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STOCK ASSESSMENT OF BIGEYE TUNA IN THE WESTERN AND CENTRAL PACIFIC OCEAN

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EXECUTIVE SUMMARY

This paper presents the 2014 assessment of bigeye tuna in the western and central Pacific Ocean. This assessment is supported by several other analyses which are documented separately, but should be considered when reading this assessment as they underpin many of the fundamental inputs to the models. The updated assessment addresses many of the recommendations provided in the report of the "Independent Review of the 2011 bigeye tuna stock assessment" (Ianelli et al., 2012). Other key papers document: the methods used in producing the purse seine size data (Abascal et al. 2014) and catch estimates (Lawson 2013), longline size data (McKechnie 2014), longline CPUE data (McKechnie et al., 2014b), and tagging data (Berger et al. 2014); revisions to the fisheries and spatial definitions (McKechnie et al. 2014a); and the guidance of the Pre-Assessment Workshop (PAW) held in April, 2014 (SPC-OFP 2014).

Some of the main improvements in the 2014 assessment are:

- Increases in the number of spatial regions to better model the tagging and size data;
- Inclusion of catch estimates from Vietnam and some Japanese coastal longline data previously not included;
- The use of operational longline data for multiple fleets to better address the contraction of the Japanese fleet and general changes over time in targeting practices;
- Improved modelling of recruitment to ensure that uncertain estimates do not influence key stock status outcomes; and
- A large amount of new tagging data corrected for differential post-release mortality and other tag losses.

The large number of changes since the 2011 assessment (some of which are described above), and the nature of some of those changes, means that full consideration of the impacts of individual changes is not possible. Nevertheless, the report details some of the key steps from the 2011 reference case (Run3j – Ref.case) to the 2014 reference case (037_L0W0T0M0H0). Distinguishing features of the 2014 reference case model include:

- The steepness parameter of the stock recruitment relationship is fixed at 0.8.
- The mean length of the oldest age class in the model is fixed at 184 cm.
- Natural mortality at age is fixed according to an external analysis in which it is assumed that the natural mortality rate of females increases with the onset of reproductive maturity.
- The likelihood function weighting of the size data is determined using an effective sample size for each fishing observation of one-twentieth of the actual sample size, with a maximum effective sample size of 50.
- For modelling the tagging data, a mixing period of 2 quarters (including the quarter of release) is applied.
- The last six quarterly recruitments aggregated over regions are assumed to lie on the stock-recruitment curve.

The rationale for these choices, which comprise the key areas of uncertainty for the assessment, is described in detail in the report. We report the results of "one-off" sensitivity models to explore the impact of these choices for the reference case model on the stock assessment results. A sub-set of key, plausible model runs was taken from these sensitivities to include in a structural uncertainty analysis (grid) for consideration in developing management advice.

The main conclusions of the current assessment are consistent with recent assessments presented in 2010 and 2011. The main conclusions based on the results from the reference case model and with consideration of results from performed sensitivity model runs, are as follows.

1. The new regional structure, and modelling and data improvements appear to have improved the current assessment with the previously observed increasing trend in recruitment much reduced and the fit to Coral Sea tagging data greatly improved.
2. Nevertheless there is some confounding between estimated growth, regional recruitment distributions and movement which, while having minimal impact on stock status conclusions, lead to a complex solution surface and the presence of local minima.
3. Current catches exceed maximum sustainable yield (MSY);
4. Recent levels of fishing mortality exceed the level that will support the MSY;
5. Recent levels of spawning potential are most likely at (based on 2008-11 average) or below (based on 2012) the level which will support the MSY;
6. Recent levels of spawning potential are most likely at (based on 2008-11 average) or below (based on 2012) the limit reference point of 20%$SB_{F=0}$ agreed by WCPFC;
7. Recent levels of spawning potential are lower than candidate biomass-related target reference points currently under consideration for skipjack tuna, i.e., 40-60% $SB_{F=0}$; and
8. Stock status conclusions were most sensitive to alternative assumptions regarding the modelling of tagging data and the longline CPUE series included, identifying these as important areas for continued research. However, the main conclusions of the assessment are robust to the range of uncertainty that was explored.

The report also includes recommendations for future stock assessments of bigeye tuna, including research activities to improve model inputs.

1 INTRODUCTION

This paper presents the 2014 stock assessment of bigeye tuna (*Thunnus obesus*) in the western and central Pacific Ocean (WCPO, west of 150°W). Since 1999, the assessment has been conducted regularly and the most recent assessments are documented in Hampton et al. (2004, 2005 and 2006), Langley et al. (2008), Harley et al. (2009), Harley et al. (2010 b), and Davies et al. (2011). Further the 2011 assessment was the focus of a detailed independent review (Ianelli et al., 2012) and many of the improvements from the 2011 assessment reflect recommendations from this review.

This assessment is supported by several other analyses which are documented separately, but should be considered an integral part of this assessment. These include: improved purse seine catch estimates (Lawson 2013), reviews of the catch statistics of the component fisheries (Williams 2014; Williams & Terawasi 2014), standardised CPUE analyses of operational level catch and effort data (McKechnie et al. 2014b), size data inputs from the purse seine (Abascal et al., 2014) and longline fisheries (McKechnie 2014), revised regional structures and fisheries definitions (McKechnie et al., 2014a), preparation of tagging data and reporting rate information (Berger et al., 2014). Finally, many of these issues were discussed in detail at Pre-Assessment Workshop (PAW) held in Noumea in April, 2014 (SPC-OFP 2014).

2 BACKGROUND

2.1 Stock structure

Bigeye tuna are distributed throughout the tropical and sub-tropical waters of the Pacific Ocean. Analysis of mtDNA and DNA microsatellites in nearly 800 bigeye tuna failed to reveal significant evidence of widespread population subdivision in the Pacific Ocean (Grewe and Hampton 1998). While these results are not conclusive regarding the rate of mixing of bigeye tuna throughout the Pacific, they are broadly consistent with the results of SPC's and IATTC's tagging experiments on bigeye tuna. Before 2008, most bigeye tuna tagging in the Pacific occurred in the far eastern Pacific (east of about 120°W) and in the western Pacific (west of about 180°). While some of these tagged bigeye were recaptured at distances from release of up to 4,000 nautical miles over periods of one to several years, the large majority of tag returns were recaptured much closer to their release points (Schaefer and Fuller 2002; Hampton and Williams 2005). Since 2008, bigeye tuna tagging by the Pacific Tuna Tagging Programme has been focussed in the equatorial central Pacific, between 180° and 140°W. Returns of both conventional and electronic tags from this programme have been suggestive of more extensive longitudinal, particularly west to east, displacements (Schaefer et al. submitted). It is hypothesised that while bigeye tuna in the far eastern and western Pacific may have relatively little exchange, those in the central part of the Pacific between about 180° and 120°W may mix more rapidly over distances of 1,000 – 3,000 nautical miles. In any event, it is clear that there is extensive movement of bigeye across the nominal WCPO/EPO boundary of 150°W (Figure 2). While stock assessments of bigeye tuna are routinely undertaken for the WCPO and EPO separately[1], these new data suggest that examination of bigeye tuna exploitation and stock status on a Pacific-wide scale, using an appropriately spatially-structured model, should be a high priority.

2.2 Life history characteristics

Bigeye tuna are relatively fast growing, and have a maximum fork length (FL) of about 200 cm. The growth of juveniles appears to depart somewhat from von Bertalanffy type growth with the growth rate slowing between about 40 and 70 cm FL (Lehodey et al. 1999), although

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[1] The results of the most recent (2006) Pacific-wide model are compared with WCPO and EPO assessments conducted in the same year in Hampton and Maunder (2006).

this effect is not as marked as for yellowfin tuna. Recent integrated analyses of tag recapture and age-at-length data for EPO bigeye (Aires-da-Silva et al. 2014) have estimated lengths (cm) at age (yr) of 1: 55, 2: 91, 3: 123, 4: 147, 5: 165, 6: 177, 7: 185, 8: 191, 9: 194, 10: 196. These mean lengths-at-age are larger than those estimated internally in bigeye WCPO stock assessments, based on fitting to size frequency data. For example, the WCPO estimates are about 12 cm smaller at age 2 and 20 cm smaller at age 5. Differences in growth at the level of the 2011 model regions have also been detected in the WCPO (Nicol et al. 2011), but it is unknown at this stage how this might impact on stock assessment results. New information on this topic and on bigeye tuna growth generally is being collected under WCPFC-SC Project 35, and is expected to be incorporated into future bigeye tuna assessments.

Available data for the WCPO indicate that bigeye tuna begin to be reproductively active from about 100 cm FL, and that 100% of individuals >120 cm FL are reproductively mature. Regional variation in maturity-at-length is suspected to occur, and bigeye tuna appear to be reaching maturity at larger sizes in the EPO (Schaefer et al. 2005). As with other tunas, the sex ratio of bigeye tuna changes at around the age/size of reproductive maturity to favour males at larger size. This information is used to define spawning potential based on mature female biomass in stock assessments. Project 35 is collecting reproductive samples from bigeye tuna throughout the WCPO and following analysis this information will be used to revise maturity schedules and will be incorporated into future bigeye assessments.

The natural mortality rate of bigeye tuna is likely to vary with size, with the lower rates of around 0.5 yr^{-1} for bigeye >40 cm FL (Hampton 2000). Tag recapture data indicate that significant numbers of bigeye reach at least eight years of age (Hampton and Williams 2005). The longest period at liberty for a recaptured bigeye tuna tagged in the western Pacific at about 1–2 years of age is currently 14 years (SPC unpublished data). Natural mortality of female bigeye is hypothesised to increase at around the age of reproductive maturity, due to the physiological stresses of spawning, resulting in male-biased sex ratios at larger size. This feature of the population dynamics has been incorporated into the fixed natural-mortality-at-age schedules used in recent, and the current, reference-case bigeye tuna assessments. However, the current assessment also includes estimation of natural mortality-at-age in a sensitivity analysis.

2.3 Fisheries

Bigeye tuna are an important component of tuna fisheries throughout the Pacific Ocean and are taken by both surface gears, mostly as juveniles, and longline gear, as valuable adult fish. They are a principal target species of both the large, distant-water longline fleets of Japan, Korea, China and Chinese Taipei and the smaller, fresh sashimi longline fleets based in several Pacific Island countries and Hawaii. Prices paid for both frozen and fresh product on the Japanese sashimi market are the highest of all the tropical tunas. Bigeye tuna are the cornerstone of the tropical longline fishery in the WCPO; the longline catch in the WCP-CA had a landed value in 2013 of approximately US$600 million, the lowest for the past six years (Williams and Terawasi 2014).

Bigeye in purse catches are taken almost exclusively from sets on natural and artificial floating objects (FADs). Estimation of the bigeye (and to a lesser extent yellowfin) tuna catch from associated sets has been the focus of considerable research over several years. Section 3.4.1 and references within provide details of this work.

A small purse seine fishery also operates in the coastal waters off Japan with an annual bigeye catch of approximately 1,000 mt. A similar level of bigeye catch is taken by the coastal Japanese pole-and-line fishery. In recent years, collaborative work between SPC, WCPFC, CSIRO (primarily in Indonesia), and fisheries agencies in Indonesia, Philippines, and Vietnam has yielded improved catch statistics for these fleets. In some instances data are available at the individual fisheries level (e.g., longline or large-fish handline), but often statistics are aggregated across a variety of gears that typically catch small bigeye tuna, e.g., ring-net, surface handline, and troll.

3 DATA COMPILATION

The data used in the assessment consist of catch, effort, length-frequency and weight-frequency data for the fisheries defined in the analysis, and tag release-recapture data. There have been significant improvement to these data inputs since the 2011 assessments based on implementation of recommendations from the independent review (Ianelli et al., 2012) and the 2014 PAW (SPC-OFP, 2014). These analyses are the subject of detailed working and information papers. We will not repeat the full details of these analyses here, rather we will provide a brief overview of the key features and direct interested readers to the relevant papers which are referenced throughout this section.

3.1 Spatial stratification

The spatial stratification for the assessment was modified for the current assessment (Figure 1), in particular the western equatorial region. The western boundary for this region was moved to 110°E to include additional catch from several fleets. This new area was then divided into three regions, the far western region was created to compartmentalise the impact of uncertainty in the catch time series from Indonesia, Philippines, and Vietnam (region 7 for bigeye and yellowfin and region 4 for skipjack). For bigeye tuna this also allowed for separation of the offshore fleets in this area which catch significantly larger fish. A new region was added covering the area best described as the Bismarck and Solomon Seas (region 8 for bigeye and yellowfin and region 5 for skipjack). Considerable tagging has occurred here and analyses of skipjack tuna showed slower mixing compared to the wider western equatorial region. Finally, a new region was added covering the specific region of the Coral Sea in south-western region of the bigeye and yellowfin models where specific tagging of bigeye and yellowfin tuna occurred (region 9 for bigeye and yellowfin).

It should be recognized that the eastern boundary for the assessment regions was 150°W and as such excludes the WCPFC Convention area component that overlaps with the IATTC area. These overlap area catches are included in IATTC stock assessments. For bigeye tuna these are primarily longline catches.

3.2 Temporal stratification

The primary time period covered by the assessment is 1952–2012, thus including all significant post-war tuna fishing in the WCPO. Within this period, data were compiled into quarters (January–March, April–June, July–September, October–December). As agreed at SC9, the assessment did not include data from the most recent calendar year. This is because these data are only finalised very late and are often subject to significant revision post-SC. This year the 2013 data were not finalized until the end of the first week of July – far too late to be included in assessments due only two weeks later. In the discussion section we consider potential mechanisms to address this matter.

3.3 Definition of fisheries

MULTIFAN-CL requires the definition of “fisheries” that consist of relatively homogeneous fishing units. Ideally, the fisheries so defined 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 creation of new regions in the current assessment required the definition of new fisheries and these were discussed in detail during the PAW. An important consideration in whether multiple fisheries were included in a region was the availability of CPUE and size data (discussed below). The 33 fisheries defined for the bigeye and yellowfin assessments are provided in Table 1. A graphical summary of the availability of data for each fishery is provided in Figure 3.

A change from the 2011 assessment is the removal of the Hawaiian handline fishery which, while having very low catches, was associated with informative weight frequency data. These data have not been updated for several years and therefore were no longer informing the model with respect to recent recruitment. A major change was the addition of a new offshore fishery in region 7responding to a previous analysis (Harley et al. 2010a) that found strong spatial patterns in the sizes of fish taken in the east and west of the original region 3. New purse seine and pole and line fisheries were added for regions 7 and 8. For regions 5 and 6 the previous L-ALL and L_PICT fisheries were combined as it was found that neither had full temporal coverage of size data. Region 9 also received two longline fisheries (L-AU and L-ALL), though the latter had very low catches and no catches in recent years. The previously defined Bismark Sea PNG longline fleet was amalgamated into a single longline fishery in region 8.

A full summary of the basis for the spatial and fishery definitions is provided in McKechnie et al. (2014a) and there is also discussion of these matters within the PAW report and the independent review mentioned previously.

3.4 Catch and effort data

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.

Total annual catches by major gear categories for the WCPO are shown in Figure 4 and a regional breakdown is provided in Figure 5. The spatial distribution of catches over the past ten years in provided in Figure 6. Most of the catch occurs in the tropical regions (3, 4, 7, and 8).

As noted above, only data through 2012 was used in the current assessment to overcome the delays and data issues that commonly occur, e.g., in the 2011 assessment data for the main longline fisheries was incomplete as indicated by atypical catch proportions among quarters in the final year.

Within the model, effort for each fishery was normalised to an average of 1 to assist numerical stability. Some longline fisheries were grouped to share common catchability parameters in the various analyses. For such grouped fisheries, the normalisation occurred over the group rather than for the individual fisheries so as to preserve the relative levels of effort between the fisheries. For some data no effort is used - this is typically in cases where effort data are either considered unreliable or the fishery is composed of different ‘other’ fishing gears such that their effort units are not compatible.

3.4.1 Purse seine

Previous assessments have considered two sets of purse-seine input catch data, but the problems surrounding logsheet reporting of skipjack catches and grab-sample bias have been clearly demonstrated and only a single set of purse seine catch estimates have been included in the current assessment. Details of the analyses, including the independent review and response are provided in Lawson (2013), Cordue (2013), Powers (2013), and McArdle (2013).

Briefly, catch data are estimated by 1° latitude, 1° longitude, month, flag, and set-type. Though the exact algorithm depends on the year and data available, total catches are taken from the logsheet declared totals and then the grab samples are corrected for bias based on the estimates of the correction factors from the paired spill and grab paired sampling trials. For some fleets and time periods we use reported catch by species rather than estimating it, e.g., for Spanish purse seine vessels fishing in the east that report high proportions of bigeye tuna and recent Japanese purse seine estimates which are based on unloadings sorted by species.

As in previous assessments, effort data units for purse seine fisheries are defined as days fishing and/or searching, and are allocated to set types based on the proportion of total sets attributed to a specified set type (associated or unassociated sets) in logbook data. Recently it has been discovered that some fleets have changed their reporting practices (SPC-OFP 2013) such that far fewer searching days are reported and these are instead reported as non-fishing transit days. This practice essentially represents effort creep and we have not yet specifically corrected recent data to ensure consistency of reporting. Therefore the impact of this is not known, but it will be minimized by the practice of estimating frequent time-based changes in catchability.

3.4.2 Longline fisheries

The major change to longline catch data used in the current assessment was the incorporation of some of the Japanese coastal fishery catches that could not previously be assigned to a region because they were not associated with a location (Williams 2014). Collaborative work between SPC and Japan confirmed that some of these catches were occurring in the waters of the Federated States of Micronesia and were already in the assessment, but some new catches were added to regions 1 and 7. Also included for the first time were some longline catches from Vietnam (Williams 2014).

The longline CPUE indices for the main longline fisheries in each region are one of the most important inputs to the assessment as they provide information on trends in abundance over time for each region.

For the current assessment, two sources of standardized CPUE series were used in various stages of the assessments. The first set of indices was derived from Japanese operational-level longline data using generalized linear models (GLM) and a delta-lognormal approach (Hoyle and Okamoto 2011). These were only available to 2009 for the old regions 1-6, and for some regions the indices for 2009 were very uncertain. In order to have time series that went through until 2012 it was necessary to use Japanese aggregate catch and effort data and then 'splice' these together. The procedures for this are described in McKechnie et al. (2014b).

As these indices were not available for the new regional structure, as an intermediate step, the CPUE indices for old region 3 was applied to new regions 3, 7, and 8.

The independent review of the bigeye assessment highlighted the spatial contraction of the Japanese fleet (and therefore the indices based on it) and accounting for targeting changes as the two major issues to address with longline CPUE (Ianelli et al. 2012). The new CPUE indices developed for the current assessment attempt to address these issues in two ways: 1) by using data across multiple fleets in order to minimize the spatial/temporal gaps in longline CPUE coverage; and 2) using operational data which allows us to consider vessel effects and other operational details to better account for targeting changes.

Accounting for changing targeting practices was achieved through the use of clustering analysis at the level of the trip based on the composition of albacore, bigeye, and yellowfin tunas in the catch. See McKechnie et al. (2014b) for further details of the how the clustering was undertaken and the GLM models used to create the standardized indices.

The operational CPUE data used for the analysis included all of the SPC data holdings, plus some data only held by Chinese Taipei which was integrated into the analyses undertaken for regions 4 and 6. Unfortunately, for this assessment it was not possible to incorporate non-SPC data holdings from Korea and Japan which are the two historically dominant distant-water longline fleets.

Coefficients of variation (CVs) for region-specific standardised effort were averaged to 0.2 the period 1980-1990. This is different to the previous assessment which had much higher CVs for regions 5 and 6 due to the paucity of data. Using all flags led to CVs which were comparable across all regions (McKechnie et al., 2014b) so it was decided that a similar mean CV be used for all regions.

Another important input for the standardized indices is regional scaling factors incorporated to estimate the relative level of exploitable longline population among regions (see Langley et al. 2005, and, Hoyle and Langley 2007). In an improvement from previous years, Generalised Additive Models (GAMs) were used to model aggregate catch and effort data for the fleets from Japan, Korea, and Chinese Taipei (McKechnie et al. 2014a). This approach allowed the estimation of regional scaling factors for all years, though of course years with better coverage (and therefore less spatial interpolation) were more reliable. As some of the new CPUE series only started around 1980, the period 1980-1990 was used for the period to calculate the scalars to be applied to the standardized indices.

The final CPUE indices used in the reference case model comprised Japanese-based indices for regions 1 and 2 (no other operational data was available, apart from a short time series of US data for region 2), all flags operational for regions 3, 7, and 8, nominal for region 9 (very little fishing and only aggregate data was available). For region 4 we had initially used the all-flags CPUE, but this index led to an extreme 'blowout' in recruitment and biomass at the start of the model (see Section 10.3), so we replaced it with the Japanese index. All indices for which catchability was shared and assumed constant, i.e., the L-ALL fisheries in each region, are presented in Figure 7.

For the other longline fisheries, the effort units were defined as the total number of hooks set.

3.4.3 Other fisheries

There has been continual improvement in the catch estimates from Indonesia and the Philippines through the GEF-WPEA project and for the first time we include some catch data from the small-fish fisheries in Vietnam. There is some uncertainty around the 'other' gears catch estimate for Indonesia in 2012 so the 2011 estimate was carried forward to 2012 pending further investigation.

For these other fisheries, effort is either included in days fished, or more often set to 'missing'. For the reference case model effort was set to missing for five fisheries, the three small-fish miscellaneous fisheries, the combined Indonesia and Philippines handline and ex-EEZ purse seine fisheries. A nominal effort of one was added for the final year of the model to allow the estimation of a catchability coefficient to assist with projections which are reported in Pilling et al. (2014a).

3.5 Size data

Available length-frequency data for each of the defined fisheries were compiled into 95 2-cm size classes (10–12 cm to 198–200 cm). All weight data were recorded as processed weights (usually recorded to the nearest kg). Processing methods varied between fleets requiring the application of fishery-specific conversion factors to convert the available weight data to whole fish equivalents. Details of the conversion to whole weight are described in Langley et al. (2006). For each fishery, quarterly weight frequency data were compiled by 1 kg weight intervals over a range of 1-200 kg. Data were either collected onboard by fishers, through observer programmes, or through port sampling. Davies et al. (2011) provides more details on the source of the size data.

Each length-frequency record in the model consisted of the actual number of bigeye tuna measured and Figure 8 provides details of the temporal availability of length and weight (for longline) frequency data and the relative sample sizes. Note that a maximum sample size of 1000 was implemented in the assessment.

3.5.1 Purse seine

Only length frequency samples are used in the assessments and the previous assessment used only observer samples which had been corrected for grab sample bias. As observer coverage had been very low and unrepresentative in early years, there were many gaps and the time series of size data did not show evidence of model progression. Two major changes were made for the current assessment and are described in detail in Abascal et al. (2014): first the long time series of port sampling data from Pago Pago was included, and second all samples were weighted by the catch – both at the set and strata level, with thresholds applied to ensure that small samples from important catch strata did not get too much weight (as was done for the longline fishery). Unfortunately full Pago Pago data are not available since 2008 as they have not yet been fully processed (V. Chan pers. comm.).

3.5.2 Longline

A detailed review of all available length and weight frequency data for bigeye tuna was undertaken, and McKechnie (2014) provides details of the analytical approaches for constructing this year's data inputs. Key principles used in constructing the data inputs were that a) we would not use weight and length data at the same time – even if it was available – as it would either introduce conflict (if data were in disagreement) or dominate the model fit (if they were in agreement). Therefore, we considered the coverage and size of samples and typically chose to use weight frequency data where it was available. Japanese weight data were not available for regions 4, 5, and 6 in recent years and had to be supplemented by Japanese training vessel length data in region 4 and all flags length data in regions 5 and 6.

The general approach used by McKechnie (2014) was that Japanese size data was weighted spatially in respect of the spatial distribution of catch within the region, and the size data from all fleets data were weighted by flag for some fisheries. For the catch weighting, a moving 11 quarter time window was used to calculate the relative importance of each stratum.

3.5.3 Other fisheries

Size data were either missing or poor for the Indonesian and Vietnamese small-fish fisheries and the Indonesian-Philippines ex-EEZ purse seine fishery. In the case of the first two, selectivity was assumed shared with the Philippines small-fish fishery and in the last case it was shared with the associated purse seine fishery also in region 7.

Philippines: Size composition data for the Philippines domestic fisheries derived from a sampling programme conducted in the Philippines in 1993–94 were augmented with data from the 1980s and for 1995. In addition, data collected during 1997–2012 from the Philippines hand-line (PH HL 3) and surface fisheries (PH MISC 3) under the National Stock Assessment Project and in more recent years under the GEF-WPEA project were included in the current assessment.

As for the 2011 assessment the length frequency samples from the small fish hook and line and large fish handline fisheries were adjusted to exclude all reported fish lengths greater than 90 cm for PH MISC 3 from the current assessment. This was done on the basis that it is suspected that the presence of these large fish may be due to mis-reporting of the fishing gear in some of the regional sampling programmes.

Japan coastal: Length data from the Japanese coastal purse-seine and pole-and-line fleets were provided by the National Research Institute of Far Seas Fisheries (NRIFSF).

Pole-and-line: For the equatorial pole-and-line fishery, length data were available from the Japanese distant-water fleet (sourced from NRIFSF) and from the domestic fleets (Solomon Islands and PNG). Since the late 1990s, most of the length data were collected by observers covering the Solomon Islands pole-and-line fleet.

3.6 Tagging data

In previous assessments a modest amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. These data consisted of bigeye tuna tag releases and returns from the OFP's Regional Tuna Tagging Project (RTTP) conducted during 1989-1992, and more recent (1995, 1999-2001) releases and returns from tagging conducted in the Coral Sea (CS) by CSIRO (Evans et al. 2008). Tags were released using standard tuna tagging equipment and techniques by trained scientists and technicians. The tag release effort was spread throughout the tropical western Pacific, between approximately 120-E and 170-W (Kaltongga 1998; Hampton and Williams 2005).

For the 2011 bigeye tuna assessment (Davies et al. 2011), an additional tag data set was available from the recent Pacific Tuna Tagging Programme (PTTP) undertaken mainly in the western tropical Pacific from Indonesia to the Gilbert Islands of Kiribati (Caillot et al. 2013). For the current assessment, all previously used tagging data were included, as well as additional PTTP releases undertaken up to and including the 2nd quarter of 2012. This represented an additional 18,753 bigeye tuna tag releases (unadjusted) compared to the data used for the 2011 assessment.

In the current assessment, the numbers of tag releases input to the assessment model were adjusted for a number of sources of tag loss – unusable recaptures due to lack of adequately resolved recapture data, estimates of tag loss (shedding and initial mortality) due to variable skill of taggers, and estimates of base levels of tag shedding/tag mortality. The procedures used in re-scaling the releases are described in detail in Berger et al. (2014), but essentially the re-scaling preserves the recovery rates of tags from the individual tag groups as if none of the tag loss had occurred.

The complete data set includes a total of 15,245 adjusted releases, which were classified into 56 region/quarter tag release groups (Table 2). A total of 4,219 tag returns could be assigned to the fisheries included in the model. As for previous assessments, tag releases were stratified by release region, time period of release (quarter) and the same length classes used to stratify the length-frequency data. As was done for the 2011 assessment, tags released in the vicinity of Hawaii were not included in the tagging data set used in this assessment. Inclusion of these data in the model is problematic as all tags are released and recovered around the boundary of regions 2 and 4 (latitude 20° N). This results in large changes in the estimated movement coefficients between regions 2 and 4 and in other model parameters influenced by tagging data. Due to a paucity of recaptures and no information for reporting rates, bigeye tagging data from the Japanese tagging programme has been excluded.

The returns from each size class of each tag release group were classified by recapture fishery and recapture time period (quarter). Because tag returns by purse seiners were often not accompanied by information concerning the set type, tag-return data were aggregated across set types for the purse seine fisheries in each region. The population dynamics model was in turn configured to predict equivalent estimated tag recaptures by these grouped fisheries.

4 MODEL DESCRIPTION – STRUCTURAL ASSUMPTIONS, PARAMETERISATION, AND PRIORS

The model can be considered to consist of several components, (i) the dynamics of the fish population; (ii) the dynamics of the fisheries; (iii) the dynamics of tagged fish; (iv) observation models for the data; (v) parameter estimation procedure; and (vi) stock assessment interpretations. Detailed technical descriptions of components (i) – (iv) in respect of the MULTIFAN-CL modelling software are given in Hampton and Fournier (2001) and Kleiber et al (2013), and are not repeated here.

4.1 Population dynamics

The model partitions the population into 9 spatial regions (see section 3.1) and 40 quarterly age-classes (see section 3.2). The last age-class comprises a “plus group” in which mortality and other characteristics are assumed to be constant. The population is “monitored” in the model at quarterly time steps, extending through a time window of 1952–2012. The main population dynamics processes are as follows:

4.1.1 Recruitment

Recruitment is defined as the appearance of age-class 1 fish in the population. Tropical tuna spawning does not follow a clear seasonal pattern but at least for yellowfin tuna it occurs sporadically when food supplies are plentiful (Itano 2000). It was assumed that recruitment occurs instantaneously at the beginning of each quarter. This is a discrete approximation to continuous recruitment, but provides sufficient flexibility to allow a range of variability to be incorporated into the estimates as appropriate.

The distribution of recruitment among the model regions was estimated within the model and allowed to vary over time in a relatively unconstrained fashion. The time-series variation in spatially-aggregated recruitment was somewhat constrained by a lognormal prior. The variance of the prior was set such that spatially aggregated recruitments of about three times and one third of the average recruitment would occur about once every 25 years on average.

Spatially-aggregated recruitment was assumed to have a weak relationship with the spawning biomass via a Beverton and Holt stock-recruitment relationship (SRR) with a fixed value of steepness (*h)*. Steepness is defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Mace and Doonan 1988; Maunder and Watters 2001).

The SRR was incorporated mainly so that yield analysis could be undertaken for stock assessment purposes, particularly the determination of equilibrium based reference points. We therefore opted to apply a relatively weak penalty for deviation from the SRR so that it would have negligible effect on the recruitment and other model estimates (see Hampton and Fournier 2001, Appendix D).

Typically, fisheries data are not very informative about the steepness parameter of the SRR parameters; hence, the steepness parameter was fixed at a moderate value (0.80) and the sensitivity of the model results to the value of steepness was explored via model sensitivities with lower (0.65) and higher (0.95) values of steepness.

4.1.2 Initial population

The population age structure in the initial time period in each region was assumed to be in equilibrium and determined as a function of the average total mortality during the first 20 quarters. This assumption avoids having to treat the initial age structure, which is generally poorly determined, as independent parameters in the model. The initial age structure was applied to the initial recruitment estimates to obtain the initial populations in each region.

4.1.3 Growth

The standard assumptions made concerning age and growth are (i) the lengths-at-age are normally distributed for each age-class; (ii) the mean lengths-at-age follow a von Bertalanffy growth curve; (iii) the standard deviations of length for each age-class are a log-linear function of the mean lengths-at-age; and (iv) the probability distributions of weights-at-age are a deterministic function of the lengths-at-age and a specified weight-length relationship. These processes are assumed to be regionally invariant.

As noted above, the population is partitioned into quarterly age-classes with an aggregate class for the maximum age (plus-group). The aggregate age class makes possible the accumulation of old and large fish, which is likely in the early years of the fishery when exploitation rates were very low.

Based upon previous analyses assuming a standard von Bertalanffy growth pattern, substantial departures from the model may be indicated, particularly for fish of small sizes (see Section 2.2). We therefore modelled growth by allowing the mean lengths of the first eight quarterly age-classes to be independent parameters, with the remaining mean lengths following a von Bertalanffy growth curve. These deviations attract a small penalty to avoid over-fitting the size data. Early model runs indicated a tendency for the model to converge to implausibly large estimates of the mean length of the oldest age class (L2). Therefore, we opted to fix L2 in the reference case at 184 cm, based on examination of the likelihood profile. Two other values of L2 (178 and 190 cm) were used in sensitivity analysis.

4.1.4 Movement

Movement was assumed to occur instantaneously at the beginning of each quarter via movement coefficients that connect regions sharing a common boundary. Note that fish can move between non-contiguous regions in a single time step due to the "implicit transition" computational algorithm employed (see Hampton and Fournier 2001; Kleiber et al. 2013 for details). Movement is parameterised as the proportion of fish in a given region that move to the adjacent region. Across each inter-regional boundary in the model, movement is possible in both directions for the four quarters, each with their own movement coefficients. Thus the number of movement parameters is 2×no.regions×4quarters. The seasonal pattern of movement persists from year to year with no allowance for longer-term variation in movement. Usually there are limited data available to estimate age-specific movement and the movement coefficients are normally invariant with respect to age.

A prior of 0.1 is assumed for all movement coefficients, inferring a relatively high mixing rate between regions. A small penalty is applied to deviations from the prior. Evaluation of much lower prior values during the model development phase did not lead to different movement estimates.

4.1.5 Natural mortality

Natural mortality (M) may be held fixed at pre-determined age-specific levels or estimated as an age-specific parameters. Natural mortality at age was recalculated for previous assessments using an approach applied to other tunas (Harley and Maunder 2003, Hoyle 2008, Hoyle and Nicol 2008) in the WCPO and EPO. The generally increasing proportion of males in the catch with increasing size is assumed to be due to an increase in the natural mortality of females, associated with sexual maturity and the onset of reproduction. The externally-estimated M-at-age were assumed as fixed parameters in the model, as shown in Figure 9. Model runs were also undertaken where M-at-age was estimated.

4.1.6 Sexual maturity

Reproductive output at age, which is used to derive spawning biomass, was taken directly from the previous assessment. The maturity-at-age was calculated based on data collected in the WCPO, and based on relative reproductive potential rather than the relative biomass of both sexes above the age of female maturity. This approach was previously applied to albacore (Hoyle 2008) and bigeye (Hoyle and Nicol 2008) tunas in the WCPO. The reproductive potential of each age class was assumed to be the product of the proportion of females at age, the proportion of females mature at age, the spawning frequency at age of mature females, and the fecundity at age per spawning of mature females (Figure 9). Overall, this results in a slight shift in the age of first maturity and a substantial reduction in the reproductive potential for older age classes.

4.2 Fishery dynamics

The interaction of the fisheries with the population occurs through fishing mortality. Fishing mortality is assumed to be a composite of several separable processes – selectivity, which describes the age-specific pattern of fishing mortality; catchability, which scales fishing effort to fishing mortality; and effort deviations, which are a random effect in the fishing effort – fishing mortality relationship.

4.2.1 Selectivity

In many stock assessment models, selectivity is modelled as a functional relationship with age, e.g. using a logistic curve to model monotonically increasing selectivity and various dome-shaped curves to model fisheries that select neither the youngest nor oldest fish. Modelling selectivity with separate age-specific coefficients (with a range of 0–1), constrained with smoothing penalties, has the disadvantage of requiring a large number of parameters. Instead, we have used a method based on a cubic spline interpolation. This is a form of smoothing, but the number of parameters for each fishery is the number of cubic spline "nodes" that are deemed to be sufficient to characterise selectivity over the age range. We chose five nodes, which historically seemed to be sufficient to allow for reasonably complex selectivity patterns. For particular fisheries alternative functions were employed, including logistic and non-decreasing. In all cases, selectivity is assumed to be fishery-specific and time-invariant. However, it is possible for a single selectivity function to be "shared" among a group of fisheries that have similar operational characteristics and/or exist in similar areas and with similar size compositions. This grouping facilitates a reduction in the number parameters being estimated and the groupings used are provided in Table 4.

4.2.2 Catchability

Constant catchability (time-invariant) was estimated for all fisheries for which standardised indices of relative abundance were available. As noted earlier, this assumption is similar to assuming that the CPUE for these fisheries indexes the exploitable abundance both among areas and over time. The "main" longline fisheries were grouped for the purpose of initial catchability, and to maintain the relativity of catch rates among regions.

For all other fisheries, catchability was allowed to vary slowly over time (akin to a random walk) using a structural time-series approach. Random walk steps were taken every two years, and the deviations were constrained by prior distributions of mean zero and variance specified for the different fisheries according to our prior belief regarding the extent to which catchability may have changed. For fisheries having no available effort estimates (e.g. the Philippines and Indonesian surface fisheries), partial fishing mortalities were estimated consistent with the observed catches using a Newton-Raphson procedure. Therefore, catchability deviations (and effort deviations) are not estimated for these fisheries. For the other fisheries with time-series variability in catchability, the catchability deviation priors were assigned a variance approximating a CV of 0.10.

Apart from those fisheries for which the data were based on annual estimates, the catchabilities of all other fisheries were allowed to vary seasonally.

4.2.3 Effort deviations

Effort deviations were used to model the random variation in the effort – fishing mortality relationship, and may be constrained by pre-specified prior distributions.

The region-specific CPUE indices represent the principal indices of stock abundance, and the extent to which the model can deviate from the indices is moderated by the penalty weights assigned to the standardised effort series. The precision of the CPUE indices varies temporally and among regions and, therefore, a relative weighting on the individual effort observations in each time period was implemented according to the canonical variance estimates derived from the GLM (Francis 1999).

Unlike the 2011 assessment where the CVs varied regionally due to varying data quality, the regional differences in the estimated CVs were sufficiently small that we assumed the same average CV for all indices; the average CV for the period 1980-90 was set to 0.2 (see Section 3.4.2). The resulting scaled CVs were transformed to an effort deviation penalty for each CPUE observation in MULTIFAN-CL. Penalties are inversely related to variance, such that lower effort penalties are associated with indices having high variance, consequently these indices are less influential in fitting the model.

4.3 Dynamics of tagged fish

4.3.1 Tag mixing

The population dynamics of the fully recruited tagged and untagged populations are governed by the same model structures and parameters. The populations differ in respect of the recruitment process, which for the tagged population is the release of tagged fish, i.e. an individual tag and release event is the recruitment for that tagged population. Implicitly, we assume that the probability of recapturing a given tagged fish is the same as the probability of catching any given untagged fish in the same region and time period. For this assumption to be valid either the distribution of fishing effort must be random with respect to tagged and untagged fish and/or the tagged fish must be randomly mixed with the untagged fish. The former condition is unlikely to be met because fishing effort is almost never randomly distributed in space. The second condition is also unlikely to be met soon after release because of insufficient time for mixing to take place. Depending on the disposition of fishing effort in relation to tag release sites, the probability of capture of tagged fish soon after release may be different to that for the untagged fish. It is therefore desirable to designate one or more time periods after release as "pre-mixed" and compute fishing mortality for the tagged fish based on the actual recaptures, corrected for tag reporting (see below), rather than use fishing mortalities based on the general population parameters. This in effect de-sensitises the likelihood function to tag recaptures in the pre-mixed periods while correctly discounting the tagged population for the recaptures that occurred.

We assumed that tagged bigeye mix fairly quickly with the untagged population at the region level and that this mixing process is complete by the end of the second quarter after release.

4.3.2 Tag reporting

In principle, tag-reporting rates can be estimated internally within the model. In practice, experience has shown that independent information on tag-reporting rates for at least some fisheries tends to be required for reasonably stable estimates to be obtained. We provided reporting rate priors for all fisheries that reflect our prior information regarding the reporting rate and the confidence we have in that information.

Previous assessments have assumed that fishery-specific reporting rates are constant over time. This assumption was reasonable when most of the tag data were associated with a single tagging programme. However, tag reporting rates may vary considerably between tagging programmes due to changes in the composition and operation of individual fisheries and different levels of tag programme publicity and follow-up. Consequently, fishery-specific tag reporting rates were estimated that are also specific to individual tagging programmes, i.e. a reporting rate matrix. Tag recapture and reporting rate groupings are provided in Table 4.

The estimation of the reporting rates included penalty terms in respect of pre-determined priors. These were derived from analyses of tag seeding experiments (Berger et al. 2014) and other information (Hampton 1997). For the RTTP and PTTP, relatively informative priors were formulated for the equatorial purse seine fisheries given the larger extent of information available.

All reporting rates were assumed to be stable over time.

4.4 Likelihood components

There are four data components that contribute to the log-likelihood function — the total catch data, the length-frequency data, the weight-frequency data and the tagging data. The observed total catch data are assumed to be unbiased and relatively precise, with the SD of residuals on the log scale being 0.007.

The probability distributions for the length-frequency proportions are assumed to be approximated by robust normal distributions, with the variance determined by the effective sample size and the observed length-frequency proportion. A similar likelihood function was used for the weight-frequency data.

The size frequency data are assigned an effective sample size lower than the number of fish sampled. Reduction of the effective sample size recognises that (i) length- and weight-frequency samples are not truly random (because of clumping in the population with respect to size) and would have higher variance as a result; and (ii) the model does not include all possible process error, resulting in further under-estimation of variances. The relative weighting of the longline size frequency is comparable to the approach used in the 2011 assessment (n/20).

A log-likelihood component for the tag data was computed using a negative binomial distribution. The negative binomial is preferred over the more commonly used Poisson distribution because tagging data often exhibit more variability than can be attributed by the Poisson. We have employed a parameterisation of the variance parameters such that as they approach infinity, the negative binomial approaches the Poisson. Therefore, if the tag return data show high variability (for example, due to contagion or non-independence of tags), then the negative binomial is able to recognise this. This should then provide a more realistic weighting of the tag return data in the overall log-likelihood and allow the variability to impact the confidence intervals of estimated parameters. However, early attempts at estimating fishery-specific variance parameters from the data yielded values at either bound, suggesting insufficient information was available. A fixed value at the midpoint of the variance range was therefore assumed for all fisheries. Stock assessment results were relatively insensitive to the choice of the variance level. A complete derivation and description of the negative binomial likelihood function for tagging data is provided in Hampton and Fournier (2001) (Appendix C).

4.5 Parameter estimation and uncertainty

The parameters of the model were estimated by maximizing the log-likelihoods of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. The maximization to a point of model convergence was performed by an efficient optimization using exact derivatives with respect to the model parameters (auto-differentiation, Fournier et al. 2012). Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters. A bash shell script, *doitall*, (Annex 10.5) implements the phased procedure for fitting the model. Some parameters were assigned specified starting values consistent with available biological information. The values of these parameters are provided in the *bet.ini* file (Annex 10.6)[2].

In this assessment two approaches were used to describe the uncertainty in key model outputs. The first estimates the statistical variation **within** a given assessment run, while the second focuses on the structural uncertainty in the assessment by considering the variation **among** model runs. For the first approach, the Hessian matrix was calculated for the reference case model run to obtain estimates of the covariance matrix, which is used in combination with the Delta method to compute approximate confidence intervals for parameters of interest (the biomass and recruitment trajectories). For the second approach, a crosswise grid of model runs

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[2] Details of elements of the *doitall* and *.ini* files as well as other input files that structure a MULTIFAN-CL run are given in Kleiber et al. (2013).

was undertaken which incorporated many of the options of uncertainty explored by the key model runs and one-off sensitivity analyses. This procedure attempts to describe the main sources of structural and data uncertainty in the assessment.

For highly complex population models fitted to large amounts of often conflicting data, it is common for there to be difficulties in estimating absolute abundance (Lee et al., 2014). Therefore, a **profile likelihood analysis** was done of the marginal posterior likelihood in respect of the total population scaling parameter. Reasonable contrast in the profile was taken as indicating sufficient information existed in the data for estimating absolute abundance, and also offered confirmation of the global minimum obtained by the maximum likelihood estimate.

Due to the low number of observations for recent cohorts, recruitment estimates in the terminal model time periods may be poorly estimated. This was investigated using retrospective analysis where data from the terminal time periods (the last three years) were successively removed and the model fitted to each case. The terminal recruitments and biomass estimates were compared among the retrospective models for their robustness to the loss of data. Whether or not to estimate the terminal recruitments was based upon the outcome of this analysis (see Section 10.2).

4.6 Stock assessment interpretation methods

Several ancillary analyses using the converged model were conducted in order to interpret the results for stock assessment purposes. The methods involved are summarized below and the details can be found in Kleiber et al. (2013). Note that, in each case, these ancillary analyses are completely integrated into the model, and therefore confidence intervals for quantities of interest are available using the Hessian-Delta approach.

4.6.1 Reference points

The unfished spawning biomass ($SB_{F=0}$) in each time period was calculated given the estimated recruitments and the Beverton-Holt spawner-recruit relationship. This offers a basis for comparing the exploited population relative to the population subject to natural mortality only. WCPFC adopted 20%$SB_{F=0}$ as a limit reference point for the bigeye stock when $SB_{F=0}$ is calculated as the average over the period 2002-2011.

4.6.2 Fishery impact

Many assessments estimate the ratio of recent to initial biomass as an index of fishery depletion. The problem with this approach is that recruitment may vary considerably throughout the time series, and if either the initial or recent biomass estimates (or both) are "non-representative" because of recruitment variability or uncertainty, then the ratio may not measure fishery depletion, but simply reflect recruitment variability.

We approach this problem by computing the biomass time series (at the region level) using the estimated model parameters, but assuming that fishing mortality was zero. Because both the *real* biomass B_t and the *unexploited* biomass B_{0t} incorporate recruitment variability, their ratio at each time step of the analysis $\frac{B_t}{B_{0t}}$ can be interpreted as an index of fishery depletion. The computation of unexploited biomass includes an adjustment in recruitment to acknowledge the possibility of reduction of recruitment in exploited populations through stock-recruitment effects. This analysis was conducted in respect of groups of fisheries so as to describe the relative fishing impacts of each group on the population.

4.6.3 Yield analysis

The yield analysis consists of computing equilibrium catch (or yield) and biomass, conditional on a specified basal level of age-specific fishing mortality (F_a) for the entire model domain, a series of fishing mortality multipliers, *fmult*, the natural mortality-at-age (M_a), the mean weight-at-age (w_a) and the SRR parameters. All of these parameters, apart from *fmult*, which is arbitrarily specified over a range of 0–50 in increments of 0.1, are available from the parameter estimates of the model. The maximum yield with respect to *fmult* can easily be determined and is equivalent to the *MSY*. Similarly the spawning potential biomass at *MSY* (SB_{MSY}) can also be determined. The ratios of the current (or recent average) levels of fishing mortality and biomass to their respective levels at *MSY* are of interest as reference points. These ratios were also determined for the principal assessment model with alternative values of steepness assumed for the SRR.

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In this assessment, we use the average over the period 2008–2011. We do not include 2012 in the average as fishing mortality tends to have high uncertainty for the terminal data year of the analysis and the catch and effort data for this terminal year are usually incomplete.

The MSY-based reference points were also computed using the average annual F_a from each year included in the model (1952–2012). This enabled temporal trends in the reference points to be assessed and a consideration of the differences in MSY levels under historical patterns of age-specific exploitation.

The assessments indicate that recruitment over particular periods had higher uncertainty. Consequently, yield estimates based on the long-term equilibrium recruitment estimated from a Beverton and Holt SRR fitted to all estimated recruitments may substantially bias the yields currently available from the stock under current recruitment conditions. For this reason, a separate yield analysis was conducted based on the SRR estimated for the levels of recruitment and spawning potential that occurred in subsets of the model calculation period.

5 MODEL RUNS

5.1 Developments from the 2011 assessment

A substantial number of changes have occurred between the 2011 reference case model and the 2014 reference case model. Many of these changes came about through implementation of recommendations of the independent review (Ianelli et al. 2012) which impacted modelling assumptions, the MULTIFAN-CL software, the input data, and methods used to generate the input data. Many more occurred through general improvements to data and approaches that came about over the three years since the 2011 assessment. Subsequently the 2014 PAW discussed the need to balance the 'one-change at a time' recommendation from Ianelli et al. (2012), with a pragmatic approach that recognized the sheer magnitude of changes being made and the impossibility of keeping a 'step-by-step' account while attempting to develop the best 2014 reference case model. The PAW noted the importance of identifying the causes of significant changes in model quantities and this is what we have done here.

Section 10.3 provides results of several of the steps between the 2011 and 2014 reference case assessments. Section 10.4 describes the impact of several changes to modelling assumptions which were implemented between the two assessments, but compared to the 2014 reference case, to assist in understanding the potential impact. Below we describe the approach that was undertaken in developing the 2014 reference case.

i. Rerun the 2011 assessment with the new MULTIFAN-CL: Since the version used for the 2011 assessment, there have been at least four significant improvements in MULTIFAN-CL to the: tagging catch calculations; tagging likelihood; Newton-Raphson catch calculation; and, the penalty calculation in respect of priors on fishery-specific tag reporting rates;
ii. Update the 2011 fishery and spatial structures with data through to 2012: We undertook little examination of this model and made no attempts to improve it

through examination of model fit and fishery groupings, but did apply some of the improved approaches for constructing data inputs and did introduce the lognormal bias correction in equilibrium recruitment computations.

iii. Move to the nine-region / 33 fishery model structure: This initial move was an extremely complex task. New regions and new fisheries meant new size and weight frequency data for many fisheries. At this stage we were still using the previous Japanese CPUE which was only available for six regions – region 3 CPUE was used for regions 3, 7, and 8. We began investigation of functional forms for selectivity and different grouping for selectivity depending on the nature of data (i.e., both availability of data and whether the data were consistent through time or highly variable) in different regions. At this stage we spent three weeks [unsuccessfully] trying to understand the cause of the large spike in the most recent recruitments (see section 10.4). On the basis of the retrospective analysis, it was decided to set the deviations from the spatially-aggregated SRR equilibrium recruitment to zero for the terminal six time periods of the model.

iv. Transition to the new all-flags CPUE: We swapped in the all-flags CPUE for regions 3-8 and we immediately noticed a large increase in the early recruitment and spawning potential. Some time was spent investigating the cause of this and it was isolated to the region 4 series, for which the early data were dominated by observations in the albacore cluster (McKechnie et al. 2014b).

v. Inclusion of the Japanese CPUE for region 4: This model removed the pattern seen using the all flags series for region four and was the focus of further considerable work on selectivity groupings and functional forms. Once a reference case had been found, we undertook a likelihood profile over the population scaling parameter and determined that this model in fact represented a local minimum and that a better fit could be achieved with slightly larger mean length of the oldest age class (L2) and slightly different movement rates for region 2. These different results gave almost identical stock status results. Further profiling identified a better fit with L2 in the mid 190 cm range – this size was considered too large for the WCPO and was also associated with a considerable reduction in estimated growth variability.

vi. Final reference case: starting from the best minimum found from the first likelihood profile. We fixed L2 at 184cm and estimated all other parameters and had a fit over 60 likelihood points better than the previous model.

A summary of the major differences between the 2011 and final 2014 reference case is provided in Table 3.

5.2 Sensitivity analyses

The recommendations of the 2014 PAW formed the basis for several of the one-off sensitivity analyses undertaken from the reference case, but several other runs were undertaken in order to provide a better understanding of the impact of some of the changes in modelling assumptions. The eight 'key' sensitivity runs for which full details of management quantities have been calculated are provided in Table 5 and a further four model runs are provided in Table 10.4 1. These analyses can be divided in to five parts in respect of the assumptions being tested:

Size data relative weighting

In integrated stock assessment models such as this, the choice of weight for the size data likelihood component (**SZ_dw**) is somewhat arbitrary. It is therefore standard procedure to test the assumption used for the reference case in a sensitivity analysis. The relative influence of the length and weight composition data for all fisheries was reduced (i.e. a lower SZ_dw) by assigning an effective sample size of 0.02 (0.05 in the reference case) times the individual samples, with a maximum sample size of 20 (50 in the reference case). This explores the relative influence of size composition data upon the model estimates and illustrates data conflicts.

Mean length of the oldest age class (L2)

Model development indicated that this was a difficult parameter to estimate so it was fixed at 178 cm (**L2_178**) and 190 cm (**L2_190cm**). The smaller size represents a value close to that estimated in the previous assessment and in the model run upon which likelihood profiling occurred. The higher value is a further 6cm larger than the reference case assumption.

Tagging data

Reduce the tag mixing period to 1 quarter (**Mix_1**) and extend the mixing period for those Coral Sea releases to 28 quarters or essentially the period over which most recoveries occurred (**Mix_CS**).

Steepness

Fixed values of 0.65 (**h_0.65**) and 0.95 (**h_0.95**). Generally there is limited information available to define an appropriate value of steepness for tuna species and, consequently, lower (0.65) and higher (0.95) plausible values were examined.

In an exploratory model run ("h_est") steepness was also estimated, largely for purposes of comparison with previous assessments.

Natural mortality

Estimate age-specific natural mortality schedule (**M_est**). Given the large amount of tag-recapture data input to the model, it was considered feasible to estimate natural mortality.

Recruitment

Three exploratory models were run that tested the sensitivity to assumptions regarding the estimated recruitments and the spawner recruitment curve. The model run "Final Rdevs" included the estimation of the terminal six temporal recruitment deviates. The model run "Early Rdevs" included the recruitments estimated over the full model calculation period in fitting the SRR, and the model "Bias correction" excluded the bias correction from the fitting of the SRR.

The eight sensitivity runs in **bold** above were taken as the key model runs for examining the effects of the primary sources of uncertainty on management reference points in the current assessment.

5.3 Structural uncertainty

Following Hoyle et al. (2008) examination of uncertainty in the model structure was integrated into a single analysis that explored the interactions of the assumptions tested in the one-off sensitivity runs, i.e. for the key model runs, and that test the alternative assumptions recommended by the PAW. These interactions were tested in a grid of 108 combinations of the following options:

- Length at oldest age (L2) [3 levels]: **Ref.Case** (184cm), **L2_178** (178 cm), and **L2_190** (190cm)
- Tag mixing period [3 levels]: **Ref.Case** (2 quarters), **Mix_1** (1 quarter), and **Mix_CS** (28 quarters for Coral Sea releases)
- Steepness[3 levels]: **Ref.Case** (0.8), **h_0.65** (0.65), **h0.95** (0.95)
- Size data weighting [2 levels]: **Ref.Case** (n/20), **SZ_dw** (n/50)
- Natural mortality [2 levels]: **Ref.Case** (fixed values), **M_est** (estimated)

The independent review (Ianelli et al. 2012) recommended consideration of approaches for the weighting of various sensitivity analyses. We have not done this here but suggest this be considered by a small group following presentation of the assessment at SC10.

6 RESULTS

6.1 Model diagnostics (reference case)

A brief review follows of the fit of the model to the four data sources: the standardised CPUE for the longline fisheries, the size composition data, and the tagging data. The penalty for fitting the catch data is sufficiently high that the fit is essentially perfect so is not discussed further.

Longline CPUE

The fit to the standardised indices is provided in Figure 10 and the fit residuals, with a smoother, are provided in Figure 11. Overall the model fits very well to the observed CPUE series, but Figure 11 does suggest some slight lack of fit in regions 4 and 8 at the end of the time series. In region 4 the model predicts a greater decline in recent years and in region 8 the model predicts more stable biomass than that observed.

Size composition data

Two diagnostics are presented to illustrate the fit of the model to the observed size composition data: Figure 12 and Figure 13 show the aggregated (across all observations for a fishery) observed and predicted length and weight frequencies for each fishery, and Figure 14 and Figure 15 the predicted and observed median lengths and weight over time. Not surprisingly the same general patterns of fit or lack of fit are apparent in both sets, but the latter series of plots provides a temporal dimension to the comparison. Some of the examples of lack of fit are related to grouping of selectivity curves (Table 4) which was often necessary to avoid the poorly estimated individual selectivity curves.

The model overestimated the number of large fish in the region 3 offshore longline fishery (Figure 12), but examination of the temporal patterns suggests that most of the problem lies in conflict between samples at the start and end of the time series (Figure 14). Given that this was a mixed-fleet fishery such a pattern is not surprising and was also apparent in the length frequency samples that were used at the end of the time series for the L-ALL fisheries in region 5 and 6 to supplement the lack of Japanese weight frequency data (Figure 13 and Figure 15). We considered excluding these length samples, but given that selectivity was shared with other fisheries we decided to include them as they had little impact on the model. The L-ALL fishery in region 8 also had a relatively poor overall fit, but again there was strong variation through time in the weight frequency samples.

With the exception of the L-ALL 5 and 6 length data fits mentioned above, the fit to the length data for the fisheries was generally quite good (Figure 13 and Figure 15), recognizing that some of the data for the smaller volume fisheries was very poor. As observed in previous assessments, there is some lack of fit of smaller fish in the purse seine fisheries. This issue was investigated in detail and covered in the discussion and future work recommendations. Attempts to improve the fit using alternative selectivity curves lead to very poor growth estimates, so in the end we allowed the small systematic misfit in exchange for biologically plausible growth.

Tagging data

Three diagnostic plots have been presented to evaluate the quality of the tagging data fit: Figure 16 provides the predicted and observed recaptures of tagged fish by time period at liberty (quarter) from the region of release to the region of recapture; Figure 17 shows observed and predicted recaptures by time period specific to each release program; and Figure 18 shows observed and predicted tag attrition for the reference case across all tag release events.

The previous assessment contained poor fits to some tagging data, in particular tag releases that had occurred in the Coral Sea under the RTTP and the later Coral Sea tagging undertaken by CSIRO. The fit to these data in particular has been much improved through the new spatial and fishery structures (compare Figure 23 and 30 from Davies et al. 2011 with Figure 16 and Figure 17) but there is still a slight underestimate of tag recaptures. Predicted recaptures within region 5 and 9 of these releases is good, but outside these areas it is poor – associated with the very low general reporting rate for longline fisheries. As indicated above, overall the fit to the tagging data is much improved, but in the tag attrition plot (Figure 18) there is evidence for overestimation of tag returns at 7-9 quarters after release.

6.2 Model parameter estimates (reference case)

Tag Reporting Rates

With the expanded spatial and fishery structure, 55 individual reporting rates of recaptured tagged bigeye, specific to release group (program) and recapture fishery, were estimated and these are presented in Figure 19 with the prior distribution that was assumed. As could be expected, tag reporting rates for individual fisheries differed both among fisheries and tagging programmes. The grouping assumed among fisheries and programmes are shown in Table 4, and essentially entails the longline fisheries (1,2,4:9,13) being in the same group over all the tagging programs, while other fisheries retained the same fishery-specific grouping, but a program-specific rate was estimated for each group. Informative priors for the tag reporting rates were available for a number of the main fisheries, most notably the tag recoveries by the purse-seine fisheries from the RTTP and PTTP programmes.

For all programmes, some of the reporting rate estimates were estimated to be higher than the mode of their prior distributions and tended to vary considerably between regions. The estimate for the largest longline fishery group (1) was below the prior, while for other longline fisheries the estimates were highly variable, ranging from near zero (region 5) to the upper limit allowed (0.9, region 9). However, the estimated reporting rates from the longline fisheries are based on a very small number of tag recoveries and, consequently, the tag recovery data from these fisheries are not very informative.

Reporting rates were estimated to be at the upper bound for purse seine in region 4 and 8, and the Indonesia-Philippines purse seine fishery in region 7. The high reporting rates in regions 4 and 8 are consistent with the patterns observed in the effort deviations for the standardised fisheries in those regions – suggesting potential data conflict. Reporting rates were also high for Australian longline vessels in region 5, much higher than they were for the region 9 reporting rates.

The very low estimated reporting rates for Coral Sea release group recaptures in small-fish fisheries in regions 3 and 7 is not surprising given the sizes of fish tagged, nor is the reporting rate for Vietnam small-fish fisheries as this has not been an area of focus for tag recovery publicity.

Growth

In the reference case model the L2 parameter was fixed at 184 cm (Figure 20), slightly larger than the value estimated by Davies et al. (2011) of 179 cm. The estimated variation in length at age was quite tight compared to previous assessments and that for yellowfin tuna (Davies et al. 2014). Estimation of growth is a high priority for further biological and modelling work and this is discussed later in this paper.

Selectivity

The definition of new fisheries required new consideration of selectivity curves and grouping of selectivity across fisheries (Table 4). In the current assessment and the new fisheries structure, obtaining stable and sensible selectivity estimates was sometimes difficult (Figure 21). The smoothing splines that were used for many fisheries occasionally estimated a high selectivity for age class 1 – a spike at an age where no fish were caught so it was an issue with the functional form. In some instances this required grouping fisheries to avoid this problem, but this typically only occurred for fisheries with small catches and poor size data (e.g., LL-ALL in region 5).

The splitting of region 3 into regions 3, 7, and 8 proved important for both the L-ALL and the offshore LL fishery (region 3 and 7) with quite different selectivity curves estimated, e.g., for the L-OS-7 fishery an asymptotic curve fitted best while the L-OS-3 fishery had a strongly declining right-hand limb.

Some of the smaller and less important surface fisheries often had a increasing right hand 'limb' from their splines – the fit was slightly improved, but there were so few observations of catches at larger sizes that these curves were constrained to zero selectivity at older ages.

We had some difficulty getting high enough selectivity for the younger ages in the purse seine fishery with the current spline settings, but increased flexibility in the splines and length-based selectivity led to biologically implausible growth estimates. This is discussed in detail later in this paper.

Selectivity functions are temporally invariant. However, for a number of fisheries there is a clear temporal change in the size-frequency data and an associated lack of fit to the predicted size composition. This is particularly evident for the L ALL 2 and 4 fisheries. Further examination of these data is necessary to determine if they reflect a change in the selectivity in the fishery (through either operational changes or changes in the locations fished) or simply unrepresentative sampling data.

Catchability

Time-series changes in catchability were estimated for several fisheries and these are presented in Figure 22. Of particular interest is that in the major purse seine fisheries (regions 3, 4, and 8) catchability is estimated to have been stable or strongly increasing in recent years. The strong increasing trends are suggestive of effort creep or technological advances in the purse seine fishery such that a unit of effort is more effective than it was in the past.

Movement

Two representations of movement estimates are shown in Figure 23 and Figure 24. The estimated movement coefficients for adjacent model regions are shown in Figure 24. These patterns not surprisingly show strong movement between the new regions that make up the old region 3. Figure 23 probably provides the simplest way to understand the collective impact of the movements coefficients. They show that for regions 1, 2, 5, 6, and 9, most of the biomass comes from the model's estimates of local recruitment, while for regions 3, 4, 7, and 8 there is considerable mixing of fish. Nevertheless, these results should be taken in context of the strong confounding within the model of the regional recruitment and movement parameters, which is the focus of some discussion later in the paper.

6.3 Stock assessment results

Symbols used in the following discussion are defined in Table 6 and the key results are provided in Table 7.

6.3.1 Recruitment

The reference case recruitment estimates (aggregated by year for ease of display) for each region and the entire WCPO are shown in Figure 25. A key feature of previous assessments has been the low recruitment during the first half of the model time series followed by much higher recruitment in the second half. The extent of this phenomenon has been greatly reduced in the current assessment, mostly through higher estimated recruitment in the first half of the time series (Section 10.2.2; Figure 10.2 2). As seen in previous assessments, recruitment over the first 10-15 years is estimated with much less certainty and this is the reason why these were not included in the estimation of the SRR parameters. Further, as noted in Section 5.1, the last six recruitment deviates were not estimated and set to zero. This was because the retrospective analysis showed that these were poorly estimated (Section 10.2.1). We reiterate that this will have no impact the spawning potential reference points as these cohorts do not contribute to SB_{latest} or $SB_{current}$, and minimal impact on $F_{current}/F_{MSY}$ as we already ignore F estimates from the terminal year.

The estimated distribution of recruitment across regions should be interpreted with caution as MULTIFAN-CL can use a combination of movement and regional recruitment to distribute the population in a way that optimises the objective function. Generally the regional recruitment patterns are similar to those from the 2011 assessment. The large recruitments early in the time series for regions 1 and 2 persist – presumably driven by the longline CPUE trends (CPUE in these regions is the same as used in the previous assessment). The strong increase over time seen previously in region three is much less pronounced, even when recruitment is combined across regions 3, 7, and 8.

6.3.2 Biomass

Trends in biomass are represented using the estimated spawning potential, although some key total biomass reference points are included in the results tables.

The estimated spawning potential trajectory for each region and for the entire WCPO for the reference case are shown in Figure 26 and Figure 27. Consistent with the recruitment patterns, spawning potential at the start of the model is estimated to be higher than that estimated for previous assessments (Section 10.2.2; Figure 10.2 2). The eastern equatorial region (region 4) remains the region with the greatest spawning potential and the northeastern region (region 2) is the second most important. The western equatorial regions combined (3, 7, and 8), while important in the early years of the model, comprise about the same spawning potential as region 2 by the end of the model.

WCPO spawning potential is estimated to have been relatively stable during the 1950s, declined rather rapidly through to the mid 1970s and has been undergoing a slow continual decline since. WCPO patterns in spawning potential are likely to be more reliable than regional recruitment trends, which are primarily driven by the standardised CPUE assumed for the region. WCPO patterns in spawning potential are similar to the previous assessment, and key differences are in the nature and time of the initial decline and the trend in recent years. Over the last 10-15 years spawning potential in the northern regions is estimated to have been flat to slightly increasing while declines are estimated to be continuing in the other model regions.

6.3.3 Fishing mortality

Average fishing mortality rates for adult age-classes increase throughout the time series while juvenile mortality increases strongly through to the late 1990s and has been relatively stable since. Levels of juvenile mortality are greater than those for adults (Figure 28).

Changes in fishing mortality-at-age and population age structure are shown for decadal time intervals in Figure 29. Since the 1980s, the increase of juvenile fishing mortality to the current high levels is due to the catches of small fish beginning at that time from both associated purse seine sets and the mixed small-fish fisheries in the Philippines and Indonesia. Fishing mortality on intermediate ages (12-20 quarters) is also increasing through time consistent with the increased fishing mortality from the longline fishery.

6.3.4 Fishery impact

We measure fishery impact at each time step as the ratio of the estimated spawning potential to that which would have occurred in the historical absence of fishing. This is a useful variable to monitor, as it can be computed both at the region level and for the WCPO as a whole.

This information is plotted in two ways, first the fished and unfished spawning potential trajectories (Figure 30) and second as the depletion ratios themselves (Figure 31). The latter is relevant for the agreed limit reference point and discussed in more detail in Section 6.4.1.

The previous assessment suggested that recent unfished spawning potential was much greater than that in the early 1950s, but in the current assessment these are similar. The unfished trends should illustrate the impact of regional recruitment on local biomass, but again must be considered in the context of the potential confounding between regional recruitment and movement. The analysis suggests that the declines in spawning potential in regions 2 and 6 are being driven primarily by the estimated recruitment, while fishery impacts are greatest in regions 3, 4, 7, and 8. As seen in previous assessments, the model estimates moderate initial depletion in the northwest region in the 1950s. This could be real or reflect regional growth differences (see Section 2.2).

It is also possible to ascribe the fishery impact to specific fishery components in order to see which types of fishing activity have the largest impact on the spawning potential (Figure 32). The early impacts on the population were primarily attributable to longline fishing, but in recent years, at the WCPO level the impacts of associated purse seine sets and longline fishing are similar. In areas where they operate, fisheries that catch small fish have a significant impact, and the impact of these fisheries can also be seen in areas in which they do not operate, but at a much lower level (e.g., purse seine fishery impacts in regions 2, 5, and 6).

6.3.5 Yield analysis

The yield analyses conducted in this assessment incorporate the SRR (Figure 33) into the equilibrium biomass and yield computations. Importantly in the reference case model the steepness of the SRR was fixed at 0.8, so only the scaling parameter was estimated.

The equilibrium unfished spawning potential was estimated at 1,207,000 mt and the spawning potential that would support the *MSY* was estimated to be 345,400 or 28.6% of SB_0. The total equilibrium unfished biomass was estimated to be 2,286,000 mt.

The yield analysis also enables an assessment of the *MSY* level that would be theoretically achievable under the different patterns of age-specific fishing mortality observed through the history of the fishery (Figure 35). Prior to 1970, the WCPO bigeye fishery was almost exclusively conducted using longlines, with a low exploitation of small bigeye. The associated age-specific selectivity resulted in a substantially higher level of *MSY* (>200,000 mt per annum) compared to that estimated for the fishery based on the recent age-specific fishing mortality pattern (about 110,000 mt). The decline in the *MSY* over time follows the increased development of those fisheries that catch younger bigeye, principally the small-fish fisheries in the far west (Figure 35).

6.4 Stock status

6.4.1 Stock status based on the traditional Kobe plot

For continuity with previous practice, and while the SC and WCPFC consider the use of target and limit reference points, we have included the traditional Kobe plot for spawning potential versus fishing mortality (Figure 36). We have included both $SB_{current}$ and SB_{latest} for reference on this figure. $SB_{current}$ (2008-11 average) and SB_{latest} (2012) are estimated to be 94% and 77% respectively of SB_{MSY}.

As noted in Section 6.3.3, fishing mortality has generally been increasing through time, and for the reference case $F_{current}$ (2008-11 average) is estimated to be 1.57 times the fishing mortality that will support the *MSY* (Table 7).

6.4.2 Spawning biomass in relation to limit reference point

The SBF=0 calculated for the period 2002-11 is the basis for the limit reference point and this is a spawning potential of 1,613,855 mt which is 33.7% higher than SB_0 (Table 7). This indicates that recruitment has been generally above the estimated spawner recruitment curve during this more recent period. The limit reference point is 20% $SB_{F=0}$ and this is a spawning potential of 322,771 mt. $SB_{current}$ (2008-11 average) and SB_{latest} (2012) are estimated to be 20% and 16% respectively of $SB_{F=0}$ (Figure 37).

6.4.3 Spawning biomass in relation to potential target reference points

There are currently no agreed biomass-related target reference points for any species, but the WCPFC has requested investigation of spawning potential in the range of 40-60% $SB_{F=0}$ for skipjack for potential biomass-related target reference points. As $SB_{current}$ (2008-11 average) and SB_{latest} (2012) are estimated to be 20% and 16% respectively of $SB_{F=0}$, these levels are well outside (below) the range of those candidate biomass-related target reference points currently under consideration for skipjack tuna.

6.5 Sensitivity of the reference case

6.5.1 Impact of key model developments

Detailed results of the stepwise changes are provided in Section 10.3, which can be found in the Annex.

The use of the new MULTIFAN-CL executable had minimal impact on the 2011 assessment, far less than for skipjack and yellowfin tuna and this is likely due to the lesser amounts of tagging data in the bigeye assessment compared to the others. The addition of new data and the inclusion of the bias correction factor had a significant impact on MSY, but as seen in Section 10.4, this is mostly driven by the bias correction and confirmed by the minimal change in absolute levels of recruitment and spawning potential. One important observation is that the terminal recruitment deviate which was very low in the 2011 assessment was estimated to be much closer to average with the updated data. This confirms the conclusion from the retrospective analysis to not estimate terminal recruitment deviates.

By necessity, the move to the nine region model required numerous changes to model structure and assumptions, and in the stepwise model "New regions-JP" we also implemented the fixing of the terminal recruitment deviates and exclusion of the early deviates from the SRR (see Section 10.4). These changes resulted in a lifting of the absolute levels of recruitment and spawning potential across the temporal domain of the model, but especially for the first half of the model. This is important as one of the key concerns with previous assessments has been the much lower recruitment during the first half of the model domain, and this was greatly reduced when moving to the nine-region model and making other model improvements. *MSY* estimates were further increased in this model, but overall stock status was generally similar to earlier runs. This model was not considered valid though as region 3 CPUE was being used for regions 3, 7, and 8.

The shift to the all-flags CPUE did not go smoothly – it lead to very high recruitment (and thus spawning potential) in the early years of the model. Spawning potential in the 1950s was 10-12 times the SB_{MSY} level and 3-4 times SB_0. *MSY* was slightly higher, but stock status was much worse in terms of both $SB_{latest}/SB_{F=0}$ and $F_{current}/F_{MSY}$. The extremely non-equilibrium conditions were attributed to the steep decline in the all-flags region 4 CPUE series (McKechnie et al., 2014b). Once this series was swapped with the Japanese series, the model returned to a condition more similar to that with all Japan CPUE. This reference case, which replaced the previous model after the likelihood profile exercise, had similar model outputs.

6.5.2 One-off changes from the structural uncertainty analysis

Comparisons of the recruitment and spawning potential trajectories for the reference case and one-change sensitivity runs from the structural uncertainty analysis are provided in Figure 39, the key reference points and likelihood components are compared in Table 7 and Table 8, and Kobe plots are provided in Figure 40 and Figure 41. In addition, we compare $F_{current}/F_{MSY}$ for the period 2001 and 2011 for the same suite of models (Table 9). We summarise results for each sensitivity axis.

Size and maximum age (L2)

Stock productivity as estimated by *MSY* and general stock status indicators worsened with increased L2, but the differences were not particularly large, e.g., range for $F_{current}/F_{MSY}$ was 1.53 – 1.63 and the range for $SB_{latest}/SB_{F=0}$ was 0.15 – 0.17. Overall model fit improved with increasing L2, mostly through improvements to the fit to the length and weight frequency data and at the expense of the fit to the tagging data.

Weight to the size data (SZ_dw)

Down-weighting the size data had little impact in the current assessment. Spawning potential over the first 25 years of the model was lower than the reference case, but *MSY* was only very slightly lower and the key reference points were often identical. The reduced impact compared to previous assessments is possibly a consequence of both the reduced volume of size frequency data used in the assessment (e.g., using either length or weight data not both) and reduced conflict between the size and other data sets due to better preparation and modelling of these data (e.g., changes to fishery definitions).

Steepness (h)

Following the bigeye review recommendation to reduce the penalty on the spawner recruitment curve fitting, the assumed value of steepness had almost no impact on the estimated recruitment and spawning potential trajectories. However, steepness does impact on the *MSY*-related quantities.

The steepness sensitivities provided the most pessimistic (h=0.65) and optimistic (h=0.95) results in terms of *MSY* (101,880 mt versus 116,240 mt) and stock status. The impact of steepness on stock status based on the $SB_{latest}/SB_{F=0}$ (0.14 versus 0.18) reference point was much less than it was on the *MSY* quantities ($F_{current}/F_{MSY}$ equal to 1.95 versus 1.27; and SB_{latest}/SB_{MSY} equal to 0.62 versus 0.96).

Natural mortality (M)

The estimation of natural mortality required the estimation of a further 41 parameters (though they were constrained in various ways) with an improvement to the overall fit of 25 likelihood points. Improved fits to the size composition and tagging data was partially offset by the additional penalties added in the M-estimation process. The level and age-specific pattern of the estimated M in fact compare quite well with the fixed values used in the reference case (Figure 9).

When *M* was estimated the spawning potential of the population was lower in absolute terms and recruitment was generally higher, but aside from a small reduction in *MSY*, the stock status indicators were almost identical.

Tag mixing

Two distinct tag mixing scenarios were examined – the first comparing tag mixing of one quarter instead of two, and the second set the tag mixing for Coral Sea tag releases to 28 quarters to essentially remove the impact of the recaptures from these releases on the overall model fit. The model was quite sensitive to these alternatives.

Tag mixing of one quarter had minimal impact on *MSY*, but did lead to more pessimistic stock status indicators ($F_{current}/F_{MSY}$ equal to 1.73 versus 1.57 for the reference case and $SB_{latest}/SB_{F=0}$ equal to 0.14 versus 0.16). This model had lower biomass levels.

Reducing the impact of the Coral Sea tags also had a minimal impact on MSY, but instead led to more optimistic stock status indicators ($F_{current}/F_{MSY}$ equal to 1.49 versus 1.57 for the reference case and $SB_{latest}/SB_{F=0}$ equal to 0.18 versus 0.16). This model had higher biomass levels.

6.5.3 Structural uncertainty analysis

Comparisons of the impacts of different axes of the structural uncertainty analysis are shown in two ways, first through a series of Kobe plots which show $F_{current}/F_{MSY}$ and SB_{latest}/SB_{MSY} with colour coding for each option within the axes (Figure 42), and second through a series of box and whisker plots (Figure 43 and Figure 44). Finally the probability of exceeding the key reference points across all grid runs, and grid runs using the reference case assumption for steepness are provided in Table 10.

The general patterns for each option within the five axes are the same as described in Section 6.5.2 so we do not repeat them again here. The positive (or negative) impacts of the different options were found to be somewhat additive, e.g., model runs with more options that individually gave better outcomes gave even better outcomes when combined. Considering $F_{current}/F_{MSY}$, the model with the lowest value (1.17) included steepness of 0.95, L2=178cm, and long tag mixing for Coral Sea tag release groups; conversely the model with the highest value (2.25) included steepness of 0.65, L2=190cm, tag mixing of one quarter and *M* was estimated.

6.5.4 Other sensitivity analyses

As noted in Section 6.5.1 above, several changes to MULTIFAN-CL assumptions, particularly relating to recruitment and the SRR curve were made in the current assessment. In order to allow better understanding of the impacts, we ran one-off sensitivity analyses to the reference case model and these are described in Section 10.4. In addition we ran a model in which we attempted to estimate steepness with a uniform prior over the range 0.2-1.

As expected, for those model runs relating to the SRR curve (bias correction, exclusion of early deviates, and estimation of steepness), there was little or no change to the estimated recruitment and spawning potential trajectories. The bias correction and estimation of steepness did have a significant impact on the *MSY*-related quantities. Without bias correction the *MSY* is 16% lower and $F_{current}/F_{MSY}$ was 3% higher. The estimate of steepness hit the upper bound of one, possibly assisted by the exclusion of the early, less certain, but higher recruitments from the estimation of the SRR. This run gave a 10% higher MSY and a 25% lower $F_{current}/F_{MSY}$.

The impact of the non-estimation of the last six quarterly recruitment deviates was somewhat surprising - it lifted the absolute levels of spawner potential and recruitment. We believe the impact was large because the terminal recruitment deviates were just so large and inconsistent with the rest of the time series. For now we view this development as a positive one, but will further examine how this operates in future assessments.

6.6 Overall stock status conclusions

Based on the results from the reference case model provided in Sections 6.4.1, 6.4.2, and 6.4.3 and the consideration of results from other model runs in Section 6.5, we make the following conclusions regarding stock status:

- Current catches exceed *MSY*;
- Recent levels of spawning potential are most likely at (based on 2008-11 average) or below (based on 2012) the level which will support the *MSY*;
- Recent levels of fishing mortality exceed the level that will support the *MSY*;

- Recent levels of spawning potential are most likely at (based on 2008-11 average) or below (based on 2012) the limit reference point of 20%$SB_{F=0}$ agreed by WCPFC; and
- Recent levels of spawning potential are lower than candidate biomass-related target reference points currently under consideration for skipjack tuna, i.e., 40-60% $SB_{F=0}$.

7 DISCUSSION AND CONCLUSIONS

The gap between the 2014 and 2011 assessments is the longest between bigeye assessments in the past ten years, and combined with the implementation of many of the recommendations from the Independent Review of the 2011 bigeye assessment (Ianelli et al., 2012), significant changes and improvements have been made to the 2014 assessment. In Section 7.1 we will comment on some of the most significant changes to the assessment, and some of the similarities. We will also touch briefly on some of the problems encountered or areas of uncertainty, but these will be covered in more detail in Sections 7.2 and 7.3.

7.1 Changes from the 2011 assessment

As a general introduction, previous assessments have featured very strong non-stationary behaviour such as very strong recruitment trends and large mismatches between equilibrium unfished and non-equilibrium unfished biomass. Through improvements to the stock assessment these features are greatly reduced in the current assessment. We believe that is the result of reduced data conflict achieved through better model inputs and structural model assumptions.

First we compare the overall stock status conclusions from the 2011 and 2014 assessments and then there are three general areas of changes to the assessment which we will discuss below: spatial and fisheries structure; data inputs; and structural modelling assumptions.

The 2010 and 2011 assessment concluded that the bigeye stock was overfished with $F_{current}/F_{MSY}$ in the order of 1.41-1.46 and that the stock was at or below the newly adopted limit reference point. These assessments were also characterised by strongly increasing recruitment trajectories over time and a large mismatch between *MSY* and recent catches. In general the conclusions from the 2014 stock assessment are consistent with those from previous assessments – especially with respect to the limit reference point. $F_{current}/F_{MSY}$ is estimated to be slightly higher in the 2014 assessment, but aside from 2010, total removals have been relatively constant over the past 7-8 years. Therefore an increase in $F_{current}/F_{MSY}$ is not surprising. What is encouraging is that the recruitment trajectory is far more normal and the difference between the estimated *MSY* and recent catches is much less.

The biggest change to the 2014 assessment was the subdivision of model regions to bring the assessment to a nine region model with 33 fisheries. This was done to achieve several recommendations of the bigeye review and other data conflicts that had been observed in the 2011 assessment. Given the uncertainty and often significant revisions that occur with catch statistics from Indonesia, the Philippines, and likely Vietnam in the future, separation of this area should help compartmentalise the impact of these changes on the estimated dynamics in other regions. This also allowed us to better model the offshore longline fleets which showed very strong east-west trends in fish sizes that had been identified as extremely influential (and problematic) in previous assessments (Harley et al., 2010; Davies et al., 2011).

The separation of the region that generally encompasses the Bismark and Solomon Seas and adjacent areas was not necessarily done for the benefit of the bigeye assessment. Rather, it was done partly in response to the analysis of Hoyle et al. (2013), which found that skipjack tagged in this area appeared to mix less than fish tagged in the wider region 3 area, and partly because some of the purse seine fleets fishing here have different fishing power to other region 3 fleets, complicating the analysis of management options.

The final change was the introduction of a specific region to cover the area within the Coral Sea where feeding aggregations of bigeye and, to a lesser extent, yellowfin were tagged and recaptured over a long period of time (Evans et al., 2008). This change, in combination with other model improvements, resulted in a greatly improved fit to these tagging data.

Considerable improvements were made to the size and CPUE inputs in response to the independent review. The use of all operational available data lead to a much improved CPUE series for region 6 (see the black line in Figure 12 of Davies et al., 2011). New indices were also derived for areas 3-8. The use of operational data and clustering methods allowed us to better account for changes in targeting than was ever possible with aggregate data, and the use of data from multiple fleets allowed better spatial and temporal coverage to overcome the concern of declining effort from the Japanese fleet. Notwithstanding these improvements, we were not able to create new indices for region 1 and 2 and the index for region 4 was ultimately not used in the reference case. We will discuss this further in the sections below.

Both the longline and purse seine size data were subject to considerable improvements, and the principle of using either the length or weight data – not both, and the additional regional stratification likely reduced the conflict in these data that had been evident in previous assessments. As a result, the sensitivity analysis with the size data down weighted had much less impact on the stock assessment outcomes than previously. There were some examples of lack of fit to size data, such as the poor fit to size data from the purse seine fisheries, which we will discuss in the following sections.

Following the detailed evaluation of the tagging data and modelling requirements by Hoyle et al. (2013), considerable effort was directed at all aspects of the tagging data from the initial data selection criteria to the reporting rate priors. This work will need to continue, particularly for bigeye tuna, as the Central Pacific tagging activities continue and plans are made towards a Pacific-wide stock assessment.

Four major structural modelling changes were made with respect to recruitment and the SRR in the current assessment, though only two reflect recommendations from the independent review and the other two relate to issues that became apparent during the assessment. The application of the lognormal bias correction to the estimate of the SRR led to an increase in *MSY* and a slight decrease in $F_{current}/F_{MSY}$, but because it also increases the estimate of SB_0, stock status in relation to SB_{MSY} is worse. We also reduced the weight on fitting the SRR as recommended by the reviewers, and this is why the estimated recruitment and spawning potential trends do not differ across the assumed values of steepness. The estimation of very large terminal recruitment deviates in early model runs, with no single obvious data driving them, combined with the results of the retrospective analyses led to us not estimating recruitment deviates for the last six quarters. Not estimating recruitment deviates when data are deficient, such as with terminal recruitment deviates, is a practice sometimes used in New Zealand stock assessments (N. Davies pers. comm.). We consider this a good general development as it will reduce the impact that such poorly estimated recruitments have on projections – we already exclude fishing mortality estimates during the final year from the *MSY* calculations. We note that in the 2011 assessment, the retrospective analyses showed clearly that the extremely low recruitment estimated for the final year was revised upwards with additional years data.

7.2 Sources of uncertainty

In this section we comment on some of the difficulties encountered in the assessment or issues that arose in the modelling which led to potential uncertainty. This will include discussion of some of the factors that were included in the uncertainty framework used in the assessment, i.e., sensitivity analyses and the structural uncertainty analysis (grid).

Due to delays in the finalization of data from the most recent year, the three tropical tuna assessments used data up until 2012 instead of 2013 as would normally be the practice.

For such short lived species such as tunas, this can lead to a mismatch between information on stock status from the assessment, management actions, and the actual stock status on the water. This year the 2013 data were only 'finalized' at the end of the first week of July and is expected to be subject to revision after SC10 (P. Williams pers. comm.). Purse seine catch estimates, which depend on observer data, are also impacted by incomplete data and subject to revision. It is important to note that the longline data used for the final year of the 2011 assessments were subsequently revised considerably, but the assessments, with incorrect data, had to be used for evaluation of management options.

In the Section below we will make a recommendation regarding the importance of some of the 'electronic' or E-reporting initiatives currently underway in the region, but here we talk about how we have used the results from retrospective analyses to come up with a better reference point for spawning potential depletion. Previous assessments typically used the estimate of spawning potential for the 'current' period which excludes the most recent year, and takes the average of the four years before that, e.g., in this assessment current is 2008-11. While this approach might be suitable for fishing mortality, especially where it can change from year to year with the mix of FAD and free school sets, it is not as sensible for spawning potential depletion, which retrospective analyses demonstrate is generally well estimated in the final year of the assessment. For bigeye tuna, recent recruitments do not contribute to spawning potential in the terminal year so we define SB_{latest} as the final year of the model (i.e., 2012). For skipjack tuna, the low age and maturity means that spawning potential the final year of the model is less well estimated so the penultimate year should be used (i.e., 2011). Therefore, we recommend that conclusions on stock status be based on this $F_{current}/F_{MSY}$ and $SB_{latest}/SB_{F=0}$.

While we believe that many of the data conflicts have been reduced in the current assessment, the use of likelihood profiling uncovered the presence of local minima in what is likely a complex solution surface. While it was reassuring that these different parts of the parameter space (with different growth and movement patterns) gave very similar stock status outcomes (e.g., see similarities between the penultimate stepwise run in Table 10.3 2 and the three L2 model runs in Table 7), it did highlight uncertainty in growth, regional recruitment distributions, and movement. It might not be necessary to solve each of these, but better information on one or two will allow better estimation of them all. We provide some recommendations in the following section.

While purse seine CPUE data have not been given much weight in bigeye assessments, i.e., we allow a random walk in purse seine catchability, recent changes in reporting have the potential to impact estimates of catchability and the evaluation of management options. Further, such changes in reporting are a hindrance to the potential increased use of purse seine CPUE as was done in the 2014 yellowfin and skipjack assessments (Davies et al. 2014; Rice et al. 2014; Pilling et al. 2014b).

One notable 'lack of fit' in the 2014 and preceding assessments, has been small fish from the purse seine fishery. This was the focus of considerable investigation in the current assessment with over 50 combinations of selectivity options considered over a period of three weeks. We examined age and length-based selectivity, increasing the number of nodes on those fisheries that used splines, and even examined estimating selectivity-at-age as free parameters. While many of these developments greatly improved the fit to these data, they were all associated with implausible growth estimates, in particular the estimate of L2 would often approach the upper bound of 200 cm and the estimated variation in length at age (the spread around the growth curve – see Figure 20) would go to the lower band. This requires further investigation, in conjunction with efforts to improve growth estimates, and is included as a recommendation for further work.

Longline CPUE data remain one of the most important drivers of the bigeye stock assessment and while considerable progress has been made in the 2014 assessment, the impact of the all-flags CPUE for region 4 serves as a reminder of the importance of continued work. For regions 3, 5, 7, and 8, we were able to address the two key CPUE recommendations of the independent review through the use of all the operational data available to SPC. We express our appreciation to Chinese Taipei for the collaboration that allowed the integration of their data into our all-flags analyses for regions 4 and 6. The demonstrated importance of combining data across fleets emphasises the need for a collaborative approach in the future and we provide some specific recommendations below.

The current assessment had the greatest update of tagging data in many years and the limited sensitivity analyses demonstrated that key model outputs are sensitive to tagging data assumptions such as the assumed mixing period. At the same time these data allowed the estimation of natural mortality and providing 'absolute abundance' scaling information to go with the 'relative abundance' information provided by longline CPUE.

Finally, one area of reduced uncertainty in the current assessment has been impact of steepness on the spawning potential reference point. The previously used reference point of SB/SB_{MSY} was extremely sensitive to the assumed value of steepness, but the new limit reference point $20\%SB_{F=0}$, is far less sensitive to this (Table 7). There is however a new issue to be addressed, which is how to present stock status information in the light of the newly adopted limit reference point. The terms "overfished" and "overfishing" are also open to reconsideration, as is the Kobe plot. We see this as an important task for the SC in determining how best to communicate stock assessment results to the Commission. This issue was first raised at MOW2 in the paper also submitted to SC10 (McDonald 2014) and we attempt to further stimulate discussion on this issue with our new figure provided as Figure 38.

7.3 Recommendations for further work

As discussed in the sections above, there are areas of uncertainty in the current assessment, and many of these can be addressed by further work. This section outlines some recommendations, some directed at those undertaking future assessments, and some at the SC and WCPFC itself.

WCPFC-specific recommendations

- WCPFC continue the evaluation of E-reporting initiatives for both logbook and observer data and implement these with urgency where it is found to be practical and cost-effective. This will allow stock assessments to be undertaken with up to date data;
- WCPFC should consider the potential impacts of changes in purse seine effort reporting by some fleets on: stock assessments, evaluation of management measures, and the ability of management measures to achieve their desired outcomes.
- WCPFC should consider the demonstrated importance of combining operational longline logsheet data across fleets to improve key stock assessment inputs and determine how operational data for key fleets, currently not available for such analyses, can be included in the future.

Biological studies

- Conduct direct ageing of available collections of bigeye tuna otoliths, and those of other tropical tunas if possible, so that these data can be included in the stock assessments. Examine regional patterns in growth where samples are sufficient.
- Apply the approach of Aires-da-Silva et al. (2014) to available tag-recapture and direct ageing data for bigeye in the WCPO and potentially integrate this into MULTIFAN-CL.
- Continued tagging across the range of the stock (associated with tag seeding work where necessary) to support the ability of tagging data to improve estimates of growth, natural mortality, movement, and fishing mortality. Analyses of these data to inform mixing periods and spatial structure should continue.

MULTIFAN-CL/Modelling

- Examine the potential for orthogonal recruitment structure to reduce the number of recruitment parameters estimated to simplify the objective function solution surface.
- Further investigate selectivity functional forms, including length-based selectivity for purse seine and other small-fish fisheries. Careful examination will be required of impacts on growth estimates and this work may not be possible until improved data are available for growth estimation.
- Likelihood profiling on the population scaling parameter and other important model quantities, e.g., L2, should be routine in all assessments (Lee et al. 2014).
- Future assessments should consider a wider range of uncertainty around the tagging data including reporting rates, data weighting, and mixing periods.

Longline CPUE

- Continue the analysis of operational data – combining fleets to maximize spatial and temporal coverage and clustering and other methods to account for changes in targeting over time.
- Develop an operating model that can include changes in the distribution in fishing effort and targeting shifts and examine the ability of current approaches to successfully address these issues.
- Review the recommendations of Hoyle et al. (2014a; 2014b) in the future development and presentation of CPUE analysis.

Longline size data

- Further examination of the size frequency samples from the 'mixed-fleet' longline fisheries to see if it is also possible to introduce spatially-based catch weighting in addition to flag-based catch weighting.

Reference points

- SC should consider the best way to summarise and present information on stock status in the light of the adoption of a limit reference point and steps towards target reference points and eventually harvest control rules. This will involve a dialogue with the Commission.

7.4 Main assessment conclusions

The main conclusions of the 2014 assessment are as follows.

1. The new regional structure and modelling and data improvements appear to have improved the current assessment with the previously observed increasing trend in recruitment much reduced and fit to Coral Sea tagging data greatly improved.
2. Nevertheless there is some confounding between estimated growth, regional recruitment distributions, and movement which, while having minimal impact of stock status conclusions, lead to a complex solution surface and the presence of local minima.
3. Current catches exceed *MSY*;
4. Recent levels of spawning potential are most likely at (based on 2008-11 average) or below (based on 2012) the level which will support the *MSY*;
5. Recent levels of fishing mortality exceed the level that will support the *MSY*;
6. Recent levels of spawning potential are most likely at (based on 2008-11 average) or below (based on 2012) the limit reference point of 20%$SB_{F=0}$ agreed by WCPFC; and
7. Recent levels of spawning potential are lower than candidate biomass-related target reference points currently under consideration for skipjack tuna, i.e., 40-60% $SB_{F=0}$.
8. These conclusions are similar to those obtained in 2010 and 2011 assessments.

9. Stock status conclusions are sensitive to alternative assumptions regarding the modelling of tagging data, and the longline CPUE series included, identifying tagging and longline CPUE analyses as important areas for continued research.

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Table 1. Definition of fisheries for the nine-region MULTIFAN-CL analysis of WCPO bigeye tuna.

Fishery	Nationality	Gear	Region
1. L ALL 1	All	Longline	1
2. L ALL 2	All, except US	Longline	2
3. L US 2	United States	Longline	2
4. L All 3	All, except CT-Offshore, CN, FSM, MH, PH, ID, and PW	Longline	3
5. L OS-E 3	Eastern LL region 3: CT-Offshore, CN, FSM, MH, PH, PW, and ID	Longline	3
6. L OS-W 7	Western LL region 7: CT-Offshore, CN, FSM, MH, PH, PW, VN, and ID	Longline	7
7. L All 7	All, except CT-Offshore, CN, FSM, MH, PH, ID, and PW	Longline	7
8. L All 8	All	Longline	8
9. L All 4	All, except US	Longline	4
10. L US 4	United States	Longline	4
11. L AU 5	Australia	Longline	5
12. L All 5	All excl. Australia	Longline	5
13. L All 6	All	Longline	6
14. S-ASS All 3	All, except ID and PH dom	Purse seine, log/FAD sets	3
15. S-UNS All 3	All, except ID and PH dom	Purse seine, school sets	3
16. S-ASS All 4	All	Purse seine, log/FAD sets	4
17. S-UNS All 4	All	Purse seine, school sets	4
18. Misc PH 7	Philippines	Miscellaneous (small fish), including purse seine within PH archipelagic waters.	7
19. HL ID-PH 7	Philippines, Indonesia	Handline (large fish)	7
20. S JP 1	Japan	Purse seine, all sets	1
21. P JP 1	Japan	Pole-and-line	1
22. P All 3	All, except Indonesia	Pole-and-line	3
23. P All 8	All	Pole-and-line	8
24. Misc ID 7	Indonesia	Miscellaneous (small fish), including purse seine within ID archipelagic waters.	7
25. S PHID 7	Philippines and Indonesia	Offshore purse seine in waters east of about 125°E (and outside of PH and ID archipelagic waters).	7
26. S-ASS All 8	All	Purse seine, log/FAD sets	8
27. S-UNS All 8	All	Purse seine, school sets	8
28. L AU 9	Australia	Longline	9
29. P All 7	All	Pole-and-line	7
30. L All 9	All	Longline	9
31. S-ASS All 7	All, except ID and PH dom	Purse seine, log/FAD sets	7
32. S-UNS All 7	All, except ID and PH dom	Purse seine, school sets	7
33. Misc VN 7	VN	Miscellaneous including purse seine and gillnet within VN waters	7

Table 2. Number of tagged fish released and recaptured by program, release group, region, and time period input to the assessment.

Prog	Coral Sea			PTTP			RTTP		
Years	1991-2001			2006-2012			1989-1992		
Region	Groups	Releases	Recaptures	Groups	Releases	Recaptures	Groups	Releases	Recaptures
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	1238.45	354	5	292.89	65
4	0	0	0	6	4534.11	2056	3	907.98	107
5	0	0	0	1	28.66	7	1	131.84	4
6	0	0	0	0	0	0	0	0	0
7	1	277.11	102	3	384.2	116	4	940.96	268
8	0	0	0	12	1742.16	755	5	530.66	48
9	5	4235.54	337	0	0	0	0	0	0
Total	6	4512.65	439	32	7927.58	3288	18	2804.33	492

Table 3: Summary of the major changes from the 2011 reference case to the 2014 reference case.

Component	**2011 assessment (Run3j – Ref.case)**	**2014 assessment (037_L0W0T0M0H0)**
Regional structure	Six regions	Nine regions with two new regions added to the western equatorial region and one to the south western region.
Fishery structure	26 fisheries	33 fisheries and the first inclusion of some Japanese and Vietnamese coastal fishery catches
Longline CPUE	Operational indices based on Japanese logsheet data.	Operational CPUE indices based on either Japanese logsheet data, or all operational data (combined flags) available to SPC.
Longline size data	All available data. Japanese data spatially weighted by CPUE	Either weight or length used for fisheries depending on quality and coverage. Japan data and all fleets data for some fisheries weighted spatially by catch.
Purse seine size data	Selectivity bias corrected observer samples	Selectivity bias-corrected observer samples plus Pago Pago port sampling data. All weighted by set catch.
Recruitment and spawner recruitment relationship	All deviates estimated and moderate constraint on fitting the SRR curve	Terminal six recruitment deviates not estimated and these and the first 40 recruitment deviates (first 10 years) not included in the estimation of the SRR. Lognormal bias correction applied to the SRR and low penalty on fitting the SRR.
Growth	Estimated	Length at the maximum age (L2) fixed at 184 cm.

Table 4: Summary of the groupings of fisheries within the assessment for selectivity curve, catchability (used for the implementation of regional weights), tag recaptures (typically for purse seine fisheries within a region), and tag reporting rates. Note for the last, for some fishery groups different reporting rates were estimated for different tag release programmes. See Table 1 for further details on each fishery.

Fishery	Region	Selectivity	Catchability	Tag recaptures	Tag reporting
1. L ALL 1	1	1	1	1	1
2. L ALL 2	2	1	1	2	1
3. L US 2	2	2	2	3	2
4. L All 3	3	3	1	4	1
5. L OS-E 3	3	4	3	5	1
6. L OS-W 7	7	5	4	6	1
7. L All 7	7	6	1	7	1
8. L All 8	8	7	1	8	1
9. L All 4	4	3	1	9	1
10. L US 4	4	2	5	10	2
11. L AU 5	5	8	6	11	3
12. L All 5	5	3	1	12	4
13. L All 6	6	3	1	13	1
14. S-ASS All 3	3	9	7	14	5
15. S-UNS All 3	3	11	8	14	5
16. S-ASS All 4	4	10	9	15	6
17. S-UNS All 4	4	15	10	15	6
18. Misc PH 7	7	12	11	16	7
19. HL ID-PH 7	7	13	12	17	8
20. S JP 1	1	14	13	18	9
21. P JP 1	1	14	14	19	10
22. P All 3	3	14	15	20	11
23. P All 8	8	14	16	20	12
24. Misc ID 7	7	12	17	21	13
25. S PHID 7	7	9	18	22	14
26. S-ASS All 8	8	9	19	23	15
27. S-UNS All 8	8	11	20	23	15
28. L AU 9	9	8	21	24	16
29. P All 7	7	12	22	25	17
30. L All 9	9	3	1	26	18
31. S-ASS All 7	7	9	23	27	5
32. S-UNS All 7	7	11	24	27	5
33. Misc VN 7	7	12	25	28	19

Table 5: Summary of the reference case model and one-off sensitivities to the reference case, which were also included in the grid.

Run	Name	Description
037_L0W0T0M0H0	Ref.Case	JP CPUE for regions 1,2, and 4, all flags for regions 3, 7, 8, 5, and 6, and nominal for region 9. Size data weighted as nsample/20, steepness fixed at 0.8, M fixed, and the mean length of fish in the oldest age class (L2) fixed at 184 cm.
001_L1W0T0M0H0	L2_178	the mean length of fish in the oldest age class (L2) fixed at 178 cm
073_L2W0T0M0H0	L2_190	the mean length of fish in the oldest age class (L2) fixed at 190 cm
038_L0W0T0M0H1	h_0.65	Steepness=0.65.
039_L0W0T0M0H2	h_0.95	Steepness=0.95.
043_L0W0T1M0H0	Mix_1	Tag mixing period=1 quarter
049_L0W0T2M0H0	Mix_CS	Mixing period for Coral Sea releases increased to 28 quarters
055_L0W1T0M0H0	SZ_dw	Down weight the relative influence of the size data - nsample/50.
040_L0W0T0M1H0	M_est	Estimate age-specific natural mortality schedule.

Table 6: Description of symbols used in the yield analysis. For the purpose of this assessment, 'current' is the average over the period 2008-2011 and 'latest' is 2012.

Symbol	Description
C_{latest}	Catch in the latest year
$F_{current}$	Average fishing mortality-at-age[3] for a recent period
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (*MSY*[4])
MSY	Equilibrium yield at F_{MSY}
C_{latest}/MSY	Catch in the most recent year relative to *MSY*
$F_{current}/F_{MSY}$	Average fishing mortality-at-age for a recent period relative to F_{MSY}
B_0	Equilibrium unexploited total biomass
$B_{current}$	Average annual total biomass over a recent period
SB_0	Equilibrium unexploited spawning potential.
SB_{latest}	Spawning potential in the latest time period
$SB_{F=0}$	Average spawning potential predicted to occur in the absence of fishing for the period 2002-11
SB_{MSY}	Spawning potential that which will produce the maximum sustainable yield (*MSY)*
$SB_{latest}/SB_{F=0}$	Spawning potential in the latest time period relative to the average spawning potential predicted to occur in the absence of fishing for the period 2002-11
SB_{latest}/SB_{MSY}	Spawning potential in the latest time period relative to that which will produce the maximum sustainable yield (*MSY)*

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[3] This age-specific pattern is dependent on both the amount of fishing and the mix of fishing gears, e.g. relative catches of small and large fish

[4] MSY and other MSY-related quantities are linked to a particular fishing pattern and the MSY will change, for example, based on changes in the relative catches of small and large fish

Table 7: Estimates of management quantities for the reference case, one change sensitivity runs and the quantiles from the structural uncertainty analysis (grid). 'Current' is the average over the period 2008-2011 and 'latest' is 2012.

	Ref.case	L2=178cm	L2=190cm	h=0.65	h=0.95	M_est	Mix_1qtr
MSY(mt)	108,520	109,200	107,120	101,880	116,240	107,400	107,880
C_{latest}/MSY	1.45	1.45	1.47	1.55	1.36	1.47	1.45
$F_{current}/F_{MSY}$	1.57	1.53	1.63	1.95	1.27	1.57	1.73
B_0	2,286,000	2,259,000	2,244,000	2,497,000	2,166,000	2,049,000	2,183,000
$B_{current}$	742,967	754,713	700,360	744,596	741,549	673,199	640,645
SB_0	1,207,000	1,180,000	1,209,000	1,318,000	1,143,000	1,056,000	1,153,000
SB_{MSY}	345,400	338,300	346,600	429,900	275,200	294,400	328,700
$SB_{F=0}$	1,613,855	1,553,489	1,654,017	1,848,385	1,483,216	1,415,672	1,585,331
SB_{curr}	325,063	331,447	305,803	326,007	324,283	279,409	269,820
SB_{latest}	265,599	267,649	255,775	266,290	264,937	224,371	218,679
$SB_{curr}/SB_{F=0}$	0.20	0.21	0.18	0.18	0.22	0.20	0.17
$SB_{latest}/SB_{F=0}$	0.16	0.17	0.15	0.14	0.18	0.16	0.14
SB_{curr}/SB_{MSY}	0.94	0.98	0.88	0.76	1.18	0.95	0.82
SB_{latest}/SB_{MSY}	0.77	0.79	0.74	0.62	0.96	0.76	0.67

Table 7 cont.

	Ref.case	Mix_CS	SZ_dw	Grid median	Grid 5%ile	Grid 95%ile
MSY(mt)	108,520	109,480	107,960	107,580	100,988	116,812
C_{latest}/MSY	1.45	1.44	1.47	1.47	1.35	1.57
$F_{current}/F_{MSY}$	1.57	1.49	1.57	1.61	1.22	2.14
B_0	2,286,000	2,362,000	2,245,000	2,239,500	1,919,500	2,543,350
$B_{current}$	742,967	808,387	733,109	696,811	571,589	808,916
SB_0	1,207,000	1,247,000	1,188,000	1,184,000	1,014,150	1,364,200
SB_{MSY}	345,400	357,000	341,200	338,250	231,240	444,490
$SB_{F=0}$	1,613,855	1,640,146	1,603,120	1,594,624	1,349,538	1,943,070
SB_{curr}	325,063	361,150	320,676	302,264	236,614	366,379
SB_{latest}	265,599	295,780	265,627	246,063	194,090	296,027
$SB_{curr}/SB_{F=0}$	0.20	0.22	0.20	0.19	0.14	0.23
$SB_{latest}/SB_{F=0}$	0.16	0.18	0.17	0.15	0.12	0.19
SB_{curr}/SB_{MSY}	0.94	1.01	0.94	0.90	0.64	1.25
SB_{latest}/SB_{MSY}	0.77	0.83	0.78	0.75	0.53	1.01

Table 8. Objective function components for the reference case and one-change sensitivity runs.

Run	npars	Total	Catch	Length freq.	Weight freq	Tag	Penalties
Ref.Case	8467	-1081859.73	15.78	-174013.96	-914922.94	3913.44	3138.59
L2_178	8467	-1081841.48	15.72	-174012.47	-914903.86	3895.74	3153.58
L2_190	8467	-1081928.78	15.89	-174076.19	-914940.57	3923.28	3139.87
h_65	8467	-1081859.38	15.78	-174014.11	-914922.81	3913.1	3138.91
h_95	8467	-1081860.04	15.78	-174013.94	-914922.84	3913.02	3138.83
M_est	8508	-1081884.84	15.81	-174025.28	-914938.58	3896.48	3157.55
Mix_1	8467	-1081478.78	18.22	-174025.05	-914900.06	4250.99	3167.75
Mix_CS	8467	-1082164.84	15.65	-174015.61	-914936.49	3635.79	3122.75
SZ_dw	8467	-909244.42	14.74	-136994.85	-778977.70	3750.99	2953.11

Table 9: Comparison of historical estimates of $F_{current}/F_{MSY}$ for each year from 2001-2011 and the average for the period 2001-04 for the reference case and one-off sensitivity model runs described in Table 5. For this analysis we estimated the MSY quantities based on the fishing mortality at age profile for that year.

	$F_{current}/F_{MSY}$											
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2001-04
2011	1.28	1.51	1.11	1.65	1.43	1.64	1.33	1.42	1.46			1.39
Ref.Case	1.24	1.36	1.26	1.56	1.34	1.51	1.28	1.67	1.67	1.33	1.61	1.36
L2_178	1.19	1.30	1.22	1.50	1.31	1.45	1.24	1.61	1.62	1.30	1.56	1.30
L2_190	1.30	1.46	1.35	1.63	1.40	1.59	1.35	1.72	1.72	1.38	1.68	1.44
h_65	1.52	1.69	1.54	1.94	1.66	1.87	1.59	2.06	2.08	1.65	2.01	1.67
h_95	1.01	1.10	1.04	1.26	1.09	1.23	1.03	1.36	1.36	1.07	1.28	1.10
M_est	1.20	1.36	1.23	1.54	1.32	1.49	1.27	1.62	1.65	1.34	1.65	1.33
Mix_1	1.34	1.50	1.34	1.75	1.47	1.67	1.42	1.82	1.85	1.48	1.74	1.48
Mix_CS	1.16	1.28	1.19	1.47	1.27	1.43	1.21	1.59	1.59	1.26	1.52	1.27
SZ_dw	1.24	1.42	1.30	1.59	1.37	1.52	1.28	1.65	1.66	1.37	1.58	1.39

Table 10. Probability that terminal spawning potential is lower than $\mathbf{0.2SB_{F=0}}$ and fishing mortality exceeds F_{MSY} based on all model runs undertaken for the structural uncertainty analysis (All grid), and for those grid runs with steepness fixed equal to 0.8.

	Structural uncertainty	
	All grid	h=0.8
$p(SB_{latest} < 0.2SB_{F=0})$	98%	100%
$p(F\_current/F\_MSY > 1)$	100%	100%

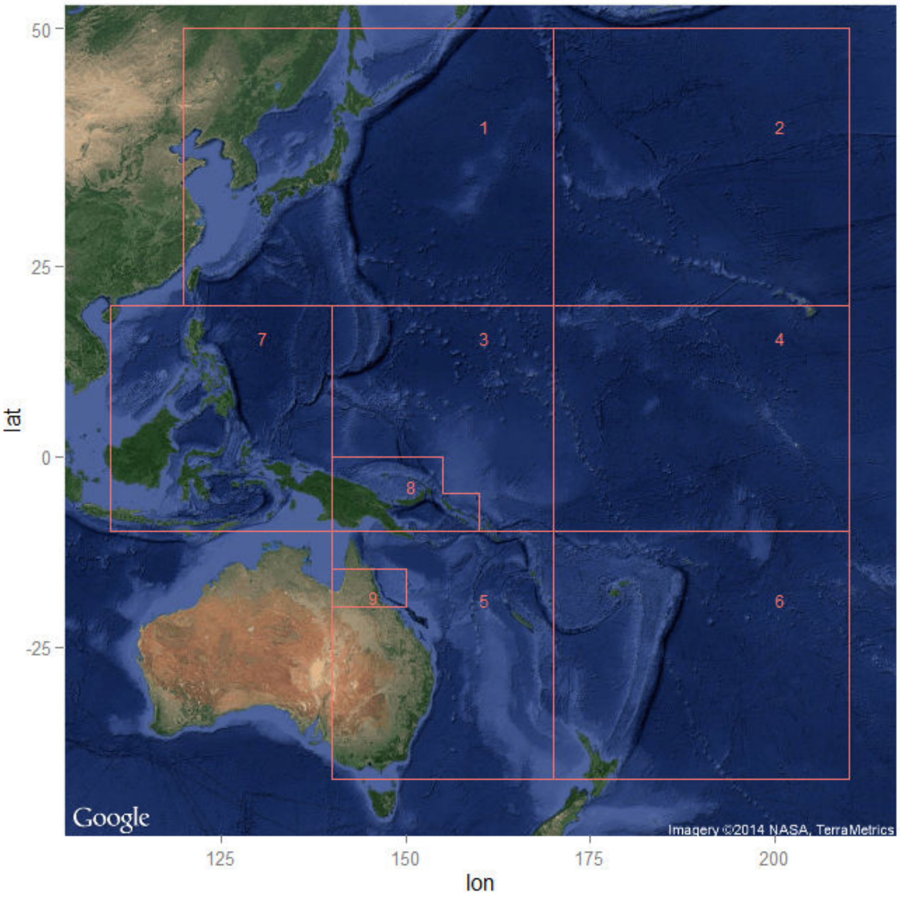


Figure 1. Regional structure of the reference case model.

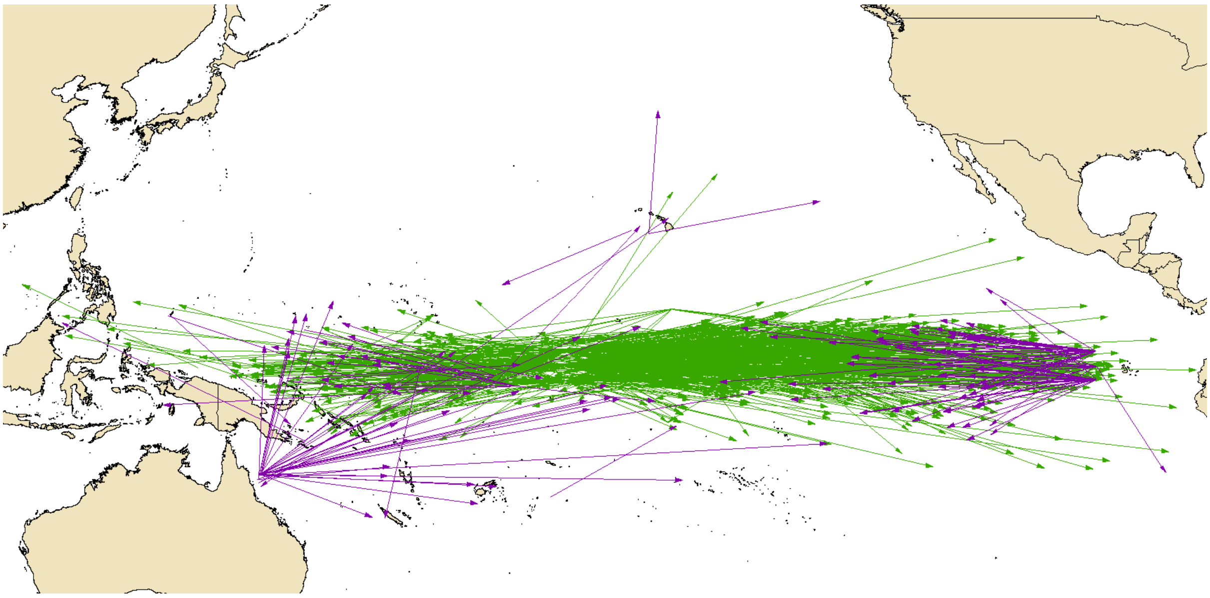


Figure 2. Long-distance (>1,000 nmi) displacements of tagged bigeye in the Pacific Ocean from data available to SPC. The green arrows are data from the Pacific Tuna Tagging Programme (2008 – current). The purple arrows are from earlier SPC tagging in the western Pacific (Regional Tuna Tagging Project, 1989-1992), the IATTC in the eastern Pacific and the University of Hawaii in the North Pacific around Hawaii.

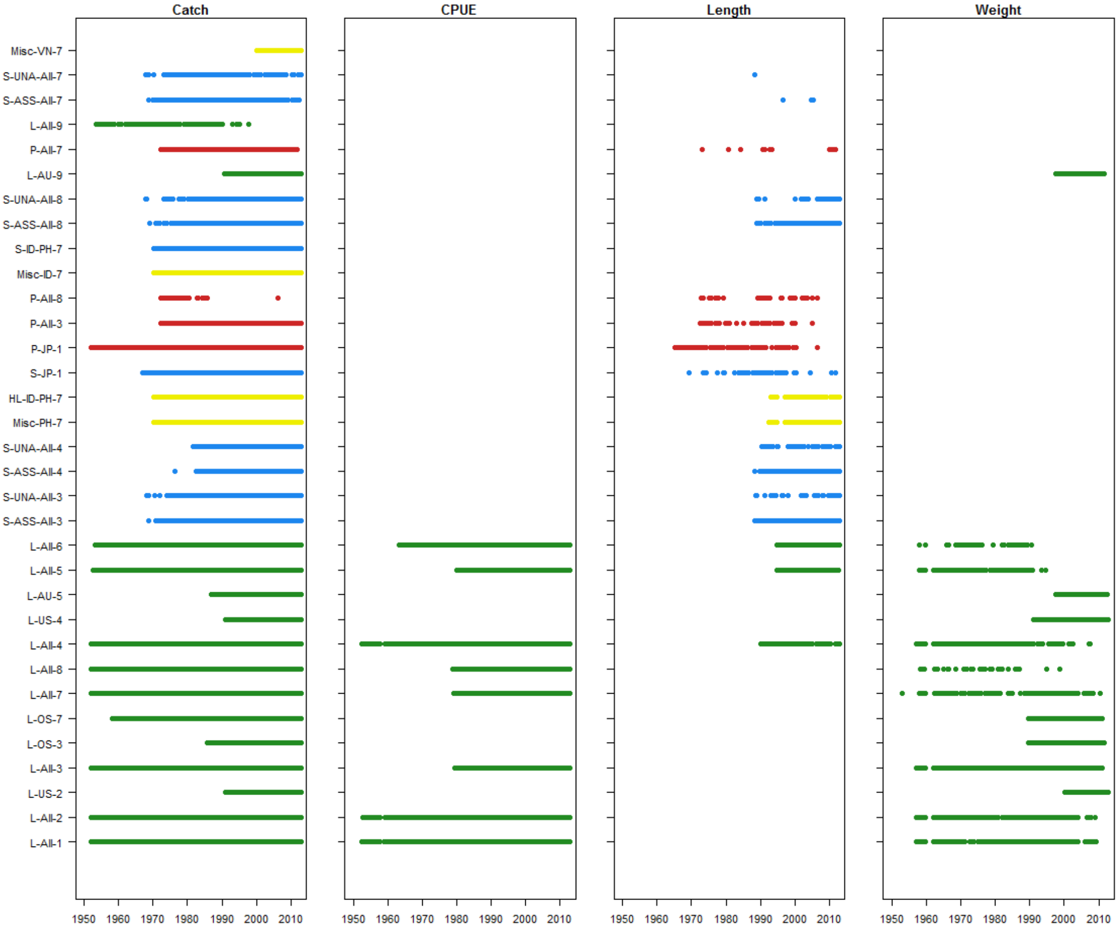


Figure 3. Presence of catch, standardised CPUE, and length and weight frequency data by year and fishery for the reference case model. The different colours refer to purse seine (blue), pole-and-line (red), longline (green) and other gears (yellow).

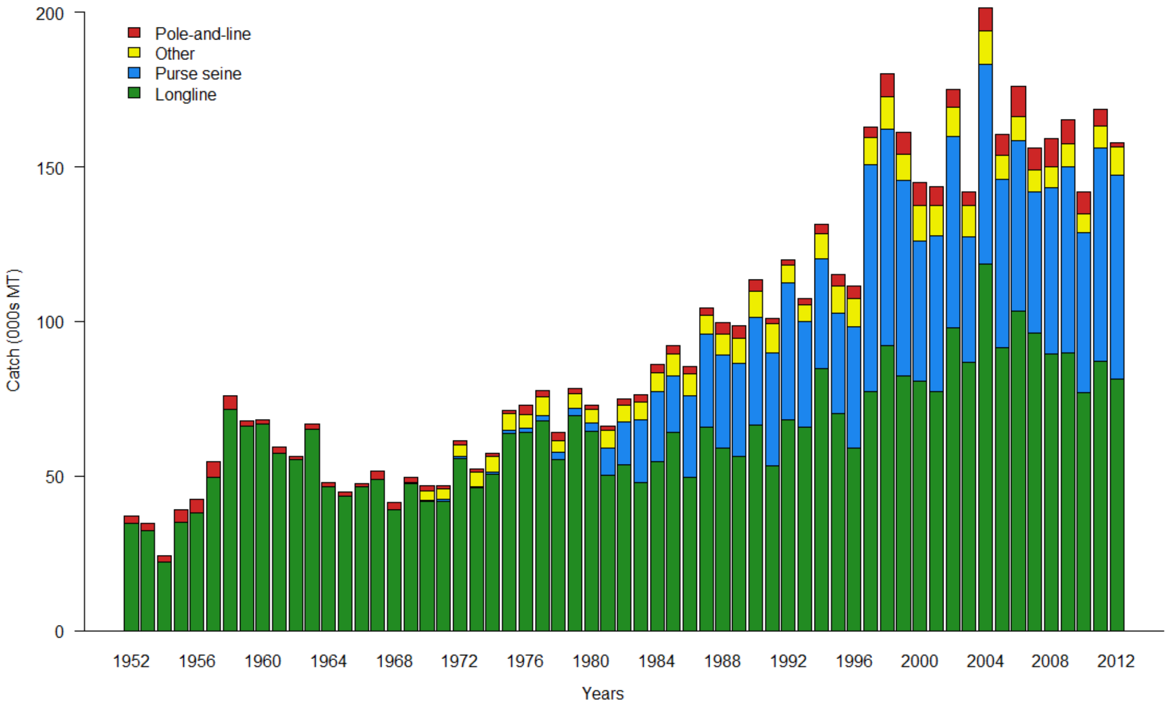


Figure 4. Total annual catch (1000s mt) by fishing gear from the reference case model.

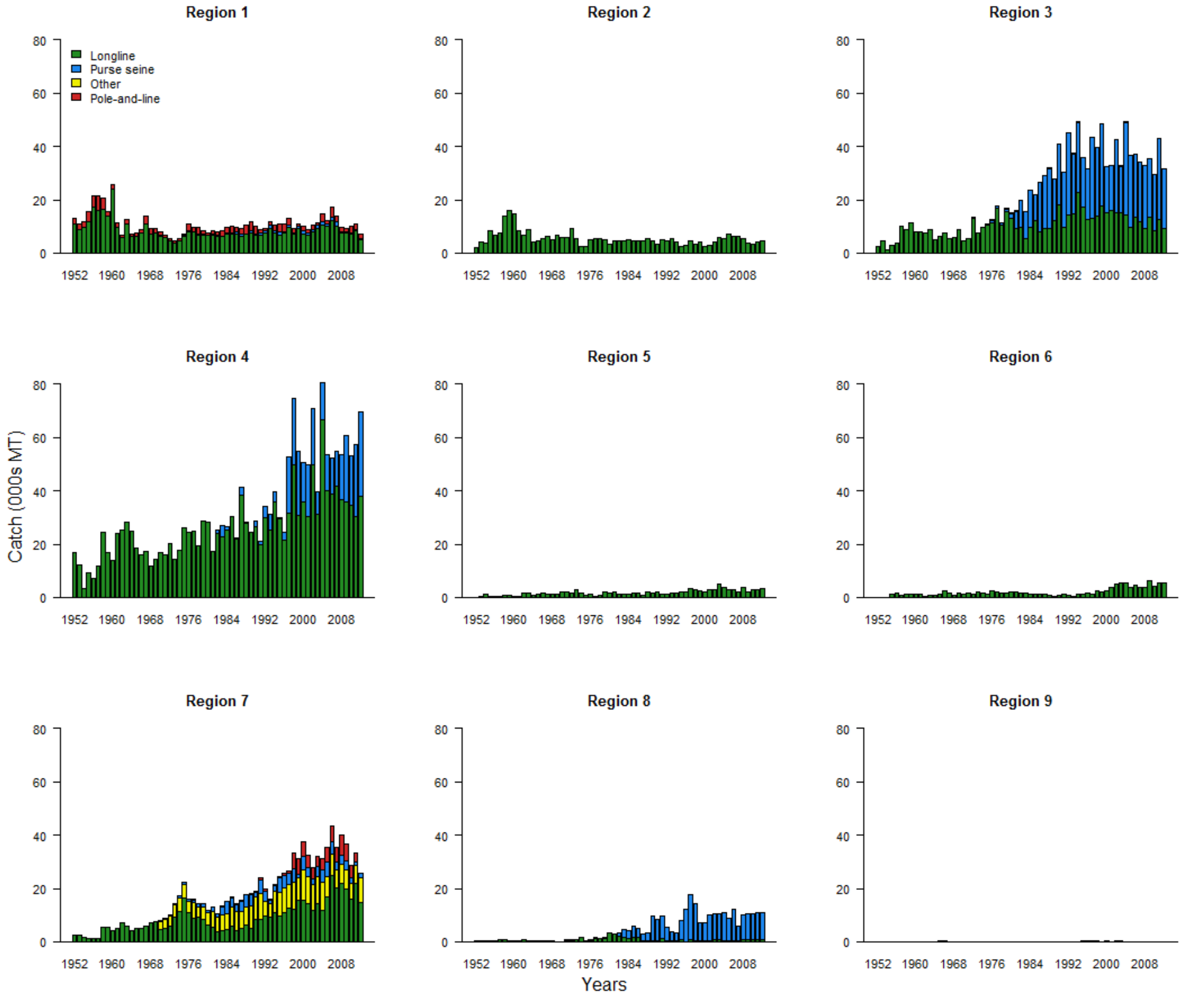


Figure 5. Total annual catch (1000s mt) by fishing method and assessment region from the reference case model.

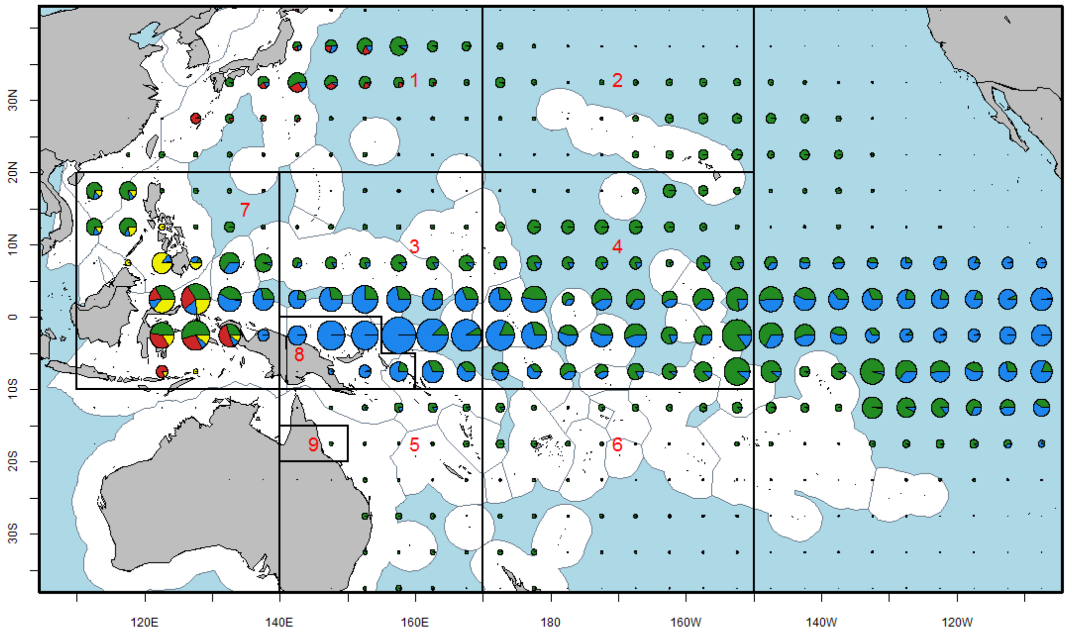


Figure 6. Catch distribution (2003-2012) by 5 degree squares of latitude and longitude and fishing method: longline (blue), purse-seine (green), pole-and-line (red), and other (yellow). Overlayed are the regions for the assessment model.

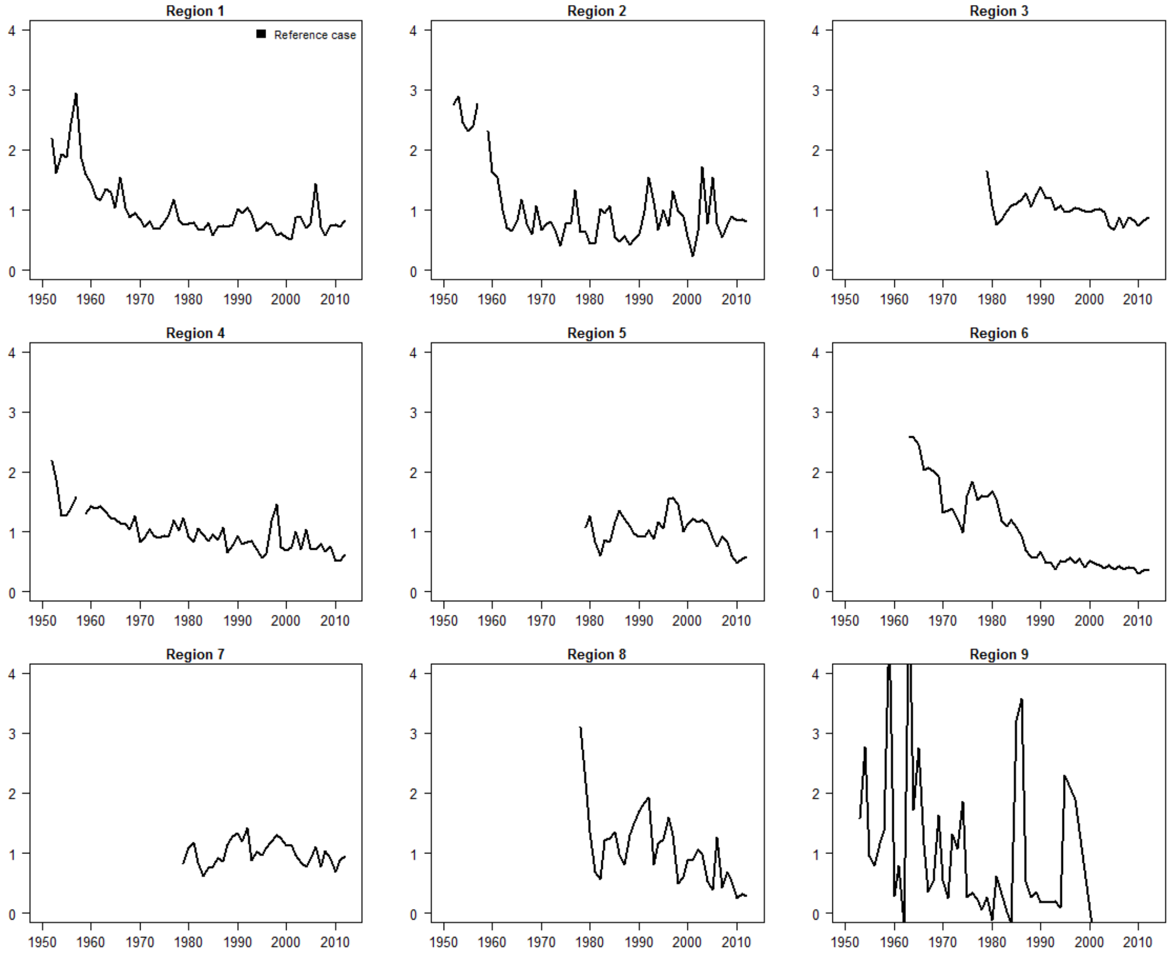


Figure 7. GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (L ALL 1–9) from the reference case model. Indices are scaled by the respective region scalars. See McKechnie (2014b) and McKechnie et al. (2014a) for further details of the CPUE and region scalars. Note: region 9 CPUE is based on nominal rather than standardised CPUE.

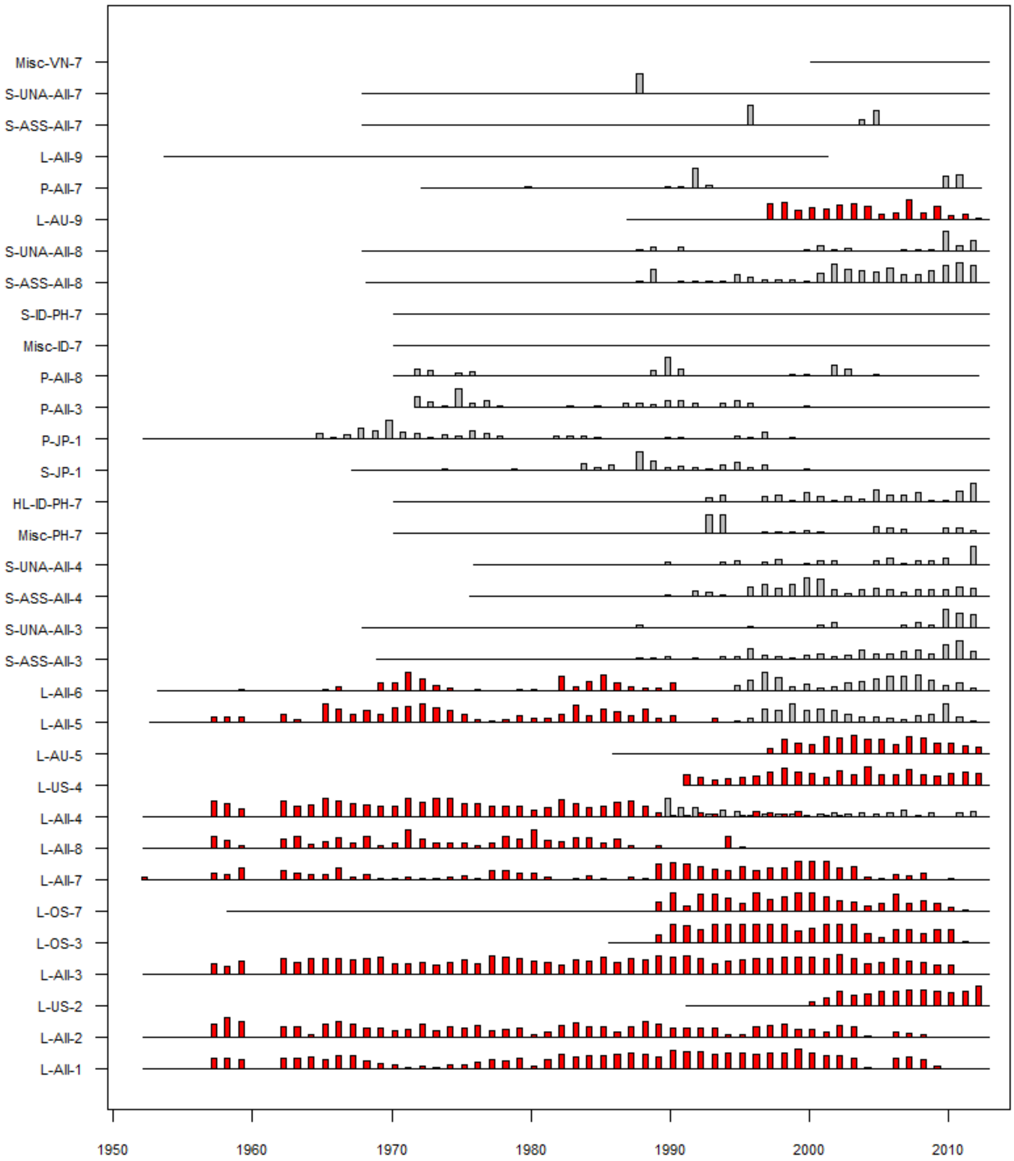
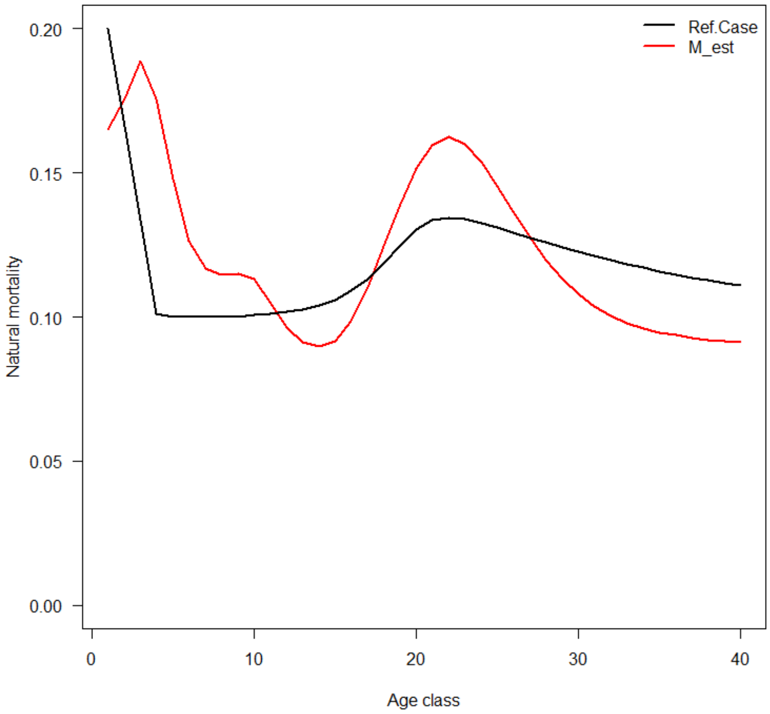


Figure 8. Number of weight (red) and length (grey) frequency samples from the reference case model. The maximum value is 12444, but note that in the reference case model a maximum sample size of 1000 is allowed.



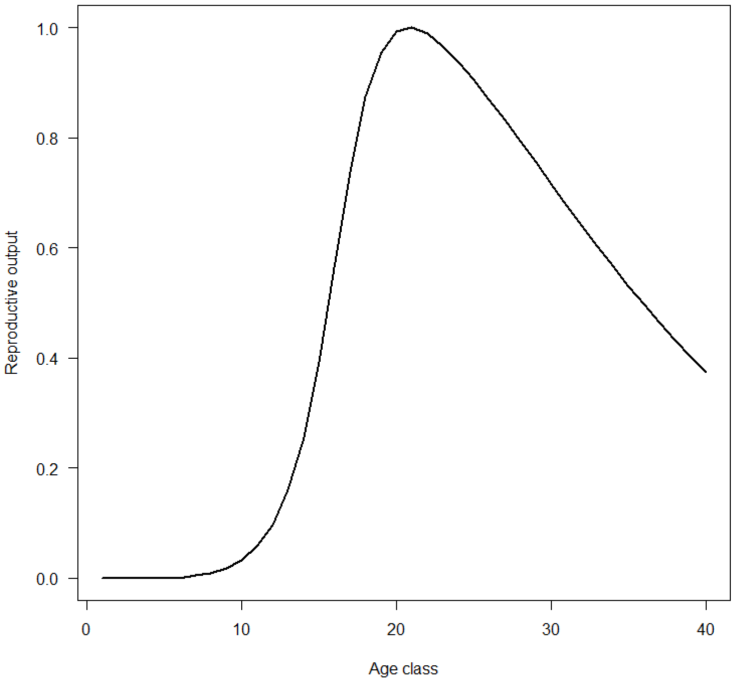


Figure 9. Natural mortality-at-age as assumed in the reference case and estimated in the one-change sensitivity (top) and % mature (bottom) . Note that the estimate of maturity is actually used to define an index of spawning potential incorporating information on sex ratios, maturity at age, fecundity, and spawning fraction (see Hoyle and Nicol 2008 for further details).

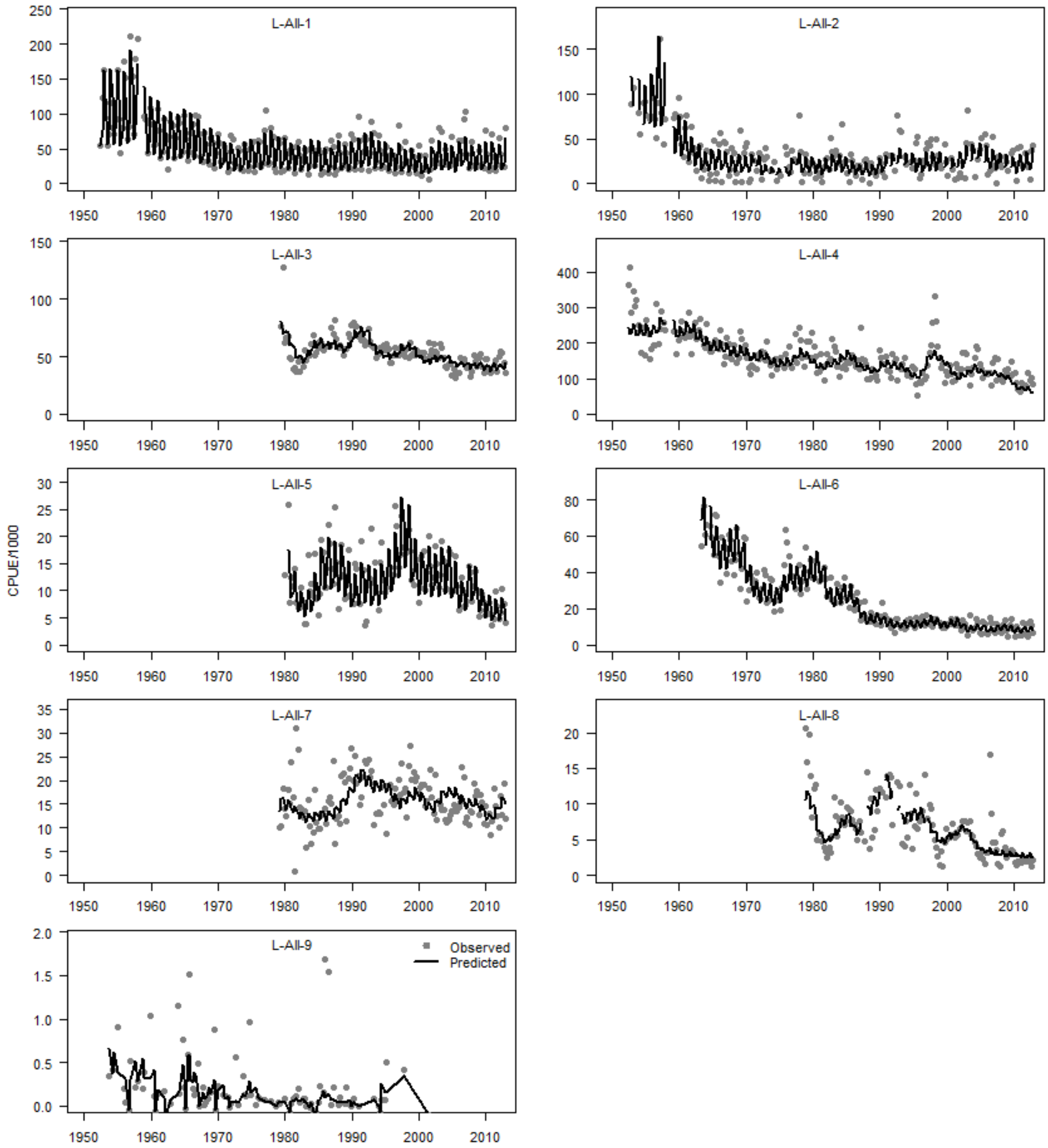


Figure 10. Observed and predicted CPUE for the major longline fisheries for the reference case.

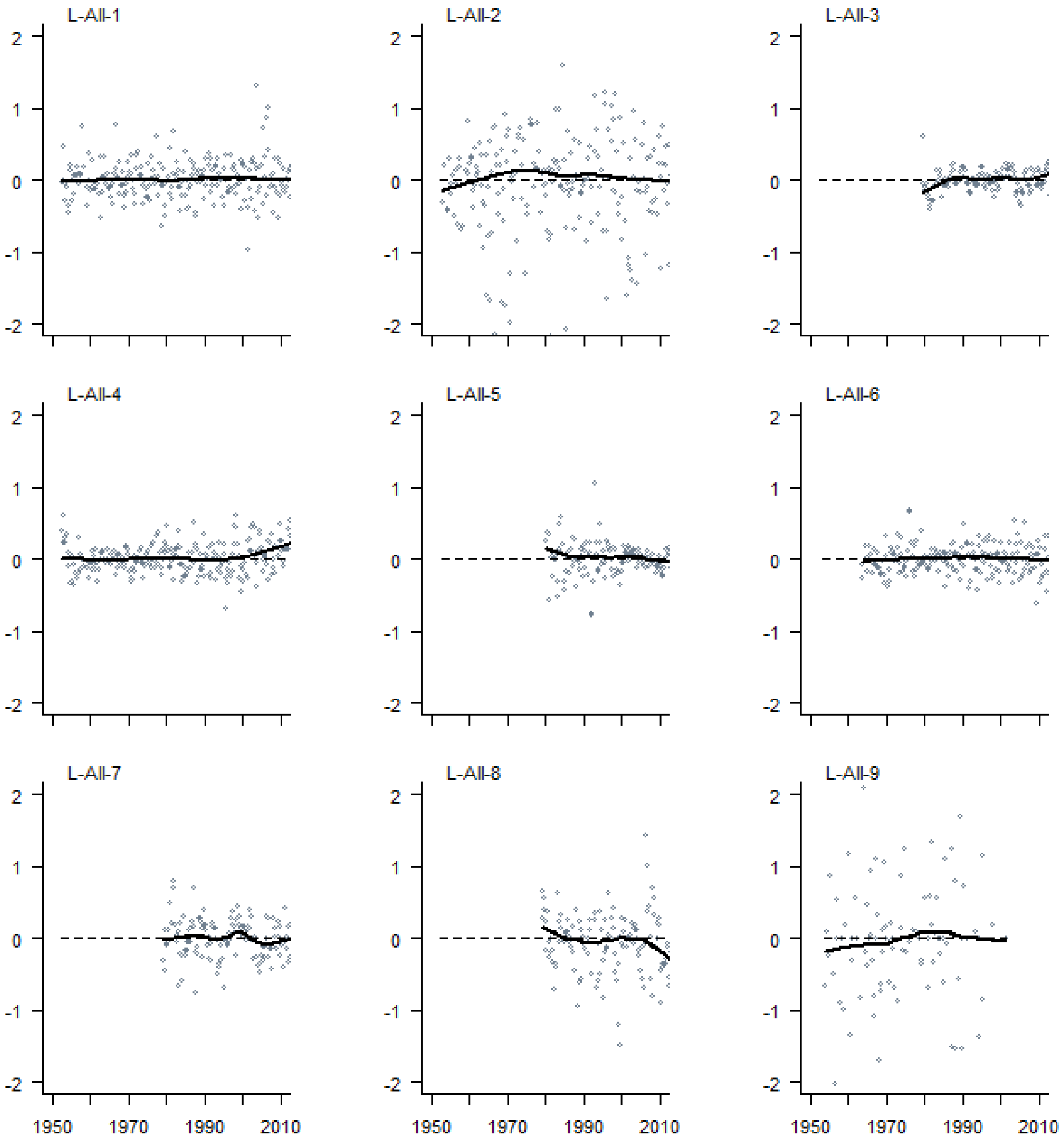


Figure 11. Effort deviations by time period for each LL-ALL fishery for the reference case. The dark line represents a lowess smoothed fit to the effort deviations. A small number of values lie outside the bounds of the plot.

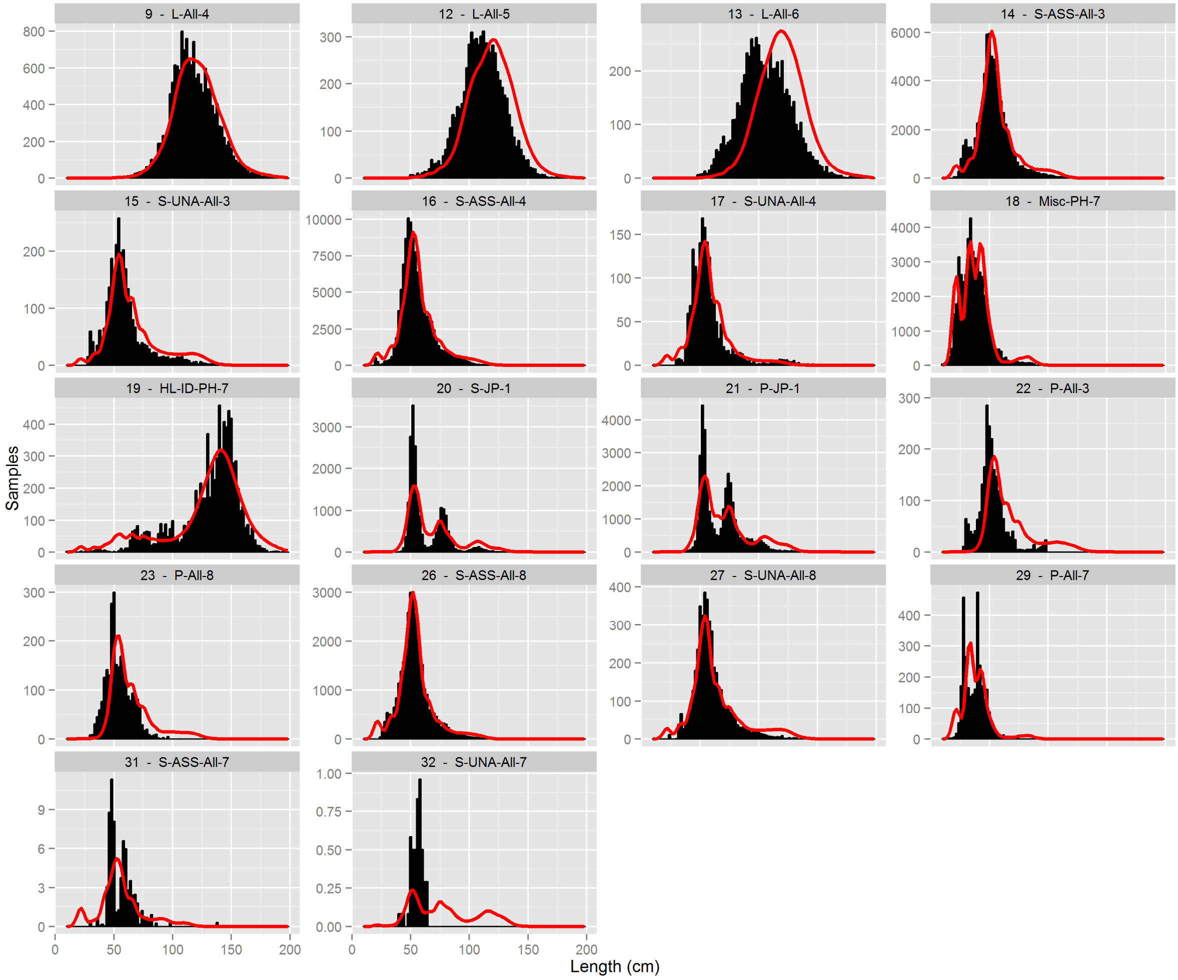


Figure 12. Composite (all time periods combined) observed (black histograms) and predicted (red line) catch at length for all fisheries with samples for the reference case.

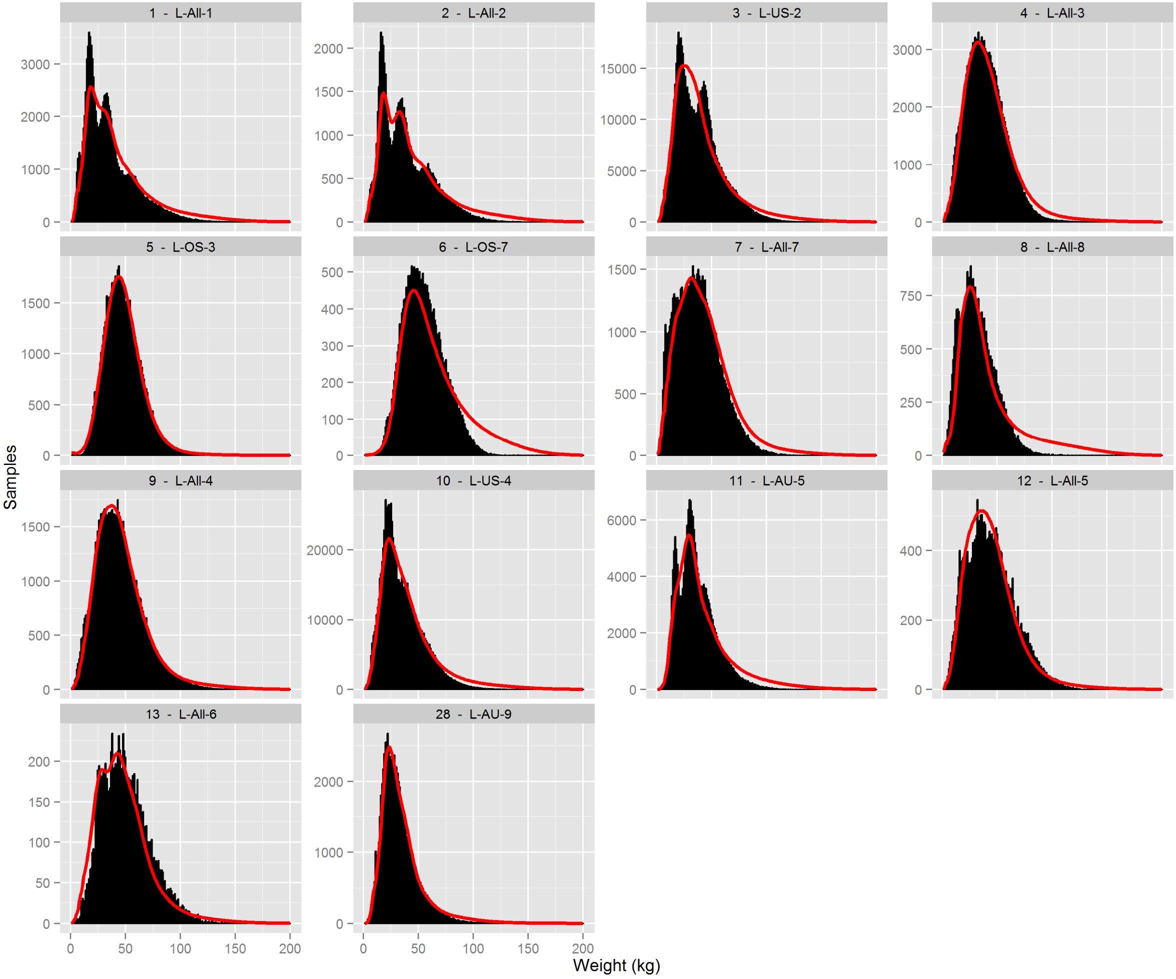


Figure 13. Composite (all time periods combined) observed (black histograms) and predicted (red line) catch at weight for all fisheries with samples for the reference case.

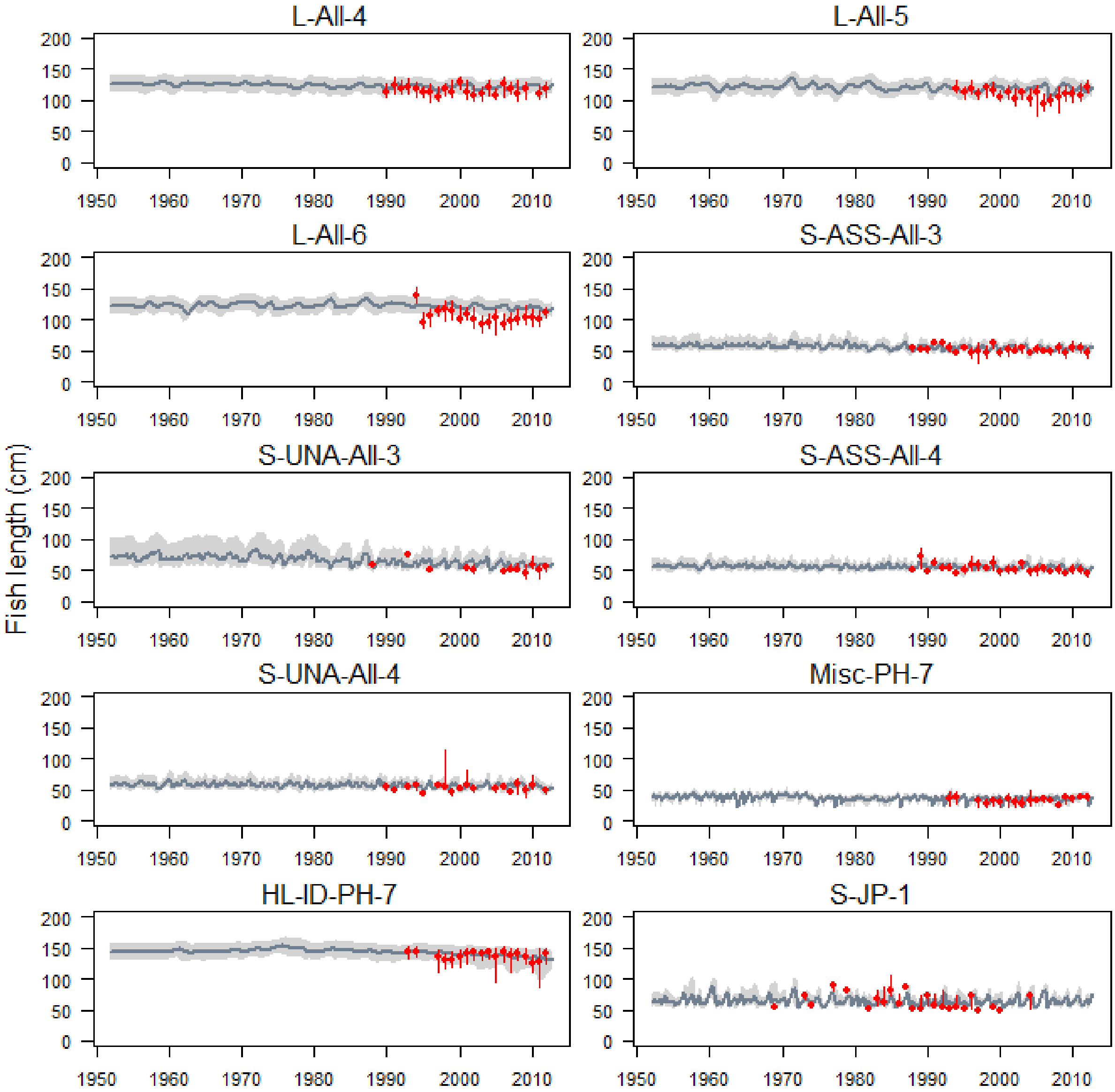


Figure 14. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) for all fisheries with samples for the reference case. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

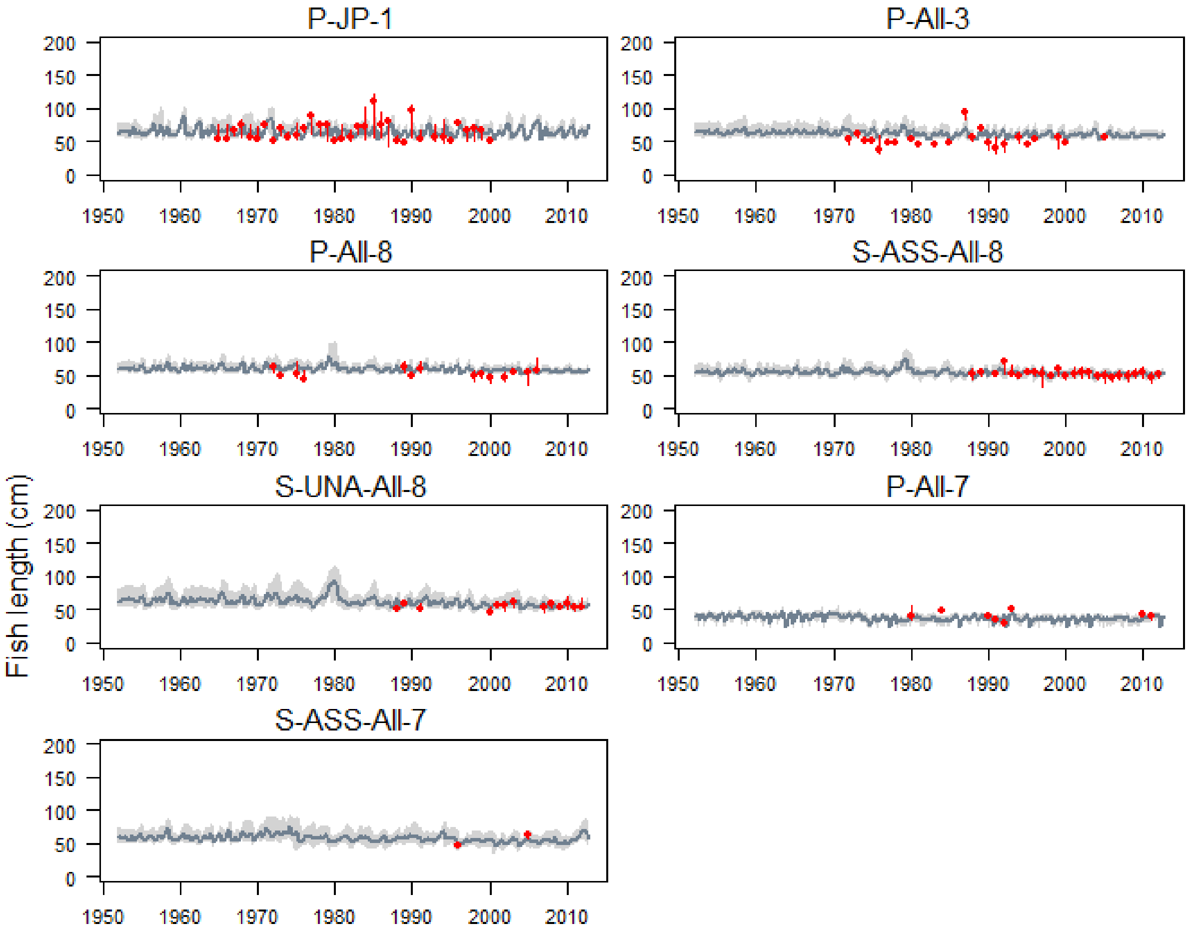


Figure 14 cont.

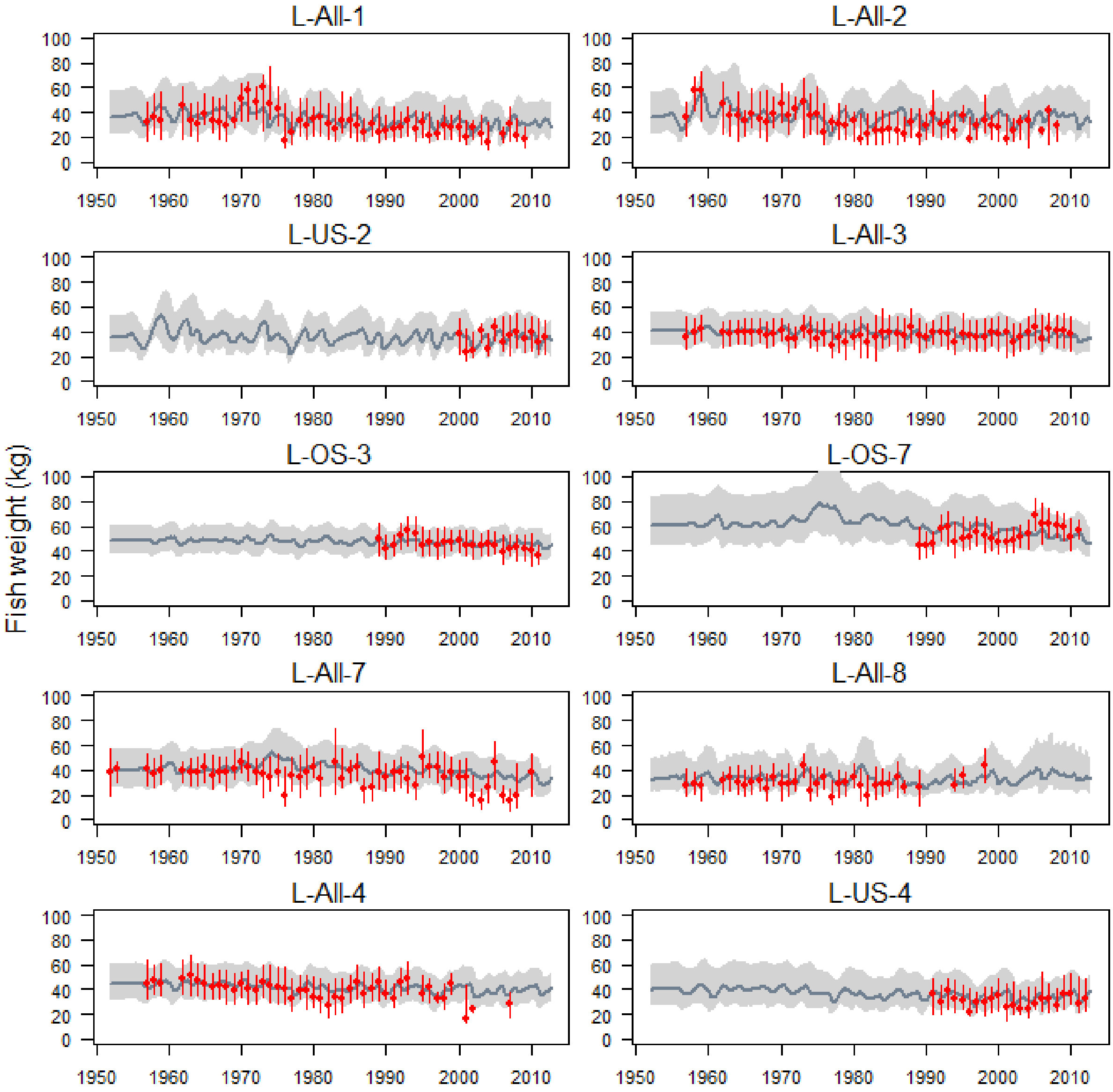


Figure 15. A comparison of the observed (red points) and predicted (grey line) median fish weight (kg) for all fisheries with samples for the reference case. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

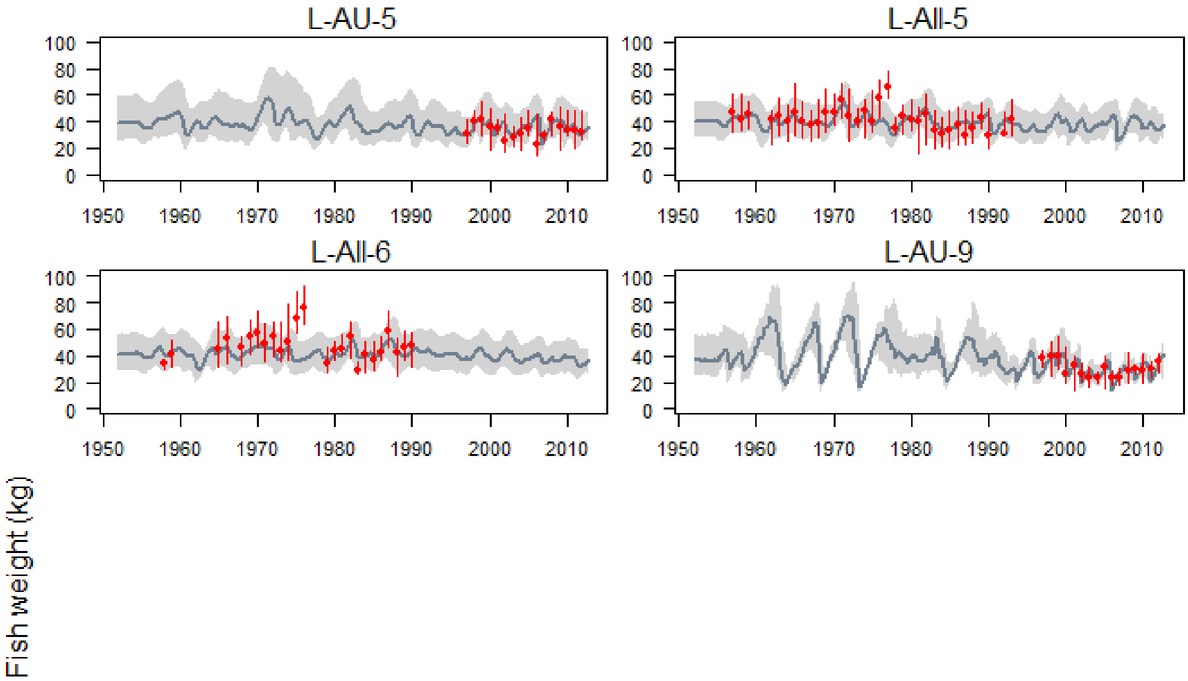


Figure 15 cont.

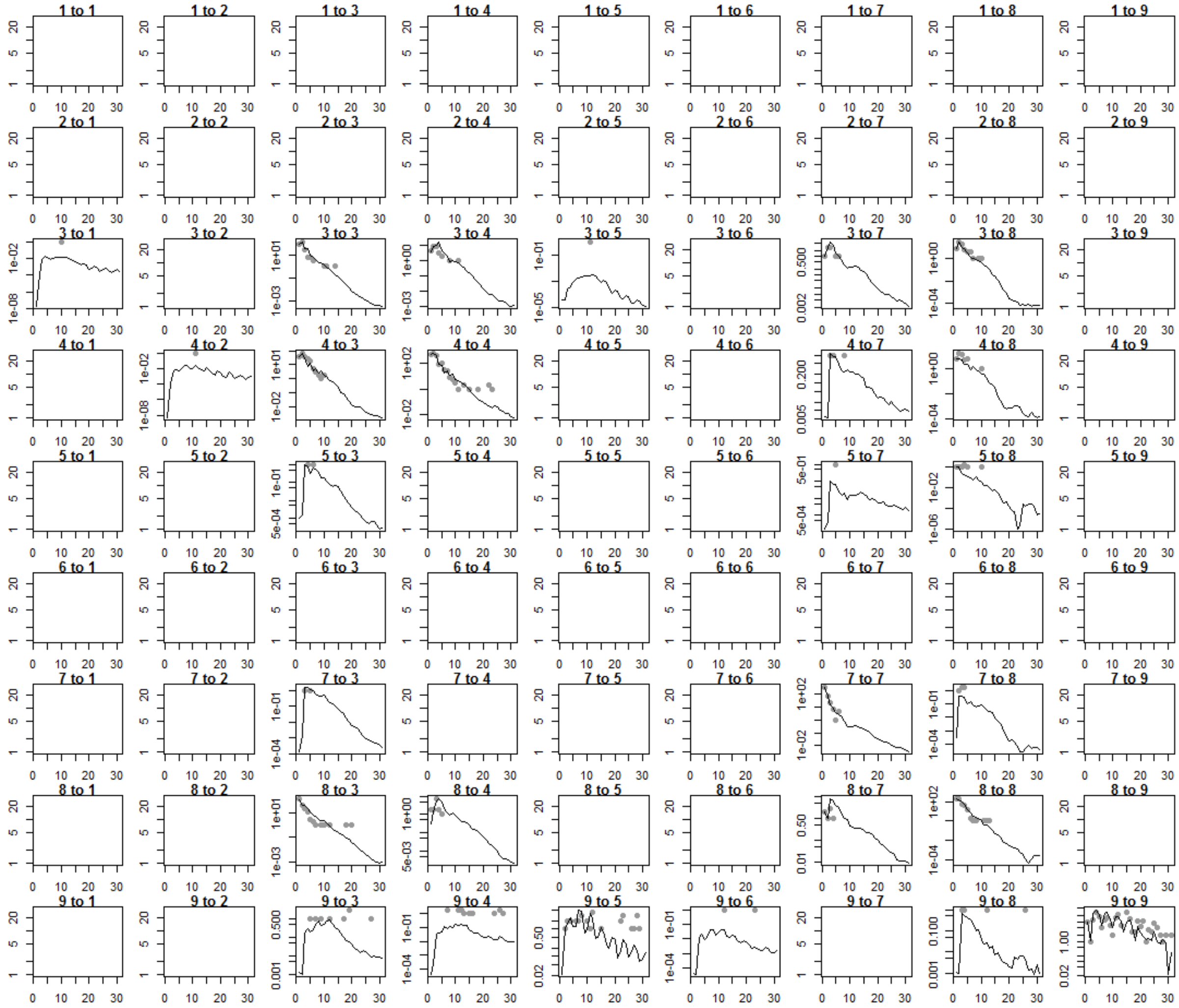


Figure 16. Predicted and observed recaptures of tagged fish by time period at liberty (quarter) from the region of release to the region of recapture.

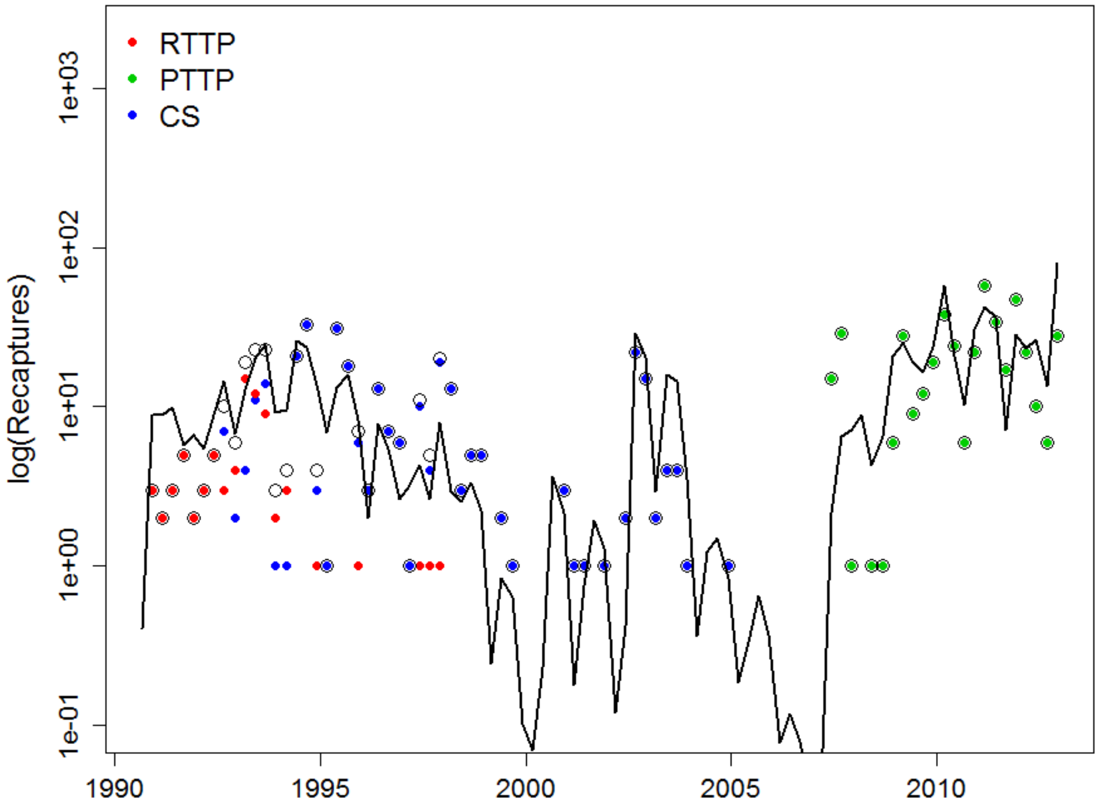


Figure 17. Observed recaptures for the reference case by time period specific to each release program shown by coloured dots: green = PTTP, blue = CS, red = RTTP. The model (black line) is fitted to the total observed recaptures in a time period (black circles), that are made up of the sum of the program-specific recaptures occurring in that time period, hence a dot and circle will coincide if recaptures are derived from only one program.

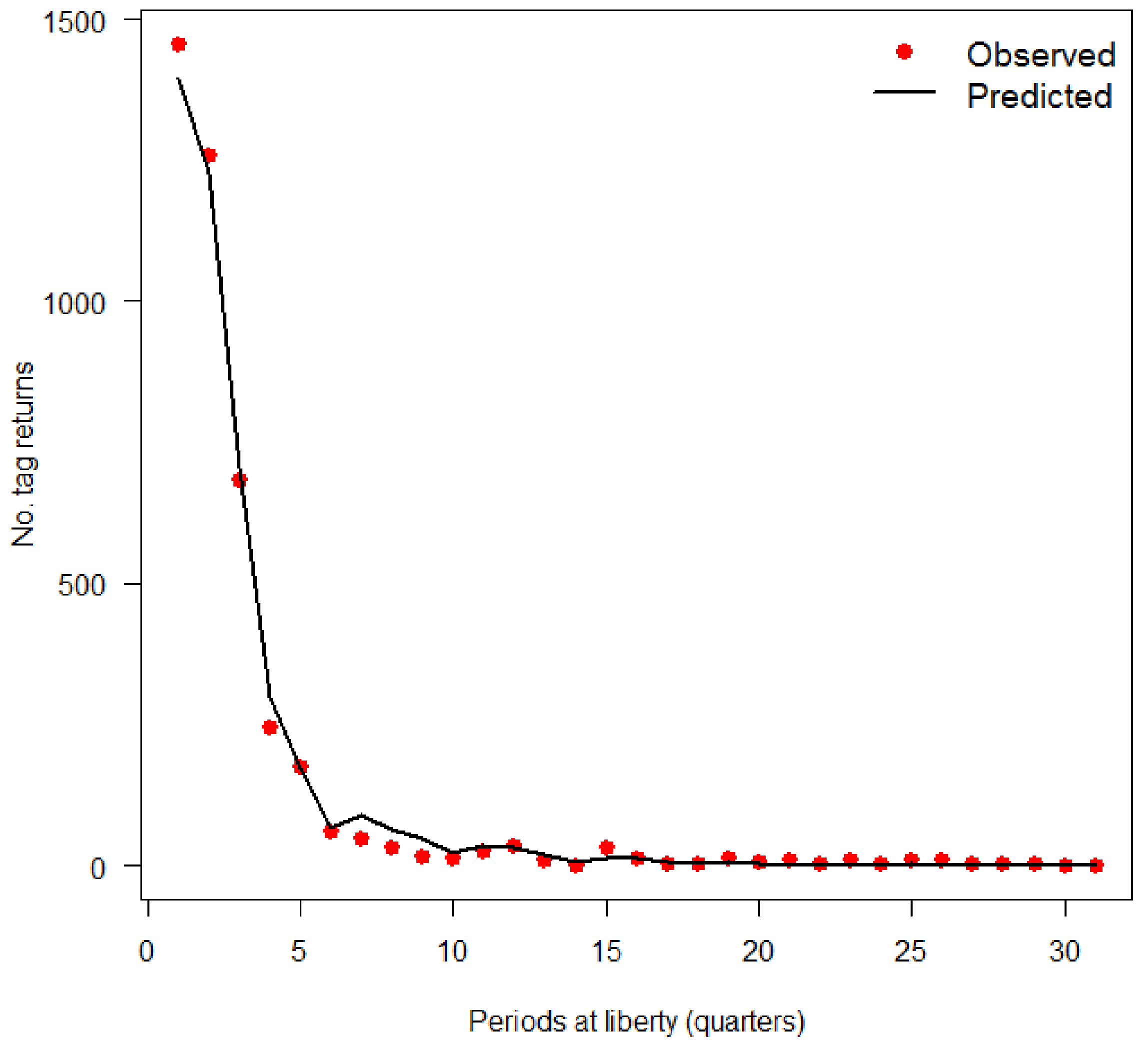


Figure 18. Observed and predicted tag attrition for the reference case across all tag release events.

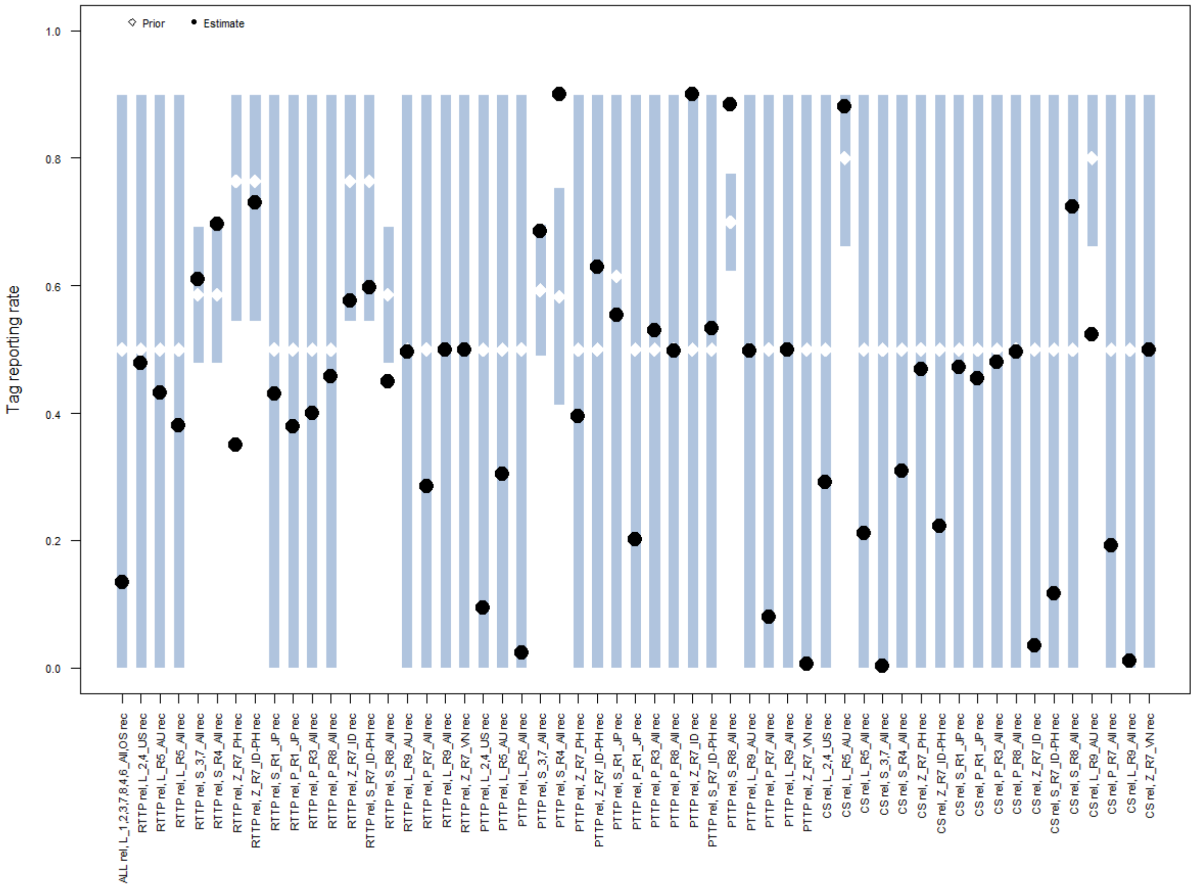


Figure 19. Estimated reporting rates for the reference case. Reporting rates can be estimated separately for each release program and recapture fishery group (histograms). See text for further details of tagging programmes. Certain estimates are grouped over release programs and over recapture fisheries, (e.g. LL-ALL and HL fisheries). The prior mean ±1.96 SD is also shown for each reporting rate group.

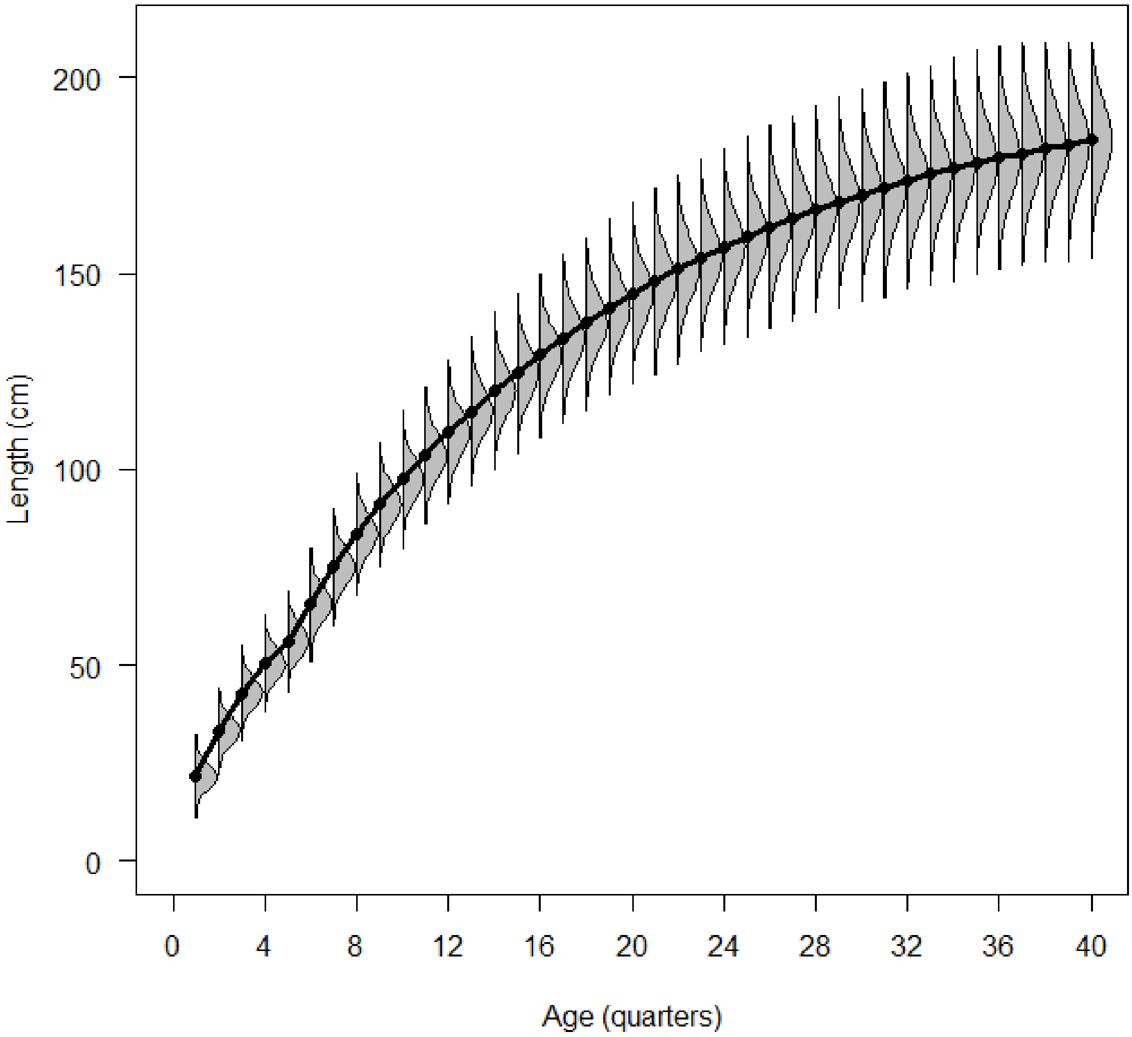


Figure 20. Estimated growth for the reference case. The black line represents the estimated mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age. For this assessment the length of the oldest age class was fixed at 184 cm.

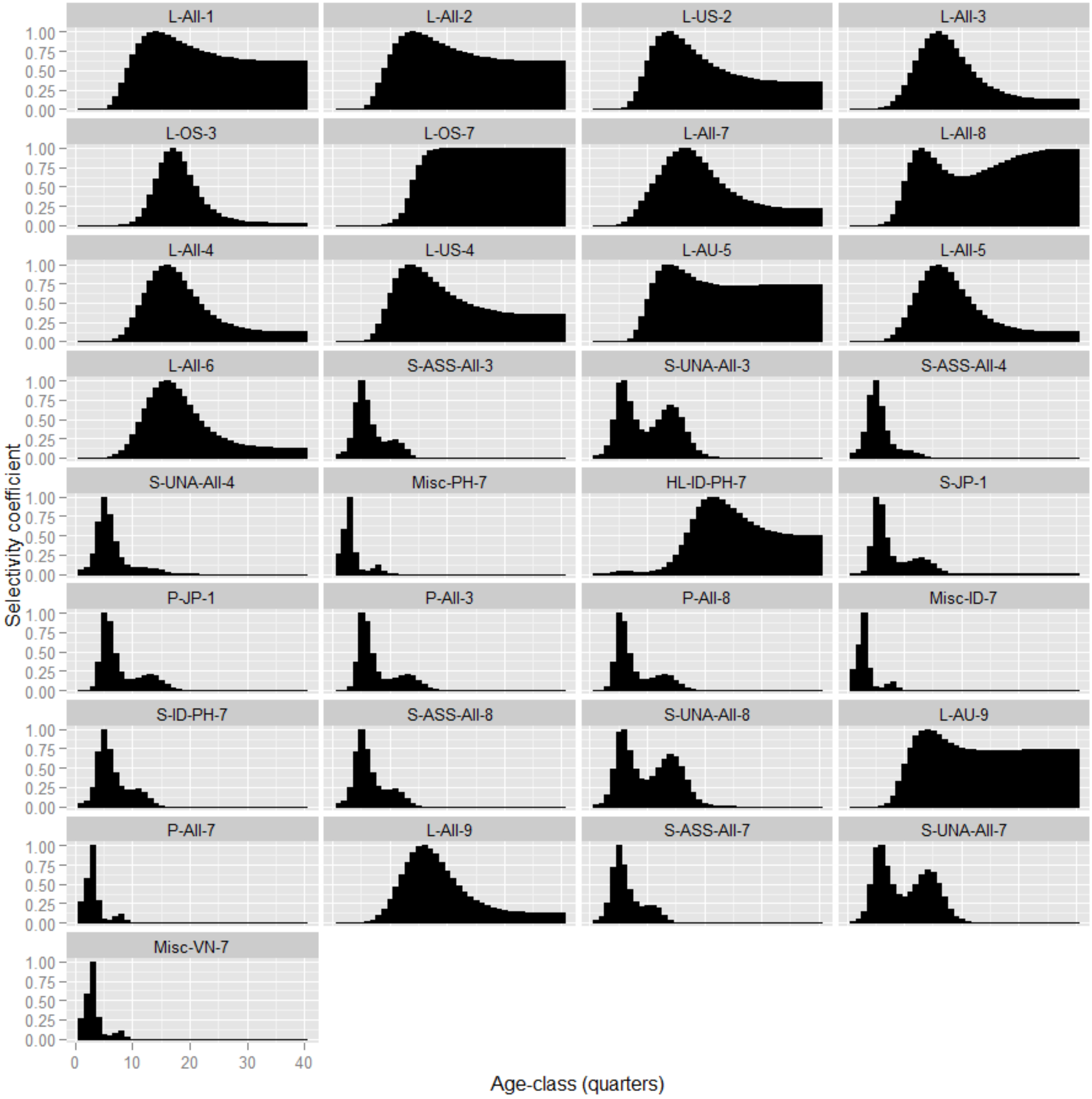


Figure 21. Selectivity coefficients by fishery.

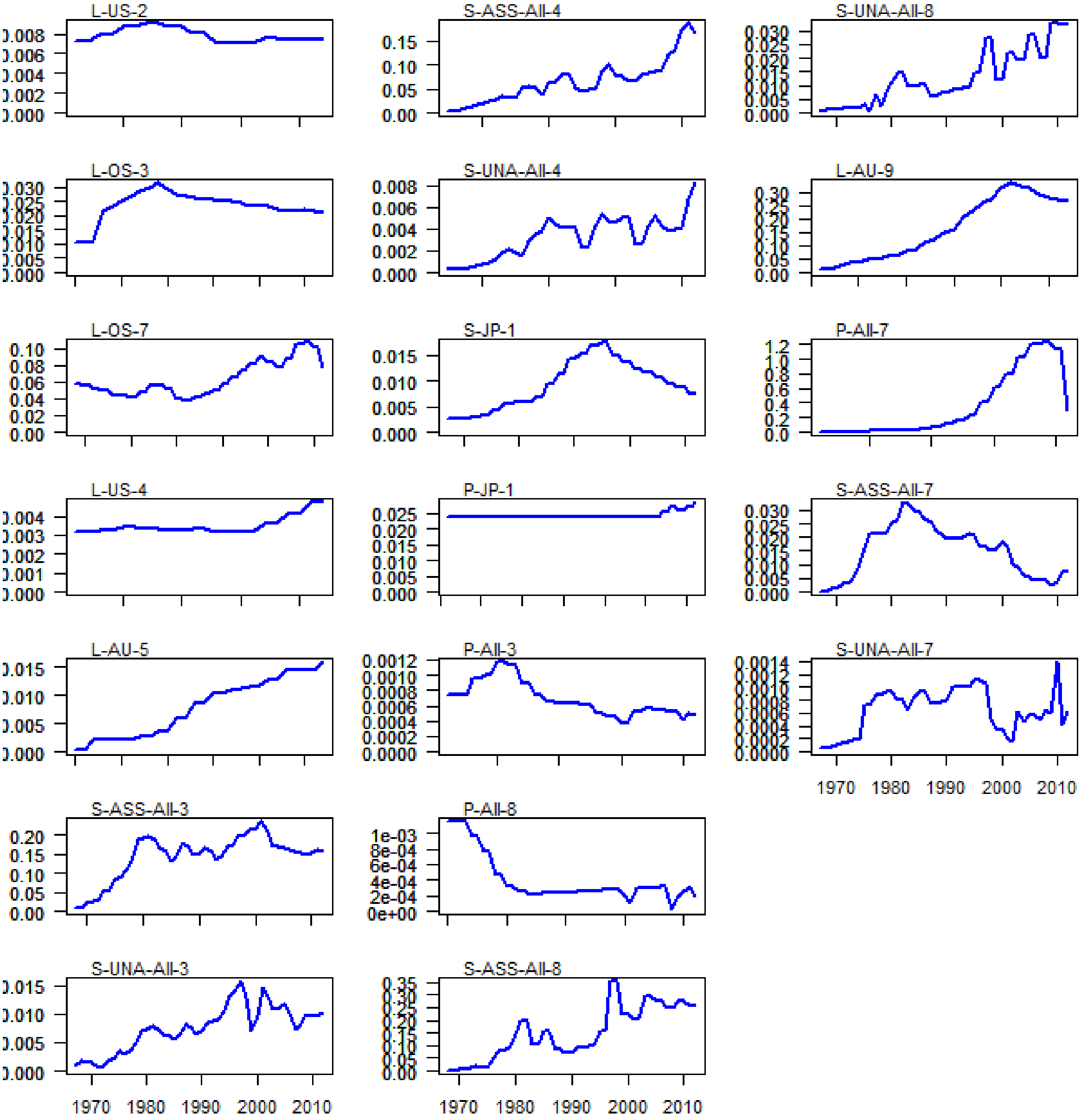


Figure 22. Estimated catchability time-series for those fisheries assumed to have random walk in catchability.

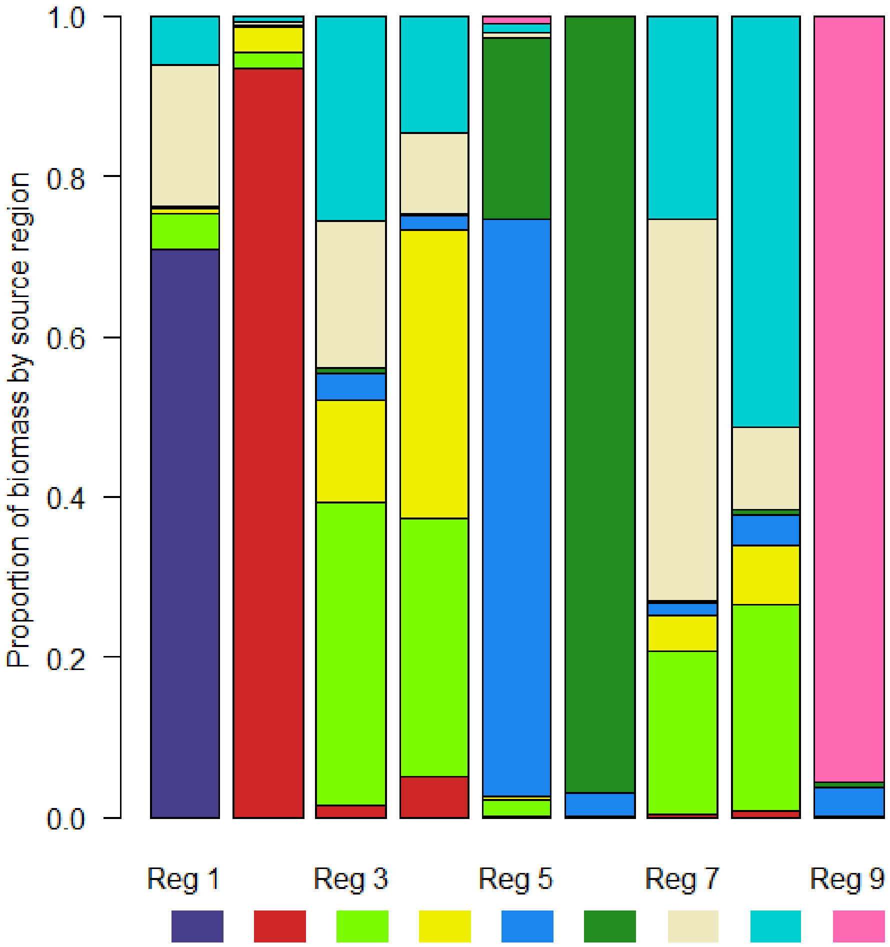


Figure 23. Proportional distribution of total biomass (by weight) in each region apportioned by the source region of the fish for the reference case. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment between regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

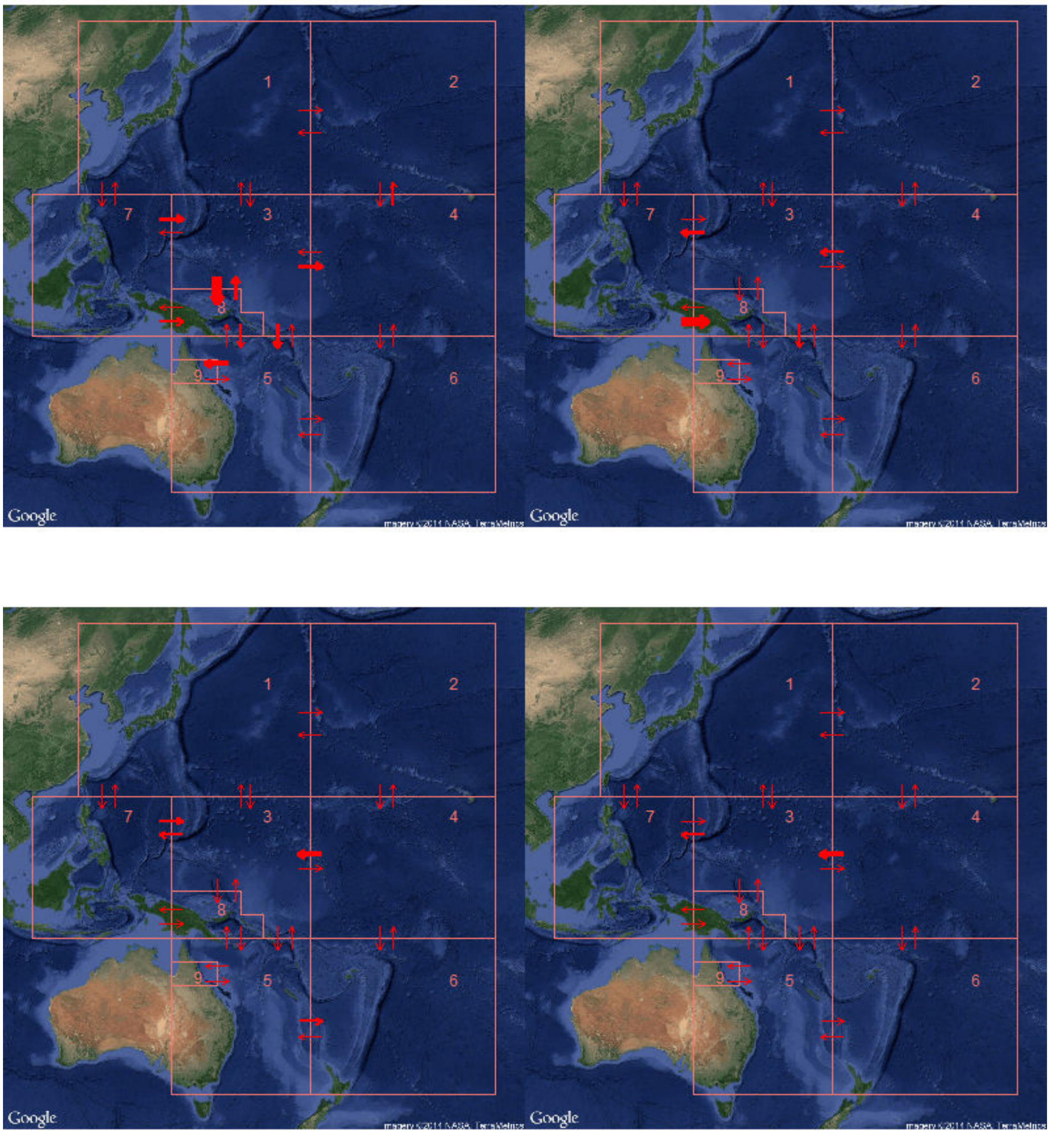


Figure 24. Estimated quarterly movement coefficients for the reference case. The movement coefficient is proportional to the width of the arrow.

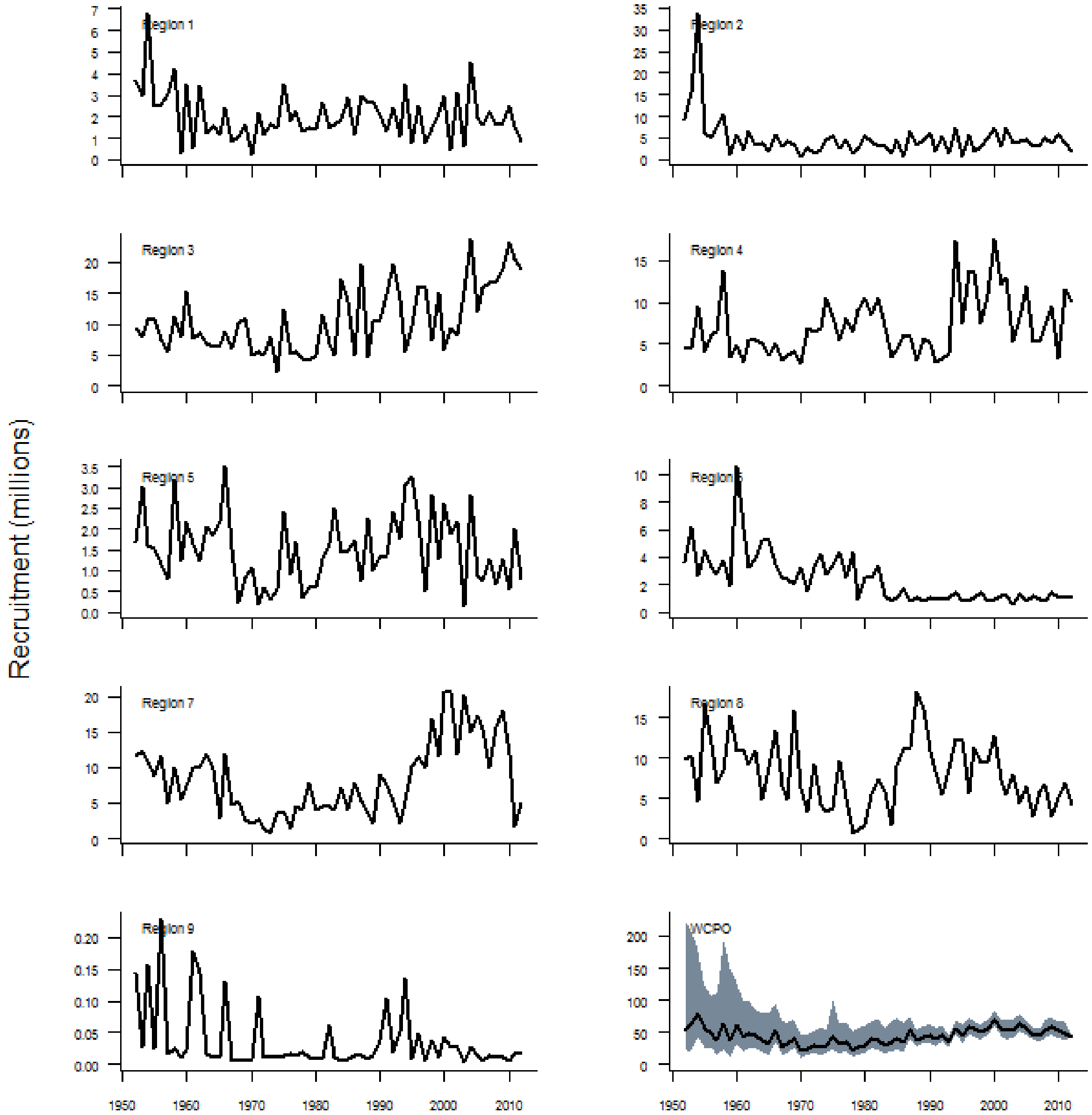


Figure 25. Estimated annual recruitment (millions) by region and for the WCPO for the reference case. The shaded areas indicate the approximate 95% confidence intervals.

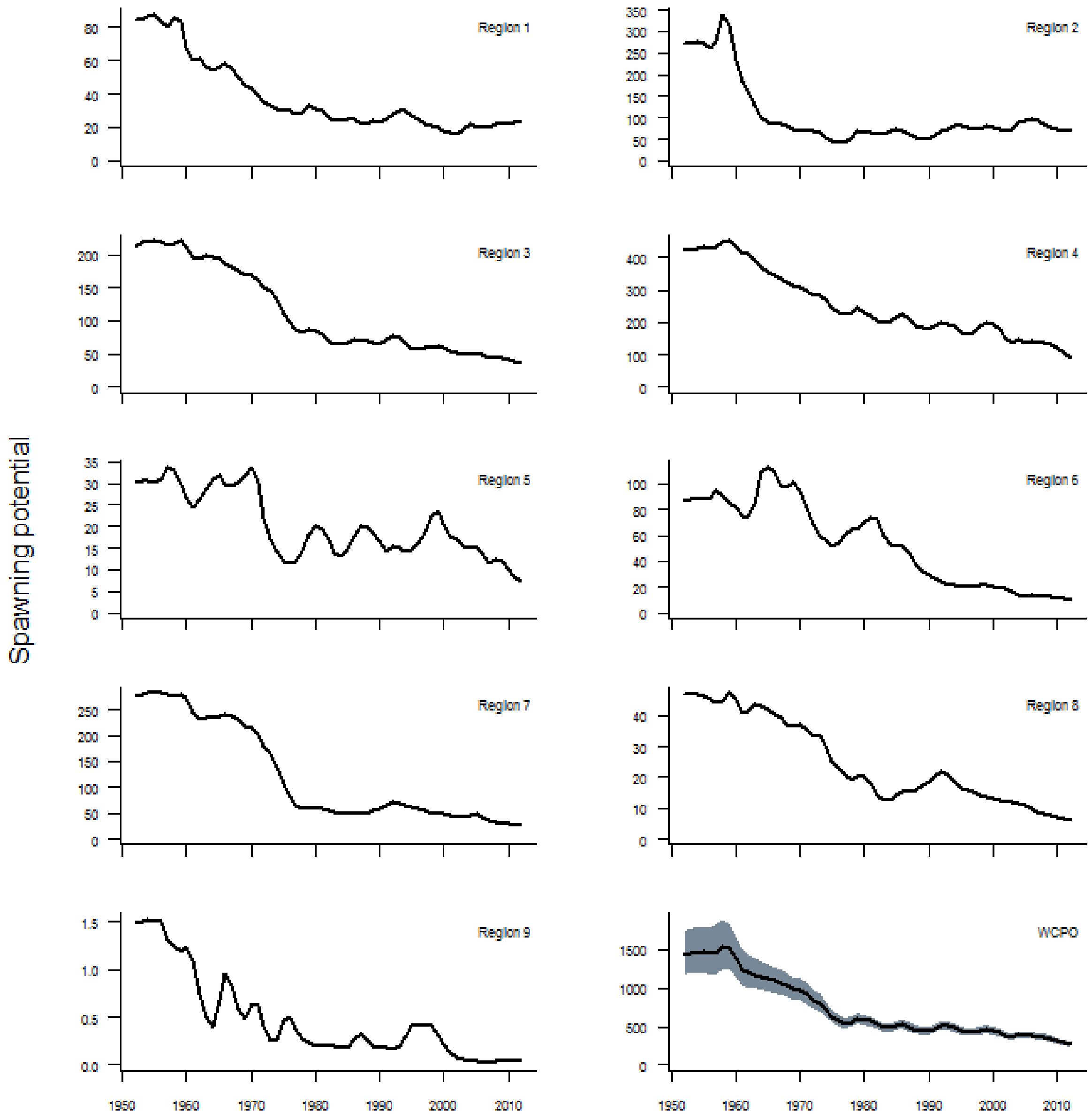


Figure 26. Estimated annual average spawning potential by region and for the WCPO for the reference case. The shaded areas indicate the approximate 95% confidence intervals.

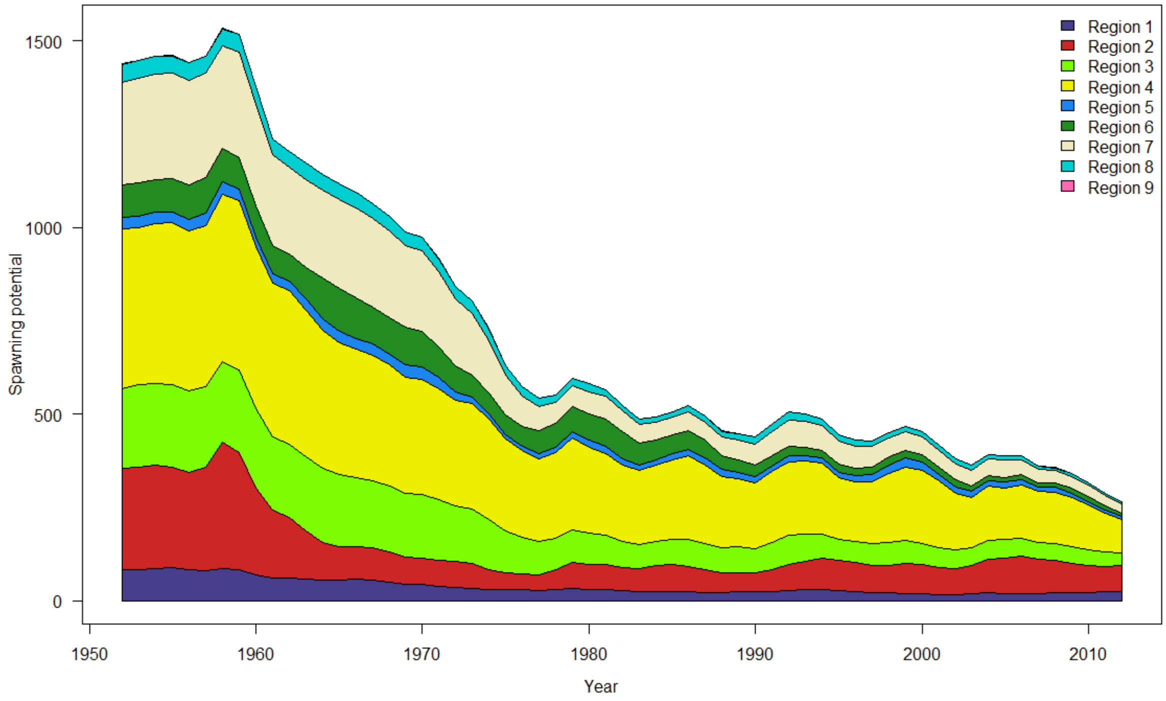


Figure 27. Estimated annual average spawning potential by model region for the reference case.

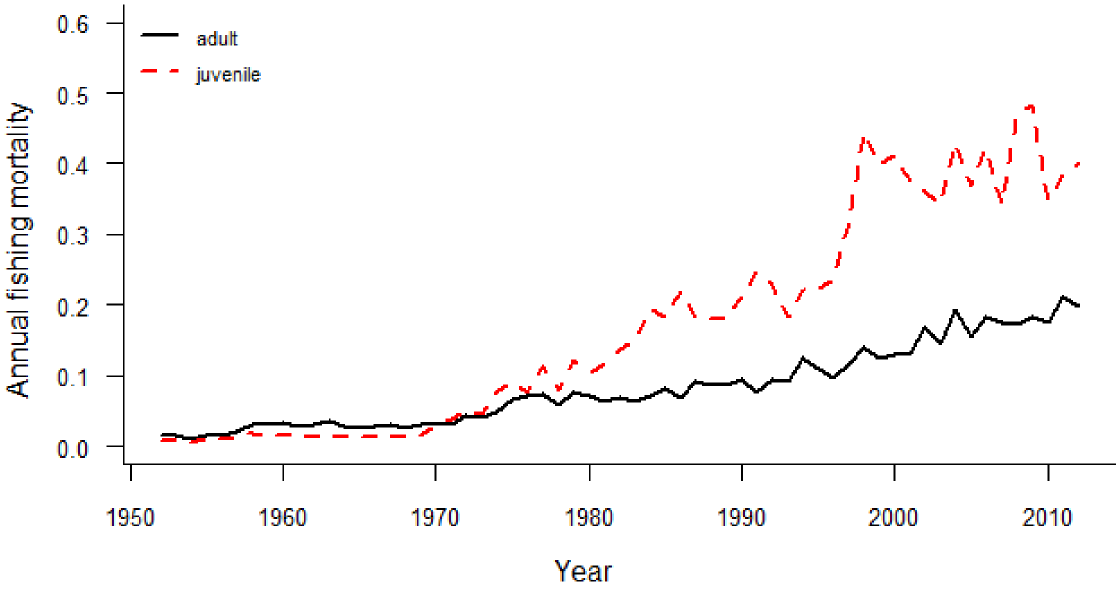


Figure 28. Estimated annual average juvenile and adult fishing mortality for the WCPO for the reference case.

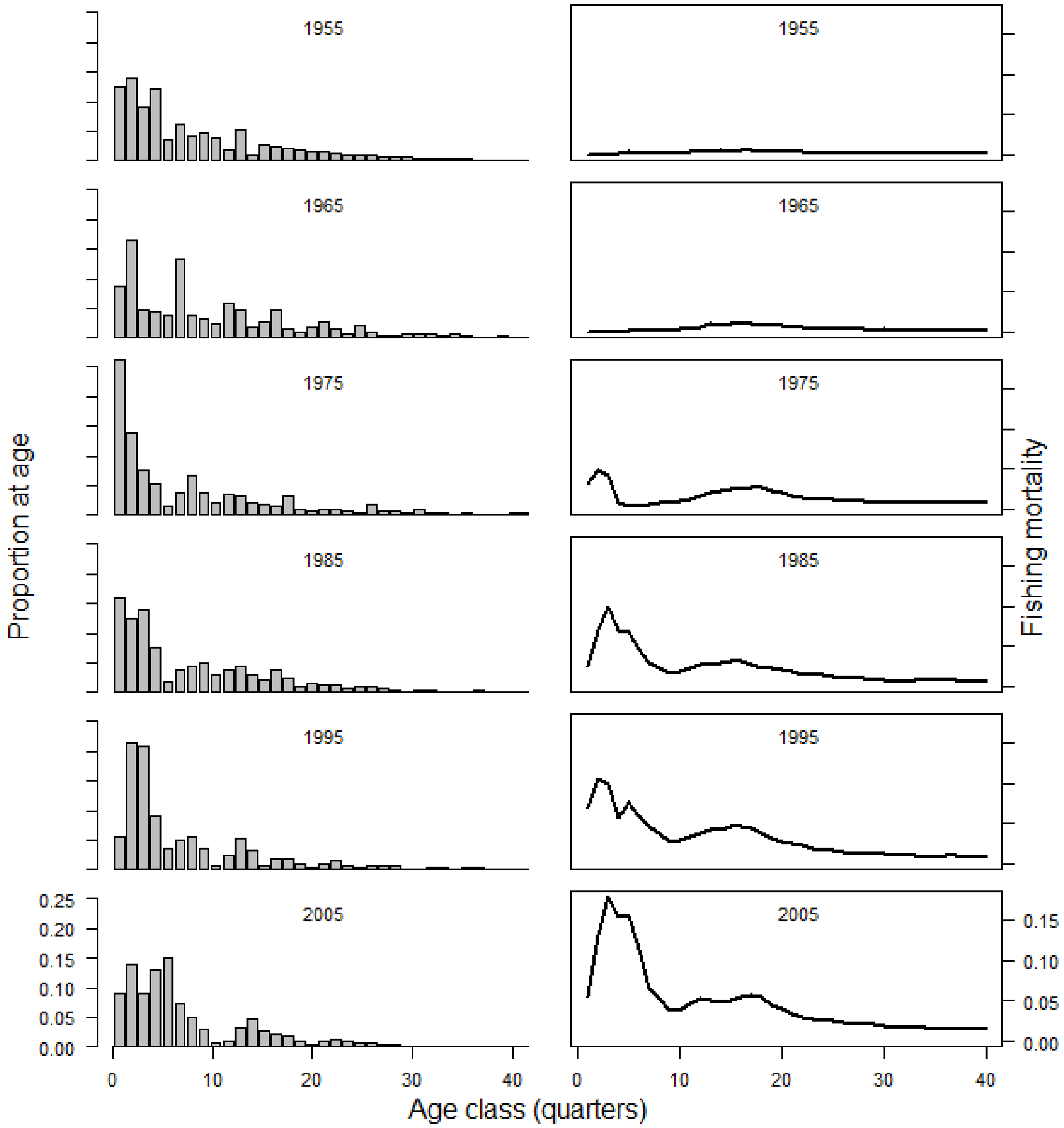


Figure 29. Estimated proportion at age (quarters) for the WCPO bigeye population (left) and fishing mortality at age (right) by year at decade intervals for the reference case.

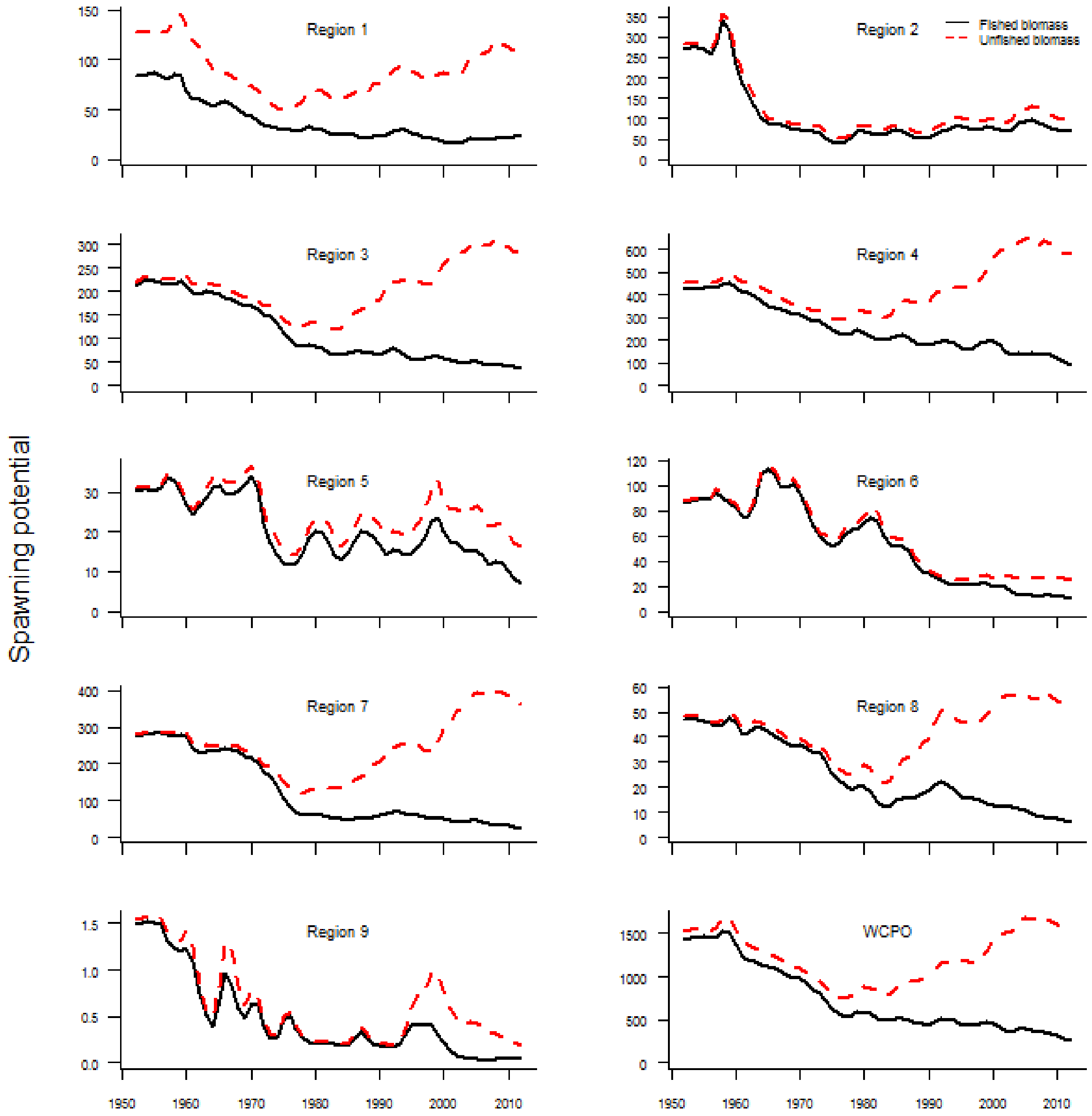


Figure 30. Comparison of the estimated spawning potential trajectories (lower solid black lines) with those trajectories that would have occurred in the absence of fishing (upper dashed red lines) for each region and for the WCPO for the reference case.

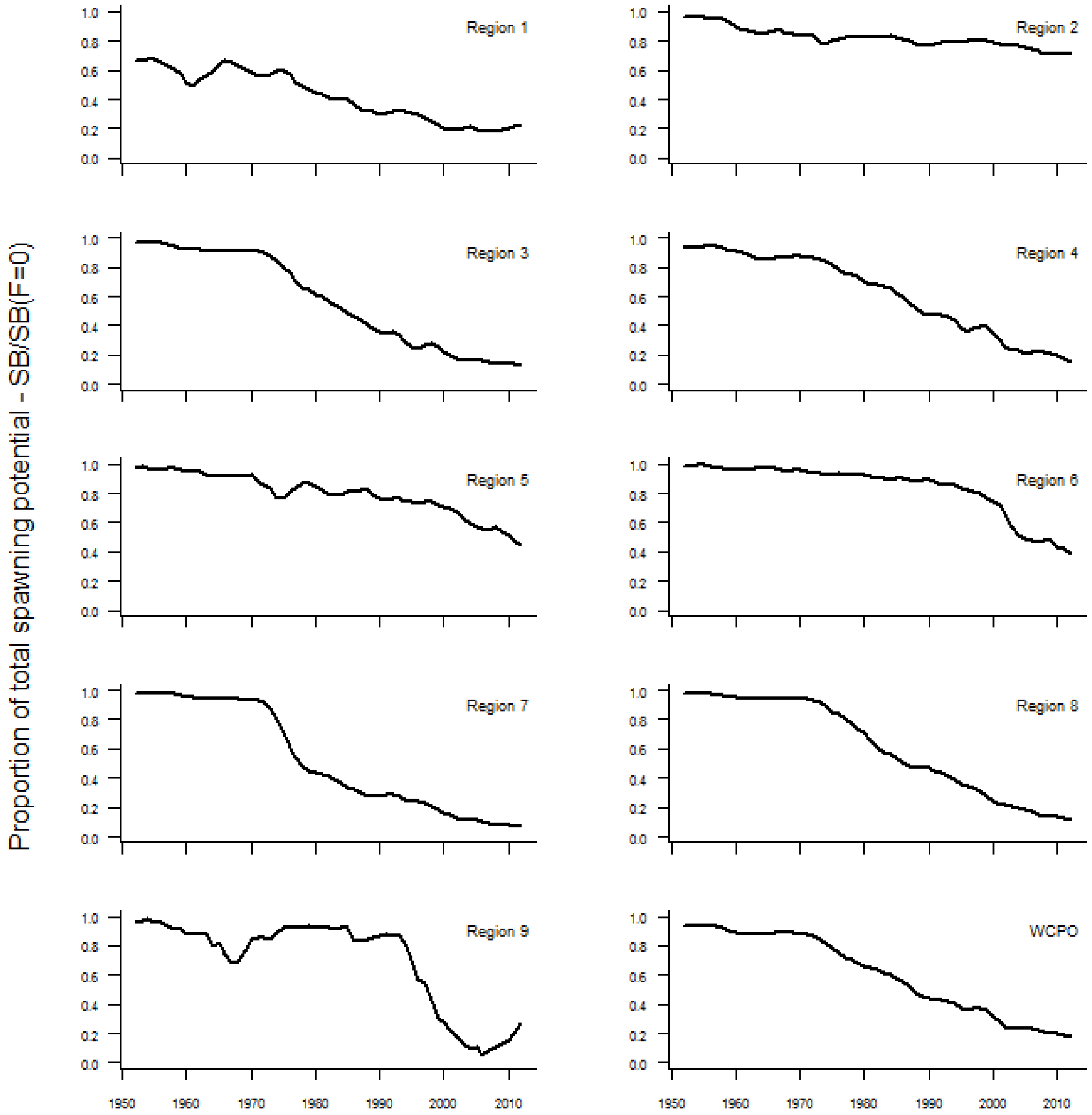


Figure 31. Ratios of exploited to unexploited spawning potential $SB_t/SB_{t_{F=0}}$ for each region and the WCPO for the reference case.

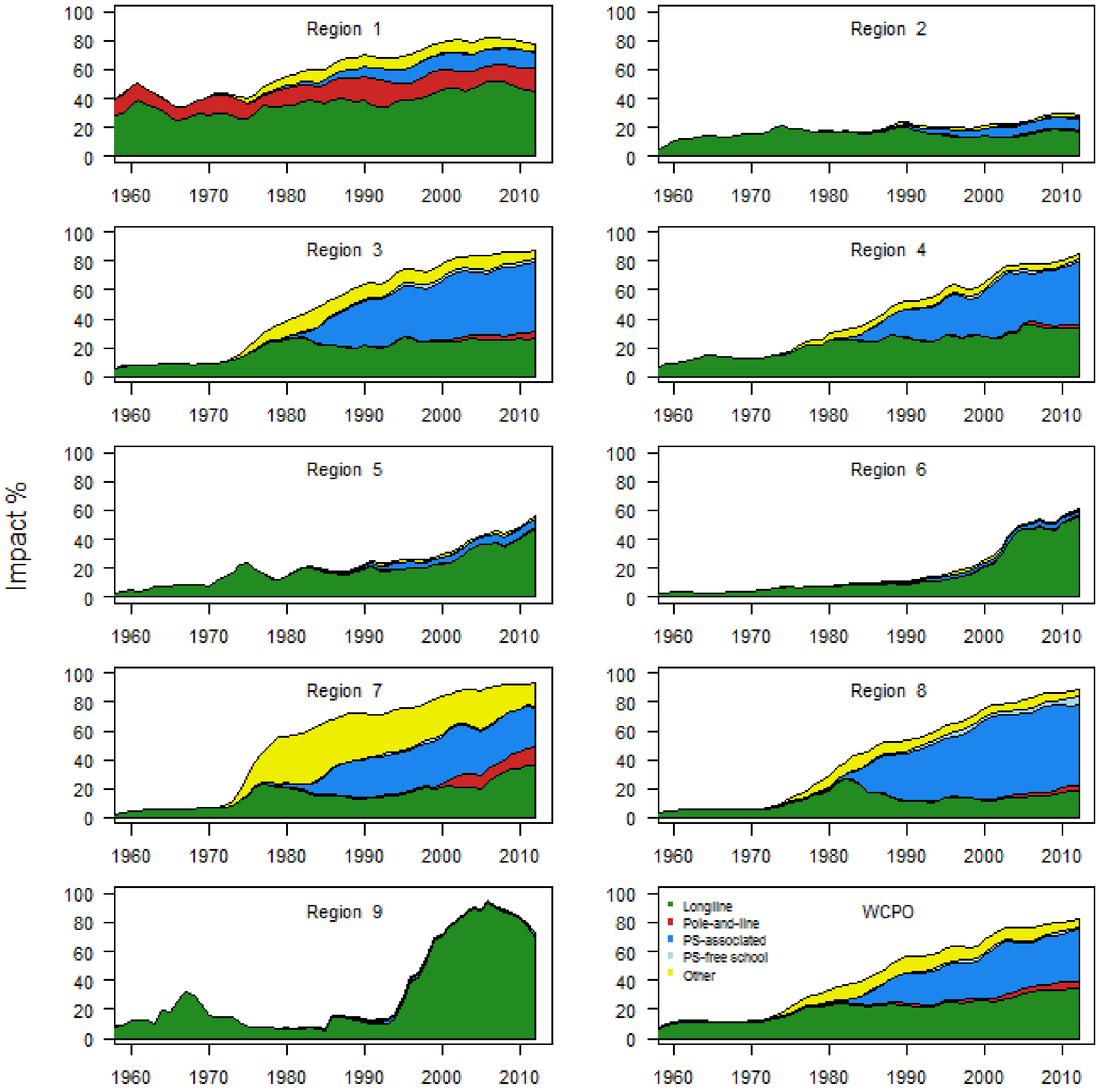
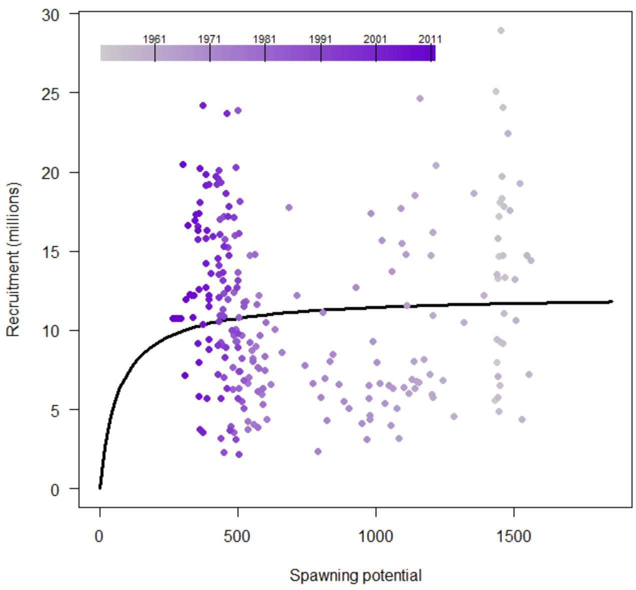


Figure 32. Estimates of reduction in spawning potential due to fishing (fishery impact = $\mathbf{1} - \boldsymbol{SB_t}/\boldsymbol{SB_{t_{F=0}}}$) by region and for the WCPO attributed to various fishery groups for the reference case.



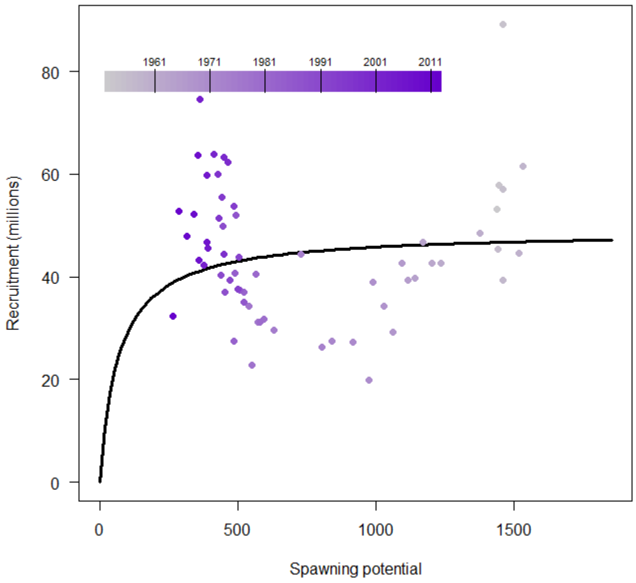


Figure 33. Estimated relationship between recruitment and spawning potential based on quarterly (top) and annual (bottom) values for the reference case.

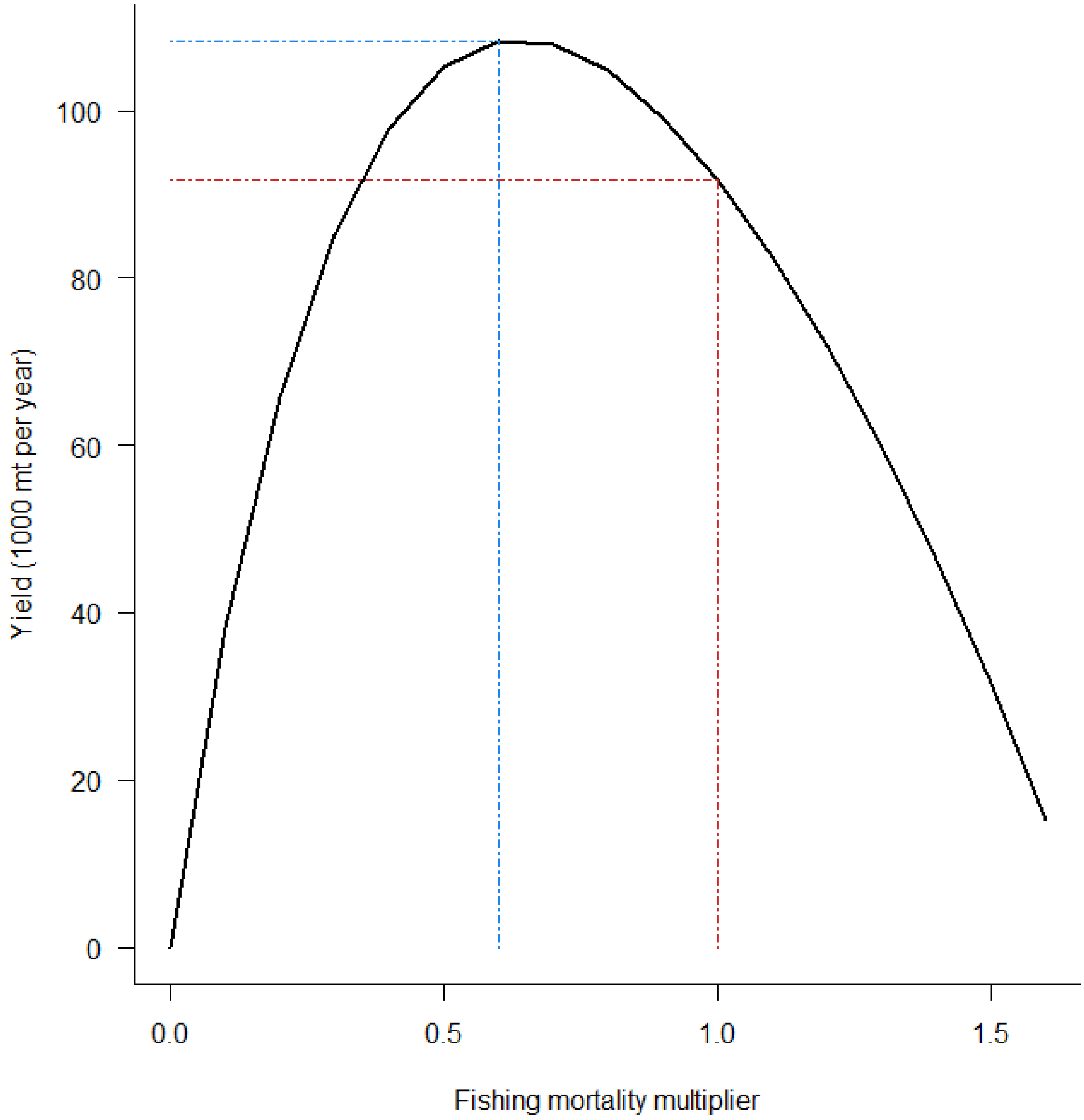


Figure 34. Estimated yield as a function of fishing mortality multiplier for the reference case. The red dashed line indicates the equilibrium yield at current fishing mortality and the blue dashed line indicates the MSY and the change in current fishing mortality required to achieve it.

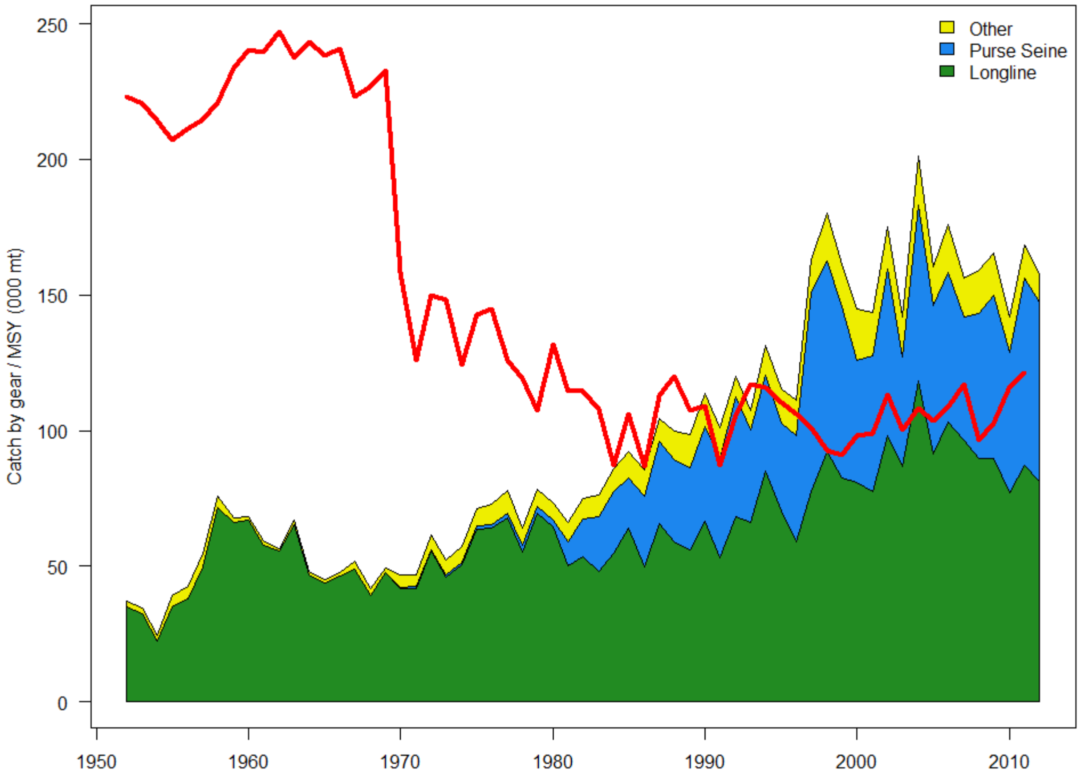


Figure 35. History of the annual estimates of *MSY* (red line) compared with annual catch split into three fishery sectors for the reference case.

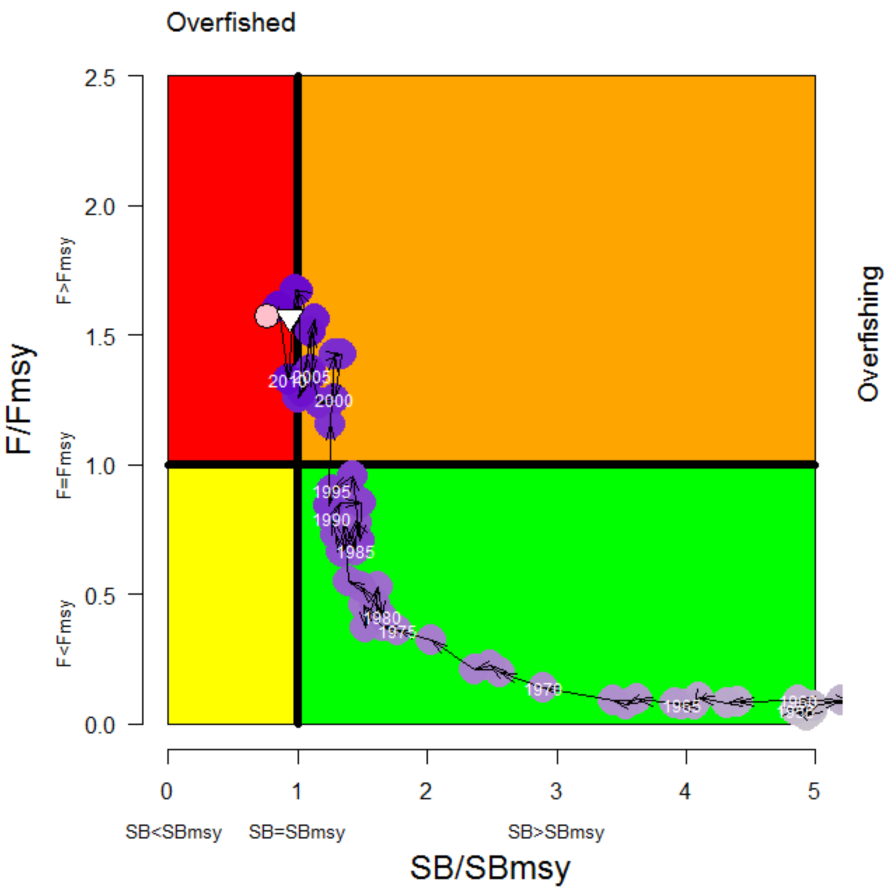


Figure 36. Temporal trend in annual stock status, relative to *SB_{MSY}* (x-axis) and *F_{MSY}* (y-axis) reference points, for the period 1952–2011 from the reference case. The colour of the points is graduated from mauve to dark purple through time and the points are labelled at 5-year intervals. The white triangle represents the average for the current period and the pink circle the latest period as defined in Table 6.

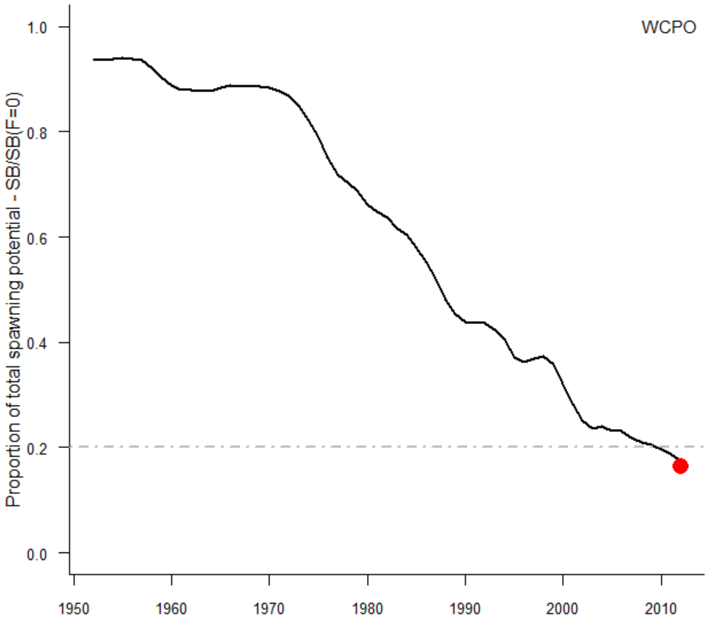


Figure 37. Ratio of exploited to unexploited spawning potential, $\boldsymbol{SB_t/SB_{t_{F=0}}}$, for the WCPO for the reference case. The current WCPFC limit reference point of 20%$SB_{F=0}$ is provided for reference as the grey dashed line and the red circle represents the level of spawning potential depletion based on the agreed method of calculating $\boldsymbol{SB_{F=0}}$ over the last ten years of the model (excluding the last year).

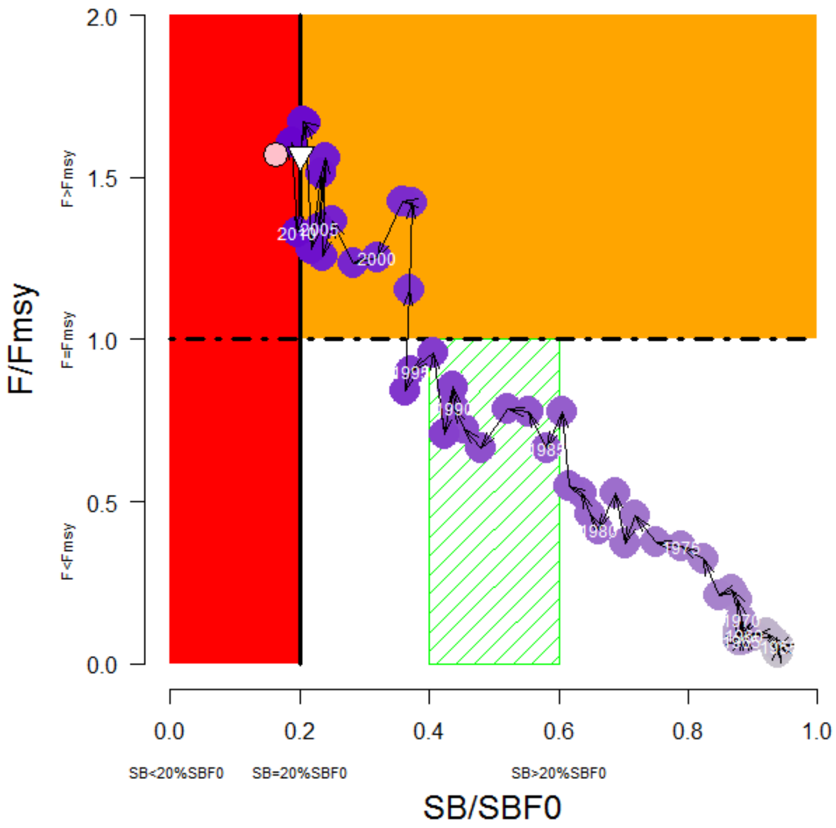
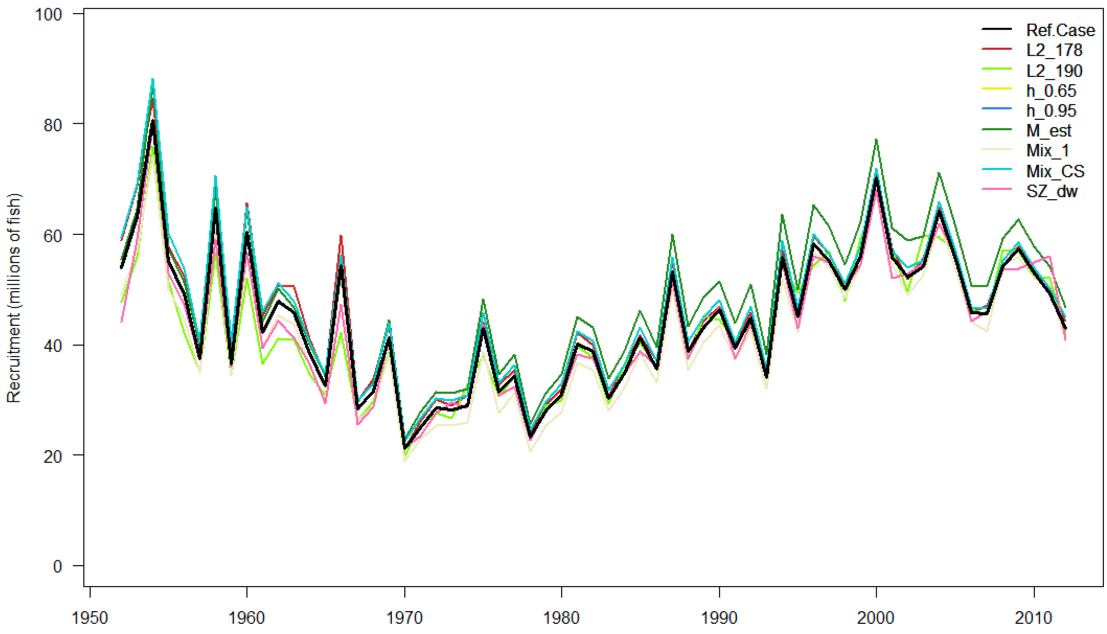


Figure 38. For discussion – a potential step towards displaying stock status with target and limit reference points. The red zone represents spawning potential levels lower than the agreed limit reference point which is marked with the solid black line. The orange region is for fishing mortality greater than FMSY (F=FMSY is marked with the black dashed line). The lightly shaded green rectangle covering 0.4-0.6SBF=0 is the 'space' that WCPFC has asked for consideration of a TRP for skipjack. The white triangle represents the average for the current period and the pink circle the latest period as defined in Table 6.



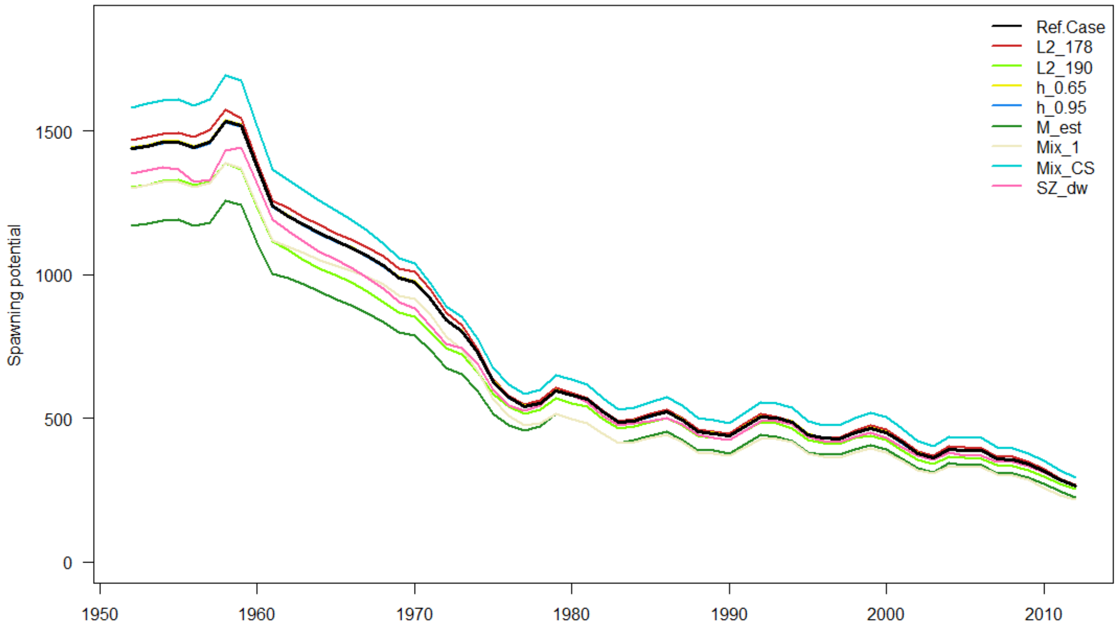


Figure 39. Estimated average recruitment (top) and spawning potential (bottom) for the WCPO obtained from the one-off sensitivity model runs to the reference case (see **Table 5** for details of each scenario).

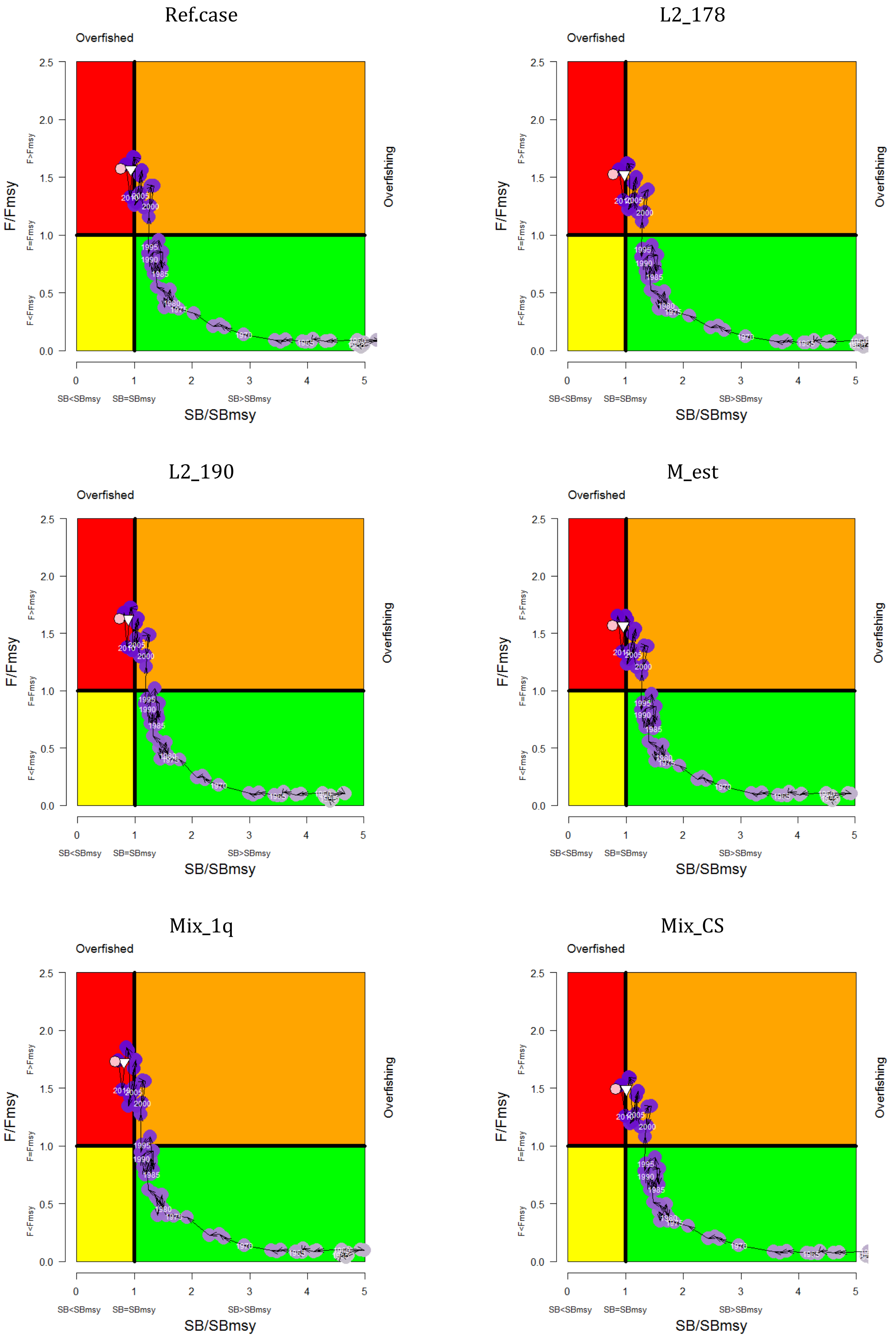


Figure 40. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points from the one-off sensitivity model runs to the reference case.

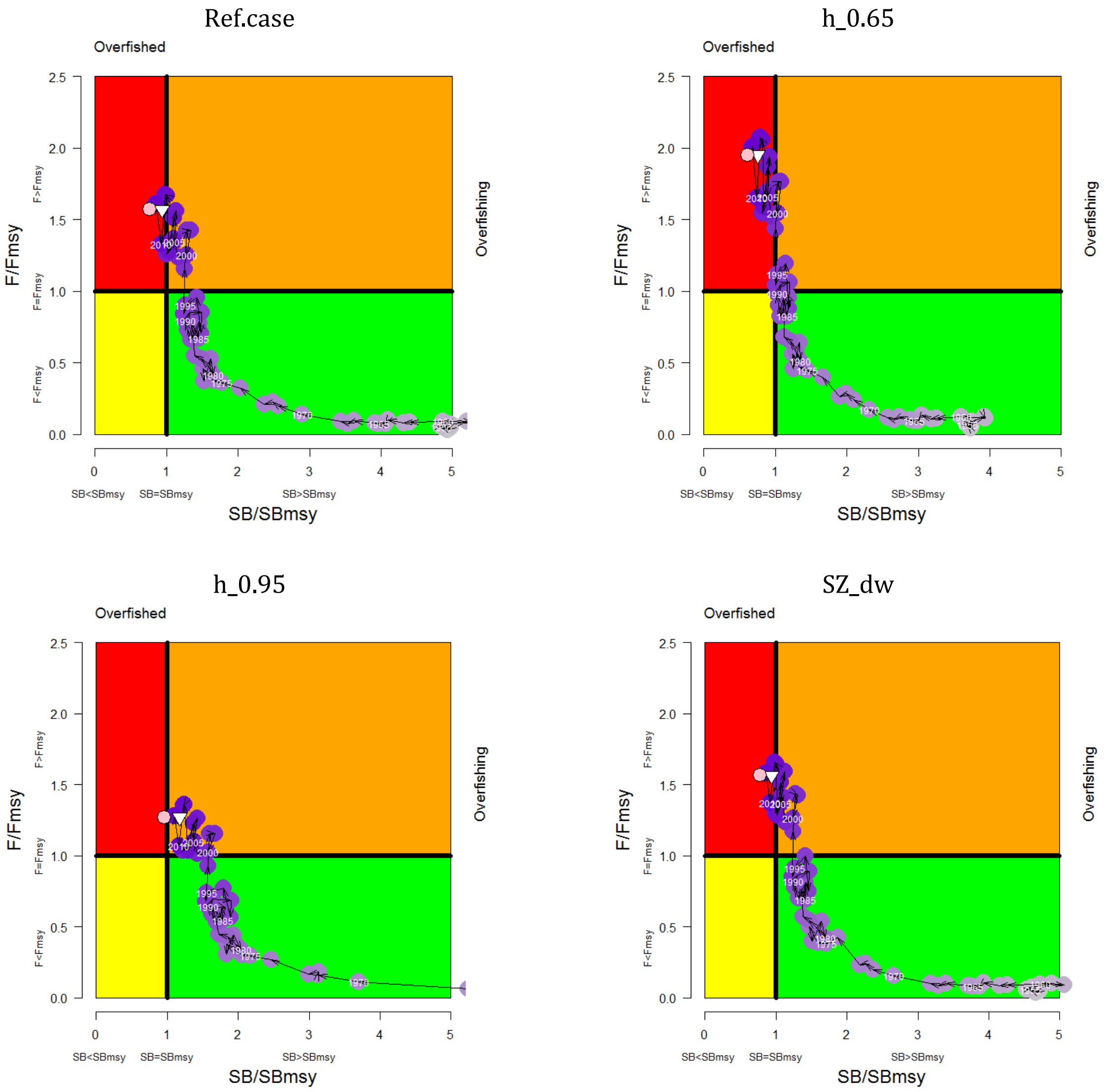


Figure 40. cont.

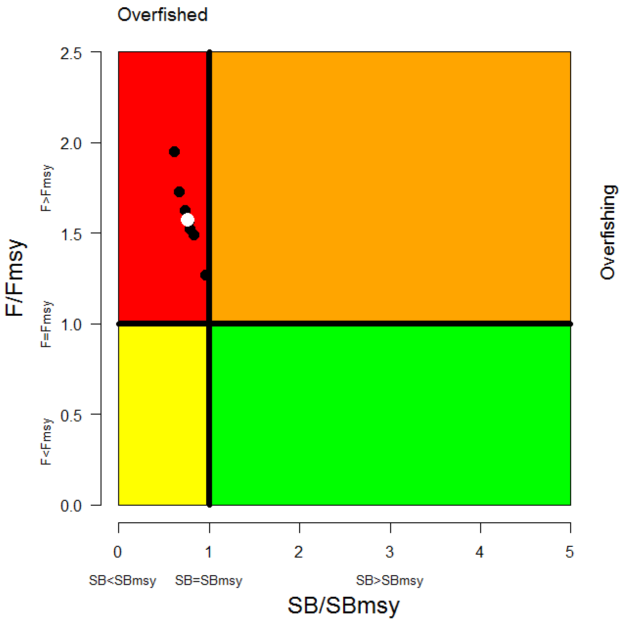


Figure 41. Summary of latest stock for the reference case (white) and one-off sensitivity runs from the structural uncertainty grid.

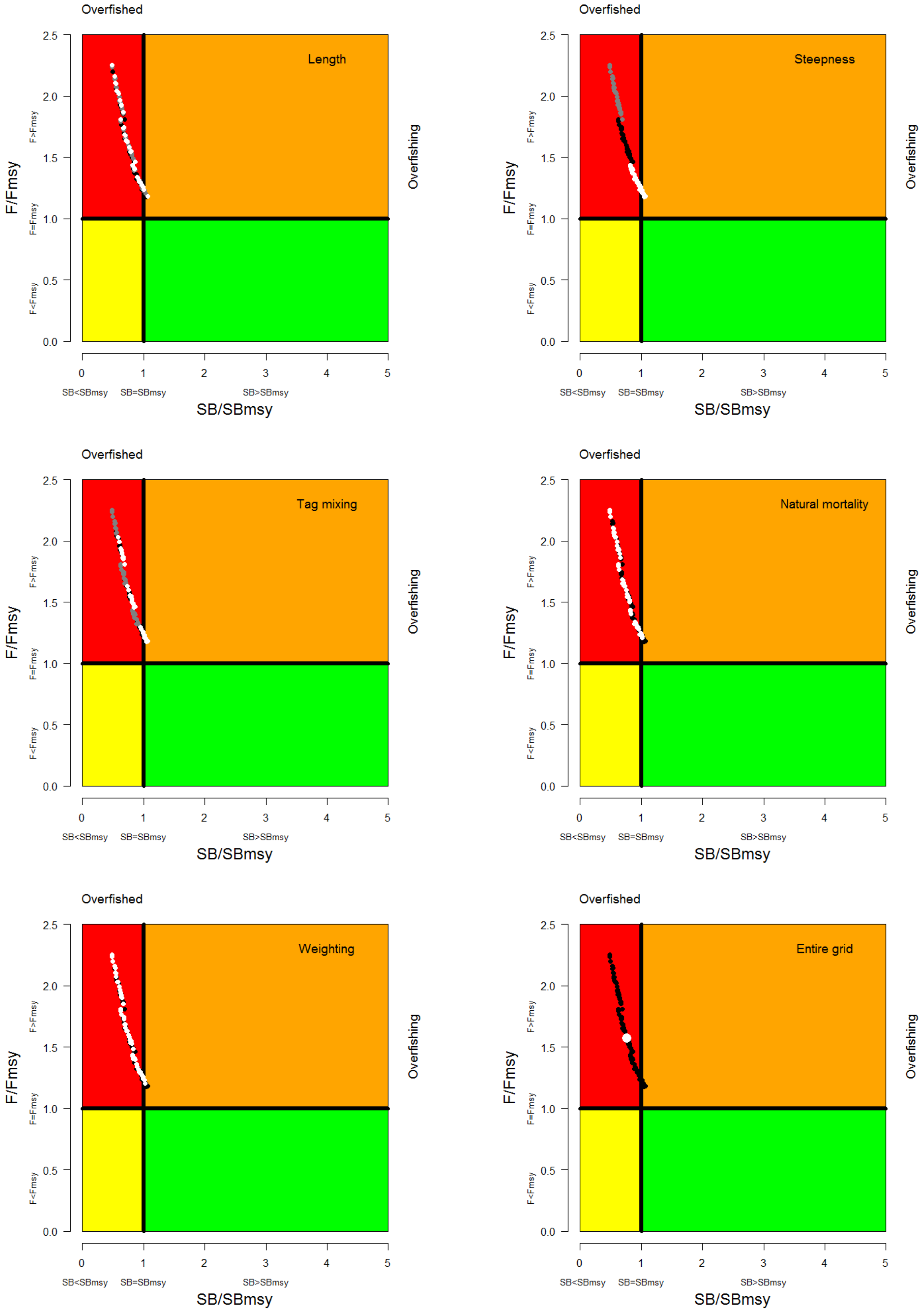


Figure 42. Plot of SB_{latest}/SB_{MSY} versus $F_{current}/F_{MSY}$ for the 108 model runs undertaken for the structural uncertainty analysis. The runs reflecting the reference case assumptions are denoted with black circles while the runs with the alternative assumption are denoted with white circles. For the steepness panel the labels are as follows: 0.65 (white), 0.95 (grey), and 0.8 (black), and for the tag mixing panel they are 2 quarters (black), 1 quarter (grey), and 28 quarters for Coral Sea releases (white).

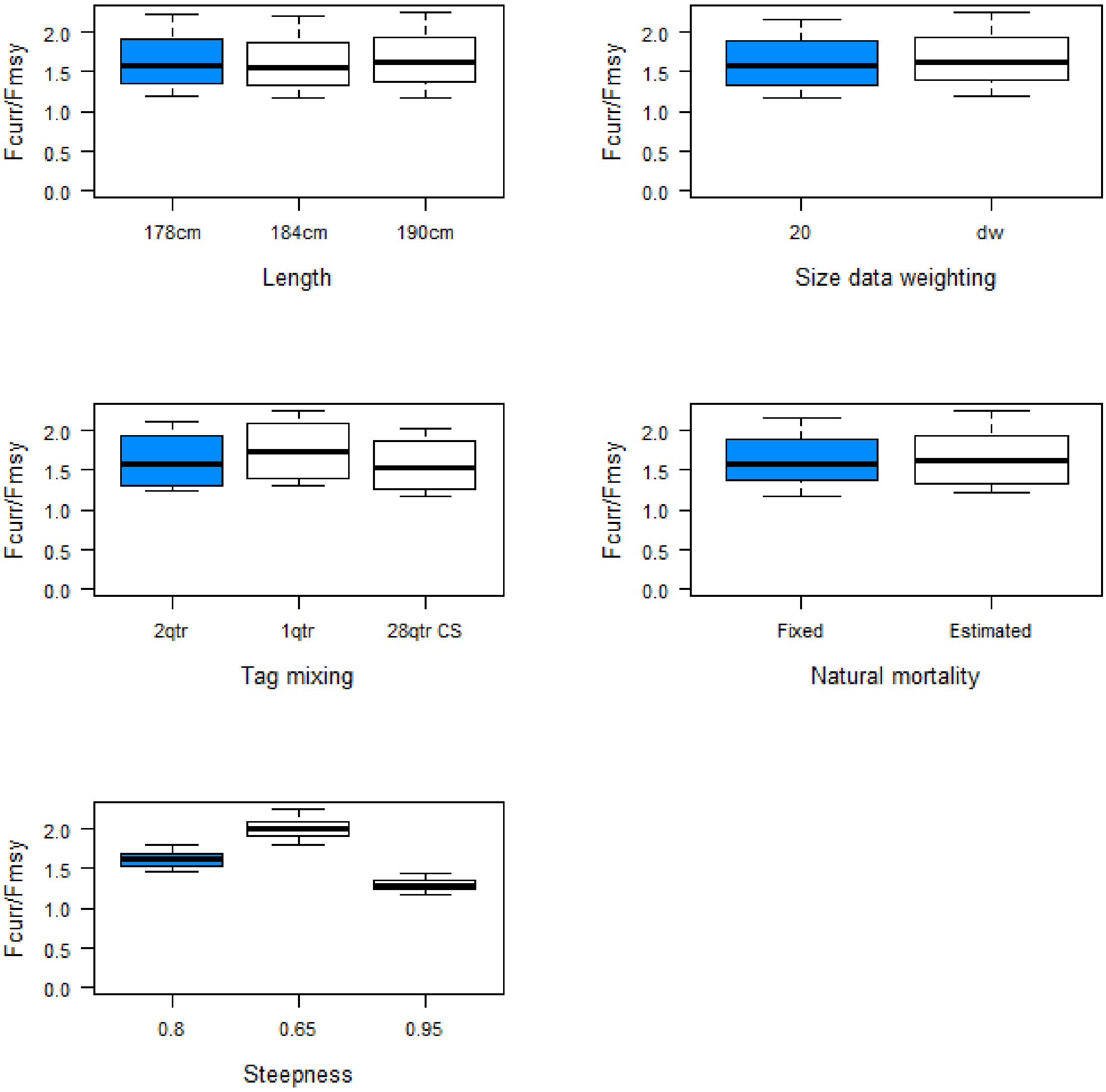


Figure 43. Box plots showing of the effects of the different factors within the structural uncertainty analysis grid on $\boldsymbol{F_{current}/F_{MSY}}$.

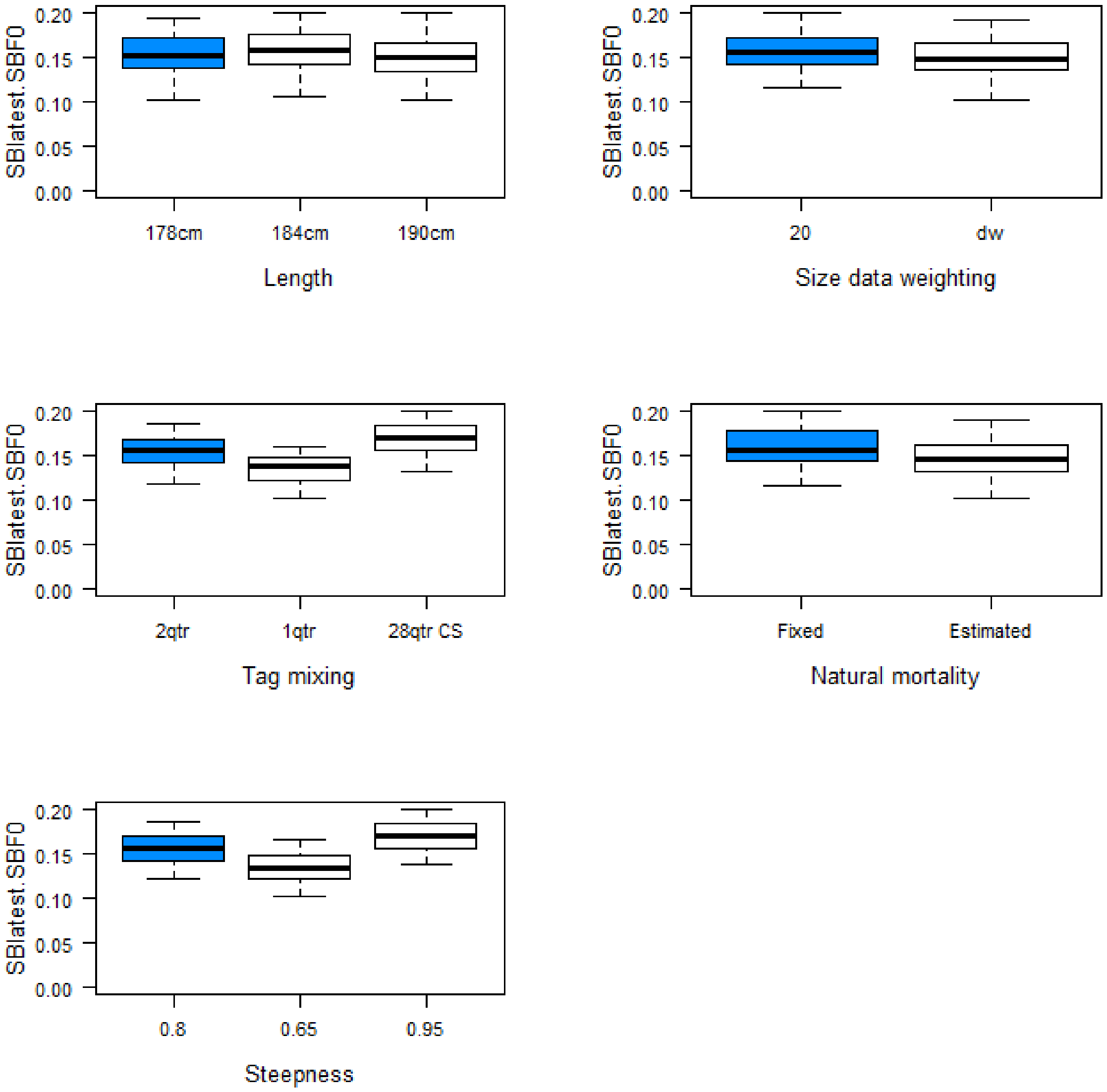


Figure 44. Box plots showing of the effects of the different factors within the structural uncertainty analysis grid on $\boldsymbol{SB_{latest}/SB_{F=0}}$.

10 ANNEX

10.1 Likelihood profile

To evaluate the information available in the observation data component on the model's estimate of scale, a maximum likelihood profile was calculated over a global scaling parameter estimated by the model ("totpop"). The profile reflected the loss of fit over all the data, i.e. the overall objective function value, caused by changing the population scale from that of the maximum likelihood estimated value. The total population scaling parameter (totpop) of MULTIFAN-CL was used to explore the range of population scale because it directly determines the level of recruitment and, hence, absolute biomass. The profile entailed fitting a set of models over a range of fixed totpop values above and below the maximum likelihood estimate.

For bigeye tuna this analysis was not undertaken with the reference case model, instead it was undertaken with the penultimate model in the stepwise development ("Swap R4 CPUE" – see Section 10.3). It was believed that this run would be the reference case model (red circle in Figure 10.1 1) until it was discovered that a better fit was found with a higher scaling parameters (green circle). The main difference between the two models was the slightly larger L2 (184cm vs. 178 cm) associated with the better fit. When the totpop parameter was freed up for estimation again (it was fixed in the likelihood profile), totpop declined closer to the previous value as the model improved its fit to the CPUE series (purple circle). The other low point on the far left (orange circle) was associated with an even larger L2 of 192 cm. This model had greatly reduced variation in length at age and was considered far less biologically plausible than the other runs and L2 values.

The difference between the model runs denoted by the red and purple points is fortunately very minimal in terms of trajectories and key reference points (see Section 10.3). therefore, the decision was made to use the purple point – with L2 fixed at 184cm as the reference case, but also include L2's of 178 cm and 190 cm in the structural uncertainty analysis.

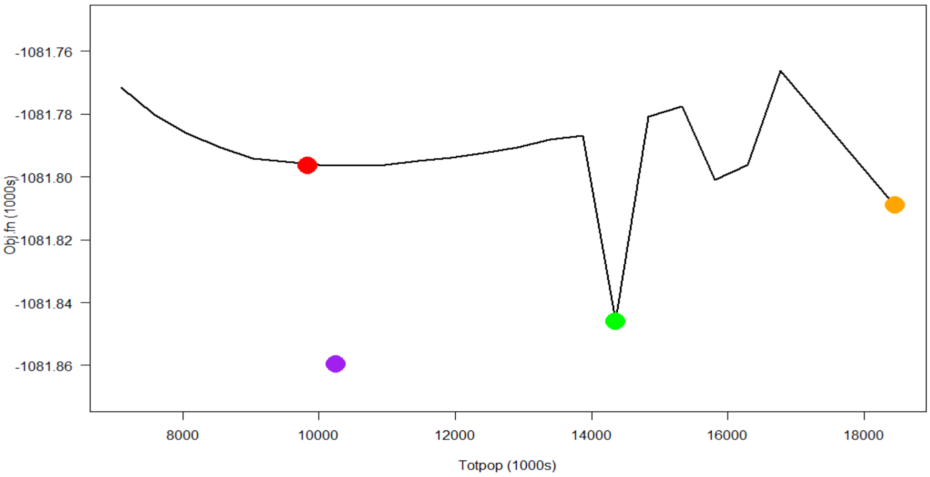


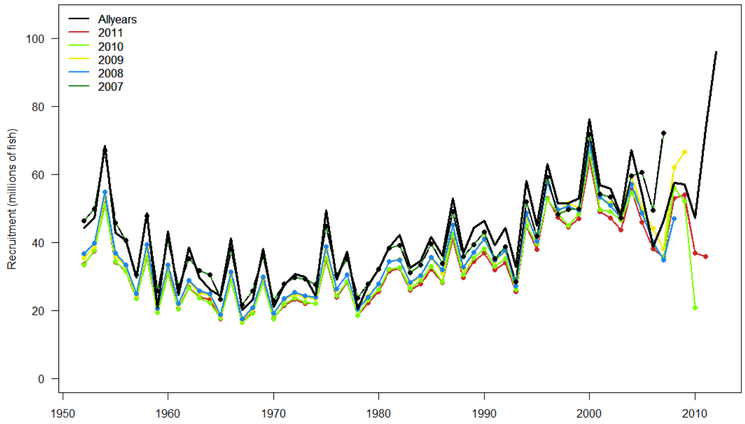
Figure 10.1 1: Profile of the marginal total negative log-likelihood in respect of the population scaling parameter, see text for description of the basis for each of the coloured circles.

10.2 Retrospective analyses

10.2.1 Removal of recent years from the 2014 assessment

Retrospective analysis involves rerunning the model by consecutively removing successive years of data to estimate model bias (Cadrin and Vaughn, 1997; Cadigan and Farrell, 2005). Note, the retrospective analyses used a different, but very similar model to the reference case with terminal recruitment estimated.

A series of models were fitted starting with the full dataset (through 2012), followed by models with the retrospective removal of all input data for the years 2012, 2011, 2010, 2009, and 2008 successively. The models are named below by the final year of data included. In addition, a one-off model was run as a variant of the reference case that included the estimation of terminal recruitments. A comparison of the recruitment and spawning biomass trajectories is shown in Figure 10.2 1.



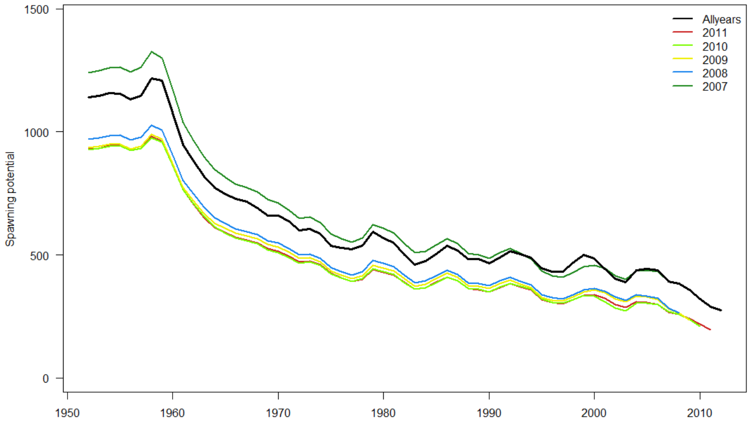


Figure 10.2 1: Recruitment estimates (top) and spawning potential (bottom) from a variant of the reference case where terminal recruitments were estimated, and for retrospective analyses for the successive removal of data from the end of the observation time series from 2012 to 2008. Model runs are denoted by the final year of data.

10.2.2 Retrospective examination of previous assessments

The reference case model for the current (2014) assessment was compared retrospectively to those for the past two assessments done in 2011 and 2010. Key management quantities for the models are listed in Table 10.2 1, a comparison of the recruitment and spawning biomass trajectories is shown in Figure 10.2 2, and a comparison of the Kobe plots of estimated stock status relative to the MSY reference points is shown in Figure 10.2 3.

Table 10.2 1: Key management quantities for the reference case models used for the WCPO bigeye tuna stock assessments in 2010, 2011, and the current assessment (2014).

Management quantity	Ref.case-2010	Ref.case-2011	Ref.case-2014
MSY	73,840	76,760	108,520
$F_{current}/F_{MSY}$	1.41	1.46	1.57
$SB_{latest}/SB_{F=0}$	0.16	0.21	0.16

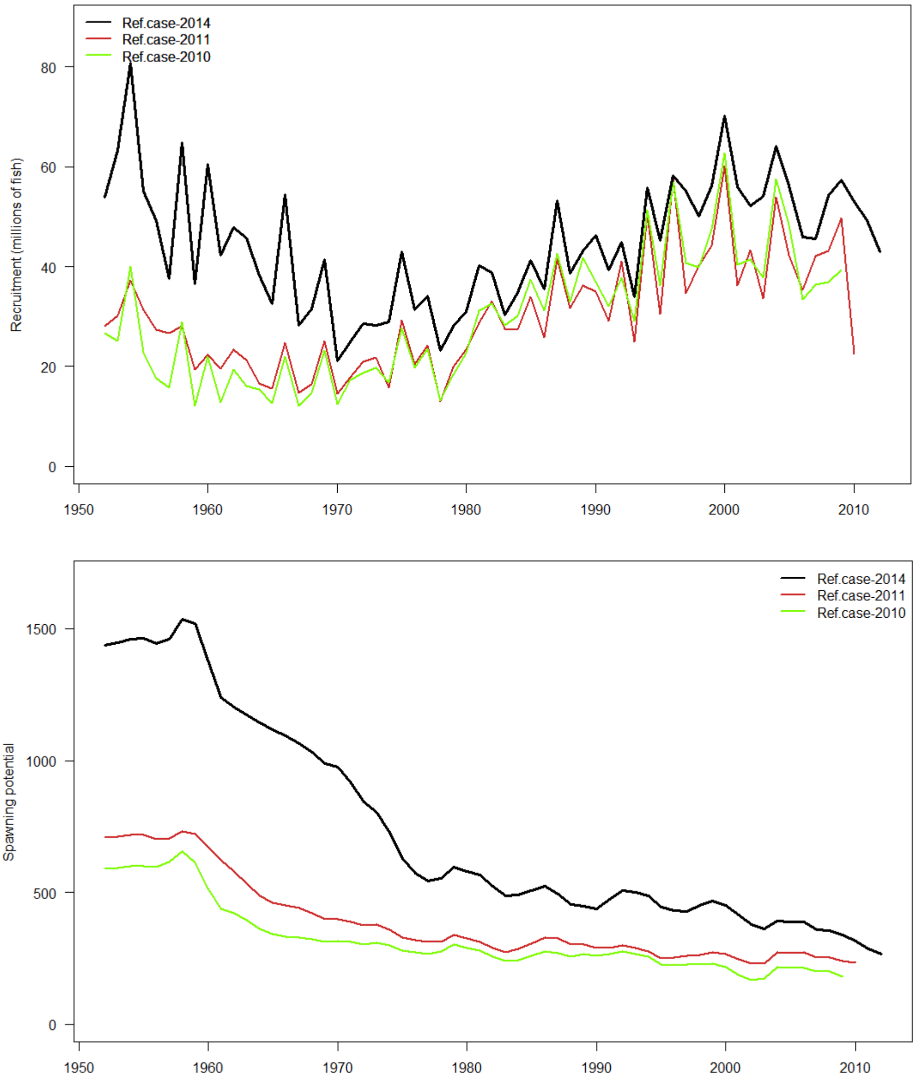


Figure 10.2 2: Annual recruitment (top) and spawning biomass (bottom) estimates from the reference case models used for the WCPO bigeye assessments from 2010, 2011 and the current assessment (2014).

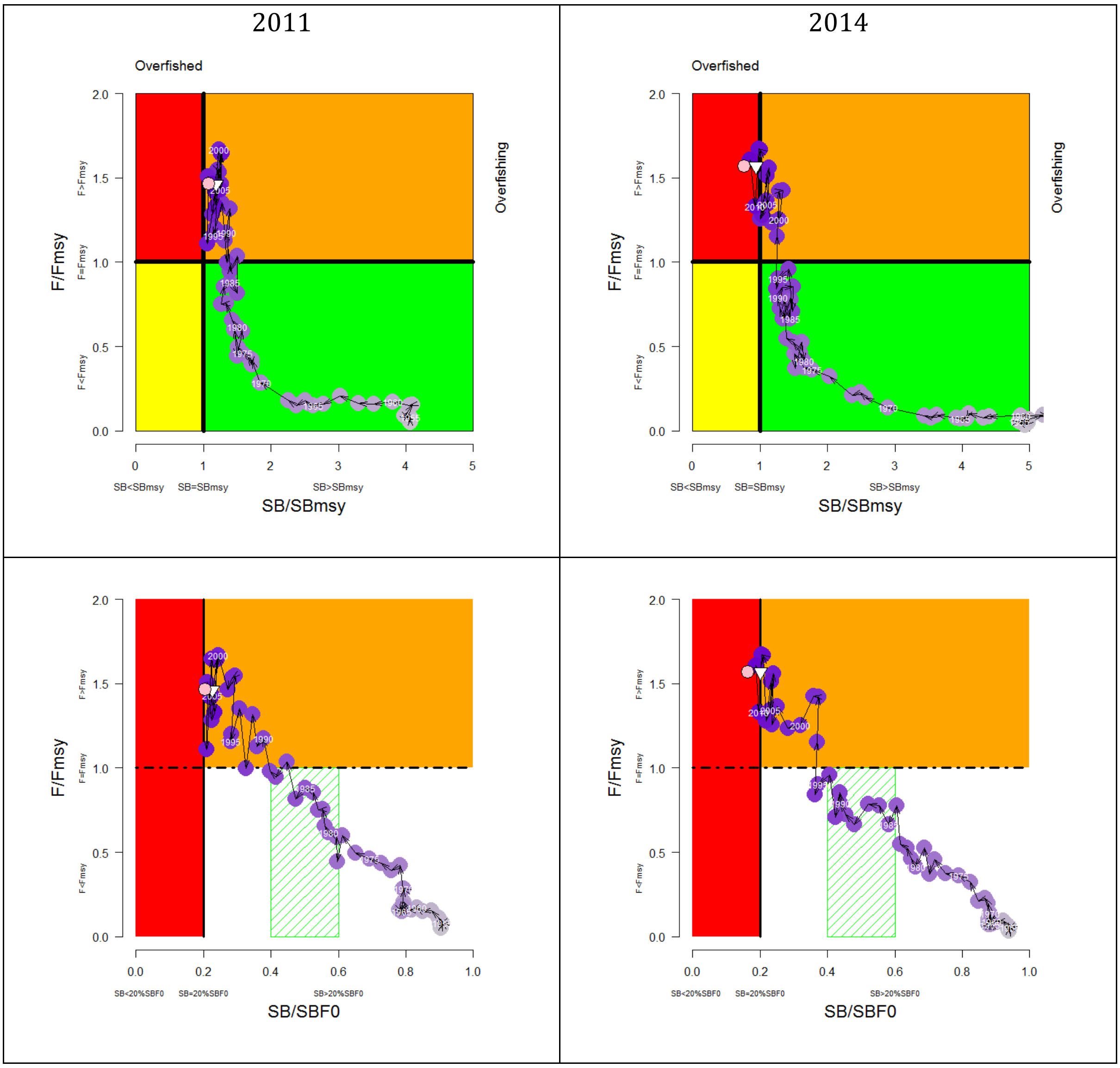


Figure 10.2 3: Comparison of the estimates of stock status in respect of spawning stock biomass relative to SB_{MSY} (top panels) and $SB_{F=0}$ (bottom panels), where the white triangle represents the average for the current period ($SB_{current}$) and the pink circle the latest period (SB_{latest}).

10.3 Stepwise model developments

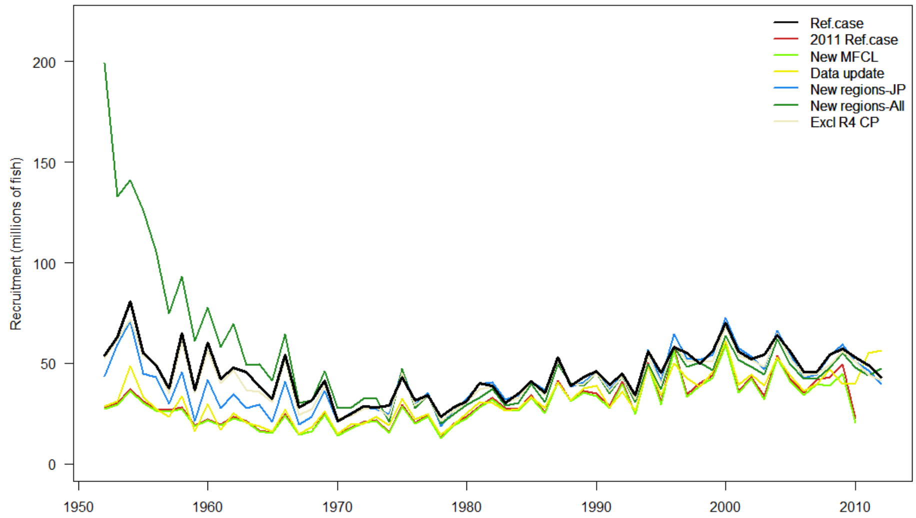
Starting with the reference case model for the 2011 bigeye tuna stock assessment, a series of stepwise developments were made towards a reference case model for the updated assessment for 2014 (Table 10.3 1). A comparison of the recruitment and spawning potential trajectories illustrates the effects of the various developments on the estimate of absolute abundance over the model period (Figure 10.3 1) and some key reference points are provided in Table 10.3 2.

Table 10.3 1: Summary of the stepwise development model runs undertaken starting with the 2011 bigeye reference case assessment model leading up to the reference case for the 2014 assessment.

Run	Description
2011	The 2011 reference case model
New MFCL	As above, but with the new MULTIFAN-CL executable
New data	Updating data to 2012, including many data treatment improvements (see Table 3). Also including the lognormal bias correction for the estimation of the spawner recruitment curve (see Section 10.4).
New regions	Extension to nine region model and expanded fisheries definitions. Changes to selectivity and reporting rate groupings as appropriate (see Table 4). This model applied the region 3 Japanese spliced operational CPUE indices to regions 7, and 8.
New CPUE	Replacing the standardized CPUE for regions 3-8 with the all-flags operational indices.
Swap R4 CPUE	Replace the all-flags operational CPUE for region 4 with the Japanese Operational spliced series. This CPUE series was leading to a blowing out in the initial conditions with 1952 spawning potential of 10-12 times the SBmsy level (or alternatively three to four times SB0).
Ref.Case	L2 was fixed at 184cm.

Table 10.3 2: Key management quantities for some selected models spanning the developments from the 2011 to 2014 reference case models. Note: *MSY* time periods are different between the first two models and the rest.

Management quantity	Ref.case-2011	New MFCL	New data	New regions	New CPUE	Swap R4 CPUE	Ref.case-2014
MSY	76,760	75,600	99,040	106,720	111,160	106,800	108,520
$F_{current}/F_{MSY}$	1.46	1.53	1.53	1.47	1.67	1.58	1.57
$SB_{latest}/SB_{F=0}$	0.21	0.20	0.18	0.18	0.15	0.16	0.16



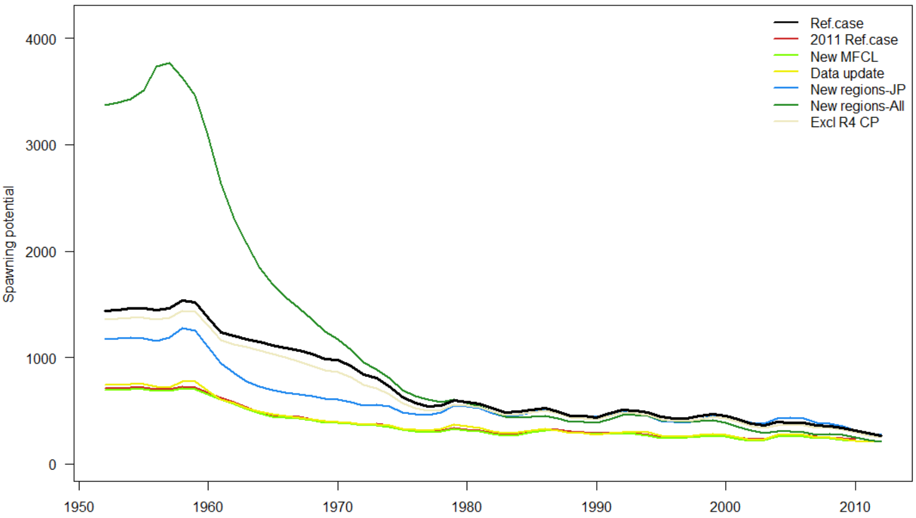


Figure 10.3 1: Estimated annual recruitment (top) and spawning potential (bottom) for the WCPO obtained from runs undertaken in the stepwise development from the 2011 reference case to the 2014 reference case. Model runs are as described in Table 10.3 1.

10.4 Other model developments

In this section we highlight a small subset of other runs undertaken during the assessment. Several of these demonstrate the impact of some MULTIFAN-CL features that were used in the changes from the previous assessment (Table 10.4 1) and there is also a model run where steepness was estimated. Many of the MULTIFAN-CL features were implemented in the step when data were updated in the six region model. To isolate the impact of these we have here shown them as one-off changes to the reference case model.

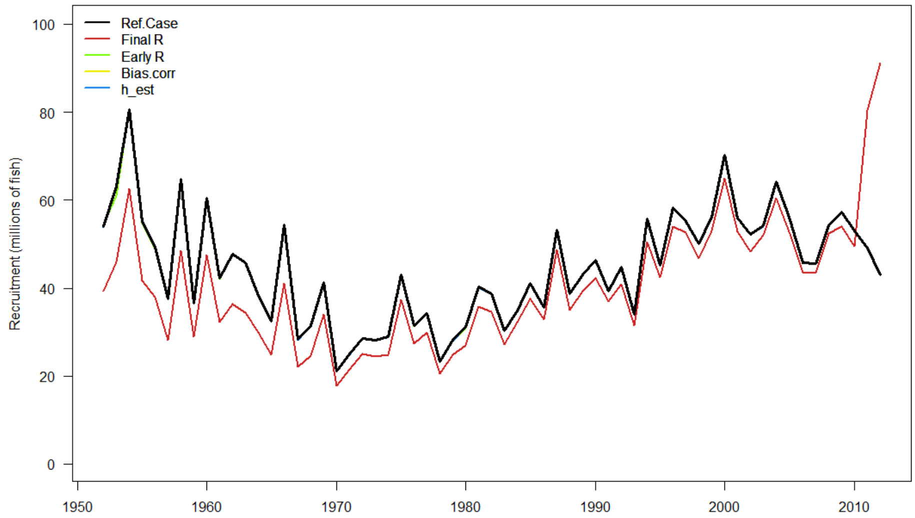
A comparison of the recruitment and spawning potential trajectories illustrates the effects of the various developments on the estimate of absolute abundance over the model period (Figure 10.4 1) and some key reference points are provided in Table 10.4 2.

Table 10.4 1: Four one of sensitivity analyses to the reference case – three demonstrate the impacts of new modelling approaches.

Run	Description
Ref.Case	2014 reference case
Final Rdevs	When the final six terminal recruitment deviates are estimated instead of being fixed at zero.
Early Rdevs	When the first ten years of estimated spawner/recruitment estimates are included in the estimation of the spawner recruitment relationship.
Bias correction	Bias correction is not applied in the estimation of the spawner recruitment relationship – so it is essentially based upon median rather than mean recruitment
Estimate steepness	Estimation of steepness using a very diffuse beta prior

Table 10.4 2: Key management quantities for the model runs described in Table 10.4 1.

Management quantity	Ref.case-2014	Fix final rdevs	Exclude early rdevs	SRR bias correction	Estimate steepness
MSY(mt)	108,520	106,240	112,160	91,000	118,720
$F_{current}/F_{MSY}$	1.57	1.74	1.57	1.62	1.18
$SB_{latest}/SB_{F=0}$	0.16	0.13	0.16	0.16	0.18



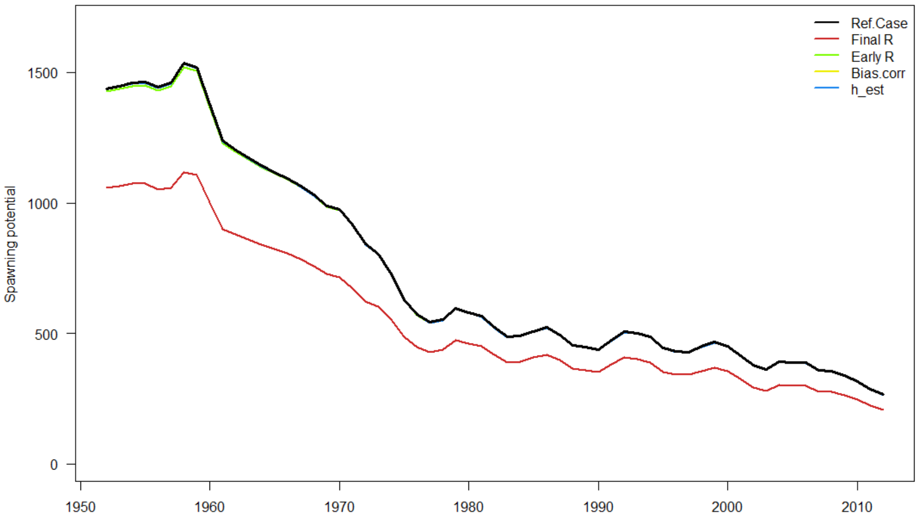


Figure 10.4 1: Estimated annual recruitment (top) and spawning potential (bottom) for the WCPO obtained from runs described in Table 10.4 1.

10.5 Doitall script

```
#!/bin/sh
cd $_CONDOR_SCRATCH_DIR
export PATH=.:$PATH
export ADTMP1=.

# Apply the recruitment functions changes to the PAR file.
# $1 Name of the PAR file.
# $2 New value.
function recruitmentConstraints {
    if [ -z $1 ]
    then
       echo "Needs filename as argument.";
       exit 1;
    elif [ -z $2 ]
    then
       echo "Needs new value argument.";
       exit 1;
    elif [ -f "$1" ]
    then
# Read line per line.
       while read LINE
       do
# Found the desired header.
           if [ "$LINE" == "# Seasonal growth parameters" ]
           then
              echo $LINE >> $1.new;
              for ((L=1 ; L < 2 ; L++))
              do
                   read LINE;
# Skip blank or comment line.
                   if [[ "$LINE" == "#" || "$LINE" == "" ]]
                   then
                      #echo "Found a matching line "$LINE;
                      L=`expr $L - 1`;
                      echo $LINE >> $1.new;
                   else
                      #echo "Processing line "$LINE;
                      I=0;
                      for VALUE in $LINE
                      do
                          I=`expr $I + 1`;
# Change the 29th value.
                          if [ $I -eq 29 ]
                          then
                             echo -n $2" " >> $1.new;
                          else
                             echo -n $VALUE" " >> $1.new ;
                          fi
                      done
                      echo "" >> $1.new;
                  fi
              done
# Write line AS IS.
           else
              echo $LINE >> $1.new;
           fi
       done < $1;
# Create a backup copie.
       mv $1 $1.bak;
# Move temporary file to target file.
       mv $1.new $1;
    fi;
}
#  ------------------------
#  PHASE 0 - create initial par file
#  ------------------------
#
if [ ! -f 00.par ]; then
  mfclo64 bet.frq bet.ini 00.par -makepar
fi
#
#  ------------------------
#  PHASE 1 - initial par
#  ------------------------
```

```
#
if [ ! -f 01.par ]; then
  mfclo64 bet.frq 00.par 01.par -file - <<PHASE1
#------------------------------------------------------------------------------
# Initial phase control option
#
  1 32 6          # keep growth parameters fixed
#
#------------------------------------------------------------------------------
# Recruitment and initial population settings
#
  1 149 100       # recruitment deviations penalty
  1 400 6         # Final six recruitment deviates set to 0
  2 113 0         # scaling init pop - turned off
  2 177 1         # use old totpop scaling method
  2 32 1          # and estimate the totpop parameter
  2 57 4          # sets no. of recruitments per year to 4
  2 93 4          # sets no. of recruitments per year to 4 (is this used?)
  2 94 2 2 95 20  # initial age structure based on Z for 1st 20 periods
  2 116 70        # default value for rmax in the catch equations
#
#------------------------------------------------------------------------------
# Likelihood component settings
#
  1 141 3         # sets likelihood function for LF data to normal
  -999 49 20      # divide LF sample sizes by 20 (default=10)
  -999 50 20      # divide WF sample sizes by 20 (default=10)
  1 111 4         # sets likelihood function for tags to negative binomial
#
#------------------------------------------------------------------------------
#
# Selectivity settings
#
  -999 3 37        # all selectivities equal for age class 37 and older
  -999 26 2        # sets length-dependent selectivity option
  -999 57 3        # uses cubic spline selectivity
  -999 61 5        # with 5 nodes for cubic spline
  -6 57 1          # logistic

  -14 16 2  -14 3 25         # FAD fisheries age-based with splines and set to zero above 25
quarters
  -25 16 2  -25 3 25
  -26 16 2  -26 3 25
  -31 16 2  -31 3 25

  -16 16 2  -16 3 25

  -15 16 2  -15 3 30         # Free school fisheries
  -17 16 2  -17 3 30
  -27 16 2  -27 3 30
  -32 16 2  -32 3 30

  -18 16 2 -18 3 12          # Forcing selectivity to zero for large fish in the small MISC
fisheries
  -24 16 2 -24 3 12
  -29 16 2 -29 3 12
  -33 16 2 -33 3 12

  -20 16 2 -20 3 25          # And also for the PL fisheries
  -21 16 2 -21 3 25
  -22 16 2 -22 3 25
  -23 16 2 -23 3 25
# grouping of fisheries with common selectivity
  -1 24 1
  -2 24 1
  -3 24 2
  -10 24 2
  -4 24 3
  -9 24 3
  -12 24 3
  -30 24 3
  -13 24 3
  -5 24 4
  -6 24 5
  -7 24 6
  -8 24 7
```

```
  -11 24 8
  -28 24 8    #SJH2014 group to fishery 11 in the early phases
  -14 24 9
  -25 24 9
  -26 24 9
  -31 24 9
  -16 24 10   #SJH2014
  -15 24 11
  -27 24 11
  -32 24 11
  -18 24 12
  -24 24 12
  -29 24 12  # much smaller fish than other PL
  -33 24 12
  -19 24 13
  -20 24 14  # group JP PS and PL together - strange LF's but with some big fish on occassion
  -21 24 14
  -22 24 14
  -23 24 14
  -17 24 15  # split it out because the fit is crap
#
#------------------------------------------------------------------------------
# Catchability settings
#
# grouping of fisheries with common catchability
  -1 29 1
  -2 29 1
  -3 29 2
  -4 29 1
  -5 29 3
  -8 29 1
  -9 29 1
  -6 29 4
  -10 29 5
  -12 29 1
  -11 29 6
  -13 29 1
  -7 29 1
  -14 29 7
  -15 29 8
  -16 29 9
  -17 29 10
  -18 29 11
  -19 29 12
  -20 29 13
  -21 29 14
  -22 29 15
  -23 29 16
  -24 29 17
  -26 29 19
  -27 29 20
  -28 29 21
  -29 29 22
  -30 29 1   # With LL-ALL9 linked
  -31 29 23
  -32 29 24
  -33 29 25
  -25 29 18
  -1 60 1
  -2 60 1
  -3 60 2
  -4 60 1
  -5 60 3
  -8 60 1
  -9 60 1
  -6 60 4
  -10 60 5
  -12 60 1
  -11 60 6
  -13 60 1
  -7 60 1
  -14 60 7
  -15 60 8
  -16 60 9
  -17 60 10
  -18 60 11
```

```
  -19 60 12
  -20 60 13
  -21 60 14
  -22 60 15
  -23 60 16
  -24 60 17
  -26 60 19
  -27 60 20
  -28 60 21
  -29 60 22
  -30 60 1    # With LL-ALL9 linked
  -31 60 23
  -32 60 24
  -33 60 25
  -25 60 18
#
#-------------------------------------------------------------------------------
# Tag dynamics settings
#
  1 33 90         # maximum tag reporting rate for all fisheries is 0.9
  2 96 30         # tag pooling at 30 quarters after release so not to have to follow them
forever
  -9999 1 1       # sets no. mixing periods for all tag release groups to 1
  2 198 1         # Estimate tag reporting rates in new tag group / fishery structure
  -999 43 0       # no longer estimating negative binomial variance
  -999 44 0
#
# grouping of fisheries for tag return data
  -1 32 1
  -2 32 2
  -3 32 3
  -4 32 4
  -5 32 5
  -6 32 6
  -7 32 7
  -8 32 8
  -9 32 9
  -10 32 10
  -11 32 11
  -12 32 12
  -13 32 13
  -14 32 14
  -15 32 14
  -16 32 15
  -17 32 15
  -18 32 16
  -19 32 17
  -20 32 18
  -21 32 19
  -22 32 20
  -23 32 20
  -24 32 21
  -25 32 22
  -26 32 23
  -27 32 23
  -28 32 24
  -29 32 25
  -30 32 26
  -31 32 27
  -32 32 27
  -33 32 28
#
#-------------------------------------------------------------------------------
# Effort deviation settings
#
# sets penalties for effort deviations (negative penalties force effort devs
# to be zero when catch is unknown)
 -999 13 -3      # to 1 for longline fisheries where effort is standardized and CV's provided
in frq file
  -1 13 1
  -2 13 1
  -4 13 1
  -7 13 1
  -8 13 1
  -9 13 1
  -12 13 1
```

```
  -13 13 1
  -18 13 3      # to 3 for those fisheries with only effort in last_yr
  -19 13 3
  -24 13 3
  -25 13 3
  -33 13 3
## use time varying effort weight for LL fisheries
 -1 66 1
 -2 66 1
 -4 66 1
 -7 66 1    #just using R3 cpue for now     SJH2014
 -8 66 1    #just using R3 cpue for now     SJH2014
 -9 66 1
 -12 66 1
 -13 66 1
#
#------------------------------------------------------------------------------
# Catchability deviation settings
#
  -14 15 1
  -15 15 1
  -16 15 1
  -17 15 1
  -18 15 1       # low penalty for PH.ID MISC.
  -24 15 1
  -25 15 1
  -26 15 1
  -27 15 1
  -31 15 1
  -32 15 1
  -33 15 1            #SJH2014
PHASE1
fi
#------------------------------------------------------------------------------
#
#
#------------------------------------------------------------------------------
#   PHASE 2
#------------------------------------------------------------------------------
if [ ! -f 02.par ]; then
  mfclo64 bet.frq 01.par 02.par -file - <<PHASE2
  -999 4 4        # possibly not needed
  -999 21 4       # possibly not needed
  1 190 1         # write plot-xxx.par.rep
  1 1 500         # set max. number of function evaluations per phase to 200
 -999 14 10       # Penalties to stop F blowing out
  2 35 10         # Set effdev bounds to +- 10 (need to do AFTER phase 1)
  2 144 100000    # Increase weight on catch likelihood
PHASE2
fi
#------------------------------------------------------------------------------
#   PHASE 3
#------------------------------------------------------------------------------
if [ ! -f 03.par ]; then
  mfclo64 bet.frq 02.par 03.par -file - <<PHASE3
  2 70 1          # activate parameters and turn on
  2 71 1          # estimation of temporal changes in recruitment distribution
  2 178 1         # constraint on regional recruitments to be equal to one each model period
#SJH2014
PHASE3
fi
#------------------------------------------------------------------------------
#   PHASE 4
#------------------------------------------------------------------------------
if [ ! -f 04.par ]; then
  mfclo64 bet.frq 03.par 04.par -file - <<PHASE4
  2 68 1          # estimate movement coefficients
  2 69 1
PHASE4
fi
#------------------------------------------------------------------------------
#   PHASE 5
#------------------------------------------------------------------------------
if [ ! -f 05.par ]; then
  mfclo64 bet.frq 04.par 05.par -file - <<PHASE5
  -999 27 1       # estimate seasonal catchability for all fisheries
```

```
  -18 27 0        # except those where
  -19 27 0        # only annual catches
  -24 27 0
  -25 27 0        #SJH2014
  -29 27 0        #SJH2014
  -33 27 0        #SJH2014
PHASE5
fi
#------------------------------------------------------------------------------
#   PHASE 6
#------------------------------------------------------------------------------
if [ ! -f 06.par ]; then
  mfclo64 bet.frq 05.par 06.par -file - <<PHASE6
  -3 10 1         # estimate
  -5 10 1         # catchability
  -6 10 1         # for all
  -10 10 1        # non-std. longline
  -11 10 1        # fisheries
  -14 10 1
  -15 10 1
  -16 10 1
  -17 10 1
#  -18 10 1
#  -19 10 1
  -20 10 1
  -21 10 1
  -22 10 1
  -23 10 1
#  -24 10 1
#  -25 10 1
  -26 10 1
  -27 10 1
  -28 10 1
  -29 10 1
  -31 10 1
  -32 10 1
#  -33 10 1
  -999 23 23      # and do a random-walk step every 23+1 months
PHASE6
fi
#------------------------------------------------------------------------------
#   PHASE 7
#------------------------------------------------------------------------------
if [ ! -f 07.par ]; then
  mfclo64 bet.frq 06.par 07.par -file - <<PHASE7
  -100000 1 1     # estimate
  -100000 2 1     # time-invariant
  -100000 3 1     # distribution
  -100000 4 1     # of
  -100000 5 1     # recruitment
  -100000 6 1
  -100000 7 1
  -100000 8 1
  -100000 9 1
PHASE7
fi

#------------------------------------------------------------------------------
#   PHASE 8
#------------------------------------------------------------------------------
if [ ! -f 08.par ]; then
  mfclo64 bet.frq 07.par 08.par -file - <<PHASE8
  1 14 1          # estimate von Bertalanffy K
  1 12 1          # and mean length of age 1
  1 13 0          # and mean length of age n
  1 1 300         # bit more of a chance
PHASE8
fi
#------------------------------------------------------------------------------
#   PHASE 9
#------------------------------------------------------------------------------
if [ ! -f 09.par ]; then
  mfclo64 bet.frq 08.par 09.par -file - <<PHASE9
  1 16 1  1 15 1  # estimate length dependent SD
  1 173 8         # activate independent mean lengths for 1st 8 age classes
  1 182 10        # penalty weight
```

```
  1 184 1         # estimate parameters
  1 1 300         # get better handle on growth as we will fix it in the final phase
PHASE9
fi

recruitmentConstraints 09.par 0.8
#-------------------------------------------------------------------------------
#   PHASE 10
#-------------------------------------------------------------------------------
if [ ! -f 10.par ]; then
  mfclo64 bet.frq 09.par 10.par -file - <<PHASE10
  2 145 -1       # use SRR parameters - low penalty for deviation
  2 146 1        # estimate SRR parameters
  2 161 1        # lognormal bias correction
  2 163 0        # use steepness parameterization of B&H SRR
  1 149 0       # set to 0 for the moment
  2 147 1       # time period between spawning and recruitment
  2 148 20       # period for MSY calc - last 20 quarters
  2 155 4       # but not including last year
  2 199 204      # start period for SRR estimation is start 1962
  2 200 6        # end period for SRR estimation is mid 2010
  -999 55 1      # Do impact analysis
  2 171 1        # Include SRR-based equilibrium recruitment to compute unfished biomass
  2 193 1        # Recognises that initial population has some exploitation
  1 1 3000       # function evaluations for the final phase - TO BEGIN WITH
  1 50 -3        # convergence criteria
PHASE10
fi
```

10.6 Initialization (ini) file

```
# ini version number
1001
# number of age classes
40
# tag fish rep
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.586 0.586 0.586 0.586 0.764 0.764 0.5
0.5 0.5 0.5 0.764 0.764 0.586 0.586 0.5 0.5 0.5 0.586 0.586 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.586 0.586 0.586 0.586 0.764 0.764 0.5
0.5 0.5 0.5 0.764 0.764 0.586 0.586 0.5 0.5 0.5 0.586 0.586 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.586 0.586 0.586 0.586 0.764 0.764 0.5
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0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.586 0.586 0.586 0.586 0.764 0.764 0.5
0.5 0.5 0.5 0.764 0.764 0.586 0.586 0.5 0.5 0.5 0.586 0.586 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.593158 0.593158 0.583295 0.583295 0.5
0.5 0.614833 0.5 0.5 0.5 0.5 0.5 0.699724 0.699724 0.5 0.5 0.5 0.593158 0.593158 0.5
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0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.593158 0.593158 0.583295 0.583295 0.5
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50 50 69.9724 69.9724 50 50 50 59.3158 59.3158 50
50 50 50 50 50 50 50 50 50 50 80 50 50 50 50 50 50 50 50 50 50 50 50 50 50 50 50 80 50 50 50
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50 50 50 50 50 50 50 50 50 50 80 50 50 50 50 50 50 50 50 50 50 50 50 50 50 50 50 80 50 50 50
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50 50 50 50 50 50 50 50 50 50 80 50 50 50 50 50 50 50 50 50 50 50 50 50 50 50 50 80 50 50 50
50 50
50 50 50 50 50 50 50 50 50 50 50 50 50 58.6 58.6 58.6 58.6 76.4 76.4 50 50 50 50 76.4 76.4
58.6 58.6 50 50 50 58.6 58.6 50
# tag_fish_rep penalty
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1 1 1 1 1 1 1 1 1 1 1 1 1 84 84 84 84 20 20 1 1 1 1 20 20 84 84 1 1 1 84 84 1
1 1 1 1 1 1 1 1 1 1 1 1 1 89 89 33 33 1 1 2 1 1 1 1 1 163 163 1 1 1 89 89 1
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1 1 1 1 1 1 1 1 1 1 1 1 1 89 89 33 33 1 1 2 1 1 1 1 1 163 163 1 1 1 89 89 1
1 1 1 1 1 1 1 1 1 1 1 1 1 89 89 33 33 1 1 2 1 1 1 1 1 163 163 1 1 1 89 89 1
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1 1 1 1 1 1 1 1 1 1 1 1 1 89 89 33 33 1 1 2 1 1 1 1 1 163 163 1 1 1 89 89 1
1 1 1 1 1 1 1 1 1 1 1 1 1 84 84 84 84 20 20 1 1 1 1 20 20 84 84 1 1 1 84 84 1
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1 1 1 1 1 1 1 1 1 1 1 1 1 84 84 84 84 20 20 1 1 1 1 20 20 84 84 1 1 1 84 84 1
1 1 1 1 1 1 1 1 1 1 1 1 1 89 89 33 33 1 1 2 1 1 1 1 1 163 163 1 1 1 89 89 1
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1 1 1 1 1 1 1 1 1 1 1 1 1 84 84 84 84 20 20 1 1 1 1 20 20 84 84 1 1 1 84 84 1
1 1 1 1 1 1 1 1 1 1 50 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 50 1 1 1 1 1
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1 1 1 1 1 1 1 1 1 1 50 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 50 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 84 84 84 84 20 20 1 1 1 1 20 20 84 84 1 1 1 84 84 1
# maturity at age
0 0 0 0 0 0 0.00400395317140697 0.0090620208084776 0.0180060612167527 0.0330387520958537
0.0573902985342996 0.0970236867822348 0.159884640300079 0.255818526902294 0.392823118863806
0.563563999511659 0.737564543664718 0.873349855376351 0.955121228431595 0.992835343697603 1
0.988646552503548 0.965853785531792 0.937021774261042 0.904720819463276 0.869108374445115
0.831895989848481 0.793643708326688 0.754806283338424 0.715835214976602 0.677079000946573
0.638837166188084 0.601362904388722 0.564866117183414 0.529516747617393 0.495448303636788
0.462761472717955 0.431527738429156 0.401792922120901 0.373580586698095
# natural mortality (per year)
0.117807903982688
# movement map
1 2 3 4
# diffusion coffs (per year)
```

```
0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
0.1 0.1 0.1
0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
0.1 0.1 0.1
0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
0.1 0.1 0.1
0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
0.1 0.1 0.1
# age_pars
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0.529511970569348 0.344963492569347 0.126636607569348 -0.153068886430652 -0.163617164430652 -
0.163885179605751 -0.163885179605751 -0.163885179605751 -0.163885179605751 -0.156486849146481
-0.152600947794065 -0.1465977706647 -0.137688051002927 -0.124742019083764 -0.105564246936977 -
0.0779704787956052 -0.0401084957979585 0.00771857746052794 0.0589327039802937
0.101721152591393 0.125959977021629 0.132366430407387 0.127815281660447 0.117724684936128
0.105376111973827 0.092101082809219 0.078781111843572 0.0657134265134084 0.0527459978289533
0.0401450777775319 0.0279429933437338 0.0161670693500227 0.00483956407764969 -
0.00602228380189533 -0.0164061088045999 -0.0263041869763792 -0.0357131347138716 -
0.0446335543122571 -0.0530696422103984 -0.0610287749575805
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
# recruitment distribution by region
0.05 0.1 0.2 0.35 0.04 0.05 0.15 0.05 0.01
# The von Bertalanffy parameters
# Initial  lower bound  upper bound
# ML1
21 20 40
# ML2
173 140 200
# K (per year)
0.075 0 0.3
# Length-weight parameters
1.9729e-05 3.0247
# sv(29)
0.9
# Generic SD of length at age
6.71 3 12
# Length-dependent SD
0.7289 -1.5 1.5
# The number of mean constraints
0
```