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# Stock assessment of skipjack tuna in the western and central Pacific Ocean

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# Executive Summary

This paper describes the 2016 stock assessment of skipjack tuna *Katsuwonus pelamis* in the western and central Pacific Ocean. A further three years data were available since the last stock assessment was conducted in 2014, and the model time period extends to the end of 2015. New developments to the stock assessment include addressing the recommendations of the 2014 stock assessment report (Rice et al., 2014), exploration of uncertainties in the assessment model, particularly in response to the inclusion of additional years of data, and to improve diagnostic weaknesses of previous assessments.

This assessment is supported by the analysis of catch-per-unit-effort data for pole-and-line (Kiyofuji, 2016) and purse seine fisheries (Bigelow et al., 2016; Tremblay-Boyer et al., 2016), tagging data (McKechnie et al., 2016) and the data summaries for fisheries definitions used in the stock assessment (McKechnie, 2016).

Changes made in the progression from the 2014 to 2016 reference case models include: a modified tagging input file that no longer includes Japanese tag releases before 1998; changes, and exploration of the relative weightings of CPUE, length composition and tagging data; application of new features in MULTIFAN-CL; and modifications to model parameters such as selectivity to improve fit to the various data sources.

In addition to a single reference case model that we present, we report the results of one-off sensitivity models to explore the impact of key data and model assumptions for the reference case model on the stock assessment results and conclusions. We also undertook a structural uncertainty analysis (model grid) for consideration in developing management advice where all possible combinations of those areas of uncertainty from the one-off models were included.

The main conclusions of the current assessment are largely consistent with previous assessments and are based on the results of the reference case model and consideration of the results of sensitivity runs (including the structural uncertainty grid). These general conclusions can be summarised concisely as:

1. The current stock assessment estimates stock status to be very similar to the 2014 assessment, with a period of moderately higher spawning biomass over the subsequent years.

2. Current catches are lower than, but approaching estimated MSY.

3. Fishing mortality of all age-classes is estimated to have increased significantly since the beginning of industrial tuna fishing, but fishing mortality still remains below the level that would result in the MSY, and is estimated to have decreased moderately in the last several years.

4. Recent levels of spawning biomass are well above the level that will support the MSY, and are well above the limit reference point, $20\%SB_{F=0}$.

5. Depletion-based reference points (including $SB_{latest}/SB_{F=0}$, $SB_{recent}/SB_{F=0}$ and $SB_{2015}/SB_{F=0[2015]}$) for the reference case model, sensitivity analyses and uncertainty grid suggest that the skipjack stock is most probably at or close to the target reference point of $50\%SB_{F=0}$.

6. Modelling assumptions explored in sensitivity and structural uncertainty analyses had a moderate impact on model output but did not change the broad conclusions about recent stock status.

7. Modelling results were most sensitive to assumptions about weighting of data components, tag mixing period and steepness, and several important avenues of research related to these assumptions have been identified and will improve future assessments.

# 1 Introduction

This paper presents the 2016 stock assessment of skipjack tuna (*Katsuwonus pelamis*; SKJ) in the western and central Pacific Ocean (WCPO; west of 150° W). Since 2000, the assessment has been conducted regularly and the most recent assessments are documented in Hoyle et al. (2010), Hoyle et al. (2011), and Rice et al. (2014). The independent review of the 2011 bigeye tuna assessment (Ianelli et al., 2012) made several recommendations that also improved the subsequent assessment of the WCPO skipjack stock (Rice et al., 2014). The current assessment continues the implementation of the review recommendations that have been facilitated by the ongoing development of the statistical stock assessment software, known as MULTIFAN-CL[3] (MFCL; Fournier et al., 1998; Hampton and Fournier, 2001; Kleiber et al., 2014), that is used by the Pacific Community (SPC). Further developments to the stock assessment have been undertaken to address the recommendations of the 2014 stock assessment report (Rice et al., 2014), to explore uncertainties in the assessment model, particularly in response to the inclusion of additional years data, and to improve diagnostic weaknesses of previous assessments.

The objectives of this assessment are to estimate population parameters, such as time series of recruitment, biomass and fishing mortality, which indicate the stock status and impacts of fishing. We summarize the stock status in terms of reference points adopted by the Western and Central Pacific Fisheries Commission (WCPFC). The methodology used for the assessment is based on the general approach of integrated modelling (Fournier and Archibald, 1982), which is carried out using MFCL, and implements a size-based, age- and spatially-structured population model. Model parameters are estimated by maximizing an objective function, consisting of both likelihood (data) and prior information components.

This assessment report should not be seen as a standalone document and should be read in conjunction with several supporting papers, specifically the analyses of Bigelow et al. (2016); Kiyofuji (2016); McKechnie et al. (2016); McKechnie (2016) and Tremblay-Boyer et al. (2016). Finally, many of these issues were discussed in detail at the Pre-Assessment Workshop held in Noumea over 11–15 April, 2016 (Pilling and Brouwer, 2016).

# 2 Background

## 2.1 Stock structure

Surface-schooling, adult skipjack tuna (greater than 40 cm fork length; FL) are highly abundant in tropical and subtropical waters of the Pacific Ocean (Figure 1). Skipjack in the WCPO are considered a single stock for assessment purposes (Wild and Hampton, 1994). In the western Pacific, warm, pole-ward-flowing currents near northern Japan and southern Australia seasonally

[3]http://www.multifan-cl.org

extend their distribution to about 40° N and 40° S. These limits roughly correspond to the 20° C surface isotherm.

A substantial amount of information on skipjack movement is available from tagging programmes, which have documented some large-scale movement within the Pacific (Figures 2). In general, skipjack movement is highly variable (Sibert et al., 1999) and is thought to be influenced by large-scale oceanographic variability (Lehodey et al., 1997).

## 2.2 Biological characteristics

Skipjack growth is rapid compared to yellowfin and bigeye tuna. Approximate age estimates from counting daily rings on otoliths suggest that growth may vary between areas of the Pacific. At 150, 200, 300 and 400 days, fork lengths (FLs) of 30, 33, 40, and 46 cm were estimated for fish sampled mostly in the north Pacific (Tanabe et al., 2003), but growth estimates were faster (42, 47, 55, and 60 cm) for fish sampled close to the equator (Leroy, 2000). Growth has been found to vary spatially in the eastern Pacific (Maunder, 2001) and in the Atlantic (Gaertner et al., 2008), based on analyses of tagging data.

Estimates of natural mortality rate have been obtained using a size-structured tag attrition model (Hampton, 2000), which indicated that natural mortality was substantially larger for small skipjack (21–30 cm FL, M=0.8 $mo^{-1}$) compared to larger skipjack (51–70 cm FL, M=0.12–0.15 $mo^{-1}$). The longest period at liberty for a tagged skipjack to date has been 4.5 years.

Commensurate with their fast growth and relatively short lifespan, skipjack mature at an early age, when they reach a length of around 40 cm FL (Wild and Hampton, 1994).

## 2.3 Fisheries

Skipjack tuna are caught using a wide variety of fishing gears and comprise the largest component of tuna fisheries throughout the WCPO. Fisheries can be broadly classified into the Japanese pole-and-line fleets (both distant-water and offshore), domestic pole-and-line fleets based in Pacific Island countries, artisanal fleets fishing a wide range of gear based in the Philippines, eastern Indonesia and the Pacific Islands, and distant-water and Pacific-Island-based purse seine fleets.

The Japanese pole-and-line fleets operate over a large area of the WCPO, although effort and the spatial extent of this fishery has gradually declined since the 1980's. A domestic pole-and-line fishery occurred in PNG from 1970 to 1985 and active fisheries have occurred in Fiji since 1974 (now discontinued), and the Solomon Islands since 1971 (now operating at a very low level).

A variety of gear types (e.g. gillnet, hook and line, longline, purse seine, ring net, pole-and-line and unclassified) capture a significant amount of skipjack in the Philippines and Indonesia. Small but locally important artisanal fisheries for skipjack and other tuna (mainly using traditional methods and trolling) also occur in many of the Pacific Islands.

Purse seine fleets usually operate in equatorial waters from 10° N to 10° S; although a Japanese offshore purse seine fleet operates in the temperate North Pacific. The distant-water fleets from Japan, Korea, Chinese Taipei and the USA capture most of the skipjack in the WCPO, although catches by fleets flagged to or chartered by Pacific Island countries have increased considerably in recent years. The purse seine fishery is usually classified by set type categories - sets on floating objects such as logs and fish aggregation devices (FADs), which are termed "associated sets" and sets on free-swimming schools, termed "unassociated sets". These different set types have somewhat different spatial distributions, catch per unit effort (CPUE) and catch different sizes of skipjack and other tuna.

Skipjack tuna catches in the WCPO increased steadily after 1970, approximately doubling during the 1980s (Figure 4). The catch was then relatively stable during the early 1990s, approaching 1 million mt per annum. Catches increased again from the late 1990s and have varied between about 1.5 and 2 million mt since 2007, with a record catch of just over 2 million mt taken in 2014.

Pole-and-line fleets, primarily Japanese, initially dominated the fishery, with the catch peaking at 380,000 mt in 1984, but the relative importance of this fishery has declined steadily for economic reasons. Annual skipjack tuna catches increased during the 1980s due to growth in the international purse-seine fleet, combined with increased catches by domestic fleets from the Philippines and Indonesia.

Historically, most of the catch has been taken from the western equatorial Pacific (regions 2, 4 and 5) (Figure 5). During the 1990s, combined annual catches from this region fluctuated around 500,000–800,000 mt before increasing sharply to approximately 1.2 million mt in 2007–2009 (Figure 4). Since the late 1990s, there has been a large increase in the purse-seine fishery in the eastern equatorial region of the WCPO (region 3), although catches from this region have been highly variable among years. Since the terminal year of catches included in the previous stock assessment (2012), significant changes in the distribution of catch have occurred. This has been influenced by recent very strong El Nino conditions which are thought to have a strong impact on skipjack population dynamics including a significant eastward shift in biomass (Lehodey et al., 1997) which favours the eastern equatorial region, and is reflected in high catches in region 3, particularly in 2014 and 2015.

The purse seine catch history used in the assessment has been corrected for the over-reporting of skipjack and under-reporting of yellowfin and bigeye on logsheets (Hampton and Williams, 2011) and for the selection bias in grab samples (spill-sample corrected purse seine estimates) taken by observers. These corrected catches represent the primary catch data incorporated in the stock assessment and are the basis of quoted catch estimates in this paper.

# 3 Data compilation

## 3.1 General notes

Data used in the stock assessment of skipjack tuna using MFCL consist of catch, effort and length-frequency data for the fisheries defined in the analysis, and tag-recapture data. Improvements in these data inputs are ongoing and more detailed summaries of the analyses and methods of producing the necessary input files are given by Abascal et al. (2014) (length compositions for purse seine fisheries), McKechnie et al. (2016) (tagging data), and Bigelow et al. (2016), Kiyofuji (2016) and Tremblay-Boyer et al. (2016) (CPUE standardisations). In addition, a more detailed description of the fisheries definitions, their data summaries and changes in fisheries structures since the 2014 stock assessment, are provided in McKechnie (2016). The full details of these analyses are not repeated here, rather, a brief overview of the key features is provided and readers are directed to the relevant papers referenced throughout this section.

## 3.2 Spatial stratification

The geographical area considered in the assessment corresponds to the WCPO from 50° N to 20° S and from oceanic waters adjacent to the east Asian coast (110° E between 20° N and 20° S; 120° E north of 20° N) to 150° W. The assessment model area comprises five regions (Figure 1), with a single region north of 20° N (Region 1), and four equatorial regions between 20° S to 20° N. The western equatorial region is from 110° E to 140° E (Region 4), and eastern equatorial from 170° E to 150° W (Region 3). Region 2 comprises the area between 140° E and 170° W with the exception of the area south of the equator between 140° E and 155° E along with the area south of 5° S between 155° E and 160° E.

The southern regions are similar to the bigeye and yellowfin tuna regional structure, the difference being the inclusion of 10° S to 20° S in the skipjack regional structure. The assessment area covers practically the entire skipjack fishery in the WCPO, with the exception of relatively minor catches south of 20° S. 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.

## 3.3 Temporal stratification

The time period covered by the assessment is 1972–2015. Within this period, data were compiled into quarters (1; Jan–Mar, 2; Apr–Jun, 3; Jul–Sep, 4; Oct–Dec). Unlike the other recent tuna stock assessments conducted by SPC, this assessment included data from the most recent full calendar year (2015). These data are only finalized very late and can be subject to revision post-SC and this must be considered when interpreting results for the final year of the assessment. However, the skipjack population has a much shorter generation time than the other tuna species assessed in the

WCPO, therefore stock status can change very rapidly and assessment of the most recent dynamics is highly valuable. Furthermore, catch estimates for the entire fishery are less dependent on gears where there is a substantial lag between fishing and catch reporting (such as longlining) and so the most recent year's catch estimates are likely to be significantly more accurate than for other species. For these reasons the WCPFC Scientific Committee decided that it is highly desirable to include the most up-to-date data on the fishery and stock so that the most accurate status of the stock can be estimated for management purposes.

### 3.4 Definition of fisheries

MFCL requires the definition of "fisheries" that consist of relatively homogeneous fishing units. Ideally, the defined fisheries will have selectivity and catchability characteristics that do not vary greatly over time and space, although in the case of catchability some allowance can be made for time series variation. For most pelagic fisheries assessments, fisheries are defined according to gear type, fishing method and region and sometimes also by vessel flag or fleet.

Equatorial purse seine fishing activity was aggregated over all nationalities, but stratified by region and set type, in order to sufficiently capture the variability in fishing operations. Set types were grouped into associated (log, FAD, whale, dolphin, and unknown set types) and unassociated (school) sets. Further fisheries were defined for pole-and-line fisheries in each region and miscellaneous fisheries (gillnets, ringnets, handlines etc.) in the western equatorial area. A longline fishery was defined in each region to hold the long time series of skipjack length composition data from Japanese research longline cruises in the WCPO and more recently, observer-measured length composition samples.

Several changes were made to the 2014 fisheries definitions and these are presented in detail by McKechnie (2016) however the total number of fisheries in the assessment remains 23 (see Table 2 for fishery descriptions). A brief summary of these changes is as follows:

- The longline fisheries in each region only include JP data under the 2014 definitions, but this was extended to include data from vessels for all flags (except Chinese-Taipei; see McKechnie, 2016 for details) to increase the sample sizes and temporal coverage of the availability of length composition data.
- The area of the domestic purse seine fishery in region 4 (S-ID.PH-4) was extended to cover the whole region to include fishing activity in archipelagic waters, and thus be more consistent with the area used by Bigelow et al. (2016) to calculate the CPUE index received by this fishery in the assessment model.
- The pole-and-line fishery in region 2 was expanded to include all data from all flags using this gear in that region (previously the fishery included only JP). This new definition included a moderate amount of historical catch and effort data for the Pacific Island fleets that are

unlikely to have a significant influence on population dynamics, but lead to the inclusion of a moderate number of tag recaptures for the Regional Tuna Tagging Programme (1990's) which were previously excluded.

## 3.5 Catch and effort data

### 3.5.1 General characteristics

Catch and effort data were compiled by year and quarter according to the fisheries defined above. The catches of all fisheries were expressed in weight of fish, with the exception of the longline fishery (the catches of which are very small and set at a nominal level) which were expressed in numbers of fish.

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 is provided in Figure 6. Discarded catches are estimated to be minor and were not included in the analysis. Catches in the northern region are highly seasonal.

A number of significant trends in the fisheries have occurred over the model period, specifically:

- The development of the Japanese off-shore purse-seine fishery in region 1 since the mid-1990s.
- The virtual cessation of the domestic pole-and-line fisheries in Papua New Guinea (PNG) and Fiji and the recent low catches from the Solomon Islands fishery;
- The general decline in the Japanese distant-water pole-and-line fisheries in the equatorial regions, particularly region 3.
- The development of the equatorial purse-seine fisheries from the mid-1970s and the widespread use of FADs since the mid-1990s, allowing an expansion of the purse-seine fishery in region 3.
- Large changes in the purse seine fleet composition and increasing size and efficiency of the fleet.
- The steady increase in catch for the domestic fisheries of Indonesia and the Philippines.

### 3.5.2 Purse seine

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 (Hampton and Williams, 2016), total catches are taken from the logsheet-declared totals and catches by species are estimated from observer grab samples corrected for bias based on the estimates of the correction factors from the paired spill and grab sampling trials. For the Japanese fleet for which there is greater confidence in species-based reporting, we use reported catch by species rather than estimating it.

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. We minimize the impact of this by estimating time-variant changes in catchability for these fisheries, and ascribing low weight to the effort deviations.

In the two regions (4 and 5) where effort of the JP pole-and-line fleet was not adequate for conducting CPUE standardisations, purse seine fisheries instead received standardised CPUE. CPUE for the Philippines domestic purse seine was analysed using generalised linear models (GLMs) by Bigelow et al. (2016), who produced a standardised index of abundance (Figure 7). These indices were applied to the catches of the S-ID.PH-4 fishery for the years 2005–2015 and in contrast to 2014, estimates of time-variant precision were available and were implemented as time-variant effort deviation penalties in MFCL.

CPUE data for the purse seine fishery operating largely within the PNG archipelagic waters (region 5) was also analysed using GLMs (Tremblay-Boyer et al., 2016; Figure 7). These indices were applied to the catches of the S-ASS-All-5 fishery for the years 1997-2015 and time-variant effort deviation penalties were again estimated and used.

#### 3.5.3 Longline

Longline fisheries take a negligibleproportion of the total skipjack catch and longline fisheries were included in the model solely to utilise the available size frequency data. Catches are set at very low, arbitrary levels and this is detailed later in the document.

#### 3.5.4 Pole-and-line

Standardised CPUE indices of abundance applied to fisheries 1, 4, and 12 were based on Japanese pole-and-line fisheries in region 1, 2, and 3, respectively. These standardised indices were estimated using generalized linear models (GLM) fitted to operational catch and effort data (Kiyofuji, 2016). Separate analyses were conducted for each region. The uncertainty in each pole-and-line CPUE estimate, by fishery and time, was included in the model by way of time-variant penalty weights for the effort deviations.

In contrast to other tuna stock assessments in the WCPO, regional weight scaling factors were not applied to the CPUE estimates from the different regions. Significant quantities of tagging data exist in all 5 regions which provides information on region-specific fishing mortality and hence biomass, and therefore allows catchabilities for these fisheries to be estimated independently. The relative regional population sizes are therefore estimated relatively freely by the model. Nominal fishing-vessel-day was used as the unit of effort for the domestic pole-and-line fisheries of PNG, Solomon Islands, and Fiji and the mixed flag (but mainly ID) PL fishery in region 4.

#### 3.5.5 Other fisheries

Effort data for the Philippines and Indonesian surface fisheries and research longline fisheries were unavailable. Where effort data are absent, the model directly computes fishing mortality consistent with the observed catch using a Newton-Raphson procedure. This is described in more detail in Section 4.3.3.

### 3.6 Size data

#### 3.6.1 Purse seine

Only length frequency samples are used in the skipjack assessment and the penultimate assessment (2011) only used samples obtained from observer programmes 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 showed little evidence of model progression. Two major changes were made for the 2014 assessment and were carried through to 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, American Samoa, was included; and second, all samples were spatially weighted by the catch - both at the set and spatial strata level, with thresholds applied to ensure that small samples from important catch strata did not get too much weight (as was conducted for the longline fisheries in the bigeye and yellowfin tuna assessments in 2014; Harley et al., 2014 and Davies et al., 2014, respectively).

#### 3.6.2 Longline

Longline fisheries typically do not target skipjack but do catch small numbers of large skipjack within the 50–90 length range as bycatch, and the catch is usually discarded. Japanese research vessels have routinely collected measurements of the length of skipjack caught since the start of the assessment time period. Japanese research data is only available sporadically in several regions and sample sizes have decreased or ceased to exist in areas where JP longline fishery effort has declined or the fleet has contracted away from. For the 2016 stock assessment, data for other flags conducting longline fishing were added to these fisheries, resulting in substantial increases in sample size and temporal coverage. Most of these samples were collected by observer programmes (since the 2000's) and the datasets for these fisheries are covered in detail by McKechnie (2016).

These data are included to provide information to the model on the existence of these larger sized skipjack rarely caught in purse seine or pole-and-line fisheries. These data are important, because they allows selectivity of surface fisheries to be measured against these larger-sized skipjack that would otherwise be part of a "cryptic biomass" component of the population that would not otherwise be sampled by the fishery, and would consequently be difficult to model.

#### 3.6.3 Pole-and-line

Size composition for pole-and-line fisheries are largely reliant on observer data with the exception of region 1 and 2 where length data are available from the Japanese offshore and distant-water fleet (sourced from NRIFSF) from the beginning of the model period until 2015. For the equatorial (excluding region 2) pole-and-line fishery, length data are available from the Japanese distant-water fleet and from the domestic fleets.

The data from the pole-and-line fishery in region 3 (P-ALL-3) was dominated by data for the Japanese fleets (1974–2004) with additional data from Fiji in the 1990's. Length data from the pole-and-line fishery in region 4 (P-All-4) consists of mostly Japanese data from the 1972–2009, with significant data from Indonesia sporadically available, though mostly over 2009–2015. The data from the pole-and-line fishery in region 5 (P-ALL-5) are a large dataset for multiple countries with the Solomon Island and PNG contributing the majority of length composition samples. The pole-and-line fisheries in the northern region generally catch smaller fish than the equatorial fisheries (regions 2–5), (Figure 19) although over the model period, there was a slight general increase in the length of fish sampled from the pole-and-line fisheries in regions 1 and 2. No systematic trend in the length composition was evident in regions 3–5 (Figure 20).

#### 3.6.4 Other fisheries

Size composition data for the Philippines domestic fisheries (Z-PH-4) were collected by a sampling programme conducted in the Philippines in 1993–95 and augmented with data from the 1980s. In addition, data collected during 1997–2006 under the National Stock Assessment Project, and in more recent years under the GEF-WPEA project, were included in the current assessment. Despite the large catch taken by the Indonesian domestic fishery (Z-ID-4), only limited length samples from the recent sampling under the GEF-WPEA project are available for the fishery and the selectivity for this fishery was linked to Z-PH-4 (Table 3).

Data have become available for the Vietnam domestic fishery (Z-VN-4) since the last stock assessment was conducted and now number in the order of tens or thousands of samples in several years (McKechnie, 2016). Selectivity for this fishery was also shared with Z-PH-4 (Table 3).

For previous assessments, few usable size data were available for the PH-ID domestic purse seine fishery in region 4 (S-ID.PH-4), and this fishery's selectivity was linked to the associated purse seine fishery in region 2 (S-ASS-ALL-2). Considerably more length composition data have become available for the current assessment and due to differences in the compositions observed for this fishery a fishery-specific selectivity function was estimated (Table 3).

### 3.7 Tagging data

A large amount of tagging data were available for incorporation into the assessment and a summary of its characteristics and the process of constructing the MFCL tagging file are presented in detail by McKechnie et al. (2016). The data were available from SPC's Skipjack Survey and Assessment Project (SSAP) carried out during 1977–80, the Regional Tuna Tagging Project (RTTP) during 1989–92 (including affiliated in-country projects in the Solomon Islands, Kiribati, Fiji and the Philippines), and the Pacific Tuna Tagging Programme (PTTP) carried out during the period 2006 until the 3rd quarter of 2014. Tagging data from regular Japanese research tagging cruises were available for the period 1998–2015. Note that this period of availability of Japanese tagging data is shorter than in 2014 (1988–2012) and relates to the difficulties of reproducing tagging events for the tagging cruises prior to 1998, as there is an absence of measured release lengths of fish over that time. This information is a requirement for inclusion in MFCL, but the data used to estimate these lengths were unavailable for this assessment (see McKechnie et al., 2016 for further details of these issues).

Tags were released using standard tuna tagging equipment and techniques by trained scientists and technicians. Tags have been returned mostly from purse seine vessels via processing and unloading facilities throughout the Asia-Pacific region.

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) and McKechnie et al. (2016), but essentially the re-scaling preserves the recovery rates of tags from the individual tag groups that would otherwise be biased low when an often significant proportion of recaptures cannot be assigned to a recapture category in the assessment.

There is a delay between tagged fish being caught, the tag being reported and the data being entered into tagging databases. If this delay is significant then reported recaptures rates for very recent release events will be biased low and will impact estimates of fishing mortality in the terminal time periods of the assessment. For this reason, any release events occurring after the end of 2014 were excluded from the assessment (McKechnie et al., 2016).

For incorporation into the assessment, tag releases were stratified by release region, time period of release (quarter) and the same size classes used to stratify the length-frequency data. A total of

277,562 effective releases were classified into 204 tag release groups (Table 4). The returns from each size-class of each tag release group (52,929 effective, usable tag returns in total) were then 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

## 4.1 General characteristics

The model can be considered to consist of several components, (i) the dynamics of the fish population; (ii) the fishery dynamics; (iii) the dynamics of tagged fish; (iv) the observation models for the data; (v) the parameter estimation procedure; and (vi) stock assessment interpretations. Detailed technical descriptions of components (i)–(iv) are given in Hampton and Fournier (2001) and Kleiber et al. (2014). In addition, we describe the procedures followed for estimating the parameters of the model and the way in which stock assessment conclusions are drawn using a series of reference points.

## 4.2 Population dynamics

The model partitions the population into five spatial regions and 16 quarterly age-classes. 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 1972–2015. The main population dynamics processes are as follows.

### 4.2.1 Recruitment

Recruitment is defined as the appearance of age-class 1 fish (i.e. fish averaging $\sim$ 10 cm given the current growth curve) in the population. Tropical tuna spawning does not always follow a clear seasonal pattern but 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 proportion of total recruitment occurring in each region was initially set relative to the variation in recruitment predictions from Lehodey (2001) and then estimated during the later phases of the fitting procedure. 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 annual recruitment was somewhat constrained by a lognormal prior on deviations from the stock-recruitment relationship. 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.

In recent assessments of tuna in the WCPO the terminal recruitments have often been fixed at the mean recruitment of the rest of the model period to prevent the instability that has been detected by retrospective analyses. This approach has been continued here and several models were constucted with different numbers of terminal recruitments fixed.

Spatially-aggregated (over all model regions) recruitment was assumed to have a weak relationship with 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 (Francis, 1992; Harley, 2011).

In the reference case model, it was assumed that annual recruitment was related to spawning biomass, which was recommended by the 2011 Bigeye Tuna Peer Review (Ianelli et al., 2012) and was previously assumed for the south Pacific albacore assessment (Harley et al., 2015). Alternative model runs exploring the former assumption of estimating the SRR at the quarterly-scale were also undertaken.

The SRR was incorporated mainly so that yield analysis and population projections 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 recruitment and other model estimates (Hampton and Fournier, 2001), which was confirmed by sensitivity analyses. The SRR was calculated over the period from 1982 onwards to prevent the early recruitments (which appear to be part of a different "regime" to subsequent estimates) from influencing the relationship, which is consistent with the approach of the 2014 assessment.

Typically, fisheries data are not very informative about the steepness parameter of the SRR parameters (ISSF, 2011); 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 by setting it to lower (0.65) and higher (0.95) values of steepness.

#### 4.2.2 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.

#### 4.2.3 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.

#### 4.2.4 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 and Kleiber et al., 2014 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, with a log-linear relationship between age and movement rates estimated. Alternative models with age-invariant movement were also considered and are presented later in the document. The seasonal pattern of movement persists from year to year with no allowance for inter annual variation in movement. A prior mean of 0.1 is assumed for all movement coefficients, inferring a relatively high mixing rate between regions. A weak penalty is applied to deviations from the prior mean.

#### 4.2.5 Natural mortality

Natural mortality was estimated and assumed to be age-specific, but invariant over time and region. Penalties on the first difference, adjacent age classes, and deviations from the mean were applied to restrict the age-specific variability to a certain extent. The estimated M-at-age for the reference case model is shown in Figure 12.

#### 4.2.6 Sexual maturity

Sexual maturity was fixed in the model and assumed to be age-specific, knife-edge, and invariant over time and region. The onset of sexual maturity was assumed to occur at age-class 3 (7–9 months of age; Figure Wild and Hampton, 1994). The adult component of the population was therefore essentially defined as age classes 3–16. Unlike in *Thunnus* species, sex ratio does not appear to vary with size for skipjack. Sex ratio and fecundity at size were not included in the maturity parameter, so in this assessment the term “spawning biomass” refers to the biomass of adult fish, rather than female spawning biomass as in the yellowfin, bigeye, and albacore stock assessments.

## 4.3 Fishery dynamics

### 4.3.1 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, allows more flexibility but 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 seems to be sufficient to allow for reasonably complex selectivity patterns.

For particular fisheries alternative functions were employed, including logistic and non-decreasing (Table 3). 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 length compositions. This grouping facilitates a reduction in the number parameters being estimated.

The selectivities of the longline fisheries were assumed to increase with age and to remain at the maximum once attained. Two pole-and-line selectivity curves were estimated: one for region 1 and one for the equatorial fisheries (regions 2-5). Selectivity for the equatorial purse seine fisheries were grouped by set type i.e. a separate selectivity function for associated and unassociated fishing, but each was shared over the fisheries in different regions. The Indonesian, Philippines and Vietnam domestic fisheries in region 4 (Z-ID-4, Z-PH-4, Z-VN-4) were also grouped (Table 3).

### 4.3.2 Catchability

Constant catchability (time-invariant) was estimated for all fisheries for which standardised indices of relative abundance were available (Table 3). This assumption is similar to assuming that the CPUE for these fisheries indexes the exploitable abundance over time. No grouping of catchability for these fisheries was employed, and therefore the relative level of CPUE was not used to scale the relative exploitable biomass in regions 1, 2 and 3 - the model relies on other data, size and most importantly tagging, to estimate the regional distribution of abundance.

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, including those fisheries that received standardised CPUE indices (Table 3).

#### 4.3.3 Effort deviations

Effort deviations were used to model the random variation in the effort - fishing mortality relationship, and are constrained by pre-specified prior distributions (on the log-scale). There were several categories of fisheries with respect to the effort deviation penalties applied and these are outlined in Table 3. For fisheries which received standardised CPUE indices the prior was set to have a mean of zero and for the abundance index fisheries the CV was time-variant and based on the variance estimates (using the canonical variance method of Francis, 1999) from the GLMs fitted to each fishery (Bigelow et al., 2016; Kiyofuji, 2016; Tremblay-Boyer et al., 2016). The penalties for fishery 1 (P-JPN-1) were set to be time-invariant and equivalent to a CV of about 10% as there are few informative data in this region before the occurrence of tagging data in 1998, particularly since CPUE estimates are only available in two out of four quarters in any year, and so more informative priors are needed to prevent spurious results in early years.

The miscellaneous fisheries have very unreliable estimates of effort and to prevent them from influencing population dynamics they are given missing effort at all time-steps except the last four quarters, when they are given an arbitrary effort of one, and receive effort deviation penalties equivalent to a CV of about 0.22. This is done simply to provide a basis for scaling effort so that the effort deviates converge around 0 to allow effort-based population projections. This approach was also used for all longline fisheries which are only included for their length composition data and are given arbitrary catches.

Finally, for all other fisheries the nominal effort was used, but to prevent the CPUE of these fisheries from influencing population dynamics they received effort deviation penalties equivalent to a CV of about 0.7 (Table 3).

## 4.4 Dynamics of tagged fish

### 4.4.1 Tag reporting

In principal, 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 precise estimates to be obtained. We provided reporting rate priors for all reporting groups that reflect independent estimates of the reporting rates and their variance.

Previous assessments have assumed 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 publicity and follow-up. Consequently, fishery-specific tag reporting rates that are also specific to individual tagging programmes were estimated. Tag recapture and reporting rate groupings are provided in Table 3.

The estimation of the reporting rates included penalty terms in respect of pre-determined priors. These were derived from analyses of tag seeding experiments (Peatman et al., 2016). 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 within a tagging programme were assumed to be time-invariant.

### 4.4.2 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 distribution 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 removing fish from the tagged population for the recaptures that occurred. We assume that tagged skipjack gradually mix with the untagged population at the regional level and that this mixing process is complete by the end of the first quarter after release.

Tagged fish are modelled as discrete cohorts based on the region, year, quarter and age at release for the first 12 quarters after release. Subsequently, the tagged fish are pooled into a common group. This is to limit memory and computational requirements.

### 4.5 Likelihood components

There are three data components that contribute to the log-likelihood function for the skipjack stock assessment - the total catch data, the length-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 0.002.

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. Length frequency samples are assigned effective sample sizes lower than the number of fish measured. Reduction of the effective sample size recognises that (i) length- and weight-frequency samples are not truly random (because of non-independence 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 size data were considered to be moderately informative and were assigned moderate weight in the likelihood function; such that individual length frequency distributions were assigned an effective sample size of 0.05 times the actual sample size, with a maximum effective sample size of 50 (MFCL has a default limit on maximum effective sample size of 1,000 fish per time-step, per fishery). Alternative scalars for down-weighting the length composition data were explored in sensitivity analyses.

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 overdispersion parameter such that as it approaches 1, 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. A complete derivation and description of the negative binomial likelihood function for tagging data is provided in Kleiber et al. (2014).

### 4.6 Parameter estimation and uncertainty

The parameters of the model were estimated by maximizing the log-likelihood of all data components 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 relatively arbitrary starting values for most parameters. A bash shell script, "doitall", 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 skj.ini input file.

In this assessment two approaches were used to describe the uncertainty in key model outputs. The first estimates the statistical uncertainty within a given assessment model, while the second focuses on the structural uncertainty in the assessment by considering the variation among a suite of models. For the first approach, the Hessian 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 (for example, the biomass and recruitment trajectories). For the second approach, a crosswise grid of model runs 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. Therefore, a profile likelihood analysis was undertaken of the marginal posterior likelihood in respect of the total population scaling parameter (Lee et al., 2014). 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. This procedure is presented in the Appendix (Section 10.1).

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 in 2014 where data from the terminal time periods (the last three years) were successively removed and the model fitted to each case with terminal recruitments estimated. Based on that analysis the last 2 terminal recruitments were fixed at the mean of the recruitments over the rest of the time-period. The sensitivity to this assumption was explored in sensitvity analyses. Retrospective analyses also provide a more general test of the stability of the model as a robust model should produce similar output when rerun with data for the terminal year/s sequentially excluded (Cadigan and Farrell, 2005). The retrospective analyses for the 2016 reference case model are presented in the Appendix (Section 10.3.1).

## 4.7 Stock assessment interpretation methods

Several ancillary analyses using the converged model/s 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. (2014).

### 4.7.1 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 using the formulae given in Kleiber et al. (2014), and is equivalent to the MSY.

Fishing mortality-at-age ($F_a$) for the yield analysis was determined as the mean over a recent period of time (2011–2014). We do not include 2015 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 potentially incomplete.

### 4.7.2 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 over the time series, and if either the initial or recent spawning 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 spawning biomass time series (at the region level) using the estimated model parameters, but assuming that fishing mortality was zero. Because both the estimated spawning biomass $SB_t$ (with fishing), and the unexploited spawning biomass $SB_{F=0[t]}$, incorporate recruitment variability, their ratio at each quarterly time step ($t$) of the analysis $SB_t/SB_{F=0[t]}$ 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. To achieve this the estimated recruitment deviations are multiplied by a scalar based on the difference in the SRR between the estimated fished and unfished spawning biomass estimates. This analysis was conducted by estimating these quantities with no fishing activity, but also with respect to groups of fisheries (gear-types) so as to describe the relative fishing impacts of each group on the population. In the latter case fishing for each gear-type was "turned off" in turn to indicate their relative influence on fishing depletion.

We note that this approach is similar to that undertaken for the estimation of the LRP, $20\%SB_{F=0}$, except that for the LRP the level of $SB_{F=0}$ is the average over a particular time window (2005–2014 for the current assessment) rather than the fully dynamic value ($SB_t/SB_{0,t}$) predicted for a given year (Table 1).

#### 4.7.3 Reference points

The unfished spawning biomass ($SB_{F=0}$) in each time period was calculated given the estimated recruitments and the Beverton-Holt SRR as outlined in Section 4.7.2. This offers a basis for comparing the exploited population relative to the population subject to natural mortality only. The WCPFC adopted $20\%SB_{F=0}$ as a limit reference point (LRP) for the skipjack stock where $SB_{F=0}$ is calculated as the average over the period 2005–2014. The recently adopted target reference point (TRP) for this stock is $50\%SB_{F=0}$ where $SB_{F=0}$ is again calculated over 2005–2014. Stock status was referenced against these points by calculating the reference points; $SB_{recent}/SB_{F=0}$ and $SB_{latest}/SB_0$ where $SB_{F=0}$ is calculated over 2005–2014 and $SB_{latest}$ and $SB_{recent}$ are the estimated spawning biomass in 2015, and the mean over 2011–2014, respectively (Table 1).

The other key reference point, $F_{recent}/F_{\mathrm{MSY}}$, is the estimated average fishing mortality at the full assessment area scale over a recent period of time ($F_{recent}$; 2011–2014 for this stock assessment) divided by the fishing mortality producing MSY which is a product of the yield analysis and has been detailed in Section 4.7.1.

#### 4.7.4 Kobe analysis and Majuro plots

For the standard yield analysis (Section 4.7.1), the $F_a$ are determined as the average over some recent period of time (2011–2014 herein). In addition to this approach the MSY-based reference points ($F_t/F_{\mathrm{MSY}}$) were also computed using the average annual $F_a$ from each year included in the model (1972–2014, with no value calculated for the terminal year) by repeating the yield analysis for each year in turn. 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. This analysis is presented in the form of Kobe plots or the "Majuro plot", which has been presented for all stock assessments since SC10.

### 4.7.5 Stochastic projections from the reference case model

Projections of stock assessment models can be conducted routinely within MFCL to ensure consistency between the fitted model and the simulated future dynamics, and the framework for performing this exercise is detailed in (Pilling et al., 2016). The reference case model is used as the basis for stochastic 10 year projections of skipjack abundance in the WCPO, assuming similar conditions to those recently encountered: future catch (longline, domestic Indonesian and Philippines fisheries) or effort (purse seine, most pole-and-line fisheries) was assumed to remain at 2015 levels (status quo); catchability was assumed to remain constant in the projection period at the level estimated in the terminal year of the assessment model. Future recruitments were sampled from deviates from the estimated SRR over the period 1982–2014. Two hundred population trajectories were simulated and a summary of the results is given in the Appendix (Section 10.2).

# 5 Model runs

## 5.1 Developments from the last assessment

The progression of model development from the 2014 reference case to the model proposed as the reference case in 2016 was incremental, with stepwise changes to the model made in-turn to ensure that the consequences of each modification could be ascertained. Changes made to the previous assessment model include additional input data for the years 2013–2015, modified methods in producing the input files (e.g. McKechnie et al., 2016; Tremblay-Boyer et al., 2016), minor changes to the fisheries structures (McKechnie et al., 2016), and implementation of additional, or new features of MFCL (Davies et al., 2015). An outline, and basis for, the progression through the models is as follows:

1. The 2014 reference case model [*Ref14*].
2. The 2014 reference case model with the new MFCL executable [*Ref14exe*].
3. The 2014 reference case model with the new tagging file produced by McKechnie et al. (2016) but truncated so that the time period of the tagging file matched that used in 2014 [*Ref14-NewTag*].
4. The 2014 reference case model with the new tagging file produced by McKechnie et al. (2016) and fully updated data inputs extending until the end of 2015 [*Update16*].
5. The previous model with effort deviation penalties on fisheries not receiving standardised CPUE indices reduced to the equivalent of a CV of $\sim 0.7$, from, on average, $\sim 0.4$, to prevent the CPUE of these fisheries from influencing population trends as the time-variant CVs on the standardised fisheries increase late in the assessment period [*EffDev16*].

6. The previous model with the introduction of the new fisheries structures outlined by McKechnie (2016) with details of changes given in Section 3.4[*NewFish16*].
7. The previous model with terminal recruitments for the last two quarters set at the arithmetic (rather than the default geometric) mean of recruitments estimated over the remaining time periods, and the new reporting rate penalties calculated by Peatman et al. (2016). The latter change was included in this run as the consequences for model results were established to be negligible during model development [*RecRR16*].
8. The previous model with; selectivity of fishery 18 (S-ID.PH-4) estimated alone (no longer grouped with the associated purse seine fishery in region 2), due to considerably more length composition data becoming available since the 2014 assessment, and selectivities of fisheries 13 (S-ASS-ALL-3) and 14 (S-UNA-ALL-3) shared with the other equatorial associated and unassociated fisheries, respectively, for consistency due to few differences in observed length compositions since the catch- and spatially-weighted analyses of Abascal et al. (2014) [*SelMod16*].
9. The previous model with the spawner-recruit relationship estimated assuming that annual, rather than quarterly recruitments were related to spawning biomass. This is the recommended reference case model for the 2016 stock assessment [*RefCase*].

### 5.2 Sensitivity analyses and structural uncertainty

Several hundred runs were undertaken in conducting the 2016 skipjack assessment, but in terms of presenting information on the bounds of plausible model sensitivity we have focused on a small set of uncertainty axes which are described in further detail below. These axes were used for "one-off" changes from the reference case model and several of these sensitivity models were used in the structural sensitivity analyses (after Hoyle et al., 2008). The latter process involves constructing a grid of model runs where all-possible combinations of the assumptions are explored (see Section 5.3).

#### 5.2.1 Steepness [*h0.65, h0.95*]

Steepness is a particularly difficult parameter to estimate in stock assessment models, but if it is fixed in the model, the choice of value may have significant influence on most reference points used in management. As was the case in other tropical tuna, and albacore tuna assessments, we assumed a value of 0.8 for the reference case, but examined values of 0.65 (*h0.65*) and 0.95 (*h0.95*) in sensitivity runs. This choice of values is consistent with the results of the meta-analysis conducted on tuna stock-recruitment data (Anon., 2011).

### 5.2.2 Tag mixing period [*mix2qtr*]

The tag mixing period is imposed to allow tagged fish to distribute themselves throughout the region of tagging, although it is somewhat difficult to ascertain how long this period should be. In the reference case model the mixing period was set at one quarter and an alternative model was run assuming a mixing period of two quarters.

### 5.2.3 Relative weighting of length composition data [*Lgth10, Lgth50*]

The difficulties in assigning weighting to the length composition data were discussed in Section 4.5. To assess the sensitivity of model results to the weighting of this data two alternative models were considered; a model where composition data were up-weighted (corresponding to a maximum effective sample size of 100 fish) relative to the reference case model (*Lgth10*); and one where those data were down-weighted (corresponding to a maximum effective sample size of 20 fish) relative to the reference case (*Lgth50*).

### 5.2.4 Alternative growth functions [*EstVB, EstVBSD, TanGrth*]

The paucity of reliable modal progression in the length composition data means that it can be difficult to estimate all growth parameters internally in the model. Therefore, alternative models were formulated with different assumed growth functions. The reference case model used the same growth function as that assumed in the 2014 reference case model (the 2010 growth estimate). The alternative formulations were; a model with the Von Bertalanffy parameters ($k$, $L1$, $L16$) estimated but the parameters defining the SD of length-at-age fixed at the 2014 values (*EstVB*); a model with all growth parameters (Von Bertalanffy and two SD parameters) estimated (*EstVBSD*); and finally, a model (*TanGrth*) assuming the all parameters (growth function parameters and the two SD parameters) were fixed at the values estimated by Tanabe et al. (2003). The latter model was unstable, and produced unreasonable results, and so was not considered further in the modelling process.

### 5.2.5 Overdispersion in the tagging likelihood [*EstOD, ODmiddle*]

A reformulation of the negative binomial likelihood for the tagging data was undertaken in MFCL between the 2014 and current assessments to make the estimation of the overdispersion parameter more stable. Previously this parameter was fixed at an assumed reasonable value for stock assessments in the WCPO. A higher value of overdispersion suggests more variation in the tagging data than assumed by the Poisson likelihood and effectively down-weights the tagging data to some extent. The reference case model assumed the same value as used in 2014, which was equivalent to a variance just marginally greater than Poisson. Two alternative runs were considered - overdispersion estimated by the model with one overdispersion parameter common to all recapture fishery groups ([*EstOD*]; see Table 3 for these groupings) and another with a common overdispersion parameter fixed at a value approximately mid-way between the estimated parameter and the value used in the reference case model (*ODmiddle*).The relationships between the expected value and the standard deviation for these 3 options are displayed in Figure 14.

#### 5.2.6 Age-invariant movement [*InvMov*]

Age-dependent movement was estimated in the reference case model, which is facilitated by the substantial tagging dataset. An alternative model was also run to test the sensitivity of model results to age-invariant movement, which retains seasonal movement coefficients but set them constant over all age-classes.

#### 5.2.7 Quarterly stock recruitment relationship [*SRRqtrly*]

To assess the sensitivity of the model to the change to assuming annual recruitment (rather than quarterly in the 2014 assessment) was related to spawning biomass, an alternative model was run assuming an SRR function between recruitments and spawning biomass at the quarterly scale.

#### 5.2.8 Constraints on terminal recruitments [*TermRec4, TermRecFree*]

The sensitivity of the model to assumptions about terminal recruitments were explored using two alternative models; one with the 4 terminal recruitments fixed at the arithmetic mean of the recruitments over the assessment period (*TermRec4*), and another where terminal recruitments were freely estimated (*TermRecFree*).

### 5.3 Structural uncertainty

Stock assessments of pelagic species in the WCPO in recent years have utilised an approach to assess the structural uncertainty in the assessment model by running a "grid" of models that explore the interactions among selected "axes" of uncertainty. The grid contains all combinations of levels of several model quantities or assumptions and allows the sensitivity of stock status and management quantities to this uncertainty. The axes are generally selected from those factors explored in the one-off sensitivities with the aim of providing an approximate understanding of variability in model estimates due to assumptions in model structure not accounted for by statistical uncertainty estimated in a single model run, or over a set of one-off sensitivities.

The structural uncertainty grid for the 2016 assessment was constructed from 5 axes with 2–3 levels for each, with the values for the reference case model embolded and the levels used directly comparable to Sections 5.2.1–5.2.8 through identical notation:

1. Steepness [**0.8**; 0.65 (*h0.65*); 0.95 (*h0.95*)]
2. Length composition data weighting [**20**; 10 (*Lgth10*); 50 (*Lgth50*)]
3. Assumed tag mixing period, in quarters [**1**; 2 (*mix2qtr*)]
4. Tagging data weighting [**default**; estimated (*EstOD*); fixed at intermediate level (*ODmiddle*)]

resulting in a grid of 54 models (Table 5).

# 6 Results

## 6.1 Fit of the reference case model to data sources

### 6.1.1 Catch data

Very high penalties were applied to the catch data for all fisheries and so the residuals of the observed and model-predicted catches were very small (Figure 15).

### 6.1.2 Standardised CPUE

There was substantial temporal variability in the standardised CPUE indices used in the assessment, but despite this the model-predicted CPUE fitted the indices relatively well, particularly the long term trends in observed abundance (Figure 16). The model largely captured the substantial seasonal variability observed for the pole-and-line fishery in region 1 (P-JPN-1) and was able to predict the shift from lower to higher abundance observed for the standardised fisheries in regions 2 and 3 (P-ALL-2 and P-ALL-3; Figure 16).

The main source of divergence between observed and model-predicted CPUE occurred in regions 2, 3 and 5 since 2012 when the model predicted a significant increase in CPUE that either did not occur (region 3) or was less pronounced (regions 2 and 5) in the standardised CPUE indices. This pattern can be observed in a tendency for very recent effort deviates being negative (Figure 17). This is partly a consequence of the lower effort deviation penalties towards the end of the assessment period in several regions (Figures 7 and 8) and high model-predicted recruitments, and consequently spawning biomass over the last several years of the assessment period. These features of the model will be discussed in more detail in subsequent sections.

The CPUE of fisheries not receiving standardised CPUE indices have far less influence in estimating temporal trends in biomass as much lower effort deviation penalties are applied and catchability is allowed to vary over time in these fisheries. Examination of the estimated effort deviations for these fisheries did not reveal any cause for concern, with deviations centred around zero and no temporal trends (that might indicate misspecification of temporal changes in catchability etc.; Figure 18).

#### 6.1.3 Size composition data

There was a generally reasonable fit to the length composition data as revealed from a comparison of the observed and model-predicted numbers-at-length (Figure 19). There was some lack of fit to the miscellaneous fisheries in region 4, which share selectivity. This is partly due to different observed length compositions, but for several of these fisheries there are few data with which to estimate fishery-specific selectivities. The shift to allowing the domestic purse seine fishery in region 4 (S-ID.PH-4) to have its own selectivity function appears to have improved the fit to the length compositions for this fishery compared to the previous assessment.

These patterns were largely reflected in the comparison of temporal variation in observed and model-predicted median fish lengths (Figure 20). Compared to the 2014 assessment there are no longer extreme outliers for the longline fishery in region 1 (L-ALL-1) and several of the fisheries have substantially more recent data to be fitted to. Some lack of fit is evident for several of the fisheries in region 4 which is a consequence of high variability in observed median length which is not reflected in the model estimates. At least some of this variability is likely to be attributable to the sampling programmes that have occurred in this region in the past, or extremely low sample sizes (e.g. L-ALL-4).

#### 6.1.4 Tagging data

The model appeared to fit the overall tagging data very well (Figure 21), and also at the finer scale of the individual tag recapture groupings (Figures 22 and 23). The observed and model-predicted recapture numbers show large increases during the three tagging programmes that released the most fish (SSAP; $\sim$ 1980, RTTP; early 1990's, PTTP; 2006–present; Figure 21). There is close concordance between the observed and modelled values for most time-periods with some lack of fit during periods of particularly high recaptures late in the assessment period. The observed and model-predicted tag attrition rates across all tag release events for the reference case model were very similar (Figure 24).

### 6.2 Model parameter estimates (reference case)

#### 6.2.1 Catchability

Most fisheries where catchability was permitted to vary over time showed a generally increasing trend, and in some cases this increase was substantial, particularly the purse seine fisheries in regions

2–5 (Figure 28). In some cases, catchability levels off at the end of the time series, which may be due to some extent to reduced information at the end of the time series, resulting in parameters being estimated at close to their prior mean (0). The exceptions to this pattern were; the purse seine fishery in region 1 (S-ALL-1) which is likely due to differences in CPUE compared to the pole-and-line fishery in the same region and changing fleet structure during the middle period of the assessment; and pole-and-line fishery in region 5 (P-ALL-5) which showed fluctuations over a long time-scale that possibly reflect changes in the composition of the fleet (with different catchability of different flags) and the pronounced decline in effort for this fishery over time. Seasonal variation in catchability in many fisheries was high, particularly those operating in more temperate areas of the assessment region.

#### 6.2.2 Selectivity

A range of selectivity patterns are shown by the different fisheries in the model and can be largely classified by fishing gear, with the age-specific selectivity coefficients being displayed in Figure 27. The pole-and-line and purse seine fisheries select mostly young fish of around 3–8 quarters of age while the longline fisheries are estimated to catch very few fish below about 6 quarters of age and full select fish in the very old age-classes. The miscellaneous fisheries in region 4 share selectivities and the estimated coefficients reflect the highly variable length composition data available for these fisheries with a range of very small through to large fish caught, with substantial temporal variability.

#### 6.2.3 Movement

To interpret the movement among regions in the reference case model it is beneficial to examine the empirical movements of tagged fish (Figure 10), the estimated seasonal-, and age-specific movements (Figure 29), and Figure 30, which portrays the origin (which region the fish were originally recruited into) of the equilibrium skipjack biomass in each region. From these it is evident that the model estimates significant variability in seasonal movement between several pairs of regions, perhaps most notably from regions 2 and 3 into 1, which is also reflected in seasonal variability in biomass (Figure 32).

Significant movement also occurs between regions 2 and 5 (in both directions), 2 and 3 (in both directions) and 2 and 4 (Figure 29). The movement coefficients tend to increase with age, in some cases by significant amounts, though it is important to note that only a negligible proportion of the population are in these old age-classes.

#### 6.2.4 Natural mortality

The estimated age-specific natural mortality function is very similar to that estimated in the previous stock assessment. Natural mortality is estimated to be very high for the first few age-classes, declining by about half at age-classes 5–7, before increasing somewhat with increasing age beyond that point.

#### 6.2.5 Tag Reporting Rates

The estimated tag reporting rates by fishery recapture groups (see groupings in Table 3) are displayed in Figure 25. The most important groups for scaling the population size are the purse seine fisheries in regions 2–5 and which account for the overwhelming majority of recaptures for the SPC tagging programmes and the pole-and-line/purse seine fisheries in region 1 which recapture most of the JPTP tag releases. These reporting rates were all estimated to be well away from the bounds and in general were relatively consistent with the informative prior distributions assigned to these groups. A number of reporting rates are estimated at their bounds although these groups are generally unimportant for scaling population size, for example all of the reporting rate groups for region 4 fisheries are estimate at, or close, to the lower bound for the JPTP as a result of no usable recaptures for these fisheries being available for tags released on Japanese tagging cruises.

#### 6.2.6 Growth

The growth function in the reference case model was fixed at the values used in the previous two stock assessments. This Von Bertalanffy function specifies most rapid growth over the youngest age-classes, starting from a mean length of about 10cm at age-class one, before slowing down over older ages with a mean length of about 88cm for the oldest fish in the model (age-class 16). The standard deviation of length-at-age increases significantly with age (Figure 26).

### 6.3 Stock assessment results

#### 6.3.1 Recruitment

The estimated distribution of recruitment across regions must be interpreted with caution to a degree, as MULTIFAN-CL has the ability to use a combination of movement and regional recruitment to distribute the population in a way that maximises the total objective function. The reference case recruitment estimates for each region and the entire assessment domain are shown in Figures 31 and 33. The overall pattern of recruitments is similar to previous assessments; slightly lower recruitments in the 1970's, an increase in the early 1980's and a slight increasing trend over the remaining assessment period. Several very high recruitments were estimated in the years since the last assessment (2013–2015), most notably in region 3, and to a lesser degree in region 2.

Note that the final two estimates of recruitment at the full WCPO scale are constrained to equal the arithmetic mean of recruitments over the entire assessment period which was guided by the retrospective analyses conducted in 2014 (Rice et al., 2014) and in the Appendix (Section 10.3.1). This will have no impact on spawning biomass or reference points, including those that use the latest period of 2015, as the maturity schedule ensures that all these recruits would only reach maturity in the quarter following the end of the stock assessment period.

### 6.3.2 Biomasss

The relative pattern in spawning biomass at the regional scale is consistent with the results presented for the 2014 stock assessment (Figure 32 and 33). There is a period of relatively stable biomass over the first decade of the model, followed by an increase in the early 1980's resulting from the higher recruitments at this time, before the biomass fluctuates and declines slightly up until around the end of the previous assessment time period (2012).

Since that time the model estimates a strong increase in spawning biomass, peaking in 2013–2014 at a level moderately below the highest levels of biomass predicted to have occurred in the early 1980's. These increases can be largely attributed to pulses of fish in regions 2, 3 and 5 that result from very high estimated recruitments predicted to have occurred in the preceeding quarters. Part of this pattern is influenced by recent tagging data which shows lower recapture rates than tag release events in earlier years, which estimates a lower fishing mortality and consequently higher abundance. This result is corroborated when the tagging data is down-weighted (when higher overdispersion values are assumed or estimated) in the one-off sensitivity analyses (Section 6.5). Spawning biomass is estimated to have declined somewhat over 2015.

The relative spawning biomass among regions is displayed in Figure 33. Estimates are largely similar to those of the 2014 assessment although biomass in region 1 is now estimated to account for a lower proportion of overall biomass and is now more consistent with the predictions of SEAPODYM.

### 6.3.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase significantly throughout the time series with occasional fluctuations due to temporal variation in total and spawning biomass, which is particularly evident in the mid to late 2000's (Figure 34). This is also observed over the period 2013–2015 due to the significant pulse of recruitment in regions 2, 3 and 5, and to a lesser degree the reductions in catch in regions 2 and 5 over the last few years (Figure 5). This can be observed by examining the region- and age-specific fishing mortality rates in Figure 35. Also notable is that the fishing mortality of the youngest age-classes is only significant in region 4 where the small-fish (miscellaneous) fisheries operate.

Changes in fishing mortality-at-age and population age structure are shown for five-yearly time intervals in Figure 35. Since the 1980s, the increase of fishing mortality to the current levels is due to the increase of catches of both juvenile and adult fish beginning at that time from both associated purse seine sets and the mixed gear fisheries in the Philippines and Indonesia. Fishing mortality on intermediate ages (5–8 quarters) is also increasing through time consistent with the increased fishing mortality from the purse seine fishery (Figure 35).

### 6.3.4 Fishery impact

We measure fishery impact at each time step as the ratio of the estimated spawning biomass relative to the spawning biomass that which would have occurred in the historical absence of fishing. This is a useful quantity 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, firstly as the fished and unfished spawning biomass trajectories (Figure 37) and secondly as the depletion ratios themselves (Figure 38). The latter is relevant for the agreed reference points and are discussed in more detail in Section 6.4.1.

The reference case model estimated that steady declines in depletion ratio have occurred in all regions, with the exception of region 1, which was estimated to have been stable over most of the assessment period (Figure 38). The other regions were estimated to have a terminal depletion ratio in the range of about 0.3–0.6, although there has been moderate temporal variation in these ratios.

It is also possible to attribute the fishery impact with respect to depletion levels to specific fishery components (grouped by gear-type), in order to estimate which types of fishing activity have the most impact on spawning biomass (Figure 39). The early impacts on the population were primarily driven by pole-and-line fishing, but the impact of that gear has generally declined to be relatively insignificant in regions 2, 3 and 5. With the exception of region 1, purse seine fishing is estimated to have had the most significant impact on spawning biomass with the associated component generally identified as having more impact than unassociated fishing. The miscellaneous fisheries were estimated to have a significant impact on spawning biomass in region 4.

### 6.3.5 Yield analysis

The yield analyses conducted in this assessment incorporate the spawner recruitment relationship (Figure 40) 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 virgin spawning biomass ($SB_0$) was estimated at 6,764,000 mt and the spawning biomass that would support the MSY was estimated to be 1,626,000 or 24% of $SB_0$ (Table 6) with the catches in 2015 estimated to be 89% of the estimated MSY. The total equilibrium biomass in the absence of fishing ($SB_{F=0}$) was estimated to be 7,221,135 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 42). Prior to 1980, the WCPO skipjack fishery was almost exclusively conducted using pole-and-line gear, with a low exploitation of small skipjack. The associated age-specific selectivity pattern resulted in a comparable, but slightly higher estimate of MSY ($\sim$ 2 million mt per annum) in the early period compared to the recent estimates of MSY. This is probably due to the increased catch of smaller fish by associated purse seine and miscellaneous gears, compared to the early period where pole-and-line fishing was more dominant.

## 6.4 Stock status

### 6.4.1 Majuro plot and comparisons with Limit and Target Reference Points

The quantity $SB_{F=0}$ calculated for the period 2005–2014 is the basis for the limit reference point and is estimated to be a spawning biomass of 7,221,135 mt (Table 6). The limit reference point is $20\%SB_{F=0}$ which is estimated to be a spawning biomass of 1,444,227 mt, while latest (2015) spawning biomass ($SB_{latest}/SB_0$) is estimated to be 58% of $SB_{F=0}$ (4,166,815, Figure 43). The quantity $SB_{latest}/SB_{F=0}$ is more optimistic than estimated in the 2014 stock assessment (0.48) and results from the strong recruitment-driven increase in spawning biomass over the period 2013–2015. This leads to an increase in the estimate of $SB_{latest}$ relative to the previous assessment; however, the estimate of $SB_{F=0}$ for 2005–2014 is relatively unaffected. The dynamic annual terminal depletion estimate is less optimistic with $SB_{2015}/SB_{f=0[2015]} = 0.51$ . The suitability of these various depletion-based reference points for a species with very short generation time and large temporal variability in biomass is discussed in detail later in the report.

Fishing mortality has generally been increasing through time with a moderate decrease in the terminal few years (Figure 34), and for the reference case the fishing mortality reference point $F_{recent}/F_{\mathrm{MSY}}$ (the numerator is the mean over 2011–2014) is 0.45 (Figure 44, Table 6). This indicates that an increase in fishing mortality of 2.2 times is necessary to produce the MSY (Table 6). Presentation of the results in the form of a Majuro plot are displayed in Figure 44 which shows the steady depletion of the stock over most of the assessment period, along with the increase in the ratio of fishing mortality to fishing mortality at MSY. The stock is still estimated to be healthy however, and is estimated to have been close to $50\%SB_{F=0}$ for the past decade.

## 6.5 Multimodel inference - stepwise model development, sensitivity analyses and structural uncertainty

### 6.5.1 Consequences of key model developments

The progression of model development from the 2014 to 2016 reference case models is outlined in Section 5.1 and results are displayed in Figures 45–46. A summary of the consequences of this progression through the models is as follows:

- The reference case model refitted with the latest version of MFCL (green line; Figure 45a) produced almost identical results to the 2014 version.
- The new tagging input file that did not include any JPTP tagging data before 1998 produced results relatively similar to the previous model although relative abundance among years was slightly different (blue line; Figure 45a). The overall trends in biomass remained very similar and estimated depletion was extremely similar to the previous model (Figure 46a).
- The model with fully updated datasets (catch/effort, length compositions, tagging) produced results that were relatively similar to the previous model, with very similar fluctuations in abundance, although biomass (and recruitment) was scaled down moderately (red line; Figure 45a), and the model predicted a strong increase in biomass since 2012 that resulted in terminal biomass being significantly higher than the terminal biomass estimated by the reference case model in 2014. Estimated depletion for this model was also scaled downwards by several percentage points but followed a very similar trajectory, and the increase in biomass after 2012 resulted in the terminal depletion level being almost indistinguishable from the terminal depletion (2012) estimated in the 2014 assessment (Figure 46a).
- The next 2 models in the progression (*EffDev16*] and [*NewFish16*) again produced very similar relative fluctuations in biomass (green and blue lines, respectively; Figure 45b), and depletion (Figure 46b), but in both cases these metrics were scaled up slightly to lie between the previous model and the 2014 reference case model.
- The model with the new reporting rate penalties and recruitment during the terminal 2 quarters fixed at the arithmetic mean of recruitments over the remaining period was virtually indistinguishable from the previous model.
- The model with modified assumptions for grouping of selectivities of 3 fisheries was very similar to the previous model with slight inter annual deviations in biomass, most notably in the final few years of the assessment (Figure 45b), but a very similar depletion trajectory (Figure 46b).
- The last modification in the model progression was a shift to an annual SRR and this is presented as a suggested reference case model. This model was very similar to the previous

model with respect to the quantities compared above, only differing in MSY-based quantities which depend on the estimated SRR.

#### 6.5.2 One-off changes from the structural uncertainty analysis

Comparisons of the recruitment, spawning biomass, and depletion trajectories for the reference case and one-change sensitivity runs from the structural uncertainty analysis are provided in Figures 47–49, the key reference points are compared in Table 6 and the likelihood components in Table 7. Majuro plots for the one-off models are provided in Figures 50–51.

**Steepness** [*h0.65, h0.95*]

The low penalties on the SRR relationship resulted in the assumed value of steepness having a negligible effect on model fit and stock assessment output, with the exception of quantities related to yield. The alternative one-off sensitivity runs with steepness values of 0.65 (*h0.65*) and 0.95 (*h0.95*) displayed predictable results, consistent with previous assessments of skipjack and other tuna in the WCPO - namely that low, and high steepness values lead to more pessimistic and optimistic estimates of stock status, respectively (Figure 50, Table 6). This was particularly the case for MSY and MSY-based reference points while the depletion-based reference points were less sensitive to assumed steepness (Figure 49b, Table 6).

**Increased mixing period of 2 quarters** [*mix2qtr*]

The model with a mixing period of 2 quarters imposed (rather than the 1 quarter assumed for the reference case model) for tag recaptures estimated very similar relative fluctuations in biomass and recruitment, although the absolute values of these metrics were scaled higher, presumably due to lower relative recapture rates for longer times-at-liberty, which lead to lower fishing mortality and higher estimates of biomass. Estimated stock status for this run was extremely similar to the reference case model (Figure 50, Table 6).

**Weighting of the length composition data** [*Lgth10, Lgth50*]

Two alternative models were run with differing weightings given to the length composition data, one up-weighting the data relative to the reference case (*Lgth10*; scaled down by 10), and the other down-weighting the data relative to the reference case (*Lgth50*; scaled down by 50). These models predictably showed differing changes to the reference case model, most notably with the scale of the population and associated parameters. For the heavily down-weighted model (*Lgth50*) biomass, recruitment and yield were scaled up slightly and this lead to slightly lower fishing mortality and more optimistic estimates of MSY-based reference points (Table 6). The opposite of these results were estimated for the up-weighted model (*Lgth10*). Depletion-based reference points were very similar between these models and the reference case model (Table 6). While the weighting of the length composition data resulted in slightly different estimates of key stock assessment quantities, overall management consequences and estimated stock status were similar (Figures 50, 53 and 54).

**Alternative growth functions** [*EstVB, EstVBSD*]

The sensitivity model where the parameters of the Von Bertalanffy growth function were estimated ($k$, $L1$, $L16$), but the SD parameters were fixed at the values used in 2014 showed very few differences to the reference case model with respect to all model-estimated quantities (Figures 47a and 49a, Table 6). This can largely be attributed to the relatively similar estimates of the growth parameters ($k = 0.26$ and 0.20; $L1 = 9$ and 10cm; $L16 = 81$ and 88cm, for *EstVB* and the reference case, respectively; Figure 26). The model *EstVBSD* also estimated a relatively similar growth function to the reference case (Figure 26), but produced variation in length-at-age that was highest at young age-classes and decline with age. There was also some evidence of local minima when significantly different starting values were used. For this reason, this model must be treated with caution.

**Overdispersion parameter of the negative binomial tagging likelihood** [*EstOD, ODmiddle*]

The one-off sensitivity models with alternative values of the overdispersion parameter produced the most significant deviations from the estimates of the reference case model. The model with estimated overdispersion estimated absolute values for biomass and recruitment that were scaled down from the reference case. The model with a moderate fixed overdispersion parameter produced results in-between these extremes (Figures 47b, 48b and 49b, Table 6). Similarly, while the trajectory of depletion was very similar to the reference case model, it was also scaled down by about 5 percentage points on average (Figure 49b), and $SB_{latest}/SB_{F=0}$ was estimated to be 0.41 (0.47 for *ODmiddle*) against a value of 0.58 for the reference case. The value assumed of the overdispersion parameter leads to non-linear estimates with respect to $SB_{latest}/SB_{F=0}$, with the model with a "middle" value producing more similar results to *EstOD* than the reference case model. Part of these differences during the terminal period of the assessment result from these models producing a significantly reduced increase in spawning biomass over the period 2013–2015 as they down-weight the tagging dataset including the influential tagging data over these years.

**Age-invariant movement** [*InvMov*]

A model assuming age-invariant rather than age-dependent movement produced very similar results to the reference case model, both with respect to model parameters and indicators of stock status such as the reference points (Figures 47b and 49b, Table 6). The estimates of the origin (which region the fish were originally recruited into) of the equilibrium skipjack biomass in each region were also very similar (not shown) to those of the reference case model, despite the more restrictive assumptions of this sensitivity run.

**Quarterly SRR estimation** [*SRRqtrly*]

The run with the SRR fitted using quarterly (consistent with the 2014 assessment), rather than annual recruitments (assumed by the reference case model), produced negligible differences with respect to stock dynamics and population parameters. Yield for this model was significantly lower than for the reference case however, at 1,591,600 versus 1,891,600 mt for the reference case model. Other MSY-based quantities were also slightly more pessimistic than observed for the reference case model (Table 6). Minor differences from the reference case model were observed in the estimated depletion dynamics owing to small differences in the recruitments used to calculate the unfished biomass from the modified SRR. Despite this, the depletion-based reference points were still very similar to those of the reference case model (Table 6).

**Alternative constraints on terminal recruitment** [*TermRec4, TermRecFree*]

Fixing the last 4, rather than 2 recruitments at the arithmetic mean of the remaining values produced very similar results to the reference case model (Figures 47b, 48b and 49b, Table 6), with the exception that spawning biomass in the terminal year did not decline as much resulting in a slightly more optimistic $SB_{latest}/SB_{F=0}$. The model with all recruitments freely estimated produced results almost indistinguishable from the reference case model aside from estimating very low recruitments in the last 2 quarters (Figure 48b), which do not influence any of the indicators of stock status. These estimates appear to be the result of instability in estimating these parameters in the terminal period which has been identified by previous retrospective analyses. For this reason, and the very similar results for all reference points, the results for this model are not shown in Table 6 for brevity.

### 6.5.3 Structural uncertainty analysis

The results of the structural uncertainty analysis are summarised in several forms; Majuro plots showing the estimates of $F_{recent}/F_{\mathrm{MSY}}$ and $SB_{latest}/SB_0$ across all models in the grid (Figure 52), boxplots of $F_{recent}/F_{\mathrm{MSY}}$, $SB_{latest}/SB_0$ and MSY for the different levels of each of the 4 axes of uncertainty (Figures 53–55) and quantiles across the full grid of 54 models for all the reference points and other quantities of interest that have been presented for the reference case model and one-off sensitivity models (Table 8).

The results of the structural uncertainty analysis are consistent with the results of previous assessments of tuna stocks in the WCPO that used the same uncertainty axes.

The general features of the uncertainty analysis are as follows:

- The value of steepness had a significant influence on MSY-based quantities with models with higher and lower steepness resulting in more and less optimistic stock status, respectively (higher $F_{recent}/F_{\mathrm{MSY}}$ for the latter), and while a similar result was observed for $SB_{latest}/SB_0$, the differences between steepness values were less pronounced (Figures 53–55).
- The weightings assigned to the length composition data had less influence on the quantities investigated, especially the depletion-based reference point, $SB_{latest}/SB_0$ (Figure 54).
- Models with a mixing period of 2 quarters produced more optimistic estimates of stock status

with a median value of $SB_{latest}/SB_0$ of about 0.53 versus about 0.47 for models with a mixing period of 1 quarter (Figures 53–55).

- The different levels of overdispersion of the negative binomial tagging likelihood had a moderate impact on all quantities examined, with models with the default value producing the most optimistic estimates of stock status (lower $F_{recent}/F_{\text{MSY}}$, higher $SB_{latest}/SB_0$) with models with the estimated overdispersion parameter giving the most pessimistic results, and the models with fixed (middle) overdispersion roughly half way between these extremes for the MSY-related quantities, but closer to the "estimated" models for $SB_{latest}/SB_0$ (Figures 53–55).
- The quantiles across the full grid for all quantities suggested a relatively healthy stock status; median $f_{mult} = 2.07$ (95% uncertainty limits of 1.57–2.62), median $SB_{latest}/SB_0 = 0.51$ (0.39–0.67), median $SB_{recent}/SB_{F=0} = 0.49$ (0.40–0.57), median $F_{recent}/F_{\text{MSY}} = 0.48$ (0.38–0.64).
- Most models in the in the uncertainty analysis were spread relatively closely around the target reference point and well away from the limit reference point, and no models met, or even approached the thresholds of formal definitions of "overfishing" or "overfished" (Figure 52).

# 7 Discussion and conclusions

## 7.1 Changes to the previous assessment

The changes implemented since the 2014 skipjack stock assessment (Rice et al., 2014) are less profound than the major restructuring undertaken between the 2011 and 2014 assessments. However, several modifications made in the current assessment have a significant impact on conclusions and management recommendations. Three additional years of data (tagging, catch, effort, length compositions) were included in the assessment, covering a period of strong El Nino conditions, with a significant redistribution of the catch.

Model estimates of population parameters over the years since the last stock assessment suggest a more favourable period for skipjack abundance, at least in the more eastern equatorial region. This is reflected in an improvement in many of the indicators of stock status, although the overall conclusions of the current assessment are very similar to 2014, with the stock estimated to be relatively close to the target reference point and well away from the limit reference point. This recent time period has also seen a moderate drop in fishing mortality as a consequence of the recent pulse of recruits into the fishery. However, this is also consistent with a fall in overall purse seine effort in 2015 relative to 2014 of approximately 20% (Williams and Terawasi, 2016).

While the estimated stock status appears to be healthy, stock assessment models for tuna are difficult to construct and a number of sources of uncertainty must be considered when assessing the management implications of assessment results. The following section (7.2) will address some of these uncertainties, the consequences of these and other issues encountered during model fitting. Future research priorities will be discussed in Section 7.3, and the main conclusions of the assessment will be presented in Section 7.4.

## 7.2 Sources of uncertainty

### 7.2.1 Data weighting and conflict among data components

Stepwise model progression, the sensitivity analyses and the structural uncertainty grid all emphasised the importance of the tagging data for the assessment, and highlighted some conflict with other data types. This was supported by preliminary examination of data-component-specific likelihood profiles.

The weighting of the tagging data (determined by using different values of the negative binomial overdispersion parameter) had a significant influence on recruitment and spawning biomass, reduced the recent pulse in abundance and produced more pessimistic estimates of stock status. It is important to note however that the general inferences about stock status were robust to the significant variation in data weightings explored in the uncertainty analyses. However, these issues have important implications for the future modelling of tagging data for skipjack and the other tuna species in the WCPO, and a suggested approach for further investigation of the issues is presented in Section 7.3.2.

One of the difficulties in fitting integrated models is the need to assign relative weightings to the different data components. It is increasingly recognised that data components should be actively down-weight in some situations, for example down-weighting length compositions to allow CPUE data to provide the most information on trends in abundance (Francis, 2011). How to weight the tagging data is less clear and accepted recommendations are currently lacking. For skipjack tuna the tagging data provides most of the information on scaling biomass and parameters such as natural mortality and movement, as there is little evidence for long-term shifts in length compositions and the CPUE indices are either limited in duration, highly variable and in the case of pole-and-line indices, becoming more uncertain as effort of these fisheries contracts. The current approach of giving high weight to these data is consistent with previous assessments and we have explored a much wider range of uncertainty bounds in this assessment than in the past.

### 7.2.2 Robustness of CPUE indices

One feature of the pulse in recruitments and spawning biomass in recent years is that the model predicts deviation away from the standardised indices in regions 2, 3 and 5, over this period, as it attempts to fit the other data components; length compositions, tagging data and very high recent catches. Generally in stock assessments it is desirable to fit the CPUE data well over the whole assessment period, but in the case of skipjack tuna it is unclear how reliable the CPUE indices are for the pole-and-line fisheries (Kiyofuji, 2016). For example, the data used to standardise CPUE in region 3 are very sparse, effort has contracted to a restricted area in the west of the region, and estimates are not available for all time-steps in many years. The model-predicted increase is supported by the increase in purse seine CPUE observed over this period and the consequences of this result for future assessments is discussed further in Section 7.3.2.

### 7.2.3 Caution in using $SB_{latest}/SB_{F=0}$ for species with very short generation time

The increase of recruitment, and subsequent increase in spawning biomass in recent years, highlighted some of the difficulties in applying several of the reference points widely used for the other tropical tunas and south Pacific albacore in the WCPO to species such as skipjack with a shorter generation time. The problem arises when highly variable recruitments occur and these fish quickly mature ($\sim 2$ quarters later) and become part of the defined spawning biomass. The reference point $SB_{latest}/SB_{F=0}$ is therefore based on a numerator that is very high (the last year of the assessment) and a denominator that includes many values that were part of a period of significantly lower unexploited abundance (pre-2013). This leads to a very high reference point indicator, with significant deviation from the fully dynamic estimate of depletion.

This reference point was formulated to compare latest estimates of abundance with fishing impacts over a period of "typical" recent population productivity. In the case of this stock assessment however, the change in the reference point from the 2014 estimate mostly reflects the recent pattern of recruitment rather than any significant changes in fishery impacts (as measured by depletion) which conflicts with the purpose of this type of reference point. It is important to note that the opposite of the observed change would occur if skipjack abundance were to significantly decline from the high values recently estimated. In this case, the unexploited biomass giving rise to $SB_{latest}$ would be significantly lower than most of the values in the denominator (which would include the high values of $SB_{F=0}$ over 2013–2015), and the reference point would be considerably more pessimistic. For skipjack therefore, we recommend accounting for issue when interpreting the reference points presented, and to also consider the fully dynamic estimate of depletion ($SB_t/SB_{F=0[t]}$; black line in Figure 43) which better reflects current stock status and is in-line with the estimate of stock status presented in 2014.

## 7.3 Recommendations for further work

### 7.3.1 WCPFC-specific recommendations

Management recommendations of the assessment are largely consistent with previous assessments of skipjack tuna in the WCPO (Hoyle et al., 2011; Rice et al., 2014), and two of the main priorities that will affect the ability to conduct future stock assessments remain; availability of reliable CPUE analyses and tagging data.

A major priority is developing an index of abundance based on purse seine data. There is a need for continued work in this area to progress the work of Tidd et al. (2015) and others, noting the problems in quantifying effort creep. Exploration of other supplementary sources of relative abundance such as acoustic data from drifting FADs is certainly warranted. These indices would be unlikely to provide a long time series of information but over a number of years they may add valuable information to the assessment.

The tagging data is a critical component of the skipjack stock assessment and it is unlikely that these models can provide robust estimates for recent time-periods without it. It is therefore recommended that regular large-scale tagging cruises and complementary tag recovery work continue to be undertaken in a way that provides the best possible data for stock assessment purposes.

### 7.3.2 Biological studies and data investigations

**Estimation of growth functions**

The skipjack stock assessment is notable for the difficulty in reliably estimating growth within the model. Growth parameters have been shown to have a significant influence on stock status and management quantities in this and other tuna assessments (Harley et al., 2014; McKechnie et al., 2015). For skipjack, the main opportunity for additional data on growth is from tagging-based length-increment data. Incorporation of these data source into the MFCL model is currently a high priority.

**Investigation of length composition data**

A related issue is the highly variable length compositions that are available for a number of fisheries, most notably fishery 1 (P-JPN-1), the miscellaneous fisheries in region 4, and fishery 18 (S-ID.PH-4), which have a significant influence on model results. The most unusual feature of these data is that they are mostly comprised of small to medium sized skipjack, but with the sporadic appearance of very large fish. It is important to diagnose whether these unusual compositions actually reflect variation in selectivity or whether they are a consequence of the sampling schemes. We recommend examination of the raw data at the finest scale possible to see if any of the variation can be explained by temporal changes in factors such as spatial distribution of sampling or the vessels being sampled. Fishery 1 would be the highest priority in this regard, especially due to the presence of mixed targeting of skipjack and albacore by some vessels in the fishery and the very large geographical area over which they are distributed.

Further work is also required on likelihoods for the size composition data in MFCL. Recent developments include progress towards a self-scaling multinomial with random effects which may overcome some of the difficulties encountered with currently used likelihoods which fail to account for non-independence in composition data. These methods may also provide a more objective means of weighting the composition data and should be explored more thoroughly in future assessments.

**Standardised CPUE analyses**

As noted in previous assessments, the JP pole-and-line fisheries provide the standardised CPUE indices in regions 1, 2 and 3, but this fishery now makes up less than 10% of the total WCPO skipjack catch, and an even smaller percentage in the main equatorial zone, but remains the only fishery that can provide long-term information on relative biomass levels. If these fleets continue to reduce, and contract their effort to restricted areas of the assessment regions there will be ongoing problems with their utility in indexing relative abundance, and it is possible that they may not even support standardisation analyses if data becomes even more sparse.

Further work is necessary to investigate if, and how alternative indices could be constructed for purse seine fisheries, at least over recent time periods. The difficulties in performing this task, due to rapids developments in technology and increases in catchability, are well known, however successful standardisation of this data by removing time-variant catchability would have substantial benefits for future stock assessments. Consideration of how this might take place is warranted and might include investigation of whether it would be possible to define a core fleet that may provide more robust information about relative abundance than the fishery as a whole. This was the approach taken when constructing the standardised CPUE index based on purse seine fisheries in region 5 (Tremblay-Boyer et al., 2016).

**Tagging data examination**

The tagging data are extremely important for the skipjack stock assessment and several aspects of its treatment require further examination. The value of the overdispersion parameter has a strong influence on model results but it is not entirely clear how this should be modelled or what values to use in reference case models or the structural uncertainty grid. It is recommended that further investigation of the levels of overdispersion takes place including if, or how, overdispersion parameters are grouped across fisheries. Preliminary efforts have explored gear-specific overdispersion parameters that gave consistent results and provided guidance for the "middle" value used in the sensitivity analyses. An examination of the fit to the tag recaptures at the scale of the likelihood calculations using statistics such as Pearson's residuals may be beneficial in this regard.

Other uncertainties are also present in the tagging data including; the most appropriate period to use for the mixing period, the influence of the distribution of tag releases with respect to fishing effort and the relative influence of recapture (and tag reporting) rates. These issues require a multifaceted approach of stock assessment modelling, including additional likelihood profiles, examination of raw data, and comparisons with recent developments in fine-scale tag-recapture models for this stock (T. Peatman, *unpublished data*).

A more general priority for the tagging input files is further work to improve the storage and processing of the data from the Japanese tagging program. Currently these data are held externally to SPC and there are difficulties in efficiently reproducing tagging data inputs from them. We encourage more formal storage of these data and development of code to routinely filter them into a usable format.

**Alternative spatial structures and range contraction**

Alternative regional boundaries of the stock assessment area have been suggested with the objective of providing better inferences on process such as range contraction. While models with these regional structures have not been explored in the current stock assessment, ongoing research and model fitting will continue after SC12 to investigate these issues.

## 7.4 Main assessment conclusions

The main conclusions of the current assessment are largely consistent with previous assessments and are based on the results of the reference case model and consideration of the results of sensitivity runs (including the structural uncertainty grid). These general conclusions can be summarised as follows:

1. The current stock assessment estimates stock status to be very similar to the 2014 assessment, with a period of moderately higher spawning biomass over the subsequent years post 2012.
2. Current catches are lower than, but approaching estimated MSY.
3. Fishing mortality of all age-classes is estimated to have increased significantly since the beginning of industrial tuna fishing, but fishing mortality still remains below the level that would result in the MSY, and is estimated to have decreased moderately in the last several years.
4. Recent levels of spawning biomass are well above the level that will support the MSY, and are well above the limit reference point, $20\%SB_{F=0}$.
5. Depletion-based reference points (including $SB_{latest}/SB_{F=0}$, $SB_{recent}/SB_{F=0}$ and $SB_{2015}/SB_{F=0[2015]}$) for the reference case model, sensitivity analyses and uncertainty grid suggest that the skipjack stock is most probably at or close to the target reference point of $50\%SB_{F=0}$.
6. Modelling assumptions explored in sensitivity and structural uncertainty analyses had a moderate impact on model results but did not change the broad conclusions about current stock status.
7. Modelling results were most sensitive to assumptions about weighting of data components, tag mixing period and steepness, and several important avenues of research related to these assumptions have been identified and will improve future assessments.

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# 8 Tables

Table 1: Description of symbols used in the yield and stock status analyses. For the purpose of this assessment, "recent" is the average over the period 2011–2014 and 'latest' is 2015

| Symbol | Description |
|---|---|
| $C_{latest}$ | Catch in the last year of the assessment (2015) |
| $F_{recent}$ | Average fishing mortality-at-age for a recent period (2011–2014) |
| $F_{\mathrm{MSY}}$ | Fishing mortality-at-age producing the maximum sustainable yield (MSY) |
| MSY | Equilibrium yield at $F_{\mathrm{MSY}}$ |
| $F_{recent}/F_{\mathrm{MSY}}$ | Average fishing mortality-at-age for a recent period (2011–2014) relative to $F_{\mathrm{MSY}}$ |
| $SB_0$ | Equilibrium unexploited spawning potential |
| $SB_{latest}$ | Spawning biomass in the latest time period (2015) |
| $SB_{recent}$ | Spawning biomass for a recent period (2011–2014) |
| $SB_{F=0}$ | Average spawning biomass predicted to occur in the absence of fishing for the period 2005–2014 |
| $SB_{\mathrm{MSY}}$ | Spawning biomass that will produce the maximum sustainable yield (MSY) |
| $SB_{latest}/SB_{F=0}$ | Spawning biomass in the latest time period (2015) relative to the average spawning biomass predicted to occur in the absence of fishing for the period 2005–2014 |
| $SB_{latest}/SB_{\mathrm{MSY}}$ | Spawning biomass in the latest time period (2015) relative to that which will produce the maximum sustainable yield (MSY) |
| $SB_{recent}/SB_{F=0}$ | Spawning biomass in for a recent period (2011–2014) relative to the average spawning biomass predicted to occur in the absence of fishing for the period 2005–2014 |
| $20\%SB_{F=0}$ | WCPFC adopted limit reference point – 20% of spawning biomass in the absence of fishing average over years $t-10$ to $t-1$ (2005–2014) |

Table 2: Definition of fisheries for the MULTIFAN-CL skipjack analysis. Gears: PL = pole and line; PS = purse seine unspecified set type; LL = longline; DOM = the range of artisanal gear types operating in the domestic fisheries of Philippines and Indonesia. Flag/fleets: JPN = Japan; PH = Philippines; ID = Indonesia; ALL = all nationalities.

| Fishery | Nationality | Gear | Region |
|---|---|---|---|
| F1 P-JPN-1 | JPN | PL | 1 |
| F2 S-ALL-1 | ALL | PS | 1 |
| F3 L-ALL-1 | ALL | LL | 1 |
| F4 P-ALL-2 | ALL | PL | 2 |
| F5 S-ASS-ALL-2 | ALL | PS | 2 |
| F6 S-UNA-ALL-2 | ALL | PS | 2 |
| F7 L-ALL-2 | ALL | LL | 2 |
| F8 P-ALL-5 | ALL | PL | 5 |
| F9 S-ASS-ALL-5 | ALL | PS | 5 |
| F10 S-UNA-ALL-5 | ALL | PS | 5 |
| F11 L-ALL-5 | ALL | LL | 5 |
| F12 P-ALL-3 | ALL | PL | 3 |
| F13 S-ASS-ALL-3 | ALL | PS | 3 |
| F14 S-UNA-ALL-3 | ALL | PS | 3 |
| F15 L-ALL-3 | ALL | LL | 3 |
| F16 Z-PH-4 | PH | Dom | 4 |
| F17 Z-ID-4 | ID | Dom | 4 |
| F18 S-ID.PH-4 | ID.PH | PS | 4 |
| F19 P-ALL-4 | ALL | PL | 4 |
| F20 S-ASS-DW-4 | DW | PS | 4 |
| F21 S-UNA-DW-4 | DW | PS | 4 |
| F22 Z-VN-4 | VN | Dom | 4 |
| F23 L-ALL-4 | ALL | LL | 4 |

Table 3: Summary of the groupings of fisheries within the assessment and their parameterisations with respect to estimation of selectivity, seasonal catchability (SeasCat), time-variant catchability (TimVarCat) and its CV (TimVarCatCV), effort deviation penalty type (EffPen) and their mean SV (EffPenCV), tag recaptures, and tag reporting rates. Note that effort is missing for all L and Z fisheries and so effort deviation penalties only apply to the last four quarters (see Section 4.3.3). See Table 2 for further details on each fishery.

| Fishery | Region | Selectivity | SeasCat | TimVarCat | TimVarCatCV | EffPen | EffPenCV | Recaptures | Reporting |
|---|---|---|---|---|---|---|---|---|---|
| F1 P-ALL-1 | 1 | 1 | Y | N | NA | time-variant | 0.20 | 1 | 1 |
| F2 S-ALL-1 | 1 | 2 | Y | Y | 0.1 | constant | 0.71 | 2 | 1 |
| F3 L-JPN-1 | 1 | 3 | N | N | NA | constant | 0.22 | 3 | 1 |
| F4 P-ALL-2 | 2 | 4 | Y | N | NA | time-variant | 0.20 | 4 | 1 |
| F5 S-ASS-ALL-2 | 2 | 5 | Y | Y | 0.1 | constant | 0.71 | 5 | 2 |
| F6 S-UNA-ALL-2 | 2 | 6 | Y | Y | 0.1 | constant | 0.71 | 5 | 2 |
| F7 L-JPN-2 | 2 | 7 | N | N | NA | constant | 0.22 | 6 | 1 |
| F8 P-ALL-5 | 5 | 4 | Y | Y | 0.1 | constant | 0.71 | 7 | 1 |
| F9 S-ASS-ALL-5 | 5 | 5 | Y | N | NA | time-variant | 0.20 | 8 | 3 |
| F10 S-UNA-ALL-5 | 5 | 6 | Y | Y | 0.1 | constant | 0.71 | 8 | 3 |
| F11 L-ALL-5 | 5 | 8 | N | N | NA | constant | 0.22 | 9 | 1 |
| F12 P-ALL-3 | 3 | 4 | Y | N | NA | time-variant | 0.20 | 10 | 1 |
| F13 S-ASS-ALL-3 | 3 | 5 | Y | Y | 0.1 | constant | 0.71 | 11 | 4 |
| F14 S-UNA-ALL-3 | 3 | 6 | Y | Y | 0.1 | constant | 0.71 | 11 | 4 |
| F15 L-JPN-3 | 3 | 9 | N | N | NA | constant | 0.22 | 12 | 1 |
| F16 Z-PH-4 | 4 | 10 | N | N | NA | constant | 0.22 | 13 | 5 |
| F17 Z-ID-4 | 4 | 10 | N | N | NA | constant | 0.22 | 14 | 6 |
| F18 S-ID.PH-4 | 4 | 11 | N | N | NA | time-variant | 0.20 | 15 | 7 |
| F19 P-ALL-4 | 4 | 4 | Y | Y | 0.1 | constant | 0.71 | 16 | 1 |
| F20 S-ASS-DW-4 | 4 | 5 | Y | Y | 0.1 | constant | 0.71 | 17 | 8 |
| F21 S-UNA-DW-4 | 4 | 6 | Y | Y | 0.1 | constant | 0.71 | 17 | 8 |
| F22 Z-VN-4 | 4 | 10 | N | N | NA | constant | 0.22 | 18 | 9 |
| F23 L-JPN-4 | 4 | 12 | N | N | NA | constant | 0.22 | 19 | 1 |

Table 4: Summary of the number of release events, tag releases and recoveries by region and program

| Prog | JPTP | | | PTTP | | | RTTP | | | SSAP | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Years | 1998–2014 | | | 2006–2014 | | | 1989–1992 | | | 1977–1980 | | |
| Category | Grps | Rel | Rec | Grps | Rel | Rec | Grps | Rel | Rec | Grps | Rel | Rec |
| 1 | 57 | 17,391 | 1973 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 83 | 11 |
| 2 | 34 | 3,508 | 86 | 11 | 14,689 | 3,155 | 9 | 7,790 | 1,443 | 7 | 7,876 | 335 |
| 3 | 4 | 196 | 1 | 8 | 6,603 | 1,265 | 5 | 10,247 | 1,277 | 9 | 40,986 | 2,568 |
| 4 | 18 | 1,182 | 43 | 3 | 20,639 | 5,930 | 7 | 13,529 | 3,508 | 2 | 5,397 | 381 |
| 5 | 0 | 0 | 0 | 16 | 90,261 | 24,663 | 10 | 25,413 | 4,864 | 3 | 11,771 | 1,426 |
| Total | 113 | 22,277 | 2,103 | 38 | 132,193 | 35,013 | 31 | 56,978 | 11,092 | 22 | 66,114 | 4,721 |

Table 5: Description of the structural sensitivity grid used to characterise uncertainty in the assessment. The reference case option is denoted in **bold face**.

| Axis | Levels | Option |
|---|---|---|
| Steepness | 3 | 0.65, **0.80**, or 0.95 |
| Mixing period | 2 | **1 quarter mixing**, 2 quarters mixing |
| Length composition weighting | 3 | sample sizes divided by 10, **20** or 50 |
| Tagging overdispersion | 3 | **Default level**, Estimated, or Fixed (moderate) level |

Table 6: Reference points and model results for the reference case model and one-off sensitivity models.

| Quantity | RefCase | h0.65 | h0.95 | mix2qtr | Lgth10 | Lgth50 | EstVB | EstVBSD | EstOD | ODmiddle | InvMov | SRRqtrly | TermRec4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $C_{latest}$ | 1,679,528 | 1,679,517 | 1,679,522 | 1,679,609 | 1,679,535 | 1,679,467 | 1,679,194 | 1,679,283 | 1,679,169 | 1,679,313 | 1,679,538 | 1,679,520 | 1,679,698 |
| MSY | 1,891,600 | 2,026,400 | 1,832,800 | 2,076,800 | 1,84,8000 | 1,934,400 | 1,902,800 | 1,760,800 | 1,641,200 | 1,762,000 | 1,856,400 | 1,591,600 | 1,874,000 |
| $Y_{F_{recent}}$ | 1,594,800 | 1,766,000 | 1,504,000 | 1,659,200 | 1,585,200 | 1,603,200 | 1,591,600 | 1,531,600 | 1,545,600 | 1,589,200 | 1,580,000 | 1,445,200 | 1,595,200 |
| $f_{mult}$ | 2.23 | 1.96 | 2.48 | 2.47 | 2.14 | 2.31 | 2.23 | 2.04 | 1.61 | 1.88 | 2.17 | 1.69 | 2.17 |
| $F_{\mathrm{MSY}}$ | 0.24 | 0.22 | 0.27 | 0.24 | 0.26 | 0.23 | 0.25 | 0.27 | 0.24 | 0.25 | 0.24 | 0.19 | 0.24 |
| $F_{recent}/F_{\mathrm{MSY}}$ | 0.45 | 0.51 | 0.40 | 0.41 | 0.47 | 0.43 | 0.45 | 0.49 | 0.62 | 0.53 | 0.46 | 0.59 | 0.46 |
| $SB_{\mathrm{MSY}}$ | 1,626,000 | 1,972,000 | 1,423,000 | 1,858,000 | 1,496,000 | 1,761,000 | 1,560,000 | 1,346,000 | 1,470,000 | 1,509,000 | 1,597,000 | 1,813,000 | 1,622,000 |
| $SB_0$ | 6,764,000 | 7,637,000 | 6,284,000 | 7,463,000 | 6,256,000 | 7,420,000 | 6,996,000 | 5,453,000 | 5,858,000 | 6,055,000 | 6,618,000 | 6,469,000 | 6,767,000 |
| $SB_{F=0}$ | 7,221,135 | 7,802,299 | 6,877,143 | 7,751,452 | 6,744,980 | 7,825,861 | 7,449,414 | 5,981,232 | 6,436,206 | 6,539,112 | 7,086,859 | 7,205,705 | 7,212,830 |
| $SB_{latest}/SB_0$ | 0.62 | 0.55 | 0.66 | 0.68 | 0.64 | 0.59 | 0.59 | 0.59 | 0.45 | 0.51 | 0.63 | 0.65 | 0.66 |
| $SB_{latest}/SB_{F=0}$ | 0.58 | 0.53 | 0.61 | 0.65 | 0.60 | 0.56 | 0.56 | 0.54 | 0.41 | 0.47 | 0.59 | 0.58 | 0.62 |
| $SB_{latest}/SB_{\mathrm{MSY}}$ | 2.56 | 2.11 | 2.93 | 2.73 | 2.69 | 2.49 | 2.66 | 2.38 | 1.81 | 2.03 | 2.60 | 2.30 | 2.76 |
| $SB_{recent}/SB_{F=0}$ | 0.52 | 0.48 | 0.54 | 0.56 | 0.52 | 0.51 | 0.50 | 0.50 | 0.41 | 0.46 | 0.52 | 0.52 | 0.51 |
| $SB_{recent}/SB_{\mathrm{MSY}}$ | 2.31 | 1.90 | 2.63 | 2.32 | 2.36 | 2.28 | 2.41 | 2.21 | 1.80 | 1.98 | 2.29 | 2.07 | 2.28 |

Table 7: Likelihood components for the reference case model and the one-off sensitivity models.

| Component | RefCase | h0.65 | h0.95 | mix2qtr | Lgth10 | Lgth50 | EstVB | EstVBSD | EstOD | ODmiddle | InvMov | SRRqtrly | TermRec4 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Beverton Holt | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.3 | 0.2 | 0.2 | 1.8 | 0.2 |
| Effort devs | 1,624.2 | 1,615.0 | 1,614.9 | 1,638.9 | 1,745.4 | 1,540.5 | 1,594.2 | 1,547.3 | 1,512.8 | 1,531.5 | 1,619.5 | 1,615.0 | 1,637.0 |
| Catch devs | 58.0 | 57.8 | 57.8 | 55.9 | 63.3 | 49.2 | 57.2 | 56.4 | 51.2 | 53.0 | 56.8 | 57.9 | 57.1 |
| Length comps | -250,959.0 | -250,945.9 | -250,945.9 | -251,067.0 | -272,759.1 | -214,711.7 | -250,836.8 | -249,979.7 | -251,973.5 | -251,861.6 | -250,881.6 | -250,945.8 | -250,953.3 |
| Tagging | 24,488.8 | 24,490.7 | 24,491.2 | 19,651.7 | 25,589.0 | 23,273.4 | 24,398.9 | 23,804.0 | 20,196.4 | 20,437.7 | 24,737.4 | 24,489.9 | 24,494.1 |
| Total | -224,287.5 | -224,281.9 | -224,281.9 | -229,326.4 | -244,794.1 | -189,401.7 | -224,339.6 | -224,203.9 | -229,929.1 | -229,519.6 | -224,092.9 | -224,280.9 | -224,273.0 |

Table 8: Summaries of important reference points and model results summarised by quantiles across all models in the structural uncertainty grid.

| Quantity | 50% | 5% | 25% | 75% | 95% |
|---|---|---|---|---|---|
| $C_{latest}$ | 1,679,444 | 1,678,646 | 1,679,170 | 1,679,497 | 1,679,592 |
| MSY | 1,875,600 | 1,618,060 | 1,785,400 | 1,976,700 | 2,199,880 |
| $Y_{F_{recent}}$ | 1,607,000 | 1,486,660 | 1,533,200 | 1,755,200 | 1,808,860 |
| $f_{mult}$ | 2.07 | 1.57 | 1.85 | 2.29 | 2.62 |
| $F_{\text{MSY}}$ | 0.24 | 0.21 | 0.22 | 0.26 | 0.28 |
| $F_{recent}/F_{\text{MSY}}$ | 0.48 | 0.38 | 0.44 | 0.54 | 0.64 |
| $SB_{\text{MSY}}$ | 1,628,000 | 1,258,700 | 1,425,750 | 1,852,750 | 2,166,100 |
| $SB_0$ | 6,359,500 | 5,214,050 | 5,853,750 | 7,095,250 | 8,340,450 |
| $SB_{F=0}$ | 6,876,526 | 5,778,079 | 6,408,578 | 7,425,353 | 8,555,240 |
| $SB_{latest}/SB_0$ | 0.55 | 0.43 | 0.49 | 0.59 | 0.71 |
| $SB_{latest}/SB_{F=0}$ | 0.51 | 0.39 | 0.47 | 0.57 | 0.67 |
| $SB_{latest}/SB_{\text{MSY}}$ | 2.15 | 1.60 | 1.81 | 2.43 | 3.08 |
| $SB_{recent}/SB_{F=0}$ | 0.49 | 0.40 | 0.46 | 0.52 | 0.57 |
| $SB_{recent}/SB_{\text{MSY}}$ | 2.04 | 1.58 | 1.82 | 2.32 | 2.65 |

# 9 Figures

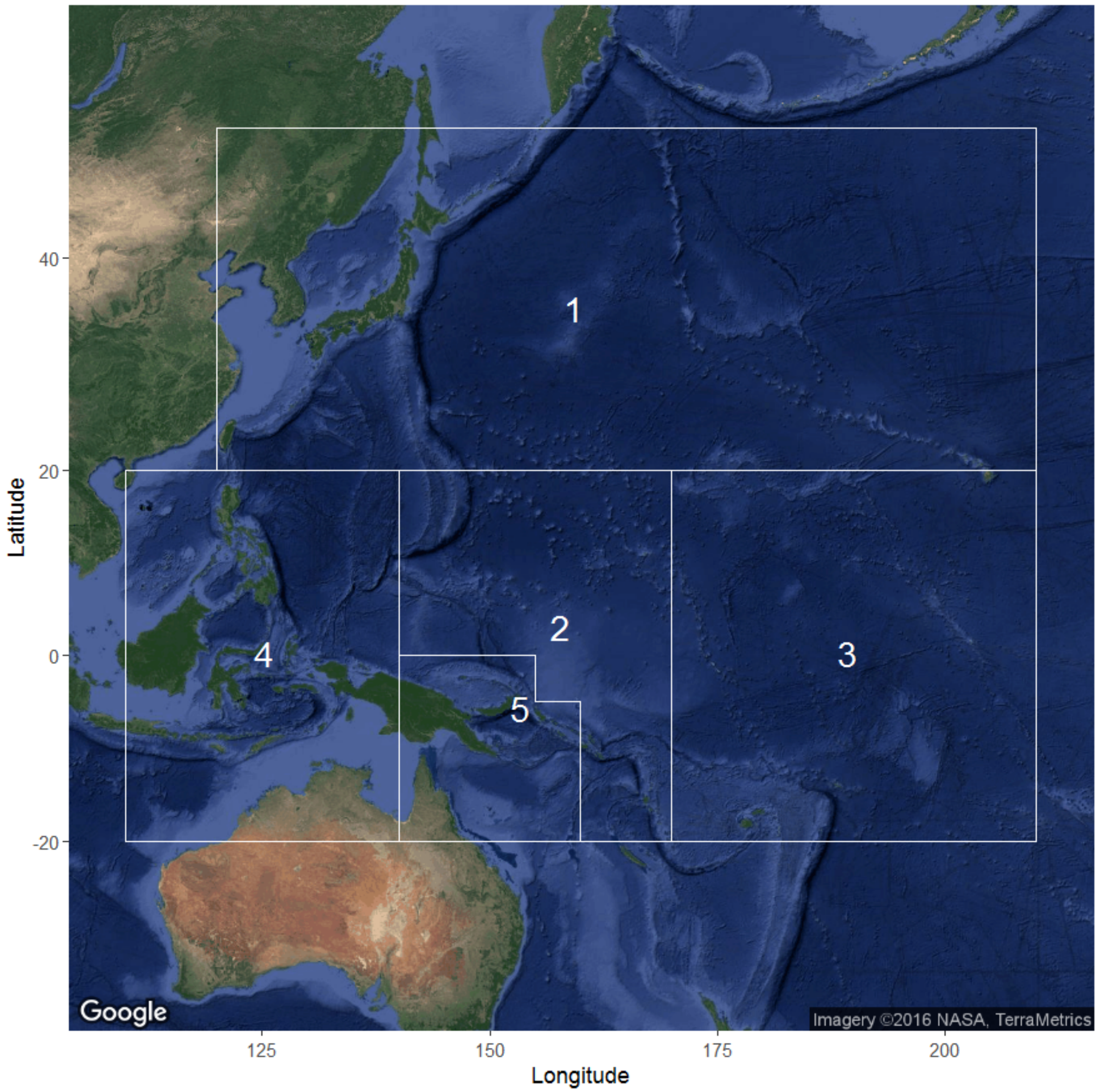



Figure 1: The geographical area covered by the stock assessment and the boundaries for the 5 regions.

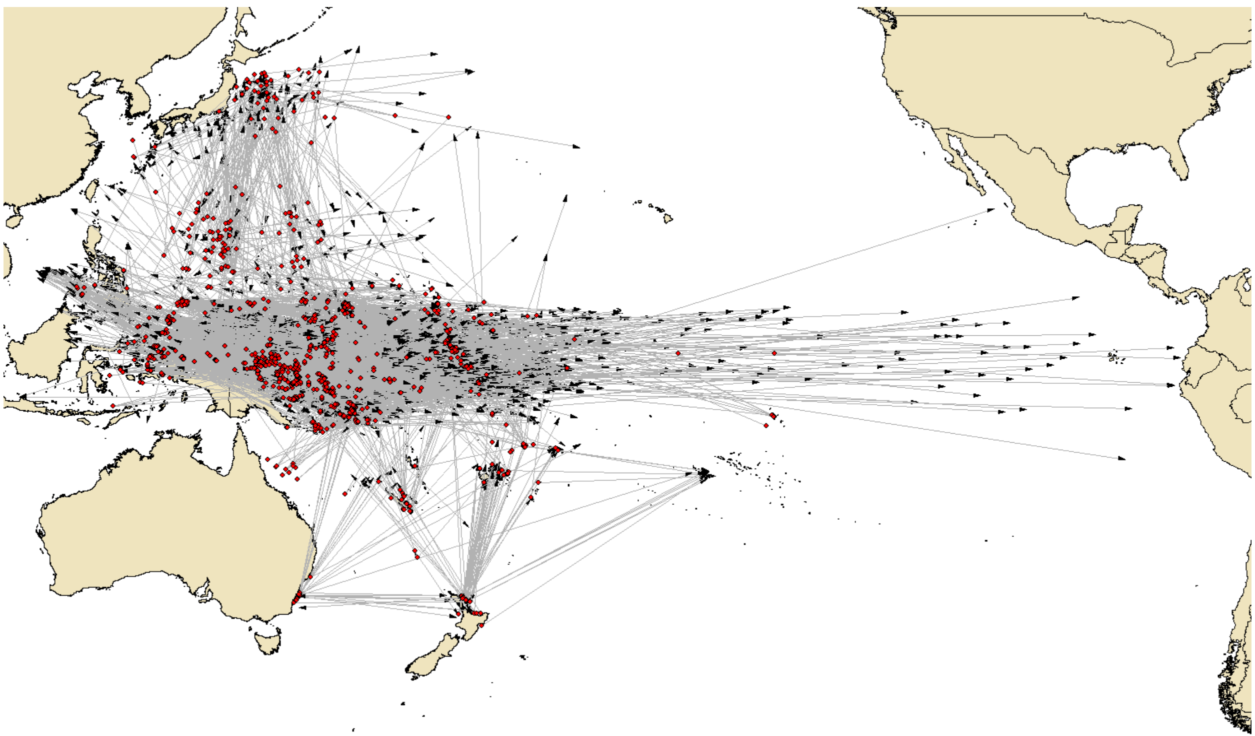


Figure 2: Map of the movements of tagged skipjack released in the WCPO and subsequently recaptured.

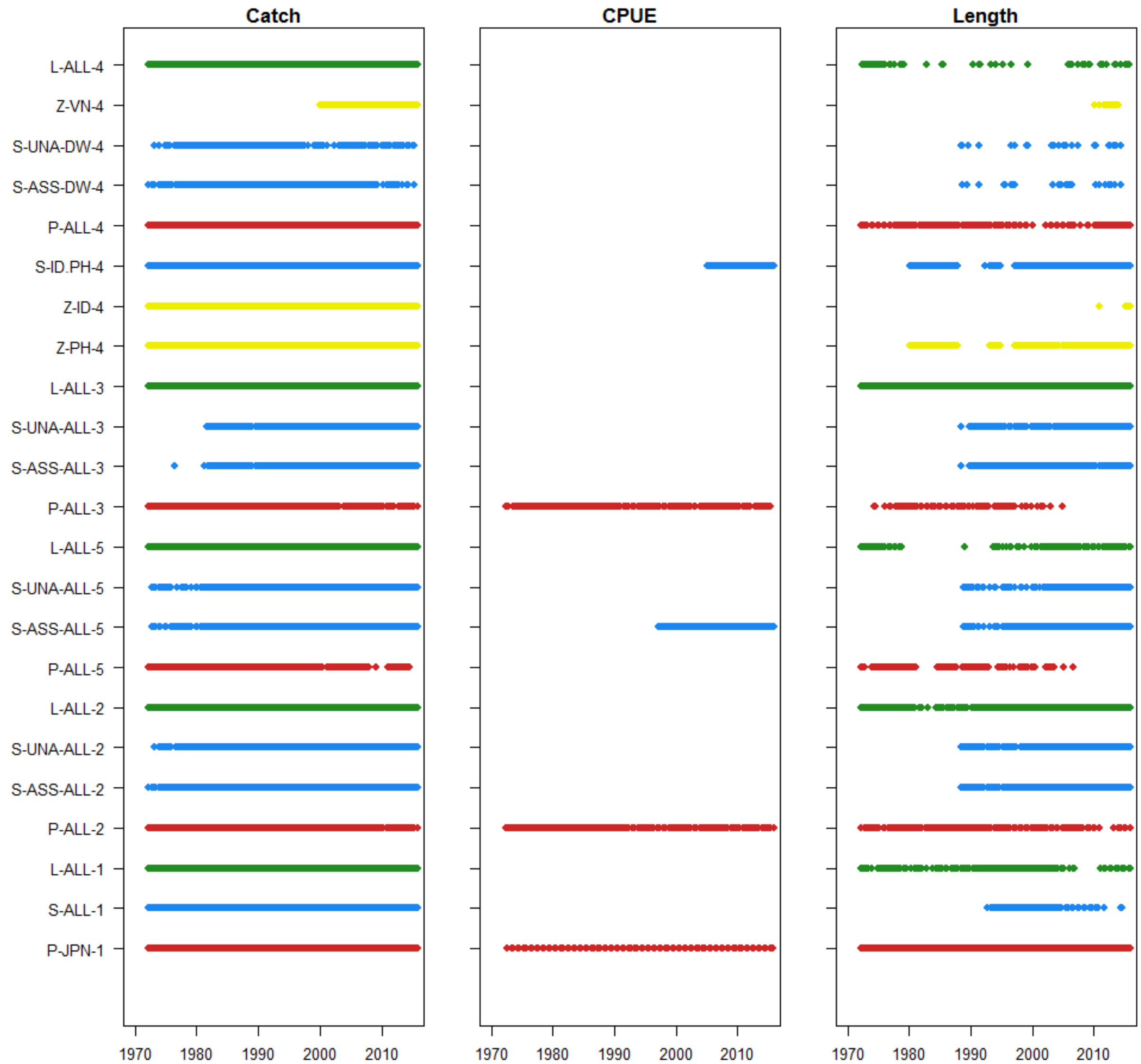



Figure 3: Presence of catch, standardised CPUE, and length frequency data by year and fishery for the reference case model. The different colours refer to longline (green), pole-and-line (red), purse seine (blue) and miscellaneous (yellow).

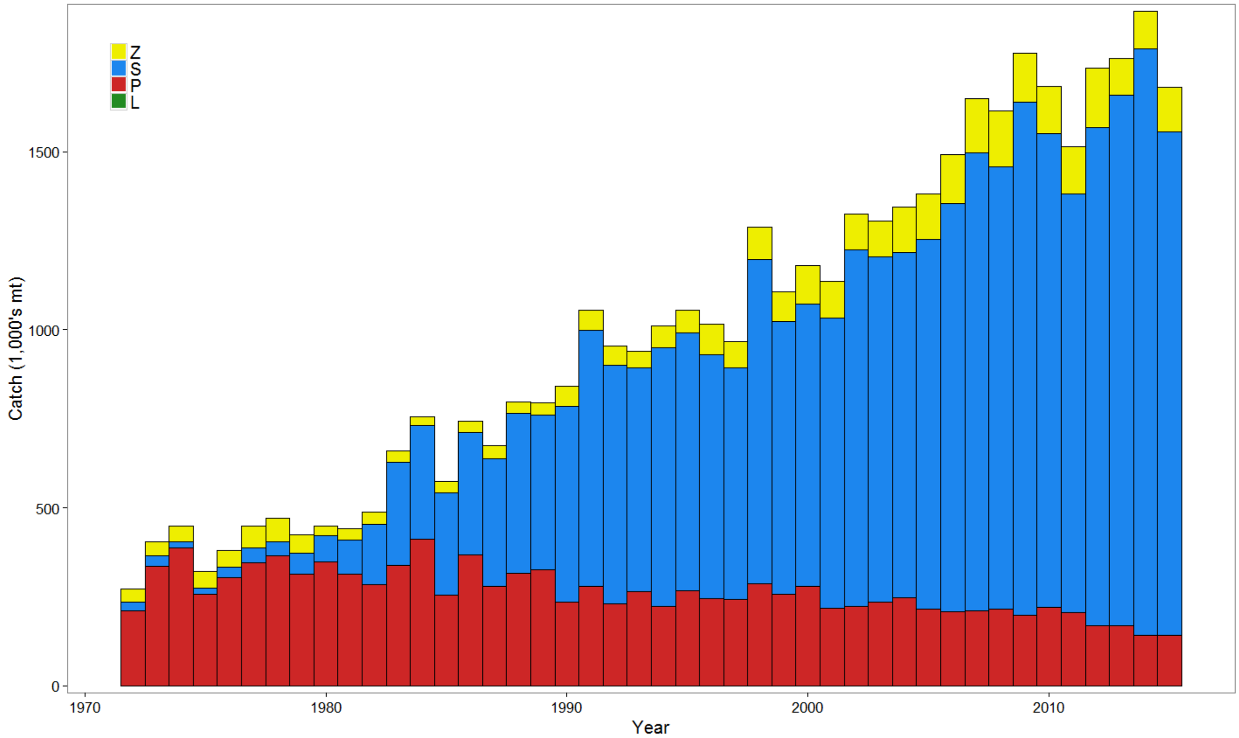



Figure 4: Time series of total annual catch (1000's mt) by fishing gear from the reference case model over the full assessment period. The different colours refer to longline (green), pole-and-line (red), purse seine (blue) and miscellaneous (yellow).

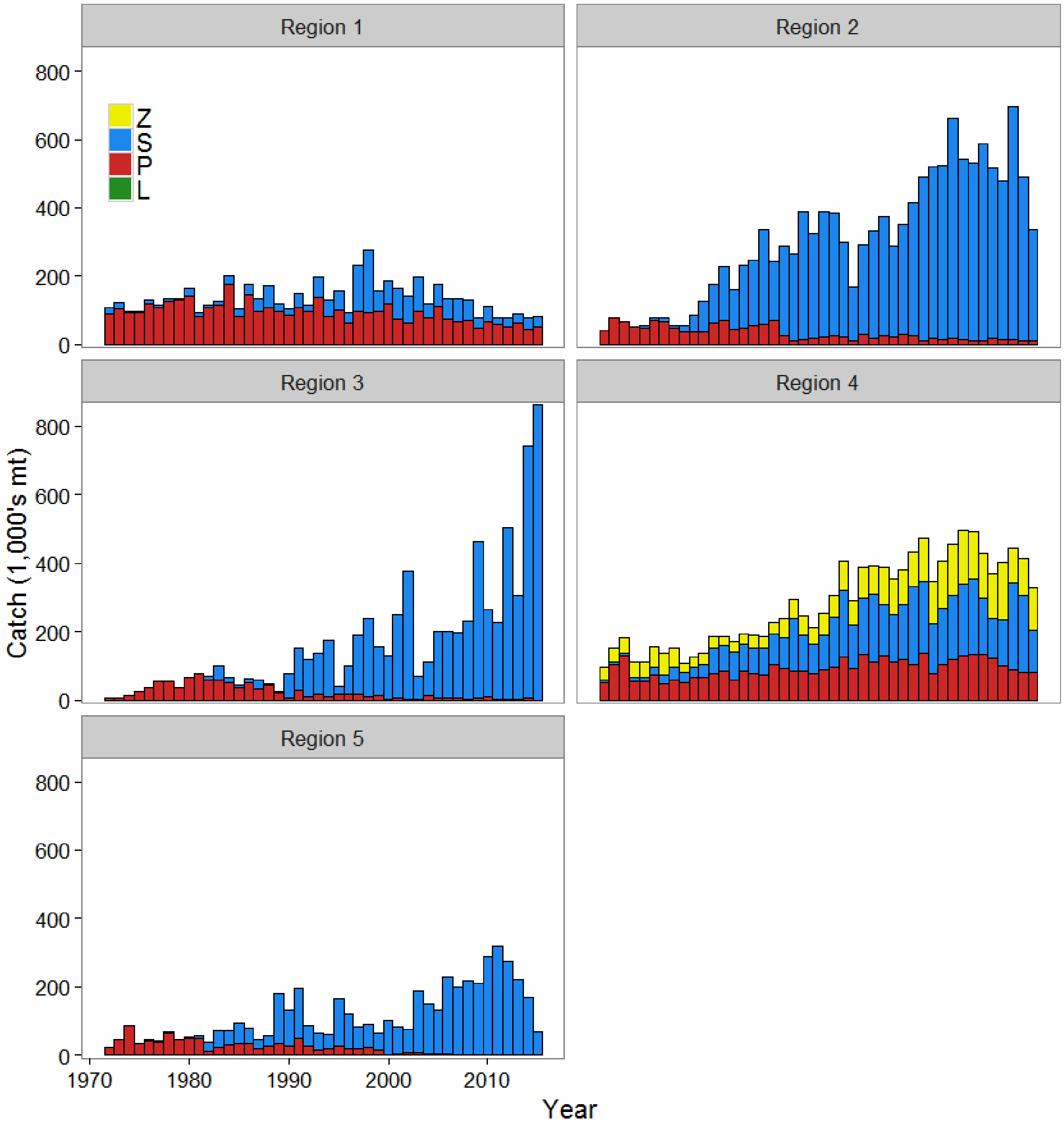



Figure 5: Time series of total annual catch (1000's mt) by fishing gear and assessment region from the reference case model over the full assessment period. The different colours refer to longline (green), pole-and-line (red), purse seine (blue) and miscellaneous (yellow).

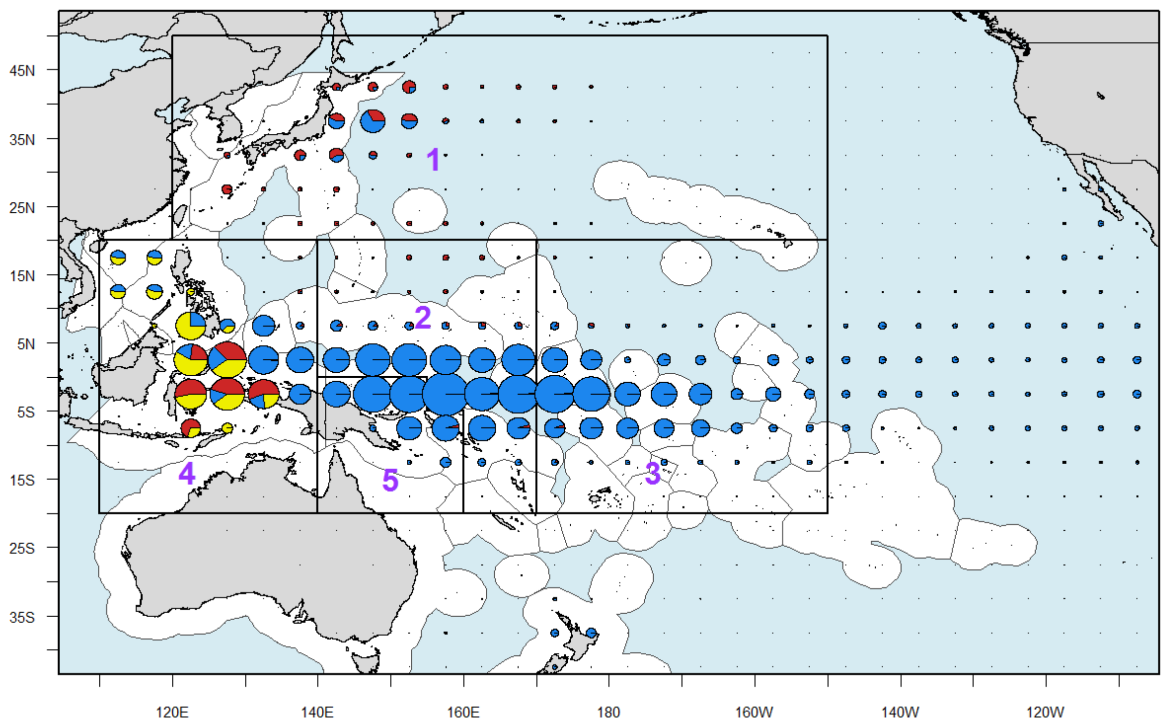



Figure 6: Distribution and magnitude of skipjack catches for the most recent decade of the stock assessment (2006-2015) by 5° square and fishing gear: longline (green), pole-and-line (red), purse seine (blue) and miscellaneous (yellow), for the entire Pacific Ocean. Overlayed are the regional boundaries for the stock assessment.

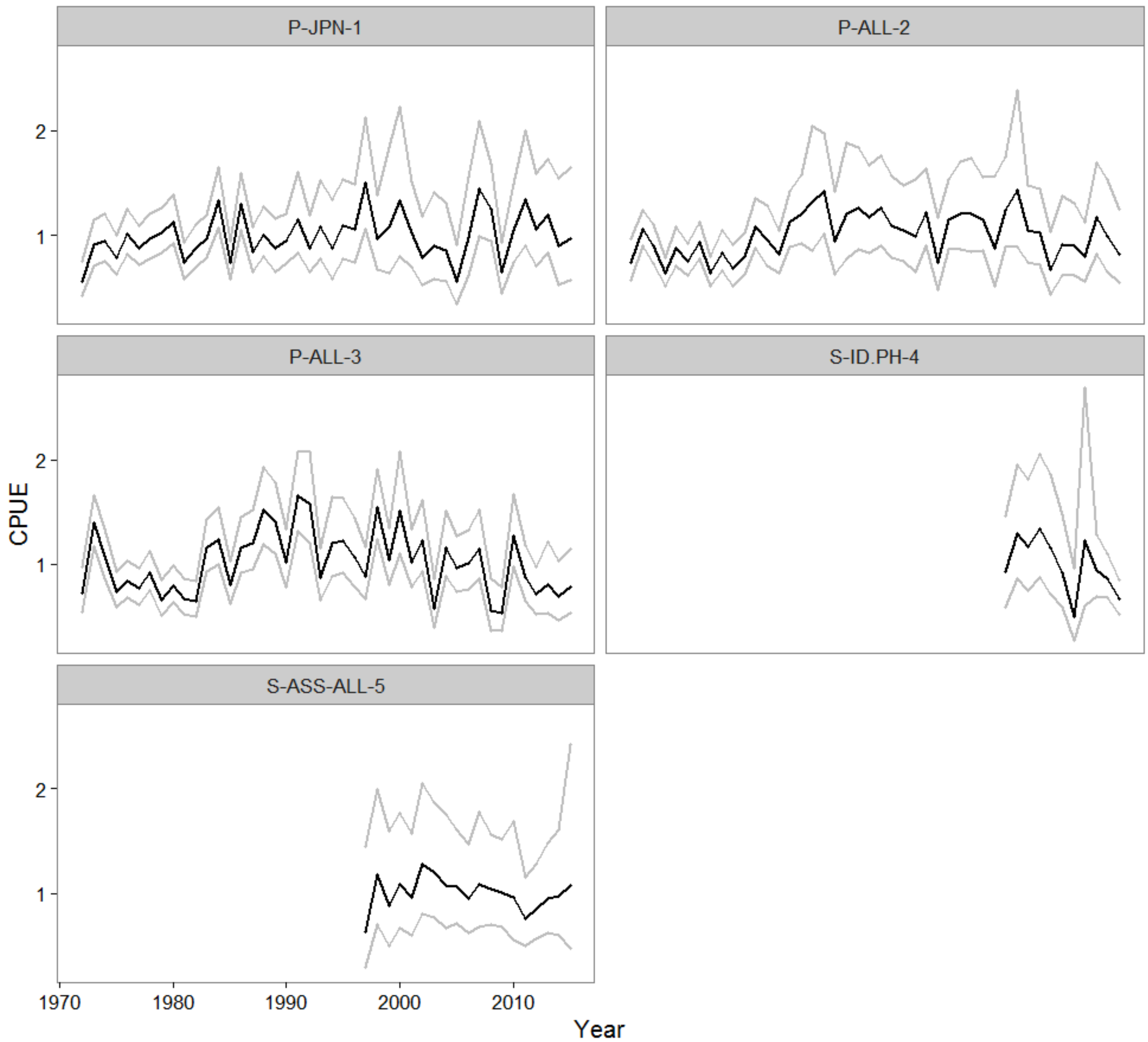



Figure 7: Standardised catch-per-unit-effort (CPUE) indices for the pole-and-line fisheries in regions 1, 2, and 3 (P-ALL-1, P-ALL-2, P-ALL-3), the ID/PH domestic purse seine fishery in region 4 (S-ID.PH-4), and the associated purse seine fishery in region 5 (S-ASS-ALL-5), used in the reference case model. See Bigelow et al. (2016), Kiyofuji (2016) and Tremblay-Boyer et al. (2016) for further details of the estimation of these CPUE indices. The light grey lines represent the 95% confidence intervals derived from the effort deviation penalties used in the reference case model.

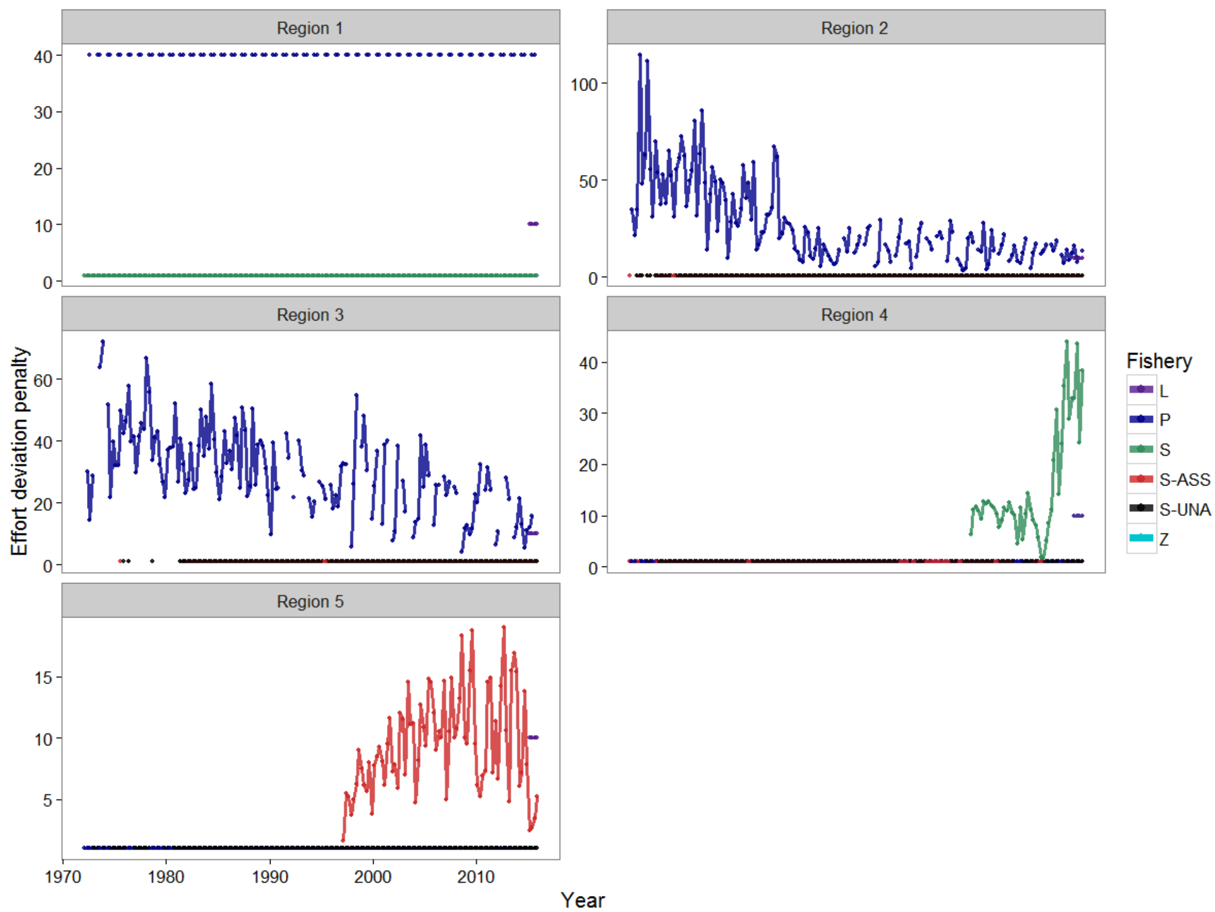



Figure 8: Plot of the effort deviation penalties applied to each fishery, by region. A higher the penalty gives more weight to the CPUE of that fishery.

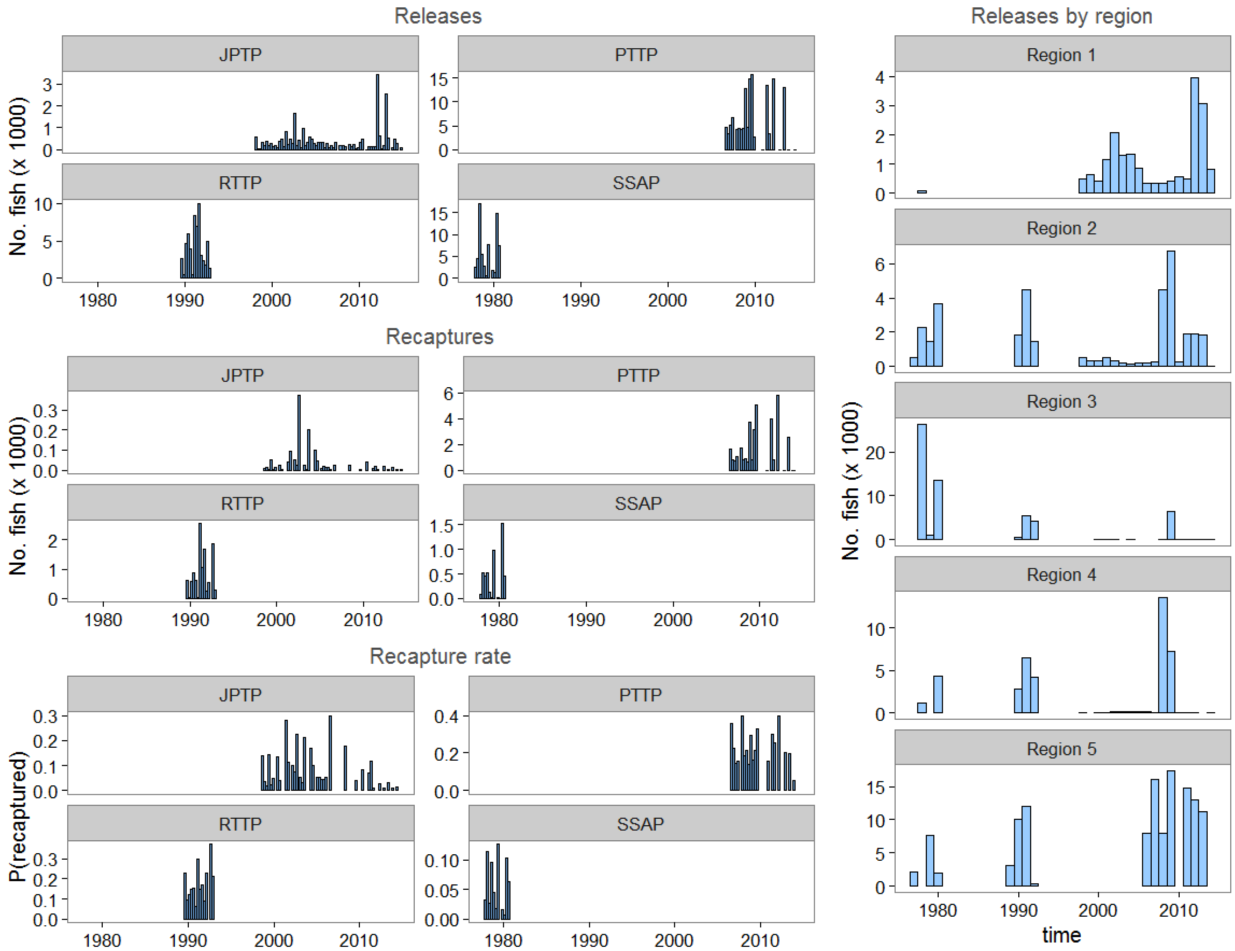



Figure 9: Summary of the number of releases, recaptures and recapture rate of tags used in the 2016 reference case model, by tagging programme and region.

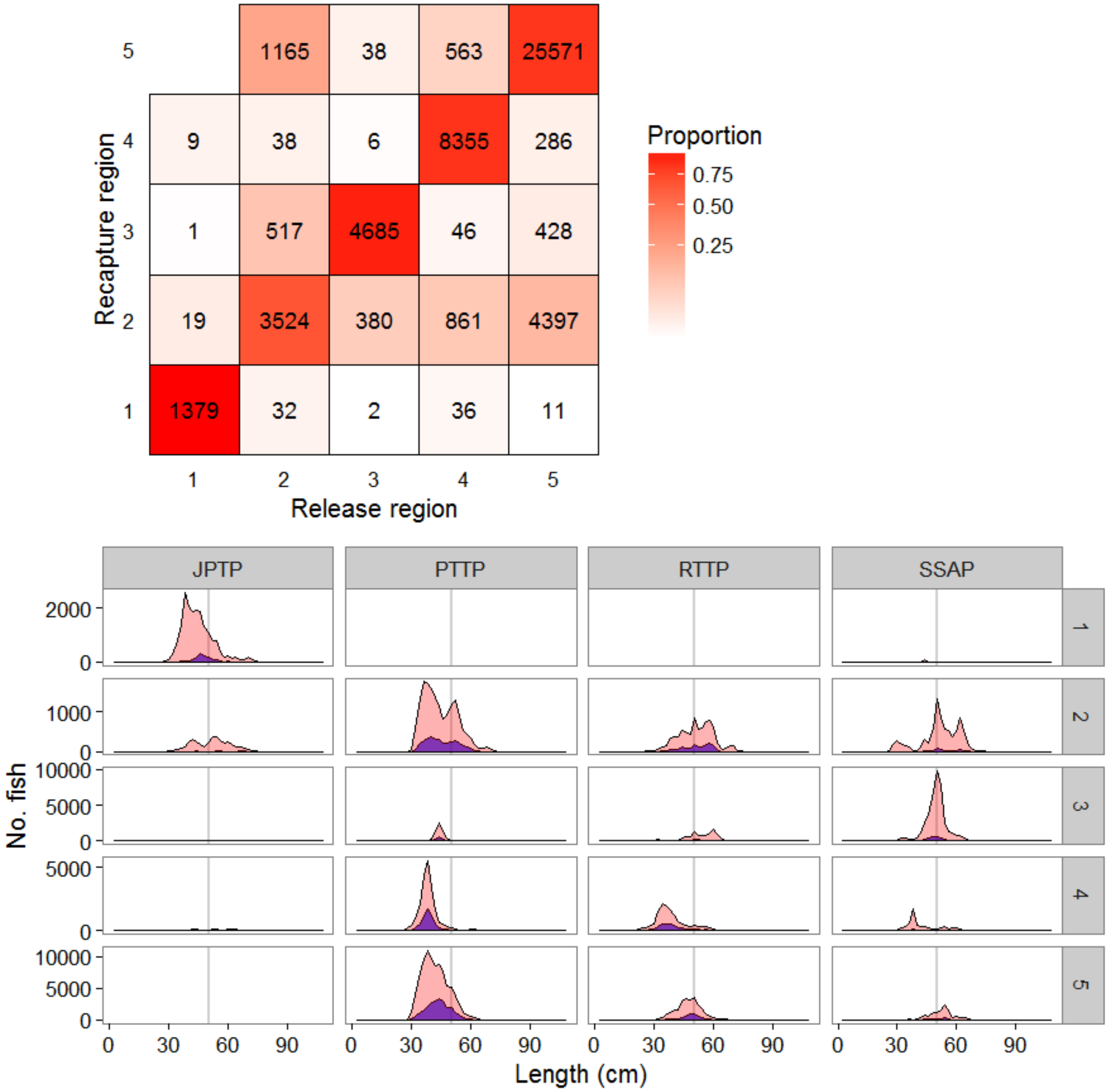



Figure 10: Summary of the tagging file used in the reference case model. The upper panel shows the observed movement of tagged fish; the x-axis is the region of release and the y axis is the region of recapture, with the number in each cell being the number of fish recaptured for that combination of release/recapture regions. The colour of the cell indicates the proportion of recaptures released in that region (x-axis) that were recaptured in that region (y-axis). The lower panel shows the length composition of released (pink) and recaptured (purple) fish for the different tagging programmes (x-axis panels) and regions (y-axis panels).

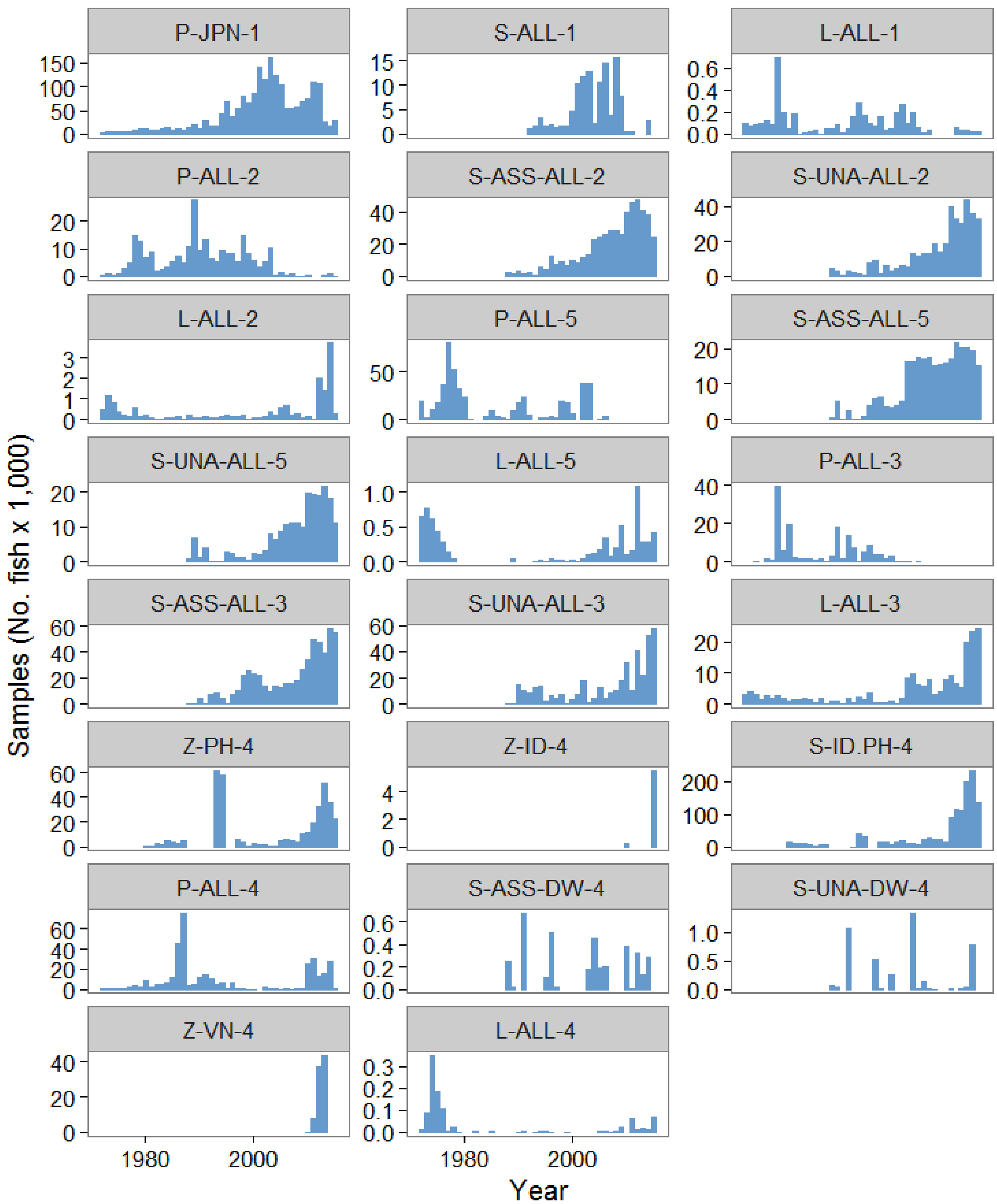



Figure 11: Number of length frequency samples available for each fishery for the reference case model. Note that in the reference case model a maximum sample size of 1,000 is allowed by MFCL and these are further downweighted in the model according to defined settings presented in Section 4.5.

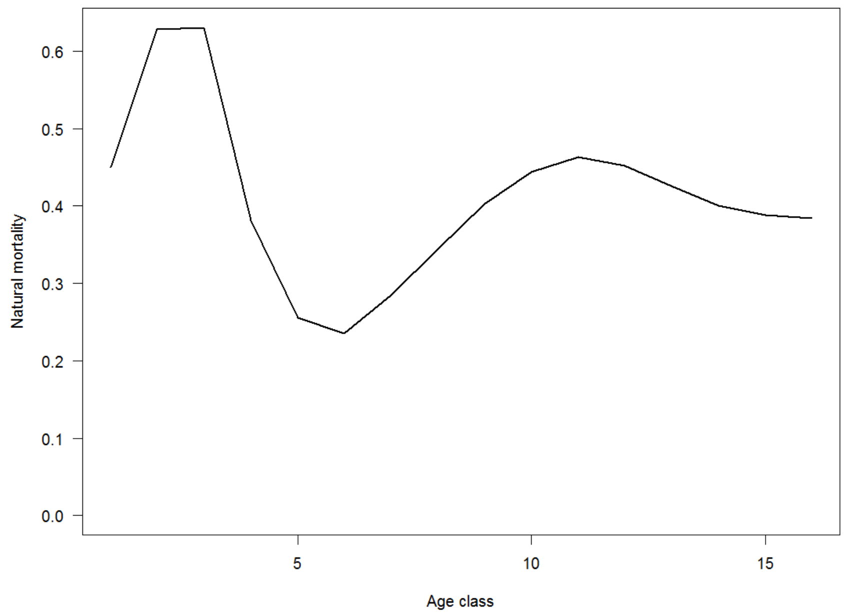



Figure 12: Quarterly natural mortality-at-age as estimated by the reference case model.

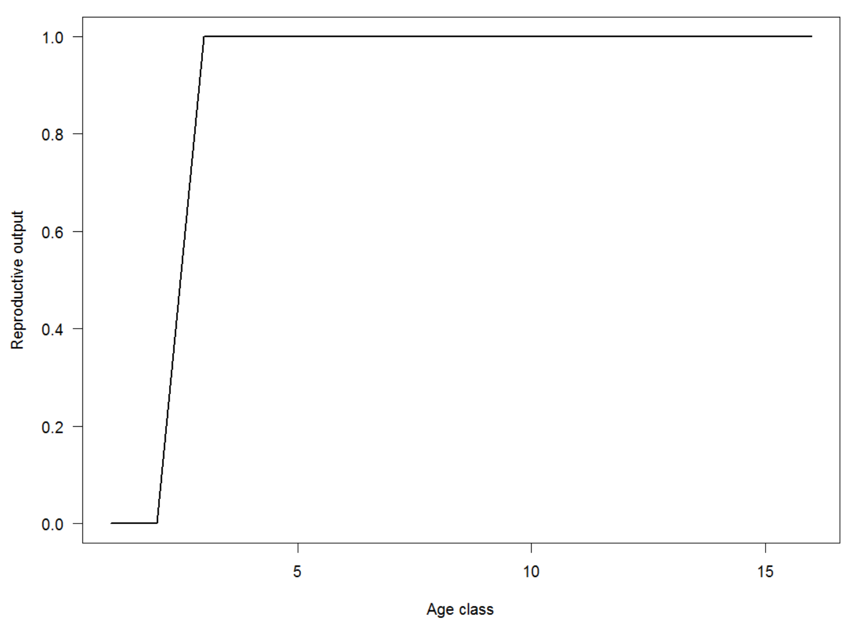



Figure 13: Maturity-at-age as assumed in the reference case model.

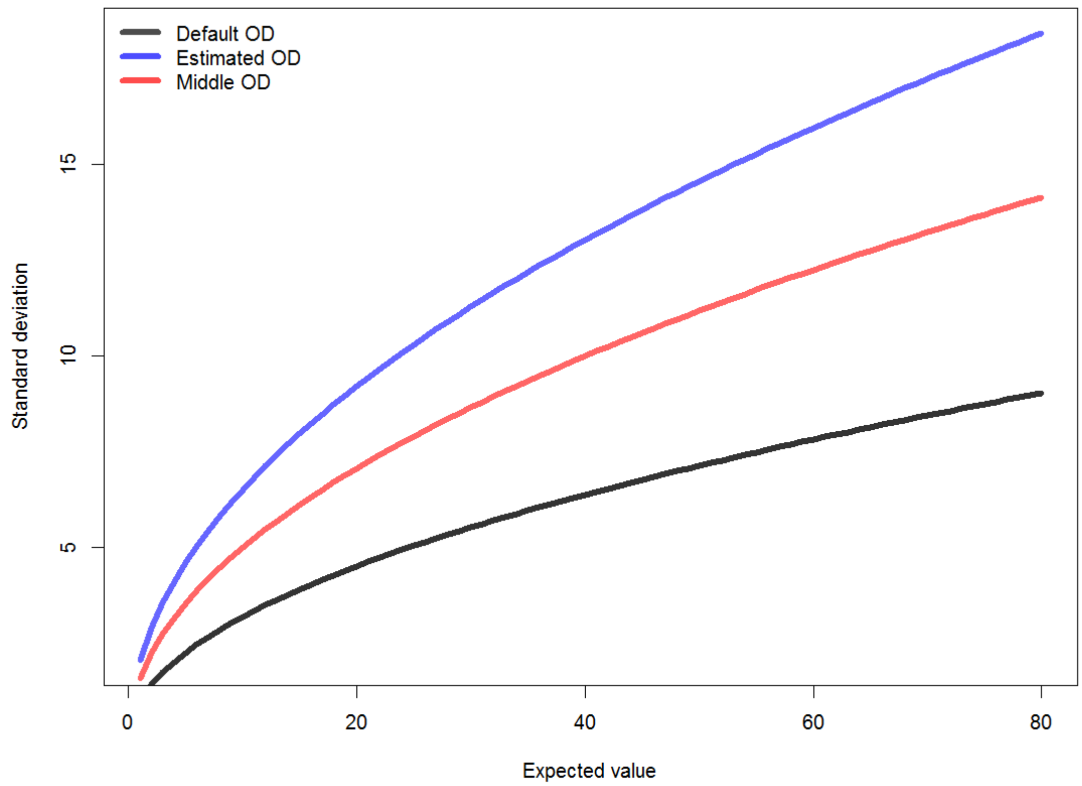



Figure 14: The relationship between the expected value and the standard deviation for the three levels of the overdispersion parameter used in the reference case model and sensitivity analyses.

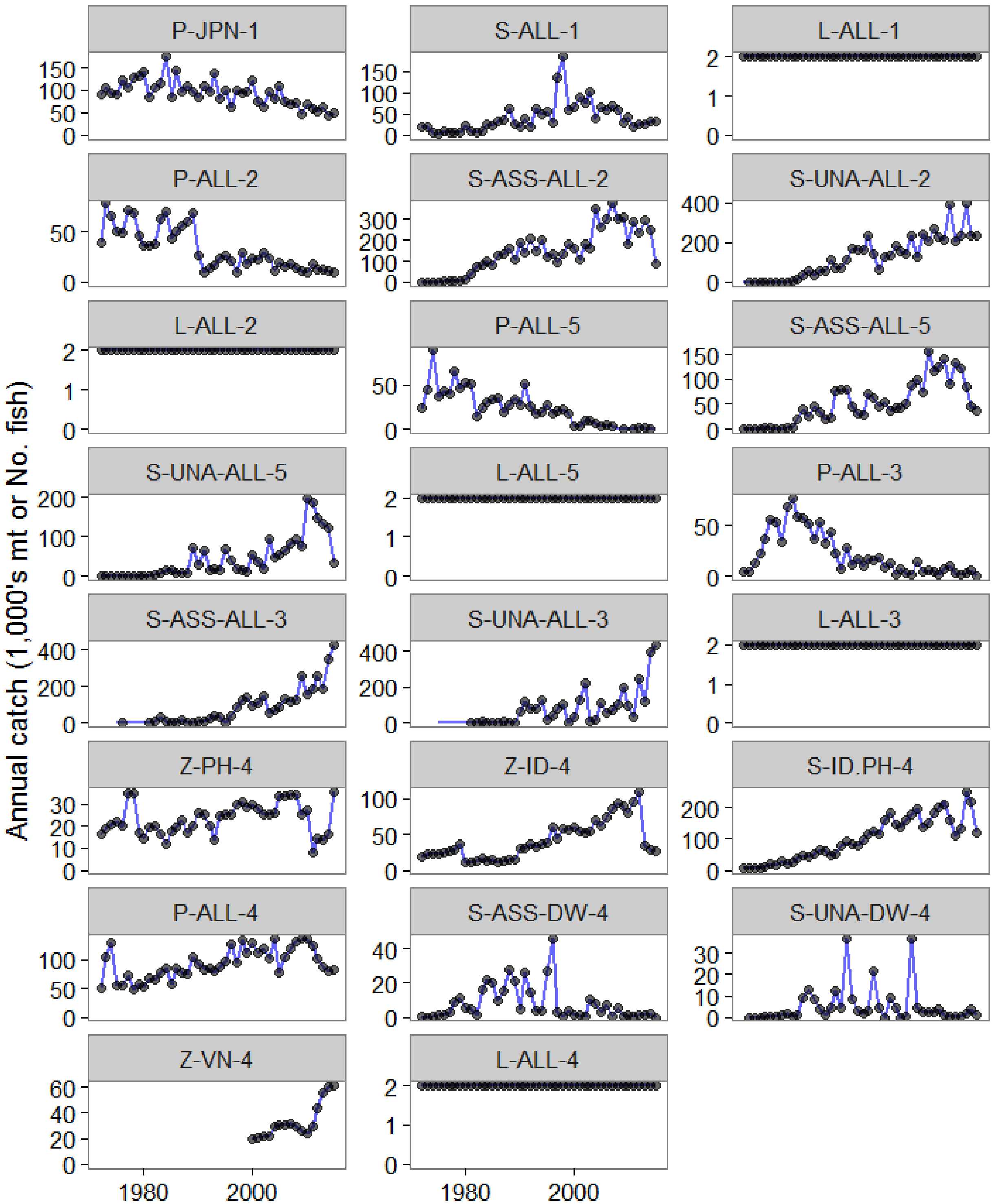



Figure 15: Observed (black points) and model-predicted (blue lines) catch for the 23 fisheries in the reference case model. Note that the longline fisheries are given nominal catches and these can be ignored.

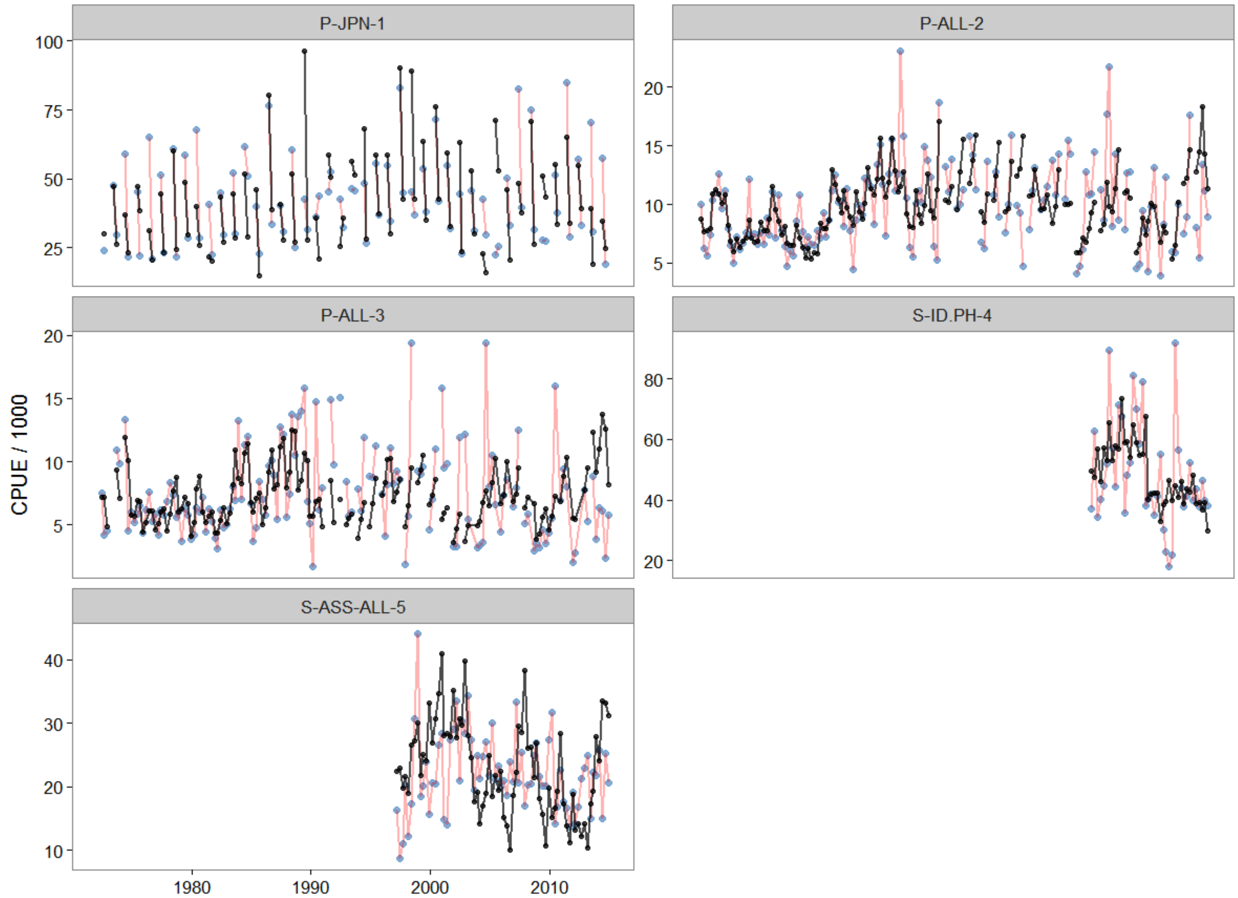



Figure 16: Observed (blue points and red lines) and model-predicted (black points and lines) CPUE for the five fisheries which received standardised CPUE indices in the reference case model.


Figure 17: Effort deviations by time period for each of the fisheries receiving standardised CPUE indices in the reference case model. The dark line represents a lowess smoothed fit to the effort deviations.

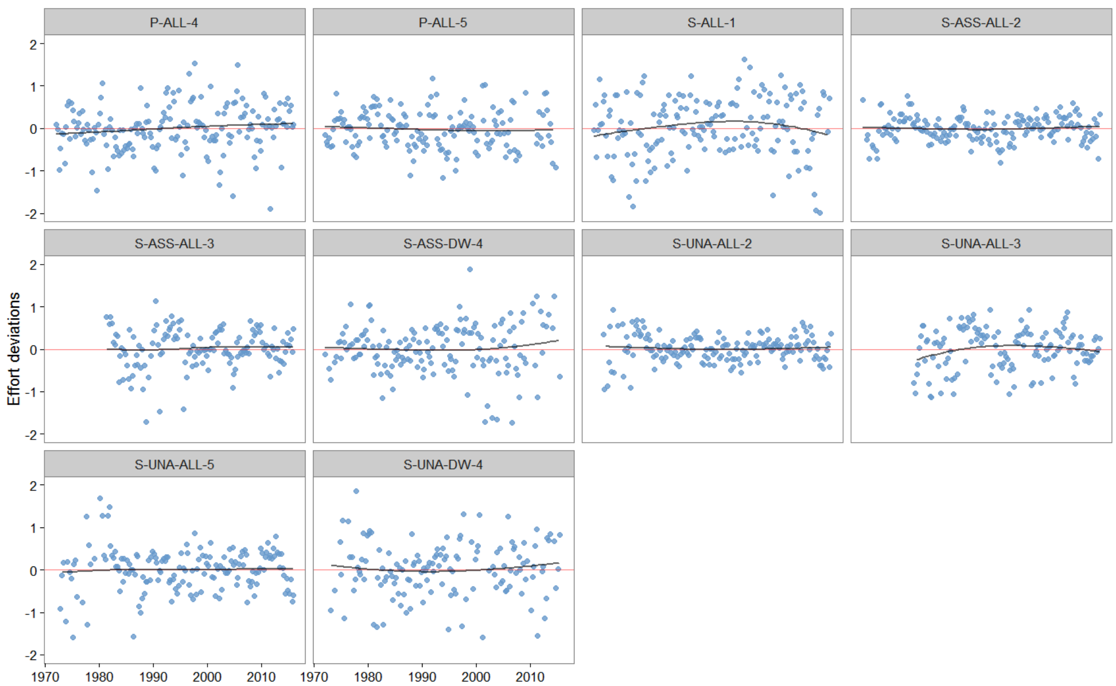



Figure 18: Effort deviations by time period for each of the fisheries that did not receive standardised CPUE indices in the reference case model. The dark line represents a lowess smoothed fit to the effort deviations.

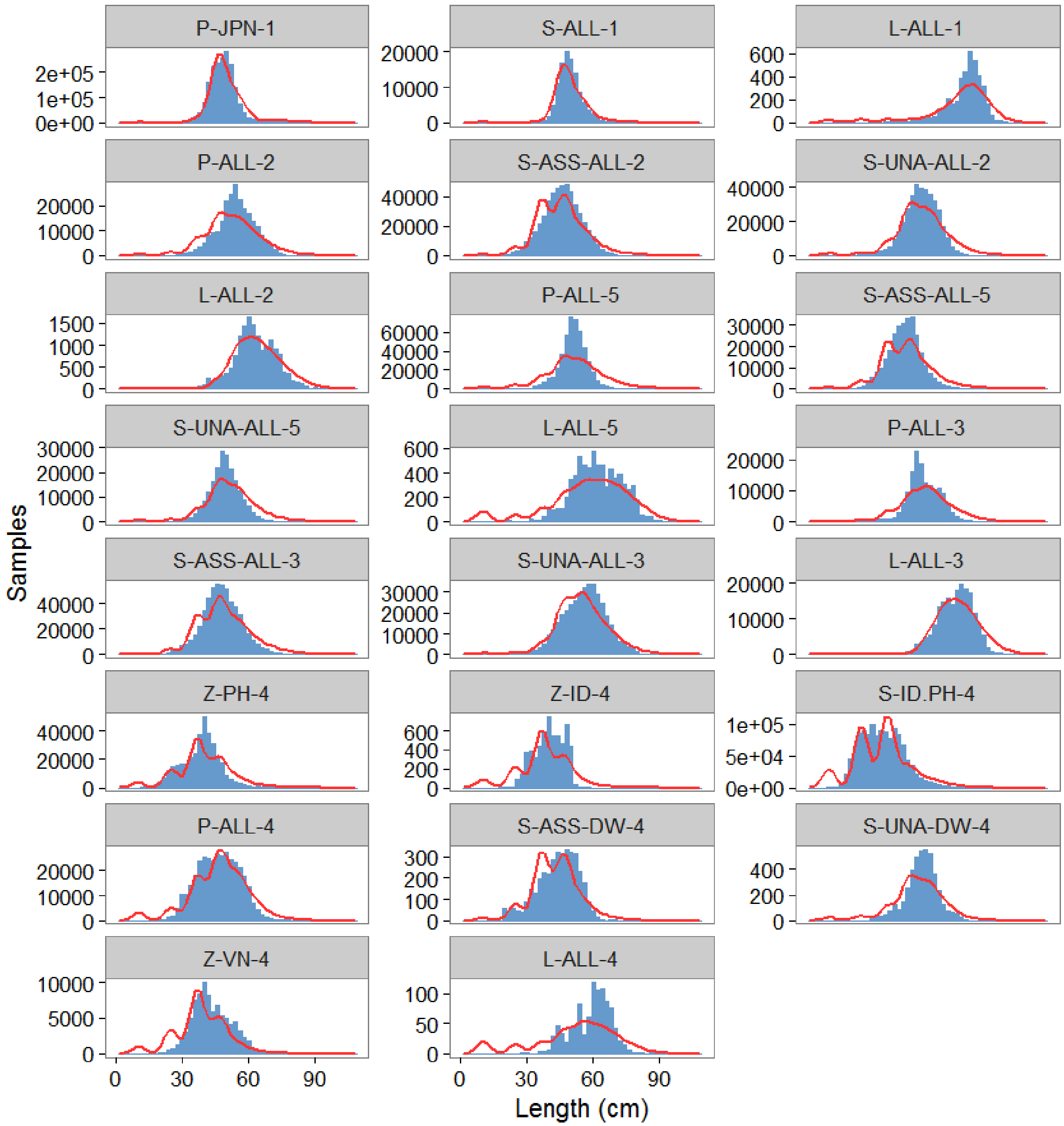



Figure 19: Composite (all time periods combined) observed (blue histograms) and predicted (red line) catch at length for all fisheries with samples for the reference case model.

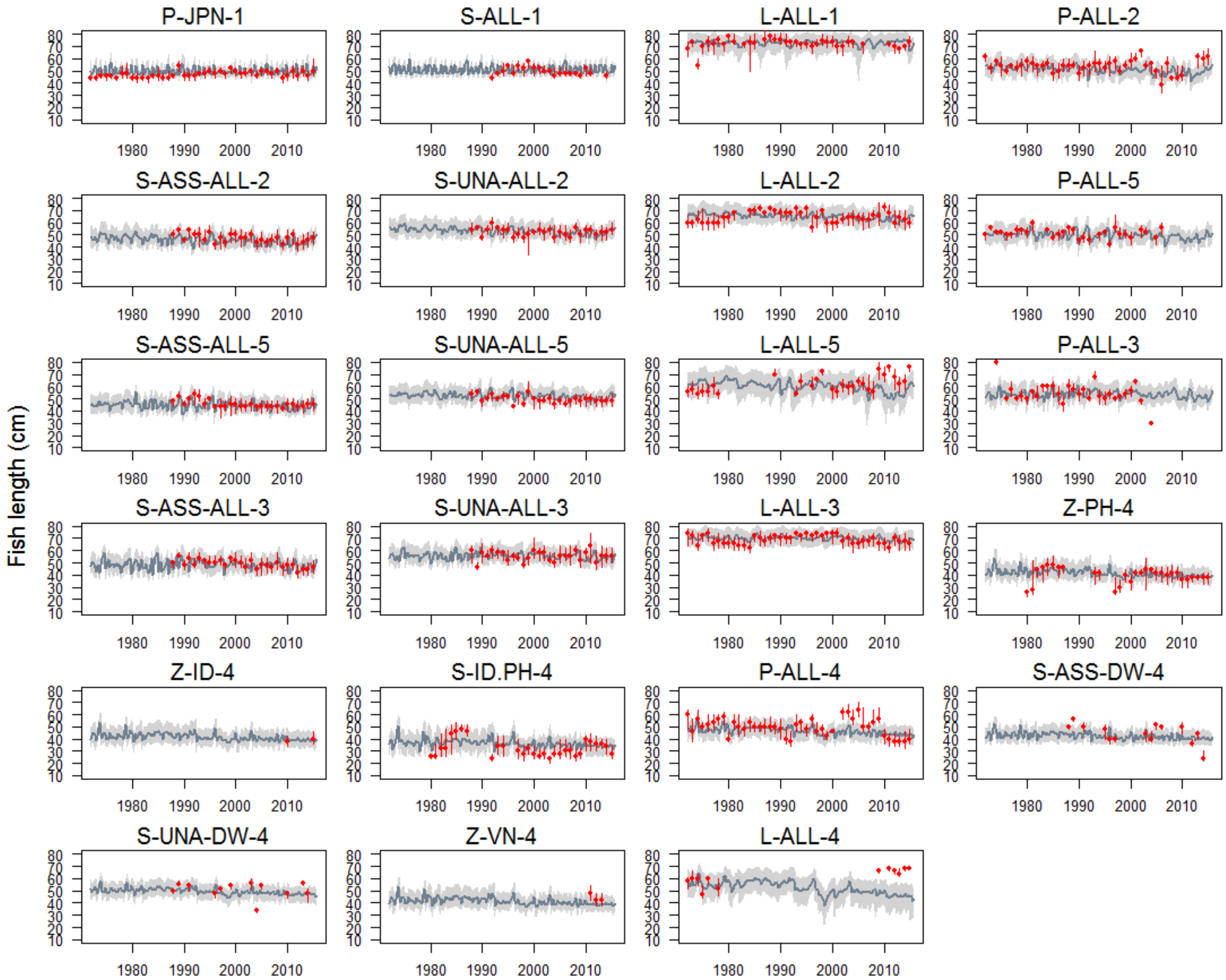



Figure 20: A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) for all fisheries with samples for the reference case model. The uncertainty intervals (grey shading) represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

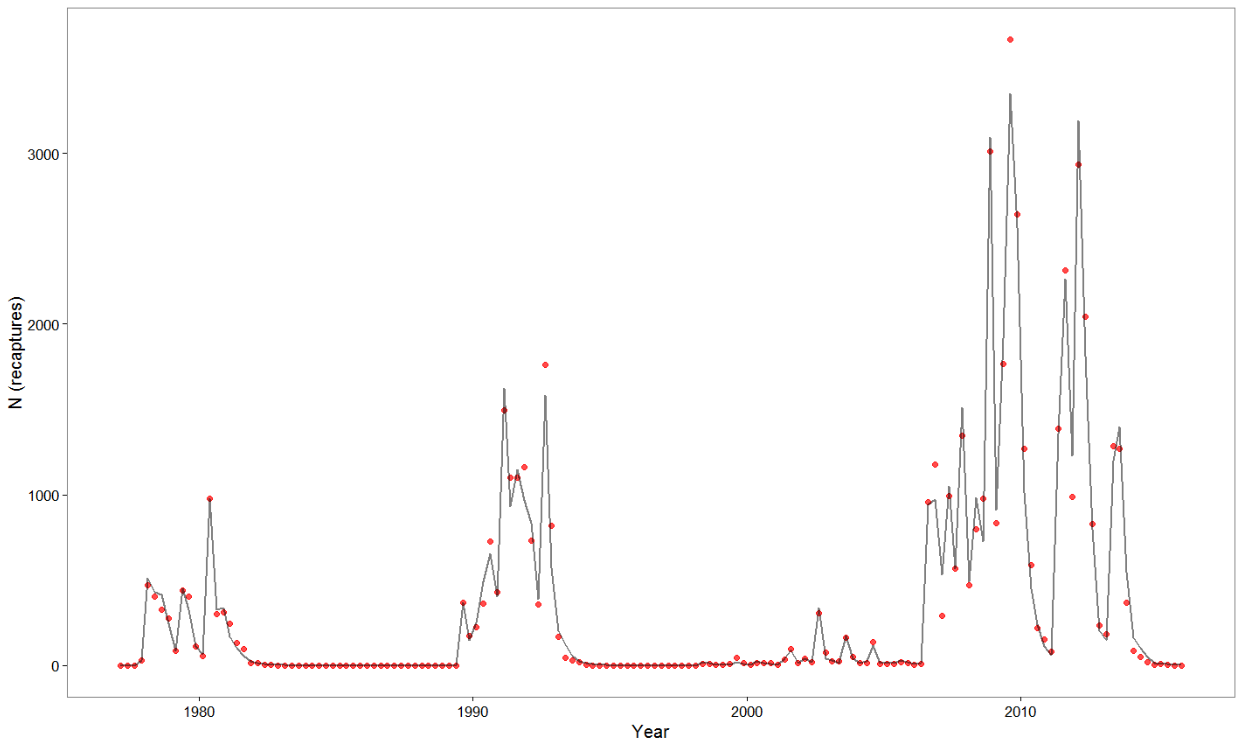



Figure 21: Observed (red points) and model-predicted (black line) tag returns over time for the reference case model across all tag release events with all tag recapture groupings aggregated.

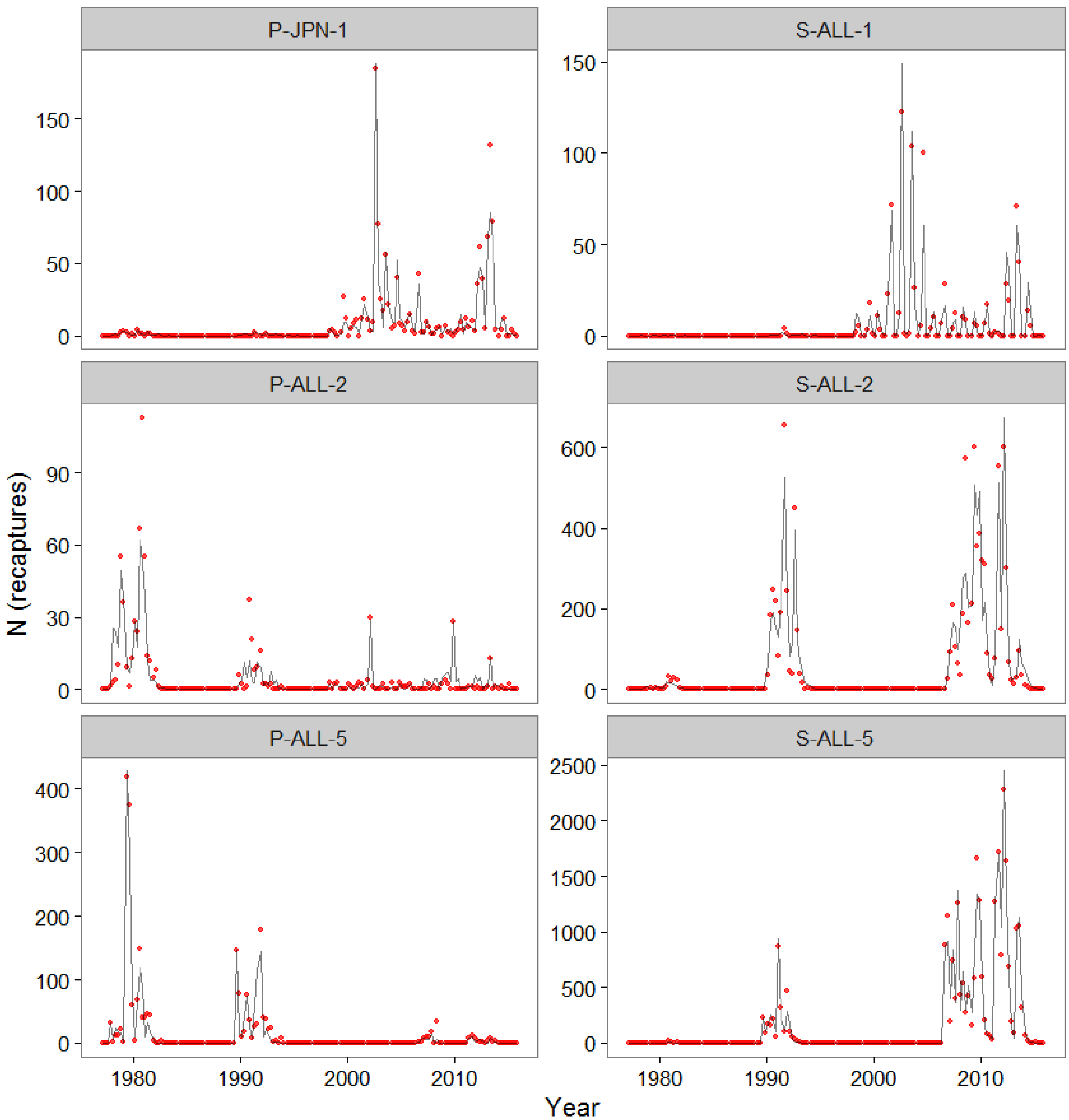



Figure 22: Observed (red points) and model-predicted (black line) tag returns over time for the reference case model by recapture group for the first 8 recapture groups. Groups with extremely low numbers of recaptures such as the longline fisheries are uninformative and not shown.

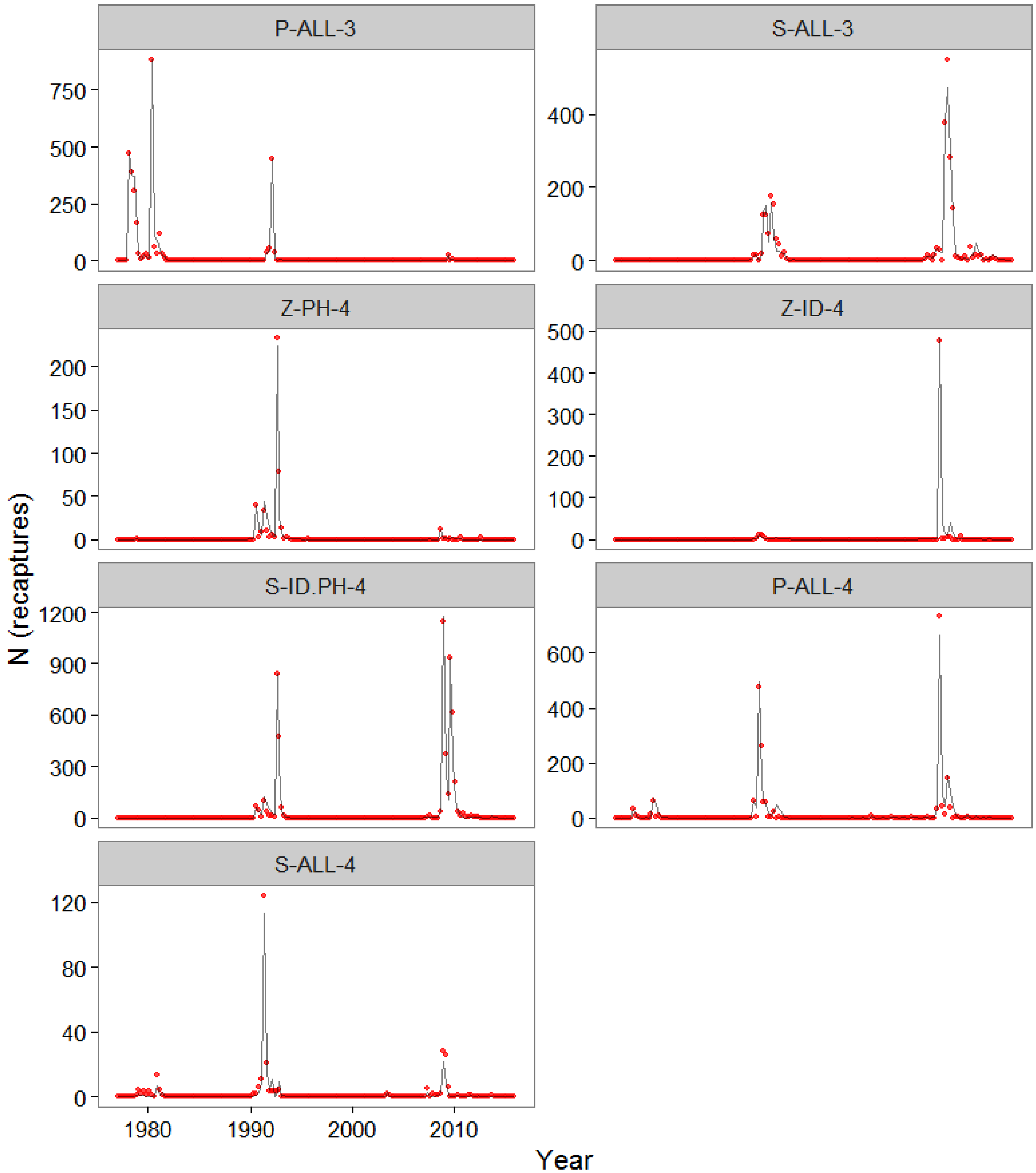



Figure 23: Observed (red points) and model-predicted (black line) tag returns over time for the reference case model by recapture group for the remaining recapture groups. Groups with extremely low numbers of recaptures such as the longline fisheries are uninformative and not shown.

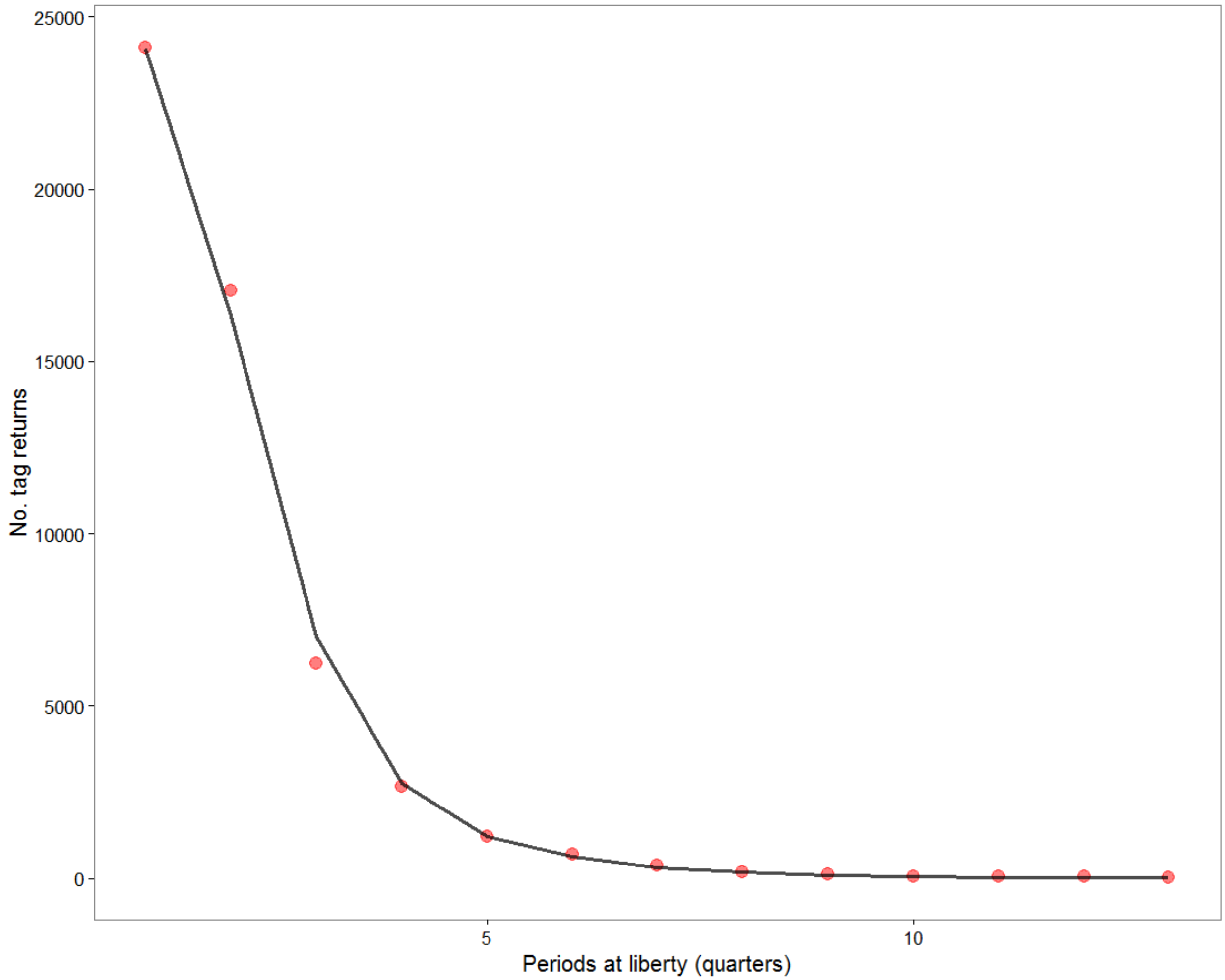



Figure 24: Observed and model-predicted tag attrition across all tag release events for the reference case model. The exact correspondence between observed and predicted values for the first quarter-at-liberty is a direct result of the mixing assumption.

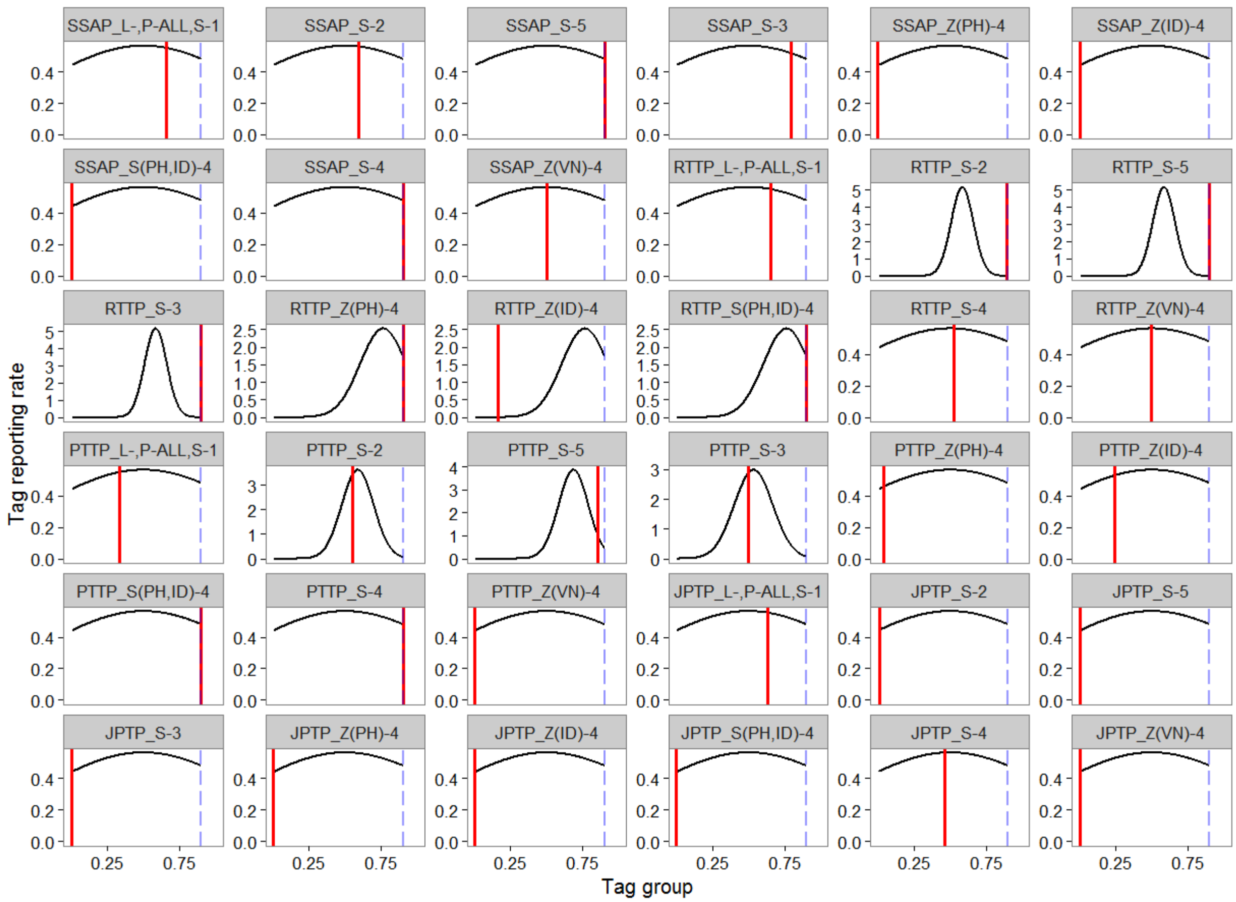



Figure 25: Estimated reporting rates for the reference case model (red lines)and the prior distribution for each reporting rate group. The imposed upper bound (0.9) on the reporting rate parameters are show as a blue dashed line. Reporting rates can be estimated separately for each release program and recapture fishery group but in practice are aggregated over some recapture groups to reduce dimensionality.

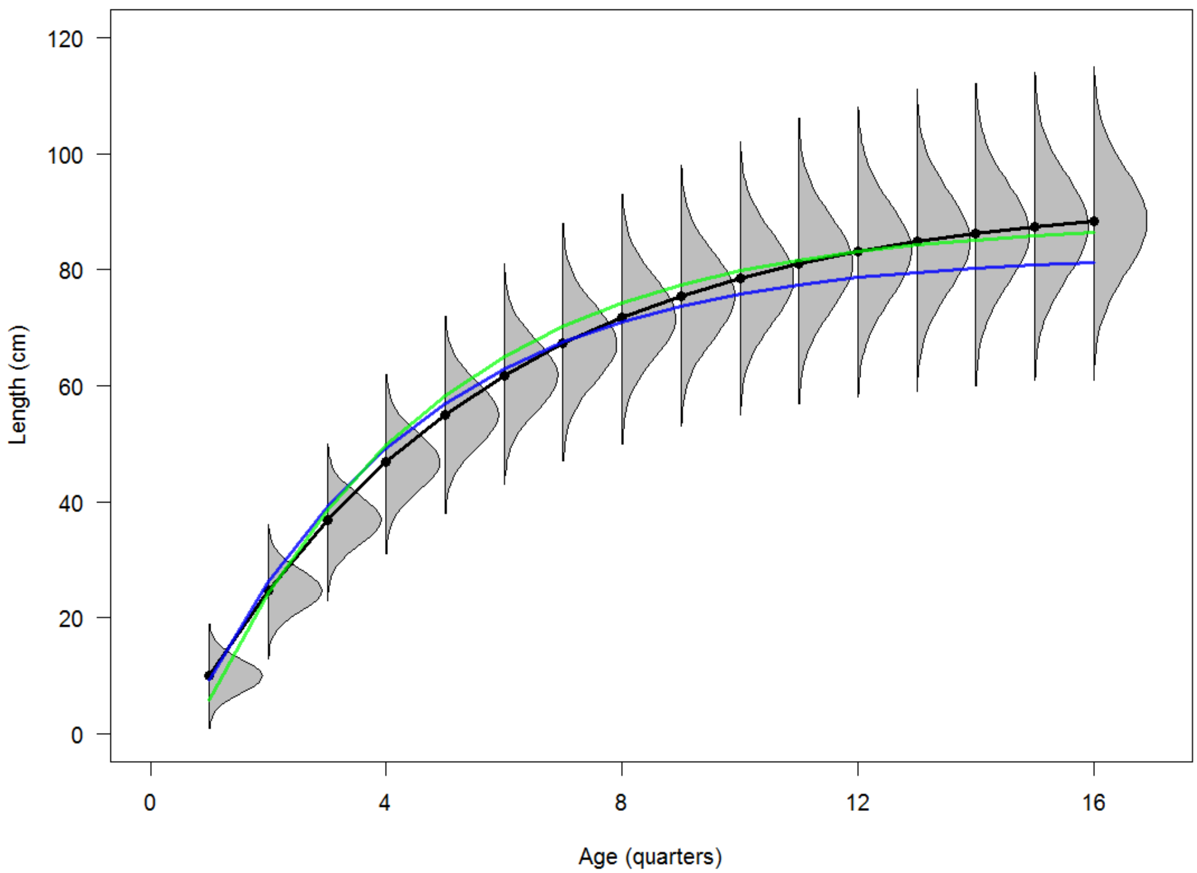



Figure 26: Estimated growth for the reference case model. The black line represents the estimated mean fork length (FL, cm) at-age and the grey area represents the estimated distribution of length at age. The blue and green lines are the estimates for the one-off sensitivity models that estimate just the Von Bertalanffy parameters (*EstVB*), and all parameters - Von Bertalanffy and standard deviation parameters (*EstVBSD*), respectively.

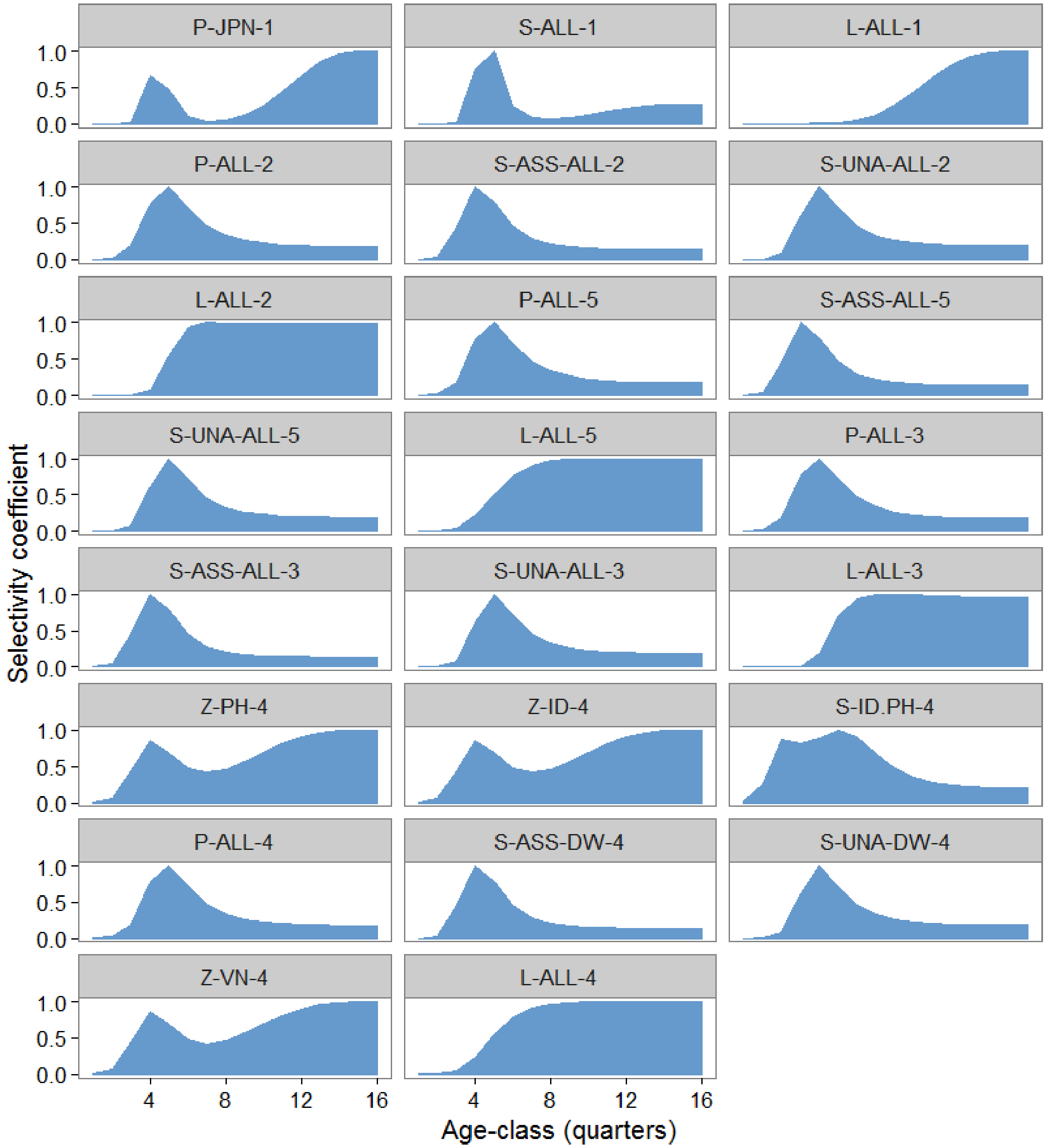



Figure 27: Age-specific selectivity coefficients by fishery.

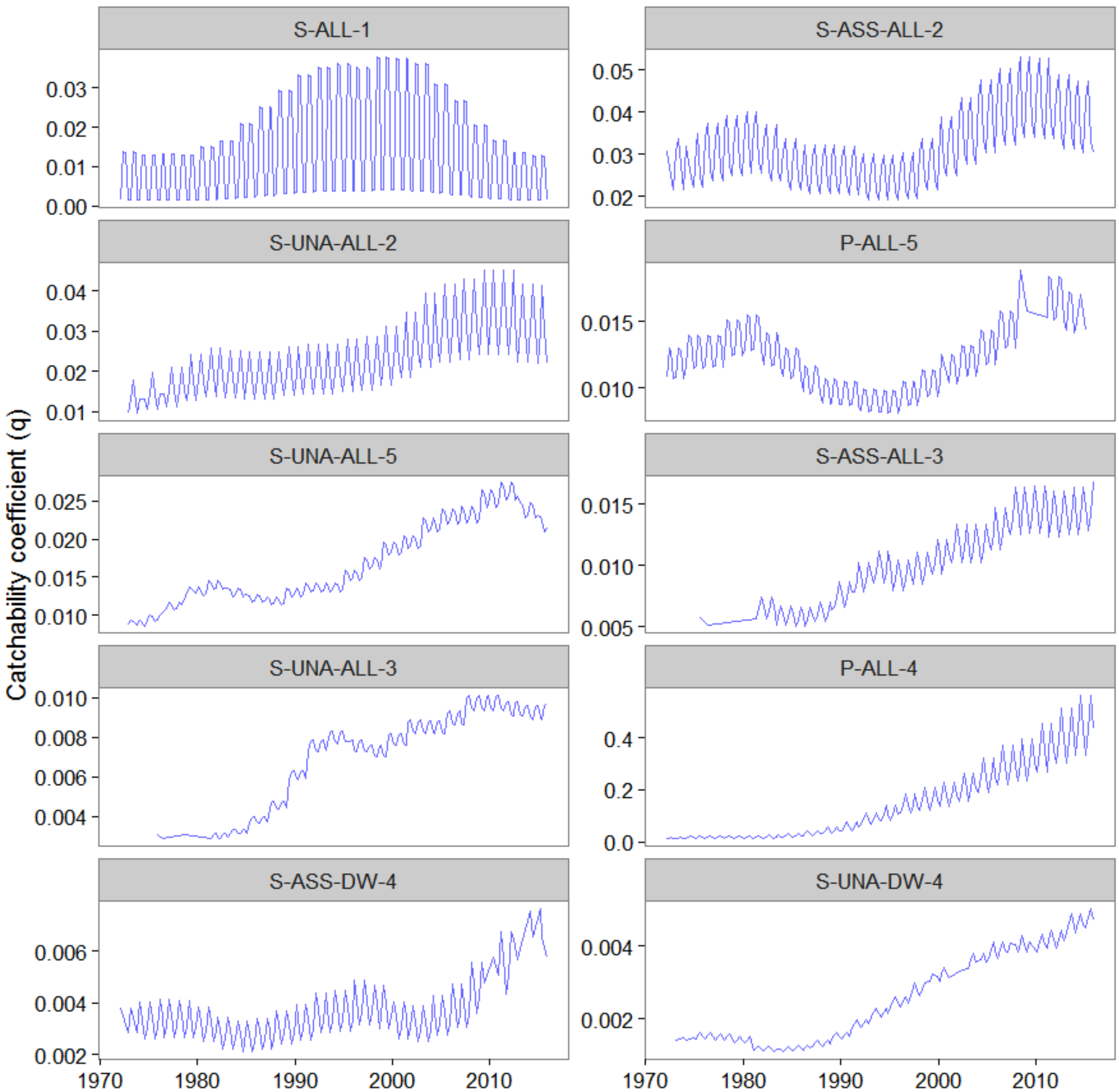



Figure 28: Estimated time series of catchability (including seasonal variability) for those fisheries assumed to have random walk in these parameters.

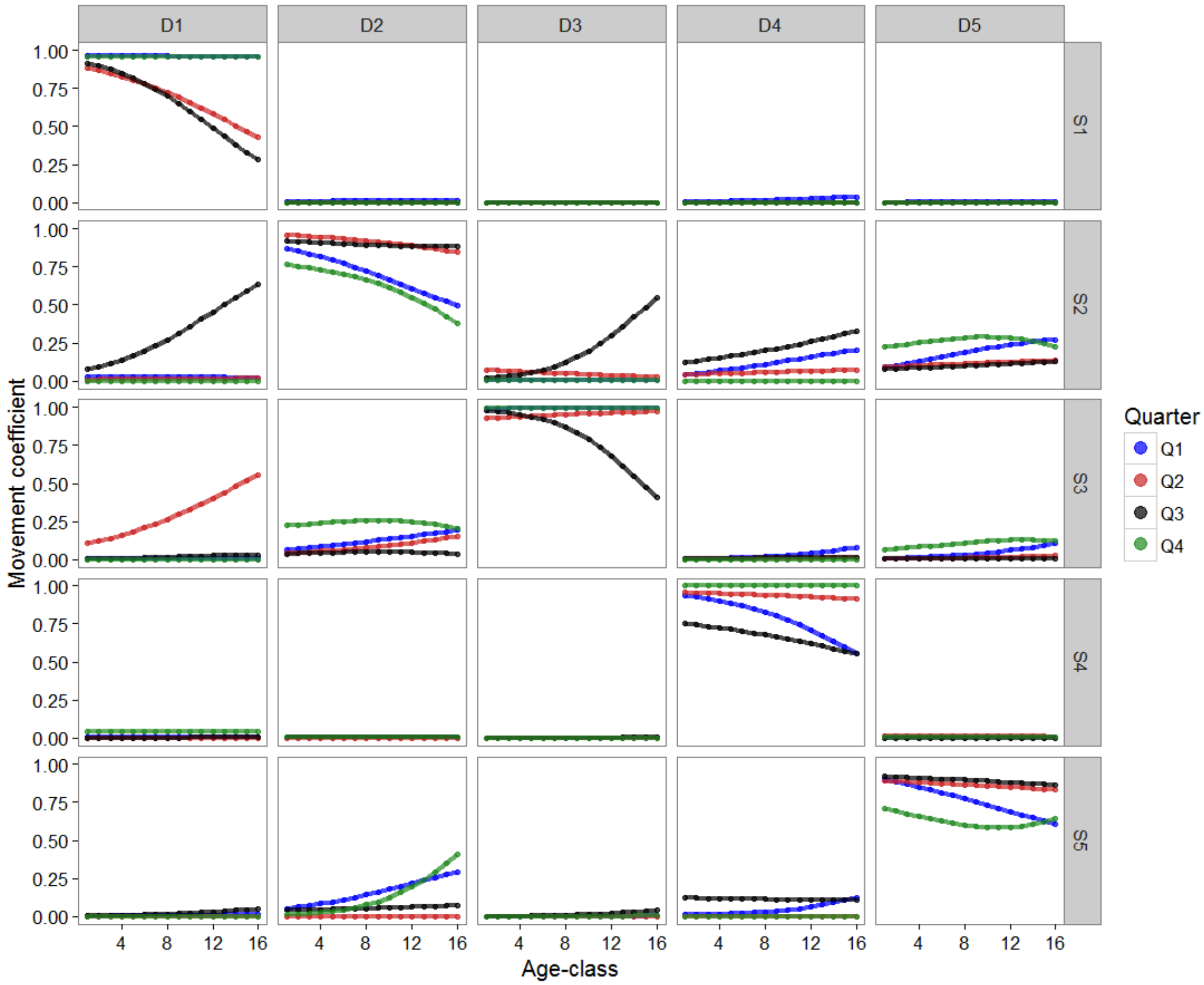



Figure 29: Estimated age-dependent movement coefficients for the reference case model. The colour of the line indicates the season (quarter) of the estimate and the y-axis and x-axis represent the "source" and "destination" region, respectively.

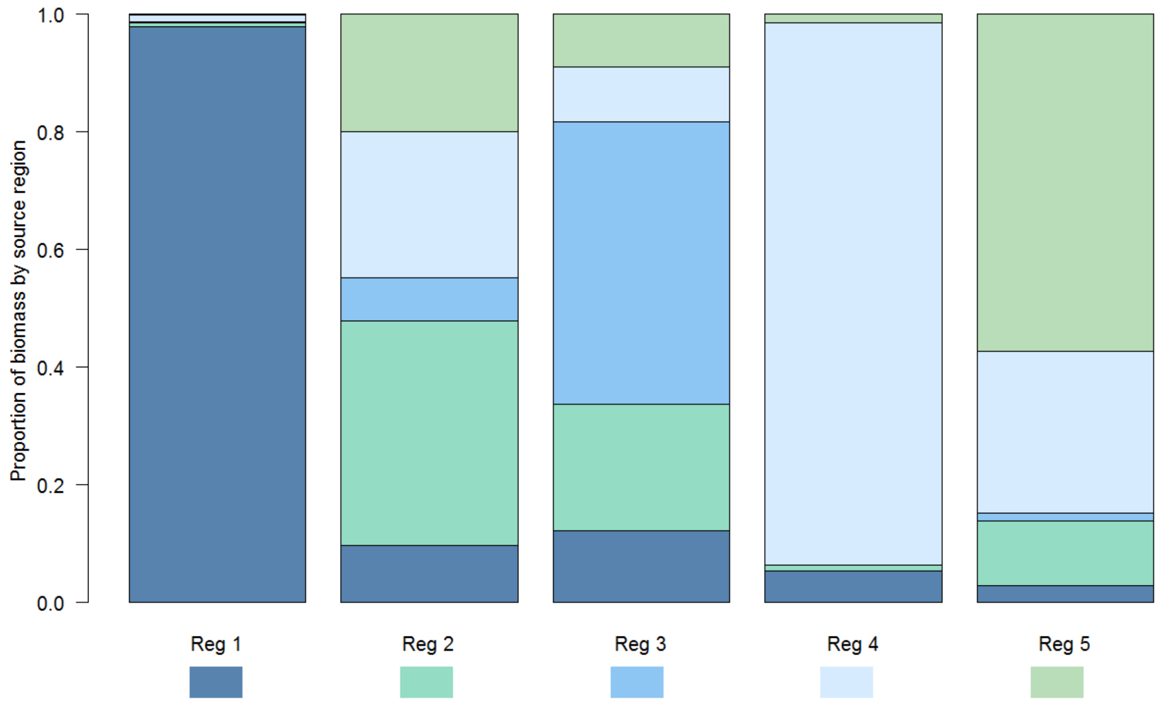



Figure 30: Proportional distribution of total biomass (by weight) in each region apportioned by the source region of the fish, for the reference case model. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment between regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

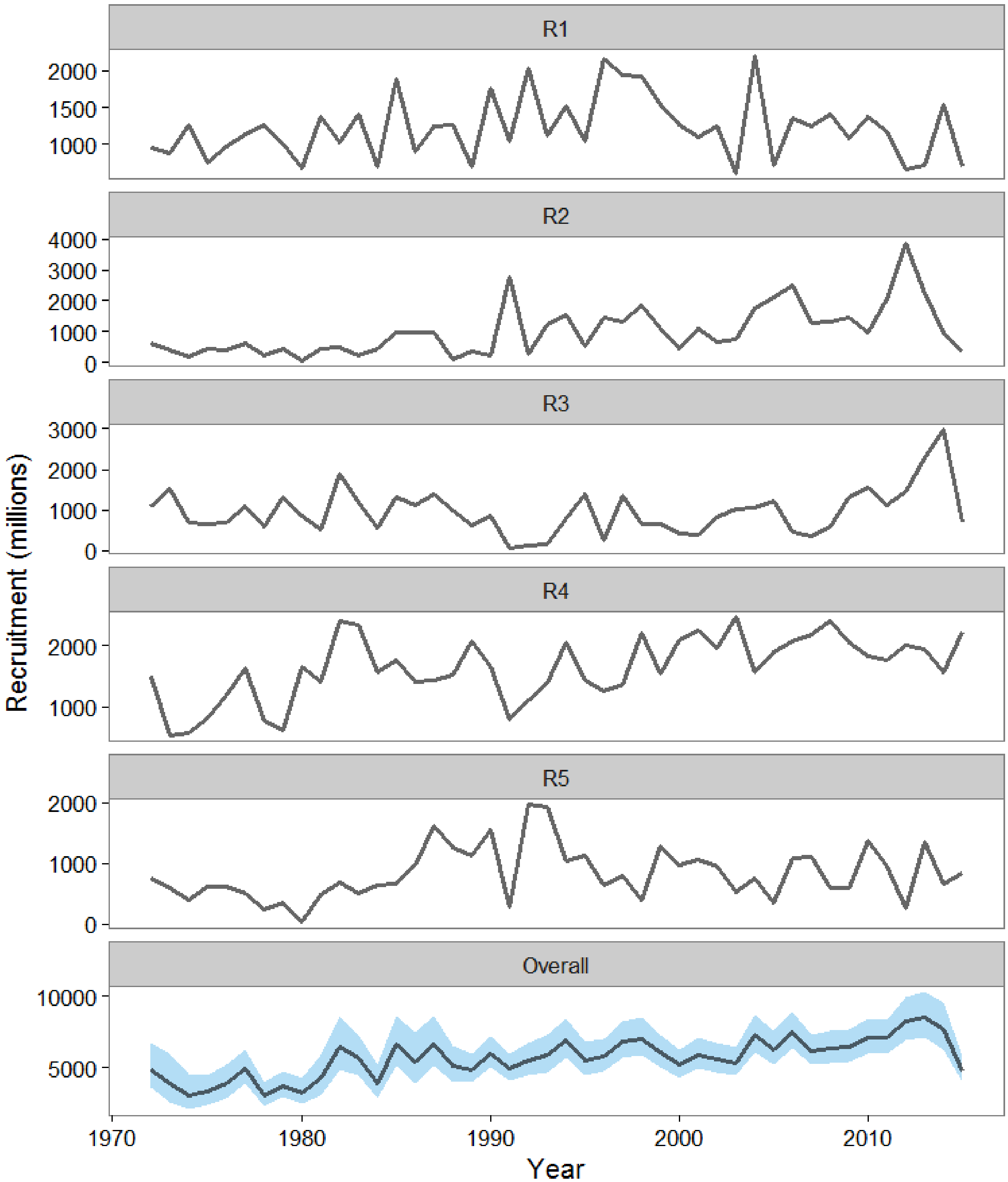



Figure 31: Estimated temporal recruitment by model region for the reference case model. Note that the scale of the y-axis is not constant across regions.

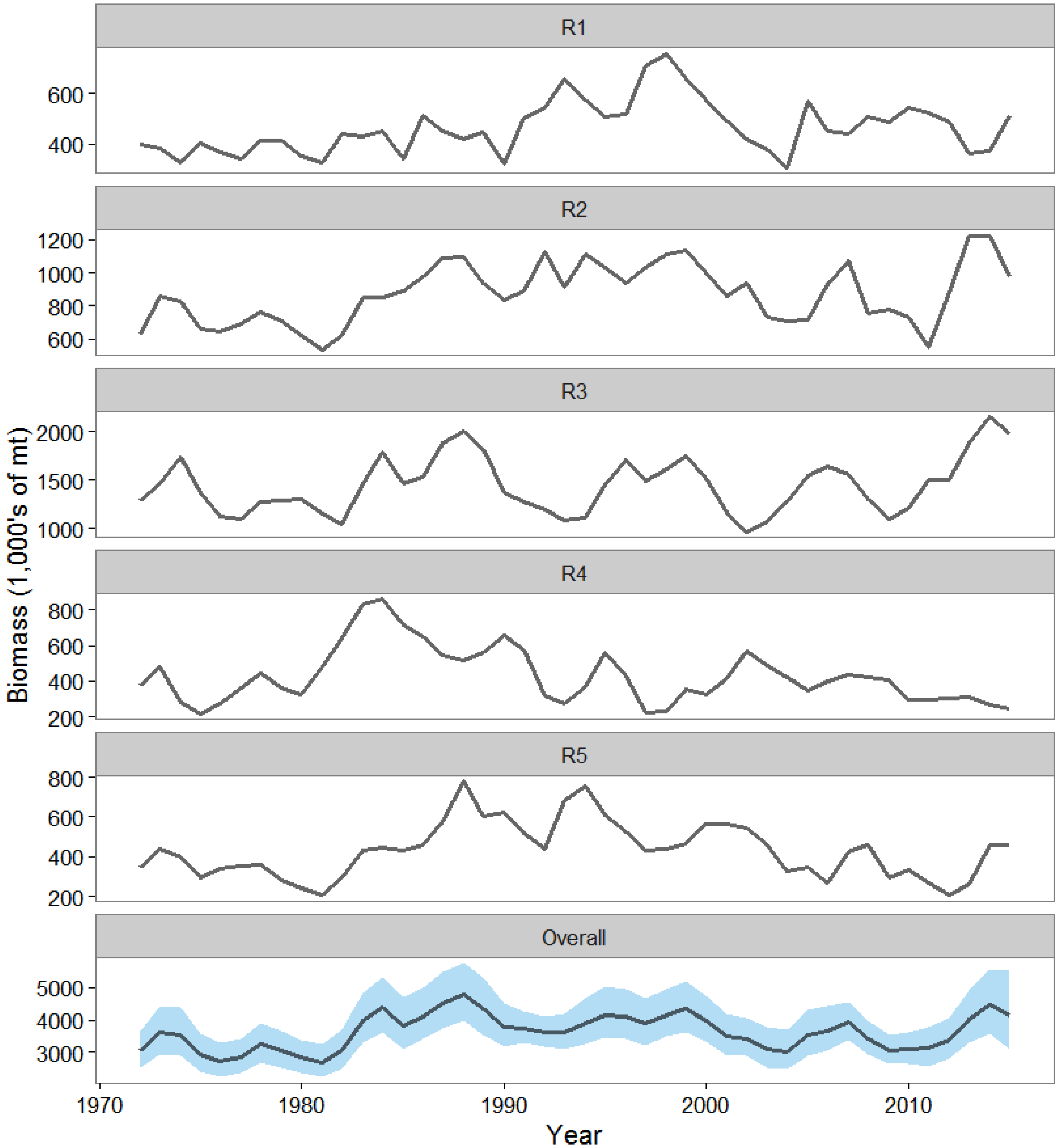
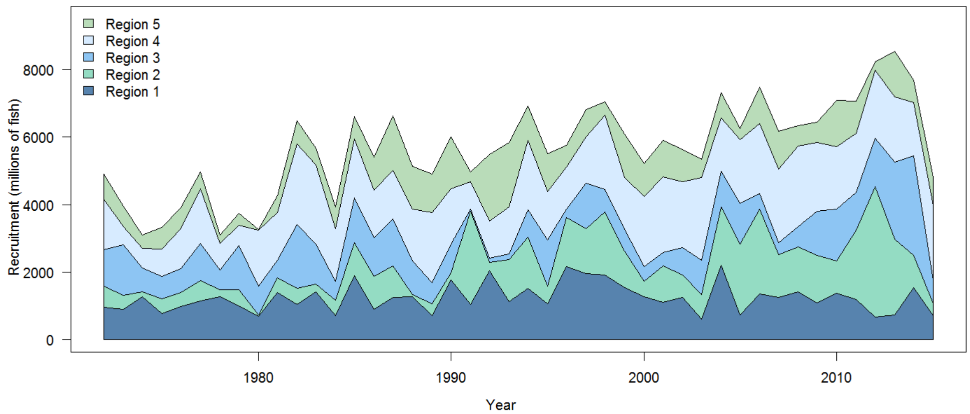
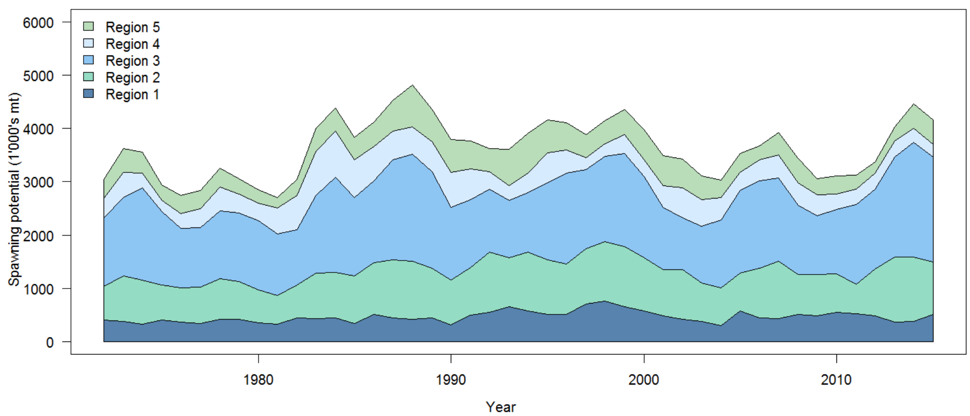


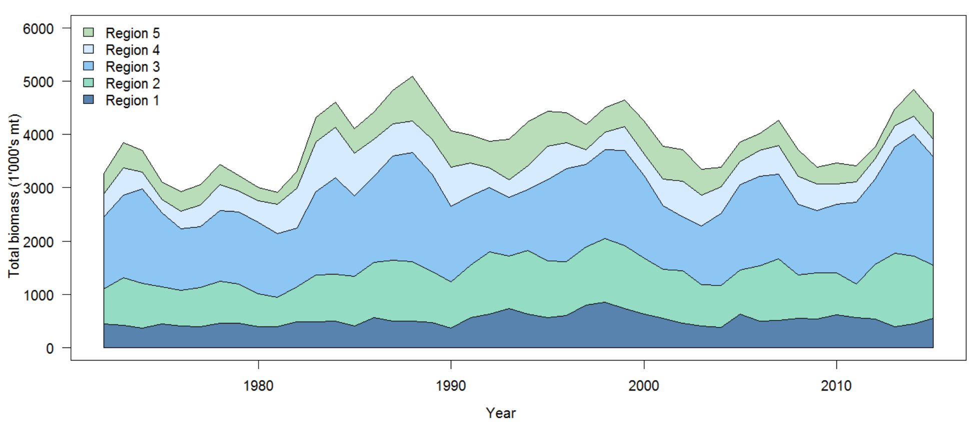

Figure 32: Estimated temporal spawning biomass by model region for the reference case model. Note that the scale of the y-axis is not constant across regions.




(a) Regional recruitment




(b) Spawning biomass




(c) Total biomass

Figure 33: Estimated annual average recruitment, spawning biomass and total biomass by model region for the reference case model, showing the relative sizes among regions.

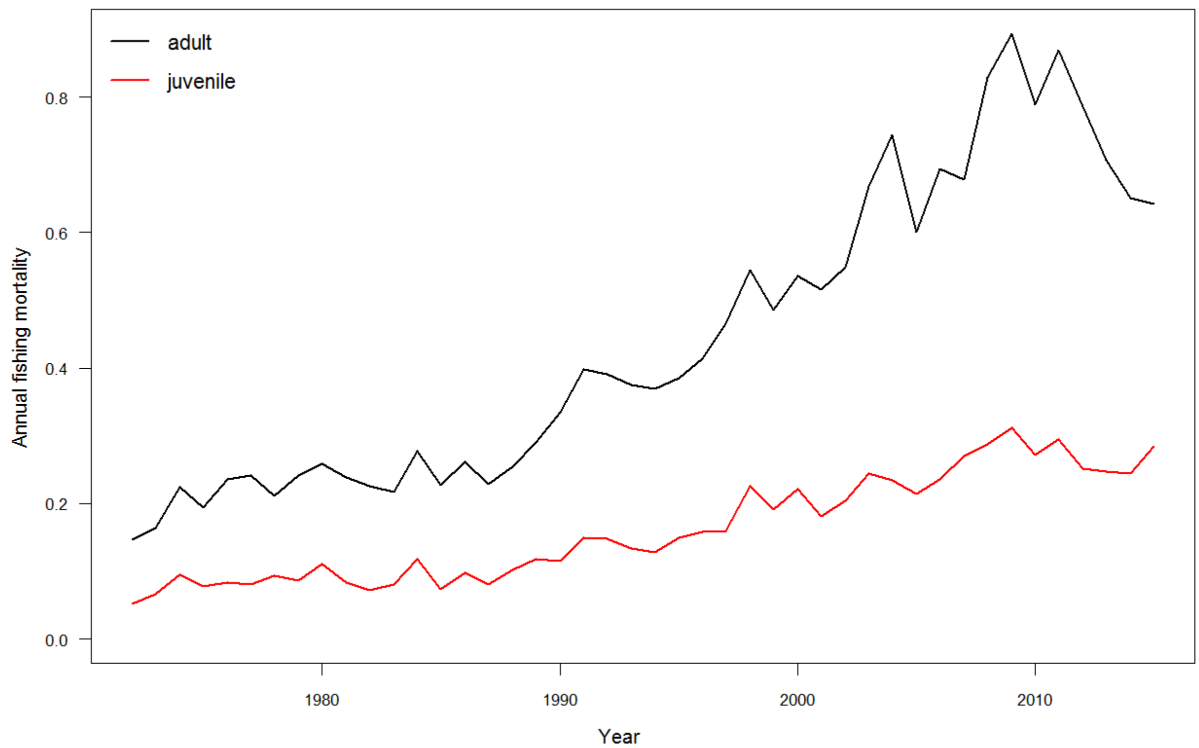



Figure 34: Estimated annual average juvenile and adult fishing mortality for the reference case model.


Figure 35: Estimated age-specific fishing mortality for the reference case model, by region and overall.

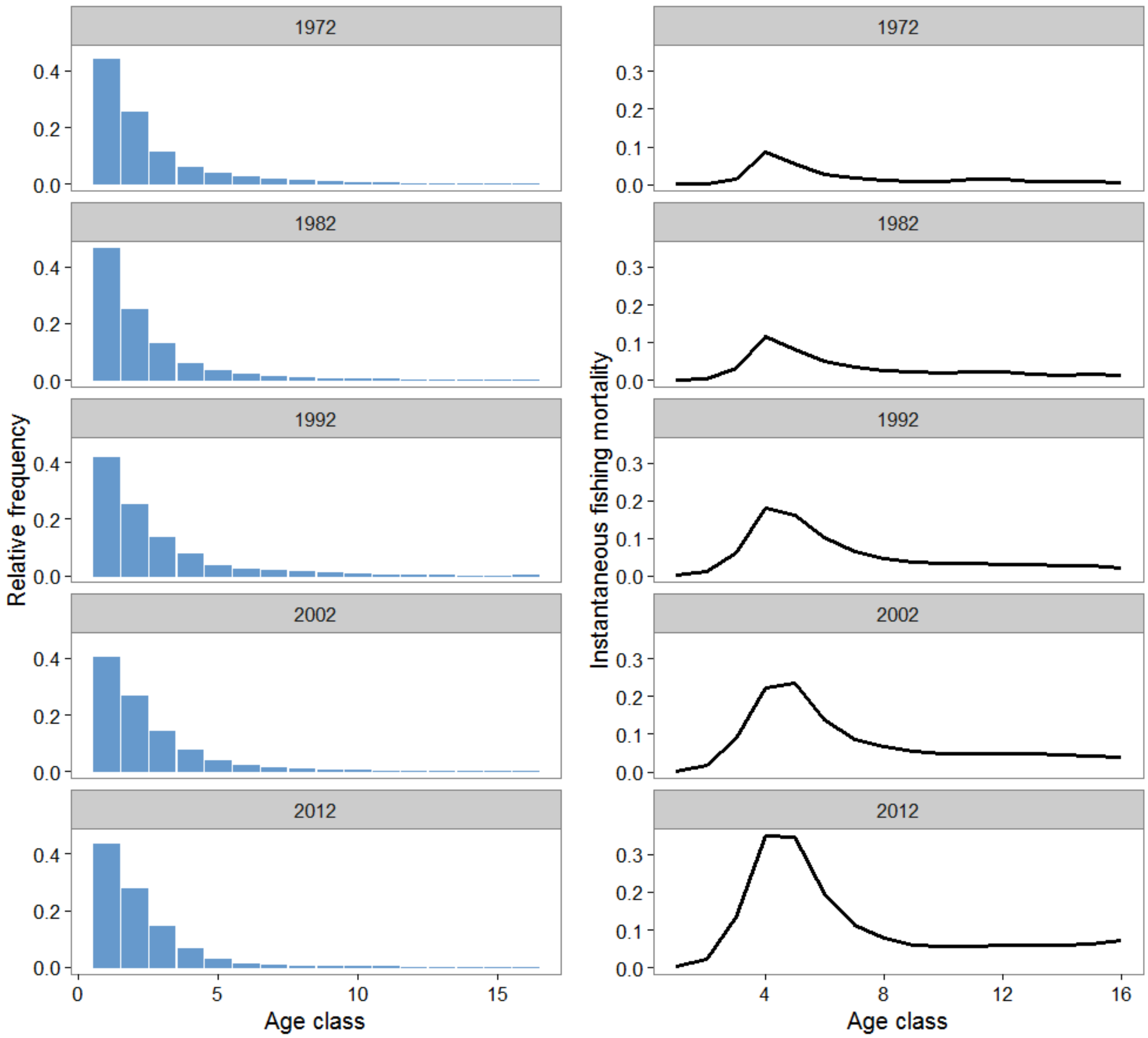



Figure 36: Estimated proportion at age (quarters) and fishing mortality at age (right), by year, at decade intervals, for the reference case model.

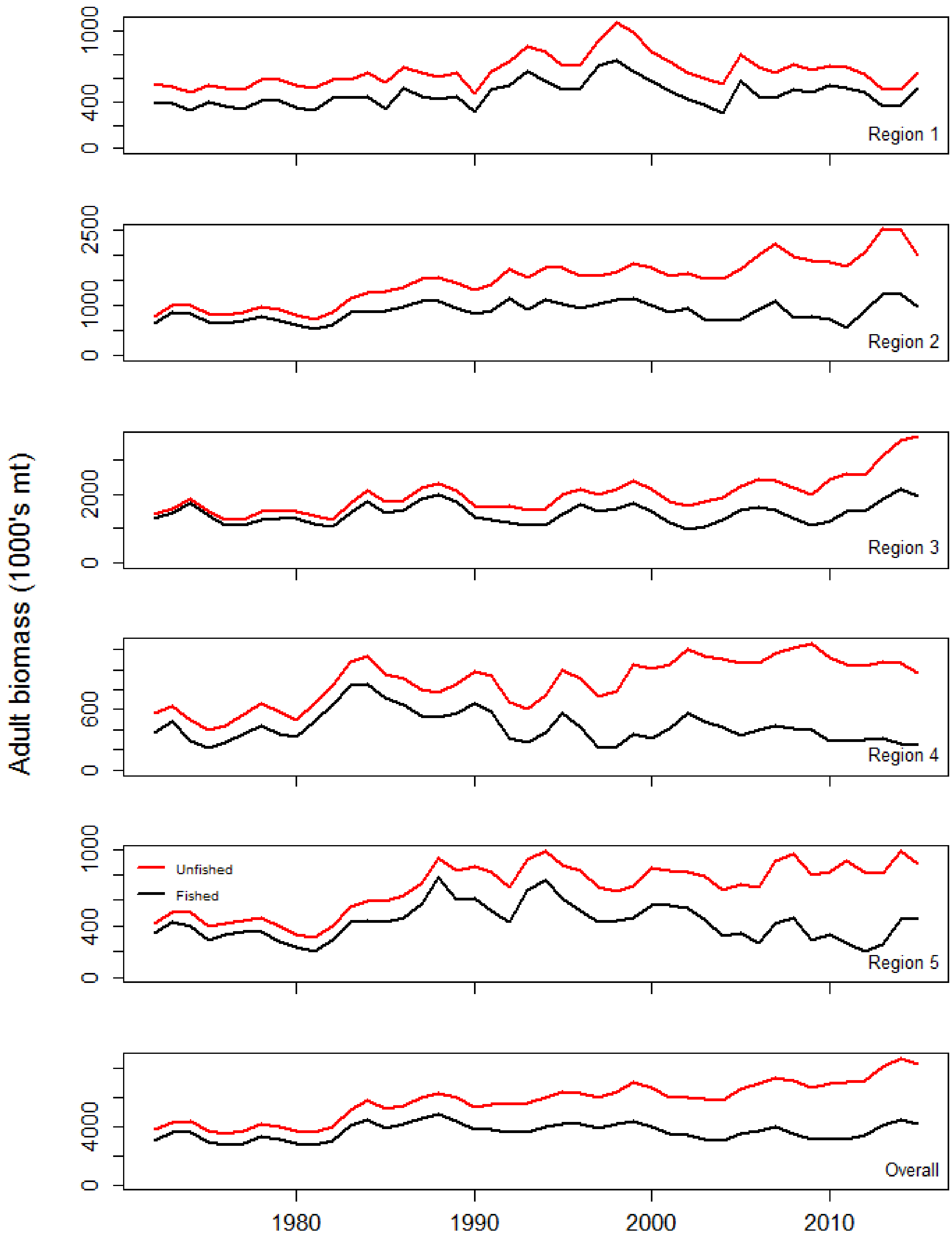



Figure 37: Comparison of the estimated annual spawning biomass trajectories (lower solid black lines) with those trajectories that would have occurred in the absence of fishing (upper dashed red lines) for each region and overall, for the reference case model.

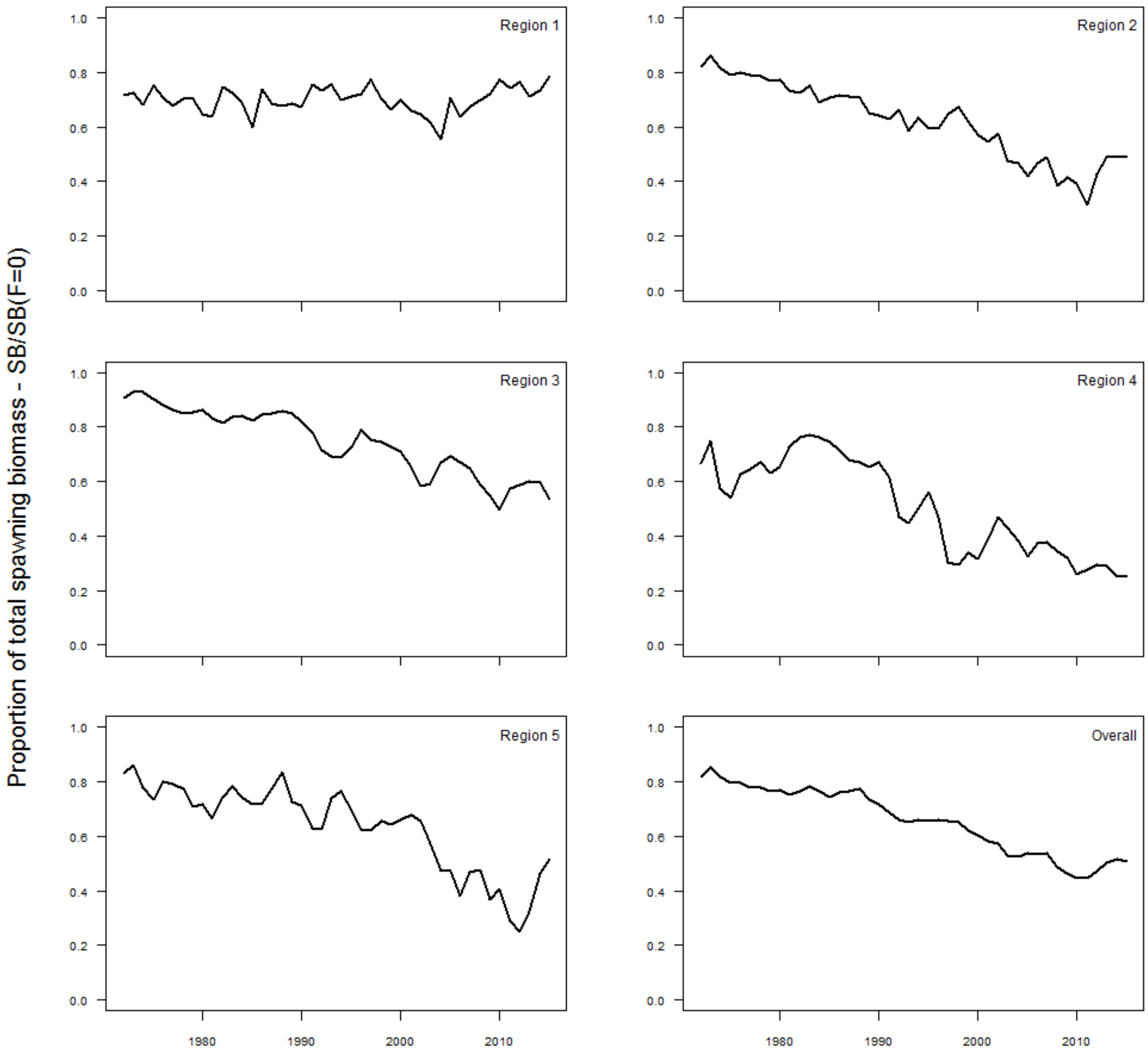



Figure 38: Ratio of exploited to unexploited spawning biomass, $SB_{latest}/SB_{F=0}$, for each region and overall for the reference case model.

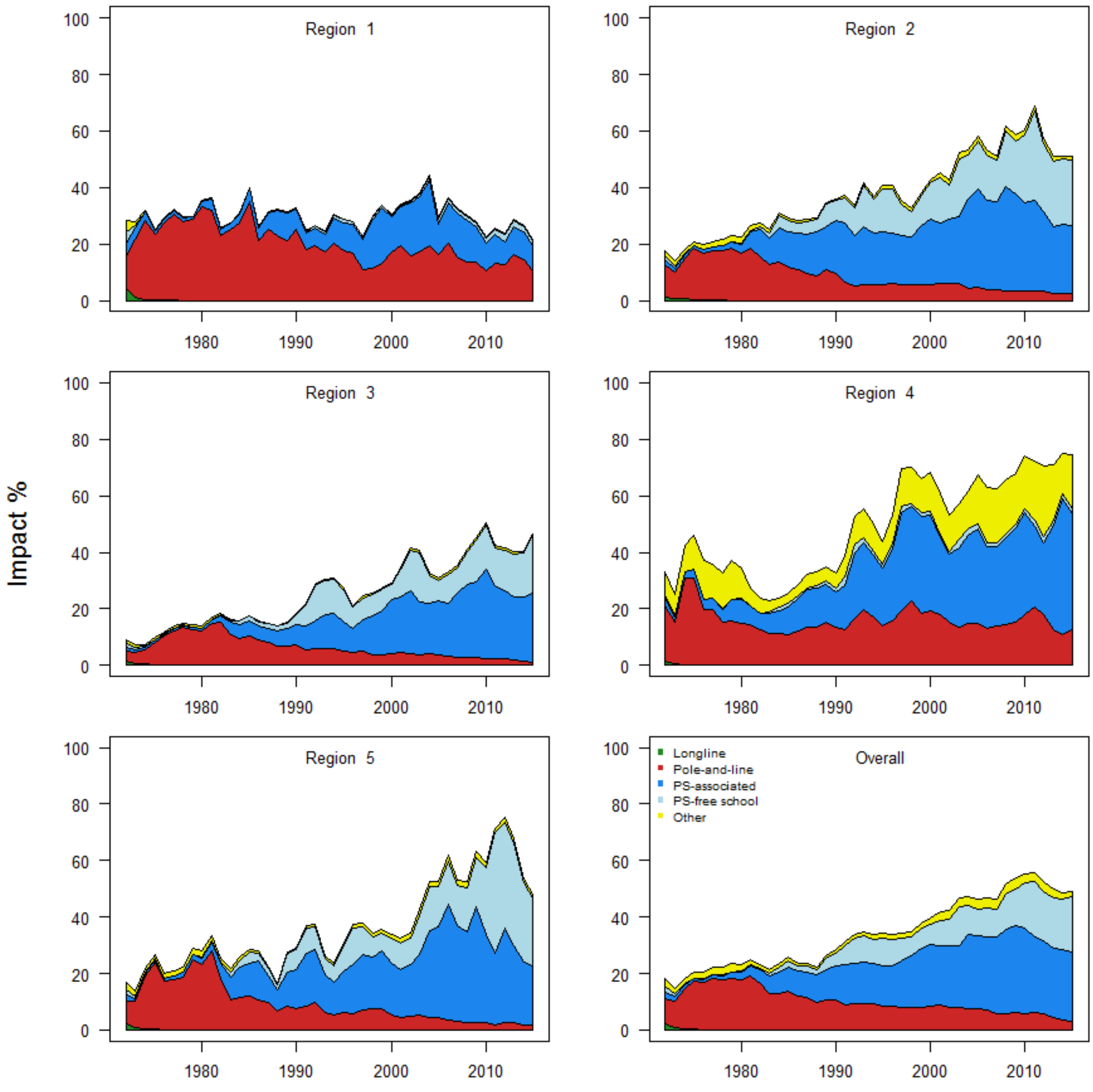



Figure 39: Estimates of reduction in spawning biomass due to fishing (fishery impact = $1-SB_{latest}/SB_{F=0}$) by region, and over all regions (lower right panel), attributed to various fishery groups for the reference case model.

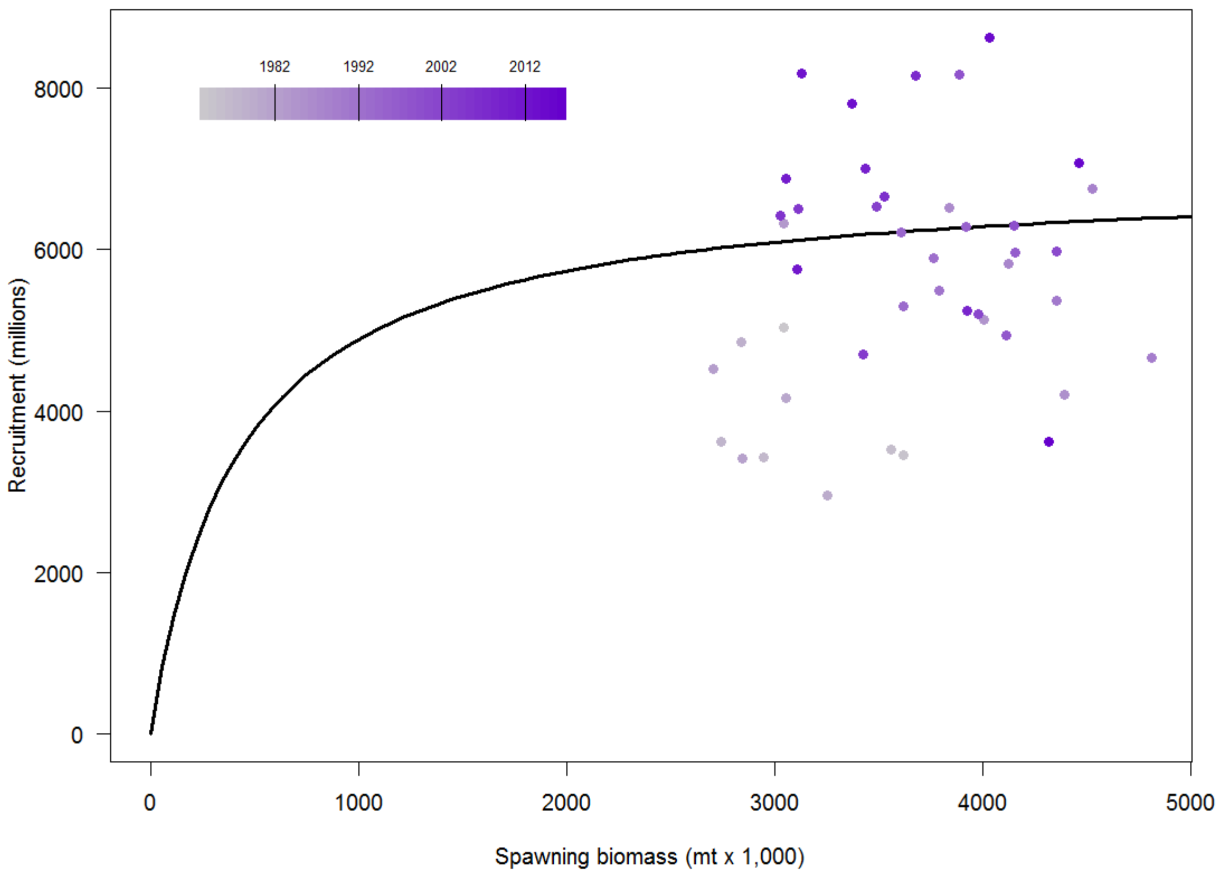



Figure 40: Estimated relationship between recruitment and spawning biomass based on annual values for the reference case model.The darkness of the circles changes from light to dark through time.

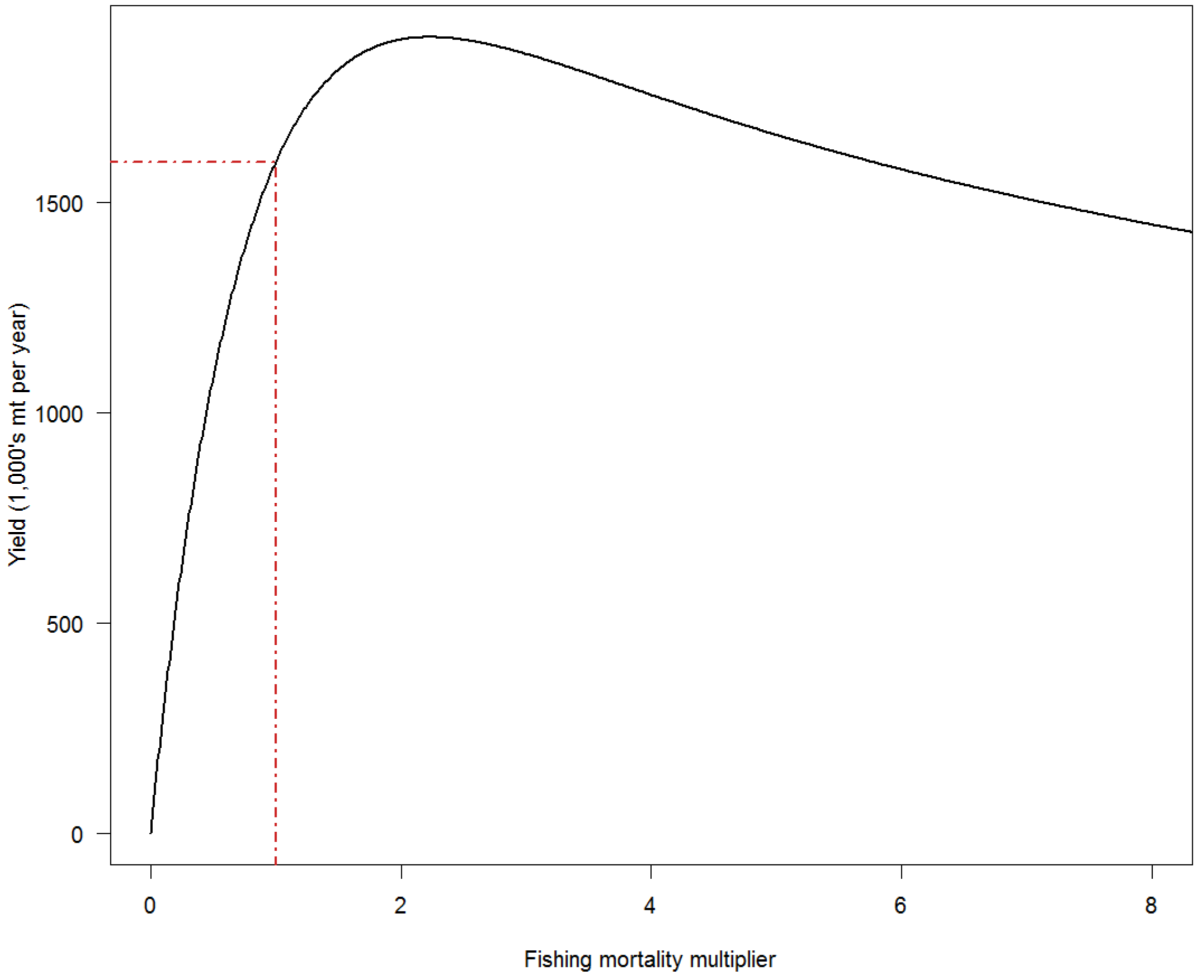



Figure 41: Estimated yield as a function of fishing mortality multiplier for the reference case model. The red dashed line indicates the equilibrium yield at current fishing mortality.

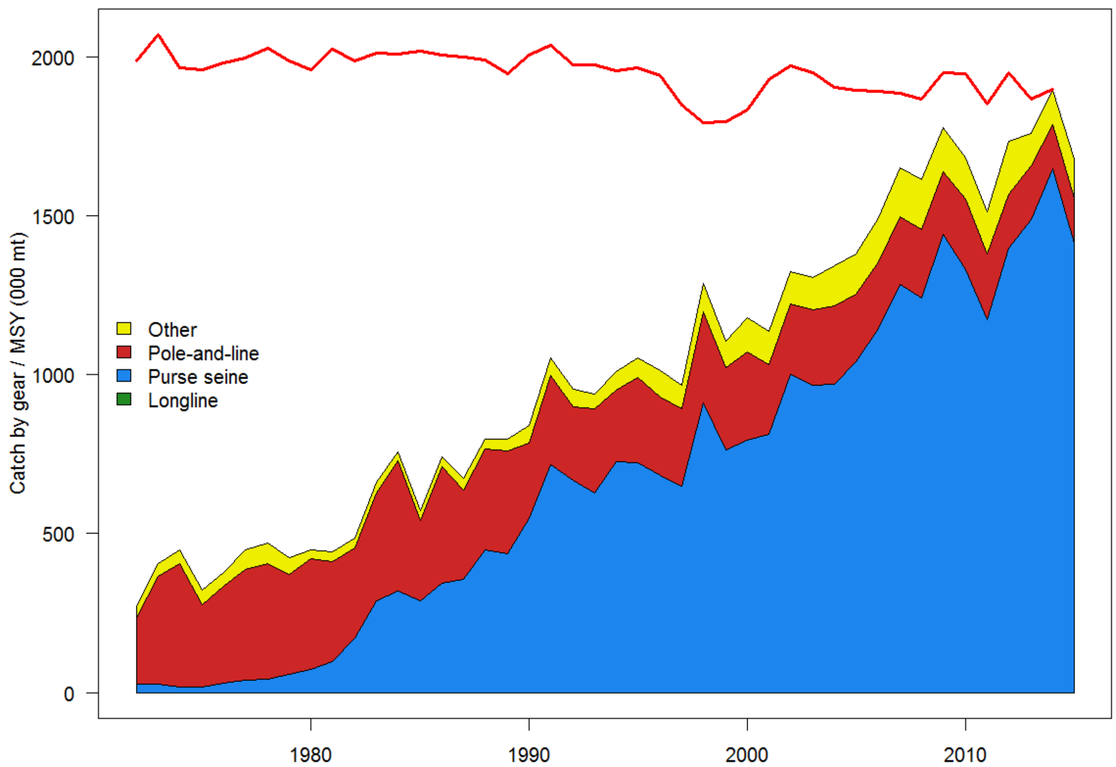



Figure 42: History of the annual estimates of MSY (red line) for the reference case model compared with annual catch by the main gear types. Note that this is a "dynamic" MSY which is explained further in Section 4.7.4.

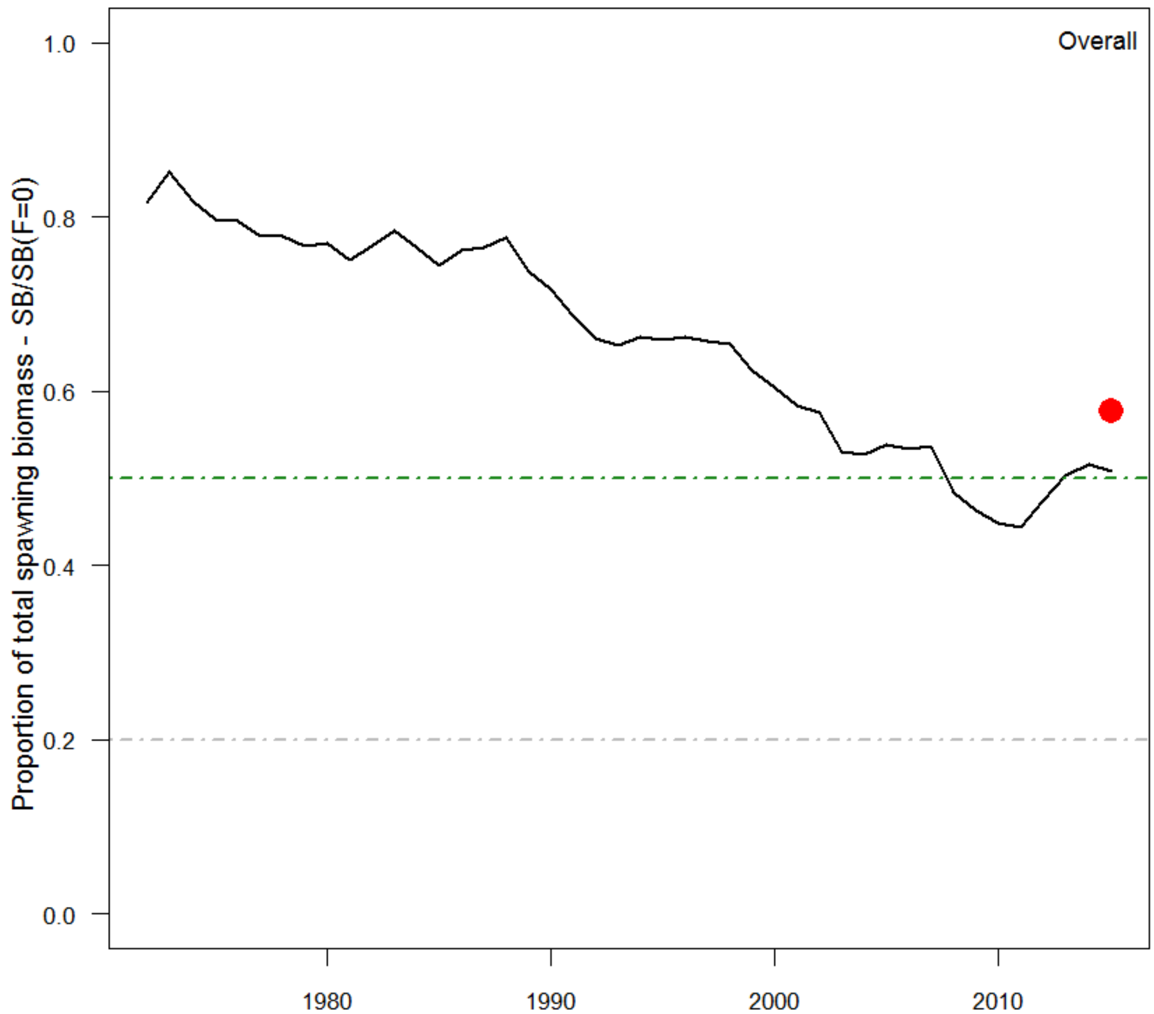
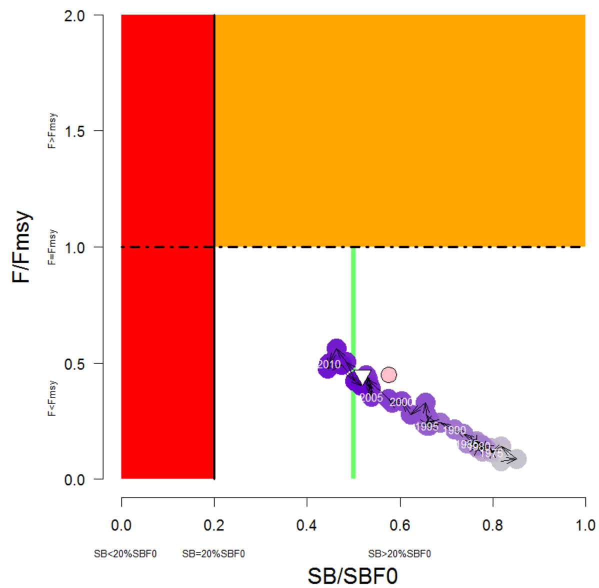
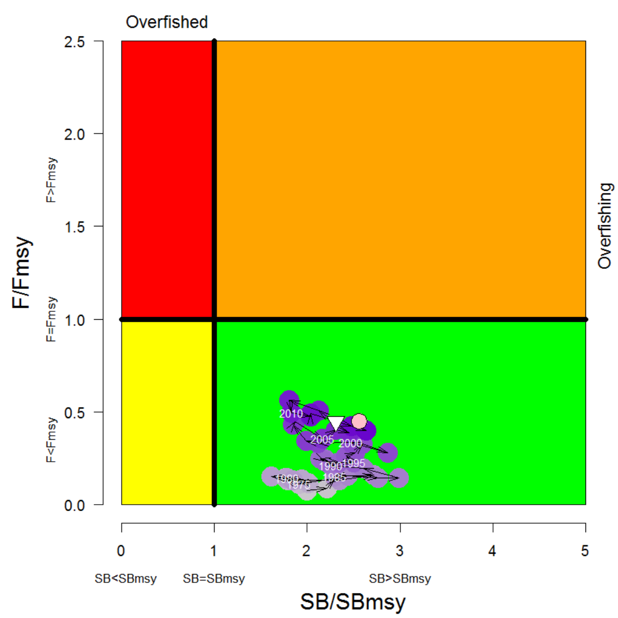



Figure 43: Ratio of exploited to unexploited spawning biomass, $SB_{latest}/SB_{F=0}$, for the reference case model. The current WCPFC limit reference point of $20\%SB_{F=0}$ is provided for reference as the grey dashed line, the adopted target reference point, $50\%SB_{F=0}$, is shown by the green dashed line, and the red circle represents, $SB_{latest}/SB_{F=0}$, the level of spawning biomass depletion based on the agreed method of calculating $SB_{F=0}$ over the last ten years of the model.

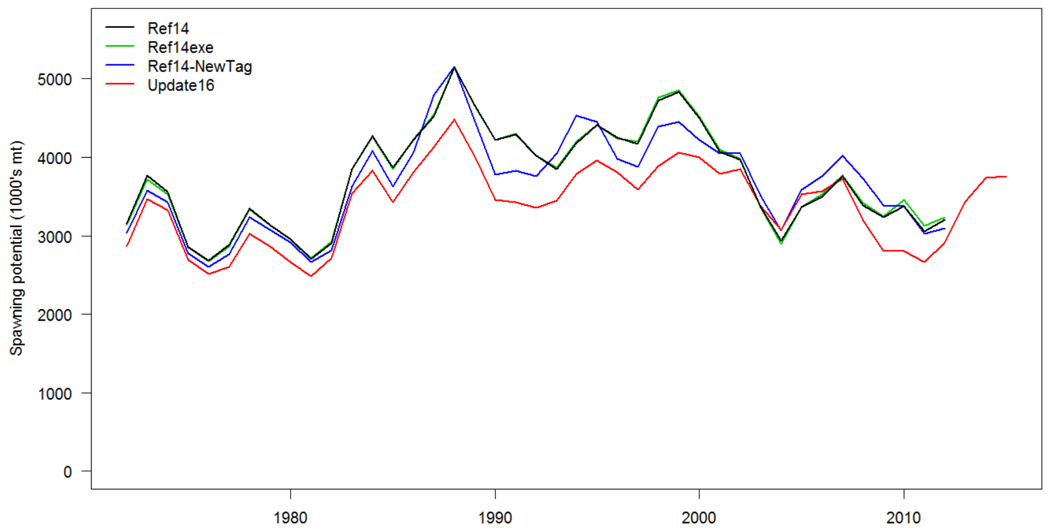



(a) Majuro plot for reference case

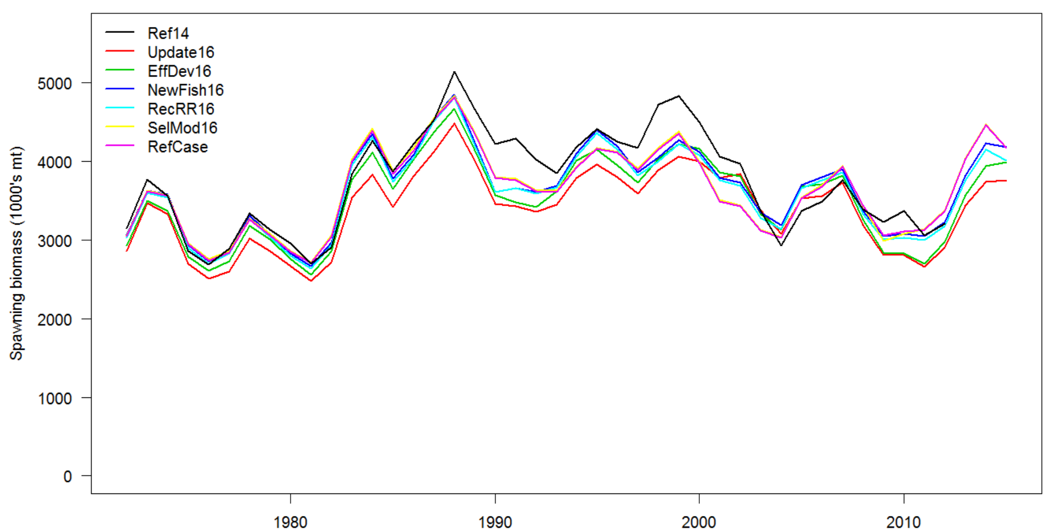



(b) Kobe plot for reference case

Figure 44: Majuro plot (a) for the reference case model representing stock status in terms of spawning biomass depletion and fishing mortality. The red zone represents spawning biomass 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 $F_{\text{MSY}}$ (marked with the black dashed line). The green line indicates the target reference point $50\% SB_{F=0}$. The pink circle is $SB_{latest}/SB_{F=0}$ and the white triangle is $SB_{recent}/SB_{F=0}$, which are both detailed in Table 1. The equivalent Kobe plot is provided for comparison.

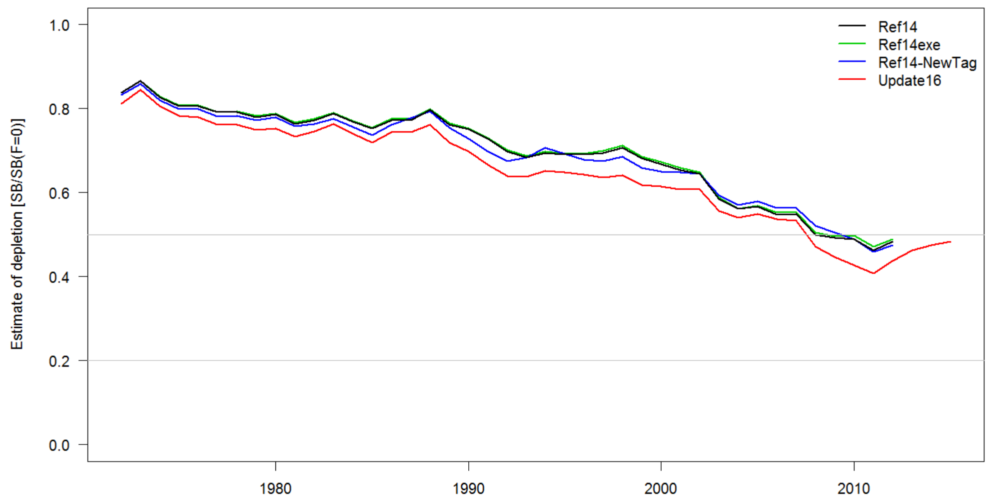



(a) Progression from 2014 to 2016 updated

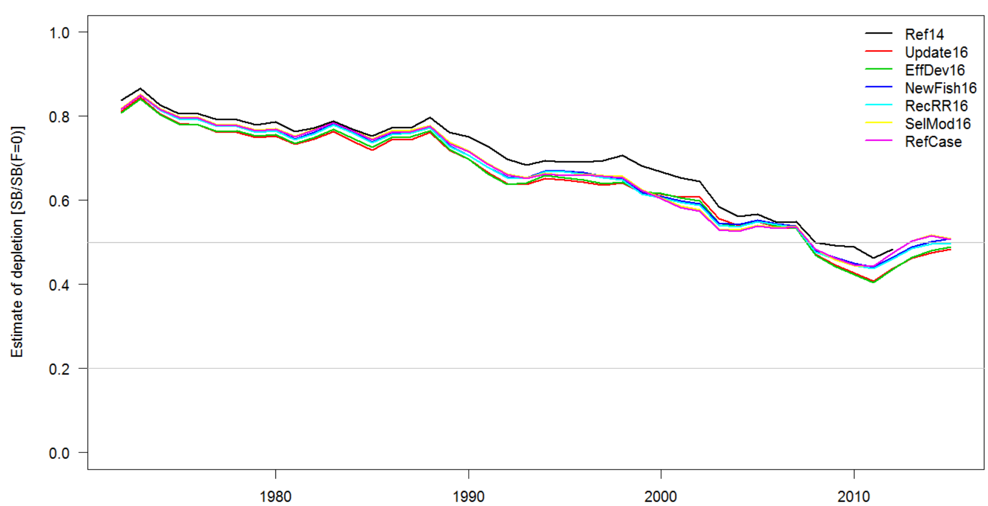



(b) Progression from 2016 updated to reference case model

Figure 45: Stepwise changes in spawning biomass from the 2014 reference case model through to a model with fully updated data (a), and from the updated model through to the 2016 reference case model.

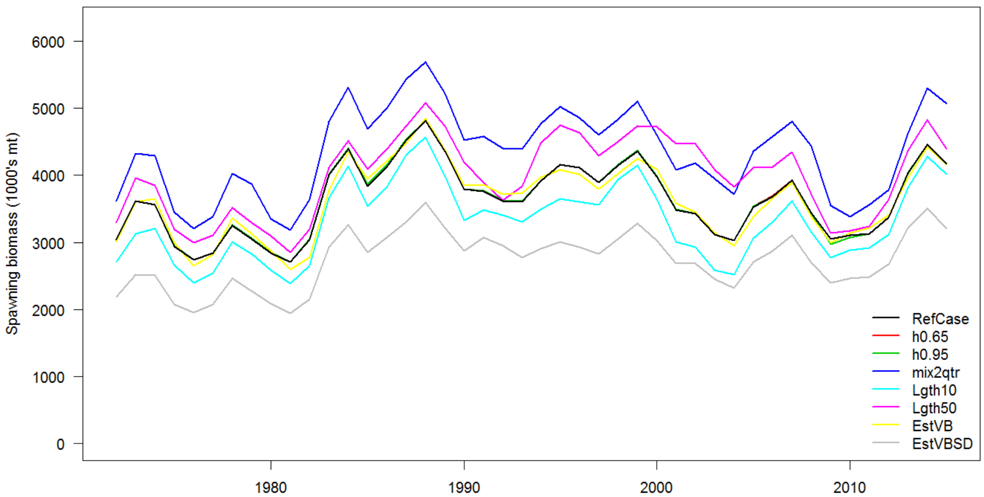



(a) Progression from 2014 to 2016 updated

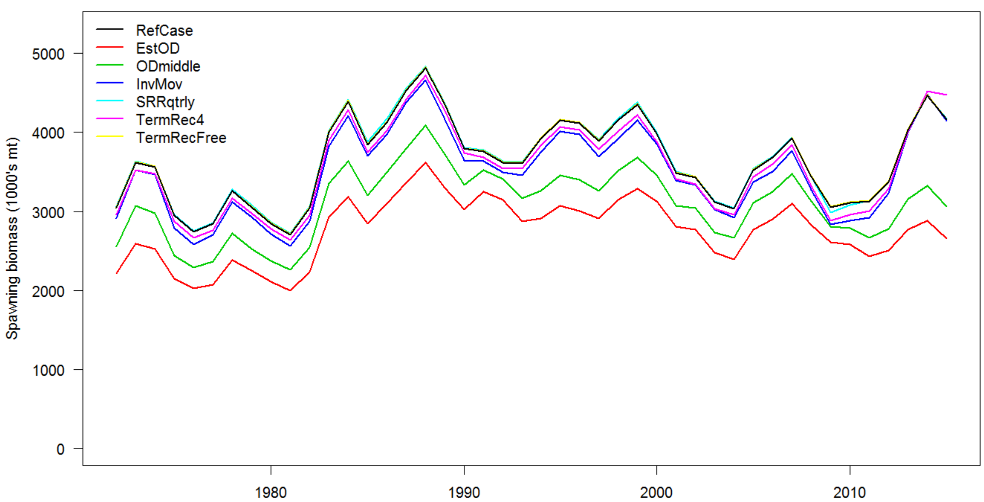



(b) Progression from 2016 updated to reference case model

Figure 46: Stepwise changes in fishing depletion from the 2014 reference case model through to a model with fully updated data (a), and from the updated model through to the 2016 reference case model.

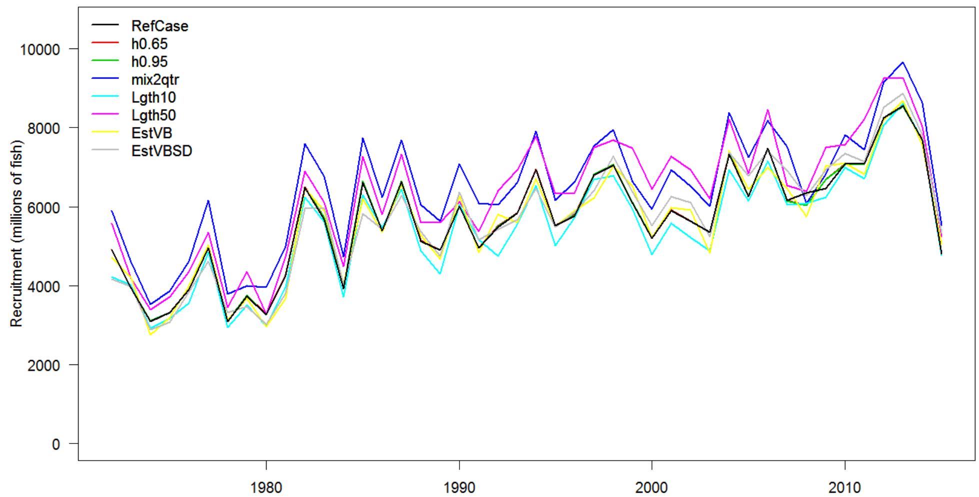



(a) First set of sensitivities

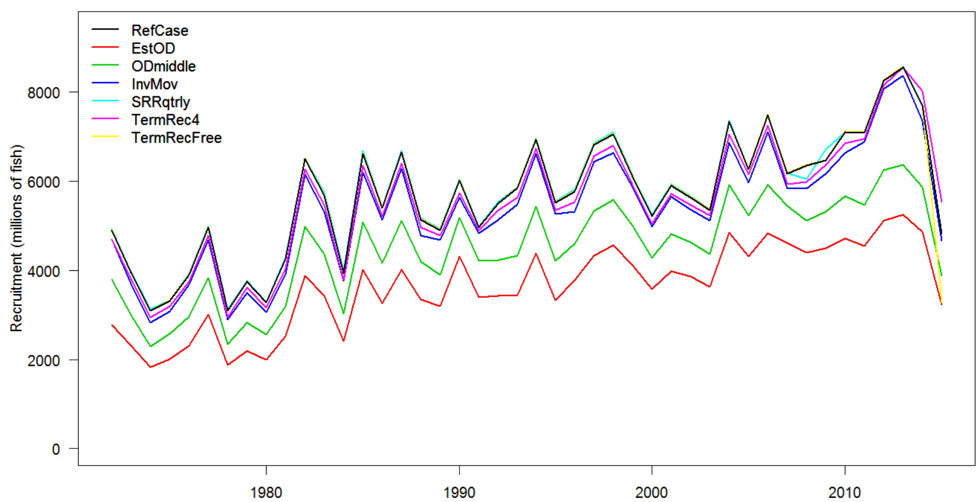



(b) Second set of sensitivities

Figure 47: Estimated spawning biomass for each of the one-off sensitivity models. The models are separated into two groups to prevent obstruction of lines.

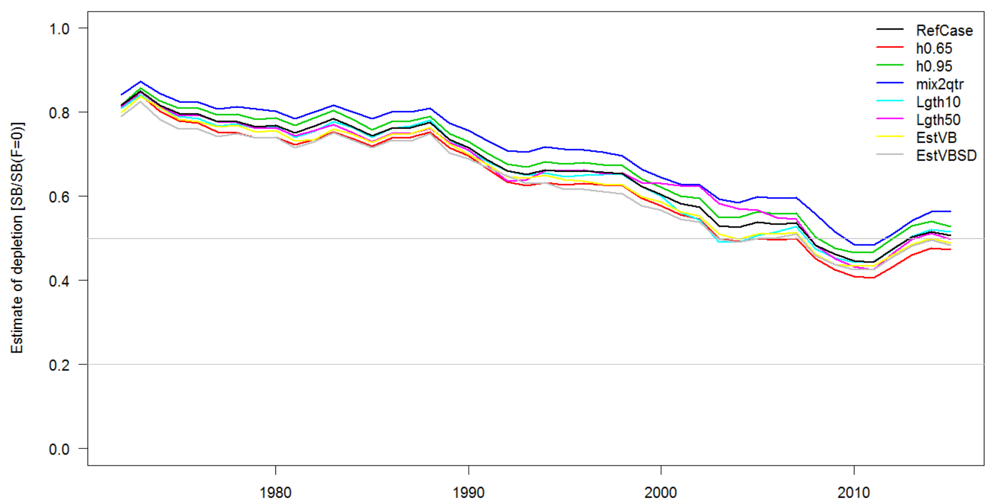



(a) First set of sensitivities

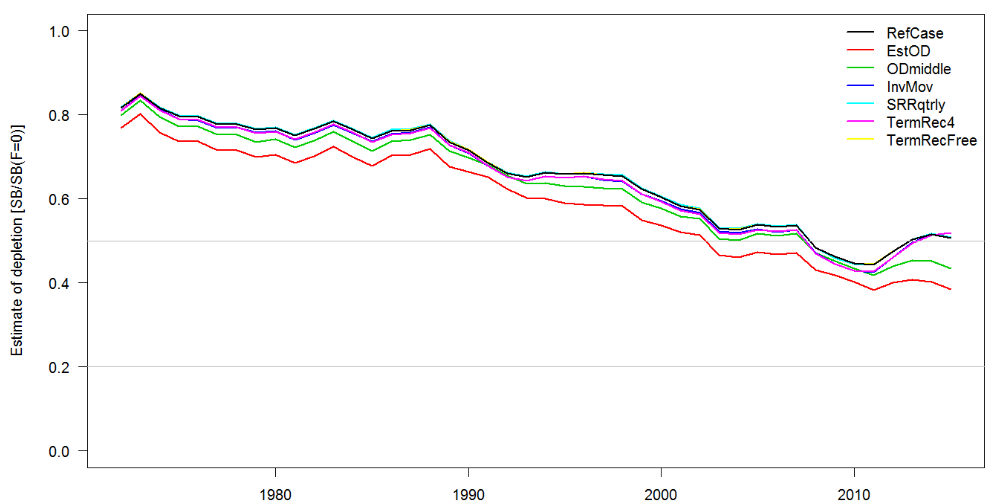



(b) Second set of sensitivities

Figure 48: Estimated recruitment for each of the one-off sensitivity models. The models are separated into two groups to prevent obstruction of lines.

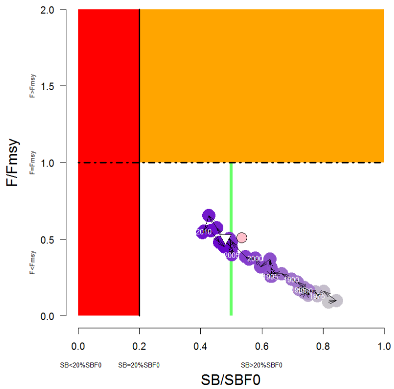



(a) First set of sensitivities

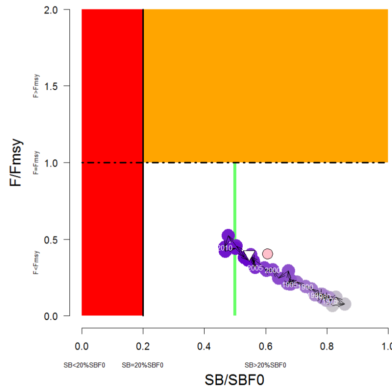



(b) Second set of sensitivities

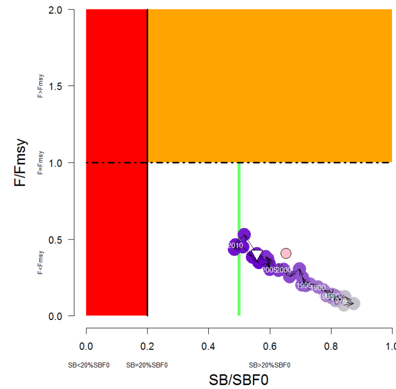
Figure 49: Estimated fisheries depletion, $SB/SB_{F=0}$, for each of the one-off sensitivity models. The models are separated into two groups to prevent obstruction of lines.



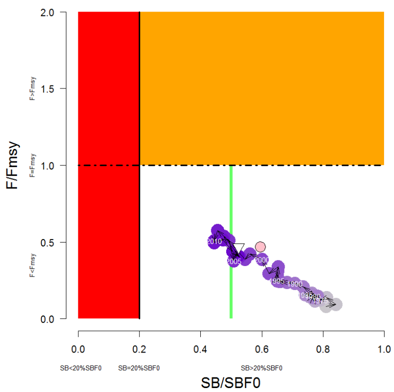

(a) Low steepness ($h = 0.65$)



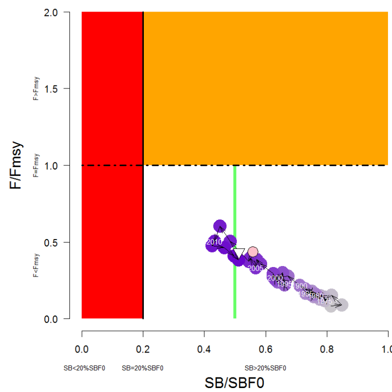

(b) High steepness ($h = 0.95$)



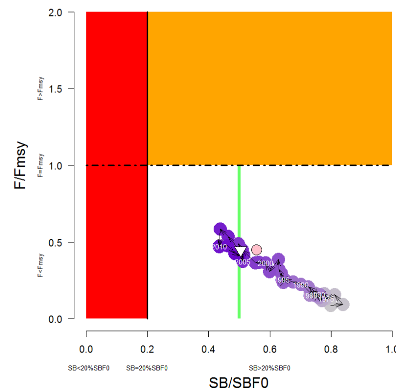

(c) Mixing period 2 quarters



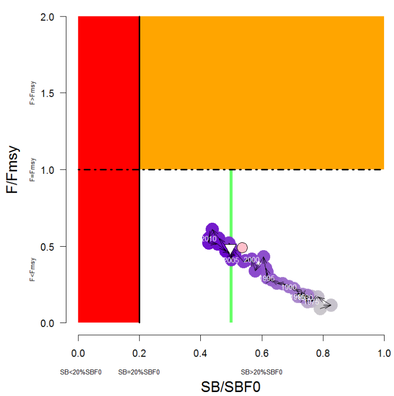

(d) Size data scalar = 10



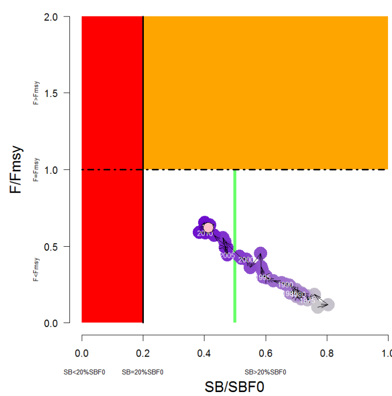

(e) Size data scalar = 50



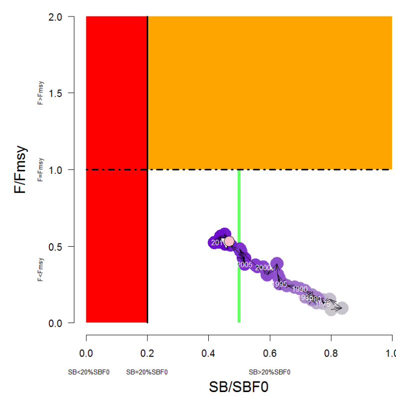

(f) Estimate growth parameters




(g) Estimate growth + SD parameters

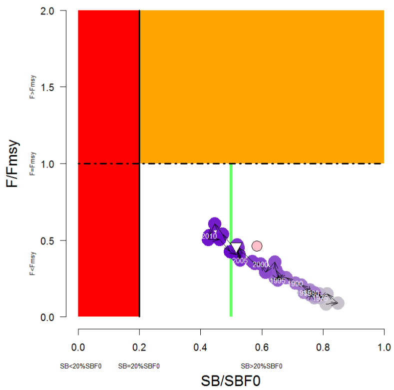



(h) Estimate tagging overdispersion

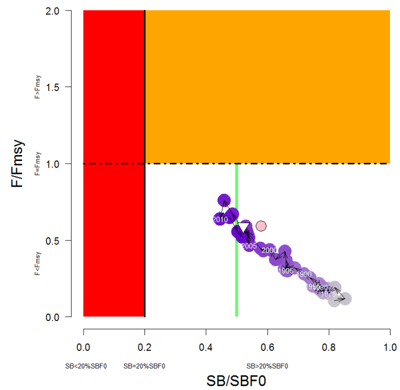



(i) Fixed moderate tagging overdispersion

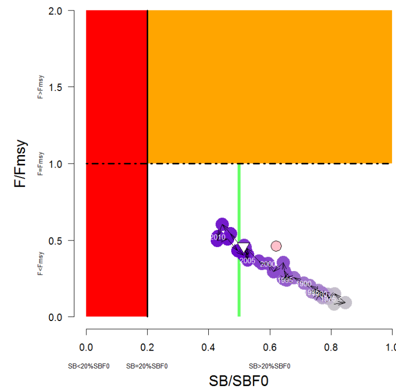
Figure 50: Majuro plots for each of the one-off sensitivity models. See Figure 44 for an explanation of the interpretation of Majuro plots.



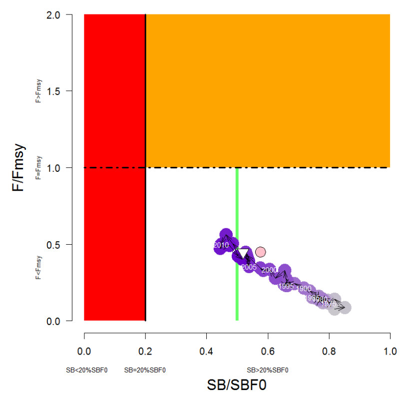

(a) Age-invariant movement




(b) Quarterly SRR function

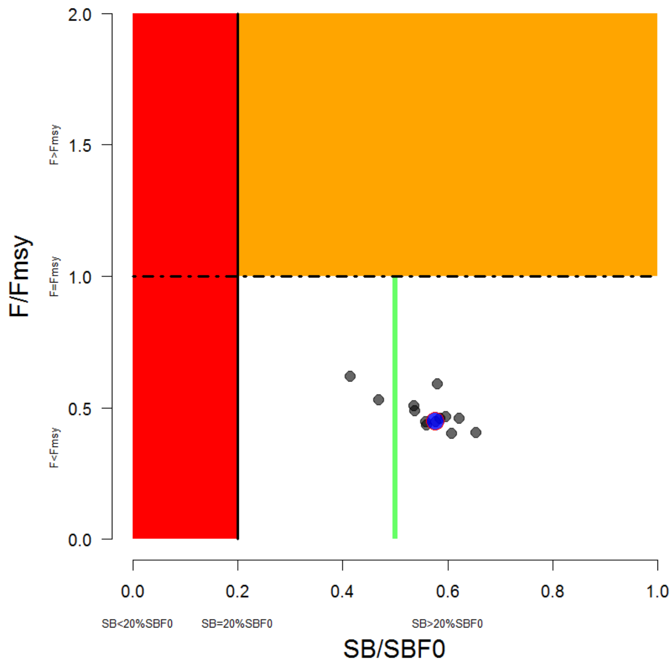



(c) 4 Fixed terminal recruitments

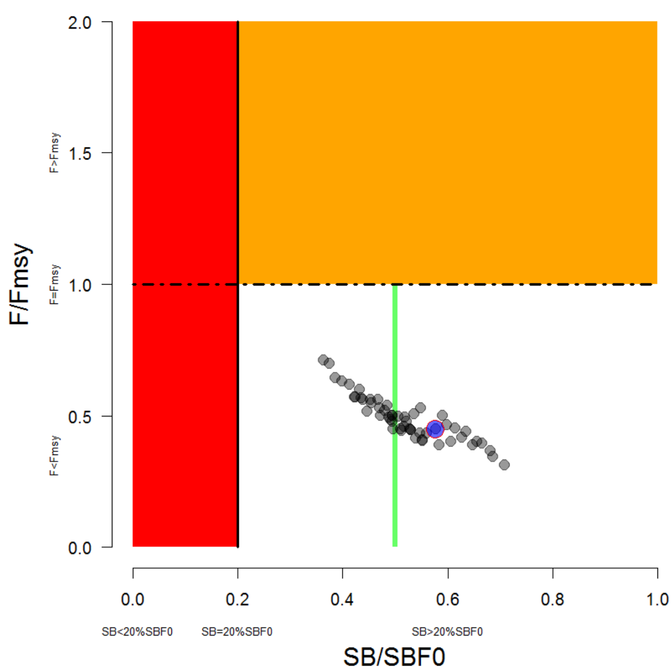



(d) Terminal recruitments freely estimated

Figure 51: Majuro plot for the one-off sensitivity models, continued. See Figure 44 for an explanation of the interpretation of Majuro plots.




(a) One-off sensitivity models




(b) Structural uncertainty grid

Figure 52: Majuro plot displaying estimated stock status for all of the one-off sensitivity models (top panel) and the structural uncertainty grid (bottom panel). See Figure 44 for an explanation of the interpretation of Majuro plots.

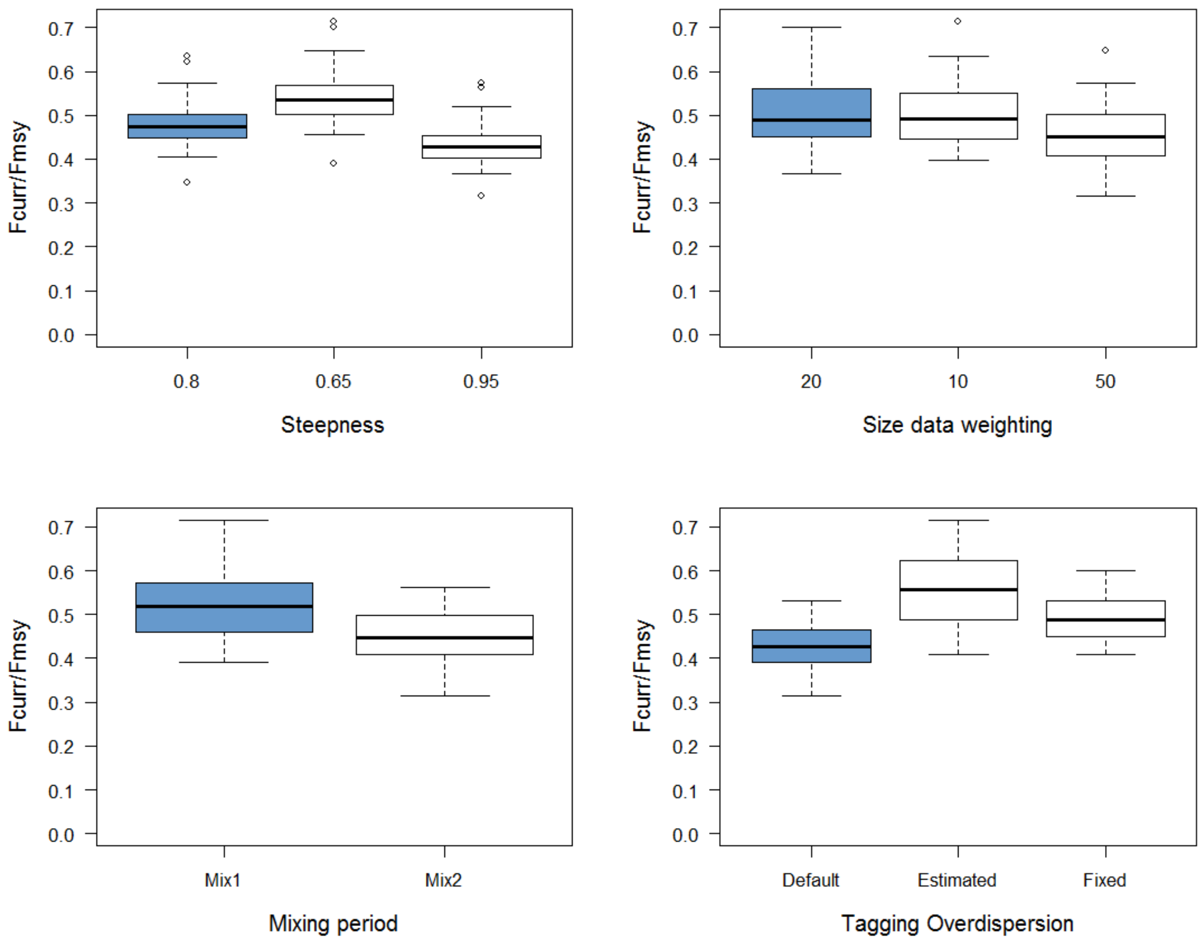



Figure 53: Estimated $F_{recent}/F_{\mathrm{MSY}}$ for each level within the 4 axes of uncertainty that make up the structural uncertainty grid.

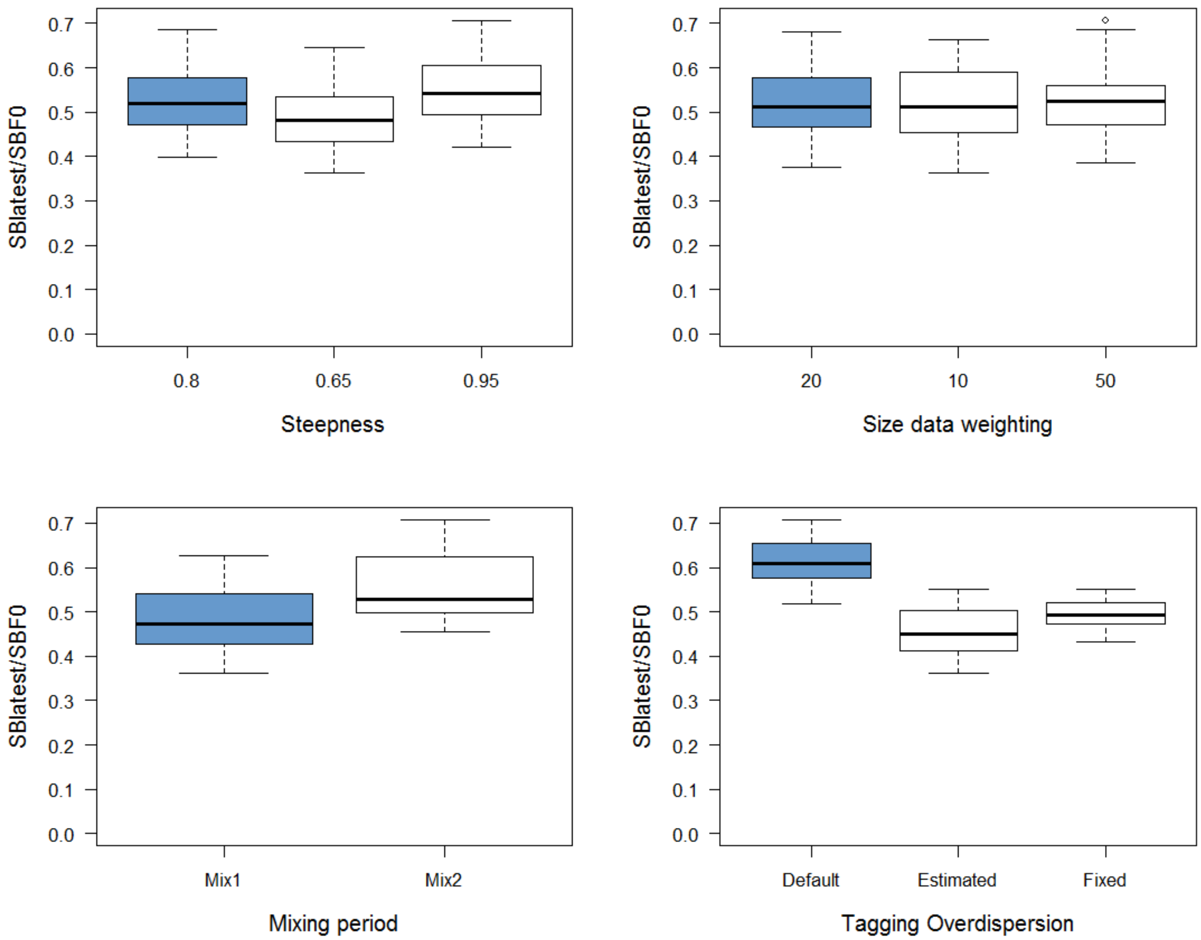



Figure 54: Estimated $SB_{latest}/SB_{F=0}$ for each level within the 4 axes of uncertainty that make up the structural uncertainty grid.

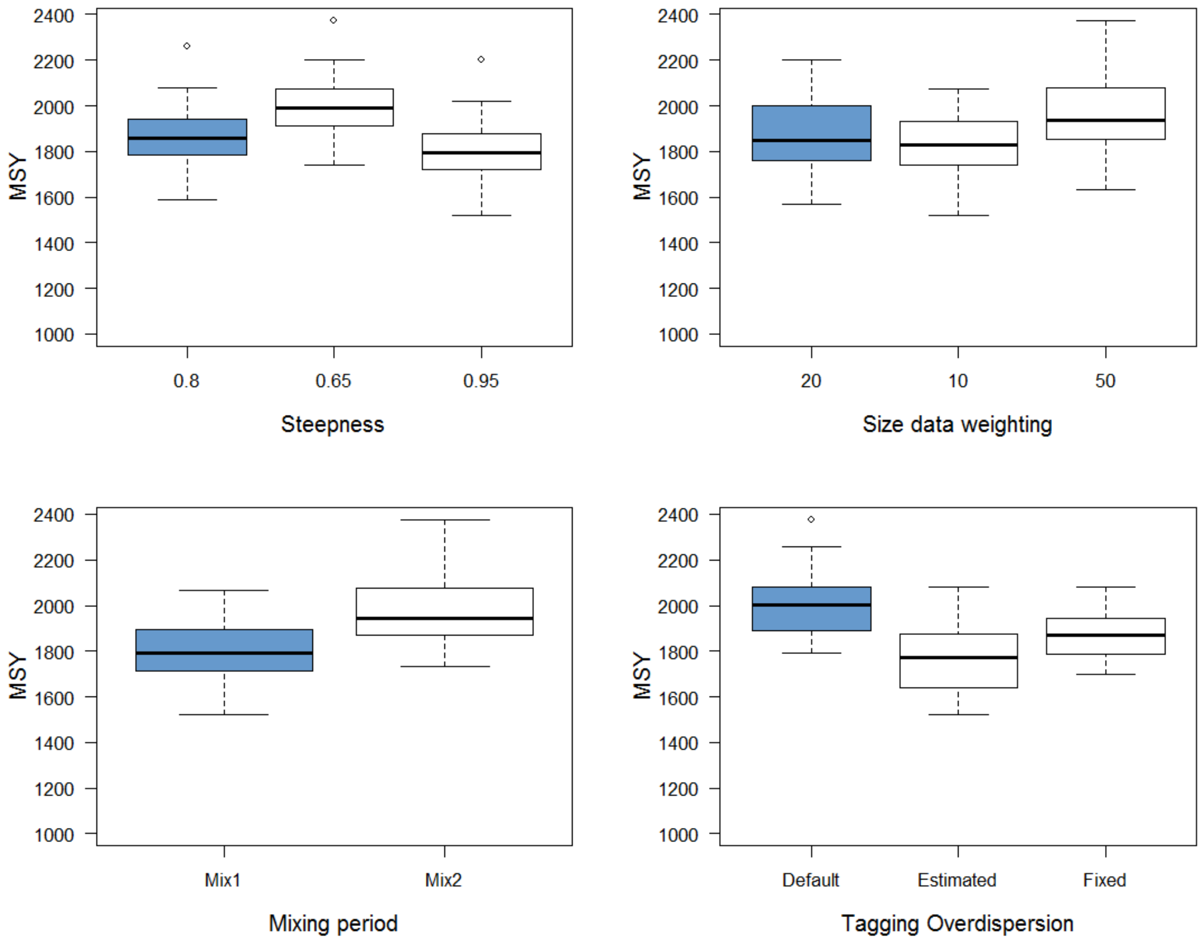



Figure 55: Estimated MSY for each level within the 4 axes of uncertainty that make up the structural uncertainty grid.

# 10 Appendix

## 10.1 Likelihood profile

The approach for calculating a likelihood profile of the total population scaling parameter (*totpop*) is outlined in Section 4.6. The profile reflects 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 vector of fixed values used for the parameter ranged from 0.6 to 1.7 times the value estimated for the reference case model. The likelihood profile is shown in Figure 56 and displays significant declines in the total log likelihood as the parameter moves further away from the maximum value of the reference case model.

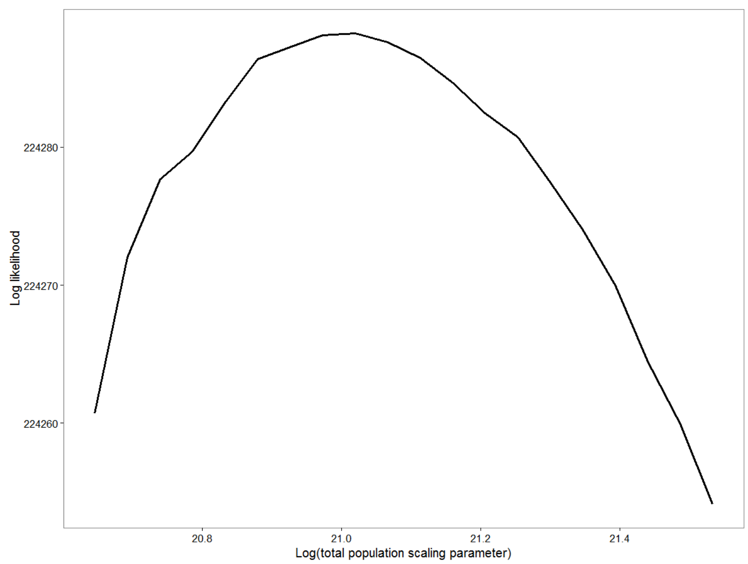



Figure 56: Profile of the total log-likelihood with respect to the total population scaling parameter across a range of fixed values for the reference case model.

## 10.2 Stochastic simulations for the reference case model

Stochastic 10 year projections were run from the proposed reference case model, where future catch (longline, domestic Indonesian and Philippines fisheries) or effort (purse seine, most pole-and-line fisheries) was assumed to remain at 2015 levels (status quo). 200 projections were performed. Variability in future recruitment was implemented by randomly re-sampling from historical recruitment deviations from the stock recruitment relationship over the period 1982-2015 (excluding the final 2 quarters that were fixed at average levels in the assessment). Catchability was assumed to remain constant in the projection period at the level estimated in the terminal year of the assessment model. In 2025, median $SB/SB_{F=0}$ was estimated to be 0.49, and there was zero risk of the stock falling below the limit reference point. Further general information on the approach to undertaking projections within the MFCL framework are presented in detail by Pilling et al. (2016).

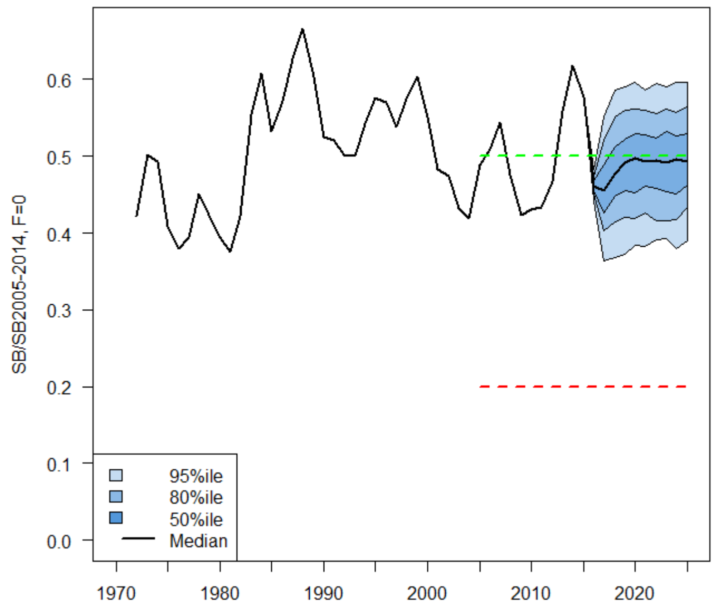



Figure 57: Predicted trajectories of spawning biomass for the reference case model from stochastic simulations and assuming status quo levels of fishing activity. The green and red horizontal dashed lines indicate the target and limit reference points, respectively.

## 10.3 Retrospective analyses

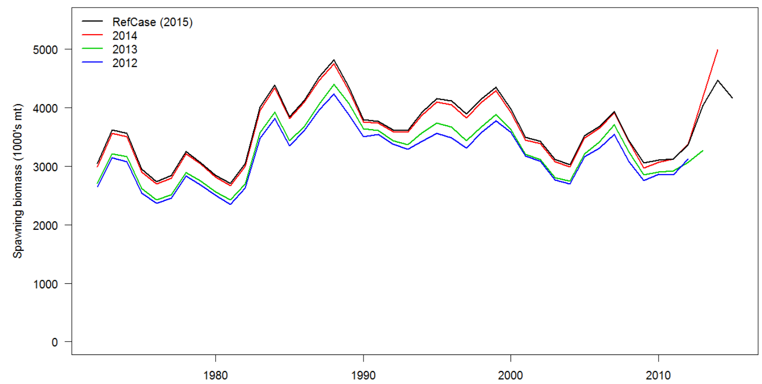
### 10.3.1 Removal of recent years data

Retrospective analysis involves rerunning the selected model by consecutively removing successive years of data to estimate model bias (Cadrin and Vaughan, 1997; Cadigan and Farrell, 2005). A series of 4 models were fitted starting with the full data-set (through 2015), followed by models with the retrospective removal of all input data for the years 2015, 2014 and 2013. The models are named below by the final year of data included (e.g., 2012–2015). A comparison of the spawning biomass, recruitment and depletion trajectories are shown in Figure 58.

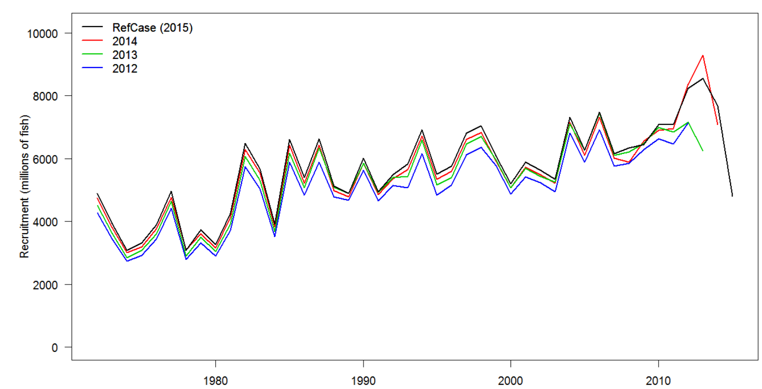
The models with each year of data removed sequentially produced estimates of spawning biomass and fishing depletion with very similar temporal dynamics to the full reference case model, with some slight downward scaling in the 2 shorter time series models (2012 and 2013; Figure 58). For further details of the retrospective approach and methods to interpret the results the reader is referred to Scott et al. (2016).

#### 10.3.2 Comparison of results to previous skipjack stock assessments in the WCPO

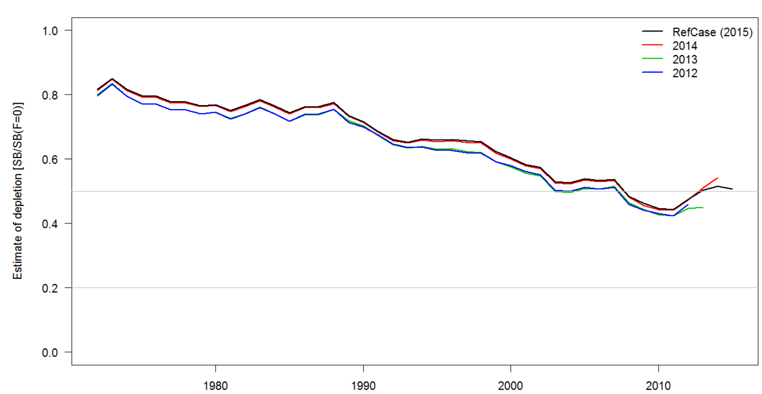
The 2016 reference case model was compared retrospectively to the previous assessments conducted in 2014, 2011 and 2010. The comparison is summarised with plots of spawning biomass, recruitment and fisheries depletion in Figure 59, and a comparison of stock status for the 2016 and 2014 reference case models are displayed in Majuro plots in Figure 60.




(a) Estimated spawning biomass.

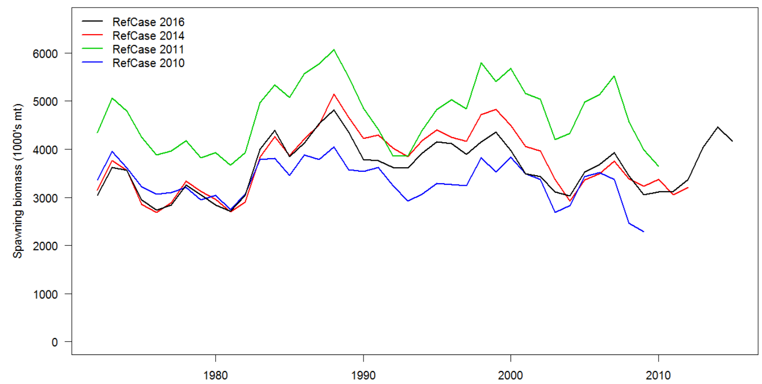



(b) Estimated recruitment.

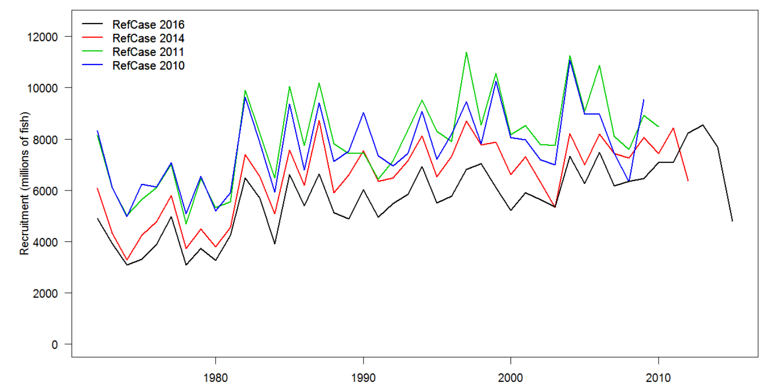



(c) Estimated fishing depletion.

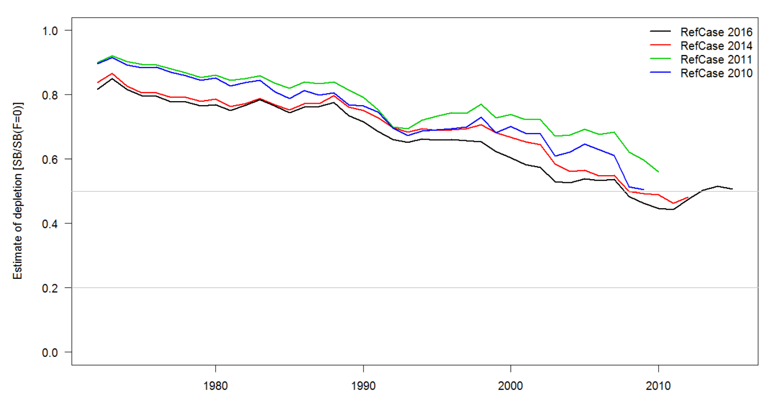
Figure 58: Estimated spawning biomass, recruitment and fishery depletion ($SB/SB_{F=0}$) for each of the retrospective models.




(a) Estimated spawning biomass.

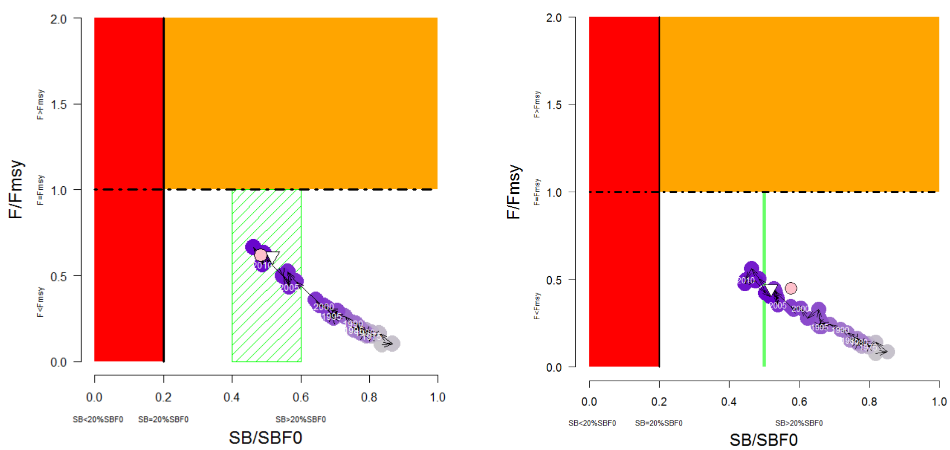



(b) Estimated recruitment.




(c) Estimated fishing depletion.

Figure 59: Retrospective comparison of spawning biomass and fisheries depletion ($SB/SB_{F=0}$) for the reference case models for the last 4 stock assessments of skipjack in the WCPO.




(a) Majuro plot 2014 reference case

(b) Majuro plot 2016 reference case

Figure 60: Comparison of Majuro plots for the reference case models of the 2014 and 2016 stock assessments of skipjack in the WCPO. See Figure 44 for an explanation of the interpretation of Majuro plots. Note that for (a), the green shaded area idicated the range of levels under consideration as potential target reference points, at that time.