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

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EXECUTIVE SUMMARY

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

Some of the main improvements in the 2014 assessment are:

- Increases in the number of spatial regions to better model the tagging and size data;
- Improved modelling of recruitment to ensure that uncertain estimates do not influence key stock status outcomes; and
- A large amount of new tagging data corrected for differential post-release mortality and other tag loss.

The large number of changes since the 2011 assessment (some of which are described above), and the nature of some of these changes, means that full consideration of the impacts of individual changes is not possible. Nevertheless, the report details some of the steps from the 2011 reference case to the 2014 reference case (Run 012_L0W0T0M0). Distinguishing features of the 2014 reference case model include:

- The steepness parameter of the stock recruitment relationship is fixed at 0.8.
- Growth fixed according to 2010 estimates used in the last two assessments.
- The likelihood function weighting of the size data is determined using an effective sample size for each fishing observation of one-twentieth of the actual sample size, with a maximum effective sample size of 50.
- For modelling the tagging data, a mixing period of 1 quarter (including the quarter of release) is applied.
- The last four quarterly recruitments aggregated over regions are assumed to lie on the stock-recruitment curve.

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

The main conclusions of the current assessment are consistent with recent assessments presented in 2010 and 2011. The main conclusions are as follows:

1. A fluctuating but consistently high level of recruitment since the early 1970s has supported a robust fishery in all regions. The analysis suggests that the regional declines in spawning potential, in all regions except region 1, are being driven primarily by the fishing impacts.

2. Although the ratio of exploited to unexploited spawning potential is estimated to have declined, with some fluctuations, throughout the model period, the average total biomass of the last five years is estimated to be above the average total biomass of the first five years of the model.

3. Latest catches slightly exceed the maximum sustainable yield (*MSY*).

4. Fishing mortality for adult and juvenile skipjack tuna is estimated to have increased continuously since the beginning of industrial tuna fishing, but fishing mortality still remains below the level that would result in the MSY.

5. Recent levels of spawning potential are well above the level that will support the *MSY*.

6. The estimated 2011 level of spawning potential represents approximately 52% of the unfished level, and is well above the limit reference point of 20%$SB_{F=0}$ agreed by WCPFC.

7. Recent levels of spawning potential are in the middle of the range of candidate biomass-related target reference points currently under consideration for skipjack tuna, i.e., 40-60% $SB_{F=0}$.

8. Stock status conclusions were most sensitive to alternative assumptions regarding steepness and growth. However the main conclusions of the assessment are robust to the range of uncertainty that was explored.

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

1 INTRODUCTION

This paper presents the 2014 stock assessment of skipjack tuna (*Katsuwonus pelamis*) 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 Bigelow et al.(2000); Hampton and Fournier 2001a; Hampton 2002; Langley et al. 2003; Langley et al. (2005); Langley and Hampton (2008); Hoyle et al. (2010), and Hoyle et al. (2011). The independent review of the 2011 bigeye tuna assessment (Ianelli et al., 2012) had several recommendations for improvement that apply equally to the skipjack assessment, and these have been incorporated into the current assessment wherever possible.

This assessment is supported by several other analyses which are documented separately, but should be considered in reviewing this assessment. These include: improved purse seine catch estimates (Lawson 2013; Lawson & Sharples 2011), reviews of the catch statistics of the component fisheries (Williams 2014; Williams & Terawasi 2014), standardised CPUE analyses of Japanese pole-and-line operational level catch and effort data (Kyofuji et al. 2014), size data inputs from the purse seine fishery (Abascal et al., 2014), revised regional structures and fisheries definitions (McKechnie et al., 2014), and preparation of tagging data and reporting rate information (Berger et al., 2014). Finally, many of these issues were discussed in detail at Pre-Assessment Workshop held in Noumea in April, 2014 (OFP 2014).

2 BACKGROUND

2.1 Stock structure

Surface-schooling, adult skipjack tuna (greater than 40 cm fork length, FL) are commonly found in tropical and subtropical waters of the Pacific Ocean (**Figure 1**). Skipjack in the western and central Pacific Ocean (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 extend their distribution to 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 (**Figure 2**). In general, skipjack movement is highly variable (Sibert *et al.* 1999) but is thought to be influenced by large-scale oceanographic variability (Lehodey *et al.* 1997).

2.2 Life history characteristics

2.2.1 Growth, Natural Mortality, Longevity and Age at Maturity

Skipjack growth is rapid compared to yellowfin and bigeye tuna. In the Pacific, approximate age estimates from counting daily rings on otoliths suggest that growth may vary between areas. 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 was 4.5 years. Skipjack tuna reach sexual maturity at about 40 cm FL.

2.3 Fisheries

Skipjack tuna, the largest component of tuna fisheries throughout the WCPO, are harvested with a wide variety of gear types. Fisheries can be classified into the Japan pole-and-line fleets (both distant-water and offshore), domestic pole-and-line fleets based in island countries, artisanal fleets 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 region in the WCPO. A domestic pole-and-line fishery occurred in PNG from 1970 to 1985 and active fisheries have occurred in Fiji and the Solomon Islands since 1974 (now discontinued) and 1971 (operating at a low level), respectively.

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

Purse seine fleets usually operate in equatorial waters from 10°N to 10°S; although a Japan 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, more than doubling during the 1980s. The catch was relatively stable during the early 1990s, approaching 1,000,000 mt per annum. Catches increased again from the late 1990s and have varied between 1.5 and 1.8 million mt[1] since 2007. 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 (which have made up to 20–25% of the total skipjack tuna catch in WCPO in recent years).

Historically, most of the catch has been taken from the western equatorial Pacific (regions 2, 4 and 5) (**Figure 3**). During the 1990s, combined annual catches from this region fluctuated about 500,000–800,000 mt before increasing sharply to approximately 1,200,000 mt in 2007–2009 (**Figure 3**). 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. From 2008-2012 the average annual catch in region 2 was 272,000 mt in the associated fishery and 254,000 mt in the unassociated fishery, while in region 3 the average was 195,000 mt in the associated fishery and 135,000 mt in the unassociated fishery.

Uncertainty remains regarding the accuracy of the purse-seine catch, since catches reported on logsheets may over-estimate actual catch levels (Lawson 2009 and 2010, Lawson & Sharples 2011). In recent years, the purse seine catch history has been corrected for the over-reporting of skipjack and under-reporting of yellowfin+bigeye on logsheets (Hampton and

[1] Catch levels referred to in this paper are relevant to the reference case assessment run, which incorporated purse seine catches that were revised according to the results of recent spill sampling trials (Lawson 2013).

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 unless otherwise noted.

3 DATA COMPILATION

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

3.1 Spatial stratification

The geographical area considered in the assessment corresponds to the western and central Pacific Ocean 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 regions. 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.

3.2 Temporal stratification

The time period covered by the assessment is 1972–2012. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec). As agreed at SC9, the assessment did not include data from the most recent calendar year. This is because these data are only finalized very late and often subject to significant revision post-SC. This year the 2013 data was not finalized until the end of the first week of July – far too late to be included in assessments due only two weeks later. In the discussion section we consider potential mechanisms to address this matter.

3.3 Definition of fisheries

MULTIFAN-CL requires the definition of "fisheries" that consist of relatively homogeneous fishing units. Ideally, the 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.

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 research longline fishery was defined to hold the long time series of skipjack size frequency data from Japanese research longline cruises in the WCPO.

Multiple changes were made to the fishery definitions from the 2011 assessment, due largely to the revised regional structure. The Japanese offshore and distant-water pole-and-line fisheries in region 1 were pooled because although these fisheries have different operational characteristics and mainly occupy different areas (within region 1), they are data deficient and as such share key parameterizations such as selectivity and reporting rate. The disparate pole-and-line fisheries in regions 2 and 3 were likewise combined into individual region-specific pole-and-line fisheries. New fisheries for regions 4 and 5 were defined from fisheries previously in region 2 of the 2011 assessment (see **Table 1.A**). New data from Vietnam has led to the addition of a domestic Vietnamese fleet in the new region 4. Overall, 23 fisheries were defined in the analysis (**Table** 1) compared to the 18 fisheries defined in the 2011 assessment. A graphical summary of the availability of data for each fishery is provided in **Figure 4**.

3.4 Catch and effort data

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

Total annual catches by major gear categories for the WCPO are shown in **Figure 5** and a regional breakdown is provided in **Figure 6**. The spatial distribution of catches over the past ten years in provided in **Figure 3**.

Discarded catches are estimated to be minor (SPC-OFP 2014) and were not included in the analysis.

Catches in the northern region are highly seasonal, as are the domestic pole-and-line fisheries operating in the regions 2 and 3. 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 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.

3.4.1 <u>Purse Seine</u>

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

Briefly, catch data are estimated by 1° latitude, 1° longitude, month flag, and set-type. Though the exact algorithm depends on the year and data available, total catches are taken from the logsheet declared totals and then the grab samples are corrected for bias based on the estimates of the correction factors from the paired spill and grab sampling trials. For some fleets for which there is greater confidence in species-based reporting (e.g. Spanish and Japanese fleets), 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 (OFP 2013) such that far few searching days are reported and these are instead reported as non-fishing transit days. This practice essentially represents effort creep and we have not yet specifically corrected recent data to ensure consistency of reporting. Therefore the impact of this is not known, but it will be minimized by the practice of estimating frequent time-based changes in catchability.

Catch-per-unit-effort for the Philippines domestic purse seine was analysed using a GLM for CPUE indices by Bigelow et al (2014) (**Figure 7**). These indices were applied to the catches of the S-ID.PH-4 fishery for the years 2005-2012 and lacked estimates of time-variant precision.

Catch-per-unit-effort for the purse seine fishery operating largely within the PNG archipelagic waters was analysed for standardised indices using the GLM (Pilling et al. 2014) (**Figure 7**). These indices were applied to the catches of the S-ASS-All-8 fishery for the years 1997-2012 and included estimates of time-variant precision.

3.4.2 Longline

Research longline fisheries were included to utilise the available size frequency data. Longline fisheries typically do not target skipjack however Japanese research vessels routinely collect measurements of the length of skipjack caught.

3.4.3 Pole-and-line

Standardised effort series for fisheries 1, 4, and 12 were based on Japanese pole-and-line fisheries in region 1, 2, and 3, respectively. These the standardized effort time series were estimated using generalized linear models (GLM) analyses of the operation al catch and effort data (Kiyofuji et al 2014). Separate analyses were done for each region. The uncertainty in each pole-and-line CPUE estimate, by fishery and time, was included in the model by way of a scaled penalty weight for the effort deviations. Regional scaling factors were not applied to the CPUE estimates from the different regions. Pole-and-line catchabilities were estimated independently, so that the relative regional weightings were estimated by the model. Nominal fishing-vessel-day was used as the unit of effort for the domestic pole-and-line fisheries of Papua New Guinea, Solomon Islands, and Fiji.

3.4.4 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..

3.5 Size Data

Available length-frequency data for each of the defined fisheries were compiled into 54 2-cm size classes (2–4 cm to 108–110 cm). Length-frequency observations consisted of the actual number of skipjack measured in each fishery/quarter. A graphical representation of the availability of length samples is provided in **Figure 8**.

3.5.1 Purse seine

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

3.5.2 Longline

Longline fisheries principally catch small amounts of large skipjack, within the 50–90 length range, and the catch is usually discarded. We utilise a long time series of longline size data obtained from Japanese training and research longline vessels to provide information to the model on the existence of these larger sized skipjack rarely caught in purse seine or pole-and-line fisheries. The data are important, because it allows selectivity of surface fisheries to be measured against these larger-sized skipjack.

3.5.3 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 is available from the Japanese off shore and distant water fleet (sourced from NRIFSF) from the beginning of the model period until 2009. For the equatorial (excluding region 2)-and-line fishery, length data were 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 observer 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 in the years 2009-2012. The data from the pole and line fishery in region 5 (P-ALL-5) is a large multiple countries dominated by the US in the years 1988-1997 and PNG in the years 1998-2012. The pole-and-line fisheries in the northern region generally catch smaller fish than the equatorial fisheries (regions 2 -5), (**Figure 13**) although over the model period, there was a general increase in the length of fish sampled from the pole-and-line fisheries in regions 1 and 2, while variation in the sample sizes is evident, no systematic trend in the size composition was evident in regions 3, 4, or 5 (**Figure 14**).

3.5.4 Other fisheries

Size composition data for the Philippines domestic fisheries (Z-PH-4) were collected by a sampling programme conducted in the Philippines in 1993–94 and augmented with data from the 1980s and from 1995. 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. No size data were available for the Vietnam domestic fishery (Z-VN-4) and selectivity for this fishery was also linked to Z-PH-4. 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).

3.6 Tagging data

A large amount of tagging data was available for incorporation into the assessment. The data used consisted of the OFP's Skipjack Survey and Assessment Project (SSAP) carried out during 1977–80, the Regional Tuna Tagging Project (RTTP) during 1989–92 and in-country projects in the Solomon Islands (1989–90), Kiribati (1991), Fiji (1992) and the Philippines (1992). Tagging data from regular Japanese research cruises were available for the period 1988–2012. Tagging data from the Pacific Tuna Tagging Programme (PTTP) were available for the period 2006 until the 2nd quarter of 2012.

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), but essentially the re-scaling preserves the recovery rates of tags from the individual tag groups as if none of the tag loss had occurred. These processes were able to be applied only to the RTTP and PTTP releases.

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 314,555 effective releases were classified into 251 tag release groups (Table 2). The returns from each size-class of each tag release group (50,087 effective 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 – STRUCTURAL ASSUMPTIONS, PARAMETERISATION, AND PRIORS

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) observation models for the data; (v) parameter estimation procedure; and (vi) stock assessment interpretations. Detailed technical descriptions of components (i) – (iv) are given in Hampton and Fournier (2001b) and Kleiber et al. (2013). Brief descriptions of the various processes, including information on structural assumptions, estimated parameters, priors and other types of penalties used to constrain the parameterisation were provided in Hoyle et al. (2011 – Table 2) and only changes to these assumptions are reported here **Table 3** . 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.

4.1 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 1972–2012. The main population dynamics processes are as follows:

4.1.1 Recruitment

Recruitment is defined as the appearance of age-class 1 fish (i.e. fish averaging 10 cm given the current growth curve) in the population. Tropical tuna spawning does not 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 recruitment was somewhat constrained by a lognormal prior. The variance of the prior was set such that spatially aggregated recruitments of about three times and one third of the average recruitment would occur about once every 25 years on average

Spatially-aggregated recruitment was assumed to have a weak relationship with the spawning biomass via a Beverton and Holt stock-recruitment relationship (SRR) with a fixed value of steepness (h). Steepness is defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Francis 1992; Maunder and Watters 2003).

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

Typically, fisheries data are not very informative about the steepness parameter of the SRR parameters; hence, the steepness parameter was fixed at a moderate value (0.80) and the sensitivity of the model results to the value of steepness was explored via a range of model sensitivities with lower (0.65) and higher (0.95) values of steepness. Model options that estimated the value of steepness internally in the model were also explored. In this case, an uninformative (uniform) prior was assumed on steepness of the SRR.

4.1.2 Initial population

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

4.1.3 Age and 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 (see table). These processes are assumed to be regionally invariant. For the results presented here, 16 quarterly age-classes have been assumed. Growth was not estimated in the model, except for one sensitivity analysis (**Figure 9**).

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

4.1.4 Movement

Movement was assumed to be time invariant and to occur instantaneously at the beginning of each quarter between regions sharing a common boundary. Note however 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 2001c; Kleiber *et al.* 2013 for details). Movement is parameterised as the proportion of fish in a given region that move to the adjacent region. Across each inter-regional boundary in the model, movement is possible in both directions for the four quarters, each with their own movement coefficients. Thus the number of movement parameters is 2×no.regions×4quarters. The seasonal pattern of movement persists from year to year with no allowance for longer-term variation in movement. Usually there are limited data available to estimate age-specific movement and the movement coefficients are normally invariant with respect to age. A prior of 0.1 is assumed for all movement coefficients, inferring a relatively high mixing rate between regions.

4.1.5 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 10**.

4.1.6 Sexual maturity

Sexual maturity was estimated and assumed to be age-specific, nearly knife edge and invariant over time and region. The onset of sexual maturity was assumed to occur at age-class 3 (6-9 months of age). The adult component of the population was defined as the 3–16 age classes. Unlike in *Thunnus* species, sex ratio does not appear to vary with size for skipjack. Maturity 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 spawning potential as in the yellowfin, bigeye, and albacore stock assessments.

4.2 Fishery dynamics

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

4.2.1 Selectivity

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

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, with the exception of region 3 which was independently estimated. The Indonesian, Philippines and Vietnam domestic fisheries in region 4 (Z-..-4) were also grouped.

4.2.2 Catchability

Constant catchability (time-invariant) was estimated for all fisheries for which standardised indices of relative abundance were available (P-ALL-1, P-ALL-2, P-ALL-3 and S-ASS-ALL-5). 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 CPUE was not used to scale the relative exploitable biomass in regions 1, 2 and 3 – the model relies on other data, size and 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.

4.2.3 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. In this assessment the prior was set to have a mean of zero and for the abundance index fisheries the CV was time-varying and based on the variance estimates from the GLMs. For all other fisheries, the CV was set to 0.2.

4.3 Dynamics of tagged fish

4.3.1 Initial tag mixing

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

We assume that tagged skipjack gradually mix with the untagged population at the region level and that this mixing process is complete by the end of the first quarter after release.

4.3.2 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 fisheries that reflect our prior opinion regarding the reporting rate and the confidence we have in that opinion.

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 change, and different levels of publicity and follow-up. Consequently, fishery-specific tag reporting rates were estimated that are also specific to individual tagging programmes, i.e. a reporting rate matrix. Tag recapture and reporting rate groupings are provided in **Table 4**.

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

All reporting rates were assumed to be stable over time.

4.4 Likelihood components

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

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

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

The 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 0.2 times the actual sample size, with a maximum effective sample size of 50.

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

4.5 Parameter estimation and uncertainty

The parameters of the model were estimated by maximizing the log-likelihoods of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. The maximization to a point of model convergence was performed by an efficient optimization using exact derivatives with respect to the model parameters (auto-differentiation, Fournier 2012). Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters. A bash shell script, doitall, (Annex 10.5) implements the phased procedure for fitting the model. Some parameters were assigned specified starting values consistent with available biological information. The values of these parameters are provided in the skj.ini file (Annex 10.4)2.

In this assessment two approaches were used to describe the uncertainty in key model outputs. The first estimates the statistical variation within a given assessment run, while the second focuses on the structural uncertainty in the assessment by considering the variation among model runs. For the first approach, the Hessian matrix was calculated for the reference case model run to obtain estimates of the covariance matrix, which is used in combination with the Delta method to compute approximate confidence intervals for parameters of interest (the biomass and recruitment trajectories). For the second approach, a crosswise grid of model runs 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. Reasonable contrast in the profile was taken as indicating sufficient information existed in the data for estimating absolute abundance, and also offered confirmation of the global minimum obtained by the maximum likelihood estimate.

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

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

4.6 Stock assessment interpretation methods

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

4.6.1 Reference points

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

4.6.2 Fishery impact

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

We approach this problem by computing biomass time series (at the region level) using the estimated model parameters, but assuming that fishing mortality was zero. Because both the real biomass B_t and the unexploited biomass B_{0t} incorporate recruitment variability, their ratio at each time step of the analysis B_t/B_{t0} can be interpreted as an index of fishery depletion. The computation of unexploited biomass includes an adjustment in recruitment to acknowledge the possibility of reduction of recruitment in exploited populations through stock-recruitment effects. This analysis was conducted in respect of groups of fisheries so as to describe the relative fishing impacts of each group on the population.

4.6.3 Yield analysis

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

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

The MSY based reference points were also computed using the average annual Fa from each year included in the model (1972–2012). This enabled temporal trends in the reference points to be assessed and a consideration of the differences in MSY levels under historical patterns of age-specific exploitation.

5 MODEL RUNS

5.1 Developments from the 2011 assessment

There are six main differences in the input data and structural assumptions of the current assessment compared to the reference case from the 2011 assessment.

i. Updated catch, size and tagging data to the end of 2012.

ii. Expanded the number of regions from 3 to 5.

iii. An additional 5 fisheries added to accommodate the 5 region structure, bringing the number to 23 from 18.

iv. Updated CPUE indices derived from operational catch and effort data from Japanese pole-and-line fisheries.

v. Set-based weighting of purse-seine length frequency samples to enhance representativeness of these data (Abascal 2014).

vi. Exclusion of the four terminal spatially-aggregated recruitment deviates from the parameter estimation process.

For comparison to the 2011 stock assessment, a step-wise sequence of models was formulated that modified the 2011 reference case model to sequentially incorporate each of the changes identified above. A summary of the sequential changes (**Table 3**) is also presented in the Annex section 10.3.

5.2 Sensitivity analyses

The key uncertainties identified in the current assessment are the assumed level of steepness of the SRR, the growth curve, the weighting of the length samples and the tag mixing period (**Table 5**).

- The reference model assumed a value of 0.80 for the steepness of the SRR; model sensitivities included alternative values of 0.65 and 0.95.
- Due to the lack of strong length modes in the length frequency data, growth was fixed at the level estimated in the 2010 stock assessment (Hoyle et al. 2010), and two alternatives were used - one estimating the growth curve within the current model and one using a fixed growth curve obtained from daily growth rings on otoliths sampling conducted in the western north Pacific (Tanabe, Kayama, and Ogura 2003).
- The reference model assumed a mixing period of 1 quarter between the tagged population and the population at large, a sensitivity of 2 quarters was tested.
- The influence of the size data was explored by halving the relative weight by assigning lower (n/50) effective sample sizes, with a maximum sample size of 20, across all size data.

5.3 Structural Uncertainty

The interactions between each of the principal models and the various model sensitivities were assessed by conducting model runs that combined the various model options described above. This represented a grid of 36 combinations of the following factors: the steepness of the SRR (0.65, 0.80, or 0.95), and the growth model (2010 estimate, estimate or Tanabe growth curve), and sample size weighting (20, 50). mixing period (1, 2 quarters). A separate model was run for each of the combinations in the grid.

6 RESULTS

This section provides a detailed summary of the results from the reference case assessment. A general summary of the sequential changes made during model development (Annex Table 10.3.1) is also presented.

6.1 Model Diagnostics (reference case)

A brief review follows of the fit of the model to the three predicted data classes: the total catch data, the length frequency data and the tagging data. In addition, the estimated effort deviations provide an indication of the consistency of the model with the effort data. The following observations are made concerning the various fit diagnostics:

- A high penalty was applied to the catch deviations in the model likelihood and consequently the catch residuals were very small for all fisheries.
- The model estimates of pole-and-line exploitable biomass trends were generally consistent with the observed pole-and-line CPUE indices (**Figure 11**). Despite the shorter time series, the model predicted CPUE was also consistent with the observed indices for the purse seine fisheries in regions 4 and 5, (S-ASS-ALL-5 and S-ID.PH-4). In all cases the model predictions traced the temporal variation and long-term trends in observed CPUE. Standardised CPUE for the pole-and-line fisheries were seasonally discontinuous in either the later part (P-ALL-2) or the entirety of the series (P-ALL-1 and P-ALL-3). A lower penalty was assumed for these data, and consequently the model predictions and the observations were not closely consistent, however, the general trends are similar. The declines in the standardised purse seine CPUE were also adequately predicted by the model. An increasing trend in the effort deviations exists for fishery S-ASS-ALL-5, particularly for the period later period, indicating that the trends in nominal catch rate were unable to be well predicted by the model (**Figure 12**). However, this has little influence given its relatively shorter duration, the small region size and the fact that in the adjacent regions 2 and 3, the effort deviations are small and appear generally more stable.
- For most fisheries, there is a reasonable fit to the length data as revealed from a comparison of the observed and predicted proportions at length (**Figure 13**). The apparent lack of fit to a mode of small fish in the Z-PH-4 and Z-ID-4 fisheries is due to the near lack of data in Z-ID-4 and a shift in the observed length frequency in fishery Z-PH-4 from the early period (not well fit) to the late period, which was better fit. Close consistency between the model and observed length frequencies was obtained for the relatively large samples from the purse seine fisheries in regions 1, 2, 3, and 5. Generally the model adequately describes the variability in catch length frequencies observed among the regions (**Figure 13**).
- The generally good fit to the size data was also revealed from a comparison of the observed and predicted median lengths over time (**Figure 14**). Model predictions in median size through time were a reasonable reflection of the observed trends in size for the purse seine fisheries in regions 3, 4 and 5; and the pole-and-line fisheries in regions 1, 2 and 3. However, for fisheries in which there are few recent (L-ALL-5, S-ID.PH-4, Z-ID-4, Z-PH-4, S-ASS-DW-4, L-JPN-4, S-UNA-DW-4) there is an increased lack of fit.
- Generally the model predictions of the movement of tagged fish among the regions reflected the observed recaptures of tagged fish by time period at liberty (quarter) from the region of release to the region of recapture (**Figure 15**). Region 5 has the majority of observed tag recaptures (n=27,452; **Table 2**), followed by region 4(n=9,650; **Table 2**), and the relatively equal movement of tagged fish into these regions was well described by the model predictions. This relative stationarity was also adequately described for regions 1, 4, and 3. Reasonable estimates of the movement of tagged fish out of the most release

regions were obtained, but poorly estimated for movements that lacked long term recaptures (5 to 1, 1 to 4, 3 to 4, 3 to 5, 4 to 1, 3 to 1 (**Figure 15**).

- The fit of the model to the total numbers observed recaptures of tagged fish by calendar time is shown in **Figure 16** (recaptures plotted in log-space). The observed recaptures have relatively low variability through the recovery phase, and the model predictions were broadly consistent with the observations, including the high numbers obtained from the PTTP in 2008-12. Model predicted recaptures exceeded those observed for some of the later years of the JP and RTTP programs, but overall the model fit to these data was good.
- The overall good fit to the tagging data is also reflected in the predicted recaptures in respect of time at liberty closely matching the observations (**Figure 17**), indicating that model estimates of tag attrition due to fishing and natural mortality adequately describe that observed over all tag release programmers. A steep decline in recaptures was observed in the first 4 quarters following release, but a sustained number of tagged fish were recaptured up to 13 quarters at liberty.

6.2 Model Parameter estimates (reference case)

6.2.1 <u>Tag Reporting Rates</u>

Estimated tag-reporting rates by fishery are shown in **Figure 18**. As could be expected, tag reporting rates for individual fisheries differed both among fisheries and tagging programmes. The groupings assumed among fisheries and programmes are shown in **Table 4** and essentially entails the grouping of pole-and-line and longline fisheries (1:4, 7,8, 11,12,15,19,23) over all the tagging programs, while other fisheries retained the same fishery-specific grouping, but a program-specific rate was estimated for each group. Informative priors for the tag reporting rates were available for a number of the main fisheries, most notably the tag recoveries by the purse-seine fisheries from the RTTP and PTTP programmes.

For all programmes, some of the reporting rate estimates were estimated to be higher than the mode of their prior distributions and tended to vary considerably between regions. The estimate for the largest purse seine fishery (regions 2, 3, 4 and 5) group was above the prior for the SSAP, RTTP and PTTP (region 4 and 5), while for the PTTP region 2 and 3 and JP programs the reporting rate in the purse seine fisheries approached near zero. The estimated reporting rates from the longline fisheries are based on a very small number of tag recoveries and, consequently, the tag recovery data from these fisheries are not very informative.

6.2.2 <u>Selectivity</u>

The estimated selectivity coefficients are generally consistent with expectations such that the longline fisheries principally select larger, older fish and the miscellaneous domestic gears and associated purse-seine sets (FAD and log sets) catching smaller skipjack (**Figure 19**). Unassociated purse-seine sets generally select larger fish than associated sets with a moderate selectivity for the older age classes. The selectivity of the miscellaneous Philippines, Indonesia and Vietnamese fisheries have the highest coefficients for the age-class 3 quarter with a subsequent decrease..

The Japanese pole-and-line fishery (P-ALL-1) and the equatorial pole-and-line fisheries P-All-2, P-All-3, P-ALL-4 and P-All-5) are estimated to select fish of approximately the same size, although the westernmost region (region 4) has a much broader selectivity for the same gear. However, there are also some observations of larger fish in the catch and higher variability observed that results in the higher selectivities for the northern pole-and-line fisheries.

For the principal purse seine fisheries: S-ASS-ALL 2,3,5 and S-ASS-ALL 2,3,5, the selectivity is estimated to be highest for age-classes 4-6 with lower selectivity of the youngest fish compared to the oldest fish.

6.2.3 Catchabilty

Model estimations of the fishery-specific catchability (**Figure 20**) show a generally increasing trend in all fleets where catchability is allowed to vary, except S-ALL-1 and P-All-5.

6.2.4 Movement

The estimated movement coefficients for adjacent model regions are shown in **Figure 21**. The model estimates substantially more east-west than north-south movement, although there is strong movement from region 1 to region 2 in the third quarter.

The distribution of regional biomass by source region derived from a simulation using the movement coefficients is presented in **Figure 22**. For regions 1, 3 and 4, a relatively high proportion of the biomass is predicted to be sourced from within those regions.

6.3 Stock assessment results

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

6.3.1 Recruitment

The reference case recruitment estimates (aggregated by year for ease of display) for each region and the entire WCPO are shown in **Figure 23**. A key feature of previous assessments has been the low recruitment during the early part of the assessment followed by an increasing, but fluctuating recruitment. This feature persists in the current assessment and is similar to the two previous assessments in this respect (Annex **Figure 10.2.3**). As noted in Section 4.1.1, the last four recruitment deviates were not estimated and instead set to zero. This was because the retrospective analysis showed that these were poorly estimated (Annex **Figure 10.2.2**). This will have no impact the spawning biomass estimates or reference points as these cohorts do not contribute to SB_{latest} or SB_{curr}, and minimal impact on F_{curr}/F_{MSY} as we ignore F in the terminal year already.

The estimated distribution of recruitment across regions should be interpreted with caution as MULTIFAN-CL can use a combination of movement and regional recruitment to distribute fish. Generally the regional recruitment patterns are similar to those from the 2011 assessment.

6.3.2 Biomass

The estimated spawning potential trajectory for each region and for the entire WCPO for the reference case are shown in **Figure 24** and **Figure 25**. The eastern equatorial region (region 3) remains the region with the greatest spawning potential and the central equatorial region (region 2) is the second largest with the single northern region the third largest. The spawning potential in the western equatorial regions 4 and 5 are similar.

WCPO spawning potential is estimated to have been relatively stable during the 1970s, before increasing in the early 1980's due to higher recruitment, before declining over the past decade due to fishing.

6.3.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase throughout the time series for all model runs and in all cases (**Figure 26**). Changes in fishing mortality-at-age and population age structure are shown for decadal time intervals in **Figure 27**. 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.

6.3.4 Fishery impact

We measure fishery impact at each time step as the ratio of the estimated spawning potential to that which would have occurred in the historical absence of fishing. This is a useful variable to monitor, as it can be computed both at the region level and for the WCPO as a whole. This information is plotted in two ways, first the fished and unfished spawning potential trajectories (**Figure 28**) and second as the depletion ratios themselves (**Figure 29**). The latter is relevant for the agreed limit reference point and discussed in more detail in Section 7.

The analysis suggests that the declines in spawning potential in regions 1 and 3 are being driven primarily by the estimated recruitment, while fishery impacts are greatest in regions 4, 5 and to a certain extent in region 2.

It is possible to ascribe the fishery impact to specific fishery components in order to see which types of fishing activity have the largest impact on the spawning potential (**Figure 30**). The early impacts on the population were primarily driven by pole-and-line fishing, but in recent years, at the WCPO level the most significant impacts have been from the purse seine fisheries and in region 4 the miscellaneous domestic gears.

6.3.5 Yield analysis

The yield analyses conducted in this assessment incorporate the spawner recruitment relationship (**Figure 31**) into the equilibrium biomass and yield computations. Importantly in the reference case model the steepness of the SRR was fixed at 0.8 so only the scaling parameter was estimated.

The equilibrium unfished spawning potential was estimated at 5,940,000 mt and the spawning potential that would support the MSY was estimated to be 1,683,000 or 28.3% of SB_0 (**Figure 32**). The total equilibrium unfished biomass was estimated to be 6,281,000 mt.

The yield analysis also enables an assessment of the *MSY* level that would be theoretically achievable under the different patterns of age-specific fishing mortality observed through the history of the fishery (**Figure 33**). Prior to 1980, the WCPO skipjack fishery was almost exclusively conducted using pole-and-line, with a low exploitation of small skipjack. The associated age-specific selectivity resulted in a similar higher level of *MSY* (>1,500,000 mt per annum) to the recent estimates of *MSY*.

6.4 Stock status

6.4.1 Stock status based on the traditional Kobe plot

For continuity with previous practice, and while the SC and WCPFC consider the use of target and limit reference points, we have included the traditional Kobe plot for spawning potential versus fishing mortality (**Figure 34**). We have included both $SB_{current}$ and SB_{latest} for reference on this figure. $SB_{current}$ (2008-2011 average) and SB_{latest} (2011) are estimated to be 1.94 and 1.8 time SB_{MSY}, respectively. As noted in Section 6.3.3, fishing mortality has generally been increasing through time $F_{current}$ (2008-2011 average) is estimated to be 0.62 times the fishing mortality that will support the *MSY* (**Table 7**).

6.4.2 Spawning biomass in relation to limit reference point

$SB_{F=0}$ calculated for the period 2002-2011 is the basis for the limit reference point and this is a spawning potential of 6,303,358 mt, which is 6.1% higher than SB_0 (**Table 7**). This indicates that recruitment has been slightly above the estimated spawner recruitment curve during this recent period. The limit reference point is 20% $SB_{F=0}$ and this is a spawning potential of 1,260,672mt. $SB_{current}$ (2008-11 average) and SB_{latest} (2011) are estimated to be 52% and 48% respectively of $SB_{F=0}$. An exploratory graphical representation of this is shown in **Figure 36**.

6.4.3 Spawning biomass in relation to potential target reference points

The WCPFC has requested investigation of spawning potential in the range of 40-60% $SB_{F=0}$ for skipjack for potential biomass-related target reference points. As SB_{curr} (2008-2011 average) and SB_{latest} (2011) are estimated to be 52% and 48%, respectively of $SB_{F=0}$, these levels are within the range of candidate biomass-related target reference points currently under consideration.

6.5 Sensitivity of the reference case

6.5.1 Impact of key model developments

Detailed results of the stepwise changes are provided in Section **Error! Reference source not found.**, which can be found in the Annex.

New Multifan-CL executable

A repeat of the 2011 reference case using the updated version of MULTIFAN-CL (version 1.1.5.6) was undertaken to ensure the integrity of the model estimates and to determine the causes of differences, if any existed. Estimates were identical to those obtained in 2011 (Annex Figure 10.3.1, and Figure 10.3.2).

Update catch, effort and size data

Updating the data to 2014 had a very large effect on the overall biomass trend (Annex Figure 10.3.1), mostly due to the revisions and extensions of the catch history, inclusion of new CPUE time series, and updated catch at length data. The estimated biomass followed nearly the same trajectory, however it was lower throughout the time series. Recruitment was lower throughout the time series, however the fluctuations were nearly the same.

Update to 2014 region/fishery structure

Changing to the new region/fishery structure had a smaller effect on the model's biomass trends than did the inclusion of new data. In general the change to the 2014 structure showed similar but higher biomass throughout the time series until 2000, when the trend decreased below the previous stepwise change.

Update to reference case

The last major update to the model that resulted in the reference case was the cessation of estimating the last 4 recruitment deviates, with recruitment for these periods determined directly from the stock recruitment relationship. This resulted in a nearly identical biomass trajectory as the previous step, with the exception that recruitment and biomass 'spike' at the end when the last four recruitment deviates are estimated.

6.5.2 One-off changes to the reference case

Comparisons of the recruitment and spawning potential trajectories for the reference case and one-change sensitivity runs from the structural uncertainty analysis are provided in **Figure 37**. The key reference points and likelihood components are compared in **Table 7** and

Table 8. Kobe plots are provided in **Figure 38** and

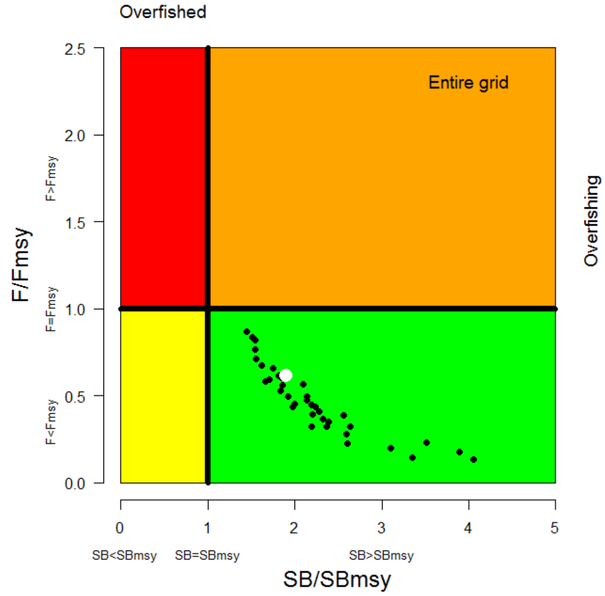

Figure 39.

6.5.3 Growth (G)

Growth was parameterized in the reference case based on the 2010 estimation; one-change sensitivities to the reference case included direct estimation, and the Tanabe et al. estimates. The estimated growth curve resulted in estimates similar to the reference case F_{latest}/F_{MSY} (Ref.case=0.62, G_est=0.60), and SB_{latest}/SB_{MSY} (Ref.case=1.81, G_est=1.85) while the Tanabe parameterization resulted in higher levels of SB_{latest}/SB_{MSY} (Ref.case=1.81, G_Tanabe=2.56) and lower F_{latest}/F_{MSY} (Ref.case=0.62, G_est=0.39). The one-change model parameterized with the Tanabe growth curve is the most optimistic of all the one-change runs.

6.5.4 Weight to the size data (SZ_dw)

Down-weighting the size data had little impact on the current assessment with slightly higher levels of SB_{latest}/SB_{MSY} (Ref.case=1.81, SZ_50=1.86) and lower F_{curr}/F_{MSY} (Ref.case=0.62, SZ_50=0.56). Spawning potential was slightly higher than the reference case (**Figure 37**).

6.5.5 Steepness (h)

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

The reference case was parameterized with a steepness of 0.8, and sensitivities of 0.65 and 0.95 were run. The steepness sensitivities provided the most pessimistic (h=0.65) and second-most optimistic (h=0.95) results in terms of *MSY* (1,334,400 mt versus 1,724,400mt) and stock status. The impact of steepness on stock status based on the $SB_{latest}/SB_{F=0}$ reference point (Ref.case 0.48, $h_{0.65}$=0.46, $h_{0.95}$ =0.5) was much less than it was on the *MSY* quantities $F_{current}/F_{MSY}$ (Ref.case=0.62, $h_{0.65}$=0.84, $h_{0.95}$ =0.45) and SB_{latest}/SB_{MSY} (Ref.case=1.94, $h_{0.65}$=1.51, $h_{0.95}$ =2.19).

6.5.6 Tag mixing

One alternative tag mixing scenario was examined – comparing tag mixing of two quarters with the Ref.case of one quarter.

The longer tag mixing period had minimal impact on MSY, but resulted in a slightly more optimistic stock status indicators, with slightly higher levels of SB_{latest}/SB_{MSY} (Ref.case=1.81, Mix_2=1.84) and lower F_{curr}/F_{MSY} (Ref.case=0.62, Mix_2=0.53).

6.5.7 Structural uncertainty analysis

Comparisons of the impacts of different axes of the structural uncertainty analysis are shown in two ways, first through a series of Kobe plots which show $F_{current}/F_{MSY}$ and SB_{latest}/SB_{MSY} with colour coding for each option within the axes (**Figure 40**), and second through a series of box and whisker plots (**Figure 41** and **Figure 42**).

The general patterns for each option within the five axes are the same as described in Section 5.3 so we do not repeat them here. The positive (or negative) impacts of the different options were found to be somewhat additive, e.g., model runs with more options that individually gave better outcomes gave even better outcomes when combined.

6.5.8 Other model runs

As an exploratory run, an alternative model formulation using age- and season-specific movement rates based on SEAPODYM (Lehodey et al, 2001) was undertaken to test the plausibility of using ecosystem model output in the place of internal estimation. The model using SEAPODYM input results in similar terminal biomass levels (**Figure 43**) and reference quantities (SB_{latest}/SB_{MSY}: Ref.case=1.81, SEAPODYM=1.82, Fcurr/F_{MSY}: Ref.case=0.62, SEAPODYM =0.77). However, the run using the SEAPODYM output indicated a >50% reduction in the spawning potential since 1999. The use of the SEAPODYM movement parameters greatly degraded the likelihood and so this model was not included in the uncertainty grid. It is, however, an area for continued research.

7 DISCUSSION AND CONCLUSIONS

The gap between the 2014 and 2011 assessments is the longest gap between skipjack assessments in the past ten years (assessments were completed in 2005, 2007, 2008, 2010 and 2011). Significant changes and improvements have been made to the 2014 assessment based on many of the skipjack-relevant recommendations from the Independent Review of the 2011 bigeye assessment (Ianelli et al., 2012),. In Section 7.1 we will comment on some of the most significant changes to the assessment, and some of the similarities. We will also touch briefly on some of the problems encountered or areas of uncertainty, but these will be covered in more detail in Sections 7.2 and 7.3.

7.1 Changes from the 2011 assessment

The 2010 and 2011 assessments concluded that the skipjack stock was not overfished with $F_{current}/F_{MSY}$ in the order of 0.34 and 0.37, respectively, while the current assessment estimates $F_{current}/F_{MSY}$ = 0.62. All three assessments were characterized with an increase in recruitment around 1980 and approximately the same trajectory of the spawning potential. In general the conclusions from the 2014 stock assessment are consistent with those from previous assessments.

The biggest change to the 2014 assessment was the subdivision of model regions to bring the assessment to a 5 region model with 23 fisheries. This was done in response to several recommendations of the bigeye review that had relevance for skipjack and to address data conflicts that had been noted in the 2011 assessment. Given the uncertainty, and often significant revisions that occur with catch statistics from Indonesia, the Philippines, and likely

Vietnam in the future, separation of this area should help isolate the impact of these changes on the estimated dynamics in other regions.

The separation of the region that generally encompasses the Coral, Bismarck and Solomon Sea's (region 5) was done partly in response to the analysis of Hoyle et al. (2013) which found that skipjack tagged in this area appeared to mix less than fish tagged in the wider region 2 area. Another motivation for splitting was because the purse seine fishery in region 5 has clearly different fishing power to the region fisheries, complicating the analysis of management options when these fisheries are combined.

Considerable improvements were made to the size and CPUE inputs in response to the independent review. Two new standardised CPUE series for region 4 and 5 (Bigelow et al. 2014; Pilling et al. 2014) were use to inform biomass trends in these regions. The purse seine size data were subject to considerable improvements and, along with the additional subregions, likely reduced the conflict in these data such that the sensitivity analysis with the data down weighted had much less impact on the results. There were some examples of lack of fit to size data, such as the poor fit to size data from the longline and miscellaneous fisheries, which we will discuss in the following sections.

Following the detailed evaluation of the tagging data and modelling requirements by Hoyle et al., (2013), considerable effort was directed at all aspects of the tagging data from the initial data selection criteria to the reporting rate priors. This work will need to continue.

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

7.2 Sources of uncertainty

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

Due to delays in the finalization of data from the most recent year, the three tropical tuna assessments used data up until 2012 instead of 2013 as would normally be the practice. For such short lived species such as tunas, this can lead to a mismatch between information on stock status from the assessment, management actions, and the actual stock status on the water. This year the 2013 data was only 'finalized' at the end of the first week of July and is expected to be subject to revision after SC10 (P. Williams pers. comm.). Purse seine catch estimates, which depend on observer data, are also impacted by incomplete data and subject to revision. It is important to note that the longline data used for the final year of the 2011 assessments was subsequently revised considerably, but the assessments, with incorrect data, had to be used for evaluation of management options.

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

Pole-and-line CPUE data are one of the most important drivers of the skipjack stock assessment; however with the continuing decline of the Japanese pole-and-line fleet particularly in the tropical regions, the ongoing reliance on this fleet to provide a suitable index of skipjack abundance will become increasingly problematic.

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

Finally, one area of reduced uncertainty in the current assessment has been impact of steepness on the spawning potential reference point. The previously used reference point of SB/SB_{MSY} was extremely sensitive to the assumed value of steepness, but the new limit reference point $20\%SB_{F=0}$, is far less sensitive to this (**Table 7**). There is however a new issue to be addressed, which is that of how to present stock status information in the light of the newly adopted limit reference point. The terms of overfished and overfishing are also open to reconsideration, as is the Kobe plot. We see this as an important task for the SC in determining how best to communicate stock assessment results to the Commission. This issue was first raised at MOW2 in the paper also submitted to SC10 (McDonald 2014) and we attempt to further stimulate discussion on this issue with our new figure provided as **Figure 36**.

7.3 Recommendations for further work

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

WCPFC recommendations

- WCPFC continue the evaluation of E-reporting initiatives for both logbook and observer data and implement these with urgency where it is found to be practical and cost-effective. This will allow stock assessments to be undertaken with up to date data;
- WCPFC should consider the potential impacts of changes in purse seine effort reporting by some fleets on: stock assessments, evaluation of management measures, and the ability of management measures to achieve their desired outcomes.

Biological studies

- Growth investigation: Modelling fisheries at a smaller spatial and temporal scale may allow better estimation of growth rates from length frequency modes, and potentially regional patterns in growth where samples are sufficient. Analyses of length increment data from tagging may provide information about spatial and temporal growth variation, and the integration of such data into MULTIFAN-CL may assist in better estimation of growth.

- Continued tagging across the range of the stock (associated with tag seeding work where necessary) to support the ability of tagging data to improve estimates of growth, natural mortality, movement, and fishing mortality. Analyses of these data to inform mixing periods and spatial structure should continue.

MULTIFAN-CL/Modelling

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

CPUE

- Review the recommendations of Hoyle et al. (2014a; 2014b) in the future development and presentation of CPUE analysis.
- As noted in the 2011 assessment this and recent skipjack assessments have used standardized CPUE from the Japanese pole-and-line fisheries as the key index that drives estimated abundance trends. This fishery now makes up less than 4% 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. We still have a limited understanding of the factors driving the patterns observed in these data. Recent analyses have made significant progress and we encourage further analysis as a high priority. The aim should be to work towards a stable protocol that can be carried forward with little extra cost.
- As noted in the 2011 assessment the purse seine fishery dominates equatorial catches, but progress has been slow in understanding the factors impacting its CPUE. An index of abundance based on this major fishery is desirable, but there are difficulties. Technologies change constantly, catchability increases rapidly, and it is difficult to define the unit of effort when fish aggregating devices are involved. Research in this area would be very rewarding if successful, but is high risk and would be difficult to apply to long term abundance indices. This assessment uses two shorter purse seine CPUE series for the additional regions and continued work on these CPUE series is warranted.

Reference points

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

7.4 Main Conclusions.

The main conclusions of the current assessment are consistent with recent assessments presented in 2010 and 2011. The main conclusions are as follows:

1. A fluctuating but consistently high level of recruitment since the early 1970s has supported a robust fishery in all regions. The analysis suggests that the regional declines in spawning potential, in all regions except region 1, are being driven primarily by the fishing impacts.
2. Although the ratio of exploited to unexploited spawning potential is estimated to have declined, with some fluctuations, throughout the model period, the average total biomass of the last five years is estimated to be above the average total biomass of the first five years of the model.
3. Latest catches slightly exceed the maximum sustainable yield (*MSY*).
4. Fishing mortality for adult and juvenile skipjack tuna is estimated to have increased continuously since the beginning of industrial tuna fishing, but fishing mortality still remains below the level that would result in the MSY.
5. Recent levels of spawning potential are well above the level that will support the *MSY*.
6. The estimated 2011 level of spawning potential represents approximately 52% of the unfished level, and is well above the limit reference point of 20%$SB_{F=0}$ agreed by WCPFC.
7. Recent levels of spawning potential are in the middle of the range of candidate biomass-related target reference points currently under consideration for skipjack tuna, i.e., 40-60% $SB_{F=0}$.
8. Stock status conclusions were most sensitive to alternative assumptions regarding steepness and growth. However the main conclusions of the assessment are robust to the range of uncertainty that was explored.

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Table 1. 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
1. P-ALL-1	Japan	Pole-and-line	1
2. S-ALL-1	Japan	Purse seine	1
3. L-JPN-1	Japan	Longline	1
4. P-ALL-2	All	Pole-and-line	2
5. S-ASS-ALL-2	All	Purse seine, log/FAD sets	2
6. S-UNA-ALL-2	All	Purse seine, school sets	2
7. L-JPN-2	Japan	Longline	2
8. P-ALL-5	All	Pole-and-line	5
9. S-ASS-ALL-5	All	Purse seine, log/FAD sets	5
10. S-UNA-ALL-5	All	Purse seine, school sets	5
11. L-JPN-5	Japan	Longline	5
12. P-ALL-3	All	Pole-and-line	3
13. S-ASS-ALL-3	All	Purse seine, log/FAD sets	3
14. S-UNA-ALL-3	All	Purse seine, school sets	3
15. L-JPN-3	Japan	Longline	3
16. Z-PH-4	PH	Miscellaneous small scale gears within PH archipelagic waters	4
17. Z-ID-4	ID	Miscellaneous small-scale gears within ID archipelagic waters	4
18. S-ID.PH-4	PH, ID	Purse seine operating in PH, ID waters, all sets	4
19. P-ALL-4	All	Pole-and-line	4
20. S-ASS-DW-4	All	Purse seine, log/FAD sets	4
21. S-UNA-DW-4	All	Purse seine, school sets	4
22. Z-VN-4	Vietnam	Miscellaneous, including small purse seine and gillnet within VN waters	4
23. L-JPN-4	Japan	Longline	4

Table 2. Summary of the number of release events, tag releases and recoveries by region and program.

Tagging Program	Years Active			Region 1	2	3	4	5	Total
JP	1988	-2012	Release Events	90	59	14	1	0	164
			Effective releases	19766	37364	6476	5	0	63612
			Effective recaptures	1887	1176	28	0	0	3091
PTTP	2006	-2012	Release Events	0	11	5	3	15	34
			Effective releases	0	14795	6582	20517	75615	117508
			Effective recaptures	0	3057	1262	5769	21281	31369
RTTP	1989	-1992	Release Events	0	9	5	7	10	31
			Effective releases	0	10216	10414	17642	32470	70742
			Effective recaptures	0	1434	1277	3500	4831	11042
SSAP	1977	-1980	Release Events	1	7	9	2	3	22
			Effective releases	83	6952	38839	5140	11678	62693
			Effective recaptures	11	287	2566	381	1340	4585

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

Component	2011 assessment	2014 assessment (Run 012_L0W0T0M0)
Data update	Current to 2010	Current to 2012
Regional structure	Three regions	Five regions with one new region added to the western equatorial region and one within region two.
Fishery structure	18 fisheries	23 fisheries due to additional data (VN domestic) and for the new regions
CPUE	Operational indices based on Japanese pole-and-line data.	In addition to the JPN PL CPUE, standardized PS data was included for the new regions (region 4 and region 5)
Purse seine size data	Selectivity bias corrected observer samples	Selectivity bias corrected observer samples plus Pago Pago port sampling data. All weighted by set catch.
Recruitment and spawner recruitment relationship	All deviates estimated and moderate constraint on fitting the SRR curve	Terminal four recruitment deviates not estimated and these and the first 40 recruitment deviates (first 10 years) not included in the estimation of the SRR. Lognormal bias correction applied to the SRR and low penalty on fitting the SRR.

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

#	Fishery	Region	Selectivity	Catchability	Tag recaptures	Tag reporting
1	P-ALL-1	1	1	1	1	1
2	S-ALL-1	1	2	2	2	1
3	L-JPN-1	1	3	3	3	1
4	P-ALL-2	2	4	4	4	1
5	S-ASS-ALL-2	2	5	5	5	2
6	S-UNA-ALL-2	2	6	6	5	2
7	L-JPN-2	2	7	7	6	1
8	P-ALL-5	5	4	8	7	1
9	S-ASS-ALL-5	5	5	9	8	3
10	S-UNA-ALL-5	5	6	10	8	3
11	L-ALL-5	5	8	11	9	1
12	P-ALL-3	3	4	12	10	1
13	S-ASS-ALL-3	3	9	13	11	4
14	S-UNA-ALL-3	3	10	14	11	4
15	L-JPN-3	3	11	15	12	1
16	Z-PH-4	4	12	16	13	5
17	Z-ID-4	4	12	17	14	6
18	S-ID.PH-4	4	5	18	15	7
19	P-ALL-4	4	4	19	16	1
20	S-ASS-DW-4	4	5	20	17	8
21	S-UNA-DW-4	4	6	21	17	8
22	Z-VN-4	4	12	22	18	9
23	L-JPN-4	4	13	23	19	1

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

Run	Name	Description
012_L0W0T0M0	Reference Case	JPN PL CPUE for regions 1,2,3, PH PS-Associated CPUE for Region 4, PNG PS-Associated CPUE for region 5. Size data weighted as nsample/20, steepness fixed at 0.8, growth fixed, mixing period of 1 quarter, terminal 4 recruitments not estimated
001_L0W0T0M1	h=0.65	Steepness = 0.65
006_L1W0T0M0	h=0.95	Steepness = 0.95
019_L2W0T0M0	Mix=2qtr	2 quarter tag mixing period
023_L0W0T0M2	SZ=50	Size weighting =50
032_L0W0T1M0	Tanabe Growth	Alternative growth model
035_L0W1T0M0	Estimate growth	Estimate growth

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

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

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

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

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

Management quantity	Units	Ref.Case	h_0.65	h_0.95	Mix_2	SZ_50
MSY	t per yr	1532000	1334400	1724400	1699200	1619600
C_{latest}/MSY		1.08	1.24	0.96	0.97	1.02
F_{curr}/F_{msy}		0.62	0.84	0.45	0.53	0.56
B_0	t	6281000	6558000	6123000	7112000	7020000
$B_{current}$	t	3615213	3613290	3612585	4374786	4077593
SB_0	t	5940000	6202000	5791000	6699000	6642000
SB_{MSY}	t	1683000	2021000	1393000	1928000	1863000
$SB_{F=0}$	t	6303358	6690474	6082301	7085699	7038653
$SB_{current}$	t	3260579	3258721	3258170	3971998	3684847
SB_{latest}	t	3052995	3050692	3049508	3548468	3469168
$SB_{curr}/SB_{F=0}$		0.52	0.49	0.54	0.56	0.52
$SB_{latest}/SB_{F=0}$		0.48	0.46	0.5	0.5	0.49
SB_{curr}/SB_{MSY}		1.94	1.61	2.34	2.06	1.98
SB_{latest}/SB_{MSY}		1.81	1.51	2.19	1.84	1.86

Table 7 cont.

Management quantity	Units	Ref.Case	Grwt_T	Grwt_est	Grid median	Grid 5%ile	Grid 95%ile
MSY	t per year	1532000	1783600	1552800	1758600	1347000	3051900
C_{latest}/MSY		1.08	0.93	1.06	0.94	0.54	1.23
F_{curr}/F_{msy}		0.62	0.39	0.6	0.45	0.17	0.82
B_0	t	6281000	7464000	6334000	7950000	6253750	13775000
$B_{current}$	t	3615213	5689424	3687267	5231839	3614732	12820772
SB_0	t	5940000	6080000	5992000	6976000	5914500	11640000
SB_{MSY}	t	1683000	1606000	1695000	2028500	1336750	3170000
$SB_{F=0}$	t	6303358	6647970	6604577	7439584	6248094	13194543
$SB_{current}$	t	3260579	4127548	3331749	4341362	3260114	10283313
SB_{latest}	t	3052995	4106077	3138285	4106686	3052419	9798792
$SB_{curr}/SB_{F=0}$		0.52	0.62	0.5	0.58	0.49	0.76
$SB_{latest}/SB_{F=0}$		0.48	0.62	0.48	0.52	0.46	0.73
SB_{curr}/SB_{MSY}		1.94	2.57	1.97	2.27	1.63	3.67
SB_{latest}/SB_{MSY}		1.81	2.56	1.85	2.14	1.53	3.61

Table 8. Details of objective function components for the reference case analysis and sensitivity analyses.

Run	Npars	Total	Catch	Length freq.	Tag	Penalties
Ref.Case	4907	-170692	122	-198130	25989	1321
h_0.65	4907	-170692	122	-198129	25989	1320
Grwt_T	4907	-166915	152	-199180	30589	1512
Grwt_est	4909	-170571	123	-198150	26129	1322
h_0.95	4907	-170692	122	-198130	25990	1320
Mix_2	4907	-176398	31	-198279	20572	1268
SZ_50	4907	-135788	113	-161929	24777	1246

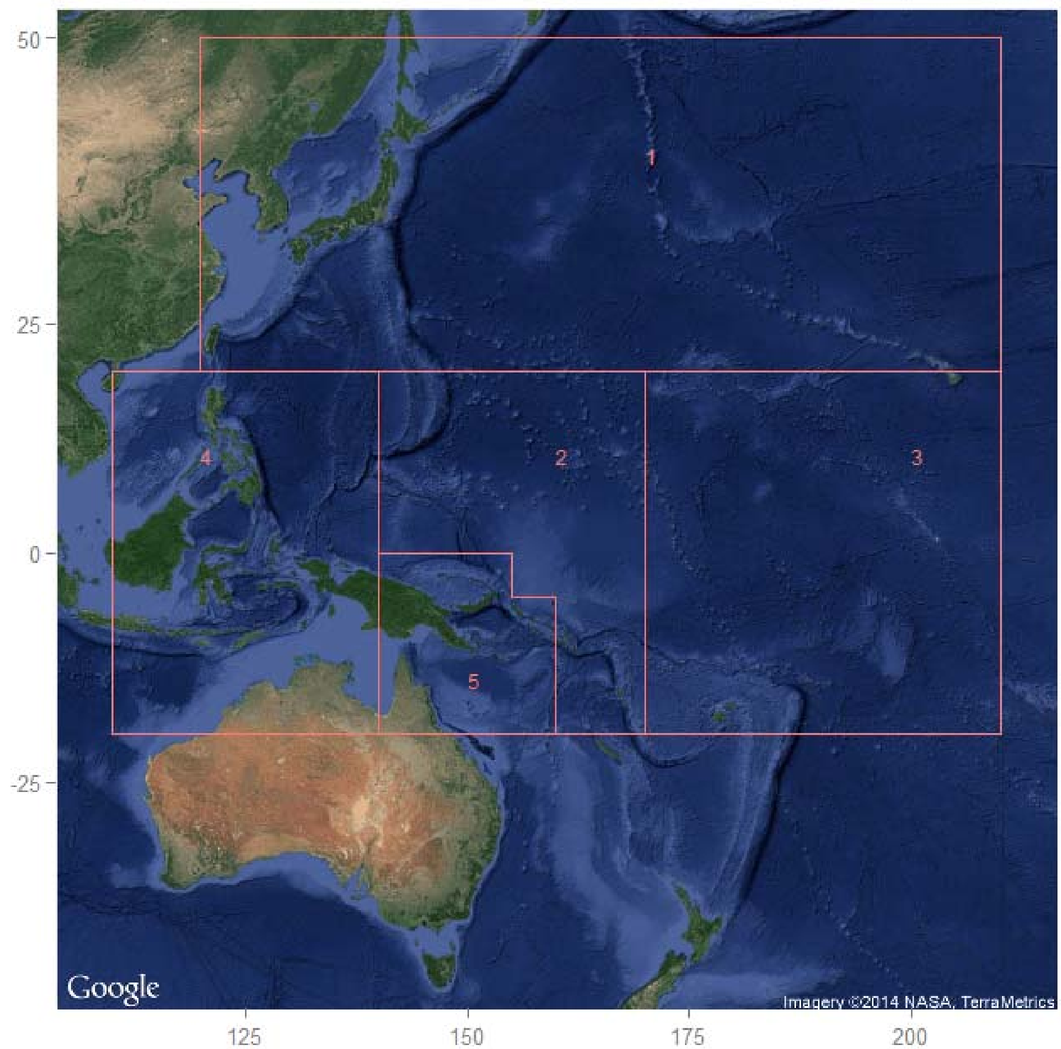


Figure 1. Regional structure of the reference case model.

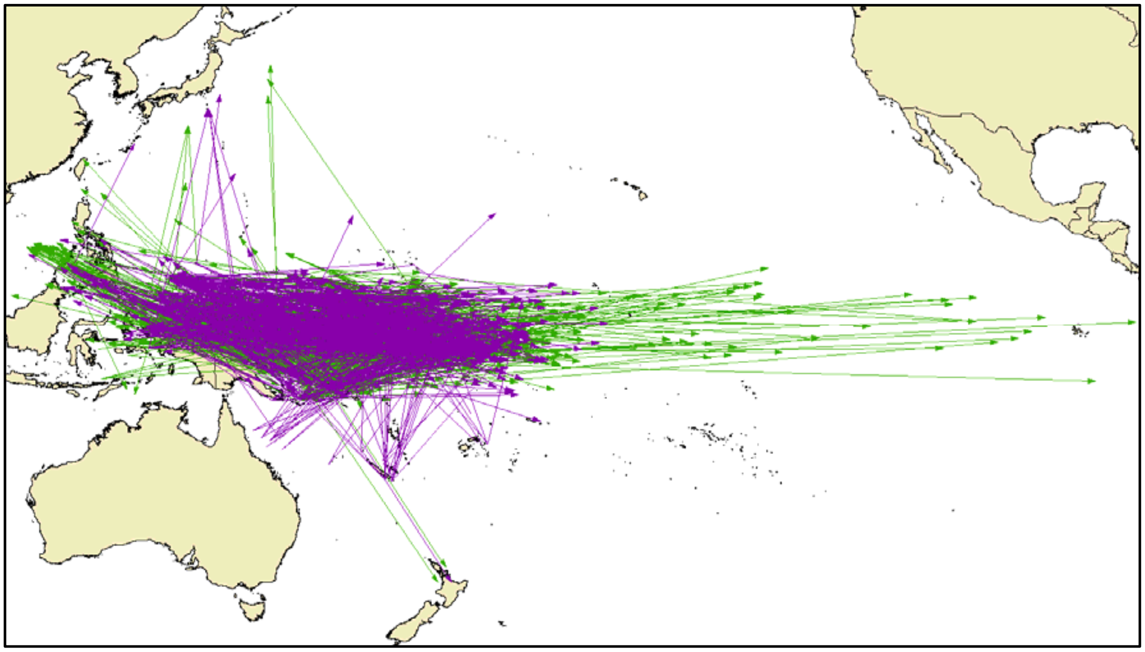


Figure 2. Released and recaptured skipjack from the RTTP (purple arrows) and PTTP (green arrow) tagging programs. Only recaptures >1,000 nautical miles shown.

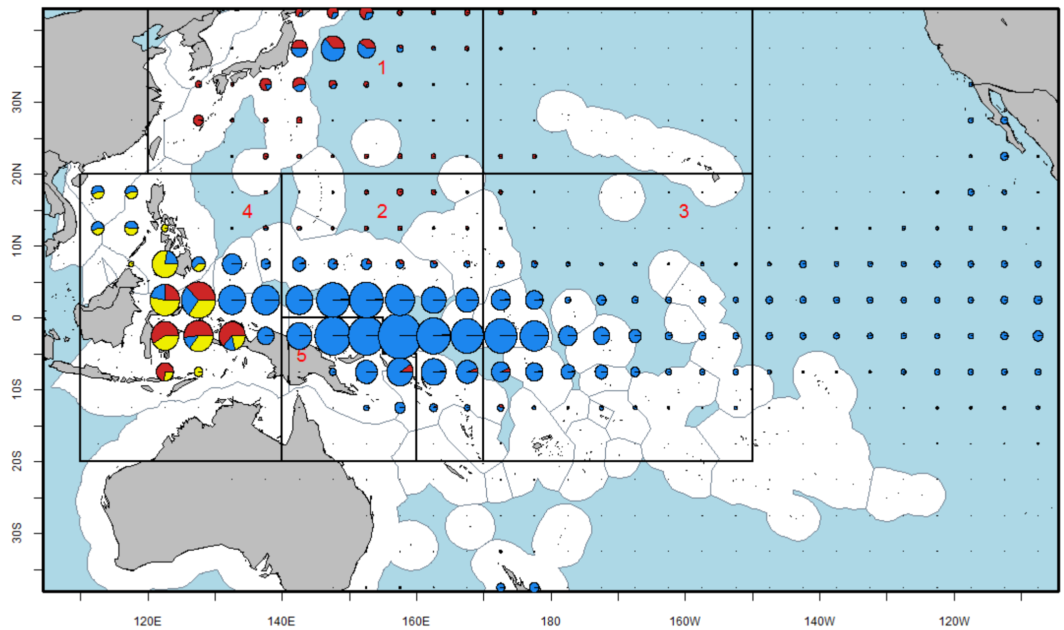


Figure 3. Catch distribution (2003-2012) by 5 degree squares of latitude and longitude and fishing method: longline (green), purse-seine (blue), pole-and-line (red), and other (yellow). Overlayed are the subregions for the assessment model. Note the break at 170 E in Region 1 is incorrect – please see Figure 1 for the correct boundary.

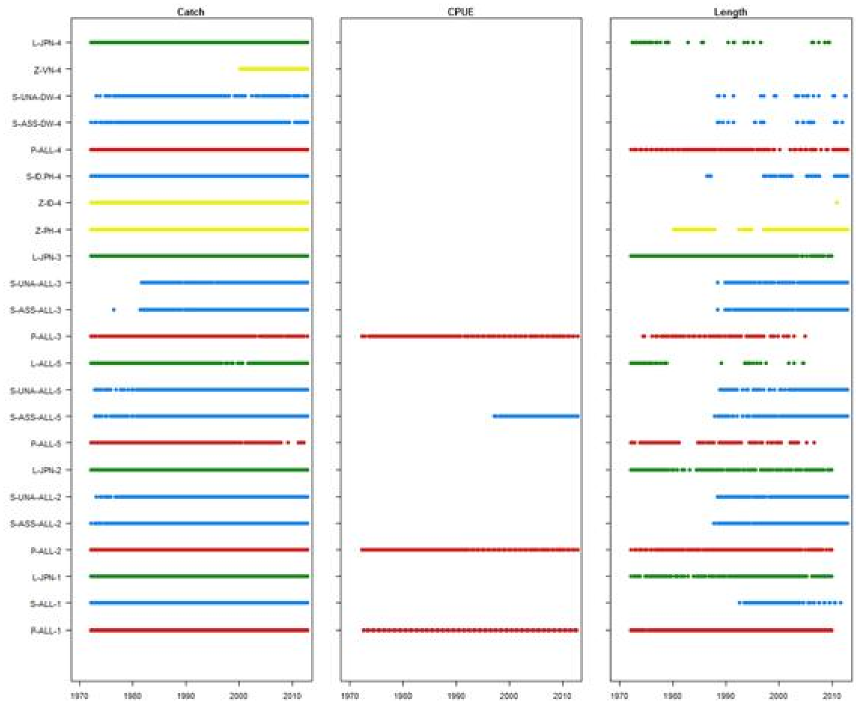


Figure 4. Presence of catch, standardised CPUE, and length and weight frequency data by year and fishery for the reference case model.

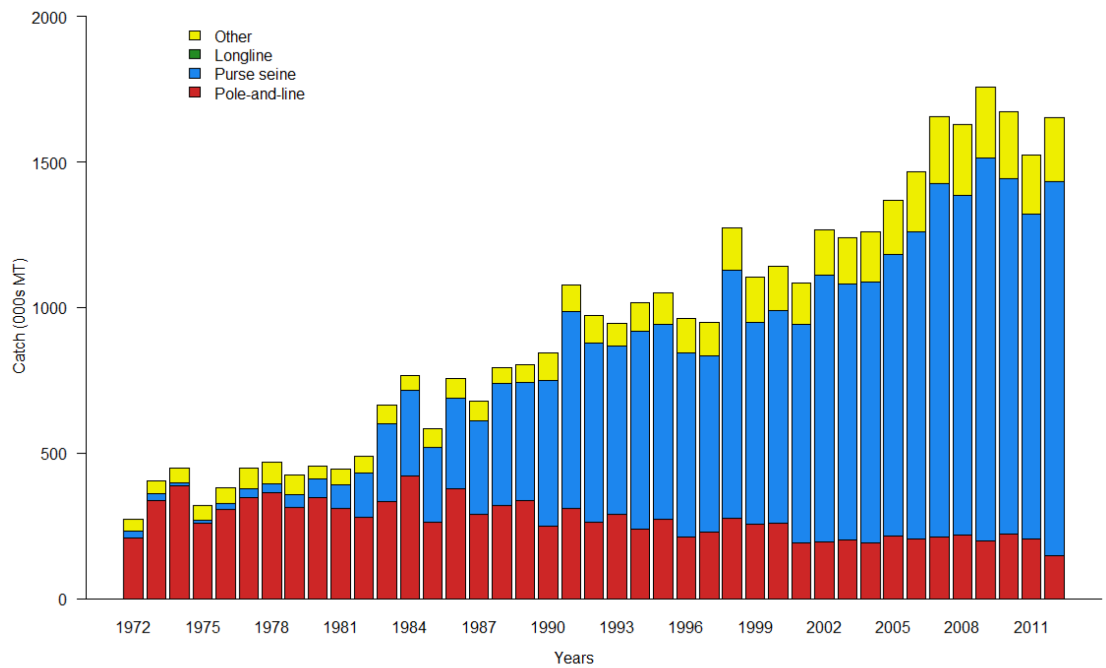


Figure 5. Total annual catch (1000s mt) by fishing gear from the reference case model.

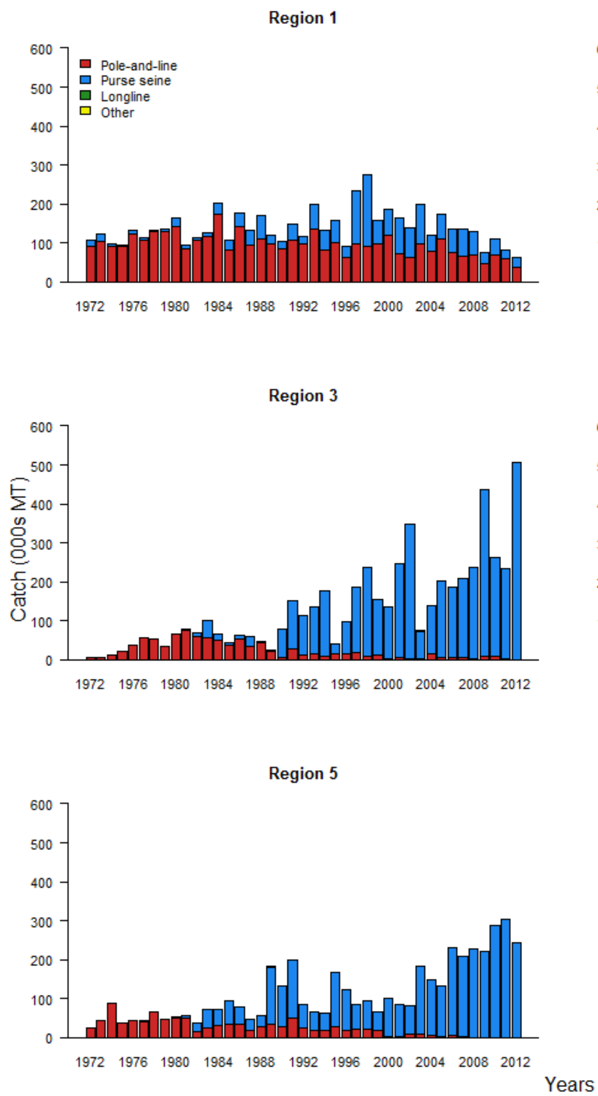


Figure 6. Total annual catch (1000s mt) by fishing method and assessment subregion from the reference case model.

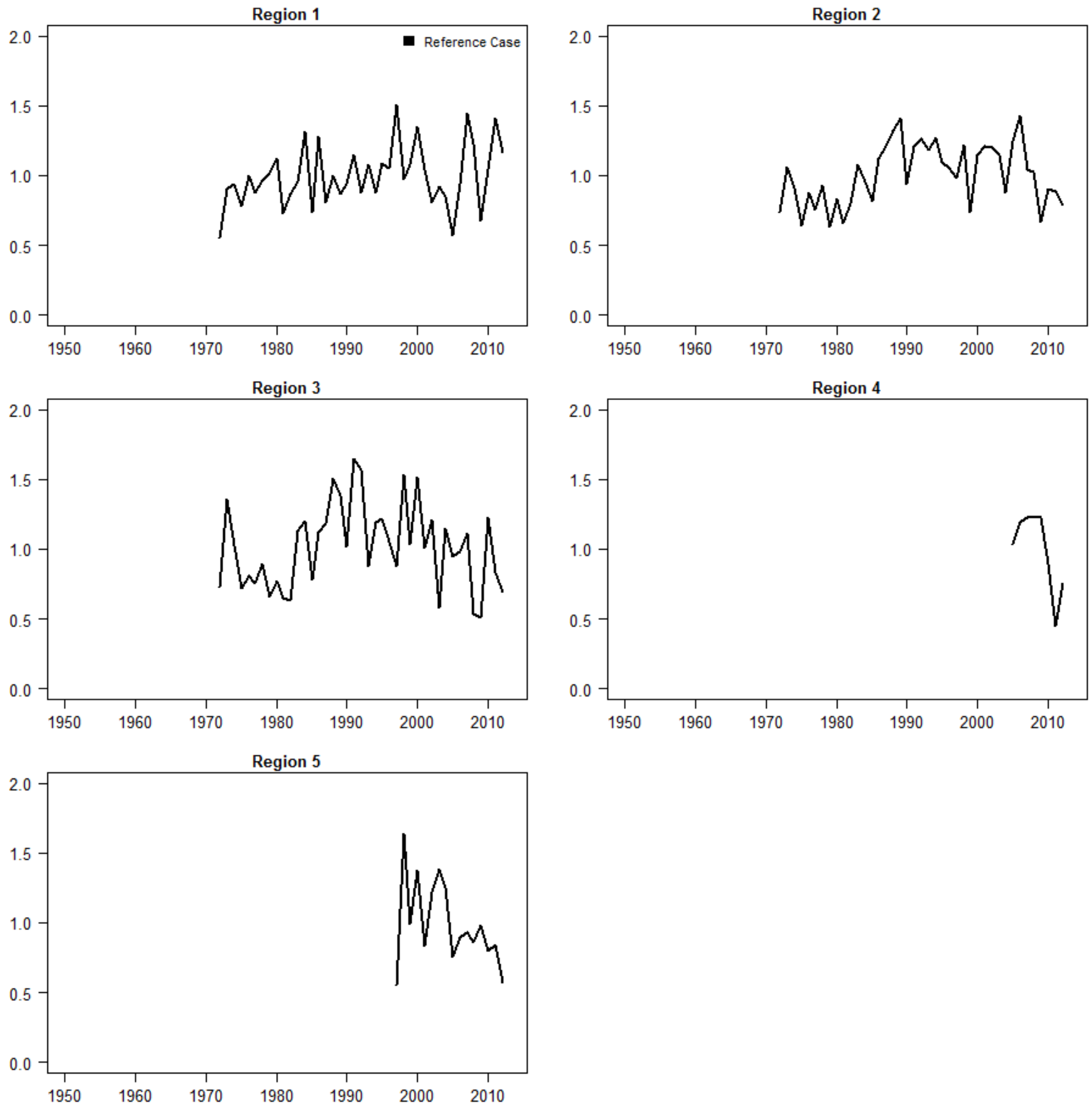


Figure 7. GLM standardised catch-per-unit-effort (CPUE) for the principal fisheries (PL ALL 1–3, and IDPH 4, PS-Assoc 5) from the reference case model. See Bigelow et al. (2014), Kiyofuji et al. (2014) and Pilling et al. (2014) for further details of the CPUE indices.

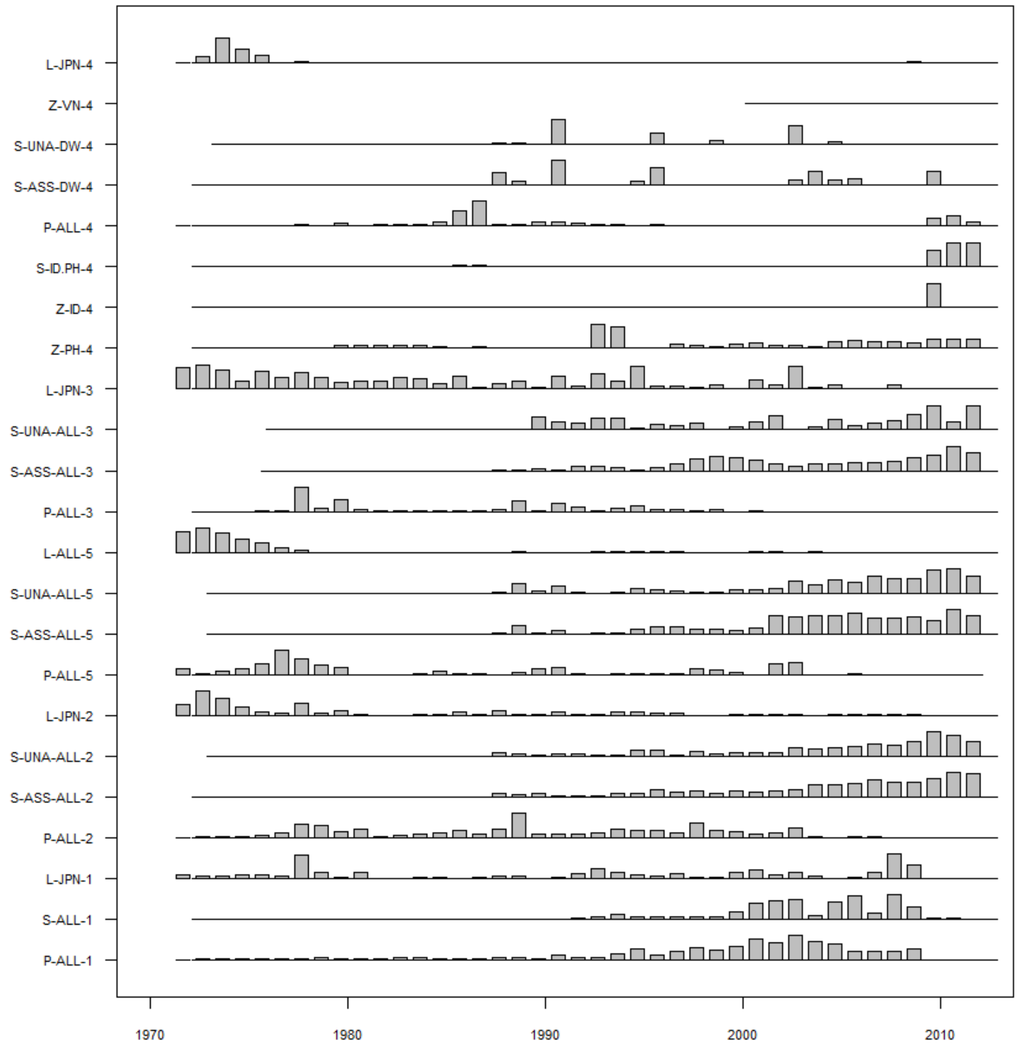


Figure 8. Number of length frequency samples from the reference case model. The maximum value is 160,854, but note that in the reference case model a maximum sample size of 1,000 is allowed.

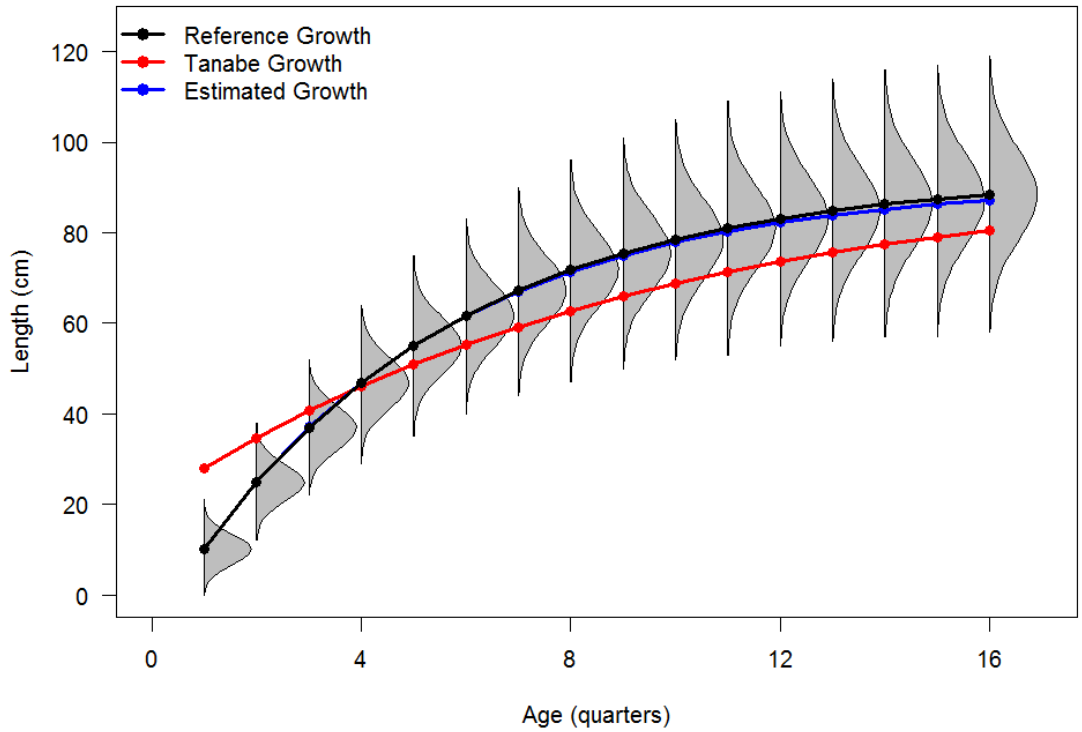
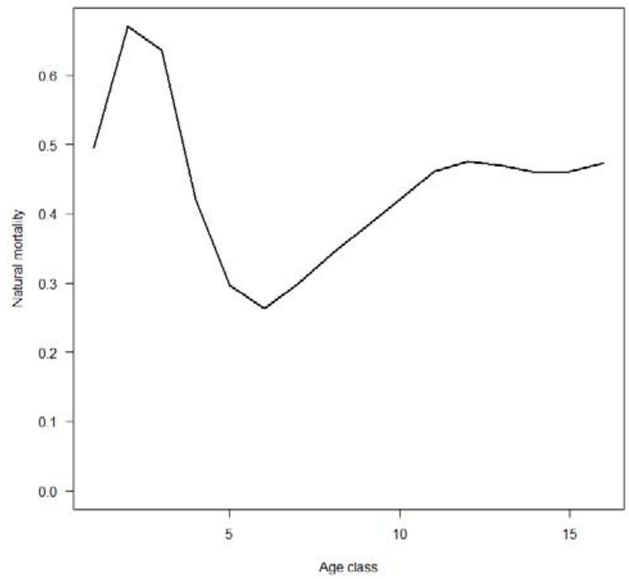


Figure 9. Growth parameterization for the reference case and sensitivities. The black line represents the 2010 parameterization of mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age. For this assessment the length of the oldest age class was fixed at 16 quarters. The red and the blue lines represent the Tanabe and estimated growth curve, respectively.



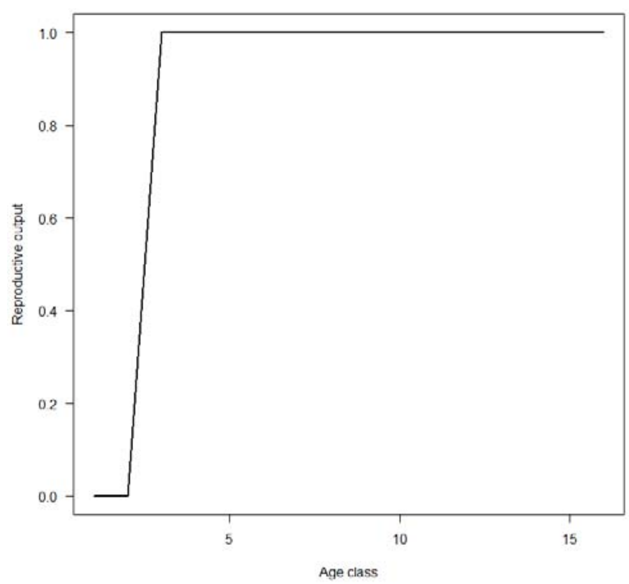


Figure 10. Natural mortality-at-age (top) and % mature (bottom) as assumed in the reference case. Note that estimate of maturity is actually used to define an index of spawning potential incorporating information on sex ratios, maturity at age, fecundity, and spawning fraction (see Hoyle and Nicol 2008 for further details).

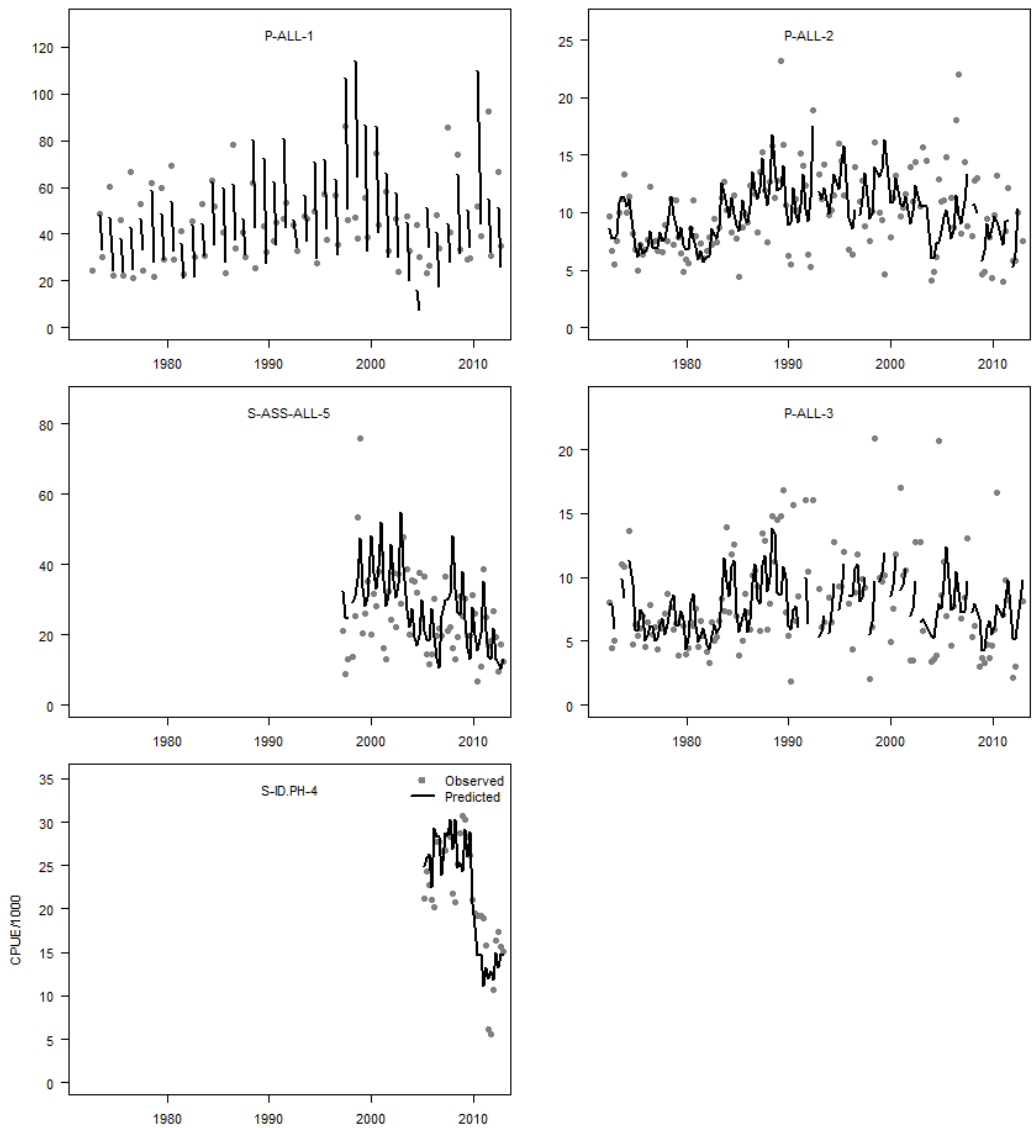


Figure 11. Observed and predicted CPUE for the pole-and-line fisheries in regions 1-3 and the PS fisheries in regions 4 and 5 for the reference case.

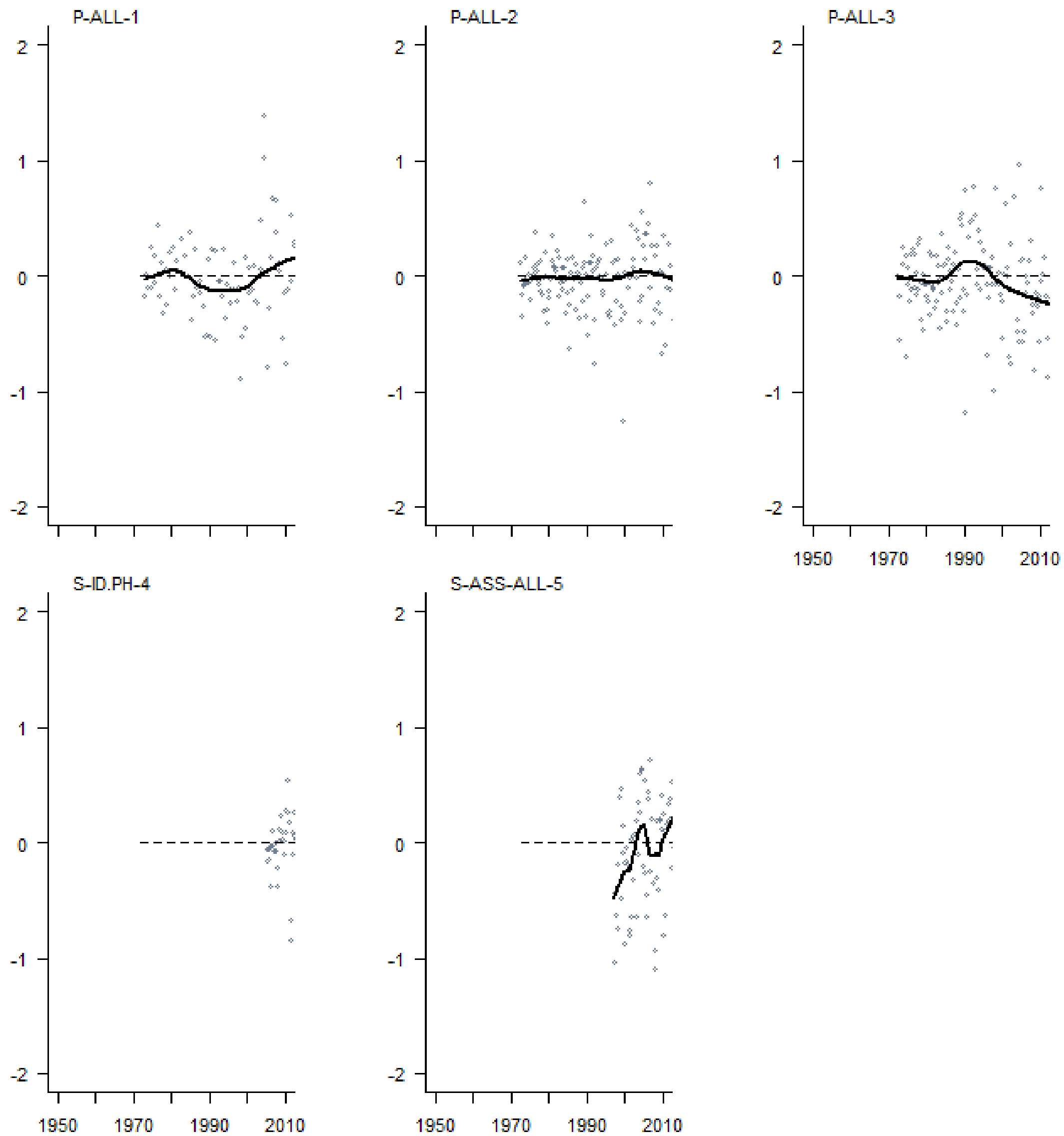


Figure 12. Effort deviations by time period for each LL-ALL fishery for the reference case. The dark line represents a lowess smoothed fit to the effort deviations. Note that Region 4 did not have enough points to fit the lowess smoother.

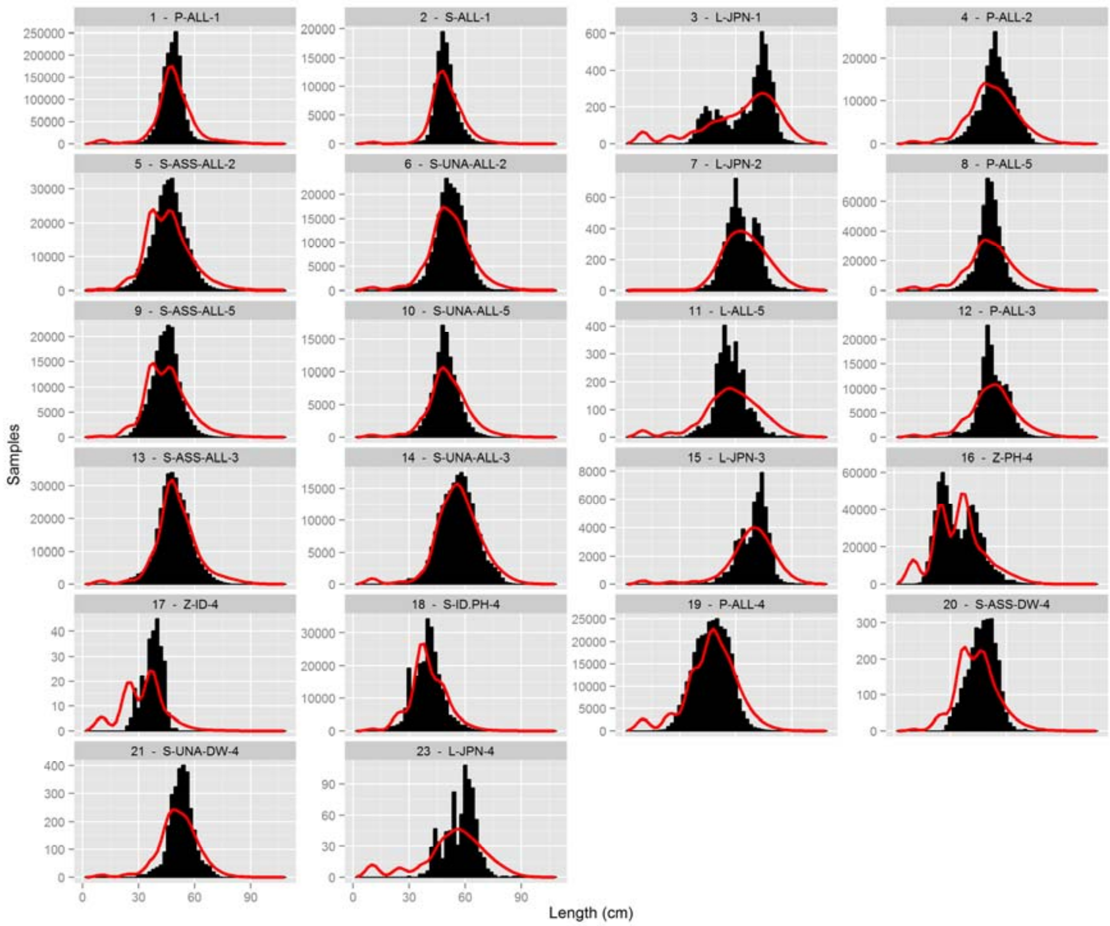


Figure 13. Composite (all time periods combined) observed (black histograms) and predicted (red line) catch at length for all fisheries with samples for the reference case.

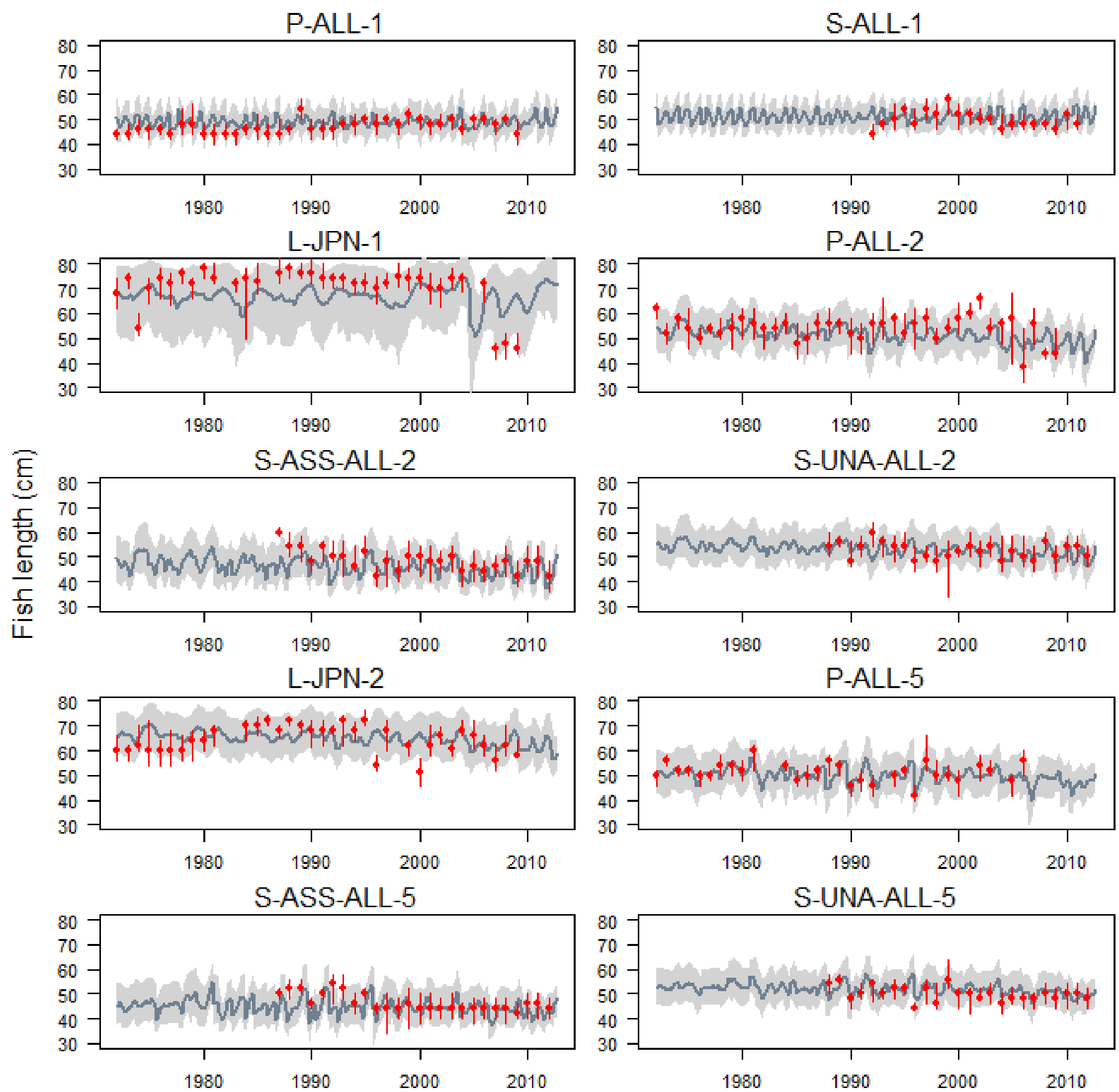


Figure 14. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) for all fisheries with samples for the reference case. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length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

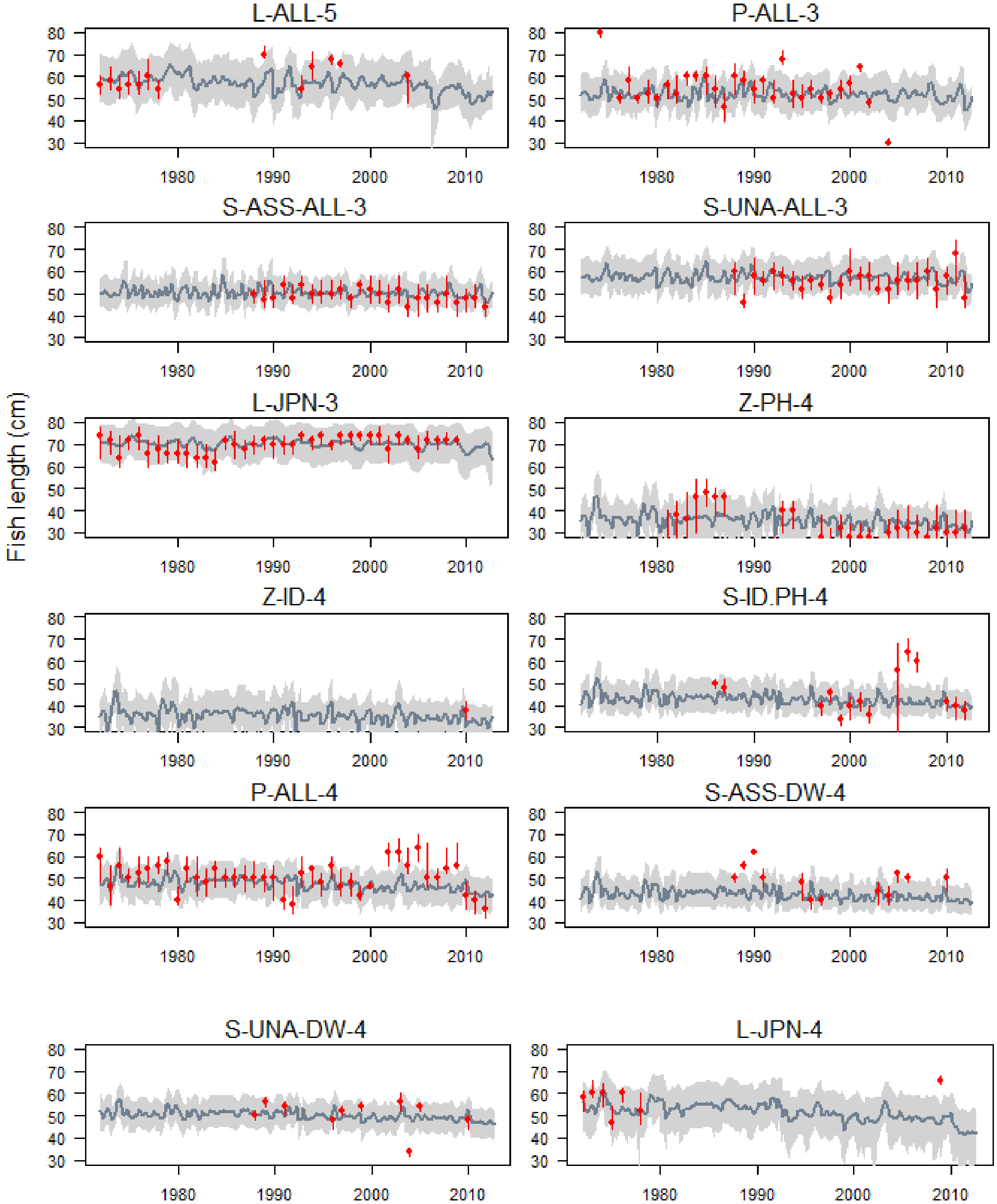


Figure 14. Cont.

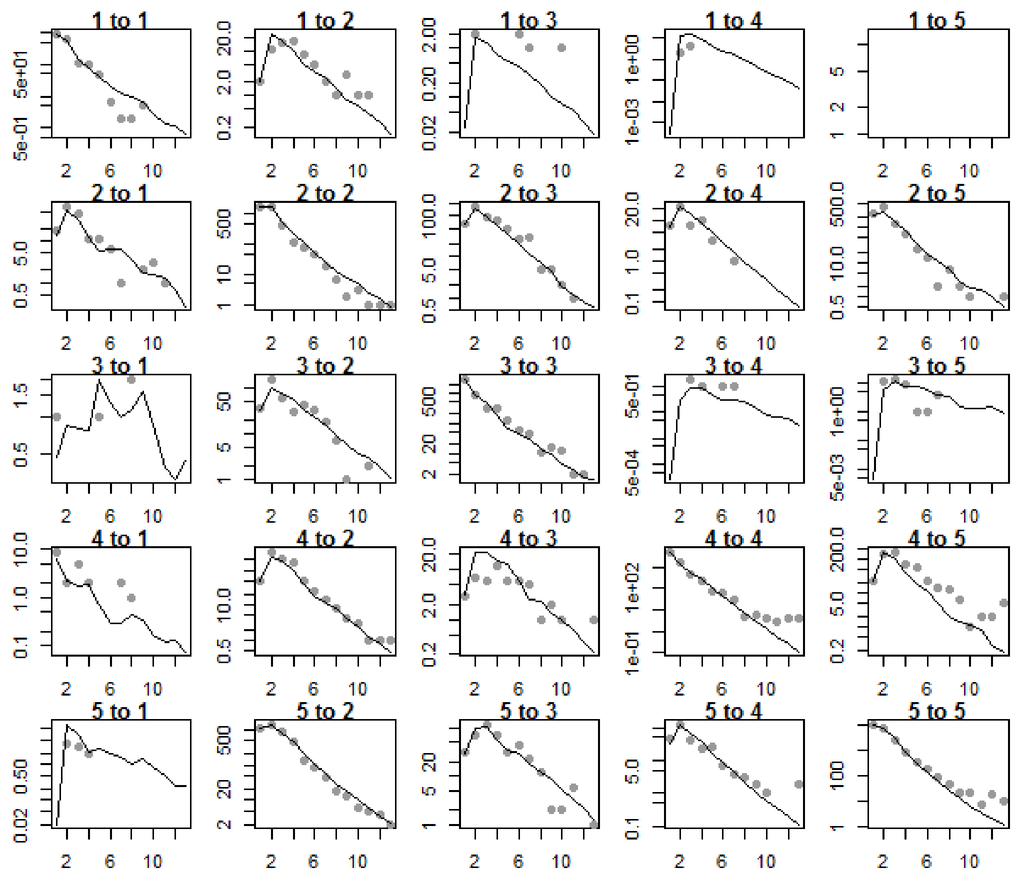


Figure 15. Predicted and observed recaptures of tagged fish by time period at liberty (quarter) from the region of release to the region of recapture.

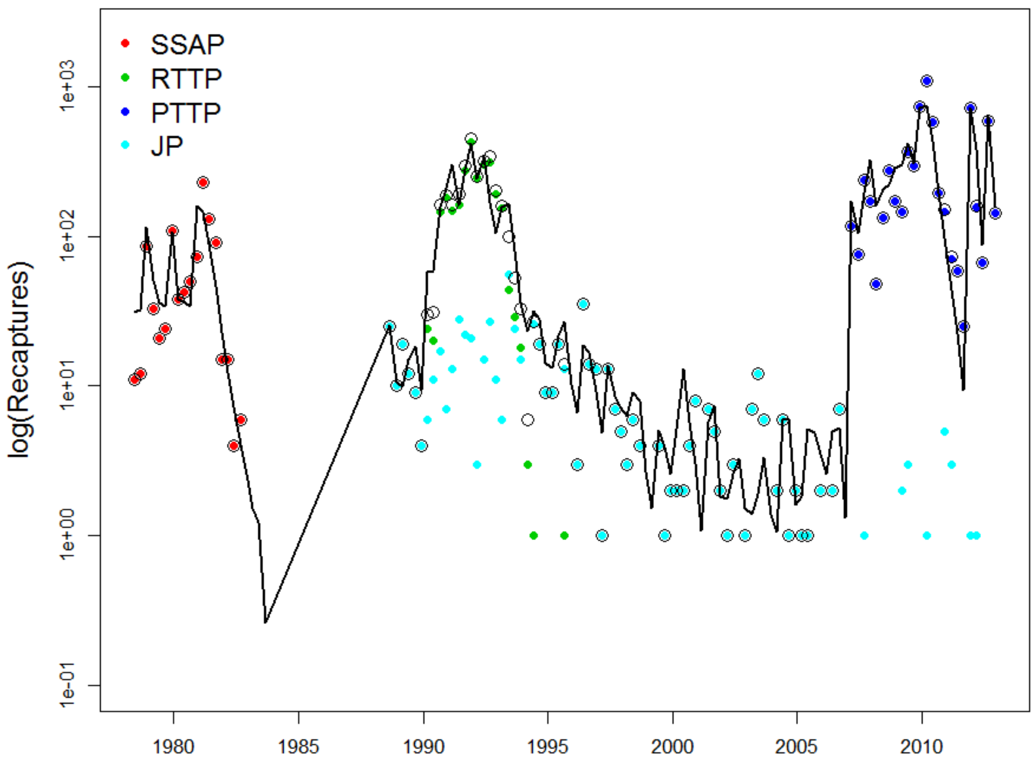


Figure 16. Observed recaptures for the reference case by time period specific to each release program shown by coloured dots: green = RTTP, blue = PTTP red = SSAP, light blue JP. The model (black line) is fitted to the total observed recaptures in a time period (black circles), that are made up of the sum of the program-specific recaptures occurring in that time period, hence a dot and circle will coincide if recaptures are derived from only one program.

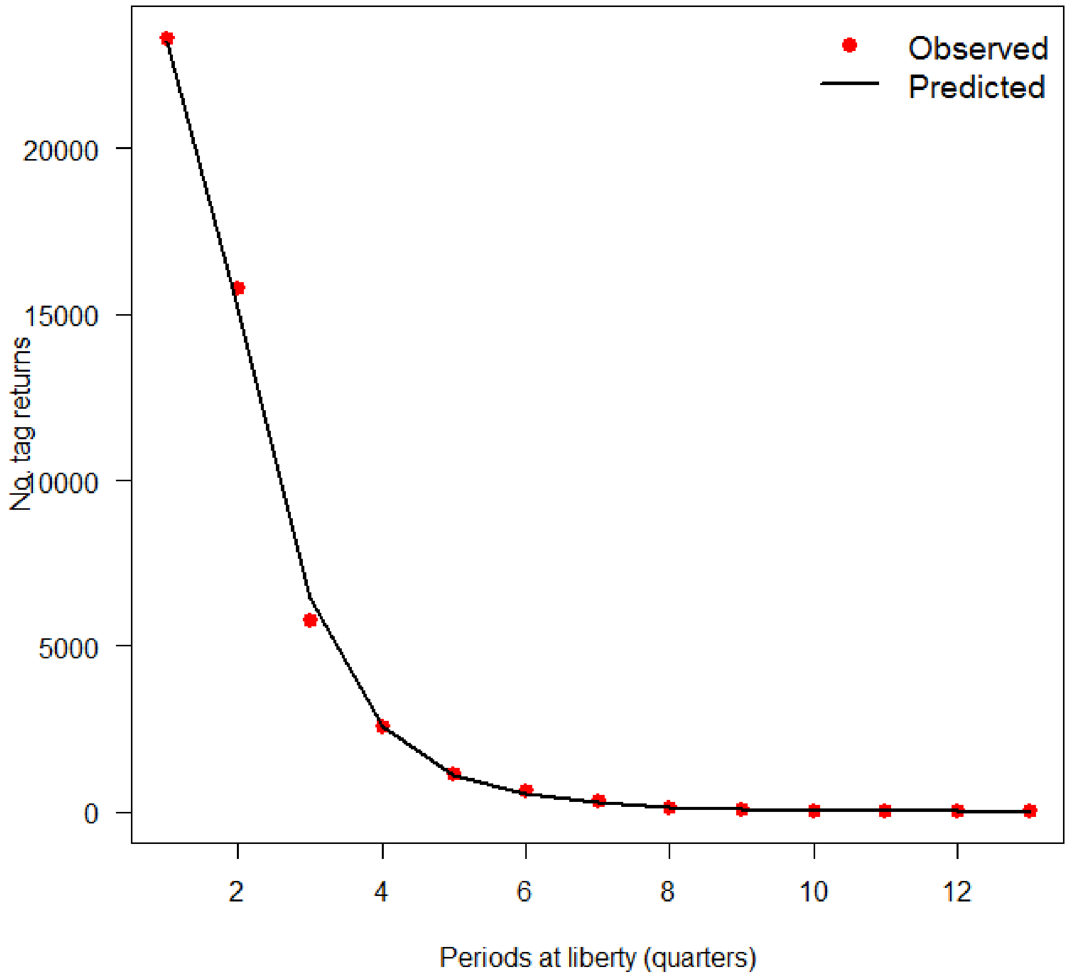


Figure 17. Observed and predicted tag attrition for the reference case across all tag release events.

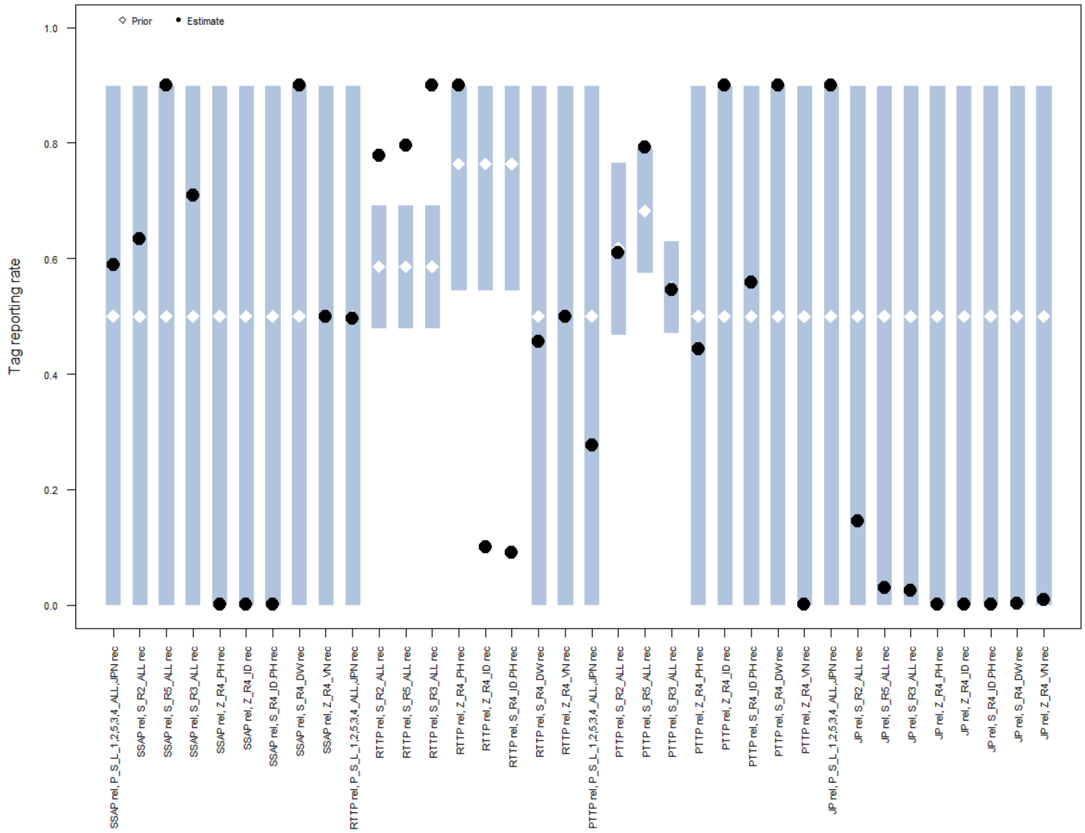


Figure 18. Estimated reporting rates for the reference case. Reporting rates can be estimated separately for each release program and recapture fishery group (histograms). See text for further details of tagging programmes. The prior mean +-1.96 SDs is shown for each reporting rate group as a grey bar.

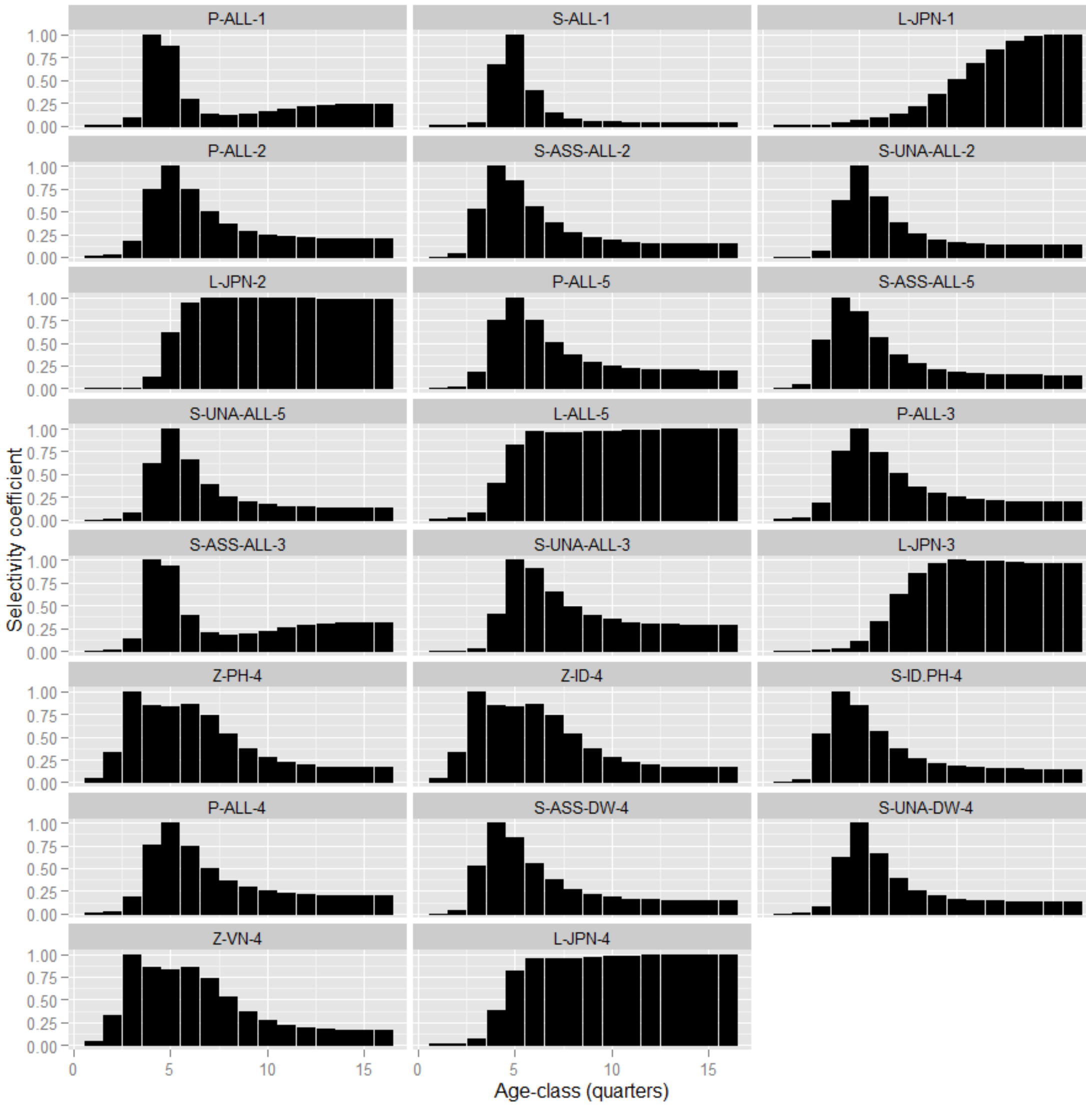


Figure 19. Selectivity coefficients by fishery.

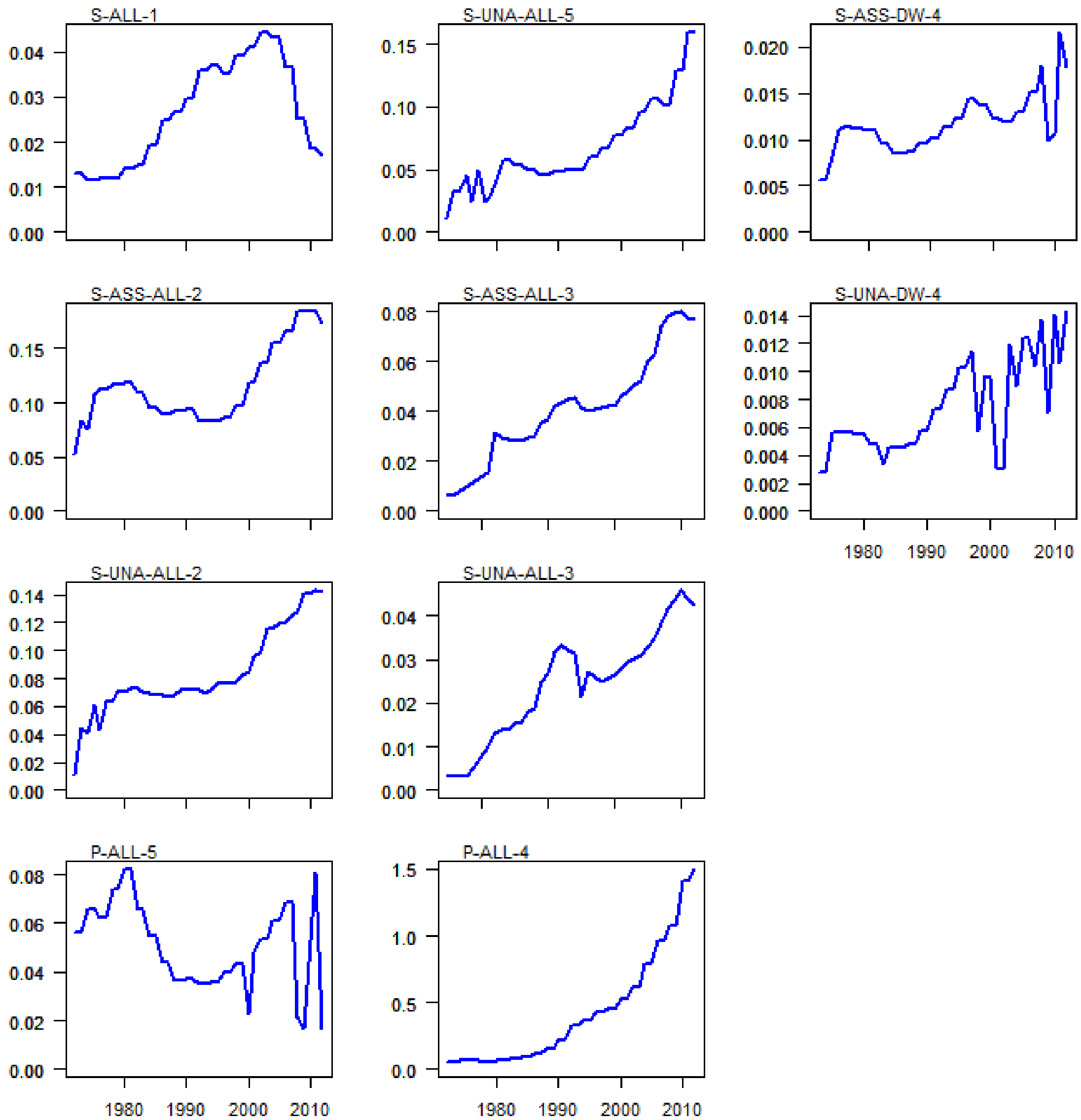


Figure 20. Catchability for fleets that do not have standardized effort .

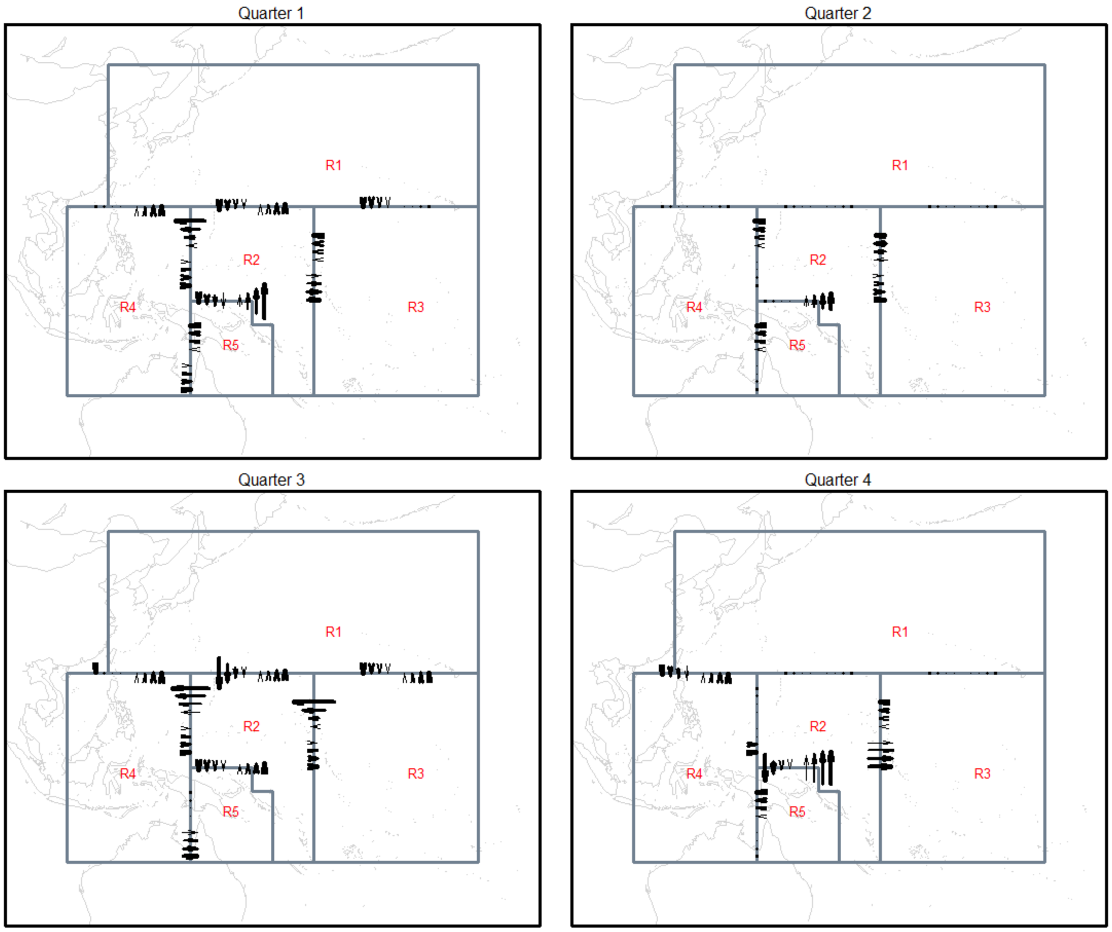


Figure 21. Estimated quarterly movement coefficients for the reference case. The movement coefficient is proportional to the width of the arrow.

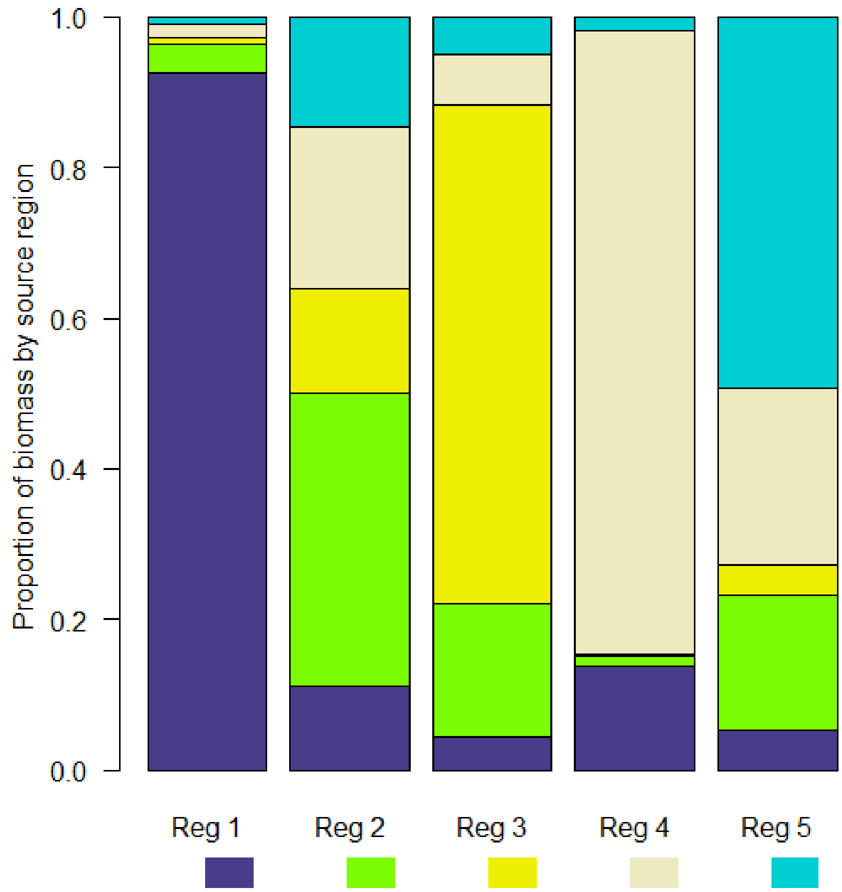


Figure 22. Proportional distribution of total biomass (by weight) in each region apportioned by the source region of the fish for the reference case. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment between regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

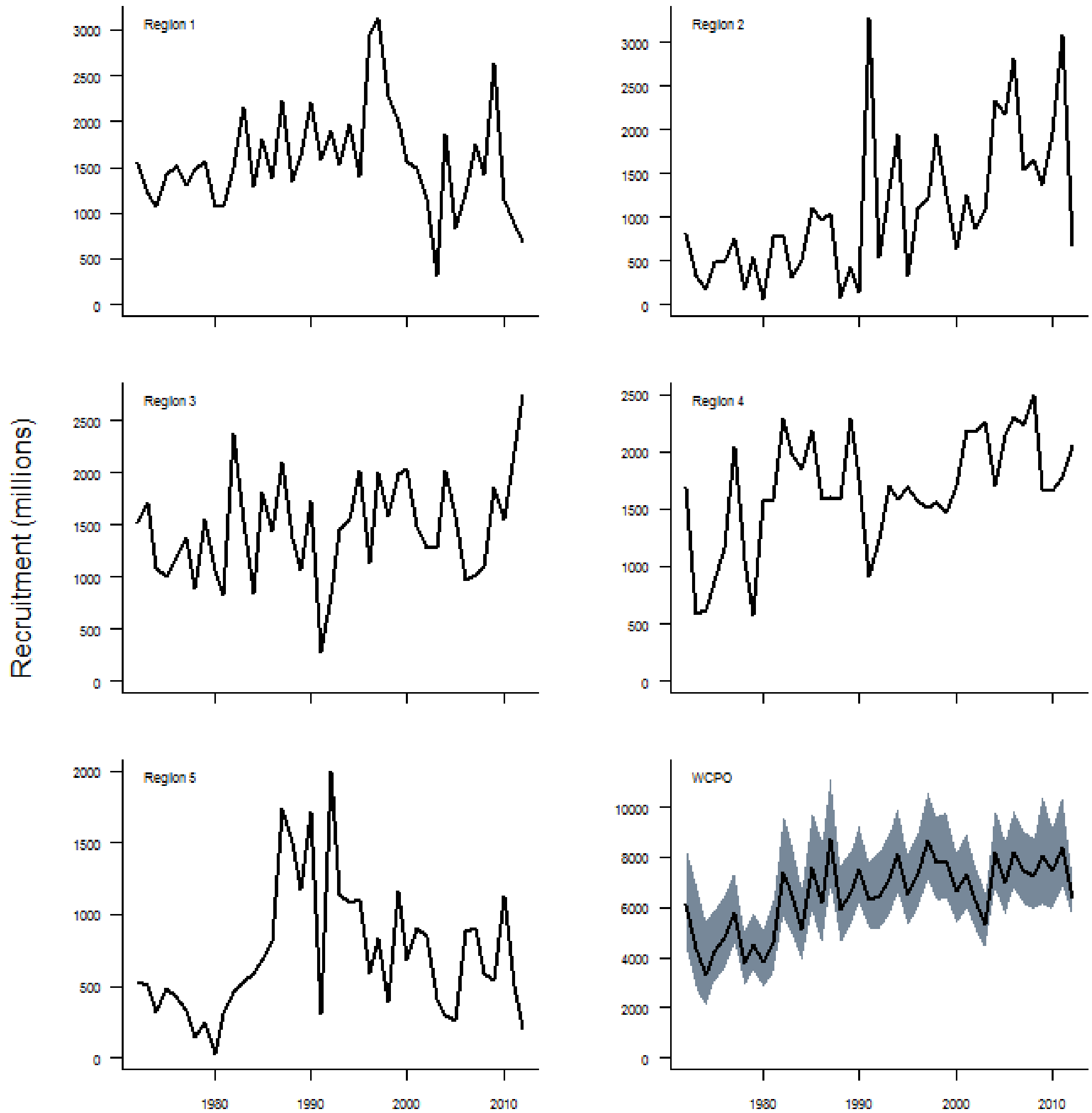


Figure 23. Estimated annual recruitment (millions) by region and for the WCPO for the reference case. The shaded areas indicate the approximate 95% confidence intervals.

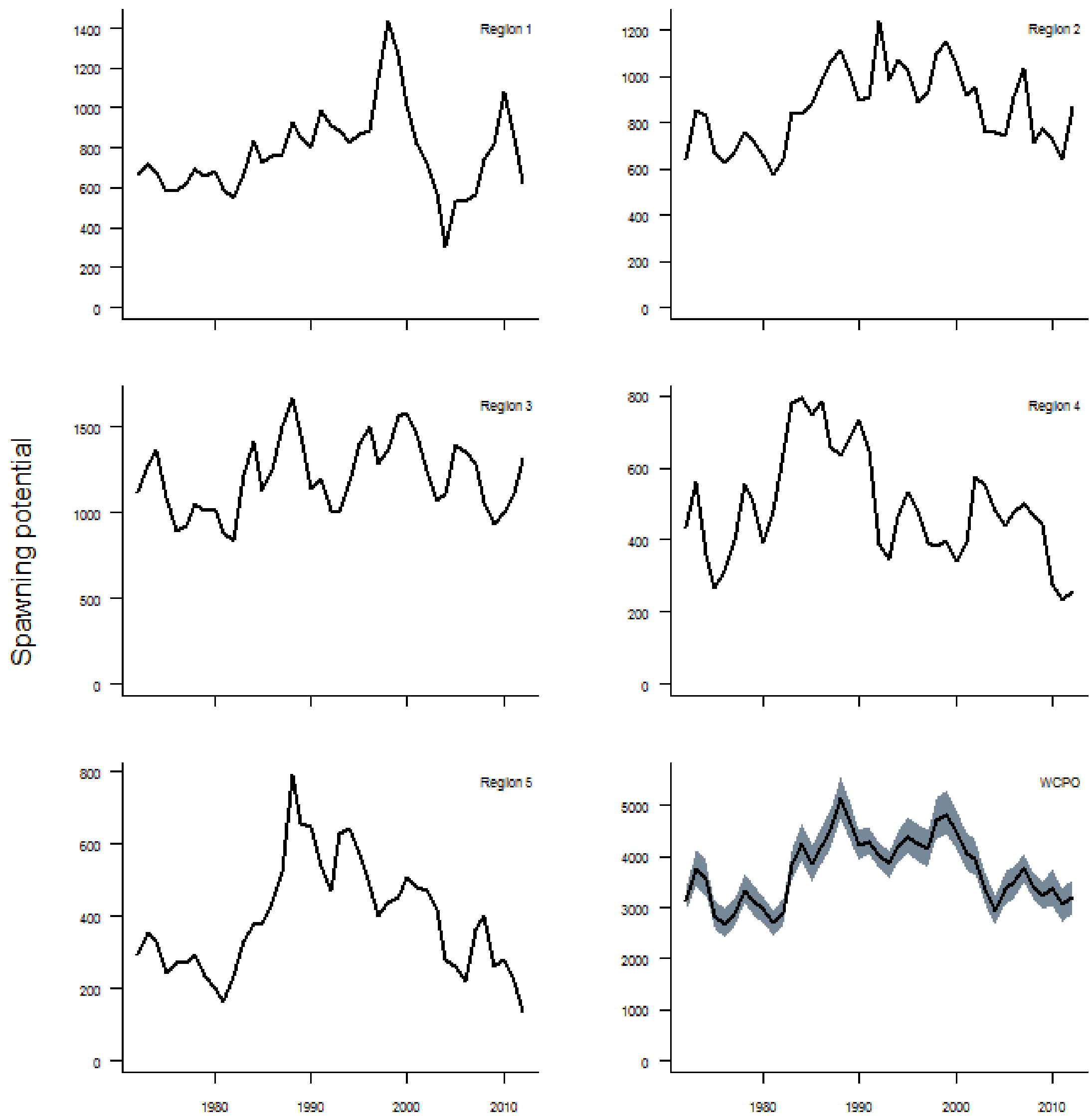


Figure 24. Estimated annual average spawning potential by region and for the WCPO for the reference case. The shaded areas indicate the approximate 95% confidence intervals.

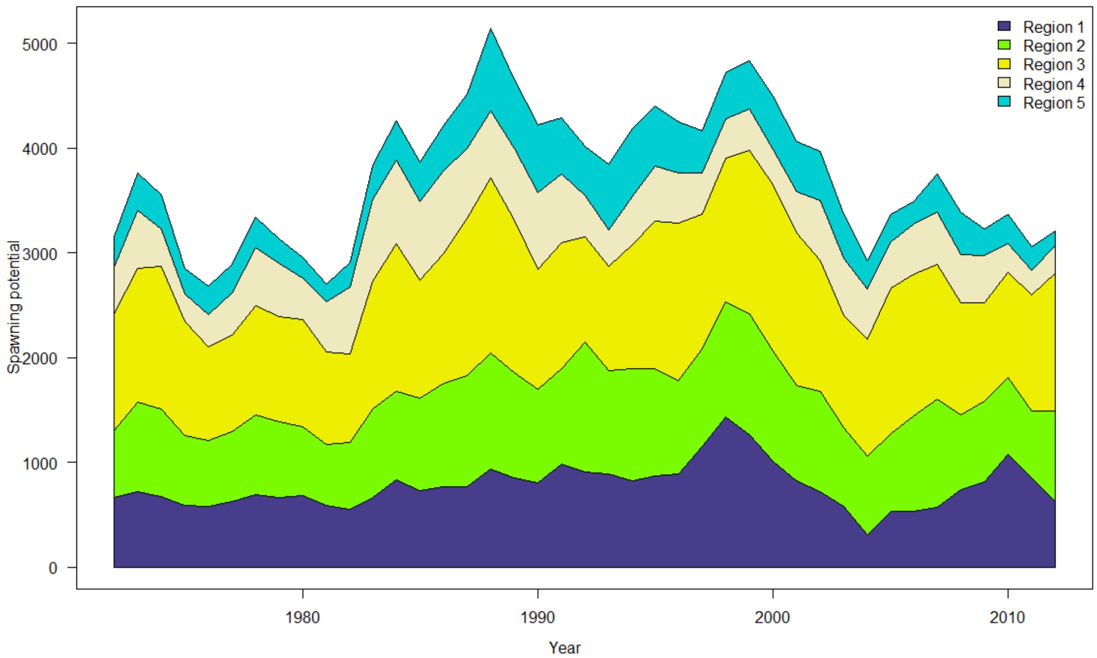


Figure 25. Estimated average annual spawning potential (mt) by model region for the reference case.

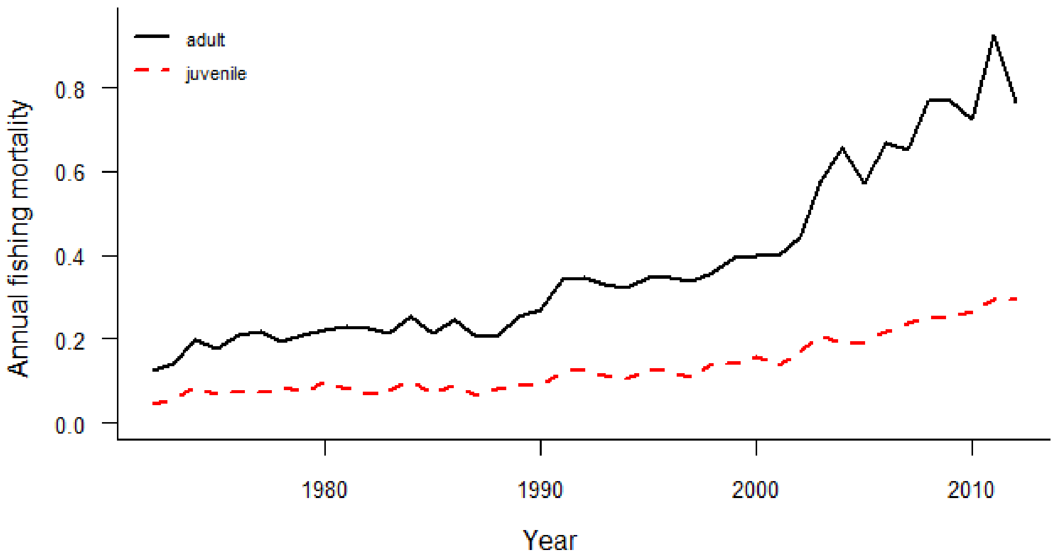


Figure 26. Estimated annual average juvenile and adult fishing mortality for the WCPO for the reference case.

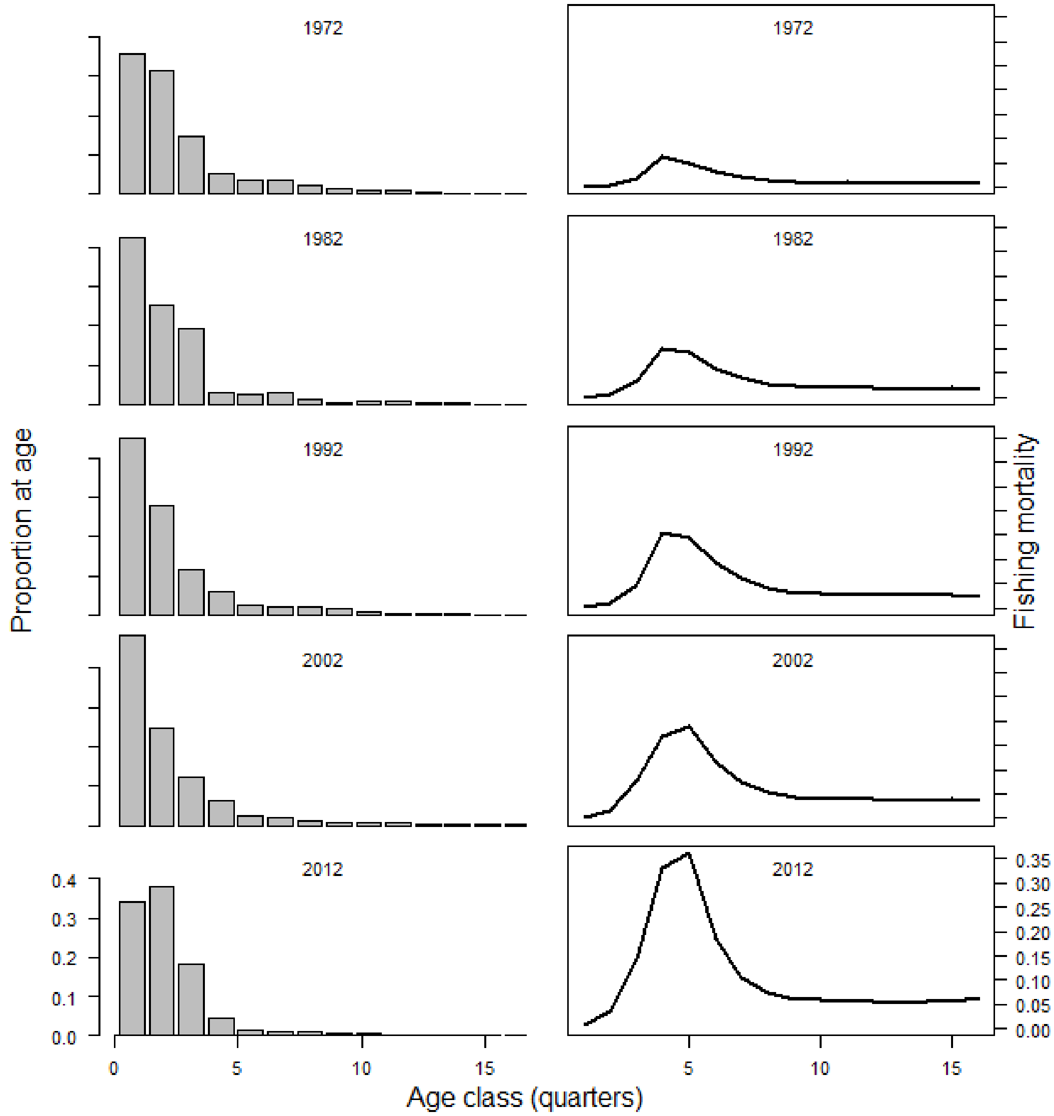


Figure 27. Estimated proportion at age (quarters) for the WCPO bigeye population (left) and fishing mortality at age (right) by year at decade intervals for the reference case.

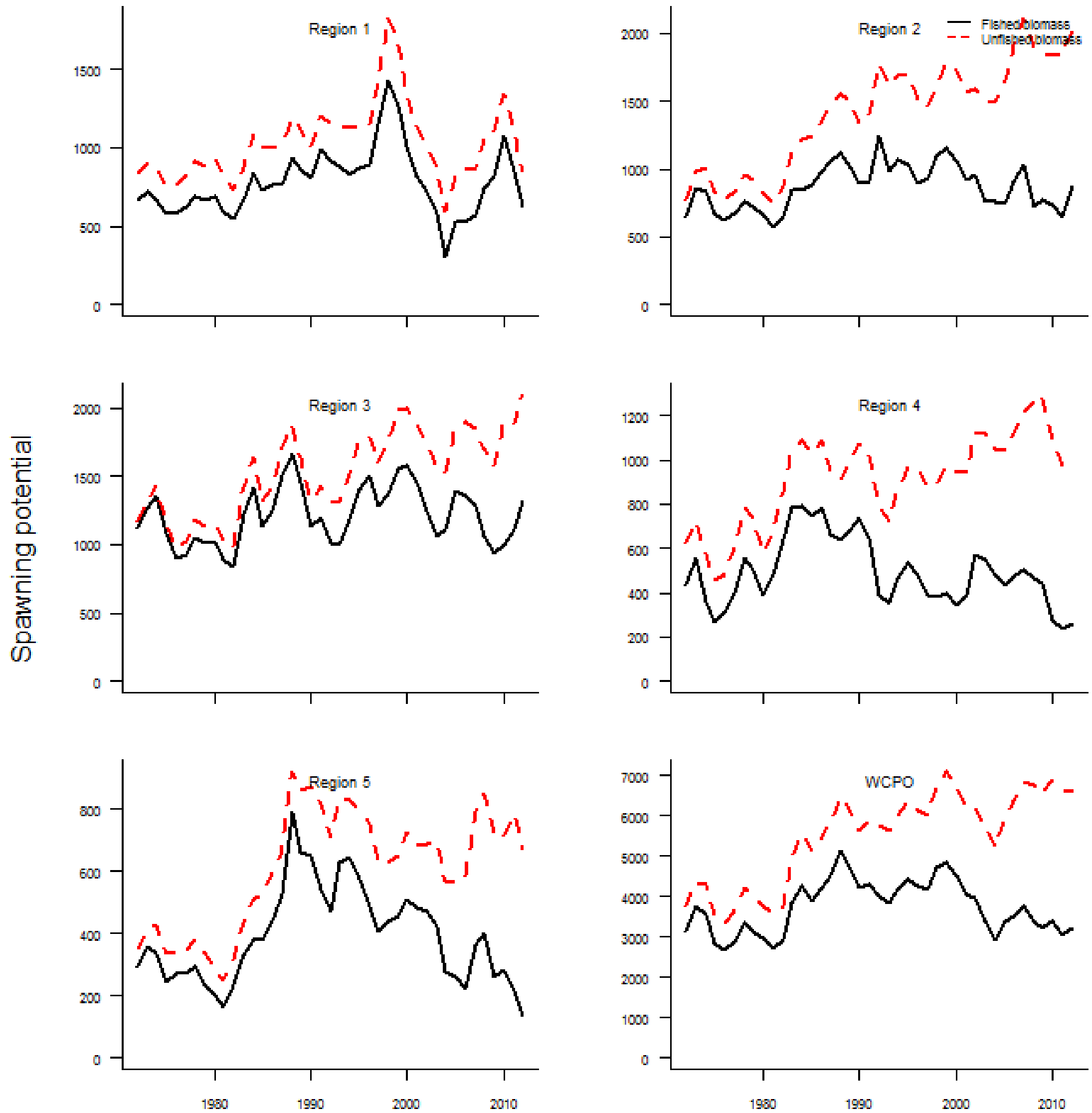


Figure 28. Comparison of the estimated spawning potential trajectories (lower solid black lines) with those trajectories that would have occurred in the absence of fishing (upper dashed red lines) for each region and for the WCPO for the reference case.

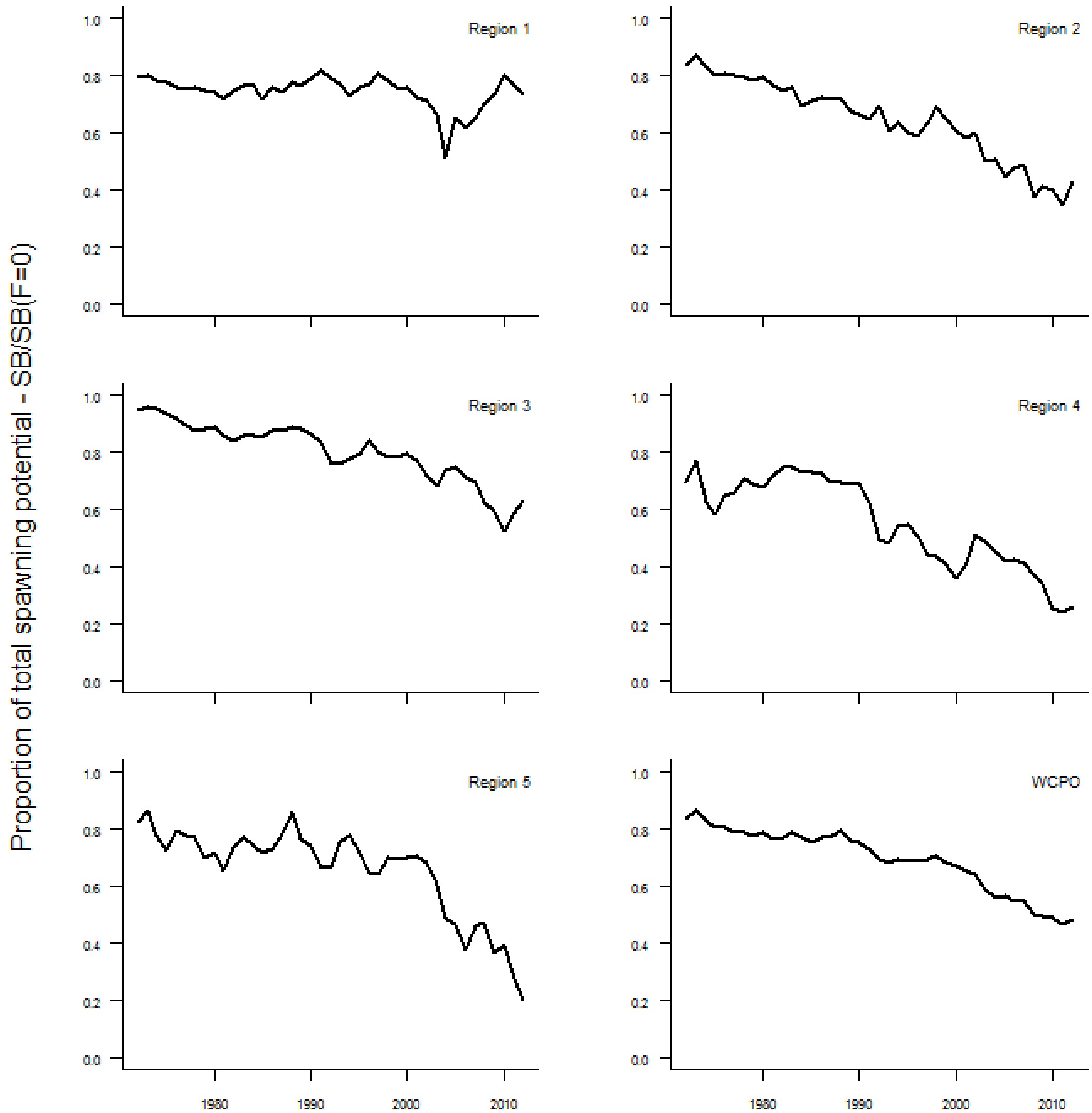


Figure 29. Ratios of exploited to unexploited spawning potential $SB_t/SB_{t_{F=0}}$ for each region and the WCPO for the reference case.

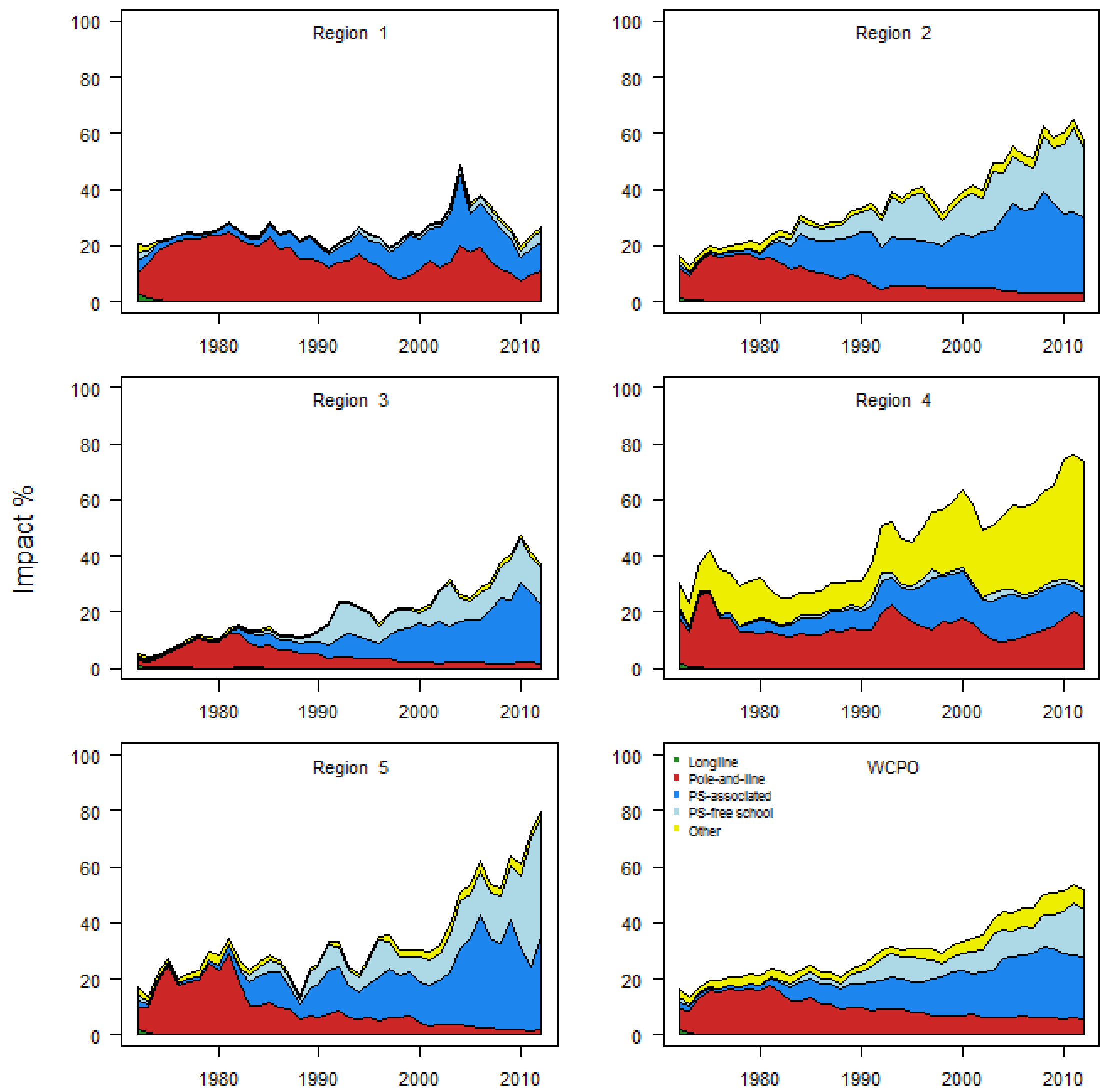


Figure 30. Estimates of reduction in spawning potential due to fishing (fishery impact = $1 - SB_t/SB_{t_{F=0}}$) by subregion and for the WCPO attributed to various fishery groups for the reference case.

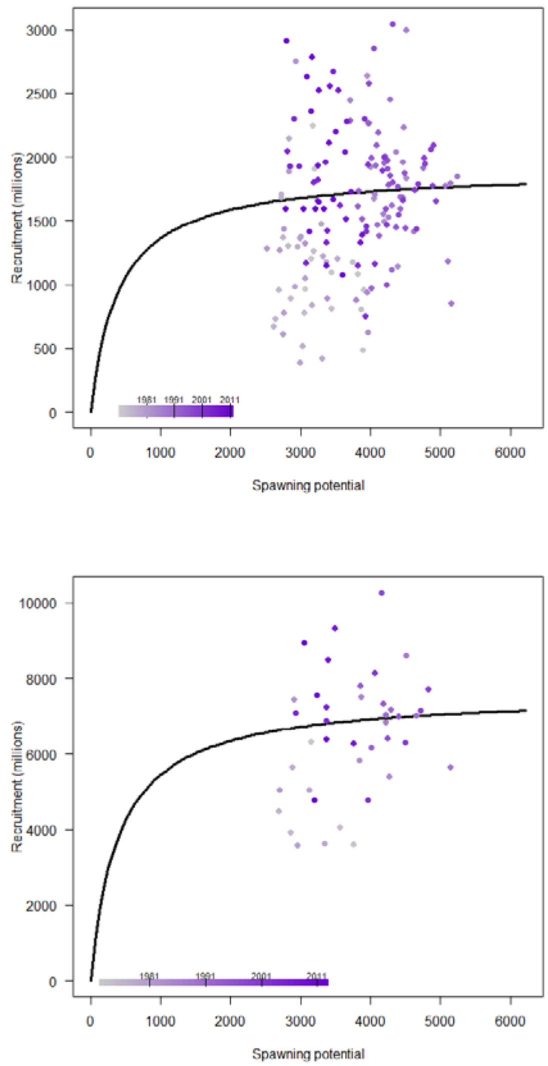


Figure 31. Estimated relationship between equilibrium recruitment and equilibrium spawning potential based on quarterly (top) and annual (bottom) values for the reference case.

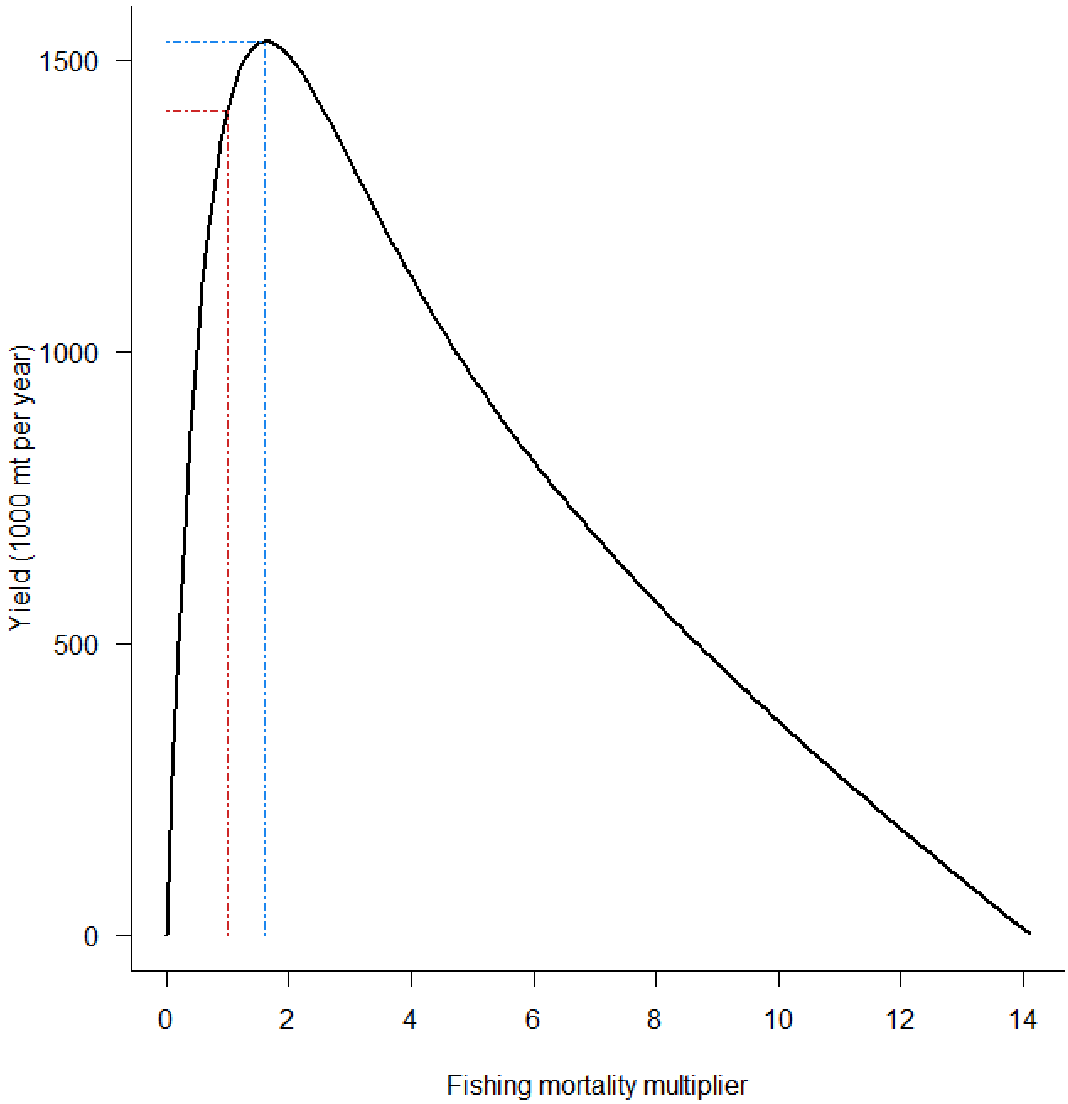


Figure 32. Estimated yield as a function of fishing mortality multiplier for the reference case. The red dashed line indicates the equilibrium yield at current fishing mortality and the blue dashed line indicates the MSY and the change in current fishing mortality required to achieve it.

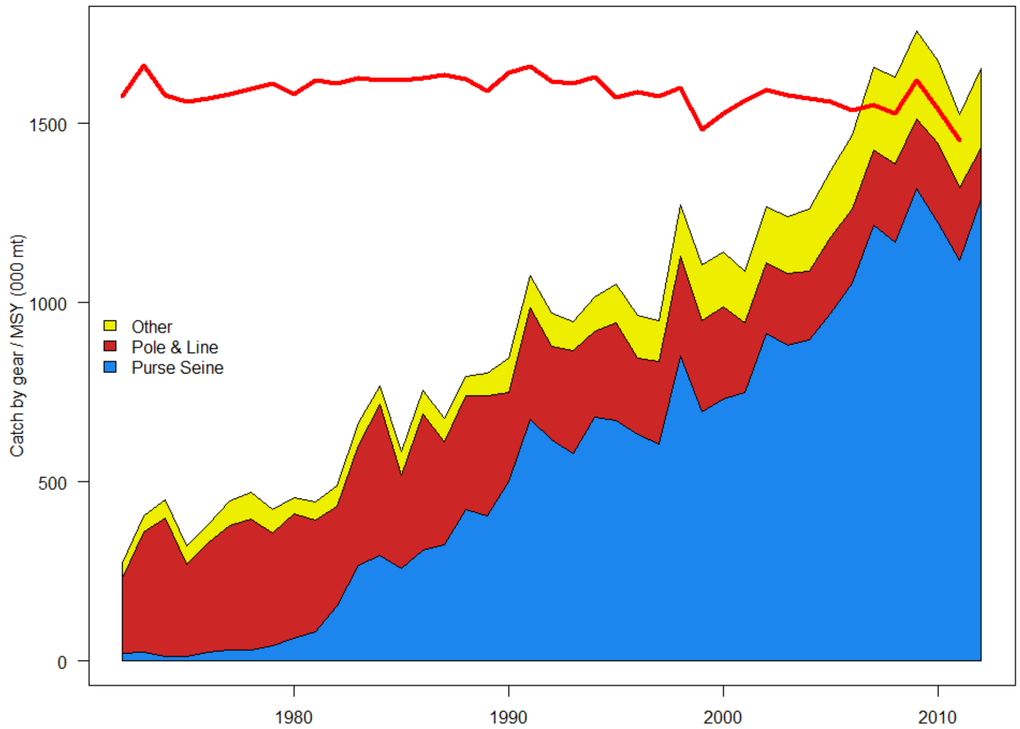


Figure 33. History of the annual estimates of *MSY* (red line) compared with annual catch split into three sectors for the reference case.

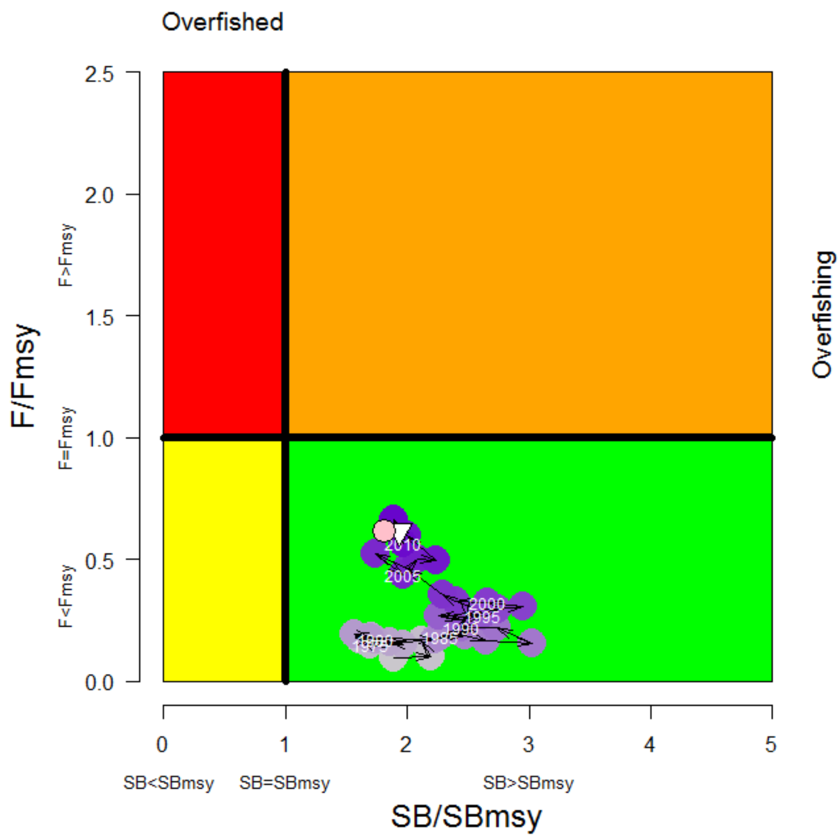


Figure 34. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the period 1972–2011 from the reference case. The colour of the points is graduated from mauve to dark purple through time and the points are labelled at 5-year intervals. The white triangle (obscured behind pink circle) represents the average for the current (2008-2011) period and the pink circle the latest period (2011).

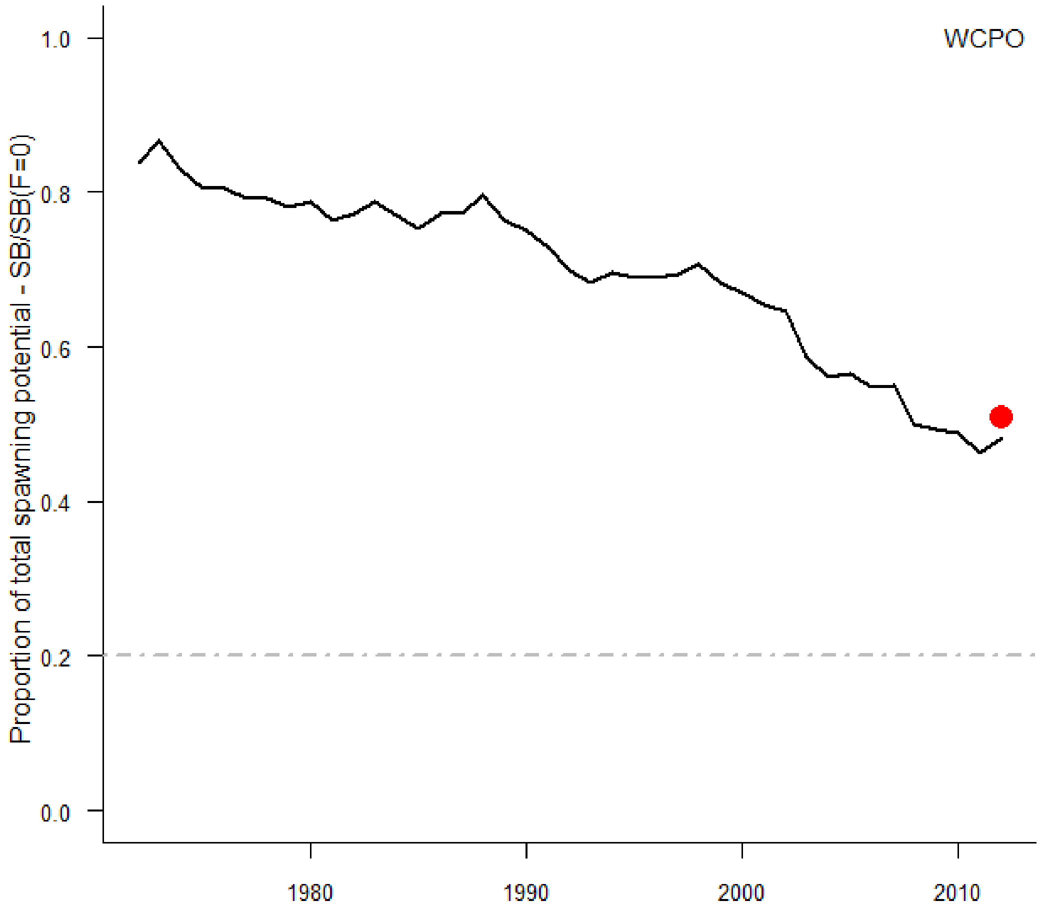


Figure 35. Ratio of exploited to unexploited spawning potential, $SB_t/SB_{t_{F=0}}$, for the WCPO for the reference case. The current WCPFC limit reference point of 20%SBF=0 is provided for reference as the grey dashed line and the red circle represents the level of spawning potential depletion based on the agreed method of calculating $SB_{F=0}$ over the last ten years of the model (excluding the last year).

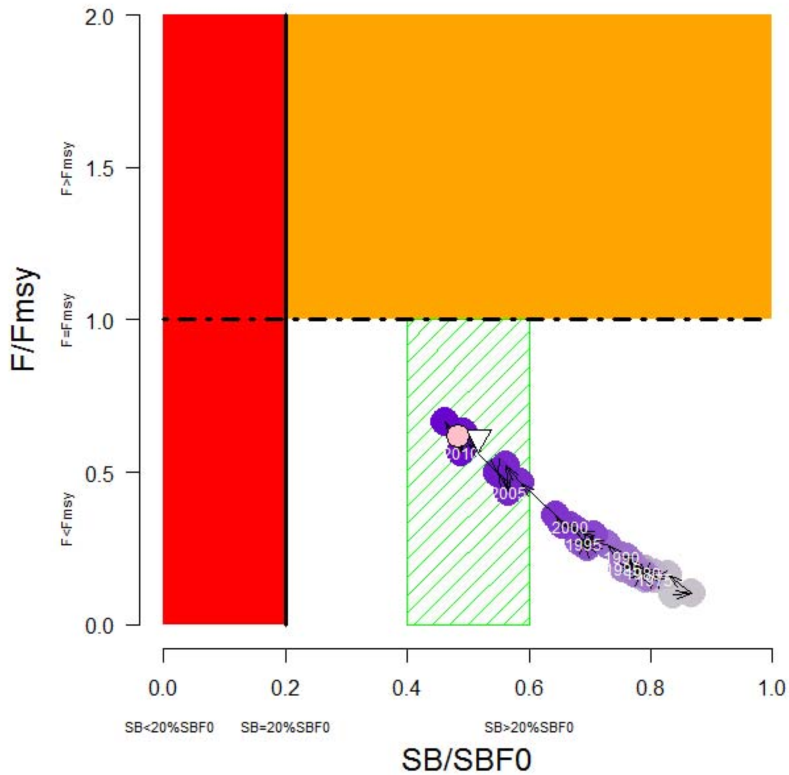


Figure 36. An alternative representation of stock status as a potential step towards displaying stock status with target and limit reference points. The red zone represents spawning potential levels lower than the agreed limit reference point which is marked with the solid black line. The orange region is for fishing mortality greater than FMSY (F=FMSY is marked with the black dashed line). The lightly shaded green rectangle covering 0.4-0.6SBF=0 is the 'space' that WCPFC has asked for consideration of a TRP for skipjack. The white triangle represents the average for the current period (2008-2011) and the pink circle the latest period (2011).

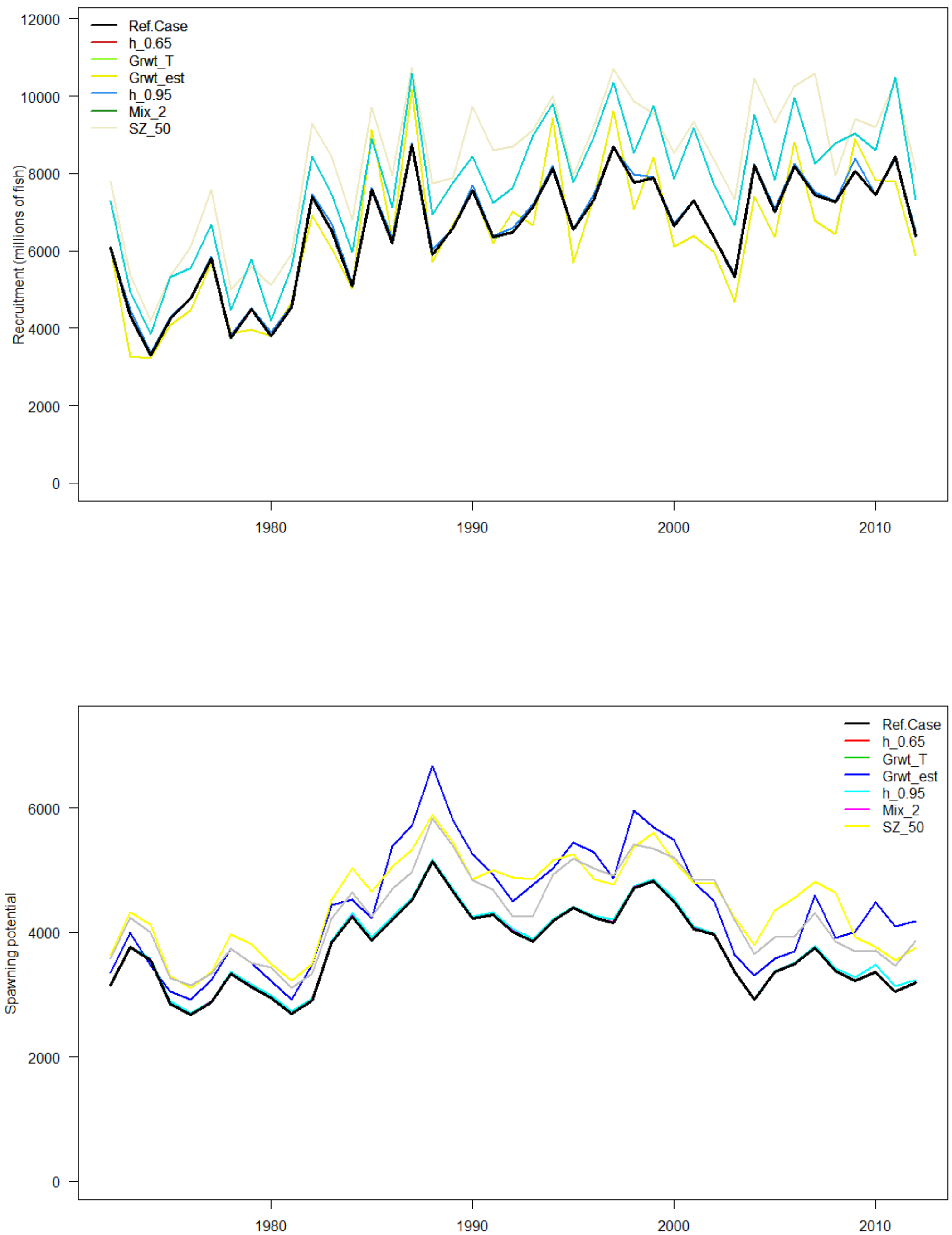


Figure 37. Estimated average recruitment (top) and spawning potential (bottom) for the WCPO obtained from the one-off sensitivity model runs to the reference case (see Table 5 for details of each scenario).

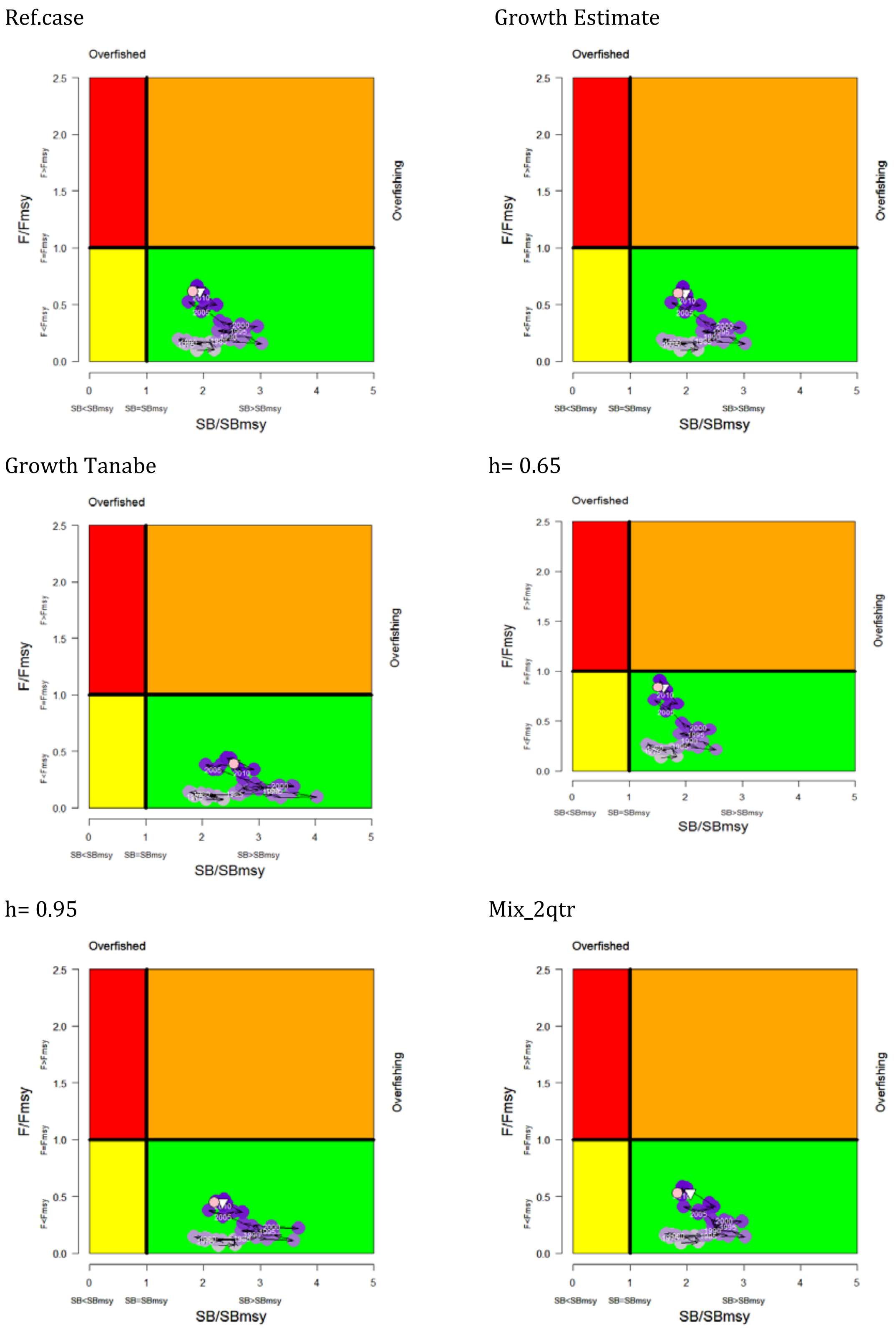
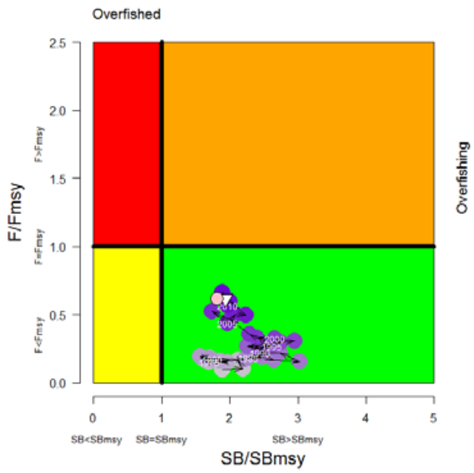


Figure 38. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points from the one-off sensitivity model runs to the reference case.

Ref.case



SZ_DW

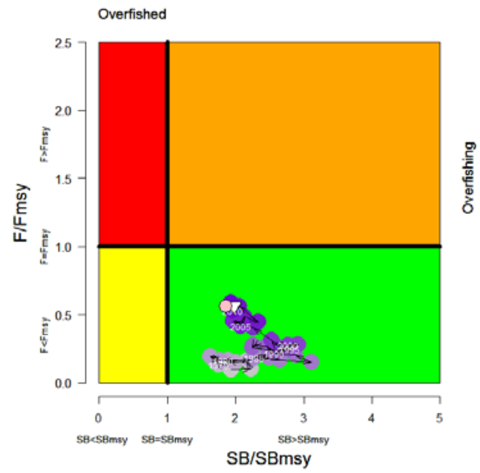


Figure 38. Cont.

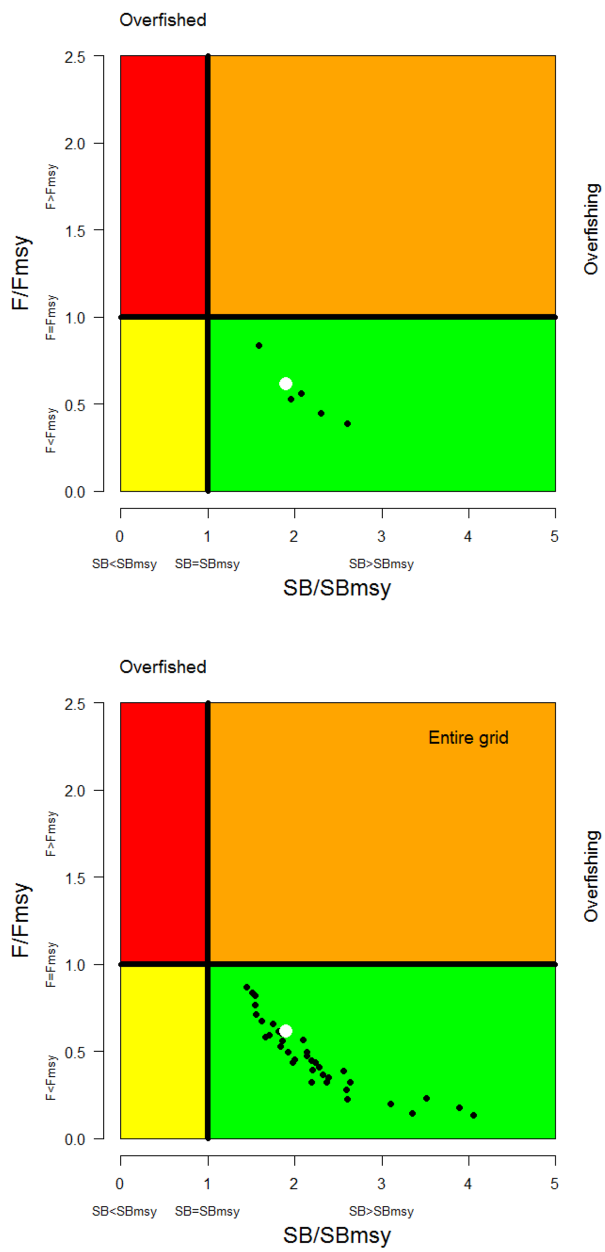


Figure 39. Summary of latest stock status (2011) for the key model runs (top panel) and the entire grid (bottom panel). The white circle represents the reference case.

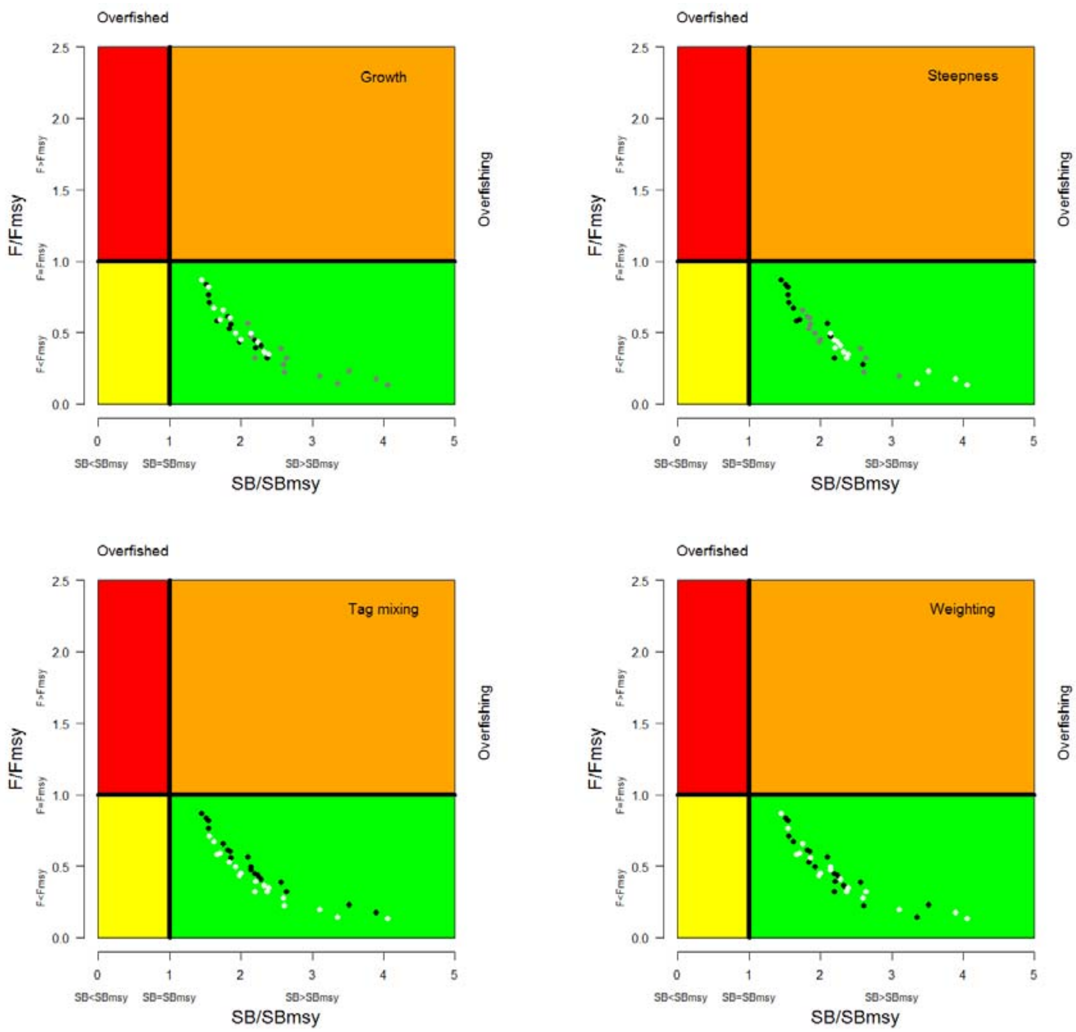


Figure 40. Plot of SB_{latest}/SB_{MSY} versus $F_{current}/F_{MSY}$ for the 36 model runs undertaken for the structural uncertainty analysis. The runs reflecting the reference case assumptions are denoted with black circles while the runs with the alternative assumption are denoted with white circles. For the steepness panel the labels are as follows: 0.65 (white), 0.95 (grey), and 0.8 (black), and for the growth panel they are 2010 parameterizations (black), Tanabe (grey), and estimated (white).

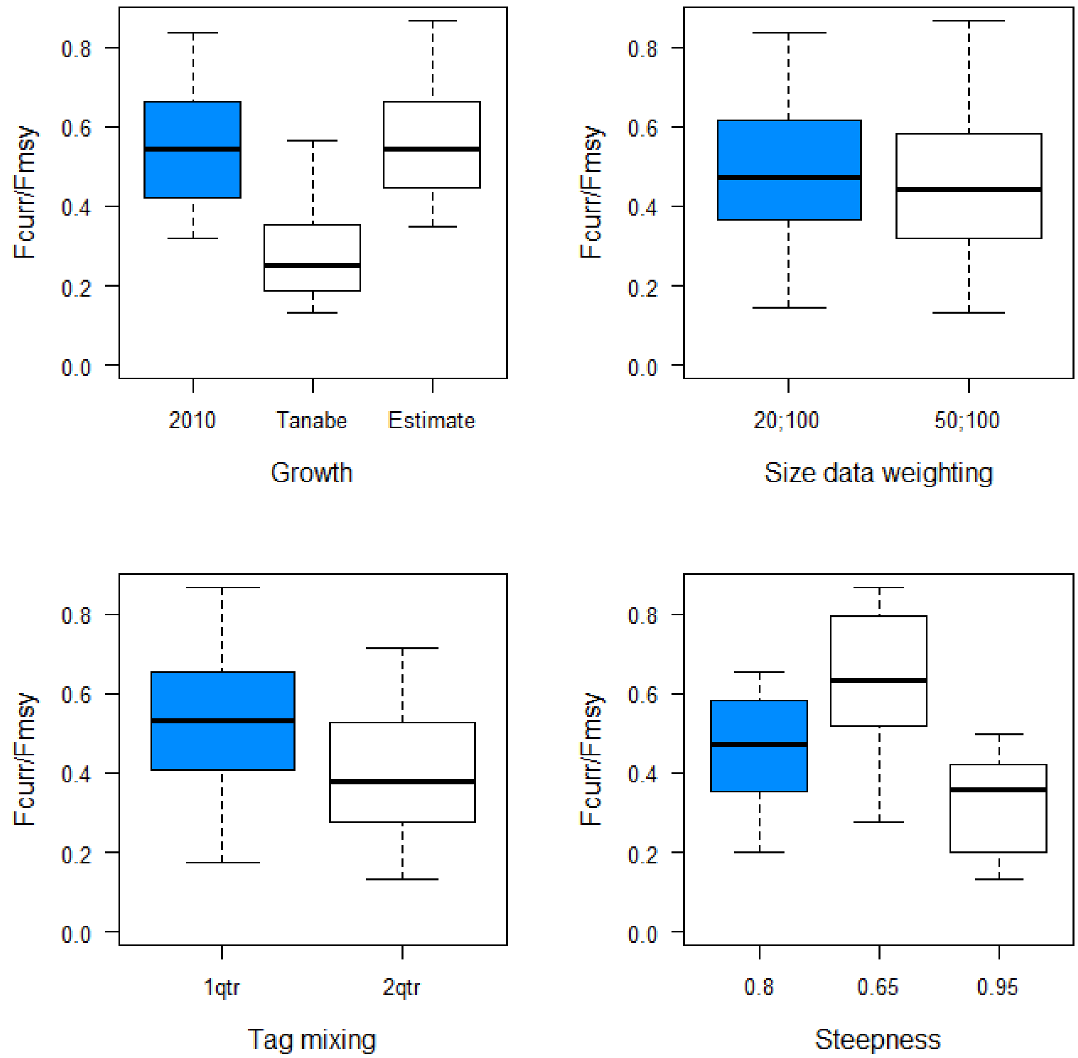


Figure 41. Box plots showing of the effects of the different factors within the structural uncertainty analysis grid on $F_{current}/F_{MSY}$.

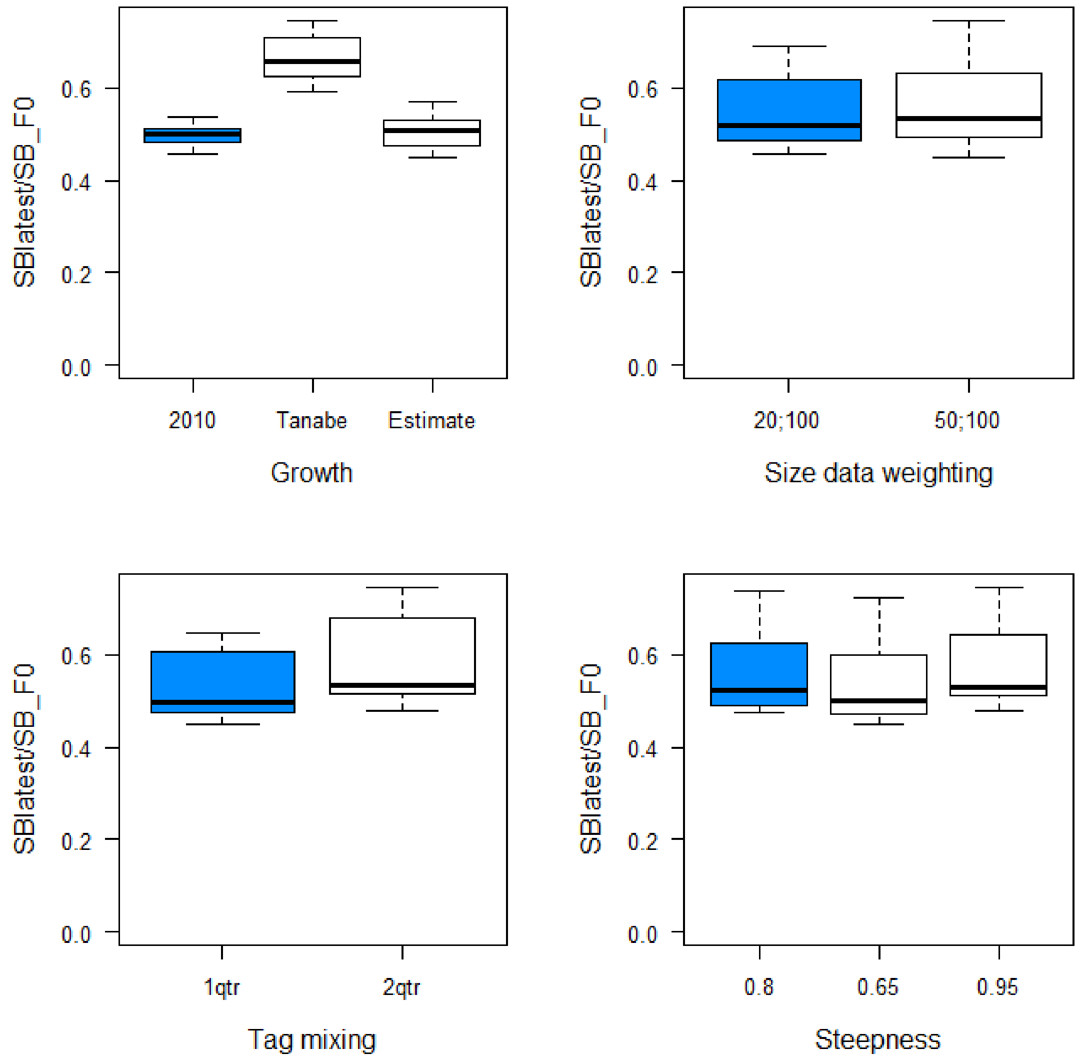


Figure 42. Box plots showing of the effects of the different factors within the structural uncertainty analysis grid on $\boldsymbol{SB_{latest}/SB_{F=0}}$.

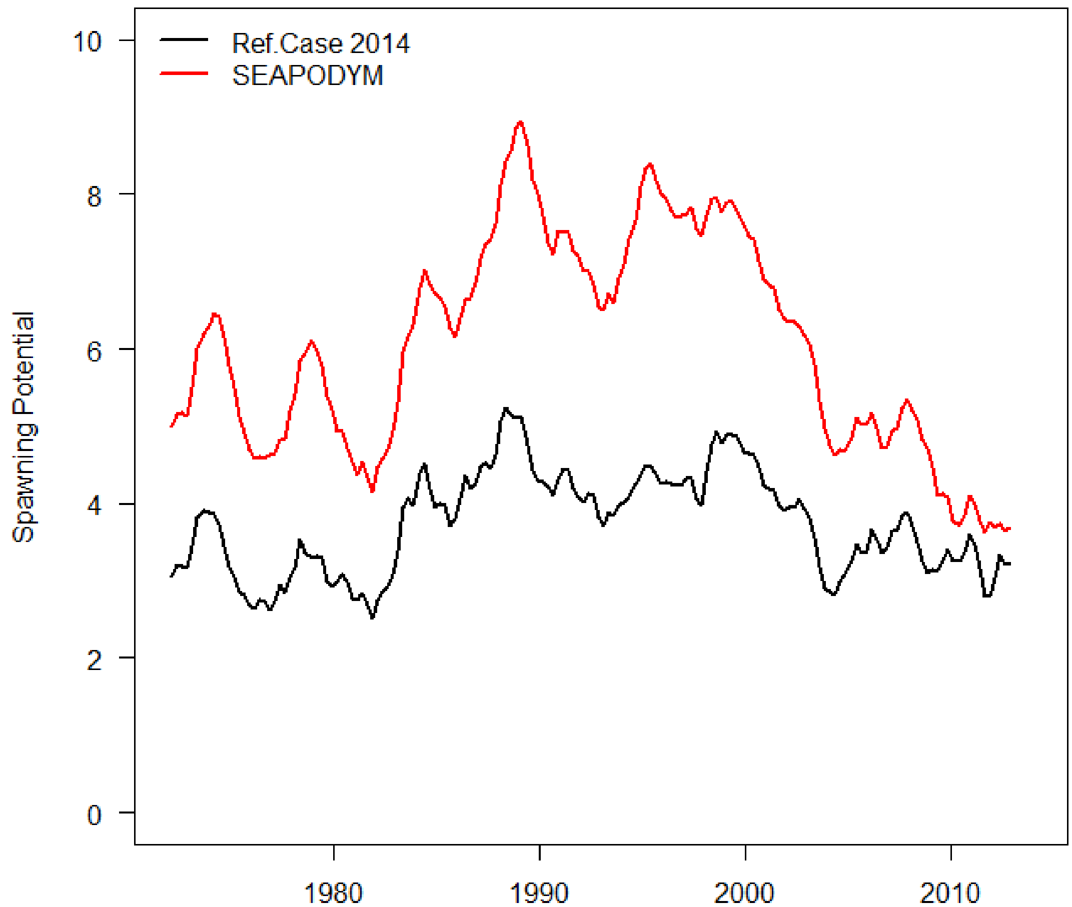


Figure 43. Annual spawning biomass estimates from a variant of the reference case where SEAPODYM output is used for the age specific movement coefficients.

10 ANNEX

10.1 Likelihood profile

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

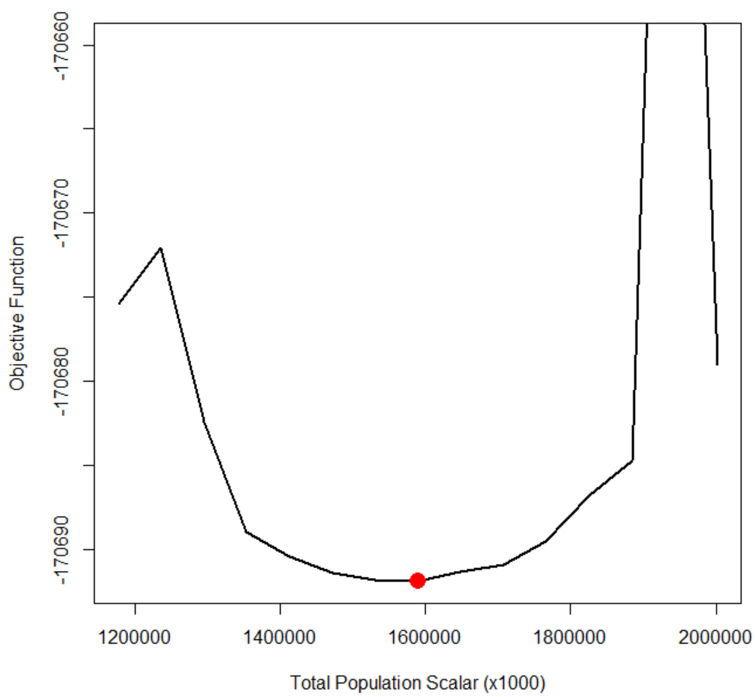


Figure 10.1.1 Profile of the marginal total negative log-likelihood in respect of the population scaling parameter, with the maximum likelihood estimate shown (red circle).

10.2 Retrospective analyses

10.2.1 Removal of recent years from 2014 updated data

Retrospective analysis involves rerunning the model by consecutively removing successive years of data to estimate model bias (Cadrin and Vaughn, 1997; Cadigan and Farrell, 2005). A series of models were fitted starting with the reference case model of the 2014 assessment, followed by models with the retrospective removal of all input data for the years 2012, 2011 and 2010 successively. In addition, a one-off model was run as a variant of the reference case that included the estimation of terminal recruitments in 2012. The models are described in Table 10.2.1 and a comparison of the recruitment and spawning biomass trajectories is shown in Figures 10.2.1 and 10.2.2, respectively.

Table 10.2.1. Description of model runs that explore retrospective fits to the reference case data input with successive removal of observations for each year from 2012 to 2009.

Model run	Description
Ref.Case	Full reference case input data time series; terminal recruitments not estimated.
Ref.Case 2014 Est Term Rec	Full reference case input data time series; terminal recruitments estimated.
Retro 2011	Exclude data for 2012 from reference case input data time series; terminal recruitments estimated.
Retro 2010	Exclude data for 2011 and 2012 from reference case input data time series; terminal recruitments estimated.
Retro 2009	Exclude data for 2010 to 2012 from reference case input data time series; terminal recruitments estimated.

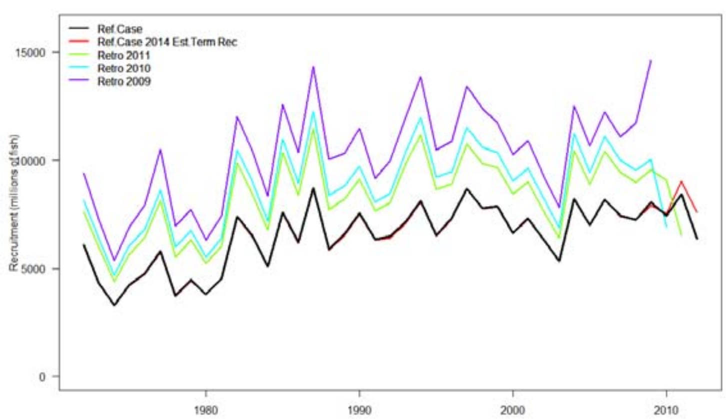


Figure 10.2.1. Recruitment estimates from a variant of the reference case where terminal recruitments were estimated (run34), and for retrospective analyses for the successive removal of data from the end of the observation time series from 2012 to 2009. Model runs are described in Table 10.2.1.

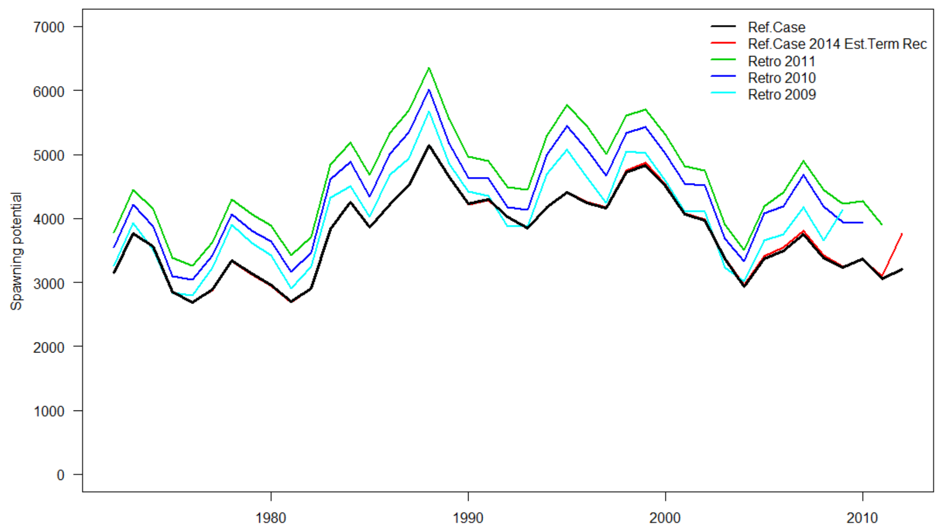


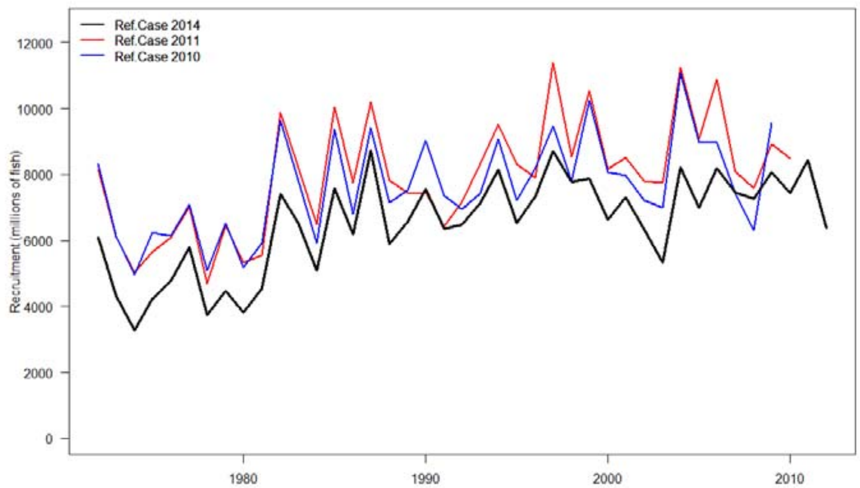
Figure 10.2.2. Annual spawning biomass estimates from a variant of the reference case where terminal recruitments were estimated (run34), and for retrospective analyses for the successive removal of data from the end of the observation time series from 2012 to 2010. Model runs are described in Table 10.2.1.

10.2.2 Retrospective examination of previous assessments

The reference case model for the current (2014) assessment was compared retrospectively to those for the past two assessments done in 2011 and 2010. Key management quantities for the models are listed in Table 10.2.2, a comparison of the recruitment and spawning biomass trajectories is shown in Figure 10.2.3, and a comparison of the Kobe plots of estimated stock status relative to the MSY reference points is shown in Figure 10.2.4.

Table 10.2.2. Key management quantities for the reference case models used for the WCPO yellowfin tuna stock assessments in 2009, 2011, and the current assessment (2014).

Management quantity	2010	2011	2014
MSY	1,375,600	1,503,600	1,532,400
$F_{current}/F_{MSY}$	0.34	0.37	0.62
$SB_{latest}/SB_{F=0}$	0.48	0.55	0.48



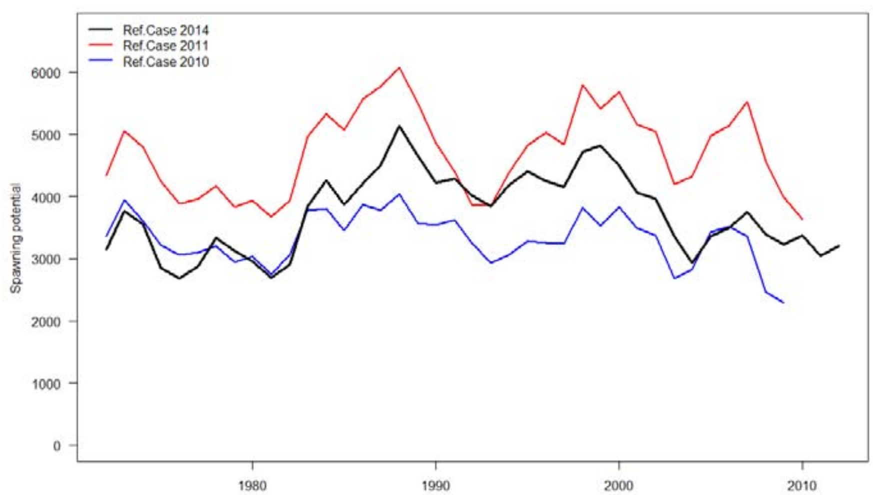


Figure 10.2.3. Annual recruitment (top) and spawning biomass (bottom) estimates from the reference case models used for the WCPO skipjack assessments from 2010, 2011 and the current assessment (2014).

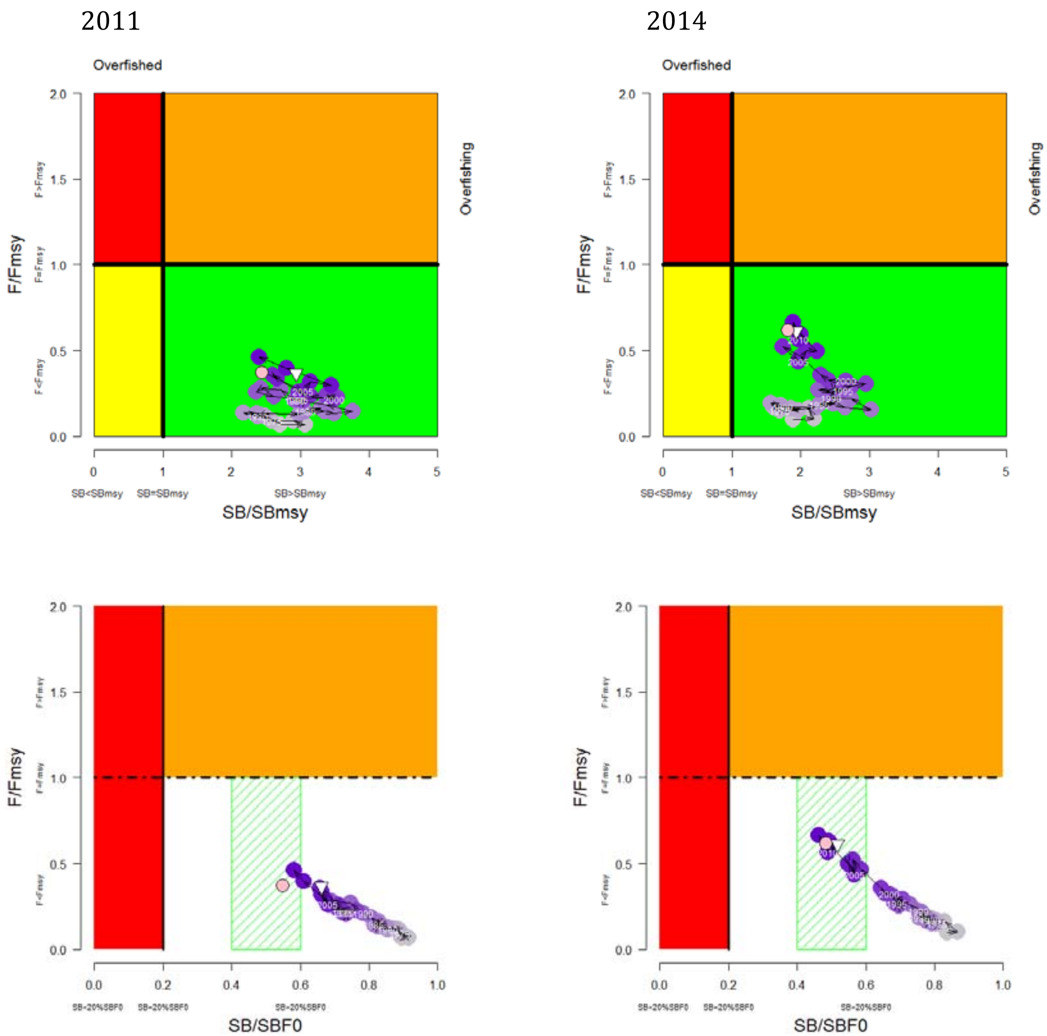


Figure 10.2.4. Comparison of the estimates of stock status in respect of spawning stock biomass relative to SB_{MSY} (top panels) and $SB_{F=0}$ (bottom panels), where the white triangle represents the average for the current period (SB_{curr}) and the pink circle the latest period (SB_{latest}) as defined in Table 6 and for the reference case models used for the 2011 (left panels) and the current (2014, right panels) assessments of WCPO skipjack tuna.

10.3 Stepwise model developments

Starting with the reference case model for the 2011 skipjack tuna stock assessment, a series of stepwise developments were made towards a reference case model for the updated assessment for 2014 (Table 10.3.1). A comparison of the total population biomass trajectory illustrates the effects of the various developments on the estimate of absolute abundance over the model period (Figure 10.3.1).

Table 10.3.1. Summary of the stepwise development model runs undertaken starting with the 2011 skipjack reference case assessment model leading up to the reference case for the 2014 assessment.

Run	Name	Description
2011	2011 reference case	Run from the 2011 assessment; 3 regions, 18 fisheries, Japanese pole-and-line CPUE. Size data weighting n/20, corrected Purse seine catch estimates, steepness = 0.8...
2011_newMFCL	R1_01	The 2011 reference case model re-fitted to the input data (unchanged) using the latest release version 1.1.5.6 of the MULTIFAN-CL software.
2014_Data	R1A_01	Run 2011_newMFCL with input data updated to 2012, Updated Japanese pole-and-line CPUE, revised estimates of the tag reporting rate priors, tag releases scaled for initial mortality.
2014_Data & Structure	R4N_step_1	Revised model structure and fisheries definitions, 5 regions, 23 fisheries, additional CPUE data from Papua New Guinea and Philippines purse seine fisheries.
Ref.Case	012_L0W0T0M0	As per 2014_Data & Structure, but with exclude estimation of terminal recruitment deviates in 2012.

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

Management quantity	Ref.case-2011	New MFCL	2014_Data	2014_Data & Structure	Ref.case-2014
MSY	1,569,600	1,569,600	1,377,200	1,546,400	1,532,000
$F_{current}/F_{MSY}$	0.34	0.34	0.45	0.61	0.62
$SB_{latest}/SB_{F=0}$	0.56	0.56	0.5	0.49	0.48

Figure 10.3.1. Estimated annual average spawning potential for the WCPO obtained from runs undertaken in the stepwise development from the 2011 reference case to the 2014 reference case. Model runs are as described in Table 10.3.1.

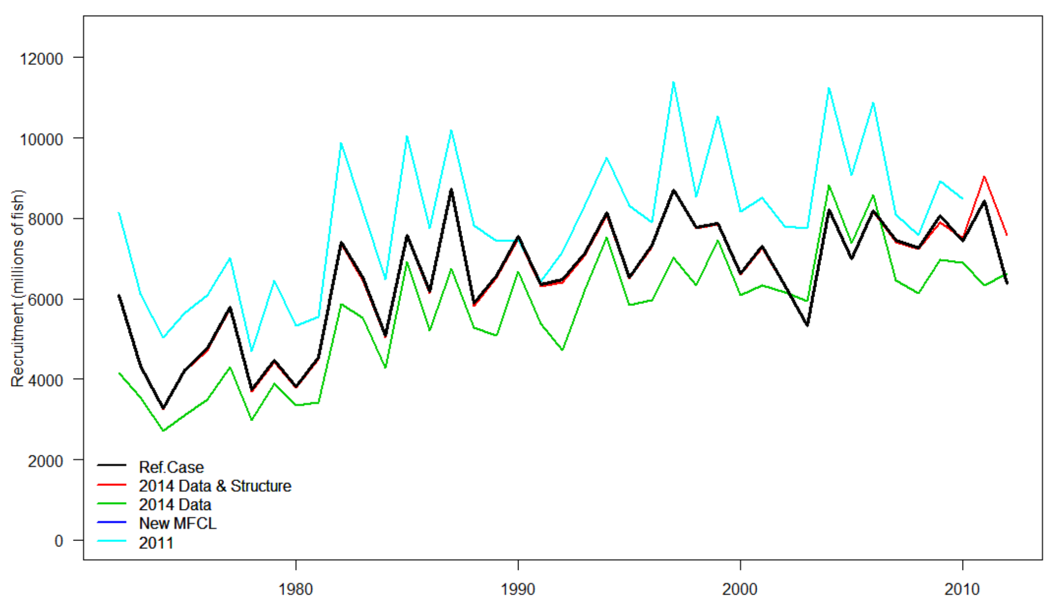


Figure 10.3.2. Estimated annual average recruitment for the WCPO obtained from runs undertaken in the stepwise development from the 2011 reference case to the 2014 reference case. Model runs are as described in Table 10.3.1.

10.4 doitall.skj

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

# Change the recruitment sd in the PAR file.
# $1 Name of the PAR file.
# $2 New value.
function changeSD {
    if [ -z $1 ]
    then
       echo "Needs filename as argument.";
       exit 1;
    elif [ -z $2 ]
```

```
    then
       echo "Needs new value argument.";
       exit 1;
    elif [ -f "$1" ]
    then
# Read line per line.
       while read LINE
       do
# Found the desired header.
           if [ "$LINE" == "# Variance parameters" ]
           then
              echo $LINE >> $1.new;
              for ((L=1 ; L < 2 ; L++))
              do
                     read LINE;
# Skip blank or comment line.
                     if [[ "$LINE" == "#" || "$LINE" == "" ]]
                     then
                     #echo "Found a matching line "$LINE;
                     L=`expr $L - 1`;
                     echo $LINE >> $1.new;
                     else
                     #echo "Processing line "$LINE;
                     I=0;
                     for VALUE in $LINE
                     do
                         I=`expr $I + 1`;
# Change the 29th value.
                         if [ $I -eq 1 ]
                         then
                            echo -n $2" " >> $1.new;
                         else
                            echo -n $VALUE" " >> $1.new ;
                         fi
                     done
                     echo "" >> $1.new;
                  fi
              done
# Write line AS IS.
           else
              echo $LINE >> $1.new;
           fi
       done < $1;
# Create a backup copie.
       mv $1 $1.bak;
# Move temporary file to target file.
       mv $1.new $1;
    fi;
}


# ---------
#  PHASE 0  - create the initial par file
# ---------
 ./mfclo64 skj.frq skj.ini 00.par -makepar
#
 # ---------
#  PHASE 1
# ---------
  ./mfclo64 skj.frq 00.par 01.par -file - <<PHASE1
#--------------------------------------------------------------------------------
#  Initial Phase Control option
  1 32 6         # control phase - keep growth parameters fixed
#--------------------------------------------------------------------------------
# Recruitment and Initial Population Settings
   1 149 100      # penalty on recruitment devs
   1 400 4        # set the last 4 recruitment deviates to 0
   2 113 0        # estimate initpop/totpop scaling parameter
```

```
   2 177 1        # use old totpop scaling method

   2 32 1         # totpop estimated from this phase
   2 57 4         # 4 recruitments per year
   2 93 4         # 4 recruitments per year
   2 94 2         # Use equilibium initial population
   2 95 20        # Use average Z for first 20 periods for equil. init. pop.
   2 116 70          #  value for rmax This is the maximum instantaneous fishing
mortality in any one yr qtr, per fishery/region.   70 = 0.70 = F
#--------------------------------------------------------------------------------
# Likelihood Component

   1 141 3        # Robust normal likelihood function for LF data
   1 111 4        # Negative binomial likelihood function for tags
   -999 49 20     # Divisor for LF sample sized effective sample size
 #--------------------------------------------------------------------------------
# Tagging Related Flags
#
  -9999 1 1       # Tag returns for first period after release disregarded
  -9999  2  0          #  Zero  means  applying  the  tag_rep_rate  in  the  tag  catch
calculation; 1 means we are excluding it
  1 33 90         # maximum tag reporting rate for all fisheries is 0.9
  2 198 1         # turn on release group reporting rates
  -999 43 0       # var parameter estimated.
  -999 44 0       # all fisheries grouped for estimating tag neg bin var parameter.
  2 96 12         # Tag are pooled across release groups after 12 periods
#--------------------------------------------------------------------------------
# Estimate movement coefficients
  2 68 1         # Estimate movement coefficients
  2 69 1         # Use generalized movement model
  1 173 0        # growth deviates


#--------------------------------------------------------------------------------
# Selectivity Settings
  -3 16 1
  -3 3 15
  #..
  -7 16 1
  -7 3 15
  #..
  -11 16 1
  -11 3 15
  #..
  -15 16 1
  -15 3 15
  #..
  -23 16 1
  -23 3 15
  #..
# -------------------------------------------------------------------------------
#   Selectivity grouping  and form     1=logistic  2=doublenormal 3=cubic spine or
length specific
 -1 24 1
 -1 57 3  #  cubic spline selectivity
 -1 61 5  #  with 5 parameters
 #..
 -2 24 2
 -2 57 3 #  cubic spline selectivity
 -2 61 5 #  with 5 parameters
 #..
 -3 24 3
 -3 57 3 #  cubic spline selectivity
 -3 61 5 #  with 5 parameters
 #..
 -4 24 4
 -4 57 3 #  cubic spline selectivity
 -4 61 5 #  with 5 parameters
```

```
#..
-5 24 5
-5 57 3 #  cubic spline selectivity
-5 61 5 #  with 5 parameters
#..
-6 24 6
-6 57 3 #  cubic spline selectivity
-6 61 5 #  with 5 parameters
#..
-7 24 7
-7 57 3 #  cubic spline selectivity
-7 61 5 #  with 5 parameters
#..
-8 24 4
-8 57 3 #  cubic spline selectivity
-8 61 5 #  with 5 parameters
#..
-9 24 5
-9 57 3 #  cubic spline selectivity
-9 61 5 #  with 5 parameters
#..
-10 24 6
-10 57 3 #  cubic spline selectivity
-10 61 5 #  with 5 parameters
#..
-11 24 8
-11 57 3 #  cubic spline selectivity
-11 61 5 #  with 5 parameters
#..
-12 24 4
-12 57 3 #  cubic spline selectivity
-12 61 5 #  with 5 parameters
#..
-13 24 9
-13 57 3 #  cubic spline selectivity
-13 61 5 #  with 5 parameters
#..
-14 24 10
-14 57 3
-14 61 5 # cubic spline selectivity with 5 parameters
#..
-15 24 11
-15 57 3 #  cubic spline selectivity
-15 61 5 #  with 5 parameters
#..
-16 24 12
-16 57 3  #  cubic spline selectivity
-16 61 5  #  with 5 parameters
#..
-17 24 12
-17 57 3  #  cubic spline selectivity
-17 61 5  #  with 5 parameters
#..
-18 24 5
-18 57 3  #  cubic spline selectivity
-18 61 5  #  with 5 parameters
#..
-19 24 4
-19 57 3   #  cubic spline selectivity
-19 61 5   #  with 5 parameters
#..
-20 24 5
-20 57 3 #  cubic spline selectivity
-20 61 5 #  with 5 parameters
#..
-21 24 6
-21 57 3 #  cubic spline selectivity
-21 61 5 #  with 5 parameters
```

```
 #..
 -22 24 12
 -22 57 3   #  cubic spline selectivity
 -22 61 5   #  with 5 parameters
 #..
 -23 24 13
 -23 57 3 #  cubic spline selectivity
 -23 61 5 #  with 5 parameters

 -999 26 2         # Use length-based selectivity
#--------------------------------------------------------------------------------
#   Grouping of fisheries with common catchability
-1     29     1
-2     29     2
-3     29     3
-4     29     4
-5     29     5
-6     29     6
-7     29     7
-8     29     8
-9     29     9
-10    29     10
-11    29     11
-12    29     12
-13    29     13
-14    29     14
-15    29     15
-16    29     16
-17    29     17
-18    29     18
-19    29     19
-20    29     20
-21    29     21
-22    29     22
-23    29     23
#--------------------------------------------------------------------------------
# Initial catchability
  -1 60 1
  -2 60 2
  -3 60 3
  -4 60 4
  -5 60 5
  -6 60 6
  -7 60 7
  -8 60 8
  -9 60 9
  -10 60 10
  -11 60 11
  -12 60 12
  -13 60 13
  -14 60 14
  -15 60 15
  -16 60 16
  -17 60 17
  -18 60 18
  -19 60 19
  -20 60 20
  -21 60 21
  -22 60 22
  -23 60 23
#--------------------------------------------------------------------------------
#   Penalties for effort deviations
#   Fishery groupings for tag return data
  -1 32 1
  -2 32 2
  -3 32 3
  -4 32 4
  -5 32 5
```

```
  -6 32 5
  -7 32 6
  -8 32 7
  -9 32 8
  -10 32 8
  -11 32 9
  -12 32 10
  -13 32 11
  -14 32 11
  -15 32 12
  -16 32 13
  -17 32 14
  -18 32 15
  -19 32 16
  -20 32 17
  -21 32 17
  -22 32 18
  -23 32 19

#-  Penalties for effort deviations  (fsh 13 )
   -999 13 -3
  # fisheries with No effort
  # JPN LL
  -3 13 10
  -7 13 10
  -11 13 10
  -15 13 10
  -23 13 10
  # Domestic PH VN and ID fisheries
  -16 13 10
  -17 13 10
  -22 13 10
  #
  # Fisheries with Standardized effort            1,4, 9, 12, 18
  -1 13 1
  -4 13 1
  -9 13 1
  -12 13 1
  -18 13 10
#--- FSH 66 is  time-varying effort wt (set internally)
 -999 66 0
  -1 66 1
  -4 66 1
  -9 66 1
  -12 66 1
  -18 66 0
#--- # Estimation of mixture pars  (for additional zeros ) in the likelihood-
  -1 46 0
  -2 46 0
  -3 46 0
  -4 46 0
  -5 46 0
  -6 46 0
  -8 46 0
  -9 46 0
  -10 46 0
  -11 46 0
  -12 46 0
  -13 46 0
  -14 46 0
  -16 46 0
  -17 46 0
  -18 46 0

PHASE1
#
changeSD 01.par 5.074696     #
#
```

```
# ---------
#  PHASE 2
# ---------
  ./mfclo64 skj.frq 01.par 02.par -file - <<PHASE2
    1 1 500        # Sets no. of function evaluations for this phase
    1 50 -1        # convergence criterion is 1E+1
    2 35 12        # Effort deviate boundary
    2 34 1         # est. effort devs  (in general)
  -999 4 4         # Estimate effort deviates
    2 144 100000   # catch likelihood penalty
PHASE2
#
#  --------- ------------ ---------- --------- -------- --------
recruitmentConstraints 02.par 0.8     # sets the steepness to 0.8
#
#
#
#   PHASE 3
#  ---------
  ./mfclo64 skj.frq 02.par 03.par -file - <<PHASE3
    1 190 1     # Write plot.rep
PHASE3
#
#
# ---------
#  PHASE 4
# ---------
  ./mfclo64 skj.frq 03.par 04.par -file - <<PHASE4

  2 70 1        # Estimate time-series changes in recruitment distribution
  2 71 1        # est. time series of reg recruitment
  2 178 1       # constraint on regional recruitments
PHASE4
#
# ---------
#  PHASE 5
# ---------
     ./mfclo64 skj.frq 04.par 05.par -file - <<PHASE5
# Estimate seasonal catchability for all fisheries
 -999 27 1
# excepth  the JPN LL/RES fisheries
 -3 27 0
 -7 27 0
 -11 27 0
 -15 27 0
 -23 27 0
# except for fisheries with annual catch 16, 17, 18
 -16 27 0
 -17 27 0
 -18 27 0
 -22 27 0
PHASE5
#
# ---------
#  PHASE 6
# ---------
  ./mfclo64 skj.frq 05.par 06.par -file - <<PHASE6
  2 82 45       # Prior for average M is 45/100 per quarter
  2 84 2        # Penalty weight
  2 33 1        # Estimate average M
PHASE6
#
# ----------
#  PHASE 7
# ----------
     ./mfclo64 skj.frq 06.par 07.par -file - <<PHASE7
# set up for estimation of growth ----LATER ON.
# 1 184 1    # Activate length estimation of independent age classes
```

```
# 1 14 1     # Estimate von Bertalanffy K
# 1 12 1     # Estimate mean length of age 11
# 1 13 1     # Estimate mean length of largest age class

# Sets variable catchability, periodicity, and penalty
      -1     10     0        #    JP PL Reg1
  -1   15     0        # catchability devs fsh(,15) don't matter when we actually
hav an index
  -1   23     0
  #..
      -2     10     1              # catchability
      -2     15     0                                 # penalty
  -2   23     23                        # periodicity
      #..
      -3     10     0

      -3     15     0
      -3     23     23
  #..
  -4   10     0      #      JP PL Reg2
  -4   15     0
  -4   23     0
  #..
      -5     10     1

      -5     15     0

      -5     23     23
  #..
      -6     10     1

      -6     15     0

      -6     23     23
  #..
      -7     10     0

      -7     15     0

      -7     23     23
  #..
      -8     10     1

      -8     15     0

      -8     23     23
  #..
      -9     10     0             # PNG purse seine

      -9     15     0

      -9     23     0
  #..
      -10    10     1

      -10    15     0

      -10    23     23

      #..
      -11    10     0

      -11    15     0

      -11    23     23

      #..
  -12  10     0        #    PL-All-3
```

```
-12  15     0
-12  23     0
#..
     -13    10     1

     -13    15     0

     -13    23     23
#..
     -14    10     1

     -14    15     0

     -14    23     23

     #..
     -15    10     0

     -15    15     0

     -15    23     23

     #..
     -16    10     0

     -16    15     0

     -16    23     23

     #..
     -17    10     0

     -17    15     0

     -17    23     23
#..
     -18    10     0   # IDID_PHPH region 4 Seine  -  CPUE from K.B.

     -18    15     0

     -18    23     0
#..
     -19    10     1

     -19    15     0

     -19    23     23
#..
     -20    10     1

     -20    15     0

     -20    23     23

     #..
     -21    10     1

     -21    15     0

     -21    23     23

     #..
     -22    10     0

     -22    15     0
     -22    23     23

     #..
```

```
      -23    10     0

      -23    15     0

      -23    23     23

PHASE7
#
# ----------
#  PHASE 8
# ----------
  ./mfclo64 skj.frq 07.par 08.par -file - <<PHASE8
  2 88 1       #  Estimate age-dependent movement
  2 89 1       #  Use age-dependent movement pars

PHASE8
#
# ----------
#  PHASE 9
# ----------
  ./mfclo64 skj.frq 08.par 09.par -file - <<PHASE9
  2 73 1       # Estimate age-dependent M
  # 2 77 50    # penalty on 2nd derivative of Ma
  2 78 100       # Increase penalty on differences between M(a) and M(a+1)  (1st
derivative)
  2 79 1       # Minimize penalty be M(average) and M(a).
  2 171 1        # Include SRR-based equilibrium recruitment to compute unfished
biomass
PHASE9
# ----------
#  PHASE 10
# ----------
  ./mfclo64 skj.frq 09.par 10.par -file - <<PHASE10
  #  Estimate regional distribution of recruitment
  -100000 1 1
  -100000 2 1
  -100000 3 1
  -100000 4 1
  -100000 5 1
#-------------------------------optimize the period over which the SRR is to be
fitted
  2 199 124    # start time period for yield calculation [4.5.11]
  2 200 4      # end time period for yield calculation [4.5.11]
PHASE10
#
# ---------
#  PHASE 11
# ---------
  ./mfclo64 skj.frq 10.par 11.par -file - <<PHASE11
  2 145 -1          # penalty wt. for SRR
  2 146 1           # make SRR parameters active
  2 147 1           # no. time periods for recruitment lag
  2 148 20          # years (year quarters) from last year for avg. F
  2 155 4           # but not including last 4
  1 149 0           # turn off recruitment penalties against mean
  2 162 0           # Estimate steepness 0 IS THE DEFAULT   meaning not estimated
  2 163 0             # BH-SRR is parameterised using steepness. Value of 0 IS THE
DEFAULT meaning it is parameterized with steepness
  -999 55 1         # turn off fisheries for impact analysis [4.5.14]
  2 193 1               # Consider initial fishing effort in calculating initial
conditions
  1 1 3000          # how many function evaluations
  1 50 -3           # CONVERGENCE CRITERIA
  2 171 1               # unfished calculations by estimated recruitment or SRR
[4.5.14]
PHASE11
```

10.5 Initialization (ini) file

```
# ini version number
1001
# number of age classes
16
# tag fish rep
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
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0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
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0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
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0.5 0.5 0.5 0.5 0.586 0.586 0.5 0.5 0.586 0.586 0.5 0.5 0.586 0.586 0.5 0.764 0.764
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0.5  0.5  0.5  0.5  0.617594  0.617594  0.5  0.5  0.682725  0.682725  0.5  0.5  0.550997
0.550997 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5  0.5  0.5  0.5  0.617594  0.617594  0.5  0.5  0.682725  0.682725  0.5  0.5  0.550997
0.550997 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5  0.5  0.5  0.5  0.617594  0.617594  0.5  0.5  0.682725  0.682725  0.5  0.5  0.550997
0.550997 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
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0.550997 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
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0.550997 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
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# maturity at age
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# natural mortality (per year)
0.4
# movement map
1 2 3 4
# diffusion coffs (per year)
0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
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# recruitment distribution by region
0.142 0.242 0.381 0.134 0.101
# The von Bertalanffy parameters
# Initial  lower bound  upper bound
# ML1
10 10 30
# ML2
88.317 60 100
# K (per year)
0.1965 0.05 0.4
# Length-weight parameters
8.6386e-06 3.2174
# sv(29)
0.75
# Generic SD of length at age
5.0747 1 9
# Length-dependent SD
0.56558 0 3
# The number of mean constraints
0
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