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Sensitivity of the WCPO bigeye tuna stock assessment results to the inclusion of EPO dynamics within a Pacific-wide model

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Executive Summary

The review of the 2011 stock assessment of bigeye tuna in the western and central Pacific Ocean (WCPO) recommended construction of a Pacific-wide stock assessment model to test the sensitivity of management advice for the WCPO to the assumption that dynamics of bigeye tuna in the Eastern Pacific Ocean (EPO) can effectively be ignored when conducting WCPO stock assessments. We address this request by building two models - an updated WCPO model (WC15) based on the reference case model of the 2014 stock assessment (WC14) with an extra year of data, and a model that represents the bigeye tuna population for the entire Pacific Ocean (PW15). The latter consisted of 12 individual regions and included all available tagging data including IATTC data for the EPO. Both models were compared to the 2014 reference case model (WC14). New CPUE indices of abundance were estimated from an extensive dataset of operational-level longline fishing data provided for this purpose by distant-water fishing nations, combined with those held by the Secretariat of the Pacific Community, and were included in both models.

Most of the modelling assumptions of WC15 and PW15 followed closely from WC14, with identical parameter settings and structural assumptions for processes such as natural mortality, catchability, effort deviation penalties, and tag reporting rates. For both models, the L2 parameter of the Von Bertalanffy growth function was initially fixed at the value assumed in WC14 with an extra phase added to the model fitting process to allow estimation of this parameter. Growth functions for these models estimated by Multifan-CL (MFCL) were compared to growth functions fitted to otolith and tag recapture data external to the stock assessment model for both the EPO and WCPO areas.

The general results of the modelling procedure, and comparisons of WC14, WC15 and PW15 (WCPO regions) results can be summarized as follows:

- Absolute estimates of recruitment, total biomass and spawning potential showed some differences between the WC15 and PW15 models, though larger differences were observed between these 2015 models and the WC14 model, which can largely be attributed to the new CPUE indices used in the 2015 models.
- Estimates of depletion and depletion-based reference points were very consistent among the three models.
- The spawning potential in 2012, as a proportion of the spawning potential in the absence of fishing ($SB_{latest}/SB_{F=0}$), was estimated to be 0.16, 0.15 and 0.14 for the WC14, WC15 and PW15 models, respectively.
- High rates of movement from the WCPO to the EPO were estimated for PW15, with a high proportion of fish in the EPO estimated to originate from the WCPO. Conversely, fish in the WCPO were estimated to comprise mainly fish that originated in the WCPO.
- All models estimated relatively similar growth functions although the estimates of L2 were higher and lower than those estimated from independent data external to the model for the WCPO and EPO, respectively.

We conclude that the dynamics of bigeye tuna in the WCPO estimated using the Pacific-wide model are not substantially different from those estimated using the WCPO-only model, especially with respect to the main stock status indicators used by WCPFC. Therefore, we suggest that it is reasonable to continue to

provide management recommendations to WCPFC on the basis of WCPO regional stock assessment models. Additionally, it should be acknowledged that a significant potential misspecification of the PW model is assuming common growth across the Pacific when actual growth may be spatially explicit, which cannot be reliably modelled using currently implemented age-based models. WCPO-specific models will be more suited to these dynamics by providing a more homogeneous population for this and other biological vital rates (natural mortality, maturity etc.) as long as management recommendations are not sensitive to the flow of fish across the WCPO/EPO boundary, as was the case in this study. We also recommend further investigation of spatial variation in bigeye tuna growth, both within the WCPO and Pacific-wide, using data already collected and processed, and otoliths that have been collected but remain unread. It will then be important to test the sensitivity of stock status indicators to using only mean growth patterns in stock assessments, given the spatial variation observed in these studies.

1 Introduction

The review of the 2011 stock assessment of bigeye tuna (BET) in the western and central Pacific Ocean (WCPO; Ianelli et al., 2012) recommended the following:

> *Previous analyses using a Pacific-wide assessment appeared to justify the current assessment approach of conducting an assessment for the WCPO only. However, recent tagging data show considerable movement of bigeye tuna between the WCPFC area and the eastern Pacific Ocean (EPO). This suggests that the assumption that migration between the WCPO and EPO need not be explicitly accounted for in the assessment needs to be re-evaluated. Given the new information, a new Pacific-wide assessment should be conducted to re-evaluate this.*

The present paper responds to that recommendation. We should stress at the outset that the intent of the study reported here is not to undertake a full assessment (incorporating full structural sensitivity analysis, projections, etc.) of bigeye tuna on a Pacific-wide (PW) basis, in order to provide a basis for management advice to the Commission, as is the case for routine assessments conducted by SPC. Rather, this work is restricted to the more specific task identified by Ianelli et al. (2012), that is, to re-evaluate the impact on WCPO bigeye tuna stock assessments of assuming a closed population of bigeye tuna west of 150°W. To undertake this task, we have built a Pacific-wide model of bigeye tuna (referred to hereafter as PW15) that fully incorporates catch, effort, size and tagging data from both the WCPO and the EPO (east of 150°W). The model has been constructed to be comparable in most respects to the reference case model described in the 2014 WCPO bigeye tuna assessment (run 037 L0W0T0M0H0, Ref.Case, Harley et al. 2014b), referred to hereafter as WC14, with the following exceptions:

- The nine-region WC14 model has been extended with an additional three regions in the EPO;
- The data time series has been extended by one year, to include catch, effort and size data to the end of 2013, and tag release data to the end of 2012 (Table 1 and 2); and
- The standardised effort for the key longline (LL) fisheries providing indices of abundance for the model have been based on analyses of an integrated set of operational-level longline data, provided specifically for this work by China, Japan, Korea, Chinese Taipei and the United States, augmented with comparable data held by SPC on behalf of its member countries and territories.

A new model for the WCPO only, referred to as WC15, was also developed for comparative purposes. This model uses the same data as the PW15, except that the EPO regions and the data pertaining to those regions are omitted. In section 2 below, we describe in more detail the various characteristics of the PW15 and WC15 models and the data used. In section 3, we describe and compare the results of the models in terms of growth (also using data external to the models), stock structure and movement, and key stock assessment-related estimates. Specific comparisons are made:

- Between WC15 and the WCPO regions of PW15, which serves as the primary indicator of the effects on WCPO assessments of non-acknowledgement of the fundamentally Pacific-wide structure of the bigeye tuna stock; and
- Between WC14 and WC15, to indicate the effects of new data usage in the current model.

In section 4, we draw conclusions regarding the performance of the WCPO and PW models for stock assessment purposes and the use of the comprehensive operational-level longline data to support bigeye tuna stock assessment models generally in the Pacific.

2 Model description

2.1 General notes

As noted above, PW15 and WC15 were based very closely on WC14, the reference case model of the 2014 WCPO BET stock assessment. A detailed description of that model is given by Harley et al. (2014a). The important features of the model are repeated here, noting any changes to that model, including the details of how EPO data are incorporated into PW15 and subsequent modifications to the model structures and assumptions.

2.2 Spatial structure

The regional boundaries for PW15 west of 150°W are identical to those used in WC14 (and WC15) and so consisted of 9 regions. These regions have been established after incremental changes in the numbers and boundaries of regions over previous stock assessments (e.g. Hampton et al., 2005; Harley et al., 2009; Davies et al., 2011; Harley et al., 2014a). Region boundaries are justified based on several considerations, including splitting the stock on the basis of occurrence of different gears (e.g. equatorial regions dominated by purse-seine (PS) fishing and temperate regions dominated by longline fishing) and attempting to ensure adequate mixing of tagged and untagged fish in a reasonable time period. A further 3 regions were established to cover the EPO from latitudes 40°S–50°N and from 150°W to the Americas landmass (Figure 1). Region 10 extends across the whole of the EPO from 10°N–50°N with the southern boundary established to separate the equatorial area with intensive purse-seine fishing from the area north of this latitude where the catch of bigeye is almost exclusively by longline vessels. The EPO area south of 10°N was divided at 120°W on the basis of the results of Schaefer et al. (2015), which postulated inter-connected putative stocks in the equatorial EPO separated at about 120°W (Figure 2).

2.3 Fisheries

MULTIFAN-CL requires the definition of "fisheries" that consist of relatively homogeneous fishing units. Ideally, these defined fisheries will have selectivity and catchability characteristics that do not vary greatly over time (although in the case of catchability, some allowance can be made for time-series variation). The definition of fisheries for PW15 and WC15 followed Harley et al. (2014a), who defined 33 fisheries in the WCPO, augmented by seven additional fisheries for the EPO regions in the case of PW15 – a longline fishery in each of the three regions and purse seine associated set and unassociated set fisheries in each of regions 11 and 12 (Table 3).

2.4 Time period

The primary time period covered by the assessment is 1952–2013, thus including all significant post-war tuna fishing in the respective model regions, and extending an extra year beyond the time period of the WC14 model. Within this period, data were compiled into quarters (1; January–March, 2; April–June, 3; July–September, 4; October–December).

2.5 Data inputs

Catch and effort

Catch and effort data were compiled according to the fisheries defined above. Catches by the longline fisheries were expressed in numbers of fish, and catches for all other fisheries expressed in weight. This is consistent with the form in which the catch data are recorded for these fisheries.

The spatial distribution of catches over the past ten years is displayed in Figure 3. Most of the catch occurs in the tropical regions (3, 4, 7, 8, 11 and 12). Total annual catches by major gear categories over the entire model period are shown in Figure 4 and a regional breakdown is provided in Figure 5.

As per standard practice, key longline fisheries (one in each region, and denoted L-ALL-1, L-ALL-2, ...) were grouped to share common catchability parameters in the model (Table 3). The effort data for these fisheries were based on standardised catch-per-unit-effort (CPUE) analyses and were scaled to preserve the estimated relative abundance of bigeye tuna among regions (McKechnie et al., 2015; shown in Figure 6). This supported modelling assumptions of constant catchability over time and among regions for these fisheries, thus providing powerful information on both time-series and spatial variation in bigeye tuna abundance. Effort data for other longline fisheries were in units of hundreds of hooks and were unstandardised. For these fisheries, catchability was not shared with other fisheries and time-series variation was allowed.

Effort data units for purse seine (PS) fisheries are defined as unstandardised days fishing and/or searching, and were allocated to set types based on the proportion of total sets attributed to a specified set type (associated or unassociated sets) in logbook data. Similarly, effort units for pole-and-line fisheries were unstandardised days fishing and searching. The catchabilities for purse-seine and pole-and-line fisheries were allowed to vary over time and were not shared.

For five fisheries (three small-fish miscellaneous fisheries, the Indonesia/Philippines handline and the Indonesia/Philippines ex-EEZ purse seine fishery; Table 3) no effort is used – this is typically in cases where effort data do not exist, are considered unreliable, or the fishery is composed of different "other" fishing gears such that their effort units are not compatible. In such cases, these fisheries provide no information on relative abundance, and their catches are simply removed from the population in the regions where they occur.

Catch data for the purse seine fisheries were based on the estimates corrected for grab sampling bias using the paired spill and grab sample trials (i.e., Method 3 in (Hampton and Williams, 2015)). Relatively minor changes to catches between the 2014 and 2015 assessments have occurred due to improvements in the estimates of catch for Indonesian vessels in several fisheries in region 7.

Size compositions

Size data for all fisheries were compiled and processed in an identical fashion to that undertaken for WP14 (Harley et al., 2014a). A graphical representation of the availability of size data used by fishery is given in Figures 7–8. Updated length composition data for PS fisheries in the WCPO were processed using the methods outlined in Abascal et al. (2014). Size compositions for PS fisheries in the EPO were supplied by the IATTC, while composition data for LL fisheries (only Japanese data was used) in those regions were processed using the spatial reweighting methods used for the WCPO and are described in detail by McKechnie (2014).

A feature of the LL compositions in the EPO is a significant change in size of fish caught from around 1990, which is thought to be related to changes in gear over this period (Aires-da Silva and Maunder, 2010), and possibly changes in the origin of the data (Okamoto, 2014). We used LL weight compositions when available (there are few weight data after $\sim$ 2000) to be consistent with the WCPO and because the majority of these data originate from commercial vessels which take most of the catch, rather than training vessels (Okamoto, 2014). Subsequent to the year 2000 we allowed length compositions to be included in the model as over this period they mostly originate from commercial vessels in comparison to earlier in the assessment time period when most lengths originated from training vessels (Okamoto, 2014).

Tagging data

The tagging dataset used in WC15 was simply an updated version of that used in WC14 (Berger et al., 2014). All additional recaptures, and extra tag releases that occurred up to the end of 2012 were incorporated into the model, which resulted in an additional 2 release groups with a total of 6,014 (uncorrected) tagged fish released. Methods of processing data, correcting releases and formulating reporting rate penalties were identical to those used by Berger et al. (2014). It is important to note that, as for WC14, the correction of releases in the WC15 tag file includes adjustment for the proportion of tags recaptured in the EPO and therefore excluded from WC15.

A separate tagging file was constructed for PW15 to allow fish tagged in the WCPO to be caught in the EPO and vice versa. This dataset included all tag releases and recaptures in both the WCPO and EPO, including for the latter, releases on Pacific Tuna Tagging Programme (PTTP) cruises to the 140°W TAO buoys and IATTC releases further to the east. The same methods of processing data, correcting releases and formulating reporting rate penalties were also used on this dataset with the exception that the adjustment of WCPO releases for the proportion of tags recaptured in the EPO was no longer required. This dataset consisted of 72 tag release groups.

Several assumptions needed to be made in order to include IATTC tagging data into PW15 – the releases were corrected for tagger effects by assuming that the tagging-related mortality of fish tagged by experienced taggers was equivalent to experienced taggers in the WCPO; for non-experienced taggers the median estimates of tagging-related mortality for the WCPO were assumed; reporting rate prior specifications for longline fisheries in EPO regions 10–12 were assumed to be the same as for the L-ALL fisheries in the WCPO; reporting rate priors for the EPO purse-seine fisheries were constructed to have a mean of 0.7 (95 % confidence interval 0.55–0.9) as estimated by Maunder et al. (2009); and reporting rate priors for WCPO fisheries capturing fish tagged in IATTC tagging programmes were assumed to be the same as those for the

PTTP.

Age-at-length data

Age-at-length data were not formally included in the model, but due to the importance of considering spatial variation in growth rates and their potential impact on the robustness of the Pacific-wide model, we performed analyses of available data external to the stock assessment model for diagnostic purposes. The model presented by Aires-da Silva et al. (2015) was fitted to data collected for the WCPO in the form of two datasets – age-length observations based on otolith ring counts for fish sampled in the WCPO, and age-length observations for WCPO tag recaptures considered to have reliable measurements of release length, recapture length and time-at-liberty. For the latter, only recaptures at liberty for longer than 180 days were included.

The external growth model uses the information on the observed age-length relationship of small fish for the otolith data combined with lengths of released and recaptured fish to simultaneously fit a growth function and estimate the ages of tagged fish at release as a random effect. The age of fish at the time of recapture is deterministically related to age-at-release by adding time at liberty. The likelihood is the product of likelihoods for the otoliths, releases and recaptures, and so are each assumed to be independent (Aires-da Silva et al., 2015). The model was fitted to the data using Template Model Builder (Kristensen et al., 2014).

Aires-da Silva et al. (2015) fit a Richard's growth curve to the EPO data; however, the p parameter of the Richard's growth function was difficult to estimate for the WCPO data and so the Von Bertalanffy function was estimated instead, consistent with the estimation of growth in MFCL. The estimated age-length function for these integrated datasets for bigeye tuna in the EPO that are shown in the results section are the same as those presented in Aires-da Silva et al. (2015), although the tagging increment dataset plotted here contains several additional fish that were recaptured and reported subsequent to their study.

2.6 Main population dynamics assumptions

The population dynamics assumptions for PW15 and WC15 are generally consistent with those used in WC14 (Harley et al., 2014a). Slight variations that were employed are described below:

- For growth estimation, we initially fixed the L2 parameter (mean length of the the oldest age class - 40 quarters) at 184 cm, as per WC14. However, it was subsequently found that stable estimates of L2 could be obtained for both PW15 and WC15, and therefore models with estimated L2 are reported here.
- As noted above, the catchability coefficients for the main longline fisheries, one per region, are assumed to be shared and are constant over time. For PW15, we include the main longline fisheries in regions 10, 11 and 12 in this scheme.
- The selectivity patterns for the main longline fisheries are also constrained – selectivity characteristics are shared (separately) for the main longline fisheries in the northern regions (1, 2, 10) and the main longline fisheries in most of the remaining regions (3, 4, 5, 6, 9, 11, 12). Including the main longline fisheries in regions 7 and 8 in this scheme was found to inadequately fit the size composition data for these fisheries and therefore they were allowed to have independent selectivity parameters.

A full description of parameter settings and sharing schemes is provided in Table 3.

2.7 Comparison of models and model summaries

The range of quantities that can be effectively compared between Pacific-wide and WCPO models is limited when the area of interest is only the WCPO regions. For example, yield calculations are undertaken at the aggregate scale for the entire stock (as defined in the model) and so it is difficult to compute many of the reference points that rely on MSY estimates for just the WCPO regions in the PW15 model. We therefore focus on tractable quantities such as fisheries-depletion-based reference points. For these purposes we define periods over which reference points are calculated as those used for the 2014 stock assessment, to ensure that all 3 models are directly comparable. Quantities defined as "latest" and "current" relate to the mean in 2012 and the mean over the period 2008–2011, respectively, while $SB_{F=0}$ is the mean spawning potential estimated to occur in the absence of fishing over the period 2002–2011.

3 Results

The main results of PW15 are described in the sections below and, where appropriate, comparisons are made between the WCPO regions of PW15 and WC15 and WC14 models.

3.1 Growth estimates

The growth estimates for the PW15 and WC15 models are almost identical (Figure 9). This was somewhat surprising, since bigeye tuna growth is thought to vary across the Pacific, with faster growth suggested to occur in the east. The results obtained from the respective models shown here do not necessarily dispel this hypothesis – it may simply be that the additional size data included in PW15 is not sufficient to provide a substantially different growth interpretation than the data for the WCPO only.

We examined a number of external data sets based on otolith ring counts and longer-term tag recaptures to examine the consistency of these data with the MFCL-derived growth estimates. The locations of the tag releases and recaptures (from which tagging increment data were obtained), and the location of collection of otoliths are shown in Figure 10. The EPO and WCPO datasets and estimated growth functions suggest relatively similar growth rates at young ages but diverge substantially at older ages such that fish in the EPO that are 10 years of age are expected to be ∼25cm larger than equivalently aged fish in the WCPO (Figure 11). There is also some evidence of variation in growth within the WCPO, with otolith age-length data from French Polynesia (PF) continuing to grow relatively linearly beyond the size where the tagging increment data for the WCPO shows a tendency for the growth rate to slow (Figure 12). The growth data from both regions are reasonably consistent with the MFCL estimates up until around 100 cm fork length or 3 years of age. Thereafter, the MFCL growth curve underestimates empirical length-at-age for the EPO and overestimates length-at-age for the WCPO (Figure 13).

It should be noted that many of the long-term tag recaptures making up the WPCO data set come from a fairly restricted area (Coral Sea - regions 5 and 9). It would be worthwhile to more carefully examine such data by spatial location to see if there is evidence of gradual change in growth with longitude, or if the changes are more abrupt.

3.2 Movement and stock structure

High rates of quarterly movement were estimated among many regions for both models, including across region boundaries separating the WCPO and EPO (Figure 14). Figure 15 provides a graphical representation of stock composition under unexploited conditions, demonstrating the regions from which fish in a focal region originate (were recruited into). Notable features of the PW15 model are; 1) mixing of fish between the northern temperate regions (e.g. 1, 2, 10), but with little mixing with the regions to the south; 2) tropical regions (3, 4, 5, 7, 8, 11, 12) receiving a large proportion of fish from many other tropical and temperate regions; 3) a general pattern of fish moving west to east into regions 11 and 12 from most other regions, with little movement the other way, e.g., region 12 receives nearly all its fish from other regions and contributes a low proportion of fish to region 11, and 4) few fish in regions 9 and 10 immigrating from other regions.

The empirical evidence for region-to-region movement observed from tag-recapture data is shown in Figure 16. The majority of tagged fish are recaught within the region they were tagged, there is moderate levels of recapture in regions adjacent to where they were tagged, but relatively low levels of recapture in non-adjacent regions. It is notable that more fish tagged in region 11 were recaptured in region 12 than in 11 itself.

3.3 Recruitment

Annual recruitment is plotted by region in Figure 17, and indicates that most recruitment ($\sim 70\%$) occurs in the WCPO. Total recruitment shows a time series pattern similar to that estimated in WC14 – high initially, low through the 1960s and 1970s, increasing in the 1980s and at a high level from about 1990.

The recruitment estimates for the WCPO regions of PW15 are generally consistent with the estimates from WC15 and WC14 (Figure 18). Notable exceptions are the absence of a strong initial decline in recruitment in region 2 of PW15; lower recruitment in region 4 and higher recruitment in region 6 in PW15; and some differences in early recruitment between WC14 and WC15 in regions 3, 5, 7 and 8, likely due to the longer time series of operational-level data available for estimating standardised CPUE indices for the WC15 analysis.

3.4 Total biomass and spawning potential

The PW15 and WC15 models produce trends in biomass very similar to those seen in previous WCPO bigeye tuna assessments. After relative stability in the 1950's, both total biomass and spawning potential declined rapidly through the 1960–70's before a continued, more moderate decline until the end of the assessment period (Figure 19). The PW15 model estimates that the EPO accounted for around 60% of spawning potential at the start of the time period, with this percentage steadily declining to just under 50% by the end of the assessment period. Most regions showed declines of similar magnitudes, with the exception of regions 7 and 8, and to a lesser extent region 3, which showed more moderate declines and are the cause of the increasing ratio of spawning potential between the WCPO and PO (Figure 20).

Comparison of the PW15 and WC15 models shows differences in absolute estimates of spawning potential, with the latter estimating higher biomass in all regions, however the relative changes is spawning potential are similar for all regions in the WCPO (Figure 20). The PW15 model estimated that spawning potential declined by about 81% over the assessment period for the WCPO area (regions 1–9), while the WC15 model estimated the decline at about 76%. Much larger differences were apparent between the WC14 model and the two 2015 models, with the former estimating significantly larger spawning potential for most regions. While trends in spawning potential were often similar for WC14, this was not always the case, with most noticeable differences again occurring in regions with differences in the temporal coverage of standardised CPUE between WC14 and WC15 (e.g. regions 3, 7 and 8).

3.5 Fishery impact and fishing mortality

Plots of the ratio of estimated spawning potential to the spawning potential estimated to occur in the absence of fishing generally show very similar dynamics between the three models(Figure 21), and this is especially the case when the WCPO regions are aggregated (upper panel of Figure 22). All three models show a largely continuous decline in spawning potential ratio over the assessment period, with decline to below the limit reference point in the early to mid 2000's. The estimates of $SB_{latest}/SB_{F=0}$ for the aggregated WCPO regions, where "latest" is 2012, are 0.16, 0.15 and 0.14 for the WC14, WC15 and PW15 models respectively (Table 4). In several regions the WC14 estimates are slightly different to WC15 and PW15, but in general the two 2015 models showed very similar patterns (Figure 21). The only exception to this was for region 2 where all three models estimate substantially different relative changes.

There was a clear pattern of the PW15 model estimating slightly higher fishing mortality rates in all WCPO regions than the WC15 model, with the only exceptions being the very young age-classes in regions 7 and 8 where fishing mortality rates are very high (Figure 23). These patterns in fishing mortality are a consequence of the higher estimates of biomass for the WC15 model.

3.6 Model fit

Model-predicted CPUE for the fisheries with standardised indices show relatively good fit to observed data for the WCPO regions, but had a tendency to consistently under- or overestimate CPUE during certain periods in the EPO regions (Figures 26–29). Partly this is a consequence of the dramatic early declines in standardised indices in these regions (Figure 26), which are unlikely to reflect changes in abundance.

Patterns of lack of fit of the PW15 and WC15 models to size composition data were similar to the WC14 model; the model over predicts the number of large fish in the length compositions of L-All-5 and L-All-6 (Figure 30) and the weight compositions of offshore fisheries (L-OS-7, L-OS-8; Figure 31). There was lack of fit to several fisheries with few composition samples (S-UNA-All-7, S-UNA-All-11), where selectivity was shared due to difficulties in separate estimation and/or abrupt changes in sizes that could not be closely modelled with time-invariant selectivity (e.g. the last several years of L-OS-7; Figure 33).

The PW15 model was unable to fit all composition data for the EPO LL fisheries well. L-All-12 was fitted the best although there was a tendency to overestimate extremely large fish in the weight compositions. This is perhaps unsurprising given large changes in sizes of fish caught by these fisheries, changes in the origin of this data and the absence of time-variant selectivity in our model.

The PW15 model predictions of tag returns by time at liberty were very close to the observed values up until about 20 quarters at liberty when the model began to underestimate tag returns, although the proportion of tag returns occurring at times longer than this is extremely low and so this is not cause for concern (Figure 36). The overall model predictions of recaptures (after removing fish caught during the 2-quarter mixing period) were relatively close to the observed numbers, with some lack of fit after 2010 and the model underestimated the extremely high observed number of fish recaptured in 2005 (Figure 37).

4 Discussion and conclusions

4.1 Impact of the "closed population" assumption in WCPO assessments

The primary motivation for this work was to compare various stock assessment indicators for the WCPO regions of the PW model with the standalone WC15 model. Overall, we have found that estimates of recruitment, spawning potential and, more particularly, spawning potential depletion, are very similar, even when compared at the individual region level. The estimates of $SB_{latest}/SB_{F=0}$ (where latest is 2012 for direct comparison) for the WC15 and PW15 (WCPO component) are very similar at 0.15 and 0.14, respectively, and are also similar to the estimate from WC14 of 0.16. On this basis, it would seem that the WC15 model, which assumes a closed population for the WCPO, is capable of accurately capturing the dynamics in general, and stock status indicators in particular, of bigeye tuna in the WCPO. While we have not done so in this study, similar comparisons could also be conducted for the EPO if an EPO-only model was developed for comparison with the PW15 results for regions 10, 11 and 12. We would be happy to work with IATTC scientists on this if it was felt to be worthwhile.

The above conclusion assumes that the PW15 model captures the important dynamics of the Pacific-wide population dynamics of bigeye tuna with respect to processes occurring across the WCPO/EPO boundary that will impact on the validity of assuming a closed population. We expect that modifications to the model to better fit certain datasets, such as changing selectivity functions or allowing time-variant selectivity may change the absolute estimates of the model, but are unlikely to substantially change the relative estimates of the impact of fishing. Furthermore, we expect changes such as this to be less influential than potential misspecification of growth.

While simplifying assumptions about model parameters, such as time-invariant biological parameters or constant catchability for a fishery, are often necessary due to a lack of information, and in many cases the results of the stock assessment will be robust to this misspecification, it is increasingly clear that significant differences in growth of bigeye tuna may occur in different parts of the Pacific Ocean. Unfortunately it is very difficult to construct models with movement between regions with different growth functions when the underlying dynamical model is age-based (most tuna stock assessments including those fitted using MFCL or Stock Synthesis). This is because individual fish moving into a new region will then have to "join" the growth curve of the new region at the expected part of the curve based on the age of the fish. This could potentially result in unrealistic sudden increases or even decreases (shrinking) in size to conform to the new curve. There is some allowance for flexibility in the growth of fish entering new regions in some models, for example fish might be able to retain the growth curve of their natal region after entering the new region (e.g. "platoons" in stock synthesis), though as far as we are aware they have not been implemented for stock assessments of this kind, and they make the very strong assumption that growth variation is genotypic rather than phenotypic or a combination of both.

For these reasons we suggest caution when interpreting the results of PW stock assessment models, although the similarities between the WC15 and PW15 models with respect to relative population dynamics and associated management implications, despite probably significant model misspecification, are somewhat reassuring. Partly, this can probably be attributed to the very similar growth curves estimated for the WC15 and PW15 models. We recommend further consideration of the interaction between spatial variation in growth and other parameters such as movement, but until models are developed which can model this variation reliably in large-scale tuna assessments we recommend continuation of separate assessments for the WCPO and EPO, as assumptions of homogeneity of biological parameters are more likely to be met.

4.2 Use of operational-level longline data

The WC15 model was developed to be closely comparable to the 2014 bigeye tuna reference case assessment, WC14. The only differences in these two models were, for WC15, the addition of data for 2013 and the use of a comprehensive data set of operational-level longline catch and effort data (most of the indices used in the WC14 model relied only on SPC-held operational data) as the basis for deriving CPUE indices and standardised effort for the main longline fisheries. The addition of 2013 data is not expected to have had a major impact, therefore, most differences in the results of WC15 and WC14 will be largely due to the use of the operational-level longline data, which are thought to provide a superior basis for estimating relative abundance trends (Hoyle and Okamoto, 2011). While the overall results of WC15 and WC14 are very similar, there are several aspects that have been affected, e.g. substantially different historical estimates of recruitment and biomass in some regions, particularly 3, 7 and 8; greater recent spawning potential depletion in region 2 and less depletion in regions 1 and 6; and slightly greater spawning potential depletion over the entire time series for the WCPO as a whole. Some of these differences result from differences in the trajectories of the indices, but many relate more to the actual length of the indices. For example, the 2015 indices for regions 3–9 all begin substantially earlier in the assessment time period than those used in WC14, and so provide more infomation for the estimation of population dynamics in these regions. Consequently, we believe that the stock assessments are enhanced by the use of the operational-level data and that such data should be used to support all WCPO assessments in the future.

4.3 Future considerations of growth

Examination of available growth data from otoliths and tagging release/recaptures provided some interesting insights into the putative spatial pattern of bigeye tuna growth in the Pacific. Our growth function estimated for a mixture of datasets from the WCPO estimated a substantially lower L_∞ parameter than that estimated for the EPO by Aires-da Silva et al. (2015), and also the WC14, WC15 and PW15 models.

A number of issues remain with these data; there are spatial and temporal differences in the origin of otolith and tagging growth data, there is uncertainty in their "representativeness" of growth in the WCPO given many of the recaptures are in the far west (Coral Sea) or far east (CPO releases recaptured in the EPO), and work is required to examine the raw data closely to construct a “high confidence” dataset (e.g. Schaefer et al., 2015) which maximises the number of returns in the dataset while maintaining the accuracy of the information they provide (time of recapture, accuracy of length and area of recapture). Growth parameters are extremely important for constructing robust stock assessments, and management quantities are frequently sensitive to these parameters (Hoyle et al., 2012), making it important for the model to represent growth accurately. Furthermore, spatial variation in growth is increasingly being detected in tuna stocks (Williams et al., 2012) but is extremely difficult to model adequately using age-structured assessment models with movement between regions with different growth rates. There appears to be significant differences in growth between the EPO and WCPO and the French Polynesia otolith data support the potential for within WCPO spatial variation in these parameters.

We recommend further investigation of growth rates of tropical tunas in the WCPO, with closer examination of previously collected data using updated analytical techniques. While spatial variation in growth is likely to exist, it is not yet clear what impact such variation, if ignored, might have on the results of tuna assessments. Simulation of population dynamics with spatially explicit growth and fitting of models with a similar structure to our stock assessments would be a challenging, but valuable undertaking. Furthermore, emphasis should be placed on estimating ages-at-length for the substantial set of otoliths recently collected over a spatially extensive area of the WCPO (Nicol et al., 2014) but for which funding has not yet been committed. Once completed these data will allow more robust comparison with not only the EPO, but also within the WCPO stock assessments which currently assume common growth among regions.

Acknowledgements

We are grateful to all fisheries agencies in the region that have contributed data to the SPC and/or the WCPFC for this assessment. We thank Peter Williams and his team for assistance with collating the input data, and Mark Maunder, Alex Aires-da-silva, Kurt Schaefer, Dan Fuller and Nick Vogel for assistance in the compilation of EPO data and reviewing the document.

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5 Tables

Table 1: Number of tagged fish released and recaptured by program, release group, region and time period for the dataset used in the WC15 model. Rounded to the nearest fish.

	CS 1991–2001			PTTP 2006–12			RTTP 1989–1992		
Reg	Grps	Rel	Rec	Grps	Rel	Rec	Grps	Rel	Rec
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	10	1,272	365	5	293	65
4	0	0	0	8	7,507	3,833	3	908	107
5	0	0	0	1	29	7	1	132	4
6	0	0	0	0	0	0	0	0	0
7	1	277	102	3	398	117	4	941	268
8	0	0	0	12	1,734	796	5	537	48
9	5	4,236	337	0	0	0	0	0	0
Total	6	4,513	439	34	10,940	5,118	18	2,804	492

Table 2: Number of tagged fish released and recaptured by program, release group, region and time period for the dataset used in the PW15 model. Rounded to the nearest fish.

	CS 1991–2001			IATTC 2000–06			PTTP 2006–12			RTTP 1989–1992		
Reg	Grps	Rel	Rec	Grps	Rel	Rec	Grps	Rel	Rec	Grps	Rel	Rec
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	10	1,274	368	5	293	65
4	0	0	0	0	0	0	8	10,411	5,695	3	908	107
5	0	0	0	0	0	0	1	29	7	1	132	4
6	0	0	0	0	0	0	0	0	0	0	0	0
7	1	277	102	0	0	0	3	398	117	4	941	268
8	0	0	0	0	0	0	12	1,734	796	5	531	48
9	5	4,270	339	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	3	2,633	2,268	0	0	0
12	0	0	0	9	15,648	8,104	0	0	0	0	0	0
Total	6	4,547	441	9	15,648	8,104	37	16,479	9,251	18	2,804	492

Table 3: Description of fisheries and some of the modelling assumptions made for the PW model.

Fsh	Gear	Flag	Reg	Selec-tivity function	Selectivity group	Catch-ability group	Tag return group	Reporting rate group	Effort penalty	Seasonal catchability	Time series catchability	CV time series catchability
1	L	All	1	spline	1	1	1	1	time-variant	Y	N	N
2	L	All	2	spline	1	1	2	1	time-variant	Y	N	N
3	L	US	2	spline	2	2	3	2	scaled, CV 0.22	Y	Y	0.1
4	L	All	3	spline	3	1	4	1	time-variant	Y	N	N
5	L	OS	3	spline	4	3	5	1	scaled, CV 0.22	Y	Y	0.1
6	L	OS	7	logistic	5	4	6	1	scaled, CV 0.22	Y	Y	0.1
7	L	All	7	spline	6	1	7	1	time-variant	Y	N	N
8	L	All	8	spline	7	1	8	1	time-variant	Y	N	N
9	L	All	4	spline	3	1	9	1	time-variant	Y	N	N
10	L	US	4	spline	2	5	10	2	scaled, CV 0.22	Y	Y	0.1
11	L	AU	5	spline	8	6	11	3	scaled, CV 0.22	Y	Y	0.1
12	L	All	5	spline	3	1	12	4	time-variant	Y	N	N
13	L	All	6	spline	3	1	13	1	time-variant	Y	N	N
14	S-ASS	All	3	spline	9	7	14	5	scaled, CV 0.22	Y	Y	0.7
15	S-UNA	All	3	spline	11	8	14	5	scaled, CV 0.22	Y	Y	0.7
16	S-ASS	All	4	spline	10	9	15	6	scaled, CV 0.22	Y	Y	0.7
17	S-UNA	All	4	spline	15	10	15	6	scaled, CV 0.22	Y	Y	0.7
18	Misc	PH	7	spline	12	11	16	7	CV 0.7	N	N	N
19	HL	ID-PH	7	spline	13	12	17	8	CV 0.7	N	N	N
20	S	JP	1	spline	14	13	18	9	scaled, CV 0.22	Y	Y	0.1
21	P	JP	1	spline	14	14	19	10	scaled, CV 0.22	Y	Y	0.1
22	P	All	3	spline	14	15	20	11	scaled, CV 0.22	Y	Y	0.1
23	P	All	8	spline	14	16	20	12	scaled, CV 0.22	Y	Y	0.1
24	Misc	ID	7	spline	12	17	21	13	CV 0.7	N	N	N
25	S	ID-PH	7	spline	9	18	22	14	CV 0.7	N	N	N
26	S-ASS	All	8	spline	9	19	23	15	scaled, CV 0.22	Y	Y	0.7
27	S-UNA	All	8	spline	11	20	23	15	scaled, CV 0.22	Y	Y	0.7
28	L	AU	9	spline	8	21	24	16	scaled, CV 0.22	Y	Y	0.1
29	P	All	7	spline	12	22	25	17	scaled, CV 0.22	N	Y	0.1
30	L	All	9	spline	3	1	26	18	scaled, CV 0.22	Y	N	N
31	S-ASS	All	7	spline	9	23	27	5	scaled, CV 0.22	Y	Y	0.7
32	S-UNA	All	7	spline	11	24	27	5	scaled, CV 0.22	Y	Y	0.7
33	Misc	VN	7	spline	12	25	28	19	CV 0.7	N	N	N
34	L	All	10	spline	1	1	29	1	time-variant	Y	N	N
35	L	All	11	spline	3	1	30	1	time-variant	Y	N	N
36	L	All	12	spline	3	1	31	1	time-variant	Y	N	N
37	S-ASS	All	11	spline	16	26	32	56	scaled, CV 0.22	Y	Y	0.7
38	S-UNA	All	11	spline	17	27	32	56	scaled, CV 0.22	Y	Y	0.7
39	S-ASS	All	12	spline	16	28	33	56	scaled, CV 0.22	Y	Y	0.7
40	S-UNA	All	12	spline	17	28	33	56	scaled, CV 0.22	Y	Y	0.7

Table 4: Comparison of management quantities among the WC14, WC15 and PW15 models. "Current" is the mean over the period 2008–2011 and "latest" is 2012, for all models, to ensure that WC15 and PW15 can be compared directly with WC14. Note that PW15–WC shows estimates for just the aggregated WCPO regions (1–9) for PW15, where several quantities are left blank as they can only be estimated over the entire Pacific-wide stock.

Parameter	WC14	WC15	PW15–WC	PW15
C_{curr}	166,438	151,455	151,455	250,765
C_{latest}	157,755	151,445	151,445	200,249
MSY	108,520	109,320	-	165,880
B_0	2,286,000	2,200,000	-	3,067,000
B_{curr}	742,967	632,880	486,770	892,858
SB_0	1,207,000	1,195,000	-	1,650,000
SB_{MSY}	345,400	337,700	-	459,800
SB_{curr}	325,063	270,398	163,851	377,379
SB_{latest}	265,599	241,312	143,270	306,703
$SB_{F=0}$	1,616,744	1,654,741	1,042,063	2,232,375
SB_{curr}/SB_{MSY}	0.94	0.80	-	0.82
SB_{latest}/SB_{MSY}	0.77	0.71	-	0.67
$SB_{curr}/SB_{F=0}$	0.20	0.16	0.16	0.17
$SB_{latest}/SB_{F=0}$	0.16	0.15	0.14	0.14

6 Figures

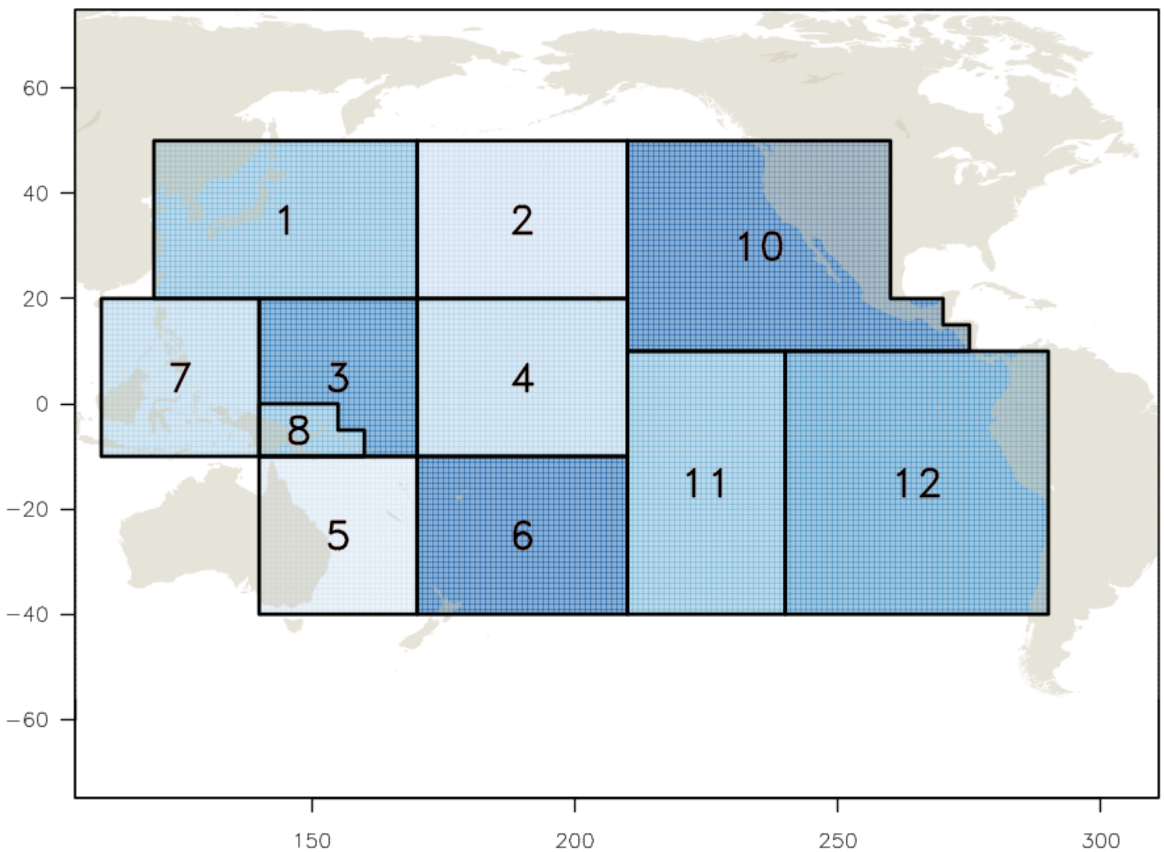


Figure 1: Map of the twelve regions used for the Pacific-wide stock assessment model. Note that the WCPO models, WC14 and WC15, are restricted to regions 1–9.

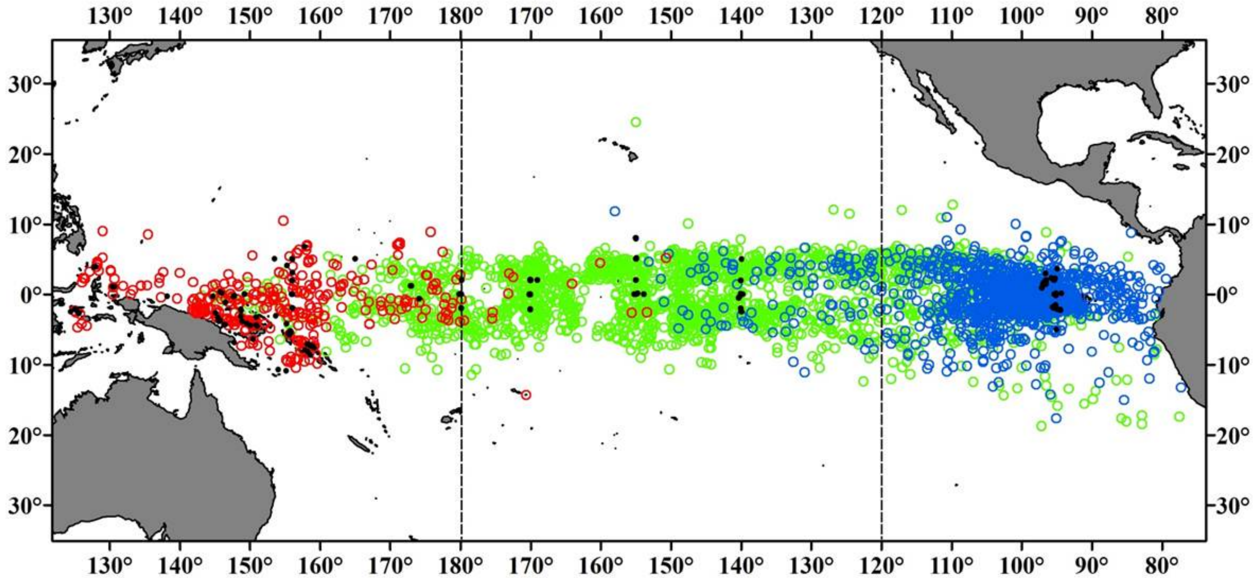


Figure 2: Release locations (black dots) and recovery locations of BET, at liberty for 30d, color coded for releases in the western (red), central (green), and eastern (blue) Pacific. The putative stock boundaries at longitudes 120W and 180are superimposed (from Schaefer et al. (2015)).

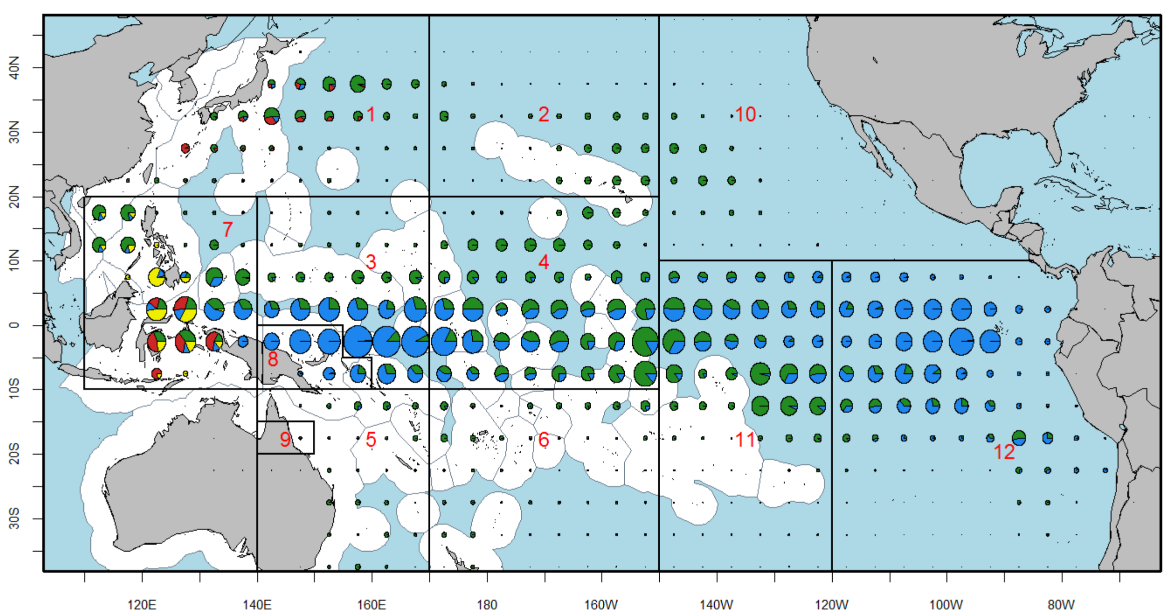


Figure 3: Catch distribution (2004–2013) by 5°squares of latitude and longitude and fishing method: longline (green), purse-seine (blue), pole-and-line (red), and other (yellow). Overlayed are the regions for the assessment model.

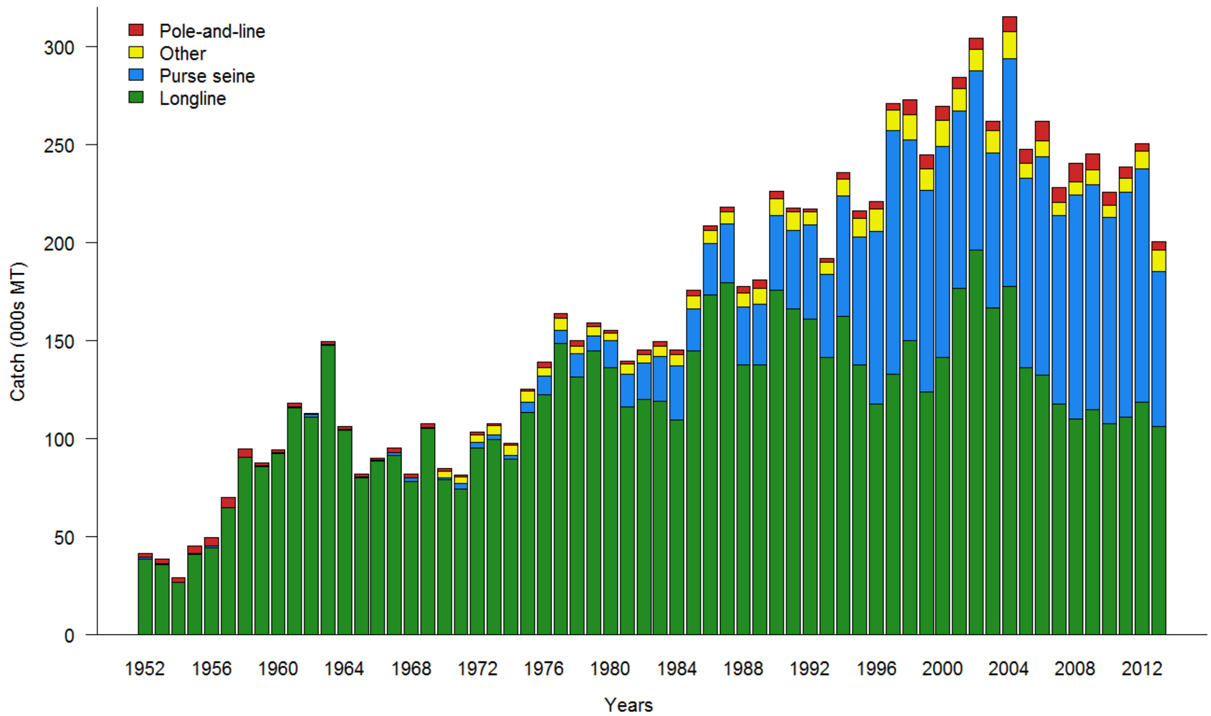


Figure 4: Total annual catch (1000s mt) by fishing gear used in the PW15 model.

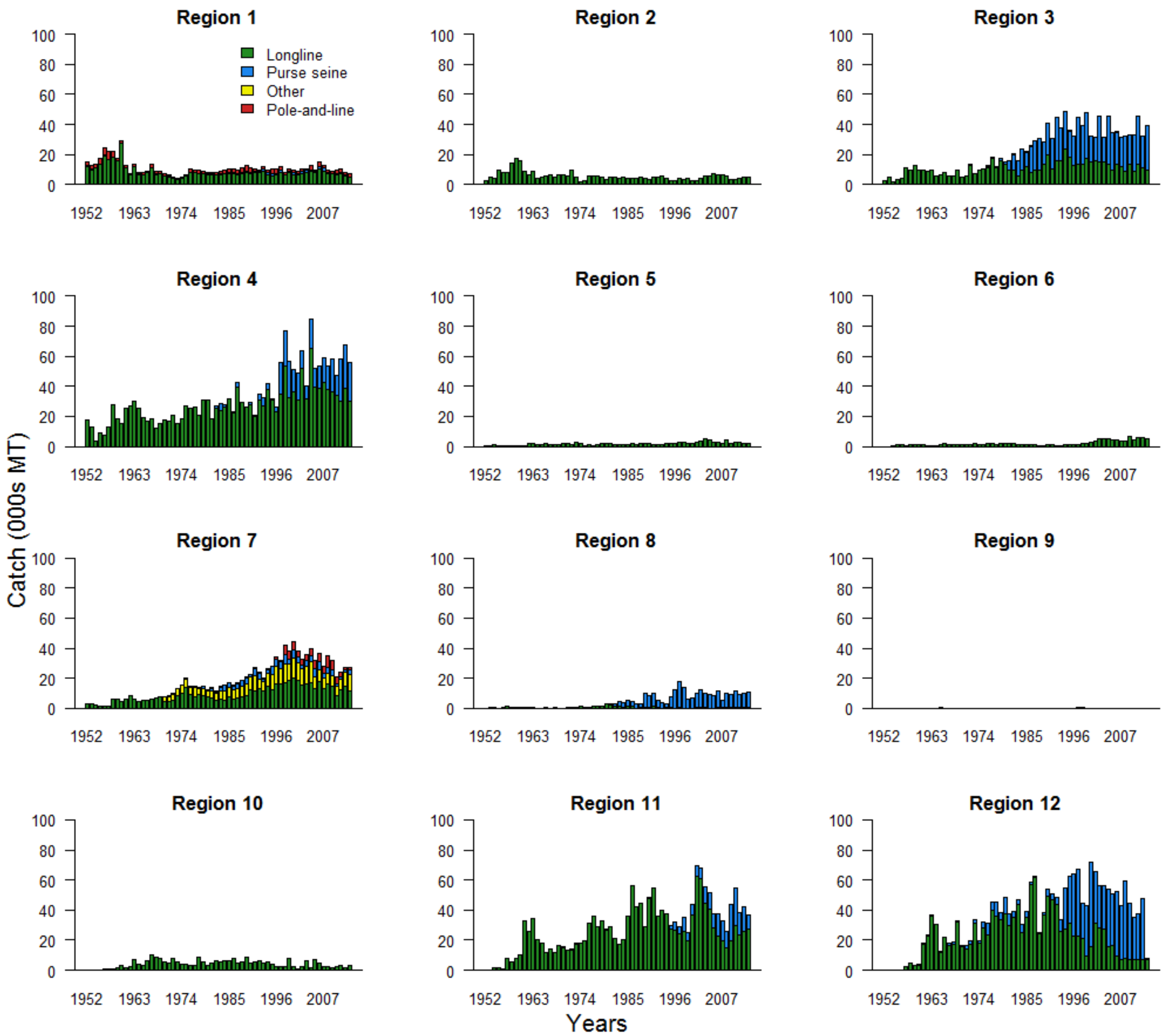


Figure 5: Total annual catch (1000s mt) by fishing method and assessment region used in the PW15 model.

Figure 6: Standardised indices of catch-per-unit-effort (CPUE) for the principal longline fisheries (L-All 1–12) used in the WC15 and PW15 models (blue lines). These are the DLN-*lg-drm-clst* models estimated by McKechnie et al. (2015). For comparison, the indices estimated by McKechnie et al. (2014) that were used in the WC14 model are shown as black lines. Note that McKechnie et al. (2015)s index for region 4 was not used in WC14 as unstable results were estimated, and so an index similar to Hoyle and Okamoto (2011) was used instead.

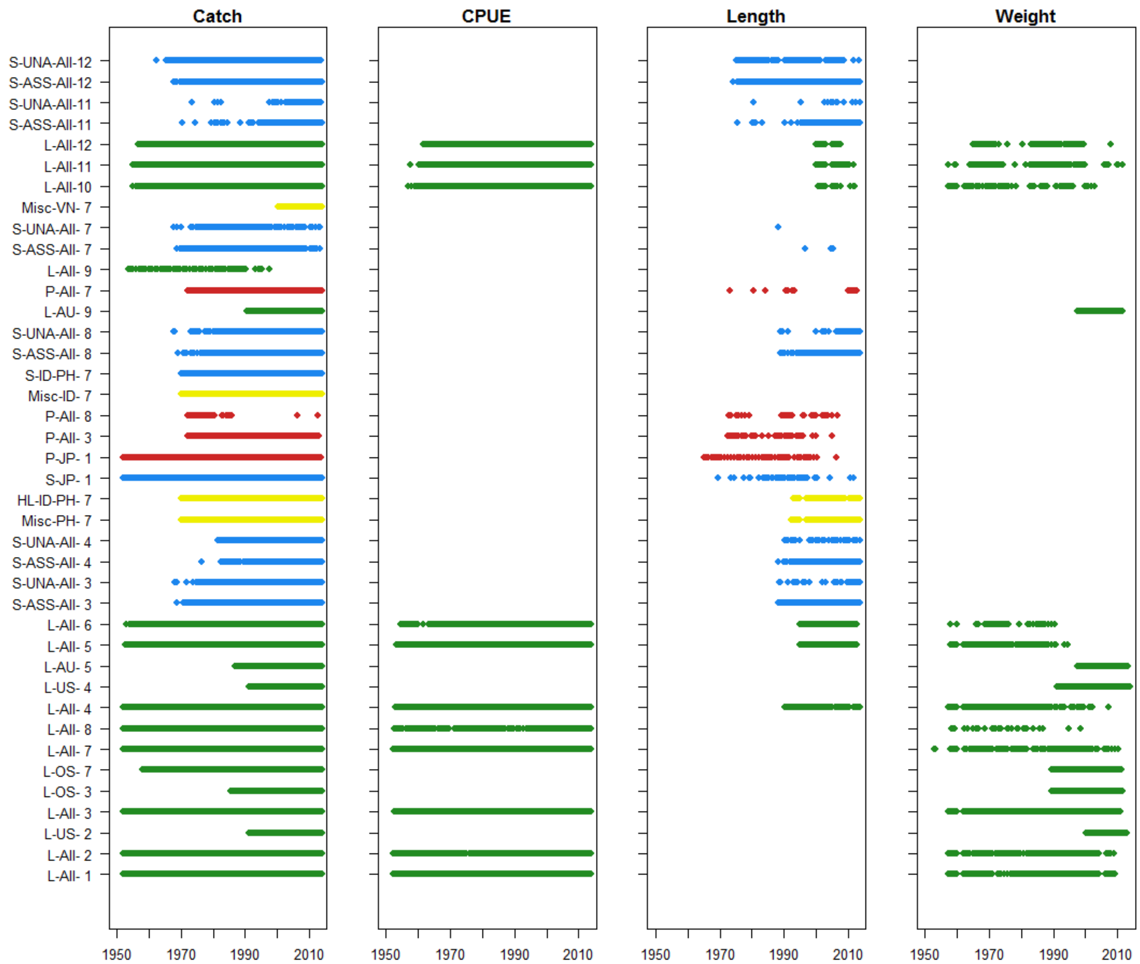


Figure 7: Presence of catch, standardised CPUE, and length and weight frequency data by year and fishery for the PW15 model. The different colours refer to purse seine (blue), pole-and-line (red), longline (green) and other gears (yellow).

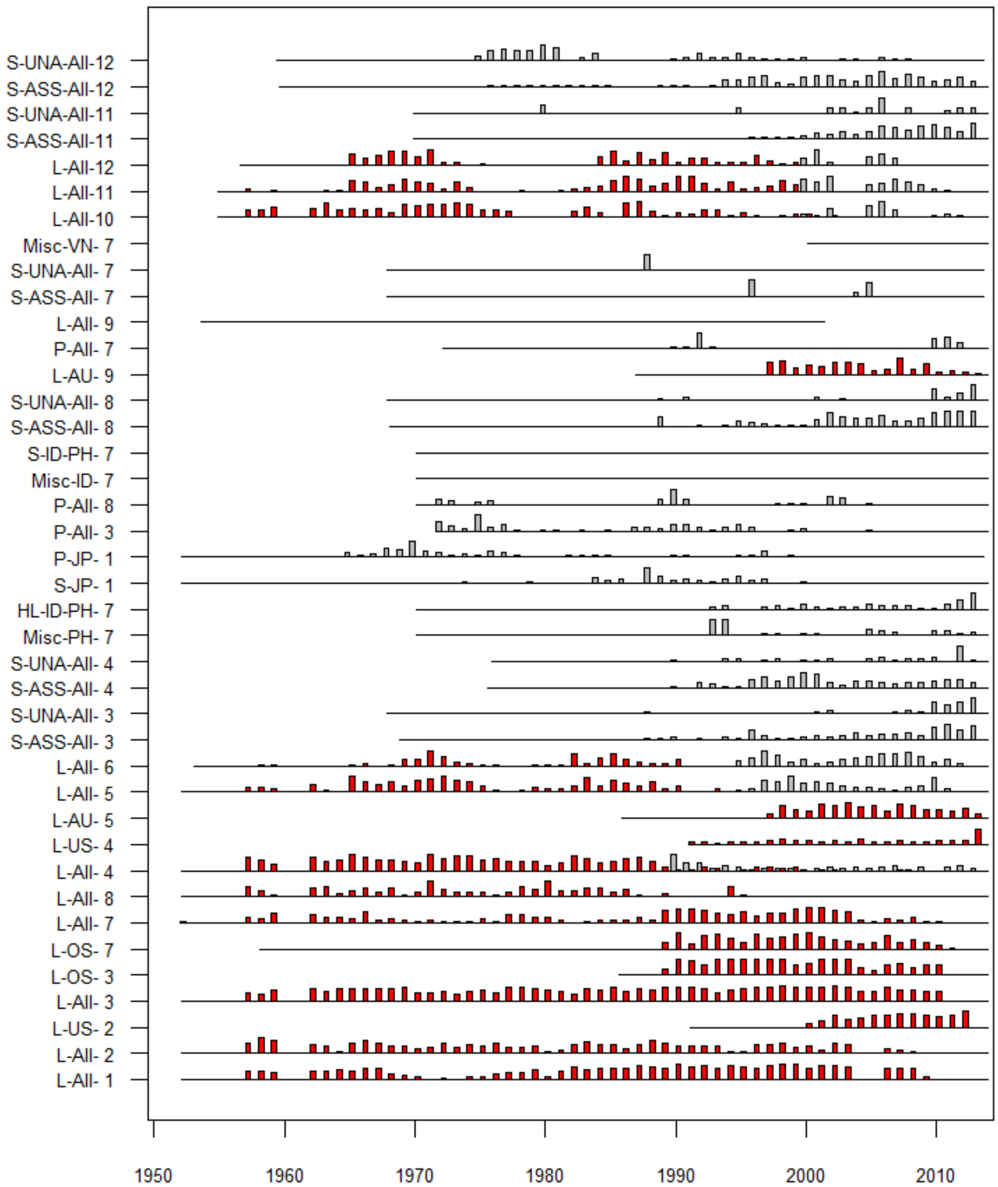


Figure 8: Number of weight (red) and length (grey) frequency samples from the reference case model. The maximum value is 12,493, but note that in these models a maximum sample size of 1,000 is allowed and so any sample greater than this were rescaled to have an effecitive sample size of 1,000.

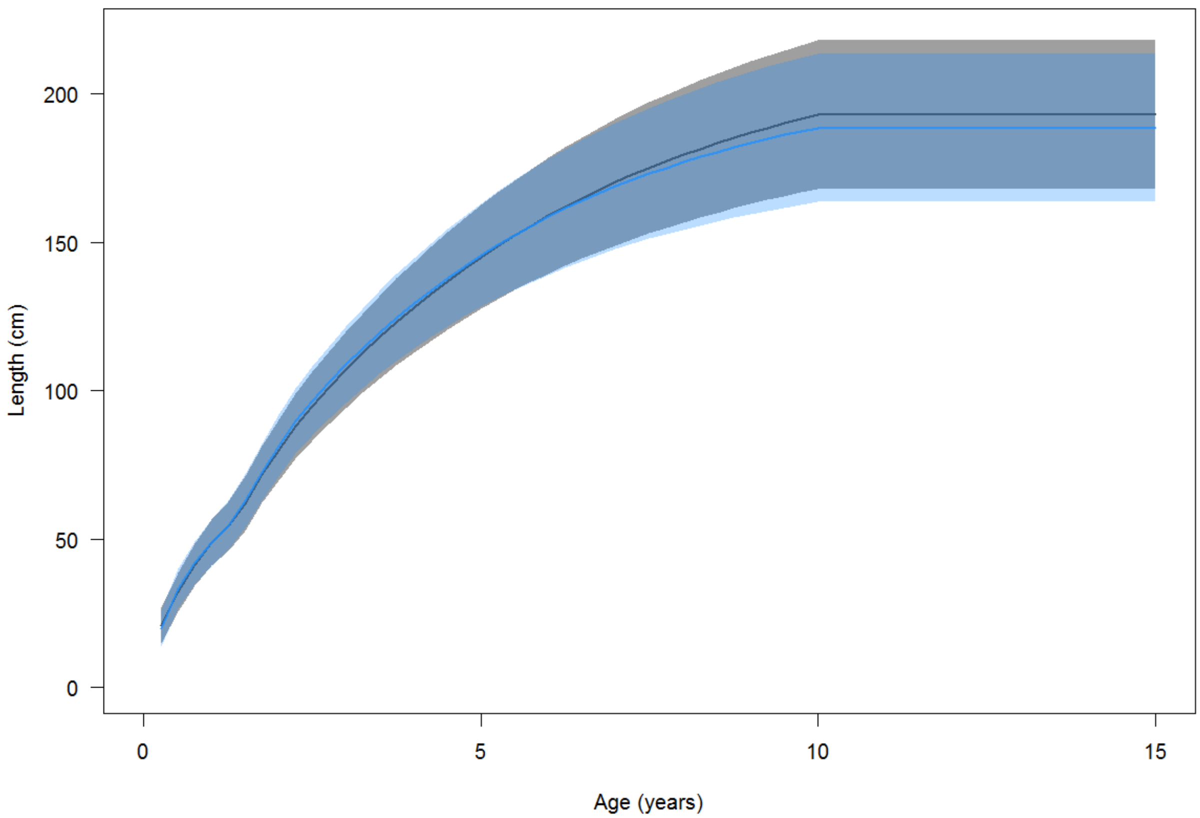


Figure 9: Comparison of Von-Bertalanffy growth functions estimated for the PW15 model (blue line and region) and the WC15 model (grey). The lines are the estimated means and the shaded regions represent 95% confidence intervals.

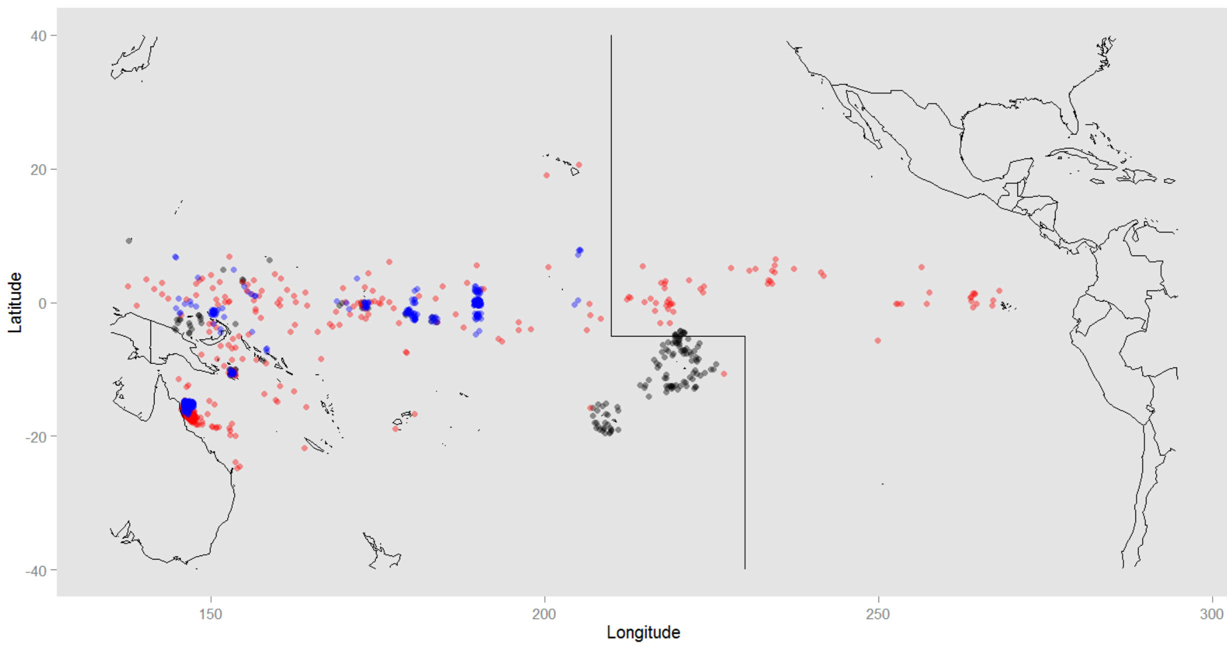


Figure 10: Locations of collection of otoliths (black points), and releases of measured tagged fish (blue points) that were subsequently recaught and remeasured reliably (red points) that make up the WCPO growth dataset.

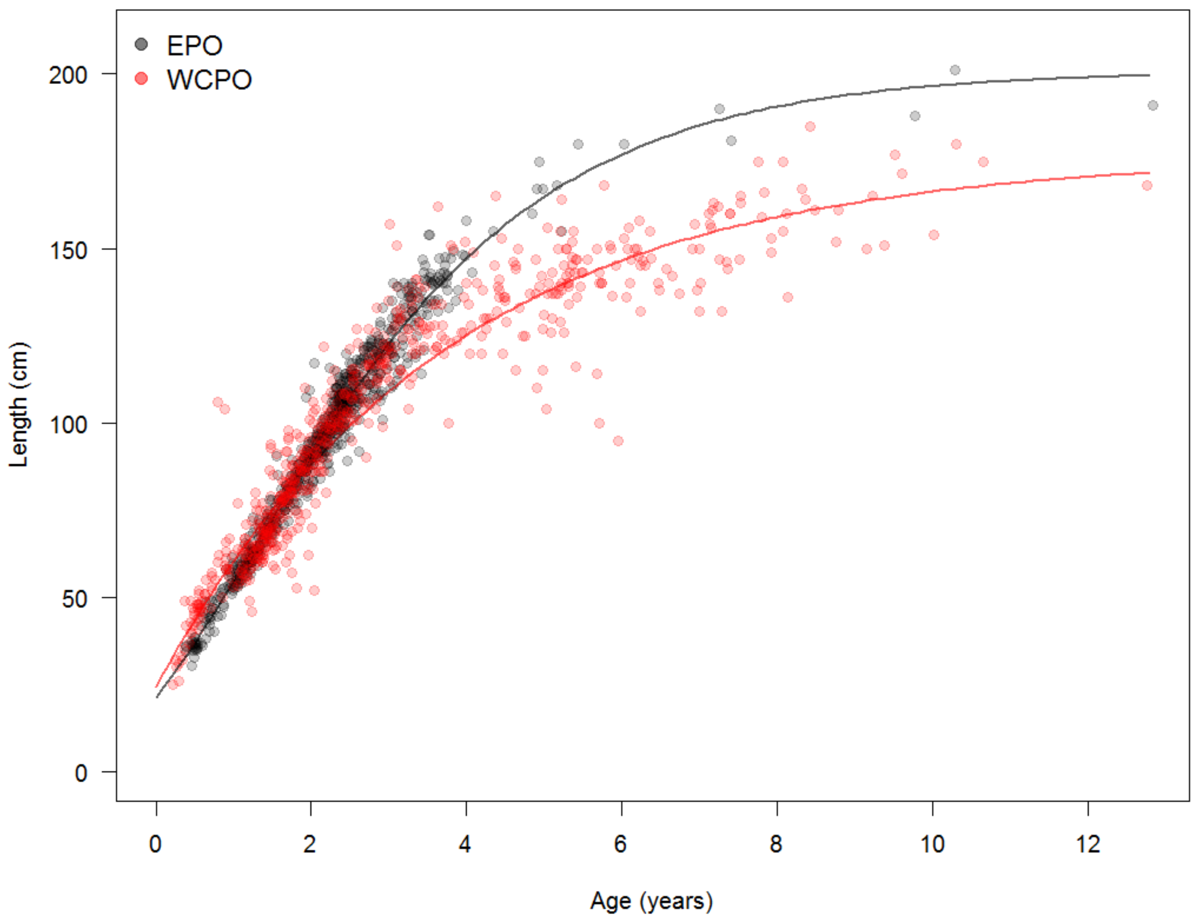


Figure 11: Length-at-age of bigeye tuna derived from otoliths and tagging increment data in the EPO (black points) and WCPO (red points) and the growth functions estimated using the integrated model of Aires-da Silva et al. (2015) fitted to these data.

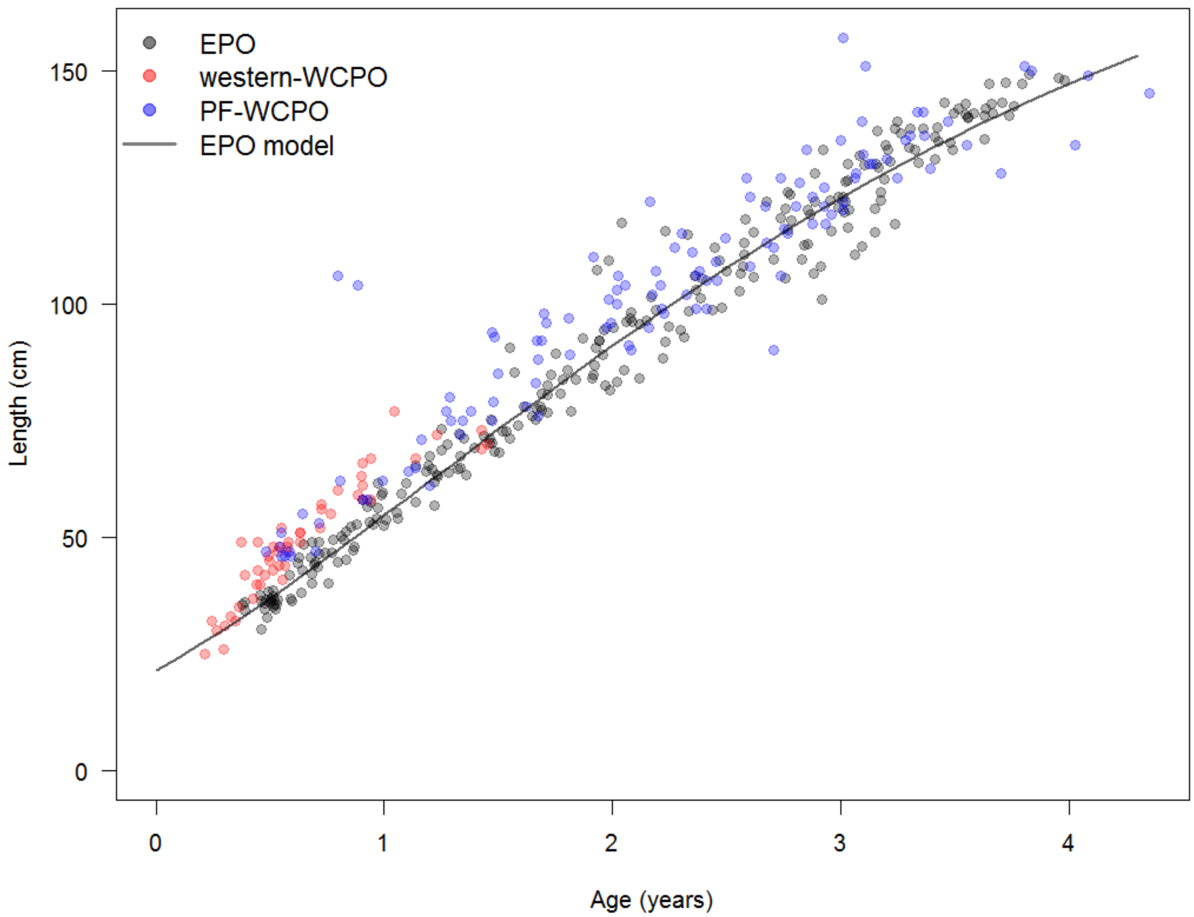


Figure 12: Comparison of lengths-at-age derived from otoliths for the EPO (black points), French Polynesia (blue points) and elsewhere in the WCPO (red points). The black line shows the growth function estimated using the integrated model of Aires-da Silva et al. (2015) fitted to otolith and tagging increment data in the EPO.

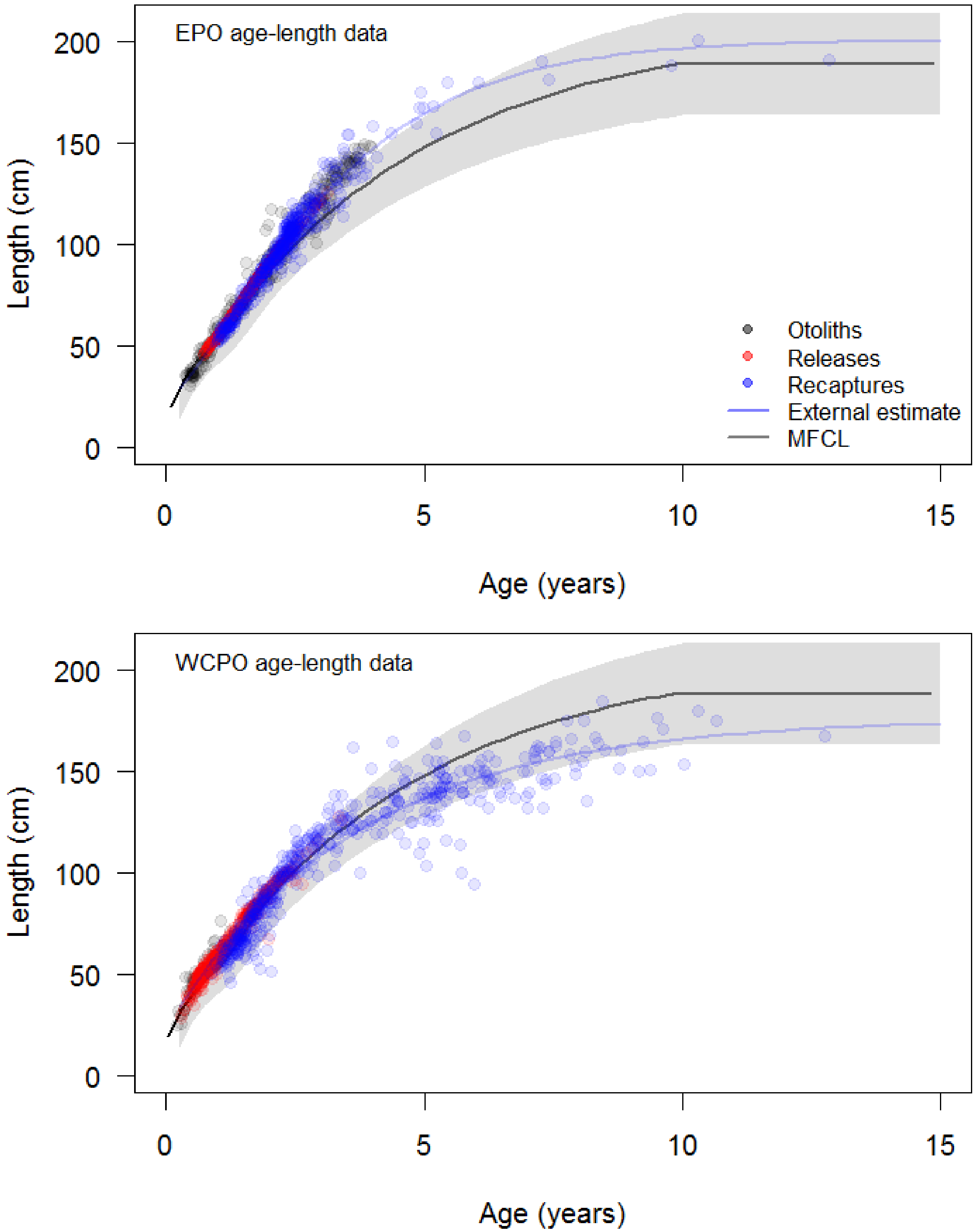


Figure 13: Comparison of observed length-at-age data and estimates of growth rates both within MFCL for the PW15 model and external to the stock assessment model for the EPO (top) and WCPO (bottom).

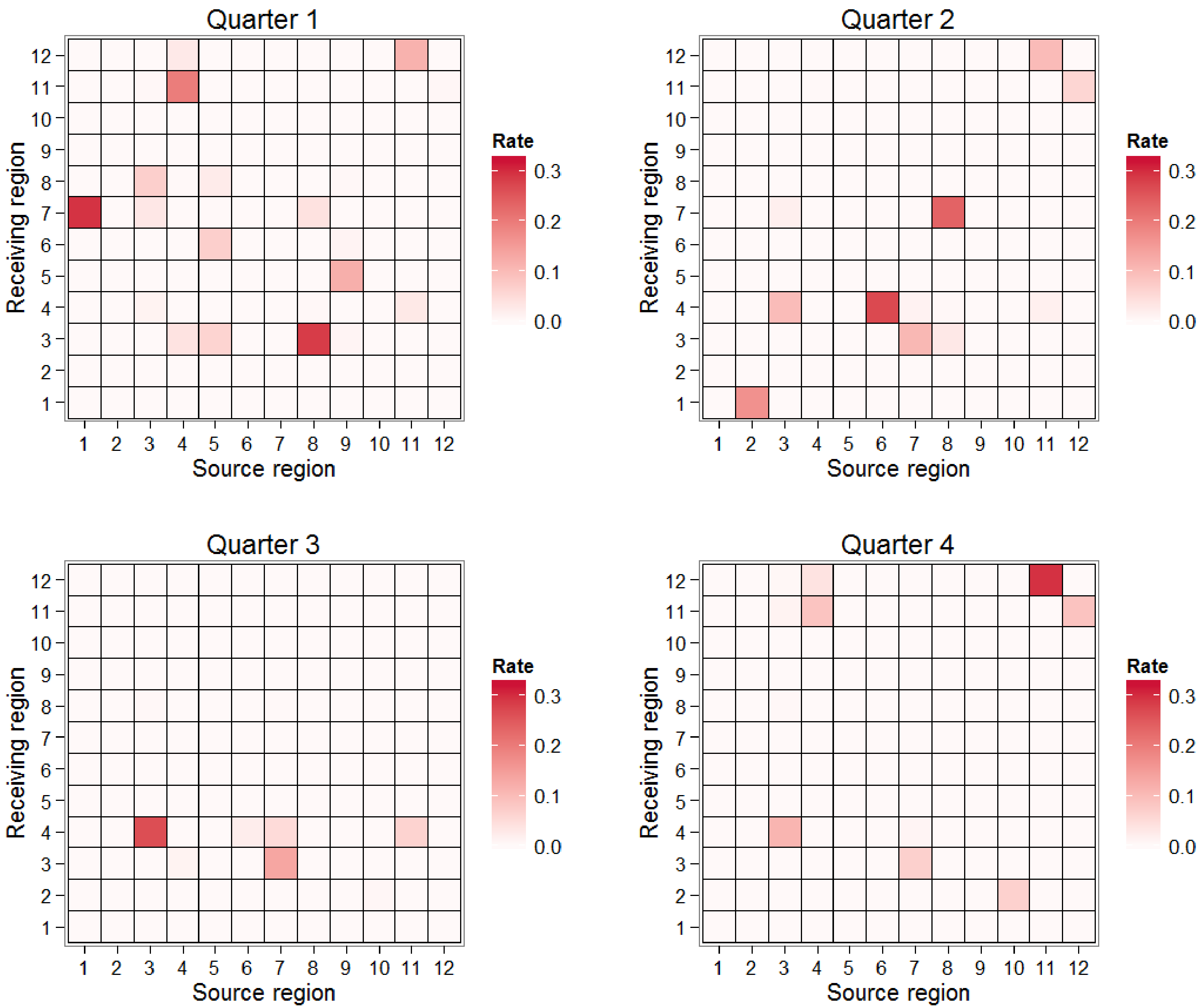


Figure 14: Estimated quarterly movement coefficients for the PW15 model. The colour of the tile indicates the magnitude of the movement rate.

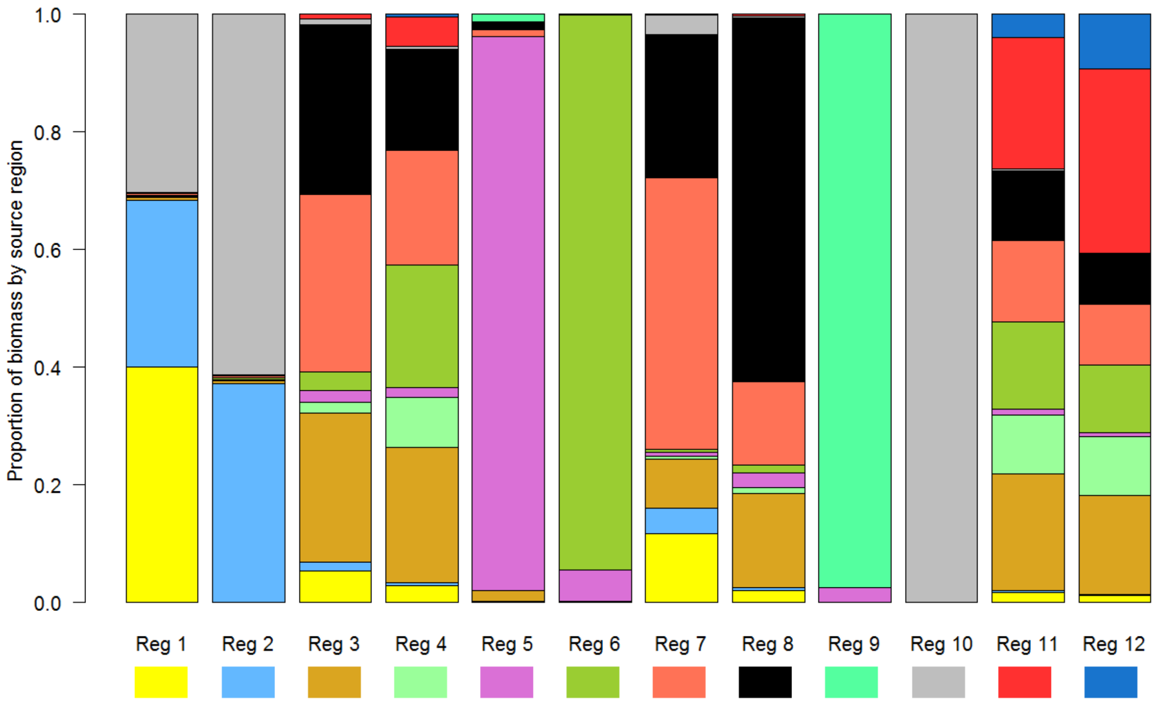


Figure 15: Proportional distribution of total biomass (by weight) in each region apportioned by the source region of the fish for the PW15 model. The colour of the source region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment between regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

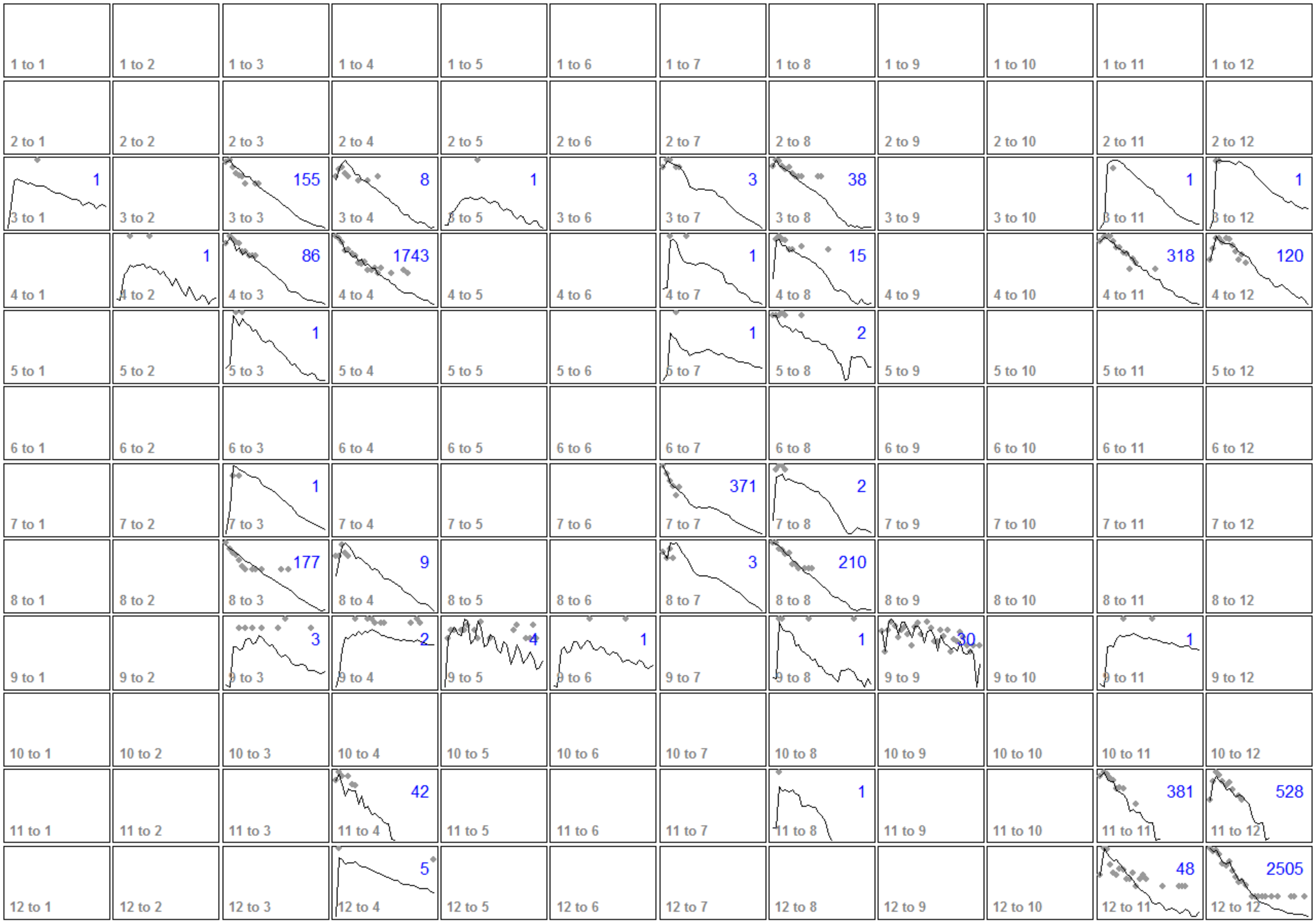


Figure 16: Observed and predicted tag returns (on the log-scale) by time-at-liberty showing the region of release (y-axis) and recapture (x-axis) for the PW15 model. The y-axis is the number of quarters at liberty and the number in blue shows the maximum number of recaptures in a time period for that region-region combination.

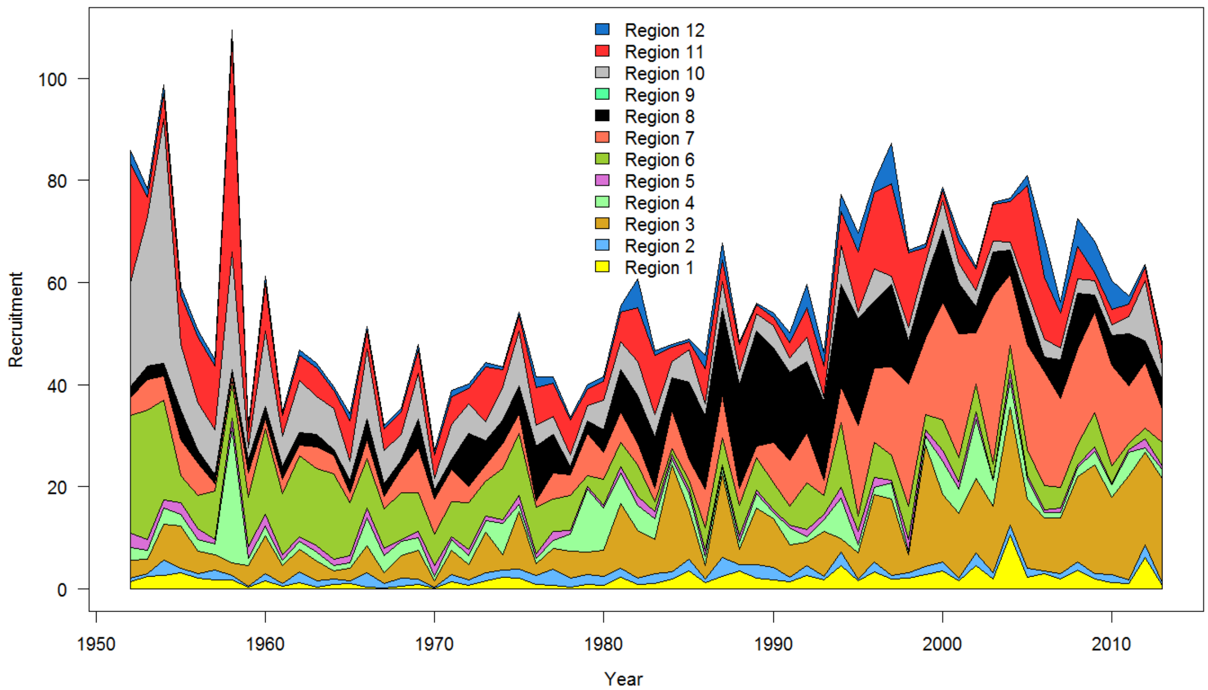


Figure 17: Time-series of estimated annual average recruitment (millions of fish) by model region for the PW15.

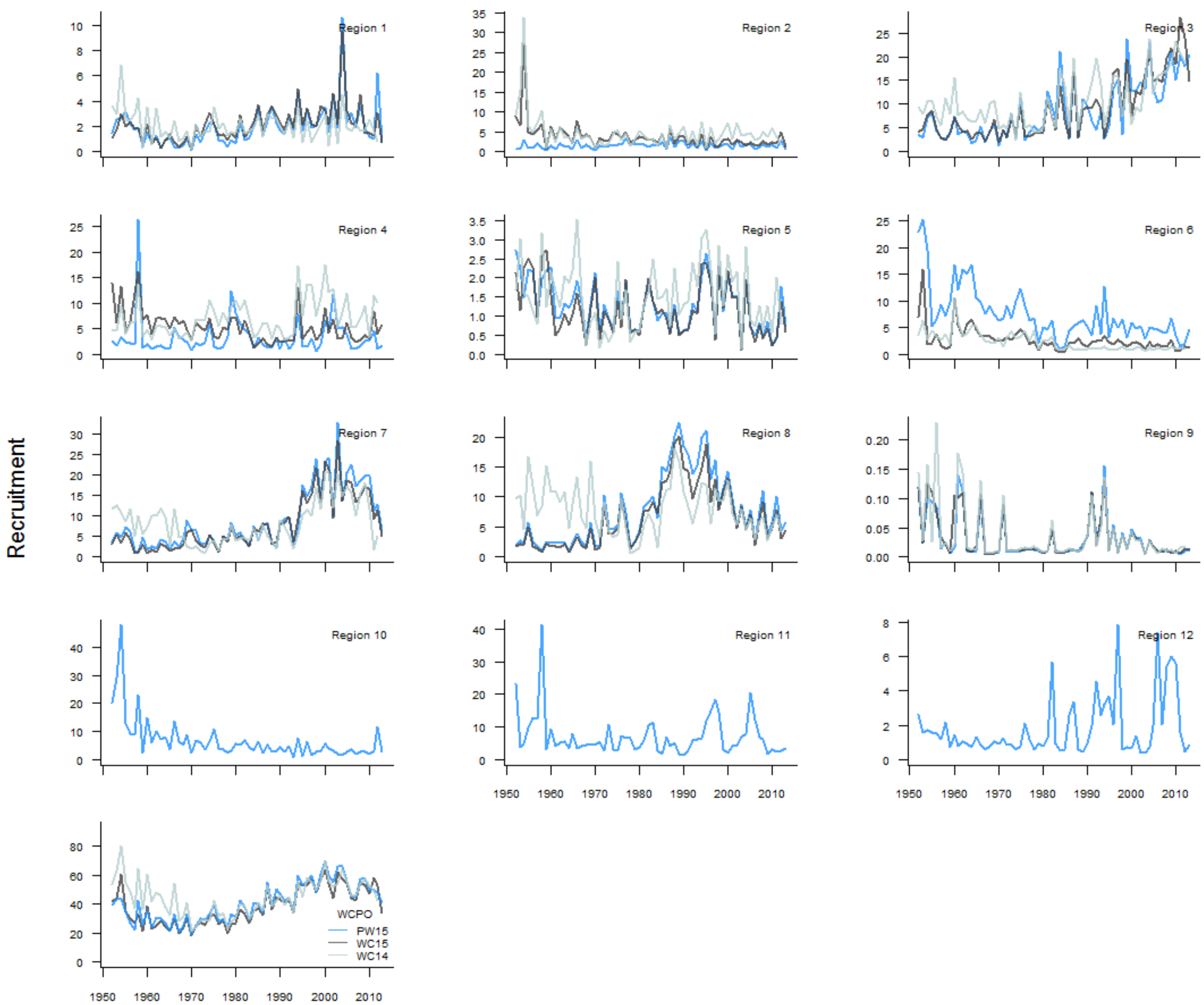
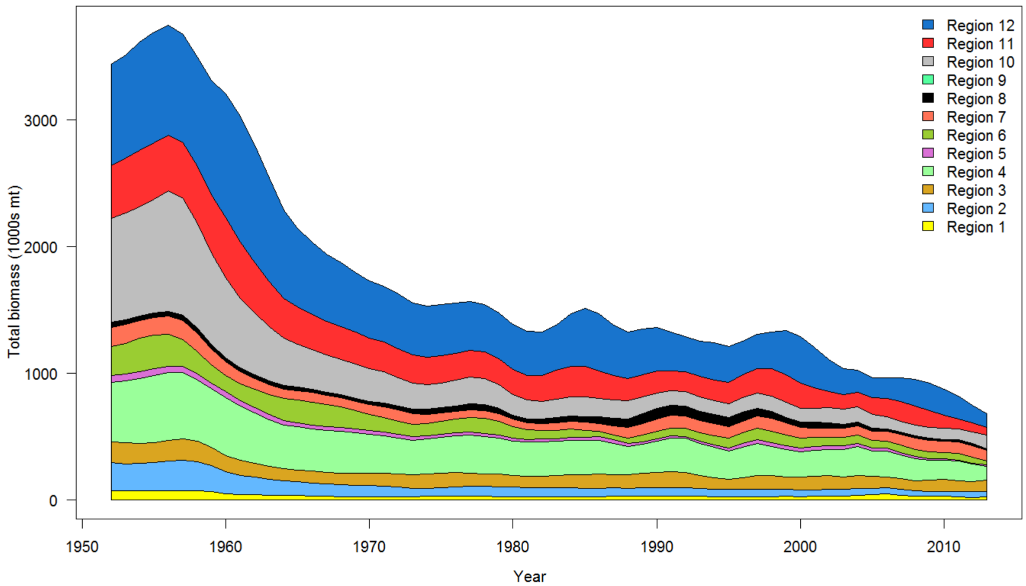


Figure 18: Estimated annual recruitment (millions of fish) by region and for the WCPO for the WC14, WC15 and PW15 models.



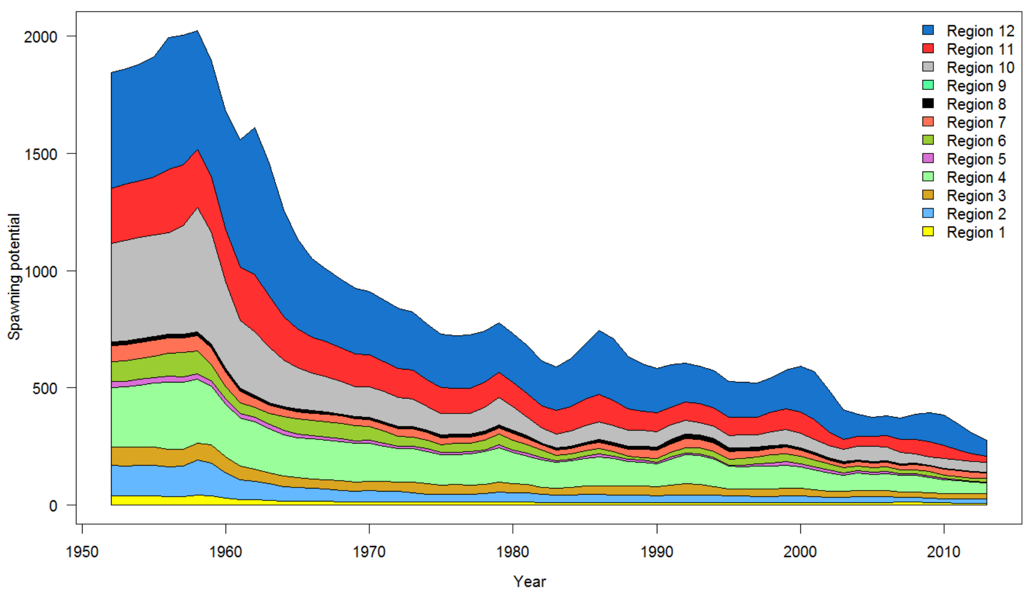


Figure 19: Time-series of estimated annual average total biomass (top) and average spawning potential (bottom) by model region for the PW15, both in 1,000s of metric tonnes.

Figure 20: Estimated annual average spawning potential (1,000s of metric tonnes) by region and for the WCPO for the WC14, WC15 and PW15 models.

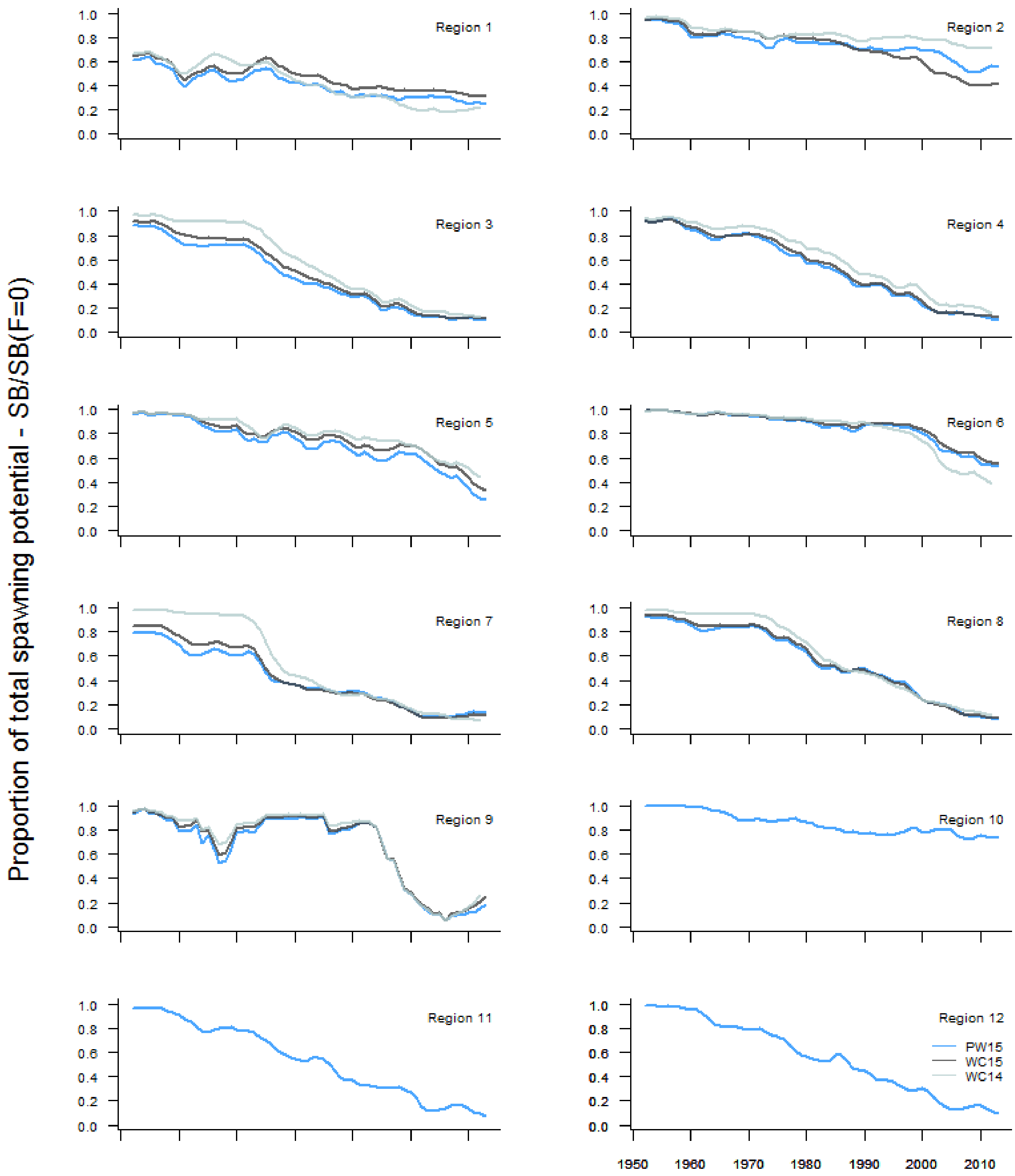


Figure 21: Ratio of exploited to unexploited spawning potential, $SB_t/SB_{t,F=0}$, by region for the WC14, WC15 and PW15 models.

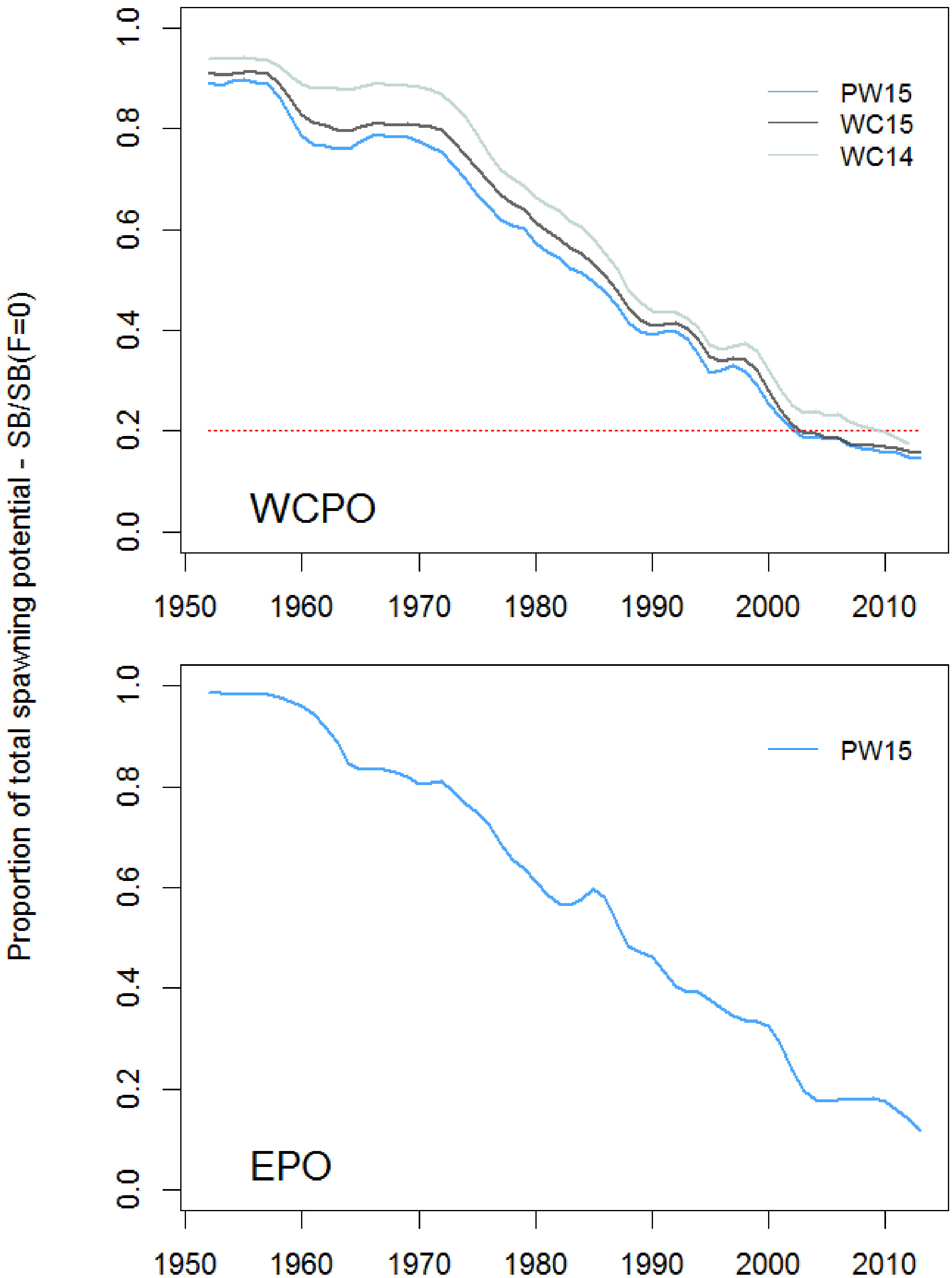


Figure 22: Ratio of exploited to unexploited spawning potential, $SB_t/SB_{t,F=0}$, for the WCPO and EPO for the WC14, WC15 and PW15 models. The current WCPFC limit reference point of $20\% SB_{F=0}$ is provided for reference for the WCPO as the red dashed line.

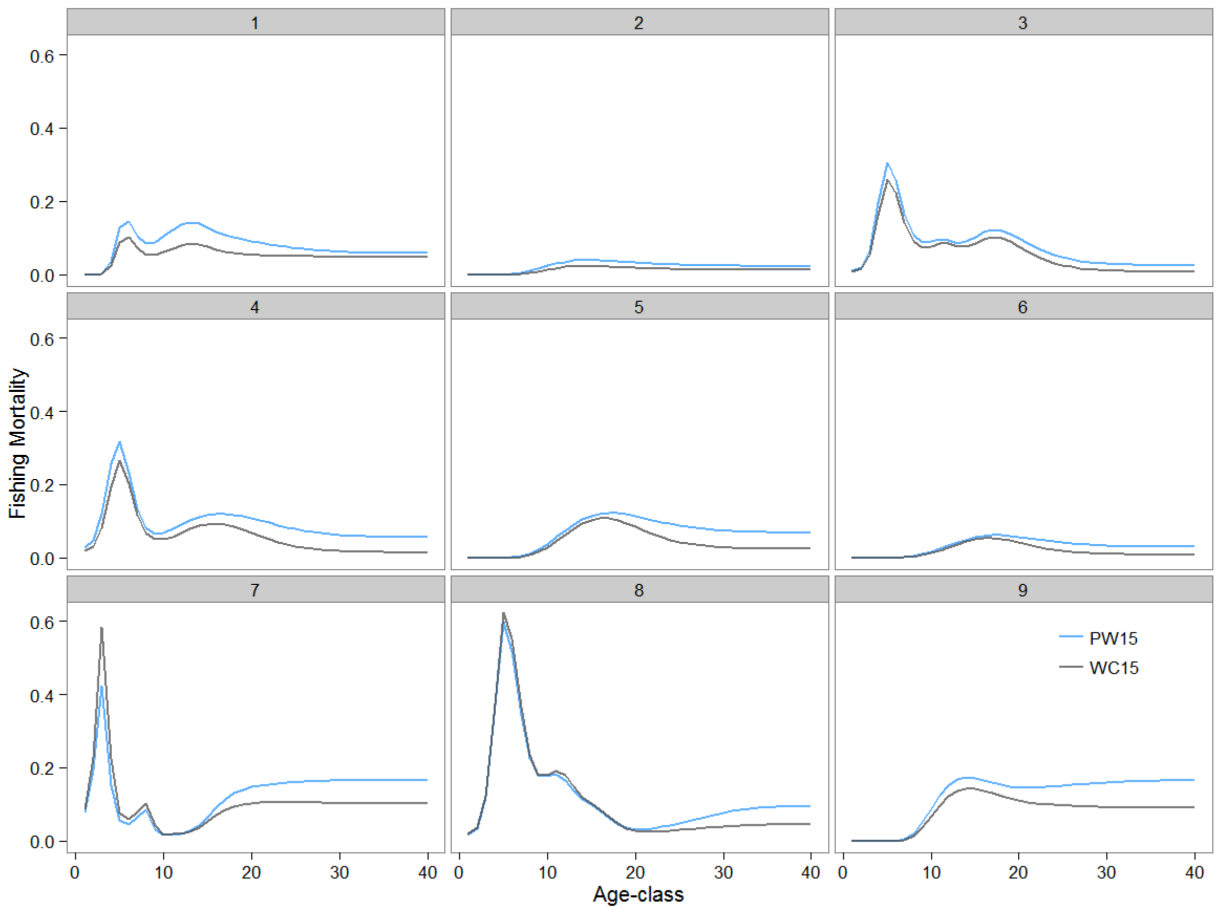


Figure 23: Comparison of fishing mortality at age between the WC15 and PW15 models, by region, over recent years (2009–2012).

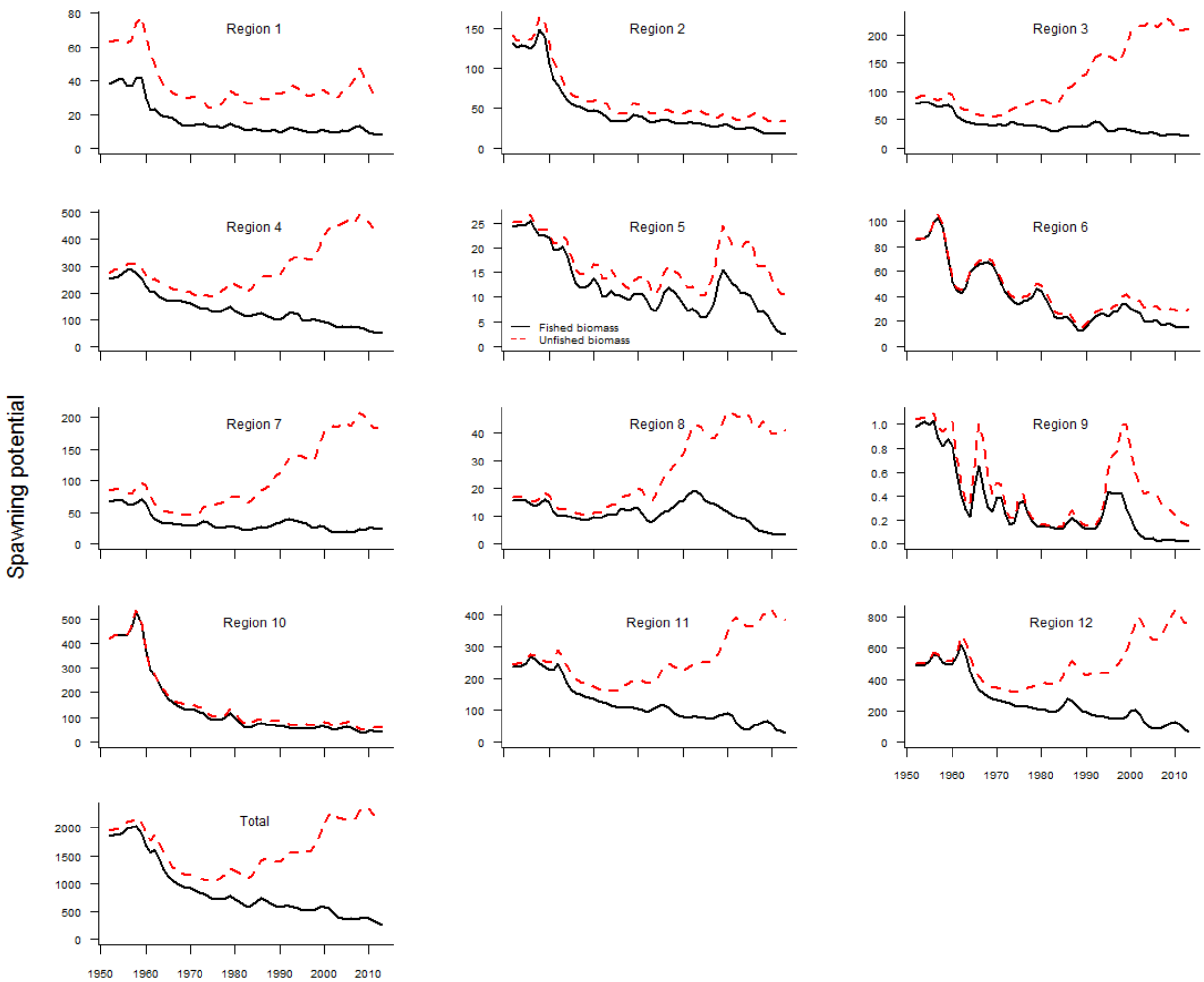


Figure 24: Comparison of the estimated spawning potential (black lines) with those estimated to have occurred in the absence of fishing (red lines) for each region and for the total PO (aggregated over all regions) for the PW15 model, both in 1,000s of metric tonnes.

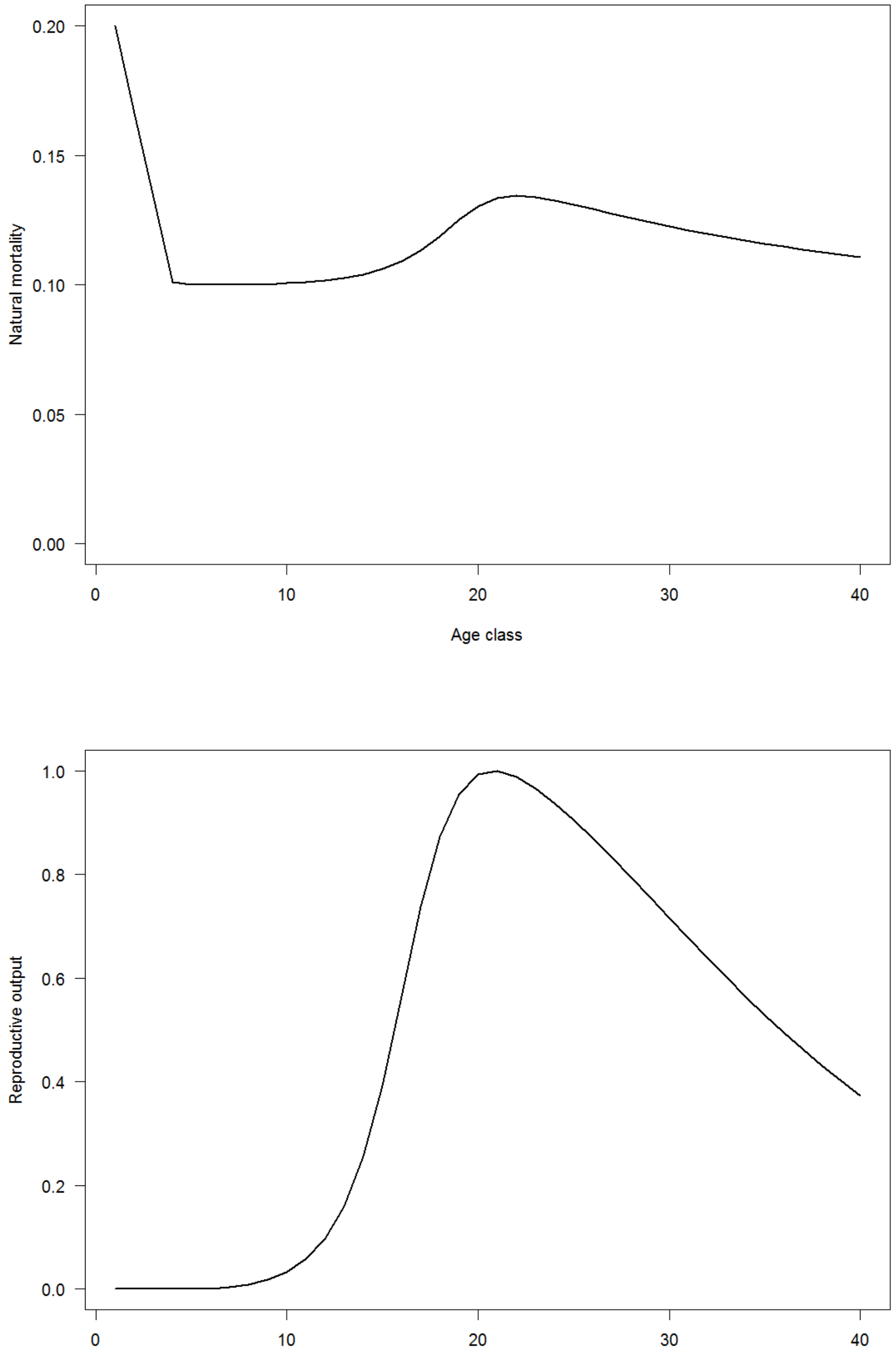


Figure 25: Natural mortality-at-age function (top) and proportion of fish mature-at-age function (bottom) as used in all models as fixed values. Note that estimate of maturity is actually used to define an index of spawning potential incorporating information on sex ratios, maturity at age, fecundity, and spawning fraction (see Hoyle and Nicol, 2008 for further details).

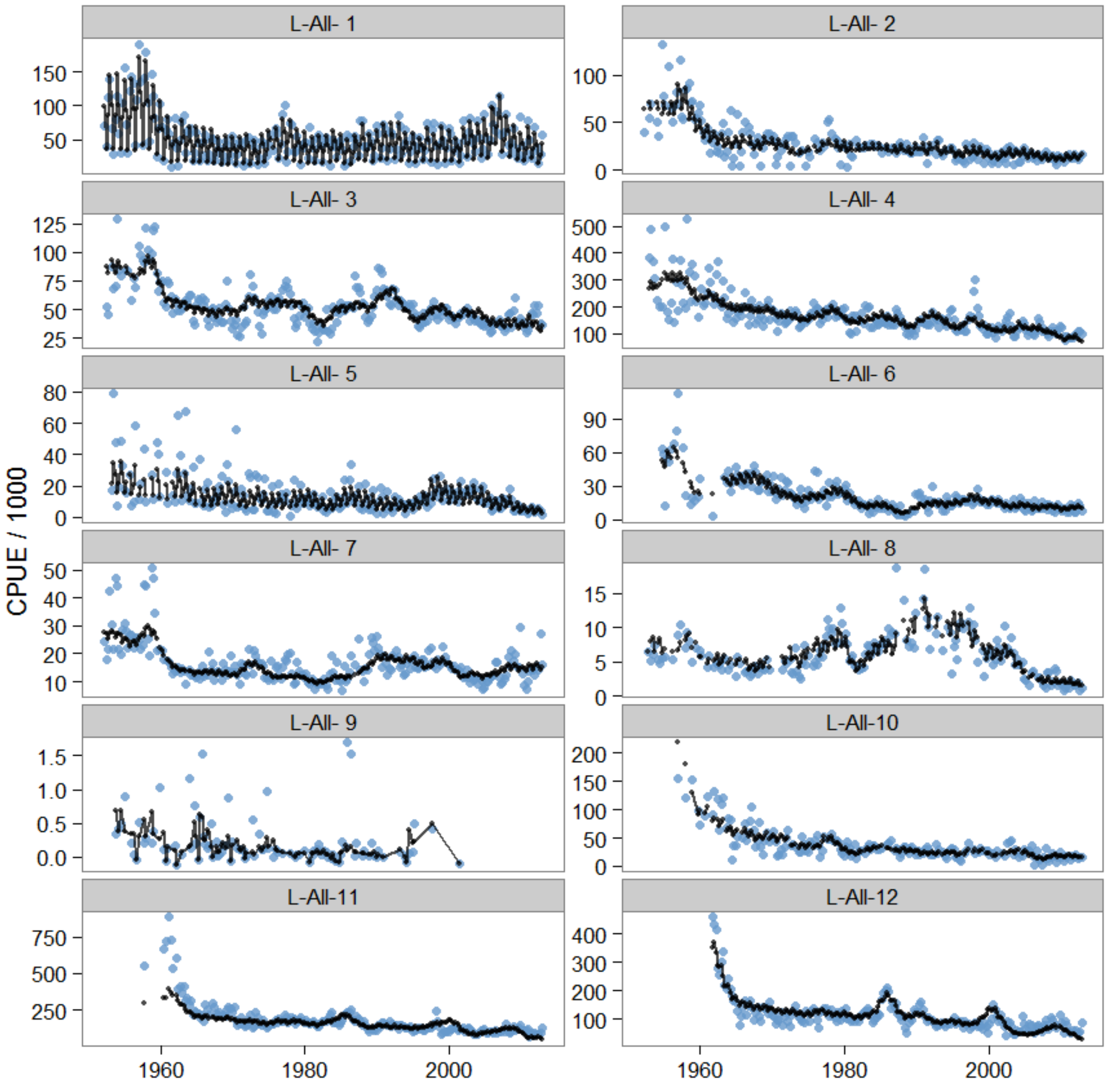


Figure 26: Observed and predicted CPUE for the major longline fisheries for the PW15 model.

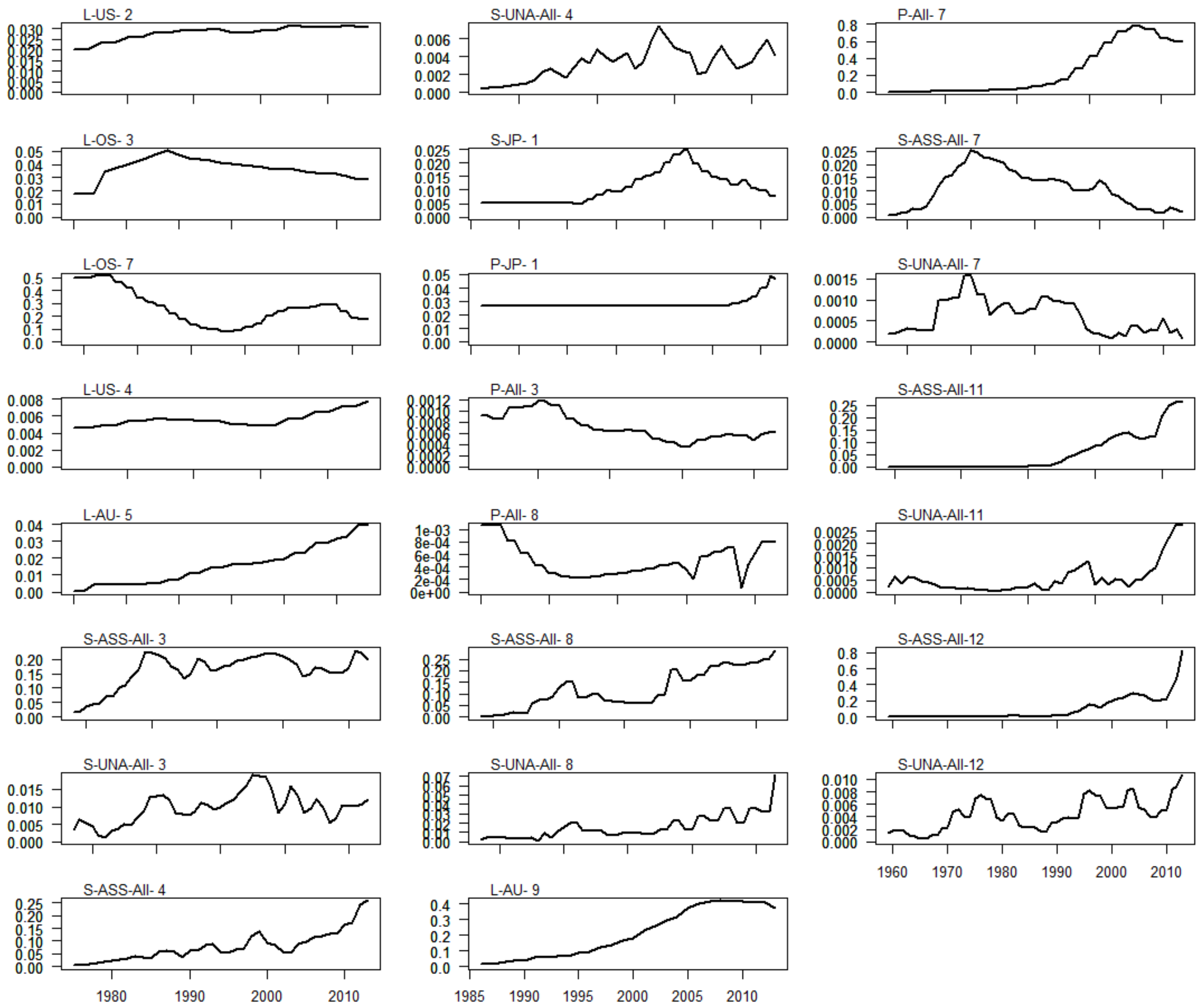


Figure 27: Estimated catchability time-series for those fisheries assumed to have random walk in catchability..

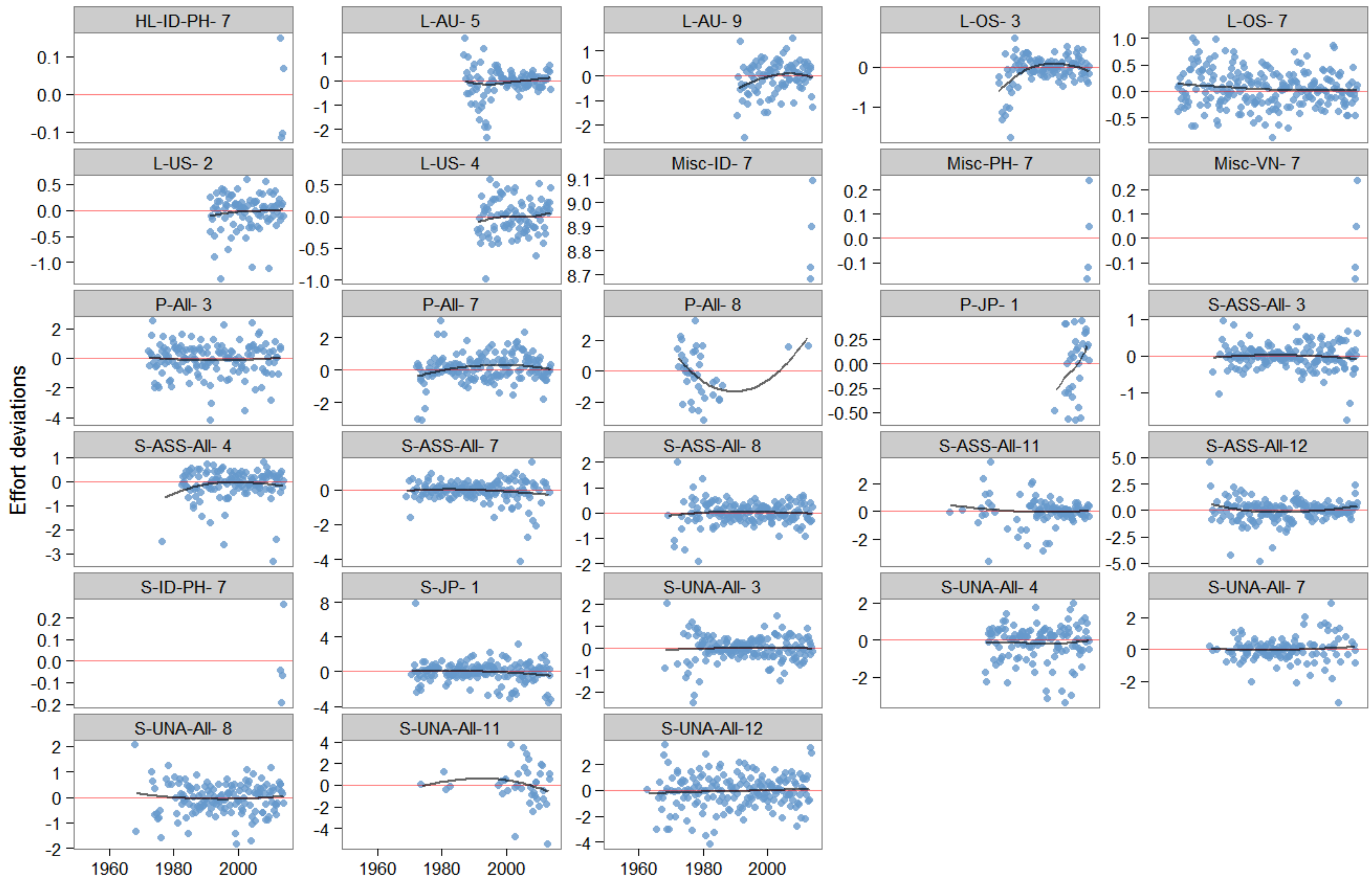


Figure 28: Effort deviations by time period for each fishery that did not have a standardised CPUE index associated with it (i.e. all fisheries except the L-All fisheries) for the PW15 model. The dark line represents a lowess smoothed fit to the effort deviations.

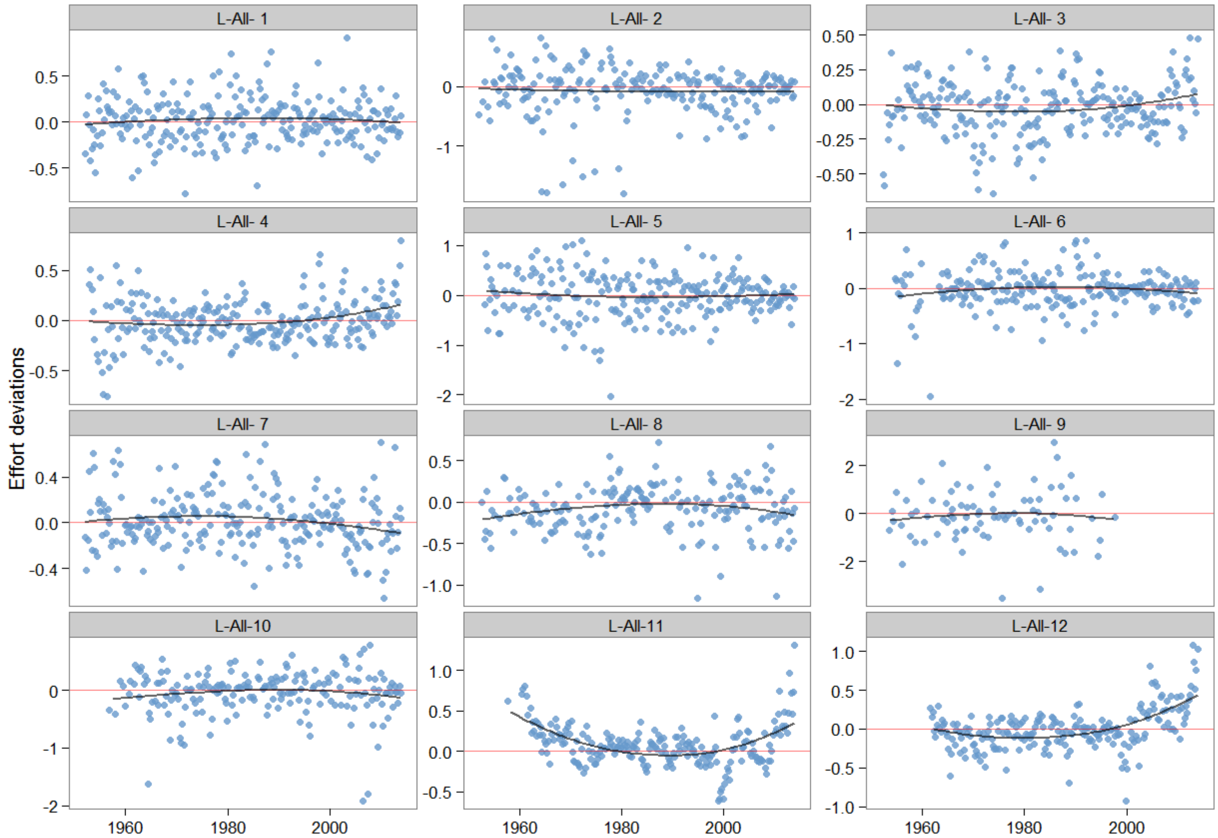


Figure 29: Effort deviations by time period for each L-All fishery for the PW15 model. The dark line represents a lowess smoothed fit to the effort deviations.

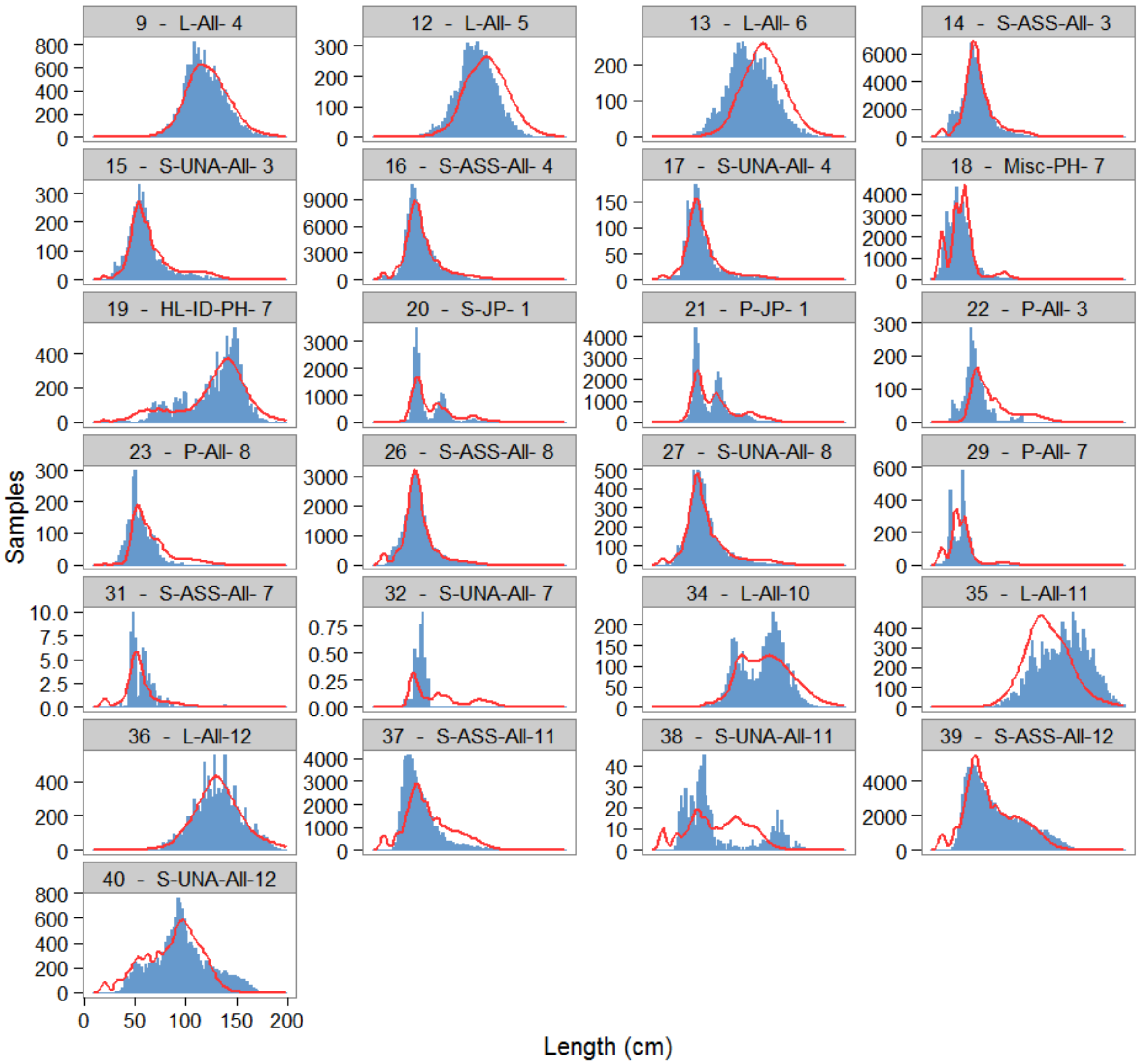


Figure 30: Composite (all time periods combined) observed (blue histograms) and predicted (red line) catch-at-length for all fisheries with samples for the PW15 model.

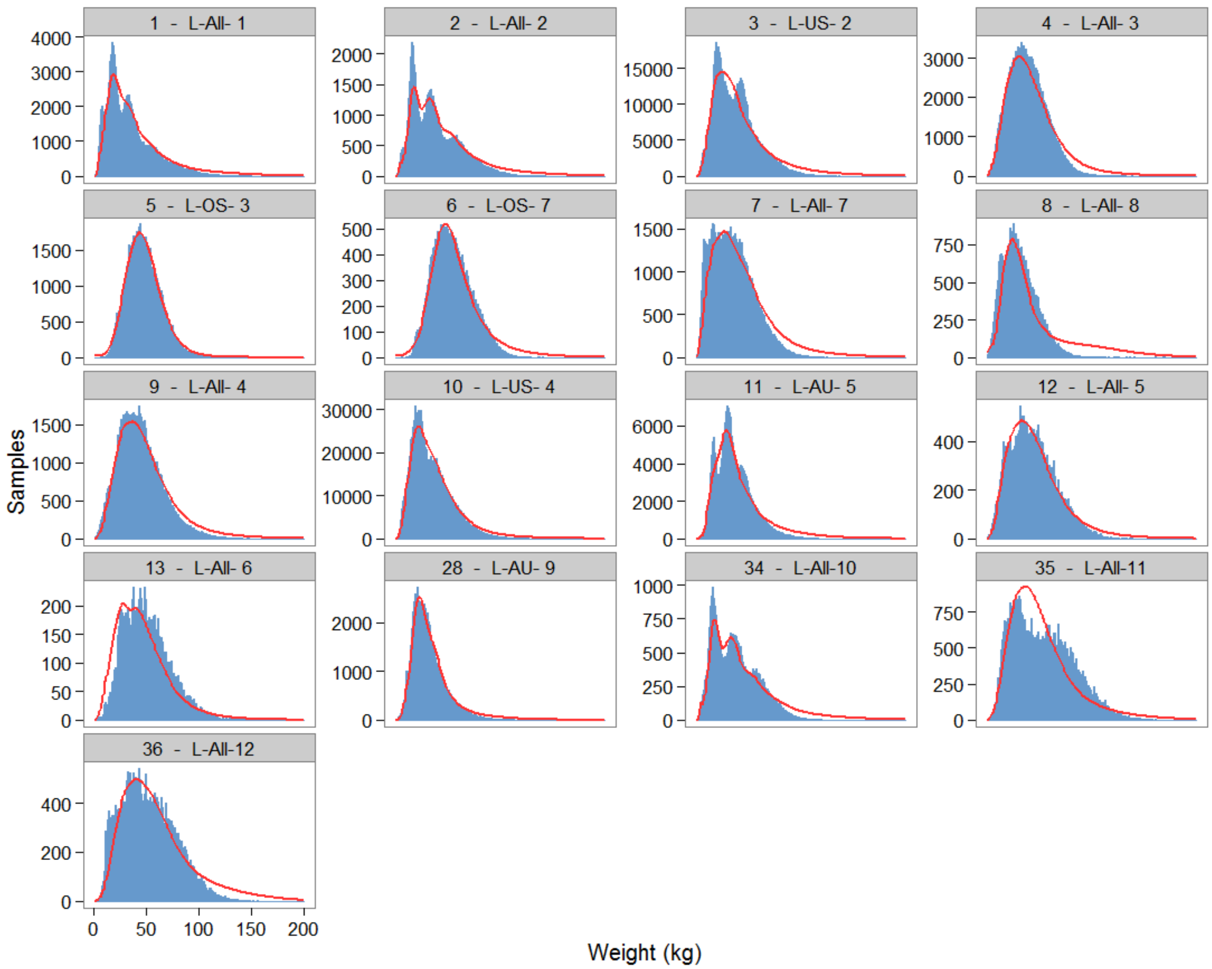


Figure 31: Composite (all time periods combined) observed (blue histograms) and predicted (red line) catch-at-weight for all fisheries with samples for the PW15 model

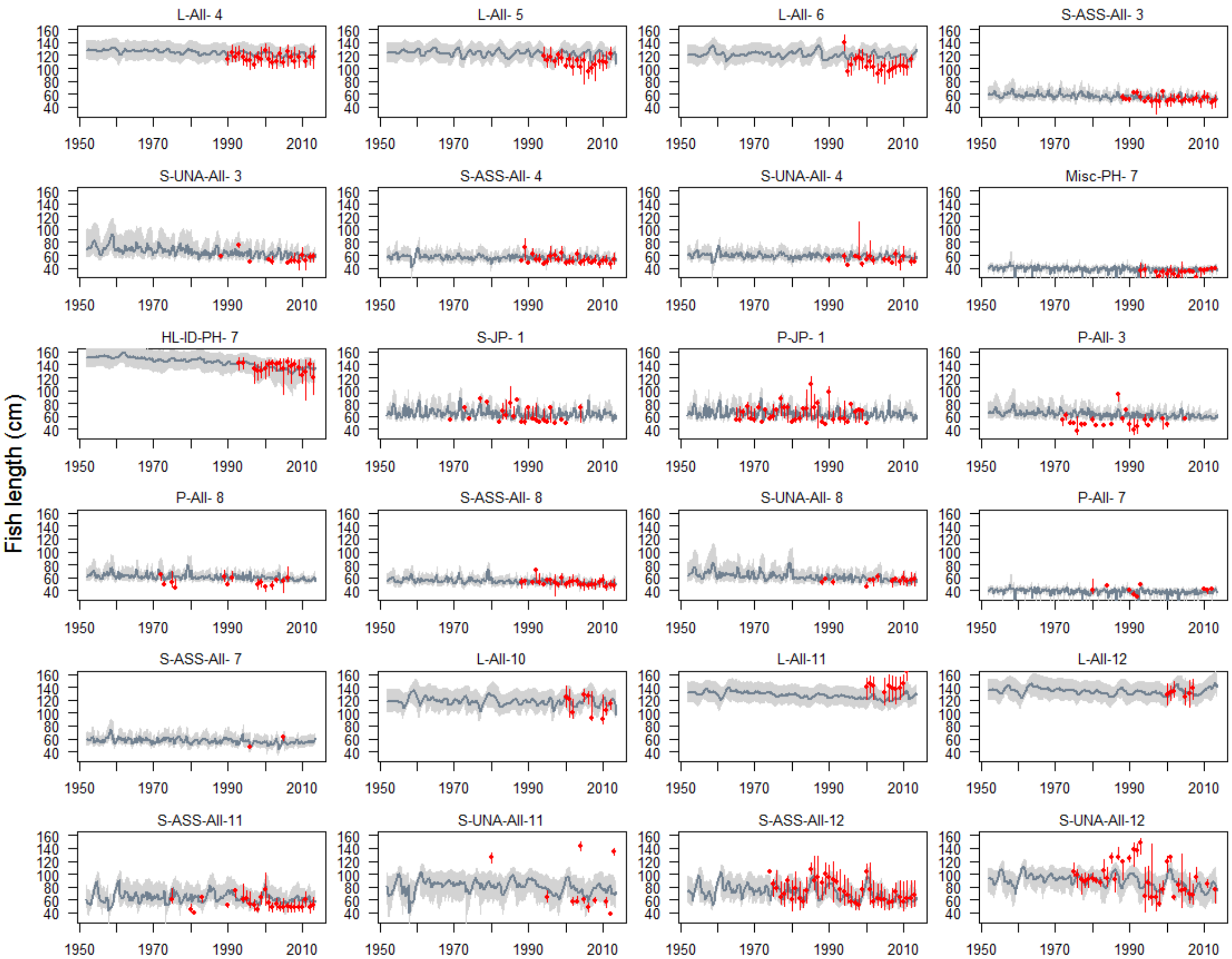


Figure 32: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) for all fisheries with samples for the PW15 model. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

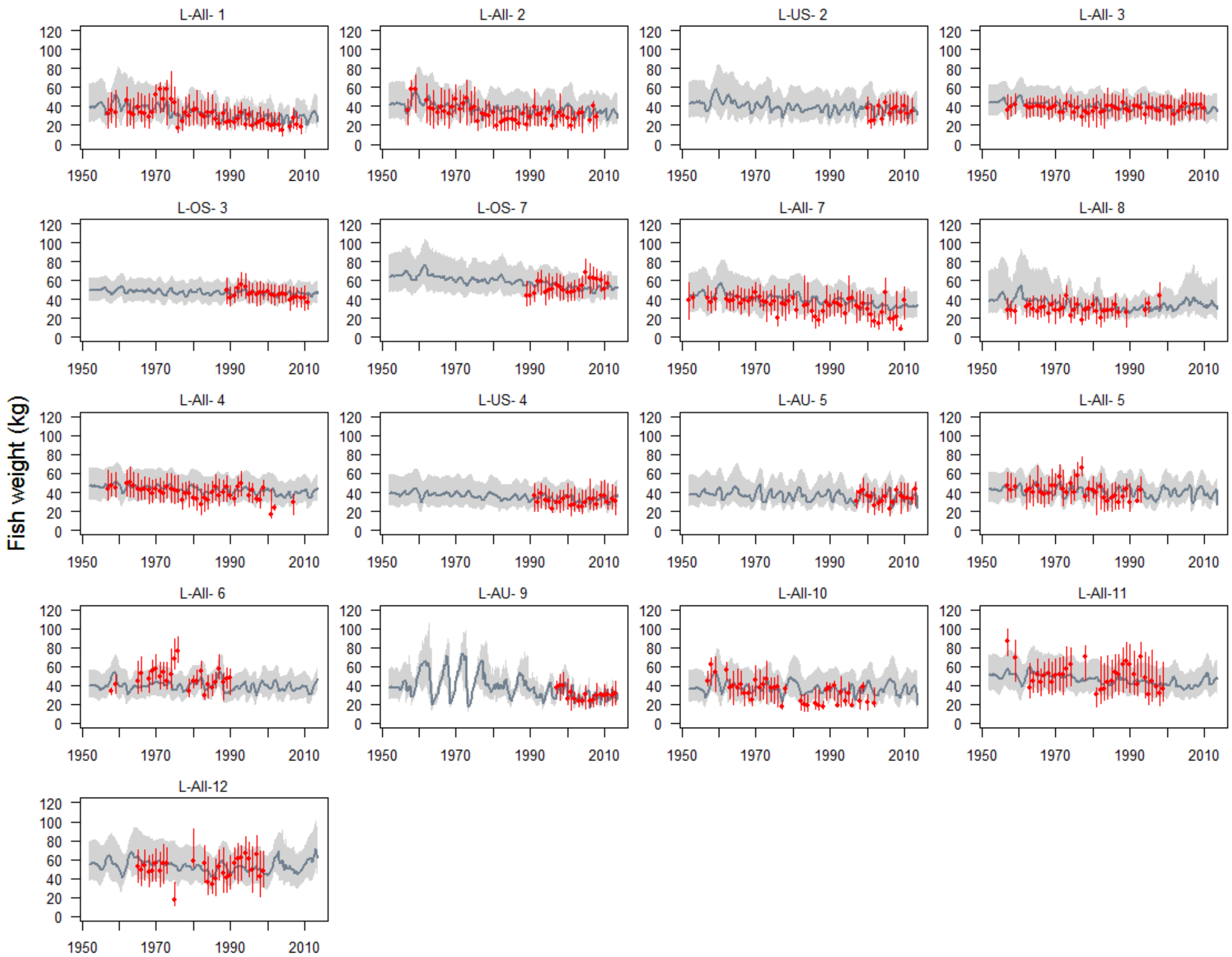


Figure 33: A comparison of the observed (red points) and predicted (grey line) median fish weight (kg) for all fisheries with samples for the PW15 model. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

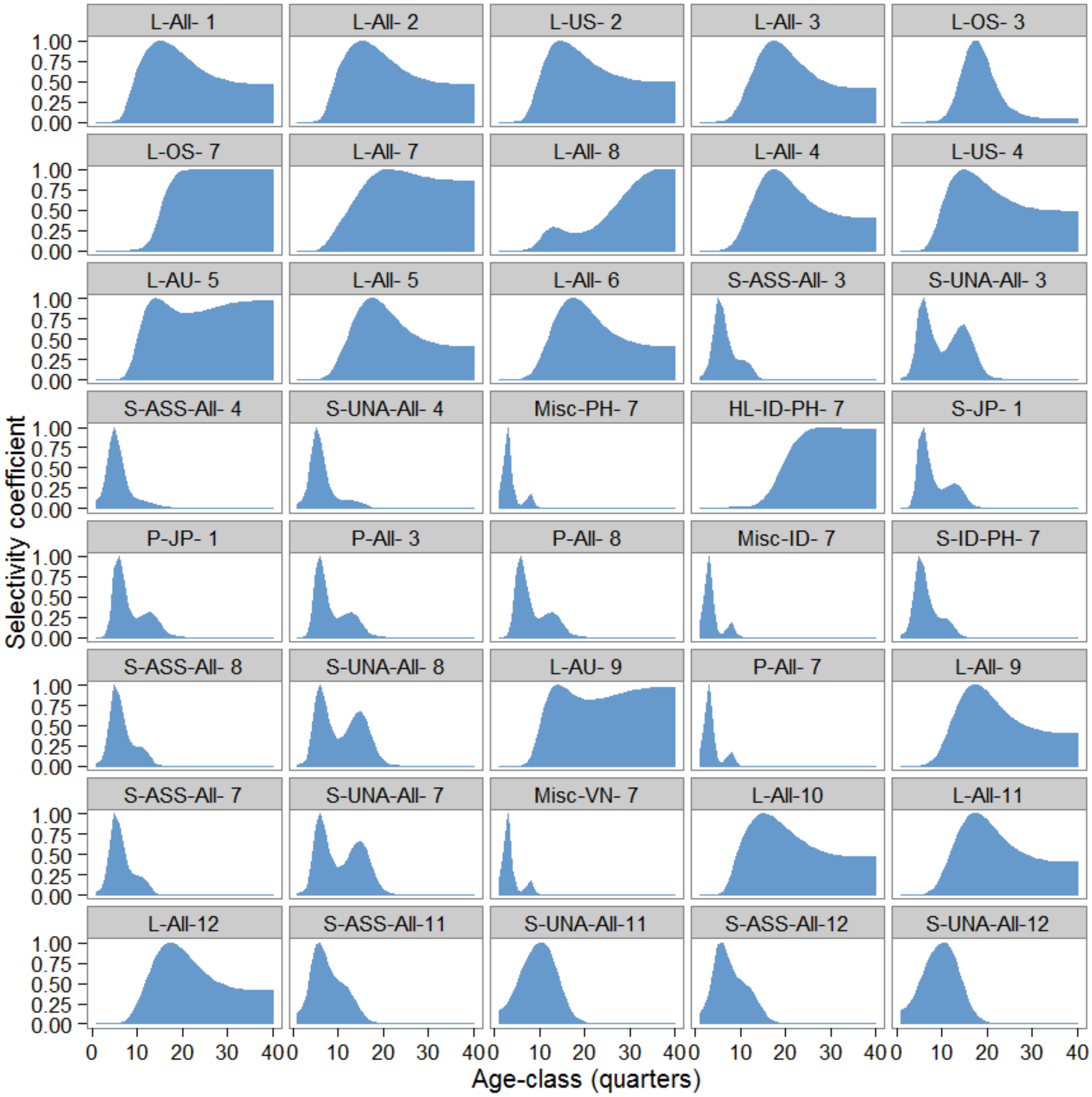


Figure 34: Selectivity coefficients by fishery estimated by the PW15 model.

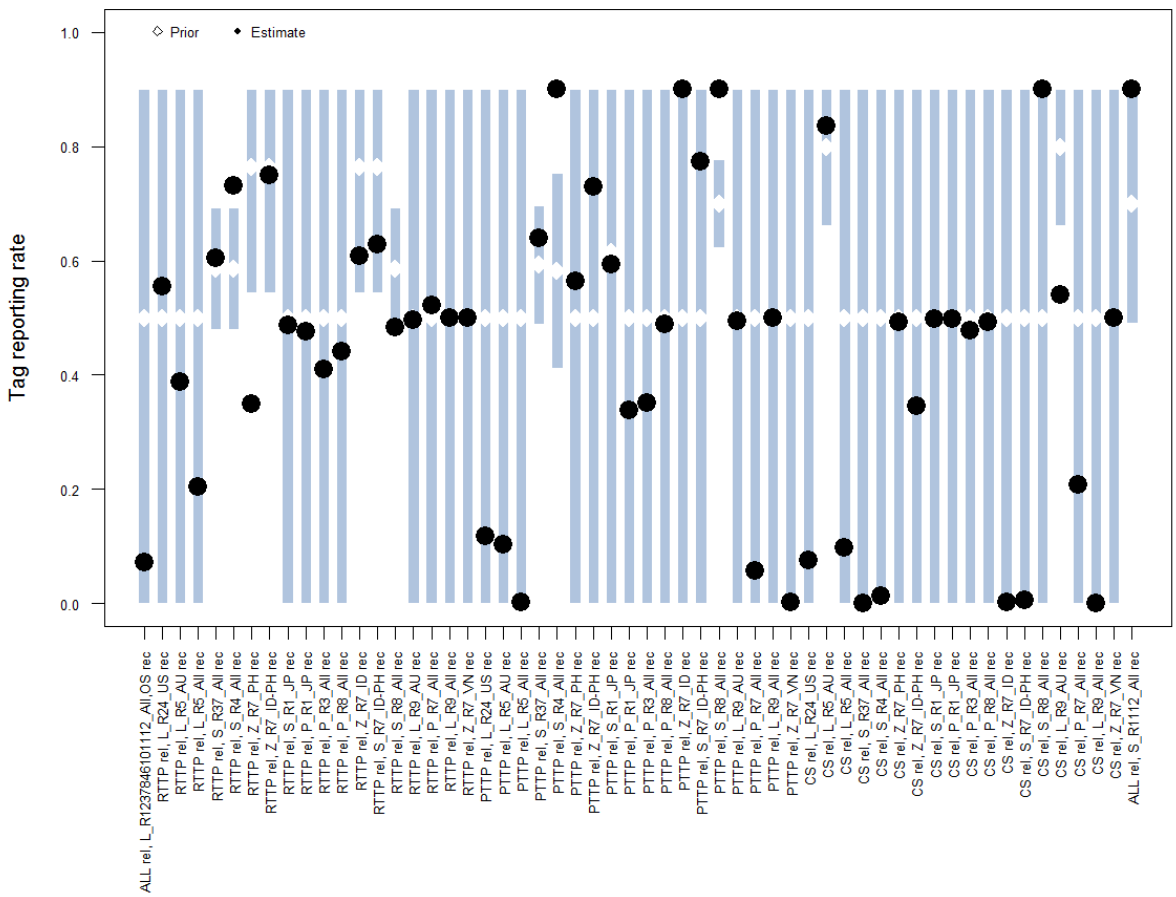


Figure 35: Estimated reporting rates for the reference case. Reporting rates can be estimated separately for each release program and recapture fishery group (histograms). See text for further details of tagging programmes. Certain estimates are grouped over release programs and over recapture fisheries, (e.g. L-ALL and HL fisheries). The prior mean and 95% confidence interval are also shown for each reporting rate group.

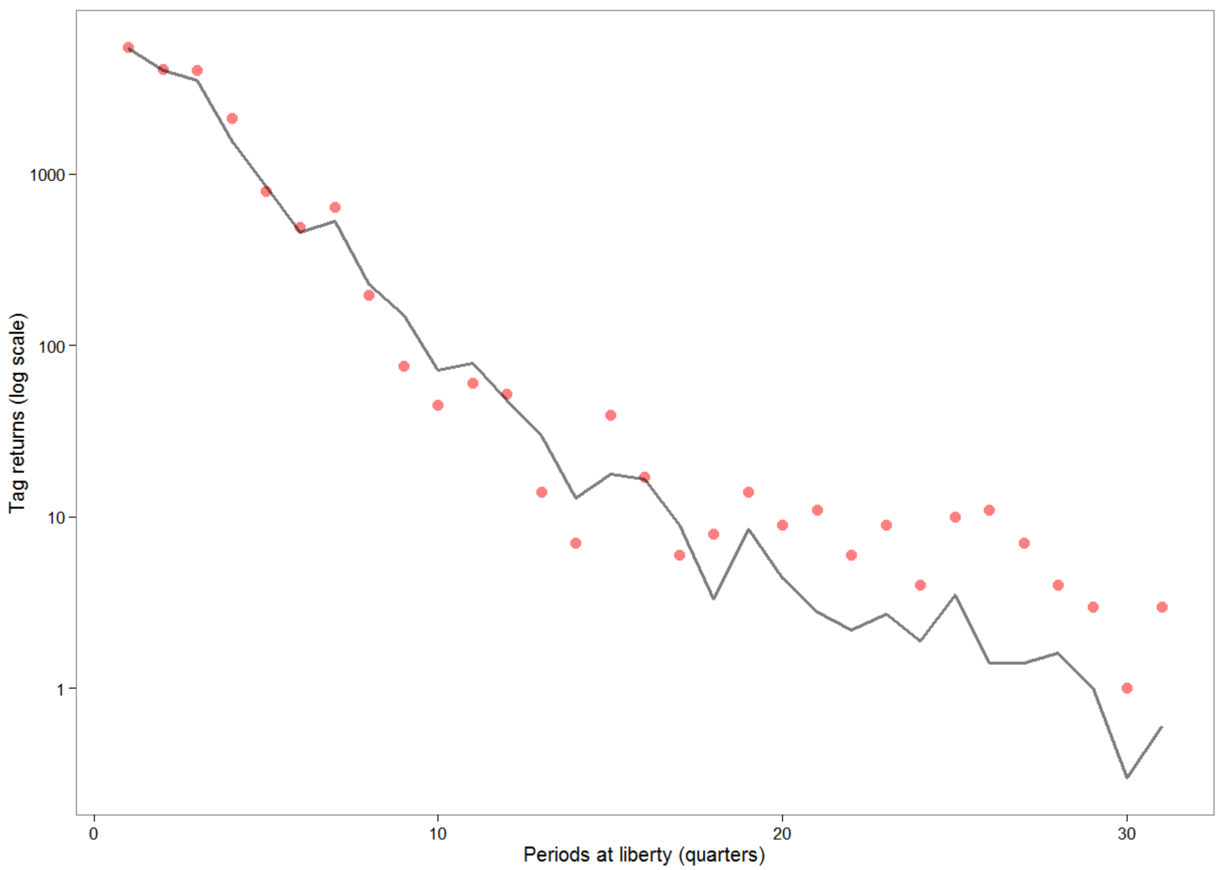


Figure 36: Observed and predicted tag returns by time-at-liberty for the PW15 model across all tag release events.

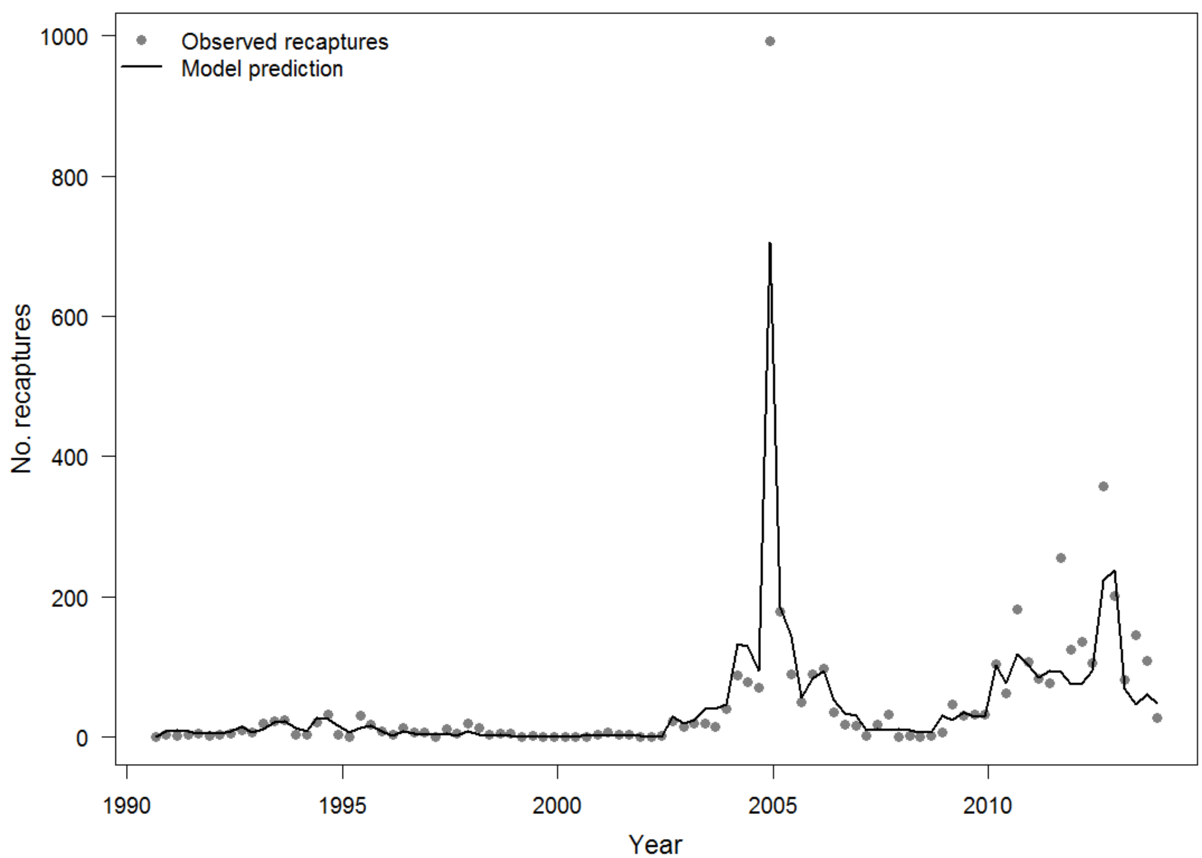


Figure 37: Observed and predicted tag returns (with tags recaptured during the two-quarter mixing period excluded) over time for the PW15 model across all tag release events.