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Comparison of MULTIFAN-CL and Stock Synthesis platforms for the 2014 skipjack assessment.

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1 Executive Summary

To date, several attempts at parallel stock assessment with different stock assessment platforms have been undertaken. Here we compare Stock Synthesis and MULTIFAN-CL(MFCL) using the 2014 WCPO skipjack stock assessment as an example. Both stock assessment platforms use an "integrated analysis" approach, which combines several sources of data into a single analysis (Maunder and Punt, 2013).

The skipjack stock assessment in the Western Central Ocean is a very unique stock assessment among those for WCPO tuna and tuna like species, because there are no longline CPUE indices that can be assumed to provide region-specific stock abundance trends. Instead, a huge amount of tag release/recapture data is available and used in the stock assessment. This amounts to 251 tag release groups stratified by time and region at release from four major tag research programs. This is probably one of the biggest tag release/recapture data sets used for stock assessments of tuna and tuna like species. Since SS implemented the capability for spatial structure with tag release/recapture data, there have been several attempts to use these features. No one has tried with as large a tagging data set as found in the WCPO skipjack stock assessment.

Notable differences were found in the implementations of tag data likelihood between the two platforms. Major differences are that 1) SS uses two types of tag data likelihoods (negative binomial and multinomial) while MFCL uses the negative binomial only, 2) MFCL is flexible in pooling multiple fisheries into groups of fisheries to calculate tag likelihood, while SS does not have such an option, 3) MFCL allows more structured tag reporting rate parameters and their priors. This third feature was fully utilized in 2014 skipjack assessment.

Unlike the previous comparisons between SS and MFCL, the results for skipjack substantially differed when stock size estimates were compared. When more structured tag reporting rate parameterizations were used as in the MFCL 2014 reference case, reporting rate estimates were substantially different between approaches and hence stock size estimates also differed. If fixed reporting rate parameters taken from the MFCL run were applied to SS, SS produced more similar stock size estimated to those from the MFCL run.

The study of Langley and Methot Jr. (2008) has previously reported that SS was capable of replicating the WCPO bigeye stock assessment in 2008. However, in this study it was more difficult to fit a model in SS comparable to the 2014 reference case model implemented in MFCL. This finding is largely attributable to the unique nature of the WCPO skipjack stock assessment, where the scaling of estimated stock size is heavily dependent on tag release / recapture data. Our comparison of several different MFCL and SS runs demonstrated that tag release/recapture data as well as the modelling of those data in the stock assessment model is very important.

In this comparison study, the skipjack data set is influenced by a very large tagging data set, which should be very influential in determining stock size. In the 2014 skipjack stock assessment (Rice et al., 2014), and the 2016 one (McKechnie, 2016) priors on fishery-specific reporting rates were used that were also specific to individual tagging programmes. To accomplish this, MULTIFAN-CL is enhanced to allow more complicated parameterization of reporting rate. Since SS lacks those features, this comparison was unable to set up SS with precisely compatible settings. When MFCL was set up with a comparable configuration to SS, uncertainties in tag reporting rate estimation increased uncertainty for both model platforms.

This comparison demonstrated that MFCL has been designed with necessary features to efficiently implement tag data model within the stock assessment model. The importance of tag reporting rate as well as its prior was also highlighted. To further improve the skipjack stock assessment performed using MFCL, improved external estimates of tag reporting rate would be desirable.

2 Introduction

Since the late 1990's stock assessments of tuna and tuna like species in the Western Central Pacific ocean have been conducted using Multifan-CL (MFCL, Fournier et al. (1998)). MFCL is an integrated fishery stock assessment model that implements size-based, age- and spatially-structured population models integrating fisheries catch, effort and size (length and weight) composition data and tag release/recovery data.

Stock Synthesis (SS) is an alternative and popular fish stock assessment platform. "35 stocks in the US, 10 tuna/billfish in three oceans, four European stocks, and 12 Australian stocks have been assessed using this approach (SS) by 2012" (Methot Jr. and Wetzel, 2013)

Both stock assessment platforms use an "integrated analysis" approach, which combines several sources of data into a single analysis (Maunder and Punt, 2013).

To date, several attempts of parallel stock assessment with different stock assessment platforms have been undertaken. They include WCPO bigeye tuna using SS and MFCL (Langley and Methot Jr., 2008). The skipjack stock assessment in the Western Central Ocean is a very unique stock assessment among those for WCPO tuna and tuna like species, because there are no longline CPUE indices that can be assumed to provide region-specific stock abundance trends. Instead, a huge amount of tag release/recapture data is available and used in the stock assessment. This amounts to 251 tag release groups stratified by time and region at release from four major tag research programs. This is probably one of the biggest tag release/recapture data sets used for stock assessments of tuna and tuna like species. For example number of tag release group included in the 2014 WCPO bigeye stock assessment was 56 (Harley et al., 2014). Since SS implemented the capability for spatial structure with tag release/recapture data, there have been several attempts to use these features. No one has tried with as large a data set as found in the WCPO skipjack stock assessment.

In this analysis, where possible, all inputs and model structure were kept identical between platforms, for example, the regional structure (5 regions), fisheries definitions (23 fisheries) and quarterly time step (from 1972 until the end of 2012). Most of the fisheries data were able to be converted without problem.

3 Methods

3.1 Fisheries and tag release/recapture data

Conversion of the MFCL input files was necessary before the model could be fitted within SS. Where possible, all inputs and model structure were kept identical between platforms, for example, the regional structure (5 regions), fisheries definitions (23 fisheries) and quarterly time step (from 1972 until the end of 2012). Most of the fisheries data were able to be converted without problem. An exception was the presence of missing catch data in the MFCL input files. In MFCL these missing values are estimated internally by the model, however for fitting the model in SS it was necessary to interpolate these values externally as the average of catches in adjacent time steps. The most challenging aspect of the conversion to SS input files was the processing of the tagging data. MFCL requires tagging data with length-at-release, which it then uses to assign age-at-release based on the growth function and its variance. SS, however, requires age-at-release information, which is perhaps the major limitation of using SS for stock assessments of tuna when tagging data is available. To produce a usable tagging input file for SS, the inverse function of von Bertalanffy growth function with fixed growth curve parameter used in 2014 MFCL run were applied to convert length at release to age at release externally before running SS.

This resulted in 1103 tag release groups stratified by time, region and age at release and 4654 tag recapture events.

3.2 Biological parameters

Where possible, all biological parameters used in SS were the same as for MFCL: 16 quarterly age-classes with the oldest age-class representing a "plus group"; the same maturity-at-age function; the same length-weight relationship; and the same Von Bertalanffy growth function parameters. Some differences were unavoidable however and these included MFCL modelling the standard deviation of mean length-at-age as a log-linear function of length, which is unavailable in SS, where they were substituted by modelling CV as a function of length. In addition, age-specific natural mortality was estimated by MFCL in the 2014 skipjack stock assessment, with the estimation constrained to some degree by the use of penalties on mean natural mortality and the 1st and 2nd order differences in mortality among adjacent age-classes. SS can also estimate natural mortality-at-age but lacks the smoothness penalties used by MFCL. Therefore, the age-specific natural mortality estimated by MFCL was used in SS as fixed values to ensure comparability.

Both MFCL and SS define the log of movement rate (proportion of fish in region A moving to region B) as a linear function of age. Although MFCL is capable of allowing movement rate invariant to age, this is not possible in SS.

3.3 Model structure

Version 3.24z of SS was used in this study[2] which was the latest available version when this manuscript was prepared in June 2016. This version solved a problem with calculation of plus group biomass with multiple region models. The SS model for this analysis was configured to be as close to the WCPO skipjack 2014 reference case stock assessment as possible. Nevertheless there are several technical differences between the two platforms and these are summarised in detail in the technical appendix.

3.4 Catch likelihood

Although both models are equipped with likelihood or penalty function of catch data, they implicitly assumed that catch was known without error by solving catch equations internally (SS) or allowed relatively negligible error by imposing large weight to the penalty (MFCL).

3.5 CPUE/effort likelihood

The 2014 skipjack stock assessment model used five standardized CPUE indices (one in each model region). The fisheries to which these were applied were assumed to have constant catchability (q) but seasonal variation was allowed. All other fisheries in the model assumed their nominal effort and the effort penalties applied were low, and time-series (similar to a random walk) variation in q was permitted.

MFCL linked fishing mortality to effort through the catchability parameter. Therefore, in principle MFCL requires effort data (either standardized or nominal) for each fishery. On the other hand, SS implicitly calculates fishing mortalities by solving the catch equation or directly estimating them as parameters without linking effort, and uses CPUE (as $\frac{catch}{effort}$) as the abundance indices to tune the model. Therefore SS does not need effort data for each fishery. In order to convert the catch and effort data to SS, only the five standardized CPUE indices were used for tuning. The nominal CPUE of the remaining 18 fisheries were therefore not included into the CPUE data likelihood. In order to implement the seasonality of catchability in SS, the standardized CPUE time series were separated into seasonal indices, allowing different catchabilities to be estimated for each.

[2] During the preparation of this work, the beta version, SS3.30, which is the next version of Stock Synthesis, that implements many new features, became available in June 2016. However given time constraints before the Scientific Committee, it was not tested herein.

3.6 Tag data likelihood

MFCL models the tagging data by first aggregating data into tag release groups (all release/recapture data in unique combinations of release year, quarter and region). The recaptures within these groups are further stratified into recovery year, quarter and fishery (or group of fisheries in the case of the skipjack model[3]).

MFCL fits the tagging data using a negative binomial likelihood while SS uses two types of likelihood; 1. recapture by tag group, tag cohort[4] with a negative binomial likelihood ignoring the information on recovery fishery, and 2. the proportion of numbers of recaptures by fishery, in the same quarter, using a multinomial likelihood (see the technical appendix for further details). The recommended configuration of SS for tag data is to activate both likelihood components for the tagging data, however to ensure comparability with MFCL, the main comparison models only the first component was invoked.

The other notable difference between SS and MFCL is that MFCL allows more structured tag reporting rate parameters and their priors. While SS only parameterizes the reporting rates and their priors by fishery, MFCL allows different reporting rates (and priors) by tag release group and fishery, as well as allowing sharing of them among fisheries and/or among tagging programmes. For example, there are four skipjack tag release programs (SSTP, PTTP, RTTP and Japanese tagging program) and the 2014 skipjack reference case model used informative priors on reporting rate for eight tag reporting rate groups over the PTTP and RTTP programmes. This structure cannot be implemented in SS and models exploring these differences are also presented in the following section.

3.7 Construction of SS comparable MFCL run

Several different sensitivity models were constructed to explore the differences between how MFCL and SS implement the tagging data component. In some cases the modifications to MFCL settings result in them not being the recommended MFCL model, but it does make for a better understanding of where differences in models results between the platforms originate from.

The sensitivity models differed in the structure of their reporting rates and priors, and in the case of SS, the structure of the tagging likelihoods. The full set of models constructed and fitted to data included three SS, and two MFCL models, the details of which are:

1. SS run 1 : SS run with tag release/recapture data with tag negative binomial likelihood
2. SS run 2 : SS run with tag release/recapture data with two types of tag likelihoods

[3]Since it is often impossible to assign recovered tags to fisheries for the WCPO skipjack stock assessment, e.g., it is very difficult to identify the specific set which caught the tagged fish, and so it is very difficult to assign these fish to associated and unassociated fisheries. These fisheries are therefore grouped with respect to the recapure of tagged fish.

[4]SS uses a Tag cohort within a Tag group as its definition of "Tag group"

3. SS run 3 : SS run with tag release/recapture data with tag negative binomial likelihood and fixed reporting rate taken from MFCL run without informative reporting rate prior
4. MFCL 2014 ref case run
5. MFCL SS-like run (run2) : MFCL run removing informative reporting rate prior and tag negative likelihood with ignoring recaptured fishery information

All the runs retain the same definition of regions and fisheries.

4 Results

4.1 Summary of results

Initially SS run 1 and 2 were compared with MFCL 2014 reference case (Figures 1 to 5). Spawning stock sizes were generally estimated to be lower by SS. For the latest year (2012) SS's spawning stock size estimates are 1.6 - 2.1 million mt substantially lower than that of the MFCL 2014 reference case (3.12 million mt) (Figure 1, Top left). Spawning biomass levels by region were relatively similarly estimated in regions 2, 3 and 5 while in regions 1 (whole stock assessment time period) and 4 (until around 1990) spawning biomass was estimated to be substantially lower by SS. The difference of spawning biomass size in region 1 may be related the substantial differences of age selectivity in the pole and line fishery in region 1 (fishery 1, Figure 5). Except for fishery 1 age selectivity by fishery was similarly estimated for younger ages although there are generally large variations for older ages when selectivity was estimated to be constant.

4.1.1 Estimated reporting rate

Estimated reporting rate is obviously very different between estimates by SS and MFCL. This is due to the use of an informative prior to reporting rate in the MFCL 2014 reference run. However one MFCL sensitivity run (MFCL run 2) which removed the informative prior on reporting rate and estimated reporting rate by fishery, estimated a very different reporting rate compared with SS (Figure 7[5]). Hence very different biomass size estimates were obtained from both the SS and MFCL 2014 ref case (see next section).

4.2 Further comparison, between SS run 3 and MFCL run 2 and 2014 ref.case

When the reporting rate in SS was fixed equal to the estimates from MFCL run 2 (which removed informative prior on reporting rate and ignored information of fisheries recovered tag for calculation of tag negative binomial likelihood) estimated total spawning stock biomass became larger than

[5] This plot compares the reporting rates estimates from SS run1 and MFCL run 2.

SS runs 1 and 2, larger than MFCL 2014 reference case, but lower than MFCL run2 (Figure 8 top left). This clearly indicates that reporting rate estimates are highly influential to the stock size estimates. When spawning stock size was compared by region, in regions 2–5, SS's spawning stock size estimates generally stayed between those of the two MFCL runs. On the other hand in region 1 while two MFCL runs estimated almost identical adult biomass levels except for initial several years, SS's estimates were substantially lower than those from MFCL (Figure 8 top right). Selectivity of each fishery was generally similarly estimated among three runs except for fishery 1 (Figure 11). Comparing the two MFCL runs in particular, this may suggest tag release/recapture data as well as reporting rate prior does not play critical role to determine stock size in region 1, while in the other regions information from tag release/recapture data may play critical role to determine stock size.

5 Discussion

The study of Langley and Methot Jr. (2008) has previously reported that SS was capable of replicating the WCPO bigeye stock assessment in 2008. However, in this study it was more difficult to fit a model in SS comparable to the 2014 reference case model implemented in MFCL. This finding is largely attributable to the unique nature of the WCPO skipjack stock assessment, where the scaling of estimated stock size is heavily dependent on tag release / recapture data. This is very different from WCPO bigeye stock assessment and other fish stock assessments routinely fitted using SS. Those stock assessments are usually configured to obtain the stock size information from indices of relative abundance (standardized CPUEs) from fisheries mainly exploiting adults, and the catch histories of each fishery. Our comparison of several different MFCL and SS runs demonstrated that tag release/recapture data as well as the modeling of those data in the stock assessment model is very important.

Stock Synthesis is one of most popular stock assessment platform for fish stocks in north America and tuna stocks. However, most of the stock assessments conducted using SS are single region models. Several exceptions do exist, including tropical tuna stock assessments in Indian Ocean and the Atlantic bigeye tuna stock assessment, but these assessments either did not rely heavily on tagging data (Indian Ocean assessments) or did not include any tagging data (Atlantic bigeye tuna).

In this comparison study, we used very unique data set which is influenced by a very large tagging data set. Ideally speaking this should be very influential in determining stock size. However in this comparison uncertainties of tag reporting rate estimation was a problem when both model platforms were set up with comparable configurations. In the 2014 skipjack stock assessment (Rice et al., 2014), and the 2016 one (McKechnie, 2016) priors on fisehry-specific reporting rates were used that were also specific to individual tagging programmes. To accomplish this, MULTIFAN-CL is enhanced to allow more complicated parameterization of reporting rate. Since SS lacks those features, this comparison was unable to set up SS with precisely compatible settings.

There are several model features implemented in MFCL, which allows it to efficiently conduct WCPO tuna stock assessments, and that are currently missing in SS. The main author of SS is planning a "reboot" of modeling of tag data in SS in the near future (Methot pers. comm.). It is potentially useful to repeat similar comparisons when SS renews its tag data model.

Apart from the comparison of MFCL and SS, the use of two types of tag likelihood simultaneously is originated from Punt et al. (2000). The original implementation in Punt et al. (2000) allow the use of tag recovery data without information of region[6] in the Poisson[7] tag likelihood, while only tag recovery data with known recovered region were used in their tag multinomial likelihood. Their idea is probably intended to avoid the problem of tag recovery reports without additional information, which often happens in practice. However SS's implementation of tag negative binomial likelihood does require all the tags to have information of the fishery that recovered them. This implementation of SS's tag likelihood reduces the merit of using two types of tag data likelihood. If they were implemented as Punt et al. (2000), it would potentially increase the utility of SS for fish stocks with tag release/recovery data.

This comparison demonstrated that MFCL has been designed with necessary features to efficiently implement tag data model within the stock assessment model. The importance of tag reporting rate as well as its prior was also highlighted. To further improve the skipjack stock assessment done by MFCL, improved external estimates of tag reporting rate would be desirable.

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[6] Punt et al. (2000) model tag data by region released and recovered

[7] they used Poisson likelihood instead of a negative binomial likelihood

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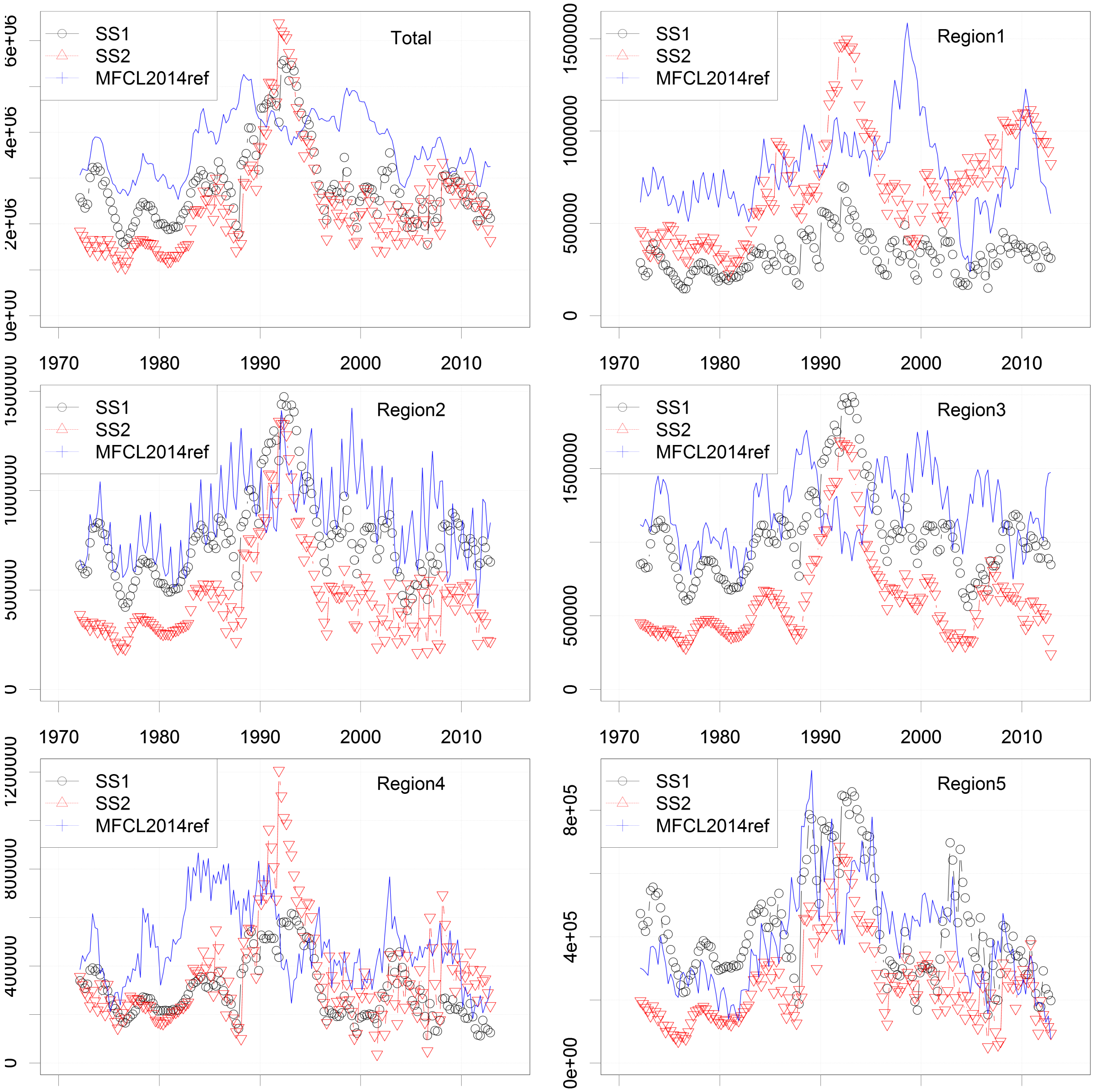

Figure 1: Estimated SSB (t) from SS runs 1 and 2 and MFCL2014 reference case. From top left Total, then regions 1 to 5.

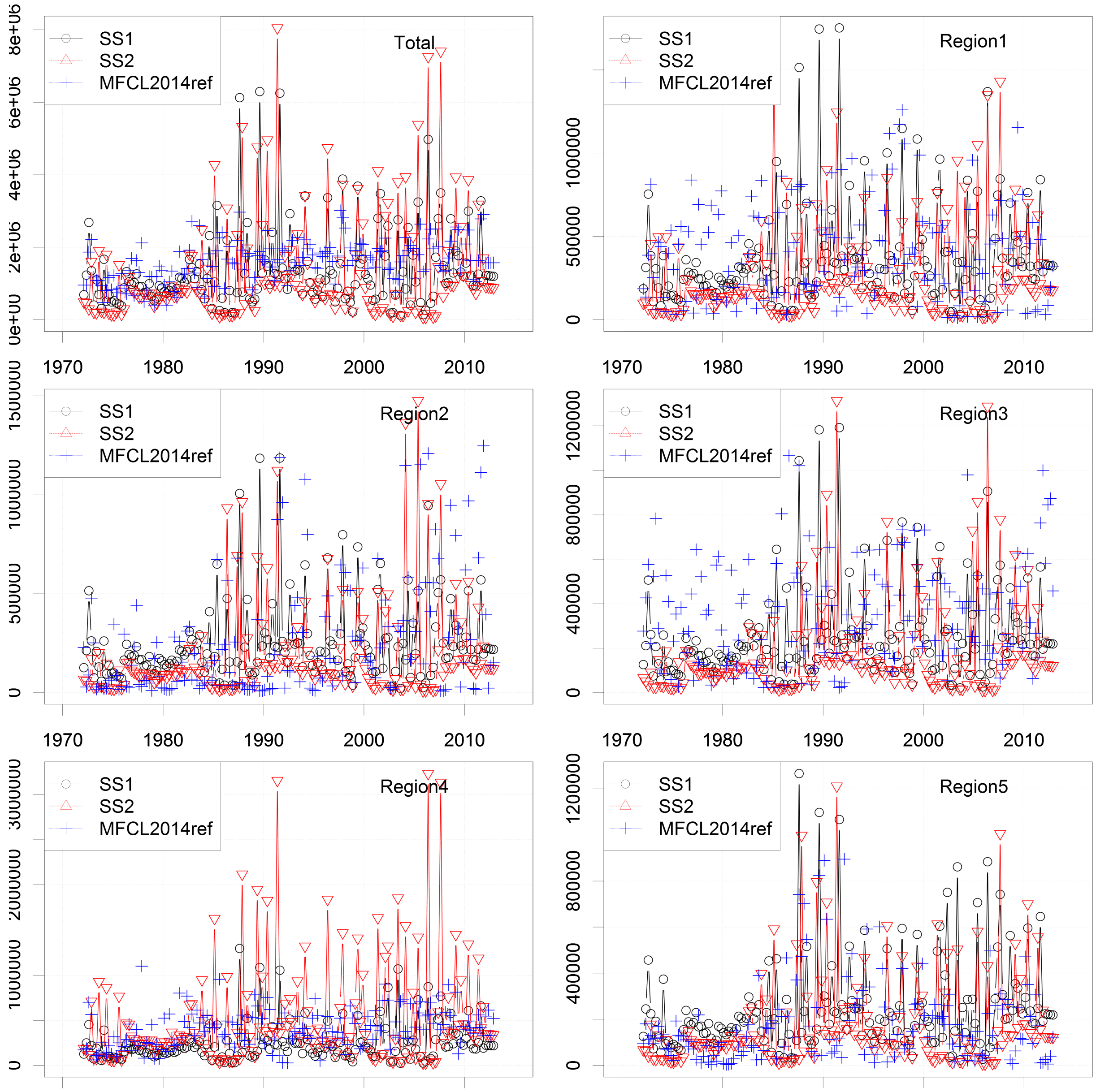

Figure 2: Estimated Recruits (1000 fish) from SS runs 1 and 2 and MFCL2014 reference case. From top left Total, then regions 1 to 5.

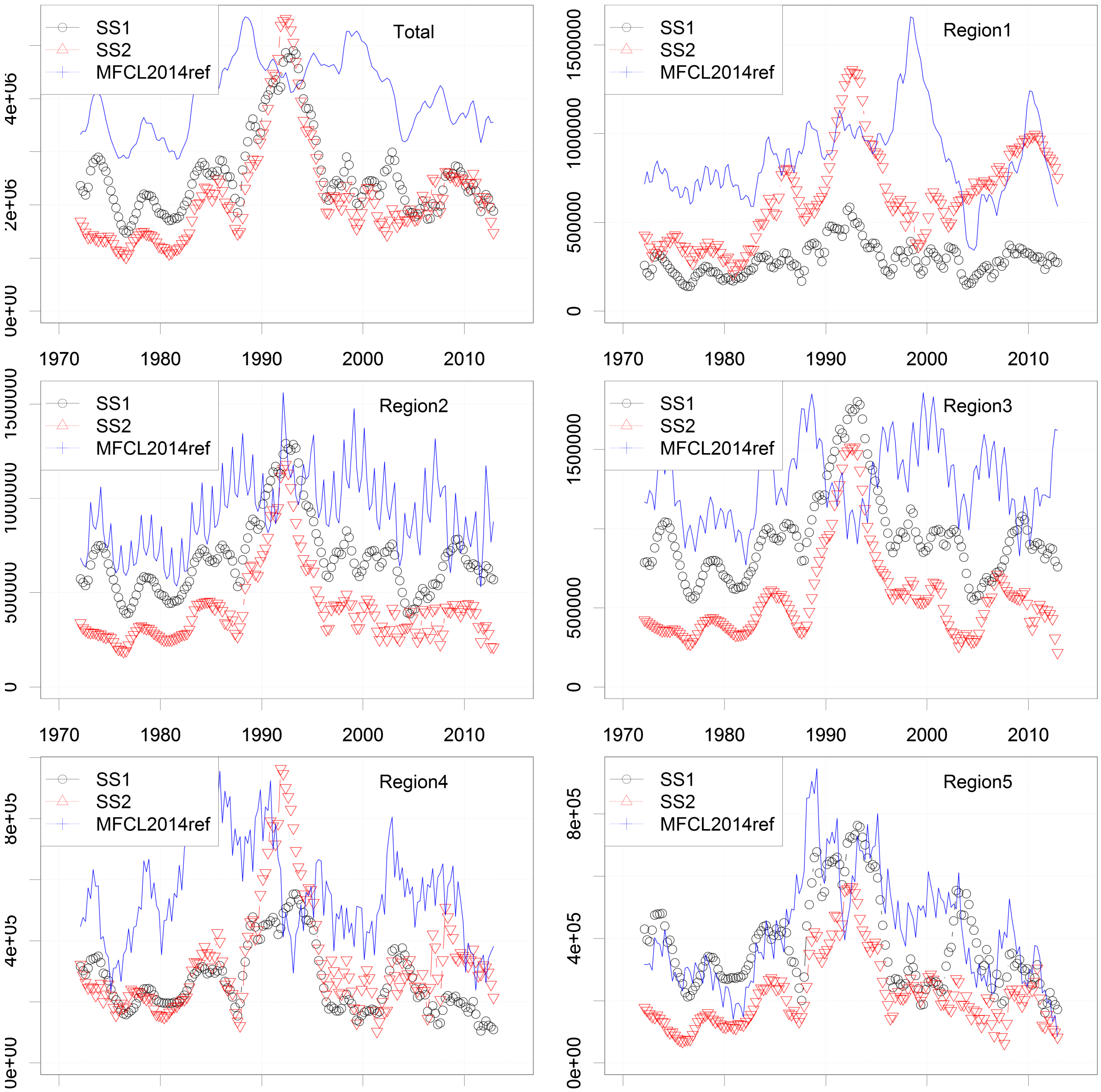

Figure 3: Estimated total biomass (t) from SS runs 1 and 2 and MFCL2014 reference case. From top left Total, then regions 1 to 5.

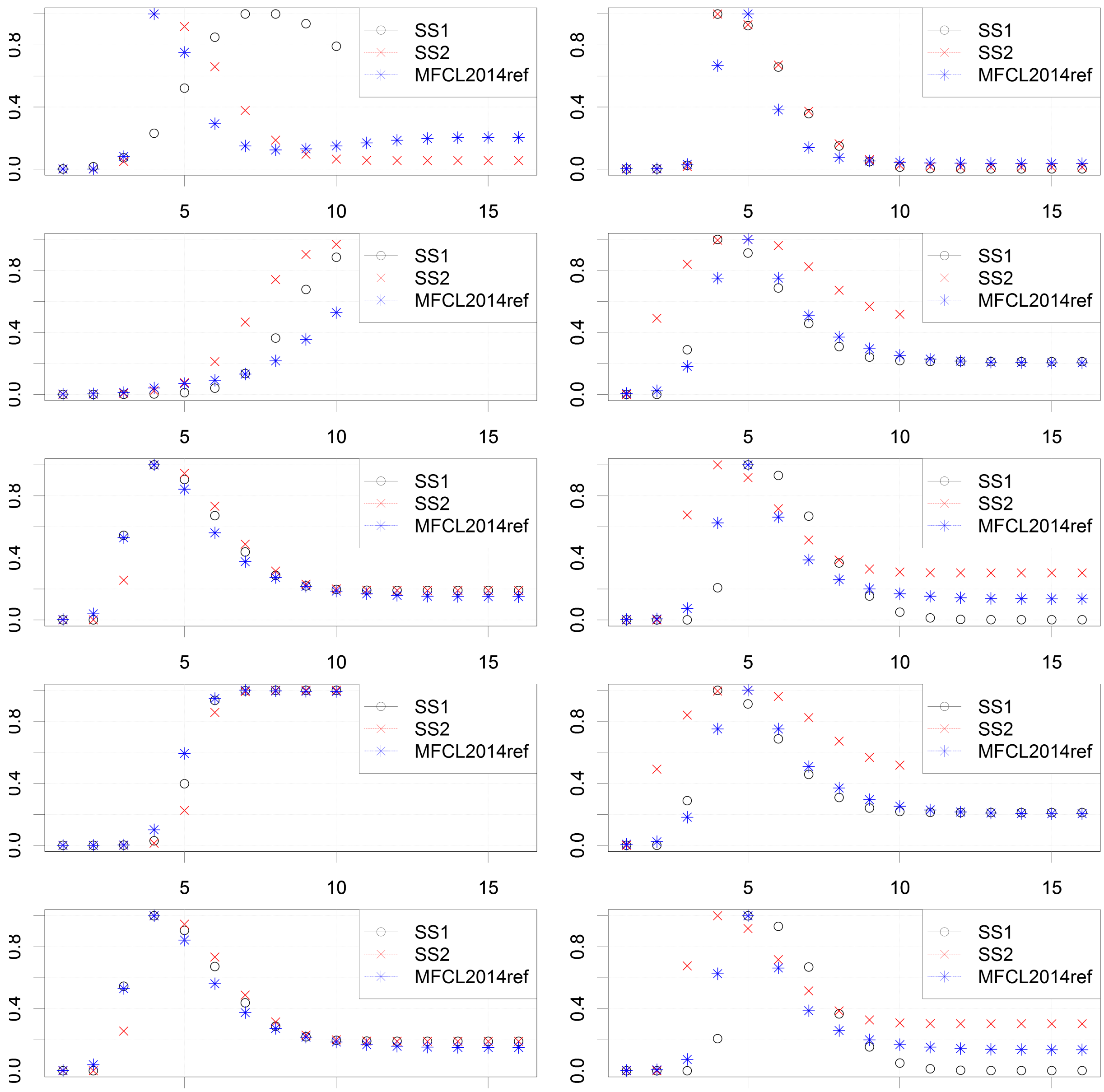

Figure 4: Estimated age selectivity from SS runs 1 and 2 and MFCL2014 reference case. From top left to right and bottom, fishery 1-10

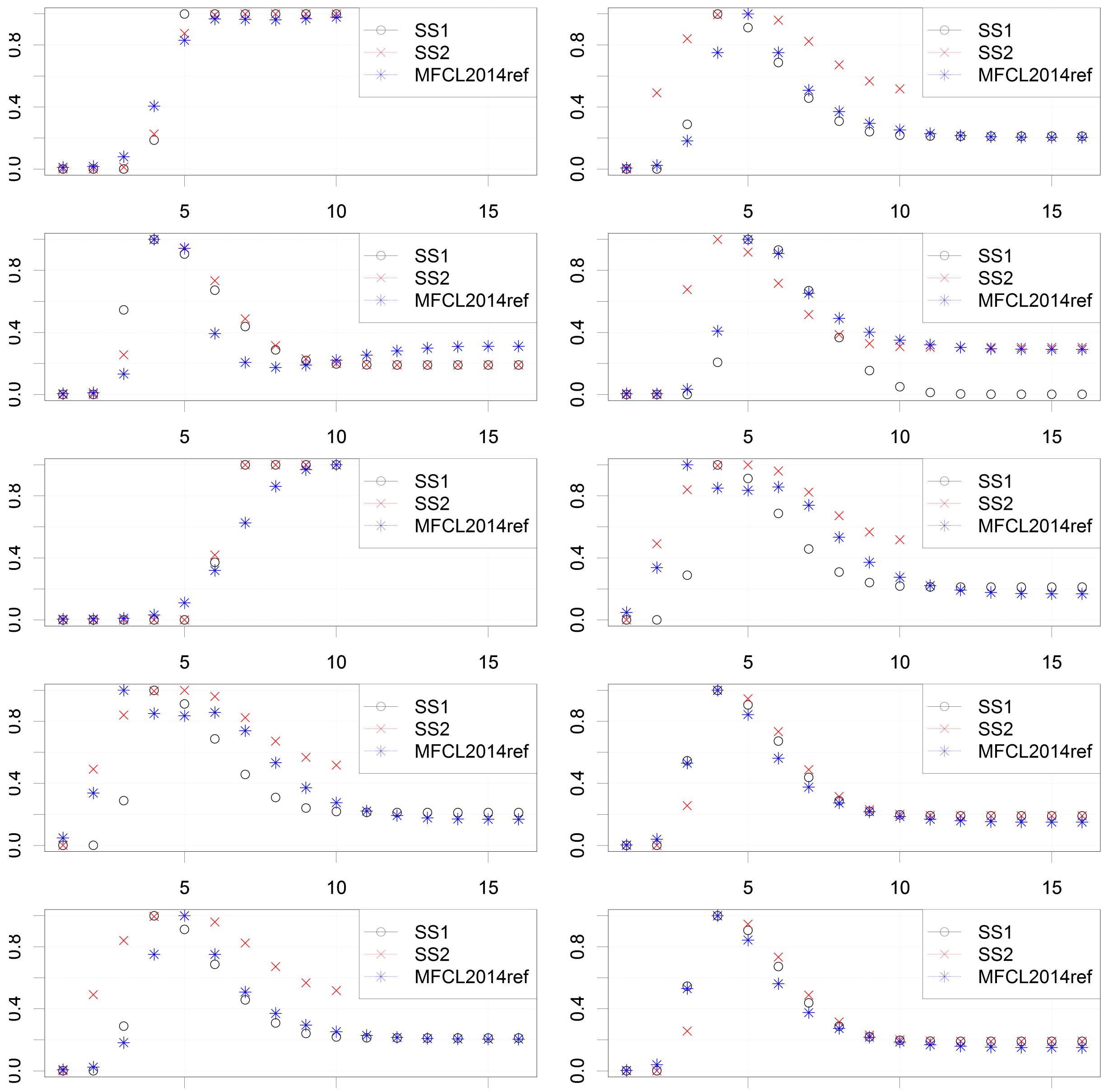

Figure 5: Estimated age selectivity from SS runs 1 and 2 and MFCL2014 reference case. From top left to right and bottom, fishery 11-20

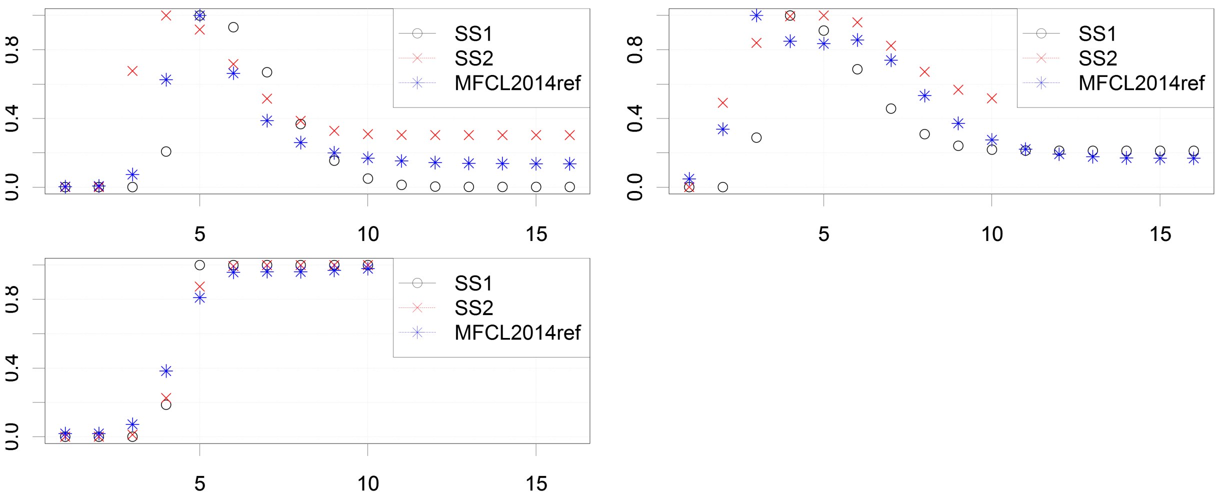

Figure 6: Estimated age selectivity from SS runs 1 and 2 and MFCL2014 reference case. From top left to right and bottom, fishery 21-23

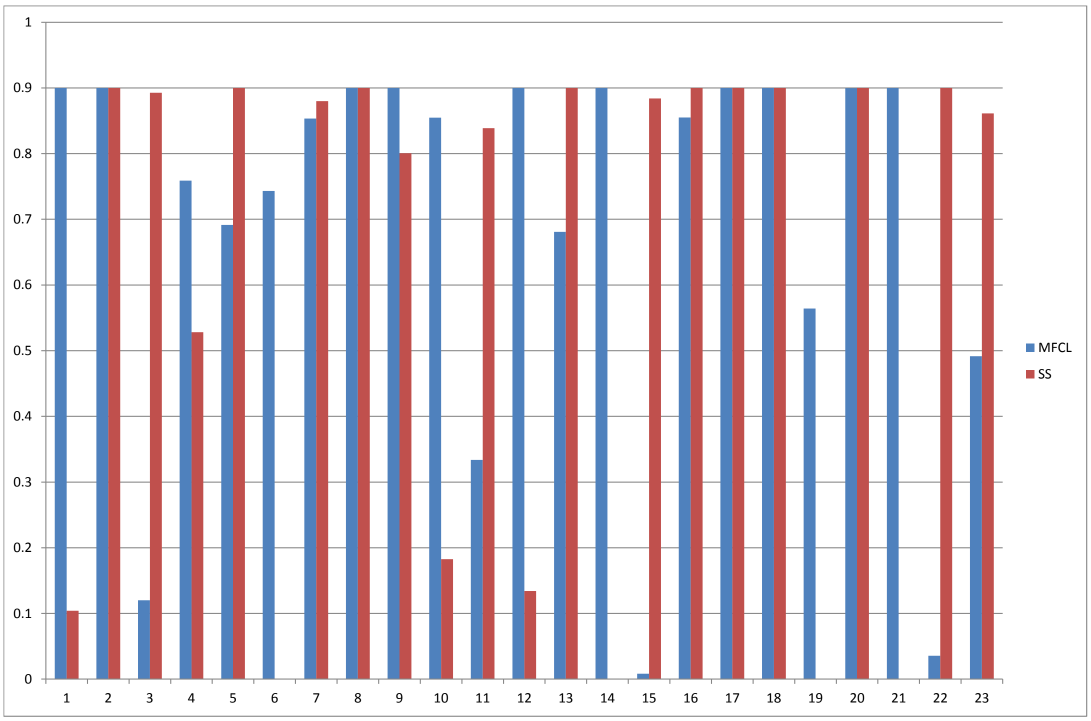

Figure 7: Reporting rate estimated by SS run1 (Red) and MFCL run2 (Blue)

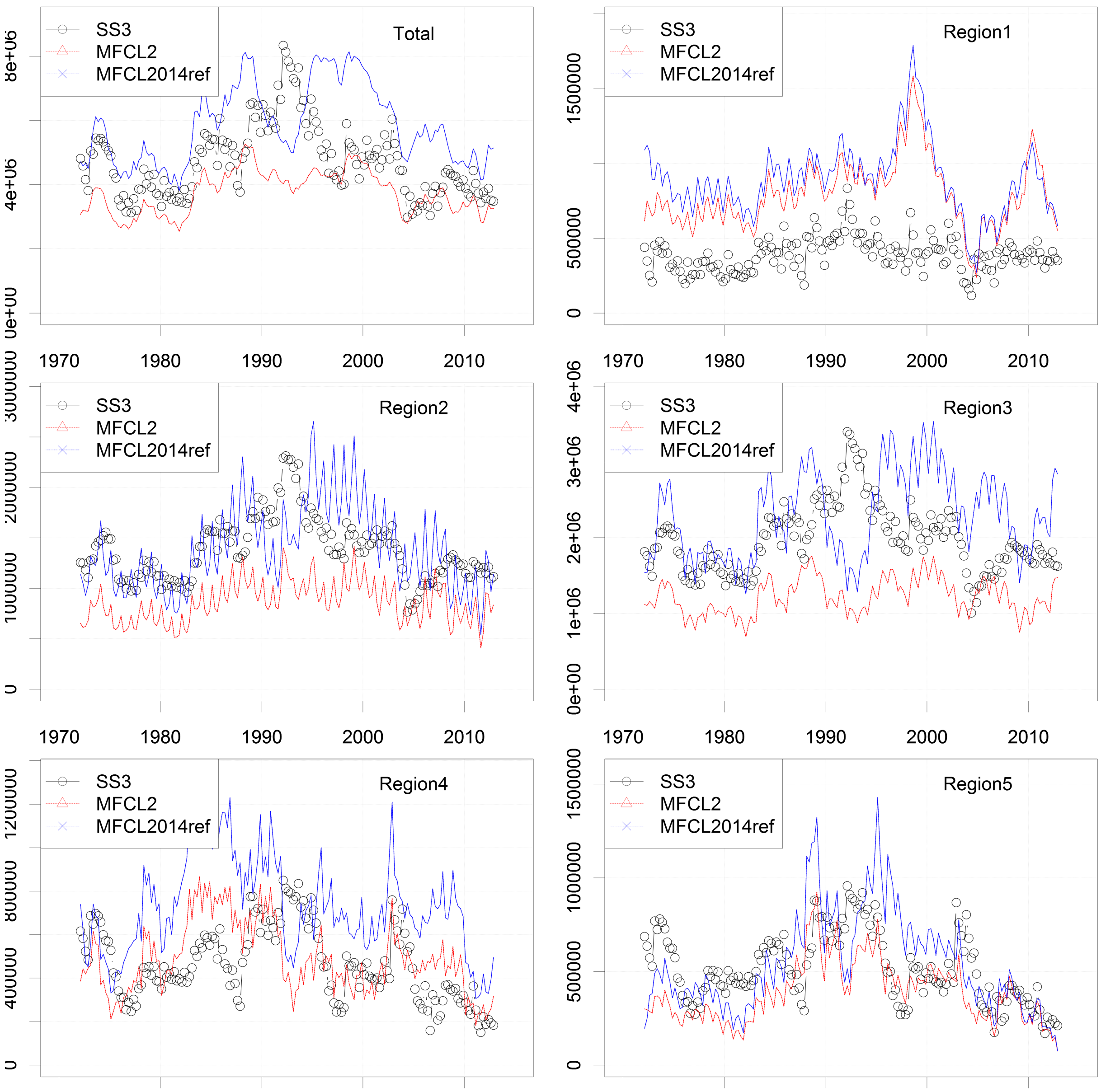

Figure 8: Estimated SSBs from SS run 3 and MFCL2014 reference case and MFCL run2. From top left Total, then regions 1 to 5.

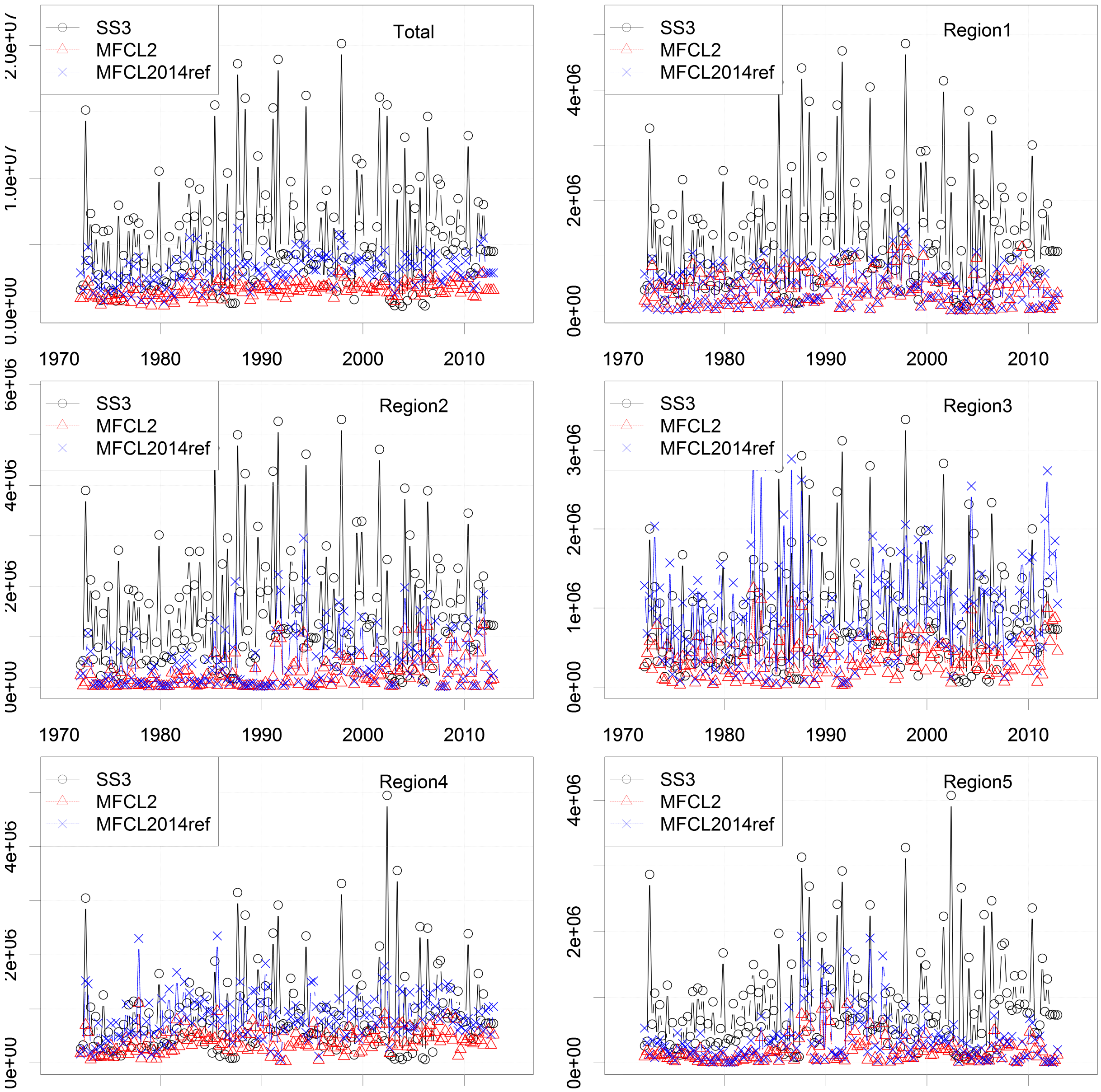

Figure 9: Estimated Recruits (1000 fish) from SS run 3 and MFCL2014 reference case and MFCL run2. From top left Total, then regions 1 to 5.

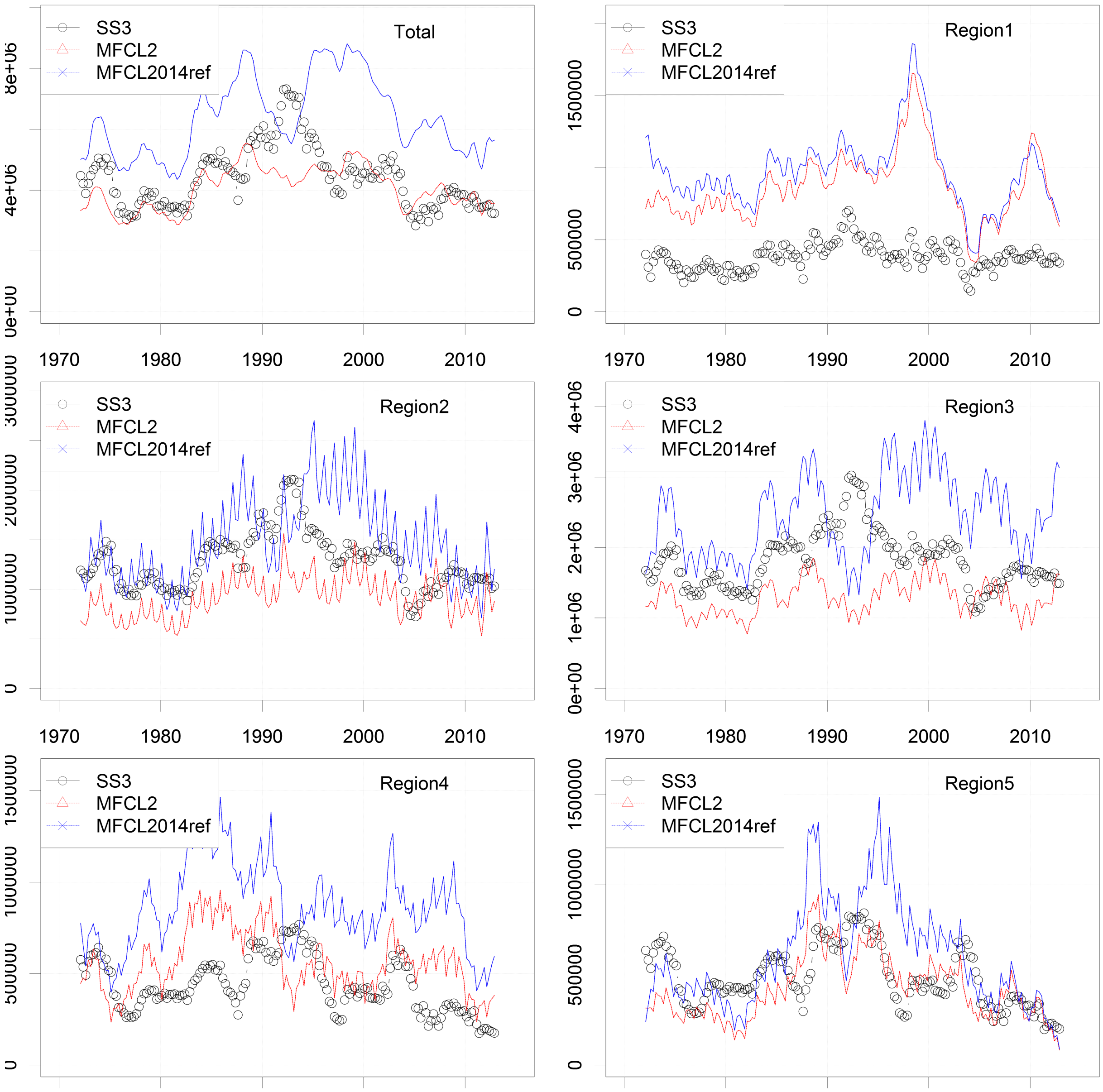

Figure 10: Estimated total biomass(t) from SS run 3 and MFCL2014 reference case and MFCL run2. From top left Total, then regions 1 to 5.

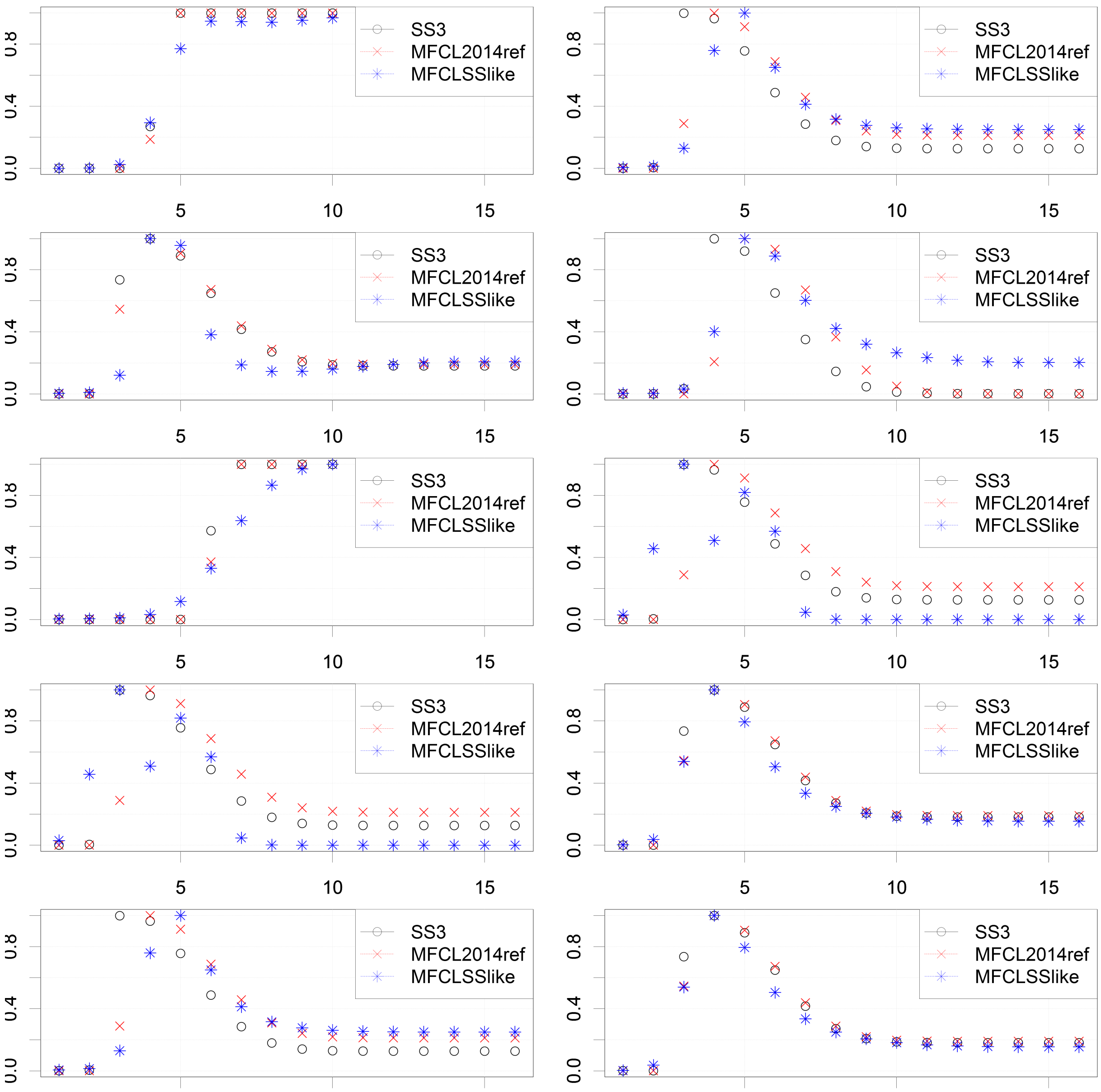

Figure 11: Estimated age selectivity from SS runs 3 and MFCL2014 reference case and MFCL SS like run. From top left to right and bottom, fishery 1-10

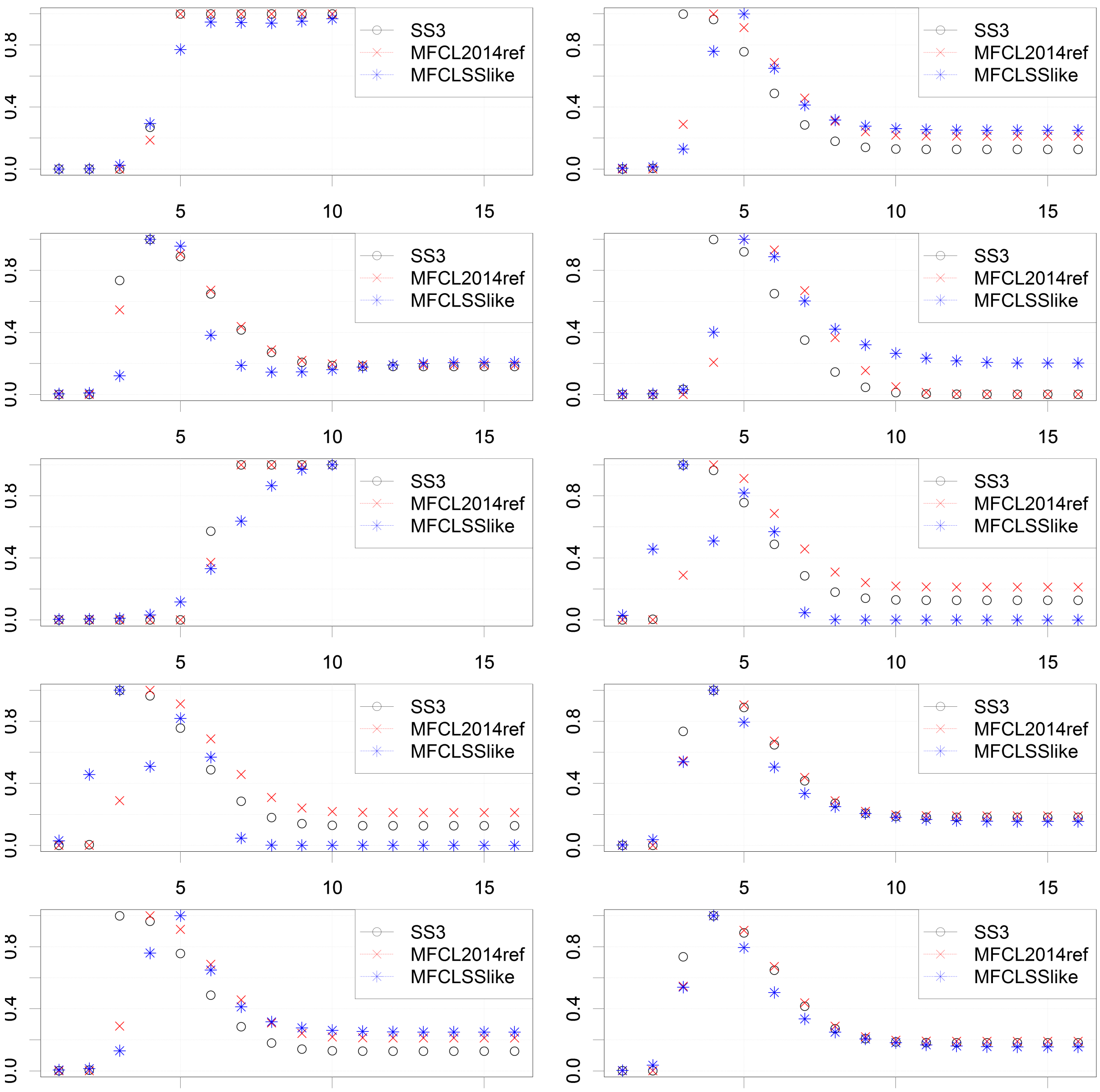

Figure 12: Estimated age selectivity from SS runs 3 and MFCL2014 reference case and MFCL SS like run. From top left to right and bottom, fishery 11-20

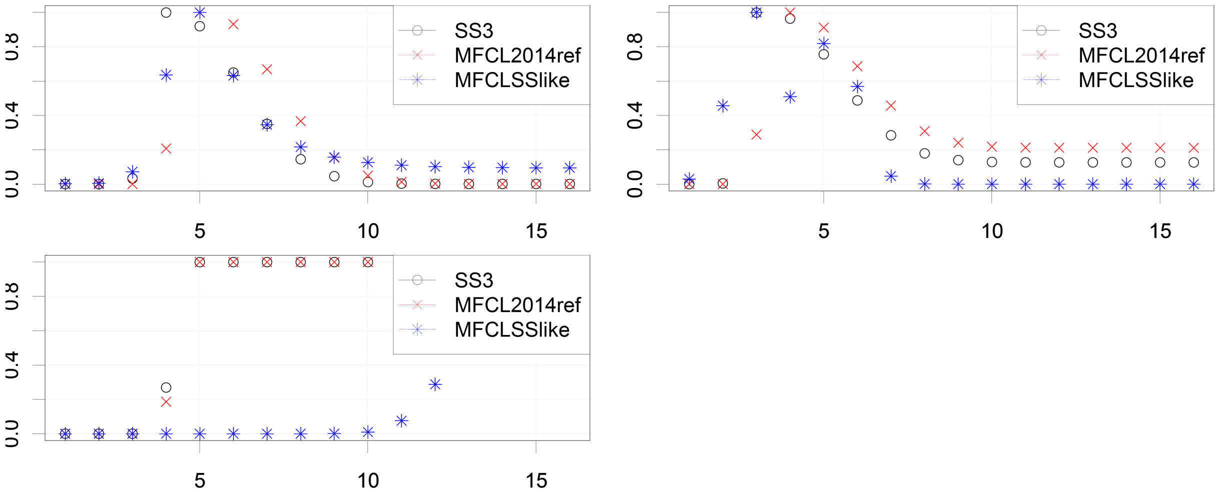

Figure 13: Estimated age selectivity from SS runs 3 and MFCL2014 reference case and MFCL SS like run. From top left to right and bottom, fishery 21-23

A Technical appendix

This appendix is intended to highlight technical differences between MFCL and SS in the context of this paper. More comprehensive techinical description can be found in Kleiber et al. (2014) for MFCL and the appendix in Methot Jr. and Wetzel (2013)

A.1 Natural mortality

The reference case of the WCPO skipjack stock assessment in 2014 using MFCL estimated quarterly age specific natural mortality (M). Several penalties were applied, square of average M with weight of 10, a Normal prior on mean M withe prior mean=0.45 per quarter with SD=0.5 with Normal smoothness penalties on differences of log M in adjacent ages with SD =0.07 and Normal smoothness penalty on 2nd order differences of log M in adjacent ages with SD=0.14. In contrast, SS, has several options to set up natural mortalities from fixed age specific M to estimation of age specific M of each age class. SS also has a option to estimate M of selected ages and to linearly interpolate intermediate ages. SS doe not come with a smoothing prior on M, but equipped with prior on age specific M on each age class if it is an estimated parameter.

A.2 Selectivity function

MFCL used age based spline selectivity with five automatically equally spaced nodes by default. Additional penalty functions are also applied depending on expected shape of selectivity of gear (dome shaped for surface fisheries, flat top for longline). Although SS is also equipped with spline age based selectivity, SS is not able to apply constraints to keep the expected shape of selectivity. Instead, this comparison used parametric forms for selectivity (double normal for gears with dome shaped selectivity, logistic for gears assumed to be asymptotic).

A.3 Tag likelihood

SS's model parameters related to the tag release/recapture data are:

- Reporting rate by fishery;
- parameter representing exponential decline or increase of reporting rate by time after release by fishery;
- parameter controlling over-dispersion of tag negative binomial likelihood by SS's tag group;
- immediate tagging mortality by SS's tag group;
- continuous tagging mortality by SS's tag group.

MFCL's model parameters related to the tag release/recapture data are

- Reporting rate by fishery and each MFCL tag group;
- parameter controlling over-dispersion of tag negative binomial likelihood by fishery.

A.3.1 Tag reporting rate

Stock Synthesis

The tag reporting rate parameter of Stock Synthesis is defined by fishery and transformed by logit function to real space

$$r = \frac{exp(x)}{1 + exp(x)}$$

There are several choices for prior distribution. Since these transformed parameters are defined a real number it may be preferable to use normal prior.

MFCL

The tag reporting rate parameters and their prior in MFCL are defined by fishery and by tag group. This allows the use of an informative prior for the reporting rate by a fishery for a particular tagging program. A normal prior is used in the original scale of tag reporting rate.

A.3.2 Tag likelihood function in MFCL

Negative binomial likelihood if $parest\_flags(111) = 4$

The 2014 WCPO skipjack stock assessment with MFCL used a negative binomial likelihood for tag release/recapture data. The negative of the log likelihood function of tag recapture data was:

$$\begin{aligned} (a + r)ap - a \log a - r \log(\hat{r}) \\ - \log \Gamma(a + r) - \log \Gamma(r + 1) + \log \Gamma(a) \end{aligned} \tag{1}$$

where summation is over tag release group, tag cohort, and time, by either fleet or group of fleets, i.e.,

$$
\begin{aligned}
&\sum_g \sum_c \sum_t \sum_f \left(a + r^f_{gct}\right) ap^f_{gct} \\
&- \sum_g \sum_c \sum_t \sum_f \left(a \log a - r^f_{gct} \log(\hat{r}^f_{gct})\right) \\
&- \sum_g \sum_c \sum_t \sum_f \left(\log\Gamma(a + r^f_{gct}) - \log\Gamma(r^f_{gct} + 1) + \log\Gamma(a)\right)
\end{aligned} \tag{2}
$$

r^f_{gtc} is observed number of tags recovered, $\hat{r}^f_{gtc}$ is expected number of tags recovered, a is a constant usually called the over-dispersion parameter, ap is defined as $ap^f_{gct} = \log(a + \hat{r}^f_{gct})$. Variance can be written as $var = \hat{r} + \hat{r}^2/a$. If a is defined as a constant independent to expected value ($\hat{r}$), variance is approximately quadratic to its expected value. As a increases, variance will approach to its expected value ($\hat{r}$). Hence it reduces to a Poisson distribution. However, since both MFCL and SS (defined in ADMB), a is defined to be proportional to expected value $\hat{r}$, quadratic term is absorbed into the linear term and consequently variance is proportional to expected value $\hat{r}$ (see below).

If $parest\_flags(305) = 0$ **(skj 2014 ref. case)**

For backward compatibility to prior to MFCL2.0.0.3, a is parametrized as $a = (fishpars(4) + 50.0001)\hat{r}$ with default value of $fishpars(4) = 0$. Using this definition, variance with default value of ($fishpars(4) = 0$)can be re-written as

$$
\begin{aligned}
var =& \hat{r} + \hat{r}^2/a \\
=& \hat{r} + \frac{\hat{r}}{50.0001} \\
=& \frac{51.0001}{50.0001}\hat{r} \\
=& 1.02\hat{r} \approxeq \hat{r}
\end{aligned} \tag{3}
$$

If $parest\_flags(305) = 1$

New parametrization of a is used. Define $\tau = 1 + \exp(fishpars(4))$. a is defined as

$$
a = \frac{\hat{r}}{\tau - 1}
$$

Then variance can be re-written in this case as

$$
var = \tau\hat{r} \tag{4}
$$

This also suggests if τ is set to 1.02, i.e., by setting $fishpars(4) = \log(\tau - 1) = \log(0.02) = -3.912$, this should duplicate the 2014 reference case.

Although the 2014 skipjack ref case used fixed value of fishpars(4), hence fixed overdispersion parameters a, MFCL is capable to estimate $fishpars(4)$ by fishery or group of fisheries. This means the multiplier to expected value to represent variance can be set differently by fishery.

A.3.3 Tag likelihoods in Stock Synthesis

The likelihood function of tag release/recovery data of SS consists of two parts, negative binomial and multinomial likelihood functions originated from Punt et al. (2000) They defined the tag likelihood function modified from those of Hilborn (1990) and Xiao (1996) to allow tag recovery data without available information of the area recovered. They consist of a Poisson likelihood for total number of recapture by year including tag recovery data with missing area information and multinomial likelihood for the data with recoveries with information of area only. The contribution of the tagging data to the likelihood function involves two parts: one that deals with the number of recaptures by year, and one that deals with the spatial distributions of the recaptures conditioned on year of recapture (Punt et al. (2000)). Stock Synthesis replaced the first part with negative binomial distribution.

Tag negative binomial likelihood in Stock Synthesis

$$\begin{aligned} &\sum_g \sum_c \sum_t (a + r_{gct})\, ap_{gct} \\ &- \sum_g \sum_c \sum_t (a \log a - r_{gct} \log(\hat{r}_{gct})) \\ &- \sum_g \sum_c \sum_t (\log \Gamma(a + r_{gct}) - \log \Gamma(r_{gct} + 1) + \log \Gamma(a)) \end{aligned} \tag{5}$$

In this version of equations ap is defined as $ap_{gct} = \log(a + \hat{r}_{gct})$. As in Punt et al. (2000), this pools recovery data across fisheries. However unlike Punt et al's model, SS does not allow tag recovery data without information of recovered fishery. Its negative of log likelihood function used *log_negbinomial_density* function of ADMB. *log_negbinomial_density* is defined similar to the case when $parest\_flags(305) = 1$ but τ itself is now the parameter to be estimated. In contrast to MFCL, SS assigns different τ by tag release group (stratified by time, region and age at release). The current version of SS is not capable of reducing the number of tau to be estimated through grouping of e.g. tag groups. Also it might be useful to note that, though MFCL uses the same over-dispersion parameter by fishery, SS by definition of τ, allows over-dispersion to be different among recoveries the by same fishery. In the case of the data set we analyzed the number of tag groups reached 1103.

Tag composition likelihood in Stock Synthesis

As explained above, the second part of tag likelihood of Stock Synthesis is a multinomial likelihood. Unlike Punt et al.'s model, SS requires all tag recovery data to come with information of the recovering fishery. This may lose the merit of having likelihood functions conditional on whether information of the recovering fishery is missing. This part of likelihood function is defined as

$$-\sum_r \sum_t \sum_f r_{gt}^f \log\left(\frac{\hat{r}_{gt}^f}{\sum_f \hat{r}_{gt}^f}\right) \tag{6}$$

Where summation in the denominator in the logarithm is taken over fleets. Although both likelihood functions are active by default, for the purpose of comparison between SS and MFCL, the second one was disabled by setting "λ" (constant of multiplier of each likelihood component in SS) of the second one to zero.

A.4 Length/Weight/Size composition likelihood

Both MFCL and SS are capable of dealing with both length frequency and weight frequency data. The 2014 skipjack reference case only used length composition data.

Both software have concise documentation for the length/weight/size composition likelihood functions used. This section focuses on differences between them.

A.4.1 MFCL's length/Weight composition likelihood

MFCL uses a robustified likelihood function. That likelihood function is

$$L = \prod_i \prod_t \prod_f \frac{1}{\sqrt{2\pi\tau_{tf}\left(\xi_{itf} + 1/I\right)}} \left(\exp\left(-\frac{\tau_{tf}(p_{itf} - \hat{p}_{itf})^2}{2(\xi_{itf} + \frac{1}{I})}\right) + 0.001\right) \tag{7}$$

where p_{itf} and $\hat{p}_{itf}$ are observed and predicted proportions of fish in i'th length bin in time step t of fishery f respectively. $\xi_{itf} = p_{itf}(1 - p_{itf})$, $\tau_{tf} = P^L / \min(1000, S_{tf})$, and S_{tf} is the size of the size-frequency sample taken from fishery f in time period t I is the number of size intervals in the samples (54 for 2014 skipjack reference case) and $const_L$ is a number to scale sample size in the log likelihood. τ can be interpreted as inverse of actual sample size applied to likelihood function For example 2014 skipjack reference case used $P_L = 20$. This means a maximum effective sample size in the length composition likelihood was 50.

Then negative of log-likelihood function is written as

$$
\begin{aligned}
-LL =& 0.5 \sum_i \sum_t \sum_f \log\left(2\pi\left(\xi_{itf} + \frac{1}{I}\right)\right) \\
&+ I \sum_t \sum_f \log(\tau_{tf}) \\
&- \sum_t \sum_f \log\left(\exp\left(-\frac{\tau_{tf}(p_{itf} - \hat{p}_{itf})^2}{2(\xi_{itf} + \frac{1}{I})}\right) + 0.001\right)
\end{aligned}
\tag{8}
$$

A.4.2 SS's multinomial composition likelihood

SS uses a multinomial likelihood. Its contribution to the objective function was

$$
-LL = \sum_f \sum_t \sum_i n_{fti} p'_{fti} \log\left(\hat{p}'_{tfi}\right) \tag{9}
$$

where p_{itf} and $\hat{p}_{itf}$ are observed and predicted proportions of fish in i'th length bin in time step t of fishery f respectively.

$$
p'_{fti} = (p_{fti} + const)/\sum_i (p_{fti} + const)
$$

and

$$
\hat{p}'_{fti} = (\hat{p}_{fti} + const)/\sum_i (\hat{p}_{fti} + const)
$$

const is a small positive constant added to proportions in order to prevent zero values. In this comparison an arbitrarily chosen value of 0.0001 was used unless another value is specified to assess its influence in sensitivity analyses.