Fisheries New Zealand

Tini a Tangaroa

A new model for the assessment of New Zealand rock lobster (*Jasus edwardsii*) stocks and an exploratory CRA 4 multi-area assessment

New Zealand Fisheries Assessment Report 2018/53

D.N. Webber
V. Haist
P.J. Starr
C.T.T. Edwards

ISSN 1179-5352 (online)
ISBN 978-1-98-857128-7 (online)

November 2018

New Zealand Government

Requests for further copies should be directed to:

Publications Logistics Officer
Ministry for Primary Industries
PO Box 2526
WELLINGTON 6140

Email: brand@mpi.govt.nz
Telephone: 0800 00 83 33
Facsimile: 04-894 0300

This publication is also available on the Ministry for Primary Industries websites at:
http://www.mpi.govt.nz/news-and-resources/publications
http://fs.fish.govt.nz go to Document library/Research reports

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Webber, D.N.; Haist, V.; Starr, P.J.; Edwards, C.T.T. (2018). A new model for the assessment of New Zealand rock lobster (*Jasus edwardsii*) stocks and an exploratory multi-area CRA 4 assessment.

***New Zealand Fisheries Assessment Report 2018/53.* 111 p.**

This document describes the development of a new semi-generalised length structured stock assessment model for New Zealand red rock lobster (*Jasus edwardsii*) stock assessments, comparisons of this new model with the existing rock lobster assessment model, and an exploratory multi-area stock assessment for CRA 4.

The new model, named lobster stock dynamics (LSD), does not support puerulus randomisation trials or management procedure (MP) simulation yet so these aspects have not been included in this document. These features will be added to LSD this year. The LSD model was developed by D'Arcy Webber with input from the rock lobster stock assessment team contracted by the New Zealand Rock Lobster Industry Council Ltd. The comparisons between the single stock CRA 4 assessments done in the multi-stock length-based model (MSLM) and LSD were done by D'Arcy Webber and Charles Edwards. The exploratory multi-stock assessment for CRA 4 was done by Vivian Haist in the MSLM and by D'Arcy Webber and Charles Edwards in LSD. Paul Starr provided data for both comparisons.

The Rock Lobster Fishery Assessment Working Group oversaw this work: data files and all technical decisions were agreed beforehand or subsequently approved (and sometimes changed) by that group. Models were fit to CPUE indices, size frequency data, puerulus index data, and tag-recapture data. This document does not describe the procedures used to find acceptable model fits, instead models with acceptable model fits that were developed in the official CRA 4 stock assessment (Breen et al. 2017) were used as a starting point for the models presented in this document.

Due to its speed increases and additional flexibility, LSD will be an excellent platform for producing single-area and multi-area rock lobster stock assessments in the future. The multi-area modelling approach that was explored shows great promise. Not only does the approach have the potential to provide a greater understanding of what is happening at finer spatial scales, it is also more than capable of providing the status quo – that is stock status as a whole.

1. INTRODUCTION

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

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

This document presents auxiliary work contributing to this objective, including a new stock assessment model and an exploratory multi-area stock assessment analysis. The development of the new stock assessment model was to be done over two years. This document describes the work carried out during the first year of development and 2017 will see the completion of the new model (including puerulus randomisation code, management procedure simulation software, plotting routines and a user interface). The exploratory multi-area stock assessment is ongoing developmental work that may provide an alternative to standard single-area stock assessments in the future.

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

During 2016, a new length structured model with similar dynamics to the MSLM was developed by D'Arcy Webber. The aim of this new model was to create software written in a modern programming language that can easily be upgraded (as needed) in the future, to decrease the time required for Bayesian inference and to add several new features or options to the assessment model. The new model was written using the Stan modelling language (Stan Development Team, 2016a). Stan is a probabilistic programming language for statistical inference written in C++. The Stan language is used to specify a (Bayesian) statistical model with an imperative program calculating the log probability density function. Stan is licensed under the New BSD License and is named in honour of Stanislaw Ulam, pioneer of the Monte Carlo method. Stan implements gradient-based Markov chain Monte Carlo (MCMC) algorithms for Bayesian inference, stochastic, gradient-based variational Bayesian methods for approximate Bayesian inference, and gradient-based optimisation for penalized maximum likelihood estimation.

It is important that any new model/software be validated using some benchmark. Therefore, the new model was fit to the same data as MSLM, and results compared. The first comparison was done assuming a single homogeneous stock as described by Breen et al. (2017). At the same time, an experimental multi-stock assessment of CRA 4 was conducted using the multi-stock capability of MSLM and the new Stan model. Thus the models tested and presented in this document include:

- Single stock models using MSLM
- Single stock models using the new model
- Multi-stock models using MSLM
- Multi-stock models using the new model

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

In the most recent stock assessment of CRA 4 in 2016, Breen et al. (2017) described the stock assessment and management procedure (MP) simulations, generated from the MSLM model. That model was fitted to tag-recapture data, standardised CPUE, historical catch rate data, length frequency data from voluntary logbooks and observer catch sampling, and puerulus settlement data. Changes in MLS and changes in selectivity caused by escape gap regulations were taken into account. Data for this work are described by Starr et al. (2017). The stock assessment was done in a workshop in

Wellington from 19 September through to 20 October; it was presented to the Mid-year Plenary on 1 November.

The present document describes the development of a new stock assessment model and some experimental multi-stock assessment models for CRA 4. This document does not provide any interpretation of the single-area CRA 4 stock assessment, which is done in Breen et al. (2017). A list of acronyms used throughout this document is provided in Table 1.

1.1 CRA 4

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

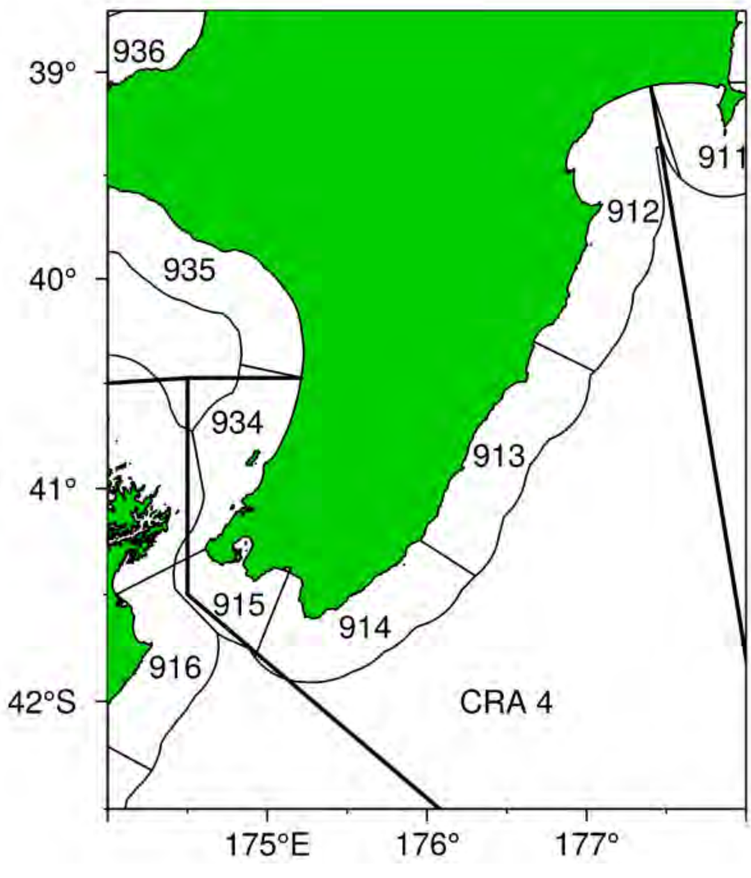


Figure 1: The CRA 4 Quota Management Area (QMA) and its statistical areas (912, 913, 914, 915 and 934).

The CRA 4 commercial fleet comprised 50 vessels in the 2016–17 fishing year[1] (Starr 2016). Most vessels in the fleet operate from coastal bases in isolated rural areas on the Hawkes Bay and Wairarapa

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

coastlines. The CRA 4 commercial catch supports several processing and export operations in Napier, Wellington and Auckland.

Potting and hand gathering are the preferred methods for recreational fishers in this area. As in most CRA areas, the majority of the recreational catch is taken in the summer months. The region also sustains a recreational fishing and dive charter industry during summer. Lobsters are very important to Maori in this area, and the customary allowance allows lobsters to be taken under permit for use by the marae. This is a trap or pot fishery, conducted by small boats on day trips, fishing in relatively shallow waters.

The stock assessment and data preparation separate the autumn-winter (AW, April through to September) and spring-summer (SS) seasons. The stock is managed with an operational management procedure (MP) that determines the TACC, the primary management tool. Allowances are added by the Minister for the non-commercial fisheries to produce a TAC. Other management measures include protection of ovigerous (berried) females, MLS by sex, and escape gaps in pots.

2. THE ROCK LOBSTER STOCK ASSESSMENT MODELS

Rock lobster assessment models (and invertebrate models in general) are typically length based because invertebrates are difficult and expensive to age, rendering the collection of age-based data infeasible. The central component of length based models is the growth model and variation within that model, which describes the transition of individuals between length classes with each time step. Modern assessment models are integrated (see Maunder & Punt 2013; Punt et al. 2013), meaning that they make use of a variety of data sources to estimate component parameters. For length based models, mark-recapture-at-length data provide the primary information for estimation of the length transition process. Length frequency data, when tracked over time, are also useful for estimation of growth, and provide additional information on the fishery selectivity. Finally, catch and abundance information (in this case the CPUE), inform the estimation of stock productivity via natural mortality and stock recruitment. Based on these fundamental ideas concerning a length based integrated approach, we describe the current New Zealand stock assessment approach for rock lobster, along with improvements being made during development of a new model.

2.1 Multi-stock length-based model (MSLM)

The Bayesian multi-stock length-based model (MSLM) was described by Haist et al. (2009). The model is implemented in AD Model Builder (ADMB, Fournier et al. 2012). The model time step is specified and the length of the time step can vary during the period being simulated. The model's number and width of size bins is specified. Fishing is modelled by taking into account the observed catch, the MLS that can change during the period simulated, estimated seasonal vulnerability, and estimated size-selectivity of the fishing gear that can vary over time. The model fits the catch that is limited by MLS and a restriction on landing ovigerous females (SL catch), comprising the commercial and recreational catches, and separately fits the catch not limited by these regulations (NSL catch), comprising the illegal and customary catches, which are assumed to take all the lobsters caught by a pot.

Differences in the growth rate between males and females justifies the two sexes being represented separately in the model. In addition, because of the restriction against landing berried females, the female partition is further divided into mature and immature individuals. The model therefore tracks three components of the population, and at each time step, the number of male, immature female and mature female lobsters in each size class is updated as a result of somatic growth and annual recruitment to the model. Recruitment occurs to a specified mean size with specified size variation and can vary over time. Somatic growth can be divided into distinct "epochs". Natural mortality is estimated but assumed to be constant over time, sizes and sexes. Handling mortality of returned lobsters (undersized and berried females) is assumed and constant.

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

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

The model is fit to abundance indices, size composition data, tag-recapture data and puerulus settlement data. The model can be fit to these data using penalised maximum likelihood or Markov chain Monte Carlo simulations (MCMC). Although Bayesian procedures are time-consuming, they are recommended to be the default method for estimating uncertainty in stock assessments (Magnusson et al. 2012).

2.2 Lobster stock dynamics (LSD) model

The new Bayesian multi-stock length-based model has been named lobster stock dynamics (LSD). Like the MSLM, LSD is an integrated model (see Maunder & Punt 2013; Punt et al. 2013) that estimates most structural parameters by fitting to several data sets simultaneously. However, LSD was written using the state of the art Stan modelling language making use of its very efficient Hamiltonian Monte Carlo (HMC) sampler (Stan Development Team, 2016b). The advantages of HMC and Stan are outlined in Monnahan et al. (2016). Although Stan is a relatively young language compared to the ADMB suite of programs, and therefore has fewer features and functions, there are many good reasons to use Stan. Stan has a much broader user group than ADMB, was built by Bayesian statisticians to do MCMC (yet it can also do optimisation and variational Bayes), deals with all parameter transformations and Jacobians automatically, and makes running multiple MCMC chains on different computer cores very easy.

There were several reasons for wanting to recode the MSLM described by Haist et al. (2009). Most importantly, recoding the assessment provided an opportunity to review and potentially improve the existing rock lobster stock assessment model. New ideas or features were often incorporated into the code during each year that the MSLM was used. While these new features were extensively tested before being used for stock assessment, the additional code was often added without much consideration for efficiency due to time constraints. Therefore, as the software ages and additional features are “bolted on”, the code can become cumbersome and slow.

The new model was redeveloped from the ground up to be efficient and (strictly) Bayesian. The plan is to develop LSD over 2 years. The first year saw the model developed and used alongside the MSLM during the CRA 4 workshop in 2016. The goal was to keep as much as possible the same between the two models during the first year so that we could compare them side-by-side. The second year (2017) will see the puerulus randomisation and MP simulation code developed and further changes to the model code. Therefore, the models will diverge somewhat during code development in 2017.

Improvements to code structure that have already been implemented include:

- Parameter mapping – the desired number of most parameters is first specified, then these parameters are mapped to the model by specifying, for example, the area, sex, and year to which the parameter is relevant. For example, the desired number of each of the selectivity parameters is specified, then each selectivity parameter is mapped to an area, sex, and year. This means the user could share selectivity parameters across areas or sexes, or change selectivity by year. While much more flexible, the new approach can mimic the current assessment easily. This same method has been rolled out to most parameters in the model (e.g., vulnerability, natural mortality, growth).

- Speed – Bayesian inference using MCMC can be slow, especially for multi-area stock assessment models. Therefore, LSD was written with computer code efficiency (speed) in mind. The LSD code is split into different modules including the base model code, parameters, priors, and various functions. When the user begins a model run only those modules that are required are gathered up and compiled into the final model. This excludes any unutilised code and helps reduce the computational workload. Code written in this way is also easier to error check and add to at a later date because the code is split up into logical chunks that can be worked on independently.
- Automation – reducing the workload for the user was another key goal when writing LSD. A user interface is being developed that will allow the user to import and groom assessment data, change model settings, and run models. Automating some of the steps involved in stock assessment can reduce the risk of user error during the stock assessment workshop. Until the user interface is finished, makefiles have been developed and these can be used to carry out the same tasks easily from the command line.

Finally, the process for conducting model runs and doing a stock assessment differs between MSLM and LSD. Like MSLM, LSD is controlled using a set of input files that contain the model specifications, data, and initial parameter values. However, LSD uses makefiles to do model runs via the CmdStan interface to Stan (Stan Development Team, 2016a). The makefiles can also be used to produce model outputs (including plots and tables) and even do MCMC remotely on the cloud.

3. SINGLE-AREA MODEL COMPARISONS

This section compares single-area model runs developed using the two different stock assessment models: the MSLM model written in ADMB; and the LSD model written in Stan. The objective was to ensure that the two models were satisfactorily similar (a perfect match would not be reasonable given they are written in different software and run on different computers/operating systems with different machine precisions).

The structure of the model run used for the comparison loosely followed the base case of the Breen et al. (2017) CRA 4 model. A great deal of effort went into trying to match the two models as closely as possible. To ensure that the two models produced as similar results as possible three different comparisons were made:

1. An MPD fit was obtained using the MSLM. Estimated parameter outputs, plus all of the model inputs (data, likelihood weights, fixed parameters and estimated parameters) were then used to do a single fixed parameter model run in LSD. The model fits to the data, derived quantities, SDNRs and MARs, and likelihood components were then compared.
2. The initial parameter values used to fit the MSLM were used to initialise an MPD fit in Stan. All of the other model inputs (data, likelihood weights, and fixed parameters) were the same in the two models. The model fits to the data, derived quantities, SDNRs and MARs, and likelihood components were then compared.
3. A Bayesian posterior was obtained using MCMC in both the MSLM model and the LSD model. In both models the initial values were the same. The posteriors were then compared.

More detail for each of these comparisons follows.

3.1 Fixed parameter comparisons

The MSLM model was fitted to the CRA 4 data providing the MPD, or the model’s best estimate of each of the model’s non-fixed parameters. Using these same parameter estimates as an input for LSD to do a single model run, along with the other fixed model inputs (data, likelihood weights, and fixed parameters) yielded very similar results (Table 2). For example, the prior contribution to the objective function in MSLM was -41.77 compared with -41.77009 in LSD. A difference this small is likely to be due to rounding by ADMB. The total objective function value was 8846.82 in MSLM compared with

8846.92 in LSD, again very close. Each of the individual components of the total likelihood (i.e. CPUE, CR, puerulus index, tags, and length-frequency) were also very similar. This was also true of several other model runs with different structures, including multi-area models (not presented here).

The SDNRs and MARs were also very similar (Table 2). For example, the CPUE SDNR was 1.208 and 1.219 in MSLM and LSD, respectively. The CPUE MAR was 0.827 and 0.854 in MSLM and LSD, respectively. The biggest difference was in the length-frequency SDNR and MAR values where the SDNR was 1.047 and 0.867, and the MAR was 0.181 and 0.055, in MSLM and LSD, respectively. These differences, although relatively small, may arise from different methods for calculating the median in ADMB and Stan and require further investigation.

Several comparisons were also made between derived quantities (e.g., MSY, B_{MSY}, B_{ref}) calculated in each model. These were all very similar as well (Table 2). The RL FAWG agreed that the fixed parameter comparisons were adequate and that LSD provides a very close match to the MSLM.

3.2 Penalised maximum likelihood comparisons

Optimisation involves finding the maximum likelihood (aka MPD, MAP, penalised maximum likelihood, etc), the set of parameter values that maximises the negative log-likelihood and provides the best fit to the data given the structure of the model. Both ADMB and Stan use gradient-based minimisers to find the optima. Before beginning any optimisation routine it is necessary to provide initial values for each of the model's estimated parameters, giving the optimisation algorithm a place to start from. It is desirable to choose sensible initial values that are reasonably close to the optimum parameter values because this usually avoids any numerical issues during optimisation and speeds up the algorithm.

In this experiment the same initial values that were provided to the MSLM model were used in the LSD model. We noted that Stan did take about 10% longer than ADMB to minimise, but found a slightly better optimum (-1337.6 for Stan compared with -1337.3 for ADMB). However, the convergence criterion might not have been directly comparable between the two models. Like ADMB, Stan has several optimisation options (i.e., *algorithm*, *iter*, *obj_tol*, *tol_rel_obj*, *tol_grad*, *tol_rel_grad*, *tol_param*, *history_size*) and tweaking these options can result in faster convergence at the expense of the accuracy of the optimum, or vice versa.

This process was repeated several times for various different models with the same outcome – ADMB and Stan finding approximately the same optimum with the same parameter estimates (implying the same derived quantities as demonstrated in section 3.1). The RL FAWG agreed that the penalised maximum likelihood comparisons were adequate and that Stan provides a very close match to the ADMB optima.

3.3 Markov chain Monte Carlo (MCMC) comparisons

The final check was to ensure that the different MCMC algorithms used by ADMB and LSD were comparable and resulted in similar posterior distributions. Again, this check was done using a single-area model. An MCMC was run in MSLM with 1 million iterations, retaining every 1000^{th} sample, and took over 48 hours to complete. Similarly, an MCMC was run in LSD but different MCMC specifications were used because Stan's MCMC sampling algorithm is much more efficient than the Metropolis-Hastings MCMC used by ADMB. A total of 1000 samples from the posterior were obtained by specifying 4 chains, each of 500 iterations, thinning every second iteration. A burn-in (or warm-up) of 500 iterations was also done, but these samples were discarded. This took approximately 24 hours for Stan to complete.

The initial MSLM MCMC mixing was tolerable during the first couple of hundred samples before abruptly switching to a different (well mixed) parameter space (Figure 2). The same unusual behaviour was observed in the initial LSD MCMC. The posterior for this particular model appeared to be bimodal in both MSLM and LSD. In LSD, chains 1 and 4 explored parameter space about one of the modes, chain 3 explored parameter space about the other mode, and chain 2 explored parameter space about the first mode, but abruptly switched modes about 70% of the way through the MCMC (Figure 3). These two posterior modes are clearly visible in Figure 4, especially for some of the growth parameters and R_0. These model runs were consequently called the **bimodal** model runs.

The mode switching behaviour seems to be caused by switches in productivity (i.e., growth) and mortality in the stock (i.e., male and female growth rates increase, while natural mortality and R_0 decrease) – both scenarios result in very similar objective function values (see f in Figure 2A and lp__ in Figure 3A and Figure 4A). Multi-modality is not surprising in stock assessment models but is rarely documented. To stop this behaviour, and make comparisons easier, weak priors were placed on the growth parameter G_{alpha}, the R_0 parameter, and each of the selectivity parameters. The Stan developers recommend the use of wide priors for all model parameters, unless we do have some prior knowledge of what the parameter value should be. We used wide normal distributions that are relatively flat across the credible range for each parameter (Figure 5). We then repeated the MCMC's outlined above using these new priors and called these the **wideprior** model runs.

In the **wideprior** model runs, both the MSLM MCMC and the LSD MCMC were well mixed (Figure 6) and no mode switching behaviours were observed (Figure 8). Figure 9 was created to compare the posterior distributions for several parameters and derived quantities for the MSLM model without the priors applied and the LSD with and without the priors applied (the ADMB model run with the priors was not completed when these figures were created). These figures suggest that the priors had little influence on the posterior distributions of most model parameters, except those parameters that were multi-modal. Overall, the posteriors produced using ADMB and Stan were very similar and result in almost identical stock assessment outcomes.

We note that each MCMC iteration is much slower in Stan, but not as many iterations are needed because mixing is much more efficient, which reduces the amount of thinning needed (e.g., in the LSD MCMCs outlined above we discarded every second iteration, rather than every hundredth or thousandth iteration in ADMB), resulting in a much faster MCMC runtime overall. It is also convenient that there is no need to start the MCMC near the MAP in Stan (but it does help to reduce the warm-up period), and positive definite Hessian (pdH) problems no longer apply because Stan approximates the covariance matrix during the warm-up phase. In fact we don't even need to optimise to run an MCMC in Stan. Because of its speed increases and additional flexibility, LSD will be an excellent platform for finer scale spatial modelling in the future.

4. EXPLORATORY MULTI-AREA MODEL

The CRA 4 multi-area model documented here is exploratory work that aims to eventually provide a framework for producing stock assessment outputs at a finer spatial scale than standard single-area stock assessments (e.g., estimates of stock size by statistical area or some combination of aggregated statistical areas). This work remains exploratory, for now, because of the number of choices and challenges that are faced when moving to multi-area models. For example, how many sub-areas should the model consider? Which statistical areas should be separate or combined? How many growth morphs (areas with different growth rates or time periods where growth differs) should be modelled? How many different selectivity curves should the model include (e.g., a different selectivity curve for each area, shared across some or all areas, one for every year)? How many natural mortality parameters should be used (one for each area, shared across areas, or some combination)? Determining best practices for these types of modelling decisions could take years of research. Despite this, we believe that, in the near future, multi-area models like this will augment the single-stock/single-area models that dominate fisheries stock assessment.

As with the single area models, fixed parameter tests and comparisons were done and the ADMB and Stan optimisers were tested. The fixed parameter tests resulted in very similar objective function values and prior contributions (Table 3). The optimisers made their way to the same place in ADMB and Stan. The RL FAWG agreed that these comparisons were adequate and that the model runs in

LSD and MSLM were sufficiently similar. We called these the **spatial** model runs. Because of the exploratory status of the **spatial** model runs we provide limited interpretation of model outputs in this document.

4.1 Multi-area model structure

CRA 4 is made up of five statistical areas (Figure 1) and it was desirable to model the stock at the finest spatial scale possible. The data used as inputs to the stock assessment are provided by statistical area, so this is currently the smallest spatial scale possible. However, summaries of the data suggested that limited data were available for statistical area 934. Therefore, 915 and 934 (adjacent statistical areas) were combined in the multi-area assessment model presented here, resulting in a four area model. These four areas will be referred to as 912, 913, 914 and 915+934. Combining two statistical areas in this way assumes that the dynamics in these two areas are the same (e.g., selectivity, vulnerability, catchability, and catch rates), requires that the data be aggregated for these two areas (e.g., annual catches need to be summed), and provides stock assessment outputs for both areas combined (e.g., the reference biomass provided by the model for 915+934 cannot be split into its constituent statistical areas).

Growth was not assumed to be consistent across all four modelled areas; instead, three different growth areas were defined. Growth in area 912 was estimated from individuals tagged in 911 and 912 (auxiliary data from CRA 3 were introduced because there were few recaptures in 912). Growth in areas 913 and 914 was assumed to be the same and was estimated using tag-recaptures from these two areas combined. Growth in 915+934 was estimated using tag-recaptures from 915 (there were no recaptures reported for 934). These area splits were chosen based on careful consideration of the amount of tag-recapture data available for each statistical area, geographical proximity of the areas, and inspection of the tag data residuals after fitting an initial exploratory model (largely through trial and error).

Over 30 different **spatial** model runs were done in MSLM and LSD. Several different model structures were explored during these runs including:

- 2-sex models
- 3-sex models
- Dropping logbook (LB) data
- Various different selectivity assumptions
- Various different vulnerability assumptions
- Various different natural mortality assumptions

4.2 Data

Data for the single area implementation of the CRA 4 stock assessment model are described by Starr et al. (2017). However, the multi-area implementation of the CRA 4 stock assessment required most of the data to be area-specific. The preparation of these data is described in Appendix A.

4.3 Results

We present the posterior distributions for just one of the model runs discussed above because time was limited during the assessment workshop and MCMC sampling was slow for these multi-area models. Using the LSD model, a total of 1000 samples from the posterior were obtained by specifying 4 MCMC chains, each of 500 iterations, thinning every second iteration. A burn-in or warm-up of 250 iterations was also done, but these samples were discarded. This took approximately 3 days for Stan to complete. The MCMC for the multi-stock model coded in MSLM was too slow to get adequate posteriors within a practical timeframe (Figure 10). The LSD MCMC's were well mixed within this timeframe (traces are shown in Figure 11 and histograms in Figure 12).

The area-specific model fits to the CPUE and CR series were better in some areas than others (Figure 13). The fit to the CR data is excellent in all statistical areas (Figure 13). In 912, the fit to the CPUE data is good until about 2010 where the model begins to stray from the data in both the AW and SS. In 913 and 914, the fit to the CPUE is excellent. In the last model area that consists of statistical areas 915 and 934 combined, the fit to the CPUE data is reasonable given the much more volatile CPUE series.

Fits to length-frequency (LF) data were generally very good and often better than in the single-area models (examples of these fits are provided in Figure 14). This improvement in fits to the LF data is due to different selectivity curves being estimated among areas in the model. Specifically, selectivity was parameterised to be logistic and sex-specific in all areas, and was assumed to be the same in areas 913 and 914, with different selectivities for areas 912 and 915+934 (Figure 15).

Recruitment deviations were estimated independently in each area. Despite this, many of the peaks and troughs in recruitment occurred during the same years in each area (Figure 16). Recruitment was generally higher in areas 913 and 914. In all areas recruitment was estimated to be relatively low in recent years.

Reference biomass in areas 912 and 913 was similar throughout the stock assessment timeframe, starting from approximately 0.375 tonnes and declining until the mid-1950s, followed by an increase up to the mid-1960s, then declining again until the mid-1990s (Figure 17). From the mid-1990s to about the year 2000 the reference biomass increased again in all areas, but has since declined again except in area 915+934 where the reference biomass increased up until 2014.

5. DISCUSSION

Over the past decade, the MSLM (described by Haist et al. 2009) has served as the foundation of all stock assessments for New Zealand rock lobster. The code for this model was written in ADMB, a platform that has become increasingly outdated and unsuitable for further development of the New Zealand rock lobster stock assessments. New platforms that outperform ADMB computationally have recently become available and the rock lobster team has selected Stan for development of future model code.

Stan, and therefore the new LSD model, has several benefits over ADMB. One of the most important benefits is that the Hessian matrix does not need to be positive definite in Stan for MCMC sampling to begin (this is a requirement in ADMB). This opens up a suite of models that can be taken to MCMC that were previously rejected because ADMB did not calculate a positive definite Hessian. The LSD model is also a good way forward for spatial modelling because MCMC mixing is much faster. This is because Stan's Hamiltonian Monte Carlo (HMC) is a much more efficient MCMC sampler. Model structures that were once beyond reach because MCMC mixing was too slow to produce reasonable posteriors within a practical time frame are now possible using LSD.

The multi-area modelling approach that was explored during the CRA 4 stock assessment is most likely credible as a future option for most rock lobster stock assessments. Not only does the approach provide greater understanding of what is happening at the statistical area scale, it also provides the *status quo* – that is, stock status as a whole (produced by aggregating across modelled areas). Although the current management framework in New Zealand does not manage rock lobster at the statistical area scale, information at finer spatial scales is still useful. For example, fishers could voluntarily manage their catch within statistical areas, so long as they are compliant at the QMA level.

This work is still experimental because multi-area models are a lot more complex than single-stock models. There are many more modelling choices to make, some of these choices are structural and can have potentially large effects on stock assessment outcomes. Inference is much slower than comparable single-area models. Spatially explicit data are also more difficult to generate, often requiring strong assumptions about area splits when data are lacking. And the results are more time consuming to interpret. For example, as the number of areas increases, so does the number of figures and tables required to interpret the results from each of these areas and all of these areas combined. This means that choosing what to present also becomes important. For these reasons, it is important that these models remain experimental until we are confident that good stock assessment inference is manageable within practical timeframes and that the tools to communicate the results effectively are well established.

The LSD framework as a whole is also currently incomplete. The remaining tasks to complete the LSD framework include:

- Further work on the model documentation, including a technical report with all of the model equations and a user manual – important for communication and to improve ease of use
- Development of the management procedure (MP) simulation code
- Development of the puerulus randomisation code
- Develop new procedures to groom length-frequency (LF) data and a new approach to weighting these data whereby effective number of samples are sex-specific (i.e., males, immature females and mature females have their own effective sample size). This will do away with the need for sex-specific data weighting and instead an overall LF data weight will be used (or this data weighting could be for catch sampling and logbook data sources).
- Include code and options for self-weighting LF distributions (i.e., Dirichlet, logistic normal) which have the potential to do away with iterative data weighting methods.
- May want to modify LSD in the future to deal with spatial structure better (e.g. random effects or CAR priors for parameters; fit data for each area or summed across areas to help deal with data being by statistical area from 1979 onwards).

6. ACKNOWLEDGEMENTS

This work was conducted under Objectives 4 of MPI contract CRA2015-01A, awarded to the New Zealand Rock Lobster Industry Council Ltd. We thank Daryl Sykes for encouragement, Helen Regan for logistic support, and members of the RLFAWG and the Plenary for their advice. And special thanks to Paul Breen for his time, ideas, discussion and support.

7. REFERENCES

Annala, J.H.; King, M.R (1983). The 1963-73 New Zealand rock lobster landings by statistical area. Fisheries Research Division Occasional Publication: Data Series No. 11. 20 p.

Bentley, N.; Starr, P.J.; Walker, N.A.; Breen, P.A. (2005). Catch and effort data for New Zealand rock lobster fisheries. *New Zealand Fisheries Assessment Report 2005/49*. 49 p.

Breen, P.A.; Starr, P.J.; Haist, V.; Edwards, C.T.T.; Webber, D.N. (2017). The 2016 stock assessment and management procedure review for rock lobsters (*Jasus edwardsii*) in CRA 4. *New Zealand Fisheries Assessment Report 2017/29.* 88 p.

Fournier, D.A.; Skaug, H.J.; Ancheta, J.; Ianelli, J.; Magnusson, A.; Maunder, M.N.; Nielsen, A.; Sibert, J. (2012). AD Model Builder: using automatic differentiation for statistical inference of highly parameterized complex nonlinear models. *Optimization Methods Software 27*: 233–249.

Haist, V.; Breen, P.A.; Starr, P.J. (2009). A new multi-stock length-based assessment model for New Zealand rock lobsters (*Jasus edwardsii*). *New Zealand Journal of Marine and Freshwater Research 43(1):* 355–371.

Magnusson, A.; Punt, A.E.; Hilborn, R. (2012). Measuring uncertainty in fisheries stock assessment: the delta method, bootstrap, and MCMC. *Fish and Fisheries 14(3)*: 325–342.

Maunder, M.N.; Punt, A.E. (2013). A review of integrated analysis in fisheries stock assessment. *Fisheries Research 142*: 61–74.

Ministry of Fisheries. (2011). Operational guidelines for New Zealand's Harvest Strategy Standard. Unpublished document, Ministry of Fisheries, Wellington, New Zealand. 78 p.

Monnahan, C.C.; Thorson, J.T.; Branch, T.A. (2017). Faster estimation of Bayesian models in ecology using Hamiltonian Monte Carlo. Methods in Ecology and Evolution, 8:339–348. doi:10.1111/2041-210X.12681

Punt, A.E.; Huang, T.; Maunder, M.N. (2013). Review of integrated size-structured models for stock assessment of hard-to-age crustacean and mollusc species. *ICES Journal of Marine Science 70(1)*: 16–33.

Stan Development Team. (2016a). Cmd*Stan: User's Guide*. Version 2.11.0.

Stan Development Team. (2016b). *Stan Modeling Language: User's Guide and Reference Manual*. Version 2.11.0.

Starr, P.J. (2016). Rock lobster catch and effort data: summaries and CPUE standardisations, 1979–80 to 2014–15. *New Zealand Fisheries Assessment Report 2016/36*. 122 p.

Starr, P.J.; Breen, P.A.; Haist, V.; Pomarede, M. (2012). Data for the 2011 stock assessment of red rock lobsters (*Jasus edwardsii*) in CRA 4. *New Zealand Fisheries Assessment Report 2012/08*. 48 p.

Starr, P.J.; Webber, D.N. (2016). The 2015 stock assessment of red rock lobsters (*Jasus edwardsii*) in CRA 5 and development of management procedures. *New Zealand Fisheries Assessment Report 2016/41*. 115 p.

Starr, P.J.; Webber, D.N.; Breen, P.A. (2017). Data for the 2016 stock assessment of red rock lobsters (*Jasus edwardsii*) in CRA 4. *New Zealand Fisheries Assessment Report 2017/28*. 48 p.

Table 1: Acronyms used throughout this document.

Acronym	Meaning
ADMB	AD – Model builder
AW	Autumn-winter season in model
CAR	Conditionally autoregressive (prior)
CPUE	Catch per unit effort
HMC	Hamiltonian Markov chain
LF	Length-frequency
LSD	Lobster stock dynamics model
MAR	Median of the absolute residual
MCMC	Markov chain Monte Carlo
MLS	Minimum legal size (mm)
MP	Management procedure
MPD	Maximum posterior density
MPI	Ministry for Primary Industries
MSLM	Multi-stock length-based model
pdH	Positive definite Hessian
QMA	Quota Management Area
RLFAWG	Fisheries New Zealand Rock Lobster Fishery Assessment Working Group
SDNR	Standard deviation of the normalised residual
SS	Spring-summer season in model
TAC	Total allowable catch
TACC	Total allowable commercial catch
TW	Tail-width (mm)

Table 2: Comparisons between the MSLM model and the LSD model with a single-area model run. Values compared include the total objective function value, prior contribution, components of the log-likelihood (LL) with associated SDNR and MAR data weights, and several derived quantities.

Comparison	MSLM	LSD
Total objective function	8846.82	8846.92
Prior	-41.77	-41.77009
LF SDNR	1.04686	0.867319
LF MAR	0.180631	0.055466
LF LL	6484.28	6484.29
Sex-ratio SDNR	0.976597	0.978484
Sex-ratio MAR	0.419328	0.42027
Puerulus SDNR	1.05679	1.07144
Puerulus MAR	0.743375	0.742744
Puerulus LL	-25.9415	-25.9415
CR SDNR	0.816606	0.851262
CR MAR	0.591625	0.56894
CR LL	-24.8143	-24.83061
CPUE SDNR	1.20873	1.21852
CPUE MAR	0.826705	0.853768
CPUE LL	-128.045	-127.9446
Tag SDNR	1.14928	1.14954
Tag MAR	0.545004	0.545645
Tag LL	2577.16	2577.14
MSY	673.877	673.575
B_{MSY}	245.201	245.187
B_{ref}	494.009	492.41
B_{2016}/B_{ref}	0.768529	0.7693345
B_{2016}/B_{MSY}	1.54836	1.545057
F_{mult}	3.53	3.52

Table 3: Comparisons between the MSLM model and the LSD model with a multi-area model run. Values compared include the total objective function value, prior contribution, components of the log-likelihood (LL) with associated SDNR and MAR data weights, and several derived quantities.

Comparison	MSLM	LSD
Total objective function	13377.3	13380.8
Prior	-82.861	-82.861
Tag prior	12.487	12.487
LF LL	11667.9	11667.3
CR LL	-73.34	-71.48
CPUE LL	-381.14	-378.86
Tag LL	2234.27	2234.26

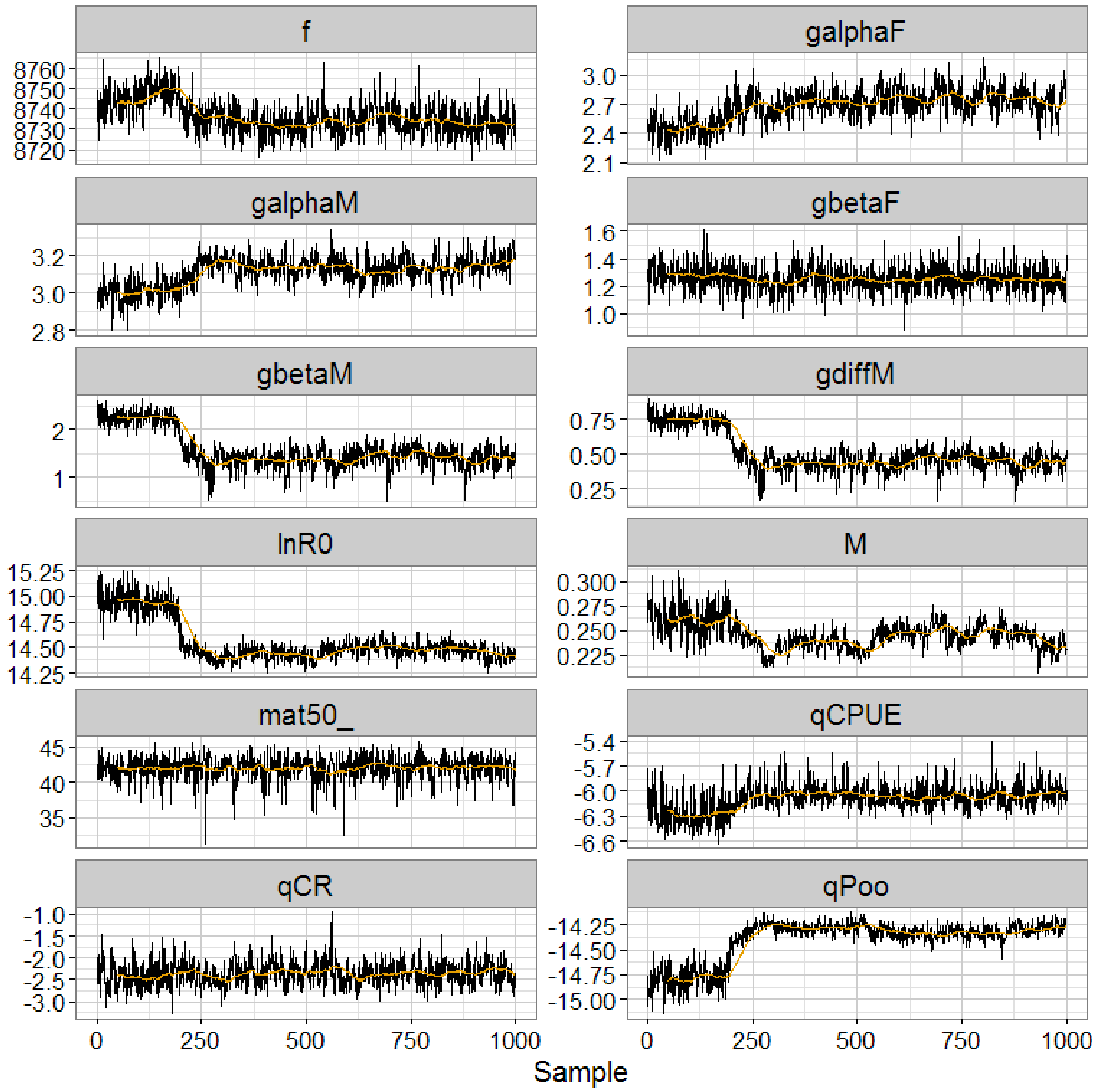


Figure 2A: MCMC trace plots of the likelihood profile (f) and model parameters from the bimodal model using the MSLM model in AMDB.

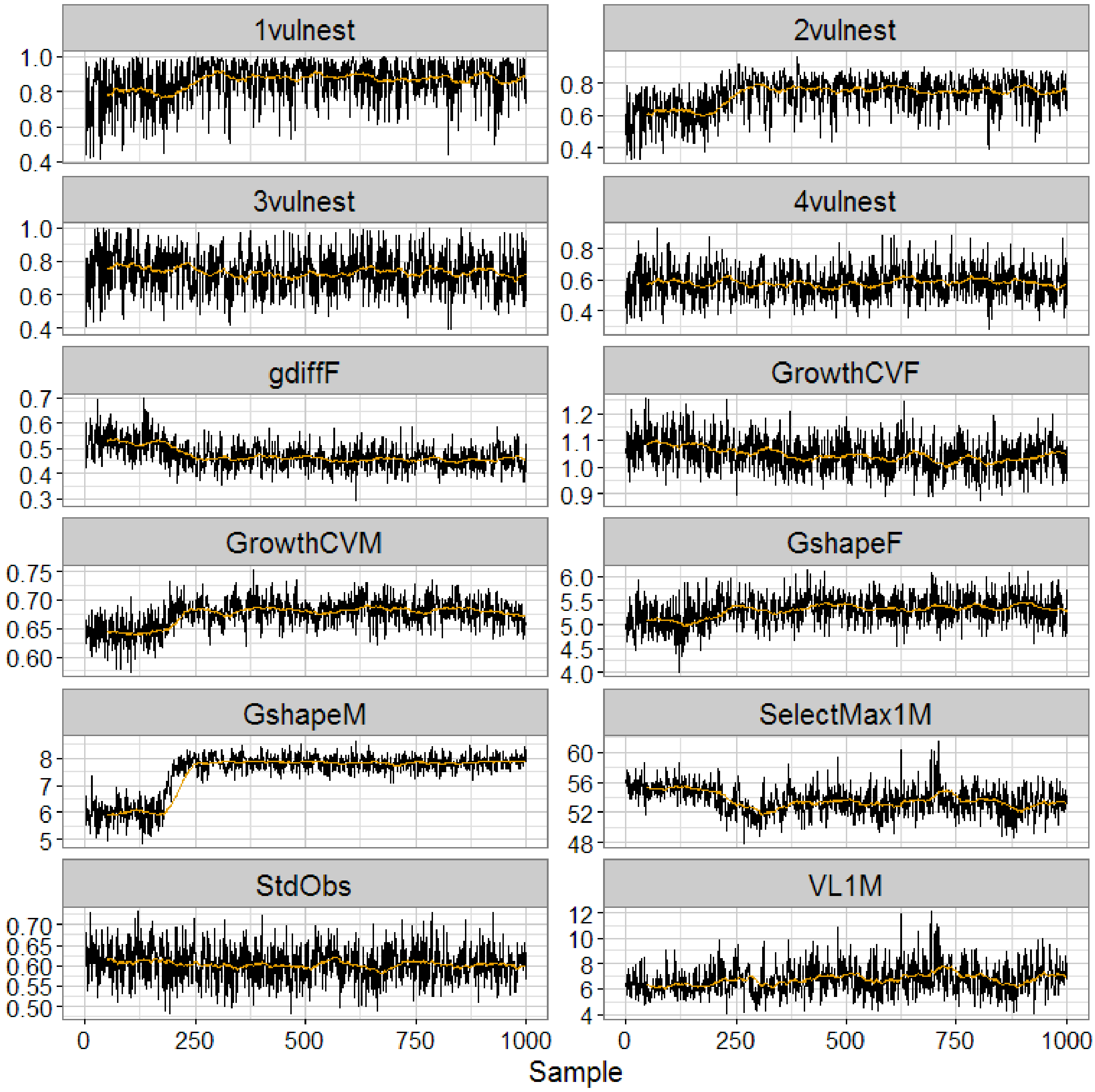


Figure 2B: MCMC trace plots of model parameters from the bimodal model using the MSLM model in AMDB.

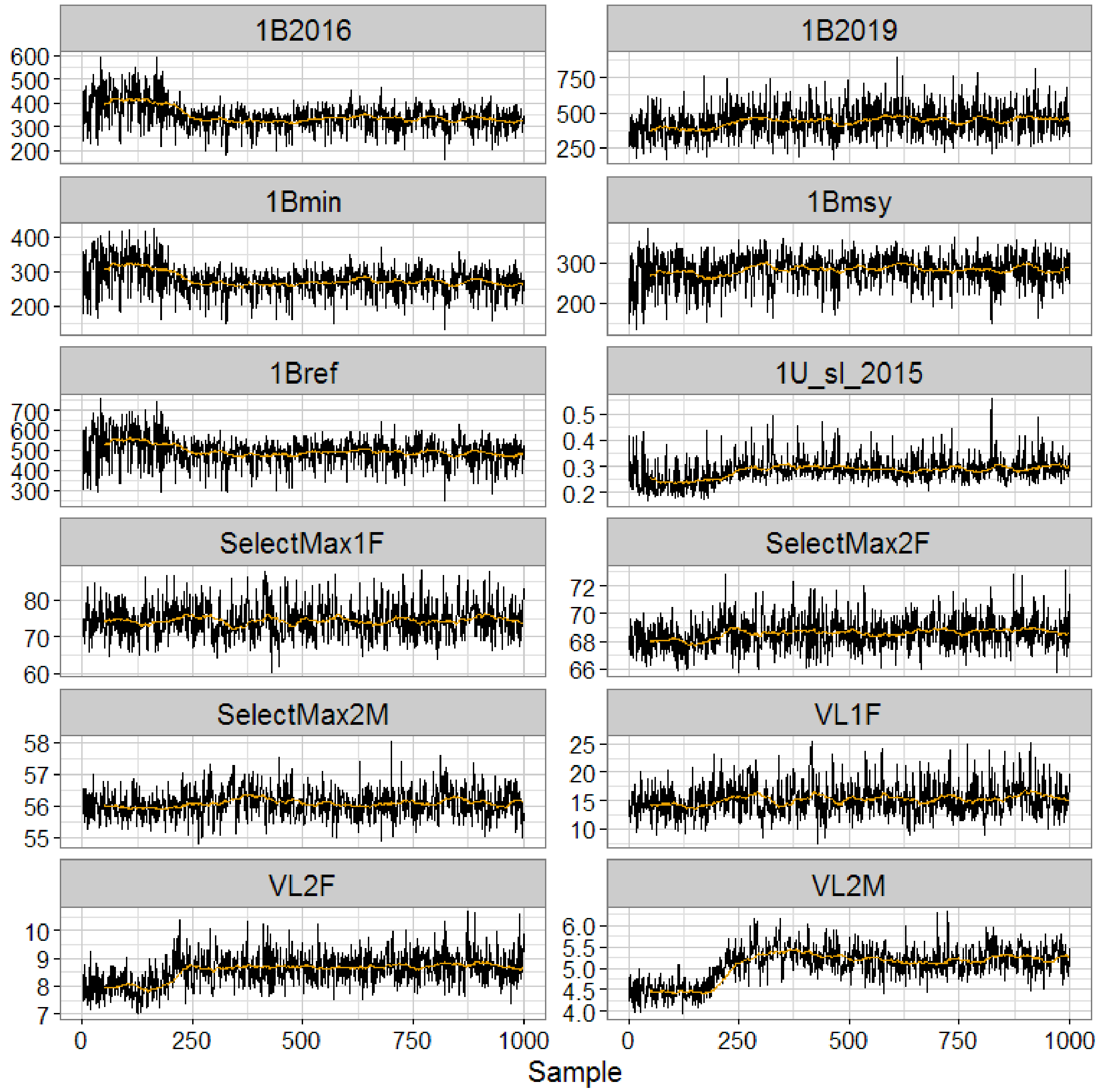


Figure 2C: MCMC trace plots of model parameters and derived quantities from the <u>bimodal</u> model using the MSLM model in AMDB.

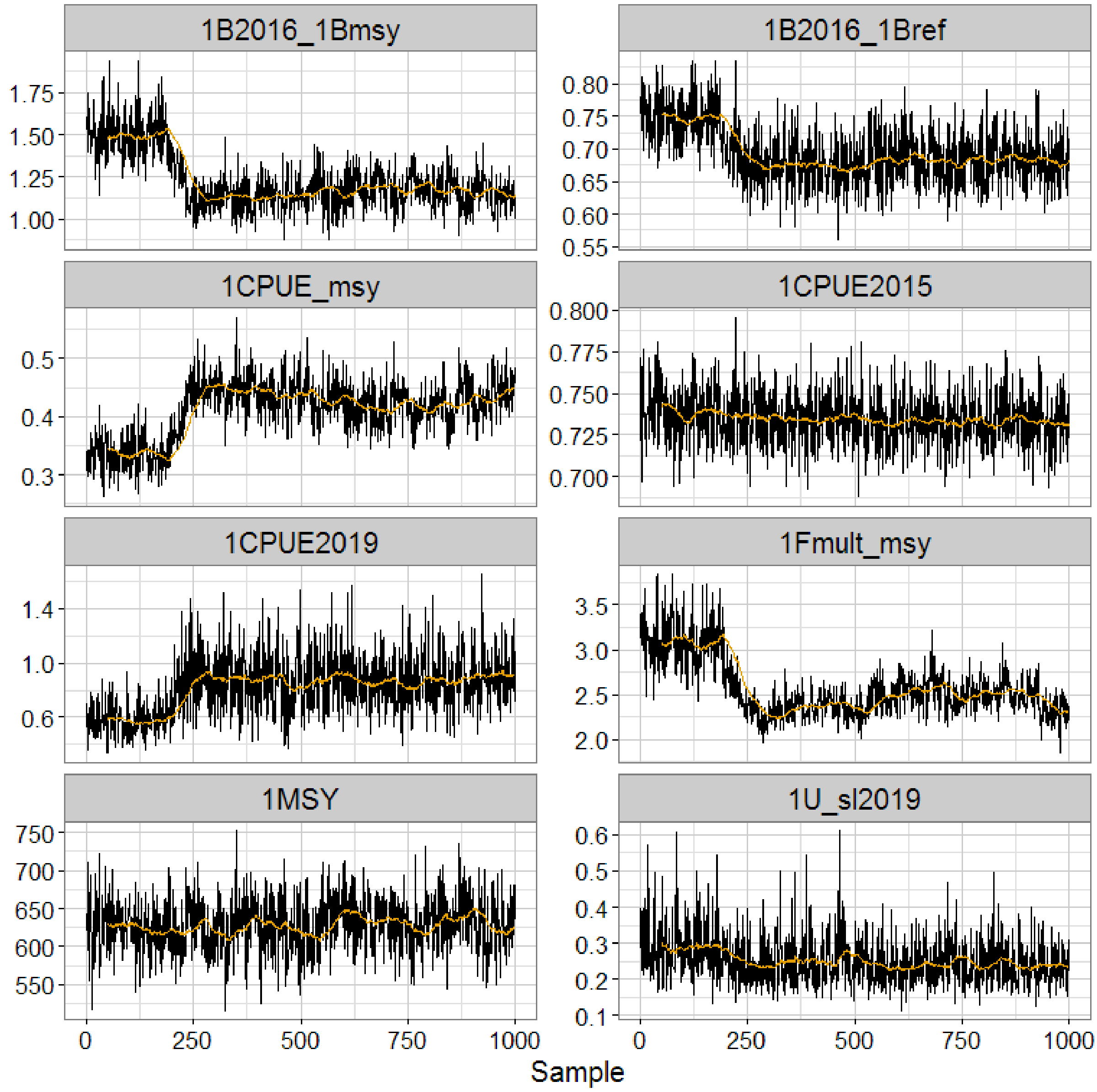


Figure 2D: MCMC trace plots of derived quantities from the bimodal model using the MSLM model in AMDB.

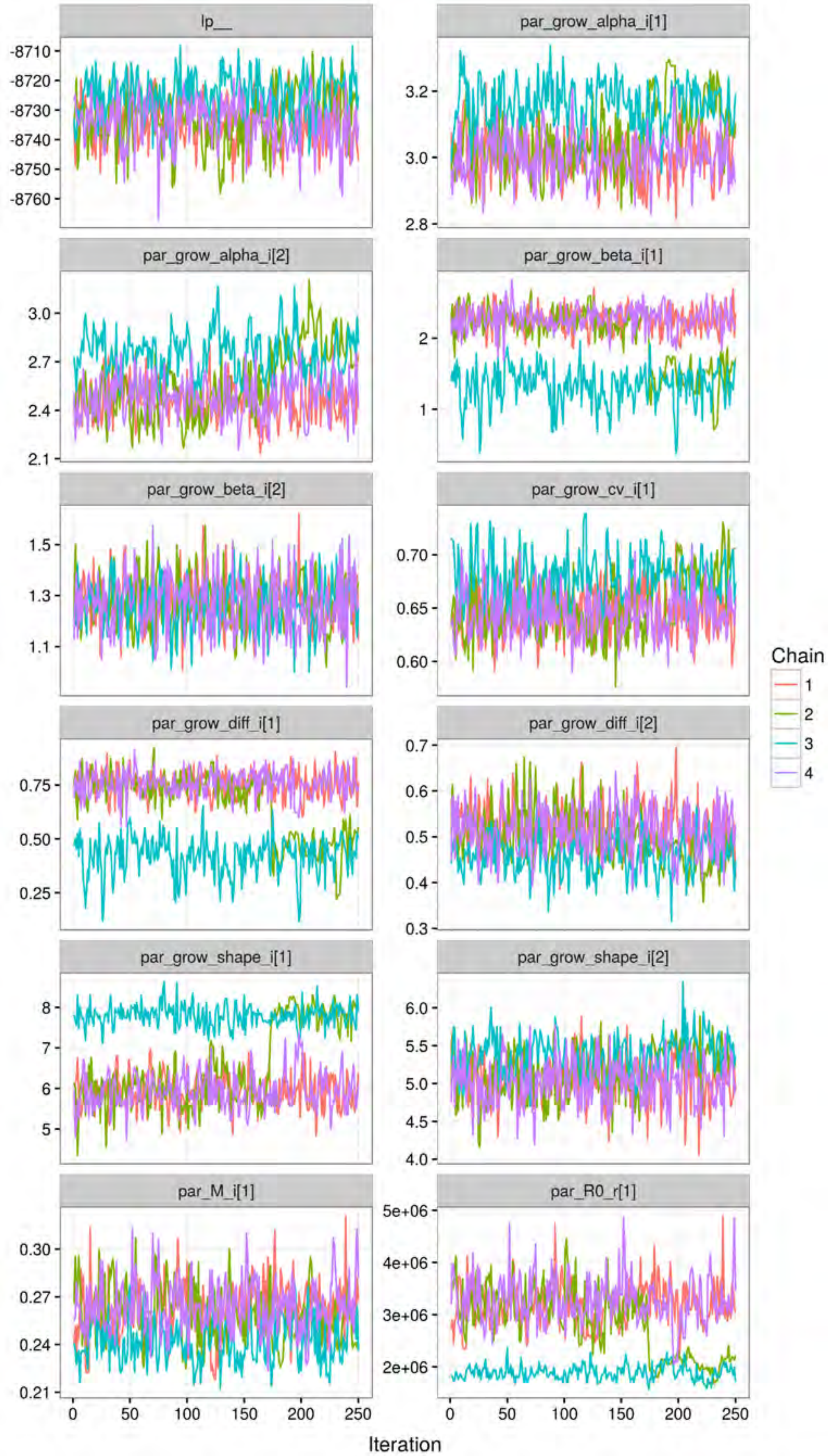


Figure 3A: MCMC trace plots of the likelihood profile (lp__) and model parameters from the bimodal model using the LSD model in Stan.

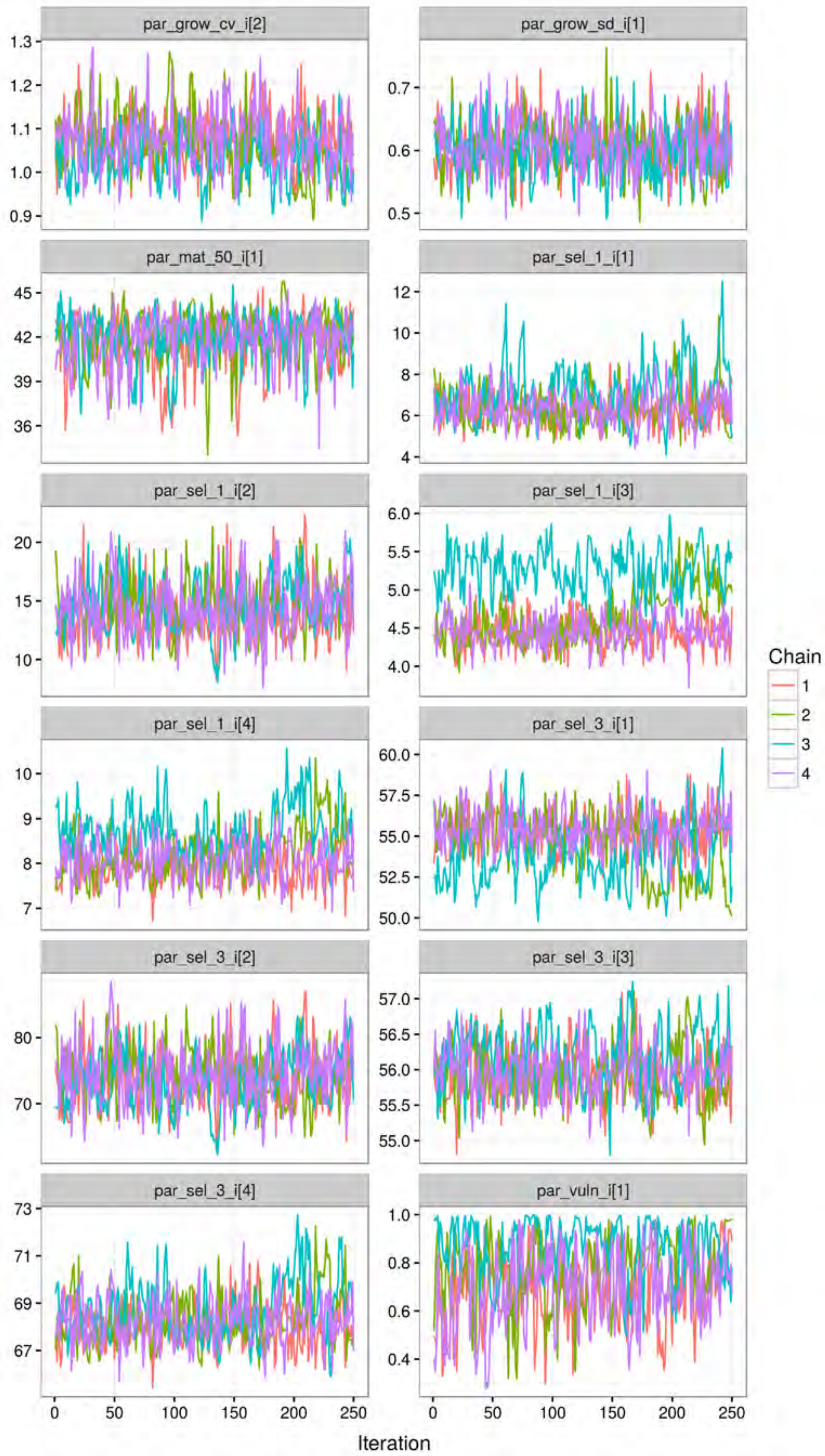


Figure 3B: MCMC trace plots of model parameters from the bimodal model using the LSD model in Stan.

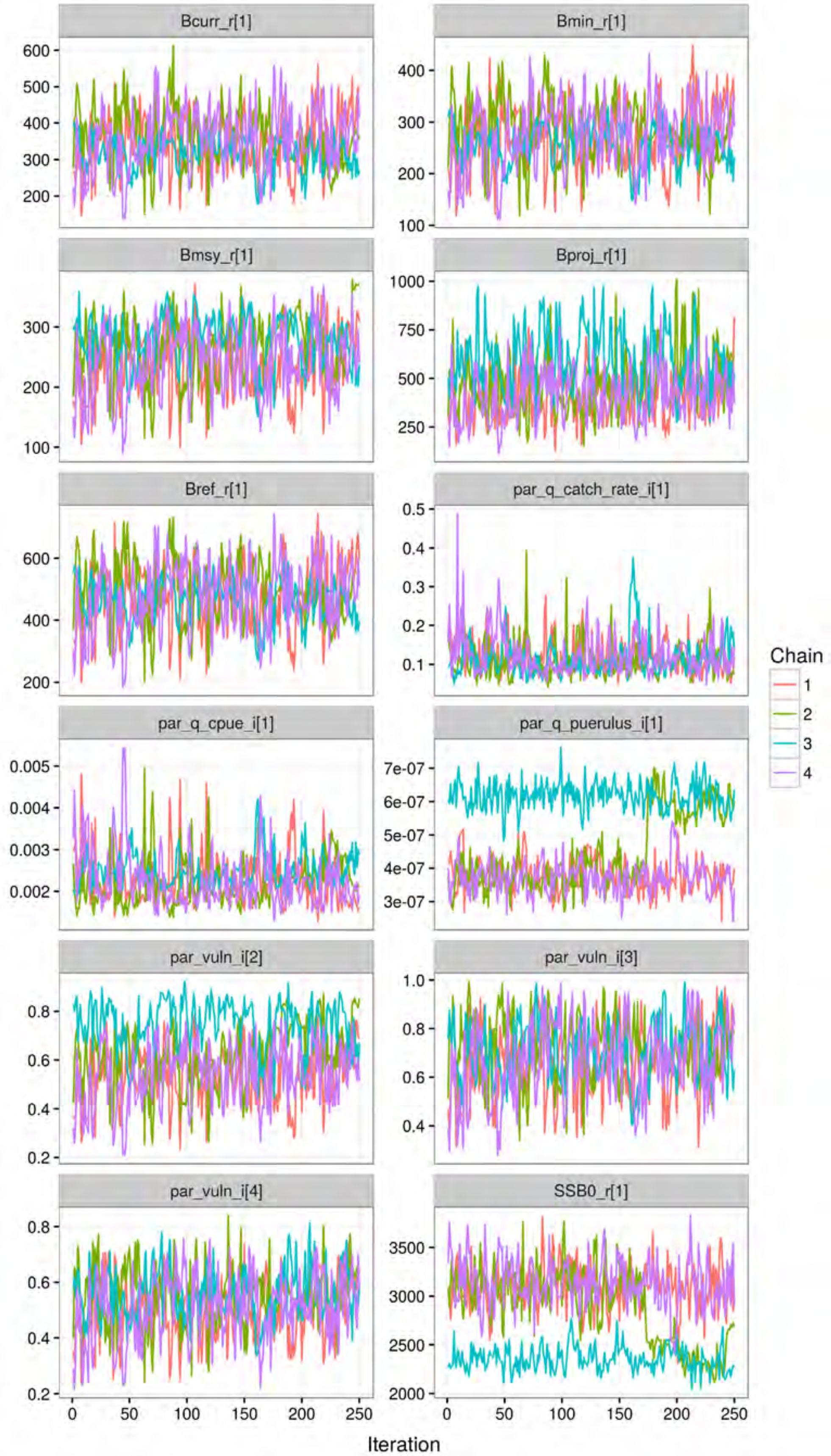


Figure 3C: MCMC trace plots of model parameters and derived quantities from the <u>bimodal</u> model using the LSD model in Stan.

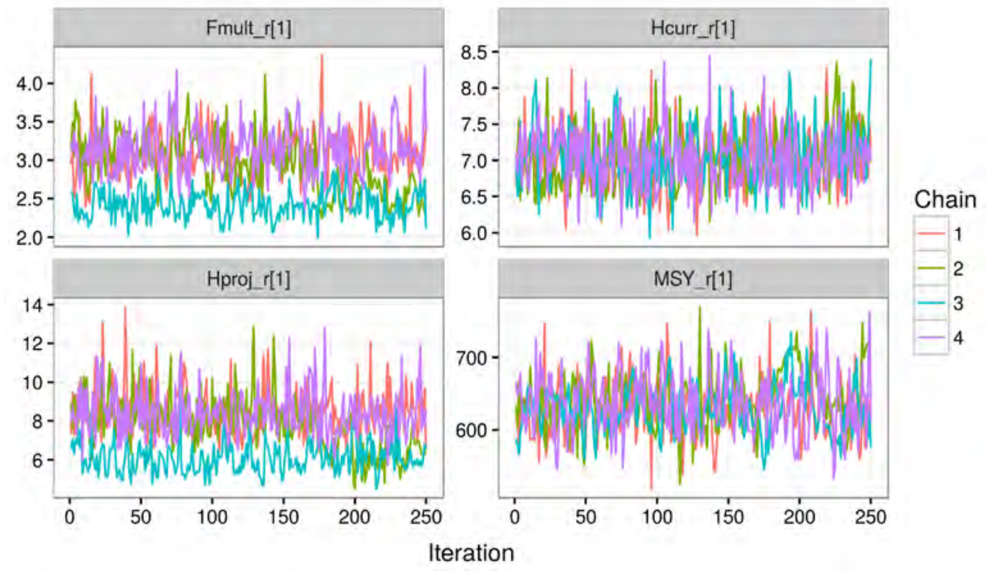


Figure 3D: MCMC trace plots of derived quantities from the bimodal model using the LSD model in Stan.

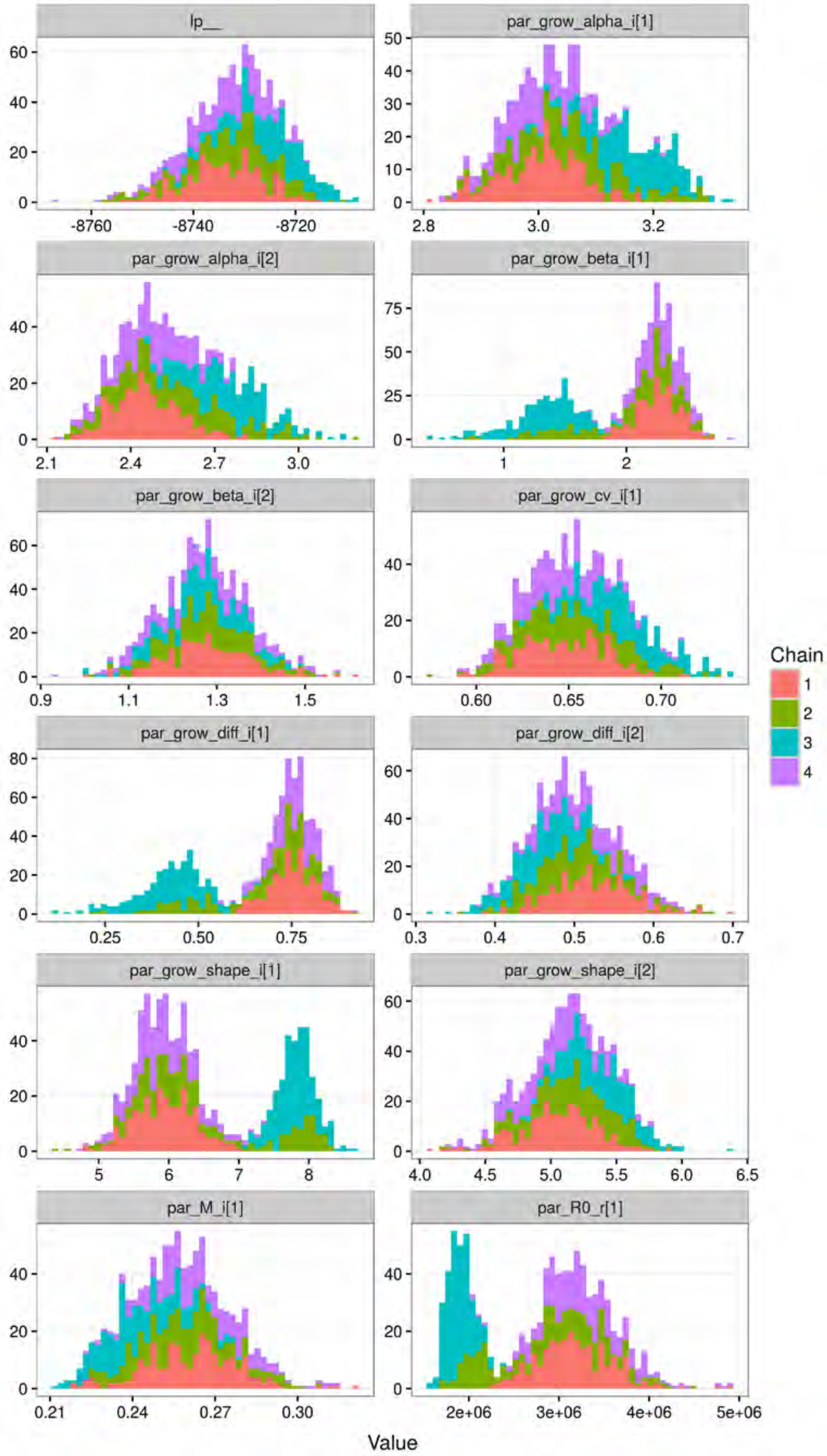


Figure 4A: MCMC histograms of the likelihood profile (lp__) and model parameters from the <u>bimodal</u> model using the LSD model in Stan.

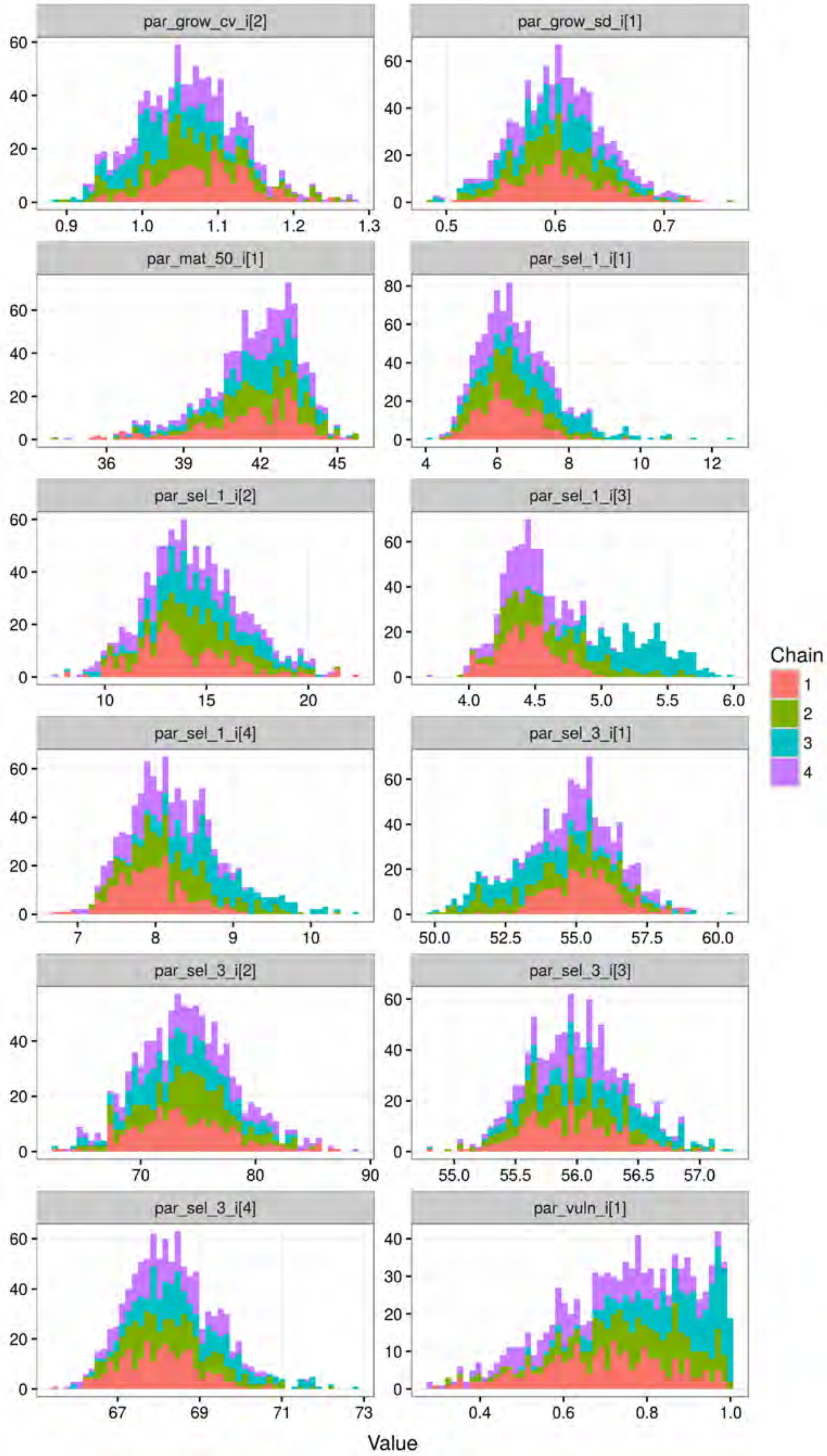


Figure 4B: MCMC histograms of several of the model parameters from the <u>bimodal</u> model using the LSD model in Stan.

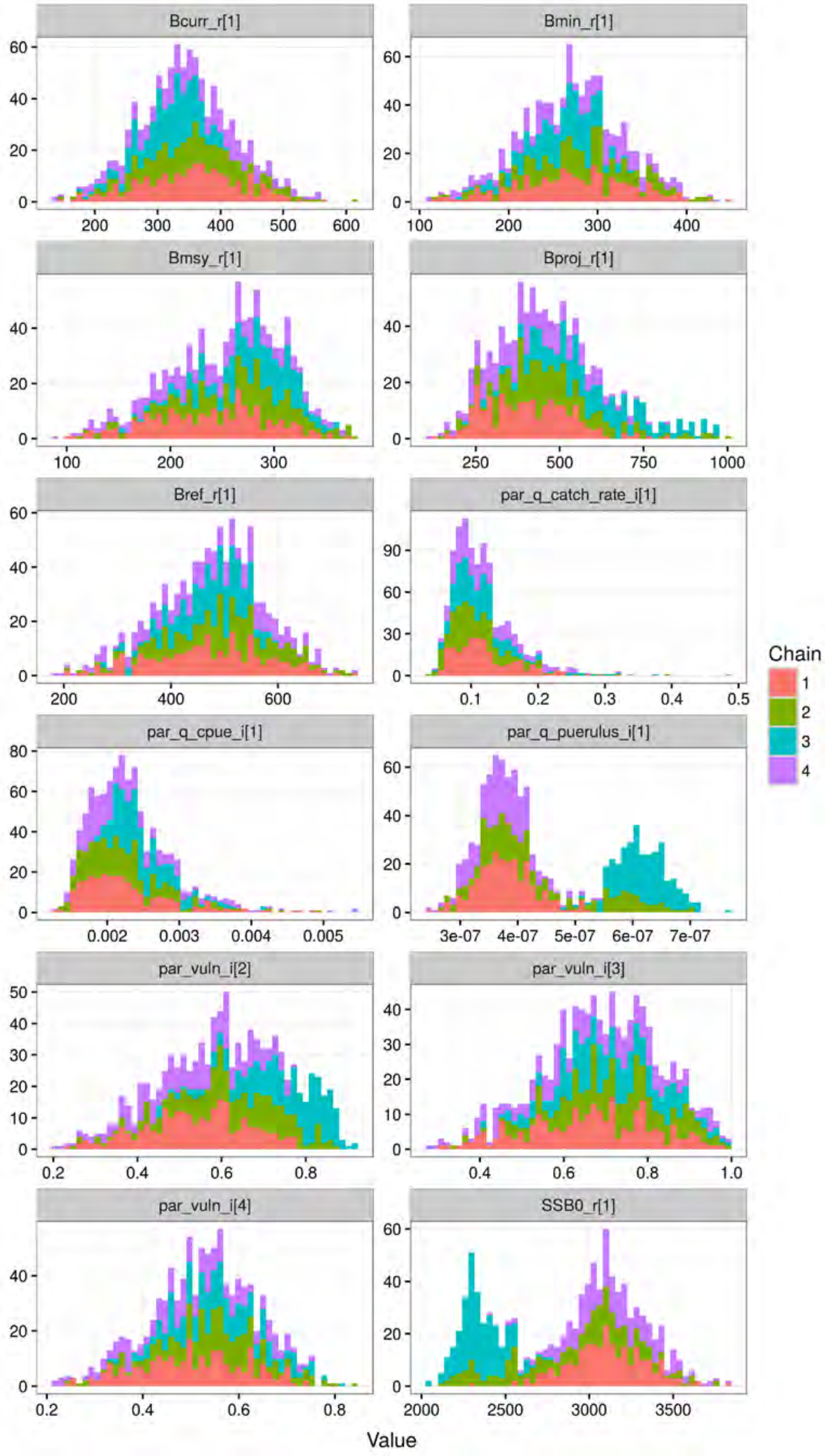


Figure 4C: MCMC histograms of several of the model parameters and derived quantities from the <u>bimodal</u> model using the LSD model in Stan.

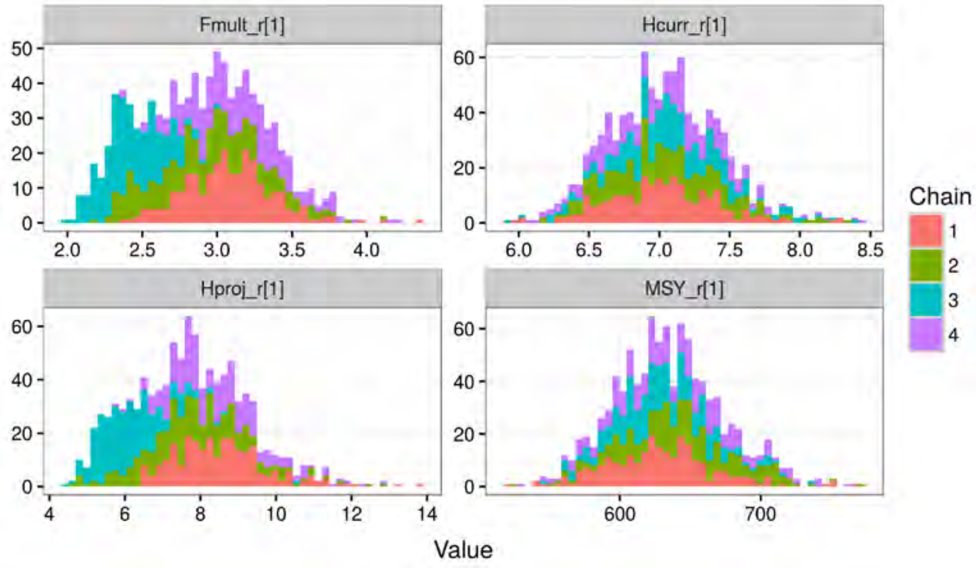


Figure 4D: MCMC histograms of several derived quantities from the <u>bimodal</u> model using the LSD model in Stan.

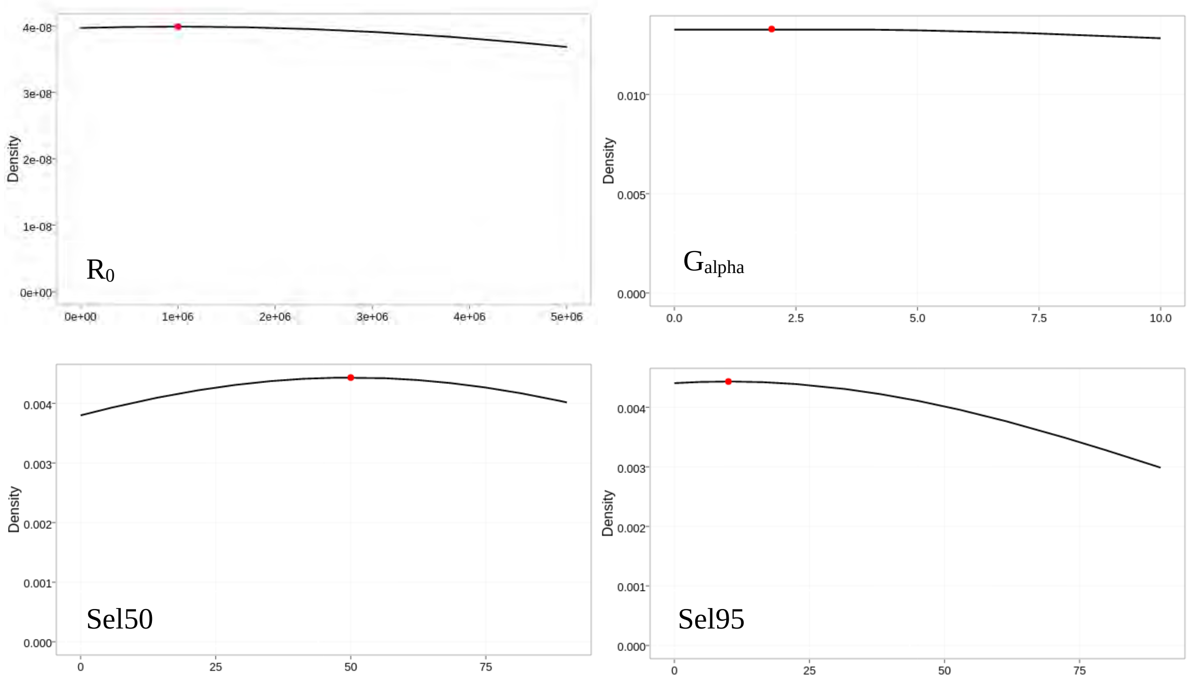


Figure 5: The priors placed on the model parameters R_0, G_{alpha}, sel50 and sel95 in the <u>wideprior</u> model runs using both the MSLM model in AMDB and the LSD model in Stan.

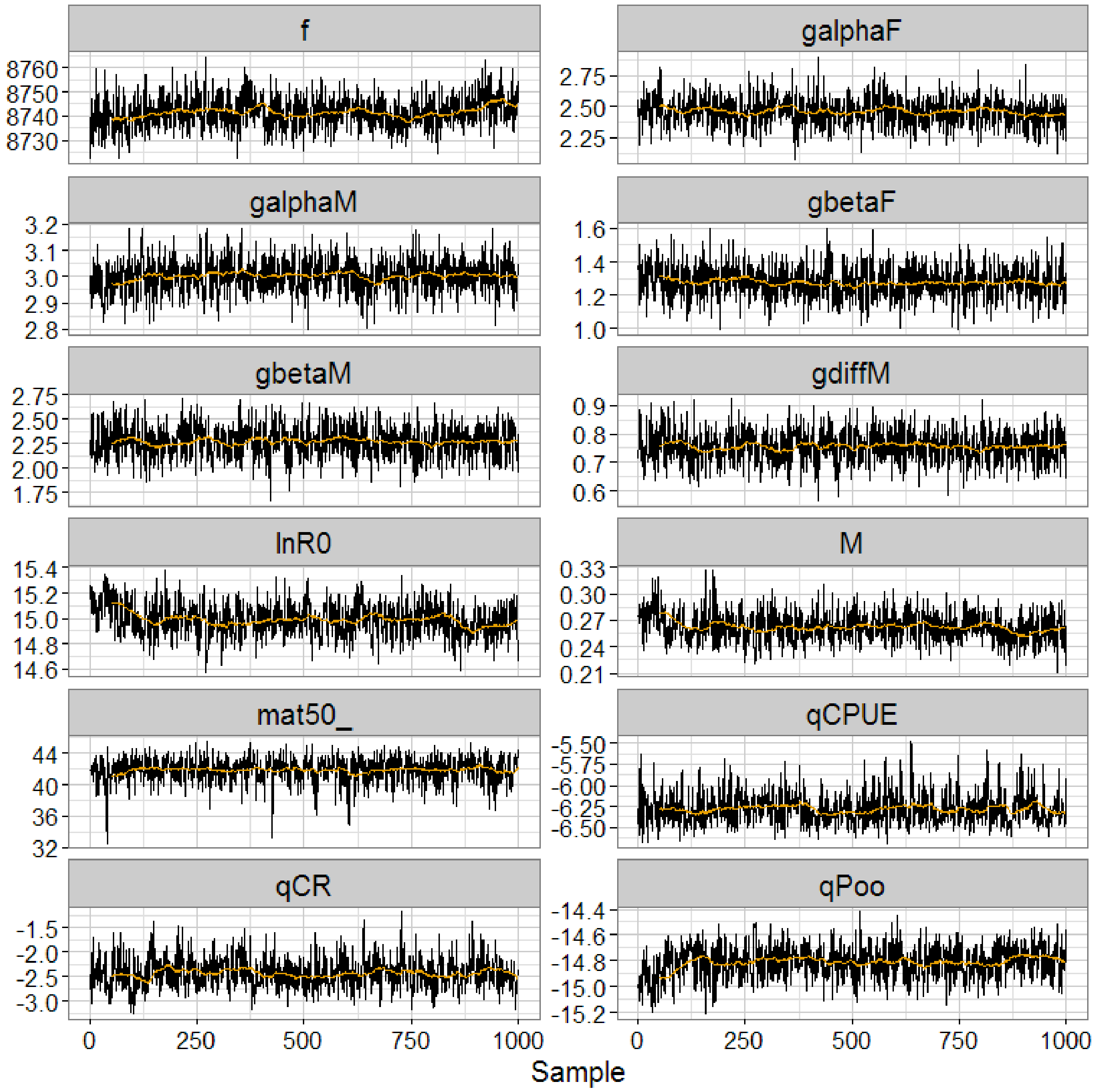


Figure 6A: MCMC trace plots of the likelihood profile (f) and model parameters from the <u>wideprior</u> model using the MSLM model in AMDB.

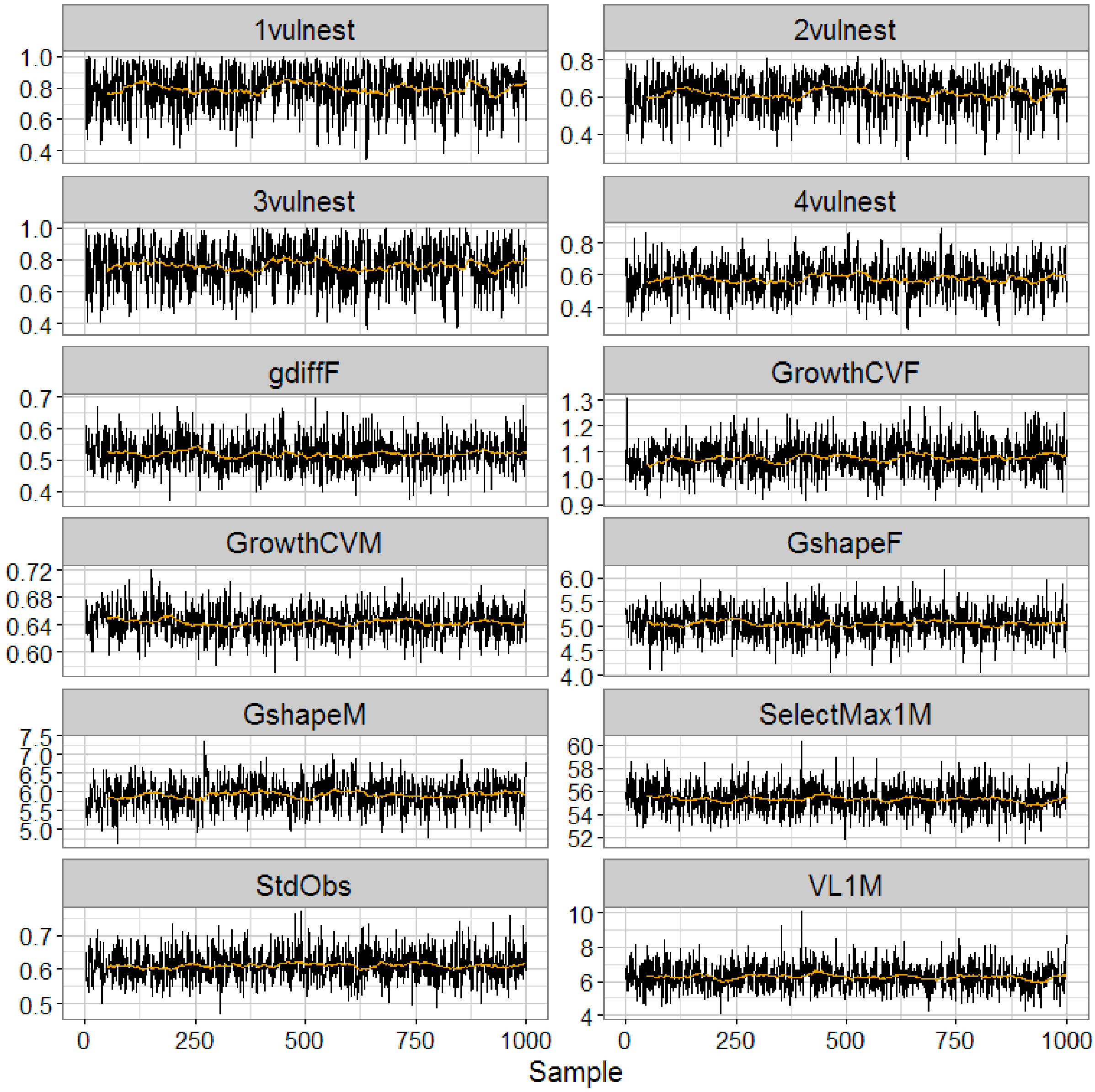


Figure 6B: MCMC trace plots of model parameters from the <u>wideprior</u> model using the MSLM model in AMDB.

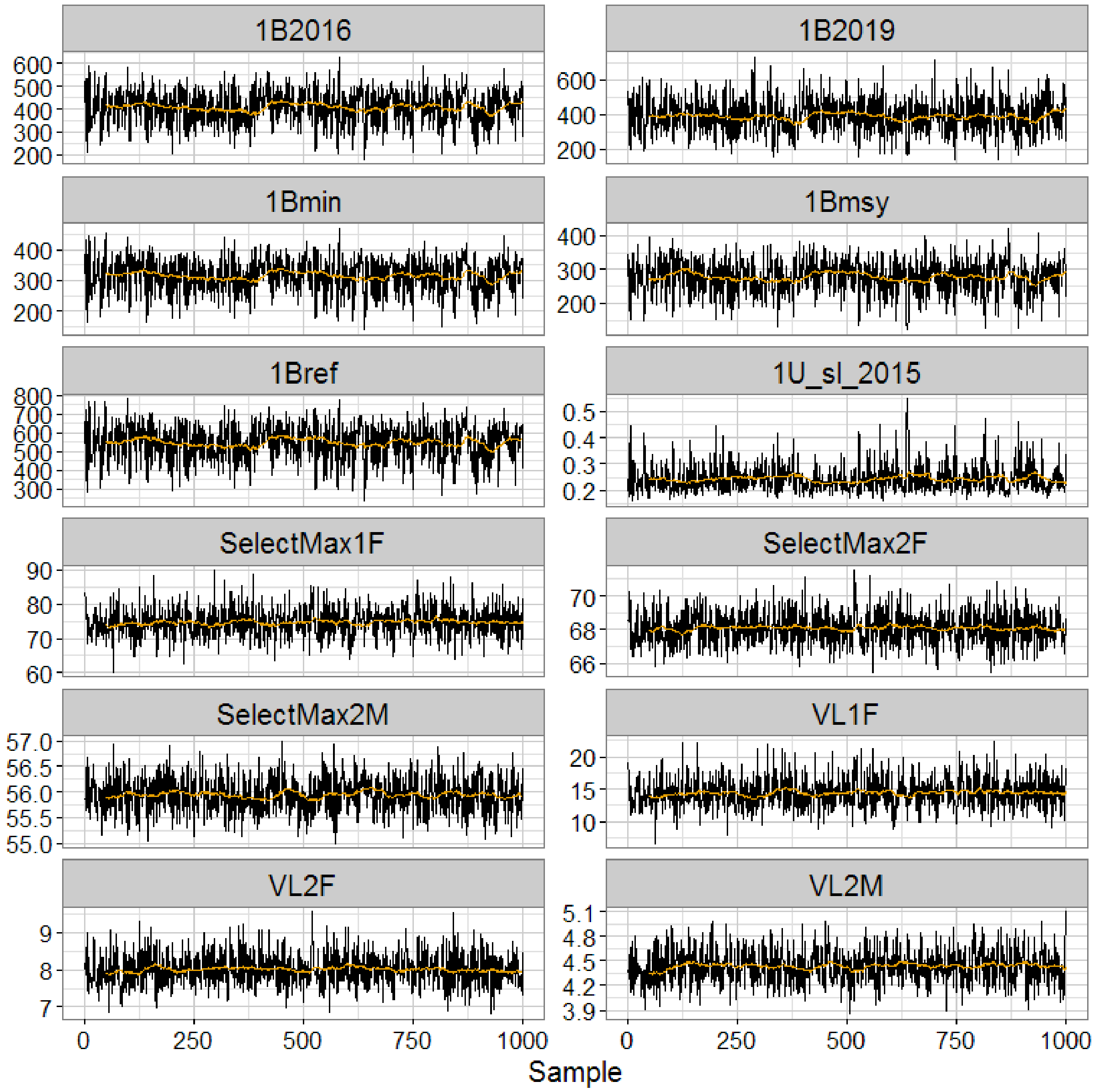


Figure 6C: MCMC trace plots of model parameters and derived quantities from the <u>wideprior</u> model using the MSLM model in AMDB.

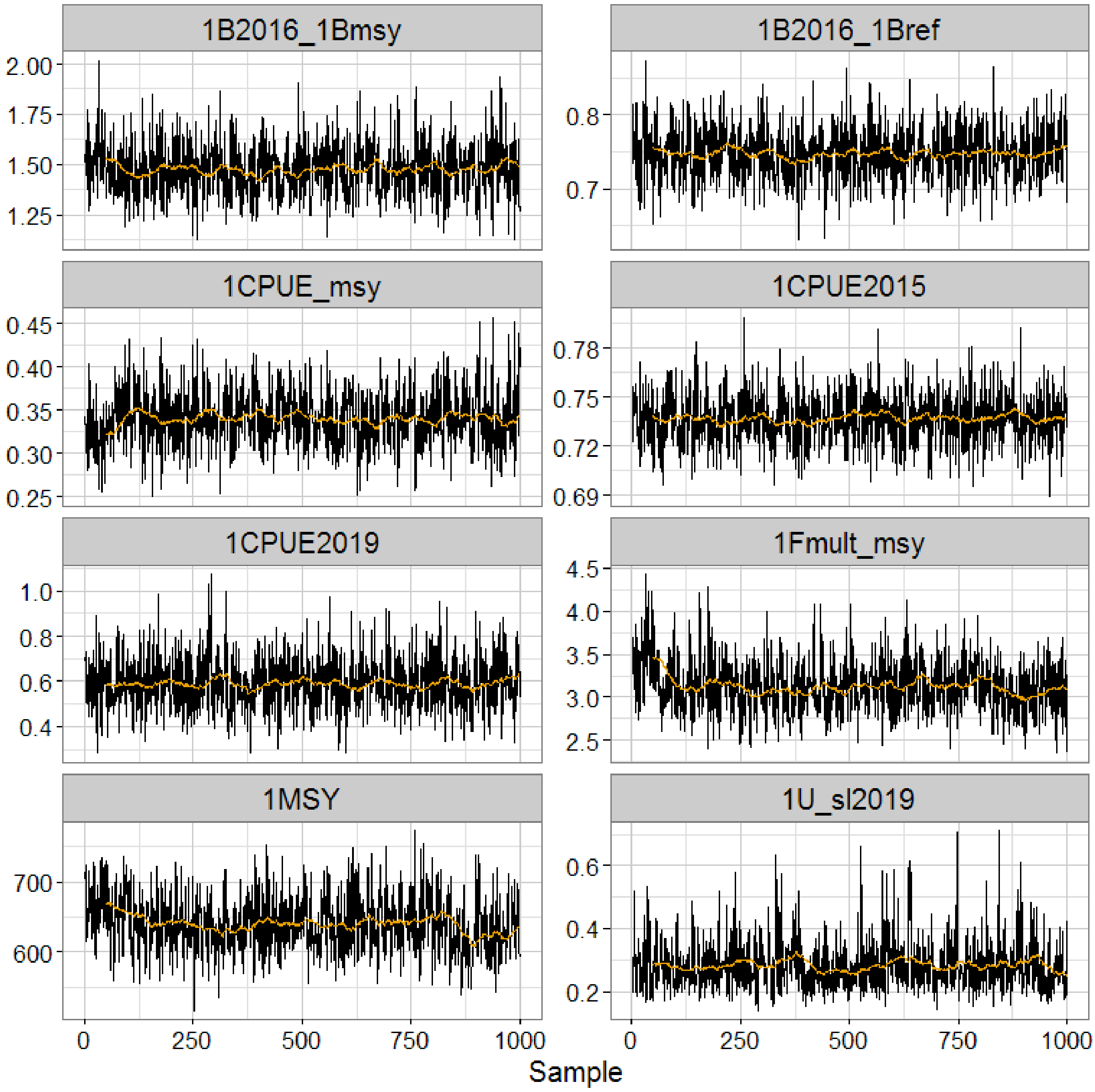


Figure 6D: MCMC trace plots of derived quantities from the <u>wideprior</u> model using the MSLM model in AMDB.

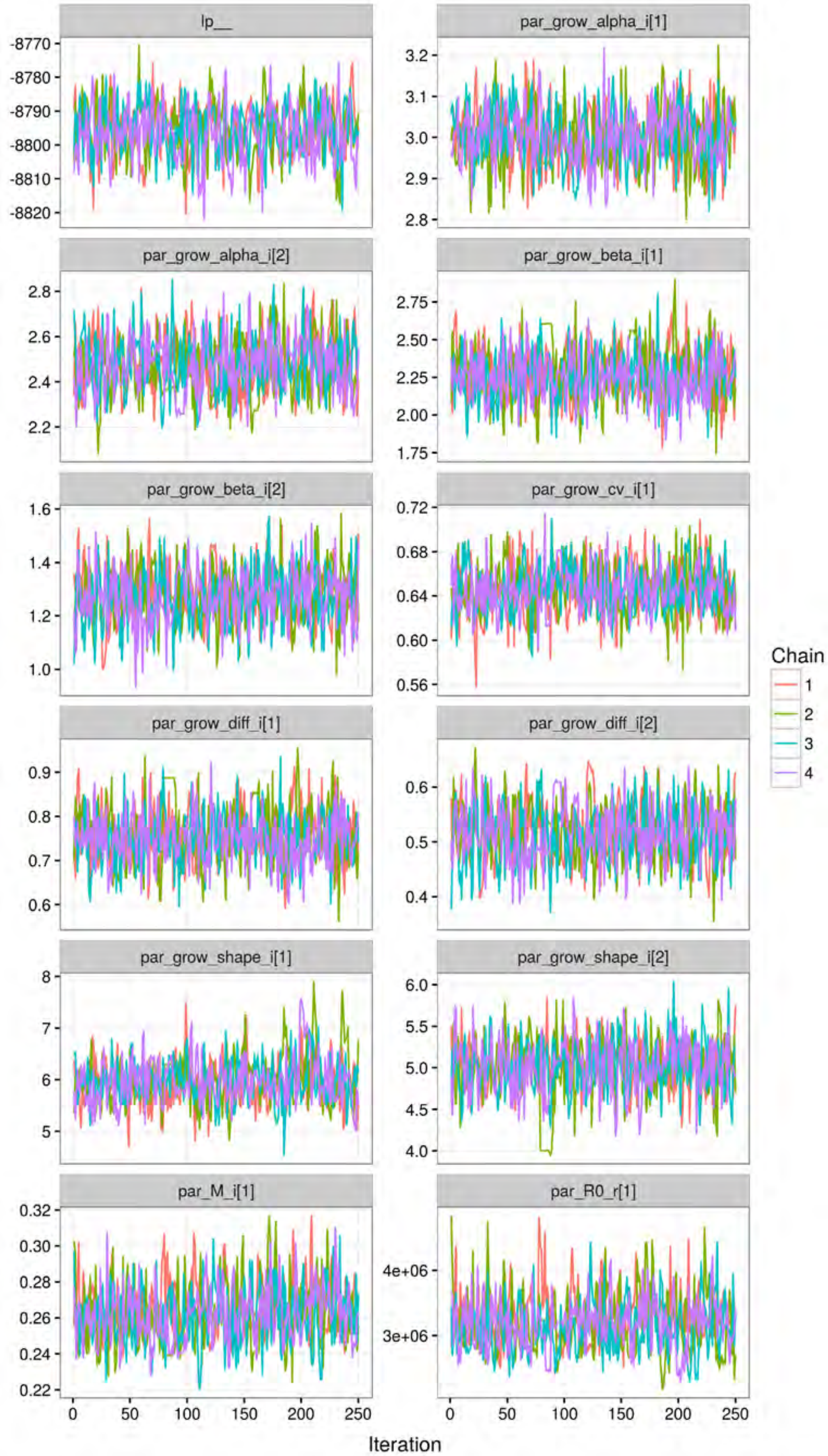


Figure 7A: MCMC trace plots of the likelihood profile (lp__) and model parameters from the <u>wideprior</u> model using the LSD model in Stan.

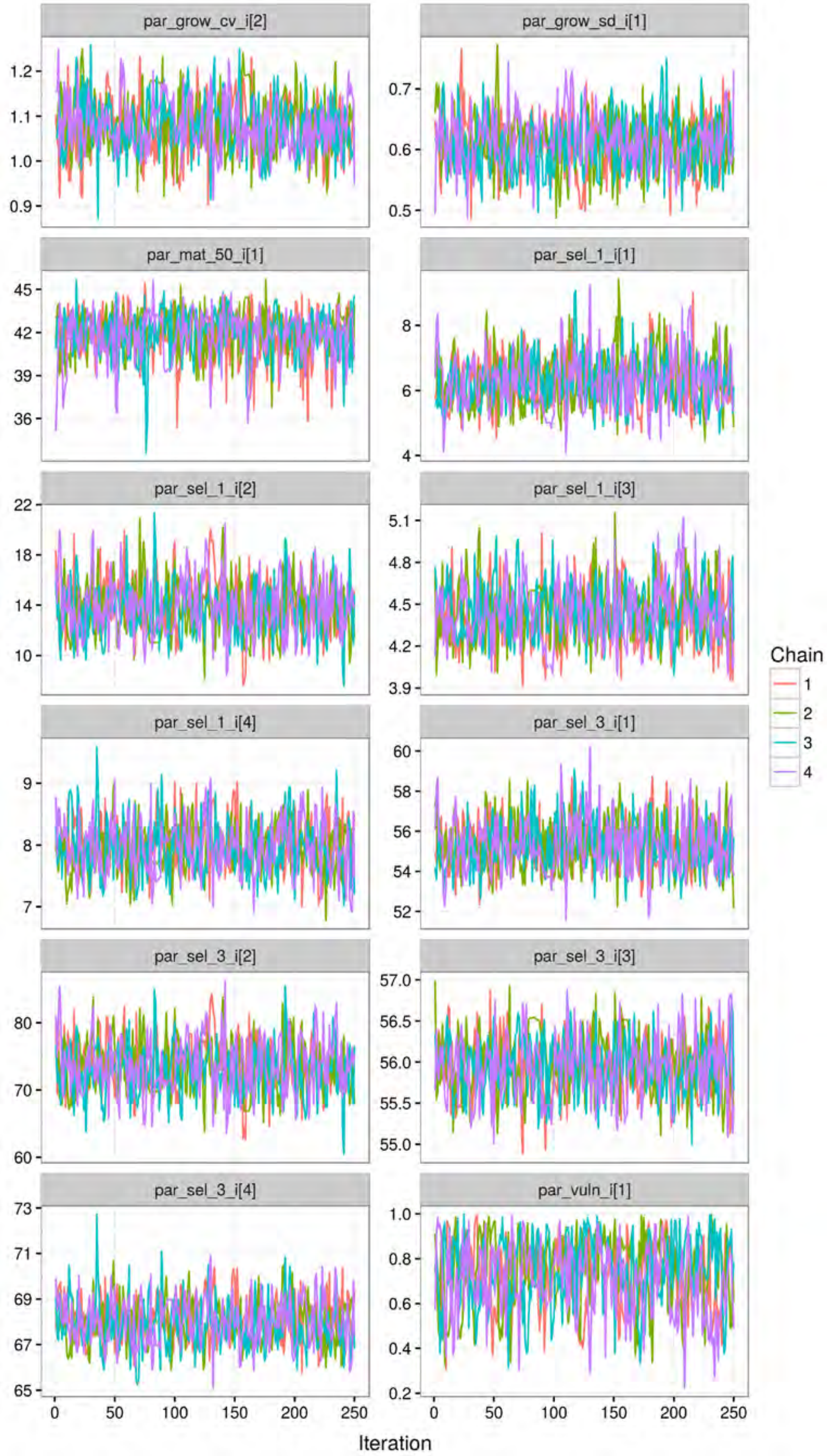


Figure 7B: MCMC trace plots of model parameters from the <u>wideprior</u> model using the LSD model in Stan.

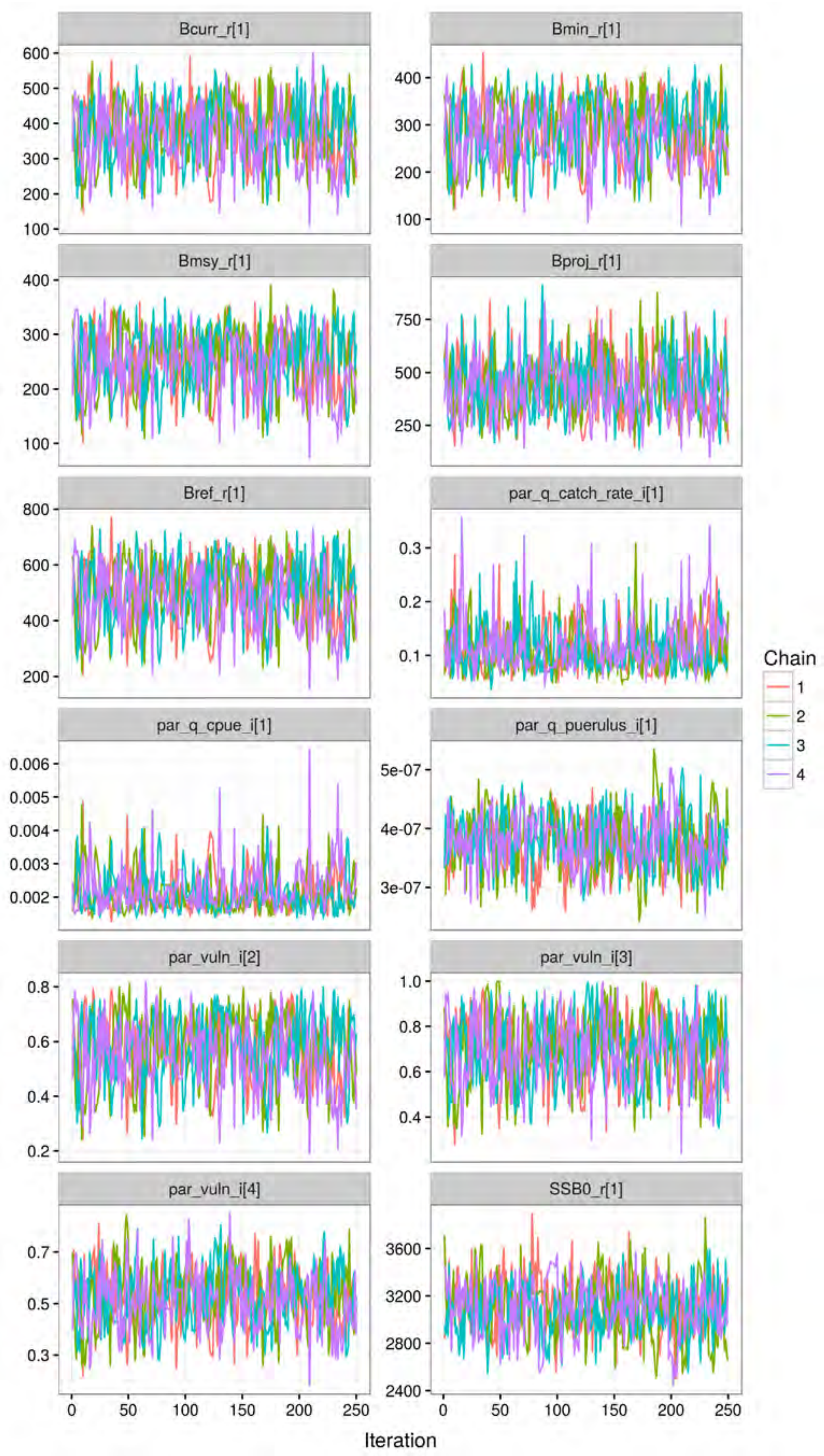


Figure 7C: MCMC trace plots of model parameters and derived quantities from the <u>wideprior</u> model using the LSD model in Stan.

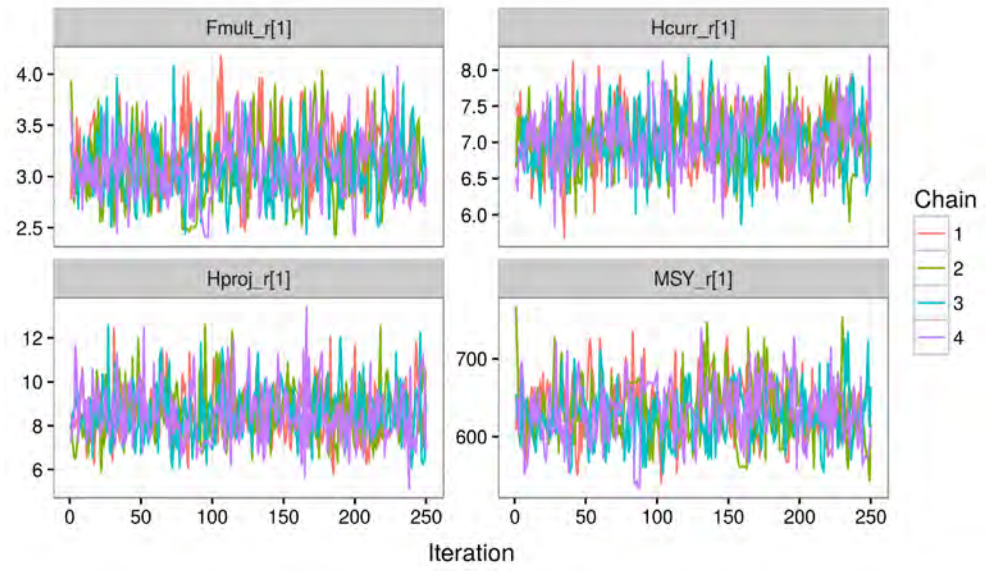


Figure 7D: MCMC trace plots of derived quantities from the wideprior model using the LSD model in Stan.

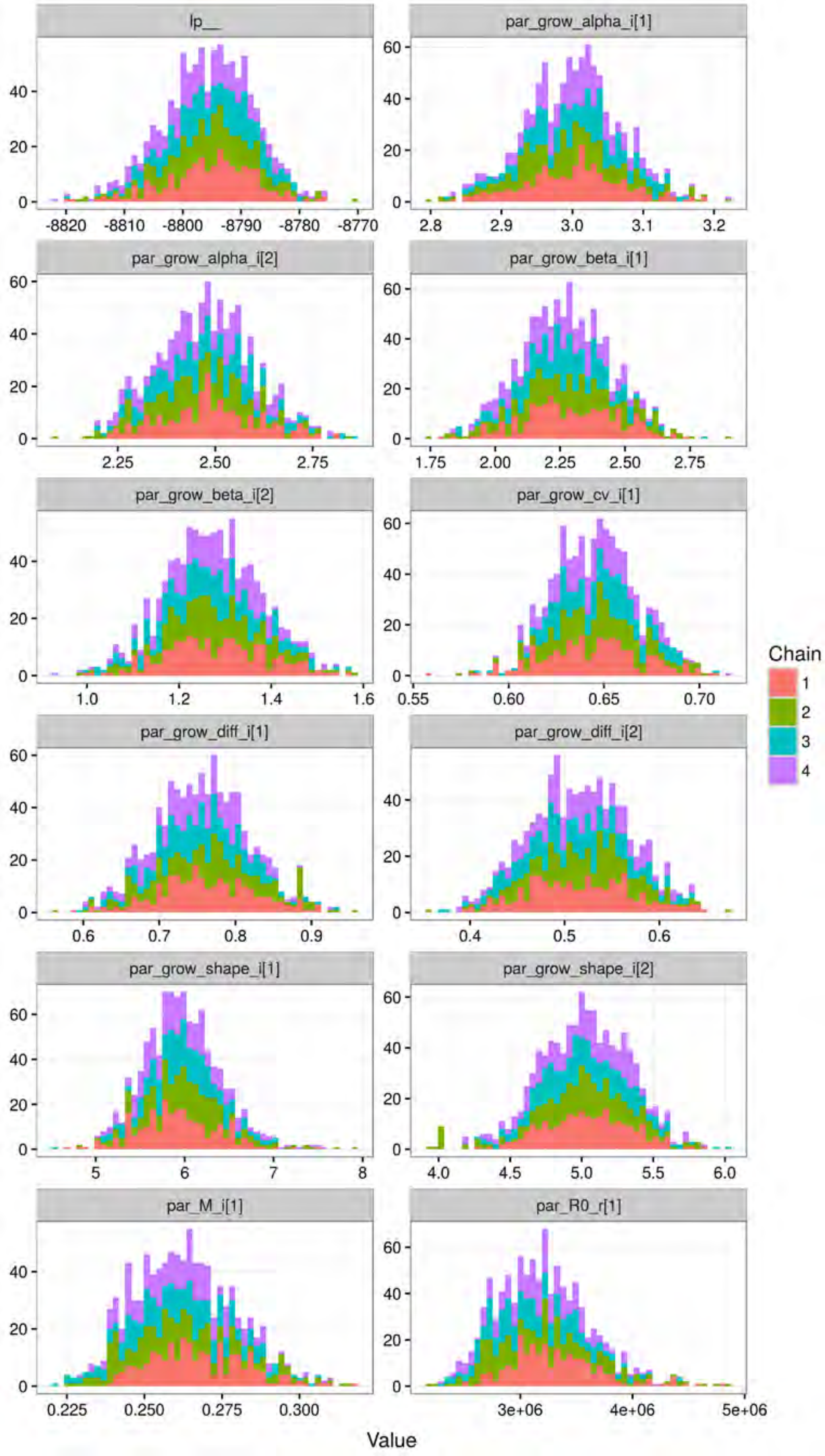


Figure 8A: MCMC histograms of the likelihood profile (lp__) and model parameters from the <u>wideprior</u> model using the LSD model in Stan.

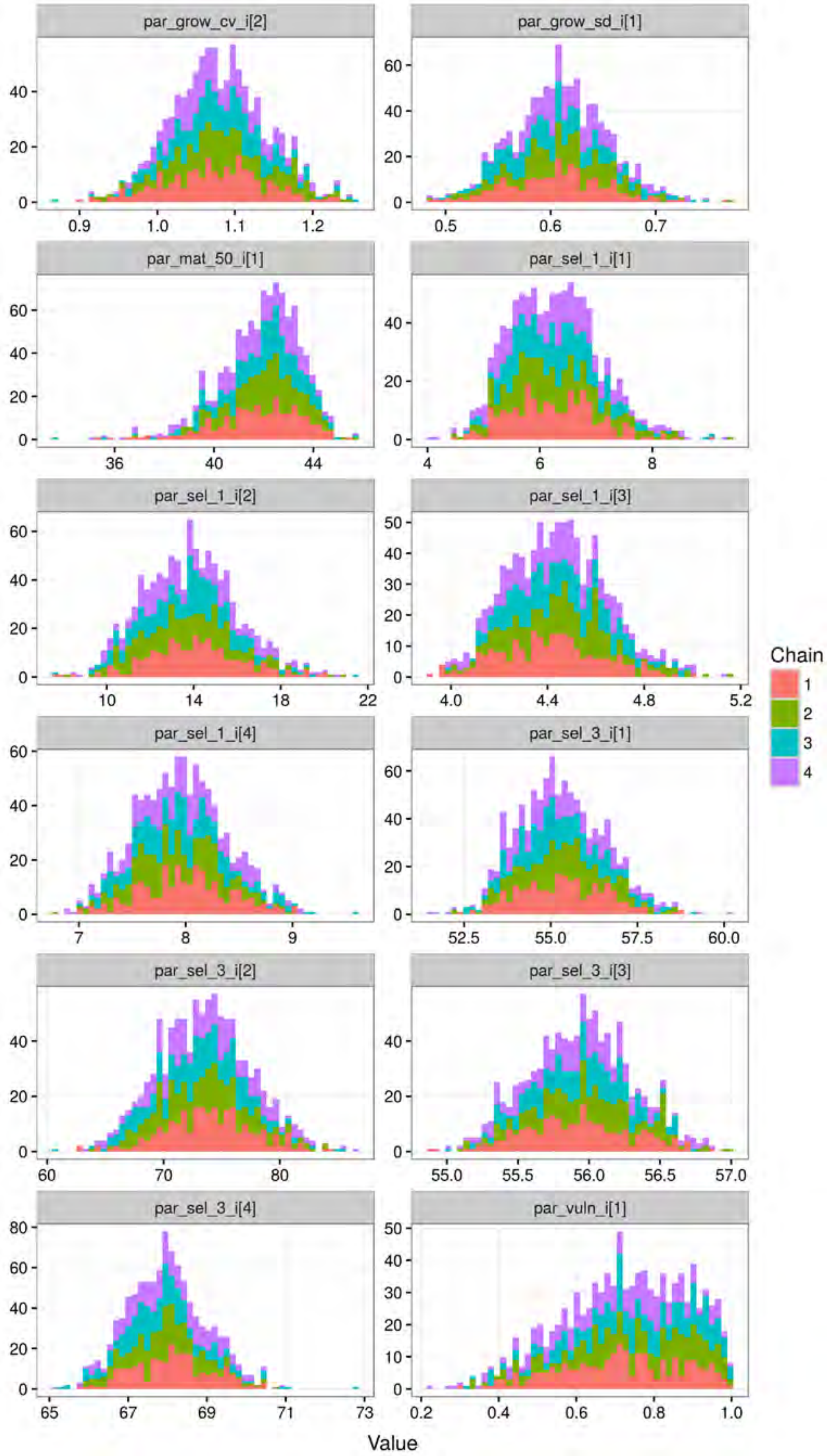


Figure 8B: MCMC histograms of model parameters from the <u>wideprior</u> model using the LSD model in Stan.

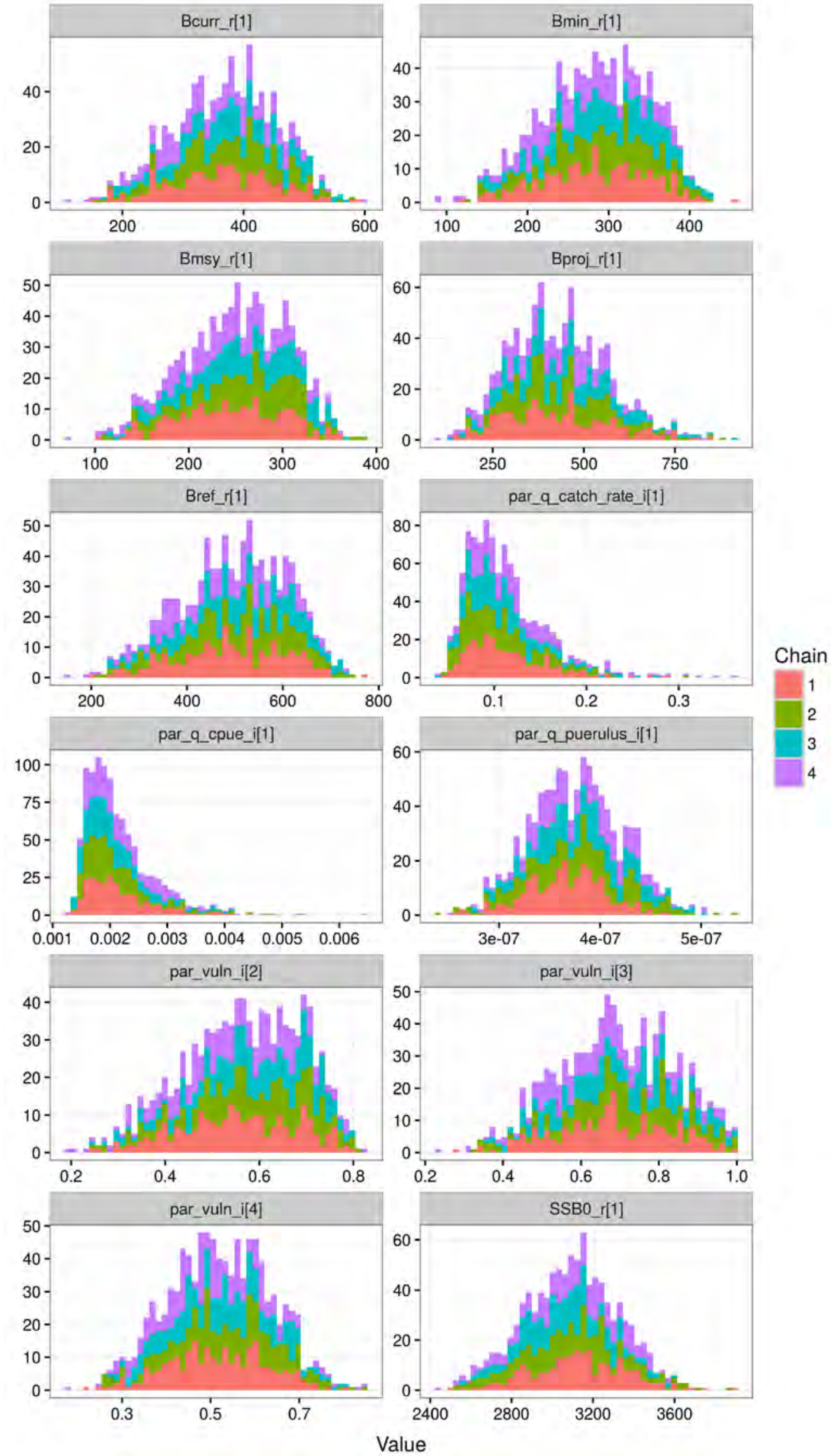


Figure 8C: MCMC histograms of model parameters and derived quantities from the <u>wideprior</u> model using the LSD model in Stan.

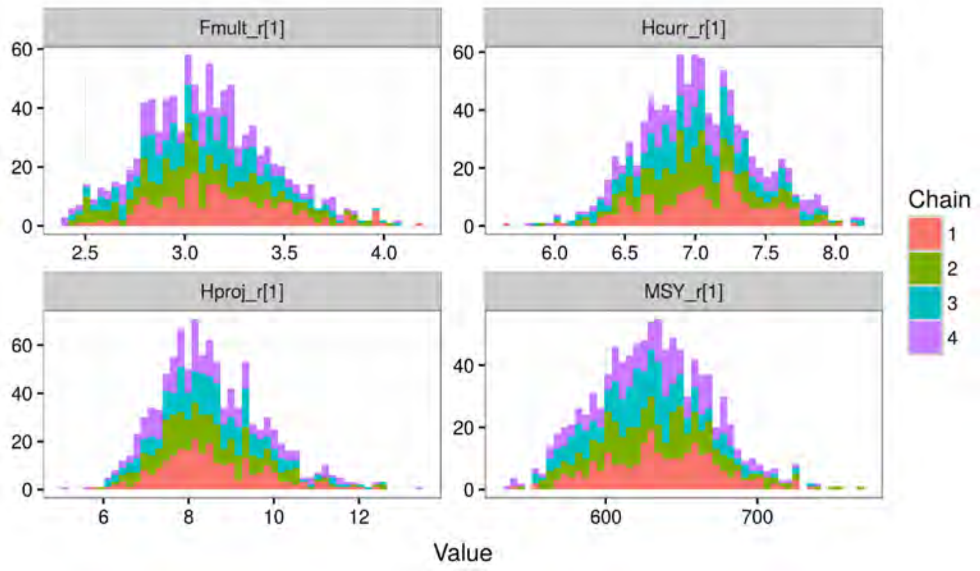


Figure 8D: MCMC histograms of derived quantities from the wideprior model using the LSD model in Stan.

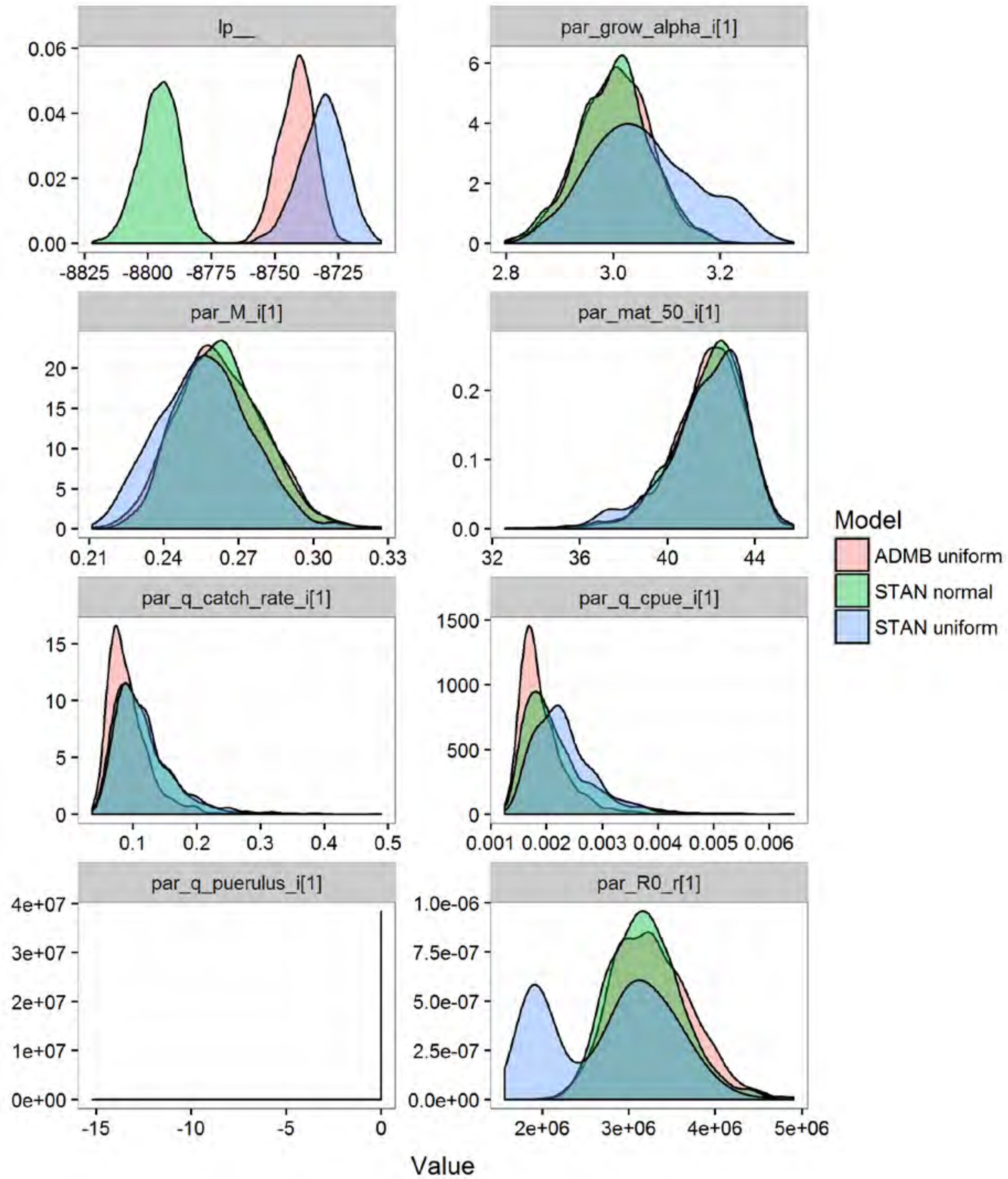


Figure 9A: MCMC densities of the likelihood profile (lp__) and model parameters comparing the <u>MSLM</u> model (ADMB uniform in figure), <u>bimodal</u> model (Stan uniform in figure), and the <u>wideprior</u> model (Stan normal in figure).

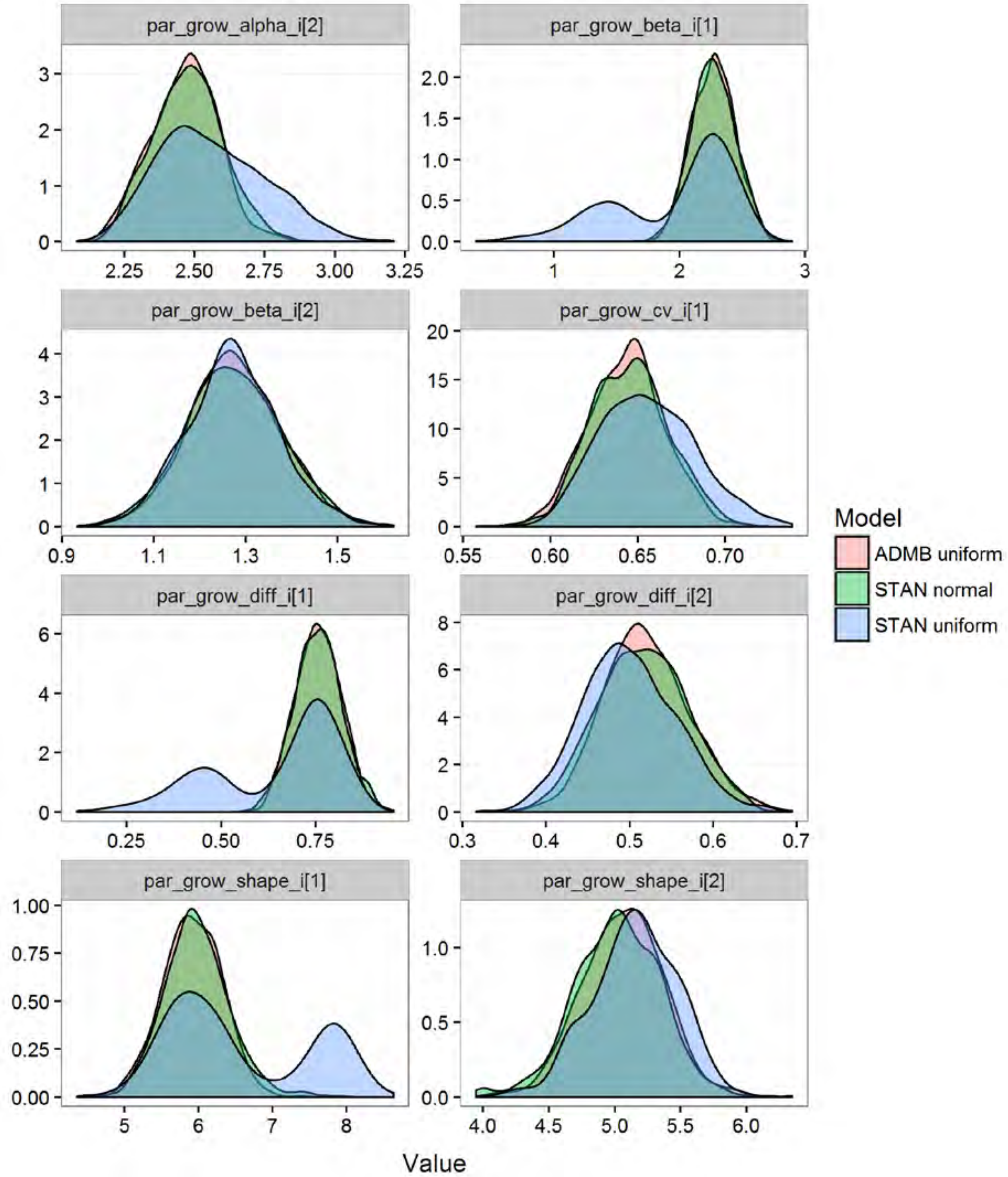


Figure 9B: MCMC densities of model parameters comparing the <u>MSLM</u> model (ADMB uniform in figure), <u>bimodal</u> model (STAN uniform in figure), and the <u>wideprior</u> model (STAN normal in figure).

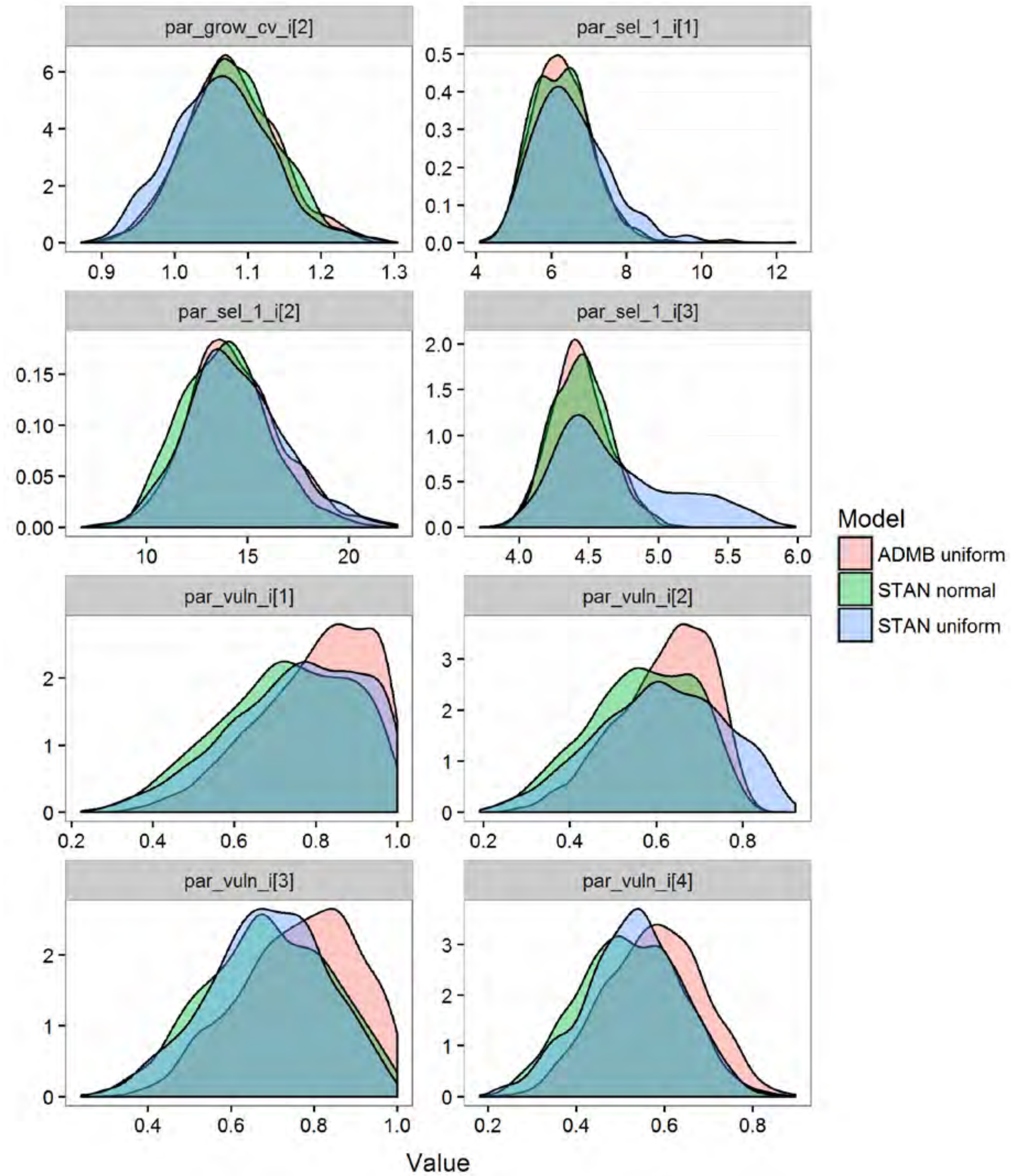


Figure 9C: MCMC densities of model parameters comparing the <u>MSLM</u> model (ADMB uniform in figure), <u>bimodal</u> model (STAN uniform in figure), and the <u>wideprior</u> model (STAN normal in figure).

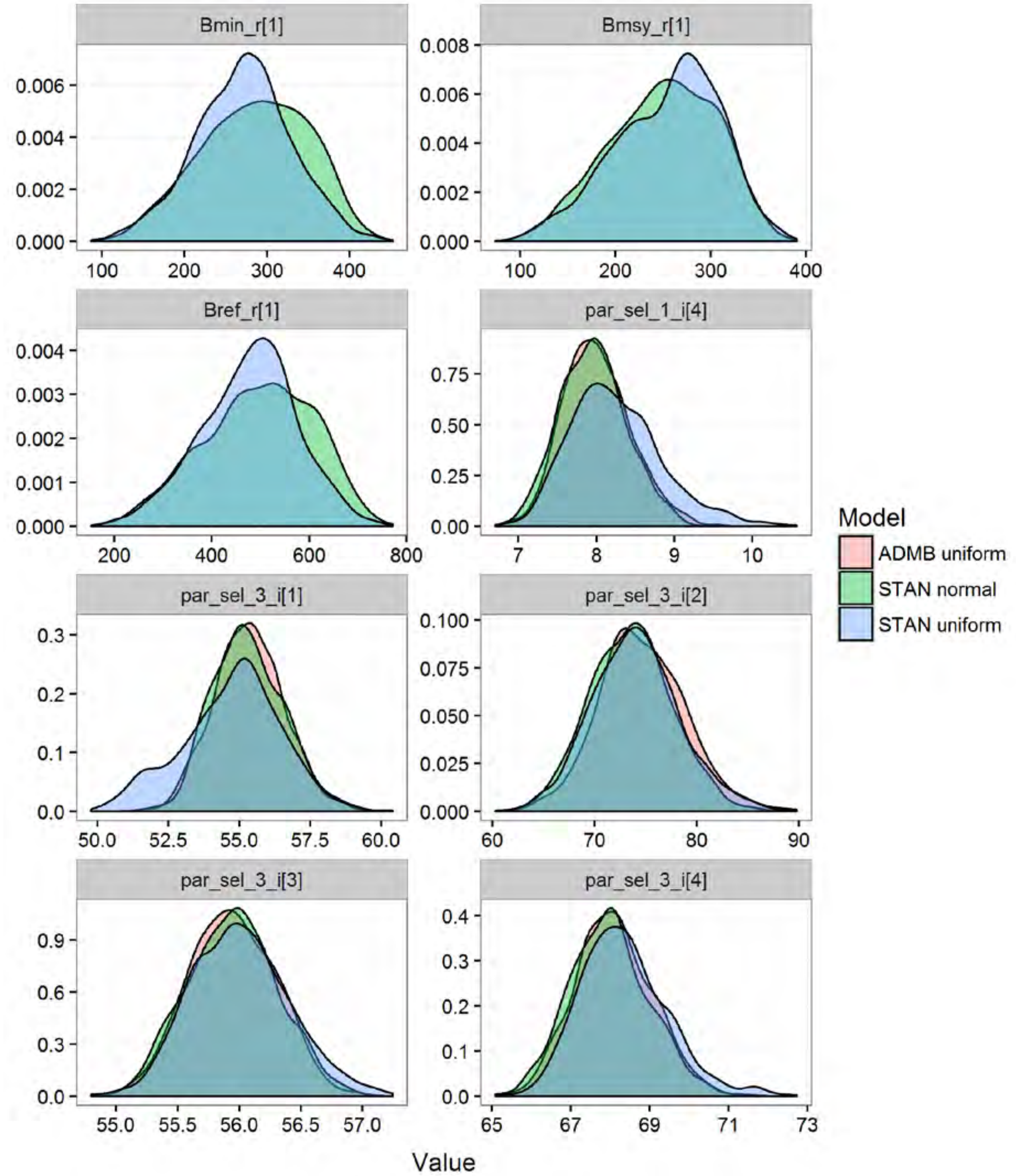


Figure 9D: MCMC densities of model parameters and derived quantities comparing the <u>MSLM</u> model (ADMB uniform in figure), <u>bimodal</u> model (STAN uniform in figure), and the <u>wideprior</u> model (STAN normal in figure).

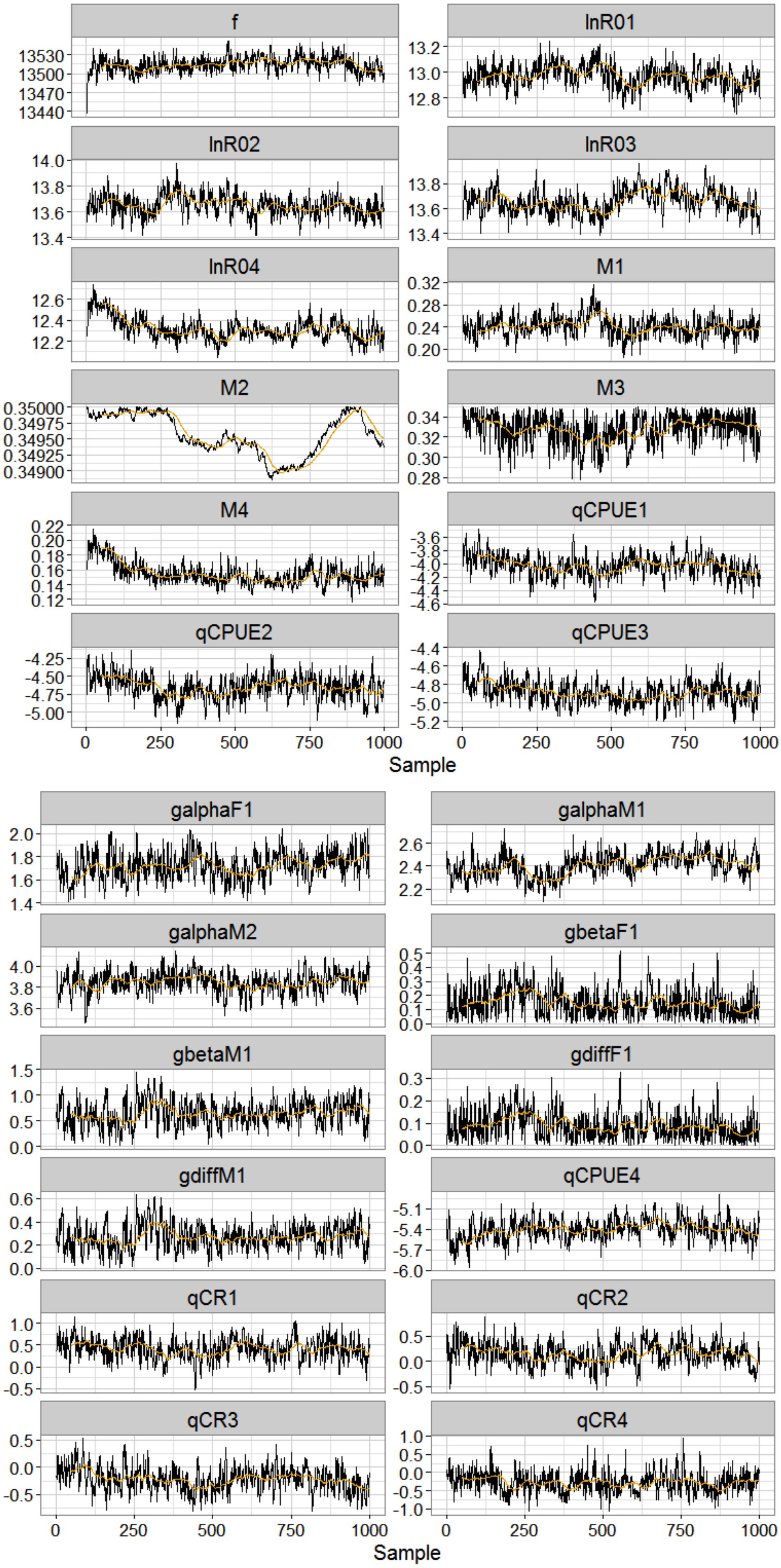
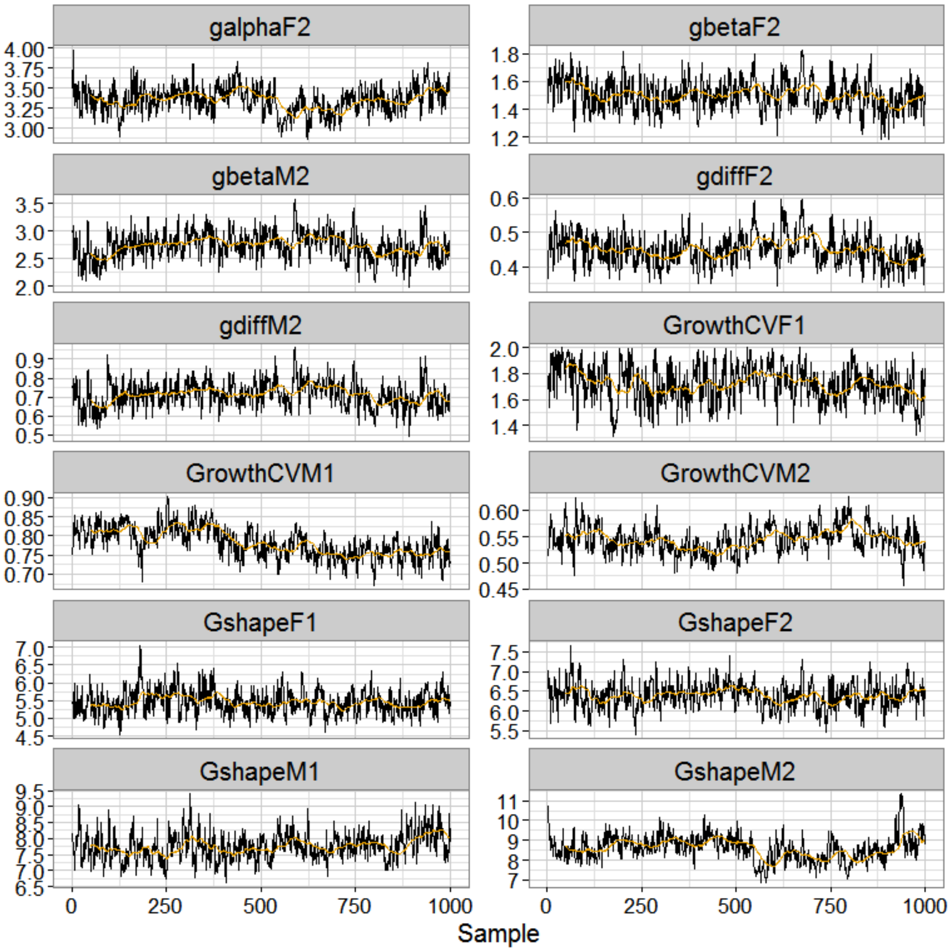


Figure 10A: MCMC trace plots of the likelihood profile (f) and model parameters from the MSLM spatial model.



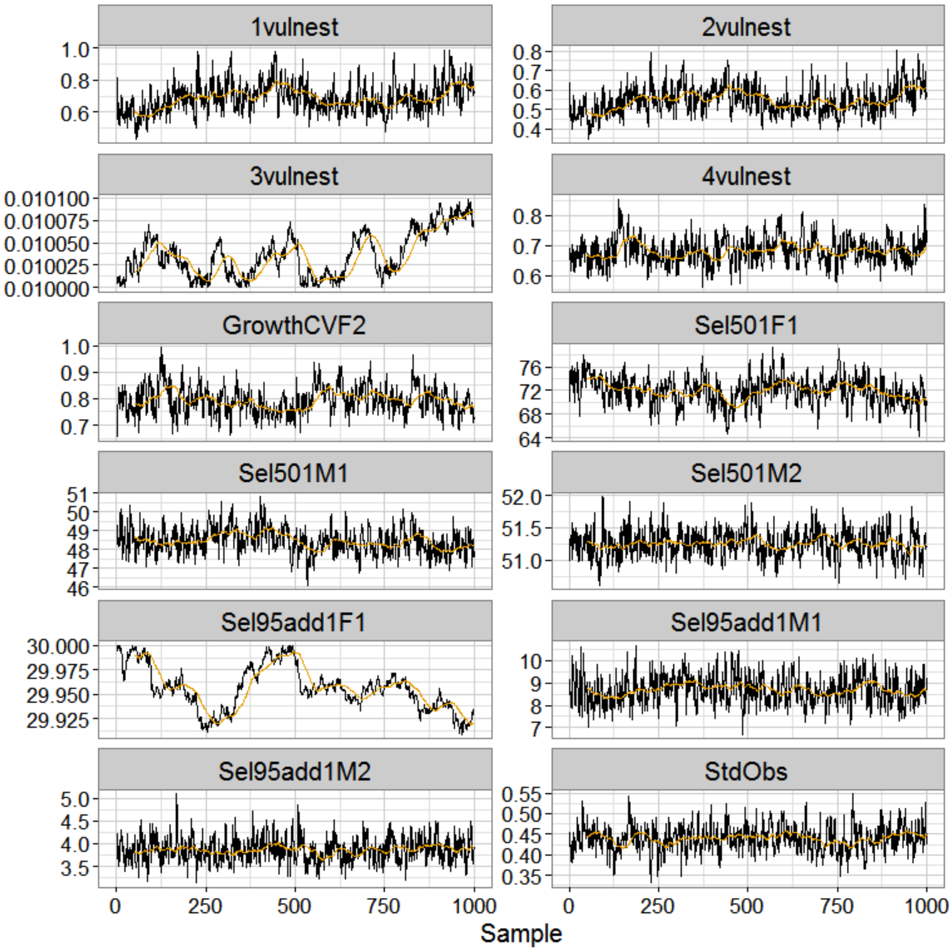


Figure 10B: MCMC trace plots of model parameters from the MSLM spatial model.

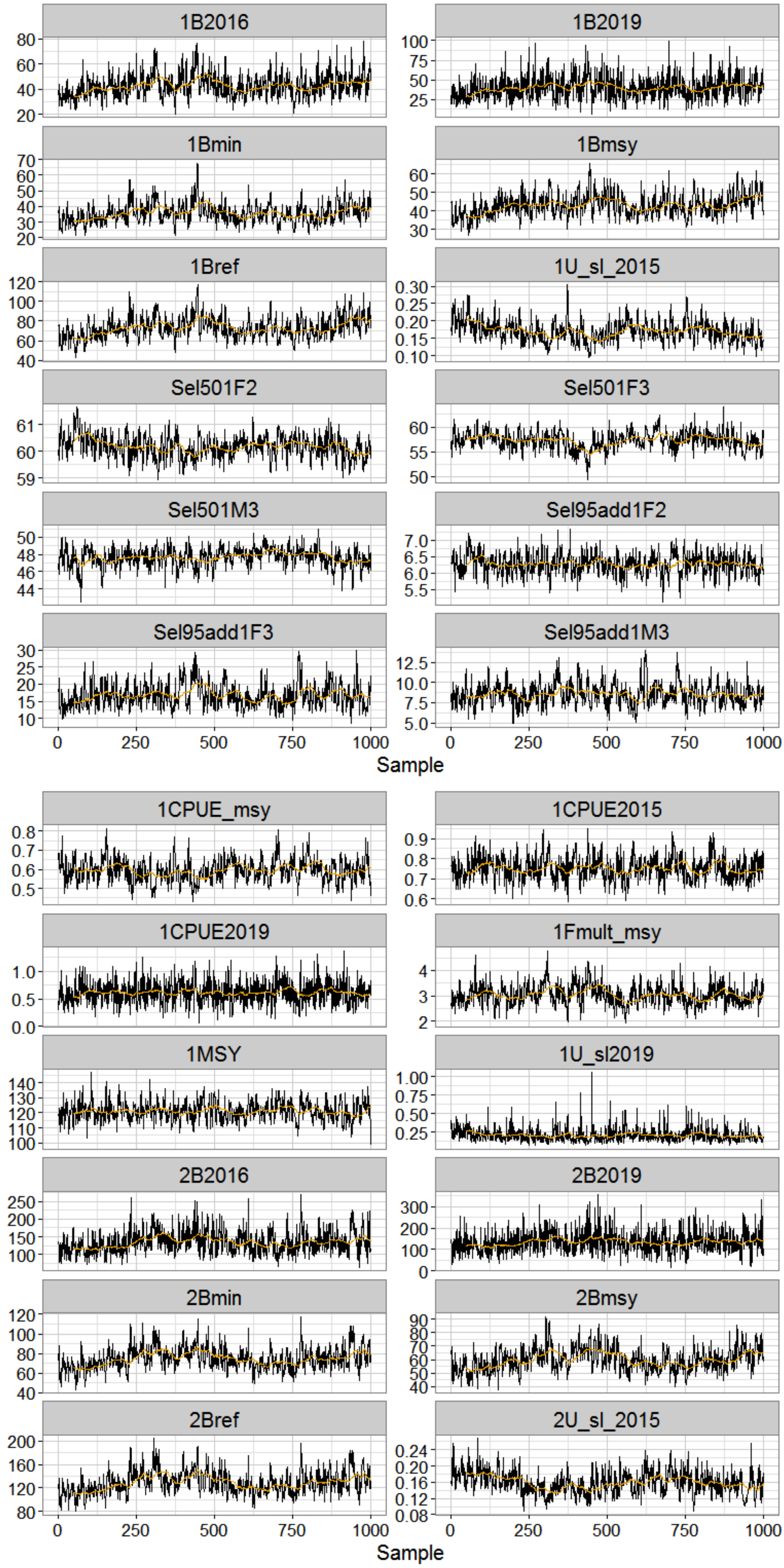


Figure 10C: MCMC trace plots of model parameters and derived quantities from the MSLM <u>spatial</u> model.

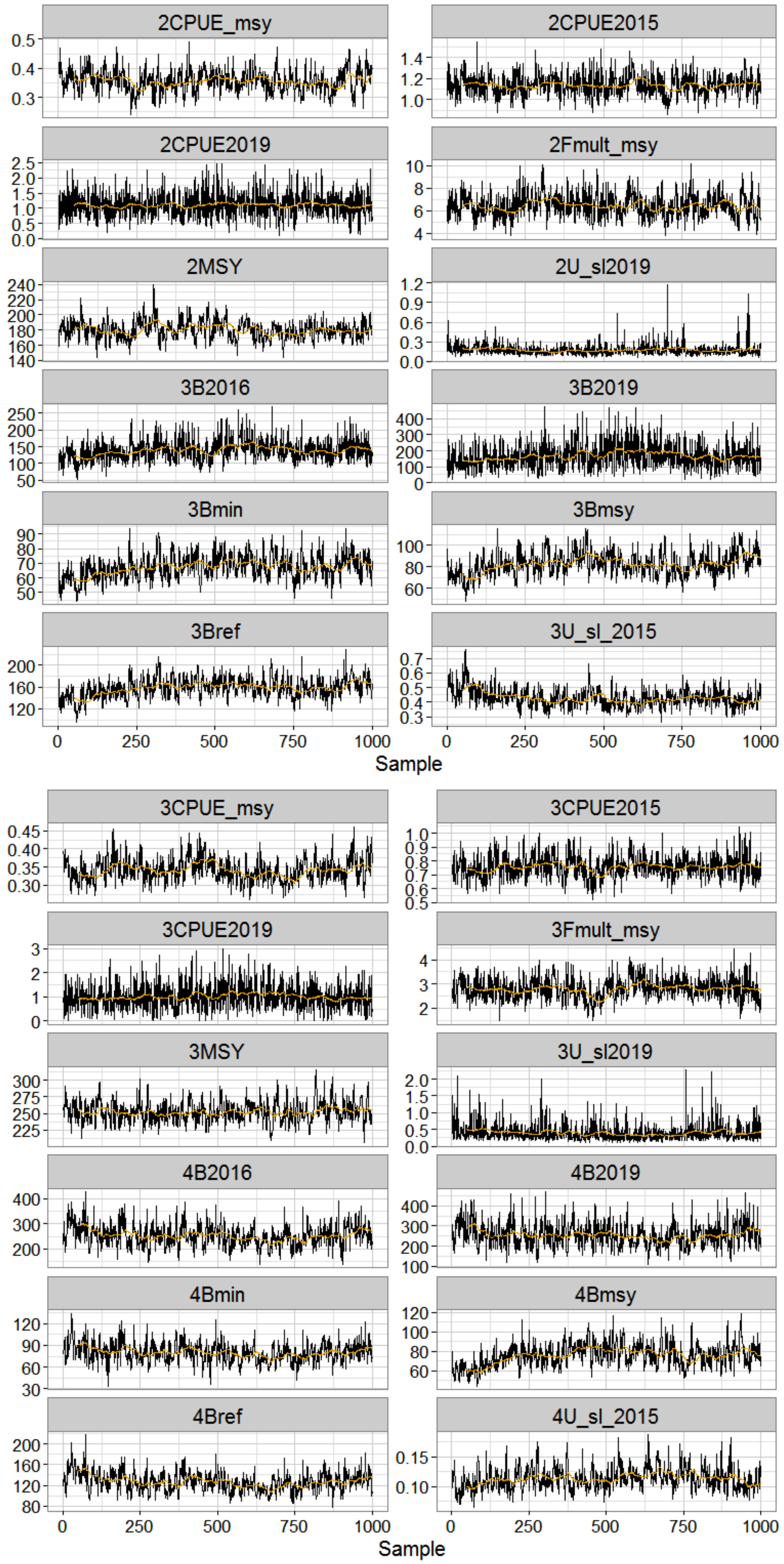


Figure 10D: MCMC trace plots of model parameters and derived quantities from the MSLM <u>spatial</u> model.

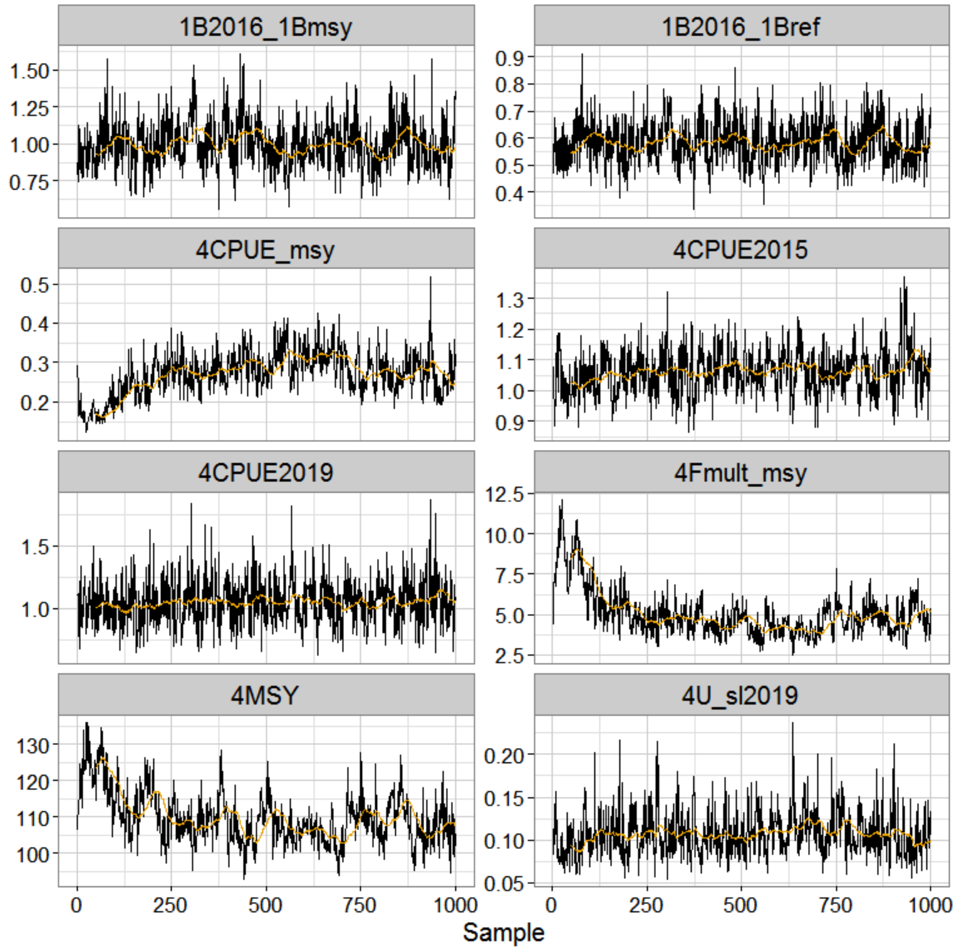


Figure 10E: MCMC trace plots of derived quantities from the MSLM spatial model.

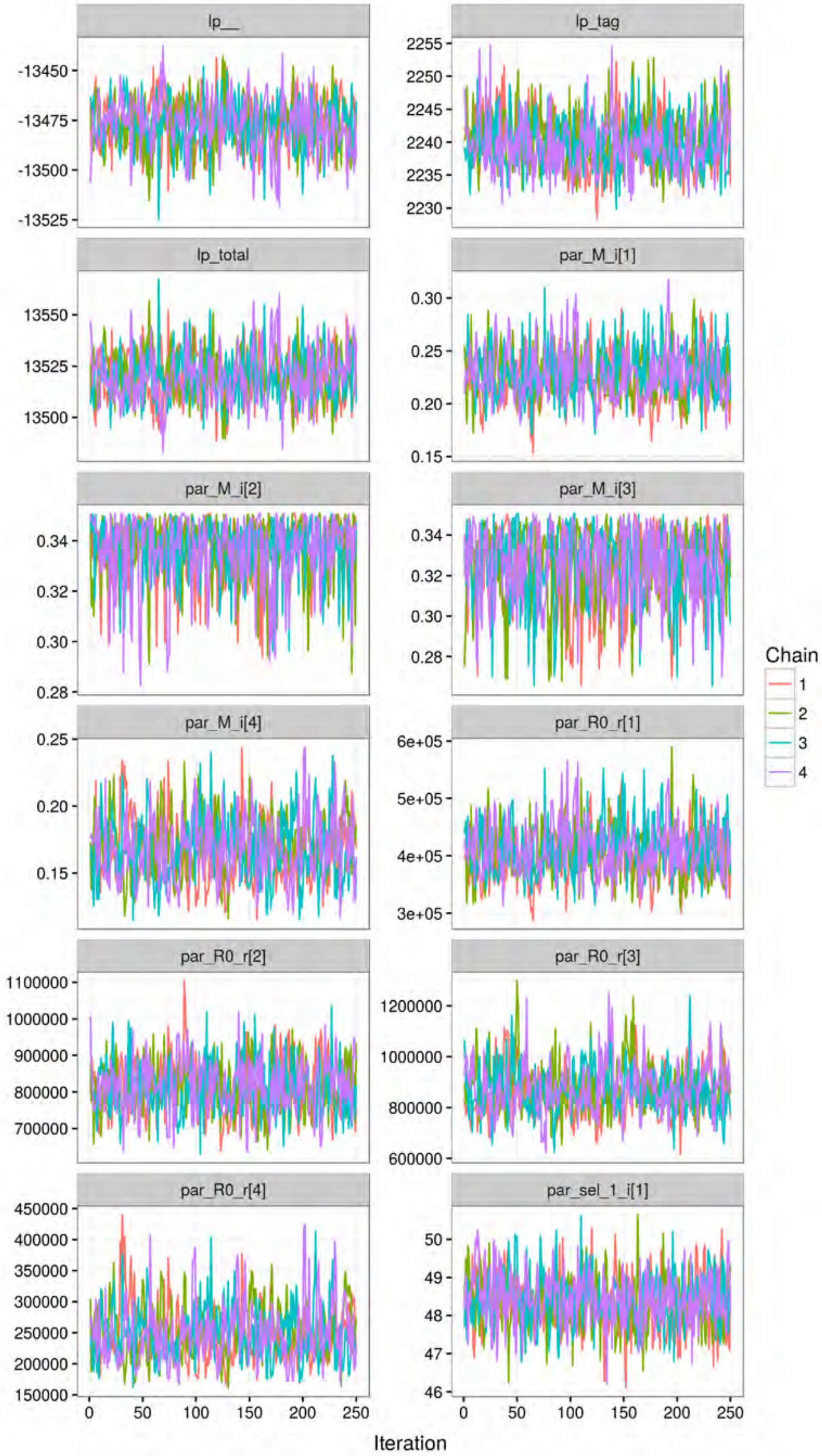


Figure 11A: MCMC trace plots of the likelihood profile (lp__) and model parameters from the LSD spatial model.

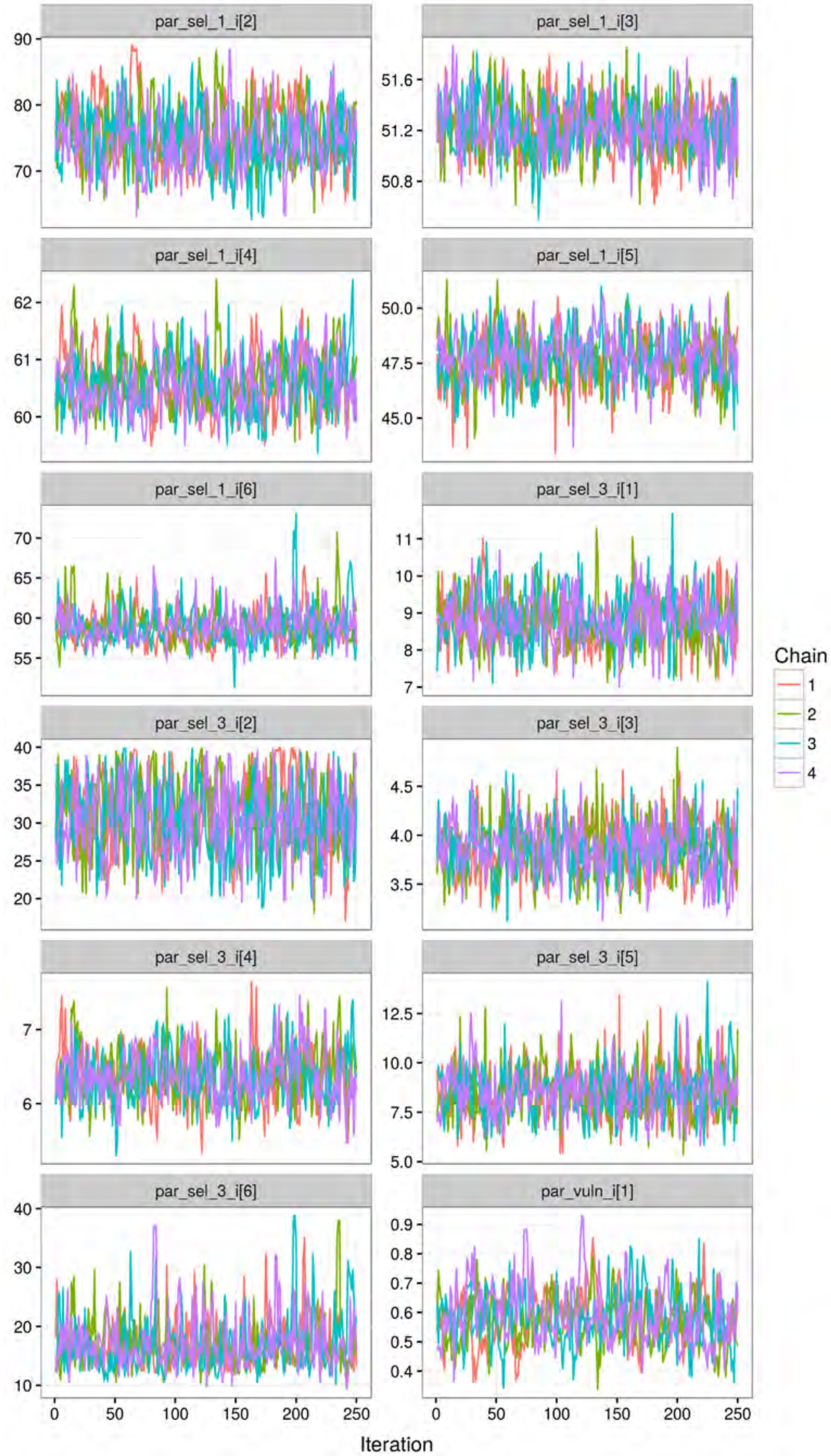


Figure 11B: MCMC trace plots of model parameters from the LSD <u>spatial</u> model.

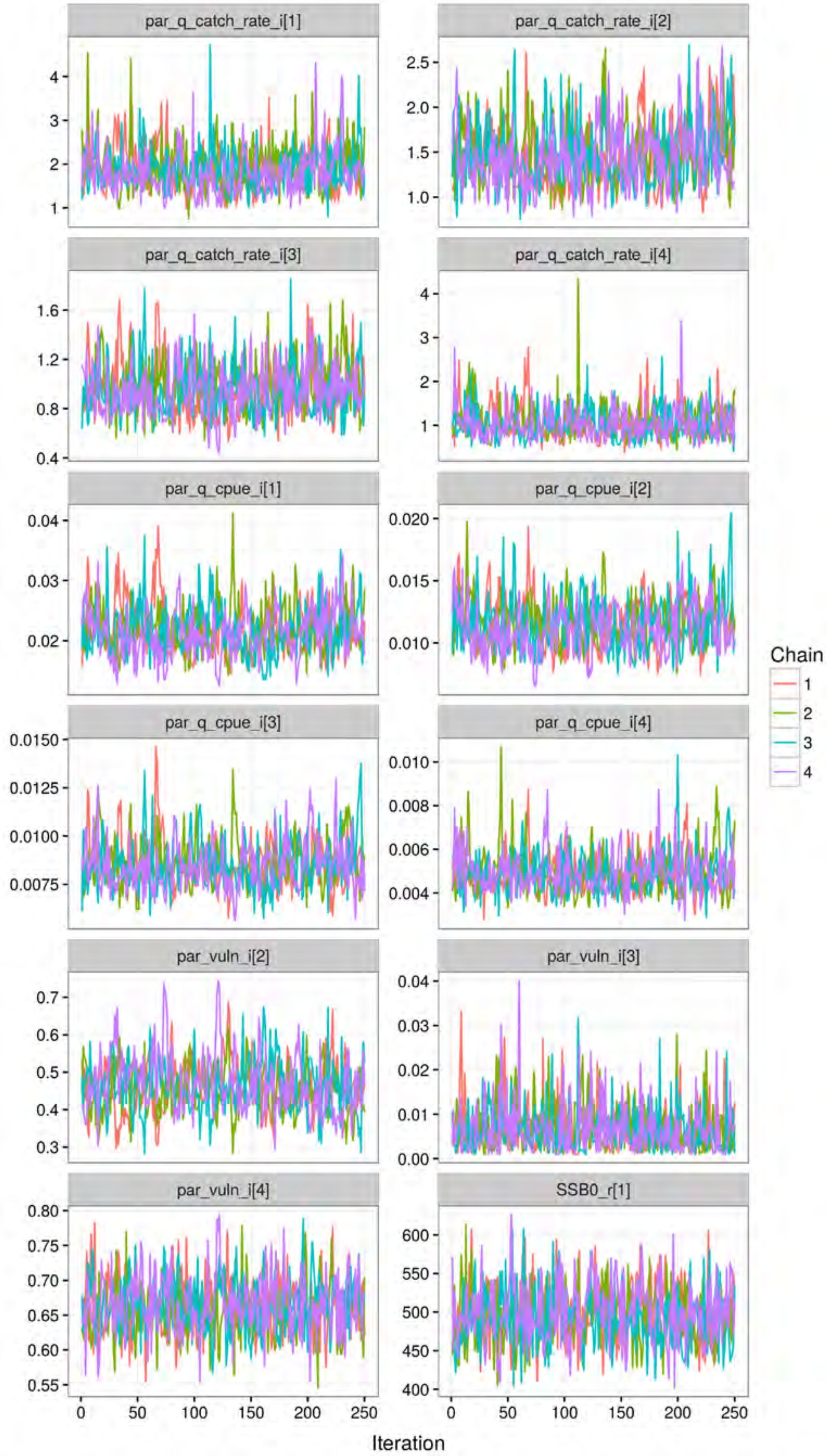


Figure 11C: MCMC trace plots of model parameters and derived quantities from the LSD <u>spatial</u> model.

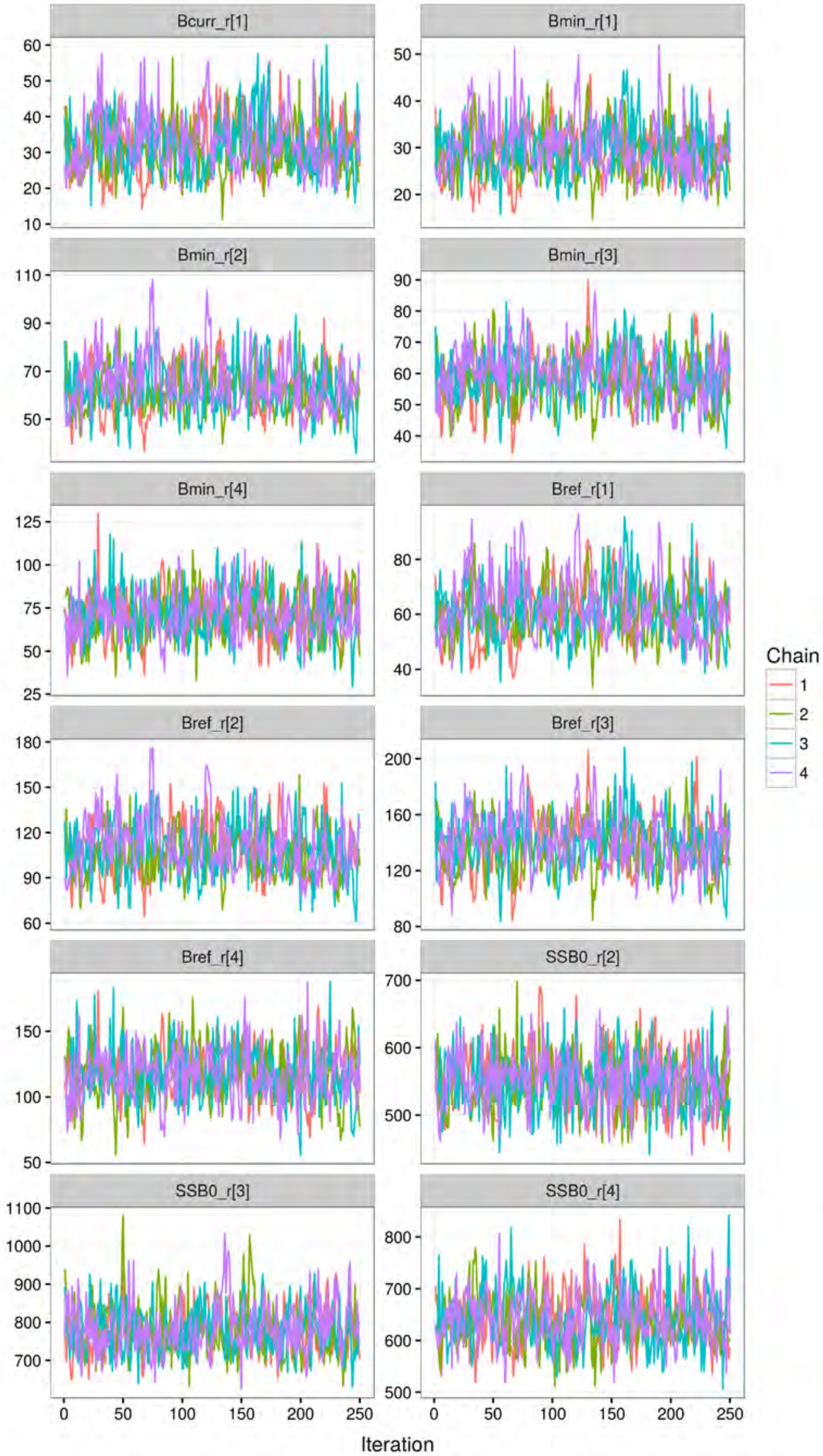


Figure 11D: MCMC trace plots of derived quantities from the LSD <u>spatial</u> model.

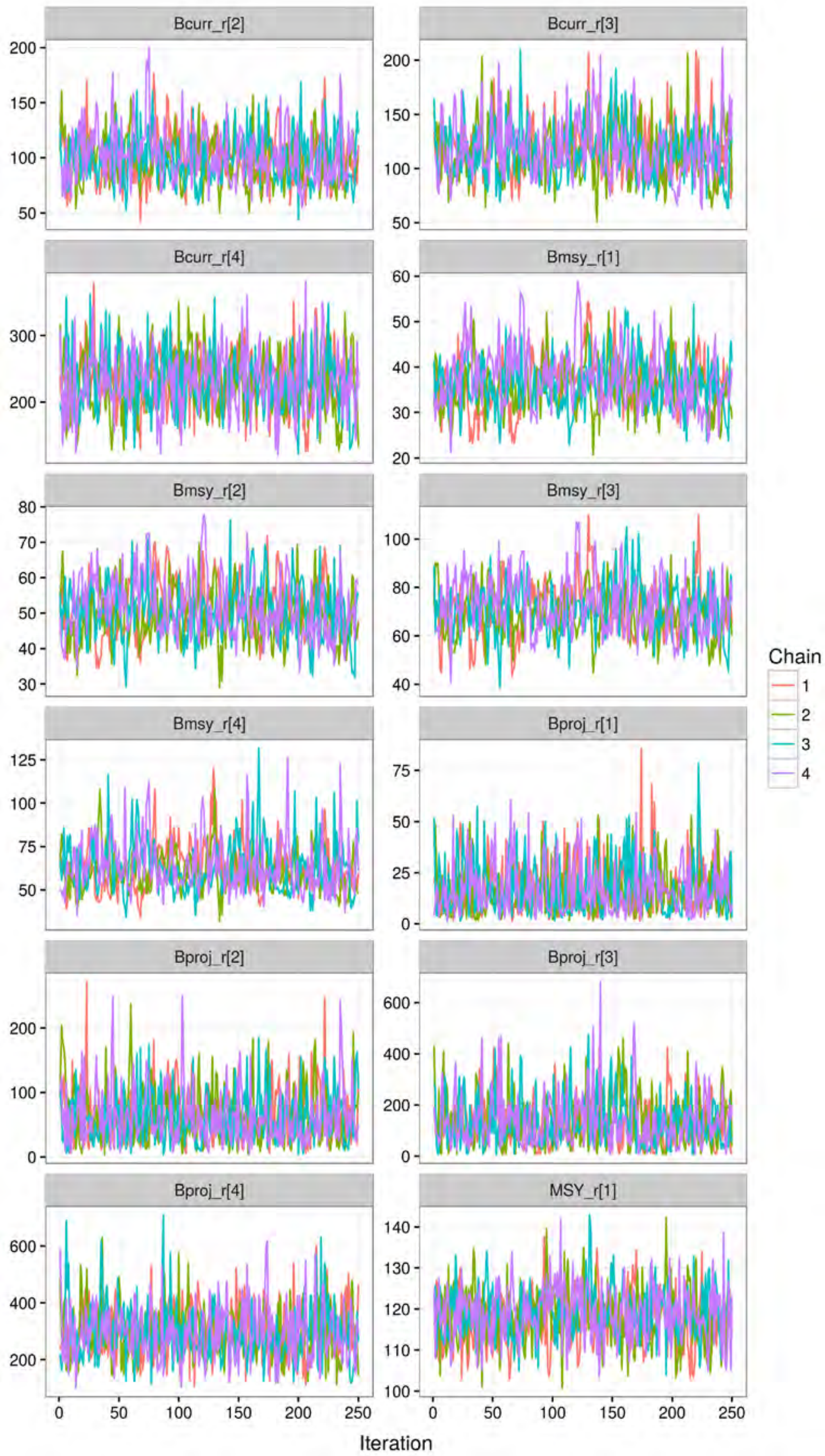


Figure 11E: MCMC trace plots of derived quantities from the LSD <u>spatial</u> model.

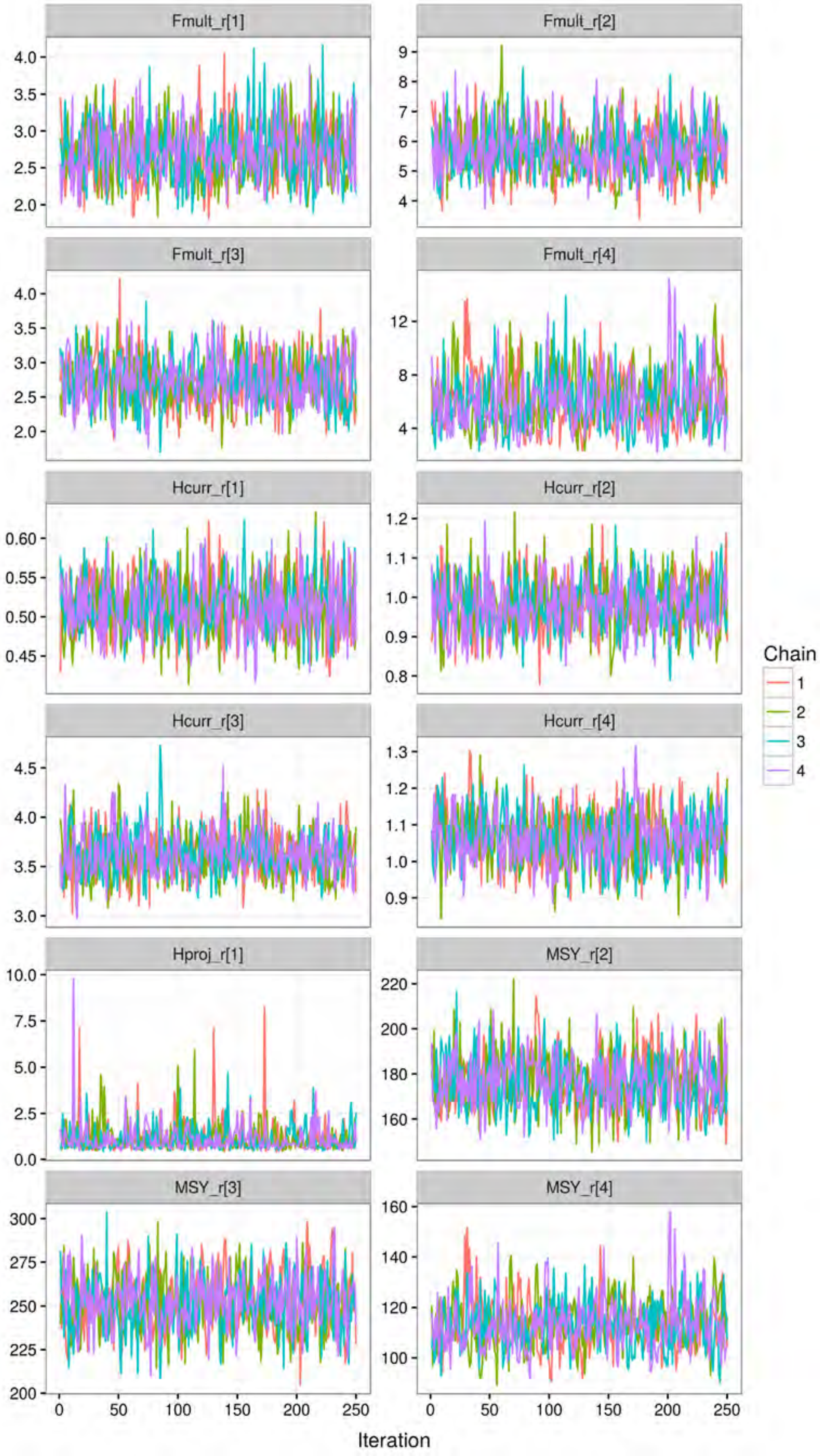


Figure 11F: MCMC trace plots of derived quantities from the LSD <u>spatial</u> model.

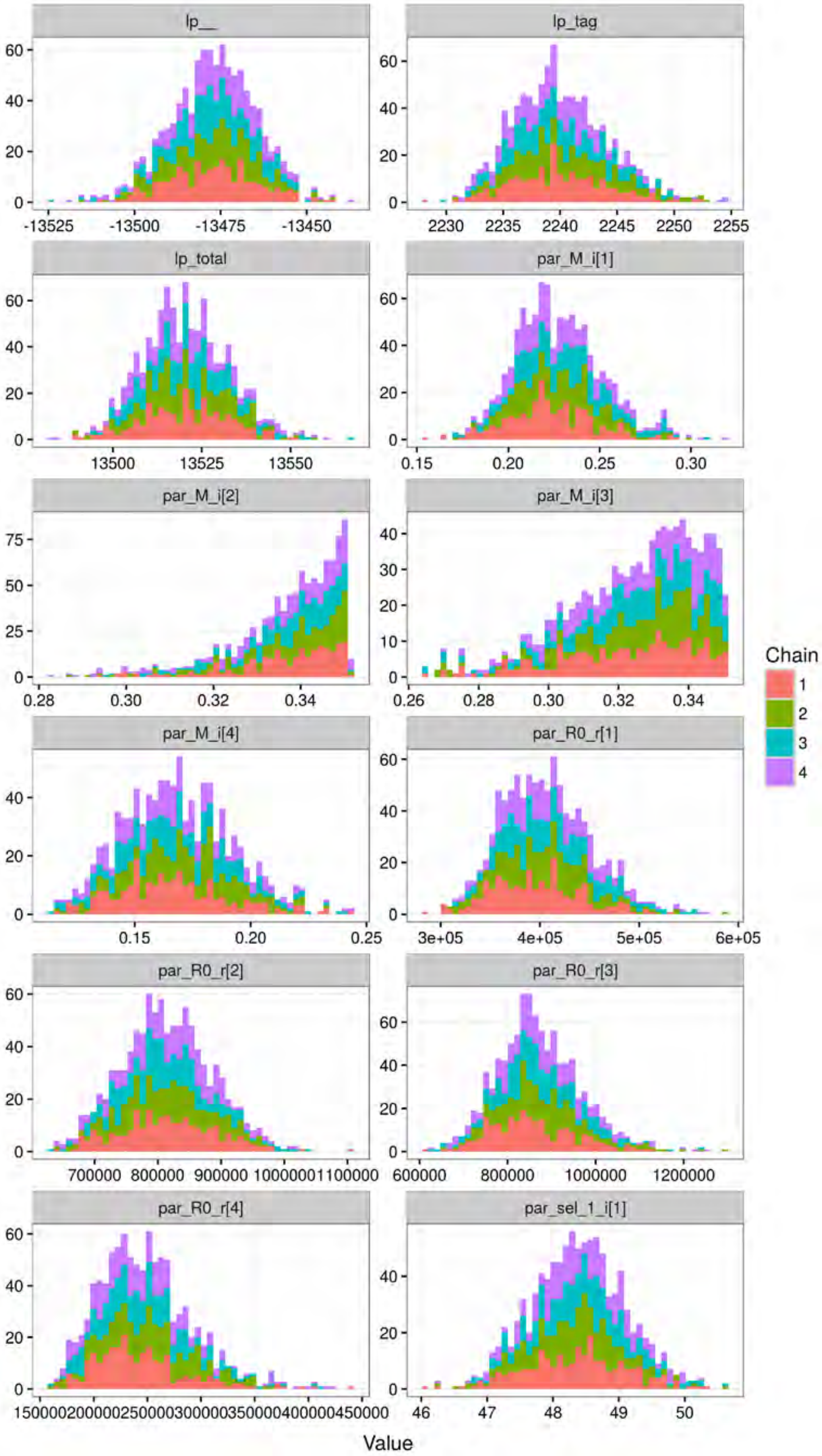


Figure 12A: MCMC histograms of the likelihood profile (lp__) and model parameters from the LSD <u>spatial</u> model.

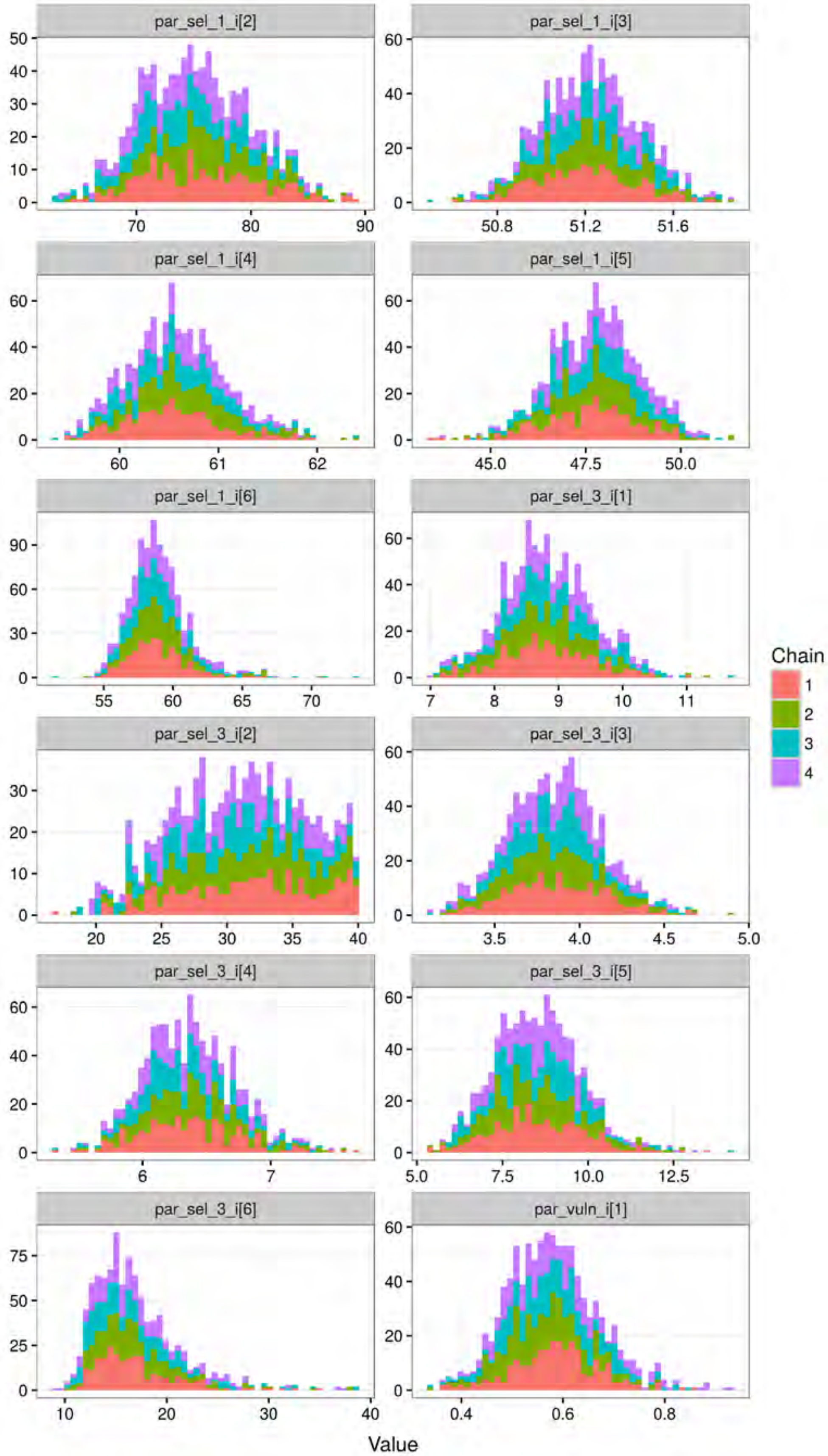


Figure 12B: MCMC histograms of model parameters from the LSD <u>spatial</u> model.

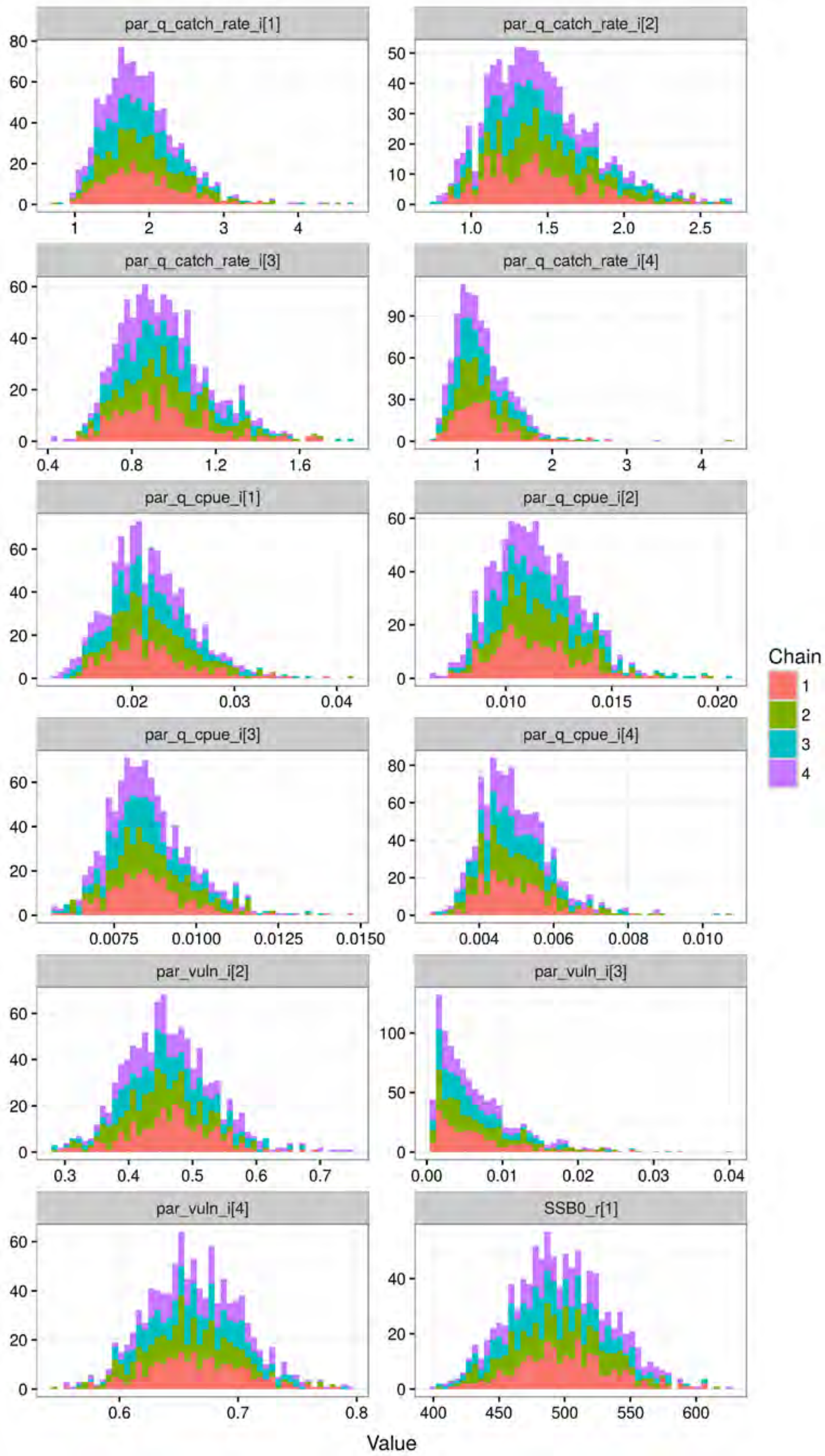


Figure 12C: MCMC histograms of model parameters and derived quantities from the LSD <u>spatial</u> model.

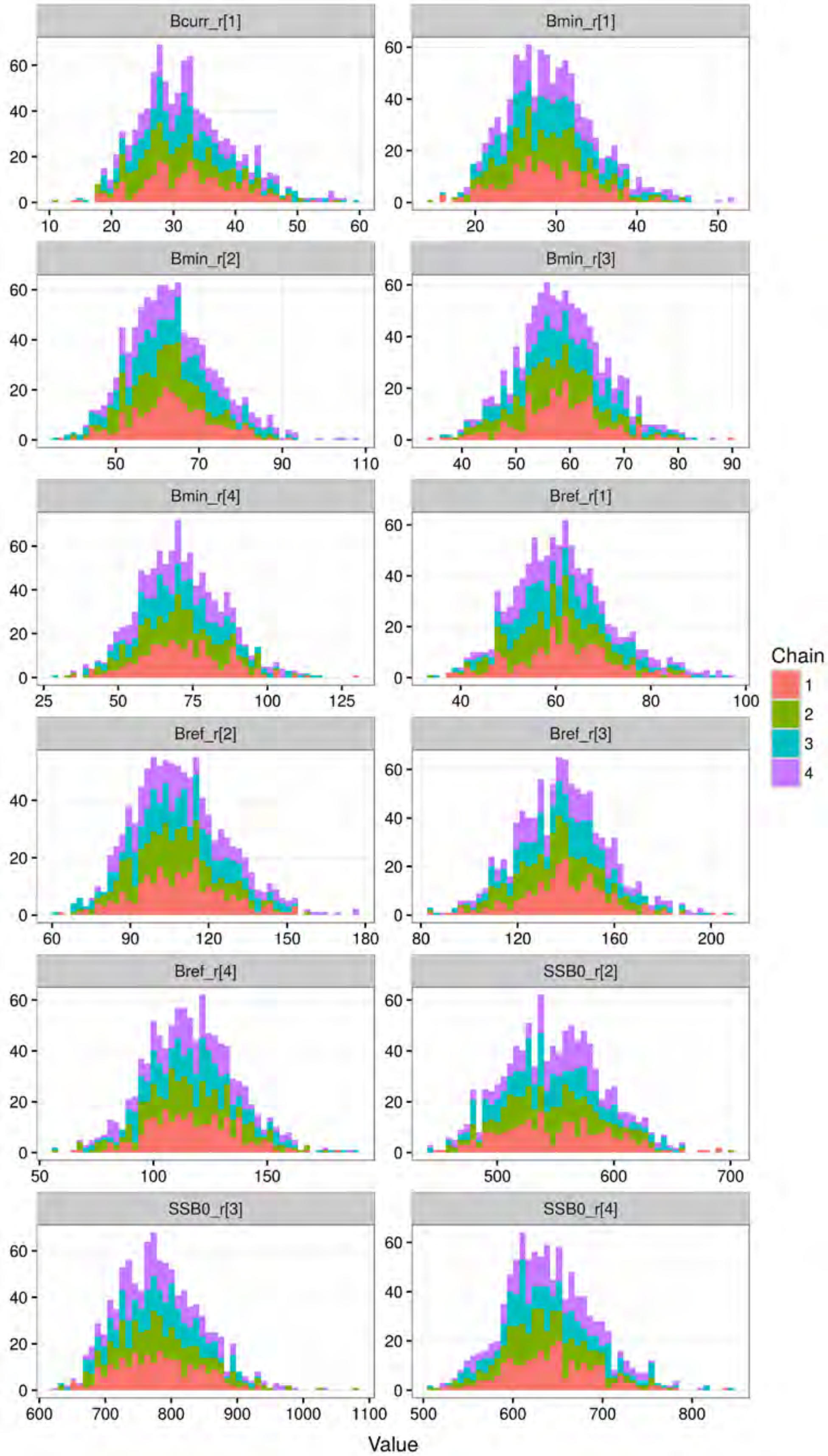


Figure 12D: MCMC histograms of derived quantities from the LSD <u>spatial</u> model.

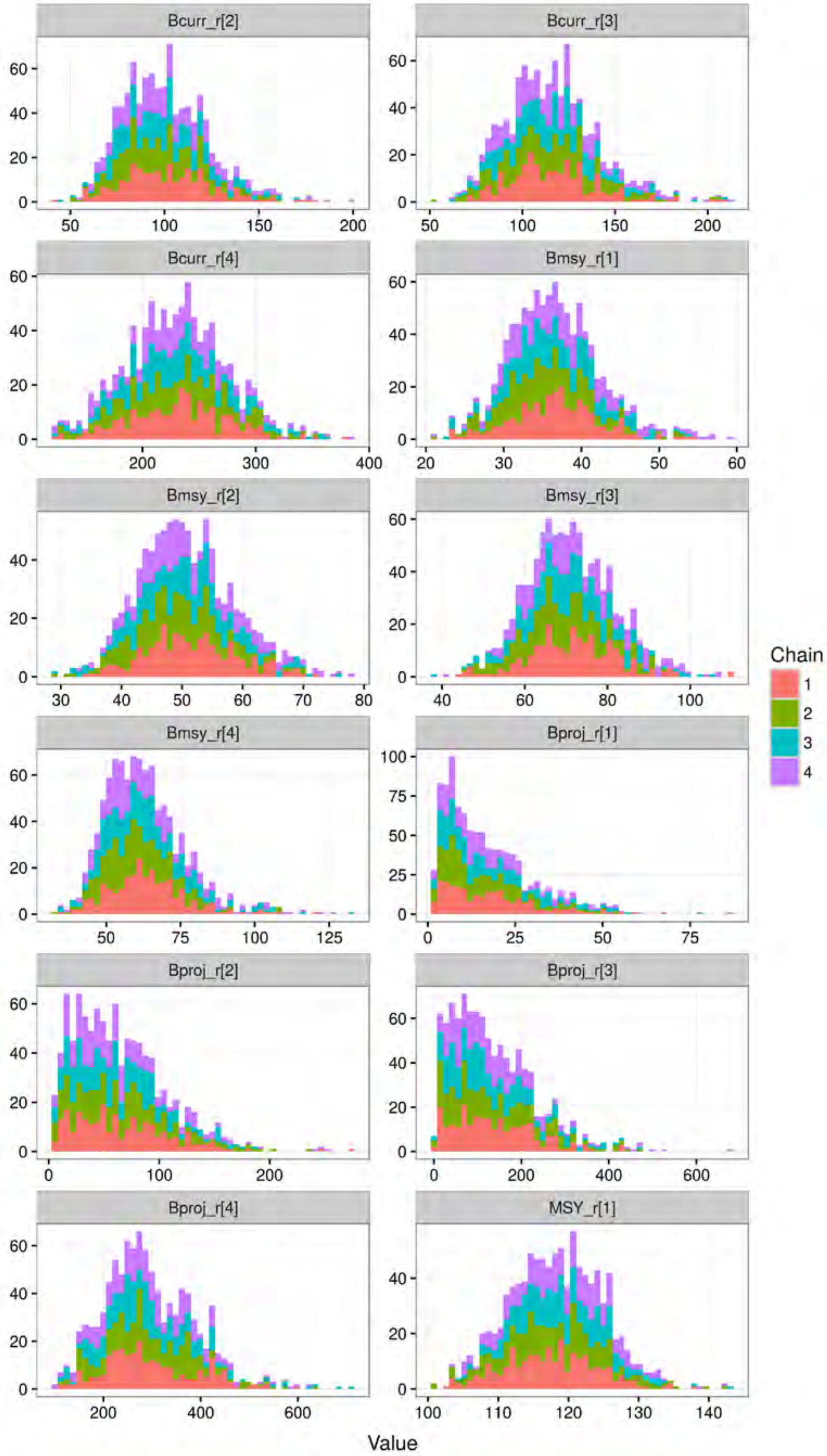


Figure 12E: MCMC histograms of derived quantities from the LSD <u>spatial</u> model.

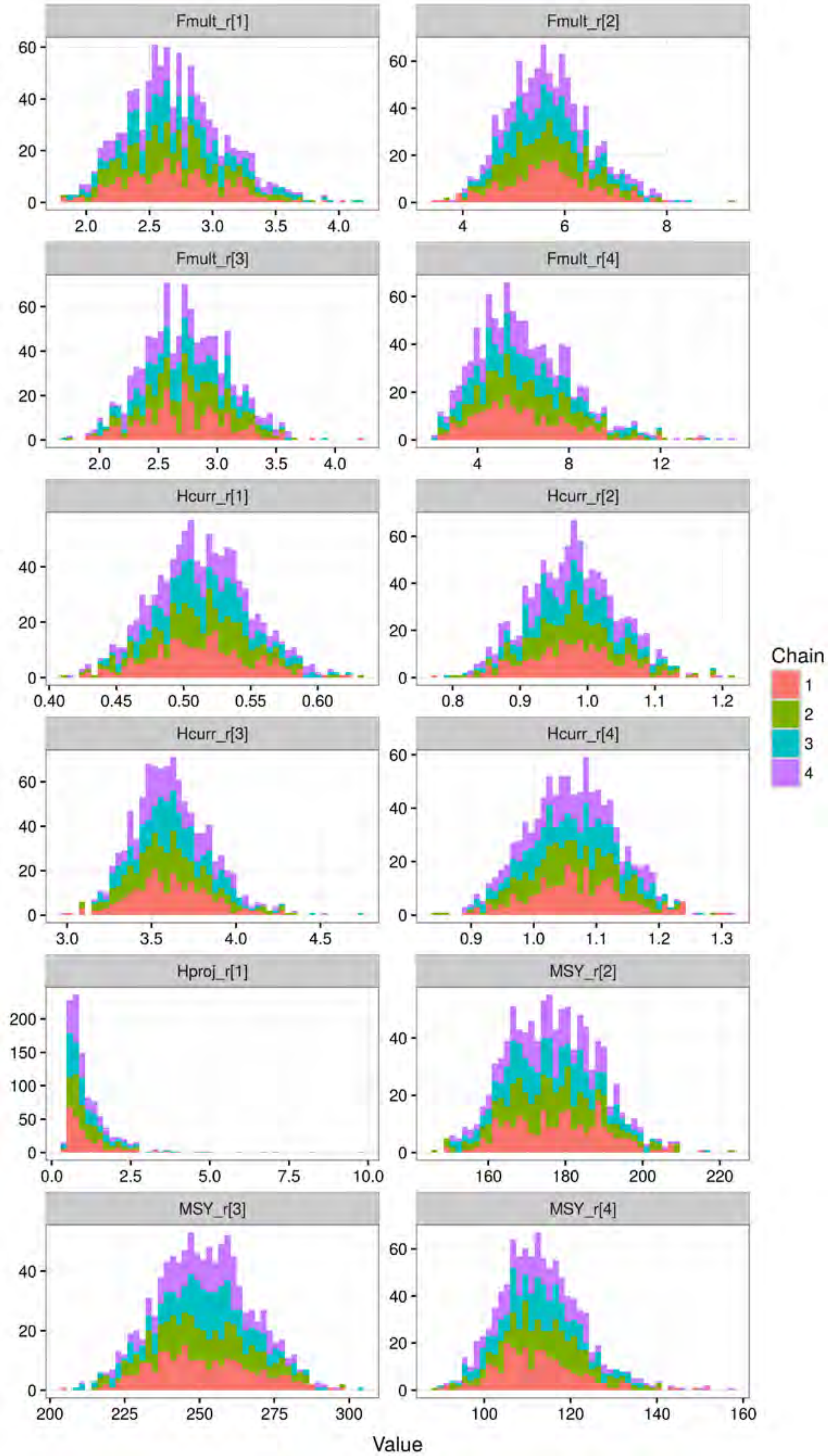


Figure 12F: MCMC histograms of derived quantities from the LSD <u>spatial</u> model.

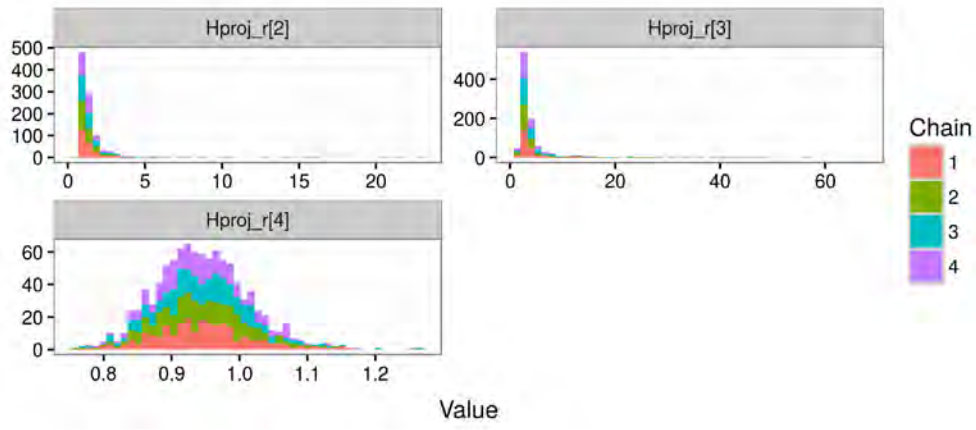


Figure 12G: MCMC histograms of derived quantities from the LSD spatial model.

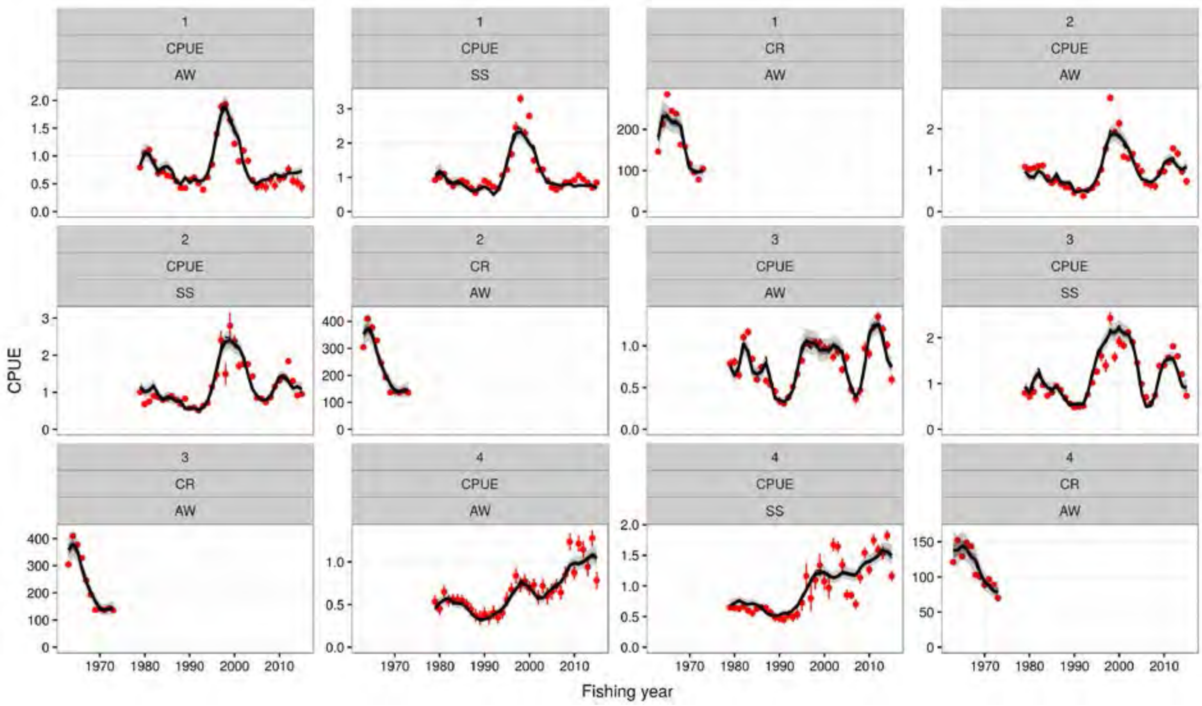


Figure 13: Posteriors of the LSD model fit to catch per unit effort (CPUE) and catch rate (CR) by area and season (AW=autumn-winter, SS=spring-summer) from the LSD spatial MCMC. The shaded areas show the 5%, 25%, 50%, 75% and 95% quantiles of the posterior; error bars about the CPUE and CR data are one standard deviation.

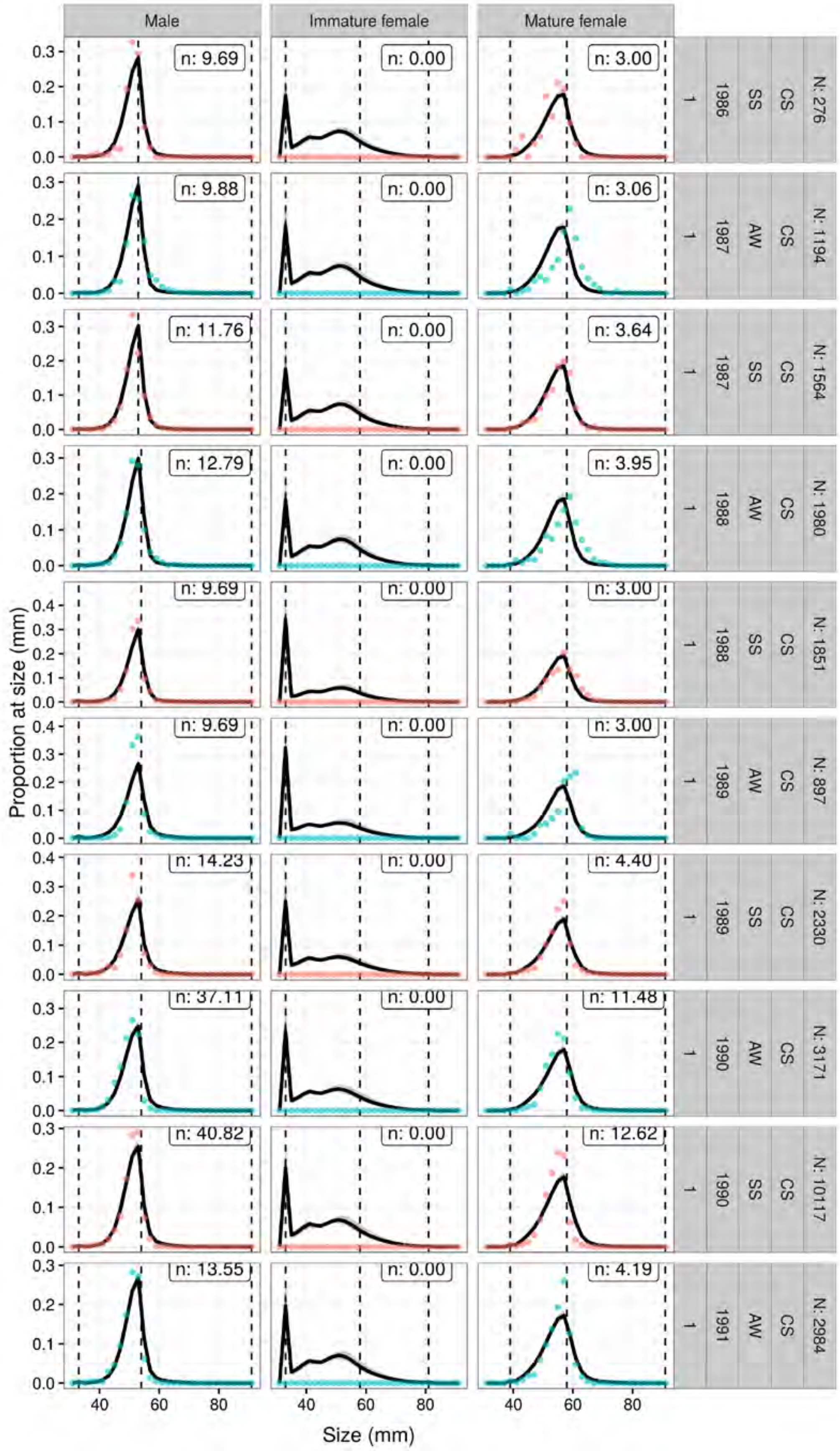


Figure 14A: Posteriors of the LSD model fit to LF data from SS 1986 to AW 1991 by area, year, season (AW=autumn-winter, SS=spring-summer), and data source (CS=catch sampling, LB=logbook) in the LSD <u>spatial</u> MCMC. The shaded areas show the 5%, 25%, 50%, 75% and 95% quantiles of the posterior (because the posterior is so tight it is often difficult to discern the shaded quantiles); the vertical dashed black lines show the lower limit of the data that is fitted in the model, the MLS, and the upper limit; the value "n" shown on each panel is the effective sample size; the value "N" is the total number of individuals measured.

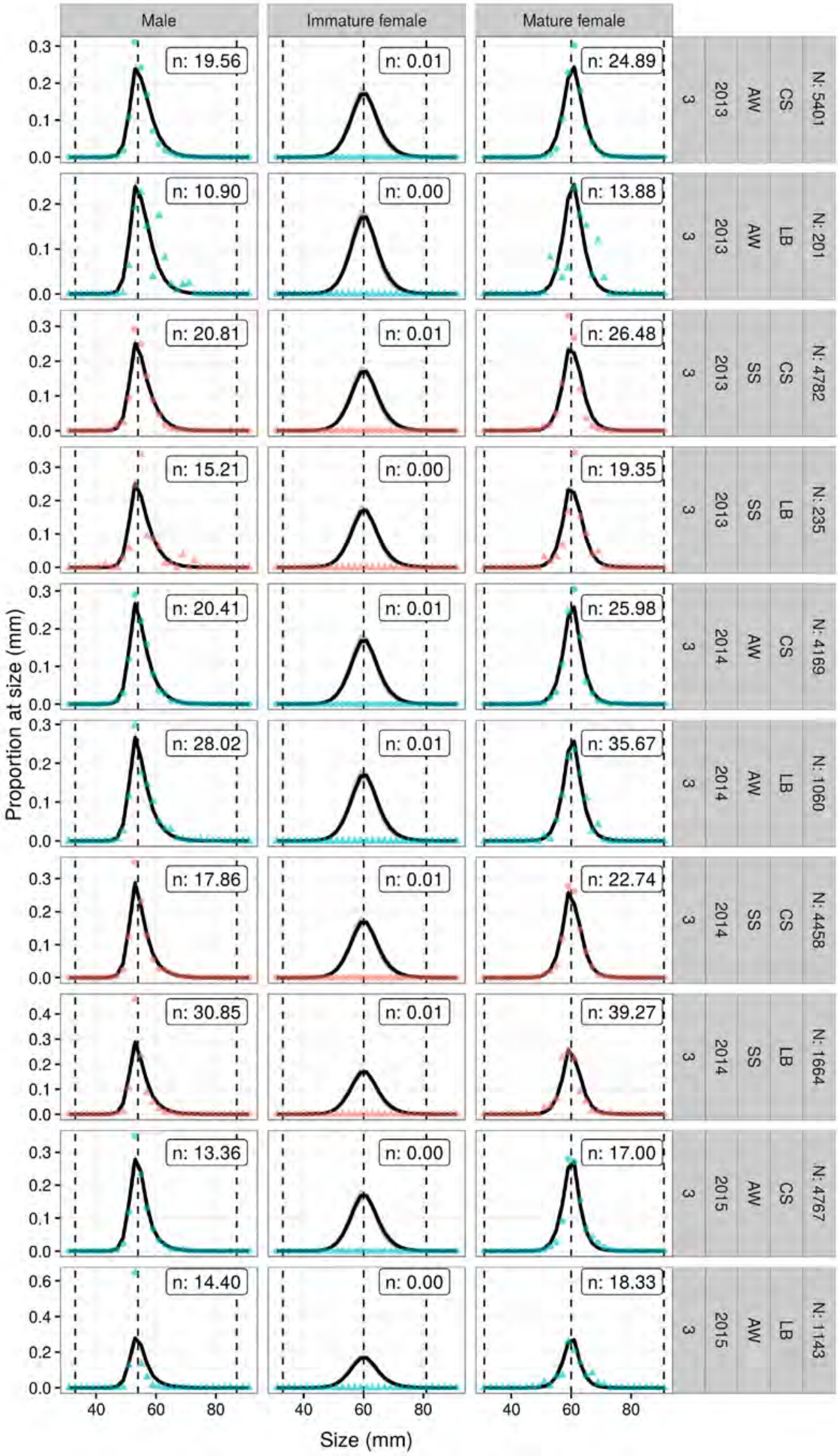


Figure 14B: Posteriors of the LSD model fit to LF data from AW 2013 to AW 2015 by area, year, season, and data source in the LSD spatial MCMC.

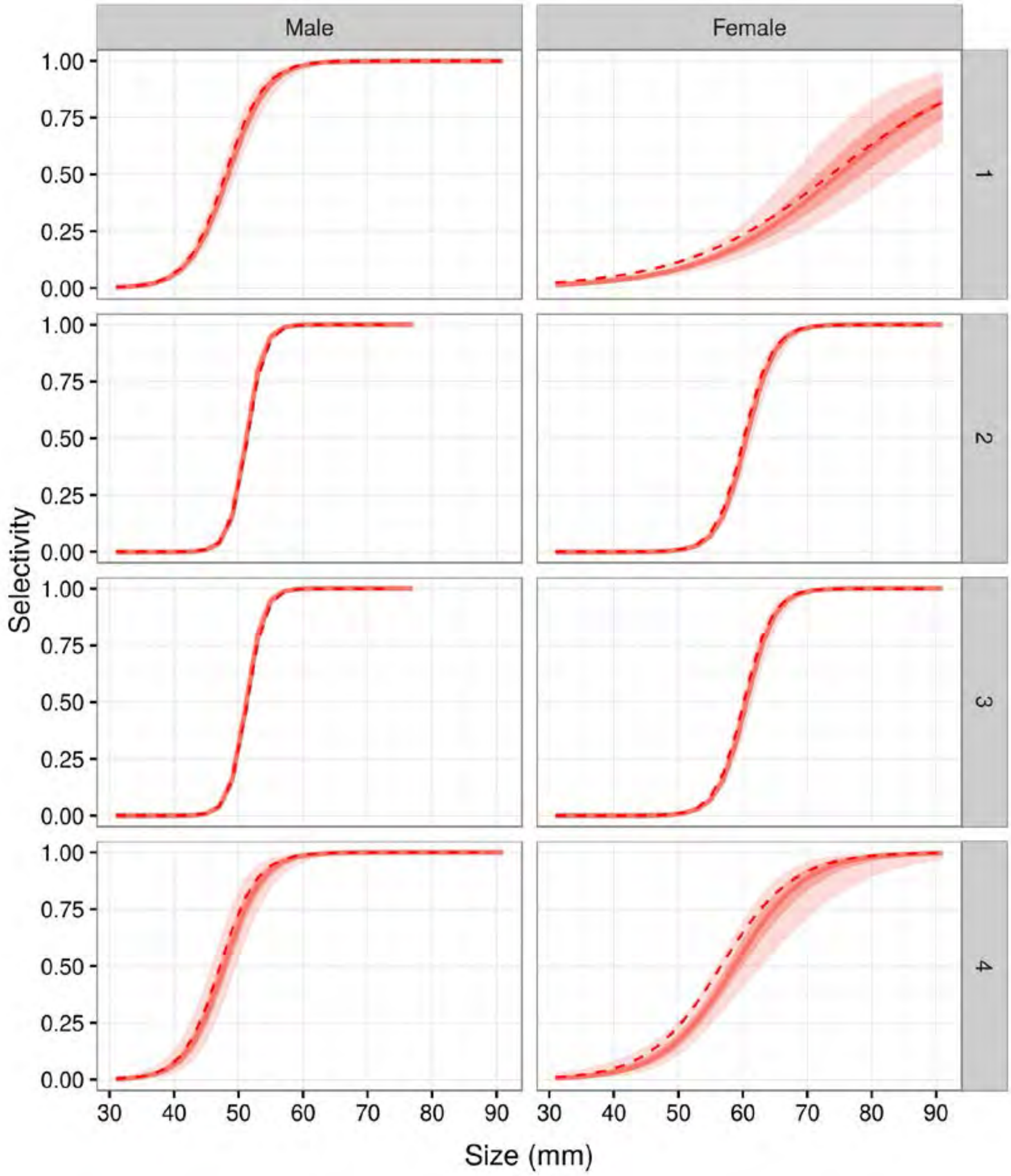


Figure 15: Posterior of the selectivity by sex and area in the LSD <u>spatial</u> MCMC. Shaded areas show the 5%, 25%, 75% and 95% quantiles of the posterior; the heavy solid line is the median of the posterior distribution; the dashed line is the MPD.

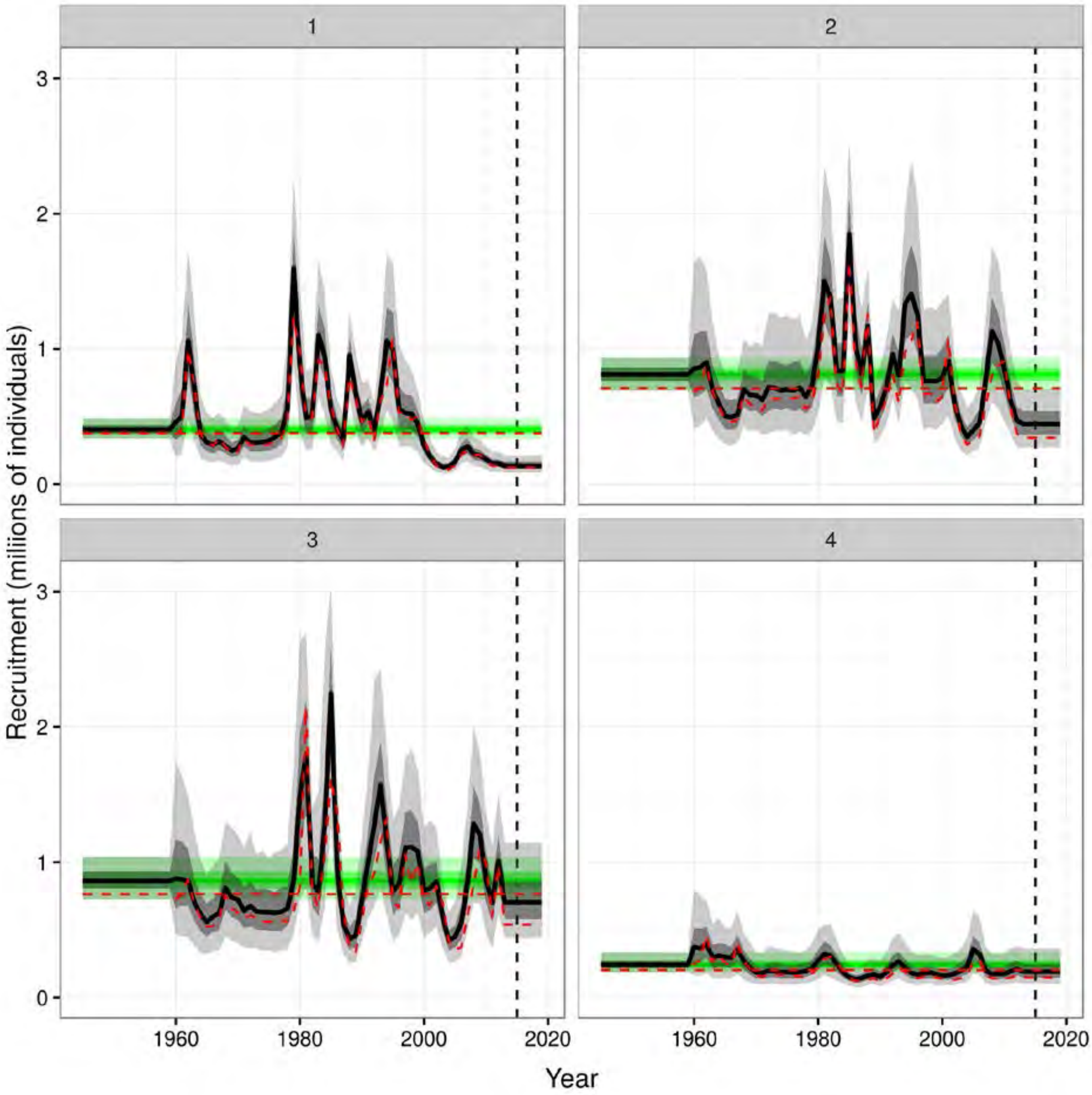


Figure 16: Posterior trajectory of recruitment (millions of individuals) to the model from 1945–2015 and projected recruits from 2016–2019 from the LSD spatial MCMC. The black shaded areas show the 5%, 25%, 50%, 75% and 95% quantiles of the recruitment posterior; the green shaded areas show the 5%, 25%, 50%, 75% and 95% quantiles of the R_0 posterior; the dashed red lines show the MPD and the MPD for R_0; the dashed vertical black line shows 2015, the final fishing year of the model reconstruction.

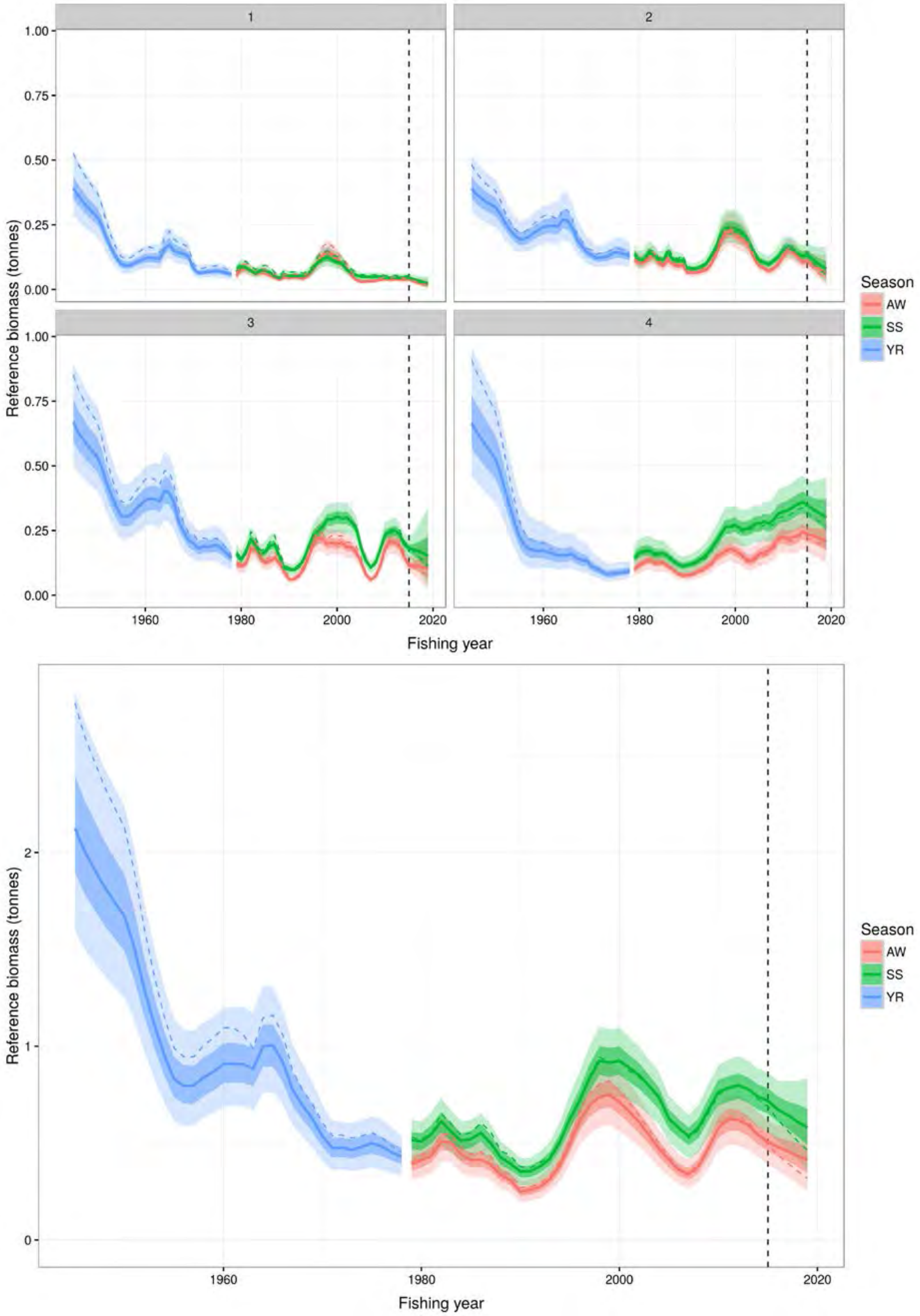


Figure 17: Vulnerable biomass trajectory from 1945–2019 by season and area [top four panels] and aggregated across all areas [bottom panel] in the LSD spatial MCMC. Shaded areas show the 90% credibility intervals; the heavy solid line is the median of the posterior distributions; the dashed line shows the MPD; the vertical line shows 2015, the final fishing year of the model reconstruction. Biomass before 1979 is annual and plotted using the YR coding.

APPENDIX A. DATA PREPARATION

A.1 INTRODUCTION

This document describes the catch and CPUE data assembled for use in the 2016 CRA 4 multi-area rock lobster (*Jasus edwardsii*) stock assessments, defined by individual statistical areas (see Table A.1 below). It also describes the biological length frequency and tagging data assembled for the same multi-area model.

Table A.1: Sub-stock definitions for CRA 4 multi-area stock assessment, showing the rock lobster statistical area definitions used.

Sub-stock name	Statistical area definition
912	Area 912
913	Area 913
914	Area 914
915+934	Area 915 + Area 934

A.2 PREPARATION OF THE CATCH INFORMATION

The preparation of catch data for each of the CRA 4 multi-area sub-stocks was hampered by inconsistent data availability, depending on the period (Table A.2). Reporting from the modern rock lobster statistical areas was not available until 1979, but the fishery was well developed by then, with significant catches taken from at least 1945. Historical catches were available by sub-area from 1963–1973, but the sub-area definitions used by Annala & King (1983) (Figure A.1) differed substantially from the rock lobster statistical area definitions used from 1979 onward (Figure A.2). There were also two periods (1945–1962 and 1974–1978) where sub-area catches were not available (Table A.2).

Table A.2: Data availability by time period for CRA 4 multi-area stock assessment. FSU: fisheries statistics unit; QMR: quota management reports; MHR: monthly harvest returns; CELR: catch/effort landing returns. See Bentley et al. (2005) for more information on the historical data sources by year.

Period	CRA 4 (QMA) data availability	CRA 4 (sub-area) data availability
1945–1962	estimates based on port of landing	not available
1963–1973	Annala & King (1983)	Annala & King (1983) area definitions
1974–1978	estimates based on Annala & King (1983)	not available
1979–1985	FSU estimates	FSU area definitions
1986–1988	QMR estimates	FSU area definitions
1989–2000	QMR estimates	CELR (=FSU) area definitions
2001–2015	MHR estimates	CELR (=FSU) area definitions

An algorithm (Section A.2.1) was developed to convert the Annala & King (1983) sub-areas into approximate FSU/CELR statistical area definitions, using the statistical area mapping definitions described in Table A.3 and averaging the observed distributions of catch by sub-area over the first decade of reliable reporting.

Table A.3: Selected mapping of Annala/King statistical areas into the NZ rock lobster statistical areas. CRA 4 statistical areas are marked with *.

Rock lobster	Annala/King statistical area		
statistical area	Area 6	Area 7	Area 8
911	x		
912*	x		
913*		x	
914*		x	
915*			x
916			x
933			x
934*			x

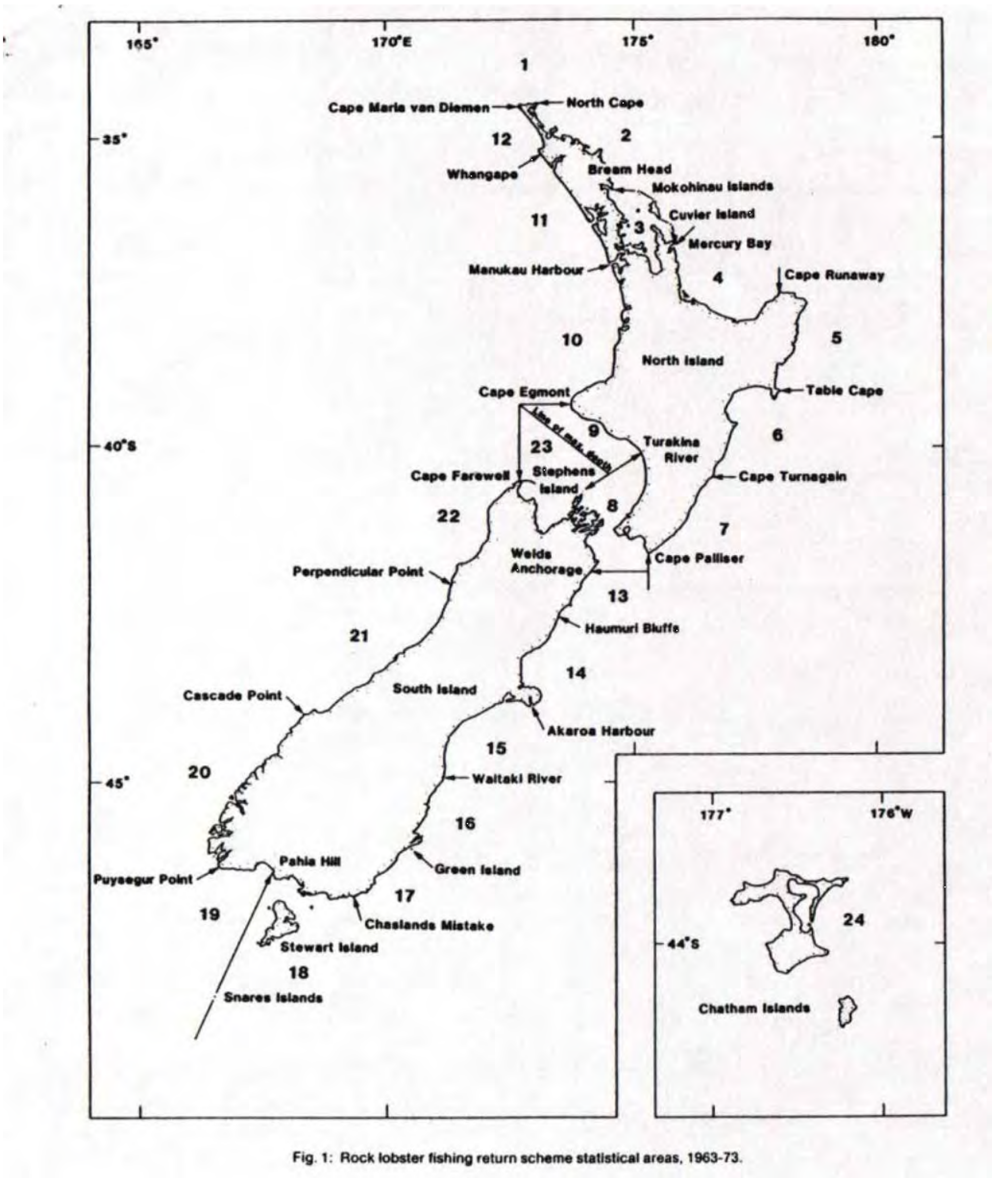


Figure A.1: Map showing Annala & King statistical areas (from Annala & King (1983).

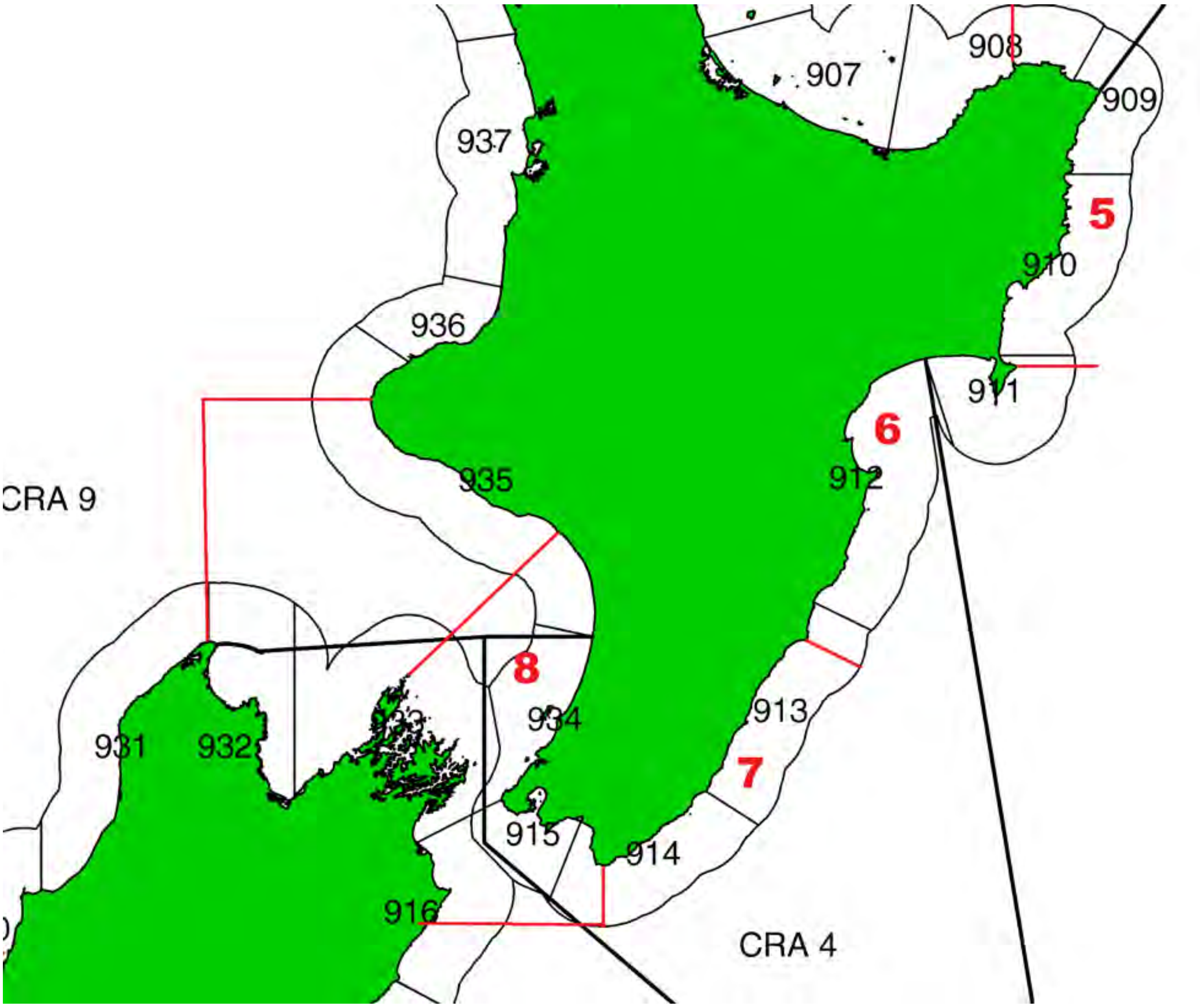


Figure A.2: Cropped map of NZ rock lobster statistical areas showing approximate location of the Annala/King statistical areas (labelled in red with red boundary lines).

A.2.1 ALGORITHM USED TO ESTIMATE CATCHES IN ROCK LOBSTER STATISTICAL AREAS BEFORE 1979:

The following algorithm was followed to apportion catches to the defined CRA 4 multi-area sub-stocks, based on distributions available when reporting was more accurate:

1. Starting from FSU (in place for rock lobster from January 1979 to June 1988) data set, sum reported catches by statistical area from 1979–80 to year Y (initially set at 1988–89):

$$C^a = \sum_{y=1979}^{Y} c_y^a$$ where *a* is one of the rock lobster statistical areas in Table A.3

2. Calculate the relative proportion of each contributing rock lobster statistical areas among the three Annala/King groupings identified in Table A.3:

$$P^a = C^a \Big/ \sum_{a=1}^{N^A} C_a$$ where N^A is the number of rock lobster statistical areas in Annala/King area *A*. See Table A.1 for these calculations.

3. By year, calculate the contribution of the five CRA 4 statistical areas based on the proportions estimated in step 2:

$k_y^a = P^a * K_y^A$ where K_y^A is the Annala/King catch in area *A* in year *y* (*y*=1963–1973).

Note: only used method codes 8 or 19 in the Annala/King data (these are the potting method)

4. Sum the five contributing CRA 4 statistical areas to get a total CRA 4 estimated catch in each year and divide to get the relative proportion of each CRA 4 statistical area in year *y*:

$pk_y^a = k_y^a \Big/ \sum_{a=1}^{5} k_y^a$ where *a* is 912, 913, 914, 915 or 934 in year *y* (*y*=1963–1973). See columns 2 to 5 in Table A.2 for these proportions. Column 6 in Table A.2 is the sum of catches from the 5 rock lobster statistical areas calculated in this manner.

5. Multiply the resulting proportions by the historical CRA 4 catch in year *y* to get the scaled statistical area catch from 1963 to 1973:

$c_y^a = pk_y^a * C_y^{\mathrm{CRA4}}$ where C_y^{CRA4} is the catch value used in the combined CRA 4 stock assessment.

This step is required because the summed k_y^a is greater than the values stored in CRACE (Bentley et al. 2005) for CRA 4 (which have been used by default in every rock lobster stock assessment; compare columns 6 and 7 in Table A.2).

6. Values for pk_y^a from 1974 to 1978 were obtained by interpolating between pk_{1973}^a and pk_{1979}^a (see Table A.3) and then applying the equation in step 5 to the appropriate value of C_y^{CRA4}.

7. Values for pk_y^a before 1963 were obtained by averaging $\sum_{y=1963}^{y=1973} pk_y^a \Big/ 11$ (see final row in Table A.2) and then applying the equation in step 5 to the appropriate value of C_y^{CRA4}.

8. The pk_y^a proportions derived in Steps 4, 6 and 7 were used to allocate the CRA 4 non-commercial catches by statistical area and year in the years before 1979. Proportions based on the reported commercial catches by fishing year from the FSU and CELR systems were used to allocate the non-commercial catches to statistical areas from 1979 onward. The commercial catch distributions were based on the B4_L algorithm (see Starr 2016).

The time series of estimated catches by category of capture are presented by CRA 4 sub-stock in Figure A.3 and in Table A.4 (Area 912), Table A.5 (Area 913), Table A.6 (Area 914) and Table A.7 (Area 915+934). Note that the procedure estimates relatively higher catches in the south coast near Wellington (Area 915+934) early in the time period relative to the catches in the other three stocks. CPUE trajectories differed among the four sub-stocks, with Area 914 and Area 915+934 not showing the strong CPUE peak in the late 1990s that was observed in the more northerly sub-stocks (Figure A.4). On the other hand, Area 912 does not show the CPUE peak around 2010 that is present in the other more southerly sub-stocks.

All four sub-stocks show a similar distribution of AW commercial catch (Figure A.5), and these seasonal distributions are used to allocate the commercial and illegal catches to the AW and SS seasons for each of the sub-stocks. Arbitrary seasonal distributions of 0.10 (AW) and 0.90 (SS), consistent with the assumptions used in all rock lobster stock assessments, allocate recreational and customary catches to a season. These seasonal proportions are then used to allocate catches from 1979 onwards into two categories: SL (size limited: the sum of commercial and recreational catches) and NSL (not size limited: the sum of illegal and customary catches) (Figure A.6, Table A.4 to Table A.7). These are the catch distributions that are used to model each CRA 4 sub-stock.

Table A.1: Percent distribution between adjacent rock lobster statistical areas in the Annala/King area groupings identified in Table A.3.

Fishing	Area 6		Area 7		Area 8			
Year	911	912	913	914	915	916	933	934
1979	60.7	39.3	44.2	55.8	25.4	53.5	20.9	0.2
1980	54.6	45.4	39.3	60.7	25.5	50.7	23.4	0.3
1981	46.0	54.0	43.5	56.5	29.1	41.7	29.2	0.0
1982	51.1	48.9	36.7	63.3	34.6	34.2	31.0	0.2
1983	59.3	40.8	41.0	59.0	34.3	34.2	31.1	0.4
1984	57.7	42.3	41.0	59.0	29.3	41.0	28.6	1.2
1985	55.0	45.0	36.7	63.3	35.9	40.5	22.5	1.1
1986	49.5	50.5	44.0	56.0	41.0	38.7	19.4	0.9
1987	39.2	60.8	36.1	63.9	40.2	42.1	17.6	0.0
1988	47.4	52.6	37.3	62.7	42.5	38.0	19.6	0.0
Mean	52.6	47.4	39.7	60.3	33.6	40.9	25.0	0.5

Table A.2: Proportions by CRA 4 sub-stock (statistical area) as calculated in Step 4 (above). The final two columns are the sums of annual catch defined in Steps 4 and 5 (above).

Calendar	Stock/statistical area				$\sum_{a=1}^{5} k_y^a$	C_y^{CRA4}
year	912	913	914	915+934		
1963	0.265	0.124	0.189	0.422	500.2	310.3
1964	0.259	0.177	0.269	0.295	757.1	459.9
1965	0.297	0.196	0.297	0.211	938.1	581.4
1966	0.195	0.225	0.341	0.239	1162.3	663.5
1967	0.197	0.210	0.318	0.274	892.2	512.6
1968	0.195	0.219	0.332	0.255	891.3	509.6
1969	0.281	0.173	0.262	0.284	982.8	606.7
1970	0.204	0.222	0.337	0.238	972.2	559.0
1971	0.159	0.222	0.337	0.281	754.1	419.3
1972	0.168	0.229	0.347	0.255	763.3	426.3
1973	0.186	0.236	0.359	0.219	661.9	373.8
Mean	0.219	0.203	0.308	0.270	–	–

Table A.3: Interpolated proportions by CRA 4 sub-stock (statistical area) as described in Step 6 (above).

Calendar	Stock/statistical area			
Year	912	913	914	915+934
1973	0.186	0.236	0.359	0.219
1974	0.191	0.247	0.362	0.199
1975	0.195	0.258	0.366	0.180
1976	0.200	0.269	0.370	0.160
1977	0.205	0.280	0.374	0.141
1978	0.209	0.291	0.378	0.122
1979	0.214	0.302	0.382	0.102

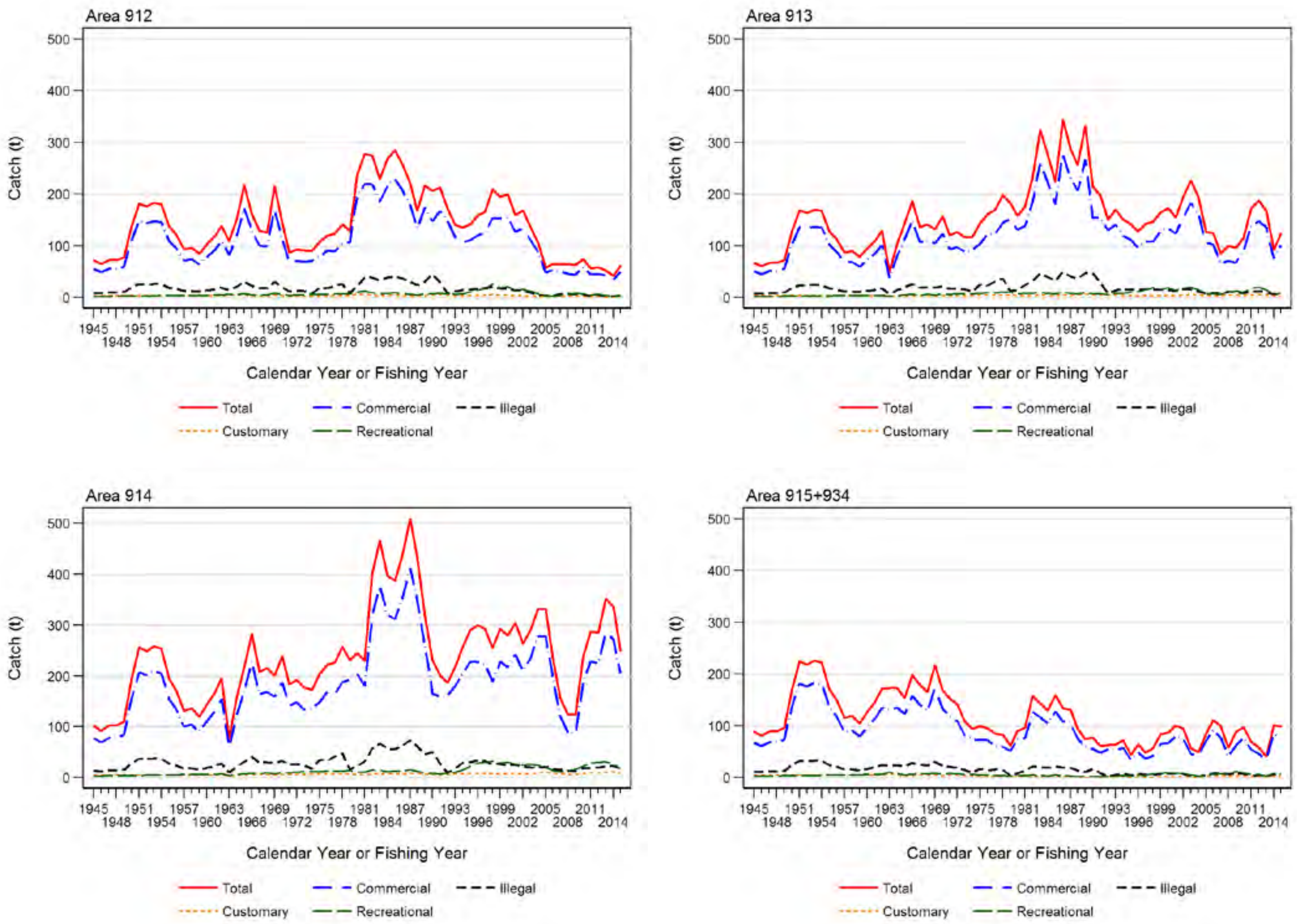


Figure A.3: Commercial, recreational, illegal and customary catch trajectories for four CRA 4 multi-area sub-stocks defined by rock lobster statistical areas (Table A.1). Year codes are annual before 1978 and from 1979 onward refer to the first year in the statutory 1 April-31 March fishing year. Catches from January–March 1979 have been added to 1978.

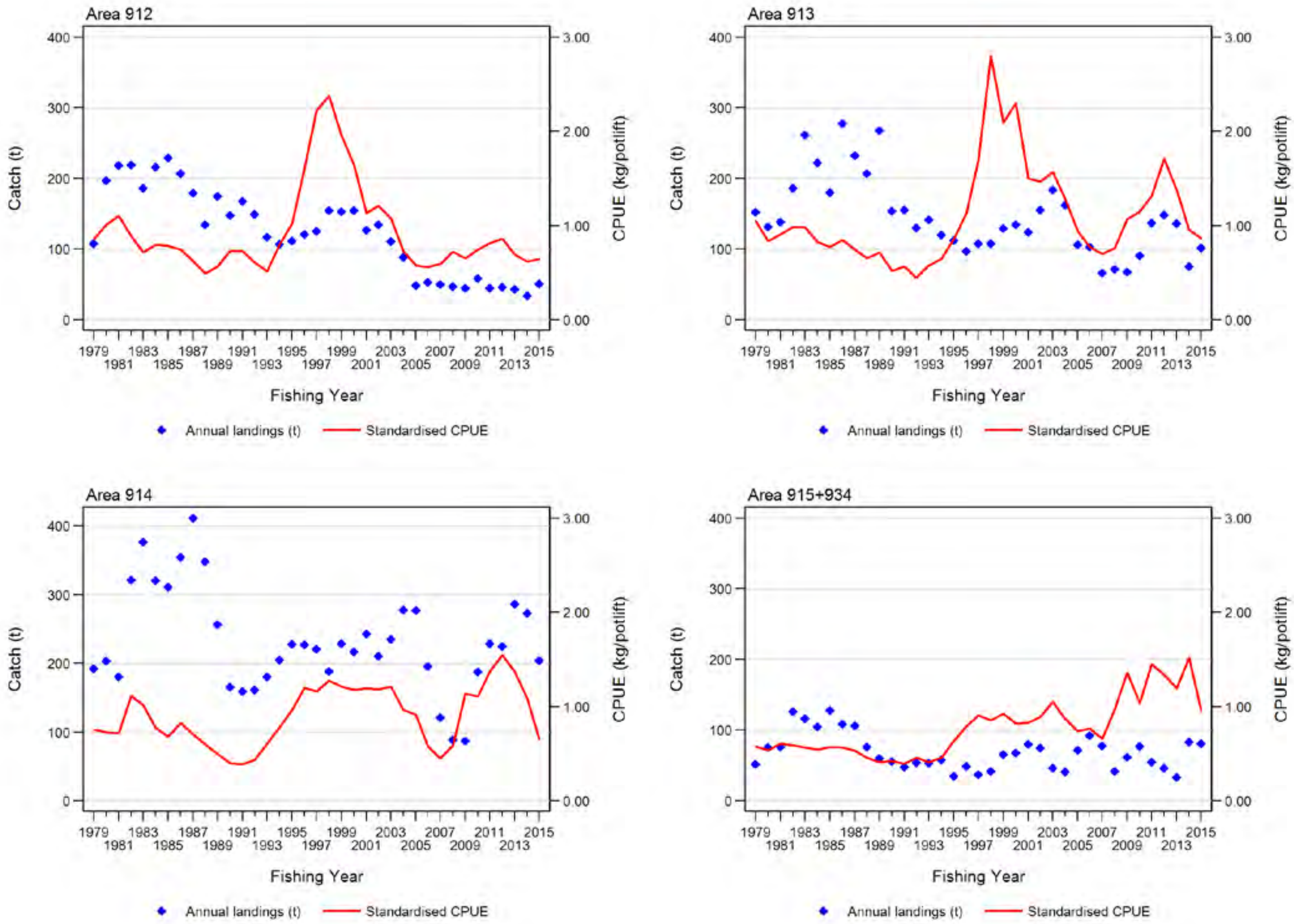


Figure A.4: Commercial catch and annual CPUE for four CRA 4 multi-area sub-stocks defined by rock lobster statistical areas (Table A.1).

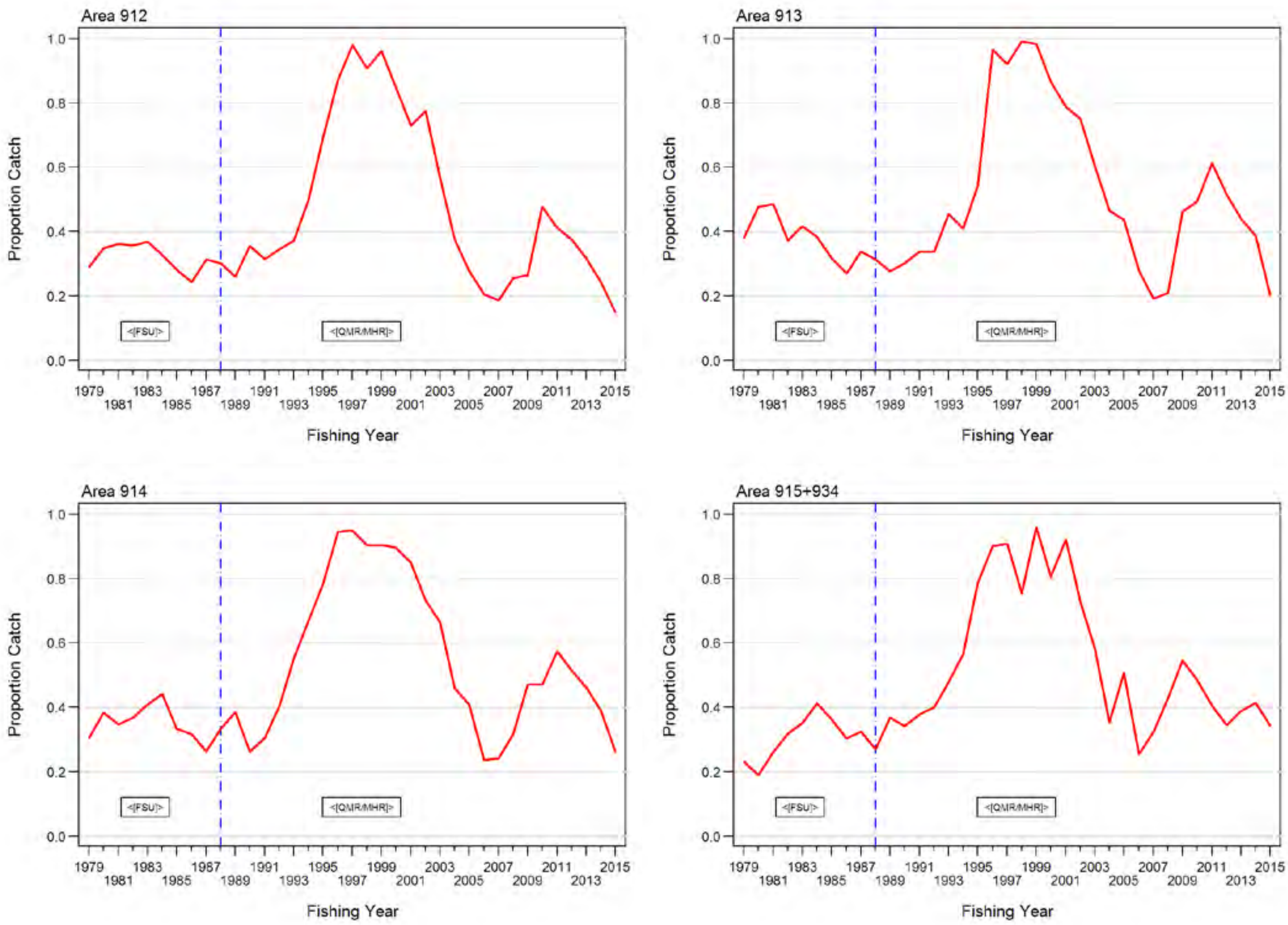


Figure A.5: Seasonal proportion of the commercial AW catch by fishing year for four CRA 4 multi-area sub-stocks defined by rock lobster statistical areas (Table A.1). These proportions have been derived from reported landings by month from the FSU or CELR catch reporting systems using the F2_LFX algorithm (Starr 2016).

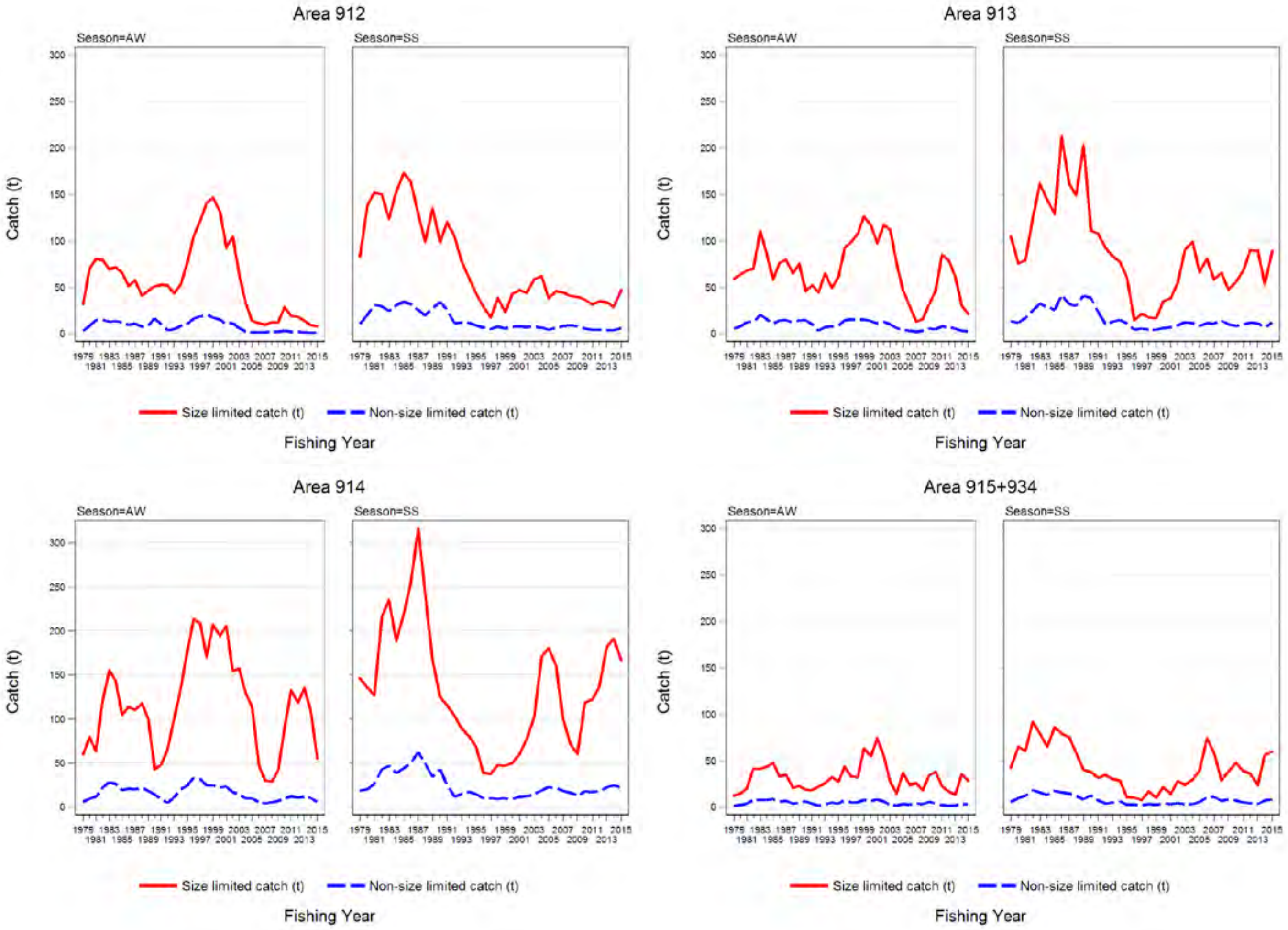


Figure A.6: The seasonal SL (size-limited) and NSL (non-size-limited) catches (t) for four CRA 4 sub-stocks, defined by rock lobster statistical areas (Table A.1), plotted by fishing year, beginning in 1979.

Table A.4: Estimated catches (t) (commercial, recreational including S.111, illegal and customary) for the Area 912 CRA 4 sub-stock, provided annually before 1979 and seasonally (AW and SS) from 1979 to 2015.

Calendar Year	Comm-ercial Annual	Recrea-tional Annual	Cus-tomary Annual	Illegal Annual	Fishing Year	Commercial		Recreational		Customary		Illegal	
						AW	SS	AW	SS	AW	SS	AW	SS
1945	55.7	2.6	4.4	10.0	1979	31.3	76.3	0.8	7.1	0.4	3.8	2.7	6.6
1946	49.3	2.8	4.4	8.8	1980	68.7	128.5	1.1	10.0	0.6	5.8	7.8	14.7
1947	55.5	3.0	4.4	9.9	1981	79.2	139.7	1.3	11.8	0.7	6.4	14.2	25.0
1948	55.4	3.1	4.4	9.9	1982	78.5	141.1	1.0	9.2	0.5	4.6	14.1	25.2
1949	59.9	3.3	4.4	10.7	1983	68.5	117.4	0.7	6.3	0.4	3.6	12.3	21.0
1950	110.2	3.4	4.4	19.7	1984	71.0	145.5	0.8	7.5	0.5	4.5	12.7	26.0
1951	147.4	3.6	4.4	26.4	1985	64.5	164.4	1.0	8.6	0.5	4.9	11.5	29.4
1952	143.0	3.8	4.4	25.6	1986	50.5	156.8	0.8	7.3	0.4	3.9	9.0	28.1
1953	148.5	3.9	4.4	26.6	1987	56.3	122.9	0.7	5.9	0.4	3.5	10.1	22.0
1954	145.8	4.1	4.4	26.1	1988	40.8	93.9	0.5	4.6	0.4	3.2	7.3	16.8
1955	110.2	4.2	4.4	19.7	1989	45.5	129.0	0.7	6.2	0.5	4.1	8.1	23.1
1956	94.9	4.4	4.4	17.0	1990	52.5	95.4	0.8	7.0	0.6	5.1	16.1	29.2
1957	71.7	4.5	4.4	12.8	1991	52.8	114.7	0.9	7.8	0.6	5.7	9.5	20.6
1958	74.5	4.7	4.4	13.3	1992	51.5	97.8	0.8	7.3	0.6	5.4	3.1	5.9
1959	64.3	4.9	4.4	11.5	1993	43.4	73.5	0.7	6.4	0.5	4.3	4.4	7.5
1960	79.2	5.0	4.4	14.2	1994	53.5	54.0	0.8	7.0	0.4	3.9	7.6	7.7
1961	91.8	5.2	4.4	16.4	1995	76.9	34.5	1.1	9.8	0.5	4.1	10.1	4.5
1962	109.7	5.3	4.4	19.6	1996	105.7	15.6	1.5	13.9	0.5	4.4	16.1	2.4
1963	82.2	6.7	5.3	14.7	1997	122.6	2.6	1.7	15.2	0.5	4.6	18.1	0.4
1964	119.2	6.7	5.2	21.3	1998	140.4	14.1	2.7	24.1	0.6	5.6	19.8	2.0
1965	172.6	7.9	5.9	30.9	1999	147.1	5.9	1.9	17.3	0.5	4.8	17.0	0.7
1966	129.6	5.3	3.9	23.2	2000	131.1	23.4	2.2	19.6	0.5	4.8	14.6	2.6
1967	101.1	5.5	3.9	18.1	2001	92.8	34.5	1.4	12.6	0.4	4.0	10.0	3.7
1968	99.1	5.6	3.9	17.7	2002	104.6	30.2	1.6	14.1	0.5	4.2	10.9	3.1
1969	170.3	8.3	5.6	30.5	2003	63.0	47.9	1.2	11.2	0.4	3.5	5.5	4.2
1970	113.8	6.2	4.1	20.4	2004	33.4	55.3	0.8	7.2	0.3	2.8	2.3	3.9
1971	66.9	4.9	3.2	12.0	2005	13.6	35.3	0.4	3.3	0.2	1.7	1.1	2.8
1972	71.8	5.3	3.4	12.8	2006	11.0	42.6	0.4	3.6	0.2	2.2	1.0	3.8
1973	69.7	6.1	3.7	12.5	2007	9.4	40.8	0.5	4.3	0.3	2.9	1.2	5.2
1974	71.6	6.3	3.8	9.2	2008	12.0	34.9	0.7	6.4	0.4	3.4	1.9	5.6
1975	79.0	6.6	3.9	19.1	2009	11.9	33.0	0.9	7.7	0.3	3.1	1.8	5.0
1976	91.2	6.9	4.0	17.7	2010	28.0	30.7	0.7	6.5	0.3	2.5	2.7	3.0
1977	89.6	7.2	4.1	23.0	2011	18.6	26.6	0.6	5.1	0.2	1.7	1.6	2.3
1978	103.8	7.6	4.2	26.6	2012	17.4	29.0	0.6	5.6	0.2	1.8	1.5	2.5
					2013	13.7	29.6	0.5	4.2	0.2	1.6	1.1	2.4
					2014	8.3	25.9	0.3	3.1	0.1	1.3	0.7	2.2
					2015	7.6	43.2	0.4	3.9	0.2	2.1	0.7	3.9

Table A.5: Estimated catches (t) (commercial, recreational including S.111, illegal and customary) for the Area 913 CRA 4 sub-stock, provided annually before 1979 and seasonally (AW and SS) from 1979 to 2015.

Calendar Year	Comm-ercial Annual	Recrea-tional Annual	Cus-tomary Annual	Illegal Annual	Fishing Year	Commercial		Recreational		Customary		Illegal	
						AW	SS	AW	SS	AW	SS	AW	SS
1945	51.7	2.4	4.1	9.3	1979	58.0	94.3	1.1	10.0	0.6	5.4	5.0	8.2
1946	45.8	2.6	4.1	8.2	1980	62.9	68.7	0.7	6.7	0.4	3.9	7.2	7.8
1947	51.5	2.7	4.1	9.2	1981	67.5	71.4	0.8	7.5	0.5	4.1	12.1	12.8
1948	51.4	2.9	4.1	9.2	1982	69.2	117.0	0.9	7.8	0.4	3.9	12.4	20.9
1949	55.6	3.0	4.1	10.0	1983	109.3	152.4	1.0	8.9	0.6	5.0	19.6	27.3
1950	102.2	3.2	4.1	18.3	1984	85.4	136.7	0.9	7.7	0.5	4.6	15.3	24.5
1951	136.8	3.3	4.1	24.5	1985	57.4	122.7	0.8	6.8	0.4	3.8	10.3	22.0
1952	132.8	3.5	4.1	23.8	1986	75.1	202.7	1.1	9.8	0.6	5.3	13.4	36.3
1953	137.8	3.6	4.1	24.7	1987	78.8	153.7	0.8	7.6	0.5	4.5	14.1	27.5
1954	135.4	3.8	4.1	24.2	1988	64.6	142.0	0.8	7.1	0.5	4.9	11.6	25.4
1955	102.3	3.9	4.1	18.3	1989	74.1	193.3	1.0	9.4	0.7	6.3	13.3	34.6
1956	88.1	4.1	4.1	15.8	1990	46.6	107.6	0.8	7.3	0.6	5.3	14.3	32.9
1957	66.6	4.2	4.1	11.9	1991	52.5	102.8	0.8	7.3	0.6	5.3	9.4	18.4
1958	69.2	4.4	4.1	12.4	1992	43.9	86.5	0.7	6.4	0.5	4.7	2.7	5.2
1959	59.7	4.5	4.1	10.7	1993	64.5	77.0	0.9	7.7	0.6	5.2	6.6	7.8
1960	73.5	4.7	4.1	13.2	1994	49.4	70.8	0.9	7.9	0.5	4.4	7.1	10.1
1961	85.3	4.8	4.1	15.3	1995	60.9	51.6	1.1	9.9	0.5	4.2	8.0	6.8
1962	101.8	5.0	4.1	18.2	1996	93.3	3.4	1.2	11.0	0.4	3.5	14.2	0.5
1963	38.6	3.1	2.5	6.9	1997	99.3	8.4	1.5	13.1	0.4	4.0	14.6	1.2
1964	81.4	4.6	3.5	14.6	1998	107.3	0.9	1.9	16.9	0.4	3.9	15.1	0.1
1965	113.8	5.2	3.9	20.4	1999	126.9	2.2	1.6	14.6	0.4	4.0	14.7	0.3
1966	149.2	6.2	4.5	26.7	2000	116.6	18.0	1.9	17.0	0.5	4.2	13.0	2.0
1967	107.6	5.9	4.2	19.3	2001	97.5	26.2	1.4	12.3	0.4	3.9	10.5	2.8
1968	111.5	6.3	4.4	20.0	2002	116.8	38.8	1.8	16.3	0.5	4.9	12.2	4.0
1969	105.0	5.1	3.5	18.8	2003	111.1	72.8	2.1	18.6	0.6	5.7	9.7	6.3
1970	124.1	6.7	4.4	22.2	2004	75.4	86.7	1.5	13.1	0.6	5.1	5.3	6.1
1971	93.2	6.9	4.4	16.7	2005	46.6	59.9	0.8	7.1	0.4	3.8	3.7	4.8
1972	97.7	7.3	4.6	17.5	2006	28.7	74.7	0.8	7.0	0.5	4.2	2.6	6.7
1973	88.4	7.7	4.7	15.8	2007	12.7	53.4	0.6	5.7	0.4	3.8	1.6	6.8
1974	92.8	8.2	4.9	11.9	2008	15.1	56.8	1.1	9.8	0.6	5.2	2.4	9.1
1975	104.4	8.8	5.2	25.3	2009	31.3	36.4	1.3	11.7	0.5	4.6	4.8	5.6
1976	122.8	9.3	5.4	23.9	2010	45.1	46.1	1.1	10.1	0.4	4.0	4.4	4.4
1977	122.8	9.9	5.6	31.5	2011	83.9	53.1	1.7	15.6	0.6	5.3	7.2	4.6
1978	144.6	10.5	5.8	37.1	2012	76.4	72.0	2.0	18.1	0.6	5.7	6.6	6.2
					2013	60.0	76.2	1.5	13.3	0.5	4.9	4.8	6.1
					2014	29.3	46.2	0.8	6.8	0.3	2.9	2.5	4.0
					2015	20.7	81.1	0.9	7.8	0.5	4.2	1.9	7.4

Table A.6: Estimated catches (t) (commercial, recreational including S.111, illegal and customary) for the Area 914 CRA 4 sub-stock, provided annually before 1979 and seasonally (AW and SS) from 1979 to 2015.

Calendar Year	Comm-ercial Annual	Recrea-tional Annual	Cus-tomary Annual	Illegal Annual	Fishing Year	Commercial		Recreational		Customary		Illegal	
						AW	SS	AW	SS	AW	SS	AW	SS
1945	78.5	3.7	6.2	14.0	1979	58.7	133.6	1.4	12.7	0.8	6.9	5.1	11.6
1946	69.4	3.9	6.2	12.4	1980	78.3	125.4	1.2	10.4	0.7	6.0	8.9	14.3
1947	78.1	4.2	6.2	14.0	1981	62.4	117.7	1.1	9.7	0.6	5.3	11.2	21.1
1948	78.0	4.4	6.2	14.0	1982	118.6	202.5	1.5	13.4	0.8	6.8	21.2	36.2
1949	84.4	4.6	6.2	15.1	1983	153.8	222.7	1.4	12.8	0.8	7.2	27.5	39.9
1950	155.1	4.8	6.2	27.8	1984	141.6	178.3	1.2	11.1	0.7	6.7	25.4	31.9
1951	207.5	5.1	6.2	37.1	1985	103.6	207.4	1.3	11.7	0.7	6.6	18.5	37.1
1952	201.4	5.3	6.2	36.0	1986	112.3	241.7	1.4	12.4	0.7	6.7	20.1	43.3
1953	209.1	5.5	6.2	37.4	1987	108.5	302.8	1.5	13.5	0.9	8.0	19.4	54.2
1954	205.3	5.7	6.2	36.7	1988	116.4	231.5	1.3	11.9	0.9	8.2	20.8	41.4
1955	155.2	6.0	6.2	27.8	1989	98.7	157.6	1.0	9.0	0.7	6.1	17.7	28.2
1956	133.7	6.2	6.2	23.9	1990	43.8	121.9	0.9	7.8	0.6	5.7	13.4	37.3
1957	100.9	6.4	6.2	18.1	1991	48.7	110.7	0.8	7.5	0.6	5.4	8.7	19.8
1958	104.9	6.6	6.2	18.8	1992	65.3	96.3	0.9	7.9	0.7	5.9	4.0	5.8
1959	90.6	6.9	6.2	16.2	1993	99.9	80.7	1.1	9.8	0.7	6.6	10.2	8.2
1960	111.5	7.1	6.2	19.9	1994	136.5	68.1	1.5	13.4	0.8	7.5	19.5	9.7
1961	129.3	7.3	6.2	23.1	1995	178.5	49.8	2.2	20.1	0.9	8.4	23.4	6.5
1962	154.4	7.5	6.2	27.6	1996	214.7	12.5	2.9	26.0	0.9	8.3	32.6	1.9
1963	58.5	4.7	3.8	10.5	1997	209.4	11.2	3.0	26.8	0.9	8.1	30.9	1.7
1964	123.5	7.0	5.4	22.1	1998	170.1	18.4	3.3	29.4	0.8	6.9	24.0	2.6
1965	172.6	7.9	5.9	30.9	1999	206.9	21.8	2.9	25.8	0.8	7.1	24.0	2.5
1966	226.4	9.3	6.8	40.5	2000	194.1	22.7	3.0	27.4	0.8	6.8	21.7	2.5
1967	163.3	8.9	6.4	29.2	2001	205.7	36.9	2.7	24.1	0.8	7.6	22.2	4.0
1968	169.2	9.6	6.6	30.3	2002	154.0	56.1	2.4	22.0	0.7	6.6	16.0	5.8
1969	159.2	7.8	5.2	28.5	2003	156.0	78.8	2.6	23.7	0.8	7.3	13.5	6.8
1970	188.2	10.2	6.7	33.7	2004	128.1	149.9	2.5	22.4	1.0	8.8	9.0	10.5
1971	141.4	10.5	6.7	25.3	2005	113.4	163.9	2.1	18.5	1.1	9.9	9.0	13.0
1972	148.1	11.0	6.9	26.5	2006	46.4	148.9	1.5	13.1	0.9	7.9	4.2	13.4
1973	134.0	11.6	7.2	24.0	2007	29.3	91.8	1.2	10.5	0.8	6.9	3.7	11.7
1974	135.9	12.0	7.2	17.4	2008	28.2	60.7	1.3	12.1	0.7	6.4	4.5	9.7
1975	148.0	12.4	7.3	35.8	2009	41.1	46.4	1.7	15.1	0.7	6.0	6.3	7.1
1976	168.8	12.8	7.4	32.8	2010	88.6	99.3	2.3	20.8	0.9	8.2	8.5	9.6
1977	163.8	13.2	7.5	42.1	2011	131.5	97.4	2.9	26.1	1.0	8.8	11.3	8.4
1978	187.6	13.7	7.6	48.1	2012	115.5	109.6	3.0	27.4	1.0	8.7	9.9	9.4
					2013	132.1	154.2	3.1	28.1	1.1	10.3	10.6	12.4
					2014	106.3	166.2	2.7	24.5	1.2	10.5	9.1	14.3
					2015	53.8	150.7	1.7	15.7	0.9	8.4	4.9	13.8

Table A.7: Estimated catches (t) (commercial, recreational including S.111, illegal and customary) for the Area 915+934 CRA 4 sub-stock, provided annually before 1979 and seasonally (AW and SS) from 1979 to 2015.

Calendar Year	Commercial Annual	Recreational Annual	Customary Annual	Illegal Annual	Fishing Year	Commercial		Recreational		Customary		Illegal	
						AW	SS	AW	SS	AW	SS	AW	SS
1945	68.8	3.3	5.4	12.3	1979	11.9	39.5	0.4	3.4	0.2	1.8	1.0	3.4
1946	60.9	3.4	5.4	10.9	1980	14.3	61.0	0.4	3.8	0.2	2.2	1.6	7.0
1947	68.5	3.6	5.4	12.3	1981	20.0	56.4	0.5	4.1	0.2	2.2	3.6	10.1
1948	68.4	3.8	5.4	12.2	1982	40.3	86.3	0.6	5.3	0.3	2.7	7.2	15.5
1949	74.0	4.0	5.4	13.2	1983	40.9	75.4	0.4	3.9	0.2	2.2	7.3	13.5
1950	136.0	4.2	5.4	24.3	1984	43.2	61.4	0.4	3.6	0.2	2.2	7.7	11.0
1951	182.0	4.4	5.4	32.6	1985	46.7	81.4	0.5	4.8	0.3	2.7	8.4	14.6
1952	176.6	4.6	5.4	31.6	1986	32.9	75.5	0.4	3.8	0.2	2.1	5.9	13.5
1953	183.4	4.8	5.4	32.8	1987	34.5	71.7	0.4	3.5	0.2	2.1	6.2	12.8
1954	180.1	5.0	5.4	32.2	1988	20.5	55.5	0.3	2.6	0.2	1.8	3.7	9.9
1955	136.1	5.2	5.4	24.4	1989	22.2	38.1	0.2	2.1	0.2	1.4	4.0	6.8
1956	117.2	5.4	5.4	21.0	1990	18.9	36.5	0.3	2.6	0.2	1.9	5.8	11.2
1957	88.5	5.6	5.4	15.8	1991	18.3	30.0	0.3	2.3	0.2	1.6	3.3	5.4
1958	92.0	5.8	5.4	16.5	1992	21.8	32.7	0.3	2.7	0.2	2.0	1.3	2.0
1959	79.4	6.0	5.4	14.2	1993	25.4	27.6	0.3	2.9	0.2	1.9	2.6	2.8
1960	97.8	6.2	5.4	17.5	1994	32.8	25.2	0.4	3.8	0.2	2.1	4.7	3.6
1961	113.4	6.4	5.4	20.3	1995	27.5	7.5	0.3	3.1	0.1	1.3	3.6	1.0
1962	135.5	6.6	5.4	24.2	1996	43.6	4.8	0.6	5.5	0.2	1.8	6.6	0.7
1963	131.0	10.6	8.4	23.5	1997	33.5	3.4	0.5	4.5	0.2	1.4	4.9	0.5
1964	135.7	7.6	5.9	24.3	1998	31.7	10.3	0.7	6.6	0.2	1.5	4.5	1.5
1965	122.4	5.6	4.2	21.9	1999	63.1	2.6	0.8	7.4	0.2	2.1	7.3	0.3
1966	158.3	6.5	4.8	28.3	2000	54.8	13.1	1.0	8.6	0.2	2.1	6.1	1.5
1967	140.6	7.7	5.5	25.2	2001	74.1	6.3	0.9	8.0	0.3	2.5	8.0	0.7
1968	129.7	7.3	5.1	23.2	2002	54.7	20.5	0.9	7.9	0.3	2.4	5.7	2.1
1969	172.3	8.4	5.7	30.8	2003	26.8	19.3	0.5	4.7	0.2	1.4	2.3	1.7
1970	132.9	7.2	4.8	23.8	2004	14.6	26.6	0.4	3.3	0.1	1.3	1.0	1.9
1971	117.8	8.7	5.6	21.1	2005	36.2	35.2	0.5	4.8	0.3	2.5	2.9	2.8
1972	108.8	8.1	5.1	19.5	2006	23.5	68.8	0.7	6.2	0.4	3.7	2.1	6.2
1973	81.8	7.1	4.4	14.6	2007	25.2	52.7	0.7	6.7	0.5	4.4	3.2	6.7
1974	74.7	6.6	4.0	9.6	2008	17.9	23.9	0.6	5.7	0.3	3.0	2.9	3.8
1975	72.7	6.1	3.6	17.6	2009	33.9	28.3	1.2	10.7	0.5	4.3	5.2	4.3
1976	73.1	5.6	3.2	14.2	2010	37.5	39.6	0.9	8.5	0.4	3.3	3.6	3.8
1977	61.7	5.0	2.8	15.9	2011	22.4	32.8	0.7	6.3	0.2	2.1	1.9	2.8
1978	60.3	4.4	2.4	15.5	2012	16.0	30.4	0.6	5.6	0.2	1.8	1.4	2.6
					2013	13.1	20.5	0.4	3.3	0.1	1.2	1.0	1.6
					2014	34.5	48.8	0.8	7.5	0.4	3.2	3.0	4.2
					2015	27.8	53.3	0.7	6.2	0.4	3.3	2.5	4.9

A.3 CATCH RATE INFORMATION

A.3.1 FSU & CELR CPUE INDICES

Catch and effort data from the FSU and CELR systems were obtained from MPI in September 2016 (Replog 10736), loaded into the CRACE database and processed using standard error checks (Bentley et al. 2005). Data spanned the period from 1 April 1979 through to 31 March 2016.

Data preparation used the F2-LFX procedure (Starr 2016). The F2 algorithm corrects the monthly estimated catch taken by a vessel in a statistical area using a "vessel correction factor" (*vcf*: the ratio of landed catch to estimated catch for one vessel in one year) (Starr 2016; Starr et al. 2012), and discards from the analysis those vessels with *vcf* less than 0.8 or greater than 1.2. The F2-LFX procedure scales the estimated catches to the combined "L" (LFR), "X" (discarded to sea) and "F" (Section 111 recreational catch) destination codes.

The CPUE standardisation procedure used sequential six-month periods as a forced explanatory variable. The only explanatory variable available for the single statistical area analyses is [`month`] of capture. The variable [`statistical_area`] was added for the Area 915+934 analysis. These analyses estimate separate relative [`month`] effects in each half-year period by using, as the reference [`month`], the [`month`] in each period with the lowest standard error.

A.3.1.1 AREA 912

The Area 912 data set shows a diminishing number of records (Table A.8). The total deviance explained by the Area 912 model was 36% (Table A.9), with only month available for standardisation apart from the time period variable. Residual patterns showed some deviation from the lognormal assumption at both tails of the residual distribution (Figure A.7).

The month categorical variable in the CRA 4 seasonal CPUE analysis appears to be cyclical, with a winter peak in June and an early summer peak in November (Figure A.8). Both the Area 912 AW and SS CPUE series showed similar patterns, with the AW series having lower absolute catch rates (Figure A.9, Table A.10). Both series peak in the late 1990s and a second peak around 2010, seen in other stocks, is not well defined here (Figure A.9). The SS series had a larger associated error than the AW series, particularly during the peak in the late 1990s, reflecting the relatively smaller amount of data in the SS series in those years (Figure A.9).

Table A.8. Number of vessel/month records in the dataset used to calculate the Area 912 CRA 4 sub-stock CPUE time series (based on the F2_LFX algorithm). '–': no data.

Fishing							AW							SS
year	Apr	May	Jun	Jul	Aug	Sep	Total	Oct	Nov	Dec	Jan	Feb	Mar	Total
1979	5	3	19	20	21	21	89	23	28	26	23	23	13	136
1980	11	6	21	22	21	20	101	27	24	25	26	26	21	149
1981	14	8	18	21	23	25	109	25	26	25	27	22	21	146
1982	14	13	22	22	25	26	122	25	26	26	25	27	18	147
1983	10	13	21	18	23	24	109	24	23	25	24	21	20	137
1984	9	11	21	19	19	20	99	21	21	23	23	18	12	118
1985	7	13	22	23	23	24	112	24	24	23	23	23	16	133
1986	7	12	20	20	20	23	102	23	22	24	23	22	13	127
1987	10	16	19	16	17	20	98	21	22	20	21	20	17	121
1988	10	12	18	16	19	19	94	18	18	18	17	17	17	105
1989	11	13	17	15	19	19	94	20	20	24	18	18	15	115
1990	6	11	19	19	18	20	93	22	20	20	19	18	14	113
1991	13	17	20	23	22	22	117	23	24	23	21	20	15	126
1992	13	22	26	26	25	27	139	29	28	27	22	19	19	144
1993	17	26	28	24	21	20	136	25	21	18	13	14	8	99
1994	13	14	17	15	16	16	91	3	15	15	7	1	6	47
1995	12	13	13	14	14	14	80	12	11	3	2	3	10	41
1996	10	11	12	12	15	14	74	7	3	3	1	1	7	22
1997	10	11	11	11	11	9	63	2	–	2	1	–	5	10
1998	9	10	13	15	15	16	78	5	2	2	–	5	2	16
1999	7	13	13	13	14	13	73	4	3	2	1	2	4	16
2000	10	14	14	15	15	11	79	10	2	4	2	3	5	26
2001	9	11	13	14	13	15	75	10	7	3	2	2	3	27
2002	13	13	13	13	12	13	77	8	5	5	6	8	9	41
2003	6	11	13	14	10	14	68	16	10	6	8	6	6	52
2004	9	7	14	13	11	13	67	14	13	11	8	9	9	64
2005	1	7	10	10	9	9	46	11	11	10	8	8	6	54
2006	3	3	7	7	5	10	35	13	13	12	10	9	8	65
2007	1	4	5	6	6	8	30	9	10	10	9	9	10	57
2008	–	–	7	8	8	8	31	8	8	10	8	8	2	44
2009	–	5	6	8	8	9	36	7	9	10	9	7	2	44
2010	8	8	7	9	10	11	53	11	9	9	10	10	2	51
2011	4	8	8	10	8	7	45	7	8	8	9	4	1	37
2012	7	7	7	7	5	5	38	8	8	8	6	5	3	38
2013	4	6	6	7	5	6	34	6	6	6	7	7	7	39
2014	3	5	6	6	6	5	31	7	7	7	8	7	6	42
2015	1	4	6	6	6	7	30	7	7	8	8	8	8	46

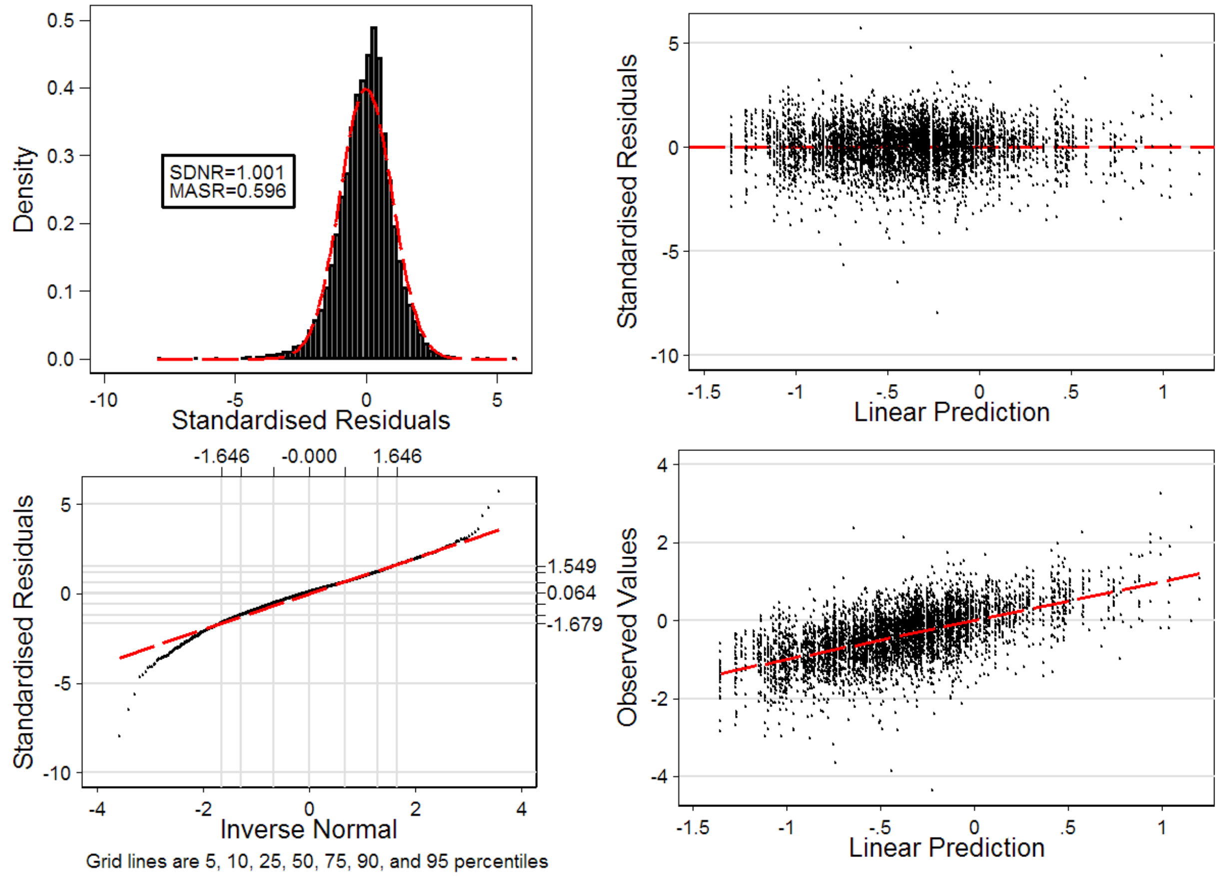


Figure A.7. Standardised residuals for the Area 912 CRA 4 sub-stock standardised seasonal F2_LFX CPUE analysis.

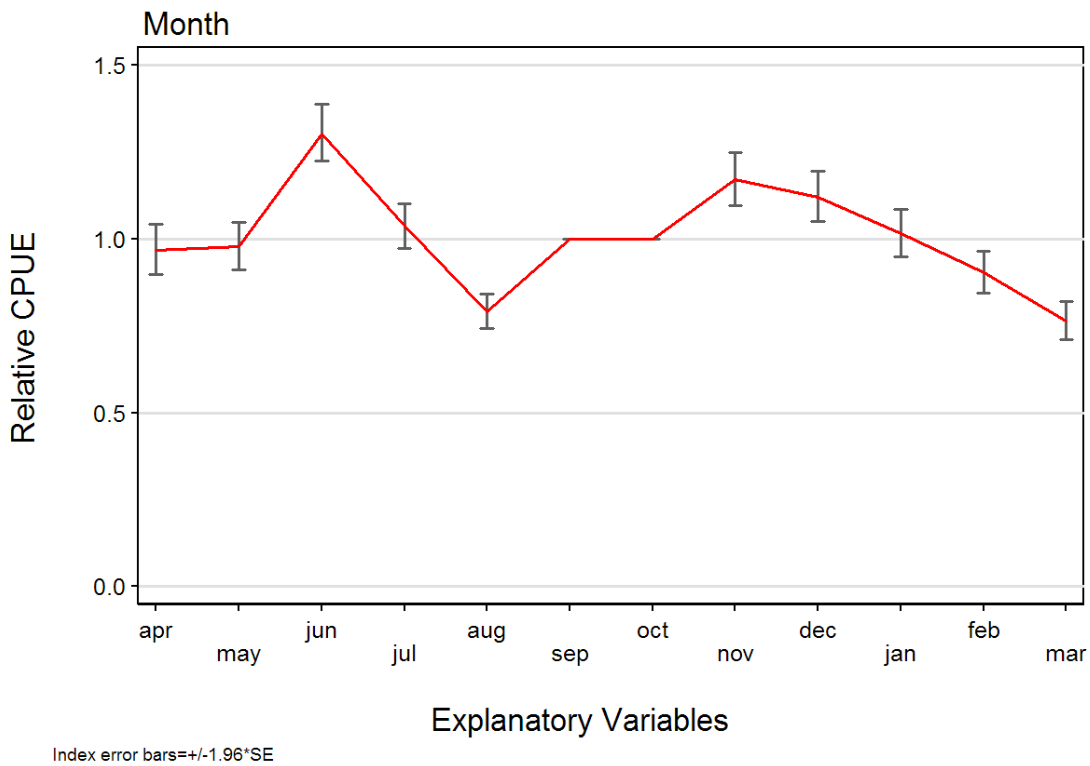


Figure A.8. Coefficients for month from the Area 912 CRA 4 sub-stock seasonal F2_LFX CPUE standardisation. Month coefficients are not in canonical form, with each of the two reference months (September and October) set to 1.0 and the associated SE set to zero.

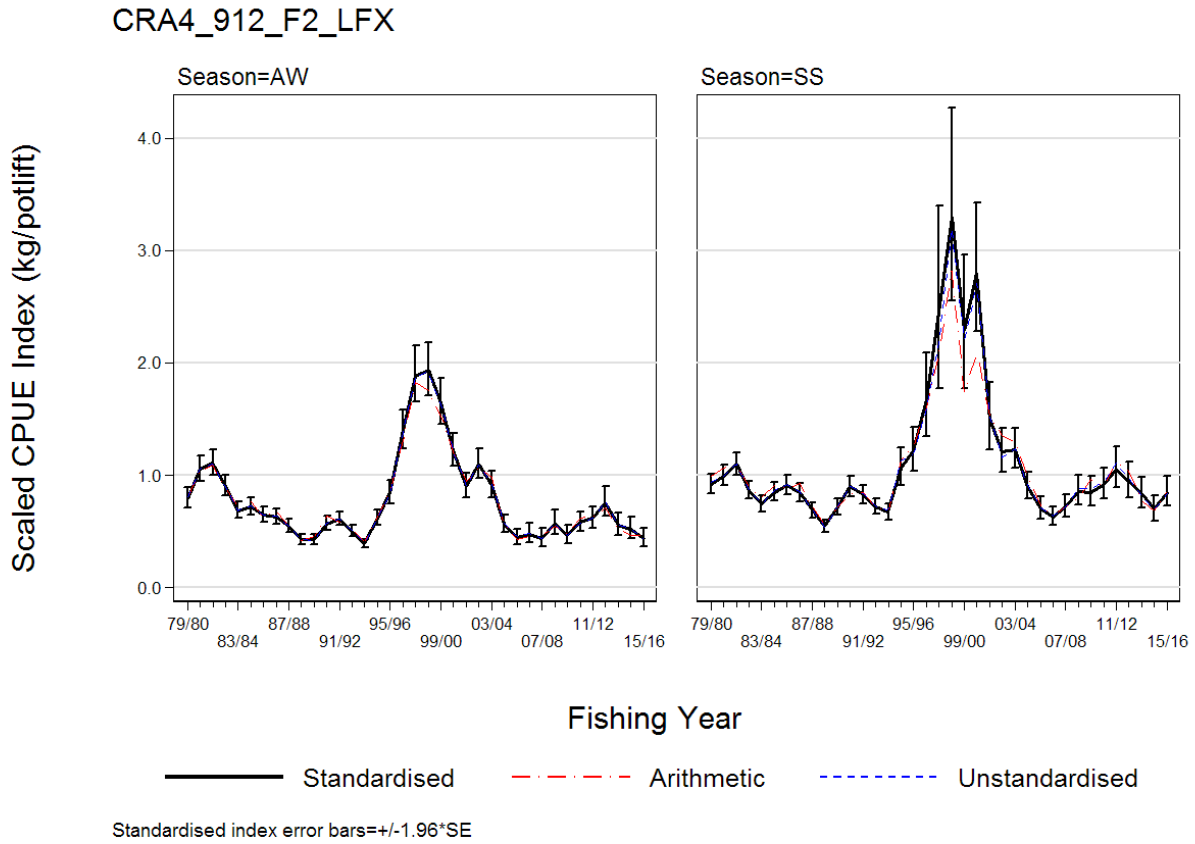


Figure A.9. Scaled standardised F2_LFX CPUE (kg/potlift) by period for the Area 912 CRA 4 sub-stock with the AW-SS seasons plotted separately. Also shown are the arithmetic or "raw" CPUE series and the geometric mean of the CPUE ("unstandardised"). The standardised and unstandardised series were scaled by multiplying each index in the unscaled series (where the geometric mean=1) by the geometric mean of the arithmetic CPUE series for each seasonal category (geometric mean for AW=0.71 kg/potlift; geometric mean for SS=1.00 kg/potlift).

Table A.9. Total deviance (R^2) explained by each variable in the Area 912 CRA 4 sub-stock standardised seasonal CPUE model.

Variable	**1**	**2**
Period	0.3112	
Month	0.0646	0.3596
Additional deviance explained	0.0000	0.0484

Table A.10: Standardised seasonal CPUE and standard errors for the Area 912 CRA 4 sub-stock.

Fishing Year	AW	s.e.	SS	s.e.	Fishing Year	AW	s.e.	SS	s.e.
1979	0.796	0.0576	0.917	0.0478	1998	1.931	0.0612	3.298	0.1311
1980	1.054	0.0544	0.994	0.0459	1999	1.645	0.0632	2.291	0.1312
1981	1.110	0.0524	1.100	0.0464	2000	1.218	0.0611	2.794	0.1031
1982	0.905	0.0499	0.867	0.0462	2001	0.905	0.0623	1.496	0.1013
1983	0.686	0.0524	0.742	0.0476	2002	1.096	0.0618	1.208	0.0831
1984	0.722	0.0549	0.850	0.0509	2003	0.914	0.0653	1.230	0.0738
1985	0.648	0.0518	0.909	0.0482	2004	0.565	0.0658	0.902	0.0671
1986	0.633	0.0540	0.844	0.0492	2005	0.449	0.0786	0.705	0.0728
1987	0.548	0.0551	0.688	0.0503	2006	0.479	0.0893	0.632	0.0667
1988	0.426	0.0562	0.544	0.0536	2007	0.440	0.0963	0.723	0.0711
1989	0.425	0.0562	0.716	0.0515	2008	0.575	0.0950	0.858	0.0803
1990	0.567	0.0564	0.899	0.0518	2009	0.468	0.0883	0.850	0.0804
1991	0.612	0.0510	0.826	0.0494	2010	0.584	0.0734	0.922	0.0748
1992	0.505	0.0472	0.721	0.0465	2011	0.618	0.0795	1.057	0.0873
1993	0.392	0.0479	0.672	0.0547	2012	0.759	0.0863	0.945	0.0861
1994	0.617	0.0572	1.066	0.0785	2013	0.553	0.0909	0.835	0.0852
1995	0.846	0.0606	1.216	0.0829	2014	0.524	0.0951	0.699	0.0822
1996	1.397	0.0628	1.675	0.1122	2015	0.440	0.0964	0.850	0.0787
1997	1.885	0.0679	2.456	0.1659					

A.3.1.2 AREA 913

The Area 913 data set shows a diminishing number of records over time (Table A.11). The total deviance explained by the Area 913 model was 39% (Table A.12), with only month available for standardisation apart from the time period variable. Residual patterns showed some deviation from the lognormal assumption at the peak of the residual distribution (Figure A.10).

The month categorical variable in the seasonal CPUE analysis appears to be cyclical, with a winter peak in May/June and a summer peak in December, but extending across November to January (Figure A.11). Both the Area 913 AW and SS CPUE series showed similar patterns, with the AW and SS series having approximately the same absolute catch rates, unlike the other three Stocks (Figure A.12, Table A.13). Both series peak twice: once in the late 1990s and a second peak around 2010 (Figure A.12). Both series have similar associated error, except during four years in the late 1990s, reflecting the small amount of data in the SS series in those years (Figure A.12).

Table A.11. Number of vessel/month records in the dataset used to calculate the Area 913 CRA 4 sub-stock CPUE time series (based on the F2_LFX algorithm). '–': no data.

Fishing							AW							SS
year	Apr	May	Jun	Jul	Aug	Sep	Total	Oct	Nov	Dec	Jan	Feb	Mar	Total
1979	2	4	19	22	18	15	80	21	25	25	22	15	5	113
1980	2	10	13	17	19	19	80	17	17	18	16	15	7	90
1981	1	9	14	16	16	16	72	16	9	12	16	17	6	76
1982	1	13	13	11	14	14	66	16	20	17	20	16	9	98
1983	1	12	17	19	18	17	84	22	20	21	23	15	10	111
1984	2	14	18	20	18	19	91	19	19	20	19	16	3	96
1985	1	12	17	17	16	14	77	16	14	12	14	15	8	79
1986	3	14	17	19	16	16	85	20	20	21	19	16	7	103
1987	4	15	17	16	14	14	80	18	17	17	16	15	11	94
1988	5	13	16	10	14	13	71	15	16	19	14	16	12	92
1989	6	15	16	18	18	18	91	18	21	21	20	18	13	111
1990	3	10	20	18	16	18	85	19	21	18	17	15	8	98
1991	8	17	22	20	21	15	103	21	22	20	22	13	7	105
1992	4	17	21	22	22	21	107	25	23	21	21	13	10	113
1993	7	19	27	26	12	10	101	24	22	25	17	8	2	98
1994	4	22	24	20	19	17	106	20	22	17	11	7	4	81
1995	8	14	16	17	10	11	76	10	10	7	6	8	8	49
1996	9	10	10	9	9	6	53	1	–	1	1	1	5	9
1997	6	10	10	6	6	3	41	–	1	1	2	–	–	4
1998	3	9	7	6	6	4	35	1	1	–	–	–	1	3
1999	2	7	6	8	8	7	38	1	–	1	–	–	–	2
2000	4	6	6	5	5	5	31	3	3	1	–	–	3	10
2001	4	8	8	7	9	6	42	6	1	4	2	3	4	20
2002	7	12	13	13	12	11	68	7	6	4	4	2	4	27
2003	9	13	14	14	11	14	75	11	11	8	3	2	6	41
2004	6	12	12	11	7	8	56	11	12	8	9	5	3	48
2005	6	11	12	12	6	6	53	9	9	8	8	6	7	47
2006	4	11	13	10	6	9	53	11	14	14	11	10	7	67
2007	–	7	6	7	4	5	29	7	8	8	8	9	9	49
2008	2	1	8	8	5	4	28	8	8	12	9	7	2	46
2009	3	4	8	9	11	5	40	7	4	8	8	5	3	35
2010	2	8	10	8	6	6	40	6	4	6	9	8	4	37
2011	5	12	11	9	10	9	56	6	5	8	11	2	3	35
2012	3	11	9	8	5	5	41	3	4	9	11	5	7	39
2013	5	7	8	6	3	2	31	5	3	2	9	8	6	33
2014	1	7	8	8	7	1	32	6	5	9	8	6	7	41
2015	1	4	8	8	5	6	32	6	9	10	10	9	6	50

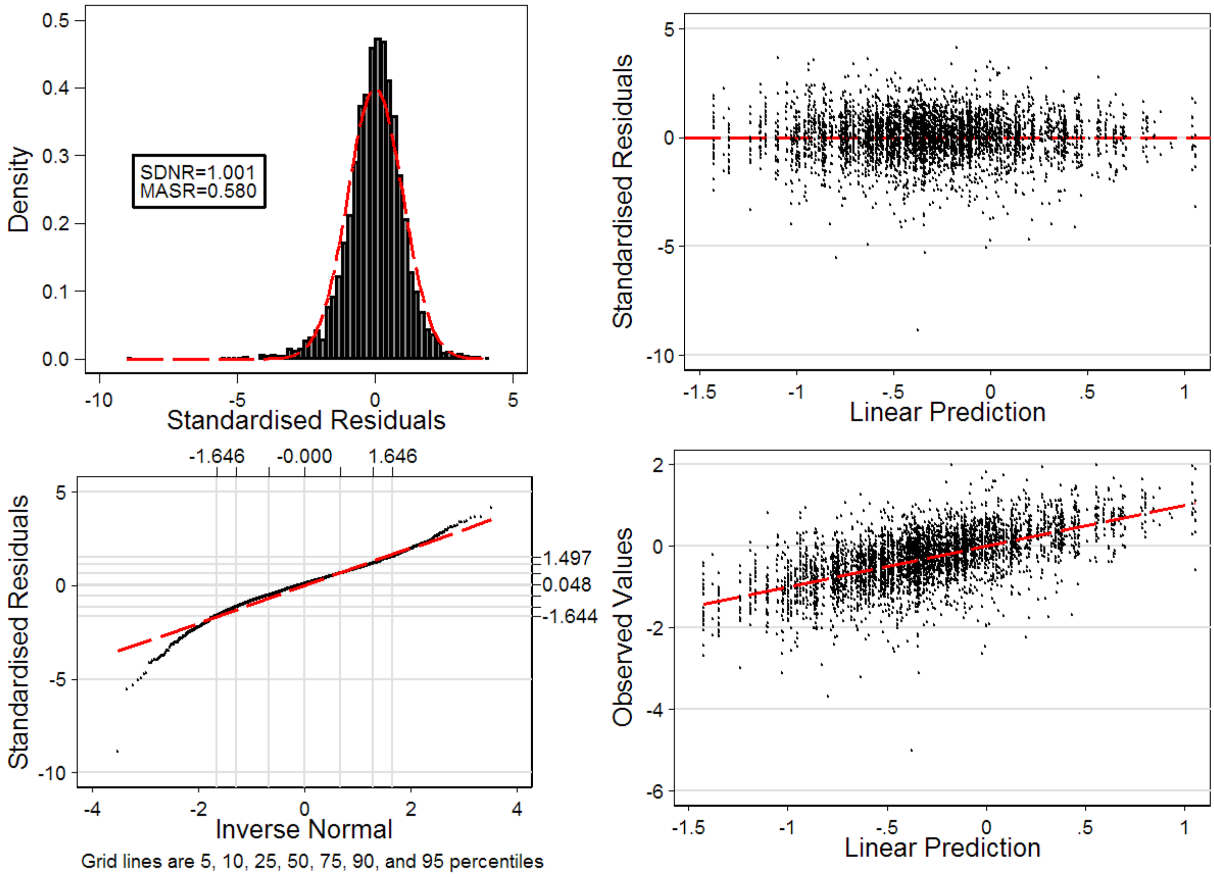


Figure A.10. Standardised residuals for the Area 913 CRA 4 sub-stock standardised seasonal F2_LFX CPUE analysis.

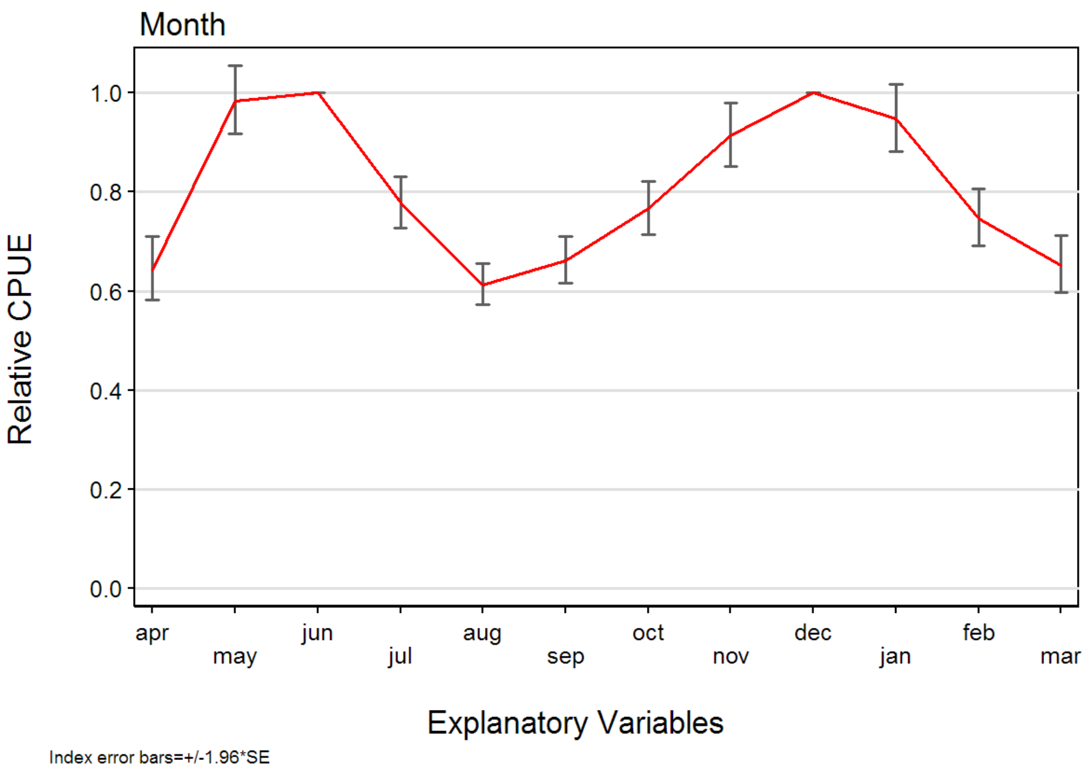


Figure A.11. Coefficients for month from the Area 913 CRA 4 sub-stock seasonal F2_LFX CPUE standardisation. Month coefficients are not in canonical form, with each of the two reference months (June and December) set to 1.0 and the associated SE set to zero.

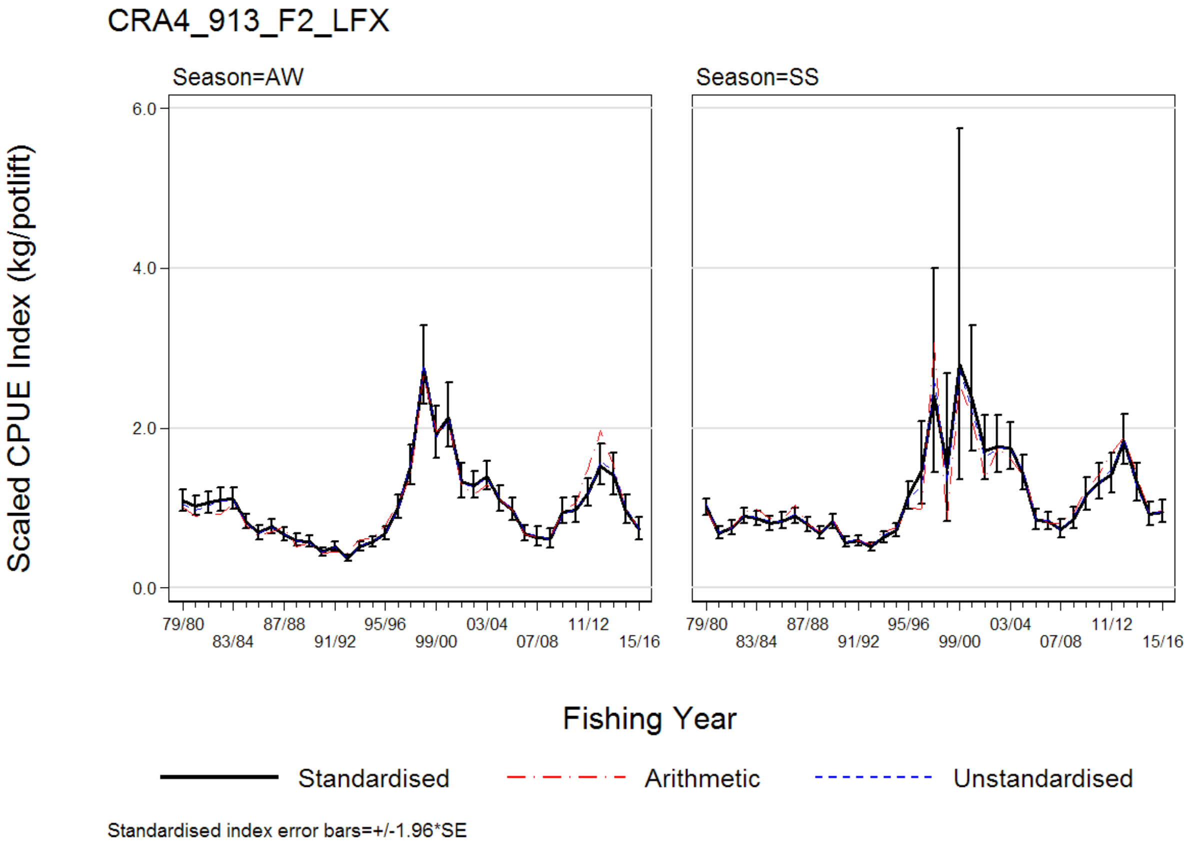


Figure A.12. Scaled standardised F2_LFX CPUE (kg/potlift) by period for the Area 913 CRA 4 sub-stock with the AW-SS seasons plotted separately. Also shown are the arithmetic or "raw" CPUE series and the geometric mean of the CPUE ("unstandardised"). The standardised and unstandardised series were scaled by multiplying each index in the unscaled series (where the geometric mean=1) by the geometric mean of the arithmetic CPUE series for each seasonal category (geometric mean for AW=0.92 kg/potlift; geometric mean for SS=1.05 kg/potlift).

Table A.12. Total deviance (R^2) explained by each variable in the Area 913 CRA 4 sub-stock standardised seasonal CPUE model.

Variable	**1**	**2**
Period	0.3233	
Month	0.0737	0.3892
Additional deviance explained	0.0000	0.0659

Table A.13: Standardised seasonal CPUE and standard errors for the Area 913 CRA 4 sub-stock.

Fishing Year	AW	s.e.	SS	s.e.	Fishing Year	AW	s.e.	SS	s.e.
1979	1.085	0.0611	1.006	0.0523	1998	2.751	0.0898	1.492	0.3004
1980	1.022	0.0614	0.683	0.0579	1999	1.920	0.0865	2.797	0.3671
1981	1.057	0.0642	0.753	0.0628	2000	2.133	0.0952	2.373	0.1656
1982	1.100	0.0668	0.900	0.0559	2001	1.330	0.0824	1.713	0.1176
1983	1.111	0.0599	0.871	0.0529	2002	1.283	0.0659	1.766	0.1018
1984	0.826	0.0578	0.802	0.0563	2003	1.397	0.0631	1.755	0.0833
1985	0.687	0.0622	0.836	0.0617	2004	1.106	0.0720	1.434	0.0774
1986	0.767	0.0595	0.902	0.0545	2005	0.979	0.0738	0.851	0.0781
1987	0.667	0.0611	0.794	0.0569	2006	0.682	0.0737	0.832	0.0661
1988	0.595	0.0644	0.684	0.0573	2007	0.635	0.0983	0.734	0.0767
1989	0.581	0.0579	0.828	0.0529	2008	0.613	0.0997	0.865	0.0786
1990	0.451	0.0594	0.570	0.0558	2009	0.951	0.0843	1.154	0.0896
1991	0.518	0.0546	0.591	0.0542	2010	0.969	0.0841	1.315	0.0876
1992	0.374	0.0538	0.510	0.0525	2011	1.184	0.0720	1.420	0.0897
1993	0.515	0.0549	0.628	0.0556	2012	1.528	0.0833	1.836	0.0852
1994	0.573	0.0539	0.717	0.0608	2013	1.402	0.0951	1.303	0.0929
1995	0.680	0.0626	1.147	0.0768	2014	0.966	0.0936	0.919	0.0832
1996	1.010	0.0740	1.477	0.1749	2015	0.731	0.0936	0.950	0.0758
1997	1.519	0.0833	2.403	0.2601					

A.3.1.3 AREA 914

As with the other CRA 4 sub-stocks, the Area 914 data set shows a diminishing number of records over time (Table A.14). The total deviance explained by the Area 914 model was 43% (Table A.15), with only month available for standardisation apart from the time period variable. Residual patterns showed some deviation from the lognormal assumption at the peak of the residual distribution (Figure A.13).

As for the other CRA 4 sub-stocks, the month categorical variable in the seasonal CPUE analysis appears to be cyclical, with a winter peak in May/June and a summer peak in November/December (Figure A.14). Both the Area 914 AW and SS CPUE series showed similar patterns, but the first peak is lower than the second peak for the AW series, and the AW series has lower absolute catch rates than the SS series (Figure A.15, Table A.16). Both series peak twice: once in the late 1990s and a second peak around 2012–13 (Figure A.15). The associated error is greater for the SS series in both of the peak years, reflecting small amounts of data in the SS series in those years (Figure A.15).

Table A.14. Number of vessel/month records in the dataset used to calculate the Area 914 CRA 4 sub-stock CPUE time series (based on the F2_LFX algorithm). '–': no data.

Fishing							**AW**							**SS**
year	Apr	May	Jun	Jul	Aug	Sep	Total	Oct	Nov	Dec	Jan	Feb	Mar	Total
1979	3	8	19	22	19	21	92	25	28	24	28	24	7	136
1980	–	16	22	20	20	24	102	26	28	28	27	21	5	135
1981	2	16	22	22	17	24	103	22	18	13	29	28	12	122
1982	1	18	22	25	26	25	117	27	28	27	29	30	16	157
1983	1	15	24	26	26	29	121	28	31	30	31	26	11	157
1984	2	25	26	26	30	28	137	31	32	31	31	18	6	149
1985	–	20	28	31	26	29	134	32	32	34	31	21	8	158
1986	1	20	27	29	30	24	131	28	29	28	31	26	10	152
1987	1	19	25	27	28	25	125	32	34	33	33	25	3	160
1988	1	21	28	29	26	22	127	28	33	29	30	22	7	149
1989	–	19	27	32	22	25	125	29	30	27	28	25	9	148
1990	1	14	24	22	22	24	107	27	26	29	22	21	14	139
1991	3	24	27	29	26	29	138	28	30	28	27	17	6	136
1992	1	19	29	29	26	20	124	28	28	25	23	12	4	120
1993	2	28	31	32	27	18	138	26	25	18	10	5	1	85
1994	5	34	35	36	34	21	165	22	17	11	4	2	2	58
1995	7	34	31	31	30	28	161	21	10	8	1	1	1	42
1996	9	26	22	25	25	15	122	8	2	1	2	–	3	16
1997	7	28	30	29	21	17	132	11	–	–	1	–	1	13
1998	7	21	21	20	24	17	110	7	2	1	2	2	1	15
1999	8	18	21	20	21	16	104	8	3	4	3	1	1	20
2000	2	18	21	22	18	17	98	12	3	1	1	1	–	18
2001	7	18	21	20	19	16	101	8	6	4	5	5	2	30
2002	14	20	20	21	20	18	113	8	8	10	10	7	4	47
2003	4	19	20	22	21	20	106	15	7	5	8	7	6	48
2004	8	24	22	22	19	18	113	16	8	10	19	16	6	75
2005	2	18	19	19	12	13	83	12	10	19	18	19	15	93
2006	3	13	20	18	17	14	85	19	20	20	21	22	16	118
2007	–	10	15	17	11	15	68	16	17	17	17	14	10	91
2008	–	1	12	12	10	13	48	15	10	11	12	6	–	54
2009	–	2	9	13	12	11	47	4	3	6	12	11	3	39
2010	5	10	15	15	13	15	73	16	10	7	13	14	7	67
2011	2	17	19	16	16	15	85	10	8	16	16	9	2	61
2012	5	18	15	16	13	16	83	10	10	14	18	9	6	67
2013	8	15	19	14	15	17	88	15	11	15	19	15	3	78
2014	5	16	18	15	18	16	88	17	15	19	19	16	7	93
2015	1	15	20	20	17	14	87	15	21	22	21	21	13	113

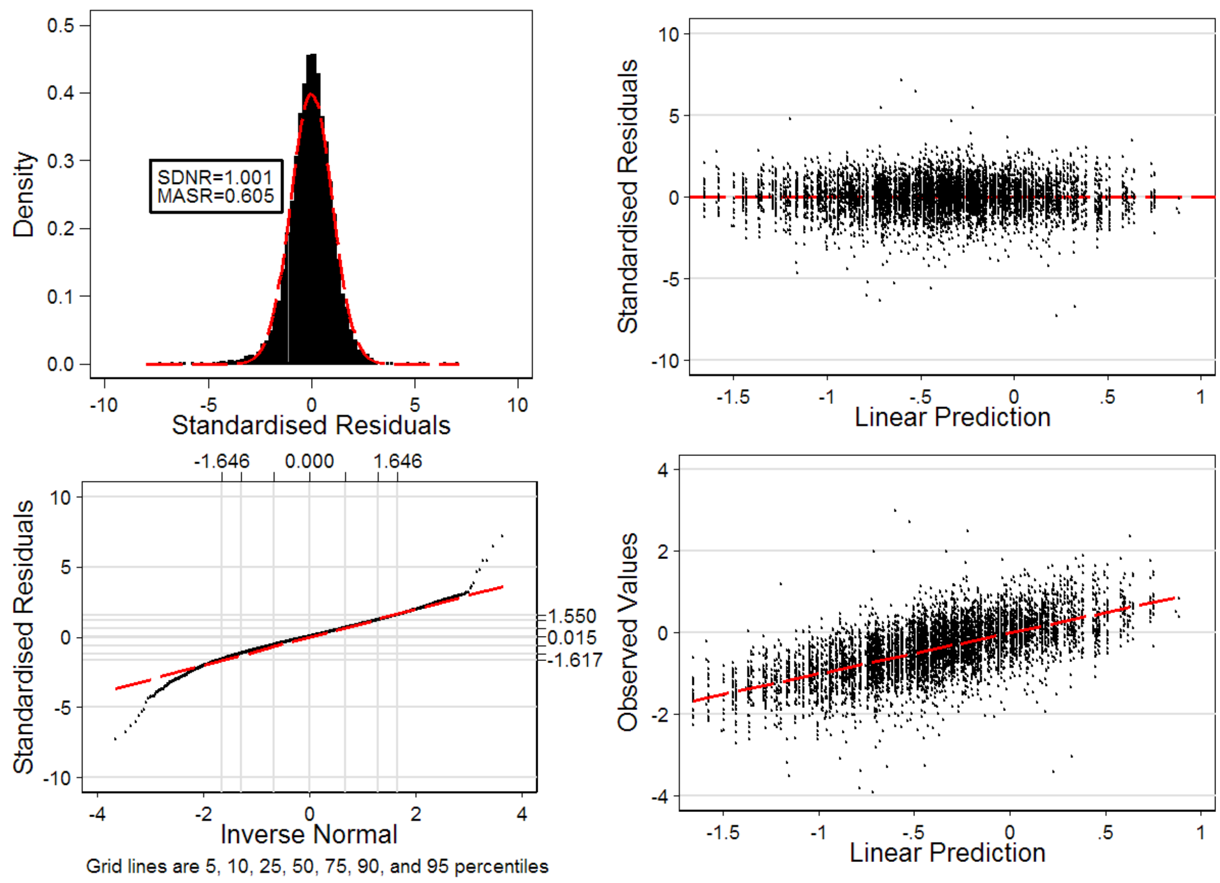


Figure A.13. Standardised residuals for the Area 914 CRA 4 sub-stock standardised seasonal F2_LFX CPUE analysis.

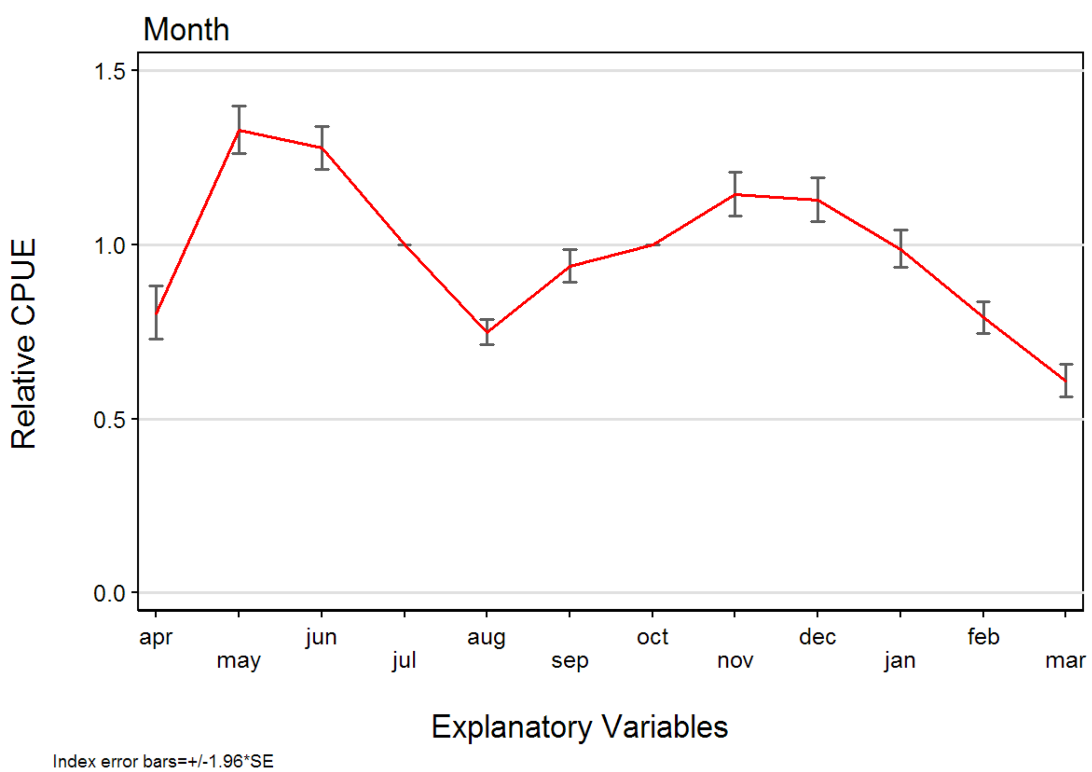


Figure A.14. Coefficients for month from the Area 914 CRA 4 sub-stock seasonal F2_LFX CPUE standardisation. Month coefficients are not in canonical form, with each of the two reference months (July and October) set to 1.0 and the associated SE set to zero.

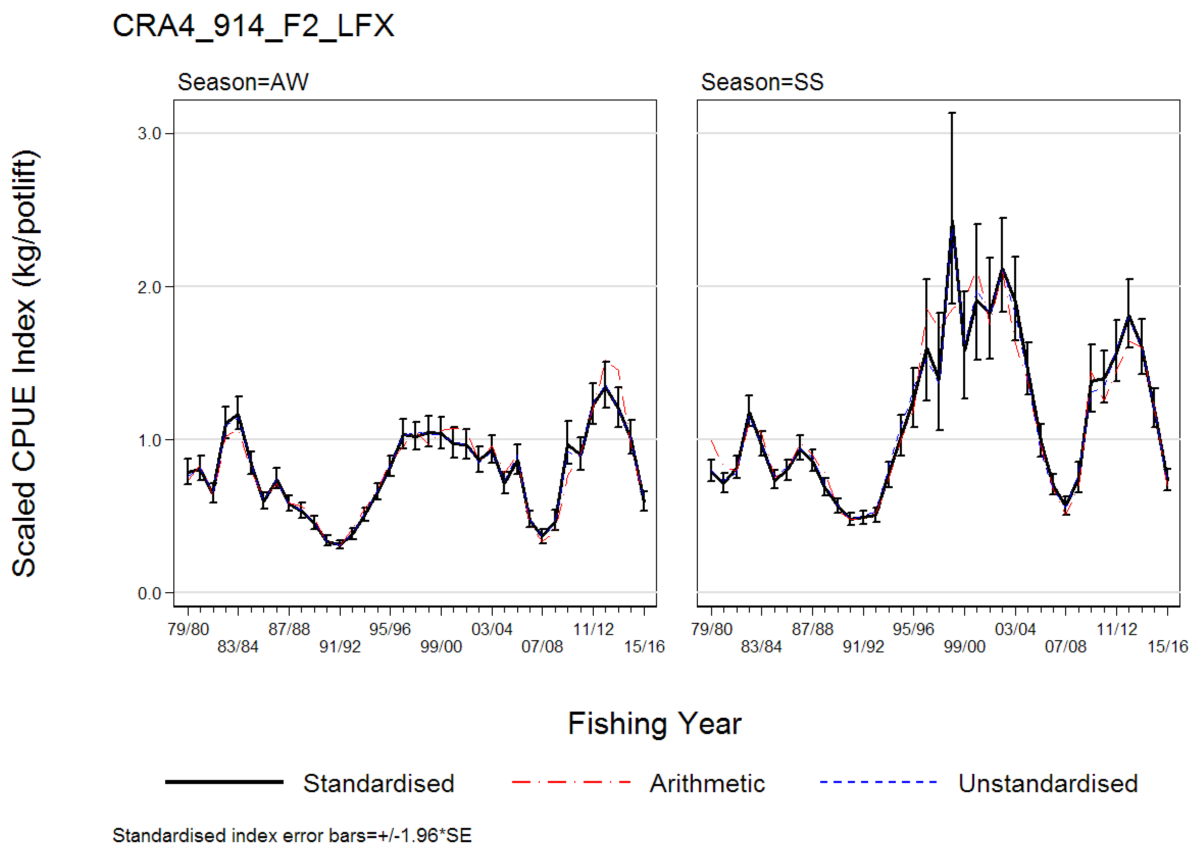


Figure A.15. Scaled standardised F2_LFX CPUE (kg/potlift) by period for the Area 914 CRA 4 sub-stock with the AW-SS seasons plotted separately. Also shown are the arithmetic or "raw" CPUE series and the geometric mean of the CPUE ("unstandardised"). The standardised and unstandardised series were scaled by multiplying each index in the unscaled series (where the geometric mean=1) by the geometric mean of the arithmetic CPUE series for each seasonal category (geometric mean for AW=0.74 kg/potlift; geometric mean for SS=1.04 kg/potlift).

Table A.15. Total deviance (R^2) explained by each variable in the Area 914 CRA 4 sub-stock standardised seasonal CPUE model.

Variable	**1**	**2**
Period	0.3460	
Month	0.0920	0.4313
Additional deviance explained	0.0000	0.0853

Table A.16: Standardised seasonal CPUE and standard errors for the Area 914 CRA 4 sub-stock.

Fishing Year	AW	s.e.	SS	s.e.	Fishing Year	AW	s.e.	SS	s.e.
1979	0.785	0.0534	0.793	0.0449	1998	1.049	0.0493	2.432	0.1288
1980	0.810	0.0510	0.715	0.0451	1999	1.039	0.0506	1.578	0.1117
1981	0.649	0.0507	0.818	0.0473	2000	0.976	0.0519	1.913	0.1176
1982	1.105	0.0478	1.184	0.0422	2001	0.967	0.0513	1.829	0.0917
1983	1.168	0.0471	0.968	0.0422	2002	0.866	0.0488	2.117	0.0739
1984	0.843	0.0446	0.737	0.0430	2003	0.932	0.0501	1.903	0.0729
1985	0.597	0.0449	0.801	0.0420	2004	0.716	0.0487	1.456	0.0591
1986	0.744	0.0454	0.942	0.0428	2005	0.867	0.0561	0.989	0.0538
1987	0.582	0.0464	0.859	0.0418	2006	0.477	0.0555	0.705	0.0481
1988	0.535	0.0460	0.689	0.0431	2007	0.366	0.0616	0.566	0.0541
1989	0.456	0.0463	0.566	0.0432	2008	0.470	0.0729	0.745	0.0689
1990	0.337	0.0499	0.481	0.0445	2009	0.970	0.0736	1.384	0.0812
1991	0.312	0.0443	0.492	0.0449	2010	0.903	0.0597	1.401	0.0622
1992	0.385	0.0465	0.508	0.0474	2011	1.226	0.0556	1.567	0.0653
1993	0.510	0.0443	0.765	0.0555	2012	1.349	0.0562	1.813	0.0625
1994	0.661	0.0409	1.019	0.0664	2013	1.201	0.0548	1.598	0.0581
1995	0.822	0.0414	1.261	0.0775	2014	1.011	0.0547	1.202	0.0535
1996	1.034	0.0470	1.604	0.1248	2015	0.596	0.0548	0.735	0.0491
1997	1.020	0.0452	1.393	0.1383					

A.3.1.4 AREA 915+934

Again, as with the other CRA 4 sub-stocks, the Area 915+934 data set shows a diminishing number of records over time (Table A.17). The total deviance explained by the Area 915+934 model was 37% (Table A.18), with area having slightly more explanatory power over month in the standardisation procedure. Residual patterns showed some deviation from the lognormal assumption at the peak of the residual distribution (Figure A.16).

The month categorical variable in the seasonal CPUE has a winter peak in June and there is no summer peak (Figure A.17, right panel). The coefficient for Area 934 exceeds that of the Area 915 coefficient (Figure A.17, left panel). Both the Area 915+934 AW and SS CPUE series showed similar patterns, with a suggestion that there might be an initial peak in the late 1990s in the SS series, although the model uncertainty is high (Figure A.18, Table A.19). Absolute catch rates are higher in the SS series and there is no AW peak in the 1990s (Figure A.18). The associated error is greater for the SS series, reflecting smaller amounts of data in the SS series (Figure A.18).

Table A.17. Number of vessel/month records in the dataset used to calculate the Area 915+934 CRA 4 sub-stock CPUE time series (based on the F2_LFX algorithm). '–': no data.

Fishing							AW							SS
year	Apr	May	Jun	Jul	Aug	Sep	Total	Oct	Nov	Dec	Jan	Feb	Mar	Total
1979	3	1	3	7	15	22	51	23	23	20	12	10	9	97
1980	5	9	10	13	12	13	62	25	23	21	18	16	14	117
1981	5	7	9	10	12	12	55	16	16	17	19	17	13	98
1982	4	3	12	13	17	16	65	18	19	19	19	20	16	111
1983	5	4	14	17	18	18	76	19	19	20	18	17	13	106
1984	1	5	15	18	19	18	76	19	16	16	15	18	12	96
1985	3	2	15	17	17	18	72	18	19	18	17	20	13	105
1986	–	8	13	15	13	18	67	18	18	17	16	15	7	91
1987	–	4	12	13	13	11	53	13	13	15	15	16	10	82
1988	–	5	13	10	15	13	56	14	14	10	10	12	6	66
1989	–	4	9	9	10	12	44	8	10	10	10	10	6	54
1990	–	1	10	12	12	14	49	14	13	12	11	11	8	69
1991	1	4	6	10	11	11	43	11	13	10	10	8	5	57
1992	–	3	10	10	11	11	45	11	10	10	10	9	6	56
1993	1	8	11	12	12	12	56	13	12	10	8	5	–	48
1994	–	10	13	12	13	12	60	13	9	7	5	3	–	37
1995	1	10	7	8	7	8	41	7	3	4	1	1	–	16
1996	4	11	7	10	9	9	50	3	1	2	–	–	–	6
1997	3	5	5	8	5	8	34	6	–	–	–	–	–	6
1998	5	8	8	7	6	7	41	3	4	2	1	1	1	12
1999	1	4	9	9	8	9	40	3	–	2	1	1	1	8
2000	4	5	8	8	10	10	45	9	2	1	1	1	2	16
2001	7	5	9	9	10	10	50	2	1	2	3	1	–	9
2002	3	4	8	10	7	7	39	5	2	5	4	4	3	23
2003	3	3	7	8	8	10	39	11	3	5	4	5	6	34
2004	5	4	6	7	6	6	34	5	3	6	5	5	3	27
2005	4	5	6	5	6	5	31	3	5	6	6	9	8	37
2006	2	5	9	12	11	11	50	11	12	12	12	13	14	74
2007	–	3	8	10	11	9	41	5	10	8	12	12	13	60
2008	–	1	5	6	8	10	30	6	7	6	8	4	–	31
2009	–	–	4	10	9	7	30	6	5	4	12	10	3	40
2010	4	4	9	12	12	12	53	11	8	6	8	10	4	47
2011	1	4	5	8	7	8	33	6	3	9	7	8	2	35
2012	–	3	3	9	8	6	29	9	6	5	7	7	3	37
2013	1	1	5	6	5	5	23	5	2	4	5	4	4	24
2014	2	4	5	6	8	7	32	5	5	5	8	7	6	36
2015	–	4	6	7	6	7	30	7	8	6	9	8	6	44

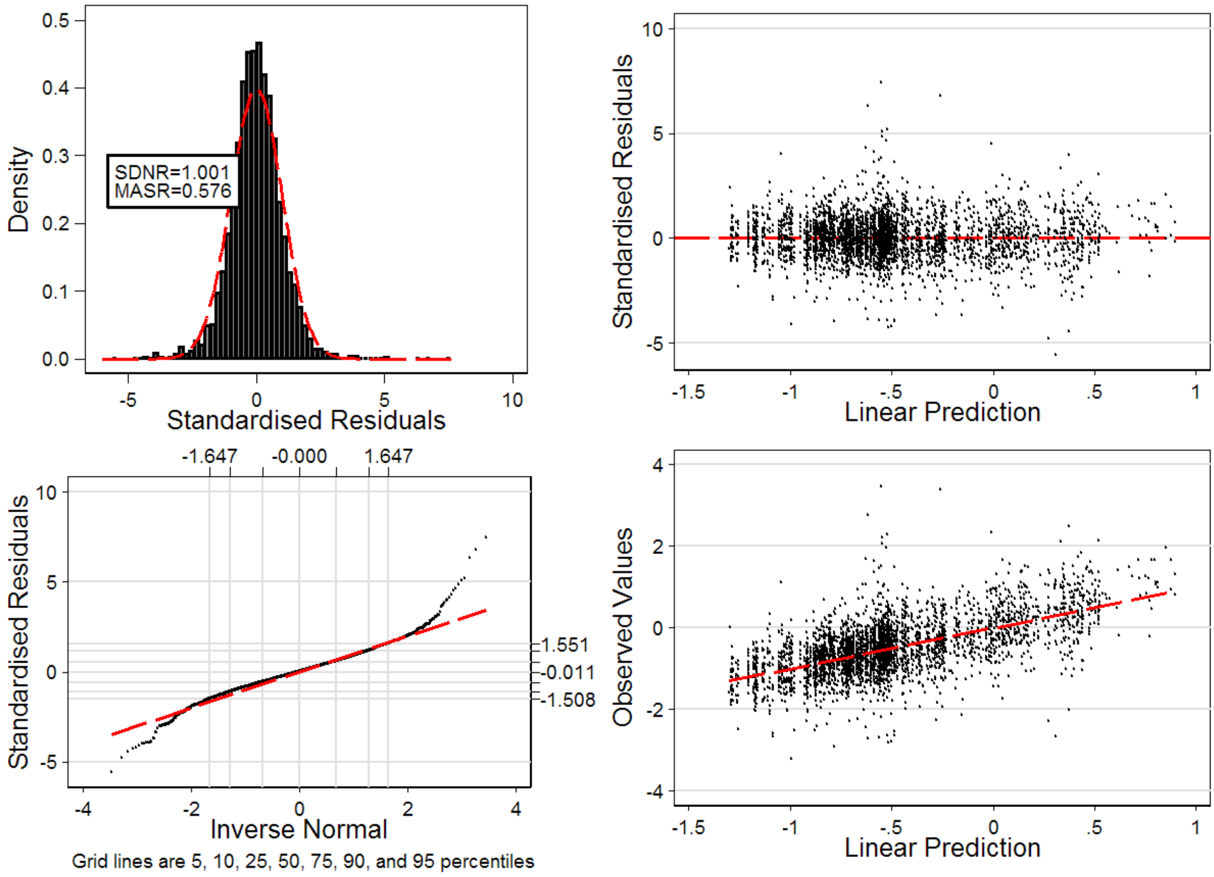


Figure A.16. Standardised residuals for the Area 915+934 CRA 4 sub-stock standardised seasonal F2_LFX CPUE analysis.

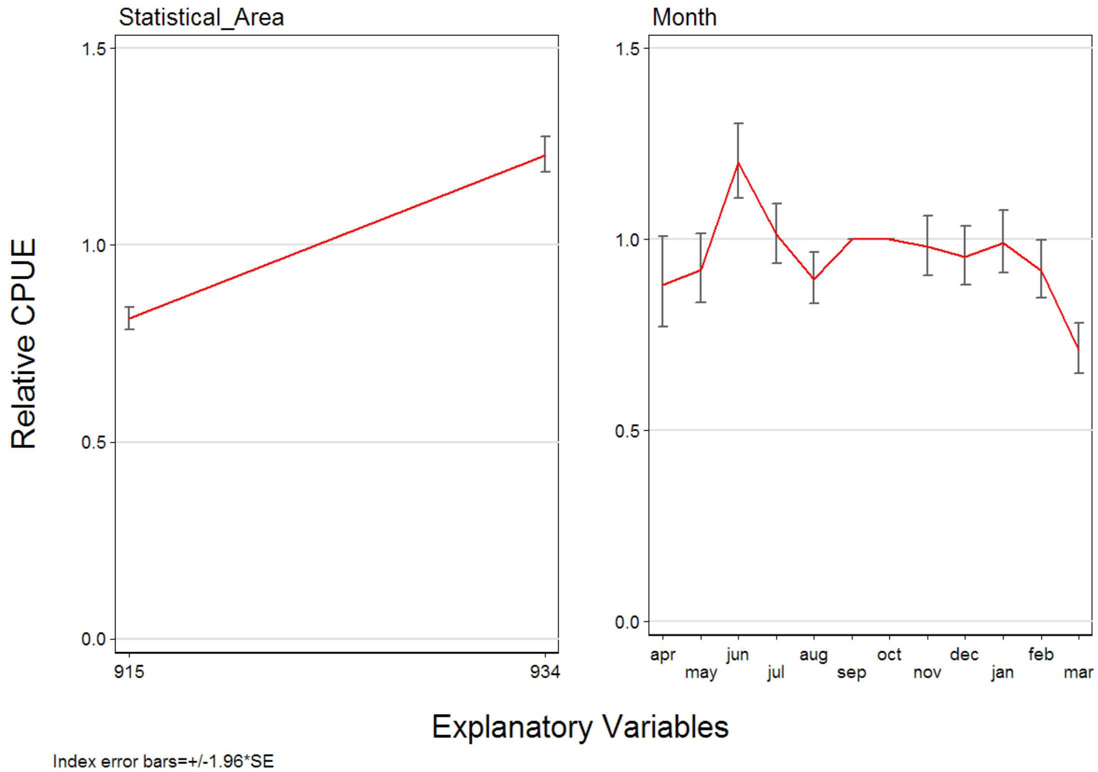


Figure A.17. Coefficients for statistical area and month from the Area 915+934 CRA 4 sub-stock seasonal F2_LFX CPUE standardisation. Month coefficients are not in canonical form, with each of the two reference months (September and October) set to 1.0 and the associated SE set to zero.

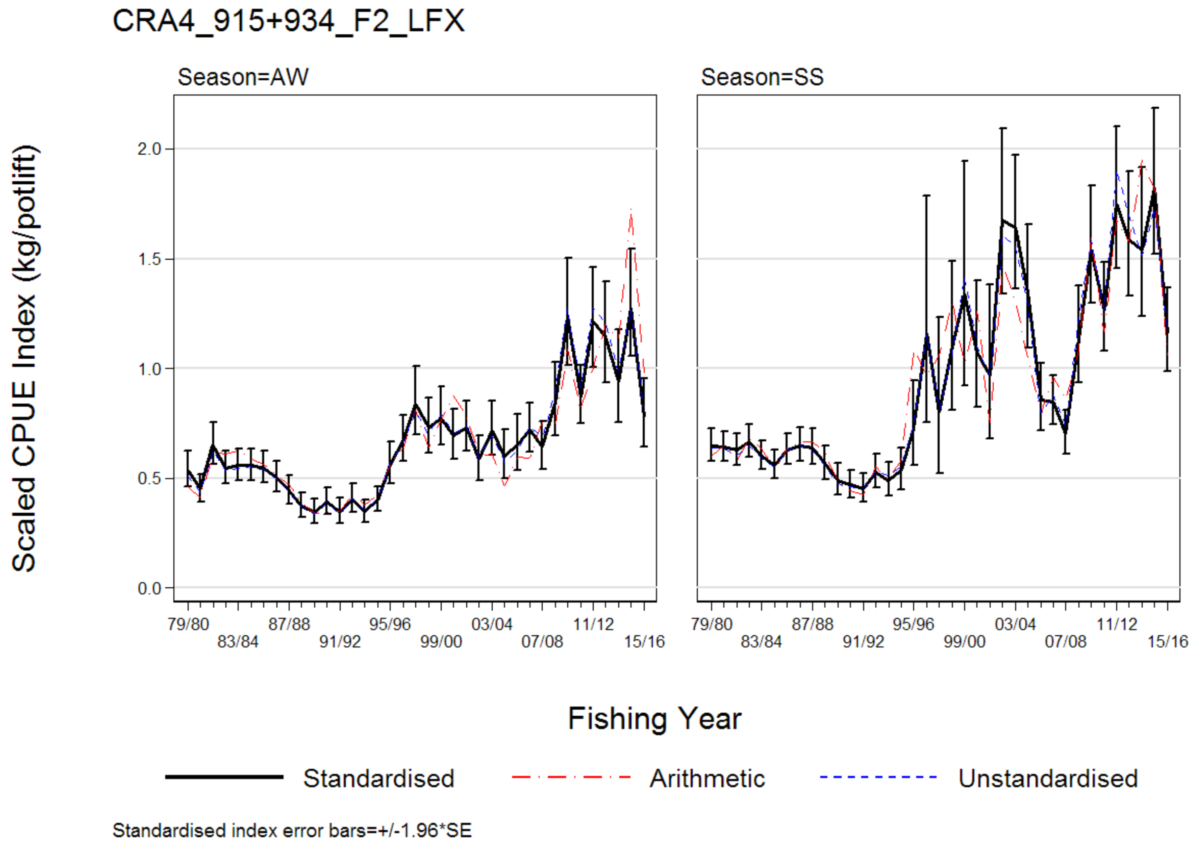


Figure A.18. Scaled standardised F2_LFX CPUE (kg/potlift) by period for the Area 915+934 CRA 4 sub-stock with the AW-SS seasons plotted separately. Also shown are the arithmetic or "raw" CPUE series and the geometric mean of the CPUE ("unstandardised"). The standardised and unstandardised series were scaled by multiplying each index in the unscaled series (where the geometric mean=1) by the geometric mean of the arithmetic CPUE series for each seasonal category (geometric mean for AW=0.62 kg/potlift; geometric mean for SS=0.87 kg/potlift).

Table A.18. Total deviance (R^2) explained by each variable in the Area 915+934 CRA 4 sub-stock standardised seasonal CPUE model.

Variable	**1**	**2**	**3**
Period	0.3233		
Area	0.0456	0.3459	
Month	0.0333	0.3458	0.3682
Additional deviance explained	0.0000	0.0226	0.0222

Table A.19: Standardised seasonal CPUE and standard errors for the Area 915+934 CRA 4 sub-stock.

Fishing Year	AW	s.e.	SS	s.e.	Fishing Year	AW	s.e.	SS	s.e.
1979	0.535	0.0772	0.649	0.0582	1998	0.729	0.0867	1.097	0.1562
1980	0.450	0.0712	0.641	0.0538	1999	0.774	0.0872	1.340	0.1906
1981	0.651	0.0752	0.627	0.0585	2000	0.692	0.0826	1.074	0.1350
1982	0.545	0.0695	0.667	0.0554	2001	0.730	0.0789	0.970	0.1800
1983	0.557	0.0648	0.601	0.0564	2002	0.585	0.0885	1.674	0.1137
1984	0.558	0.0648	0.559	0.0587	2003	0.718	0.0881	1.640	0.0940
1985	0.547	0.0663	0.629	0.0566	2004	0.601	0.0946	1.345	0.1054
1986	0.503	0.0685	0.649	0.0601	2005	0.651	0.0989	0.855	0.0914
1987	0.443	0.0766	0.640	0.0632	2006	0.722	0.0785	0.848	0.0665
1988	0.375	0.0745	0.567	0.0693	2007	0.642	0.0864	0.703	0.0737
1989	0.345	0.0832	0.490	0.0763	2008	0.846	0.0998	1.136	0.0988
1990	0.391	0.0791	0.470	0.0679	2009	1.234	0.1002	1.542	0.0878
1991	0.347	0.0841	0.453	0.0741	2010	0.873	0.0765	1.265	0.0808
1992	0.406	0.0824	0.527	0.0747	2011	1.212	0.0956	1.749	0.0935
1993	0.348	0.0746	0.491	0.0800	2012	1.144	0.1019	1.589	0.0906
1994	0.402	0.0724	0.536	0.0902	2013	0.942	0.1137	1.539	0.1115
1995	0.561	0.0866	0.726	0.1352	2014	1.277	0.0970	1.823	0.0922
1996	0.675	0.0789	1.161	0.2196	2015	0.783	0.1000	1.162	0.0838
1997	0.838	0.0942	0.802	0.2198					

A.3.2 HISTORICAL CATCH RATE (CR) DATA

Catch and effort (days fishing) data from 1963 through 1973 from the Annala & King (1983) data set were allocated to rock lobster statistical areas using the procedure described in Section A.2.1. These data were used to calculate unstandardised catch per day for each calendar year from 1963 to 1973 for the four defined stocks (Table A.20) which are plotted after being normalised to the same geometric mean (Figure A.19). Note that the series for Areas 913 and 914 are the same because they have been derived from the same Annala & King statistical area (see Figure A.2).

Table A.20: Catch rate (kg/day) from the potlift data in Annala & King (1983) calculated for each statistical area after applying the algorithm described in Steps 1 to 5 (above). The calculated pk_y^a was also applied to the days fishing field before calculating the annual catch rate. The total CRA 4 catch rate values are those that are stored in CRACE.

Calendar	Stock/statistical area				
year	912	913	914	915+934	CRA 4
1963	145.7	304.4	304.4	121.1	69.2
1964	211.8	409.9	409.9	152.3	102.2
1965	285.4	377.2	377.2	129.3	114.5
1966	245.3	328.8	328.8	148.7	108.0
1967	238.2	245.8	245.8	143.9	93.6
1968	162.4	193.2	193.2	103.1	69.1
1969	157.6	137.3	137.3	99.7	60.1
1970	115.9	141.3	141.3	88.6	53.2
1971	95.6	136.3	136.3	96.7	50.4
1972	77.9	143.6	143.6	89.1	46.8
1973	103.9	136.0	136.0	70.1	47.8

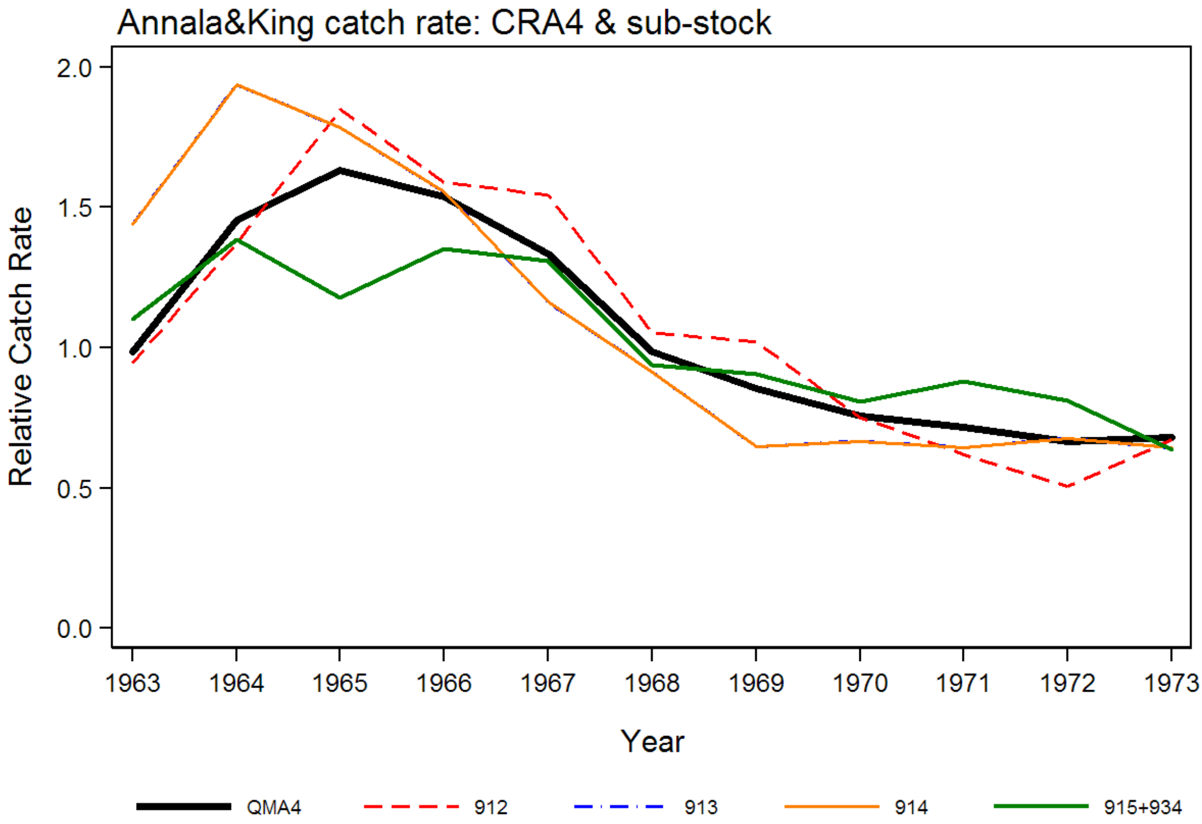


Figure A.19: Annala & King catch rates (Table A.20), normalised to the geometric mean, plotted for the four CRA 4 sub-stocks and the overall CRA 4 series.

A.4 LENGTH FREQUENCY DATA

The distribution of length frequencies for each of the five statistical areas that comprise the CRA 4 sub-stock are plotted by fishing year and season for males (Figure A.20) and females (Figure A.21). The distributions of the immature females are superimposed in black in the female plots. These plots show the availability of data in each of the four CRA 4 multi-area sub-stocks. While there are only very small amounts of data available for Area 934, they are largely consistent with the Area 915 data, justifying the amalgamation of these two statistical areas into a single region.

Table A.21 shows the number of lobsters measured by CRA 4 multi-area substock, year, season and catch sampling source.

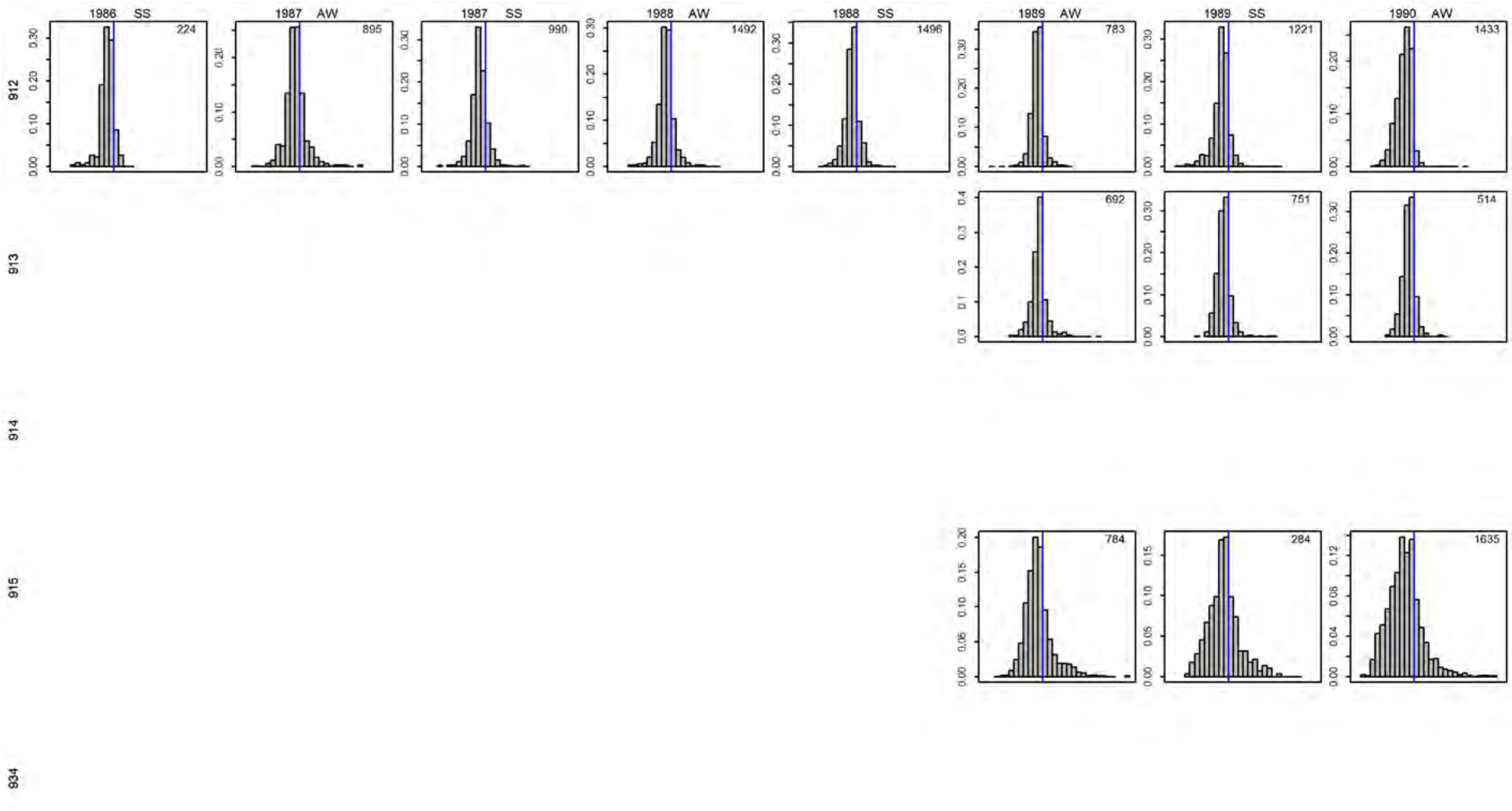


Figure A.20: Male length frequency distributions (30–90 mm) by Statistical Area, year and season. The number of males sampled is given in the upper right side of the figures. The current MLS of 54 mm is shown with a vertical blue line.

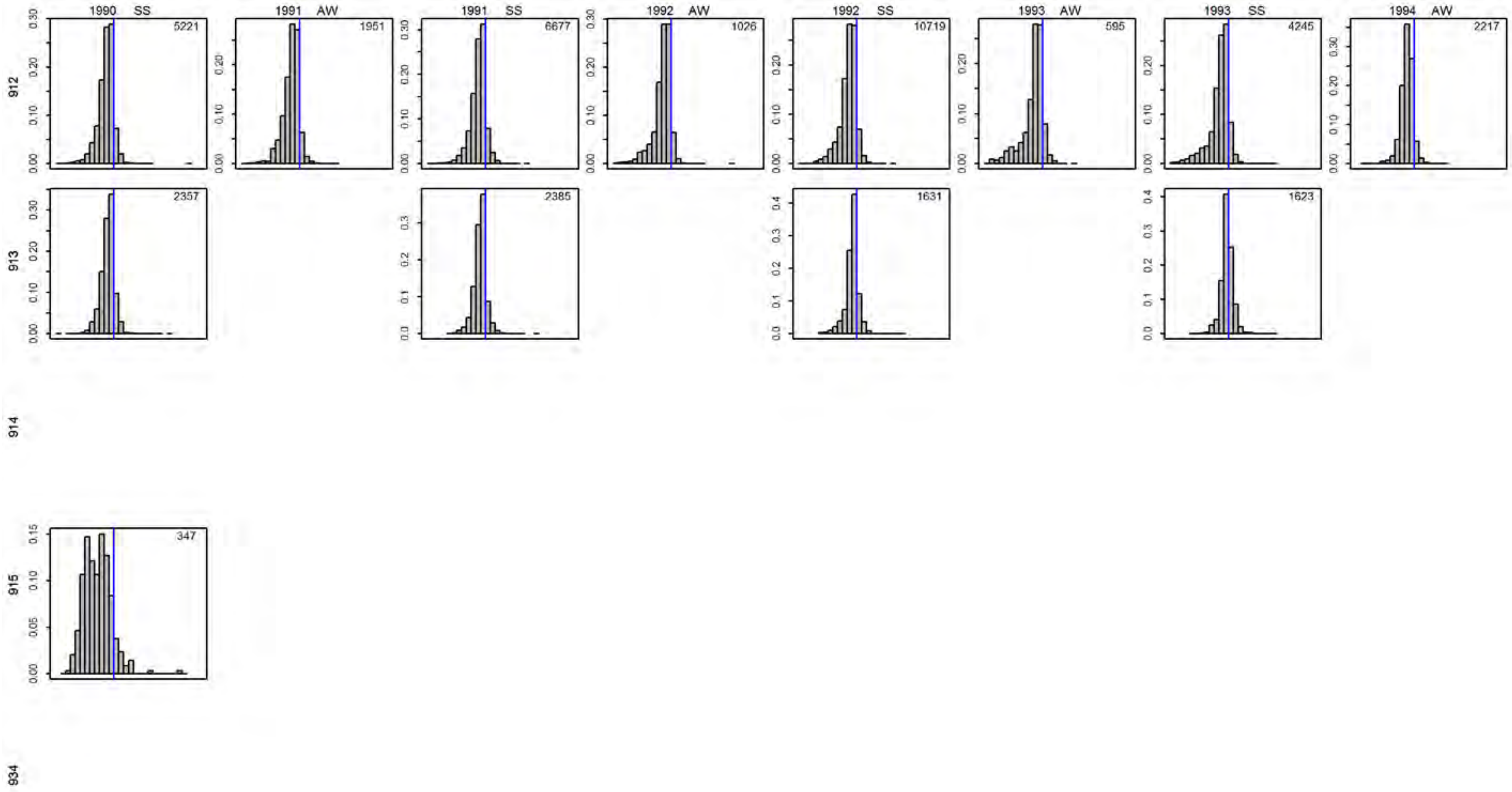


Figure A.20 (cont.): Male length frequency distributions (30–90 mm) by Statistical Area, year and season. The number of males sampled is given in the upper right side of the figures. The current MLS of 54 mm is shown with a vertical blue line.

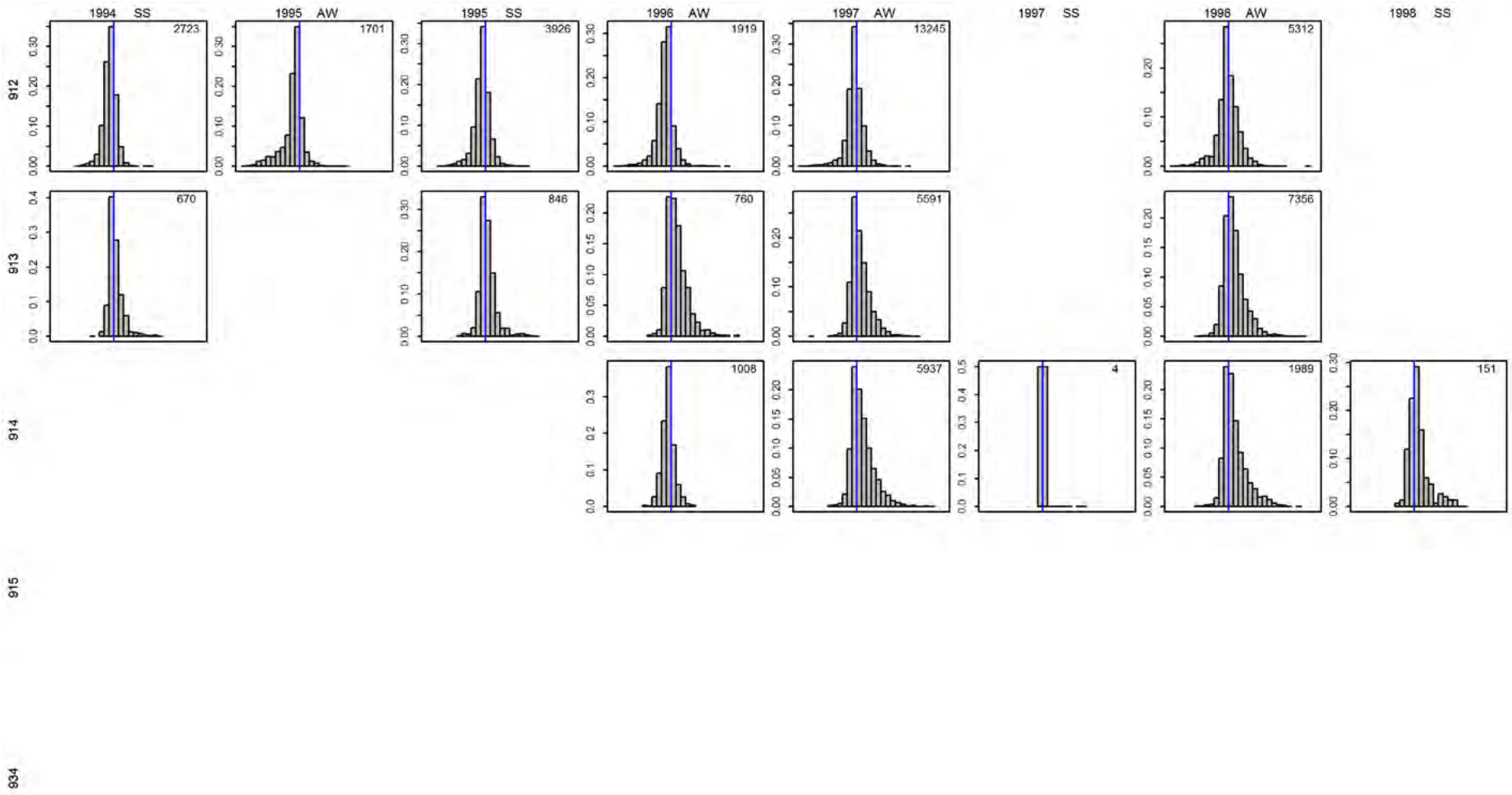


Figure A.20 (cont.): Male length frequency distributions (30–90 mm) by Statistical Area, year and season. The number of males sampled is given in the upper right side of the figures. The current MLS of 54 mm is shown with a vertical blue line.

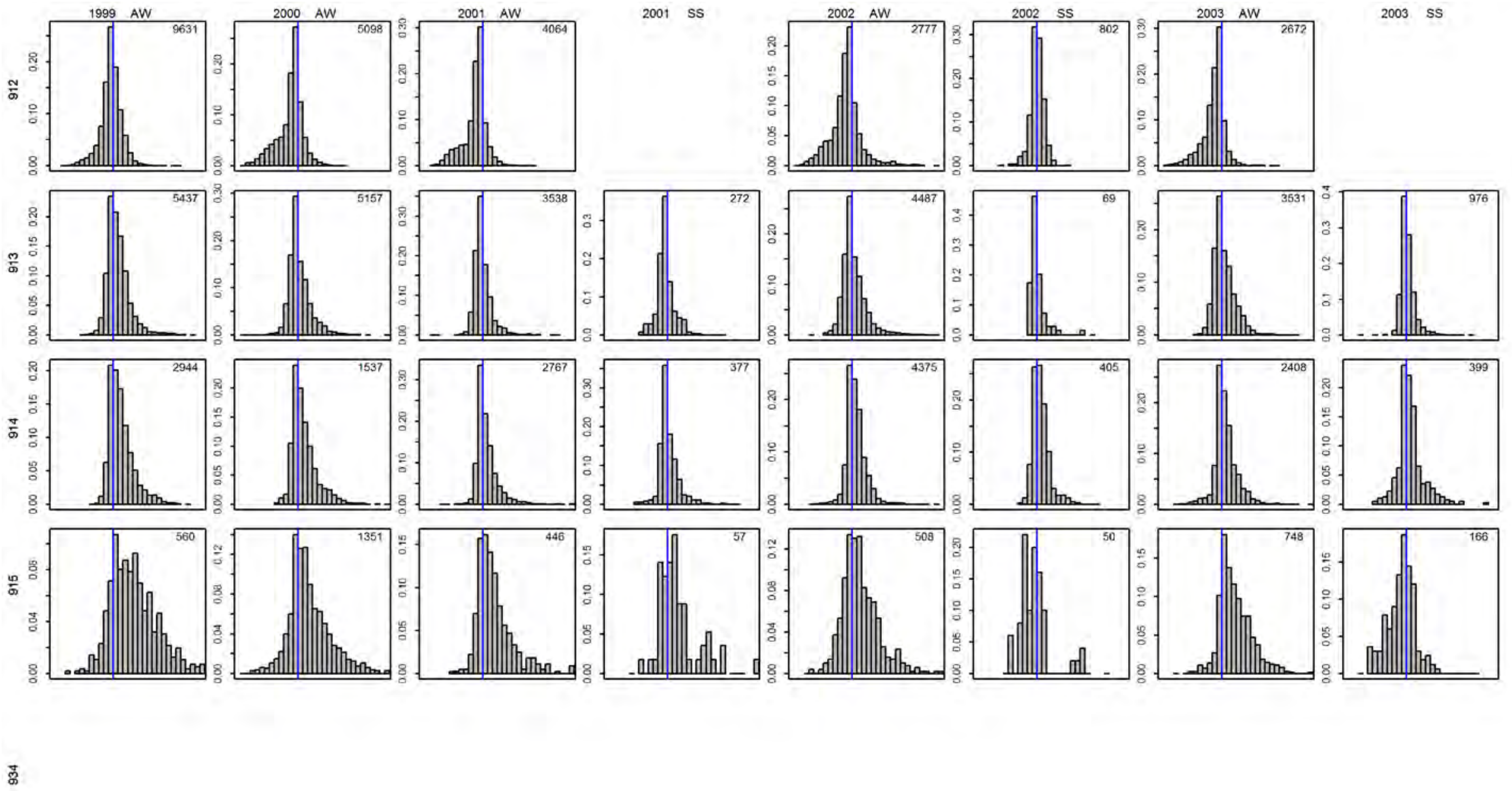


Figure A.20 (cont.): Male length frequency distributions (30–90 mm) by Statistical Area, year and season. The number of males sampled is given in the upper right side of the figures. The current MLS of 54 mm is shown with a vertical blue line.

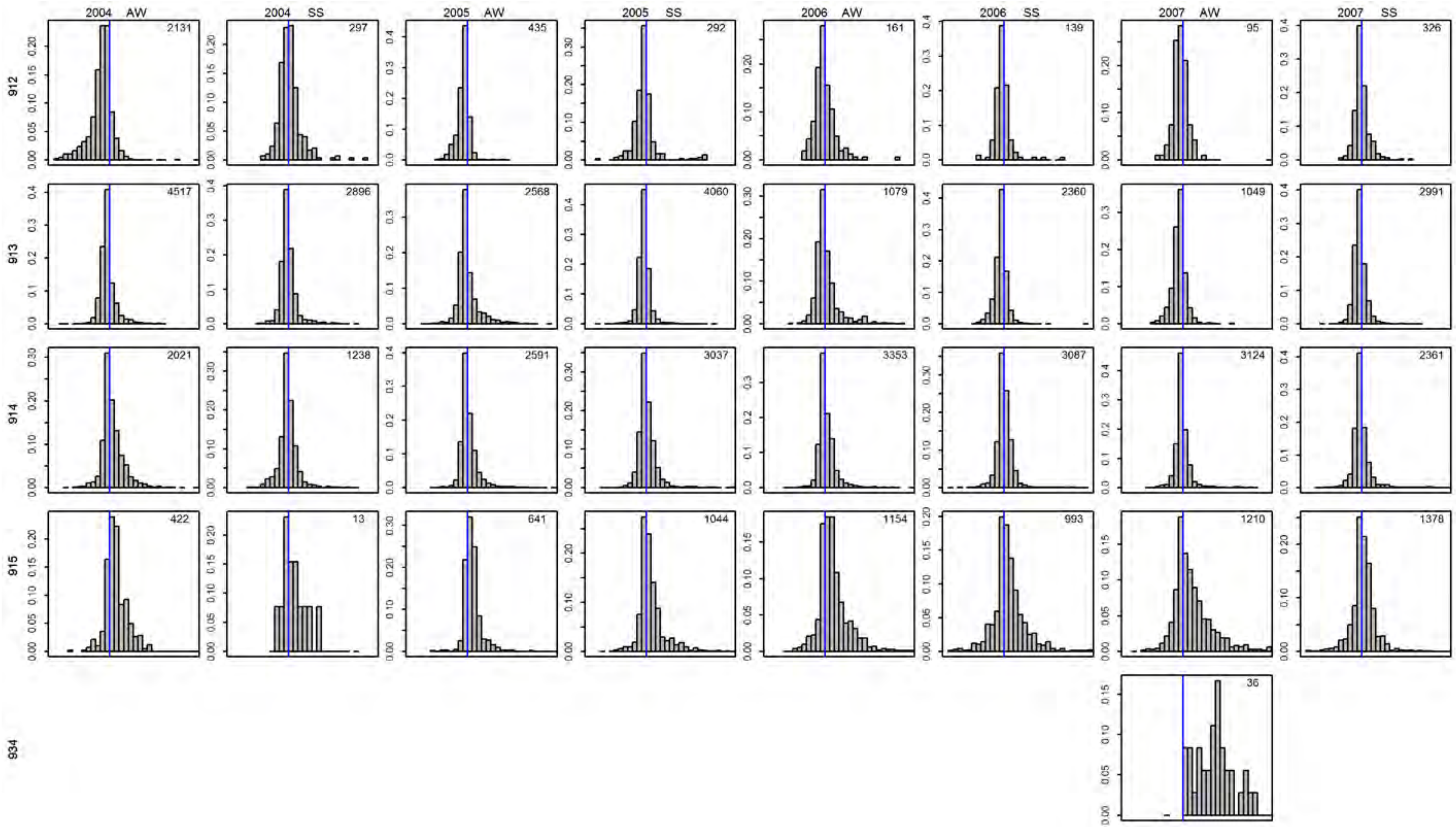


Figure A.20 (cont.): Male length frequency distributions (30- 90 mm) by Statistical Area, year and season. The number of males sampled is given in the upper right side of the figures. The current MLS of 54 mm is shown with a vertical blue line.

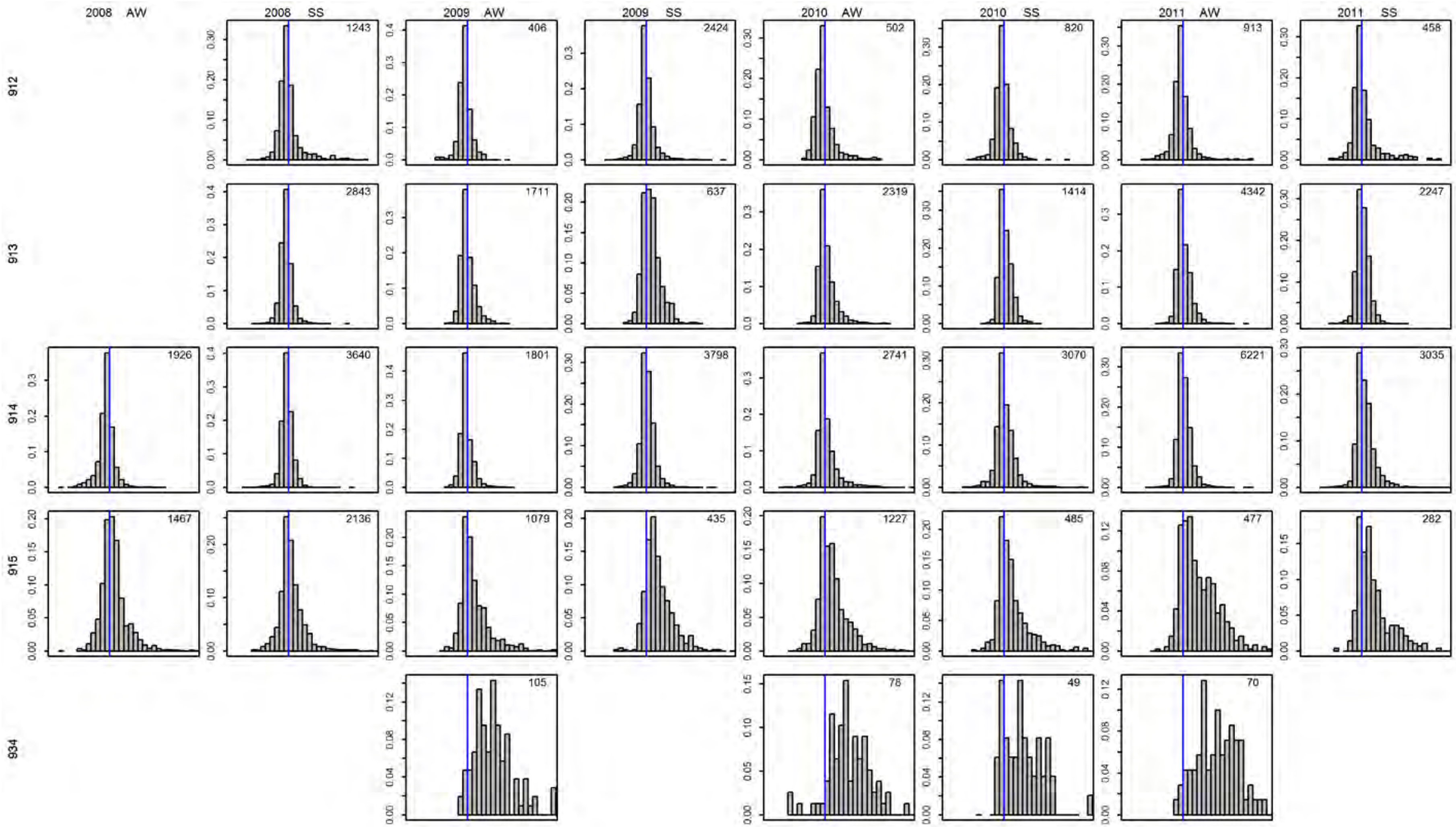


Figure A.20 (cont.): Male length frequency distributions (30–90 mm) by Statistical Area, year and season. The number of males sampled is given in the upper right side of the figures. The current MLS of 54 mm is shown with a vertical blue line.

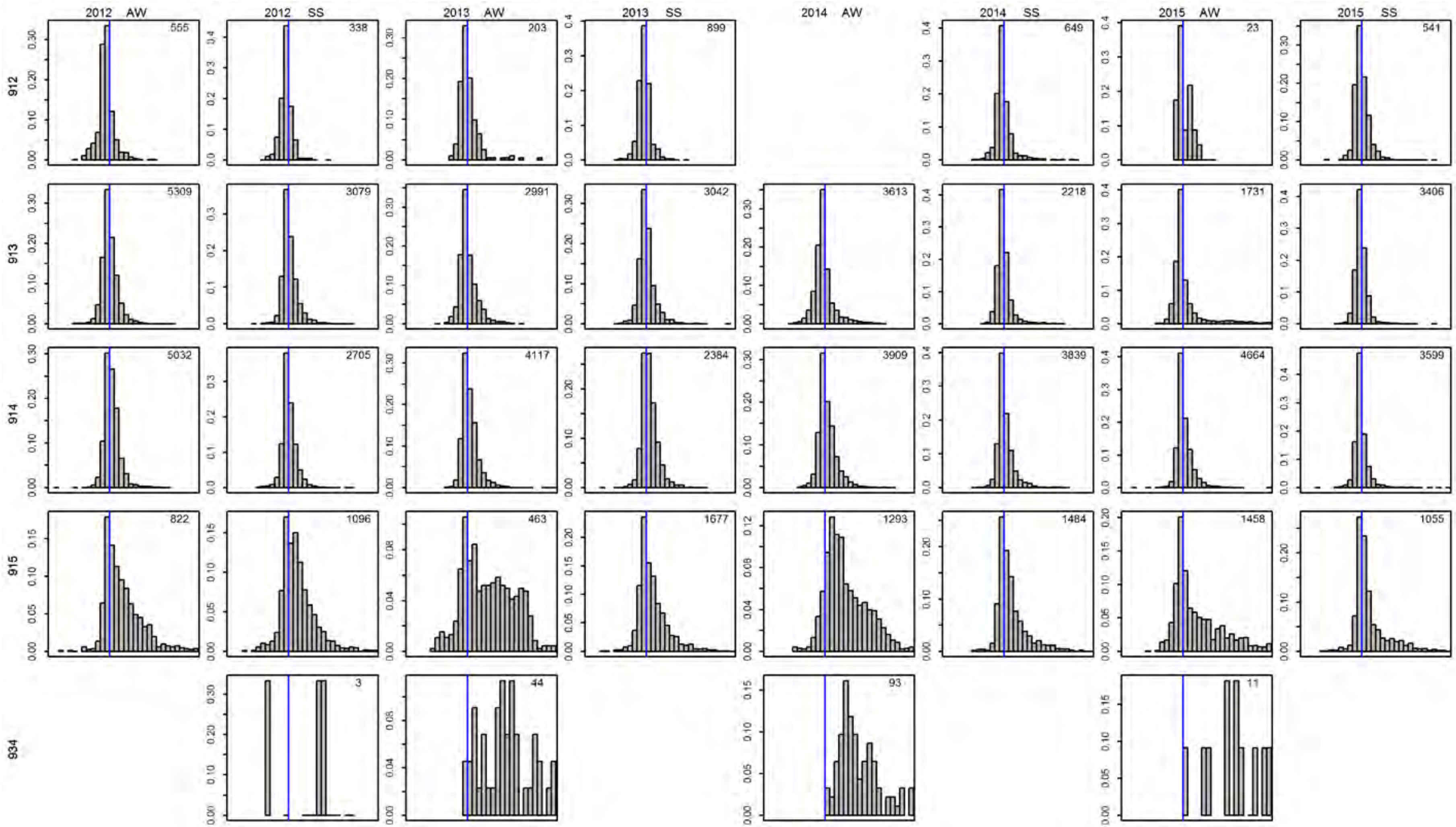


Figure A.20 (cont.): Male length frequency distributions (30- 90 mm) by Statistical Area, year and season. The number of males sampled is given in the upper right side of the figures. The current MLS of 54 mm is shown with a vertical blue line.

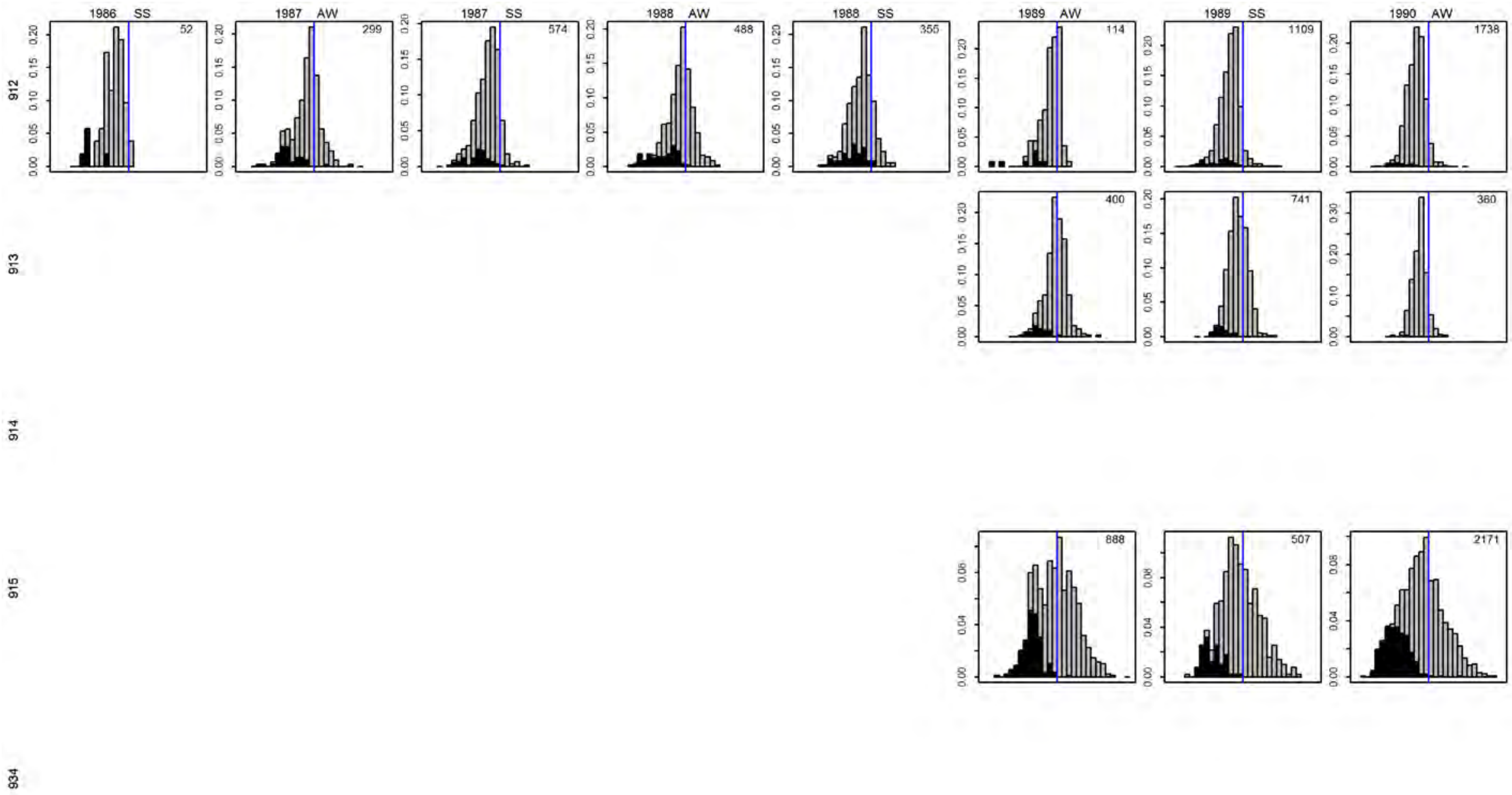


Figure A.21: Female length frequency distributions (30- 90 mm) by Statistical Area, year and season. Immature females are shown in black and mature females in grey. The number of females sampled is given in the upper right side of the figures. The current MLS of 60 mm is shown with a vertical blue line.

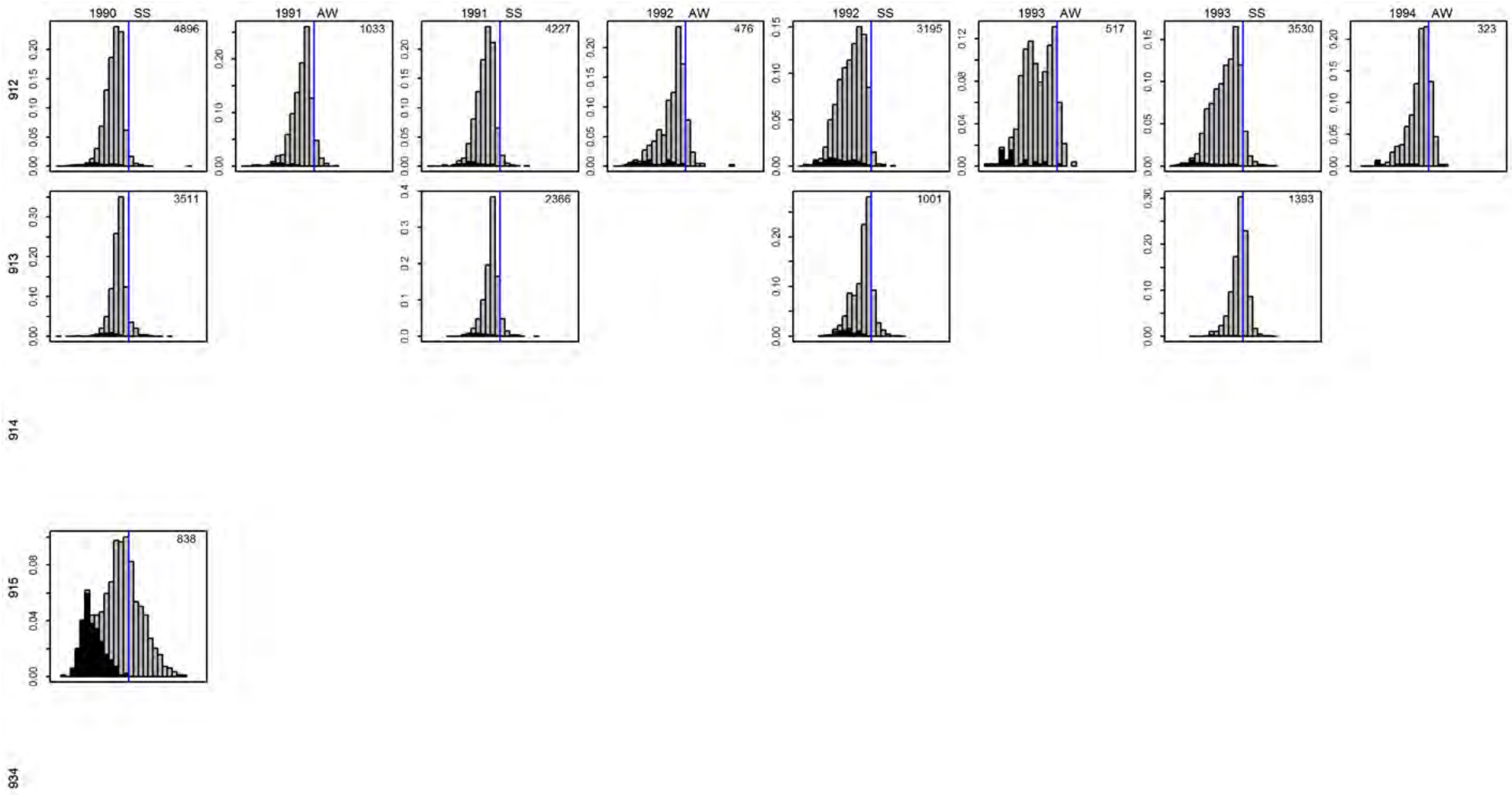


Figure A.21 (cont.): Female length frequency distributions (30- 90 mm) by Statistical Area, year and season. Immature females are shown in black and mature females in grey. The number of females sampled is given in the upper right side of the figures. The current MLS of 60 mm is shown with a vertical blue line.

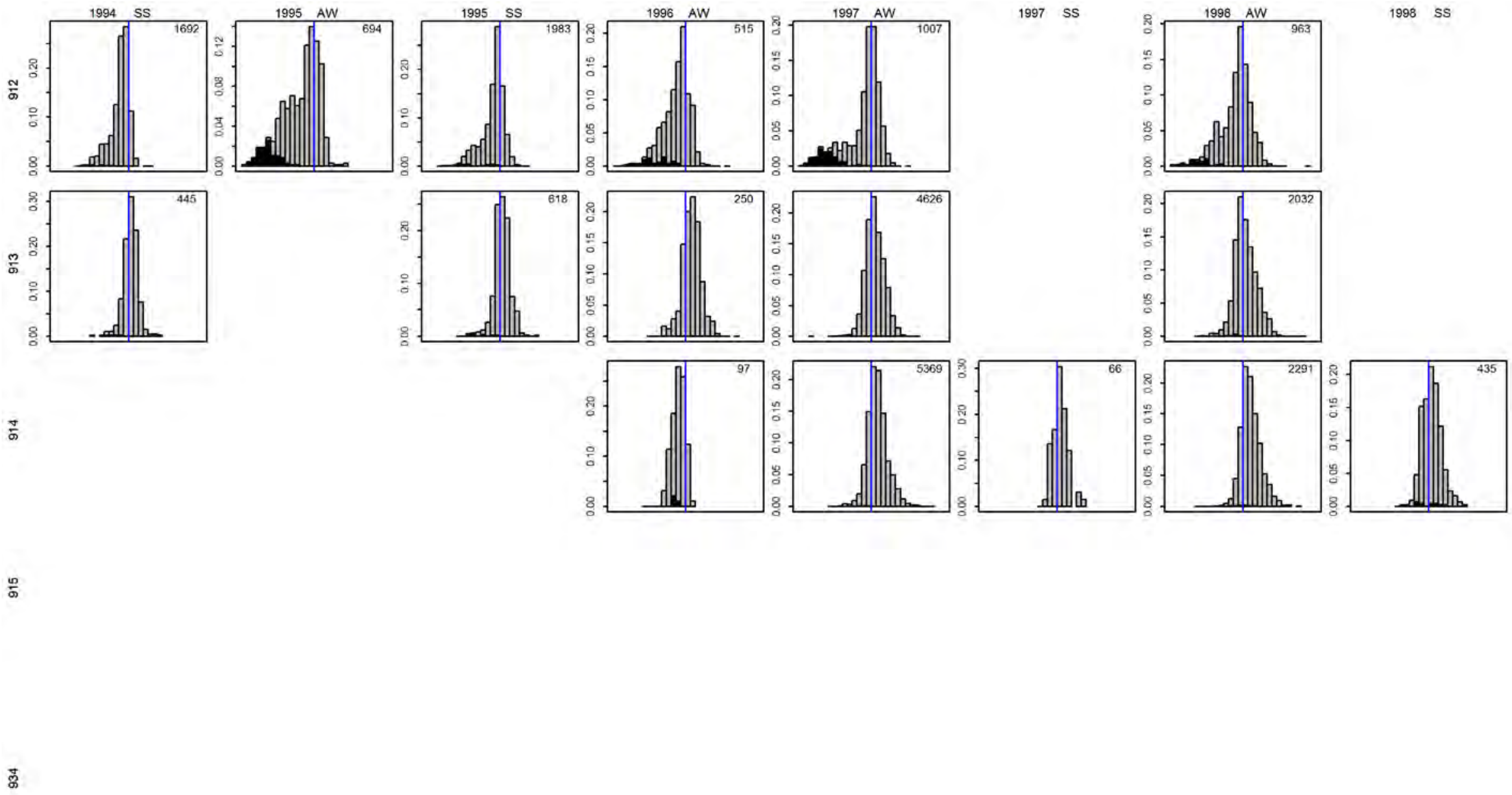


Figure A.21 (cont.): Female length frequency distributions (30- 90 mm) by Statistical Area, year and season. Immature females are shown in black and mature females in grey. The number of females sampled is given in the upper right side of the figures. The current MLS of 60 mm is shown with a vertical blue line.

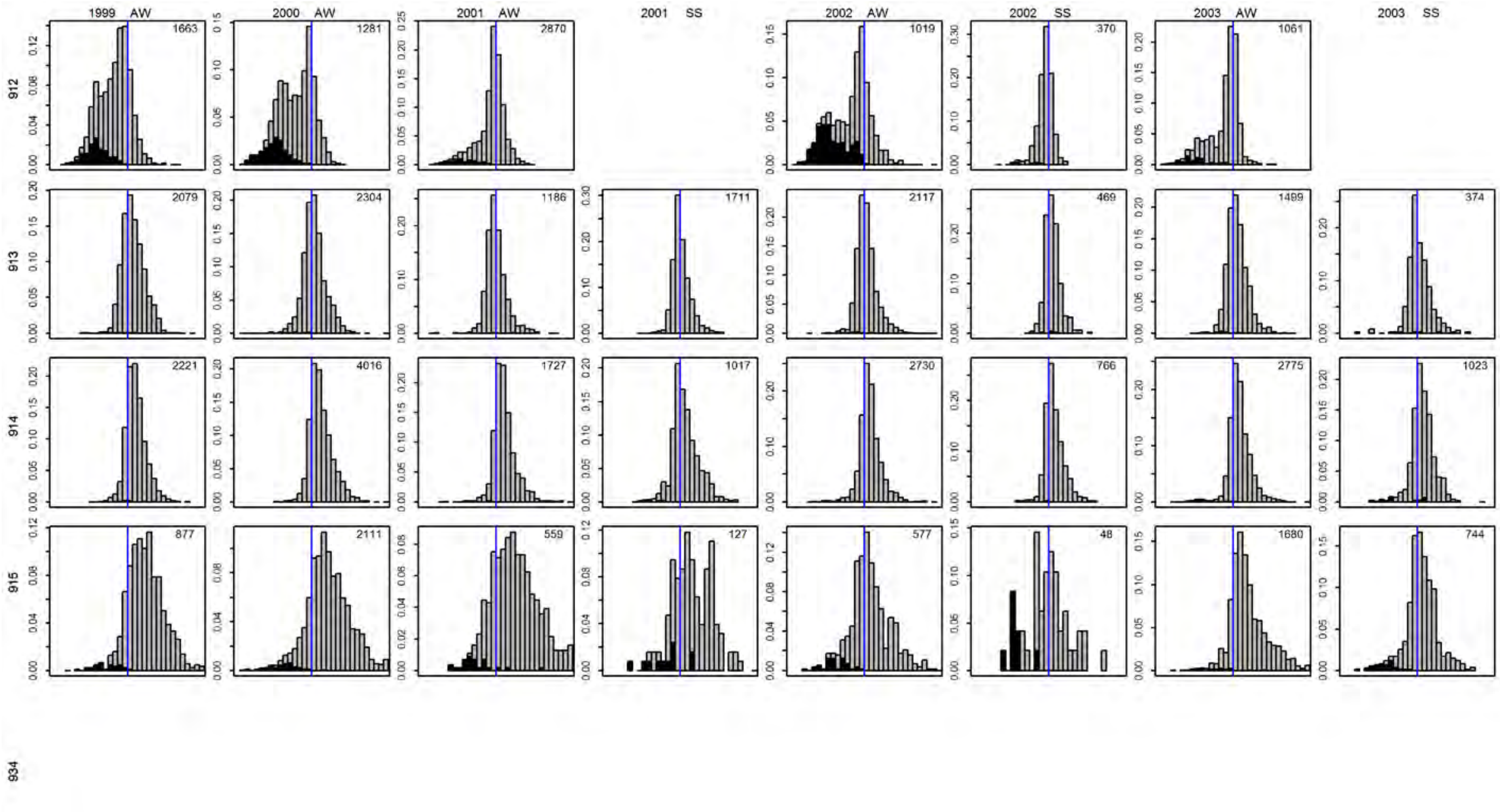


Figure A.21 (cont.): Female length frequency distributions (30–90 mm) by Statistical Area, year and season. Immature females are shown in black and mature females in grey. The number of females sampled is given in the upper right side of the figures. The current MLS of 60 mm is shown with a vertical blue line.

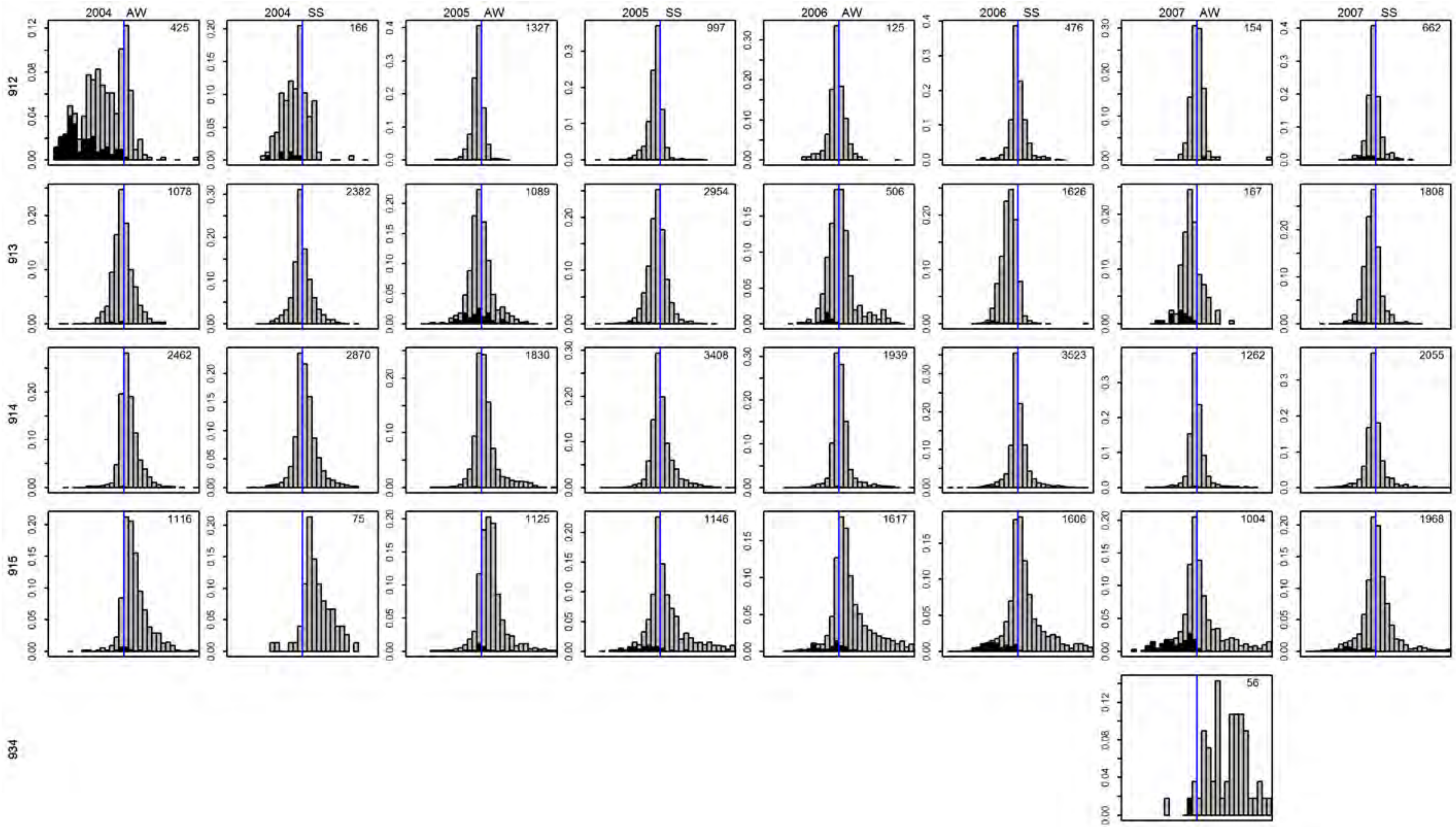


Figure A.21 (cont.): Female length frequency distributions (30–90 mm) by Statistical Area, year and season. Immature females are shown in black and mature females in grey. The number of females sampled is given in the upper right side of the figures. The current MLS of 60 mm is shown with a vertical blue line.

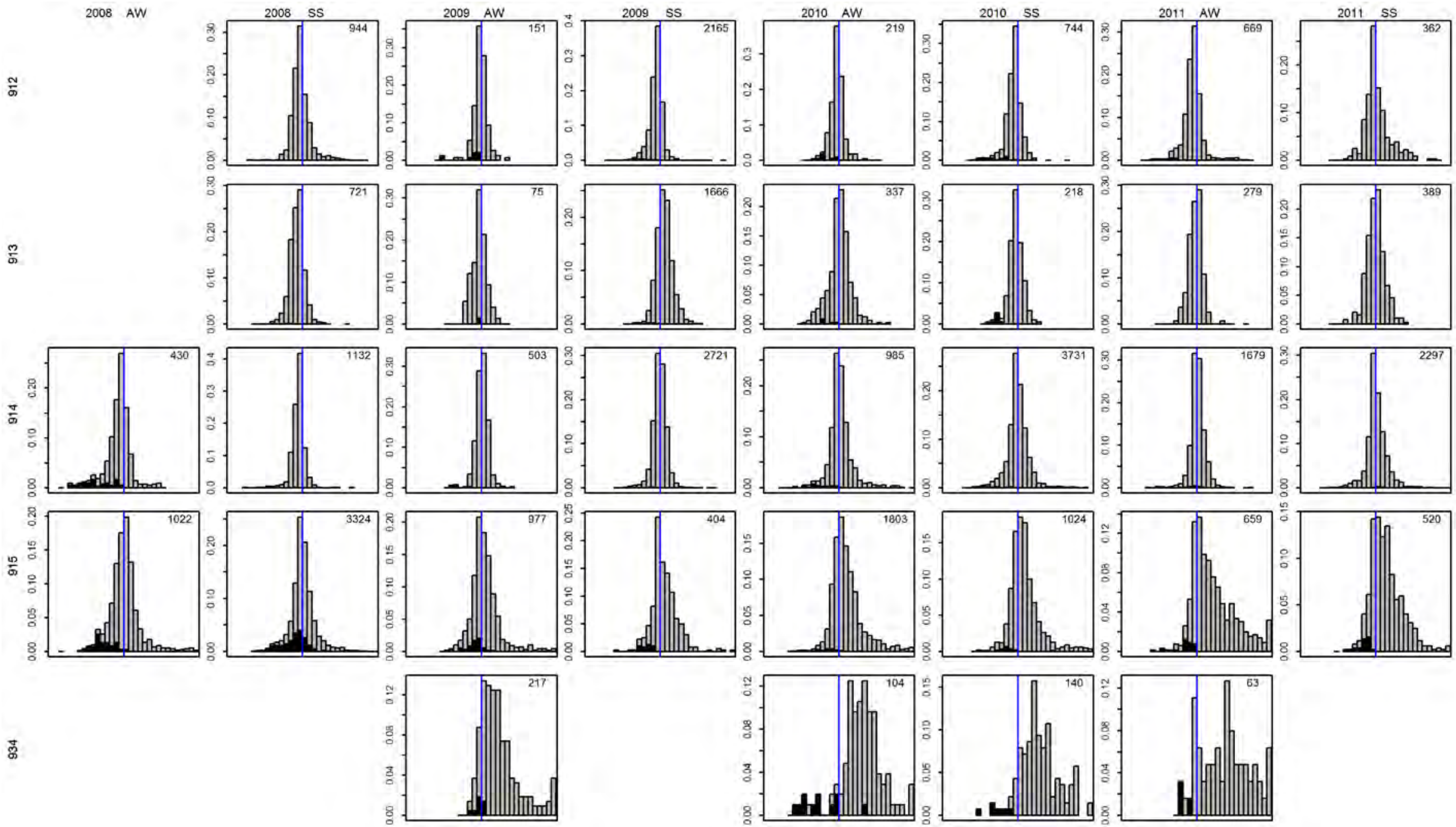


Figure A.21 (cont.): Female length frequency distributions (30–90 mm) by Statistical Area, year and season. Immature females are shown in black and mature females in grey. The number of females sampled is given in the upper right side of the figures. The current MLS of 60 mm is shown with a vertical blue line.

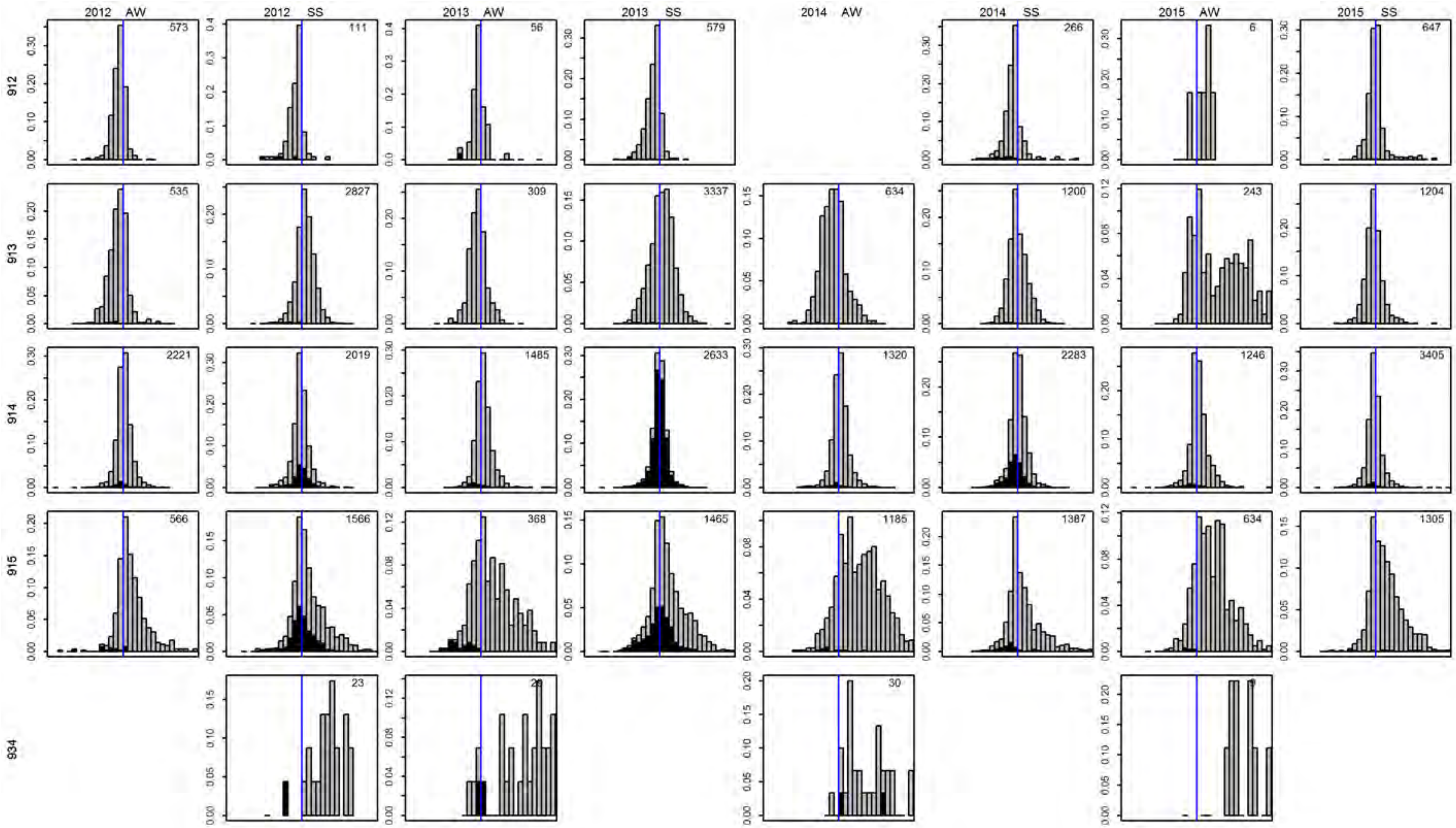


Figure A.21 (cont.): Female length frequency distributions (30–90 mm) by Statistical Area, year and season. Immature females are shown in black and mature females in grey. The number of females sampled is given in the upper right side of the figures. The current MLS of 60 mm is shown with a vertical blue line.

Table A.21: Number of lobsters measured by CRA 4 sub-stock, season and catch sampling source. codes: LB=logbook; CS=catch sampling.

	912				913				914				915+934			
Fishing	AW		SS		AW		SS		AW		SS		AW		SS	
year	LB	CS	LB	CS	LB	CS	LB	CS	LB	CS	LB	CS	LB	CS	LB	CS
1986	–	–	–	276	–	–	–	–	–	–	–	–	–	–	–	–
1987	–	1 194	–	1 564	–	–	–	–	–	–	–	–	–	–	–	–
1988	–	1 980	–	1 851	–	–	–	–	–	–	–	–	–	–	–	–
1989	–	897	–	2 330	–	1 092	–	1 492	–	–	–	–	–	1 672	–	791
1990	–	3 171	–	10 117	–	874	–	5 868	–	–	–	–	–	3 806	–	1 185
1991	–	2 984	–	10 904	–	–	–	4 751	–	–	–	–	–	–	–	–
1992	–	1 502	–	13 914	–	–	–	2 632	–	–	–	–	–	–	–	–
1993	–	1 112	–	7 775	–	–	–	3 016	–	–	–	–	–	–	–	–
1994	–	2 540	–	4 415	–	–	–	1 115	–	–	–	–	–	–	–	–
1995	–	2 395	–	5 909	–	–	–	1 464	–	–	–	–	–	–	–	–
1996	–	2 434	–	–	–	1 010	–	–	–	1 105	–	–	–	–	–	–
1997	–	14 252	–	–	–	10 217	–	–	1 774	9 532	70	–	–	–	–	–
1998	–	6 275	–	–	–	9 388	–	–	811	3 469	586	–	–	–	–	–
1999	–	11 294	–	–	–	7 516	–	–	297	4 868	–	–	–	1 437	–	–
2000	–	6 379	–	–	–	7 461	–	–	–	5 553	–	–	331	3 131	–	–
2001	–	6 934	–	–	–	4 724	–	1 983	–	4 494	–	1 394	–	1 005	–	184
2002	–	3 796	–	1 172	–	6 604	–	538	–	7 105	–	1 171	494	591	98	–
2003	–	3 733	–	–	–	5 030	–	1 350	–	5 183	–	1 422	1 252	1 176	246	664
2004	–	2 556	–	463	–	5 595	–	5 278	–	4 483	–	4 108	935	603	88	–
2005	–	1 762	–	1 289	395	3 262	–	7 014	–	4 421	–	6 445	1 766	–	300	1 890
2006	–	286	–	615	196	1 389	–	3 986	–	5 292	–	6 610	1 103	1 668	107	2 492
2007	–	249	–	988	–	1 216	–	4 799	–	4 386	–	4 416	738	1 568	662	2 684
2008	–	–	–	2 187	–	–	–	3 564	–	2 356	–	4 772	522	1 967	–	5 460
2009	–	557	–	4 589	–	1 786	–	2 303	–	2 304	37	6 482	865	1 513	43	796
2010	–	721	–	1 564	645	2 011	804	828	506	3 220	264	6 537	1 055	2 157	396	1 302
2011	–	1 582	–	820	1 742	2 879	699	1 937	1 967	5 933	1 233	4 099	31	1 238	–	802
2012	–	1 128	–	449	1 186	4 658	1 356	4 550	1 393	5 860	496	3 380	226	1 162	1 329	648
2013	–	259	–	1 478	893	2 407	406	5 973	201	5 401	235	–	596	308	1 227	1 049
2014	–	–	216	699	703	3 544	1 605	1 813	1 060	4 169	1 664	3 988	1 411	1 190	1 946	925
2015	29	–	400	788	1 382	592	2 351	2 259	1 143	4 767	1 702	5 302	1 506	606	1 656	704

A.5 TAGGING DATA

The following three tables (Table A.22, Table A.23, Table A.24) provide basic information on the availability of tagging data for each of the four CRA 4 sub-stocks.

Table A.22: Number of tag recoveries by sex and Statistical Area of release for CRA 4 tag releases.

Area	Male	Female	Total
912	333	52	385
913	655	78	733
914	695	285	980
915	155	215	370
Total	1838	630	2468

Table A.23: Number of tag recoveries by year and area of release.

Year	912+913	914+915	Total
1982	10		10
1998	325	381	706
1999	255	207	462
2000	96	80	176
2001	4	1	5
2002		4	4
2003		6	6
2004		2	2
2005	21	169	190
2006	16	78	94
2007	16	132	148
2008	3	1	4
2009	32	42	74
2010	275	8	283
2011	50	2	52
2012	6		6
2014	9	234	243
2015		3	3
Total	1118	1350	2468

Table A.24: Number of tag recoveries by Statistical Area of release and of recovery.

Area of	Statistical Area of Recovery						
release	912	913	914	915	916	934	Total
912	378		7				385
913		727	6				733
914	9	3	966	2			980
915			9	327	32	2	370
Total	387	730	988	329	32	2	2468