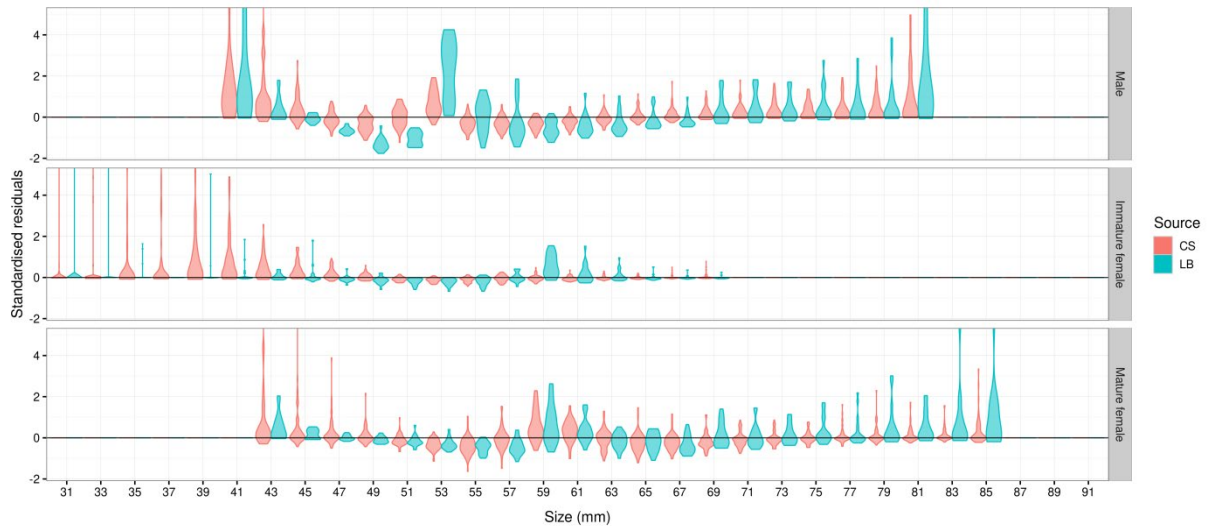


Figure 22: CRA 4 base case MAP: residuals from fit to the LF data, showing residuals by sex, 2 mm TW bin, and sampling source (CS = catch sampling, LB = logbook).

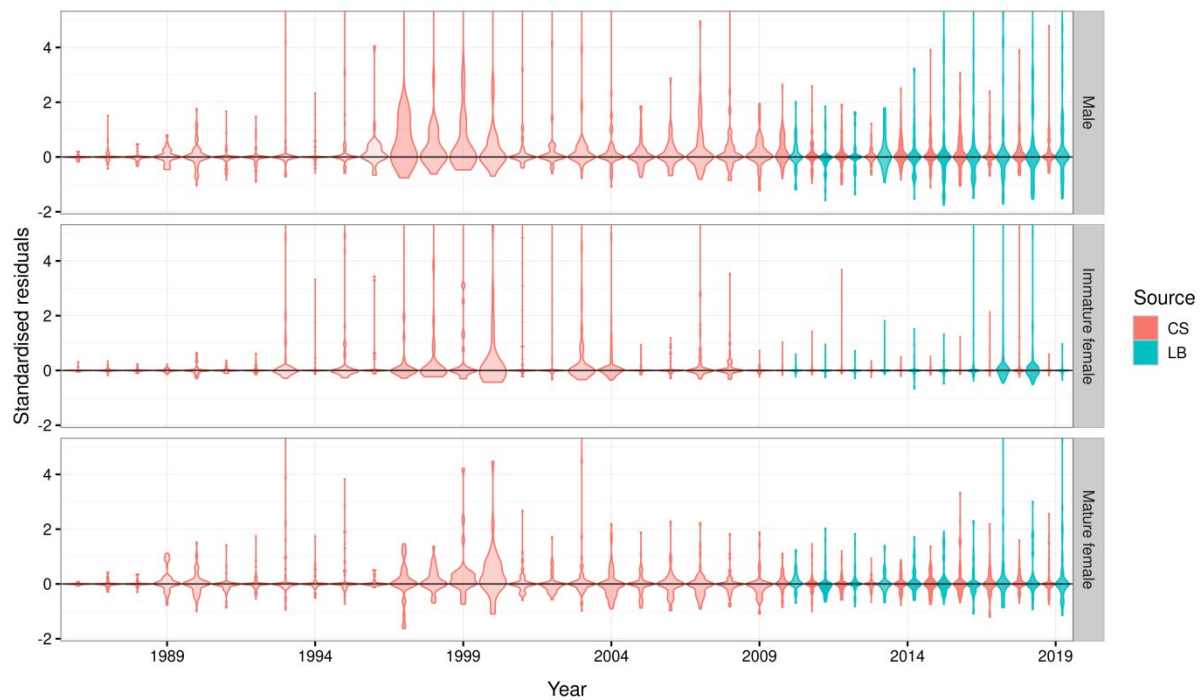


Figure 23: CRA 4 base case MAP: residuals from fit to the LF data, showing residuals by sex, year, and sampling source (CS = catch sampling, LB = logbook).

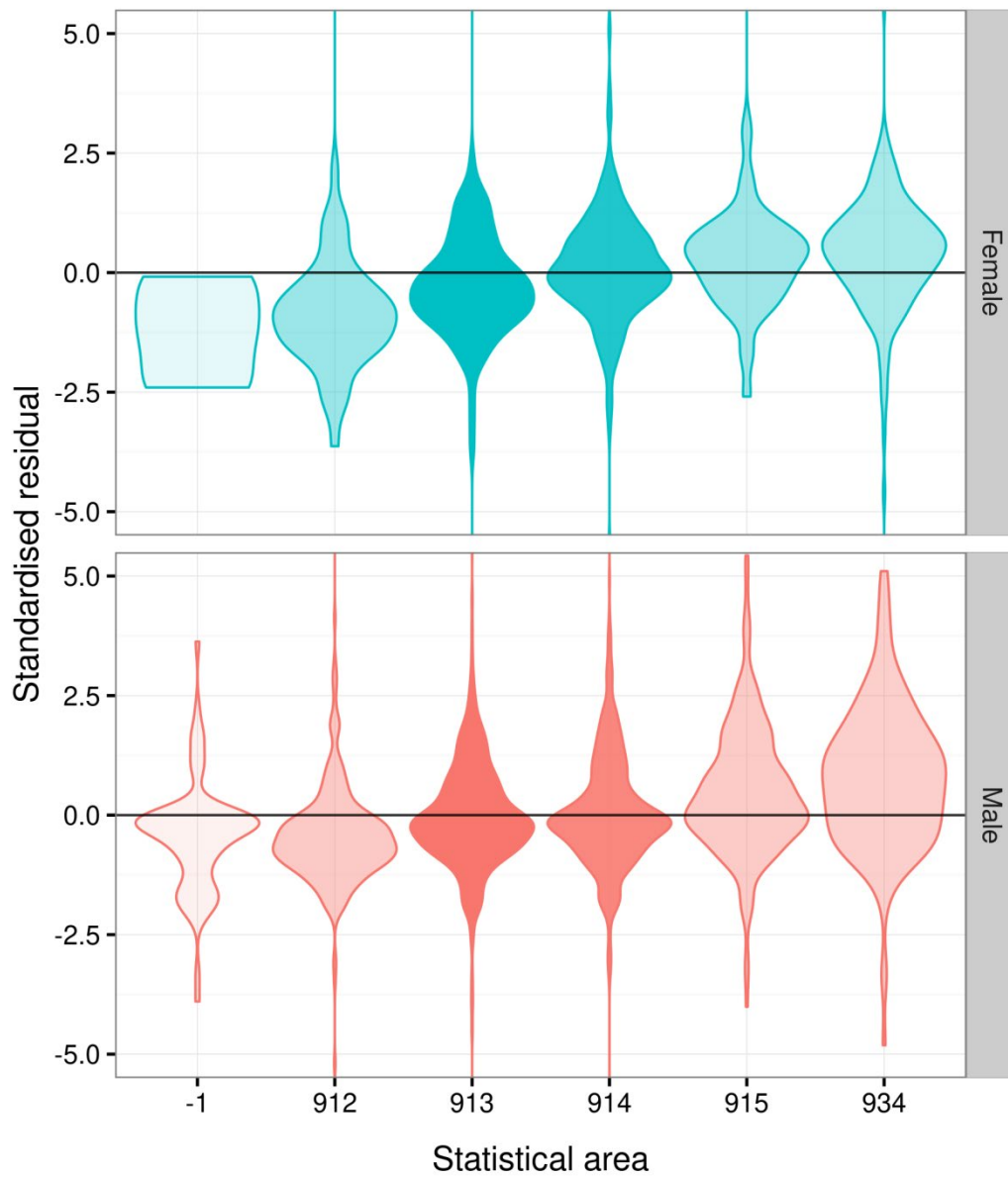


Figure 24: CRA 4 base case MAP: tag residuals by statistical area of release. Darker shading represents a higher number of tags by area.

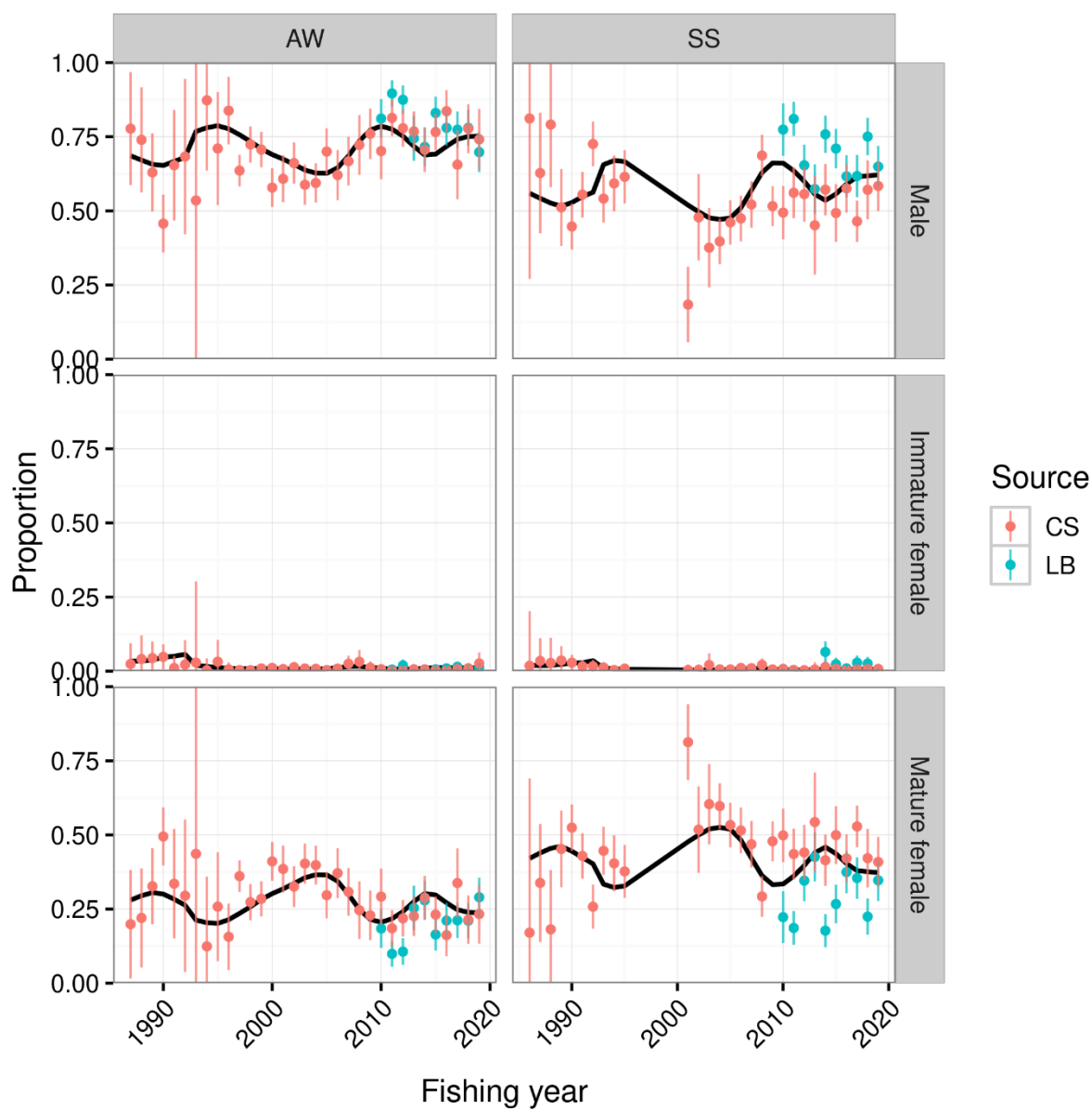


Figure 25: CRA 4 base case MAP: model fit to sex ratios, by year and LF data source (CS = catch sampling, LB = logbook).

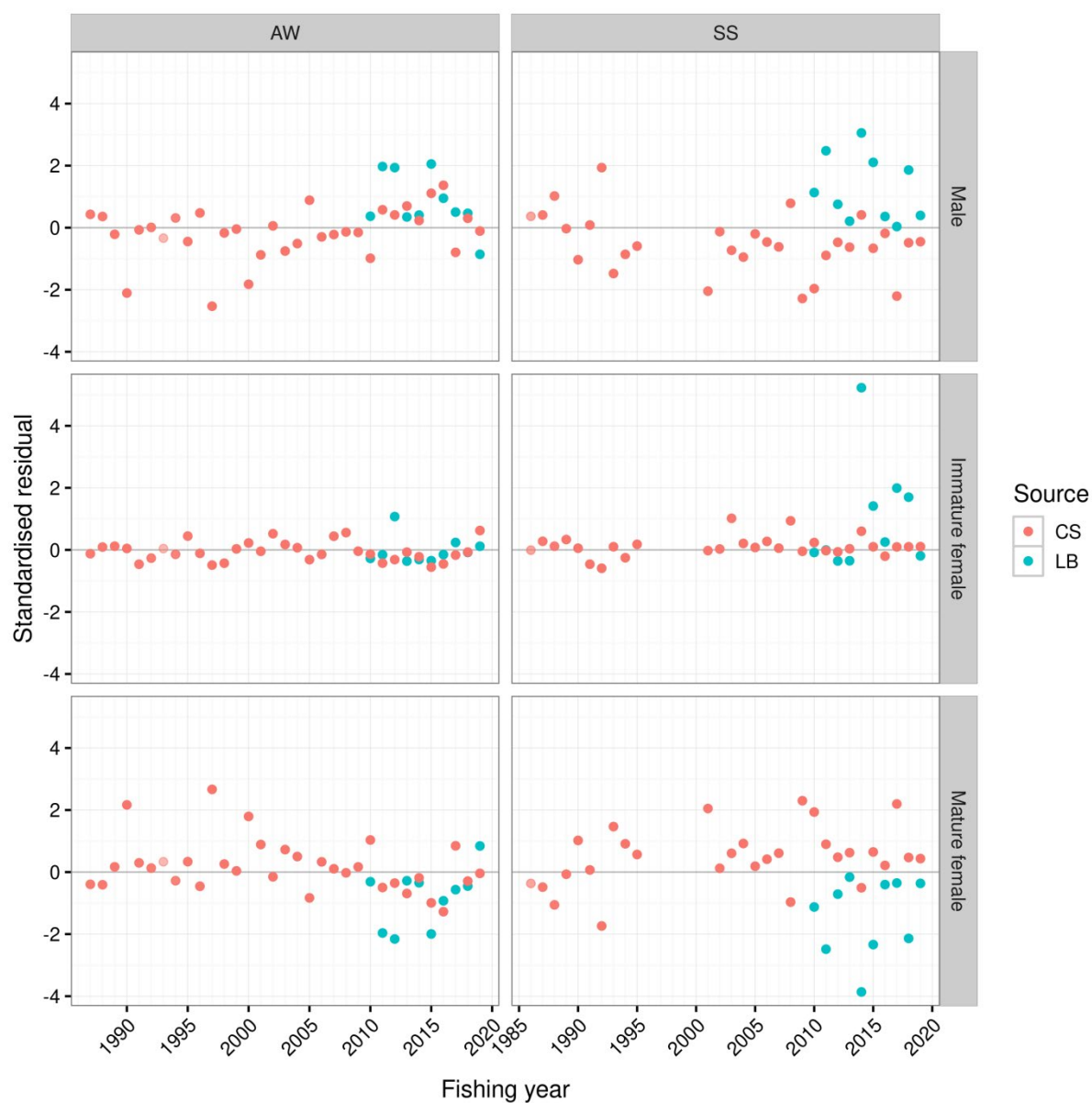


Figure 26: CRA 4 base case MAP: sex ratio residuals, by year and LF data source (CS = catch sampling, LB = logbook).

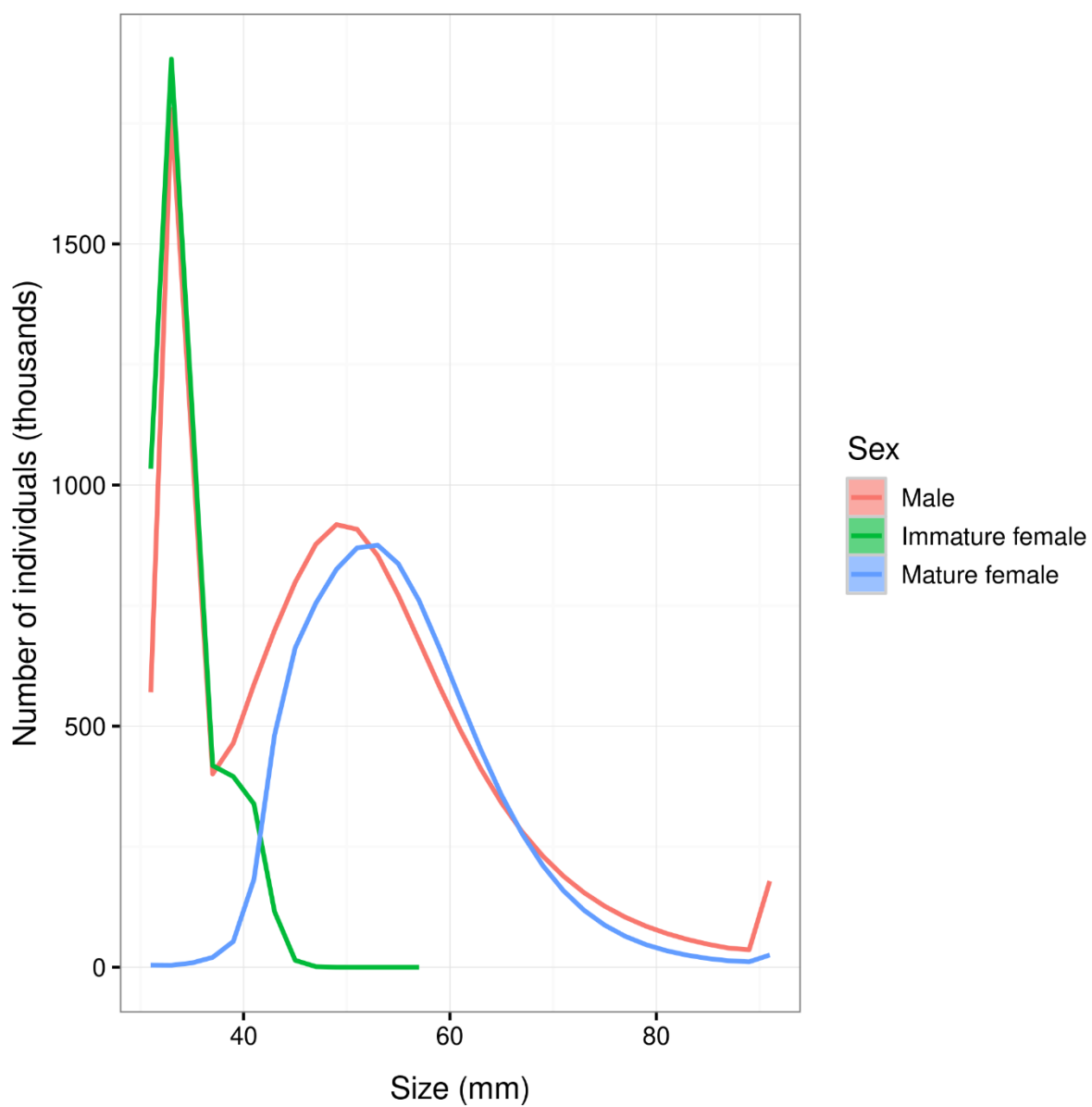


Figure 27: CRA 4 base case MAP: Initial number of individuals by sex category.

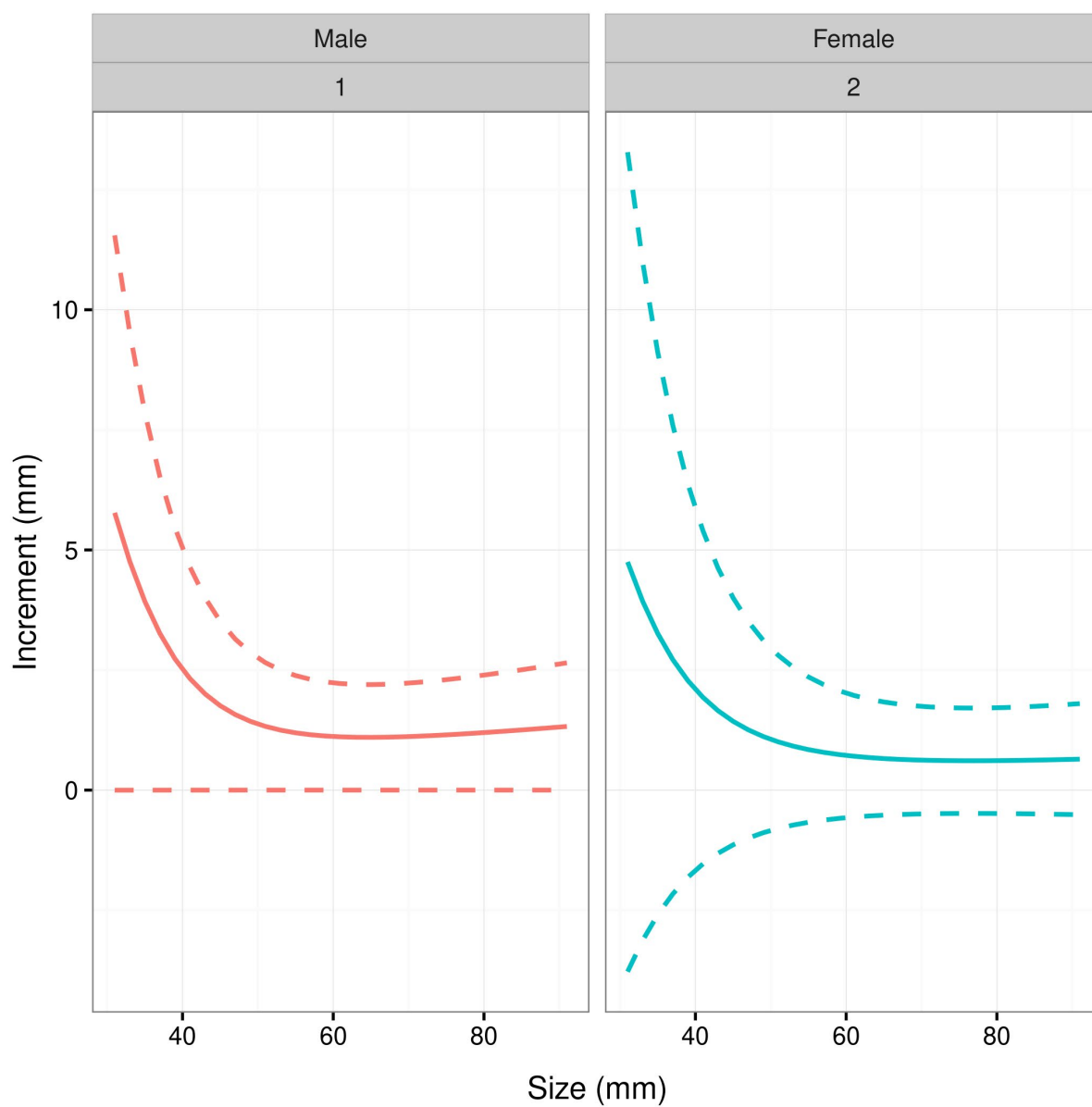


Figure 28: CRA 4 base case MAP: predicted six-month increments-at-length and ± 1 standard deviation.

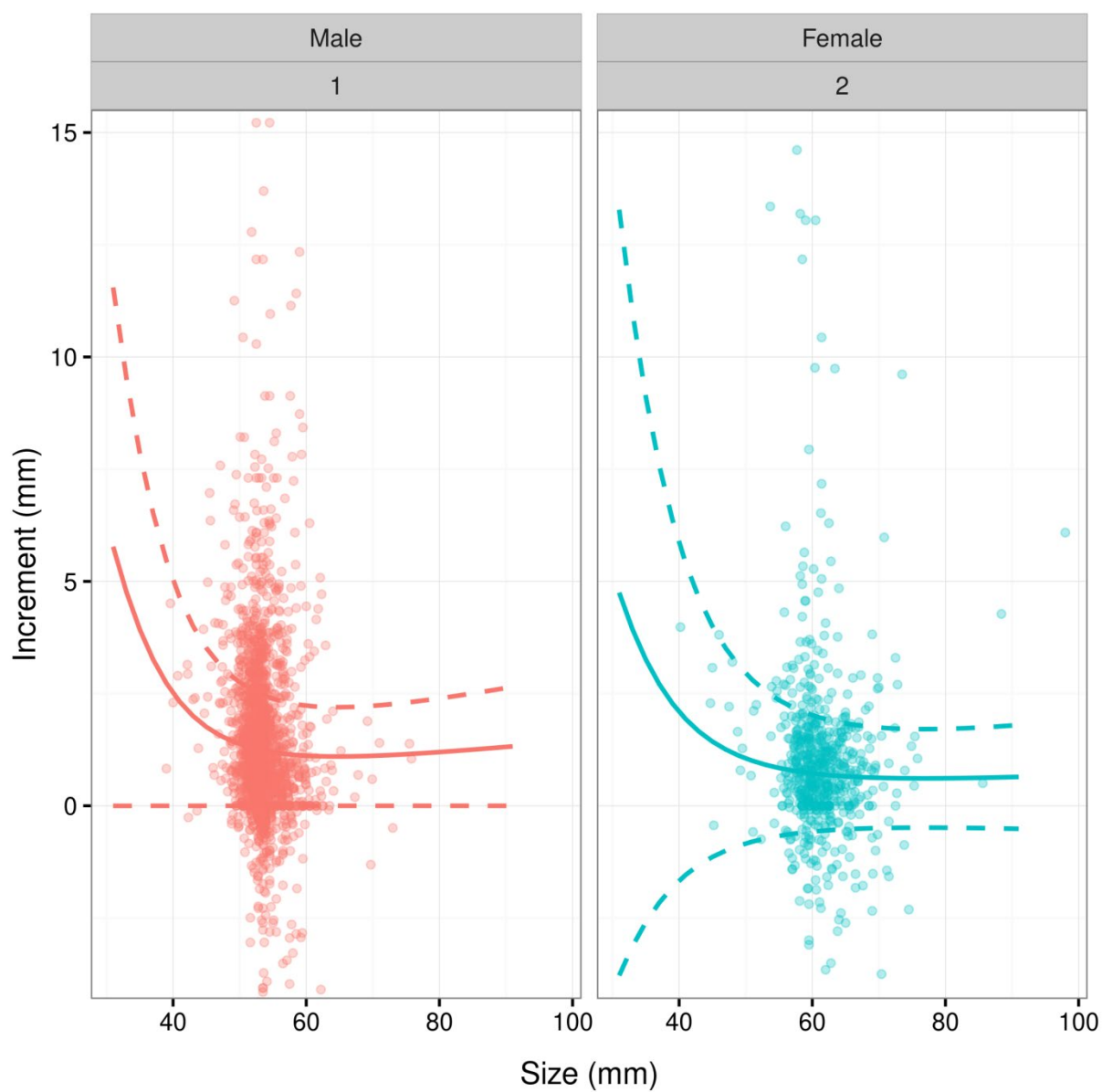


Figure 29: CRA 4 base case MAP: Predicted six-month increments-at-length and ± 1 standard deviation, with observed increments-at-length (points).

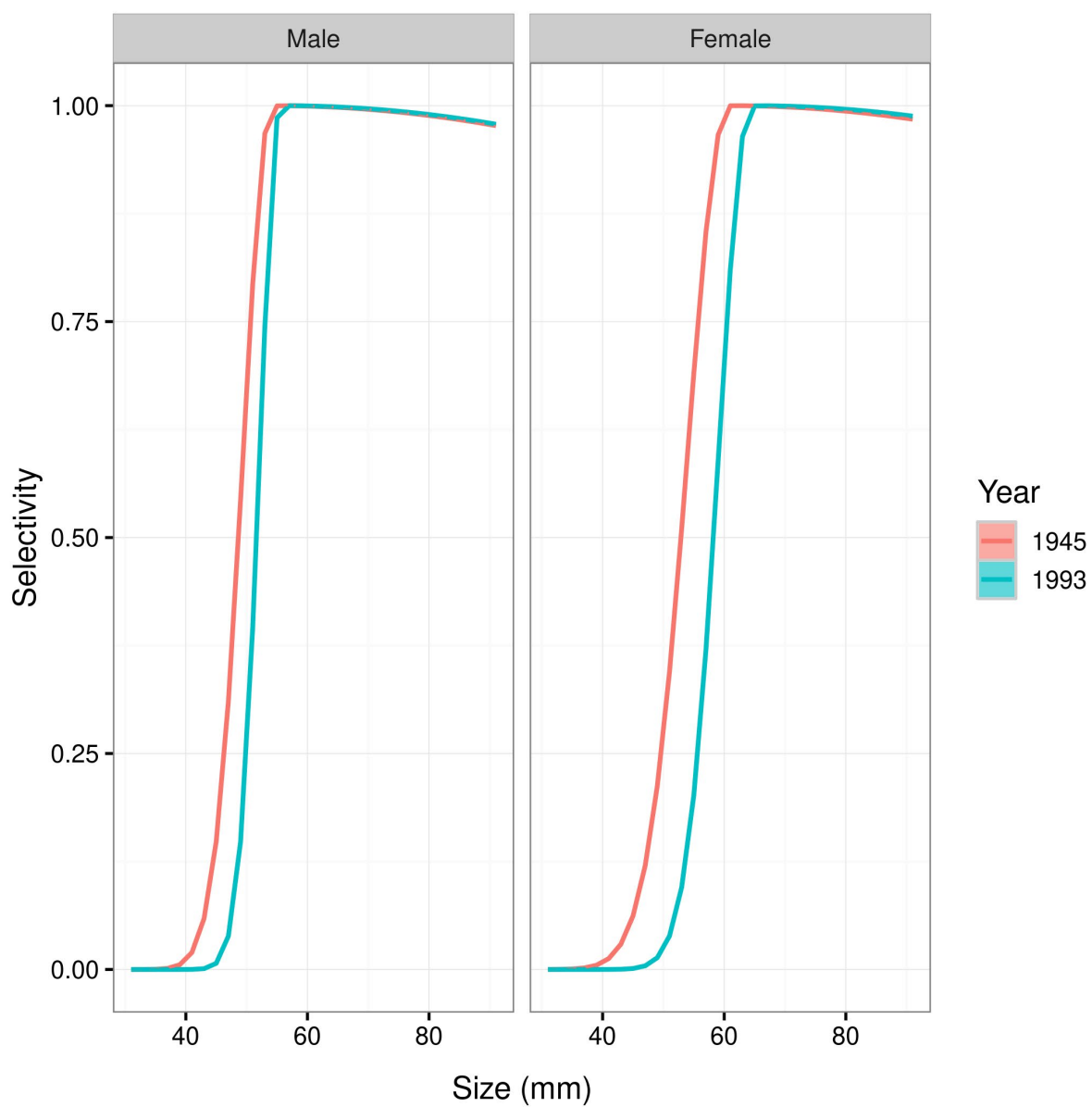


Figure 30: CRA 4 base case MAP: selectivity by sex and epoch.

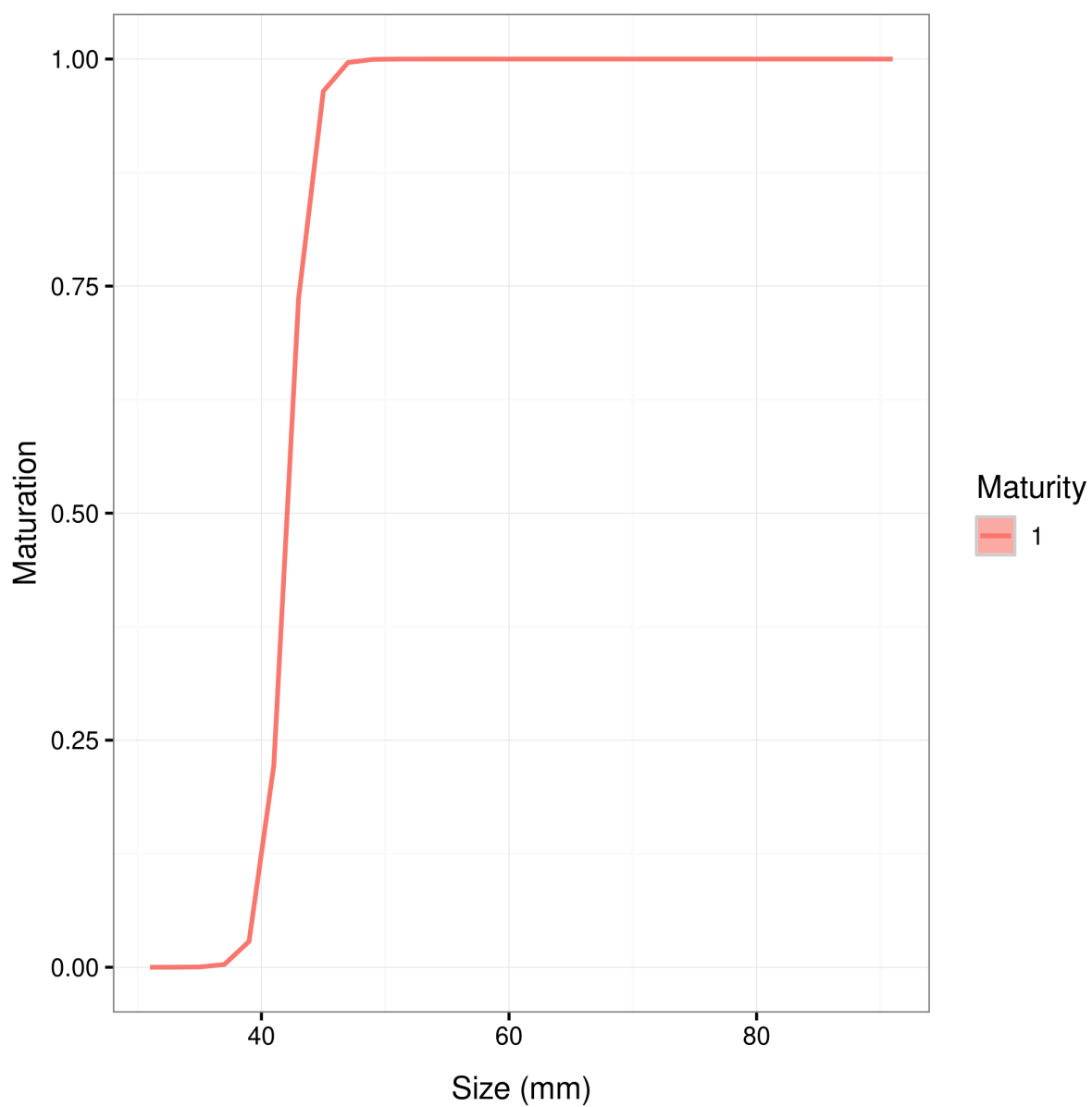


Figure 31: CRA 4 base case MAP: female maturation curve.

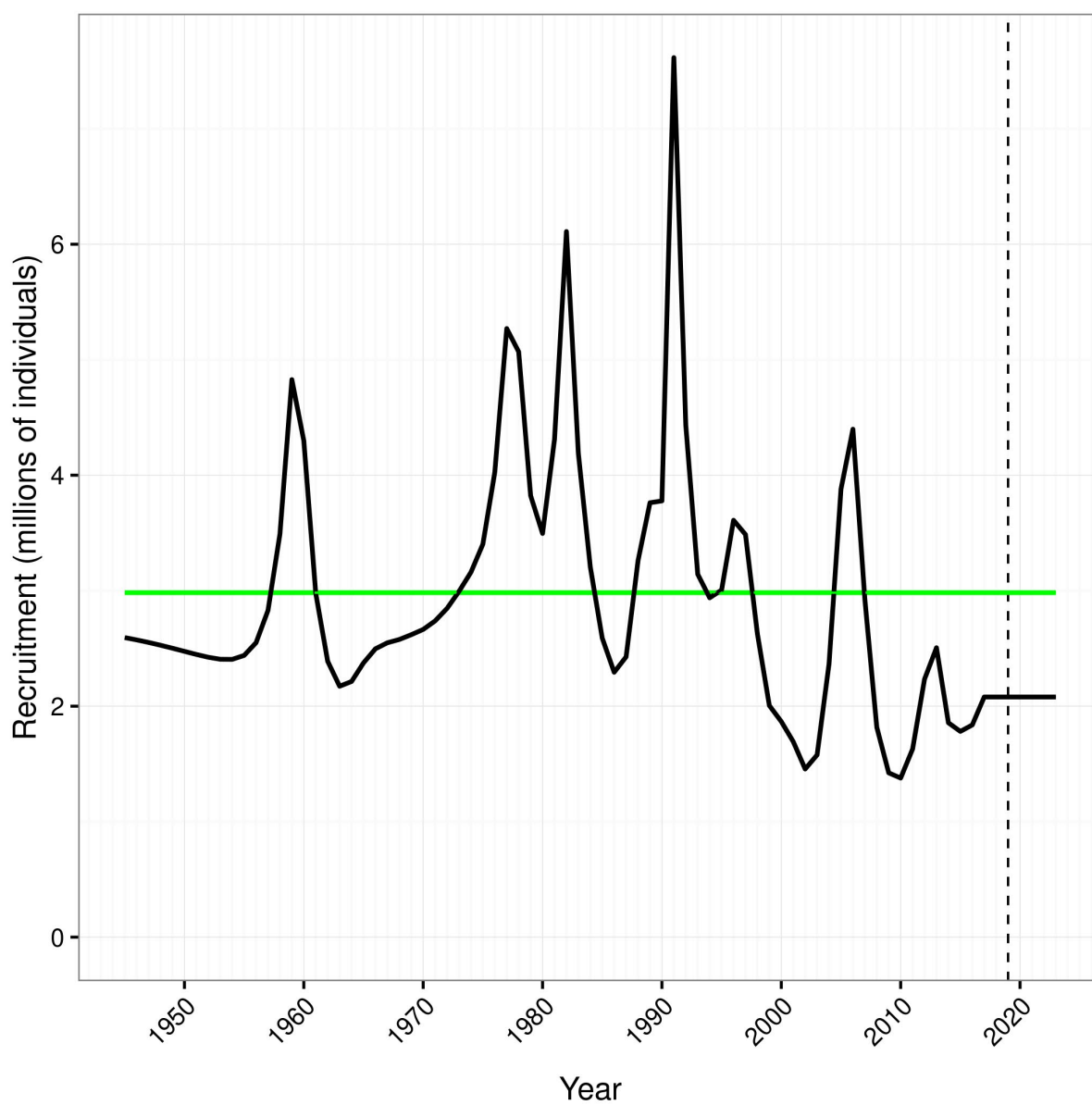


Figure 32: CRA 4 base case MAP: recruitment in 000 000s. Horizontal green line is R_0 and vertical dashed line is the final year of the reconstruction period.

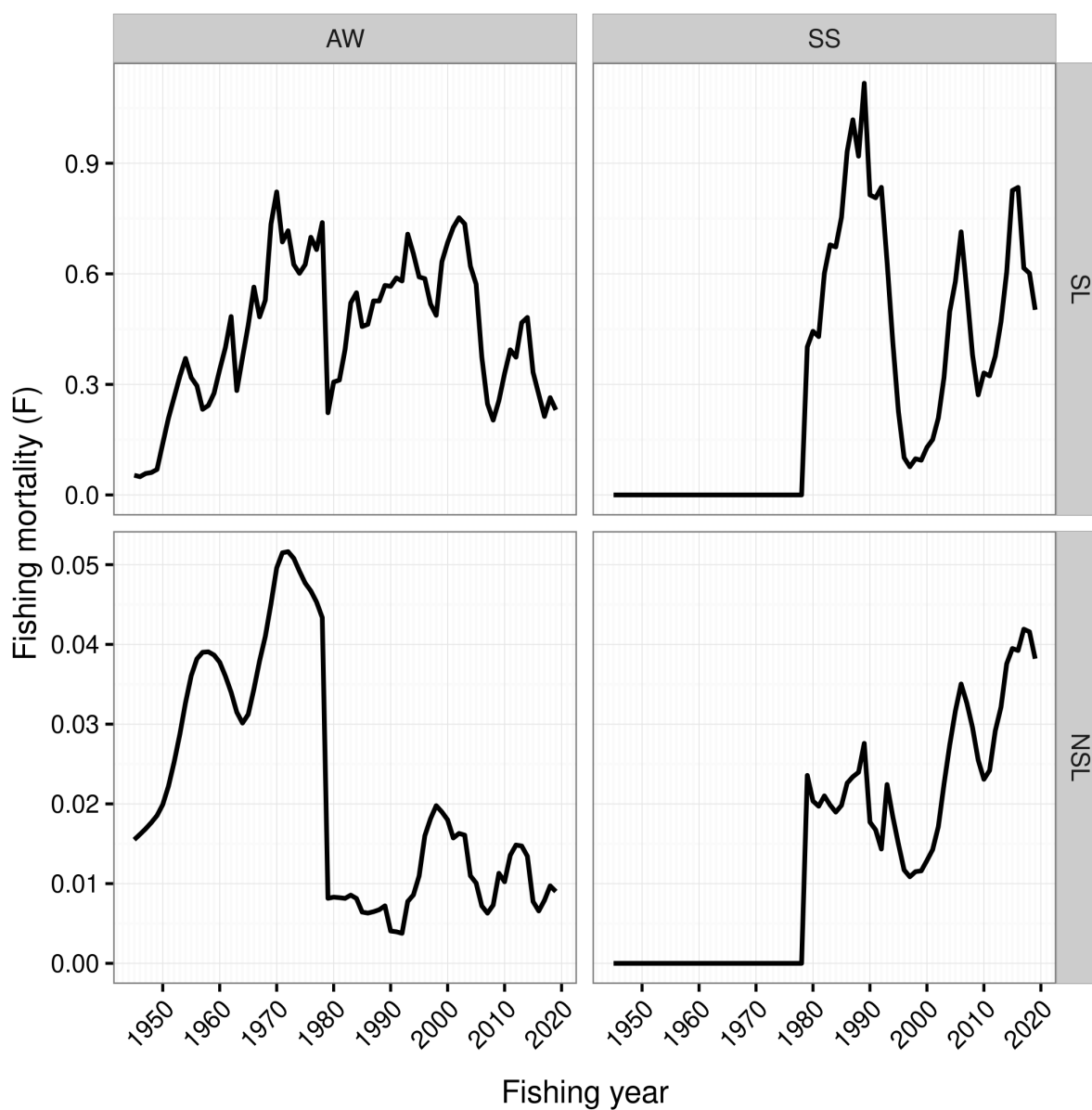


Figure 33: CRA 4 base case MAP: fishing mortality by year, season (AW = autumn/winter, SS = spring/summer), and catch category (SL = size-limited, NSL = non-size-limited).

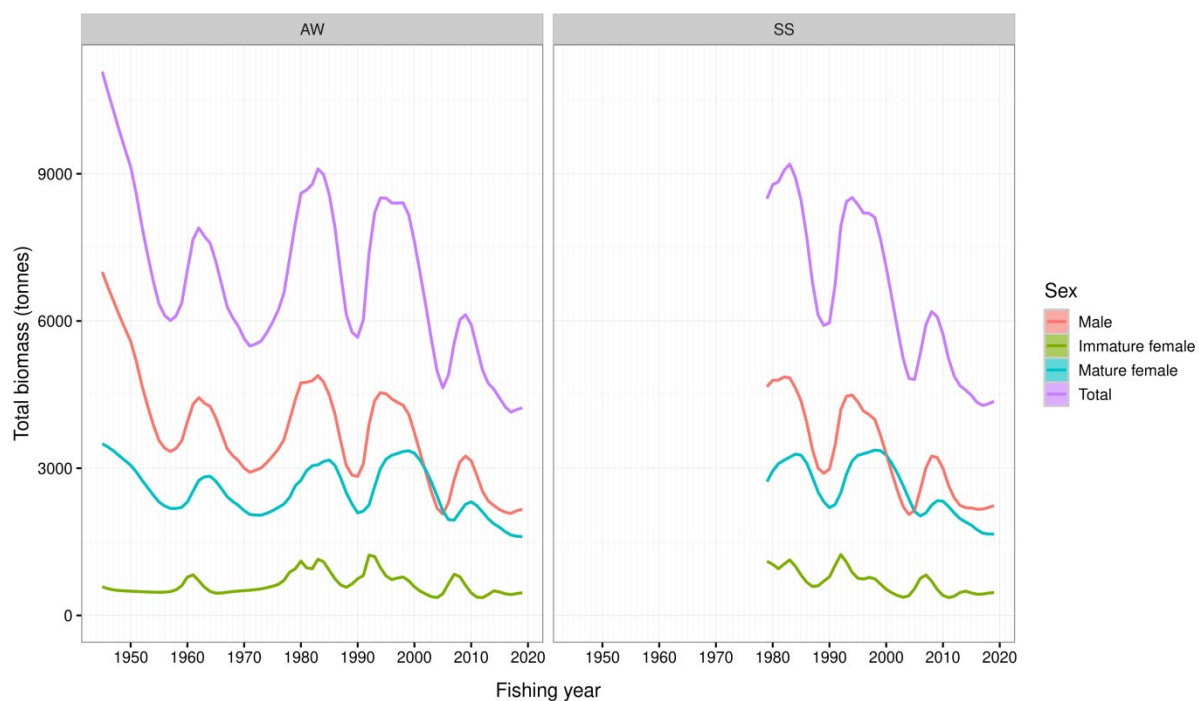


Figure 34: CRA 4 base case MAP: trajectory of total biomass by sex category and season (AW = autumn/winter, SS= spring/summer). The total biomass across all three sex categories is shown as a purple line.

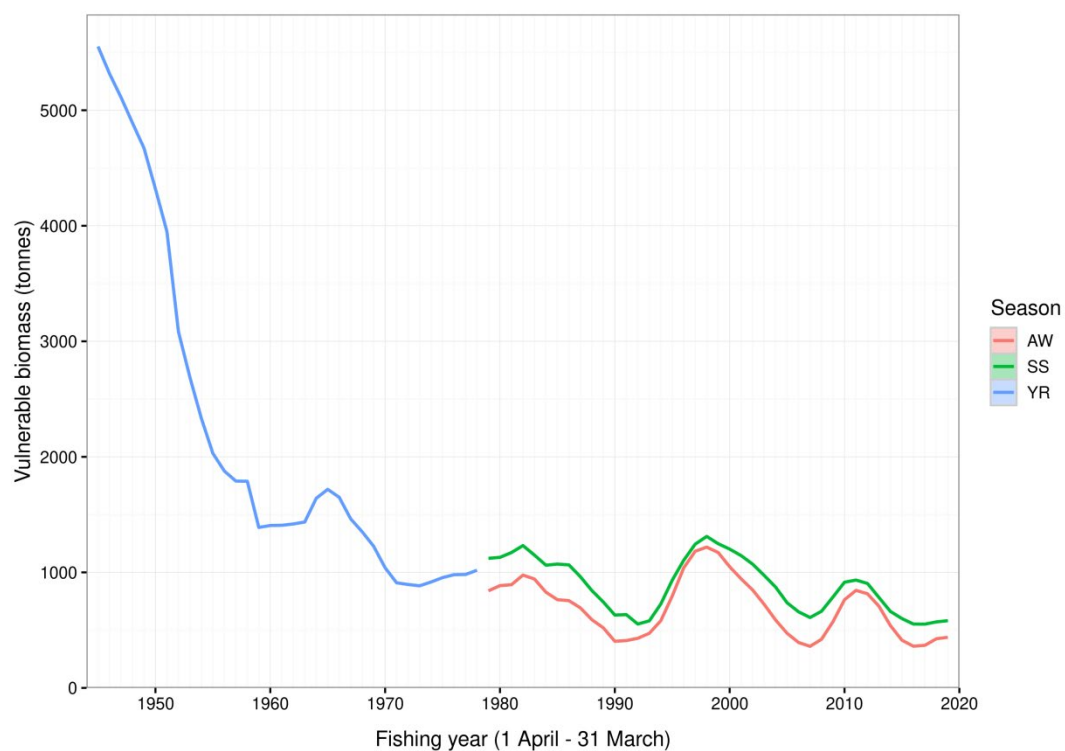


Figure 35: CRA 4 base case MAP: trajectory of vulnerable biomass (tonnes) by season (AW = autumn/winter, SS= spring/summer, YR= single time step).

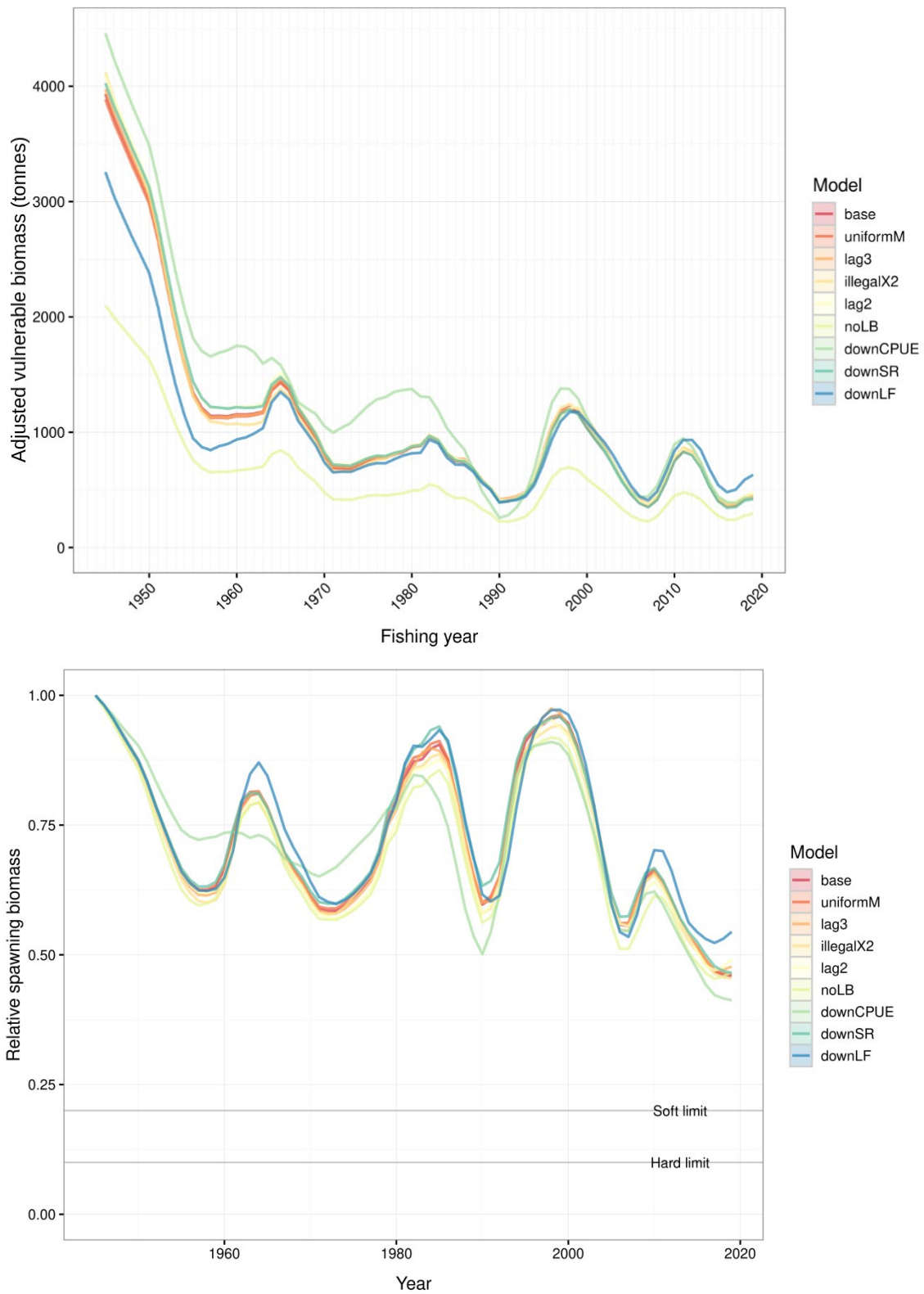


Figure 36: CRA 4 MAP comparisons: sensitivities with the base case for adjusted vulnerable biomass [top panel] and relative spawning stock biomass [bottom panel].

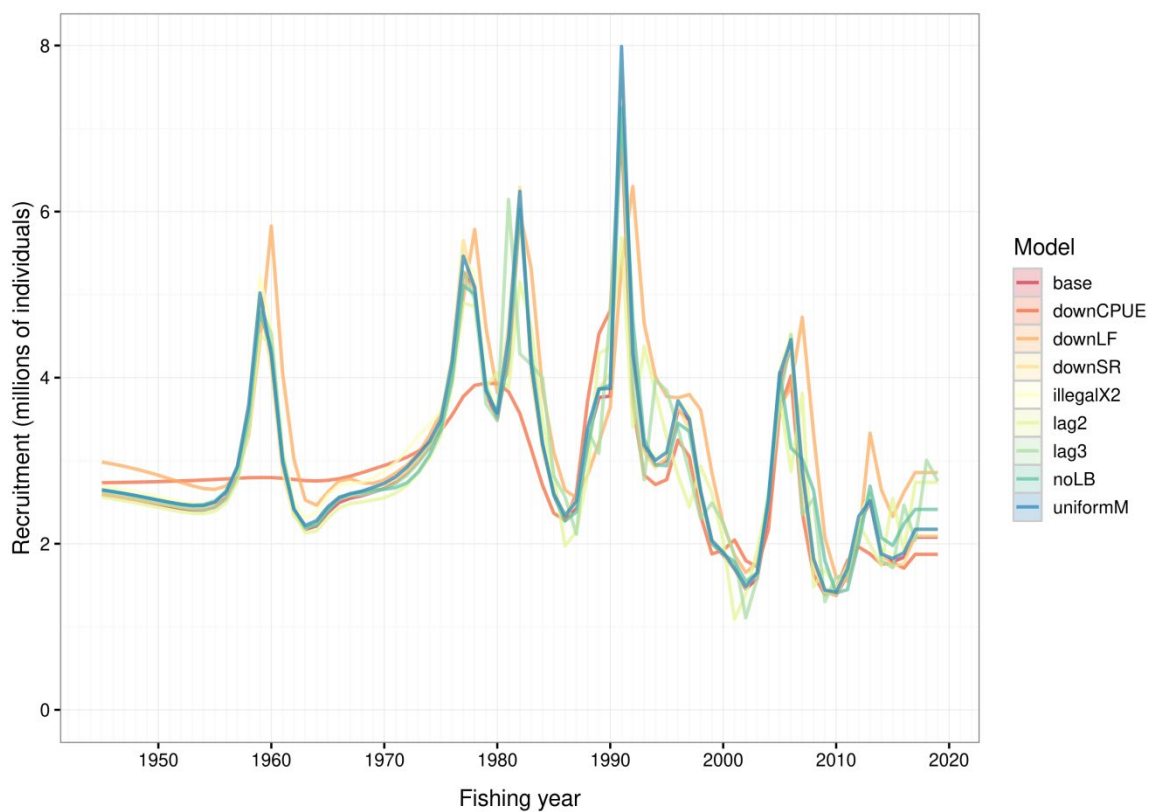


Figure 37: CRA 4 MAP comparisons: recruitment showing all sensitivities with the base case.

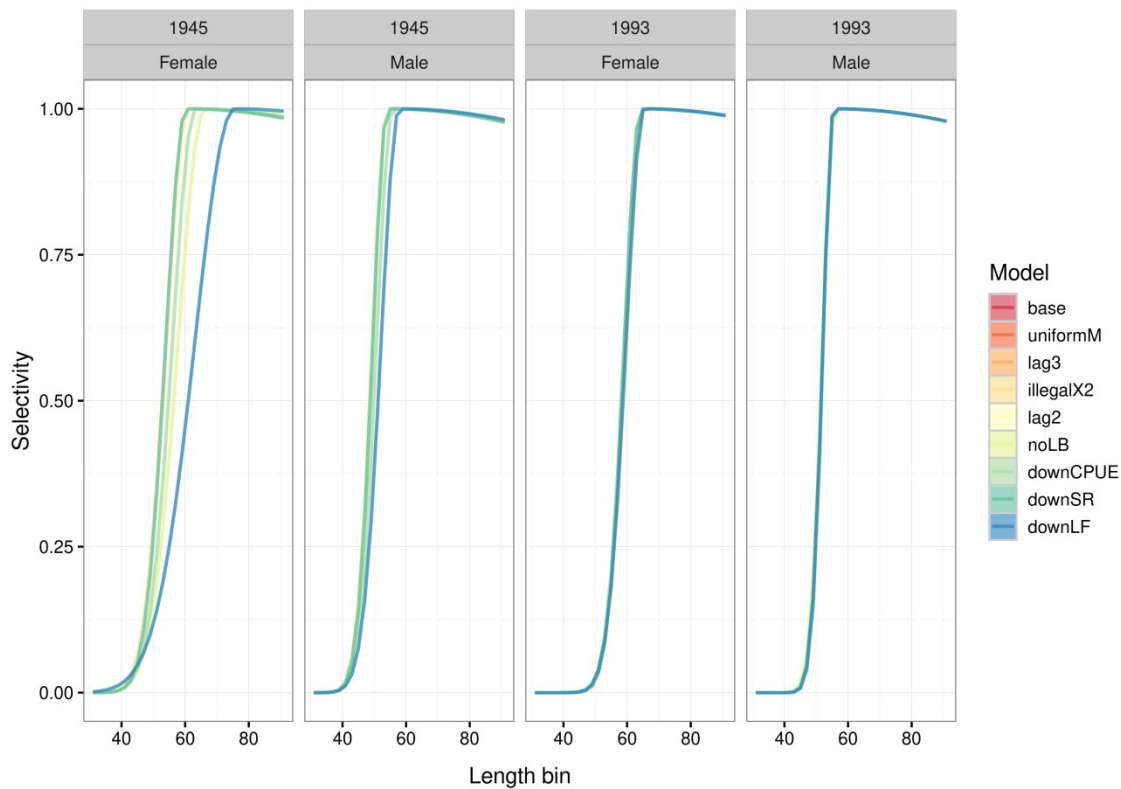


Figure 38: CRA 4 MAP comparisons: selectivity curves showing all sensitivities with the base case.

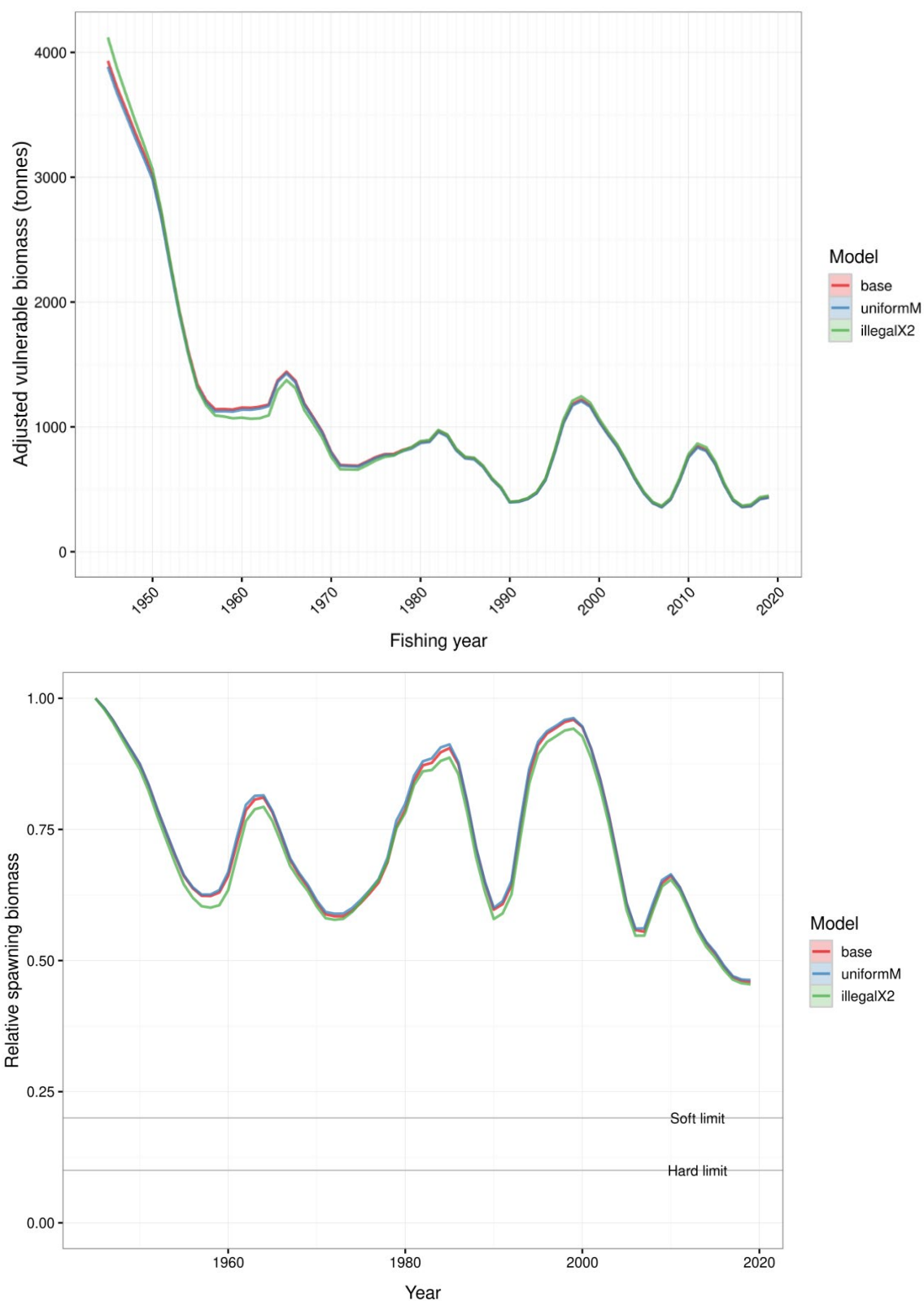


Figure 39: CRA 4 MAP comparisons: base case with the version assuming a uniform prior on M and double the illegal catch: [top panel]: absolute vulnerable biomass; [bottom panel] relative spawning stock biomass.

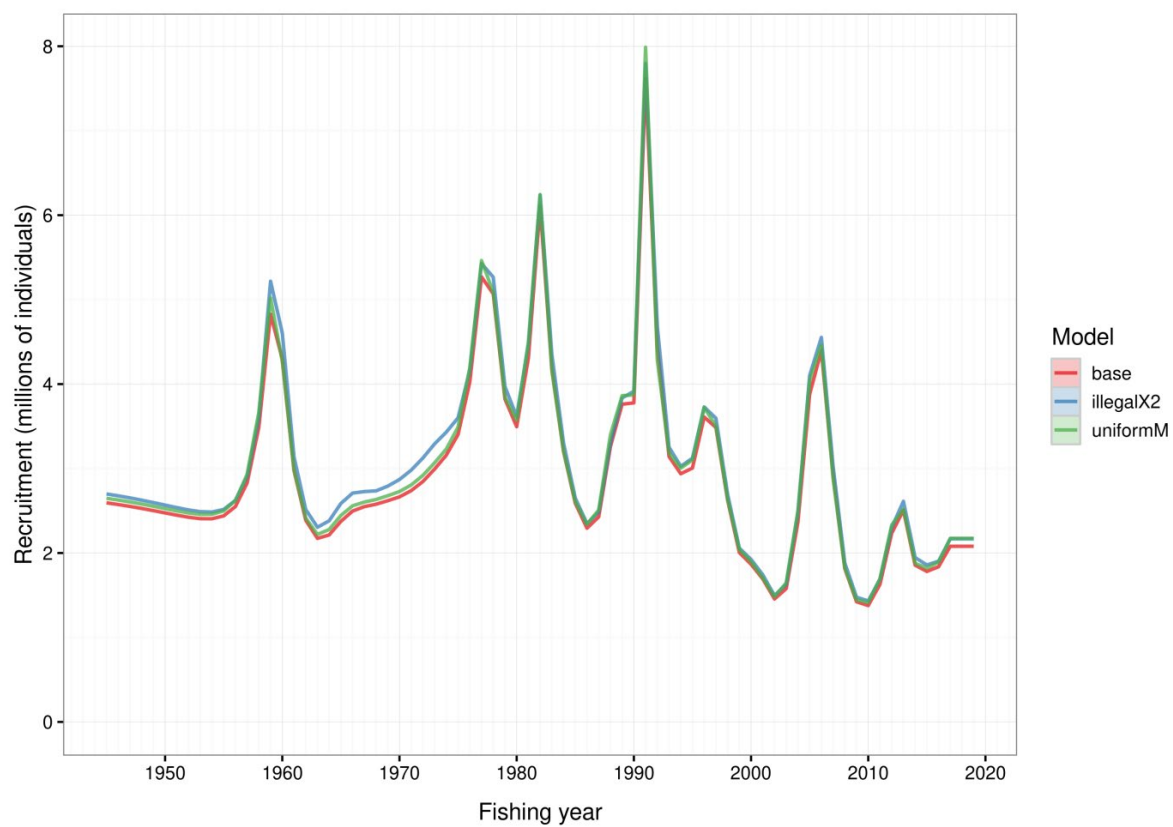


Figure 40: CRA 4 MAP comparisons: base case with the version assuming density dependence: recruitment trajectories.

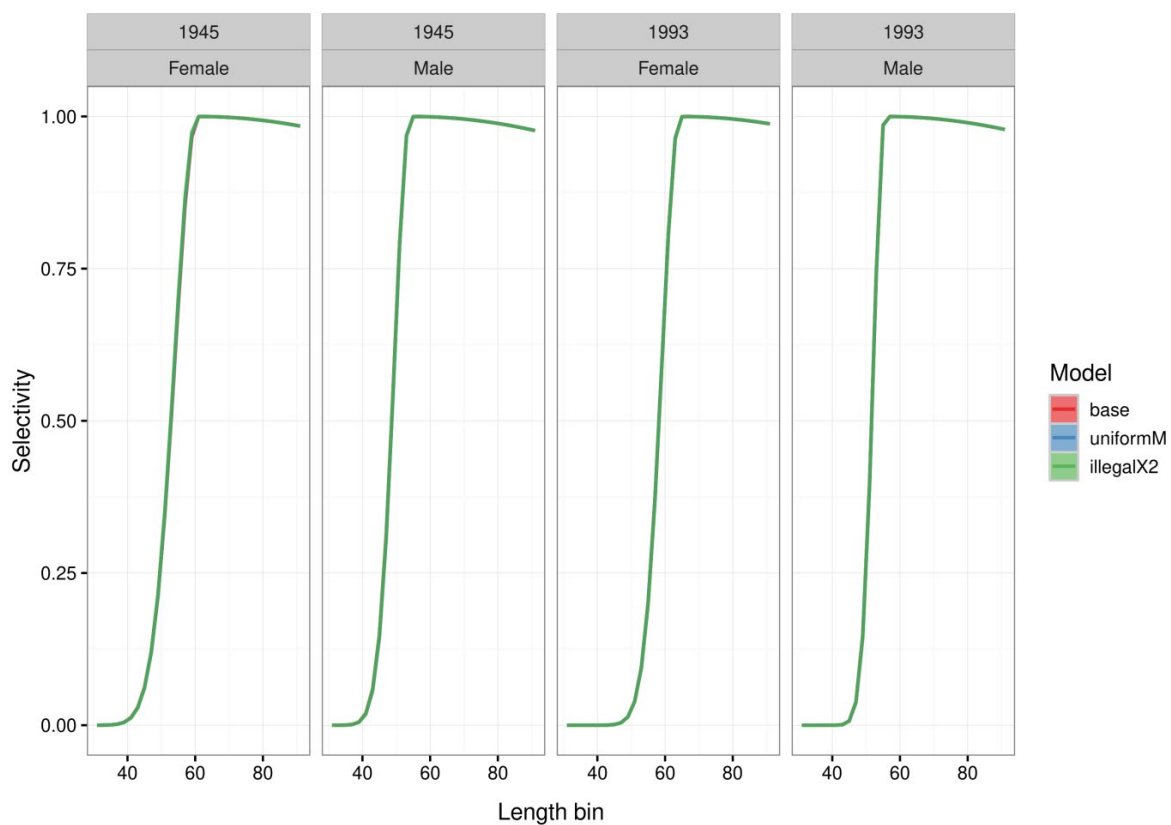


Figure 41: CRA 4 MAP comparisons: base case with the version assuming density dependence: selectivity curves. The base case is not visible because it is identical to *uniformM* and *illegalX2*.

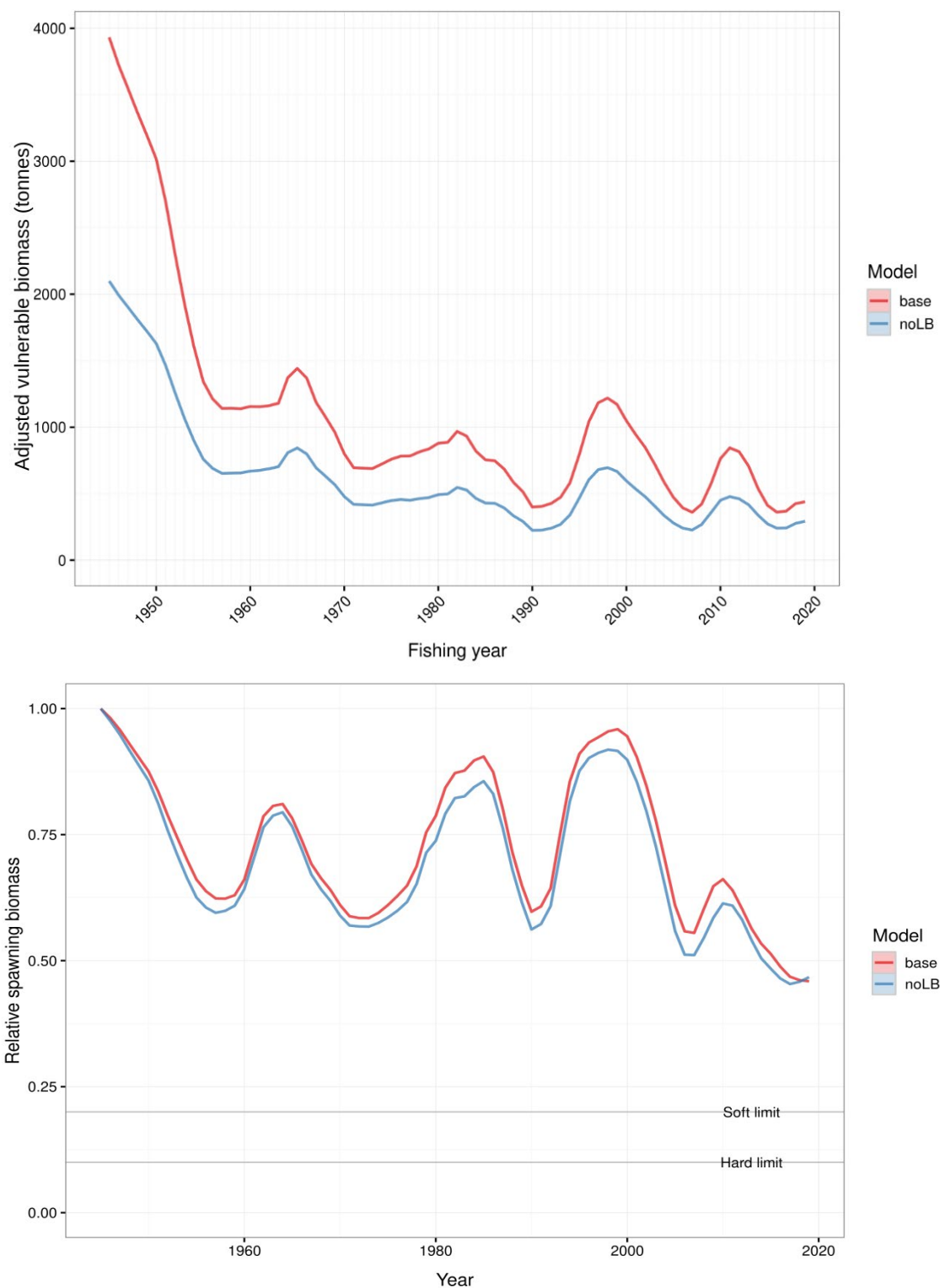


Figure 42: CRA 4 MAP comparisons: base case with the version removing logbook data: [top panel] adjusted vulnerable biomass; [bottom panel] relative spawning biomass.

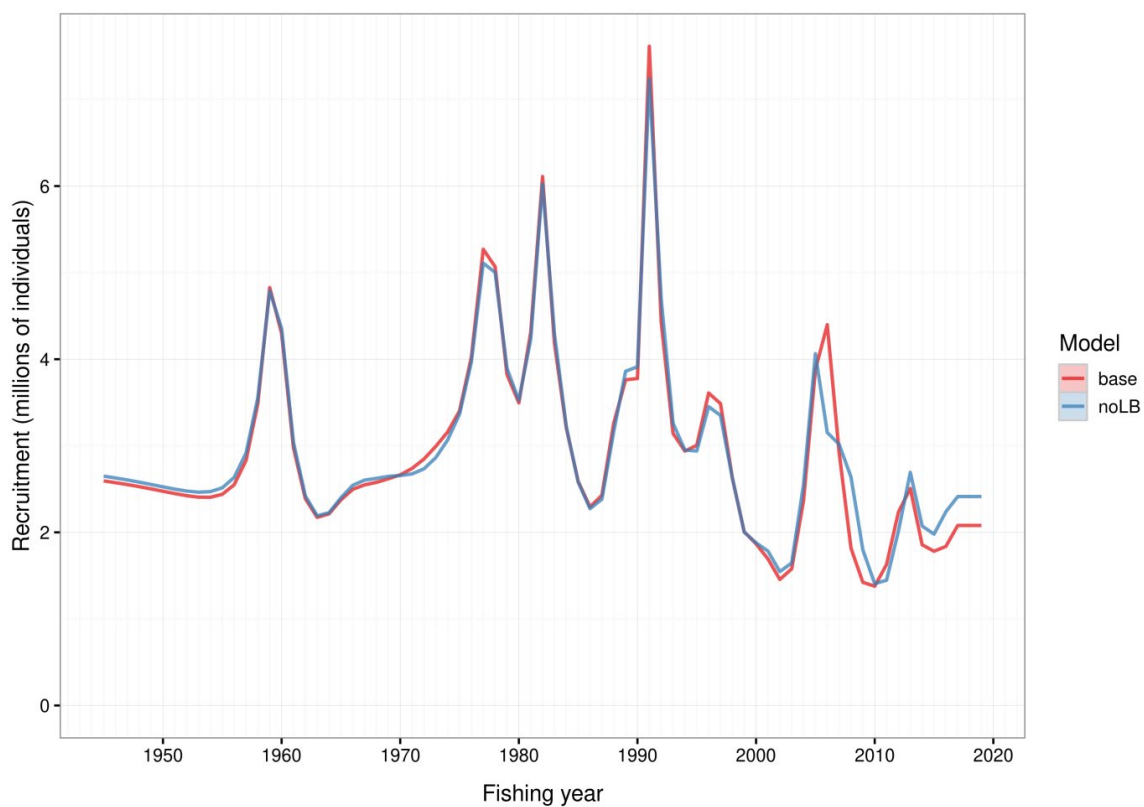


Figure 43: CRA 4 MAP comparisons: base case with the version removing logbook data: recruitment trajectories.

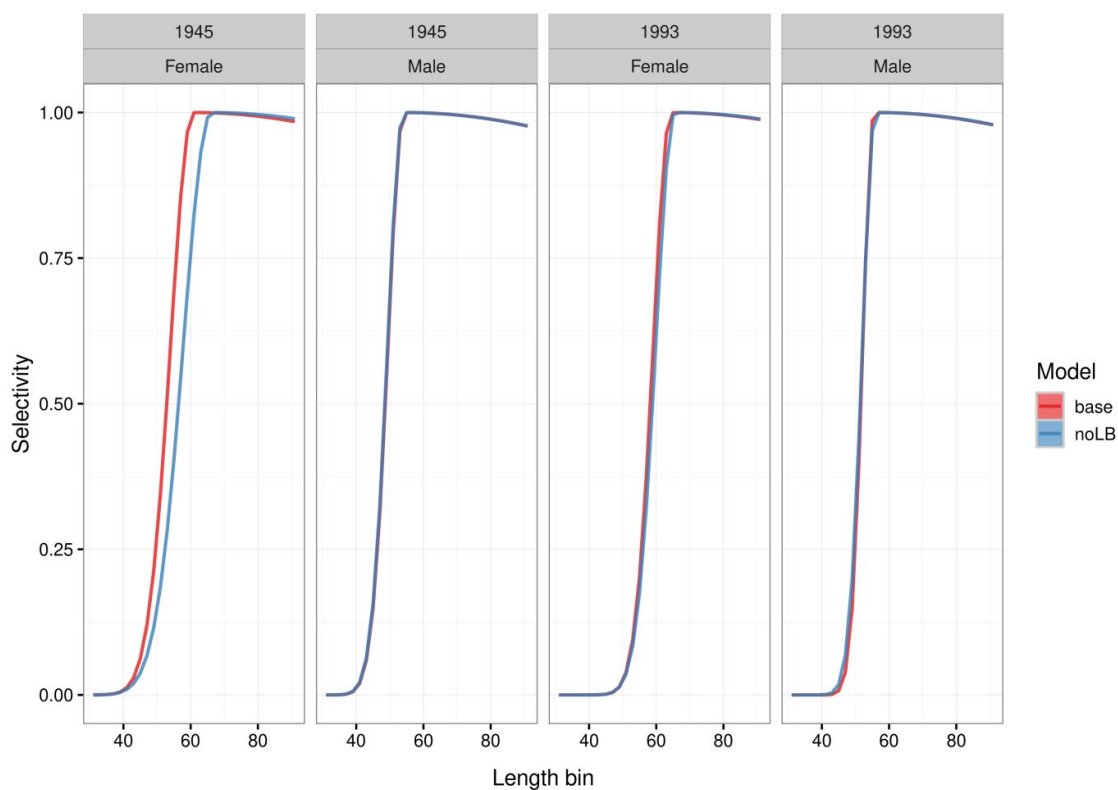


Figure 44: CRA 4 MAP comparisons: base case with the version removing logbook data: selectivity curves.

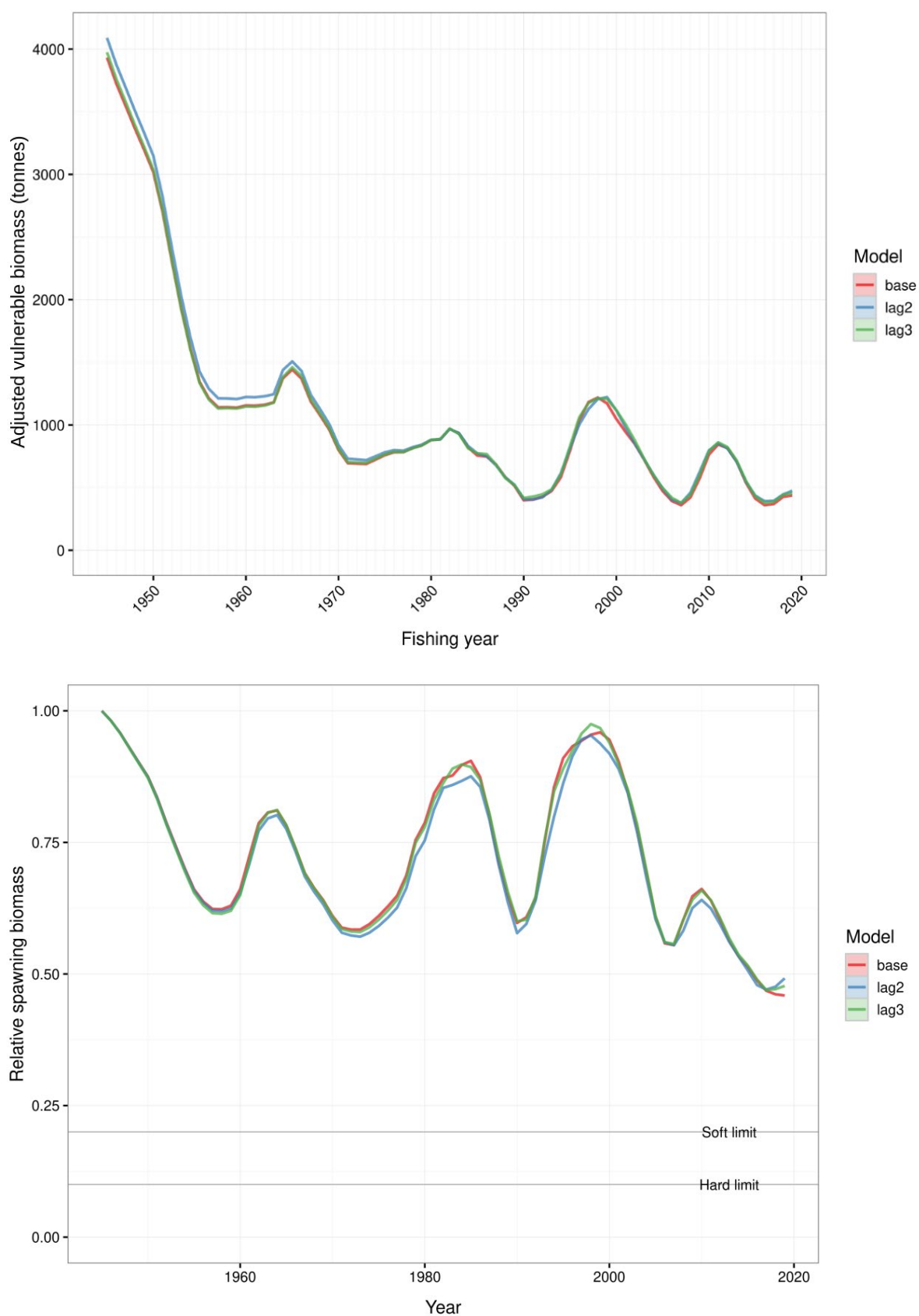


Figure 45: CRA 4 MAP comparisons: base case with sensitivities fitting to the puerulus index with two or three-year lags: [top panel] adjusted vulnerable biomass; [bottom panel] relative spawning stock biomass.

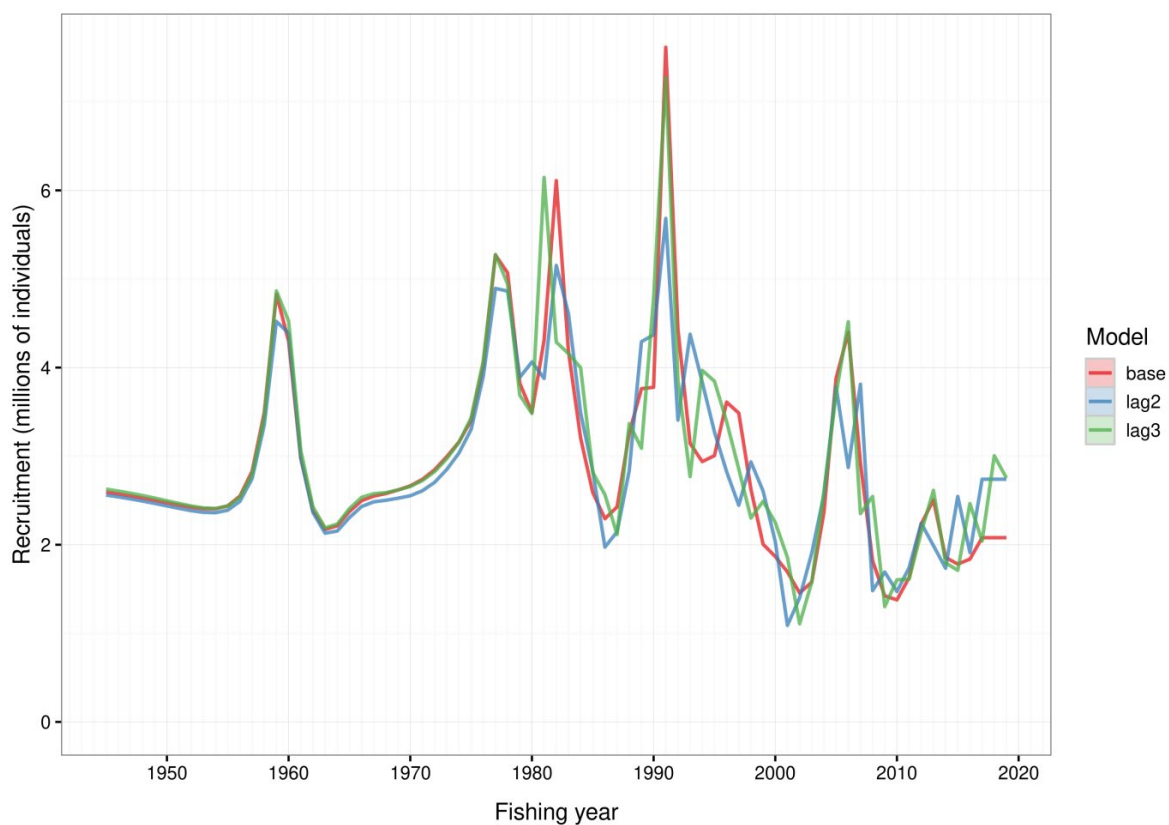


Figure 46: CRA 4 MAP comparisons: base case with sensitivities fitting to the puerulus index with two or three-year lags: recruitment trajectories.

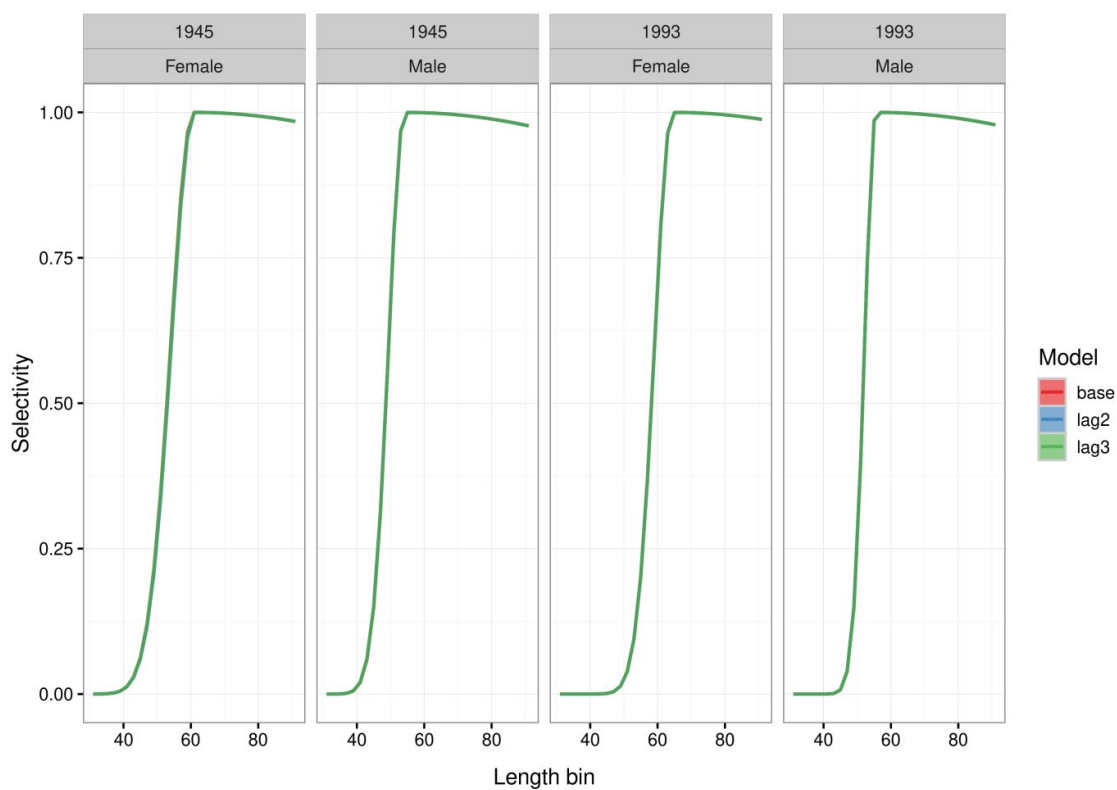


Figure 47: CRA 4 MAP comparisons: base case with sensitivities fitting to the puerulus index with two or three-year lags: selectivity curves. Selectivities for the base case and puerulus index sensitivities are identical.

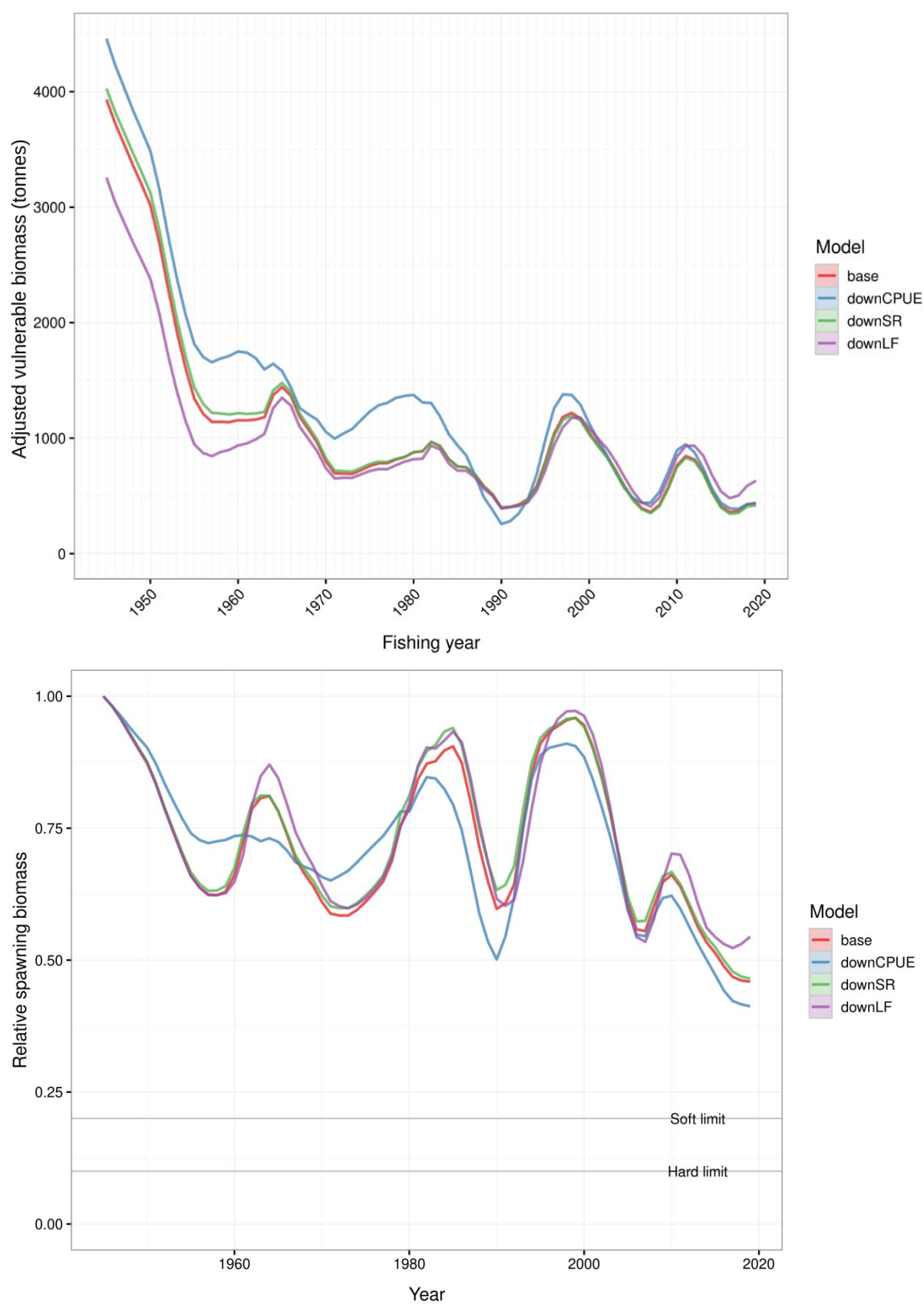


Figure 48: CRA 4 MAP comparisons: sensitivity runs down-weighting CPUE, sex ratio (SR), and length frequency (LF): [top panel] adjusted vulnerable biomass; [bottom panel] relative spawning biomass.

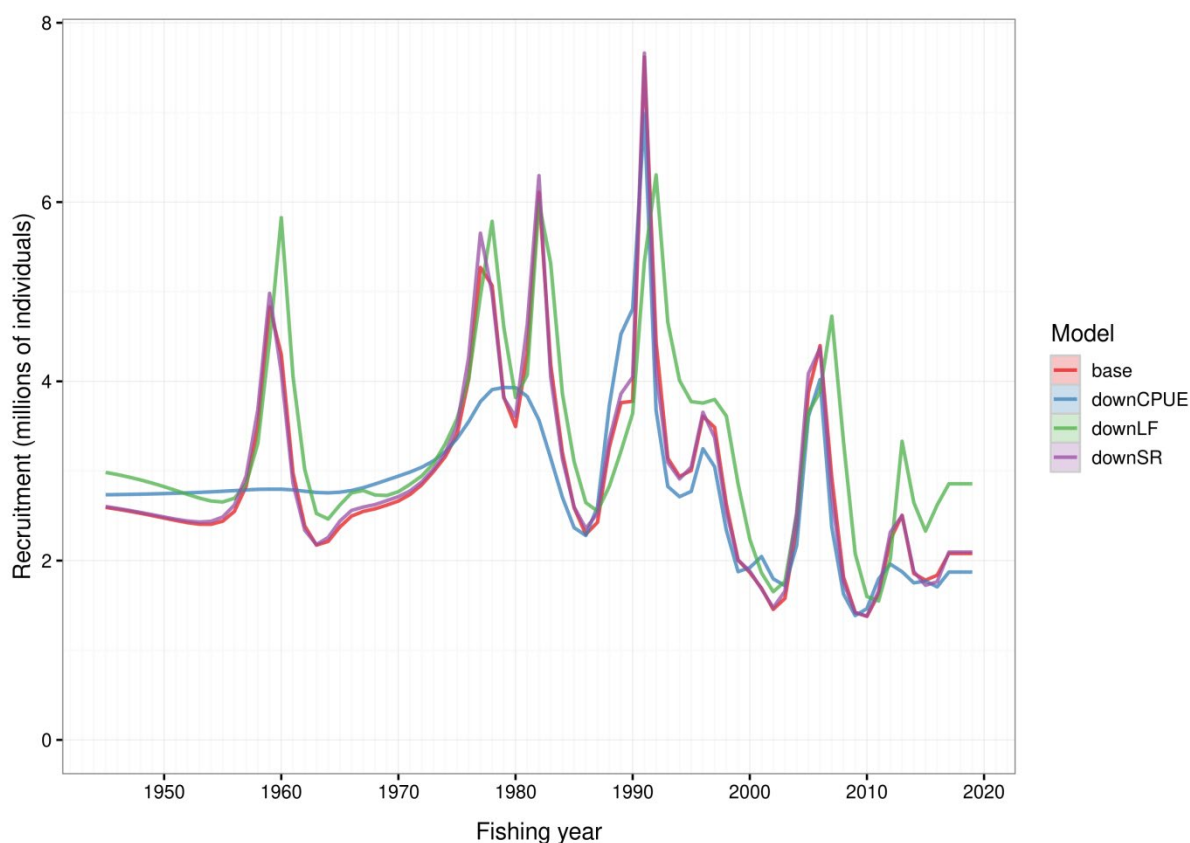


Figure 49: CRA 4 MAP comparisons: sensitivity runs down-weighting CPUE, sex ratio (SR), and length frequency (LF): recruitment trajectories.

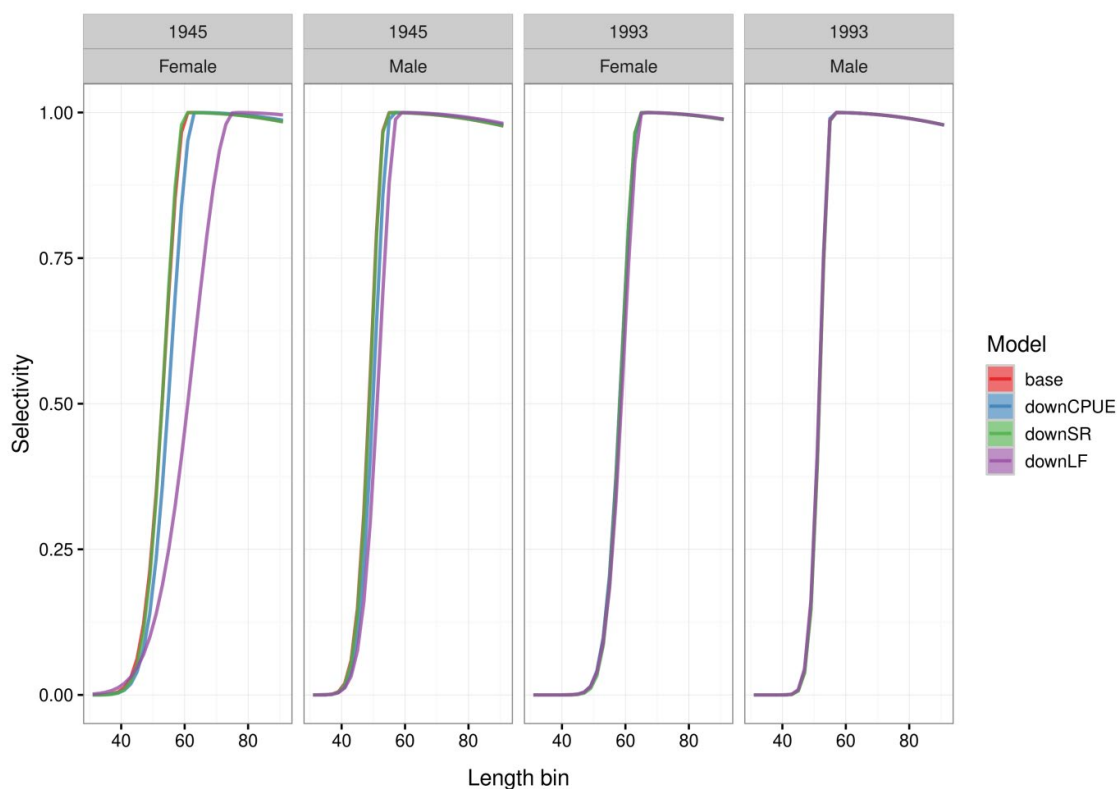


Figure 50: CRA 4 MAP comparisons: sensitivity runs down-weighting CPUE, sex ratio (SR), and length frequency (LF): selectivity curves.

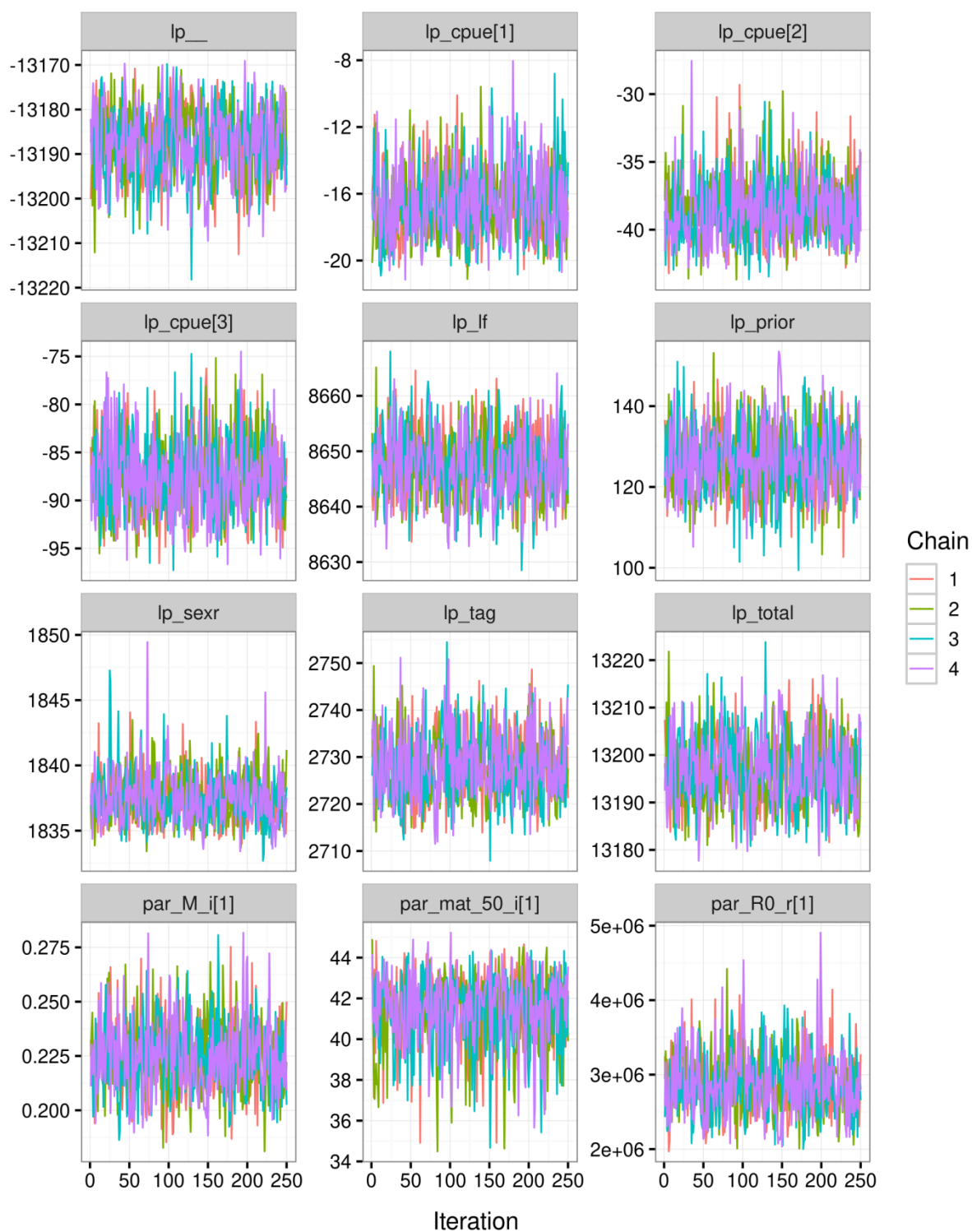


Figure 51: CRA 4 base case MCMC: trace plots by independent chain for likelihood components and estimated maturity, natural mortality (M), and R_0 parameters.

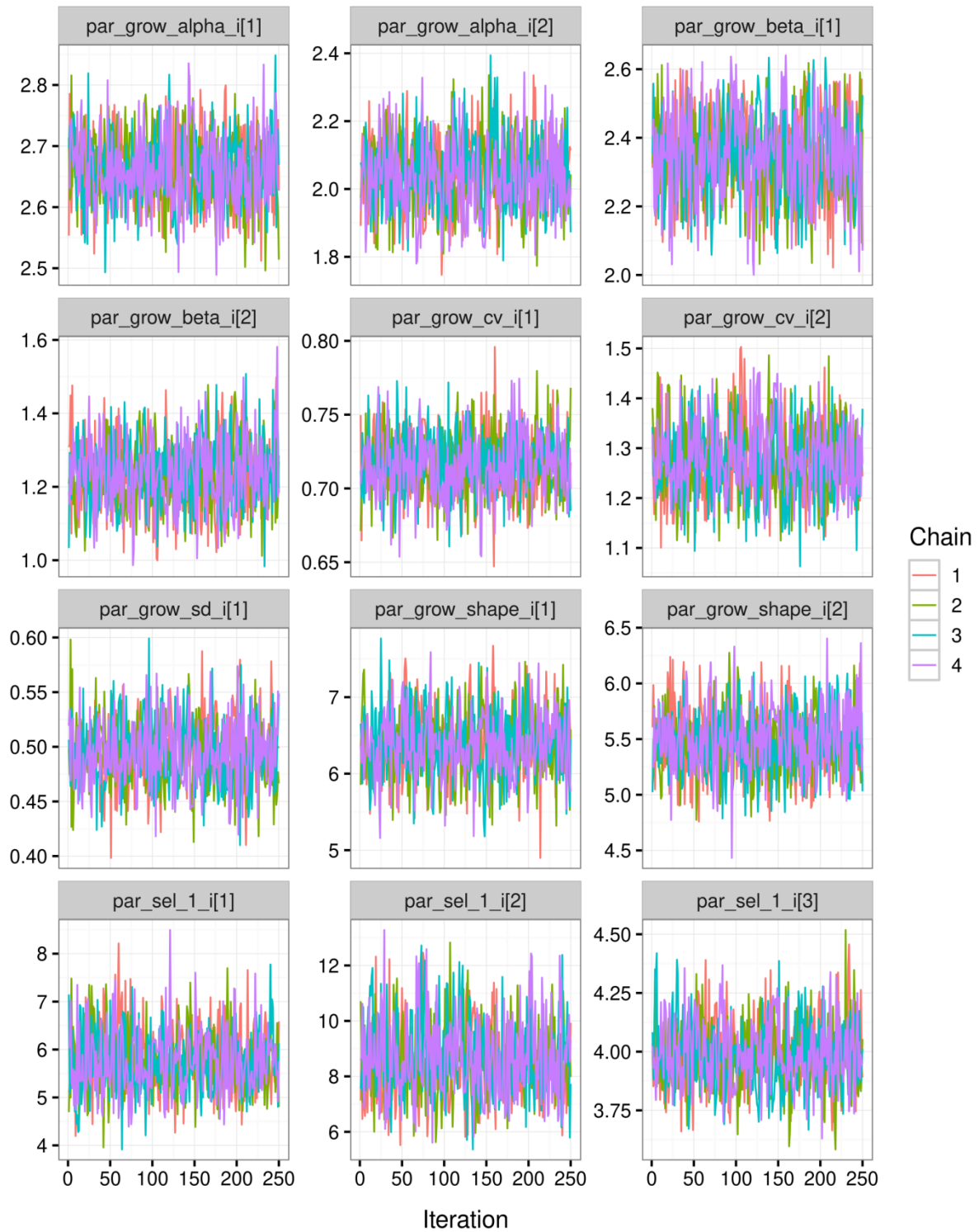


Figure 52: CRA 4 base case MCMC: trace plots by independent chain for estimated growth and selectivity parameters.

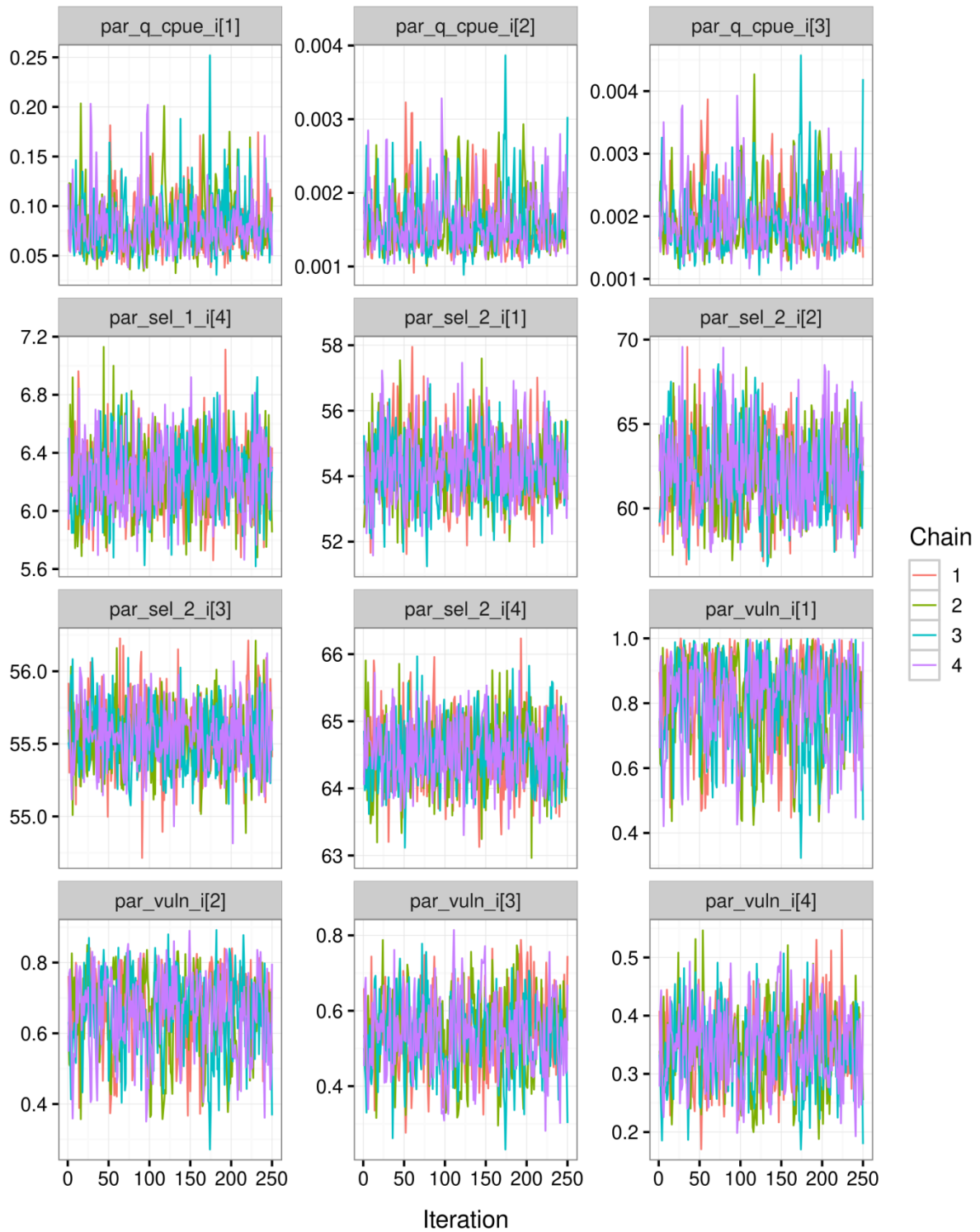


Figure 53: CRA 4 base case MCMC: trace plots by independent chain for estimated catchability (q), selectivity, and vulnerability parameters.

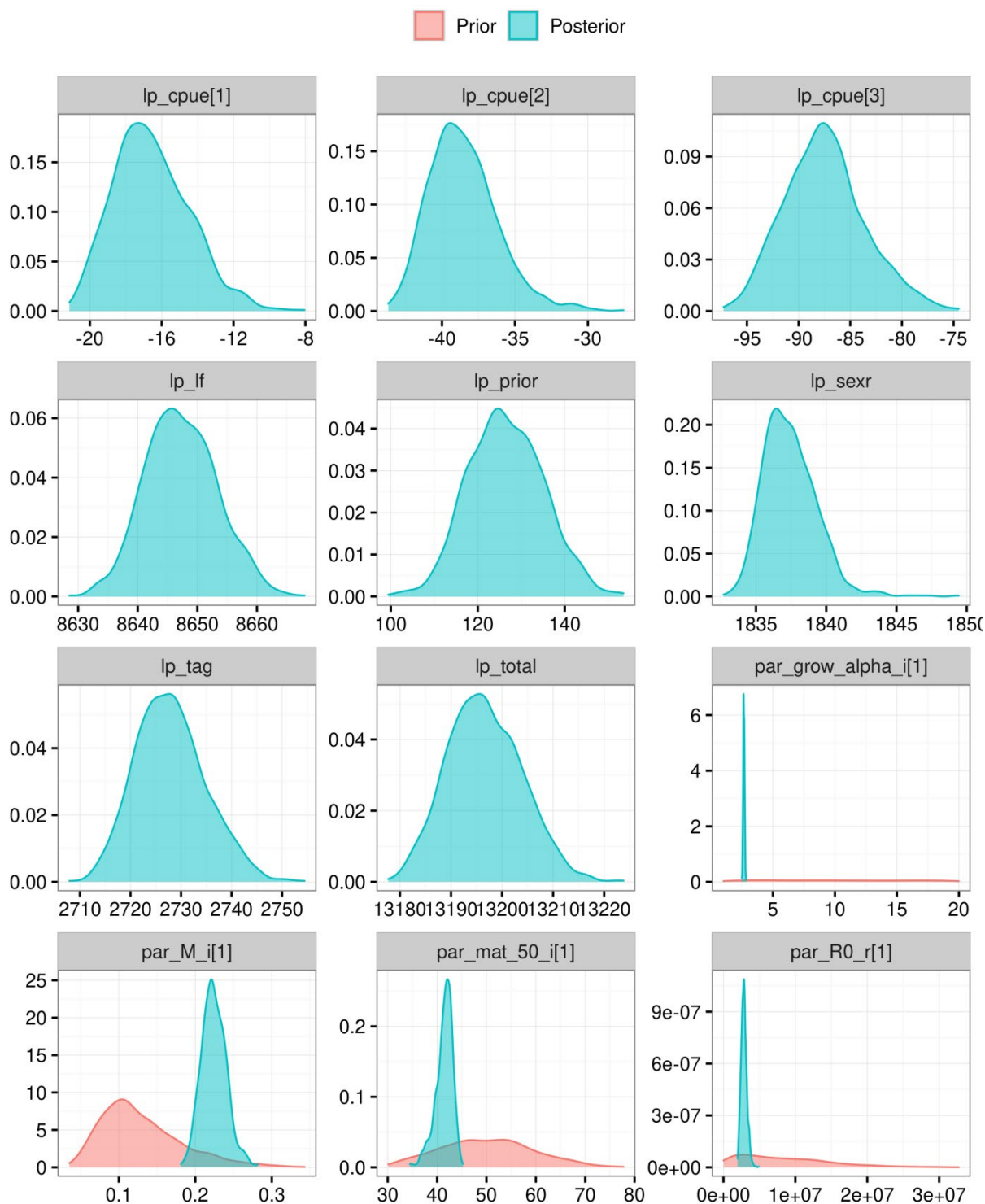


Figure 54: CRA 4 base case MCMC: density plots showing prior (red) and posterior distributions (blue) for likelihood components, maturity, natural mortality (M), and R_0 parameters.

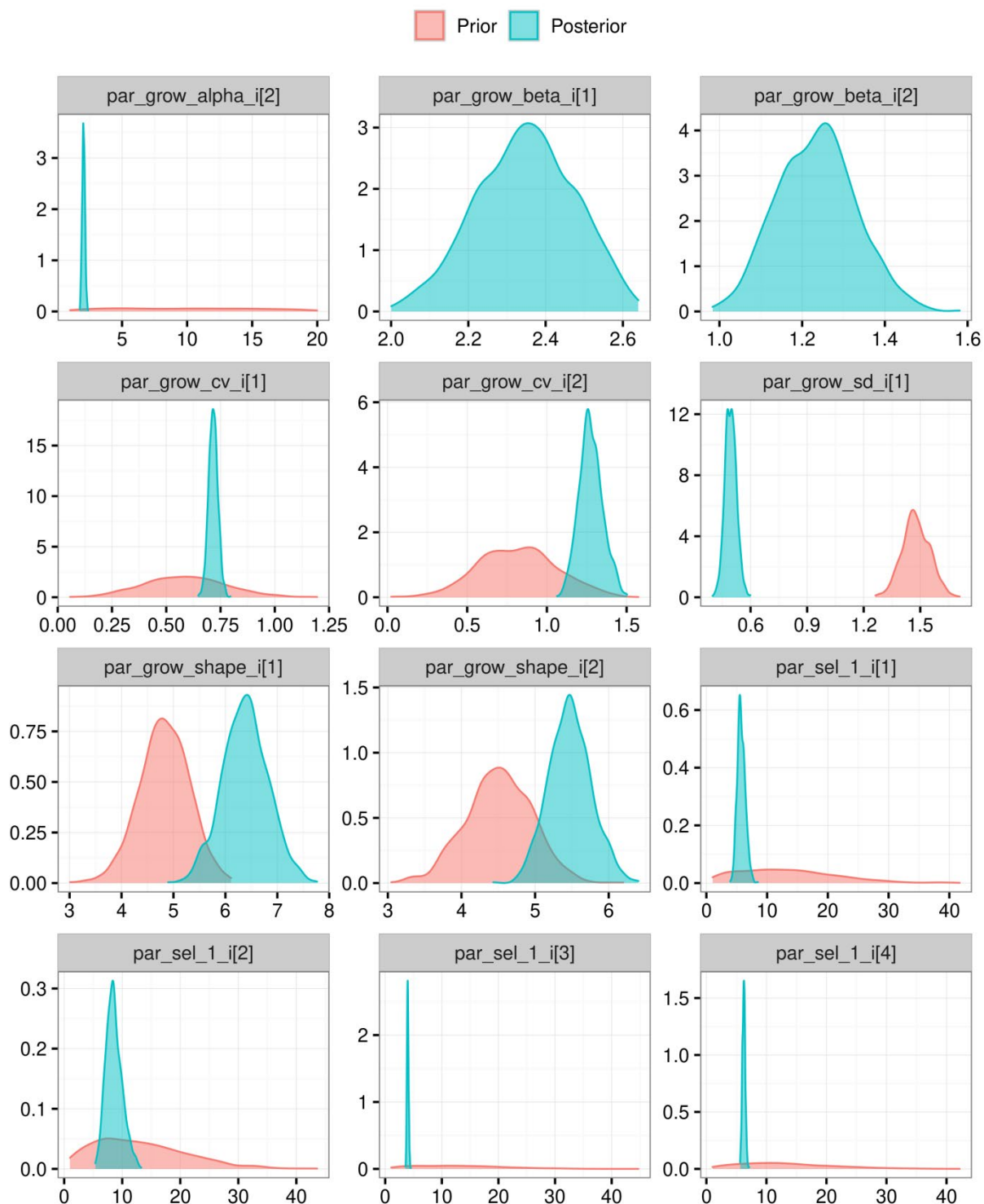


Figure 49: CRA 4 base case MCMC: density plots showing prior (red) and posterior distributions (blue) for growth and selectivity parameters.

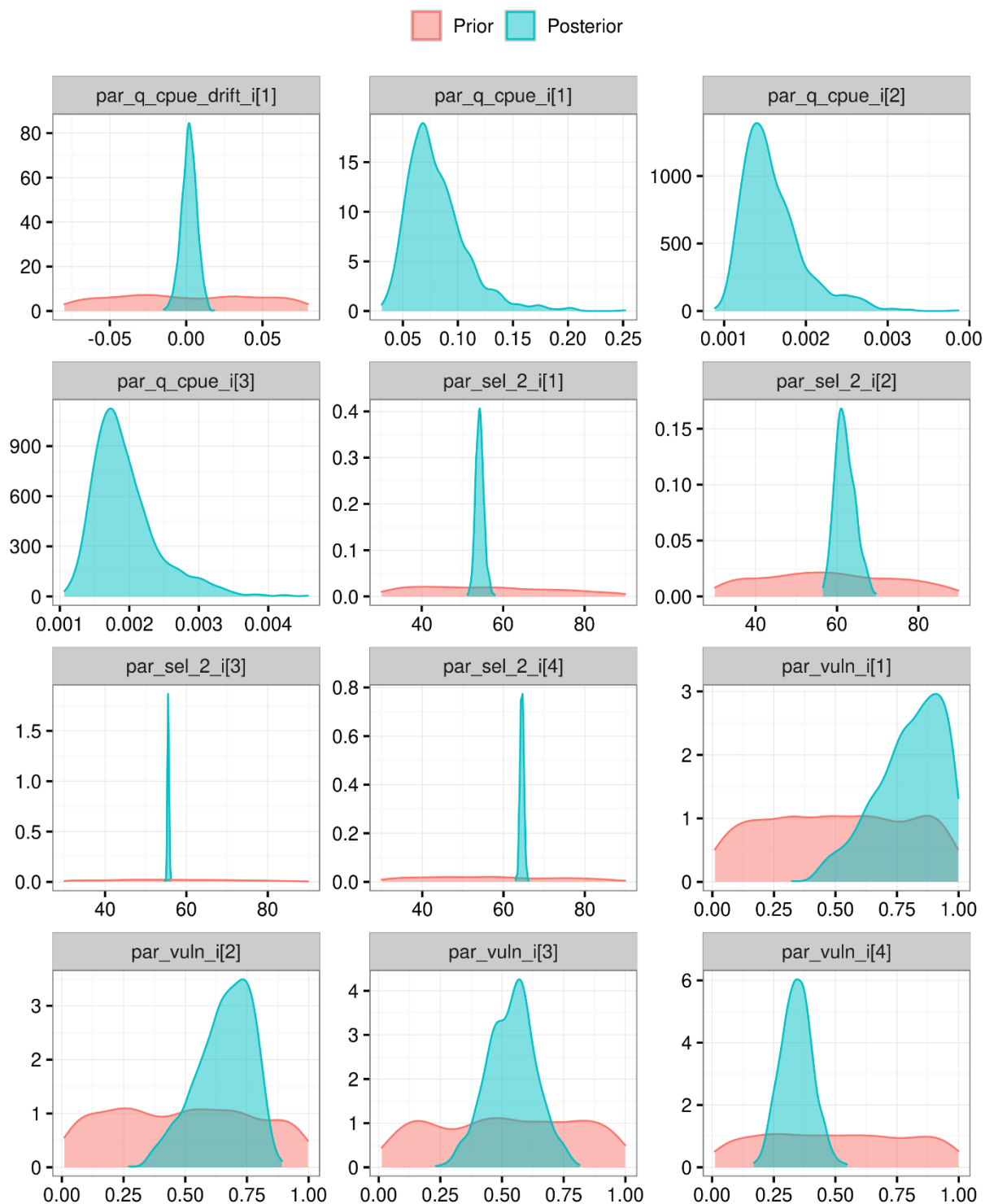


Figure 50: CRA 4 base case MCMC: density plots showing prior (red) and posterior distributions (blue) for catchability (q), selectivity, and vulnerability parameters.

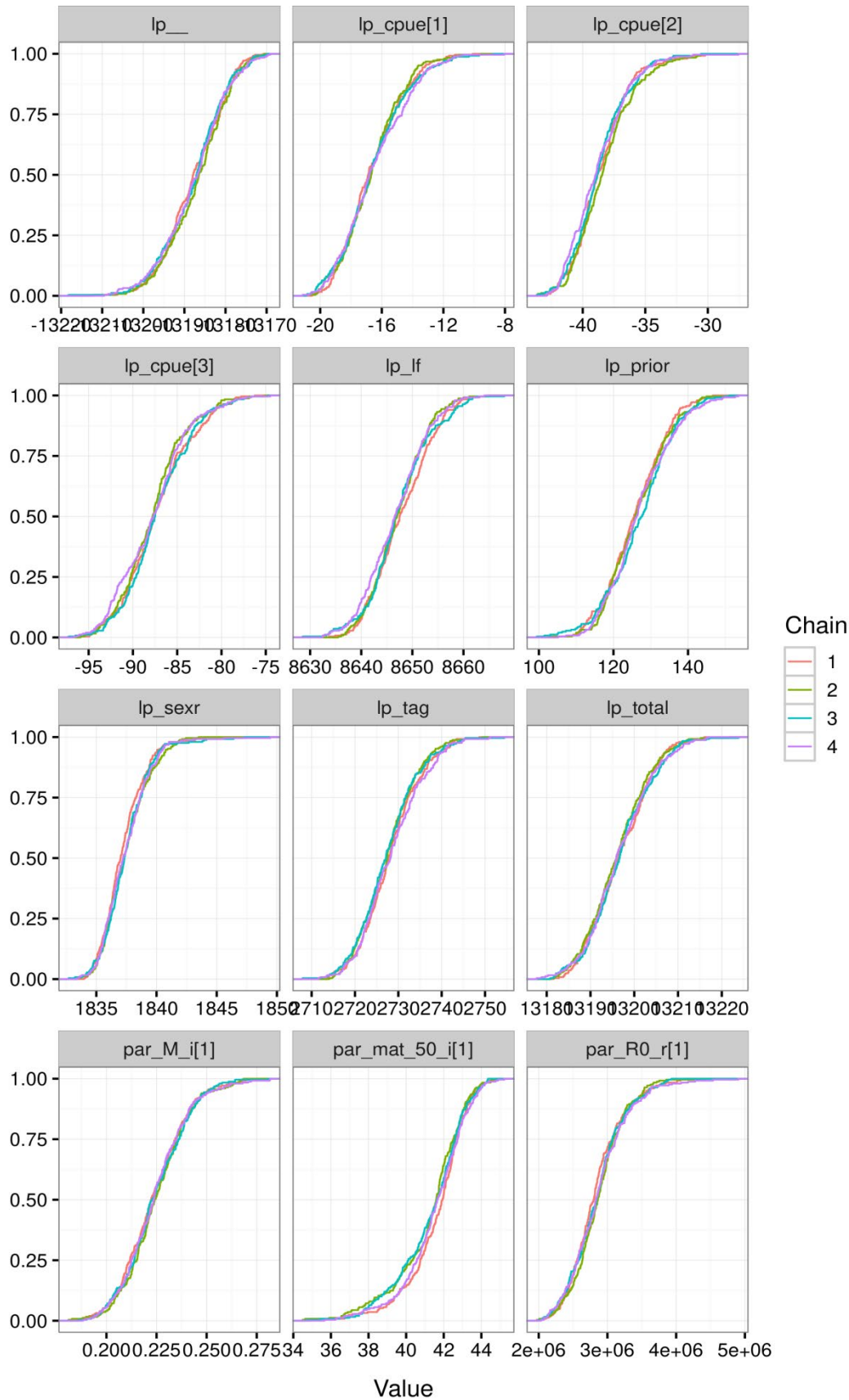


Figure 51: CRA 4 base case MCMC: empirical cumulative proportional distributions for each independent MCMC chain for likelihood components and maturity, natural mortality (M), and R_0 parameters.

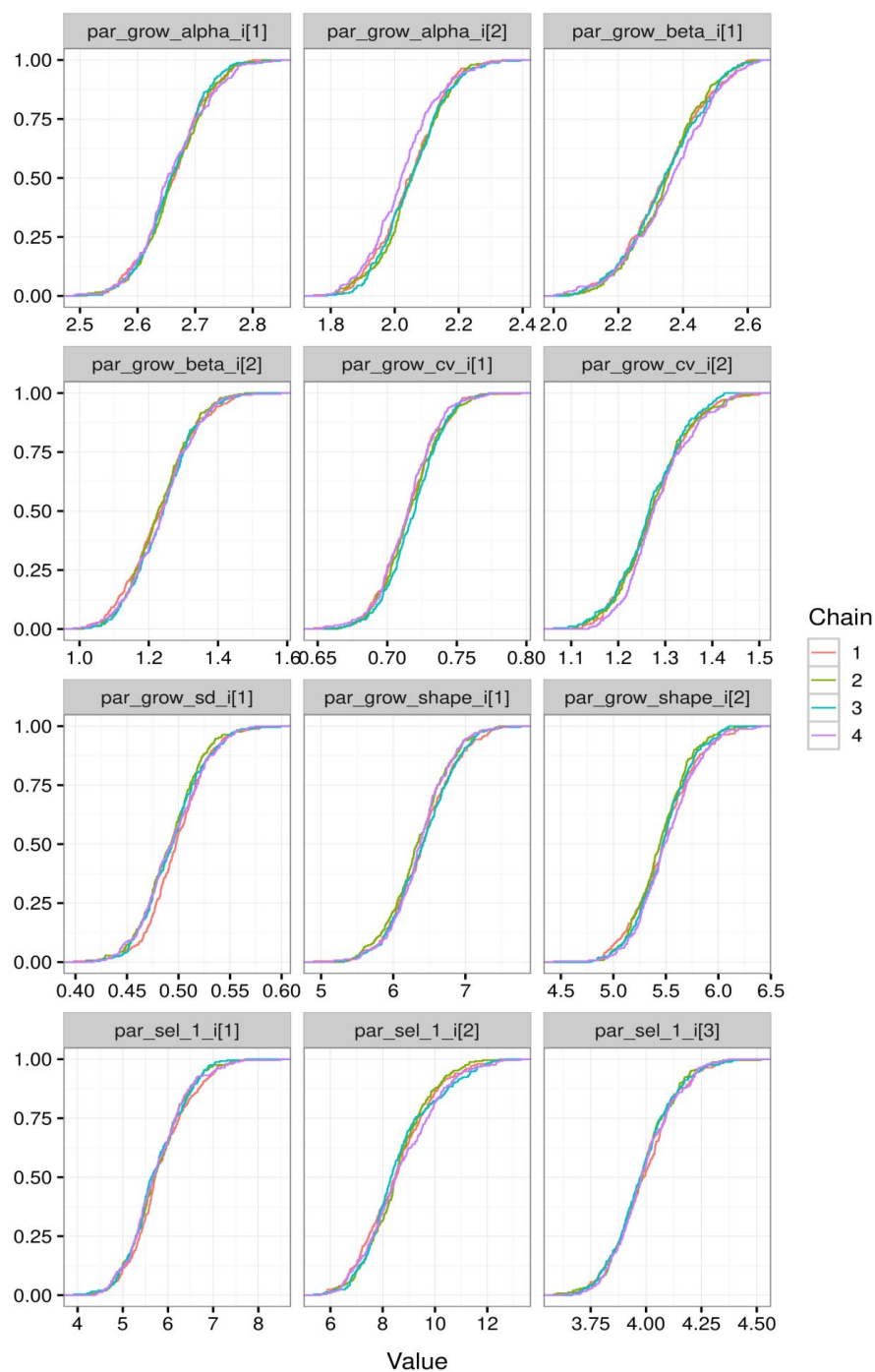


Figure 52: CRA 4 base case MCMC: empirical cumulative proportional distributions for each independent MCMC chain for growth, maturity, and selectivity parameters.

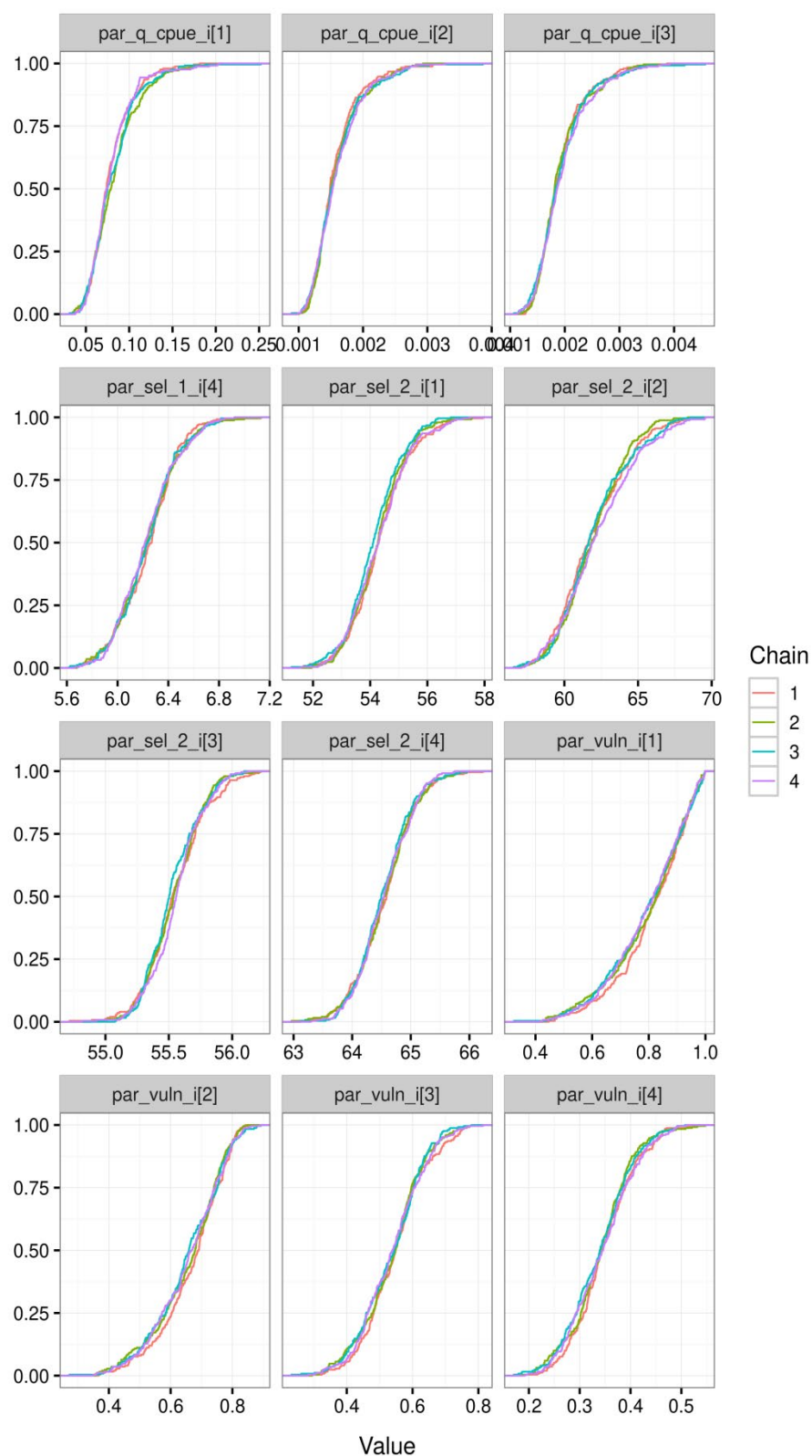


Figure 53: CRA 4 base case MCMC: empirical cumulative proportional distributions for each independent MCMC chain for catchability (q), selectivity, and vulnerability parameters.

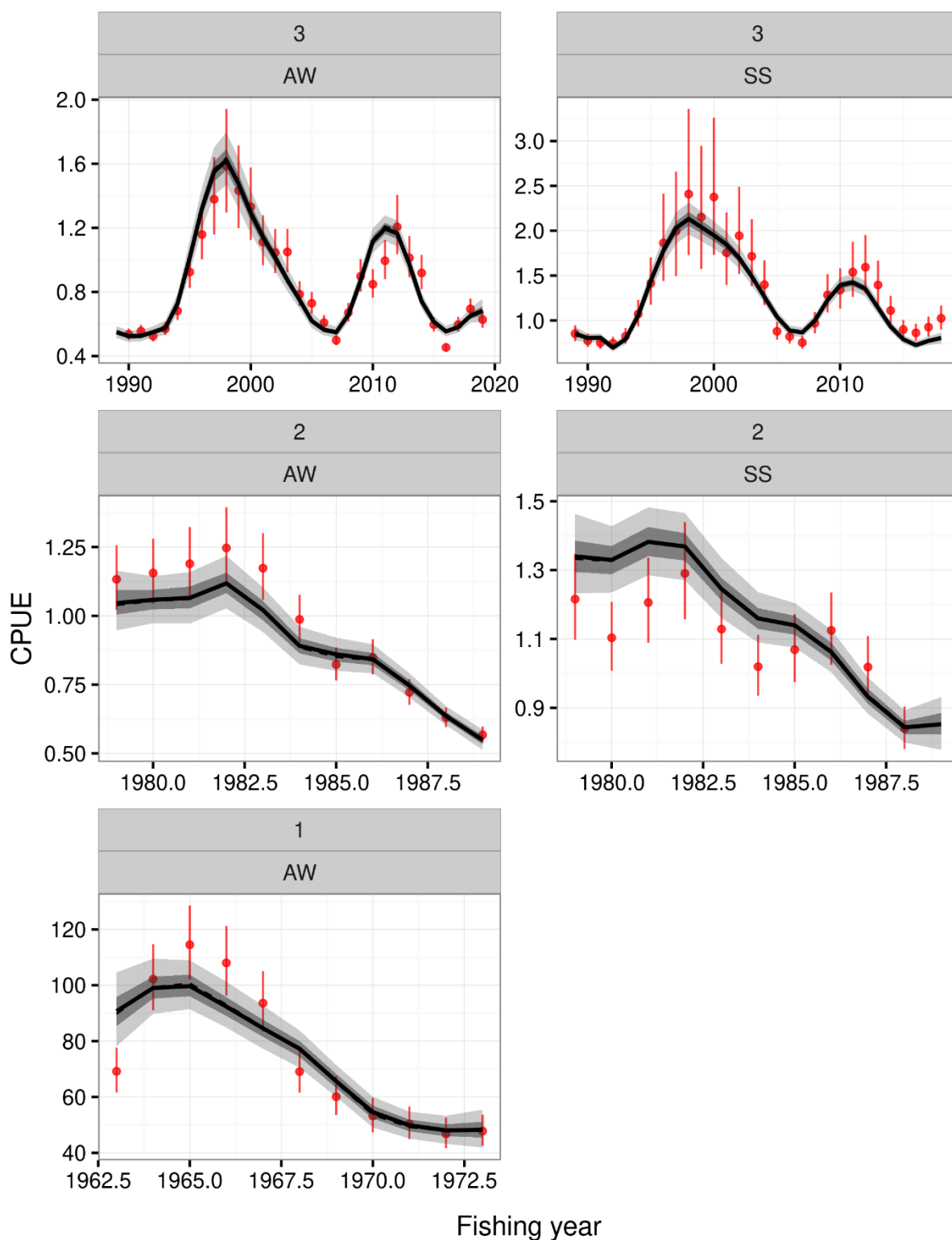


Figure 54: CRA 4 base case MCMC: posterior of predicted CPUE by season: upper panels = CELR fit; middle panels = FSU fit; lower panels = CR fit. The solid line indicates the posterior median and grey shading with variable intensity indicates the 50% and 90% credible intervals. A dashed line (often not visible as it is covered by the median line) indicates the corresponding MAP estimates.

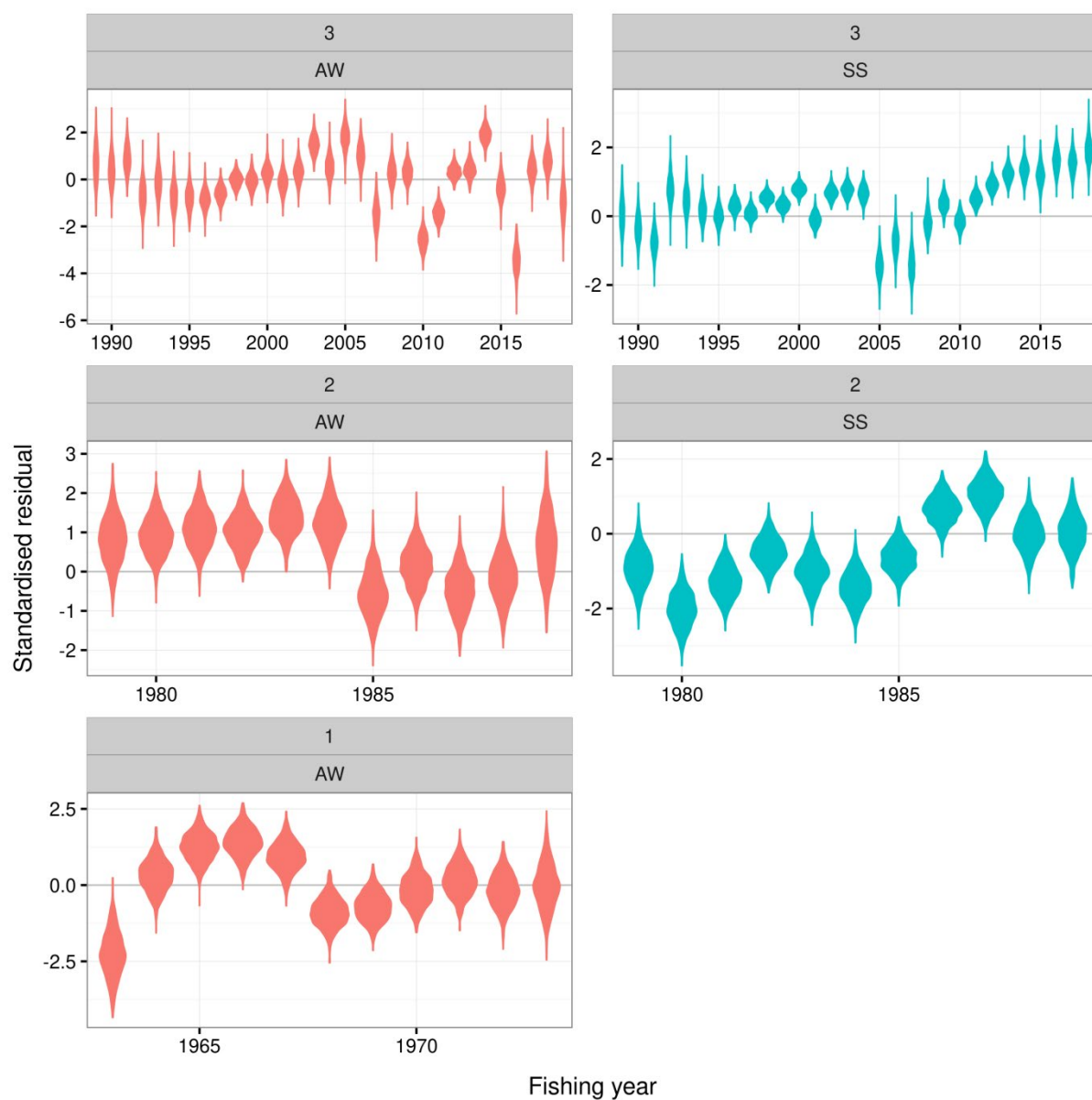


Figure 55: CRA 4 base case MCMC: distribution of standardised residuals between the predicted CPUE and observed CPUE by season for each sample from the posterior distribution. Upper panels = CELR fit; middle panels = FSU fit; lower panels = CR fit.

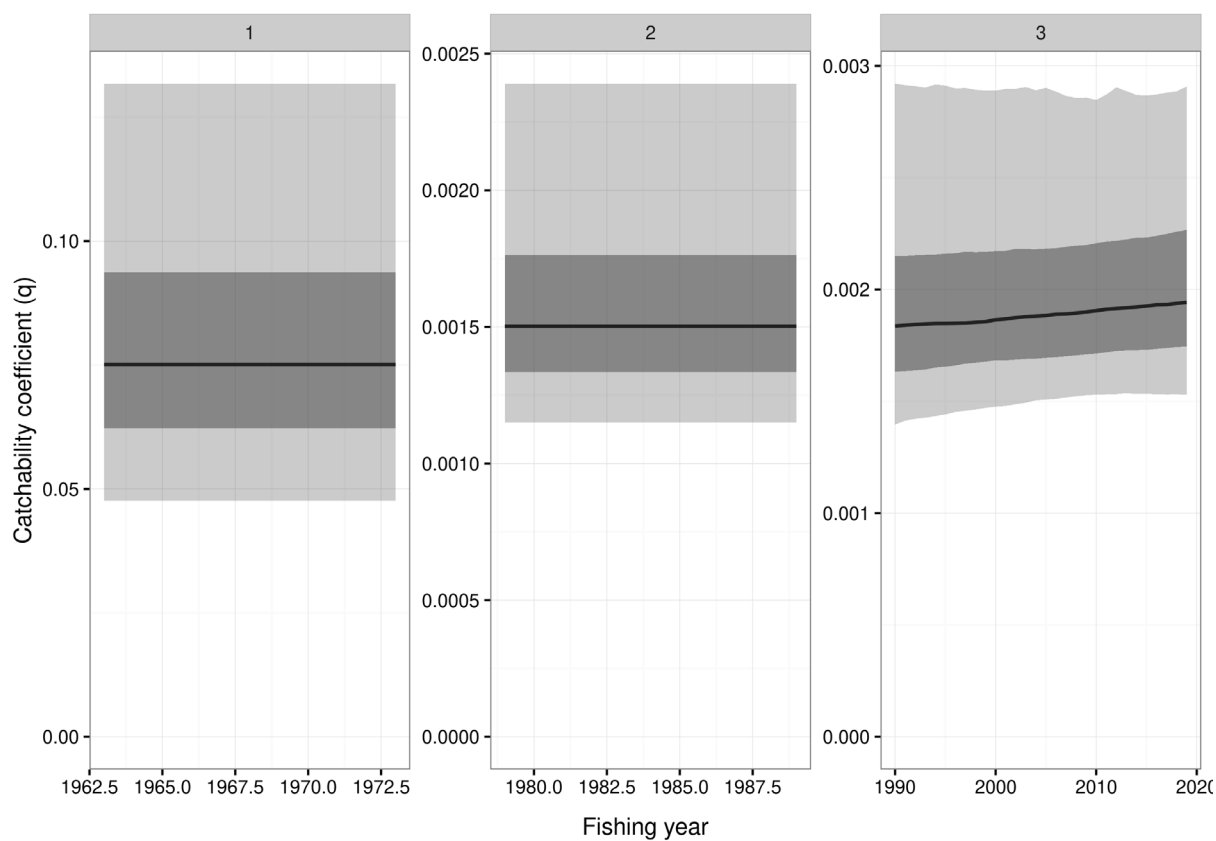


Figure 56: CRA 4 base case MCMC: catchability coefficient (q) selectivity by fishing year, with the solid line indicating the posterior median and the variable intensity grey shaded bands showing the 50% and 90% credible intervals. Left panel = CR fit; middle panel = FSU fit; right panels = CELR fit.

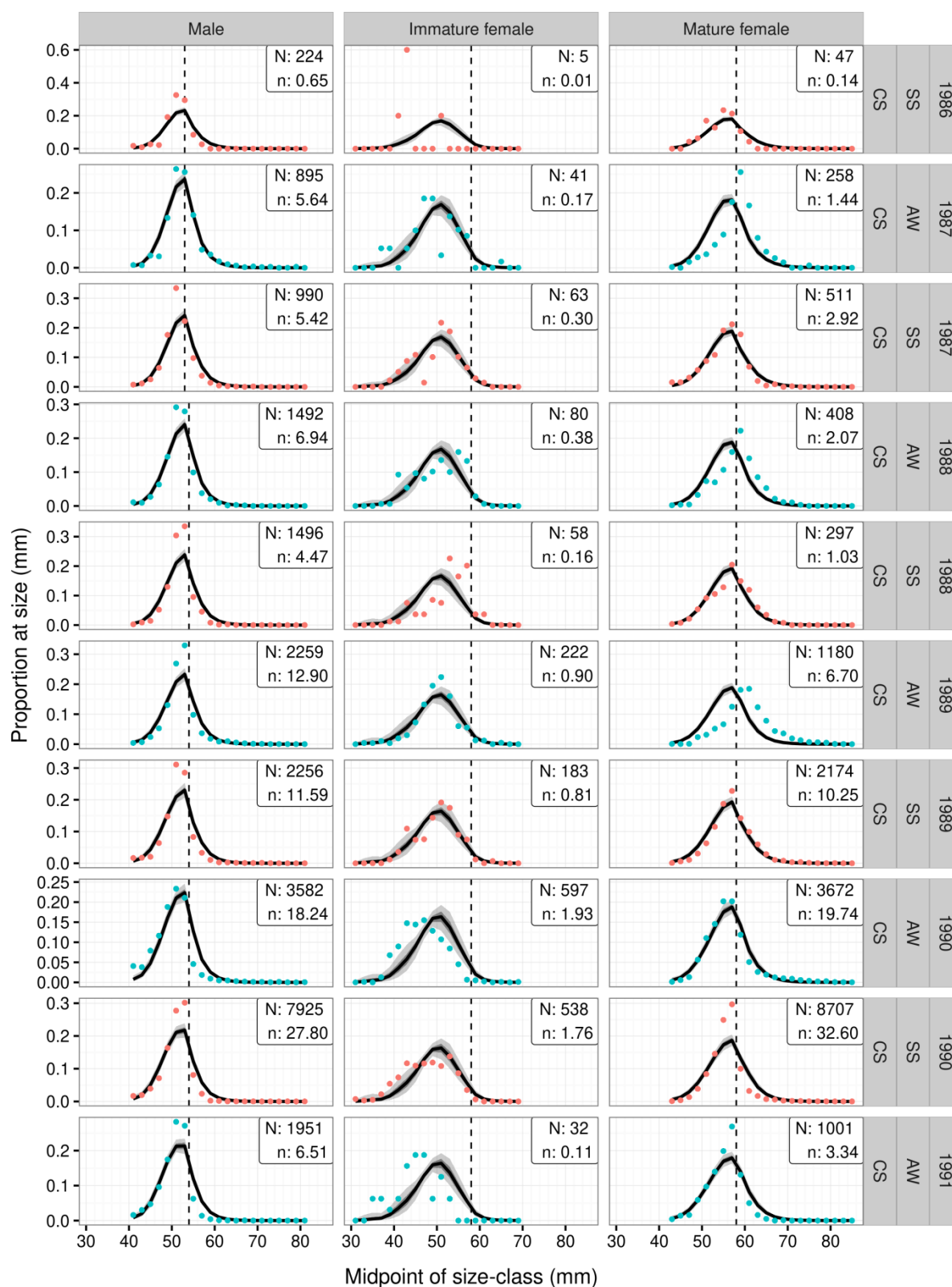


Figure 57: CRA 4 base case MCMC: posterior distribution of LFs compared with the observed LFs from 1986 SS CS to 1991 AW CS. The solid line indicates the posterior median and grey shading with variable intensity indicates the 50% and 90% credible intervals.

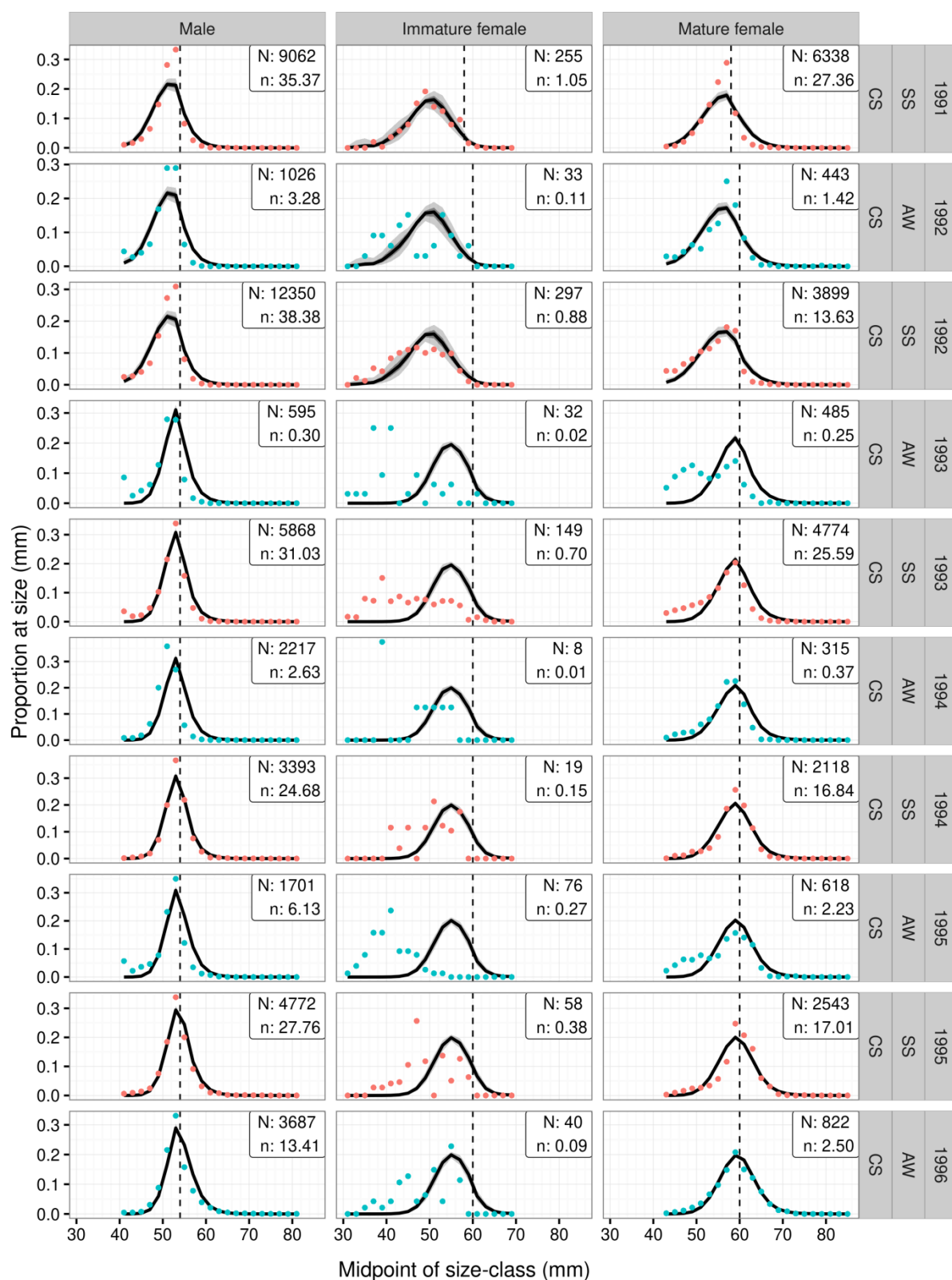


Figure 58: CRA 4 base case MCMC: posterior vs. observed LFs from 1991 SS CS to 1996 AW CS. The solid line indicates the posterior median and grey shading with variable intensity indicates the 50% and 90% credible intervals.

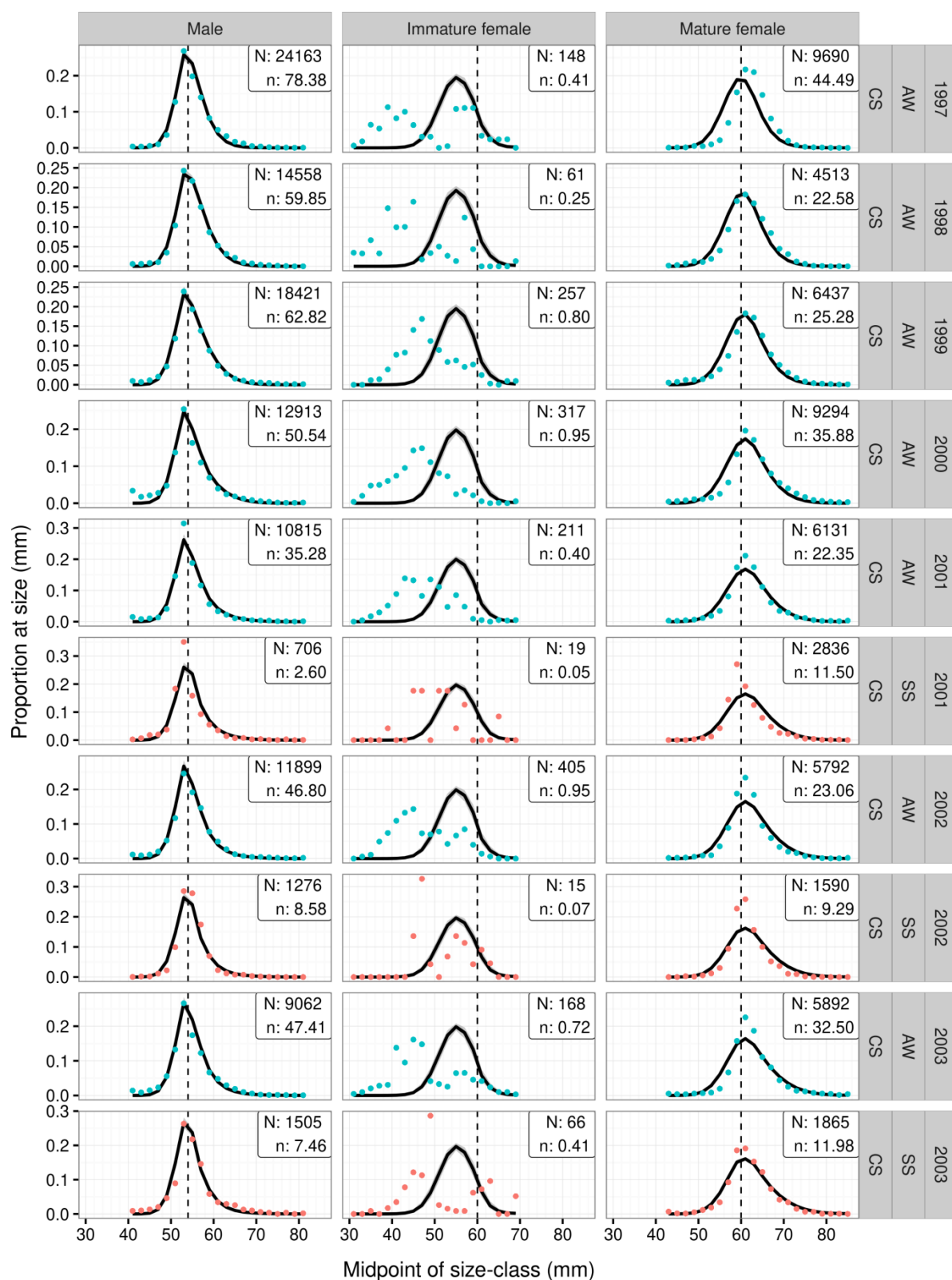


Figure 59: CRA 4 base case MCMC: posterior vs. observed LFs from 1997 AW CS to 2003 SS CS. The solid line indicates the posterior median and grey shading with variable intensity indicates the 50% and 90% credible intervals.

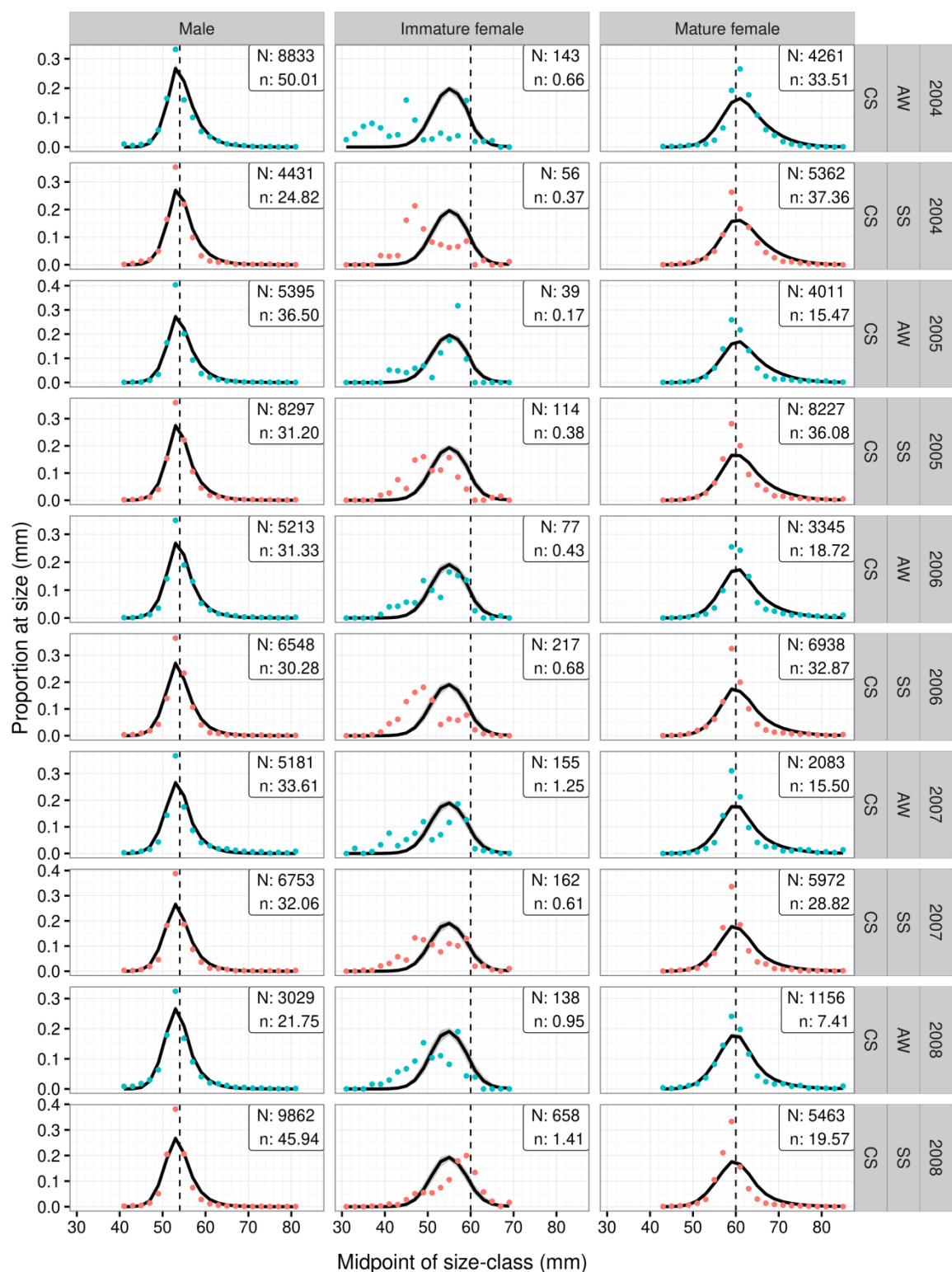


Figure 60: CRA 4 base case MCMC: posterior vs. observed LFs from 2004 AW CS to 2008 SS CS. The solid line indicates the posterior median and grey shading with variable intensity indicates the 50% and 90% credible intervals.

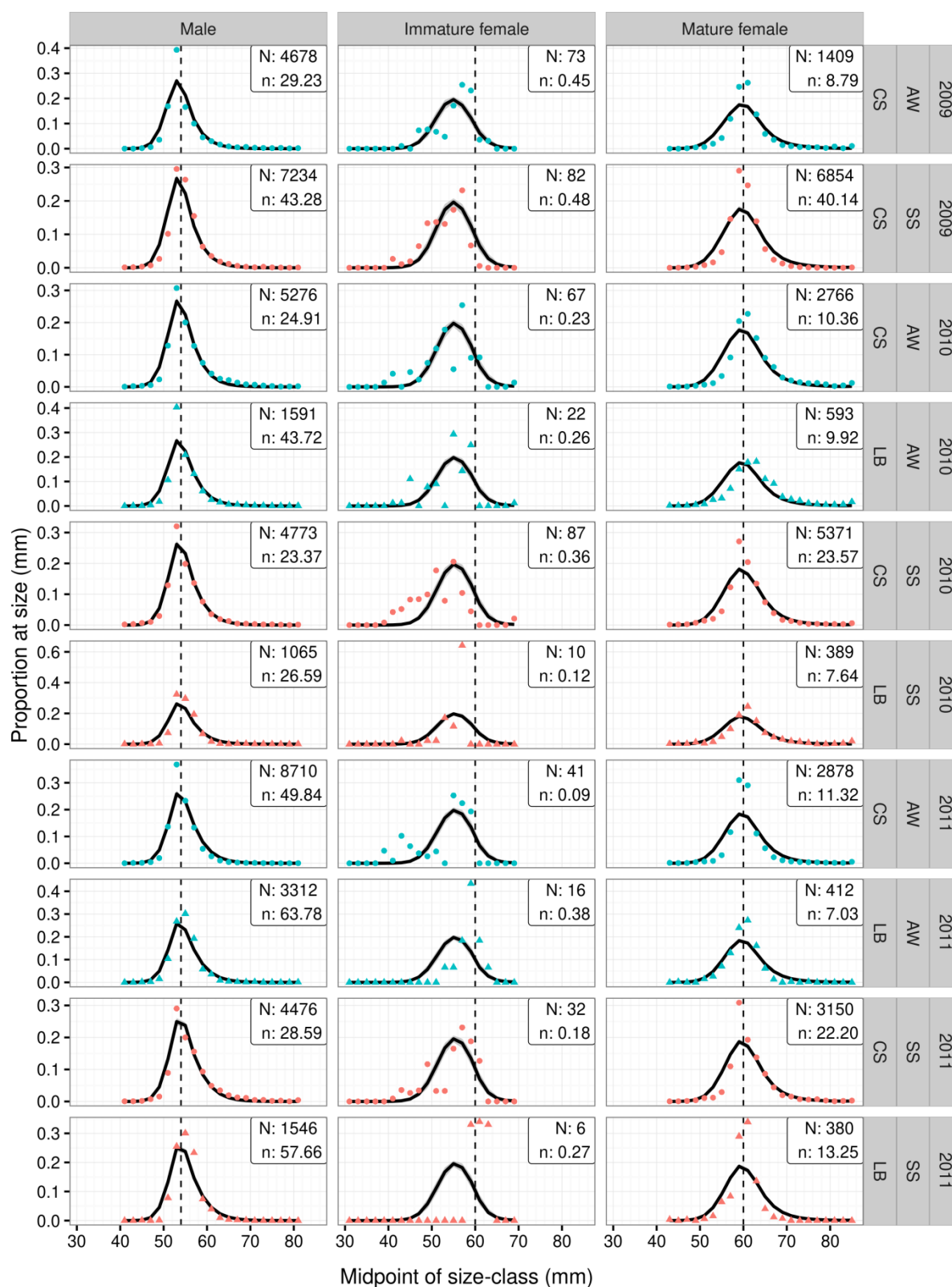


Figure 61: CRA 4 base case MCMC: posterior vs. observed LFs from 2009 AW CS to 2011 SS LB. The solid line indicates the posterior median and grey shading with variable intensity indicates the 50% and 90% credible intervals.

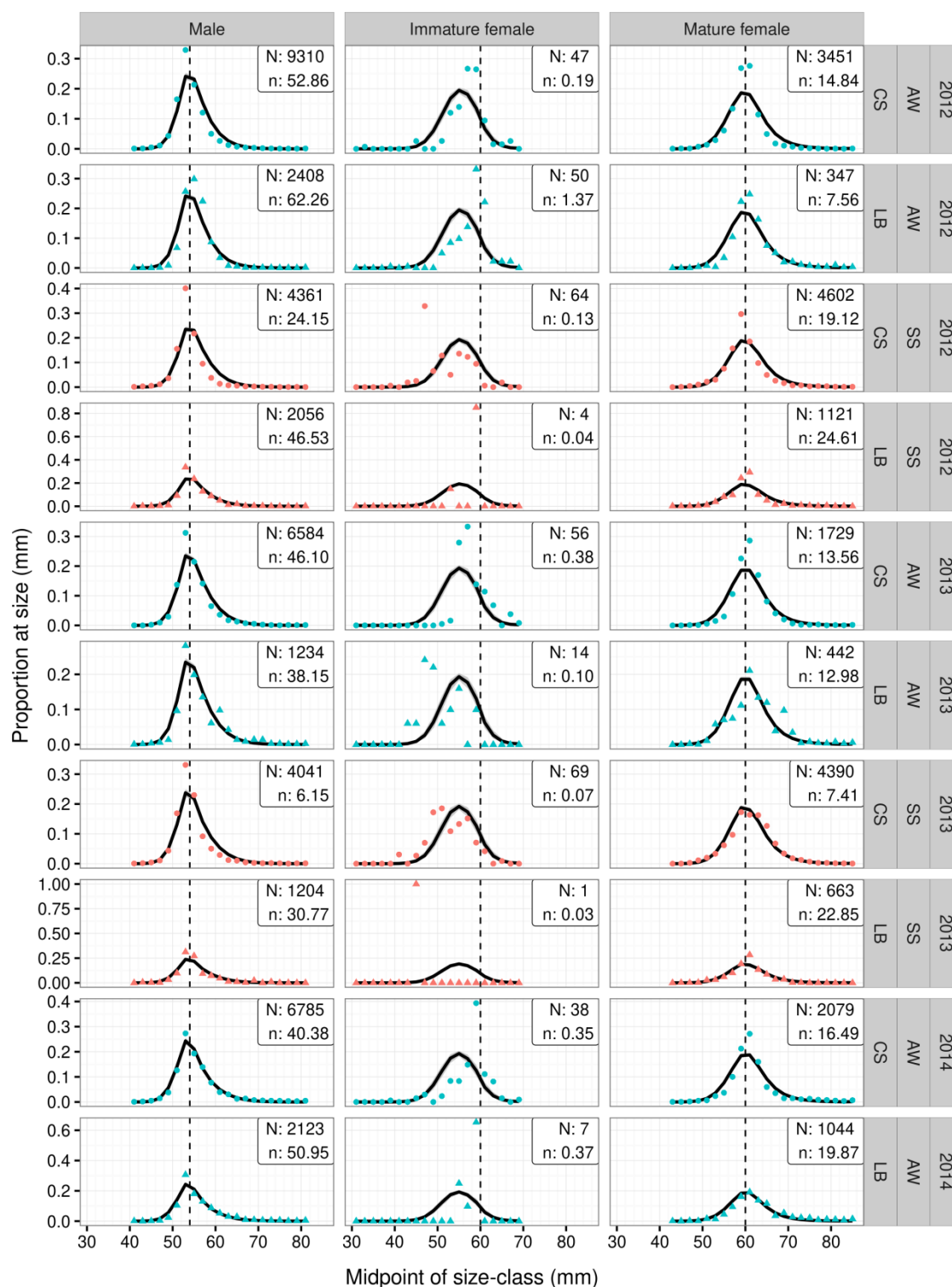


Figure 62: CRA 4 base case MCMC: posterior vs. observed LFs from 2012 AW CS to 2014 AW LB. The solid line indicates the posterior median and grey shading with variable intensity indicates the 50% and 90% credible intervals.

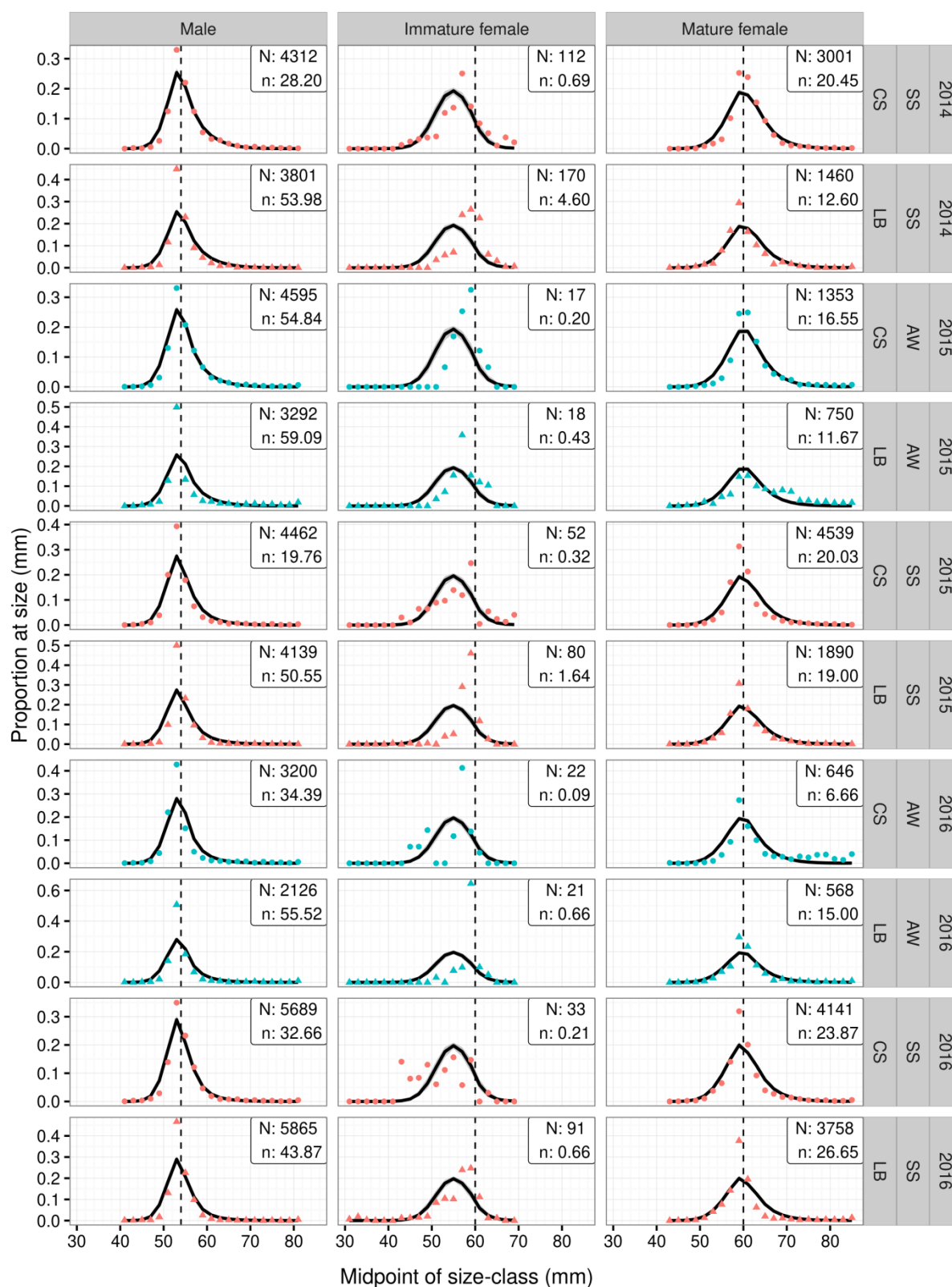


Figure 63: CRA 4 base case MCMC: posterior vs. observed LF's from 2014 SS CS to 2016 SS LB. The solid line indicates the posterior median and grey shading with variable intensity indicates the 50% and 90% credible intervals.

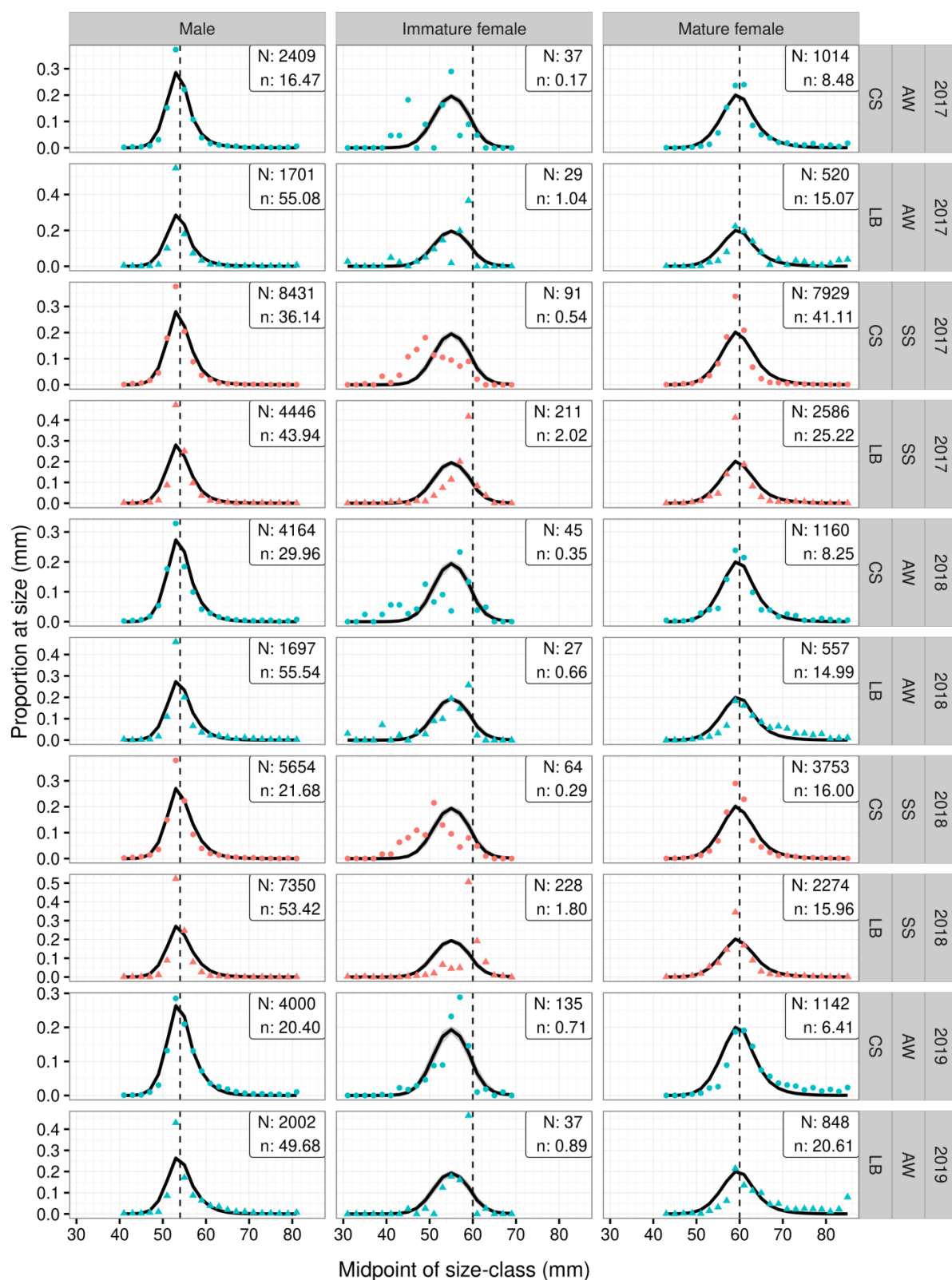


Figure 64: CRA 4 base case MCMC: posterior vs. observed LFs from 2017 AW CS to 2019 AW LB. The solid line indicates the posterior median and grey shading with variable intensity indicates the 50% and 90% credible intervals.

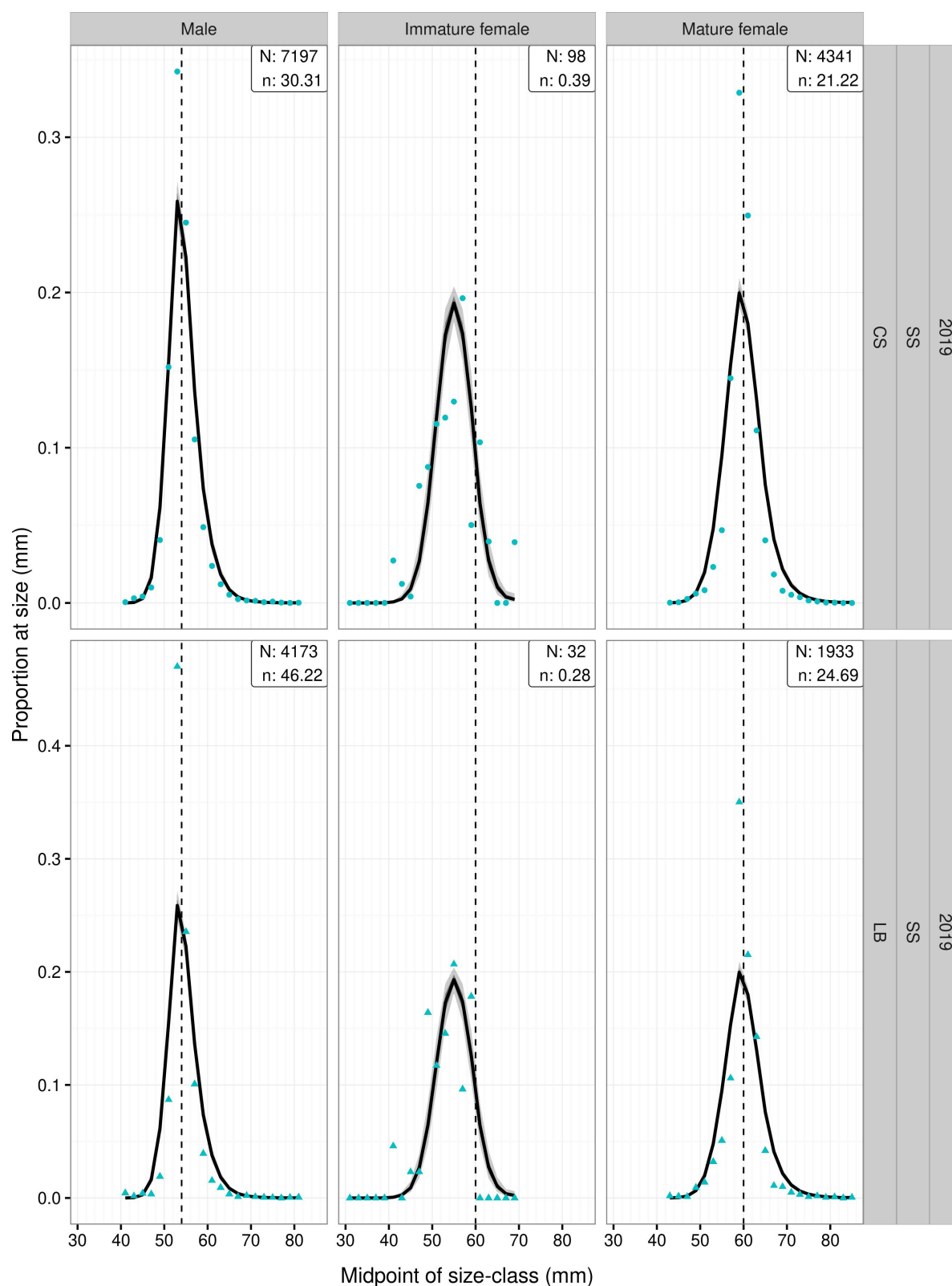


Figure 65: CRA 4 base case MCMC: case posterior vs. observed LF's from 2019 SSLB and CS. The solid line indicates the posterior median and grey shading with variable intensity indicates the 50% and 90% credible intervals.

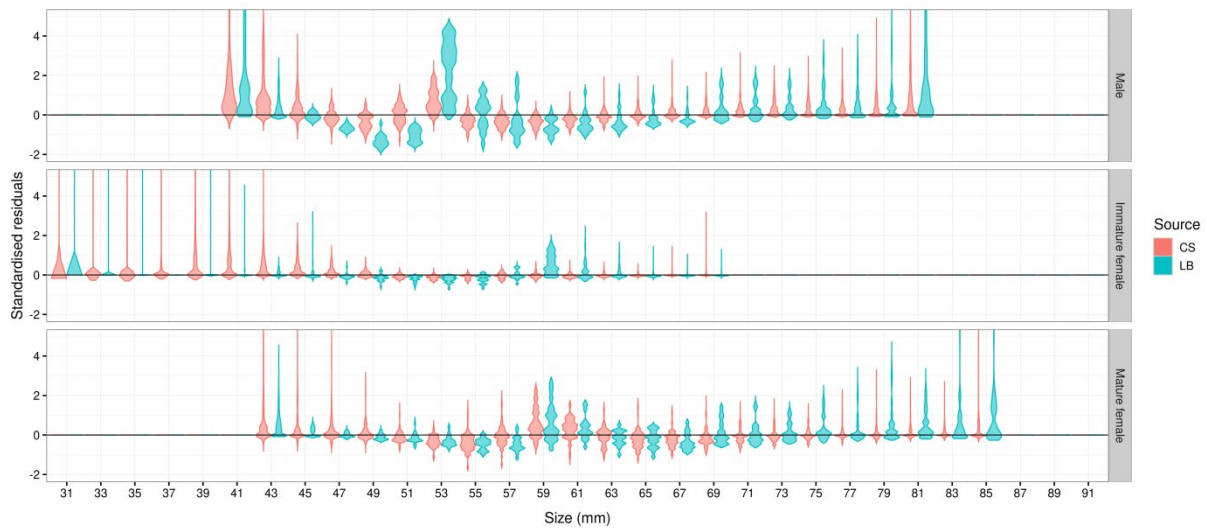


Figure 66: CRA 4 base case MCMC: distribution of standardised residuals between the predicted LF distributions and LF data for each sample from the posterior distribution, showing residuals by sex, 2-mm size bin, and sampling source (CS = catch sampling, LB = logbook). Shading intensity varies with number of observations.

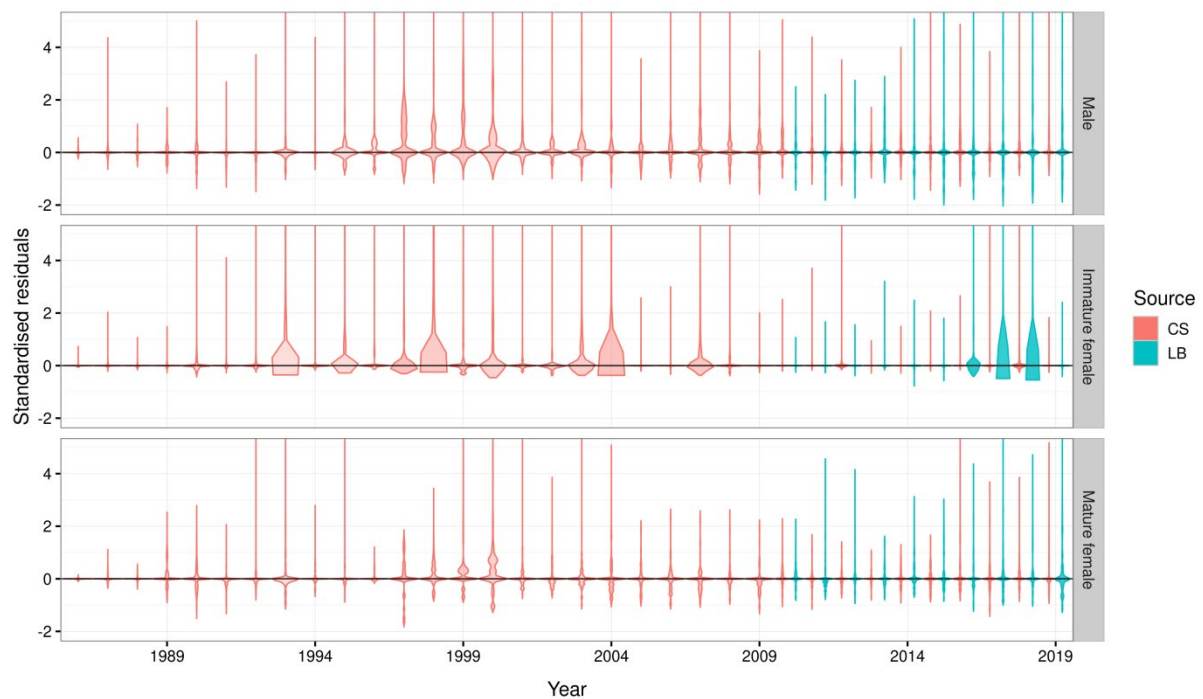


Figure 67: CRA 4 base case MCMC: distribution of standardised residuals between the predicted LF distributions and LF data for each sample from the posterior distribution, showing residuals by sex, year, and sampling source (CS = catch sampling, LB = logbook). Shading intensity varies with number of observations.

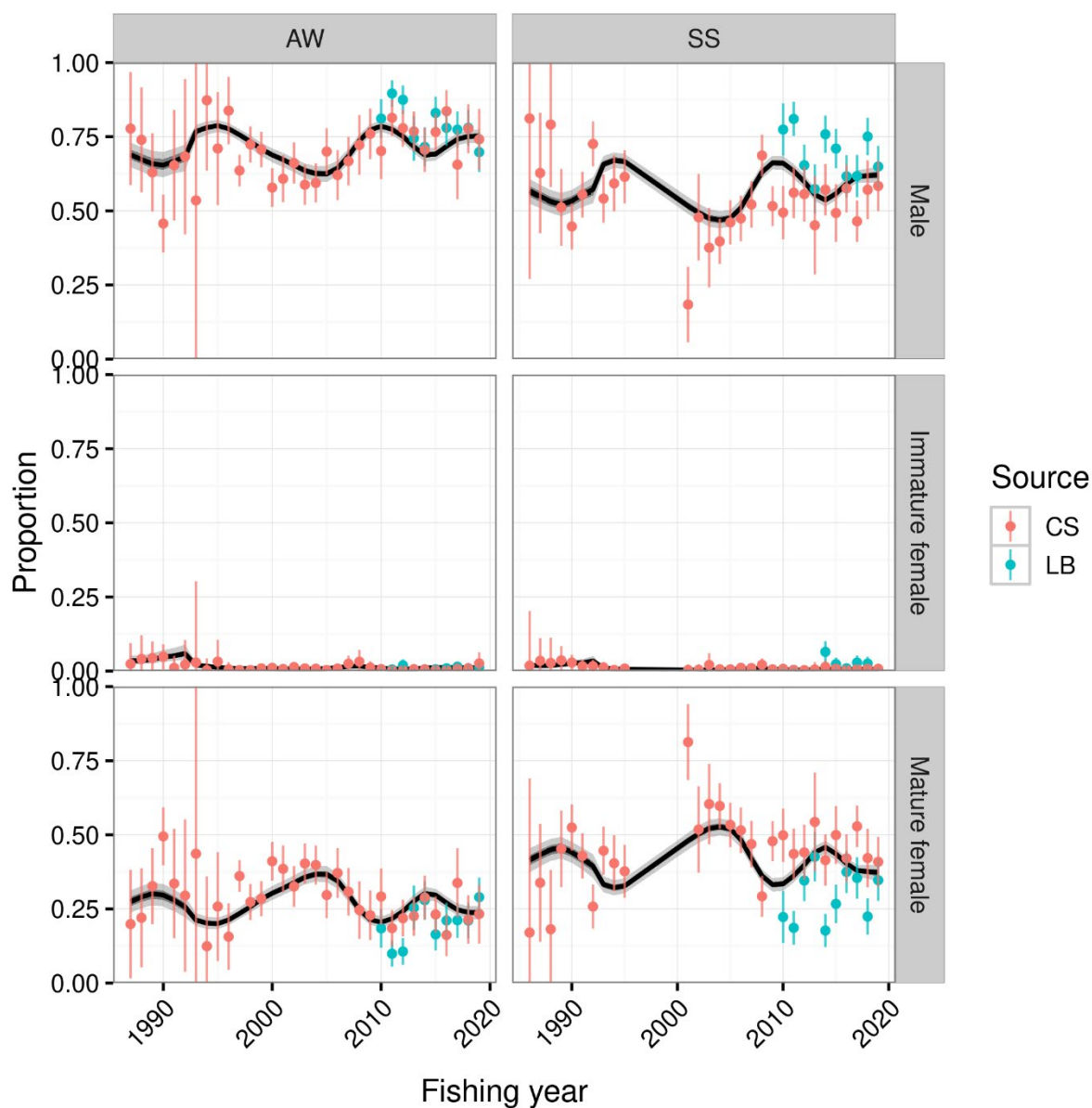


Figure 68: CRA 4 base case MCMC: model fit to sex ratios by year and LF data source (CS = catch sampling, LB = logbook). The solid line indicates the posterior median and grey shading with variable intensity indicates the 90% credible intervals.

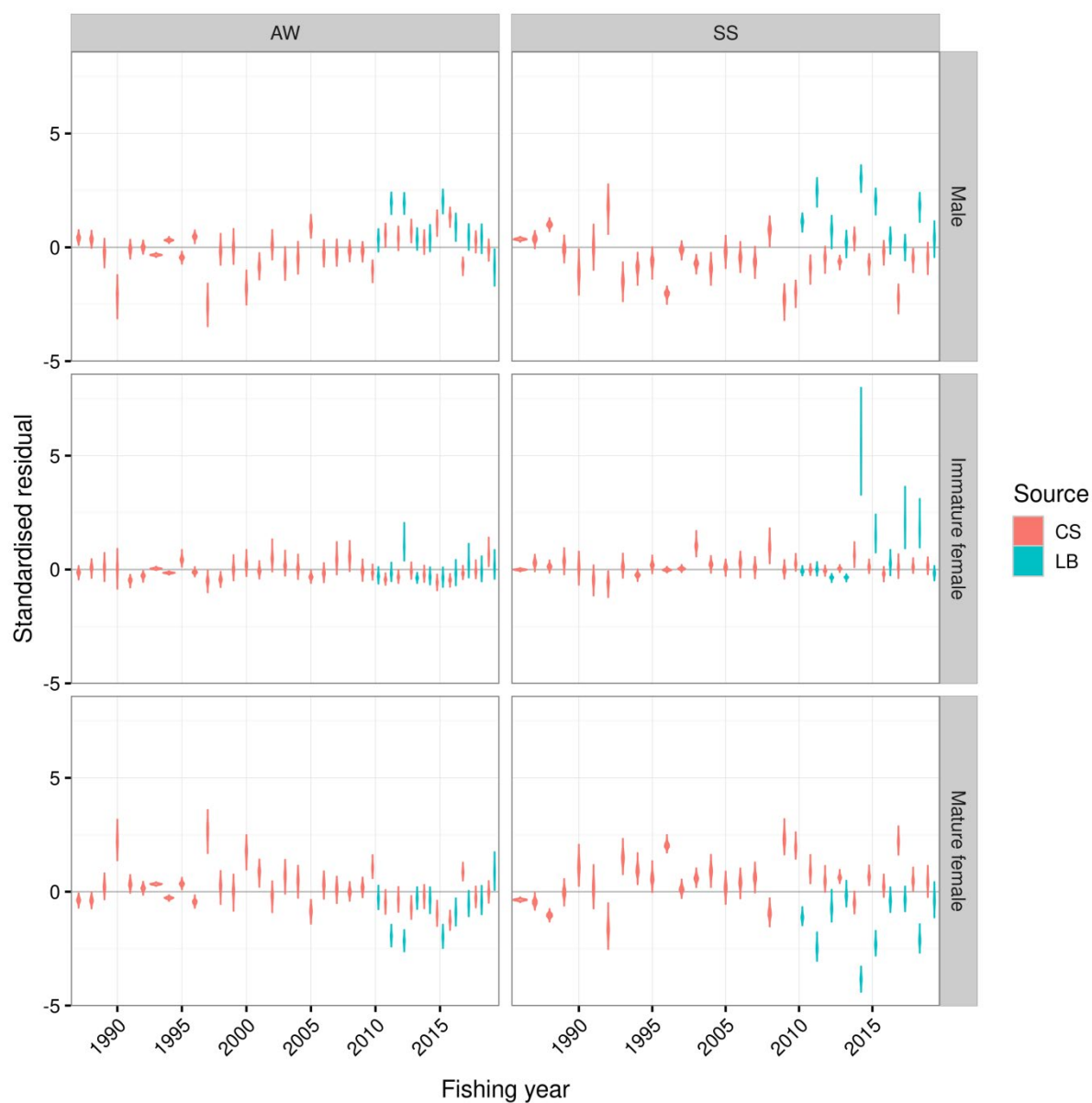


Figure 69: CRA 4 base case MCMC: standardised residuals for sex ratios by year and LF data source (CS = catch sampling, LB = logbook).

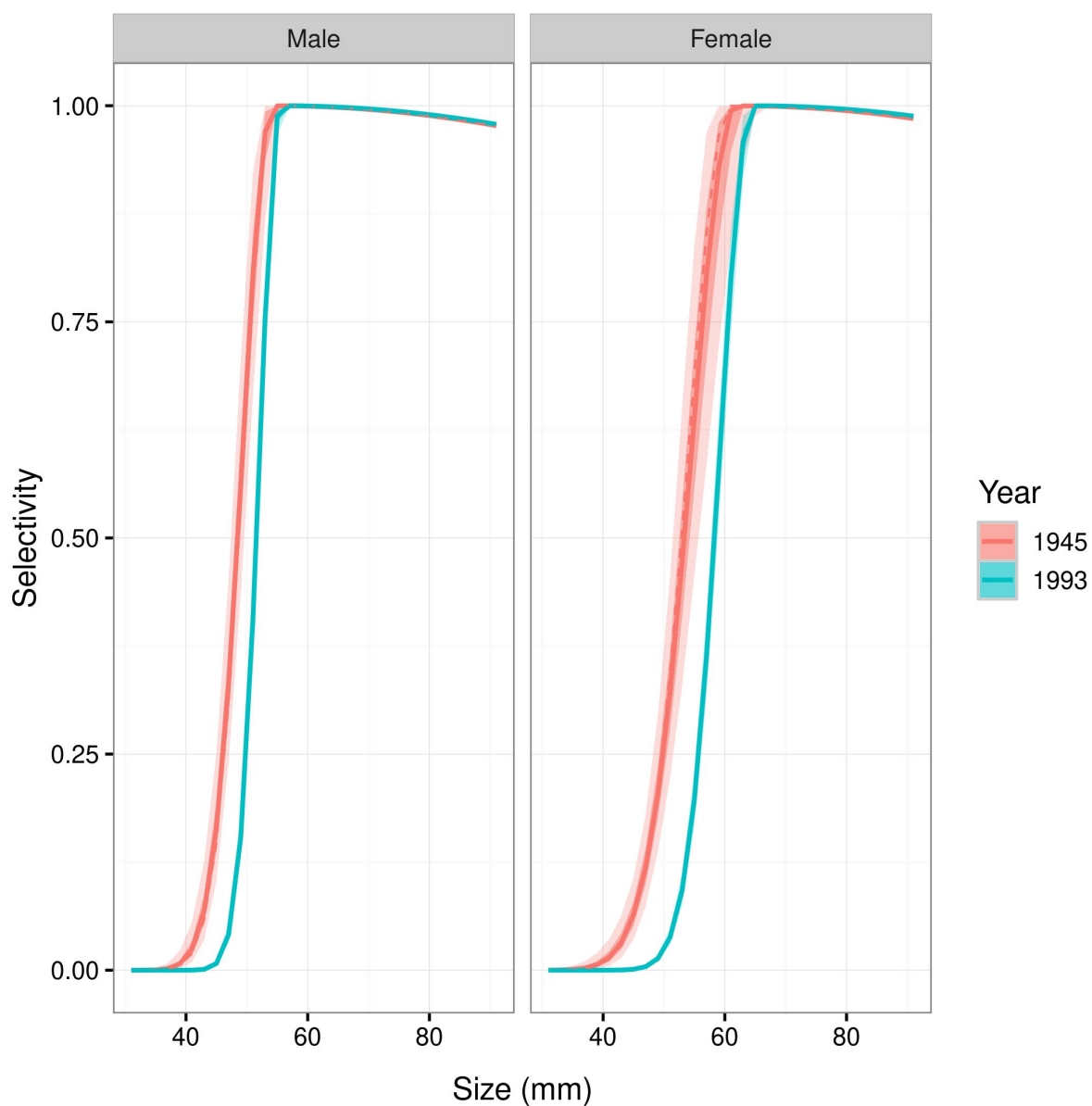


Figure 70: CRA 4 base case MCMC: selectivity by sex and epoch, with the solid line indicating the posterior median and the variable intensity bands showing the 50% and 90% credible intervals. Dashed lines indicate the corresponding MAP estimates.

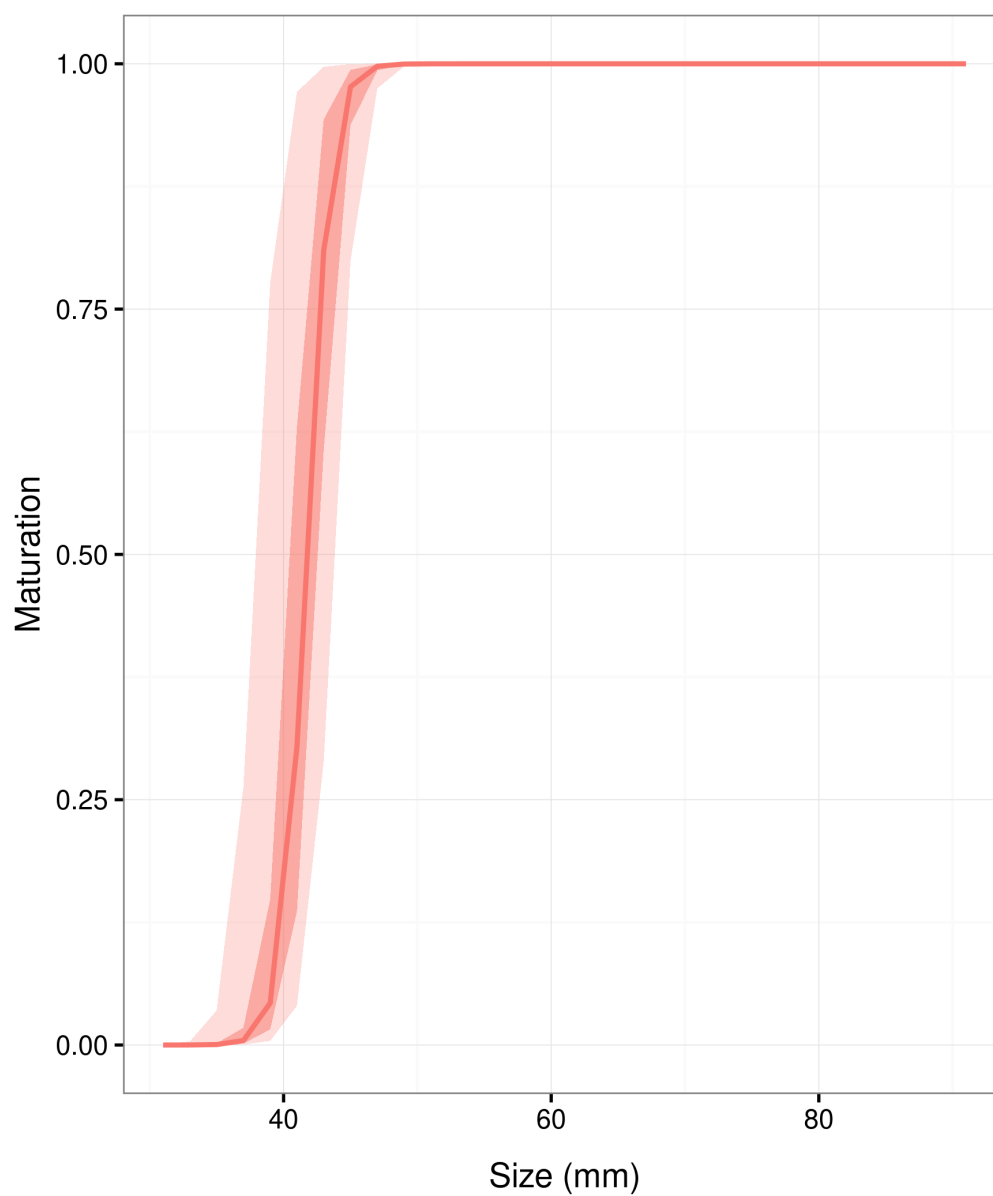


Figure 71: CRA 4 base case MCMC: female maturity, where the solid line indicates the posterior median and shading with variable intensity indicates the 50% and 90% credible intervals.

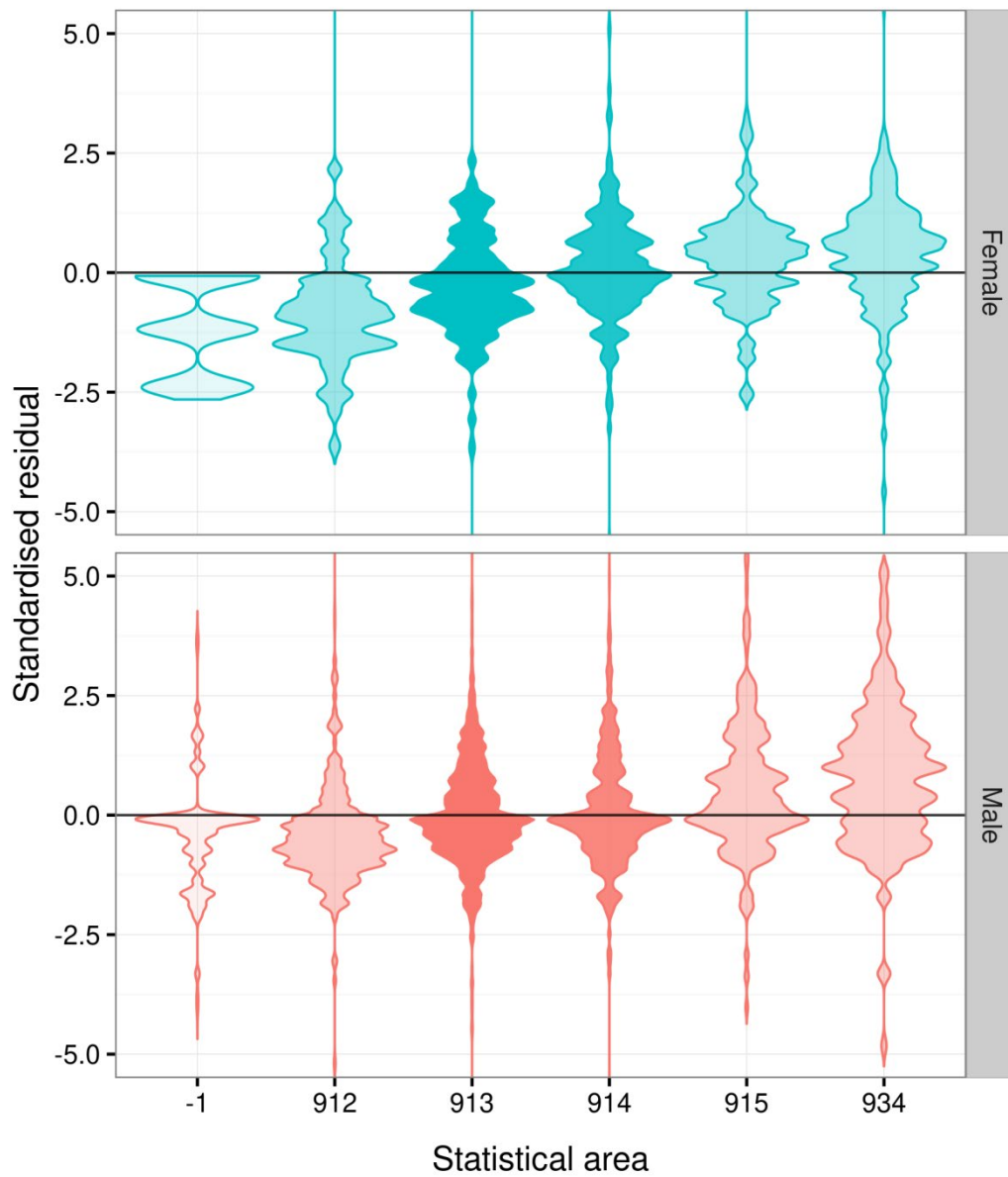


Figure 72: CRA 4 base case MCMC: distribution of tag residuals by statistical area of release and sex for each sample from the posterior distribution. Shading intensity varies with number of observations.

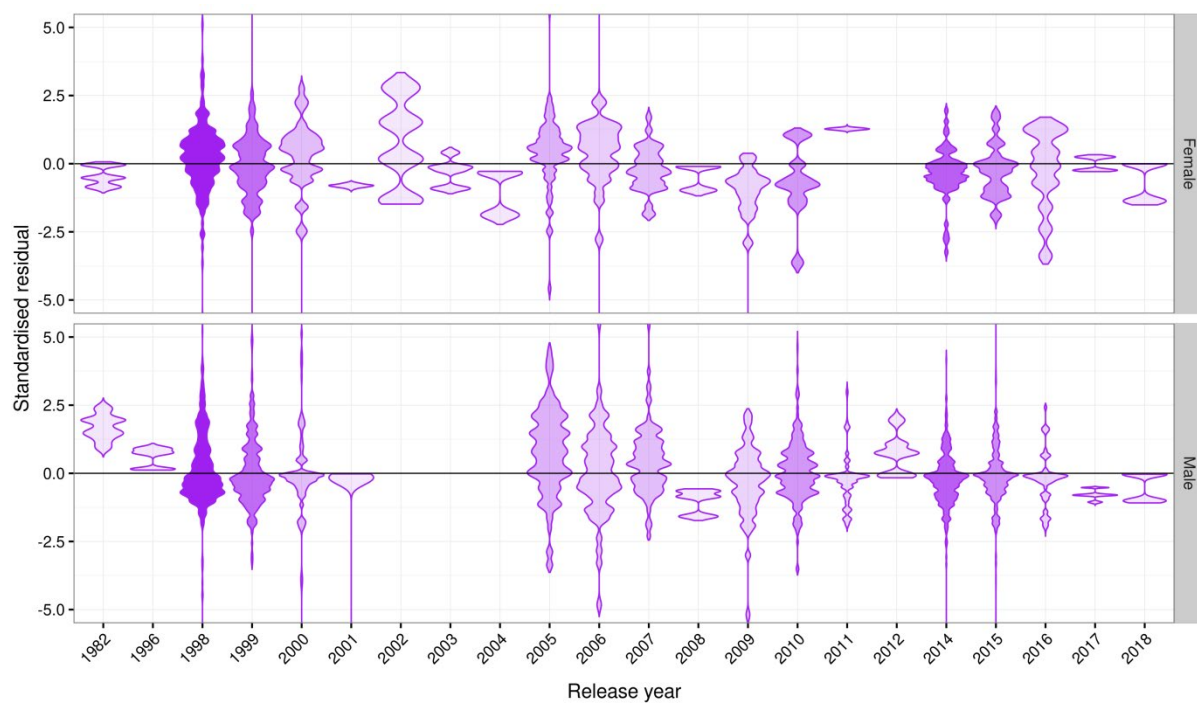


Figure 73: CRA 4 base case MCMC: distribution of tag residuals by year of release for each sample from the posterior distribution. Shading intensity varies with number of observations.

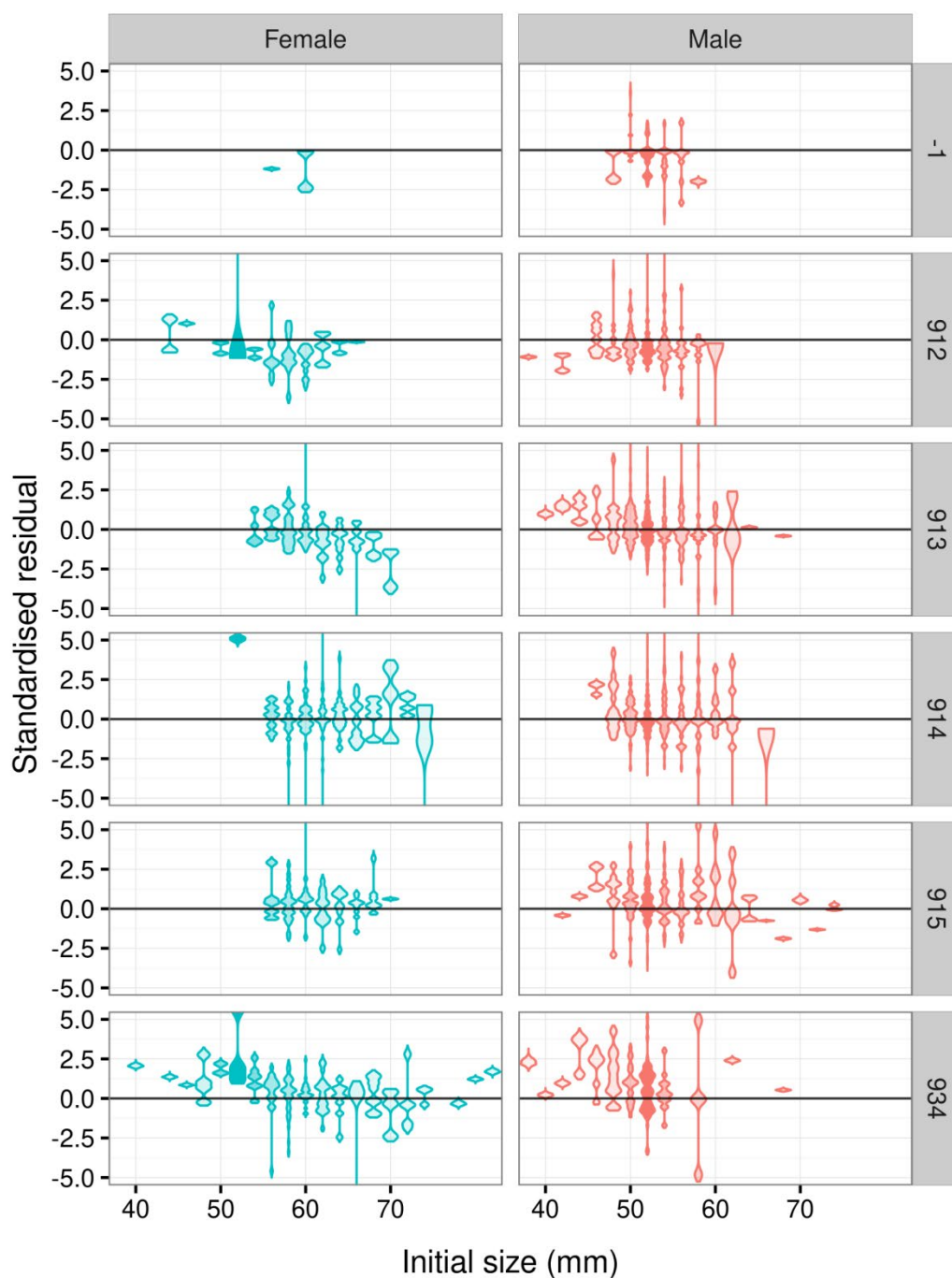


Figure 74: CRA 4 base case MCMC: distribution of tag residuals by statistical area of release, initial size (TW bin), and sex for each sample from the posterior distribution. Shading intensity varies with number of observations. “-1” indicates an unknown statistical area.

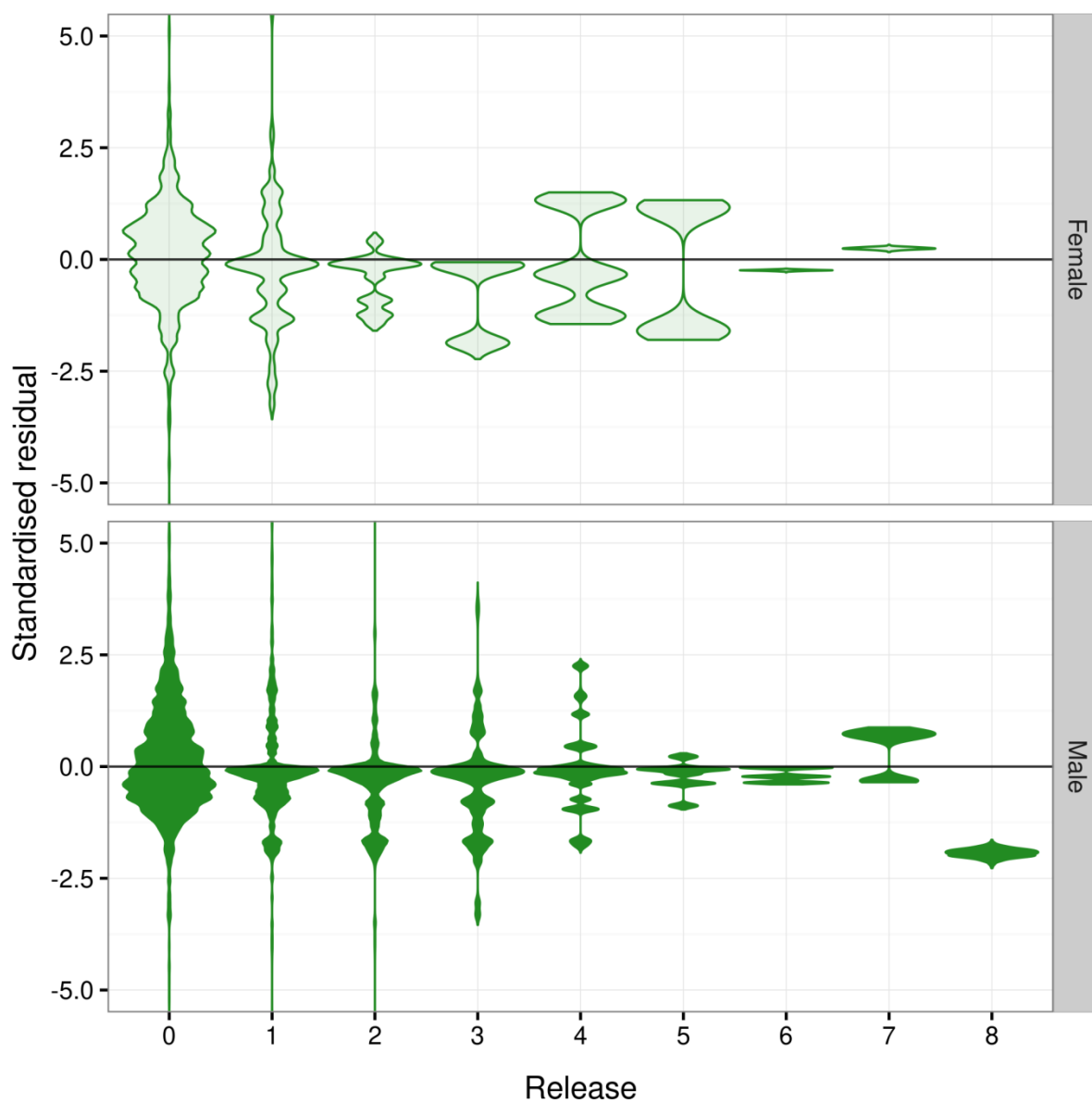


Figure 75: CRA 4 base case MCMC: distribution of tag residuals by sex at release for each sample from the posterior distribution. Shading intensity varies with number of observations.

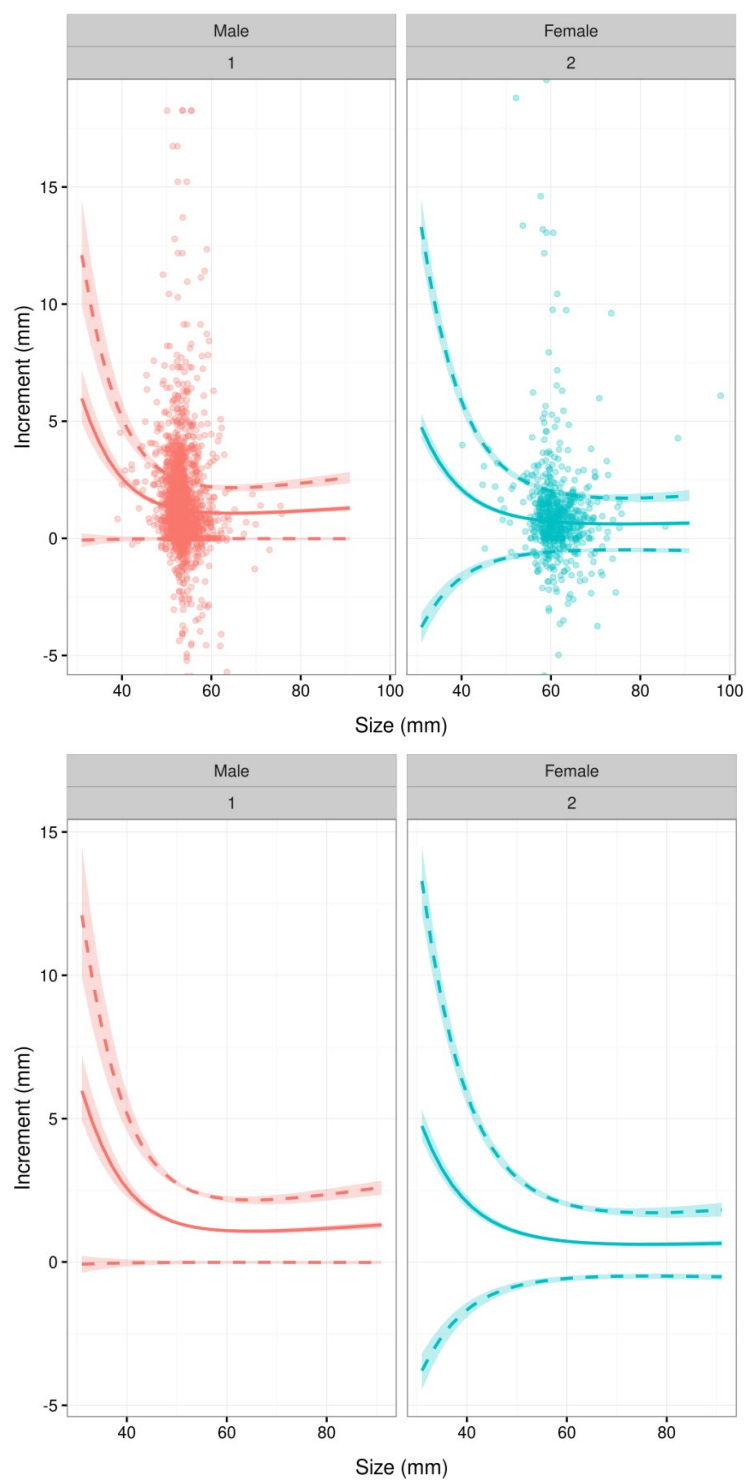


Figure 76: CRA 4 base case MCMC: Predicted increments-at-length (showing [top] and not showing [bottom] the observed recoveries) and ± 1 standard deviation (dashed coloured lines), with the solid line indicating the posterior median and the shaded bands showing the 90% credible intervals.

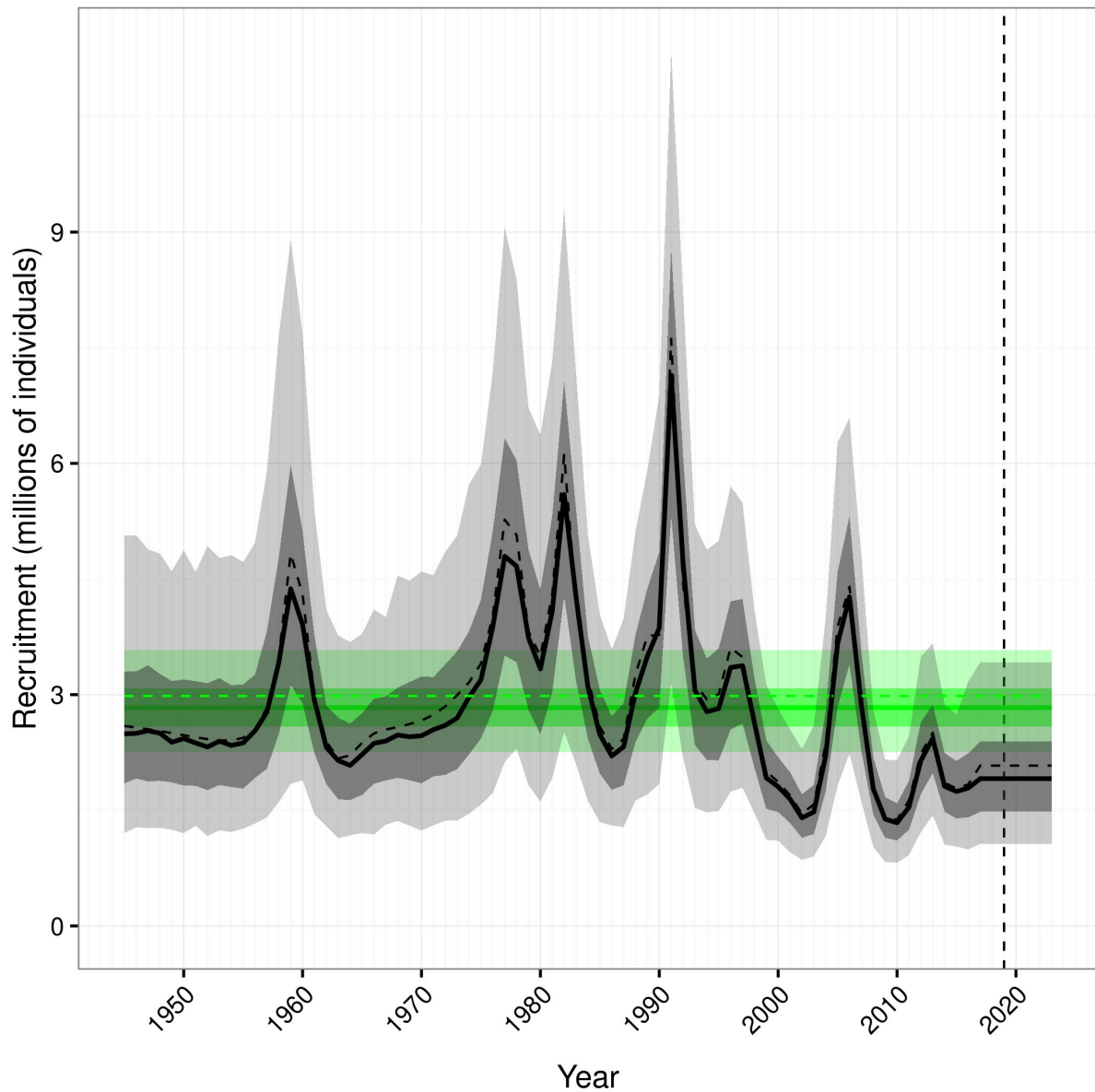


Figure 77: CRA 4 base case MCMC: recruitment in millions, where the dashed black line indicates the MAP, the solid black line indicates the median of the posterior and variable shading intensity indicates the 50% and 90% credible intervals. The horizontal solid green line is the median of the posterior for R_0 with green shading indicating the 50% and 90% credible intervals for R_0 . The vertical dashed line is the final year of the reconstruction period and the dashed green line is the MAP for R_0 . Projection recruitments (plotted to the right of the vertical dashed line) are based on the mean and standard deviation of the 2008–2017 recruitment and the 1945–2017 estimated autocorrelation.

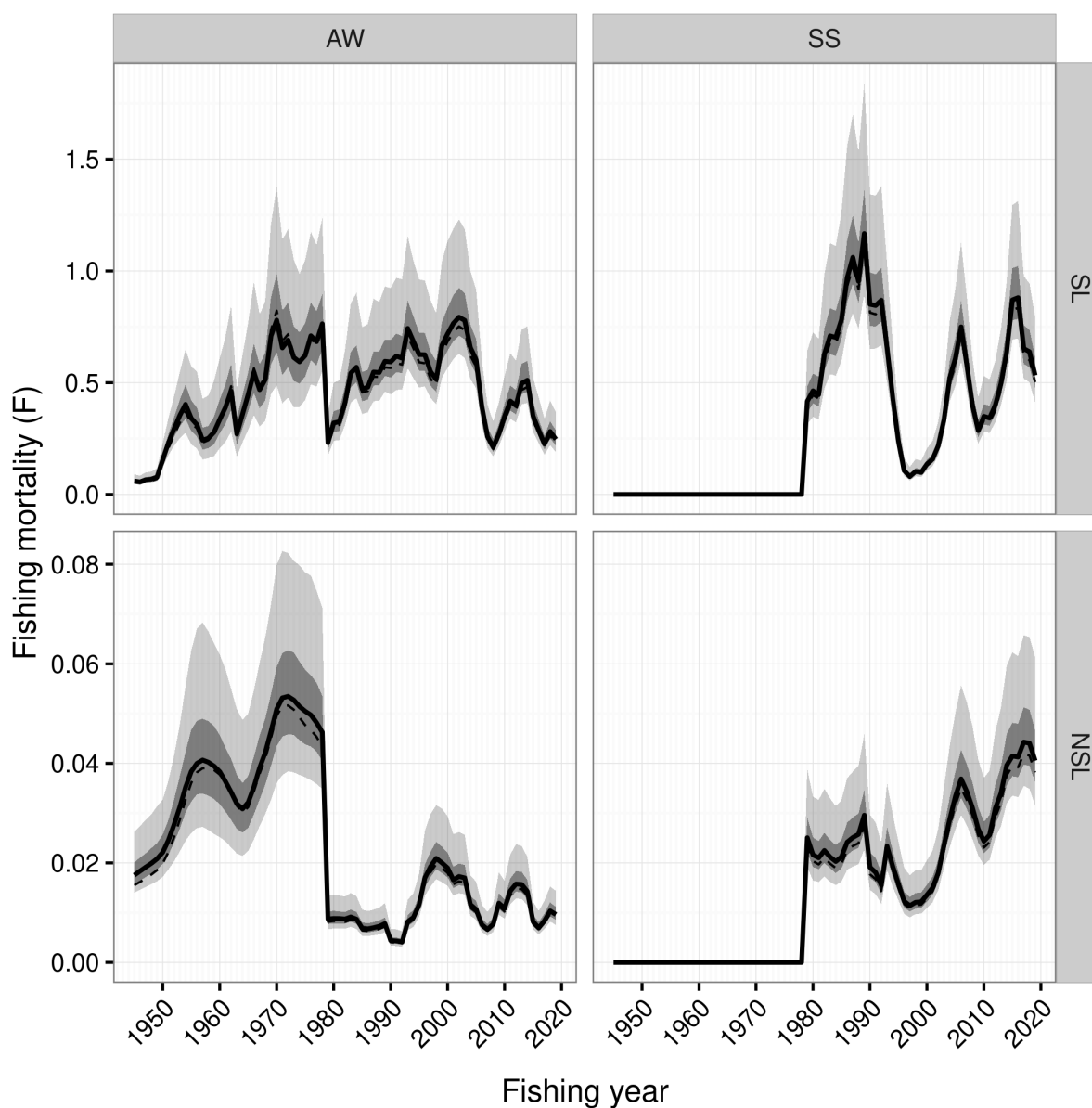


Figure 78: CRA 4 base case MCMC: fishing mortality by year, season, and fishery (SL = size limited; NSL = non size limited), with the dashed black line (not always visible) indicating the MAP, the solid black line indicating the median of the posterior and variable shading intensity indicating the 50% and 90% credible intervals.

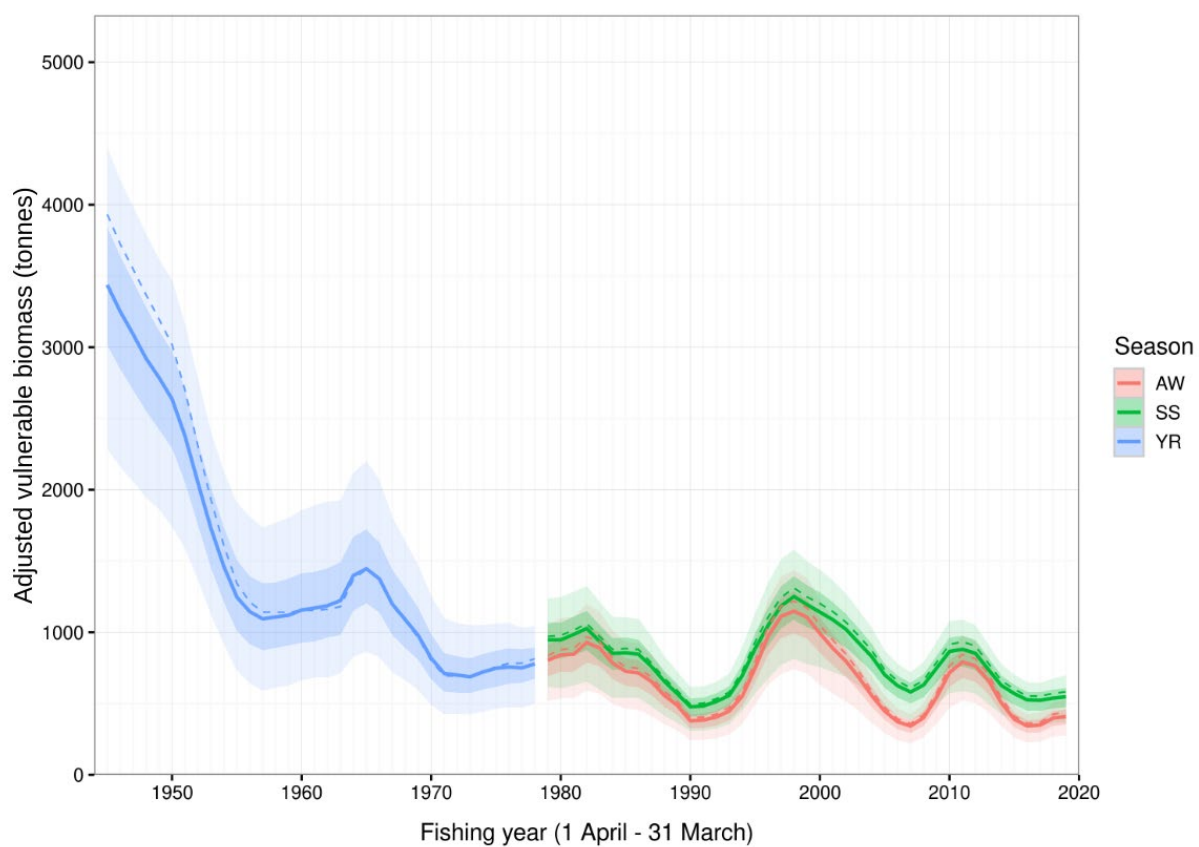


Figure 79: CRA 4 base case MCMC: Posterior distribution of the CRA 4 base case adjusted vulnerable biomass by season, with dashed lines indicating the equivalent MAP estimates. Variable shading intensity indicates the 50% and 90% credible intervals.

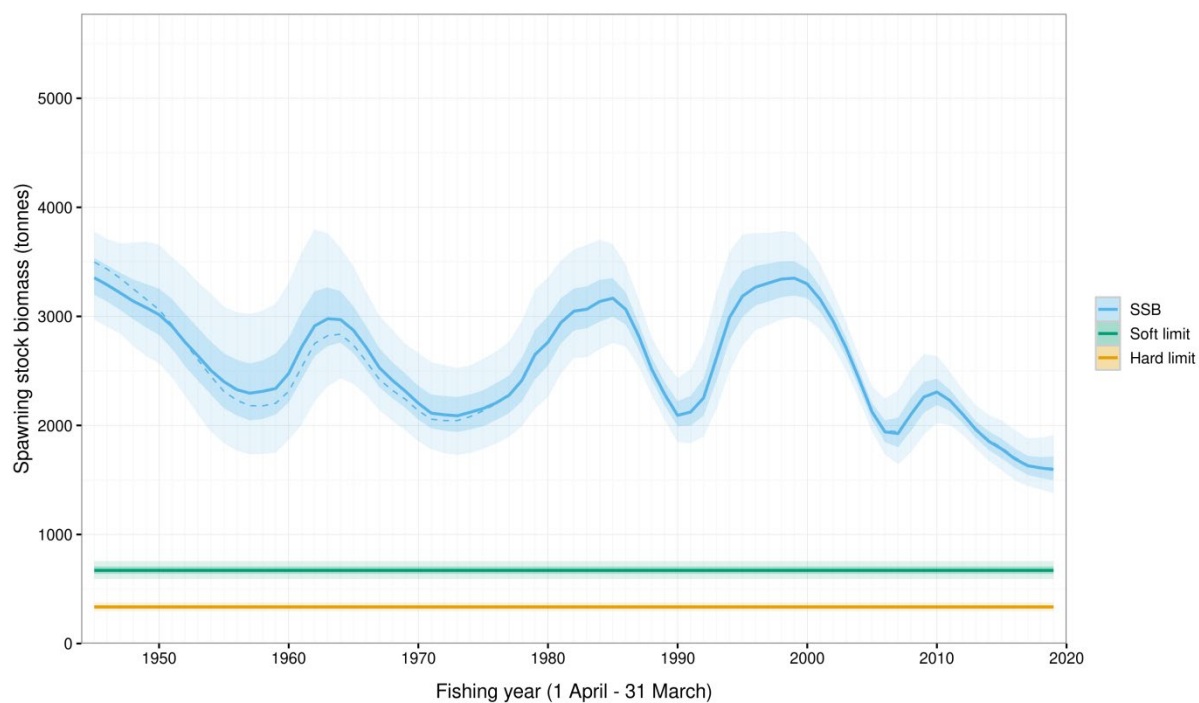


Figure 80: CRA 4 base case MCMC: Posterior distribution of the CRA 4 base case spawning stock biomass, with dashed lines indicating the equivalent MAP estimates. Variable shading intensity indicates the 50% and 90% credible intervals.

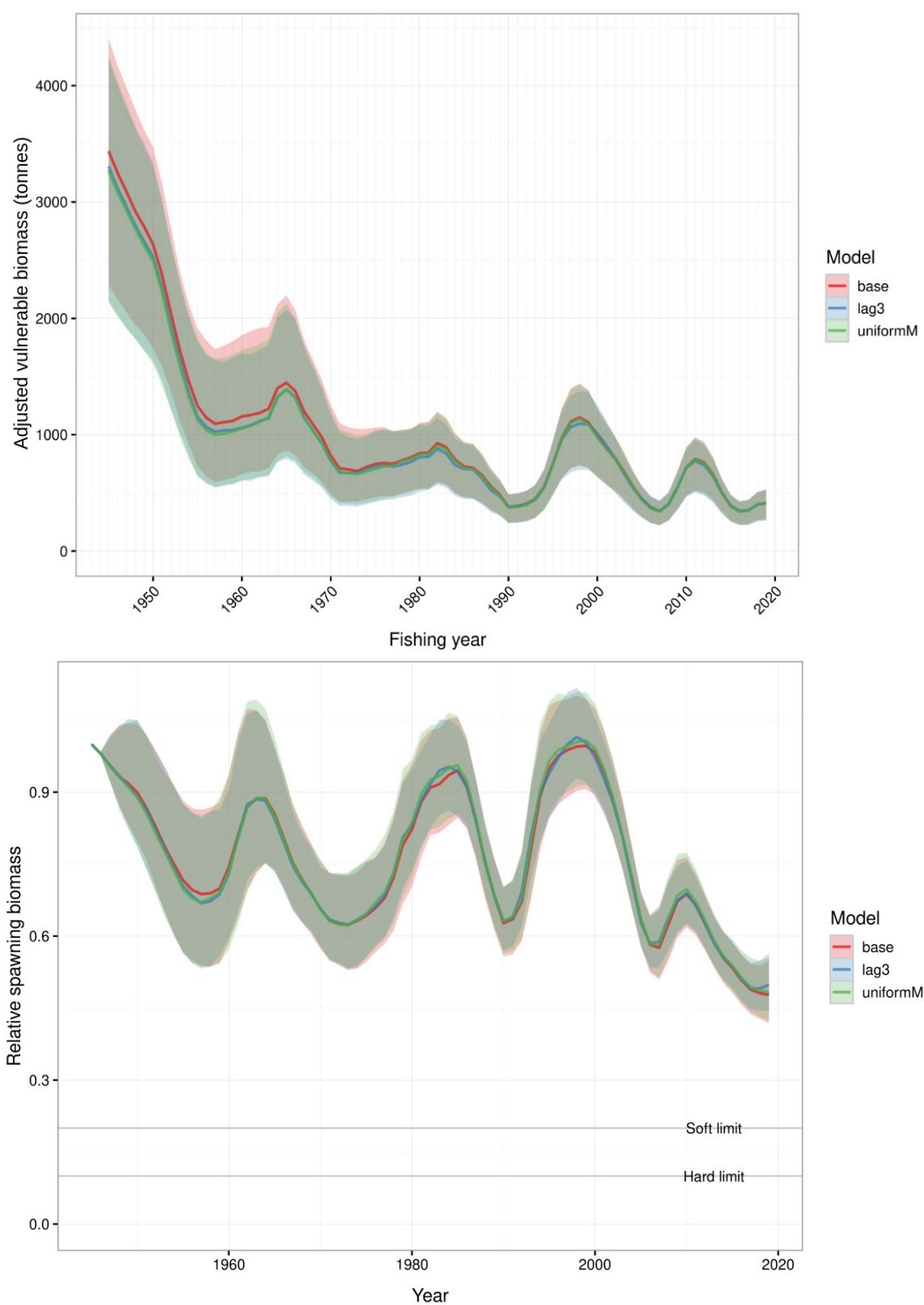


Figure 81: CRA 4 MCMC comparisons: adjusted vulnerable biomass [upper panel] and relative spawning stock biomass [lower panel] trajectories between the base run and the two sensitivity runs (*lag3* and *uniformM*).

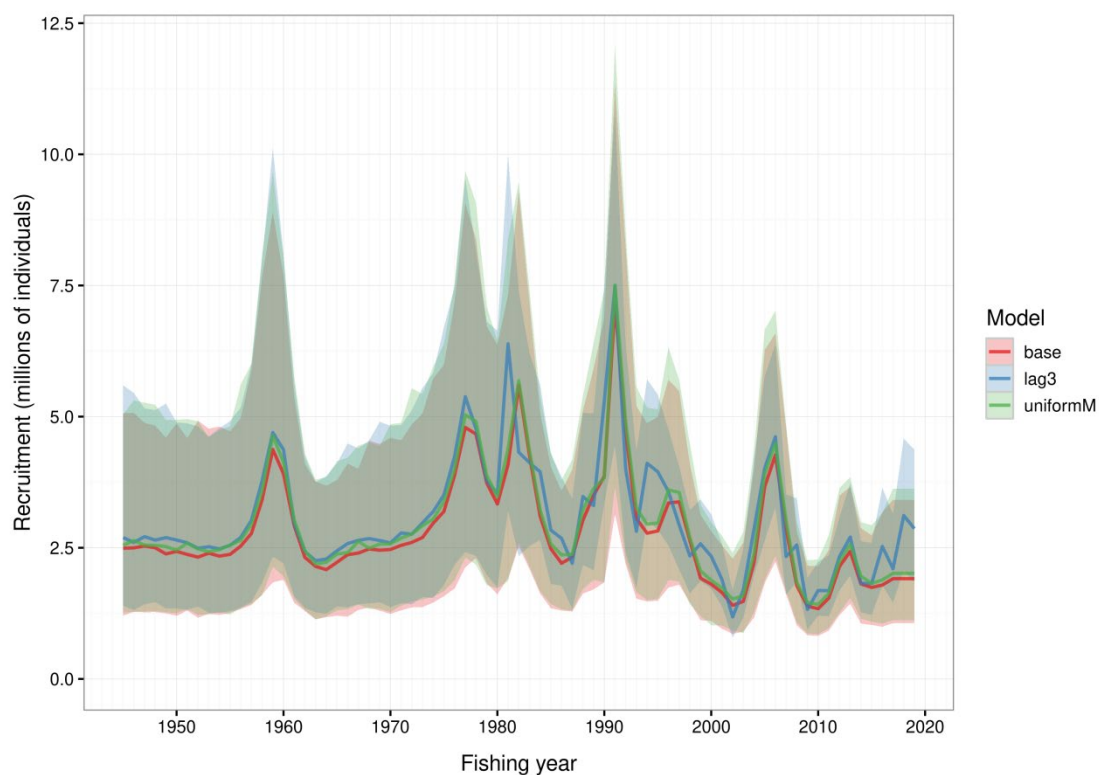


Figure 82: CRA 4 MCMC comparisons: recruitment trajectories between the base run and the MCMC sensitivities.

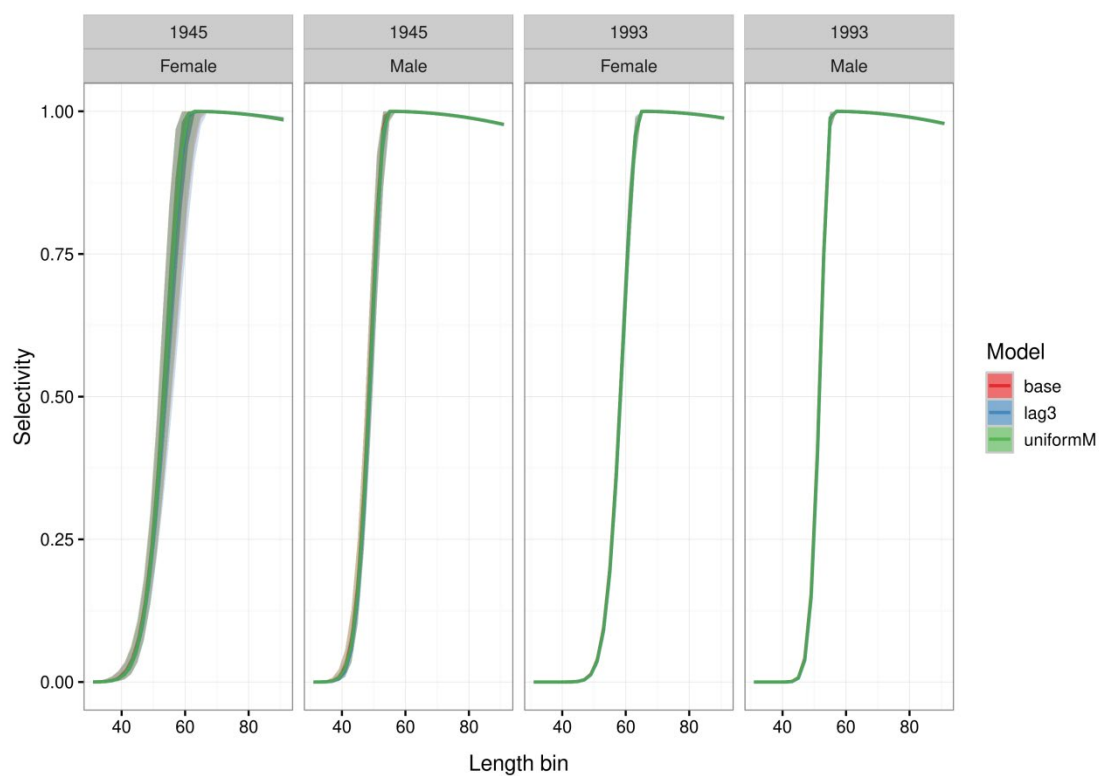


Figure 83: CRA 4 MCMC comparisons: selectivity curves between the MCMC sensitivities.

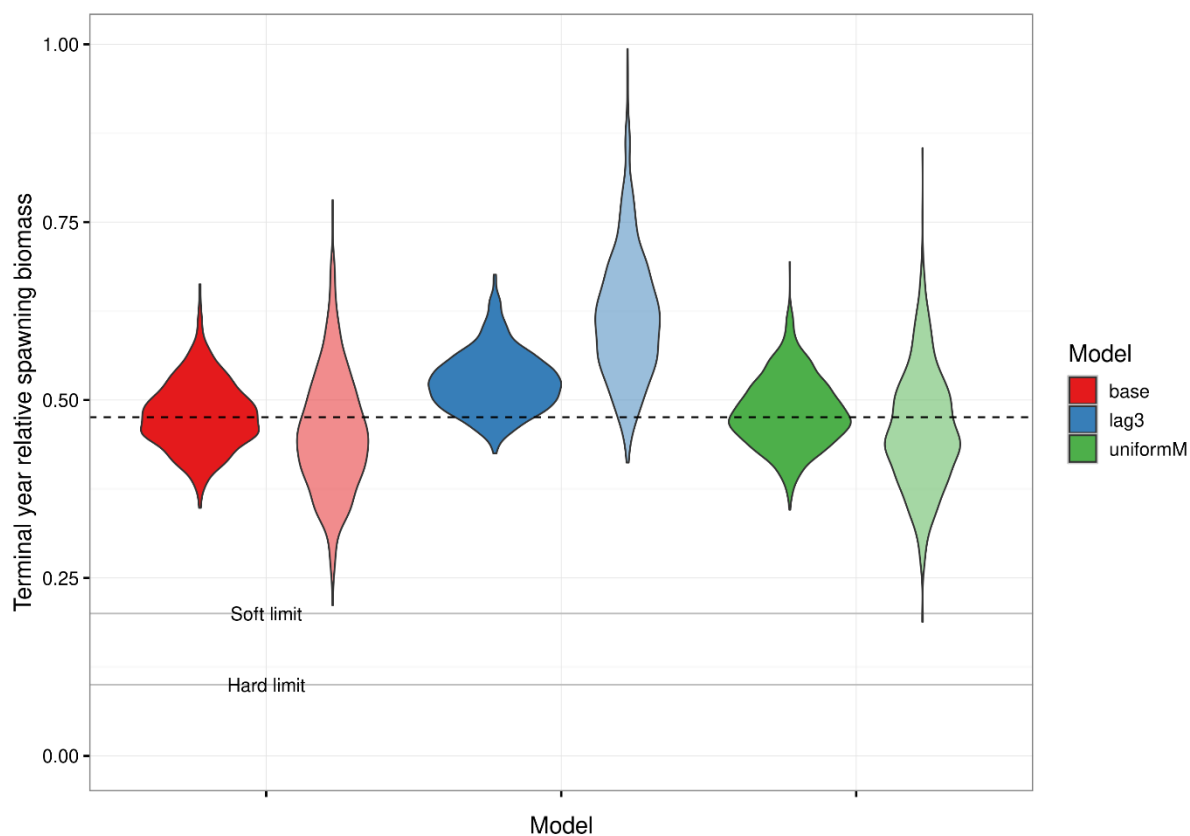


Figure 84: CRA 4 MCMC comparisons: relative spawning stock biomass as a proportion of SSB_0 in the terminal reconstruction year (dark shading, 2020) and the terminal projection year (light shading, 2024) between the *lag3* and *uniformM* runs with the *base* model. The horizontal dashed line shows the mean SSB_{2020}/SSB_0 for the base case.

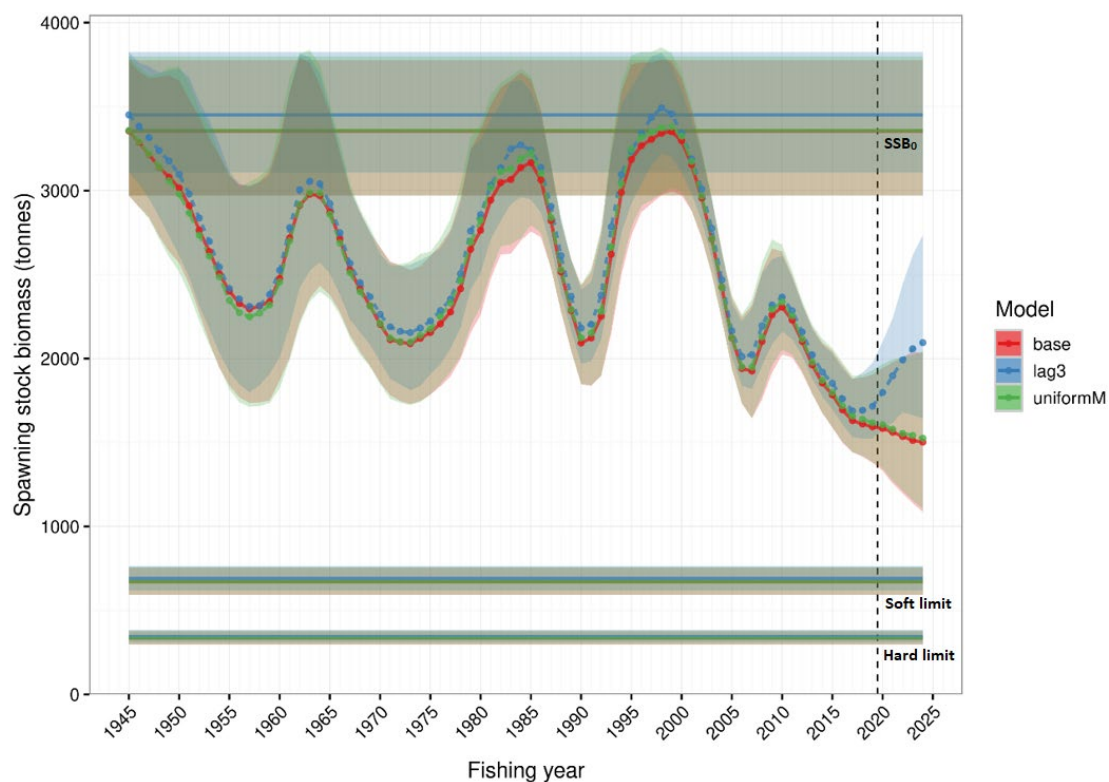


Figure 85: CRA 4 MCMC comparisons: spawning stock biomass, with unfished spawning biomass and the associated soft limits (20% SSB_0) and hard limits (10% SSB_0) for three CRA 4 runs projected five years.

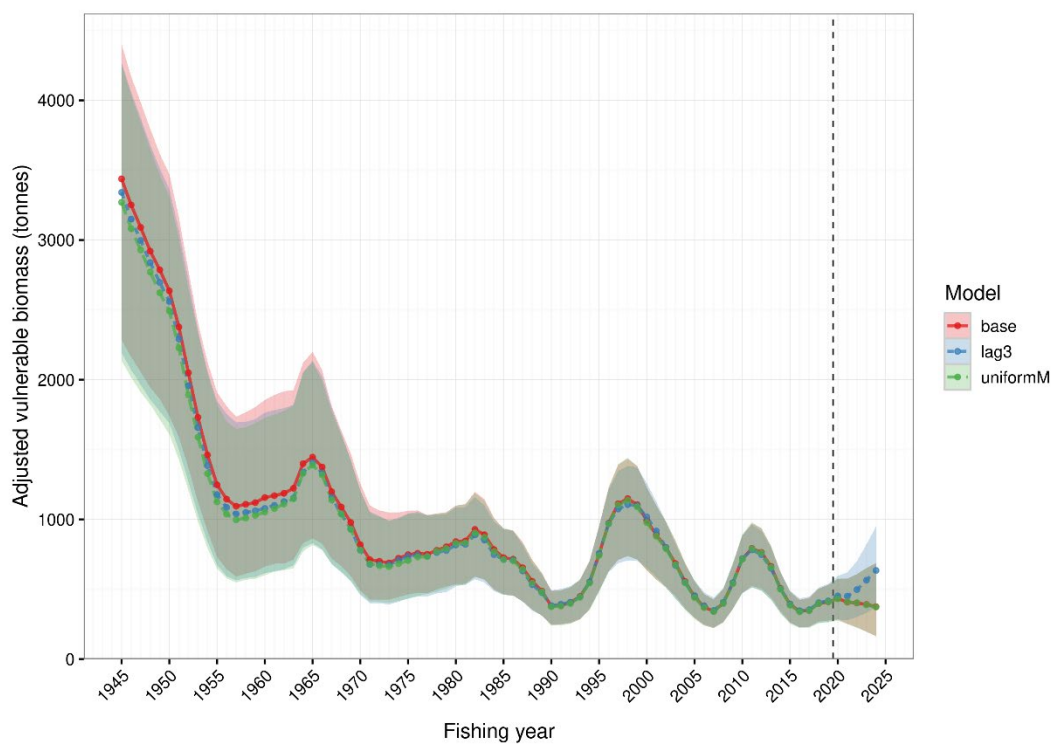


Figure 86: CRA 4 MCMC comparisons: adjusted vulnerable biomass for three CRA 4 runs projected five years.

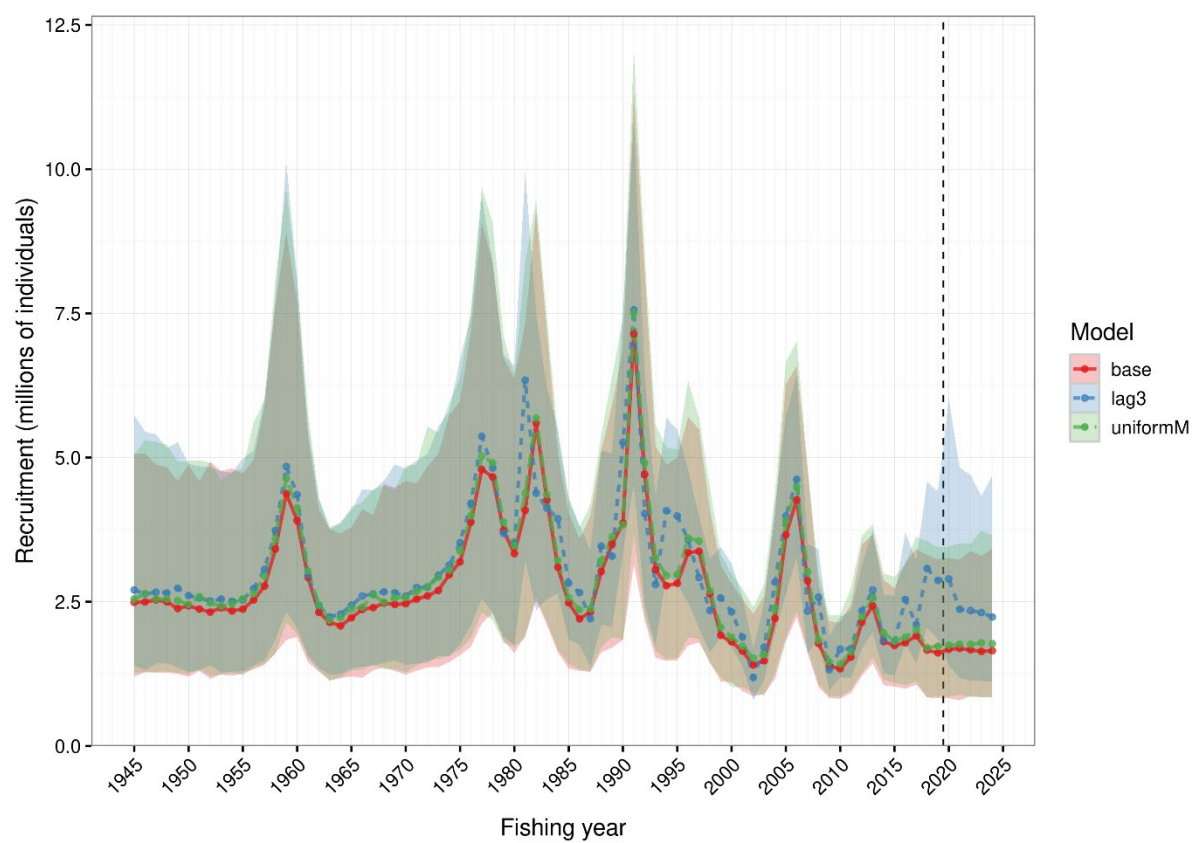


Figure 87: CRA 4 MCMC comparisons: recruitments for three CRA 4 runs projected five years.

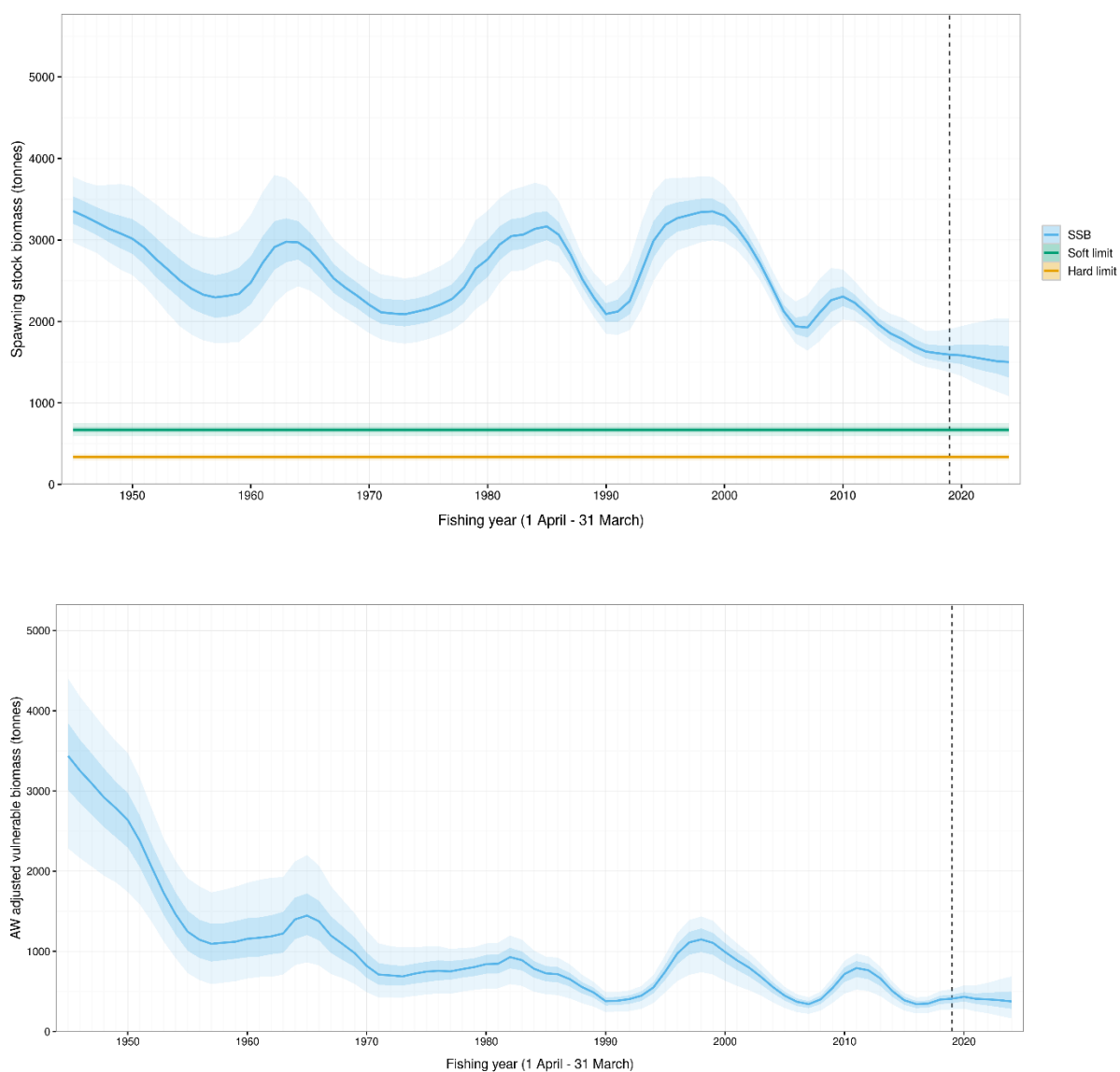


Figure 88: CRA 4 MCMC projections: base case spawning stock biomass [upper plot] and adjusted vulnerable biomass [lower plot] including five-year projections after the vertical line. Also plotted is the soft limit (20% SSB_0), and the hard limit (10% SSB_0) [upper plot].

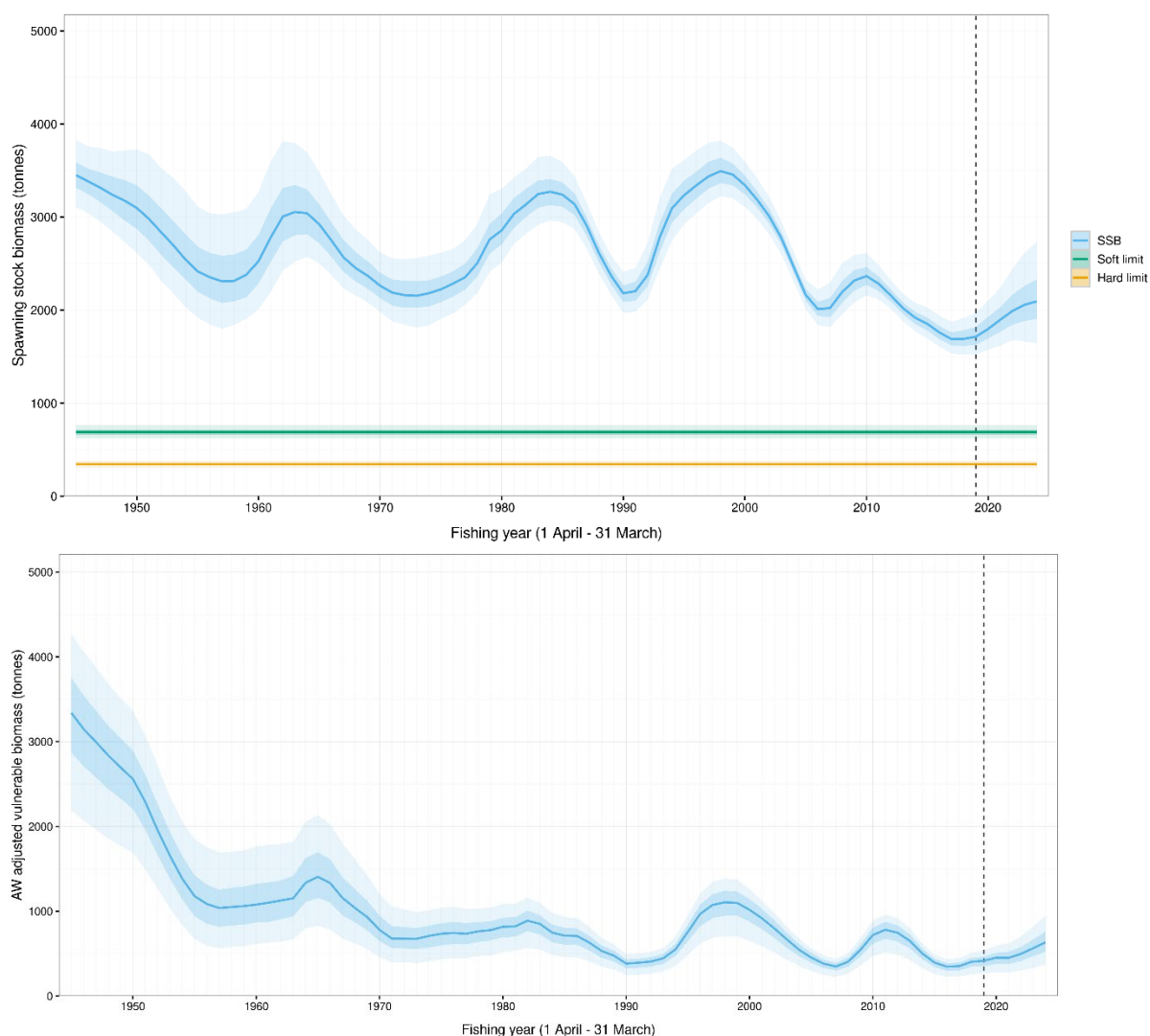


Figure 89: CRA 4 MCMC projections: *lag3* spawning stock biomass [upper plot] and adjusted vulnerable biomass [lower plot] including five-year projections after the vertical line. The associated soft limits (20% SSB_0), and hard limits (10% SSB_0) are also shown [upper plot].

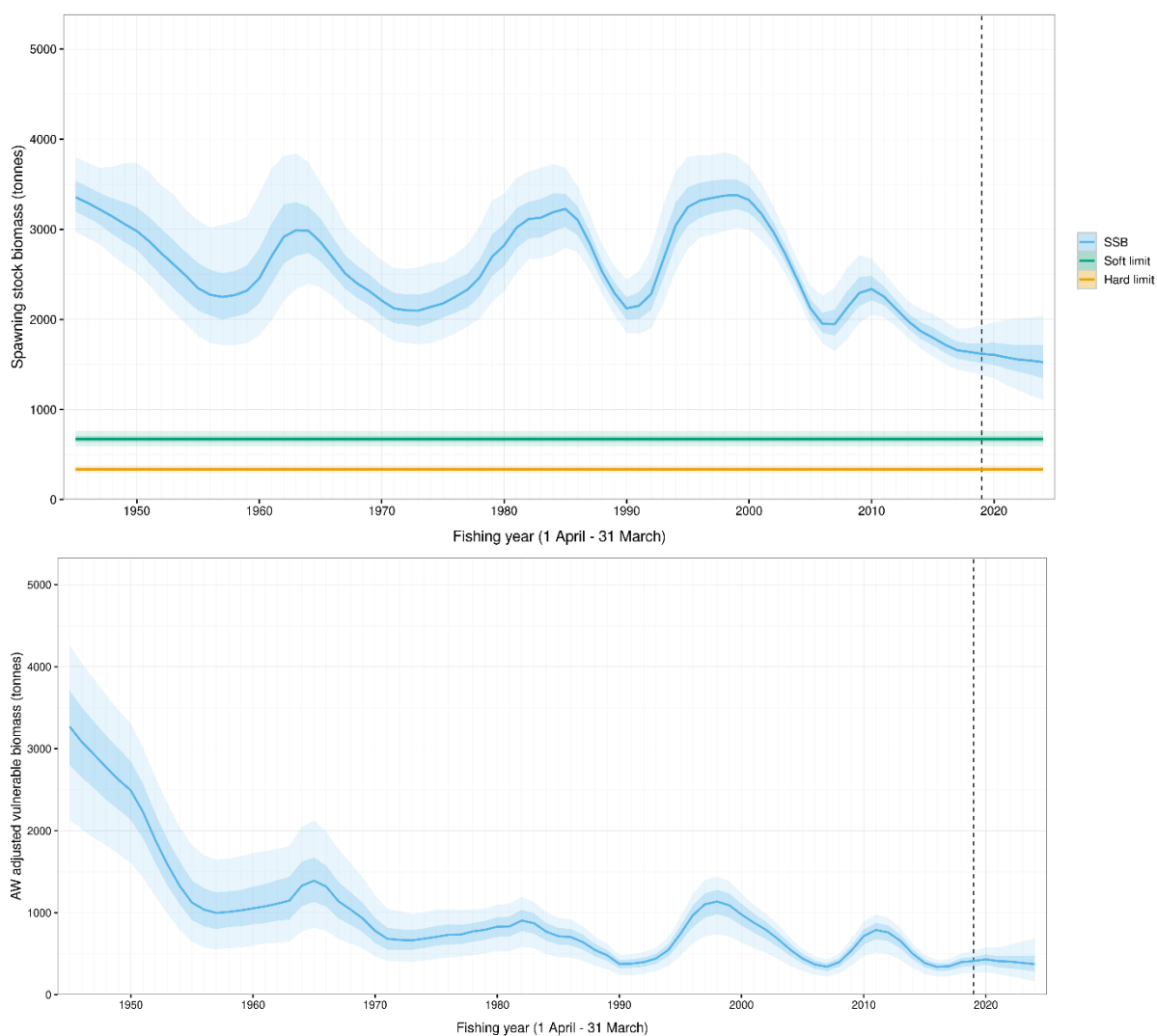


Figure 90: CRA 4 MCMC projections: *uniformM* spawning stock biomass [upper plot] and adjusted vulnerable biomass [lower plot] including five-year projections after the vertical line. The associated soft limits (20% SSB_0), and hard limits (10% SSB_0) are also shown [upper plot].