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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 2011 assessment of skipjack tuna in the western and central Pacific Ocean. The assessment uses the stock assessment model and computer software known as MULTIFAN-CL. The skipjack tuna model is age (16 quarterly age-classes) and spatially structured. The catch, effort, size composition, and tagging data used in the model are grouped into 18 fisheries (a change from the 17 fisheries used in the 2010 assessment) and quarterly time periods from 1972 through 2010.

The current assessment incorporates a number of changes from the 2010 assessment, including:

1. Updated catch, effort, and size data;
2. A revised standardised effort series for each region based on a new GLM analysis of catch and effort data from the Japanese distant-water pole-and-line fishery.
3. Adjustment of size frequency data based on observer sampling of skipjack, bigeye, and yellowfin size and species compositions, and adjustment for grab-sampling bias.
4. Changes to the modelling of the Philippines and Indonesia purse seine fisheries. These fisheries are separated into fishing activity in archipelagic waters, and fishing outside archipelagic waters to the east of longitude 125°E. Purse seine effort to the east of 125°E is included in the main associated purse seine fishery, apart from domestically-based vessels which are included in a new PI-ID domestic purse seine fishery.
5. Inclusion of tag releases and recoveries from the recent SPC-PTTP tagging programmes, which increases tagging data in the assessment by 50%.
6. Steepness, a parameter defining the shape of the stock recruitment relationship, was changed from 0.75 to 0.8 in the reference case, with alternative values of 0.65 and 0.95 included in sensitivity analyses.
7. Growth parameters were fixed at their values estimated in 2010.

In addition to these changes, a large suite of additional models were run to aid the development of the final “reference case” model. This reference case model is used as an example for presenting model diagnostics, but the most appropriate model run(s) upon which to base management advice will be determined by the Scientific Committee. The sensitivity of the reference model to key assumptions (i.e. regarding the stock recruitment relationship, the catch per unit effort time series, the purse seine catch and size data, the growth model, and the PTTP tagging data) were explored via sensitivity analyses. The results of these analyses should also be considered when developing management advice.

A number of trends in key data inputs were noted as particularly influential for the assessment results.

The large tagging data set, and associated information on tag reporting rates, is relatively informative regarding stock size. The relative sizes of fish caught in different regions are also indicative of trends in total mortality, mediated though growth, catch, and movement rates. The assessment is therefore very dependent on the growth model.

For the northern region, there was little contrast in the Japanese pole and line CPUE time-series. However, both the southern region Japanese pole and line CPUE time series showed increases early in the time series and declines at the end, with greater decline in region 2.

Overall, the main assessment results and conclusions are as follows.

1. Estimates of natural mortality are strongly age-specific, with higher rates estimated for younger skipjack.
2. The model estimates significant seasonal movements between the western and eastern equatorial regions. The performance of the fishery in the eastern region has been shown to be strongly influenced by the prevailing environmental conditions with higher stock abundance and/or availability associated with El Niño conditions (Lehodey *et al*. 1997). This is likely to be at least

partly attributable to an eastward displacement of the skipjack biomass due to the prevailing oceanographic conditions, although this dynamic cannot be captured by the parameterisation of movement in the current model.

3. Recruitment showed an upward shift in the mid-1980s and is estimated to have remained at a higher level since that time. This change in estimated recruitment is driven in the model by the CPUE data, and also by the tagging data, given the relative tag return rates from the SSAP and the RTTP tagging programmes. Recruitment in the eastern equatorial region is more variable with recent peaks in recruitment occurring in 1998 and 2004–2005 following strong *El Niño* events around those times. Conversely, the lower recruitment in 2001–2003 followed a period of sustained *La Nina* conditions. Recent recruitment is estimated to be at a high level, but is poorly determined due to limited observations from the fishery.

4. The biomass trends are driven largely by recruitment and fishing mortality. The highest biomass estimates for the model period occurred in 1998–2001 and in 2005–2007, immediately following periods of sustained high recruitment within the eastern equatorial region (region 3).

5. The biomass trajectory is influenced by the underlying assumptions regarding the treatment of the various fishery-specific catch and effort data sets within the model. The Japanese pole-and-line fisheries are all assumed to have constant catchability, with any temporal trend in efficiency assumed to have been accounted for by the standardization of the effort series. The CPUE trends are influential regarding the general trend in both recruitment and total biomass over the model period. In all regions there is a relatively good fit to the observed CPUE data, with some deterioration when PTTP tagging data are introduced.

6. The model also incorporates a considerable amount of tagging data that provides information concerning absolute stock size during the main tag recovery periods. Including the PTTP tagging data in the model resulted in higher estimates of recent biomass and MSY. Initial analyses of the data suggest some conflict with inferences from the CPUE time series about trends in abundance. Further work on both data sources is recommended.

7. Within the equatorial region, fishing mortality increased throughout the model period and is estimated to be highest in the western region in the most recent years. The impact of fishing is predicted to have reduced recent biomass by about 47% in the western equatorial region and 21% in the eastern region. For the entire stock, the depletion is estimated to be approximately 35%.

8. The principal conclusions are that skipjack is currently exploited at a moderate level relative to its biological potential. Furthermore, the estimates of $F_{current}/\tilde{F}_{MSY}$ and $B_{current}/\tilde{B}_{MSY}$ indicate that overfishing of skipjack is not occurring in the WCPO, nor is the stock in an overfished state. These conclusions appear relatively robust, at least within the statistical uncertainty of the current assessment. Fishing pressure and recruitment variability, influenced by environmental conditions, will continue to be the primary influences on stock size and fishery performance.

9. For the model assumptions investigated, there was only moderate variation in the estimates of stock status. The most influential assumptions involved steepness and growth. There are insufficient data to estimate steepness reliably within the assessment model and many of the key management quantities are strongly influenced by the values assumed. Growth and its variation in space, through time, and among individuals is not well understood. However, only a limited range of assumptions was investigated in this assessment, and as a result the true level of uncertainty is likely to be under-estimated. A range of other assumptions in the model should be investigated either internally or through directed research. Further studies are required to refine our estimates of growth and reproductive potential, including spatio-temporal variation; to examine in detail the time-series of size frequency data from the fisheries, which may lead to refinement in the structure of the fisheries included in the model; to consider size-based selectivity processes in the assessment model; to continue to improve the accuracy of the catch estimates from a number of key fisheries; to refine the methods used to adjust catch and size data in the purse seine fisheries; to refine the methodology and data sets used to derive CPUE abundance indices from the pole and line fishery; to refine approaches to integrate the recent tag release/recapture data into the

assessment model; and to develop more formal and rigorous methods for prioritizing the many available research options.

10. ***Based on estimates of* $F_{current}/\tilde{F}_{MSY}$ *and* $B_{current}/\tilde{B}_{MSY}$ *from the reference model and associated sensitivity grid, it is concluded that overfishing of skipjack is not occurring in the WCPO, nor is the stock in an overfished state.*** These conclusions appear relatively robust, at least within the statistical uncertainty of the current assessment. Although the current (2006-2009) level of exploitation is below that which would provide the maximum sustainable yield, recent catches have increased strongly and the mean catch for 2006-2009 of 1.5 million tonnes is equivalent to the estimated MSY at an assumed steepness of 0.8, but below the grid median estimate of 1.9 million tonnes. Maintenance of this level of catch would be expected to decrease the spawning stock size towards MSY levels if recruitment remains near its long-term average level. Fishing mortality and recruitment variability, influenced by environmental conditions, will both continue to affect stock size and fishery performance.

1 Background

1.1 Biology

Surface-schooling, adult skipjack tuna (*Katsuwonus pelamis*) (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, poleward-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. 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).

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}) than 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.

1.2 Growth

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.

1.3 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 distant-water and offshore pole-and-line fleets, 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 distant-water and offshore pole-and-line fleets operate over a large region in the WCPO (
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Figure 1). 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 and 1971, 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, Taiwan 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.

The combined distribution of skipjack catch by these fleets shows tropical (mainly purse seine) and temperate (Japan-based pole-and-line and purse seine) components (Figure 1).

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 reached 1.6 million mt[4] in 2009 (Figure 2). 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 region (region 2) (Figure 3). During the 1990s, 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

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[4] 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 2010). These catches are somewhat less than the unadjusted catches reported for example in Williams and Terawasi (2011).

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 2005-2009 the average catch in region 2 was 407,000 mt in the associated fishery and 276,000 mt in the unassociated fishery, while in region 3 the average was 145,000 mt in the associated fishery and 108,000 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 Williams 2011) and for the selection bias in grab samples (spill-sample corrected purse seine estimates). This work used observer sampling data to estimate the SKJ/YFT/BET species composition, while the S_BEST method used the sampling data to estimate the YFT/BET species composition. 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. For the last decade, the corrected annual catch estimates are lower than the uncorrected catch, depending on the component of the purse seine fishery (Figure 6). The higher, uncorrected catches (S_BEST) were incorporated in the stock assessment as an alternative catch scenario.

1.4 Previous assessments

Since 2000, stock assessments of the western and central Pacific skipjack stock have been undertaken using MULTIFAN-CL (Fournier *et al.* 1998;Bigelow *et al.* 2000;Hampton and Fournier 2001a;Hampton 2002;Langley *et al.* 2003a;Langley *et al.* 2005;Langley and Hampton 2008;Hoyle *et al.* 2010). This paper updates the previous assessments and investigates sensitivities to assumptions regarding the various data sets incorporated in the analysis.

2 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. The details of these data and their stratification are described below.

2.1 Spatial stratification

The geographical area considered in the assessment corresponds to the western and central Pacific Ocean Ocean from 45°N to 20°S and from oceanic waters adjacent to the east Asian coast to 150°W. The assessment model area comprises three regions (

Figure 1), with a single region north of 20N, and two equatorial regions 20°S to 20°N, with the western equatorial region from 120°E to 170°E, and eastern equatorial from 170°E to 150°W. 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.

2.2 Temporal stratification

The time period covered by the assessment is 1972–2010. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec).

2.3 Definition of fisheries

MULTIFAN-CL requires the definition of "fisheries" that consist of relatively homogeneous fishing units. Ideally, the fisheries so defined will have selectivity and catchability characteristics that do not vary greatly over time and space, although in the case of catchability some allowance can be made for time-series variation. For most pelagic fisheries assessments, fisheries defined according to gear type, fishing method and region will usually suffice.

For this analysis, pole-and-line fishing activity was stratified by national fleet and region. The Japanese pole-and-line fleet in non-equatorial regions was further stratified by distant-water and offshore categories because of the different operational characteristics of these component fleets. 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.

Size frequency data on skipjack catches from a long history of Japanese research longline cruises in the WCPO were also available for this analysis; therefore, a research longline fishery was defined to hold these data.

Two changes were made to the fishery definitions from the 2010 assessment. The first was to alter the definitions of the associated and unassociated purse seine fisheries to match those used in the bigeye and yellowfin stock assessments. The small number of sets with unknown set type and sets on whales and whale sharks were included in the associated fishery rather than the unassociated.

The second significant change was the restructuring of the purse-seine fisheries from the Philippines and Indonesian fleets. In previous assessments, these fisheries were included as a component of the Philippines and Indonesian domestic fisheries (PH DOM 2 and ID DOM 2). However, newly available data revealed differences in the spatial distribution of the purse seine catch and the length composition of the associated catch relative to the other gear types, which warranted the additional resolution of these fisheries. The Philippines and Indonesian internationally-based industrial purse-seine fishery operating to the east of 125° E longitude is included within the generic purse seine fisheries within region 3 (PS ASS 2 and PS UNS 2), while the purse seine fisheries operating within the national archipelagic waters were retained within the respective domestic fisheries (PH DOM 2 or

ID DOM 2). A new fishery was defined for the domestically-based purse-seine fisheries that operate beyond the national archipelagic waters and to the east of 125° E longitude (PHID DOM PS 2).

Overall, 18 fisheries were defined in the analysis (Table 1) compared to the 17 fisheries defined in the 2010 assessment.

2.4 Catch and effort data

2.4.1 Catch and effort data updates and structuring

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. In all cases, catches were raised, as appropriate, to represent the total retained catches by area/time strata. Discarded catches were not included in the analysis. Total catches from 2010 are not considered complete due to late or incomplete reporting of catches from a number of the purse-seine fleets.

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 (Figure 5);
- 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 (originally only US) and increasing size and efficiency of the fleet.
- The steady increase in catch for the domestic fisheries of Indonesia and the Philippines.

As outlined in Section1.3, two alternative sets of purse-seine catch data were used in the assessment. The first set consisted of uncorrected catches extracted from the OFP database of reported catches aggregated by 1° latitude, 1° longitude, month and flag. Recent studies have shown that these catch estimates are likely to over-estimate the actual catch of yellowfin due to inaccurate reporting of the species catch composition on logsheets (Hampton and Williams 2011) and biases in the observer sampling procedures (grab sampling) (Lawson 2009;Lawson 2010;Lawson and Sharples 2011). To address these biases, the catch data were corrected using a three-species disaggregation of the total purse seine catch using observer sampling data corrected for selection bias of grab sampling using the results of paired grab and spill samples. This resulted in lower estimates of skipjack catch, particularly from associated sets (Table 2,). Uncertainty remains regarding these new estimates; however, on balance, the corrected catches are considered to be more reliable than the uncorrected catches. The corrected catches were used as the principal catch series in the assessment, while the uncorrected catches were incorporated in a sensitivity analysis (see below).

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. CPUE plots for each fishery (apart from those having missing effort, as noted) are shown in Figure 8.

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. For the equatorial purse seine fisheries, fishing day (including searching) was used as the measure of fishing effort.

2.4.2 CPUE and standardised effort time series

Revised standardised effort series for certain fisheries were used in the current assessment. For the Japanese pole-and-line fisheries (offshore (OS) and distant-water (DW)), the revised standardised effort time-series were estimated using General Linear Model (GLM) analyses of operational catch and effort data (Kiyofuji *et al.* 2011). Separate analyses were conducted for each region, for the distant-water and offshore fleets.

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.

The GLM analyses provided three types of year effect, based on the binomial, lognormal offset, and lognormal positive GLMs (Langley *et al.* 2010). These year effects were modified as follows from the values reported by Langley *et al.* (2010) and Kiyofuji et al. (2010), to provide two types of abundance indices with standard errors: the delta lognormal, and an index based on the binomial alone.

1. The binomial indices were transformed with the inverse logit function to provide annual indices of daily probability of reporting some catch for a standard vessel, $p(t) = \frac{e^{K+alpha_t}}{1+e^{K+alpha_t}}$. The parameter *K* was adjusted to ensure that the average *p(t)* was equal to 0.9 in the 1970's in the equatorial regions (DW indices) and 0.68 in the 1970's and 1980's in the northern region (OS indices). In each case, these average *p(t)* values were consistent with the observed rates of positive catches.

   The lognormal positive year effects were exponentiated to provide indices of catch rate β_t for days when fish were caught. The product $I_t = p_t \beta_t$ was the delta lognormal index of abundance.

   The coefficient of variation of the delta lognormal CPUE estimates was calculated as follows. Upper and lower 95% confidence limits were estimated for the binomial and lognormal positive indices, based the 95% CI's of the individual year effects. Conservative upper confidence limits for the delta lognormal were estimated from the product of the binomial and lognormal upper limits, and the same approach was taken for the lower limits. The overall interval was assumed to be symmetrical, with its width the distance between the upper and lower limits. The assumed standard deviation, which is used to assign penalties, was set at ¼ of the width of the confidence interval.

2. The binomial indices *p(t)* were transformed with the function $\mathrm{I_t} = -\log(1 - \mathrm{p_t})$. This transformation is based on the assumption that a single fish in a habitat of certain size has a probability a of being caught by one unit of fishing effort exerted within that habitat. Then with one unit of effort, the probability that 1 fish escapes from fishing is $(1 - \mathrm{a})$.

   If we assume that captures (and escapes) are independent of each other[5] we have for an abundance of N fish, the probability N that fish escape from fishing is $(1 - \mathrm{a})^{\mathrm{N}}$.

   Therefore, the probability that at least 1 fish is caught is $1 - (1 - \mathrm{a})^{\mathrm{N}}$.

   Now the probability that at least one fish is caught with one unit of effort at a particular time t is exactly the probability $\mathrm{p(t)}$ that is estimated by the binary GLM. So we have

   $$\mathrm{p(t)} = 1 - (1 - \mathrm{a})^{\mathrm{N(t)}}$$

   which leads to

   $$\mathrm{N(t)} = \frac{\log(1 - \mathrm{p(t)})}{\log(1 - \mathrm{a})}$$

   where $\log(1 - \mathrm{a})$ is a constant less than zero (since a is less than 1). Therefore $\mathrm{I_N(t)} = -\log\big(1 - \mathrm{p(t)}\big)$ is an index of abundance.

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[5] Of course independence is not a good assumption for schooling fish, but in that case we consider catch of schools rather than catch of individual fish. *N* will then be the abundance of schools, which is proportional to the abundance of individuals.

The standard deviations of the transformed indices of abundance were assumed to be the same as the standard deviations of the individual year effects in the binomial GLM.

The delta lognormal index of abundance was used in the reference case, and the alternative index was applied as a sensitivity analysis and as part of the grid. Both sets of indices are shown in Figure 6, along with the corresponding indices from 2010. Ratios of the 2011 indices divided by the 2010 indices show a step-change increase after 1984 in the 2011 indices for regions 2 and 3 (Figure 7).

For the northern pole and line fishery, indices were generally only available for quarters 2 and 3. Comparatively little fishing occurs in the first and fourth quarters, due to lack of available skipjack. An additional index value of 1/10th of the mean CPUE was added to the first quarter of each year in the northern Japanese offshore pole and line fishery (region 1), to reflect the lack of available fish and to inform the model about relative availability.

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.

2.5 Length-frequency 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 9.

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

For the equatorial purse-seine fleet, length data have been collected from a variety of port sampling and observer programmes since the mid-1980s. Most of the early data is sourced from the U.S. National Marine Fisheries Service (NMFS) port sampling programme for U.S. purse seiners in Pago Pago, American Samoa and the US purse-seine multilateral treaty observer programme, managed by the Forum Fisheries Agency. Since the early 1990s, Pacific Island national port sampling and observer programmes on other purse seine fleets have provided additional data.

The length frequency data collected by observers are susceptible to bias due to the grab sampling procedure (Lawson 2011). For the current assessment, a length-based correction factor was applied to the length frequency samples to correct for this source of bias. The bias correction resulted in a decline, on average, in the overall average length of the fish in the length samples from both the associated and unassociated purse-seine fisheries (PS ASS and UNASS, 2 and 3) (Lawson 2011, Figure 2). Insufficient data were available to correct the length samples from the period before 1996 and hence these data were excluded from the current assessment.

Some fisheries have not been consistently sampled at the same levels over time (Figure 9). Also, for some years, it was not possible to discriminate samples for the Japanese offshore fleet from those of the Japanese distant-water fleets in the northern region. The samples were therefore assigned to one fleet in each region, but the selectivity coefficients for these fisheries were grouped so that they were, in effect, estimated from the same length-frequency data.

Size composition data for the Philippines domestic fisheries 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 from under the National Stock Assessment Project (NSAP) were included in the current assessment. Despite the large catch taken by the Indonesian domestic fishery, only limited length samples from the mid 1980s are available for the fishery. Few usable size data were available for the PH-ID domestic purse seine fishery in region 2, and this fishery's selectivity was linked to the associated purse seine fishery in region 2.

The most consistently sampled fisheries were the Japanese pole-and-line fisheries, the equatorial purse-seine fisheries and the longline fisheries. The pole-and-line fisheries in the northern region generally catch smaller fish than the equatorial fisheries (regions 2 and 3), (Figure 10). 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 no systematic trend in the size composition was evident in region 3 (Figure 10).

There appear to be spatial patterns in the sizes of skipjack available (Hoyle, Kleiber, Davies, Harley, and Hampton 2010, Appendix 2). Some of the size trends that are apparent in some fisheries appear at least partly due to changes in sampling location. To reduce the effects of these size changes on the model, the weight (effective sample size) of all length frequency data was reduced by 50%.

Longline fisheries principally catch large skipjack, within the 50–90 length range (Figure 10). There is an indication of an increase in the length of skipjack caught over the last decade, some of which appears to be due to movement of fishing location.

The equatorial purse-seine fisheries all catch skipjack of a similar size, with the exception that fish from school (unassociated) sets are generally larger than fish caught from associated (log and FAD) sets in both region 2 and 3 (Figure 11). Purse seine data were based on analyses of observer sampling data (Lawson 2011). For region 2, there was a gradual decline in the size of fish caught by both associated and unassociated sets types from the mid 1980s to recent, while there was no systematic trend in the size composition from the region 3 purse-seine fisheries (Figure 11). Given the strong patterns in the purse seine data, and the contributions of multiple fleets, the effective sample sizes of all purse seine data was down-weighted by 80%. In future this problem might be resolved by applying spatial size stratification (Hoyle and Langley 2011).

Size data from the Philippines domestic fishery showed very strong temporal variation, with periods of large and small sizes. Such large size variations most likely reflect sampling from different fisheries with different selectivities, which will cause problems for a length-based model that assumes constant selectivity. The size data were down-weighted to 1/25th of the previous level, equivalent to a sample size of 2 fish. This left enough weight in the likelihood for the model to estimate average selectivity, but reduced the risk of imposing bias on estimates of total mortality.

2.6 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 1988–2009. Tagging data from the Pacific Tuna Tagging Programme (PTTP) were available for the period 2006-2011.

Japanese tags released in all regions were used in the analysis. This is in contrast to assessments before 2010, when Japanese tag releases south of 15°N were not included in the assessment because of suspected atypical tag reporting rates of these tags compared to the SPC tags. New functionality was added to MULTIFAN-CL in 2010 that permitted different reporting rates to be estimated by release group and fishery.

Tag release and recovery data from the PTTP tagging programme 2006–09 were also included in the assessment. The effects of adding these data were examined in a sensitivity analysis.

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

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 415,424 releases were classified into 191 tag release groups (Table 3). Release groups from 2010 and 2011 were excluded because many recaptures from these release groups within the model period are yet to be reported. The returns from each size-class of each tag release group (36,731 tag returns in total) were then classified by recapture fishery and recapture time period (quarter).

Most of the tag releases occurred within regions 2 and 3 during 1977–80, 1989–92, and 2006-09 by tagging programmes administered by SPC (Figure 12). There were also tag releases by Japanese research programmes in the two regions during 1988–2008. Tagging in region 1 was almost exclusively conducted by Japanese research programmes (Figure 12).

The total tag recoveries were dominated by recoveries from those fisheries operating in regions 2 and 3, principally the purse-seine fisheries, the domestic and distant-water pole-and-line fisheries, and the domestic fisheries in the Philippines and Indonesia (Table 3). For these two regions, most of the recoveries were from releases in the same region, although there was some transfer of tags between the two regions, particularly from region 2 to region 3 (Figure 13). Region 1 also received tags from region 2 (Figure 13). Of tags released in region 2 that were recaptured in region 1, most were recaptured in quarters 1 and 4 (Figure 14).

The length at recovery of tagged fish was broadly comparable to the length composition of the main method fishery operating in each region (Figure 15). Fish tagged in region 2 and recovered in region 1 were generally larger than recoveries of fish tagged and recaptured in region 1 (Figure 15). Similarly, fish tagged in region 3 and recovered in region 2 were generally larger than fish tagged and recaptured in region 2; and vice versa for fish tagged in region 2 and recovered in region 3.

Most of the tag recoveries occurred either within the same quarter as the release occurred or within the subsequent six-month period, and very few recoveries occurred beyond 2 years after release (Figure 16). There was a higher level of mixing of tags between regions the longer the tags were at liberty, although for region 2 to region 1 the initial rate of transfer appears to be relatively high (Figure 16).

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.

3 Model description – structural assumptions, parameterisation, and priors

As with any model, various structural assumptions have been made in the skipjack model. Such assumptions are always a trade-off to some extent between the need, on the one hand, to keep the parameterization as simple as possible, and on the other, to allow sufficient flexibility so that important characteristics of the fisheries and population are captured in the model.

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. (2003). The main structural assumptions used in the skipjack model are discussed below and are summarised for convenience in Table 5. 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.

3.1 Population dynamics

The model partitions the population into three 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. For the purpose of computing the spawning biomass, we assume a fixed maturity schedule occurring at age-class 3. The population is "monitored" in the model at quarterly time steps, extending through a time window of 1952–2010. The main population dynamics processes are as follows:

3.1.1 Recruitment

"Recruitment" in terms of the MULTIFAN-CL model is the appearance of age-class 1 fish (i.e. fish averaging 10 cm given the current growth curve) in the population. The results presented in this report were derived using four recruitments per year, which are assumed to occur at the start of each quarter. This is used as an approximation to continuous recruitment.

Recruitment was allowed to vary independently between each of the three MFCL model regions. 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 time-series variation in spatially-aggregated recruitment was somewhat constrained by a lognormal prior.

Spatially-aggregated recruitment was assumed to have a weak relationship with the parental biomass via a Beverton and Holt stock-recruitment relationship (SRR). The SRR was incorporated mainly so that a yield analysis could be undertaken for stock assessment purposes. We therefore opted to apply a relatively weak penalty for deviation from the SRR so that it would have only a slight effect on the recruitment and other model estimates (see Hampton and Fournier 2001c, Appendix D).

The steepness (h) of the stock-recruitment relationship is defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Mace and Doonan 1988;Francis 1992;Maunder *et al.* 2003). A formal derivation of the SRR parameterization and the contribution of the steepness prior to the log-likelihood are given in Hampton and Fournier (2001c). It is rare for stock assessment models to reliably estimate steepness. Steepness was therefore fixed at a value of 0.8, consistent with other WCPFC tuna stock assessments, and based on conclusions of review of steepness values for tunas (Harley 2011). Alternative steepness values of 0.65 and 0.95 were examined as sensitivity analyses and as part of the grid. The recommendations of the PAW also included a model option that estimated the value of steepness internally in the model. In this case, a beta-distributed prior was assumed on steepness of the SRR with a lower bound at 0.2, a mode = 0.85, and standard deviation = 0.16 (equivalent to previous assessments).

3.1.2 Age and growth

The standard assumptions made concerning age and growth in the MULTIFAN-CL model are (i) the lengths-at-age are assumed to be normally distributed for each age-class; (ii) the mean lengths at age are assumed to follow a von Bertalanffy growth curve; (iii) the standard deviations of length for each age-class are assumed to be a linear function of the mean length-at-age. For any specific model, it is necessary to assume the number of significant age-classes in the exploited population, with the last age-class being defined as a “plus group”, i.e. all fish of the designated age and older. This is a common assumption for any age-structured model. For the results presented here, 16 quarterly age-classes have been assumed. Growth was not estimated in the model, except for one sensitivity analysis.

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.

3.1.3 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.* 2003 for details). Movement is parameterised as the proportion of fish in a given region that move to the adjacent region. For age-independent movement, there are two transfer coefficients for each boundary between the regions, with movement possible in both directions. We allowed each of these coefficients to be age-dependent in a simple linear fashion, enabling the rate of movement across the region boundary to increase or decrease as a log-linear function with age. Four seasonal movements were allowed, each with their own movement coefficients.

A prior of 0.1 is assumed for all movement coefficients, inferring a relatively high mixing rate between regions. A small penalty is applied to deviations from the prior.

3.1.4 Natural mortality

Natural mortality was estimated and assumed to be age-specific, but invariant over time and region. Penalties on the first difference, second difference, and deviations from the mean were applied to restrict the age-specific variability to a certain extent.

3.1.5 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 and the average recruitment in quarters 2–20 in each region. This assumption avoids having to treat the initial age structure, which is generally poorly determined, as independent parameters in the model.

3.2 Fishery dynamics

3.2.1 Selectivity

Selectivity is fishery-specific and was assumed to be time-invariant. Selectivity coefficients have a range of 0–1, and for the research longline fisheries were assumed to increase with age and to remain at the maximum once attained. In the past, selectivities for all Japanese pole-and-line fisheries were constrained to be equal. Two Japanese pole-and-line selectivity curves were estimated: one for region 1 and one for the equatorial fisheries. Selectivity for the Philippines-Indonesia domestic oceanic purse seine fishery was shared with the region 2 equatorial purse seine fishery, due to lack of available size data for the former fishery. Selectivities for all other fisheries were independently estimated.

The selectivities at age were estimated using a cubic spline parameterisation. Each selectivity function was parameterised with five nodes allowing considerable flexibility in the functional form while minimising the number of parameters required to be estimated. The coefficients for the last two age-classes, for which the mean lengths are very similar, are constrained to be equal for all fisheries.

3.2.2 Catchability

Annual average catchability was held constant over time for all the Japanese offshore and distant-water pole-and-line fisheries and the Japanese offshore purse-seine fishery. In initial runs it was assumed to be equivalent for the three principal pole-and-line fisheries. For all other fisheries for which effort data were available, catchability was allowed to vary over time (akin to a random walk). Random walk steps were taken every two years, and the deviations were constrained by a prior distribution of mean zero and CV (on the log scale) of 0.7.

Catchability was allowed to vary seasonally for all fisheries, with the exception of the Philippines and Indonesian archipelagic fisheries, and research longline fisheries.

3.2.3 Effort variability

Effort deviations, constrained by prior distributions of zero mean, were used to model the random variation in the effort – fishing mortality relationship. For all fisheries except the Japanese pole and line fisheries with standardized CPUE, we set the prior variance at a high level (equivalent to a CV of about 0.7 on the log scale), to allow the effort deviations to account for fluctuations in the catch caused by variation in real effort. For the fisheries with standardized CPUE, the variance was set at the level estimated in the data standardization.

3.3 Dynamics of tagged fish

3.3.1 Tag mixing

In general, the population dynamics of the tagged and untagged populations are governed by the same model structures and parameters. An obvious exception to this is recruitment, which for the tagged population is simply the release of tagged fish. 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. 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 desensitises 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.

3.3.2 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. Tag reporting rates were estimated separately by fishery group and tagging programme.

Assessments before 2010 assumed fishery specific reporting rates that were 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 as the composition and operation of individual fisheries change. The inclusion of the tagging data from the PTTP required fishery tag reporting rates specific to the individual tagging programmes. This flexibility in the estimation of tag reporting rates has been accommodated in recent developments to MFCL.

Tags in MULTIFAN-CL are grouped into tag release groups, which represent the tags released by quarter x region x tagging programme strata. The new approach permits individual reporting rate parameters to be estimated for each release group for each fishery. This, however, would require too many parameters to be estimated, so parameters were shared among specified release groups and fisheries, as follows:

a. Reporting rates were grouped for all Japanese fisheries, as in previous assessments.

b. Equatorial purse seine fisheries within each region shared reporting rates. This is a change from last year when purse seine reporting rates were shared across regions. The change was motivated by the observation that the purse seine fisheries are made up of flags with different reporting rates, and different flags fish to a different extent in each region.

c. The Papua New Guinea, Solomon Islands, and Fiji Islands pole and line fisheries, and the Philippines and Indonesia domestic fisheries each had their own reporting rate parameters. The Philippines domestic fisheries reporting rate was shared with the Philippines-Indonesia oceanic purse seine fishery.

For each fishery or group of fisheries, separate reporting rates were estimated for a) Japanese tagging programmes, b) the SSAP tagging programme, c) the RTTP tagging programme, and c) the PTTP tagging programme. This differentiation is made because reporting rates among these programmes may have differed because of variation in the levels of publicity, fleet cooperation and resources devoted to tag recovery.

While the model has the capacity to estimate tag-reporting rates, we used a penalised likelihood approach to assign prior distributions (similar to Bayesian priors) to the release-group and fishery-specific reporting rates.

Relatively informative priors were provided for reporting rates for the RTTP and PTTP purse seine fisheries, as independent estimates of reporting rates for these fisheries were available from tag-seeding experiments and other information (Hampton 1997;Hoyle 2011). The external estimates of reporting rate for the purse-seine fisheries were modified by the estimates of average tag loss and tagger-specific mortality of tagged fish. The proportions of tag returns that were provided with sufficient information to allow them to be classified to the various fisheries and time periods in the model were also incorporated into the reporting rate priors (Hoyle 2011). For the various Japanese pole-and-line fisheries, we have no auxiliary information with which to estimate reporting rates, so relatively uninformative priors were used for these fisheries – the reporting rates were essentially independently estimated by the model. For tags released within a tagging program, reporting rates were assumed to be constant through time.

3.4 Observation models for the data

Three data components contribute to the log-likelihood function – the total catch data, the length-frequency data and the tagging data. The observed total catch data were assumed to be unbiased and relatively precise, with the SD of residuals on the log scale being 0.07.

The probability distributions for the length-frequency proportions were assumed to be approximated by robust normal distributions, with the variance determined by the sample size and the observed proportion. The effective sample size is assumed to be, at most, 0.025 times the actual sample size, which is limited to a maximum of 1000. This assumption recognises that length-frequency samples are not truly random and that even very large samples (greater than 1000) taken from a particular fishery in a quarter would have a variance equivalent to a random sample of 25 fish. Reasons for this reduction from the effective sample size of 50 fish used in previous skipjack assessments are discussed in section 2.5 on length frequency data.

A log-likelihood component for the tag data was computed using a negative binomial distribution in which fishery-specific variance parameters were estimated from the data. 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 parameterization 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 would then provide a more realistic weighting of the tag return data in the overall log-likelihood and allow the variability to impact the confidence intervals of estimated parameters. A complete derivation and description of the negative binomial likelihood function for tagging data is provided in Hampton and Fournier (2001a) (Appendix C).

3.5 Principal model runs

At a preparatory meeting (Noumea, April 2011), a range of model changes and sensitivity analyses were considered and agreed for the current assessment (SPC-OFP 2011). These analyses included (1) S_BEST purse seine catch estimates (based on logbooks) rather than estimates corrected with analyses of spill sampling data; (2) a range of values for steepness, including estimation of steepness; (3) inclusion of PTTP tagging data; (4) alternative CPUE time series; and (5) alternative growth curves.

These options were considered as sensitivity analyses. Additional changes were made during model development, and the effect of each significant change is presented in the run sequence. Each change is described in Table 6, along with some potential changes that were not carried forward.

In addition, options 1, 2, 4 and 5 were included in a factorial grid, in which all combinations of model options were considered.

3.6 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 was performed by an efficient optimization using exact derivatives with respect to the model parameters. Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters. A bash shell script, doitall.skj, documenting the phased procedure is provided in Appendix A. Some parameters were assigned specified starting values consistent with available biological information. The values of these parameters are provided in the skj.ini file (Appendix B)[6].

The Hessian matrix computed at the mode of the posterior distribution was used to obtain estimates of the covariance matrix, which was used in combination with the Delta method to compute approximate confidence intervals for parameters of interest.

3.7 Stock assessment interpretation methods

Several ancillary analyses are conducted in order to interpret the results of the model for stock assessment purposes. The methods involved are summarized below and the details can be found in Kleiber et al. (2003). 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.

3.7.1 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, 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 $\frac{B_t}{B_{0t}}$ can be interpreted as an index of fishery depletion. The computation of unexploited biomass includes an adjustment in recruitment to acknowledge the possibility of reduction of recruitment in exploited populations through stock-recruitment effects.

3.7.2 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 α and β. 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 total ($\tilde{B}_{MSY}$) and adult ($\widetilde{SB}_{MSY}$) biomass at *MSY* can also be determined. The ratios of

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[6] 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. (2003).

the current (or recent average) levels of fishing mortality and biomass to their respective levels at MSY are of interest as reference points. These ratios were also determined for the principal assessment model with alternative values of steepness assumed for the SRR. The confidence intervals of these metrics were estimated using a likelihood profile technique.

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 2006–2009. The last year in which a complete set of catch and effort data is available for all fisheries is 2009. We do not include 2010 in the average as fishing mortality tends to have high uncertainty for the terminal data year of the analysis and the catch and effort data for this terminal year are usually incomplete.

The MSY based reference points were also computed using the average annual F_a from each year included in the model (1972–2010). 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.

3.8 Comparison with the 2010 assessment

There are six main differences in the input data and structural assumptions of the current assessment compared to the base-case from the 2010 assessment.

i. Fixing the steepness parameter (*h*) of the SRR at 0.8 in the reference case rather than 0.75 as used in the 2010 assessment.
ii. Update of CPUE indices derived from operational catch and effort data from Japanese pole and line fisheries. The 2011 standardized CPUE indices incorporated vessel identifiers prior to 1984, resulting in some differences in the region-specific CPUE indices (Kiyofuji, Uosaki, and Hoyle 2011).
iii. The correction of the purse-seine length frequency data to account for sampling bias and the exclusion of length data from the fisheries prior to 1996 (bias correction not available) (Lawson 2011).
iv. A revision of the corrected (spill sample) purse-seine fishery catch estimates (Lawson & Sharples 2011).
v. Refinement to the Philippines and Indonesian fishery definitions, including the definition of a new fishery encompassing the Philippines and Indonesian purse-seine fleets operating east of 125° E and outside of archipelagic waters.
vi. Inclusion of the PTTP tagging data.

For comparison to the 2010 stock assessment, a step-wise sequence of models was formulated that modified the 2010 base-case model to sequentially incorporate each of the changes identified above.

3.9 Sensitivity analyses

The sensitivity analyses focused on a number of key model uncertainties. Initially, the sensitivities were examined as a single change to the reference model, and a more comprehensive grid-based (factorial) analysis of the range of sensitivities was undertaken to investigate the interactions between the various sensitivities (see below).

The key uncertainties identified in the current assessment are the assumed level of steepness of the SRR, catch history of the purse-seine fisheries, the CPUE time series, and the growth curve.

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.

As noted above, corrected catches from the purse-seine fisheries (PS ASS, PS UNA 2 & 3) are lower than previously reported, principally for the associated fisheries (Figure 4). However, the current estimates are based on limited sampling data and are considered preliminary. The sensitivity of the model results to the assumed level of purse-seine catch was examined by comparing the reference model results with a model with the purse-seine catches determined using the previous methodology ("*S_BEST*").

The assessment model was not able to estimate growth consistently, due to the lack of strong length modes in the length frequency data. Growth was therefore fixed at the level estimated in the 2010 stock assessment (Hoyle, Kleiber, Davies, Harley, and Hampton 2010), and two published growth estimates were used as sensitivity analyses. Both alternative growth curves were obtained from daily growth rings on otoliths, the first set from waters near Papua New Guinea (Leroy 2000), and the second set from waters in the western north Pacific, mostly north of 25N (Tanabe, Kayama, and Ogura 2003). Finally, a run was conducted in which growth was estimated.

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 72 combinations of the following factors: purse-seine catch history (corrected or uncorrected catch), the CPUE series (delta lognormal or binomial), the steepness of the SRR (0.65, 0.80, or 0.95), the growth model (2010 estimate, Leroy, or Tanabe growth curve), and variability of length at age (2010 estimate or high variance). A separate model was run for each of the combinations in the grid.

4 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 (see Table 6) is also presented.

4.1 Run sequence

The current assessment paper describes a number of model runs. These models can be grouped into 3 main categories:

1. ***Development series***: Models used to help develop the final "reference" model. This series of models shows the impact of each change made to the 2010 base case model in transitioning to the current reference model.
2. ***The reference model***
3. ***Sensitivity models:*** Models derived from the sensitivity grid analyses, which explore (via one-off model structure changes) the sensitivity of key model derived outputs (e.g. biological reference points) to key assumptions in the reference model.

It is the reference model and associated sensitivity analysis models that form the basis of the conclusions regarding skipjack stock status provided in this paper.

4.2 Development model series

A series of figures shows the effects on total biomass and recruitment through time of stepwise changes, beginning with the WCPO model and the data used in the 2008 assessment. Each option is accompanied by its model number from Table 6. Biomass and recruitment trends are presented in Figure 17. Growth was fixed in all models leading up to the reference case.

4.2.1 Rerun with new version of MULTIFAN-CL

A repeat of the 2010 base case using the updated version of MULTIFAN-CL was done 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 2010.

4.2.2 Update catch, effort and size data

Updating the data to 2011 had a very large effect on the overall biomass trend (Figure 17), mostly due to the new CPUE time series, exhibiting a large increase in 1984 (Figure 6 and Figure 7). Estimated biomass was higher for the whole time series, but the largest increase occurred after 1984. Recruitment was lower throughout the time series, and natural mortality was lower for young fish than in the preceding model.

4.2.3 Adjust size frequency for spill sampling correction

Changes to the purse seine size data resulted in relatively little change to the biomass and recruitment time series. Growth is fixed and so the changed size data could not affect the growth curve. There was a slight reduction in average estimated biomass.

4.2.4 New ID/PH fishery structure

Changing to the new fishery structure, with changes to the Philippines and Indonesian fisheries, had quite a small effect on the model's biomass trends, with a small increase on average. It had more effect on recruitment, increasing it throughout the time series.

4.2.5 Add PTTP tag data

Adding the PTTP tag data increased average biomass throughout the time series, but particularly during the period of the PTTP, 2006-2010. It also resulted in a change to the trend with continuing decline at the end rather than a late increase.

4.2.6 Change steepness to 0.8

Changing the assumed steepness of the stock recruitment relationship had no effect on either the biomass or recruitment trends.

This model was the reference case.

4.2.7 Sensitivity analyses

Four issues were investigated as part of a sensitivity analysis. These were the use of the S_BEST purse seine catches and size data uncorrected for grab selectivity sampling bias, rather than the spill sampling purse seine catches and corrected size data; alternative CPUE time series; the inclusion of the PTTP tag data; alternative steepness values; and alternate growth curves. More detail on these results is given in later sections.

4.3 Reference case

Detailed results and diagnostics are presented for the reference case. Uncertainties in the reference case model are explored via a sensitivity analysis.

4.3.1 Fit of the model to the data, and convergence

A summary of the fit statistics for the reference case and sensitivity analyses is given in Table 8. Due to differences in the tag and effort data sets, the total likelihood values are not comparable between runs, except for the comparison between the reference case and the growth runs.

The fit of the model to the total catch data by fishery is mostly good (Figure 19), which reflects our assumption that observation errors in the total catch estimates are relatively small. The largest differences occur when tag data are available, because the expected rate of tag returns depends on the size of the catch, and therefore affects the catch likelihood. This is particularly apparent in the purse seine fisheries. There are also some moderately large deviates for the JP PL OS fishery.

For most fisheries, the size composition of individual length samples is consistent with the predicted size composition of the fishery-specific exploitable component of the population (Figure 20). The pole-and-line fisheries tend to catch skipjack within a relatively narrow length range and, for most fisheries there is limited contrast in the size of fish caught over the model period. However, several fisheries show changes in the sizes of fish caught through time. The two largest fisheries in region 1, the combined Japanese pole and line fisheries and the Japanese offshore purse seine fishery, caught consistently larger fish from 1995 onwards. Similarly, the region 2 Japanese pole and line fishery caught larger fish than expected after 1995. In contrast to the 2010 assessment, fish size did not trend smaller than expected in the western equatorial purse seine fishery 8, due to the spill sample size correction.

These temporal trends in the size of fish caught are not reflected in the model dynamics and may indicate changes in the length-based selectivity of skipjack between the two periods (Figure 20). One possible explanation is changes through time in the locations from which samples were obtained, since skipjack sizes are quite significantly area-dependent (Hoyle, Kleiber, Davies, Harley, and Hampton 2010). The average size increases in the region 2 Japanese pole and line fishery at about the time that the fishery moves out of the core skipjack area near the equator.

Similarly, the region 3 research longline fishery caught larger fish than expected after 1995, the region 2 longline fishery caught larger fish after 1980, and the region 1 longline fishery caught smaller fish after 2006. The research longline fishery data are included to inform the model that skipjack can grow to sizes larger than typically encountered by surface gears. However, the model is unable to fit both the large fish before 2006 and the small fish after 2006, which suggests that the fish after 2006 would be better omitted. Sizes are particularly spatially variable in longline size data, and their effect has been down-weighted in the likelihood to reflect the variability in the data. The length samples from the Philippines domestic fishery were highly variable among and within sampling periods (Figure 20 and Figure 21). The observed variation in the length composition is likely to reflect variation in the distribution of sampling effort between the individual fisheries that constitute the Philippines domestic fishery. The effect of these data has also been down-weighted in the likelihood to reflect this variability.

The model accurately predicts the number of short-term tag returns for fish both released and recaptured in region 2, but tends to over-predict recoveries after about 1 year. Recoveries of fish moving from region 1 to region 2, and vice versa, are also over-predicted (Figure 23). Recoveries in region 3, on the other hand, may be slightly under-predicted for releases in region 2 and region 3.

The fit of the model to the tagging data compiled by calendar date is presented in Figure 24, and in Figure 25 disaggregated by sampling programme. The aggregated fit is good, with low divergence between observed and predicted tag returns. Minor discrepancies are evident when the observed and predicted data are broken down by fishery groups (Figure 26), but these are not significant.

In contrast to previous assessments the Solomon Islands pole-and-line fishery tag returns are well predicted, with observed recoveries close to predicted (Figure 26). This better fit may be due to the greater freedom given to tag reporting rates in this assessment, which allows the model to compensate for different reporting rates between tagging programmes.

4.3.2 Tag reporting rates

Where possible, reporting rates were estimated separately by fishery and by tagging programme. Results are presented here for the Japanese tagging programmes, and for the SPC tagging programmes SSAP, RTTP, and PTTP.

There is considerable variation among fisheries in the estimated tag-reporting rates (Figure 27). The equatorial purse seine fishery reporting rates for SSAP releases were given a weak prior and relatively high reporting rates were estimated, with 0.63 in region 2 and 0.9 in region 3; for RTTP releases the estimates were slightly lower but higher than the prior mean of 0.46, with 0.58 in region 2 and 0.76 in region 3. For PTTP releases, estimates were only slightly above the priors, with 0.54 versus a prior mean of 0.52 in region 2 and 0.50 against a prior mean of 0.44 in region 3. Estimates for Japanese releases were considerably lower, at 0.18 in region 2, and 0.03 in region 3.

For Japanese fisheries, reporting rates for tags released during the SSAP (0.35), the RTTP (0.13), and the PTTP (0.08), were lower than for tags released by Japanese tagging programmes (0.47).

For the Solomon Island and Fiji pole-and-line fisheries, the estimated reporting rates for SPC tags were very high at 0.9 – the upper bound stipulated for all reporting rates. For Japanese tags however, their reporting rates were effectively zero.

The Philippines and Indonesian fisheries had higher reporting rates for tags released during the RTTP (0.65 and 0.56) than for the SSAP (0 and 0) or for Japanese tags (0 and 0). Reporting rates during the PTTP were estimated to be 0.7 and 0.15.

4.3.3 Age and growth

Attempts to estimate growth were unsuccessful. Depending on the starting point, the model estimated considerably faster growth than in the 2010 stock assessment, but the estimate may have been an unstable local minimum. It also appeared that estimated growth was frequently faster than the current understanding of skipjack growth rates from tagging and otolith studies. Examination of the length frequency data among fisheries revealed a lack of consistent modal progression through time from which to infer growth rates. The purse seine length frequency data have changed considerably with the spill sample size correction, perhaps masking modal progression and resulting in a worse fit to these data.

For the reference case, the growth curve was fixed at the 2010 estimate, to provide consistency. Given the uncertainty about growth, alternative growth curves were investigated. Two estimates for the western and central Pacific were available from the literature, one for the equatorial western Pacific (Leroy 2000) and one for the north western Pacific (Tanabe, Kayama, and Ogura 2003). All three curves are plotted (Figure 28), with the latter two curves offset so that they meet at about 25 cm, the length when significant numbers of skipjack start to occur in the size data.

The 2010 estimated growth rate was faster than determined by Tanabe et al. (2003) from daily otolith increments, and similar to the Leroy estimates up to about 55 cm. Age estimation from daily rings is thought to be effective up to about one year, i.e. a little over 55cm for the Leroy curve. The discrepancy between the Tanabe length-at-age and the Leroy and model estimates (up to 15 cm) is maintained for older age classes. They suggest that fish “recruit” into the model population (i.e. age class 1) at the second quarter following hatching.

Limited length data are included in the model from the younger age classes in the population, with only the Philippines fishery catching significant numbers of fish in the 20–30 cm length range and no observations of smaller fish in the sampled catches. Due to problems with variable selectivity through time, the Philippines size data were given low weight in the assessment.

4.3.4 Selectivity

Estimated selectivity functions are generally consistent with expectation (Figure 29). The pole-and-line fisheries have high selectivity for age-classes 4–6 and declining selectivity for the older age-classes, although selectivity increases again for older age classes where numbers are low. The purse seine fisheries select slightly smaller fish, beginning at 3 or 4 quarters of age. The associated purse seine fisheries have high selectivity for age-classes 3–6, while the unassociated purse seine fisheries select mainly ages 4-6. Selectivity of age classes 8–16 increases with age, which suggests that further investigation of the growth curve is warranted. Few fish remain in the older age classes, which both reduces the impact on model results of patterns that may appear counter-intuitive, and gives the model more freedom to produce them.

The domestic Philippines mixed fishery catches the smallest fish with relatively high selectivity for fish in the 2–3 age-classes, but also maintains some selectivity for older age classes reflecting the presence of some larger fish in the sampled catch. The research longline fisheries have been assumed to have a monotonically increasing selectivity with age.

4.3.5 Catchability

Estimated catchability trends are shown in Figure 30.

Catchability was assumed to be time-invariant for the Japanese offshore pole and line fishery in region 1 and the Japanese distant-water pole-and-line fisheries in regions 2 and 3,(as temporal trends in catchability are assumed to have been removed during the CPUE standardisation process), while temporal trends in catchability were estimated for the remaining fisheries.

Most notably, the model predicts increases in catchability for all of the purse seine fisheries to 1990, a short-term stabilisation or decline (particularly the FAD fisheries in area 2), and then increases, but with a sharp recent increase in region 3 during the 2000s (Figure 30). The most recent data show particularly high catchability for unassociated fisheries, which may be associated with the FAD closure.

Seasonal variability is strong for many of the pole-and-line fisheries, particularly for the Japanese fleets in region 1. This is partly explained by the imposition of a low assumed CPUE in season 1. Lower levels of seasonal variation in catchability are evident in the equatorial fisheries. Note that seasonal variability in CPUE might also be explained by seasonal variability in movement – this alternate hypothesis has not yet been examined in detail.

4.3.6 Effort deviations and fits to exploitable biomass

Time-series plots of effort deviations are useful to see if the catchability assumptions employed are appropriate, i.e. they result in even distributions of effort deviations about zero and no time-series trends. For most of the fisheries temporal trends in the effort deviates are minor (Figure 31), as expected given the flexible estimation of catchability trends. The relative lack of trend in the standardized PL fisheries in all regions indicates moderately low levels of data conflict – the model is able to fit to the information provided in the CPUE time series. This is also apparent in the close relationship between CPUE and exploitable biomass in regions 2 and 3 (Figure 32). In region 1 the model fits the CPUE is seasons 2 and 3, but is not able to fit the artificial season 1 CPUE.

4.3.7 Natural mortality

Natural mortality was estimated to be high for the young age classes (1–4 quarters), and declining steadily with increasing age up to age class 7 (Figure 33). There is a steady increase in estimated natural mortality for the older (9+) age-classes. Lower natural mortality was estimated for quarterly age classes 1 and 2 than for 3 and 4. This is due to the growth curve including small fish, about which there is little information, and so the age deviates are penalized towards the mean. The relative natural mortality of these age classes has no significant effect on the overall results of the stock assessment as these two initial age-classes do not contribute significantly to the fisheries.

4.3.8 Movement

A representation of the dispersal pattern resulting from the estimated movement parameters is shown in Figure 34. This figure shows the movement of the proportion of four age groups between each region by quarter. The following figure (Figure 35) presents the same information in terms of the biomass of the movement, i.e. taking into account the larger biomasses in the equatorial regions and varying biomass by age class. A small proportion moving from an area with a high population (e.g. region 2) may represent as many fish as a large proportion of fish from a small population (e.g. region 1).

The model estimates high movement coefficients from the northern region 1 to region 2 during quarters 2 and 4. These movements are high for all age classes, but higher for older age classes in quarter 2, and slightly higher for younger age classes in quarters 1 and 4. There are also high movement coefficients in the first quarter from region 1 to 3, and between regions 2 and 3 (Figure 34). Movement coefficients between other regions and at other times are estimated to be small.

The distribution of regional biomass by source region derived from a simulation using the movement coefficients is presented in Figure 36. The simulation indicates that the model estimates a relatively low degree of mixing for region 1, but moderate for regions 2 and 3. For example, the model estimates that about 70% of the biomass in region 3 is sourced from recruitment within the home region, with another 15% sourced from region 2 and 15% from region 1. Significant transfer of biomass is estimated between regions 2 and 3, matching past studies suggesting movement of skipjack biomass between these regions on a seasonal and inter-annual basis (e.g. Lehodey et al., 1997) in response to climate driven oceanographic processes.

The movement of fish from the northern region into region 2 is inconsistent with the observations from the tagging data which tend to show a general northern movement of fish from region 2 into region 1 (see Section 2.6). However, low recapture numbers and poor reporting rate estimates result in very little influence of the tagging data on model estimates for this region. The southern movements from region 1 are also inconsistent with the observations of peak seasonal catch and CPUE from these fisheries during the second and third quarters.

4.3.9 Recruitment

The time-series of recruitment estimates is shown in Figure 37. Overall recruitment is estimated to be distributed throughout the three regions, with similar levels in all three regions. All three regions show seasonal variation. There are temporal trends in recruitment in all regions; for region 1 the recruitment peaks in the late 1990's and then drops, followed by a large peak in 2010. Recruitment in region 2 is variable, increasing strongly in the early 1980's and with a large dip in the mid-1990's (Figure 37). Region 3 shows considerable medium-term variability, with a strong increase in the early 1980's, and low levels in 2002 and 2008.

The high recruitment in region 1 appears unrealistic, given the prevailing water temperatures, but this is mitigated by the fact that recruitment in MFCL is driven by observations in the fisheries, and in this case fish at the age of recruitment are too small (10cm) to be observed. Given that the fish are not observed by the fisheries until well after recruitment, and after considerable movement has occurred, the overall recruitment estimate is more informative and better estimated than the regional recruitment estimates. Relative levels for age class 3 are more in line with expectation.

Overall, recruitment was estimated to be lower during the first decade of the model period (1972–84), and higher subsequently, with recruitment since 2000 11% above the long-term average (Figure 37). The strong short-term recruitment variability is consistent with our understanding that environmental conditions can have large effects on recruitment. The overall recruitment trends are driven to a large extent by other information in the model, including the CPUE time series, and the numbers of tags returned. As with most fishery stock assessments, there is a high level of uncertainty associated with the model's estimates of recruitment for the last few years.

4.3.10 Biomass

The biomass trajectories by region are presented in Figure 38. Overall, most of the total biomass is within regions 2 and 3 (43% and 48% respectively of the biomass in 2006-2009), and a relatively small proportion of the biomass is within region 1 (9%). The 2010 assessment estimated higher biomass in region 2 than region 3, and 17% of biomass in region 1.

The trend in total biomass is consistent with the trend in overall recruitment, and with the CPUE time series (Kiyofuji, Uosaki, and Hoyle 2011). There is relatively low biomass during the early period, followed by an increase to a higher level of biomass throughout 1984–2000, and declining biomass over the most recent 5 years (Figure 38). In both regions 2 and 3, the average biomass 1986-88 is 59% higher than the average of 1979-81. These strong trends in WCPO total biomass are largely driven by similar biomass trends in regions 2 and 3, with region 2 declining slightly more as expected given the higher fishing pressure.

4.3.11 Fishing mortality and the impact of fishing

Quarterly average fishing mortality rates are shown in Figure 40 for each region. Recent fishing mortality rates on both juvenile and adult skipjack are estimated to be seasonally highest within region 1, but highest overall in region 2. Fishing mortality rates in region 2 steadily increased from 1972 to 1990 and remained at that level until about 2005, before increasing significantly in the last 10 years. In region 1, fishing mortality is highly seasonal and overall exploitation rates have been moderate throughout the model period. Fishing mortality rates in region 3 were low for most of the model period apart from a large increase in 2009.

These trends are reflected in the recent age-specific fishing mortality rates which are highest for age classes 4-6 within region 2 (Figure 41). By comparison, recent fishing mortality rates are slightly lower in region 1 and low in region 3.

For a complex model such as this, it is difficult to readily interpret fishing mortality rates and other parameters to obtain a clear picture of the estimated impact of fishing on the stock. To facilitate this, we have computed total biomass trajectories for the population in each region using the estimated recruitment (modified by the SRR), natural mortality and movement parameters, but assuming that the fishing mortality was zero throughout the time series. Comparison of these biomass trajectories with those incorporating the actual levels of observed historical fishing provides a concise, integrated picture of the impacts of the total fishery on the stock. Biomass trajectories for each region are shown in Figure 42 and the level of stock depletion is presented in Figure 43.

The impact of fishing on the total biomass has been relatively stable for region 1 at about 20 to 30%. It is highest in region 2, where the stock is reduced by 47% of the unfished level in recent years (2006-2009) (Figure 43). For region 3, fishery impacts are estimated to have reduced the total biomass by 21%. For the entire stock, the depletion is estimated to be 35%.

4.3.12 Yield and reference point 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, *F*mult, the natural mortality-at-age (Ma), the mean weight-at-age (w_a) and the SRR parameter steepness (*h*). All of these parameters, apart from *F*mult which is arbitrarily specified over a range of 0–50 in increments of 0.1, are available from the model as either fixed or estimated parameters. The maximum yield with respect to *F*mult can easily be determined and is equivalent to the MSY. Similarly the total and adult biomass at MSY can also be determined. The ratios of the current (or recent average) levels of fishing mortality and biomass to their respective levels at MSY are of interest as reference points. These ratios are also determined and their confidence intervals estimated using a likelihood profile technique.

For the standard yield analysis, the F_a are determined as the average over some recent period of time and across regions. In this assessment, we use the average over the period 2006–2009. The last year in which catch and effort data are available for all fisheries is 2010. We do not include 2010 in the average as fishing mortality tends to have high uncertainty for the terminal data years of the analysis, and the catch and effort data for this terminal year are usually incomplete.

Biomass estimates, yield estimates, and management quantities for the sequence of models runs leading up to the reference case are presented in Table 10. The reference case and the structural uncertainty grid are presented in Table 11. Table 12 presents results for an alternative grid, which includes models with growth fixed at the Tanabe (2003) growth curve.

The stock assessments are uninformative regarding the relationship between spawning biomass and recruitment, and a value of *h*=0.8 was assumed in the reference case (Figure 44). Sensitivity analyses for other values of steepness are presented in Table 13, including an implausible estimated steepness of 0.39. Model runs from the sensitivity analyses are presented in Table 14, with the SBEST purse catch and size data, alternative (binomial) CPUE time series, the CPUE series from 2010, and a model run without the PTTP tag data. Table 15 has results for 3 alternative approaches to growth, including an estimated growth curve, the Leroy (2000) growth curve, and the Tanabe (2003) growth curve. The alternative fixed growth curves estimate higher MSY and lower F/F_{MSY}, while the estimated growth model suggests lower MSY and less optimistic stock condition.

For the reference-case, MSY is estimated to be 1.50 million mt per annum at a level of fishing effort (*Fmult*) approximately 2.7 times the current level of effort. Because of the extent of extrapolation required to reach the maximum of the yield curve, the estimate of MSY is uncertain. Further, there is little contrast in the estimated yield across a wide range of effort levels (from *Fmult* 2 to 10) indicating F_{MSY} is poorly determined. As a comparison, the estimated MSY for the *equatorial* model in 2008 was 1.28 million mt per annum, which is not far below the level estimated here. The maximum yield that is projected if the recent 20 year (1990-2009) average recruitment is maintained (i.e. without considering the stock recruitment relationship) is approximately 1.9 million mt per annum. When the stock recruitment relationship is considered, the same run gives maximum yield of 1.7 million mt.

The portion of the yield curve near the current level of F-at-age is flat (Figure 48). Therefore, it might reasonably be expected that, in the absence of further increases in catchability in the purse seine fisheries in particular, CPUE, would, on average, be expected to significantly decline with higher fishing effort than at present.

For the reference-case, levels of equilibrium biomass levels are estimated to be relatively low at F_{MSY} ($\widetilde{SB}_{MSY}/\widetilde{SB}_0$ = 0.27 and $\widetilde{B}_{MSY}/\widetilde{B}_0$ = 0.30).

4.3.13 Sensitivity analyses and structural uncertainty grid

Sensitivity to several alternative scenarios was included in a grid, in which all scenarios were interacted with one another. We investigated the effects of each of these alternative scenarios on the ratio-based management indicators $F_{current}/\tilde{F}_{MSY}$ (Figure 51), $B_{current}/B_{msy}$ (Figure 52), and $SB_{current}/SB_{msy}$ (Figure 53).

Steepness had the largest effect on all three management parameters, with higher steepness as expected resulting in a more robust stock and higher MSY. The full array of management parameters for each steepness level is also presented (Table 13).

The CPUE series based on the transformed binomial showed more decline than the delta lognormal indices of abundance. However, using this time series tended to raise the average biomass, which resulted in only slightly lower median estimates of $F_{current}$ / $\tilde{F}_{MSY}$, and slightly higher $B_{current}/B_{msy}$. However, there was considerable overlap in the range of results. Using the lognormal offset CPUE time series had mixed effects, but again there was considerable overlap in the range of the ratio-based management indicators.

The different time series of purse seine catch had little influence on the ratio-based management parameters.

The distributions of management parameters under the different model structure scenarios are also presented (Figure 54 and

Figure 55). Most of the uncertainty captured by this analysis was contributed by the alternative steepness values. In none of the scenarios did any of the management indicator ratios $F_{current}/\tilde{F}_{MSY}$, $B_{current}/B_{msy}$, or $SB_{current}/SB_{msy}$approach 1. The structural uncertainty distribution of MSY ranged from approximately 1.32 million to 2.7 million metric tonnes.

4.3.14 Stock status

Fishing mortality rates tended to be higher during the last decade than for the preceding period, although they remained substantially below the F_{MSY} level ($F_{current}/\widetilde{F}_{MSY}$ = 0.37 for the reference case and 0.28 for the grid) (Figure 49 and Figure 50). All runs in the grid estimated $F_{current}$ to be below $\tilde{F}_{MSY}$. Therefore, overfishing of skipjack is not occurring. Total biomass remained higher than the $\widetilde{B}_{MSY}$ level throughout the model period and current total biomass is approximately 82% (and 87% for the grid) of the equilibrium unexploited level ($\widetilde{B}_0$) due to the higher levels of recruitment in recent years ($B_{current}/\widetilde{B}_{MSY}$ = 2.68, or 2.74 for the grid). The probability distribution of $B_{current}/\widetilde{B}_{MSY}$, obtained from the structural uncertainty grid, indicates a high degree of uncertainty associated with the *MSY*-based biomass performance indicators (Table 11). Nonetheless, none of the grid runs indicated that $B_{current}/\widetilde{B}_{MSY}$ is close to 1.0 and, on this basis, the stock is not in an overfished state.

However, catches since 2007 are in the vicinity of or slightly exceed the estimated MSY. Therefore, if recent catch levels are maintained or increased, decline in spawning biomass towards the MSY level would be predicted under the estimated dynamics of the reference case model and main sensitivity runs.

5 Discussion

This assessment has estimated that the skipjack stock is not experiencing overfishing, and is not in an over-fished state. Skipjack is a very difficult species to assess, due to its high and variable productivity, which make it difficult to observe the effect of fishing on the population's biomass. Continuous and variable recruitment make it difficult to observe length frequency modes in the size data, and so estimate growth (e.g. Maunder 2011). The WCPO assessment is very reliant on the tagging data to estimate population size, the Japanese pole and line CPUE time series to estimate biomass trend, and assumptions about growth to provide the framework for modelling these data.

A number of significant changes were made to the input data for this assessment. These occurred in three main areas: a) a large quantity of new tagging data has been added, from the PTTP tagging program, which increased the number of tags in the model by 50%, b) the CPUE time series was changed, giving the two equatorial regions significantly different trends, and c) an adjustment was applied to the purse seine length frequency data based on analysis of spill sampling data. It is largely these new data that have changed the stock assessment results.

Despite these changes the major conclusions are largely unchanged, in that the stock is neither overfished nor experiencing overfishing. Estimates of potential biological yield are also consistent with estimates from previous assessments, within the margin of error. The most recent extractions from the stock are approaching those yield levels.

Addition of the PTTP tagging data resulted in a higher estimated MSY level, by 13%, and reduced the F/F_{MSY} by 15%. This large effect is because the information on biomass changes provided by the tagging data does not entirely agree with the CPUE data. There is a downward trend in the effort deviates in regions 2 and 3 during the period of the PTTP data. The model seems to fit the tagging data quite well, but predicts more observations than expected for longer times at liberty in region 2. This suggests that the model may be underestimating the combined total mortality and movement from this region.

The PTTP tagging data required programme-specific reporting rates, because of evidence that reporting rates for individual fisheries have changed through time. In addition, it is clear that different fisheries report tags from different sources at different rates (e.g. Japanese vs SPC administered tagging programmes). The new functionality was added to MULTIFAN-CL in 2010. In this assessment a number of reporting rates were estimated at the parameter boundary. The implications of these limits requires further investigation.

While tagging data show that individual skipjack are capable of undertaking long-distance movements of several thousand kilometres, fine-scale spatial analyses of the tagging data in relation to the distribution of fishing effort suggest some degree of regional-scale stock fidelity (Sibert, Hampton, Fournier, and Bills 1999;Sibert and Hampton 2003). The population-level estimates of dispersal obtained from the current assessment show a moderate level of stock mixing, both between the equatorial and temperate regions, and also east and west. These dispersal rates appear generally consistent with the observations from the tagging data, as well as trends in the catch and effort data. However, the north-south movement dynamics and recruitment distribution appear less realistic. The tagging data suggest a general northern movement of fish from the equatorial regions. The southern movement estimated from the model is likely to be attributable to other structural assumptions.

There are a great many tag releases and, in some regions, tag recoveries, but for many fisheries there is no information available regarding the reporting rates. This leaves the reporting rate prior estimates for the RTTP and PTTP (Hampton 1997;Hoyle 2011) among the most influential information about overall stock size. The model has the flexibility to accommodate moderately different estimates of stock size, given different reporting rate estimates. Further work on estimating the components of reporting rates, for both the PTTP and the Japanese tagging programmes, and changes to include them in MULTIFAN-CL, is therefore recommended. The PTTP reporting rate estimates are based on tag seeding experiments. A number of development areas have been identified for this work (Hoyle 2011), which is ongoing, and given the influence of the tagging data and the number of reporting rates estimated at the bounds, this is a high priority for the skipjack stock assessment.

The new standardized CPUE time series showed a significant increase in CPUE in about 1984, in both equatorial regions. This change helps to drive a steep biomass increase by almost 60% in a 10 year period. This increase occurred at the same time in both region 2 and region 3, but was not observed in region 1. Investigation of the data used in the CPUE analysis is suggested, since one of the major changes to the analysis this year was the introduction of vessel identity information prior to 1984 for the first time, for regions 2 and 3 only. There may have been changes in catch and effort data collection methods around this time. The change in the time series input to the model from that used in 2010 to the 2011 CPUE series reduced the MSY by 9% but increased the F/F_{MSY} by only 2% (Table 14). It had a substantial effect on the estimated biomass trend.

Adding the spill-sampling corrected sizes to the model reduced the MSY estimate by 6% and increased the F/F_{MSY} by 12% (Table 10 and Table 14), at least when growth rates were fixed. Including these corrected sizes reduced the ability of the model to estimate growth, since the relative sizes of length frequency modes were changed. Further observer collections of spill-sample size data, and work on the methods for modelling the size data correction, are expected, and it is hoped that this work will result in size data that are more informative about growth rates.

The model estimates a reasonably low biomass in the northern region, compared with the level of catch. The artificial quarter 1 CPUE added to the region 1 pole and line fishery may be contributing to this lower biomass. This assumption may be relaxed in future assessments.

There is considerable uncertainty about the growth model. The 2010 estimated growth rate was faster than that estimated from otolith length at age data from the north western Pacific (Tanabe, Kayama, and Ogura 2003), though similar to growth estimates for skipjack from the equatorial Pacific (Leroy 2000), for the sizes of fish that are comprise most of the purse seine catch in region 3. The main difference occurred at large sizes and ages over one year, where daily ring ageing is less reliable and purse seine selectivity may have biased the Leroy growth curve by selecting a higher proportion of slower growing fish at large sizes. Nevertheless, it is clear that the assumed growth curve has a large effect on management parameters (Table 15, Figure 51, Figure 52). The Leroy growth curve increased MSY by 30%, and reduced F/F_{MSY} by 38%, while the Tanabe curve increased MSY by 40% and reduced F/F_{MSY} by 43%.

Both of these otolith-based growth curves show tightly distributed length-at-age, and skipjack daily growth rings are not considered difficult to read up to one year of age, by experienced readers (Bruno Leroy personal communication). Given the supporting evidence for spatial growth variation in the Atlantic (Gaertner, gado de Molina, Ariz, Pianet, and Hallier 2008), and evidence of spatial variation in skipjack size across the Pacific (Hoyle, Kleiber, Davies, Harley, and Hampton 2010, Appendix 2), it seems likely that spatial growth variation is a reality for skipjack. If growth varies spatially, the stock assessment modelling will benefit greatly if we understand the nature of this variation.

Modelling spatial growth variation will require two things: firstly biological work; and secondly development of modelling tools to deal with the variation.

Biological work would involve aging otoliths using daily growth rings from sampling stratified across spatial and temporal sources of variation. This would give us a better understanding of the patterns of spatial size and growth variation and its biological basis. It would also clarify the relative contributions of growth and movement to the observed spatial growth variation, and how patterns vary with age and environmental conditions. Until we understand the biological causes behind the observed dynamics, we are unlikely to be able to model them successfully.

Development work is currently under way to permit MULTIFAN-CL to model sub-stocks with varying growth rates. It may also be possible to accommodate growth variability via the assumed variability of length at age, or by modelling smaller sub-regions with less variable growth. Identifying the best approach requires considerable model development and simulation work.

6 Conclusions

The major conclusions of the skipjack assessment are similar to those of the last five assessments (Hampton 2002;Langley *et al.* 2003b;Langley, Hampton, and Ogura 2005;Langley and Hampton 2008;Hoyle, Kleiber, Davies, Harley, and Hampton 2010). The key conclusions are as follows.

1. Estimates of natural mortality are strongly age-specific, with higher rates estimated for younger skipjack.
2. The model estimates significant seasonal movements between the western and eastern equatorial regions. The performance of the fishery in the eastern region has been shown to be strongly influenced by the prevailing environmental conditions with higher stock abundance and/or availability associated with El Niño conditions (Lehodey *et al*. 1997). This is likely to be at least partly attributable to an eastward displacement of the skipjack biomass due to the prevailing oceanographic conditions, although this dynamic cannot be captured by the parameterisation of movement in the current model.
3. Recruitment showed an upward shift in the mid-1980s and is estimated to have remained at a higher level since that time. This change is driven by the CPUE data, and also by the relative tag return rates from the SSAP and the RTTP tagging programmes. Recruitment in the eastern equatorial region is more variable with recent peaks in recruitment occurring in 1998 and 2004–2005 following strong *El Niño* events around that time. Conversely, the lower recruitment in 2001–2003 followed a period of sustained *La Nina* conditions. Recent recruitment is estimated to be at a high level, but is poorly determined due to limited observations from the fishery.
4. The biomass trends are driven largely by recruitment and fishing mortality. The highest biomass estimates for the model period occurred in 1998–2001 and in 2005–2007, immediately following periods of sustained high recruitment within the eastern equatorial region (region 3).
5. The biomass trajectory is influenced by the underlying assumptions regarding the treatment of the various fishery-specific catch and effort data sets within the model. The Japanese pole-and-line fisheries are all assumed to have constant catchability, with any temporal trend in efficiency assumed to have been accounted for by the standardization of the effort series. The CPUE trends are influential regarding the general trend in both recruitment and total biomass over the model period. In all regions there is a relatively good fit to the observed CPUE data, with some deterioration when PTTP tagging data are introduced.
6. The model also incorporates a considerable amount of tagging data that provides information concerning absolute stock size during the main tag recovery period. Including the PTTP tagging data in the model resulted in higher estimates of recent biomass and MSY. Initial analyses of the data suggest some conflict with evidence from the CPUE time series. Further work on both data sources is recommended.
7. Within the equatorial region, fishing mortality increased throughout the model period and is estimated to be highest in the western region in the most recent years. The impact of fishing is predicted to have reduced recent biomass by about 47% in the western equatorial region and 21% in the eastern region. For the entire stock, the depletion is estimated to be approximately 35%.
8. The principal conclusions are that skipjack is currently exploited at a moderate level relative to its biological potential. Furthermore, the estimates of $F_{current}/\tilde{F}_{MSY}$ and $B_{current}/\tilde{B}_{MSY}$ indicate that overfishing of skipjack is not occurring in the WCPO, nor is the stock in an overfished state. However, catches since 2007 are in the vicinity of or slightly exceed the estimated MSY. Therefore, if recent catch levels are maintained or increased, decline in spawning biomass towards the MSY level would be predicted under the estimated dynamics of the reference case model and main sensitivity runs. These conclusions appear relatively robust, at least within the statistical uncertainty of the current assessment. Fishing pressure and recruitment variability,

influenced by environmental conditions, will continue to be the primary influences on stock size and fishery performance.

9. For the model assumptions investigated, there was only moderate variation in the estimates of stock status. This suggests that the model is strongly driven by the key input data: catch, CPUE, size data, and the tagging datasets. The most influential assumptions involved steepness and growth. There are insufficient data to estimate steepness reliably within the assessment model and many of the key management quantities are strongly influenced by the values assumed. Growth and its variation in space, through time, and among individuals is not well understood. However, only a limited range of assumptions was investigated in this assessment, and as a result the true level of structural uncertainty was under-estimated.

10. The following research and monitoring tasks are recommended to improve the skipjack tuna assessment.

    - Growth investigation: Otolith sampling and daily growth ring reading are recommended as a top priority, to improve the understanding of skipjack growth and its variation spatially, temporally, and among individuals. Otolith sampling may also permit collection of age frequency data from the commercial catch, which would improve current estimates of the population age structure. We also recommend analytical work with MULTIFAN-CL to model fisheries at a smaller spatial and temporal scale, to estimate growth rates from length frequency modes. Analyses of growth increments from the available tagging data may also provide information about spatial and temporal growth variation.

    - Analyses of tagging data: continued or increased levels of tag seeding are needed to provide better understanding of the factors affecting reporting rates, and more precise estimates. Reporting rates are very influential since they are directly proportional to biomass and fishing mortality rates.

    - Spill sampling work: continued spill and grab sampling data collection is required to improve estimates of size distribution and species composition. Further analytical work is also recommended as a high priority. Currently the spill sampling size adjustments seem to obscure length frequency modes in the size data.

    - 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.

    - Research prioritization: given the range of options for further research, a more formal approach to research prioritization would be beneficial. Simulation testing of management strategies is the preferred framework for this kind of prioritization, because it permits direct testing of the benefits of alternative research options for management outcomes. We recommend development of a data simulator that can be used for management strategy evaluation, research prioritization, and simulation testing of stock assessment approaches.

    - 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.

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9 Tables

Table 1: Definition of fisheries for the MULTIFAN-CL skipjack analysis. Gears: PL = pole-and-line; PS = purse seine unspecified set type; PS/LOG+FAD = purse seine log or FAD set; PS/SCH = purse seine school set; LL = longline; DOM = the range of artisanal gear types operating in the domestic fisheries of Philippines and Indonesia. Flag/fleets: JP/OS = Japan offshore fleet; JP/DW = Japan distant-water fleet; JP/RES = Japan research/training vessel fleet; PG = Papua New Guinea; SB = Solomon Islands; PH = Philippines; ID = Indonesia; FJ = Fiji; ALL = all nationalities.

Fishery definitions				
Fishery code	Gear	Flag/fleet	Area	Region
1. JPOS PL 1	PL	JP/OS		1
2. JPDW PL 1	PL	JP/DW		1
3. JPOS PS 1	PS	JP/OS		1
4. JP LL 1	LL	JP/RES		1
5. JPDW PL 2	PL	JP/DW		2
6. PG PL 2	PL	PG		2
7. SB PL 2	PL	SB		2
8. PS LOG/FAD 2	PS/LOG+FAD	ALL		2
9. PS SCH 2	PS/SCH	ALL		2
10. PH DOM 2	DOM	PH	Archipelagic	2
11. ID DOM 2	DOM	ID	Archipelagic	2
12. JP LL 2	LL	JP/RES		2
13. JPDW PL 3	PL	JP/DW		3
14. FJ PL 3	PL	FJ		3
15. PS LOG/FAD 3	PS/LOG+FAD	ALL		3
16. PS SCH 3	PS/SCH	ALL		3
17. JP LL 3	LL	JP/RES		3
18. PS PH/ID DOM	PS	PHID	Oceanic	2

Table 2: Annual catch by fishery for 2009 and the average for 2005-2009. The two alternative catch histories for the industrial purse-seine fisheries are presented using corrected and uncorrected catches (in brackets).

Fishery	Annual catch (mt)	
	Avg. 2005-2009	2009
1. JPOS PL 1	35 142	22 114
2. JPDW PL 1	31 078	15 294
3. JPOS PS 1	55 576	28 875
5. JPDW PL 2	17 129	12 515
6. PG PL 2	0	0
7. SB PL 2	2 697	3
8. PS LOG/FAD 2	407 265 (470 660)	419 301 (463 610)
. PS SCH 2	275 992 (294 628)	268 821 (293 060)
10. PH DOM 2	87 694	95 515
11. ID DOM 2	67 618	70 894
13. JPDW PL 3	5 172	7 664
14. FJ PL 3	0	0
15. PS LOG/FAD 3	145 490 (159 228)	241 658 (263 823)
16. PS SCH 3	108 112 (108 561)	199 018 (196 252)
18. PS PH/ID DOM	204 264	226 765
Total	1 443 267 (1 540 008)	1 608 479 (1 697 142)

Table 3. Summary of the number of tag releases and recoveries by region. Recovery data are also apportioned to the fishery of recovery.

Region	Releases		Fishery	Recoveries
1	38,214	1.	JPOS PL 1	957
		2.	JPDW PL 1	114
		3.	JPOS PS 1	878
		4.	JP LL 1	0
2	289,422	5.	JPDW PL 2	928
		6.	PG PL 2	872
		7.	SB PL 2	1453
		8.	FAD/LOG PS 2	16176
		9.	SCH PS 2	551
		10.	PH DOM 2	1754
		11.	ID DOM 2	3653
		12.	JP LL 2	8
		18.	PHID DOM PS 2	3910
3	87,788	13.	JPDW PL 3	487
		14.	FJ PL 3	2631
		15.	FAD/LOG PS 3	1865
		16.	SCH PS 3	490
		17.	JP LL 3	4
Total	415,424			36,731

Table 4: Reporting rate parameters for reference case runs, and priors by fishery and release programme.

RR Parameter	Release programme	Fishery group	Prior	SD	Penalty
1	JP	Dom ID	0.5	0.71	1
2		Dom PH	0.5	0.71	1
3		JP	0.5	0.71	1
4		PL FJ	0.5	0.71	1
5		PL PG	0.5	0.71	1
6		PL SB	0.5	0.71	1
7		PS R2	0.5	0.71	1
8		PS R3	0.5	0.71	1
9	PTTP	Dom ID	0.5	0.71	1
10		Dom PH	0.5	0.71	1
11		JP	0.5	0.71	1
12		PL FJ	0.5	0.71	1
13		PL PG	0.5	0.71	1
14		PL SB	0.5	0.71	1
15		PS R2	0.521	0.12	34
16		PS R3	0.442	0.18	16
17	RTTP	Dom ID	0.5	0.71	1
18		Dom PH	0.5	0.71	1
19		JP	0.5	0.71	1
20		PL FJ	0.5	0.71	1
21		PL PG	0.5	0.71	1
22		PL SB	0.5	0.71	1
23		PS R2	0.457	0.09	66
24		PS R3	0.457	0.09	66
25	SSAP	Dom ID	0.5	0.71	1
26		Dom PH	0.5	0.71	1
27		JP	0.5	0.71	1
28		PL FJ	0.5	0.71	1
29		PL PG	0.5	0.71	1
30		PL SB	0.5	0.71	1
31		PS R2	0.5	0.71	1
32		PS R3	0.5	0.71	1

Table 5. Main structural assumptions used in the reference case model.

Category	Assumption
Observation model for total catch data	Observation errors small, equivalent to a residual SD on the log scale of 0.07.
Observation model for length-frequency data	Normal probability distribution of frequencies with variance determined by sample size and observed frequency. Effective sample size varies among fisheries, assumed at most to be 0.025 times actual sample size with a maximum effective sample size of 25.
Observation model for tagging data	Tag numbers in a stratum have negative binomial probability distribution, with fishery-specific variance parameter
Tag reporting	Informative priors for equatorial purse seine fisheries for tags released by the RTTP and PTTP (based on tag seeding), and relatively uninformative priors for all other combinations of fishery and tagging programme. All reporting rates vary between tagging programmes but are constant for tags released by each programme. A common reporting rate was assumed for all Japanese fisheries.
Tag mixing	Tags assumed to be randomly mixed at the model region level from the quarter following the quarter of release.
Recruitment	Occurs as discrete events at the start of each quarter. Spatially-aggregated recruitment is weakly related to spawning biomass in the prior quarter via a Beverton-Holt SRR (steepness fixed at 0.8).The spatial distribution of recruitment in each quarter is allowed to vary in an unconstrained fashion. The proportion of total recruitment in each region (1-3) was estimated.
Initial population	Is a function of the equilibrium age structure in each region, which is assumed to arise from the total mortality and movement rates estimated for the initial 20 quarters of the analysis.
Age and growth	16 quarterly age-classes, with the last representing a plus group. Juvenile age-classes 2–6 have independent mean lengths; adult age-class mean lengths constrained by von Bertalanffy growth curve. Mean weights (W_j) computed internally by estimating the distribution of weight-at-age from the distribution of length-at-age and applying the weight-length relationship $W = aL^b$ (*a*=0.8.6388e-06, *b*=3.2174 estimated from available length-weight data).
Selectivity	Constant over time. Various smoothing penalties applied. Coefficients for the last 2 age-classes are constrained to be equal. The two region 1 Japan pole and line fisheries share common selectivity parameters. The two equatorial Japan pole-and-line fisheries share common parameters. The Philippines domestic oceanic purse seine shares selectivity with the region 2 associated-set purse seine. The Research longline selectivities are non-decreasing with increasing age.
Catchability	Catchability is estimated independently for all fisheries. Seasonal variation for all fisheries apart from Philippines and Indonesian fisheries and the Japanese pole and line fishery in region 1. Fisheries other than all Japanese pole-and-line have structural time-series variation, with random steps (catchability deviations) taken every 2 years. Catchability deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.7.
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.7 (SD is at estimated levels for Japanese pole and line fisheries).
Natural mortality	Age-dependent but constant over time and among regions. Smoothing penalties constrain the age-dependency.
Movement	Age-dependent but constant over time and among regions. Age-dependency for each coefficient (2 per region boundary) is linear.

Table 6. Run sequence progression from the 2010 model to the reference case.

Run	C/E	Spill catch	Size data	CPUE	ID/PH	tag	Steepness	Growth	Comments
R1	Old	2010	2010	Delta	Old	Old	0.75	2010	2010 data, new MFCL code
R2	New	New	2011	Delta	Old	Old	0.75	2010	Update catch, effort, size data.
R3	New	New	Adj	Delta	Old	Old	0.75	2010	Adjust size frequency for spill
R4	New	New	Adj	Delta	New	Old	0.75	2010	New ID/PH fishery structure
R5	New	New	Adj	Delta	New	PTTP	0.75	2010	Add PTTP tag data
Ref	New	New	Adj	Delta	New	PTTP	0.8	2010	Change steepness to 0.8

Table 7. Characteristics of the sensitivity analyses, as offsets from the reference case.

Run	C/E	Size data	CPUE	ID/ PH	tag	Steepness	Growth	Comments
SB	S_BEST	2011	Delta	New	PTTP	0.8	2010	Without spill sample adjustmt
CP1	New	Adj	Binomial	New	PTTP	0.8	2010	Alternative CPUE time series
Tag	New	Adj	Delta	New	Old	0.8	2010	Without PTTP tag data
ST 0.65	New	Adj	Delta	New	PTTP	0.65	2010	Steepness = 0.65
ST 0.95	New	Adj	Delta	New	PTTP	0.95	2010	Steepness = 0.95
ST est	New	Adj	Delta	New	PTTP	Estimated	2010	Estimated steepness = 0.40
Leroy growth	New	Adj	Delta	New	PTTP	0.8	Leroy	Alternative growth model 1
Tanabe growth	New	Adj	Delta	New	PTTP	0.8	Tanabe	Alternative growth model 2
Estimate growth	New	Adj	Delta	New	PTTP	0.8	Estimated	Estimate growth

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

Objective function component	Reference case	S_BEST	Binomial CPUE	No PTTP tag data	Leroy growth	Tanabe growth	Estimate growth
Total function value	-89667.2	-100534.7	-90681.9	-94743.8	-87392.6	-86725.8	-91477.8
Total catch log-likelihood	83.9	83.2	72.7	64.6	82.2	98.2	77.9
Length frequency log-likelihood	-105868.6	-116797.0	-105877.3	-105927.6	-105798.2	-106136.5	-105220.0
Penalties	1530.1	1523.1	546.6	605.0	3077.4	1561.5	643.0
Effort dev penalty	1306.4	1302.5	323.3	423.5	437.5	1331.6	440.9
Tag log-likelihood	14561.0	14629.3	14553.1	10488.7	15221.8	17706.0	13002.8

Table 9. Description of symbols used in the yield analysis.

Symbol	**Description**
$F_{current}$	Average fishing mortality-at-age for 2006–2009
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (*MSY*)
$\tilde{Y}_{F_{current}}$	Equilibrium yield at $F_{current}$
$\tilde{Y}_{F_{MSY}}$ (or *MSY*)	Equilibrium yield at F_{MSY}, or maximum sustainable yield
$\tilde{B}_0$	Equilibrium unexploited total biomass
$\tilde{B}_{F_{current}}$	Equilibrium total biomass at $F_{current}$
$\tilde{B}_{MSY}$	Equilibrium total biomass at MSY
$S\tilde{B}_0$	Equilibrium unexploited adult biomass
$S\tilde{B}_{F_{current}}$	Equilibrium adult biomass at $F_{current}$
$S\tilde{B}_{MSY}$	Equilibrium adult biomass at MSY
$B_{current}$	Average current (2006–2009) total biomass
$SB_{current}$	Average current (2006–2009) adult biomass
$B_{current,F=0}$	Average current (2006–2009) total biomass in the absence of fishing.

Table 10: Estimates of management quantities for the series from R1 (2010 data, new MFCL code), R2 (update catch, effort, size data), R3 (adjust size frequency for spill sampling), R4 (new ID/PH fishery structure), and R5 (add PTTP data). The following model was the reference case in which steepness was changed to 0.8. For a detailed list of the characteristics of each model run, see Table 6. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading). Symbols are defined in **Table 9**.

Management quantity	Units	R1	R2	R3	R4	R5
$\tilde{Y}_{F_{current}}$	t per annum	1 092 000	1 096 800	1 086 000	1 251 600	1 124 000
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per annum	1 360 400	1 422 400	1 407 200	1 561 600	1 428 400
$\tilde{B}_0$	t	4 735 000	5 399 000	5 434 000	5 833 000	6 190 000
$\tilde{B}_{F_{current}}$	t	2 617 000	3 146 000	3 165 000	3 288 000	3 560 000
$\tilde{B}_{MSY}$	t	1 463 000	1 706 000	1 715 000	1 866 000	1 962 000
$\tilde{SB}_0$	t	4 398 000	5 111 000	5 131 000	5 460 000	5 828 000
$\tilde{SB}_{F_{current}}$	t	2 304 000	2 877 000	2 881 000	2 940 000	3 222 000
$\tilde{SB}_{MSY}$	t	1 189 000	1 469 000	1 465 000	1 559 000	1 664 000
$B_{current}$	t	3 524 942	3 998 283	4 040 475	4 375 220	5 018 960
$SB_{current}$	t	3 157 757	3 704 831	3 725 314	3 968 103	4 595 407
$B_{current,F=0}$	t	5 627 154	5 938 275	6 007 608	6 656 906	7 677 354
$B_{current}/\tilde{B}_0$		0.74	0.74	0.74	0.75	0.81
$B_{current}/\tilde{B}_{MSY}$		2.41	2.34	2.36	2.34	2.56
$B_{current}/B_{current,F=0}$		0.63	0.67	0.67	0.66	0.65
$SB_{current}/\tilde{SB}_0$		0.72	0.72	0.73	0.73	0.79
$SB_{current}/\tilde{SB}_{MSY}$		2.66	2.52	2.54	2.55	2.76
$SB_{latest}/\tilde{SB}_{MSY}$		2.25	2.27	2.28	2.40	2.07
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.55	0.58	0.58	0.56	0.58
$\tilde{SB}_{F_{current}}/\tilde{SB}_0$		0.52	0.56	0.56	0.54	0.55
$\tilde{B}_{MSY}/\tilde{B}_0$		0.31	0.32	0.32	0.32	0.32
$\tilde{SB}_{MSY}/\tilde{SB}_0$		0.27	0.29	0.29	0.29	0.29
$F_{current}/\tilde{F}_{MSY}$		0.35	0.39	0.39	0.41	0.42
$Fmult$		2.84	2.59	2.55	2.42	2.41
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.79	1.84	1.85	1.76	1.81
$\tilde{SB}_{F_{current}}/\tilde{SB}_{MSY}$		1.94	1.96	1.97	1.89	1.94
$\tilde{Y}_{F_{current}}/MSY$		0.80	0.77	0.77	0.80	0.79

Table 11. Estimates of management quantities for the reference-case and the uncertainty grid. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading). Symbols are defined in **Table 9**.

Management quantity	Units	Reference case	Grid median	Grid 5%	Grid 95%
$\tilde{Y}_{F_{current}}$	t per annum	1 136 000	1 186 750	1 108 760	1 262 160
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per annum	1 503 600	1 839 533	1 320 540	2 716 140
$\tilde{B}_0$	t	6 147 000	6 329 833	5 802 700	6 835 450
$\tilde{B}_{F_{current}}$	t	3 598 000	3 985 365	3 703 450	4 361 750
$\tilde{B}_{MSY}$	t	1 869 000	1 982 125	1 642 400	2 344 900
$\widetilde{SB}_0$	t	5 787 000	5 486 292	4 512 450	6 487 900
$\widetilde{SB}_{F_{current}}$	t	3 256 000	3 187 167	2 684 800	3 696 850
$\widetilde{SB}_{MSY}$	t	1 564 000	1 309 030	541 085	2 058 800
$B_{current}$	t	5 018 049	5 484 087	5 132 529	5 841 256
$SB_{current}$	t	4 594 557	4 486 938	3 618 165	5 394 979
$B_{current,F=0}$	t	7 676 608	7 851 073	6 996 743	8 708 943
$B_{current}/\tilde{B}_0$		0.82	0.87	0.80	0.94
$B_{current}/\tilde{B}_{MSY}$		2.68	2.81	2.34	3.31
$B_{current}/B_{current,F=0}$		0.65	0.70	0.65	0.75
$SB_{current}/\widetilde{SB}_0$		0.79	0.82	0.78	0.86
$SB_{current}/\widetilde{SB}_{MSY}$		2.94	3.89	2.48	7.06
$SB_{latest}/\widetilde{SB}_{MSY}$		2.21	2.83	1.89	4.96
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.59	0.63	0.55	0.71
$\widetilde{SB}_{F_{current}}/\widetilde{SB}_0$		0.56	0.58	0.53	0.63
$\tilde{B}_{MSY}/\tilde{B}_0$		0.30	0.31	0.26	0.37
$\widetilde{SB}_{MSY}/\widetilde{SB}_0$		0.27	0.23	0.12	0.32
$F_{current}/\tilde{F}_{MSY}$		0.37	0.30	0.09	0.52
$Fmult$		2.71	4.45	1.92	11.17
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.93	2.05	1.62	2.50
$\widetilde{SB}_{F_{current}}/\widetilde{SB}_{MSY}$		2.08	2.80	1.69	5.24
$\tilde{Y}_{F_{current}}/MSY$		0.76	0.67	0.46	0.85

Table 12: Estimates of management quantities for the reference-case and the uncertainty grid with the Tanabe growth curve included. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading). Symbols are defined in Table 9.

Management quantity	Units	Reference case	Grid median	Grid 5%	Grid 95%
$\tilde{Y}_{F_{current}}$	t per annum	1 136 000	1 236 614	1 118 200	1 393 400
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per annum	1 503 600	1 941 955	1 341 200	2 766 600
$\tilde{B}_0$	t	6 147 000	7 058 479	5 804 500	8 887 500
$\tilde{B}_{F_{current}}$	t	3 598 000	4 583 725	3 728 500	6 058 000
$\tilde{B}_{MSY}$	t	1 869 000	2 291 662	1 645 000	3 378 000
$S\tilde{B}_0$	t	5 787 000	5 858 176	4 517 500	6 981 500
$S\tilde{B}_{F_{current}}$	t	3 256 000	3 449 789	2 705 000	4 258 000
$S\tilde{B}_{MSY}$	t	1 564 000	1 345 537	560 700	2 073 500
$B_{current}$	t	5 018 049	6 147 467	5 163 350	7 973 433
$SB_{current}$	t	4 594 557	4 792 943	3 644 855	5 924 875
$B_{current,F=0}$	t	7 676 608	8 526 574	7 027 834	10 515 844
$B_{current}/\tilde{B}_0$		0.82	0.87	0.81	0.93
$B_{current}/\tilde{B}_{MSY}$		2.68	2.74	2.21	3.29
$B_{current}/B_{current,F=0}$		0.65	0.72	0.66	0.77
$SB_{current}/S\tilde{B}_0$		0.79	0.82	0.78	0.85
$SB_{current}/S\tilde{B}_{MSY}$		2.94	4.05	2.53	7.11
$SB_{latest}/S\tilde{B}_{MSY}$		2.21	3.23	1.93	6.27
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.59	0.65	0.56	0.72
$S\tilde{B}_{F_{current}}/S\tilde{B}_0$		0.56	0.59	0.54	0.63
$\tilde{B}_{MSY}/\tilde{B}_0$		0.30	0.32	0.26	0.39
$S\tilde{B}_{MSY}/S\tilde{B}_0$		0.27	0.23	0.12	0.32
$F_{current}/\tilde{F}_{MSY}$		0.37	0.28	0.08	0.51
$Fmult$		2.71	5.13	1.95	13.25
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.93	2.04	1.62	2.54
$S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$		2.08	2.95	1.70	5.26
$\tilde{Y}_{F_{current}}/MSY$		0.76	0.66	0.46	0.84

Table 13: Estimates of management quantities for the reference-case and three alternative steepness values. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading). Symbols are defined in Table 9

Management quantity	**Units**	**Reference case**	**Steepness 0.65**	**Steepness 0.95**	**Steepness estimated (0.39)**
$\tilde{Y}_{F_{current}}$	t per annum	1 136 000	1 090 400	1 174 800	886 800
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per annum	1 503 600	1 274 000	1 818 000	886 800
$\tilde{B}_0$	t	6 147 000	6 309 000	6 263 000	7 274 000
$\tilde{B}_{F_{current}}$	t	3 598 000	3 455 000	3 917 000	2 968 000
$\tilde{B}_{MSY}$	t	1 869 000	2 164 000	1 663 000	2 992 000
$\widetilde{SB}_0$	t	5 787 000	5 940 000	5 888 000	6 841 000
$\widetilde{SB}_{F_{current}}$	t	3 256 000	3 126 000	3 547 000	2 688 000
$\widetilde{SB}_{MSY}$	t	1 564 000	1 879 000	1 309 000	2 711 000
$B_{current}$	t	5 018 049	5 021 029	5 270 072	5 297 648
$SB_{current}$	t	4 594 557	4 597 375	4 826 006	4 853 503
$B_{current,F=0}$	t	7 676 608	7 679 012	7 877 644	7 914 337
$B_{current}/\tilde{B}_0$		0.82	0.80	0.84	0.73
$B_{current}/\tilde{B}_{MSY}$		2.68	2.32	3.17	1.77
$B_{current}/B_{current,F=0}$		0.65	0.65	0.67	0.67
$SB_{current}/\widetilde{SB}_0$		0.79	0.77	0.82	0.71
$SB_{current}/\widetilde{SB}_{MSY}$		2.94	2.45	3.69	1.79
$SB_{latest}/\widetilde{SB}_{MSY}$		2.21	1.83	2.82	1.35
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.59	0.55	0.63	0.41
$\widetilde{SB}_{F_{current}}/\widetilde{SB}_0$		0.56	0.53	0.60	0.39
$\tilde{B}_{MSY}/\tilde{B}_0$		0.30	0.34	0.27	0.41
$\widetilde{SB}_{MSY}/\widetilde{SB}_0$		0.27	0.32	0.22	0.40
$F_{current}/\tilde{F}_{MSY}$		0.37	0.53	0.22	1.01
$Fmult$		2.71	1.90	4.46	0.99
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.93	1.60	2.36	0.99
$\widetilde{SB}_{F_{current}}/\widetilde{SB}_{MSY}$		2.08	1.66	2.71	0.99
$\tilde{Y}_{F_{current}}/MSY$		0.76	0.86	0.65	1.00

Table 14. Estimates of management quantities for the reference-case and three alternative steepness values. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading). Symbols are defined in Table 9.

Management quantity	Units	Reference case	SBEST	Binomial CPUE	2010 CPUE	No PTTP tags
$\tilde{Y}_{F_{current}}$	t per annum	1 136 000	1 127 600	1 190 000	1 266 400	1 047 600
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per annum	1 503 600	1 590 000	1 589 200	1 645 200	1 331 200
$\tilde{B}_0$	t	6 147 000	6 481 000	6 453 000	5 794 000	5 665 000
$\tilde{B}_{F_{current}}$	t	3 598 000	3 994 000	3 808 000	3 331 000	3 253 000
$\tilde{B}_{MSY}$	t	1 869 000	1 969 000	1 965 000	1 788 000	1 765 000
$\widetilde{SB}_0$	t	5 787 000	6 097 000	6 070 000	5 423 000	5 333 000
$\widetilde{SB}_{F_{current}}$	t	3 256 000	3 627 000	3 444 000	2 979 000	2 938 000
$\widetilde{SB}_{MSY}$	t	1 564 000	1 642 000	1 639 000	1 472 000	1 481 000
$B_{current}$	t	5 018 049	5 603 408	4 984 619	4 374 328	4 707 595
$SB_{current}$	t	4 594 557	5 145 724	4 556 539	3 966 881	4 285 580
$B_{current,F=0}$	t	7 676 608	8 237 140	7 627 114	6 655 029	7 431 594
$B_{current}/\tilde{B}_0$		0.82	0.86	0.77	0.75	0.83
$B_{current}/\tilde{B}_{MSY}$		2.68	2.85	2.54	2.45	2.67
$B_{current}/B_{current,F=0}$		0.65	0.68	0.65	0.66	0.63
$SB_{current}/\widetilde{SB}_0$		0.79	0.84	0.75	0.73	0.80
$SB_{current}/\widetilde{SB}_{MSY}$		2.94	3.13	2.78	2.69	2.89
$SB_{latest}/\widetilde{SB}_{MSY}$		2.21	2.30	2.22	2.55	2.08
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.59	0.62	0.59	0.57	0.57
$\widetilde{SB}_{F_{current}}/\widetilde{SB}_0$		0.56	0.59	0.57	0.55	0.55
$\tilde{B}_{MSY}/\tilde{B}_0$		0.30	0.30	0.30	0.31	0.31
$\widetilde{SB}_{MSY}/\widetilde{SB}_0$		0.27	0.27	0.27	0.27	0.28
$F_{current}/\tilde{F}_{MSY}$		0.37	0.33	0.36	0.36	0.44
$Fmult$		2.71	3.04	2.77	2.76	2.30
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.93	2.03	1.94	1.86	1.84
$\widetilde{SB}_{F_{current}}/\widetilde{SB}_{MSY}$		2.08	2.21	2.10	2.02	1.98
$\tilde{Y}_{F_{current}}/MSY$		0.76	0.71	0.75	0.77	0.79

Table 15. Estimates of management quantities for the reference-case and three alternative steepness values. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading). Symbols are defined in Table 9.

Management quantity	Units	Reference case	Estimate growth	Leroy growth	Tanabe growth
$\tilde{Y}_{F_{current}}$	t per annum	1 136 000	1 047 600	1 204 400	1 320 000
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per annum	1 503 600	1 331 200	1 987 200	2 100 000
$\tilde{B}_0$	t	6 147 000	5 665 000	5 885 000	8 254 000
$\tilde{B}_{F_{current}}$	t	3 598 000	3 253 000	3 973 000	5 703 000
$\tilde{B}_{MSY}$	t	1 869 000	1 765 000	1 914 000	2 887 000
$\tilde{SB}_0$	t	5 787 000	5 333 000	4 580 000	6 247 000
$\tilde{SB}_{F_{current}}$	t	3 256 000	2 938 000	2 730 000	3 790 000
$\tilde{SB}_{MSY}$	t	1 564 000	1 481 000	902 700	1 321 000
$B_{current}$	t	5 018 049	4 707 595	5 171 466	7 150 172
$SB_{current}$	t	4 594 557	4 285 580	3 651 473	4 988 878
$B_{current,F=0}$	t	7 676 608	7 431 594	7 035 800	9 405 355
$B_{current}/\tilde{B}_0$		0.82	0.83	0.88	0.87
$B_{current}/\tilde{B}_{MSY}$		2.68	2.67	2.70	2.48
$B_{current}/B_{current,F=0}$		0.65	0.63	0.74	0.76
$SB_{current}/\tilde{SB}_0$		0.79	0.80	0.80	0.80
$SB_{current}/\tilde{SB}_{MSY}$		2.94	2.89	4.05	3.78
$SB_{latest}/\tilde{SB}_{MSY}$		2.21	2.08	2.92	3.61
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.59	0.57	0.68	0.69
$\tilde{SB}_{F_{current}}/\tilde{SB}_0$		0.56	0.55	0.60	0.61
$\tilde{B}_{MSY}/\tilde{B}_0$		0.30	0.31	0.33	0.35
$\tilde{SB}_{MSY}/\tilde{SB}_0$		0.27	0.28	0.20	0.21
$F_{current}/\tilde{F}_{MSY}$		0.37	0.44	0.23	0.21
$Fmult$		2.71	2.30	4.27	4.81
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.93	1.84	2.08	1.98
$\tilde{SB}_{F_{current}}/\tilde{SB}_{MSY}$		2.08	1.98	3.02	2.87
$\tilde{Y}_{F_{current}}/MSY$		0.76	0.79	0.61	0.63

10 Figures

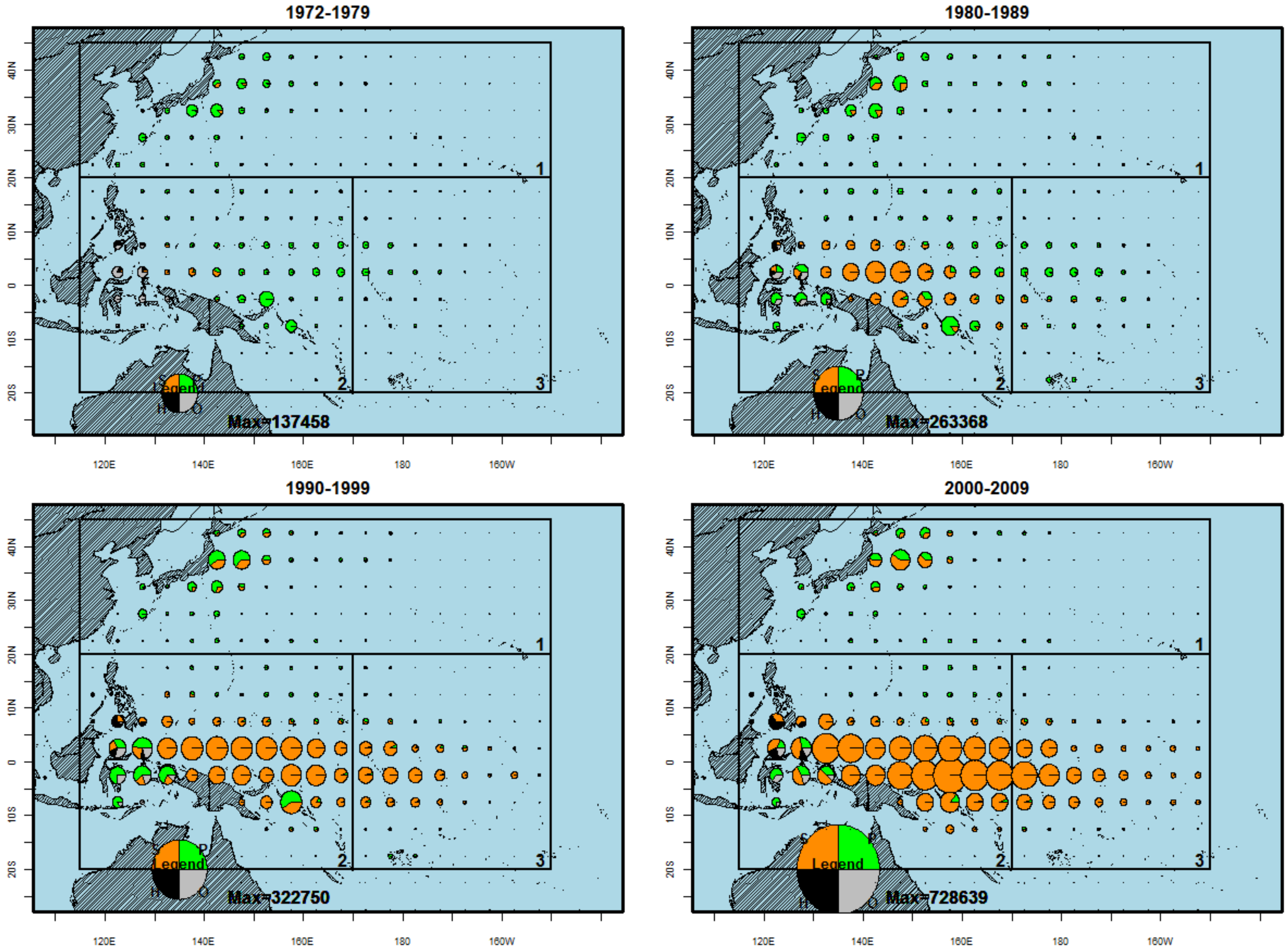

Figure 1: Distribution of total skipjack catches by method during 1972–2010 in relation to the 3-region spatial stratification used in the MULTIFAN-CL analysis. Method colours: Green, pole-and-line; Orange, purse-seine; Black: handline (small-scale); Gray, other.

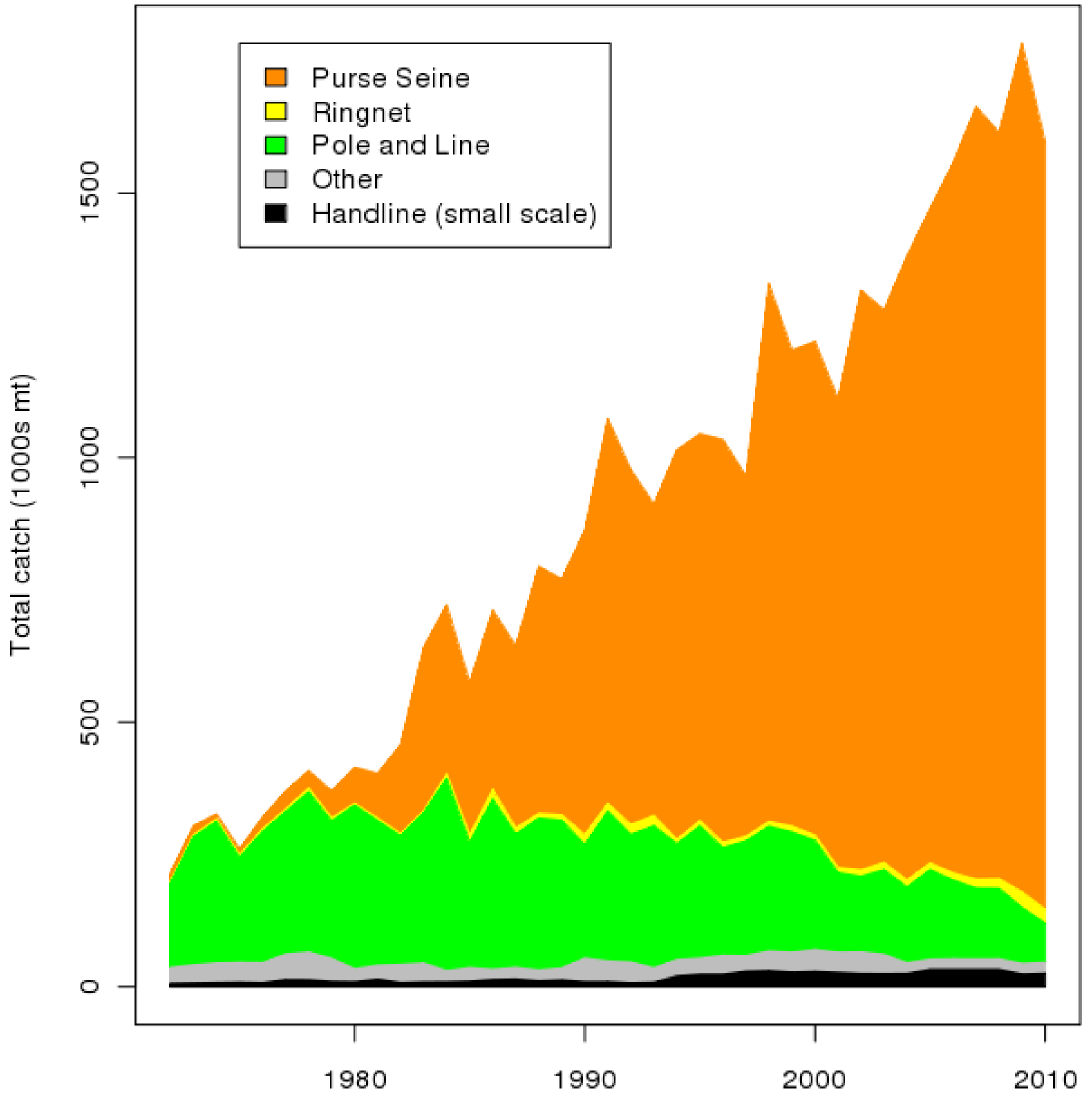

Figure 2. Annual skipjack tuna catch in the WCPO by method, 1972–2010.

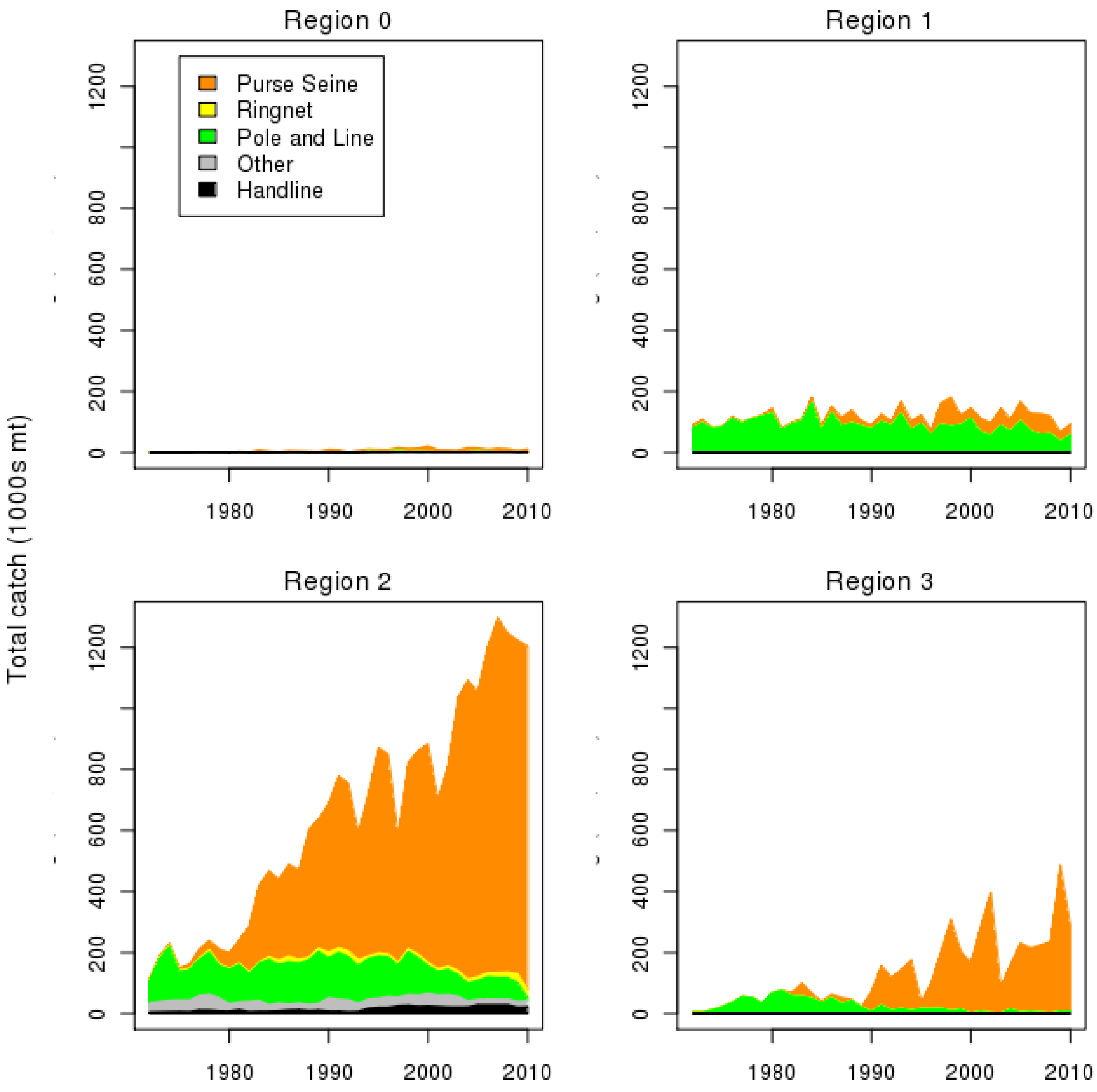

Figure 3. Annual skipjack tuna catch by region and method, 1972–2010. Region 0 represents WCPO catches outside the area included in the model.

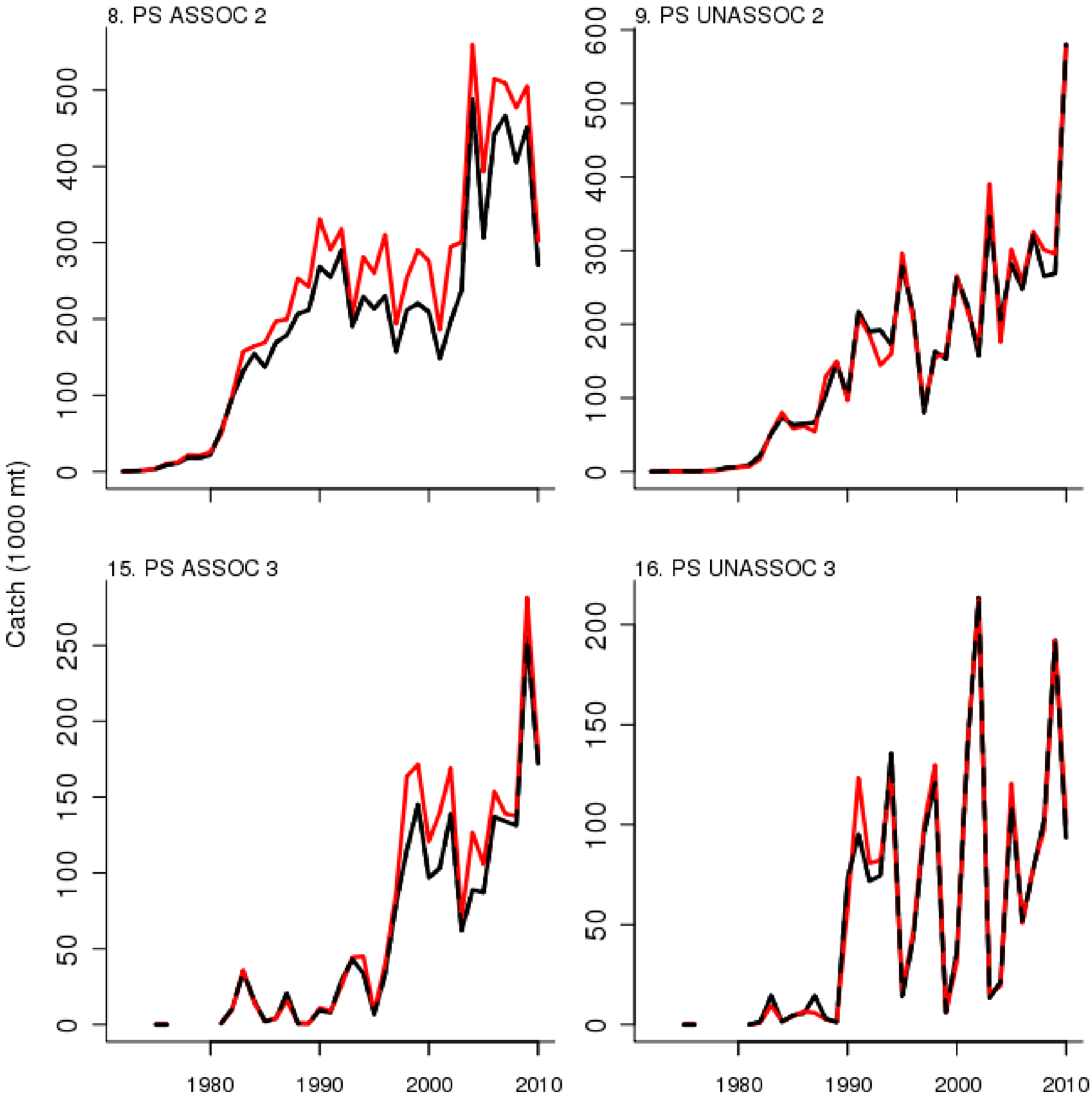

Figure 4: Comparison of S_BEST equatorial purse seine catches (red) with catches adjusted for spill sampling (black), for associated LOG/FAD (left) and unassociated (right) fisheries in regions 2 (above) and 3 (below).

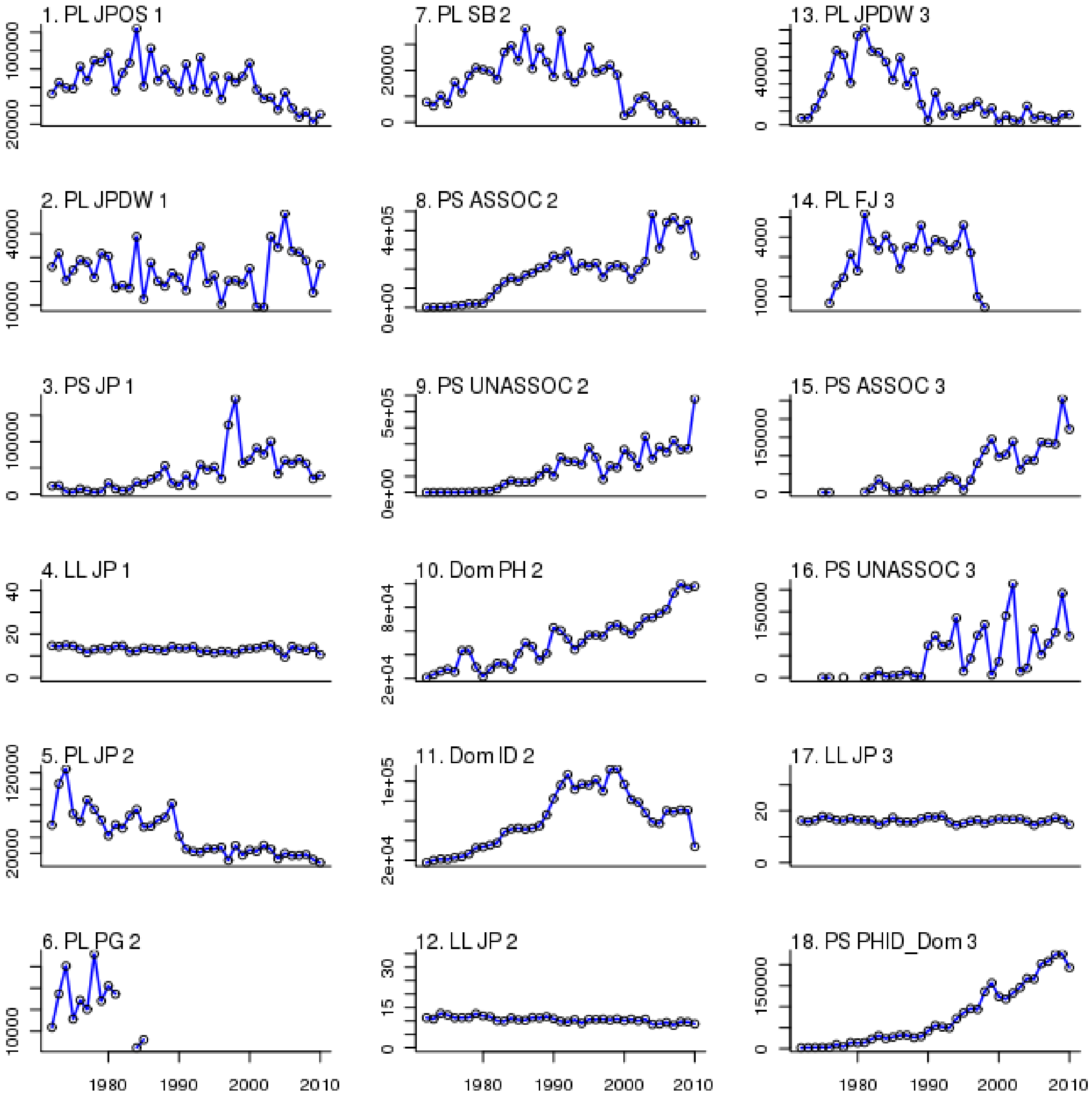

Figure 5. Annual catch by fishery and year. Catches are in thousands of tonnes for all fisheries except the longline (LL) fisheries, where the catches are in thousands of fish.

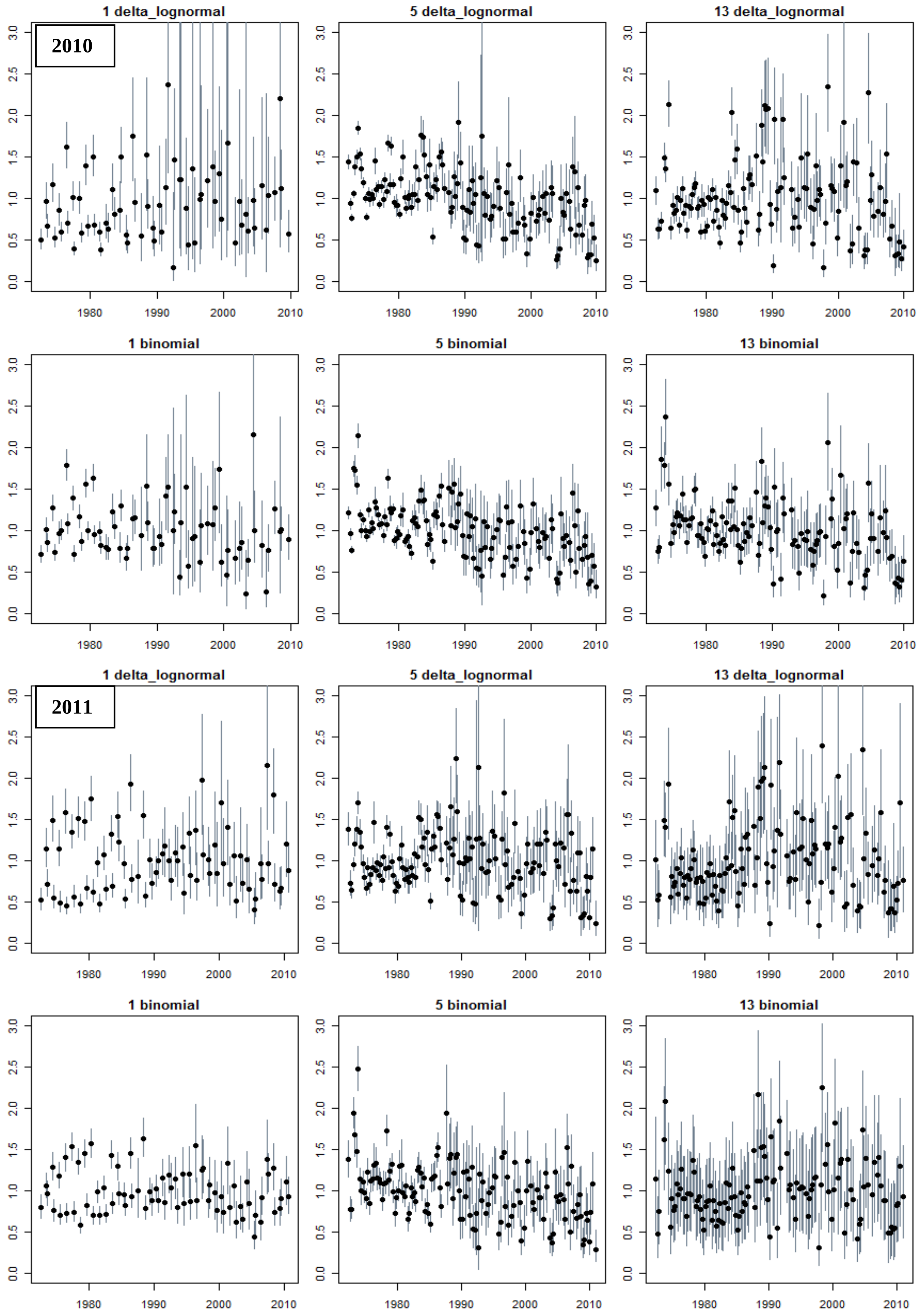

Figure 6: Catch rate time series from 2010 and 2011, by two different methods (delta lognormal and transformed binomial) for the three Japanese pole and line fisheries (fisheries 1, 5, and 13).

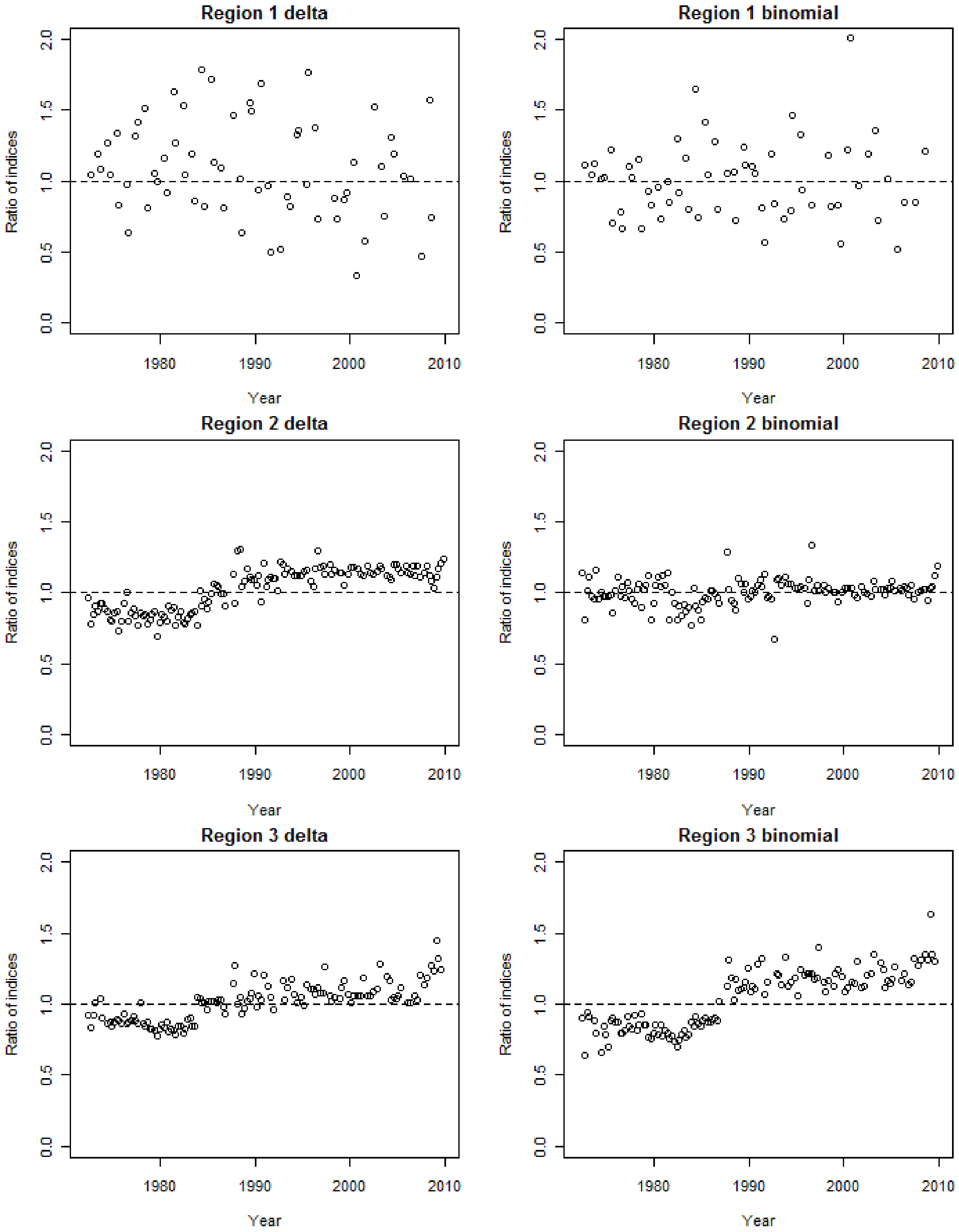

Figure 7: Ratio of CPUE indices estimated in 2011 versus indices estimated in 2010 (i.e. 2011 indices / 2010 indices), by region and index type. Delta lognormal indices are on the left, and binomial indices are on the right.

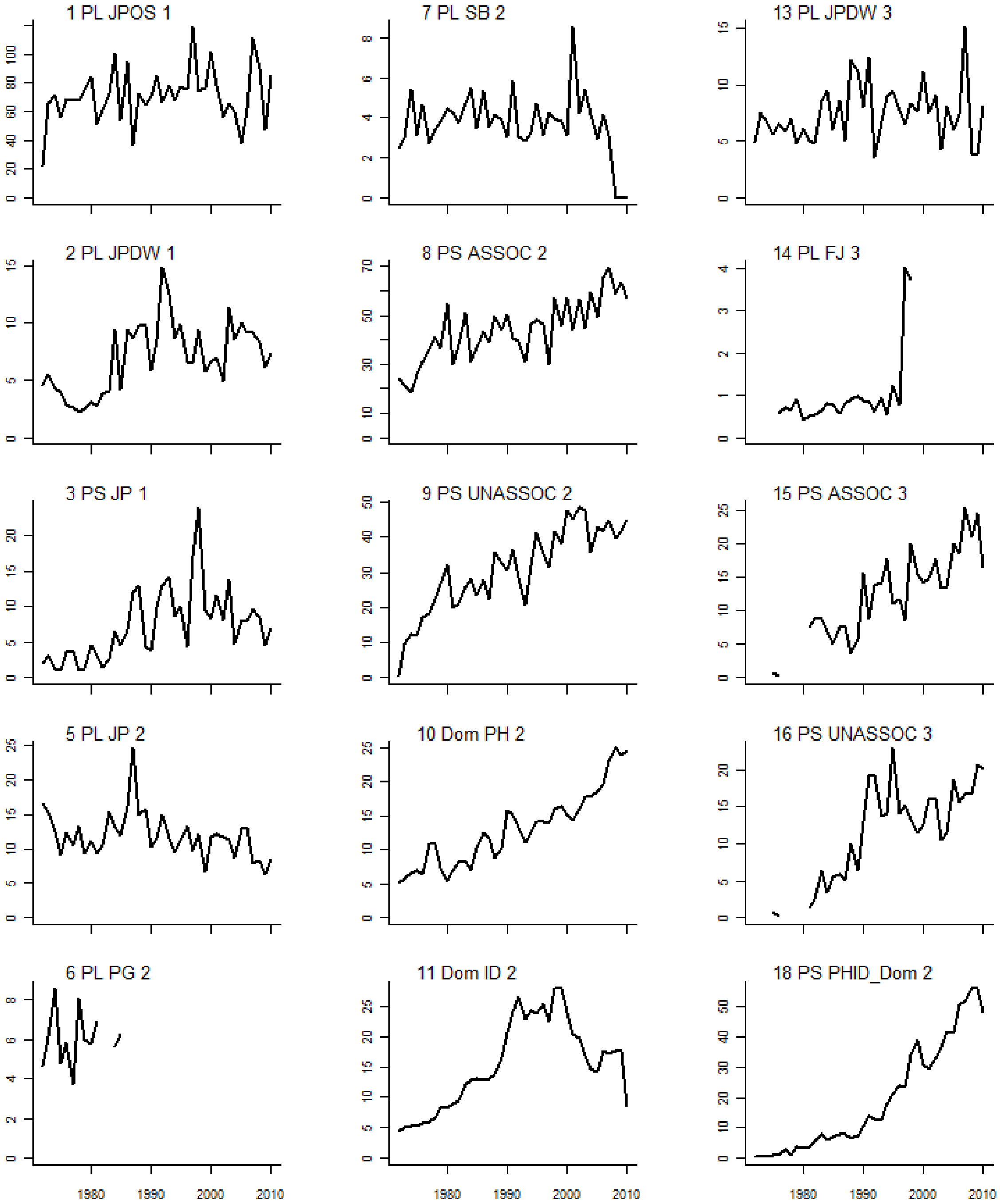

Figure 8: Annual catch per unit effort by fishery

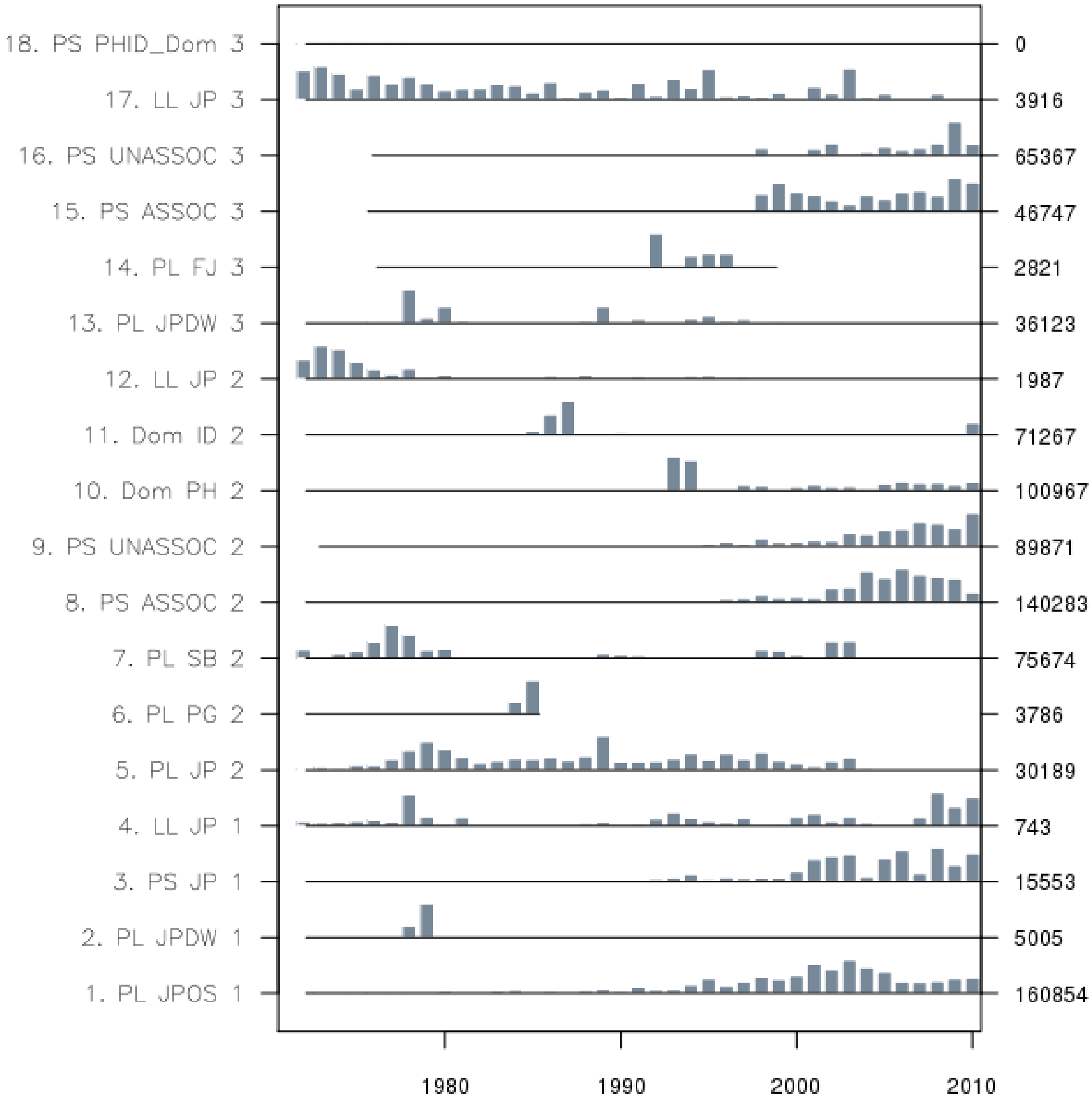

Figure 9: Number of length measurements by fishery and year. The heavy black line represents the period of operation of the fishery. The histogram bars are proportional to the maximum number of fish measured in a fishery/year (the value presented in the right hand axis).

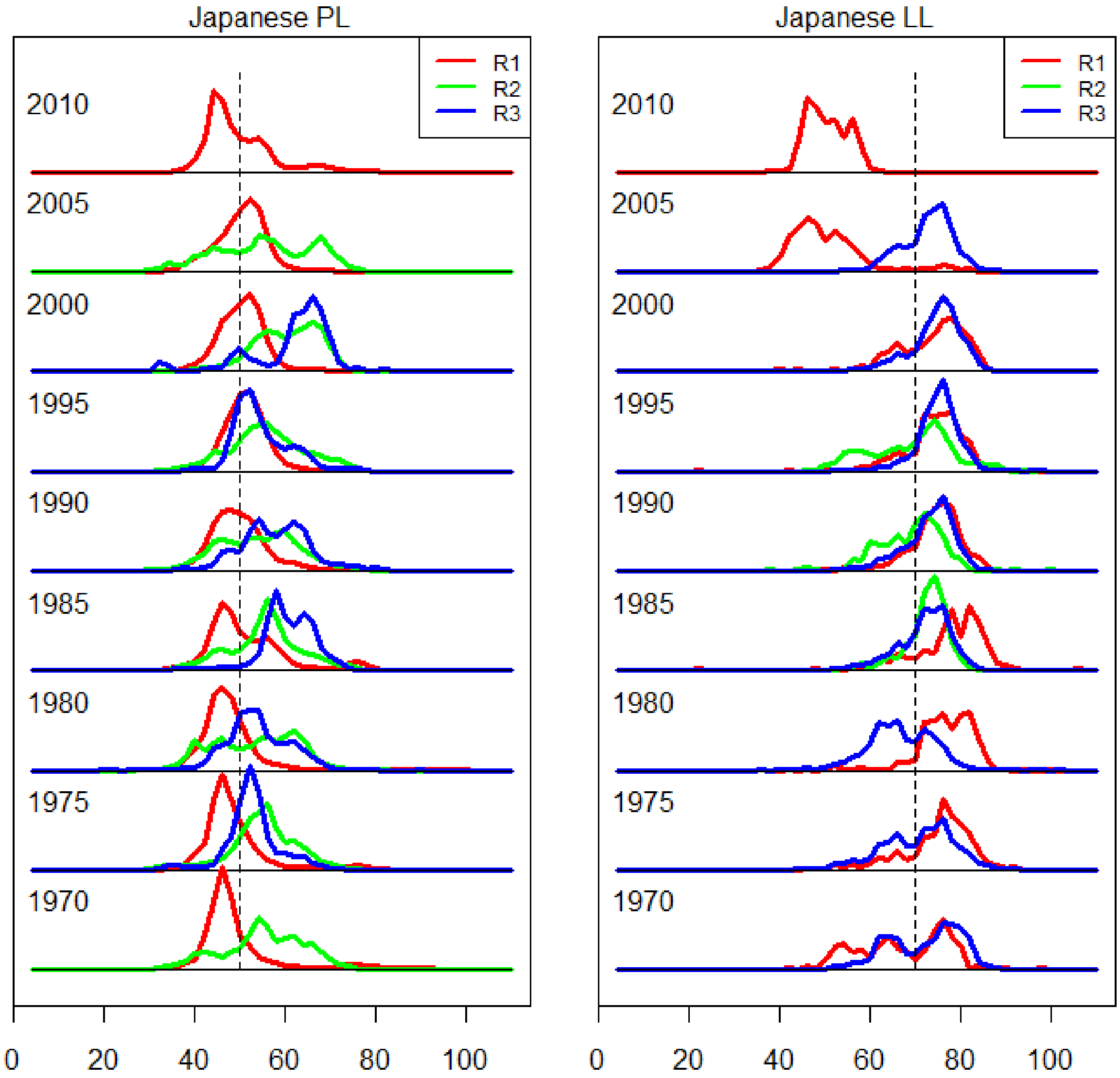

Figure 10. Proportional length compositions of skipjack from the Japanese pole-and-line and longline fisheries operating in the three MFCL regions (R 1–3). Samples are aggregated by 5-year interval. Only region/time length compositions comprised of at least 1,000 fish (PL) or 100 fish (LL) are presented. Vertical dashed lines at the mean overall size for each gear type are provided to aid comparisons.

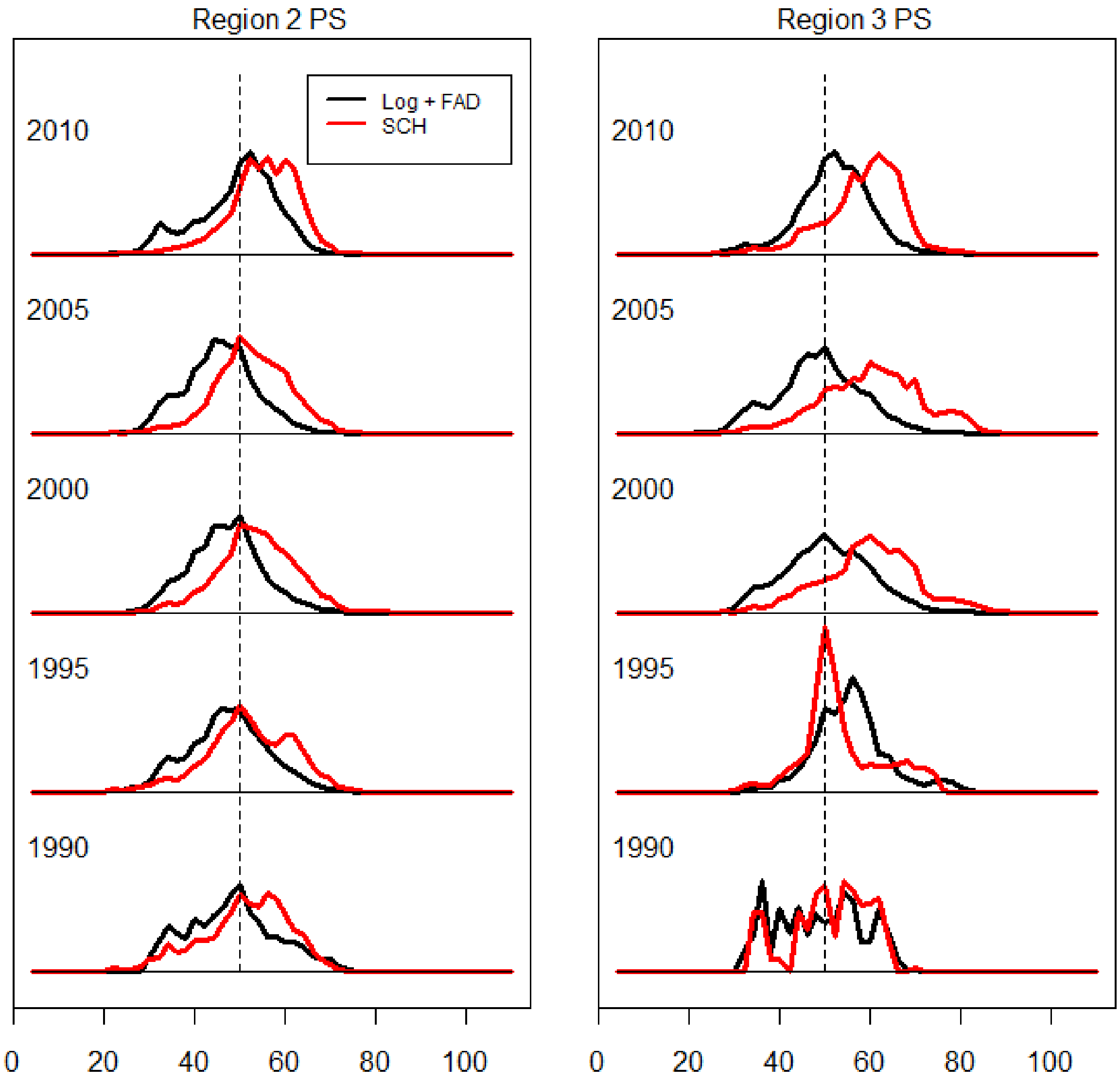

Figure 11. Proportional length compositions of skipjack from the equatorial purse-seine fisheries in the MFCL regions 2 (left panel) and 3 (right panel). Samples are aggregated by set type (log/FAD (black) and school (red)) and 5-year interval. Vertical dashed lines at 50cm for each gear type are provided to aid comparisons.

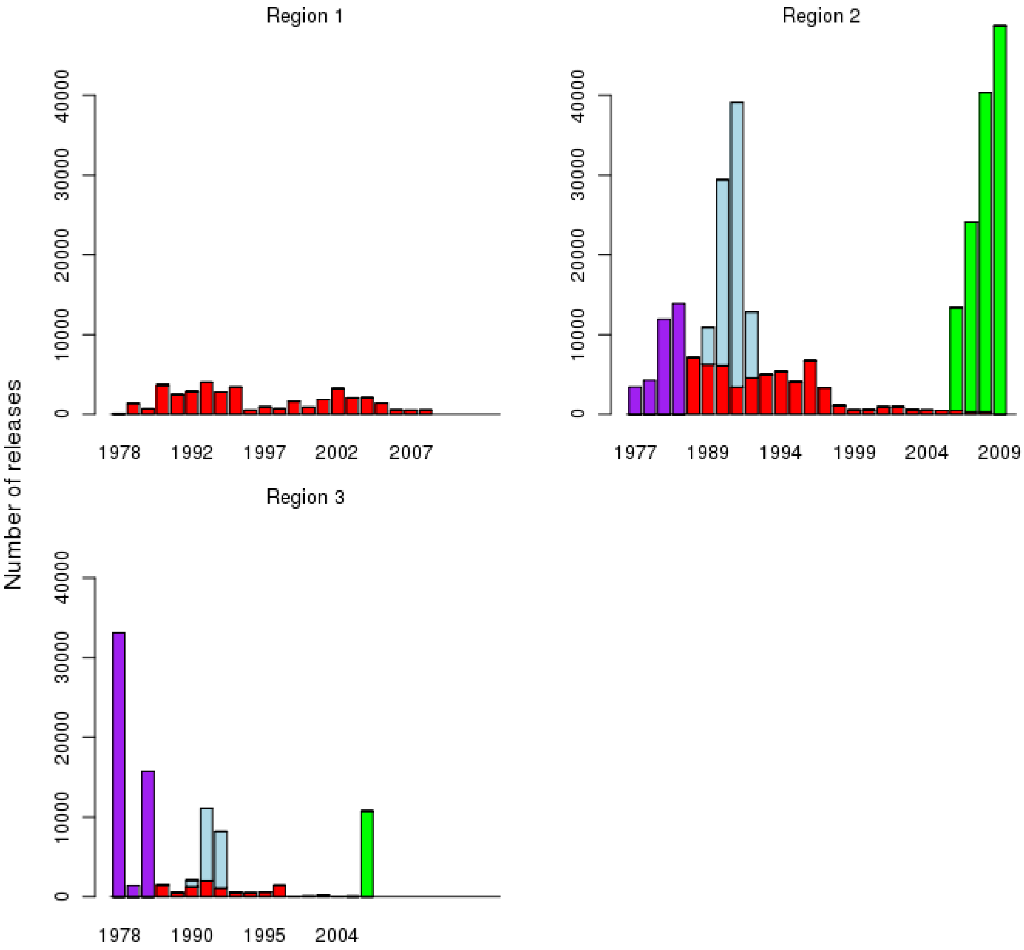

Figure 12. Number of tag releases by region, year and source of release included within the assessment model. The red represents releases by Japanese research programmes; for releases administered by SPC, the purple represents the SSAP, light blue represents the RTTP, and green represents the PTTP.

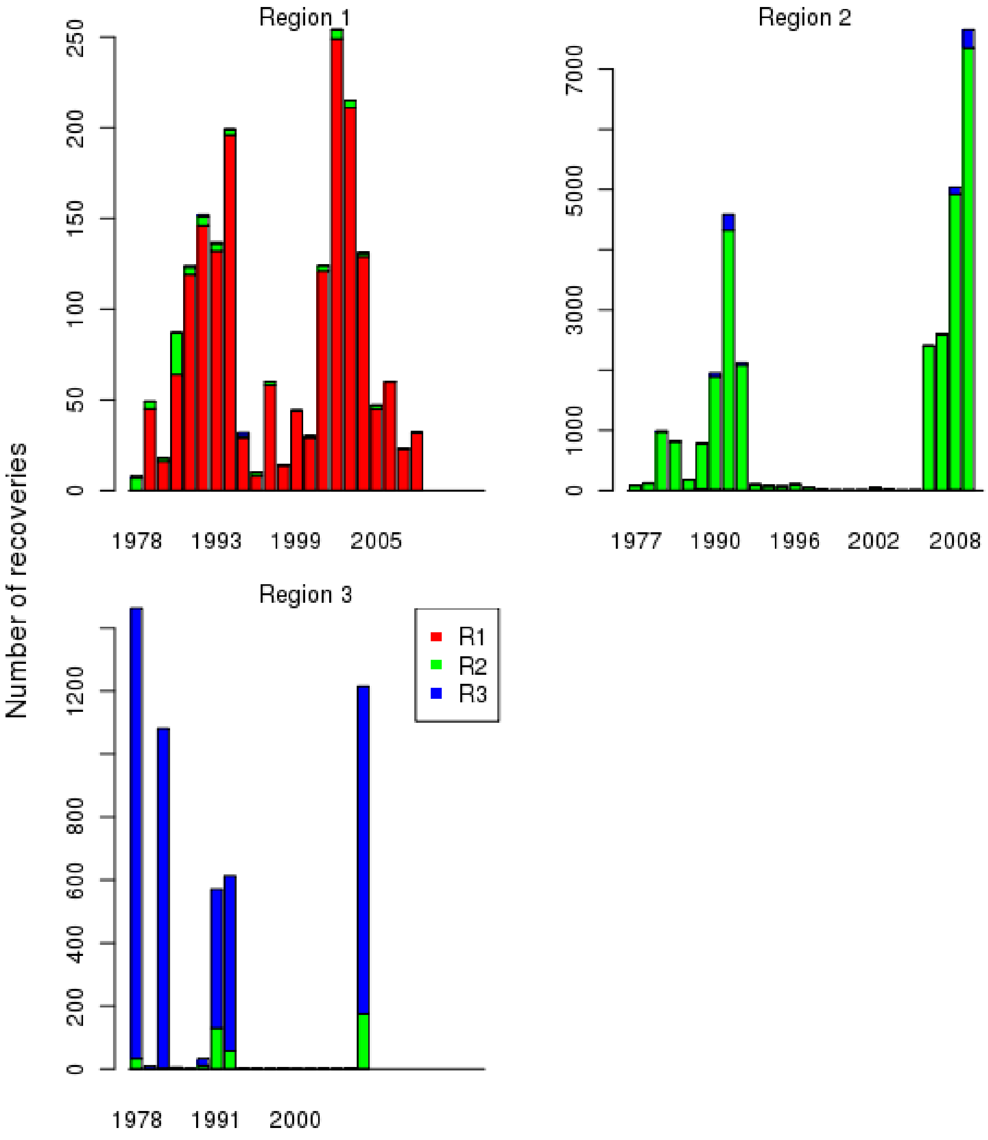

Figure 13. Annual number of tag recoveries in each region by region of release.

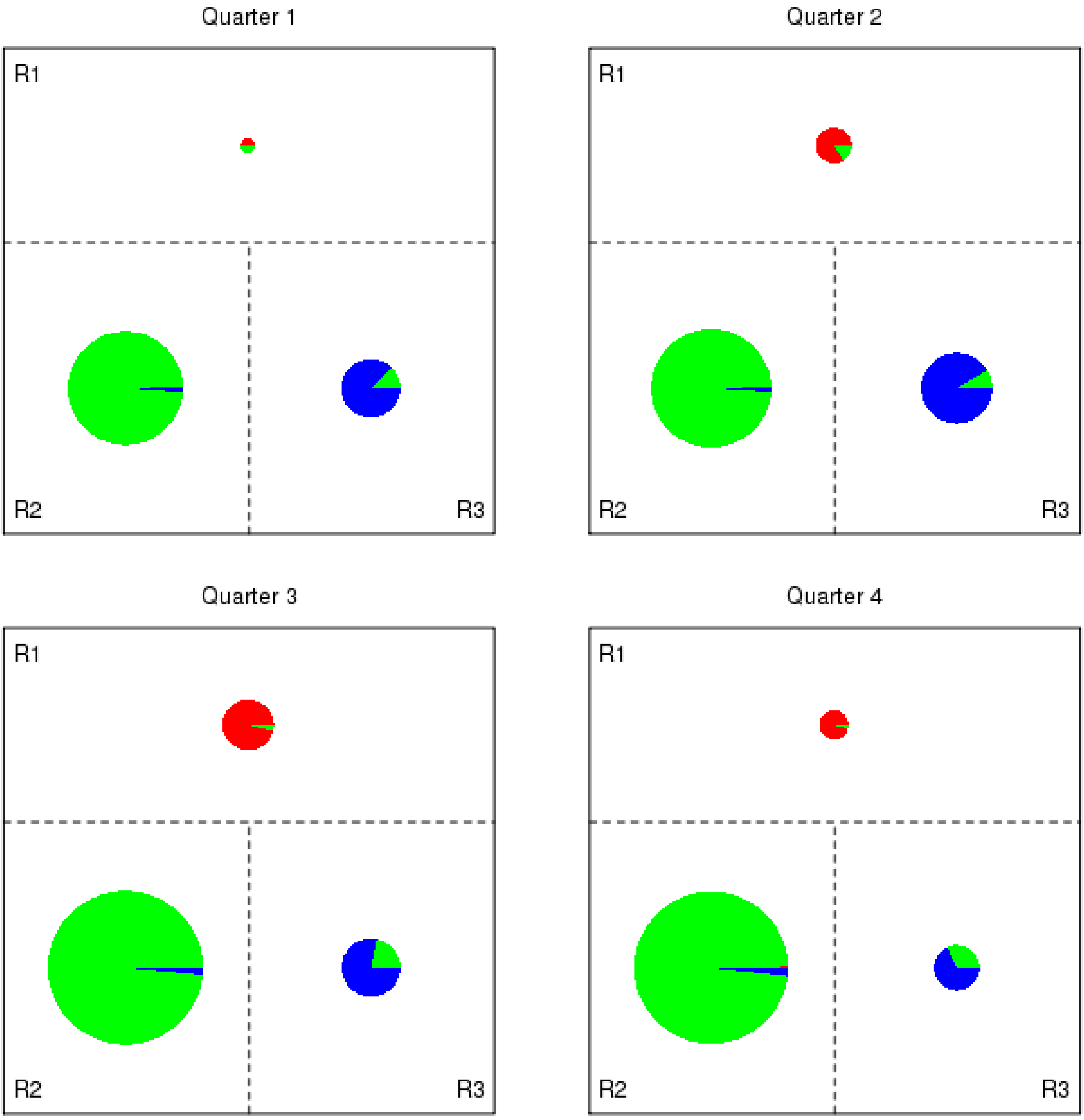

Figure 14: Number of tags recovered in each region, by quarter of recovery. The size of the pie represents the number of tags recovered, with the colour of the pie slice indicating the source region: red, green, and blue for regions 1, 2, and 3 respectively.

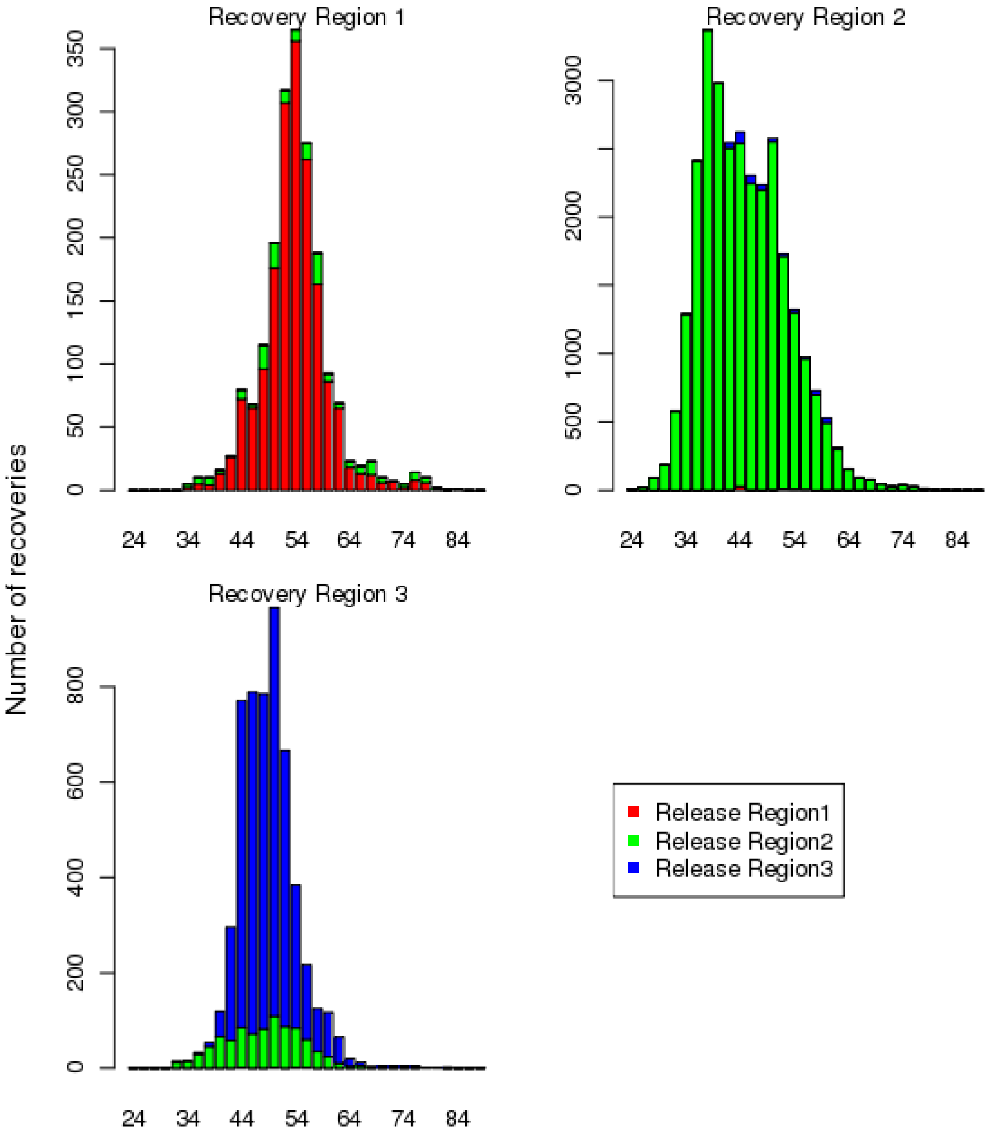

Figure 15. Number of recoveries at length for each region by region of release.

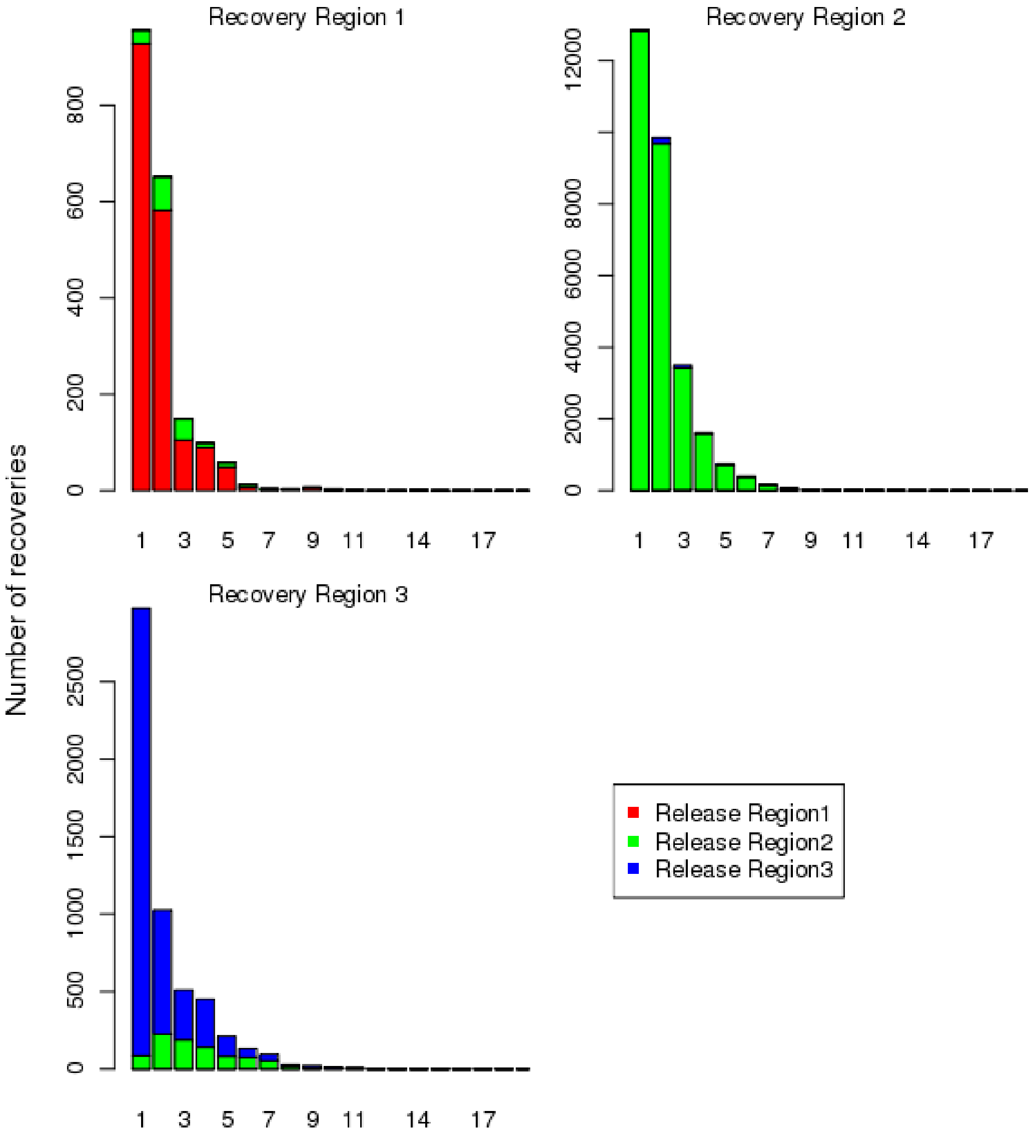

Figure 16. Number of tag recoveries by period at liberty (quarters) for each region by region of release. The first quarter represents the quarter in which the tags were released.

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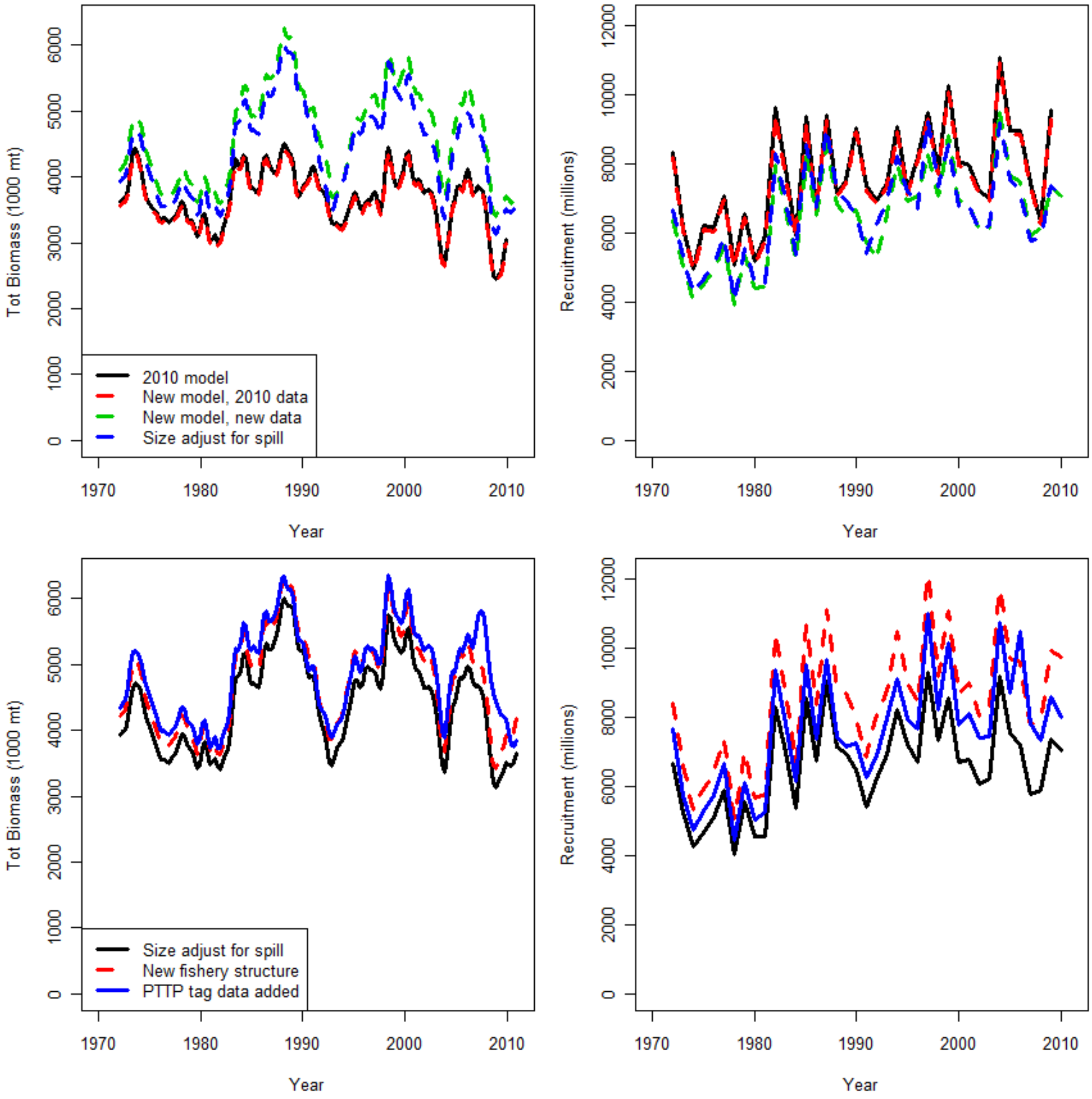


Figure 17: Effects of a series of model changes on total biomass (left) and recruitment (right). The top figures show stepwise changes from the 2010 model, updating the version of MULTIFAN-CL, adding the new catch, effort, and CPUE data, and adjusting the size data for the spill sampling size correction. The lower figures show the effects of introducing the additional PHID PS fishery, and adding the PTTP data. Changing steepness from 0.75 to 0.8 did not change the trends, so is omitted.

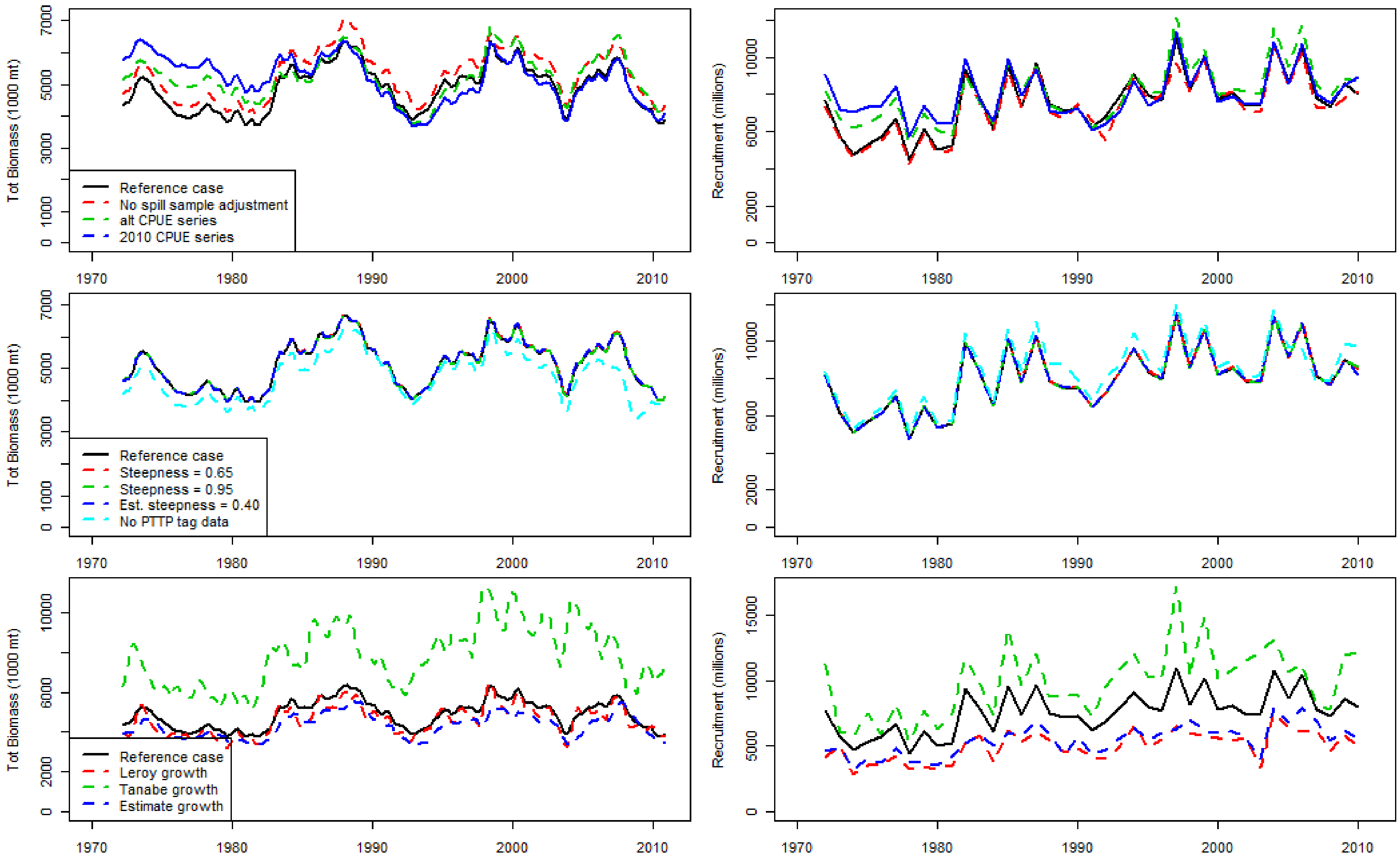


Figure 18: Sensitivity analysis effects on total biomass (left) and recruitment (right). The top figures show the effects of the spill sample size adjustment, the alternate CPUE series, and the 2010 CPUE. The middle figures show the effects of changing steepness, which do not affect biomass or recruitment trends. The lower figures show the results of changing the growth model, and the PTTP tagging data.

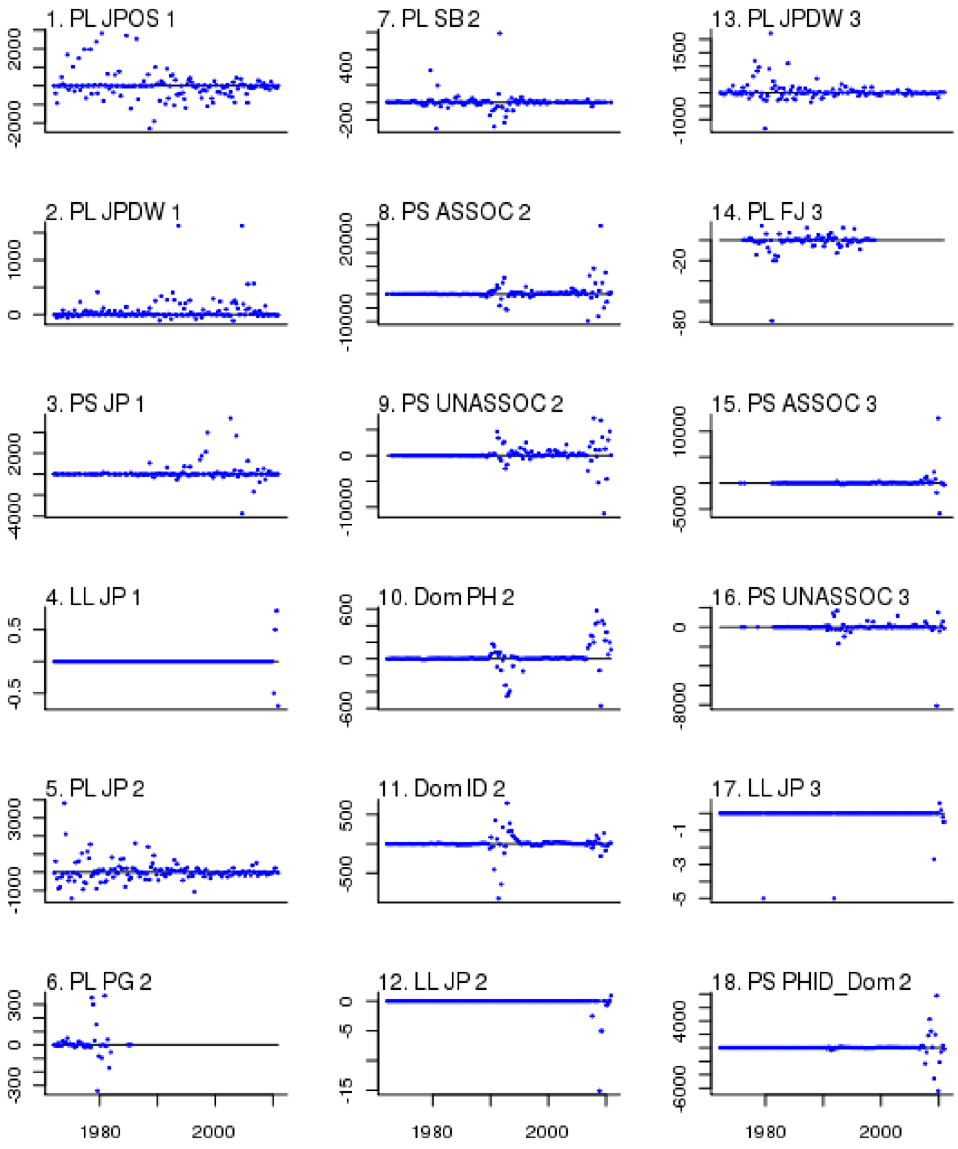


Figure 19. Residuals (observed minus predicted) of total catch for each fishery.

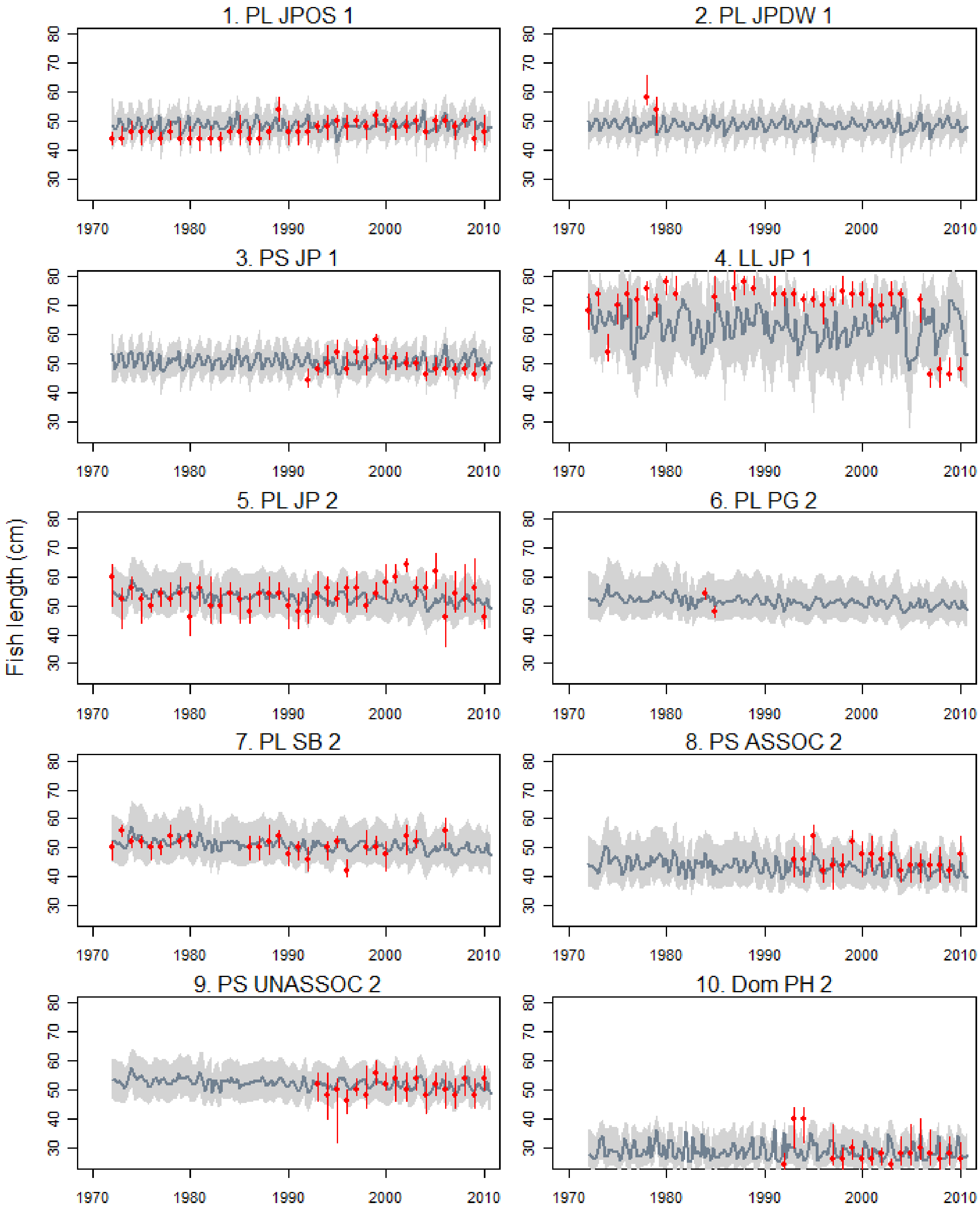


Figure 20. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of skipjack tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

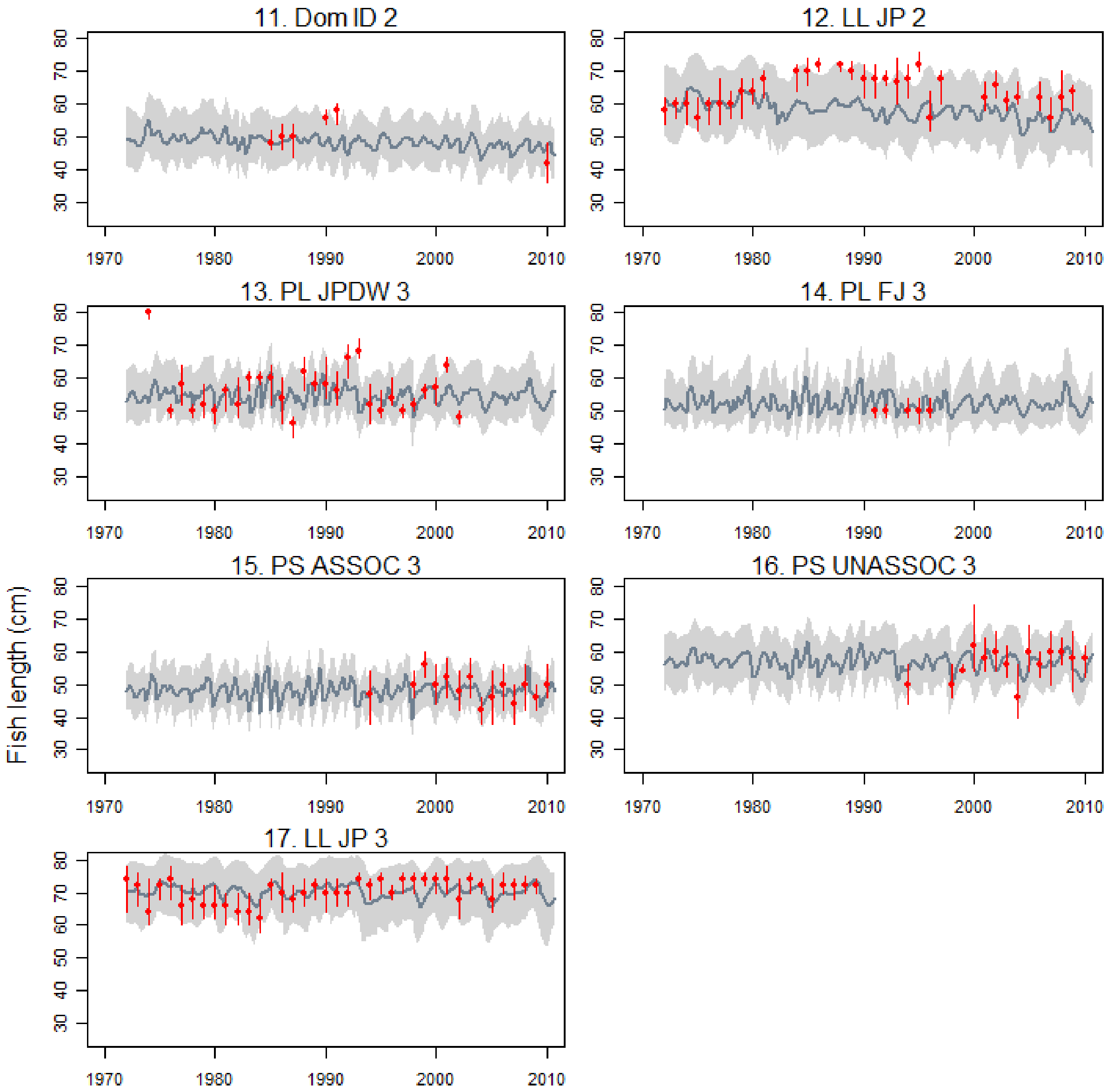


Figure 20. Continued.

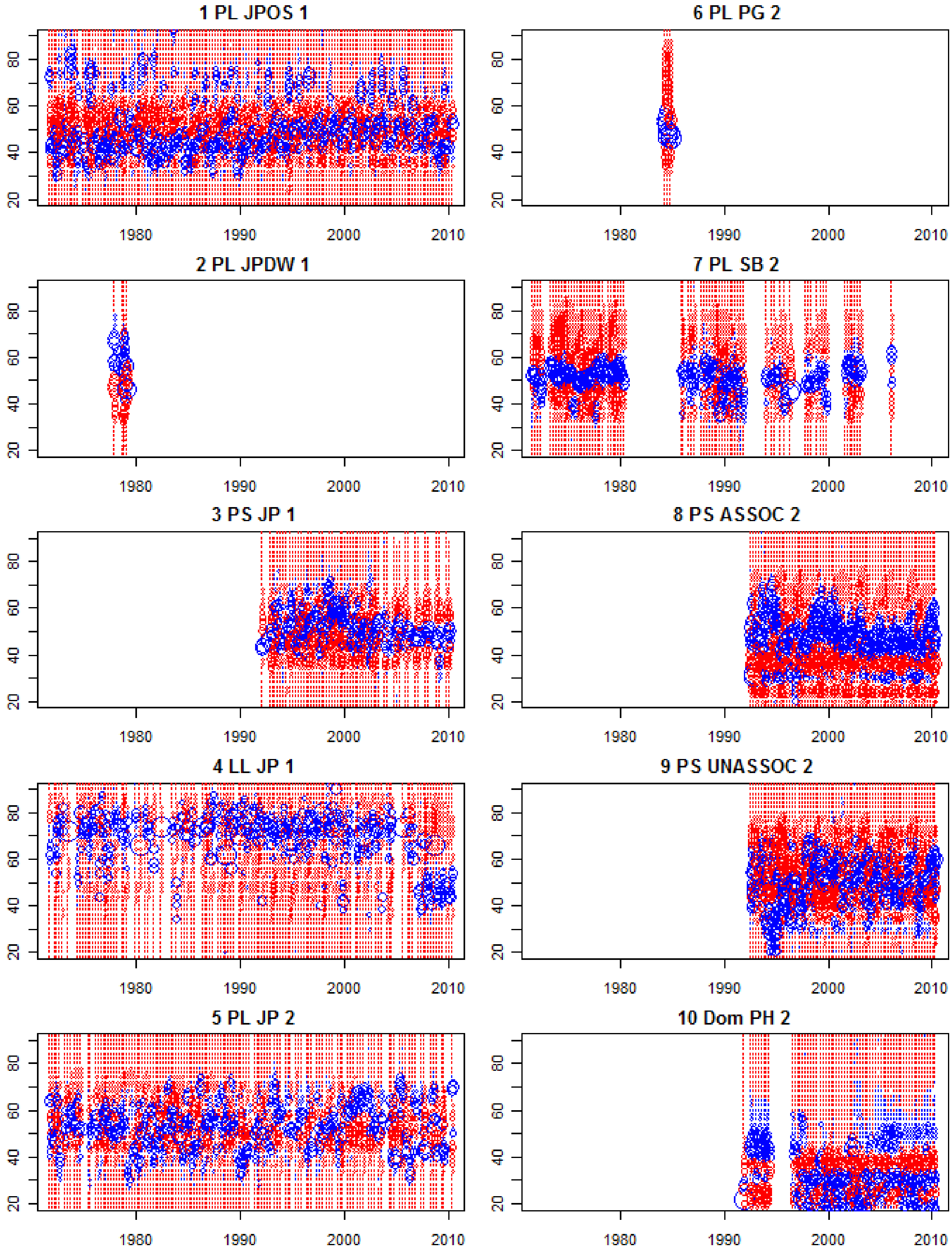
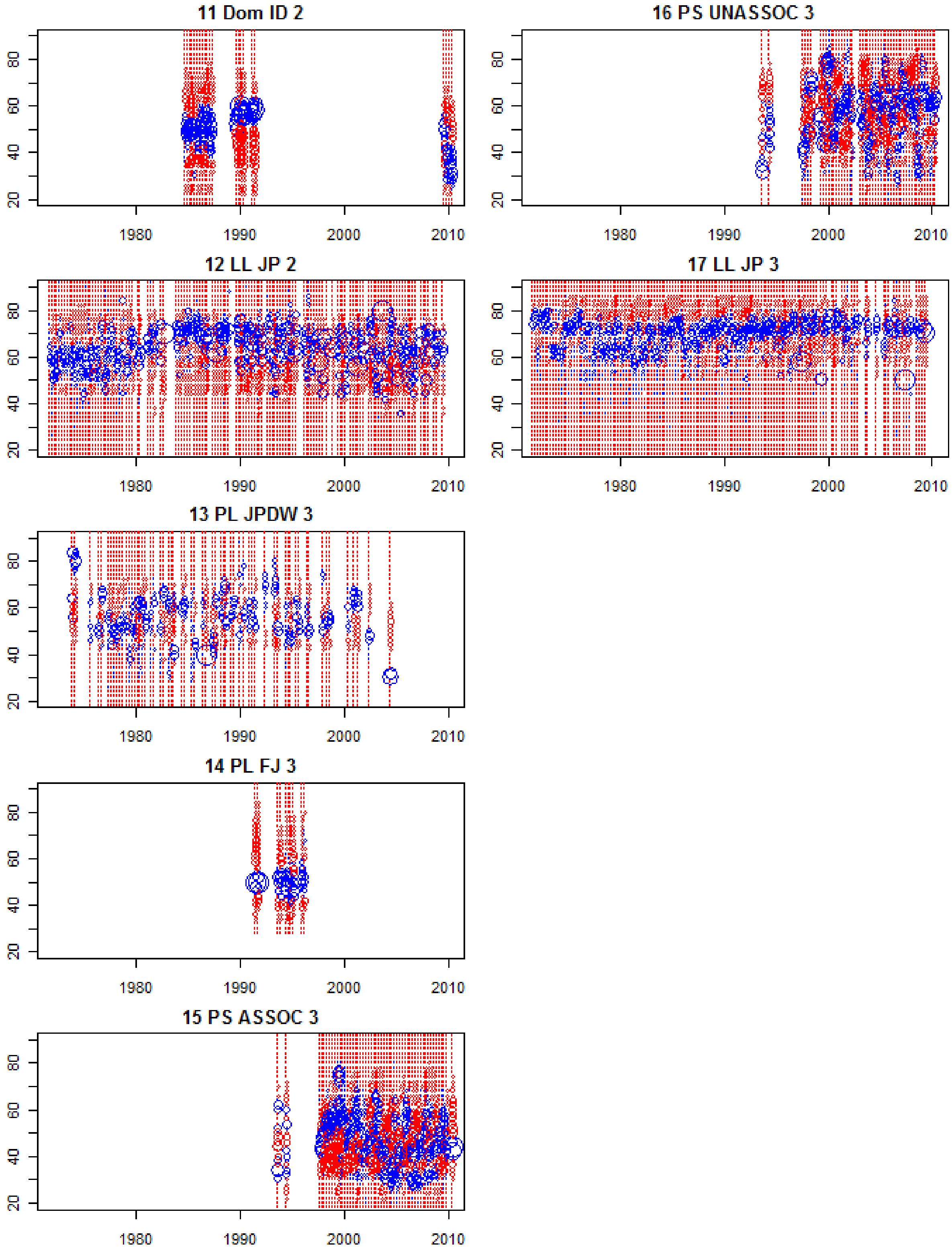


Figure 21: Residuals (observed – predicted proportions) of the fit to the length frequency data. The size of the circle is proportional to the residual; blue circles are positive residuals (i.e. more observations than expected), red circles negative residuals.



11 Dom ID 2

12 LL JP 2

13 PL JPDW 3

14 PL FJ 3

15 PS ASSOC 3

16 PS UNASSOC 3

17 LL JP 3

Figure 21 continued…

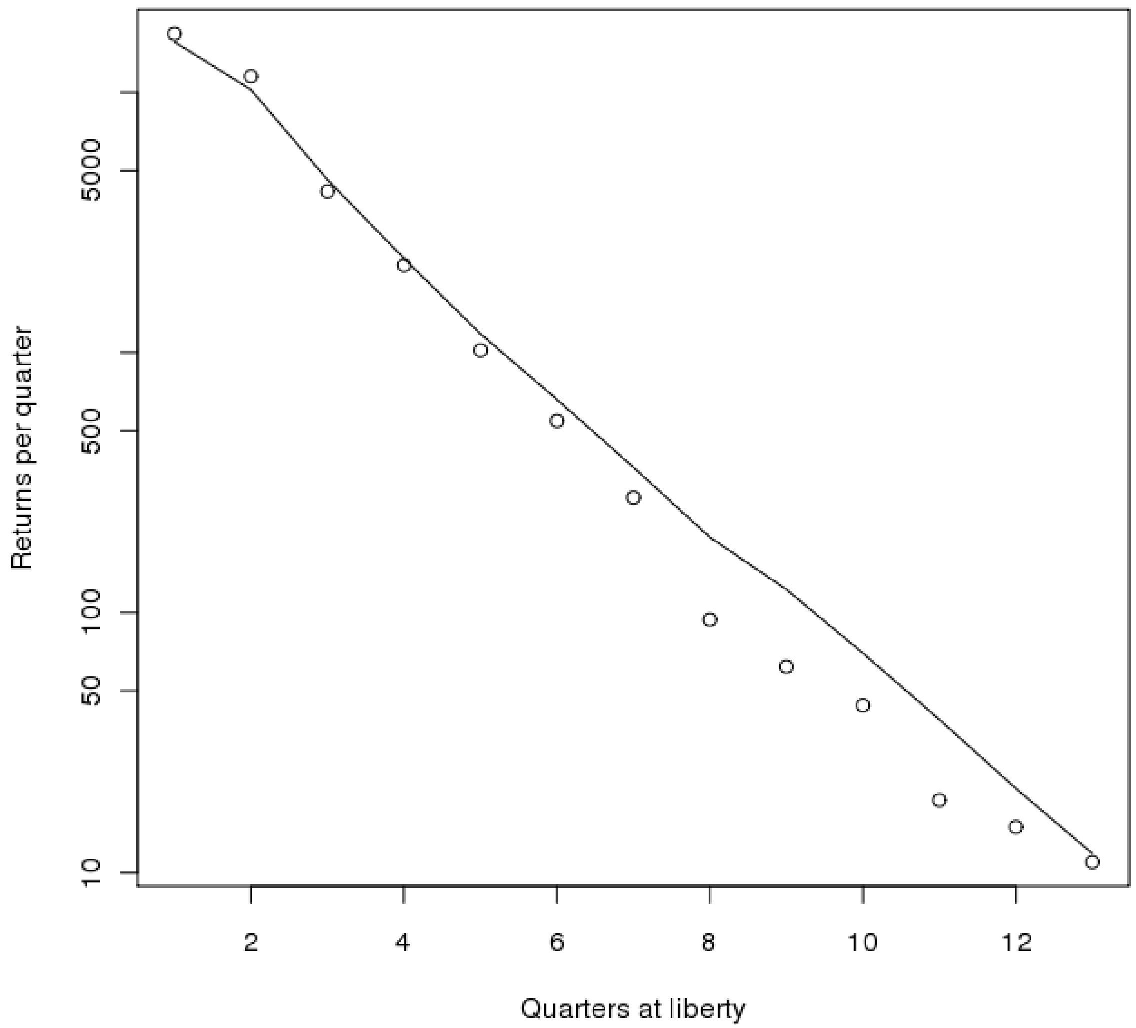


Figure 22: Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters).

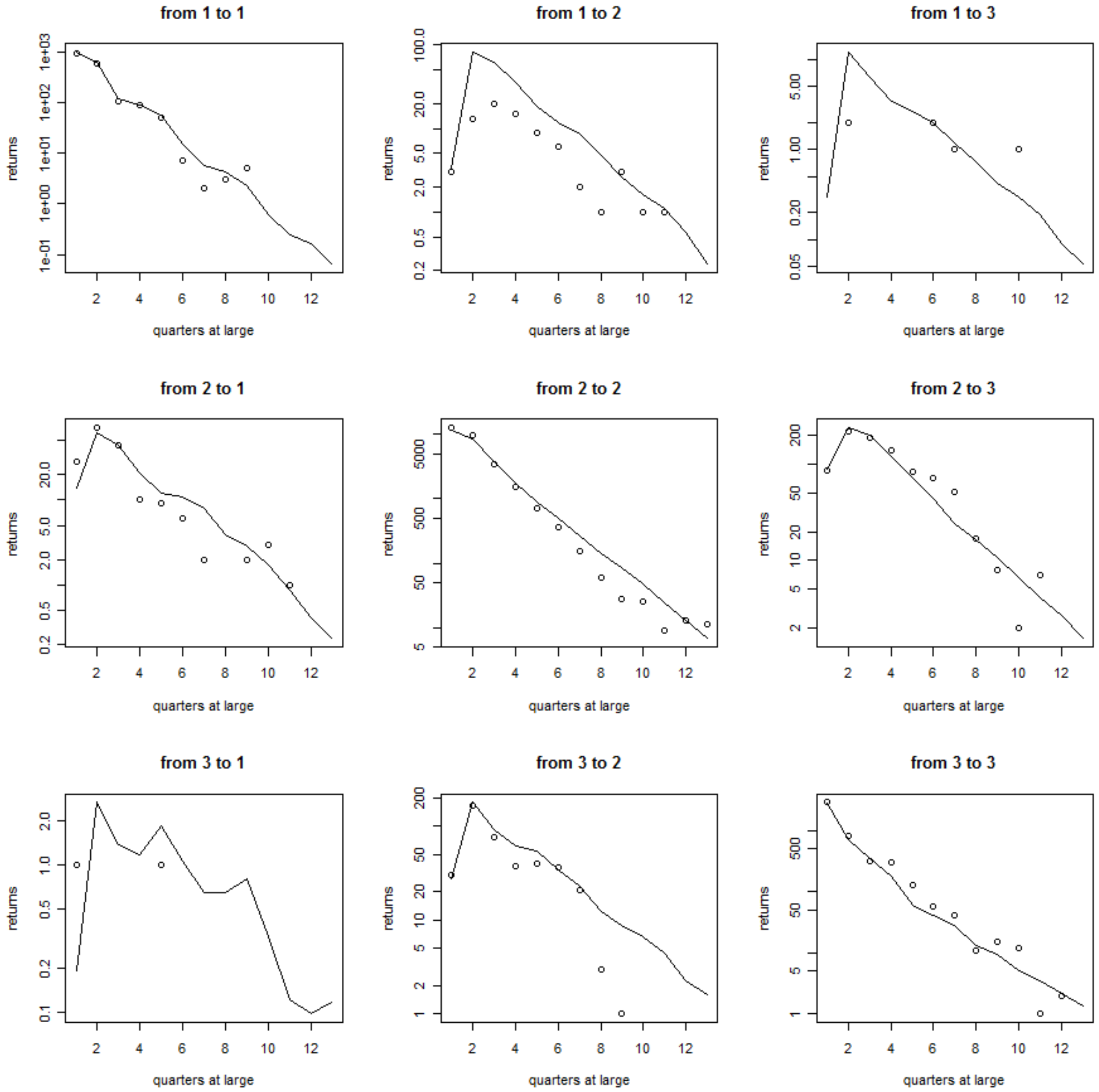


Figure 23: Number of observed (circles) and predicted (line) tag returns by periods at liberty (quarters), for tags released (from) and recovered (to) by region.

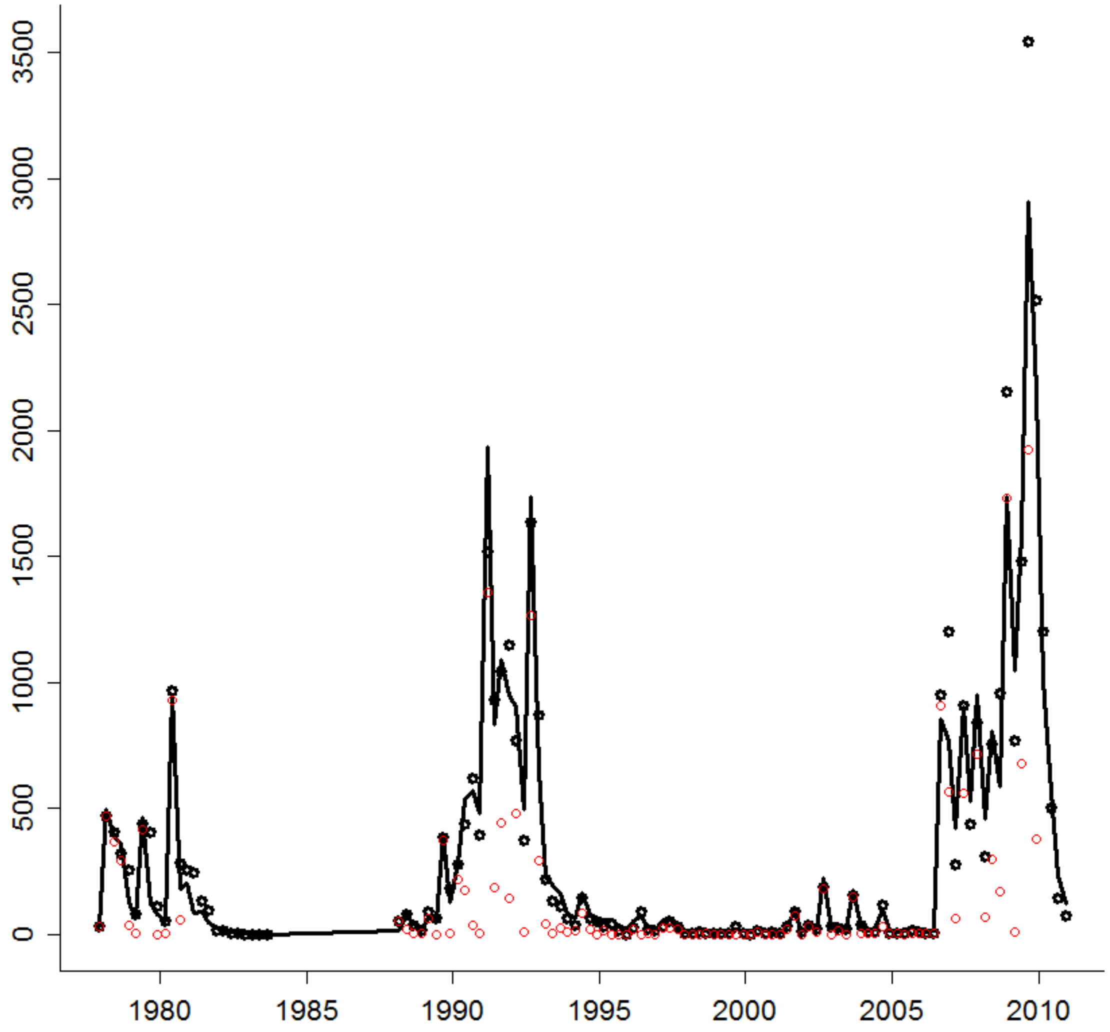


Figure 24. Number of observed (circles) and predicted (lines) tag returns by recapture period (quarter). The red circles represent tags recovered during the mixing period.

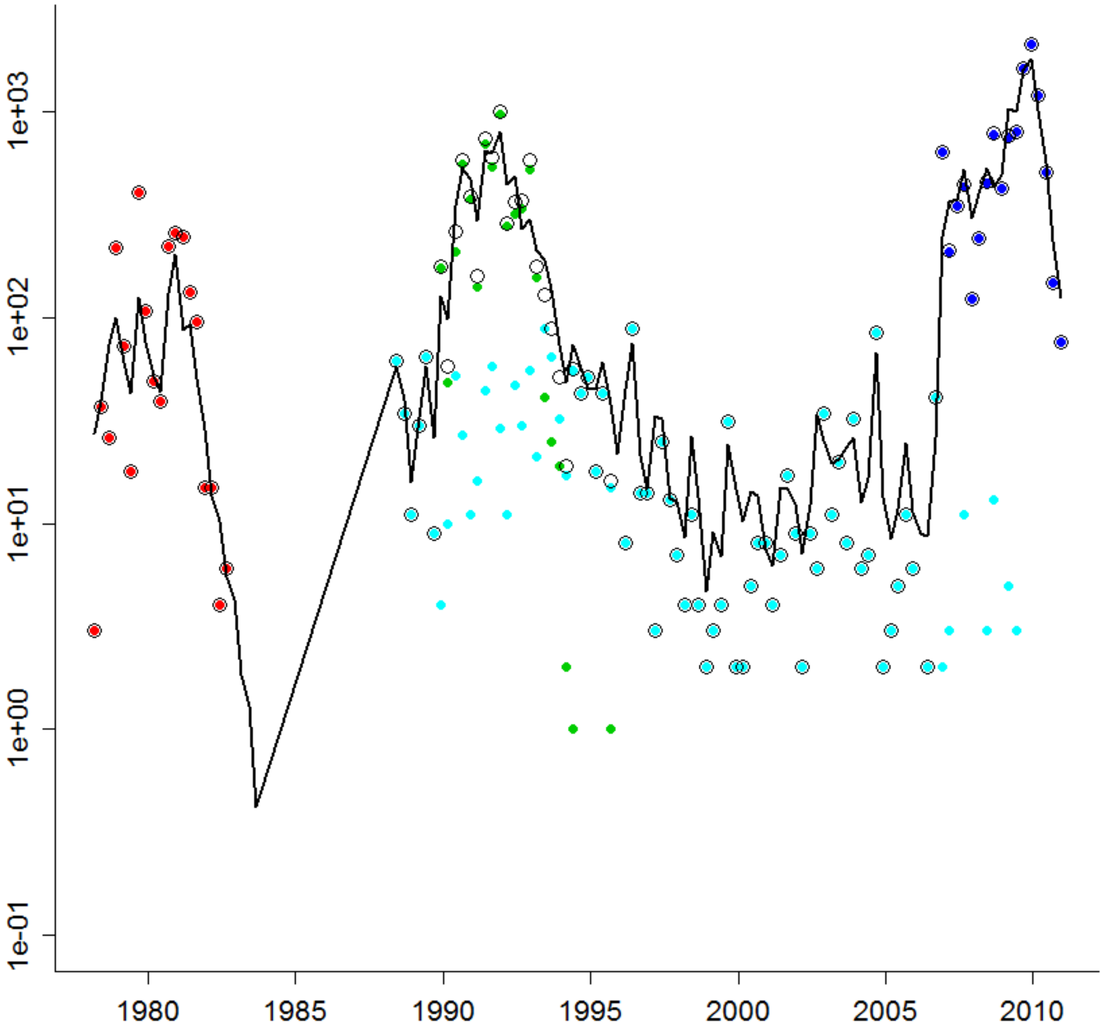


Figure 25: Number of observed (black circles) versus predicted (line) tag returns by year, plotted on a log scale. The contributions of each tagging programme are plotted as coloured circles, with SSAP in red, RTTP in green, JP light blue, and PTTP dark blue.

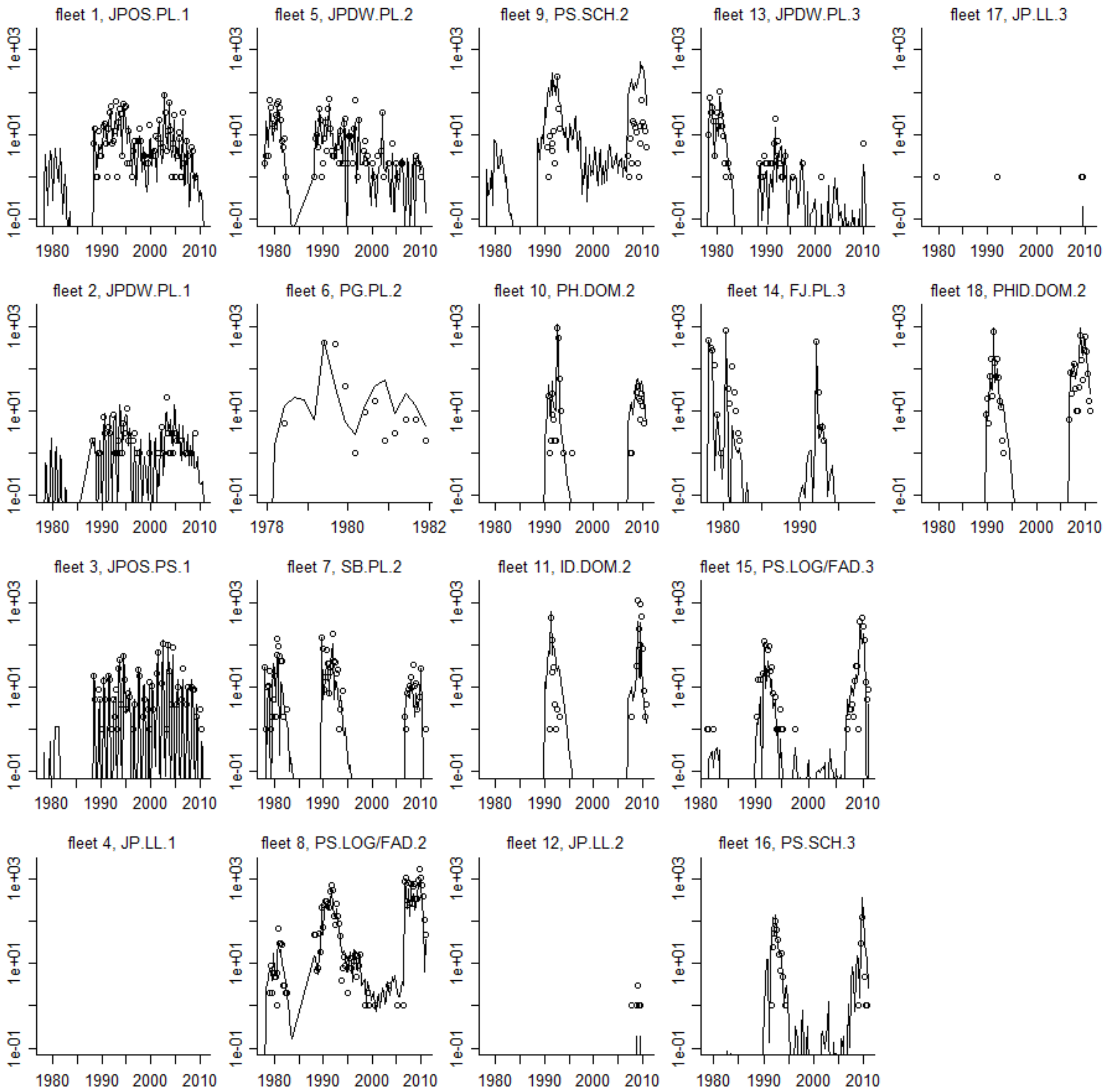


Figure 26: Number of observed (circles) and predicted (lines) tag returns by recapture period (quarter) and fishery. Recoveries in fisheries 8 and 9, fisheries 15 and 16, and fisheries 10 and 18 are combined into tag groups.

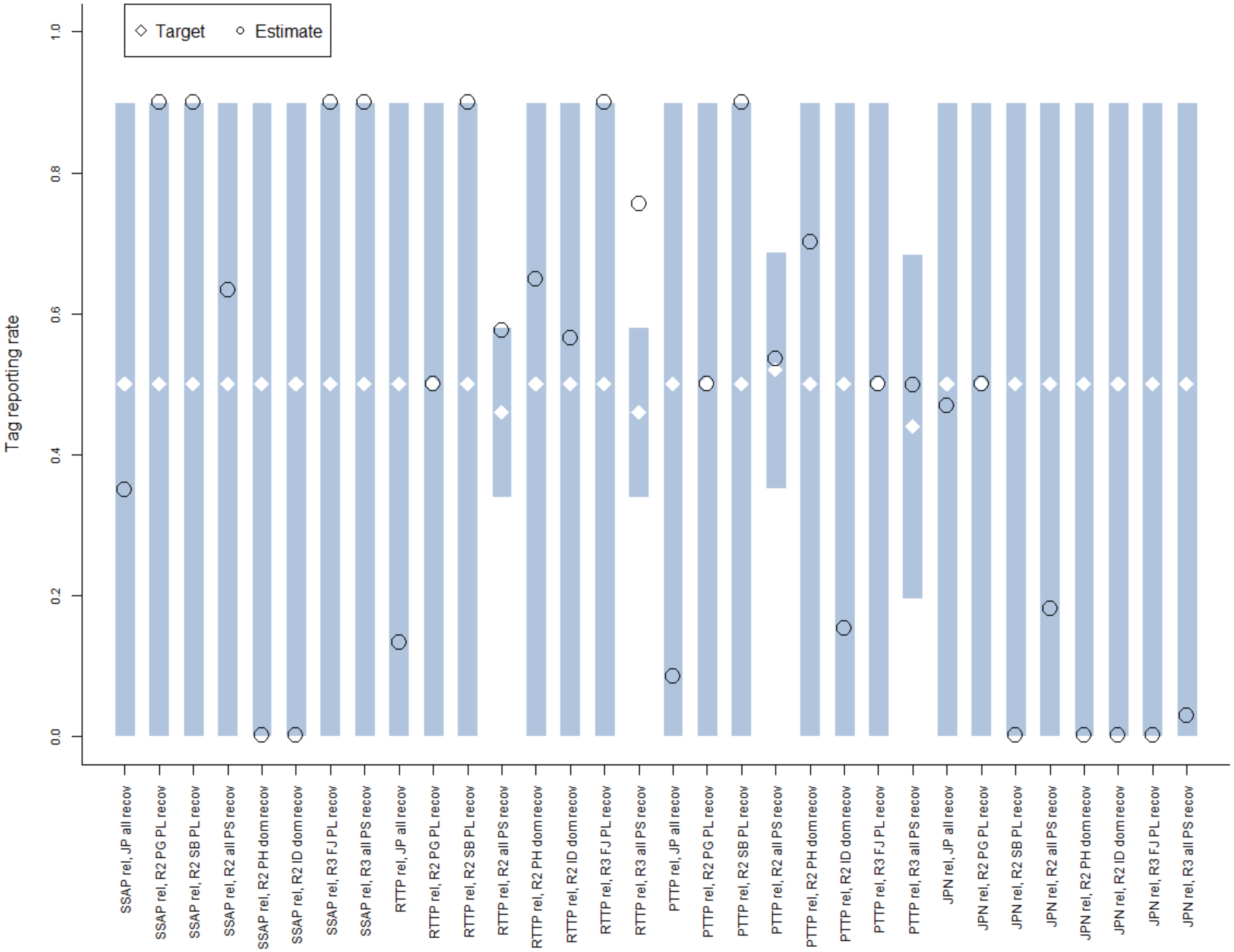


Figure 27: Estimated tag-reporting rates by tagging programme and fishery (black circles). The prior mean ±1.96 SD is also shown for each fishery by the white diamonds and coloured bars.

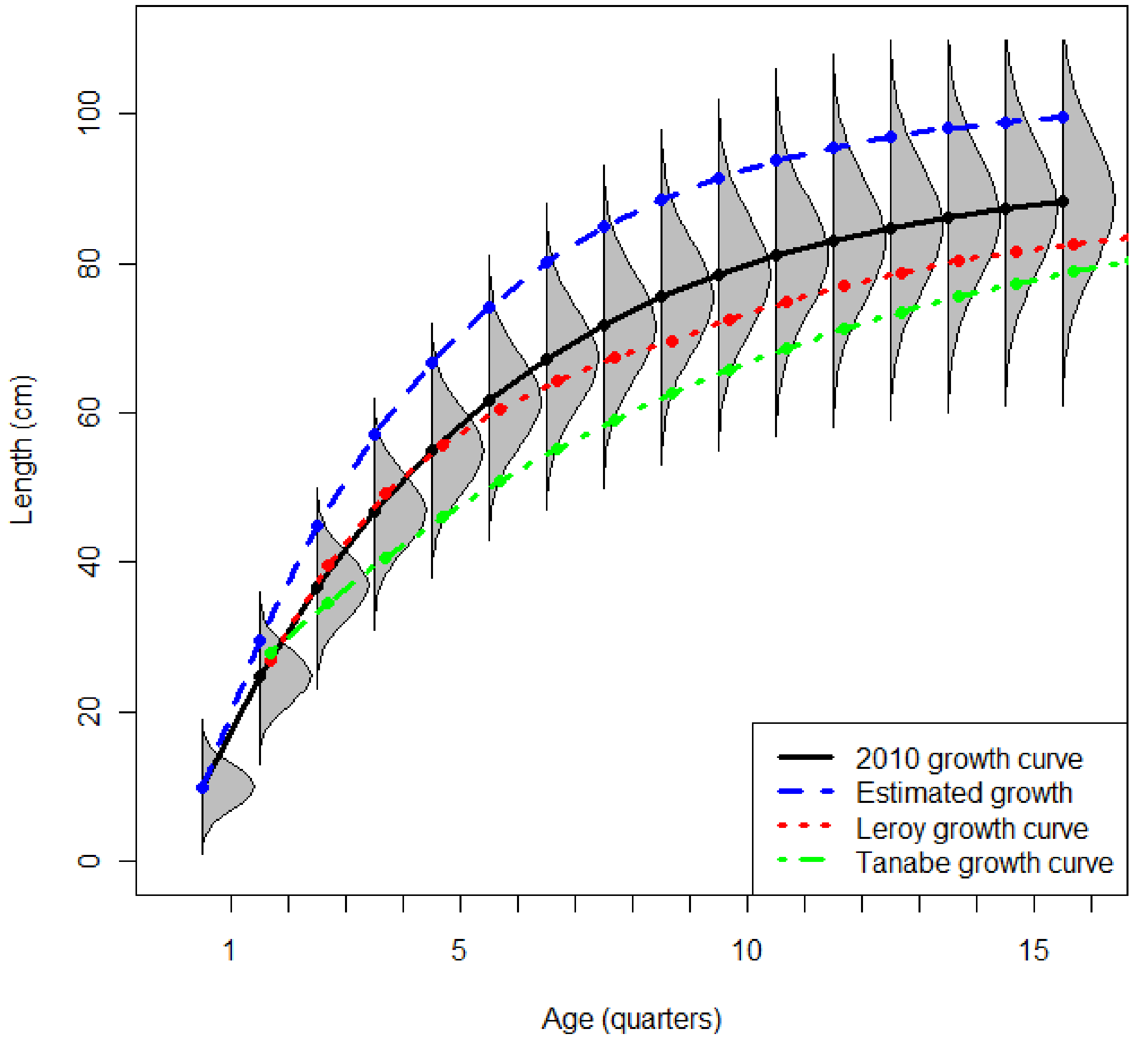


Figure 28. Estimated growth of skipjack derived from the assessment model. The black line represents the estimated length (FL, cm) at age and the grey areas represent the estimated distribution of length at age. The blue, red, and green lines represent the three alternative growth curves (estimated, Leroy, and Tanabe curves respectively).

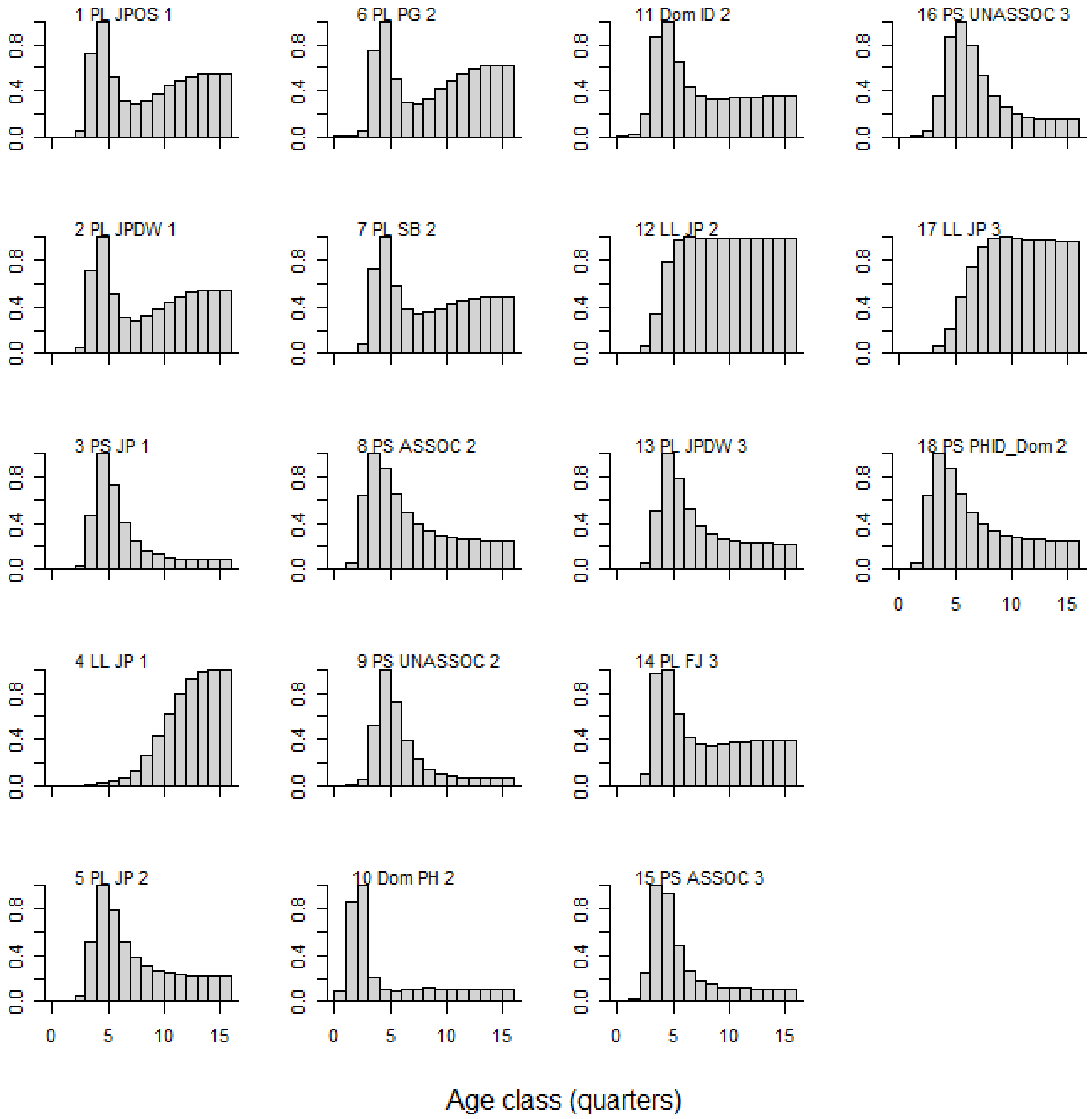


Figure 29. Selectivity coefficients, by fishery. All JP PL fisheries were assumed to have common selectivity.

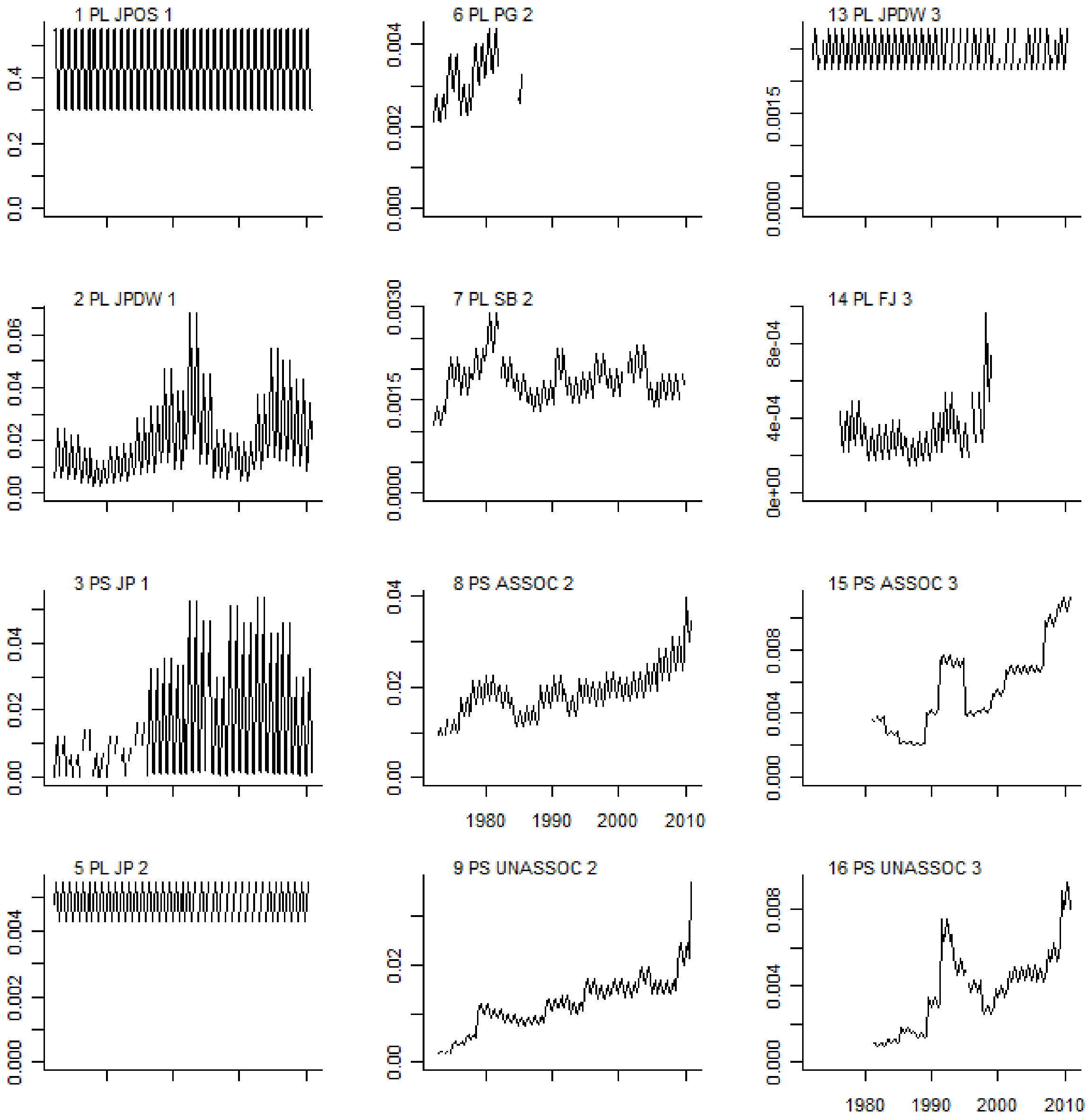


Figure 30. Estimated time-series catchability trends for each fishery.

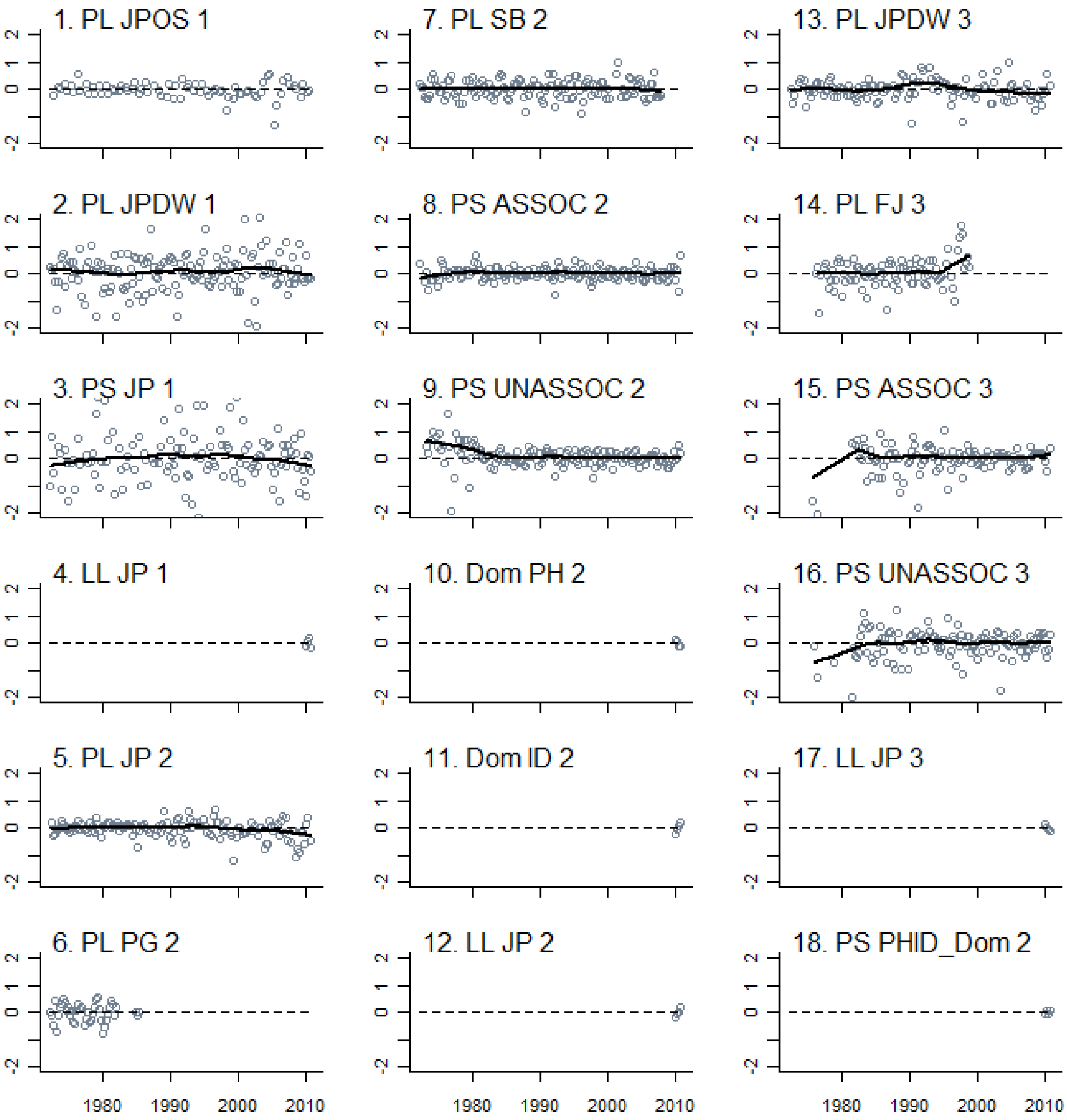


Figure 31: Effort deviations by time period for each fishery in the WCPO reference-case model. The black line is a loess smoother fitted to the deviations, to indicate the local trend.

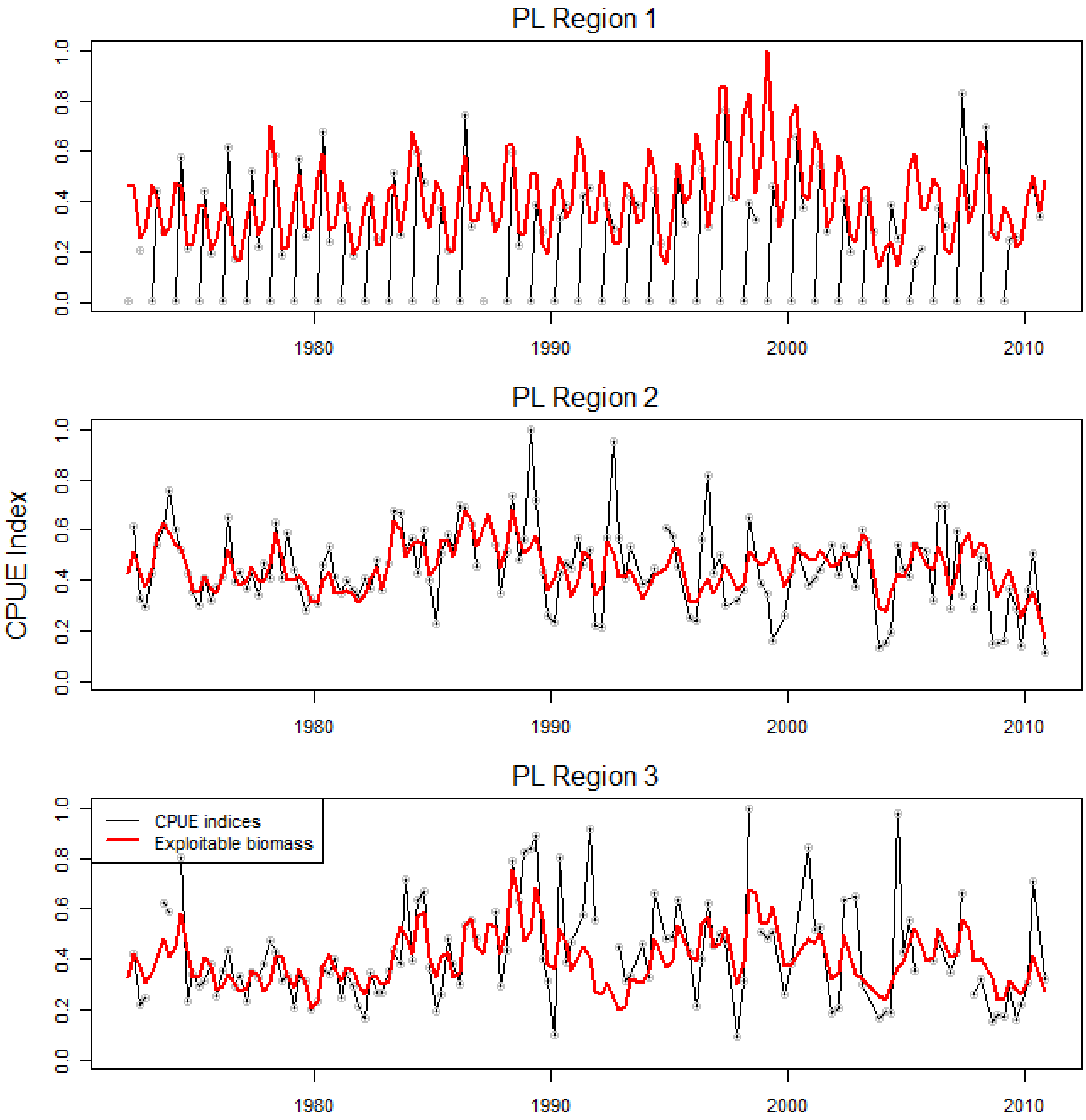


Figure 32. A comparison of pole-and-line exploitable biomass by quarter and region (red line) and the quarterly standardised CPUE indices for the fisheries, each series relative to its mean value.

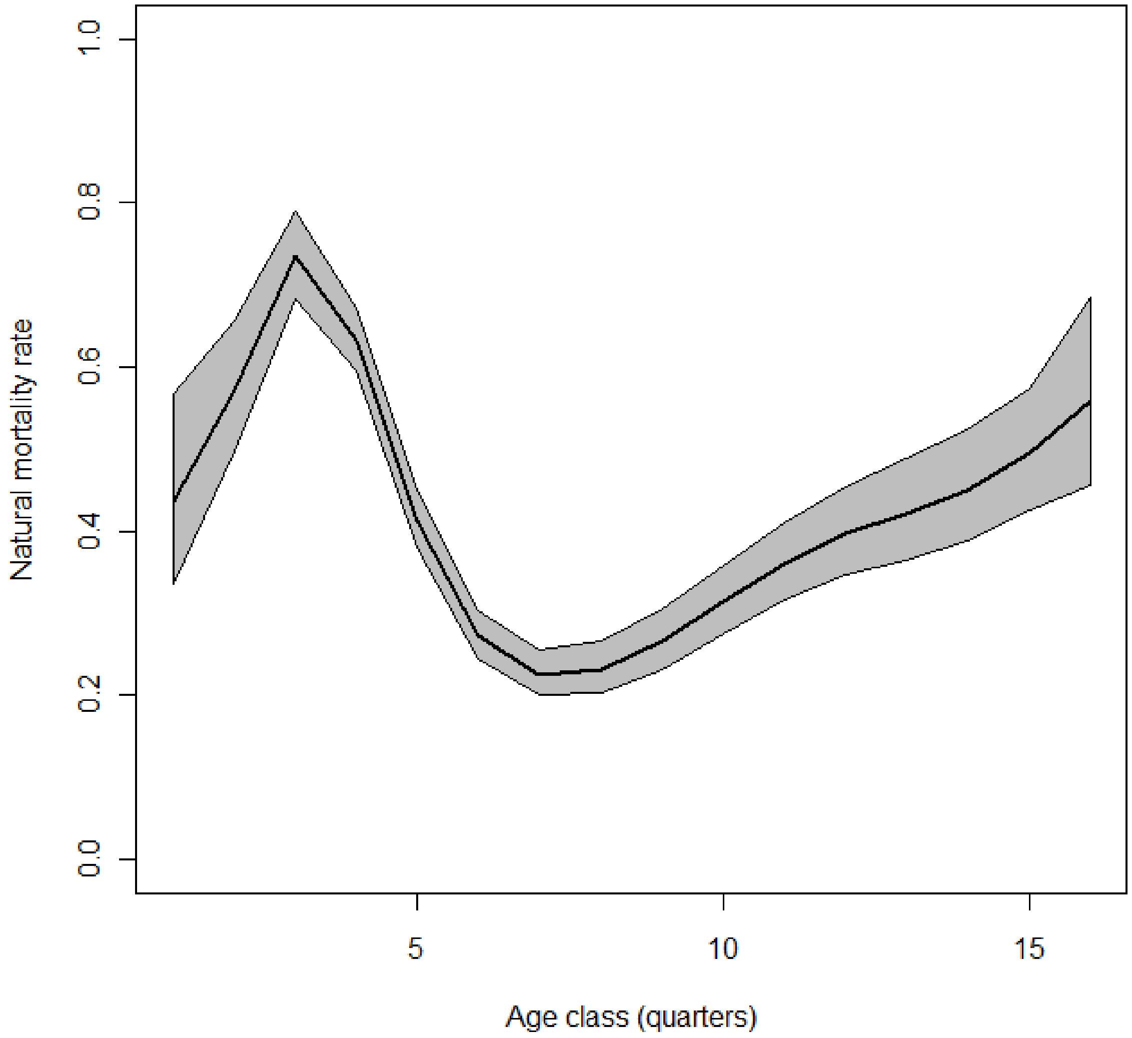


Figure 33. Estimated natural mortality rate per quarter by age-class. The gray area represents the 95% confidence interval.

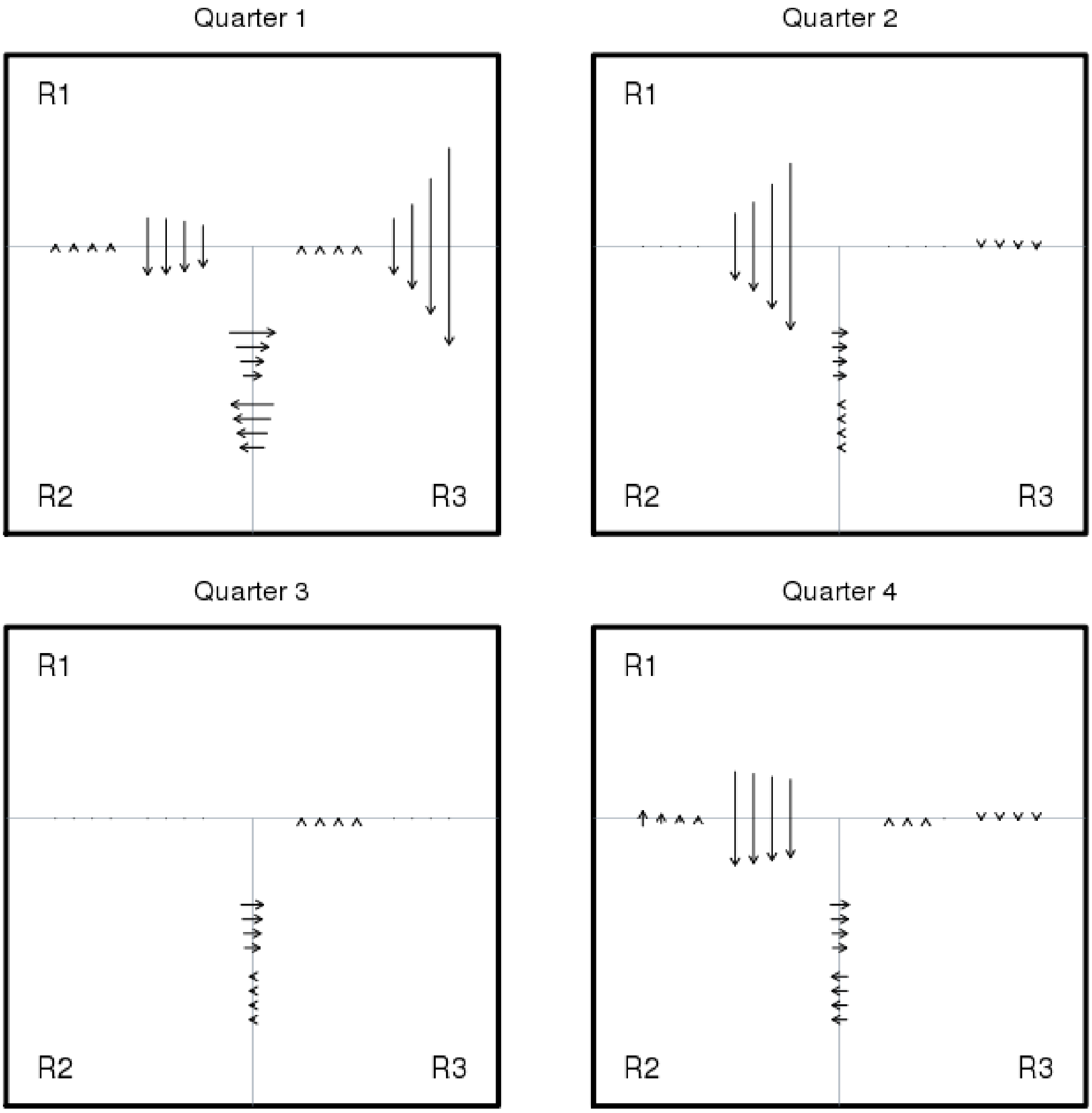


Figure 34. Graphical representation of movement coefficients among the three model regions at the beginning of each quarter. The arrows for each region boundary represent movement probabilities of 4 different age classes (1, 4, 8, and 12, with oldest age nearest the boundary edge). The maximum bar length represents a quarterly movement coefficient of 0.55 (second quarter, region 1 to 2).

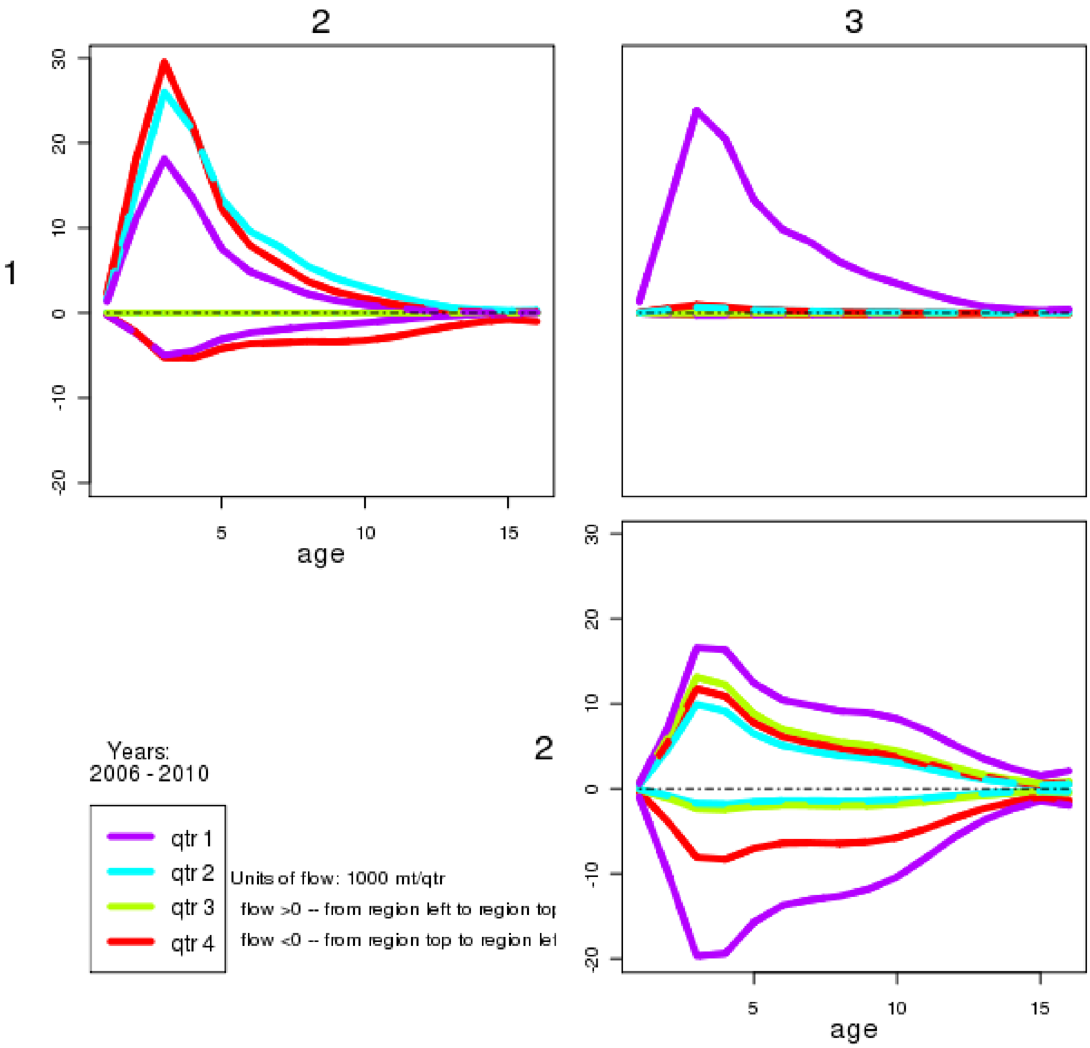


Figure 35: Estimated movements between regions. Movements from the region indicated by the row number to the region indicated by the column number are shown above the line; movements the other way are below the line. Movements by quarter are shown in different colours.

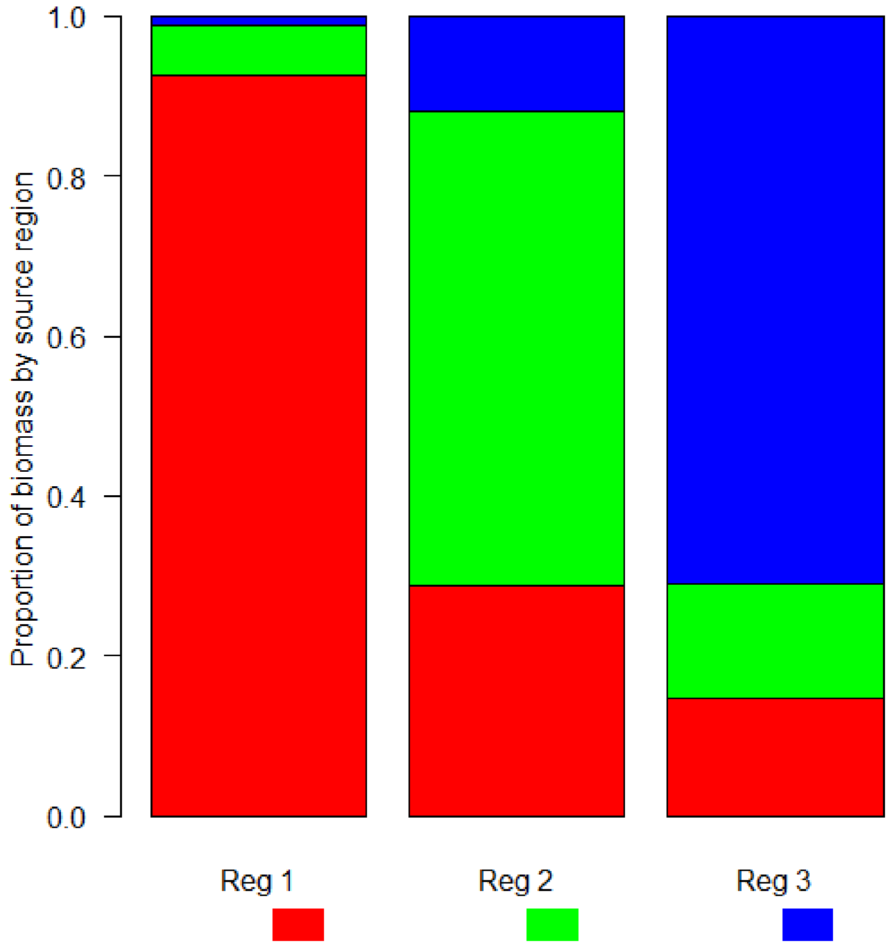


Figure 36: Proportional distribution of total biomass (by weight) in each region (Reg 1–3) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment between regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

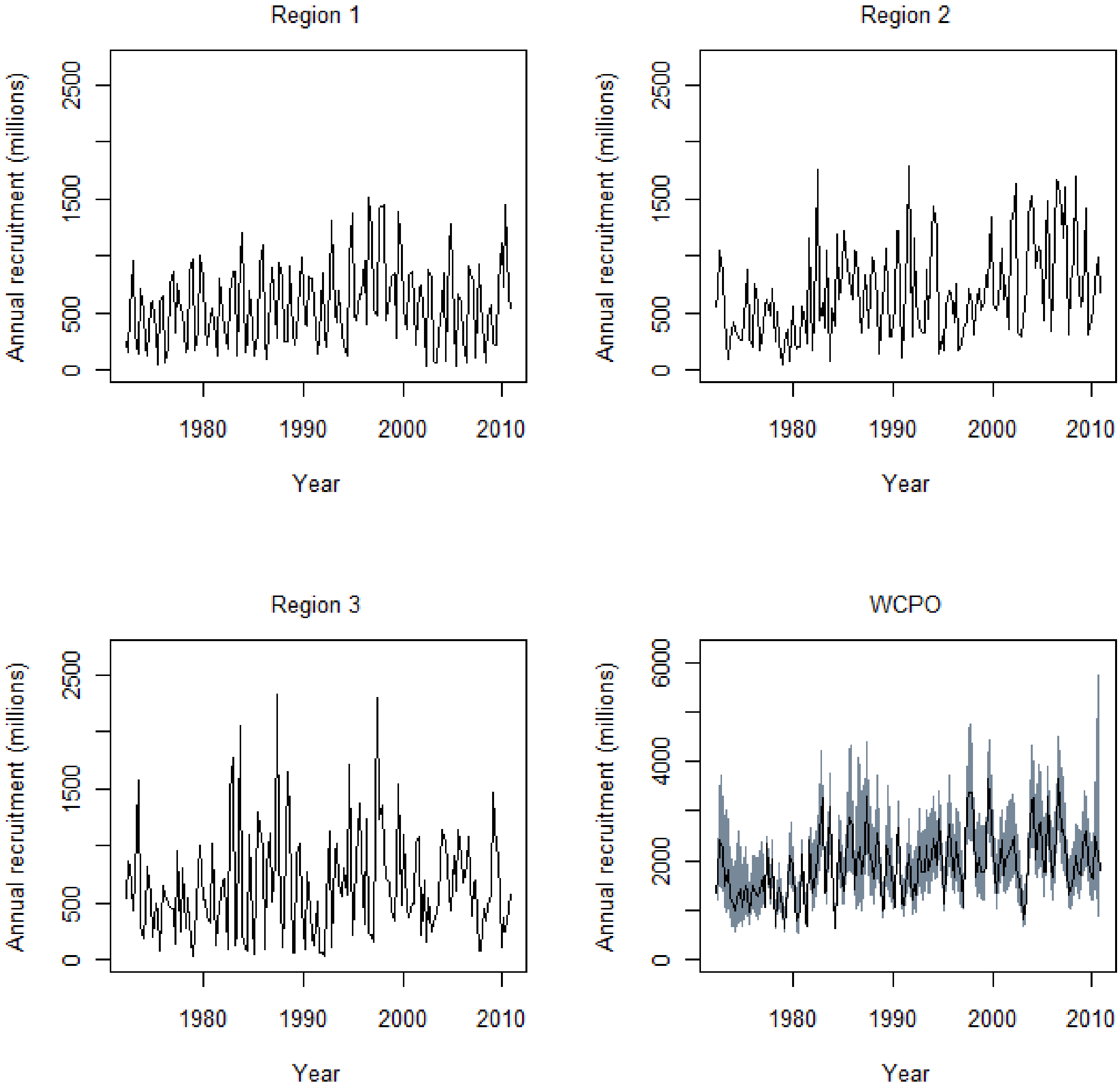


Figure 37. Estimated quarterly recruitment (millions) by region and for the WCPO for the reference-case analysis. The shaded area for the WCPO indicates the approximate 95% confidence intervals.

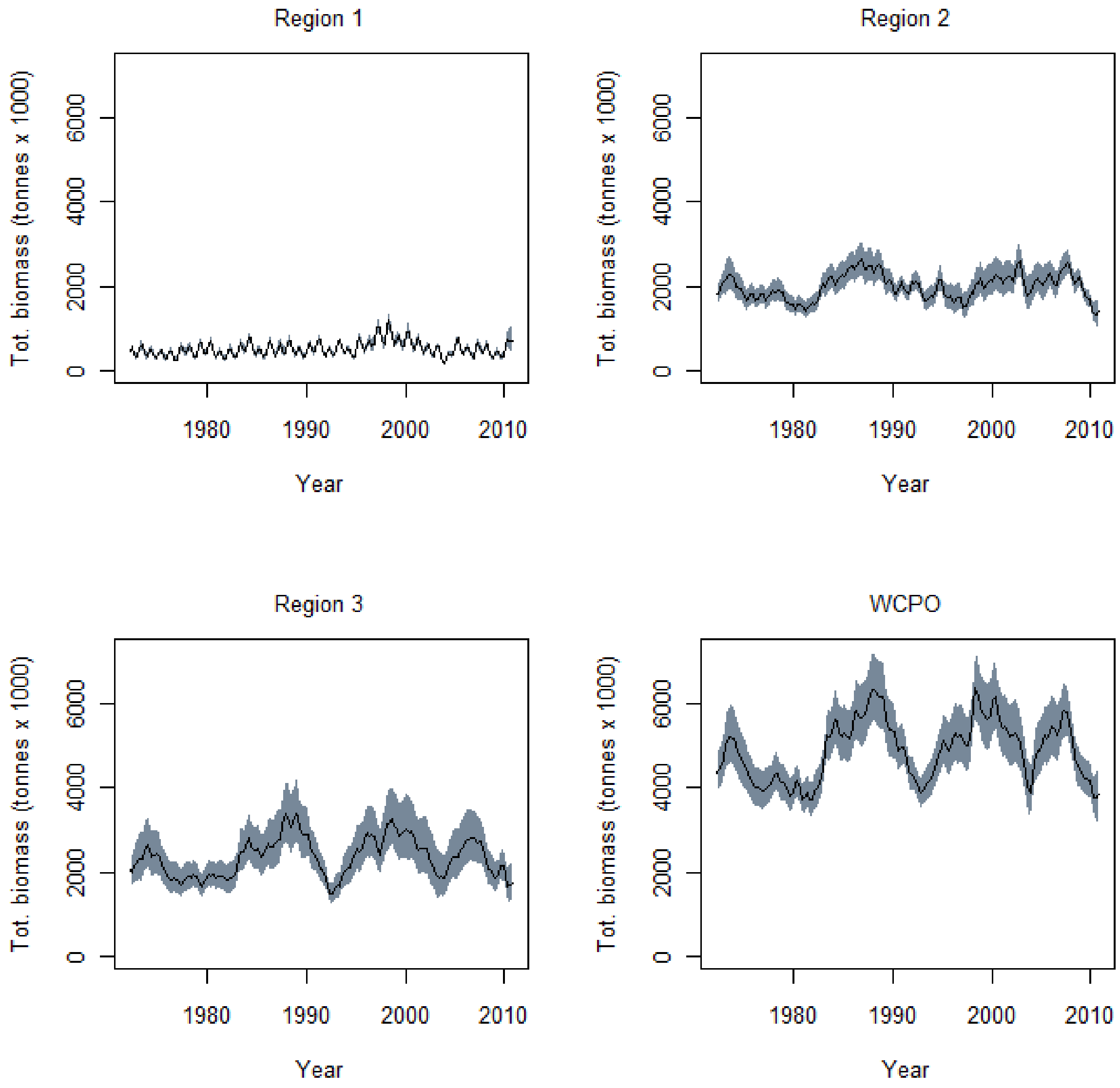


Figure 38. Estimated annual average total biomass (thousand t) by region and for the WCPO for the reference-case analysis. The shaded areas indicate the approximate 95% confidence intervals.

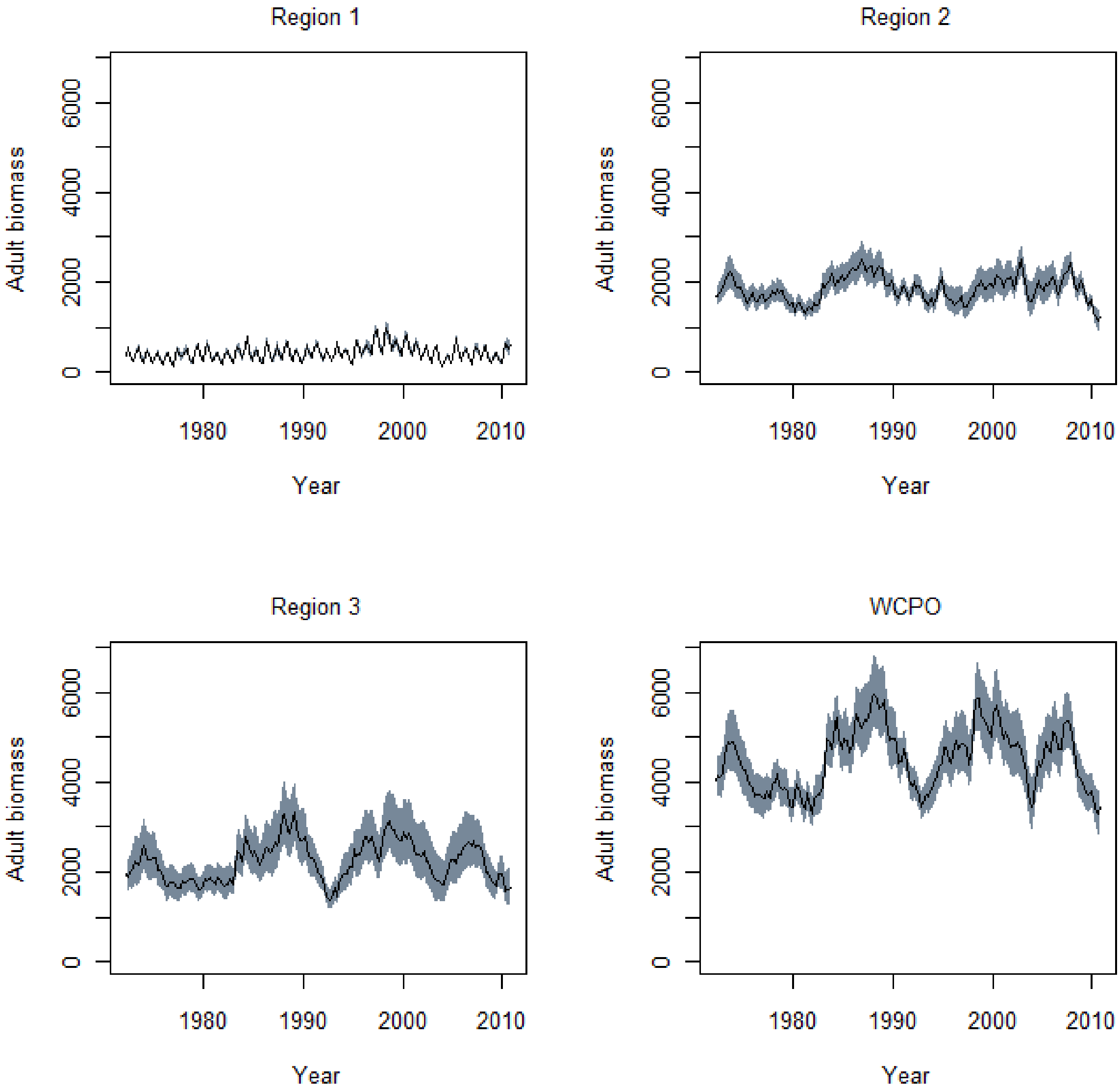


Figure 39. Estimated annual average adult biomass (thousand t) by region and for the WCPO for the reference-case analysis. The shaded areas indicate the approximate 95% confidence intervals.

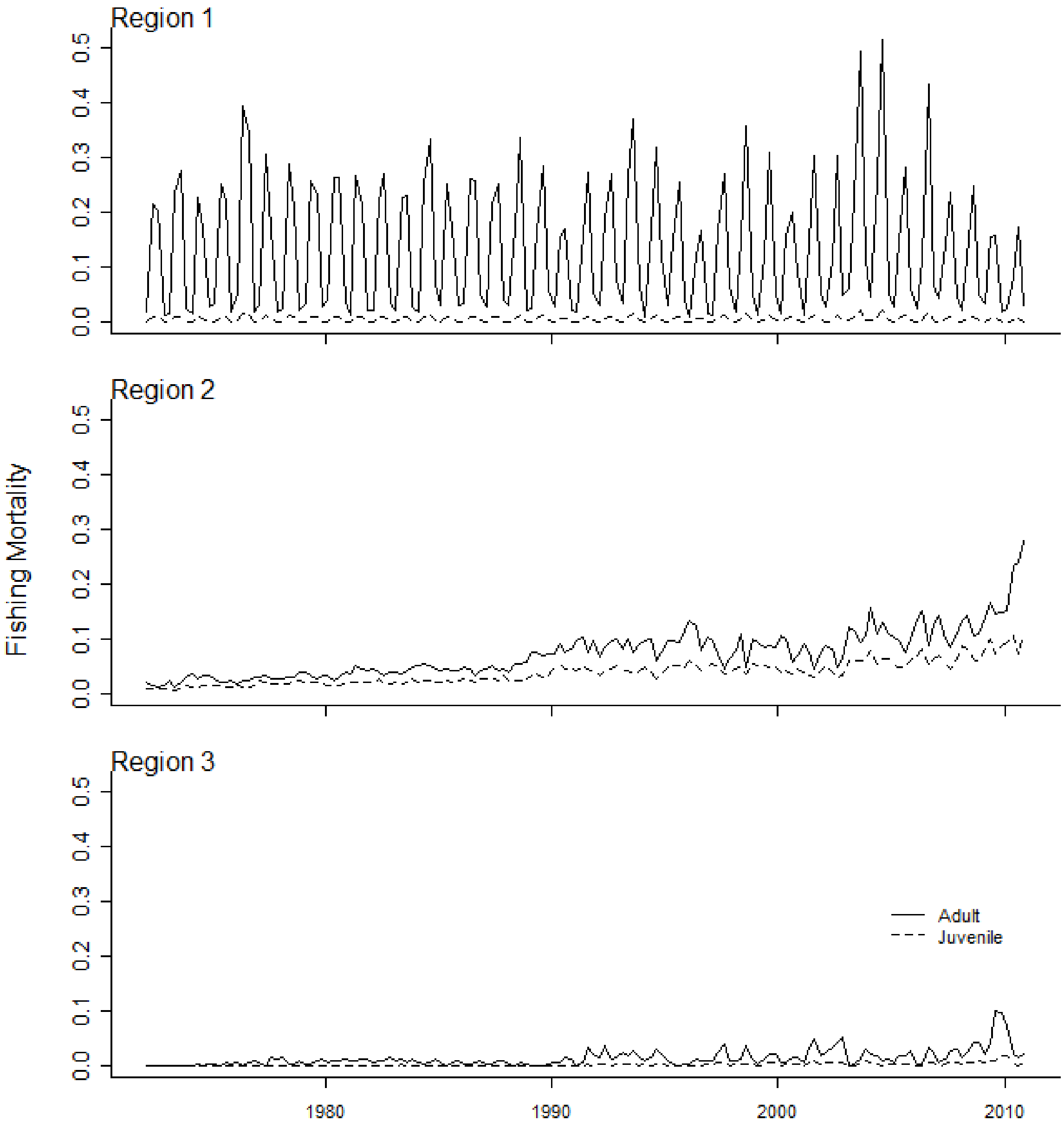


Figure 40. Estimated quarterly average fishing mortality rates for juvenile (age classes 1 and 2) (dashed line) and adult age-classes (solid line).

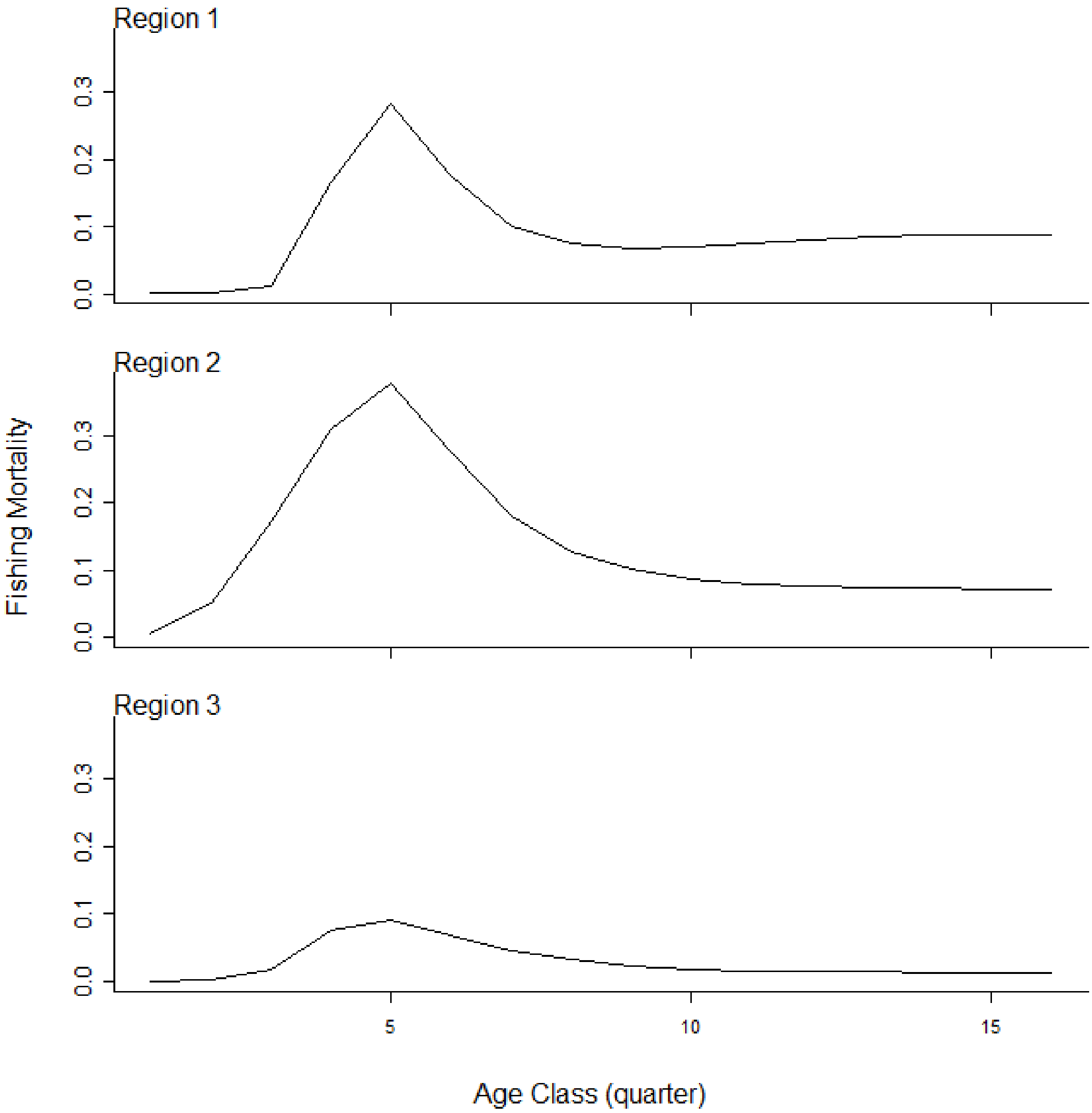


Figure 41. Fishing mortality by age class for the recent (2006-2009) period by region.

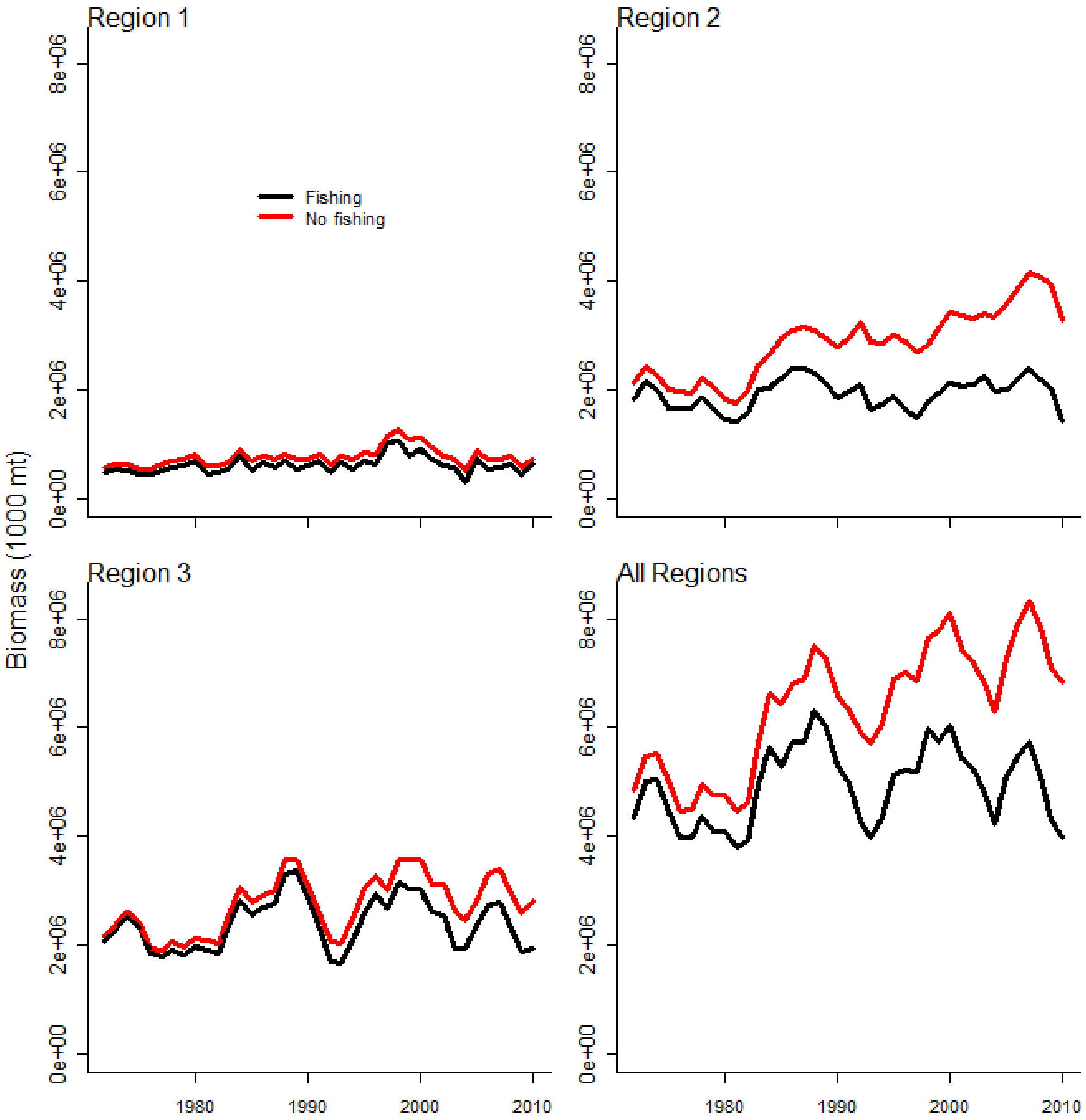


Figure 42. Comparison of the estimated biomass trajectories (lower black lines) with biomass trajectories that would have occurred in the absence of fishing (red lines) for each region and for the WCPO as a whole.

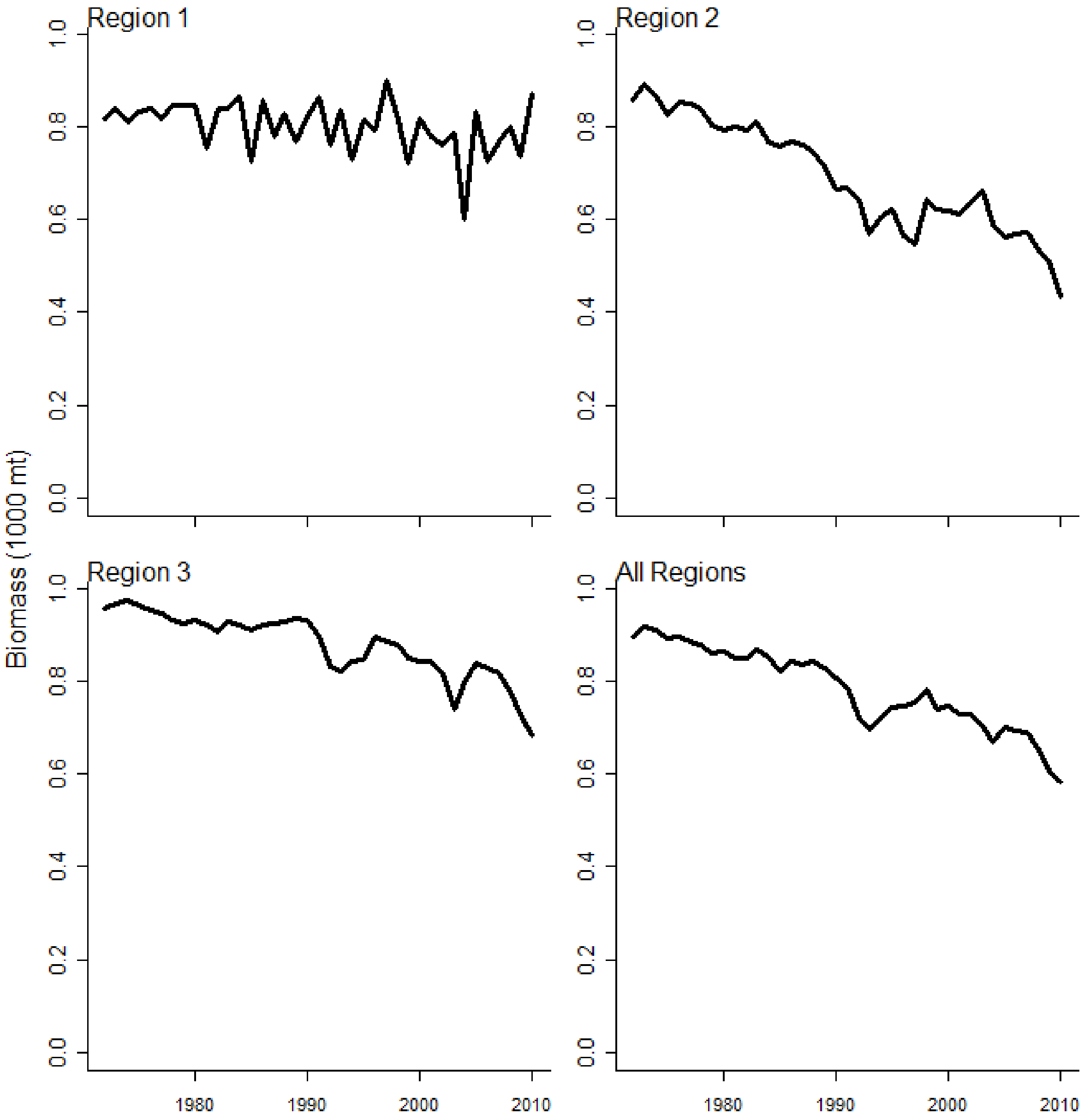


Figure 43. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the WCPO.

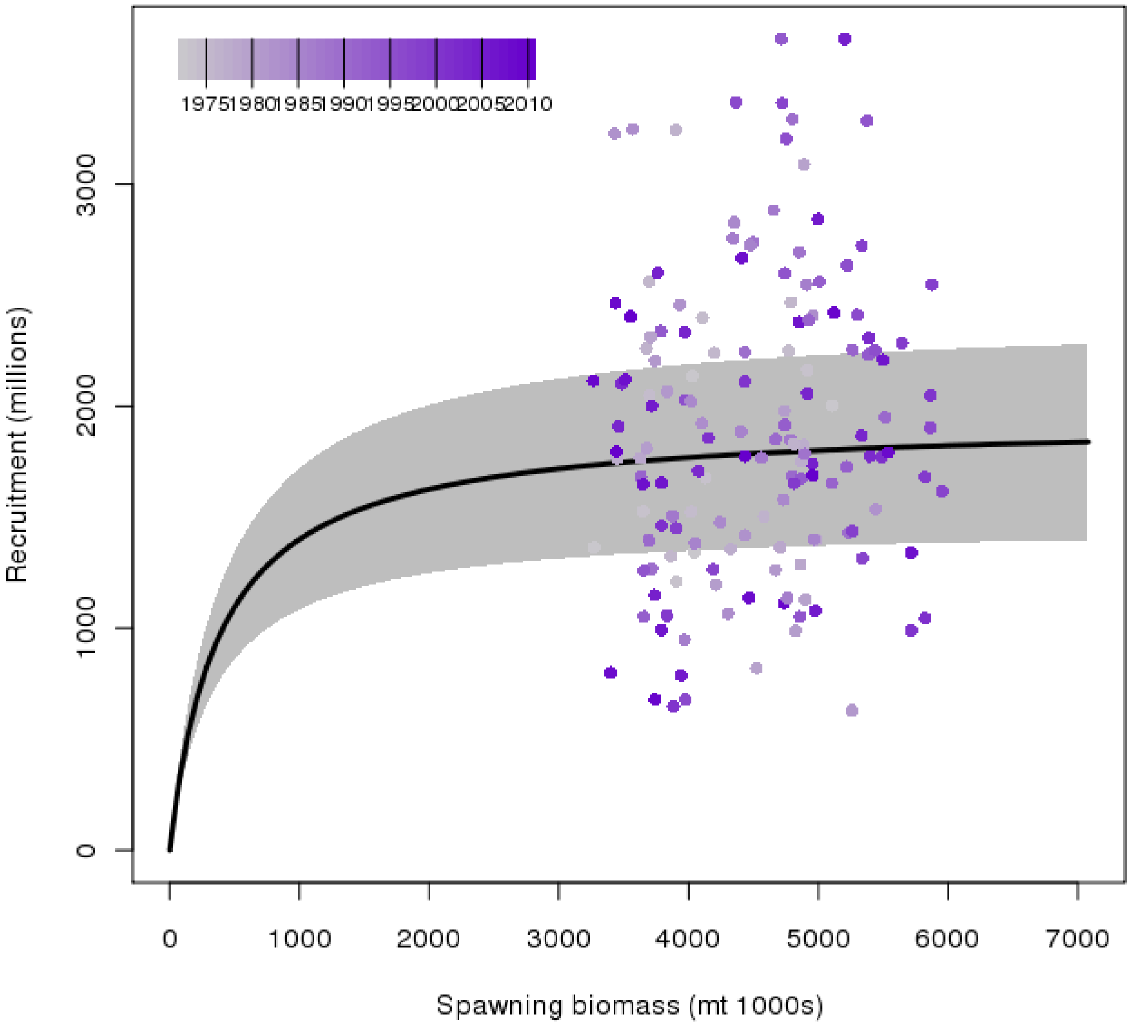


Figure 44. Spawning biomass – recruitment estimates and the assumed Beverton and Holt stock-recruitment relationship (SRR) incorporating steepness of 0.8. The shaded area represents approximate 95% confidence bounds.

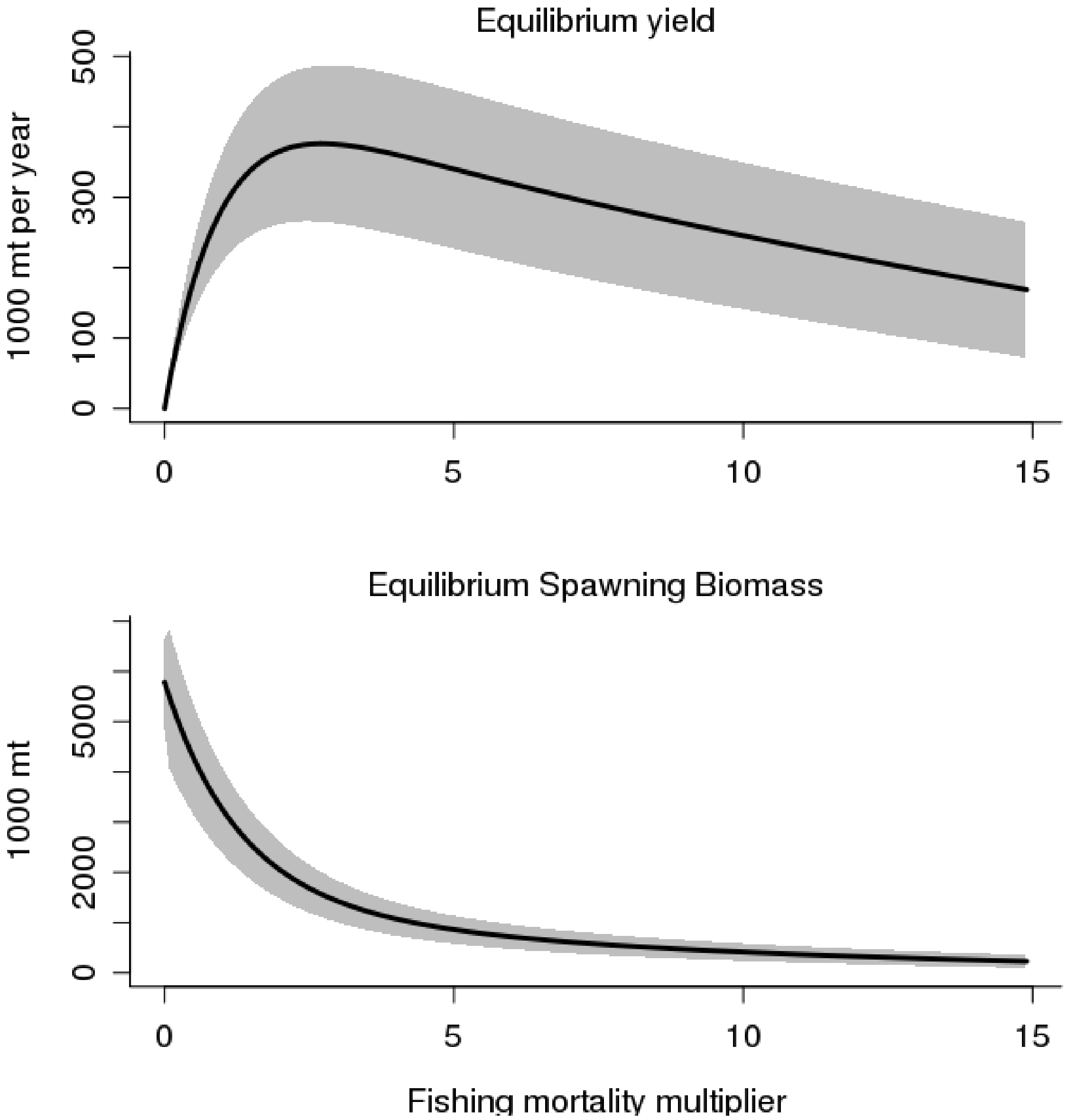


Figure 45. Predicted equilibrium yield (top) and equilibrium adult and total biomass (bottom) as a function of fishing mortality (reference-case assessment). The shaded areas represent approximate 95% confidence bounds.

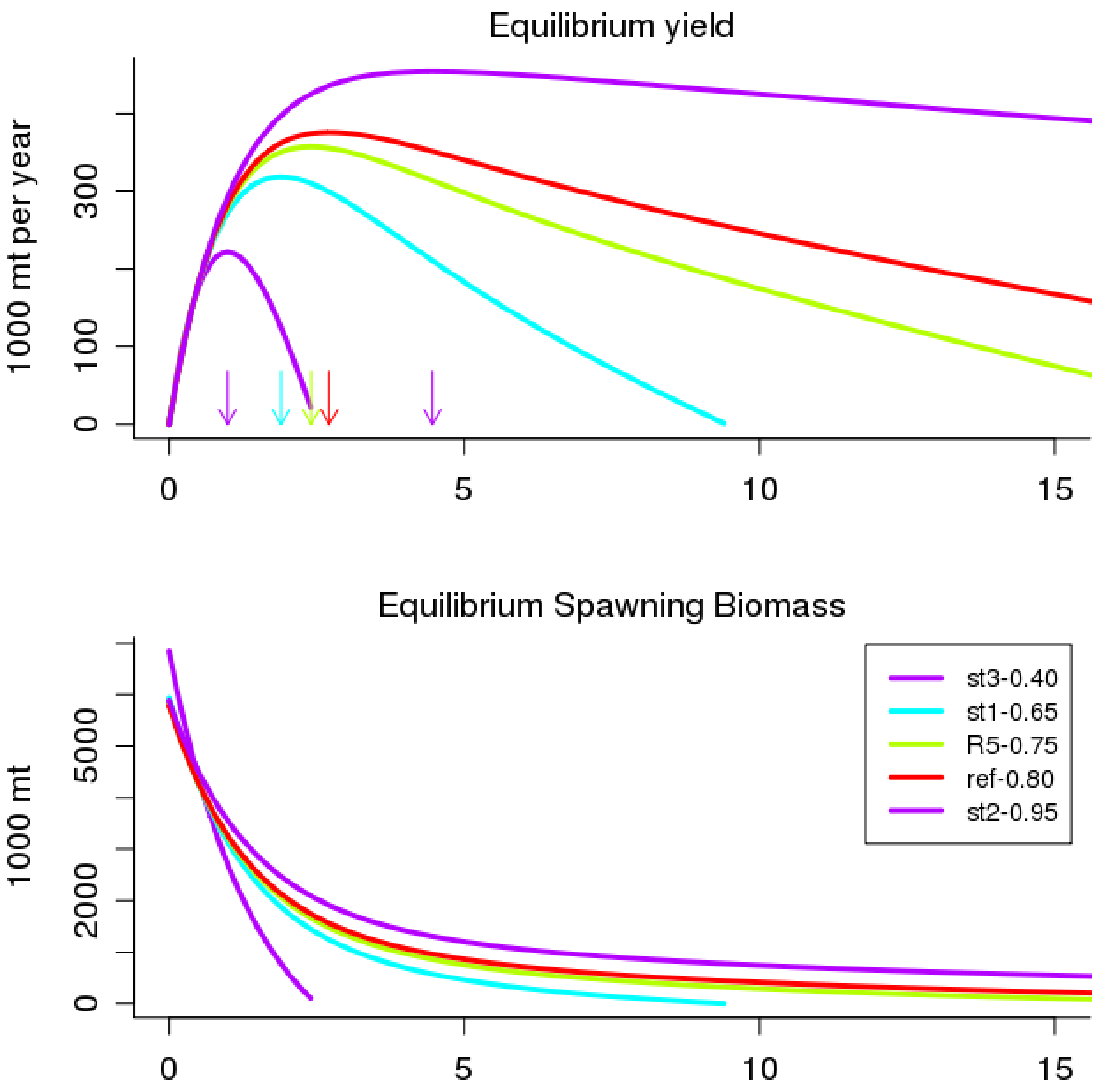


Figure 46. A comparison of equilibrium yields (top) and equilibrium adult biomass as a function of fishing mortality for the reference-case (red line) and alternative steepness models. The arrows represent the fishing mortality multiplier to achieve the MSY.

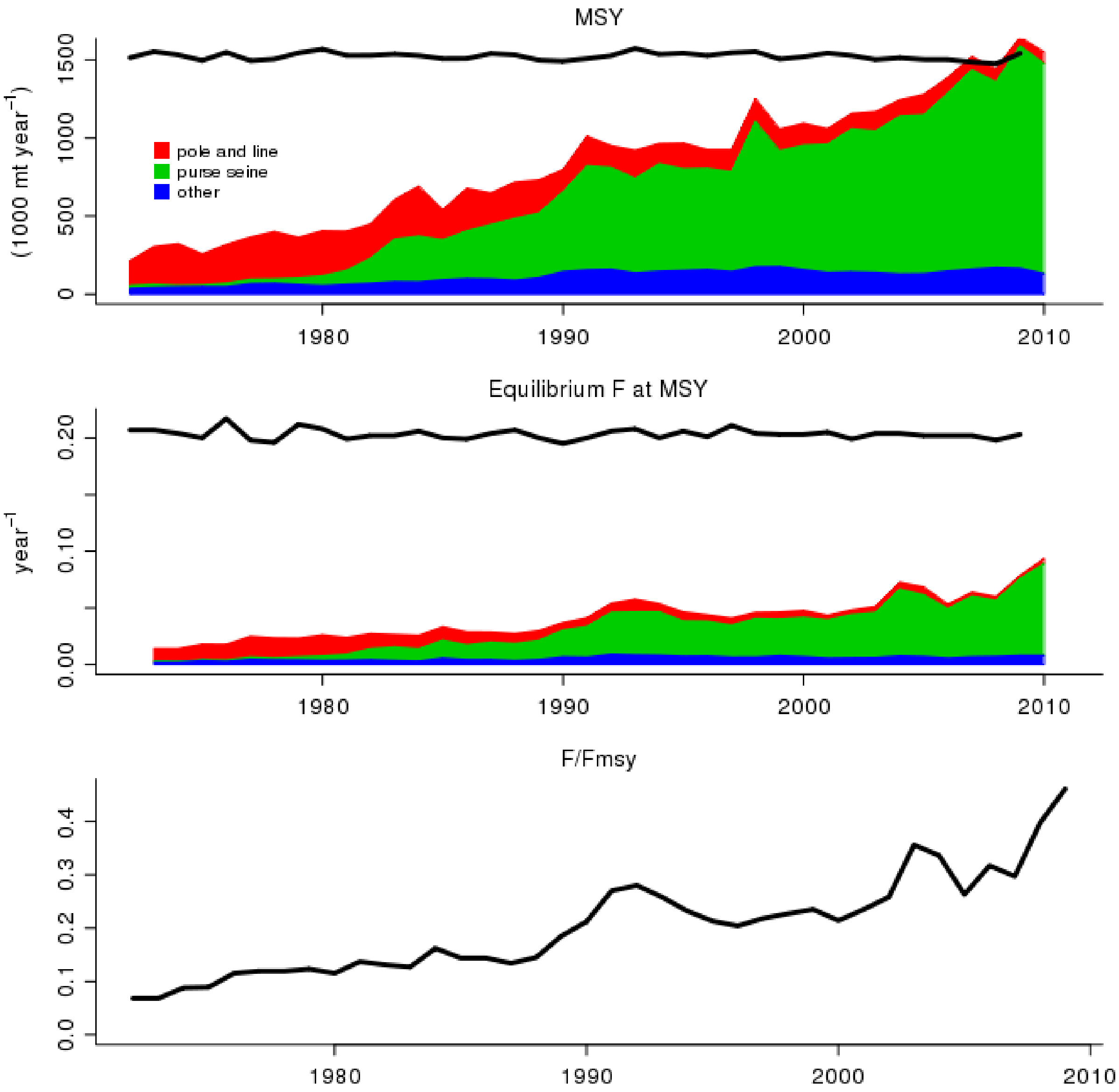


Figure 47: Quarterly time series of MSY related quantities. Top: estimated MSY compared with observed catch by three fishery sectors. Middle: estimated F at MSY (Fmsy) compared with estimated actual fishing mortality by the three fishery sectors. Bottom: estimated ratio of F to Fmsy.

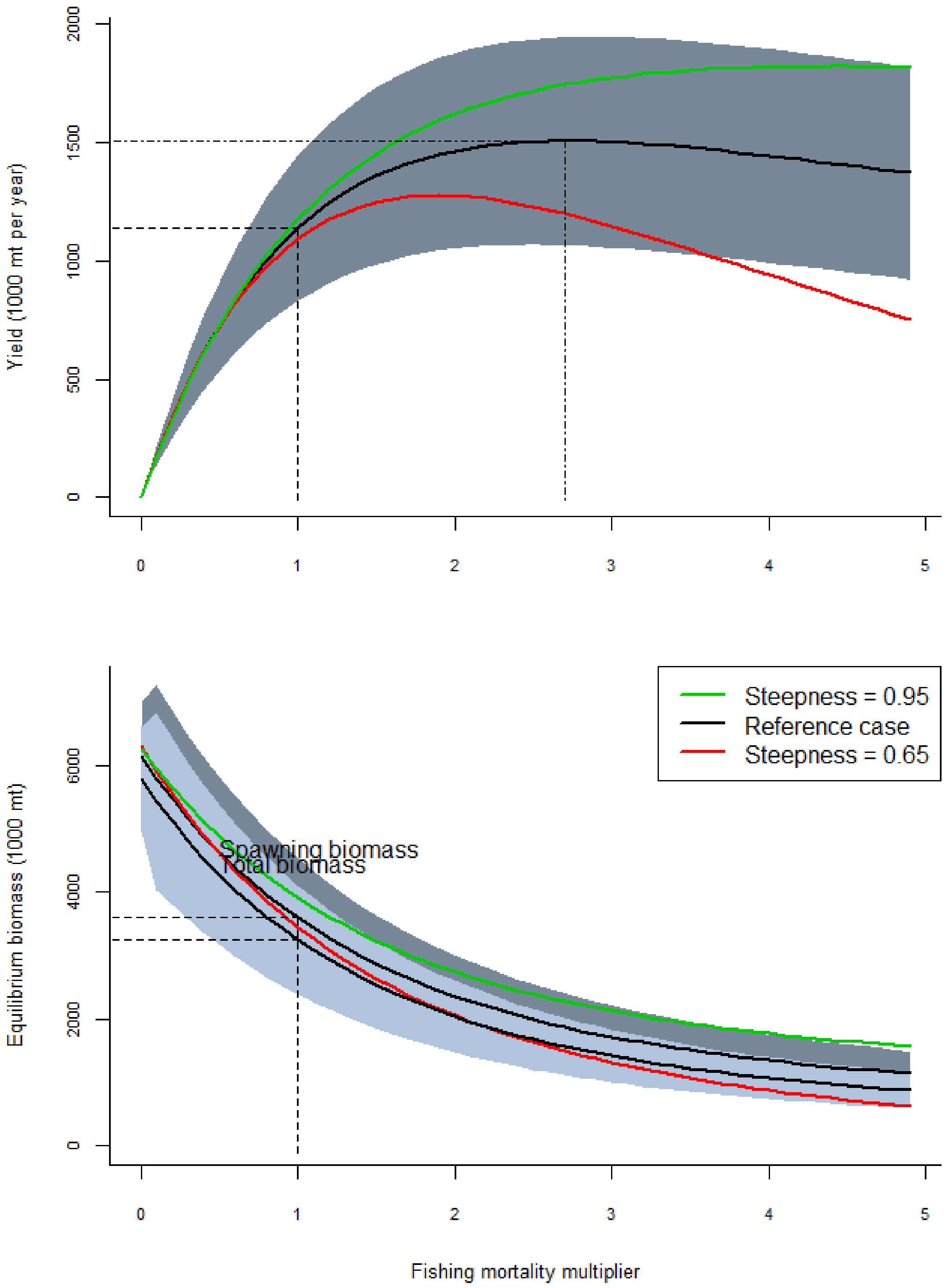


Figure 48: A comparison of equilibrium yields (top), equilibrium total biomass, and equilibrium adult biomass as a function of fishing mortality for the reference-case (red line) and the model with steepness of 0.95. The lines mark the current yield and the yield at MSY, and fishing mortality multiplier to achieve the MSY, under each steepness scenario.

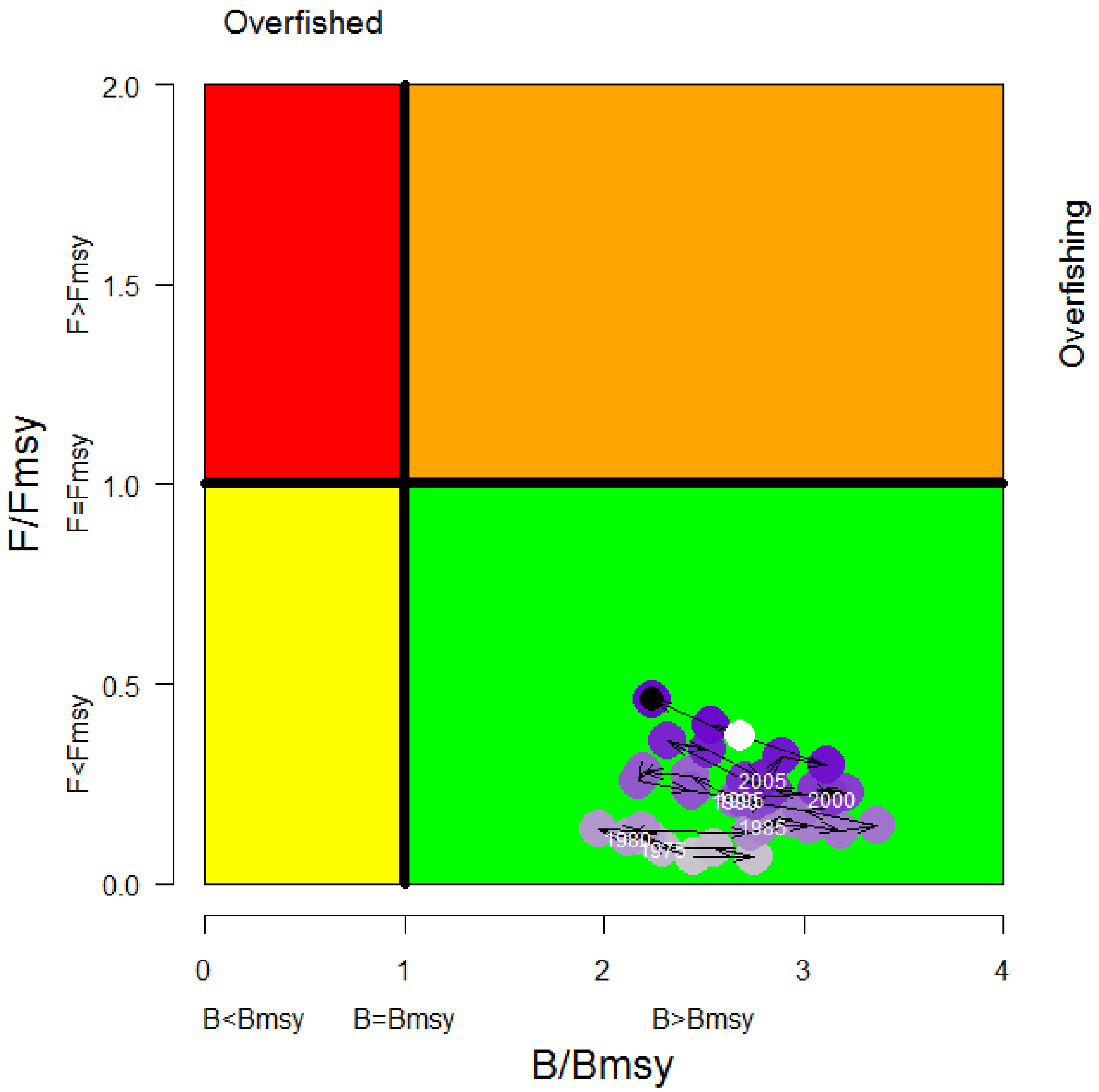
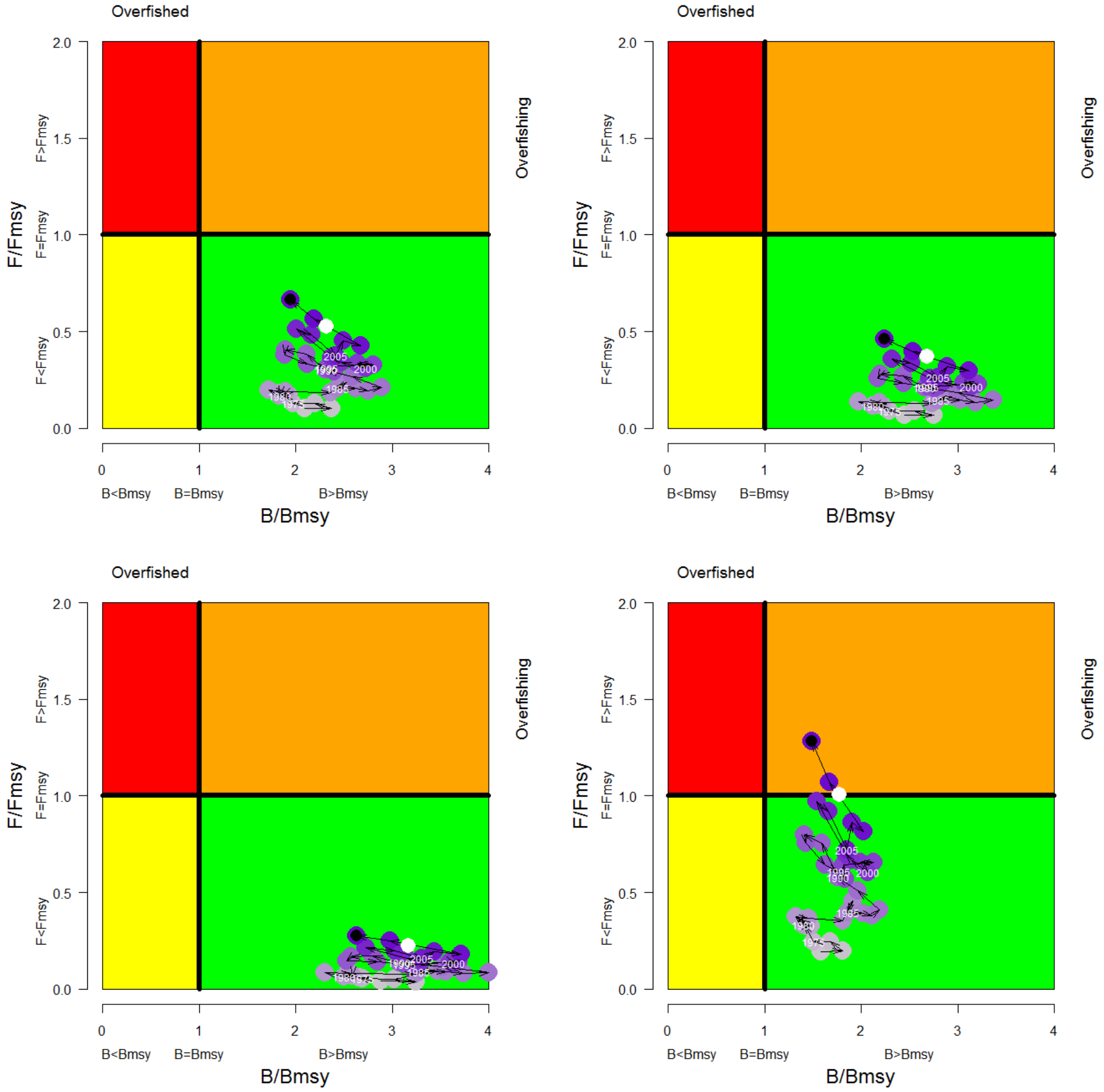


Figure 49. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1972–2010). The colour of the points is graduated from pale (1972) to dark purple (2010). The black circle represents the B_{2010}/B_{MSY} and the F_{2010} / F_{MSY}, and the white circle represents the $B_{2006\text{-}2009}$ / B_{MSY} and $F_{2006\text{-}2009}$ / F_{MSY}.

Steepness = 0.65 **Steepness = 0.8 (ref case)**



Steepness = 0.95 **Estimated Steepness = 0.39**

Figure 50: Temporal trend in annual stock status by assumed steepness value (0.65 to 0.95), relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1972–2010). The colour of the points is graduated from pale (1972) to dark purple (2010). On each plot the black circle represents the B_{2010}/B_{MSY} and the F_{2010} / F_{MSY}, and the white circle represents the $B_{2006\text{-}2009}$ / B_{MSY} and $F_{2006\text{-}2009}$ / F_{MSY}.

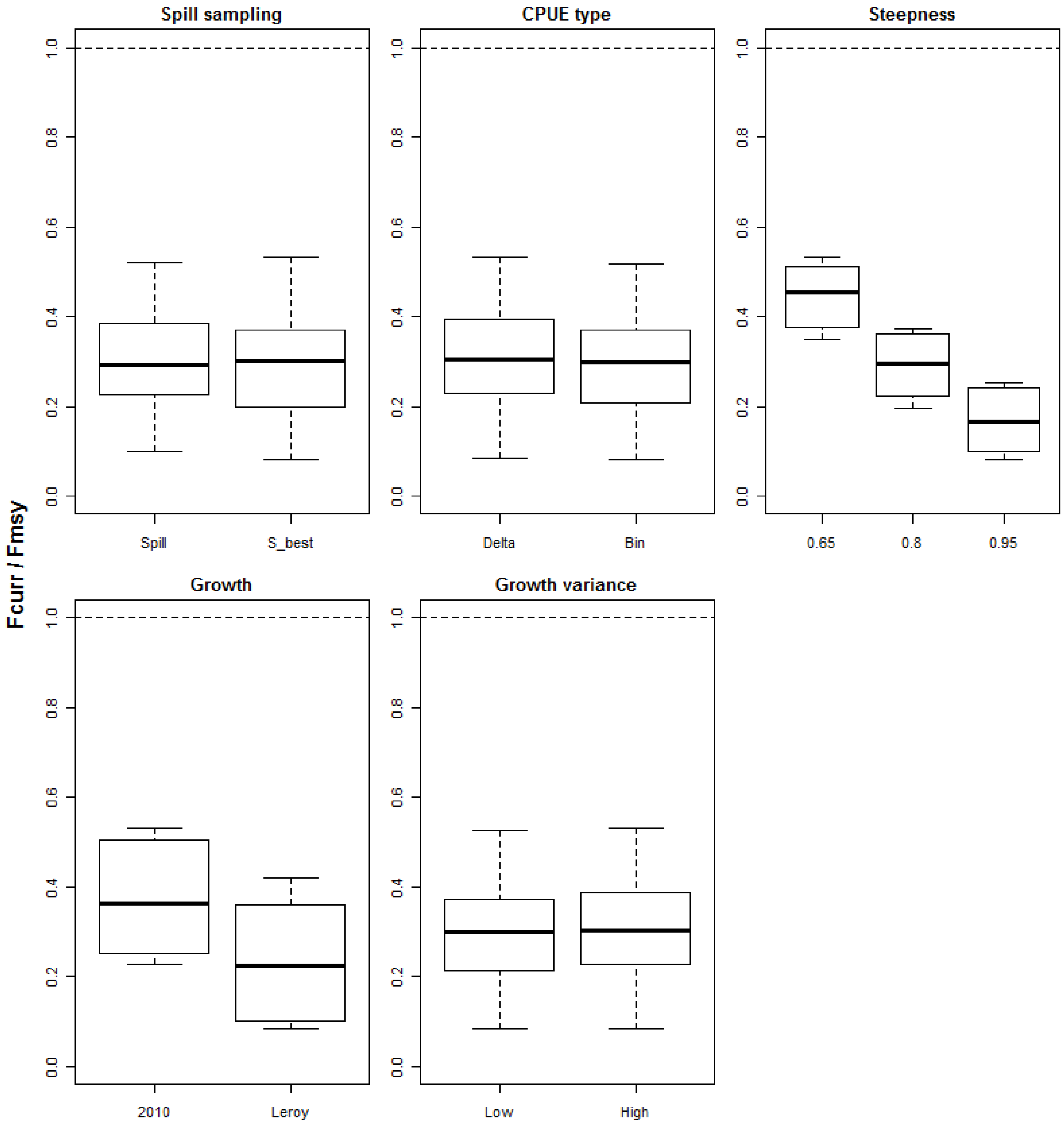


Figure 51: Box plots showing of the effects of the uncertainty grid scenarios (Spill sample correction, CPUE type, Steepness, growth, and growth variance) on the management parameter Fcurrent / Fmsy.

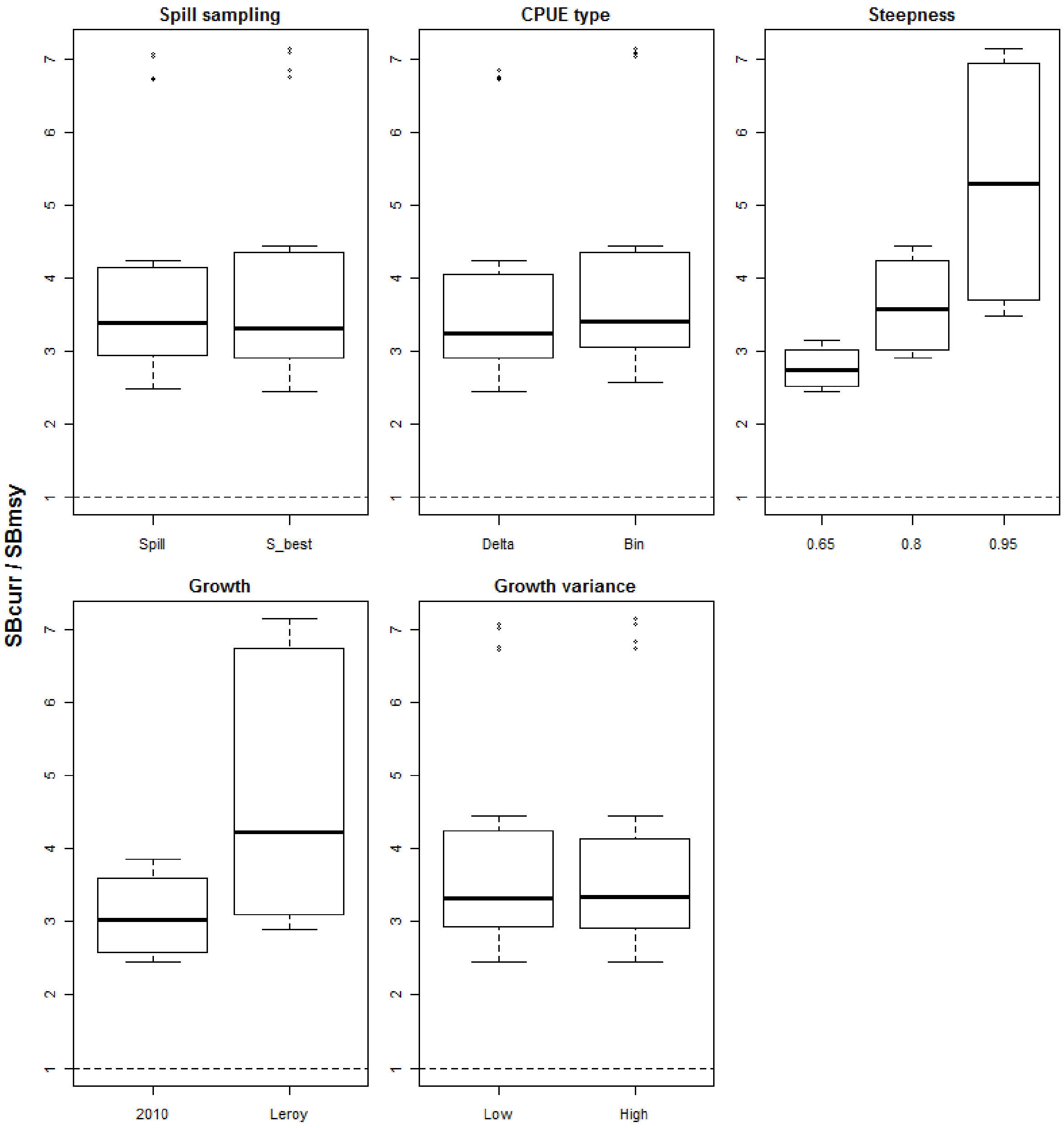


Figure 52: Box plots showing of the effects of the uncertainty grid scenarios (Spill sample correction, CPUE type, Steepness, growth, and growth variance) on the management parameter SBcurrent / SBmsy.

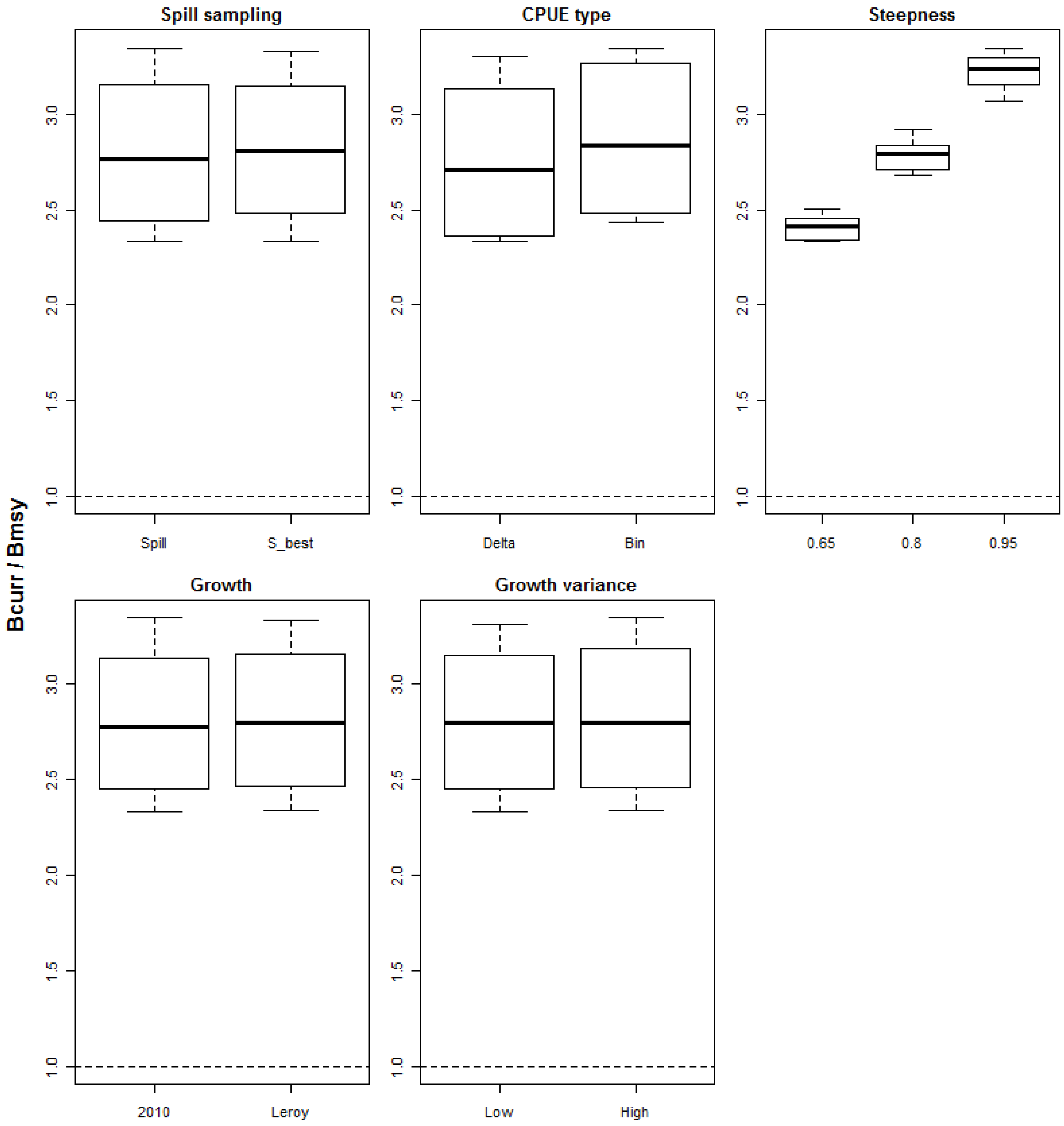


Figure 53: Box plots showing of the effects of the uncertainty grid scenarios (Spill sample correction, CPUE type, Steepness, growth, and growth variance) on the management parameter Bcurrent / Bmsy.

Figure 54: Box plots showing the distribution of management parameters under the range of values in the uncertainty grid.

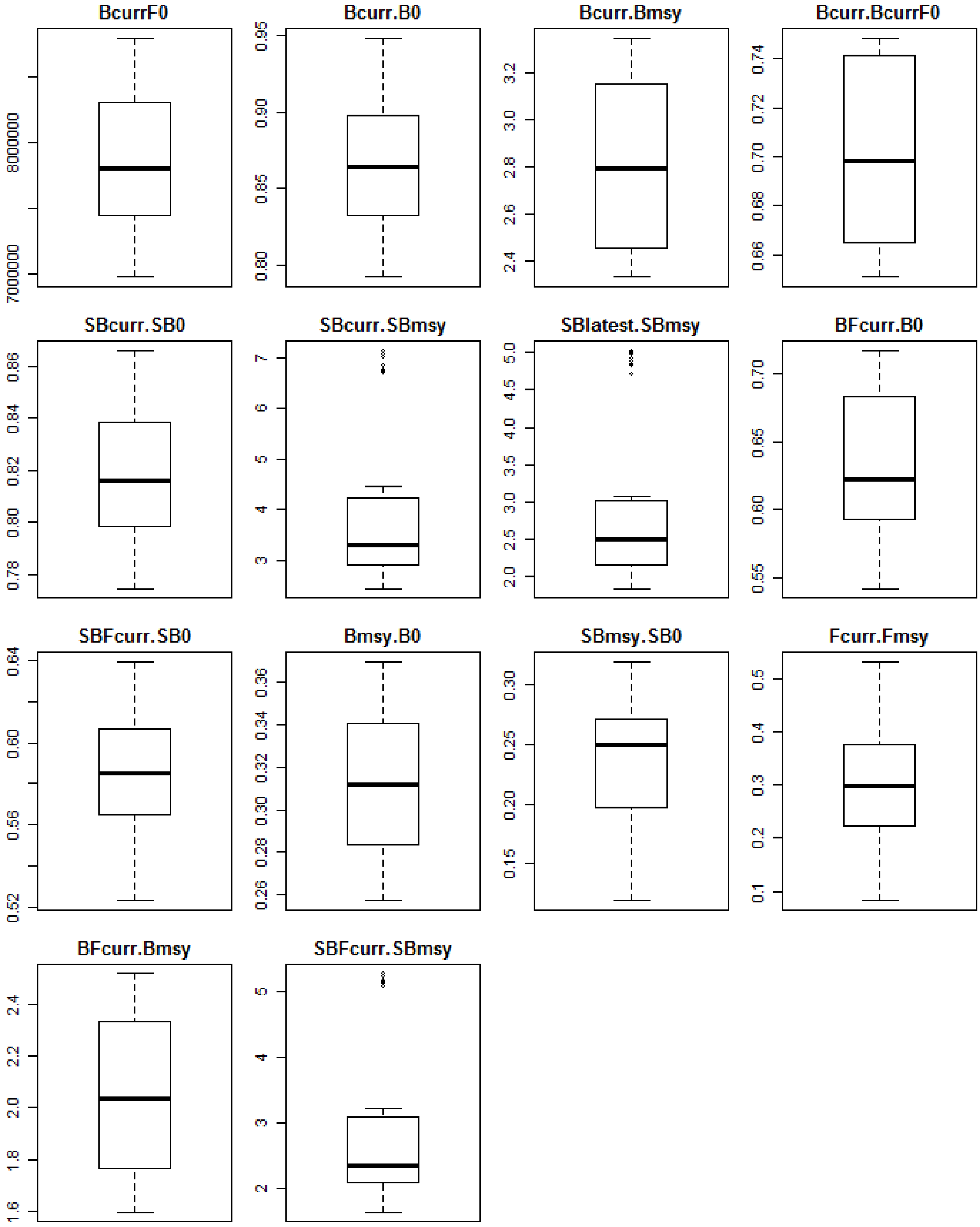


Figure 55: Box plots showing the distribution of management parameters under the range of values in the uncertainty grid.

11 Appendix A: doitall.skj

```
#!/bin/sh
cd $_CONDOR_SCRATCH_DIR
export PATH=.:$PATH
export ADTMP1=.
# export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/usr/local/lib
set

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

```
# 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;
}

  nice $MFCL skj.frq skj.ini 00.par -makepar
# ---------
#  PHASE 1
# ---------
  nice $MFCL skj.frq 00.par 01.par -file - <<PHASE1
  1 32 6
#   1 32 1         # routine initial control
#   2 113 1        # estimate initpop/totpop scaling parameter
```

```
   2 113 0        # estimate initpop/totpop scaling parameter
   2 177 1        # use old totpop scaling method
   2 32 1         # and estimate the totpop parameter
   1 149 100     #penalty on recruitment devs
  -999 49 40
   1 111 4        # Negative binomial likelihood function for tags
    -999 43 1      # var parameter estimated.
#   -999 44 1      # all fisheries grouped for estimating tag neg bin var
parameter.
   1 141 3        # Robust normal likelihood function for LF data
   2 96 12        # Tag are pooled across release groups after 12 periods
   2 57 4         # 4 recruitments per year
   2 69 1         # Use generalized movement model
   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.
   1 173 0        # growth deviates
#  Fisheries with non-decreasing selectivity with age
  -4 16 1         # The 3 JP RES LL fisheries assumed to have
 -12 16 1         # non-decreasing selectivity
 -17 16 1
  -8 16 2
  -8 3 15 # selectivity is 0 for ages 15 and 16
  -9 16 2
  -9 3 15 # selectivity is 0 for ages 15 and 16
  -15 16 2
  -15 3 15 # selectivity is 0 for ages 15 and 16
  -16 16 2
  -16 3 15 # selectivity is 0 for ages 15 and 16
#   Selectivity grouping, form
  -1 24 1
  -1 57 3
  -1 61 5 # cubic spline selectivity with 5 parameters
  -2 24 1
  -2 57 3
  -2 61 5 # cubic spline selectivity with 5 parameters
  -3 24 2
  -3 57 3
  -3 61 5 # cubic spline selectivity with 5 parameters
  -4 24 3
  -4 57 3
  -4 61 5 # cubic spline selectivity with 5 parameters
  -5 24 4
 -5 57 3
 -5 61 5 # cubic spline selectivity with 5 parameters
  -6 24 5
 -6 57 3
 -6 61 5 # cubic spline selectivity with 5 parameters
  -7 24 6
 -7 57 3
 -7 61 5 # cubic spline selectivity with 5 parameters
  -8 24 7
 -8 57 3
 -8 61 5 # cubic spline selectivity with 5 parameters
  -9 24 8
 -9 57 3
 -9 61 5 # cubic spline selectivity with 5 parameters
  -10 24 9
 -10 57 3
 -10 61 5 # cubic spline selectivity with 5 parameters
  -11 24 10
 -11 57 3
 -11 61 5 # cubic spline selectivity with 5 parameters
  -12 24 11
 -12 57 3
 -12 61 5 # cubic spline selectivity with 5 parameters
  -13 24 4
 -13 57 3
```

```
 -13 61 5 # cubic spline selectivity with 5 parameters
  -14 24 12
 -14 57 3
 -14 61 5 # cubic spline selectivity with 5 parameters
  -15 24 13
 -15 57 3
 -15 61 5 # cubic spline selectivity with 5 parameters
  -16 24 14
 -16 57 3
 -16 61 5 # cubic spline selectivity with 5 parameters
  -17 24 15
 -17 57 3
 -17 61 5 # cubic spline selectivity with 5 parameters
 -999 26 2         # Use length-based selectivity
#   Grouping of fisheries with common catchability
#   common catchability for DWPL fleet
  -1 29 1
  -2 29 2
  -5 29 5
  -13 29 13
  -3 29 3
  -4 29 4
  -12 29 12
  -17 29 17
  -6 29 6
  -7 29 7
  -8 29 8
  -9 29 9
  -10 29 10
  -11 29 11
  -14 29 14
  -15 29 15
  -16 29 16
  -1 60 1
  -2 60 2
  -5 60 5
  -13 60 13
  -3 60 3
  -4 60 4
  -12 60 12
  -17 60 17
  -6 60 6
  -7 60 7
  -8 60 8
  -9 60 9
  -10 60 10
  -11 60 11
  -14 60 14
  -15 60 15
  -16 60 16
#   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 6
  -7 32 7
  -8 32 8
  -9 32 8
  -10 32 9
  -11 32 10
  -12 32 11
  -13 32 12
  -14 32 13
  -15 32 14
  -16 32 14
```

```
  -17 32 15
#   Grouping of fisheries with common tag reporting rate
  -1 34 1
  -2 34 1
  -3 34 1
  -4 34 1
 -5 34 1
 -6 34 2
 -7 34 3
 -8 34 4
 -9 34 4
 -10 34 5
 -11 34 6
 -12 34 1
 -13 34 1
 -14 34 7
 -15 34 4
 -16 34 4
 -17 34 1
#   Penalties for tag reporting rate priors
  -1 35 50
  -2 35 50
  -3 35 50
  -4 35 50
 -5 35 50
 -6 35 100
 -7 35 100
 -8 35 234
 -9 35 234
 -10 35 100
 -11 35 100
 -12 35 50
 -13 35 50
 -14 35 100
 -15 35 234
 -16 35 234
 -17 35 50
#   Tag reporting rate priors (*100)
  -1 36 70
  -2 36 70
  -3 36 70
  -4 36 70
  -5 36 70
 -6 36 70
 -7 36 70
 -8 36 55
 -9 36 55
 -10 36 80
 -11 36 70
  -12 36 70
  -13 36 70
 -14 36 70
 -15 36 55
 -16 36 55
  -17 36 70
 -9999 1 1       # Tag returns for first period after release disregarded
 -999 33 1       # Estimate tag reporting rates
  1 33 90
  -999 13 -1
  -1 13 10
  -5 13 10
  -13 13 10
  -1 66 1
  -5 66 1
  -13 66 1
  -1 46 1
  -2 46 1
  -3 46 1
```

```
  -4 46 1
  -6 46 1
  -7 46 1
  -8 46 1
  -9 46 1
  -10 46 1
  -11 46 1
  -13 46 1
  -14 46 1
  -15 46 1
  -16 46 1
  1 12 0
  1 13 0
  1 14 0
  1 15 0
  1 16 0
  1 184 0
  1 227 0
  2 116 70
  -18 24 7
  -18 29 18
  -18 60 18
  -18 32 10
  -18 34 5
  -18 49 100
  -18 35 100
  -18 36 80
  -18 46 1
  -18 57 3
  -18 61 5
PHASE1

changeSD 01.par 5.074696


#
# ---------
#  PHASE 2
# ---------
  nice $MFCL skj.frq 01.par 02.par -file - <<PHASE2
    2 32 1          # totpop estimated from this phase
    1 1 200         # Sets no. of function evaluations for this phase
    1 149 100       # Penalty on recruitment devs set to 100/10
    1 50 -1         # convergence criterion is 1E+1
  2 35 12
  -3 49 100
  -7 49 100
  -8 49 100
  -9 49 100
  -15 49 100
  -16 49 100
  1 12 0
  1 13 0
  1 14 0
  1 15 0
  1 16 0
  1 173 0
  1 182 100
  1 184 0
  1 226 0
  1 227 0
PHASE2
#
#  ---------
#
recruitmentConstraints 02.par 0.8
#
#
```

```
#
#   PHASE 4
#  ---------
  nice $MFCL skj.frq 02.par 04.par -file - <<PHASE4
   2 68 1          # Estimate movement coefficients
     #1 189 1       # Write graph.frq
     1 190 1       # Write plot.rep
PHASE4
#
#  ---------
#   PHASE 5
#  ---------
  nice $MFCL skj.frq 04.par 05.par -file - <<PHASE5
PHASE5
#
# ---------
#  PHASE 6
# ---------
  nice $MFCL skj.frq 05.par 06.par -file - <<PHASE6
  1 1 400      # Set no. function evaluations for this phase
  2 70 1        # Estimate time-series changes in recruitment distribution
  2 71 1
  2 198 1
PHASE6
#
# ---------
#  PHASE 7
# ---------
     nice $MFCL skj.frq 06.par 07.par -file - <<PHASE7
  1 1 200         # Set no. funtion evaluations for this phase
-999 27 1         # Estimate seasonal catchability for all fisheries
 -10 27 0         # except for fisheries 16
 -11 27 0         # and 17 which only have annual data
  -4 27 0         # and the 3 LL/RES fisheries
 -12 27 0
 -17 27 0
PHASE7
#
# ---------
#  PHASE 8
# ---------
  nice $MFCL skj.frq 07.par 08.par -file - <<PHASE8
  2 82 45      # Prior for average M is 45/100 per quarter
  2 84 2       # Penalty weight
  2 33 1       # Estimate average M
PHASE8
#
# ----------
#  PHASE 9
# ----------
     nice $MFCL skj.frq 08.par 09.par -file - <<PHASE9
   1 1 500       # Set no. function evaluations for this phase
# Sets variable catchability, periodicity, and penalty
 # -1 10 1   -1 23 23   -1 15 50   # JP OS  PL 1
 # -2 10 1   -2 23 23   -2 15 50   # JP DW  PL 1
 #-5 10 1  -5 23 23  -5 15 50   # JP DW  PL 5
 #-13 10 1  -13 23 23  -13 15 50   # JP DW  PL 6
 -6 10 1
 -6 23 23
  -6 15 1
 -7 10 1
 -7 23 23
  -7 15 1
 -14 10 1
 -14 23 23
  -14 15 1
  -4 10 1
  -4 23 23
```

```
  -4 15 1
 -12 10 1
 -12 23 23
  -12 15 1
 -17 10 1
 -17 23 23
  -17 15 1
 # -3 10 1   -3 23 23   -3 15 50   # JP OS  PS 2
 -8 10 1
 -8 23 23
  -8 15 1
 -9 10 1
 -9 23 23
  -9 15 1
 -15 10 1
 -15 23 23
  -15 15 1
 -16 10 1
 -16 23 23
  -16 15 1
 -10 10 1
 -10 23 23
  -10 15 1
 -11 10 1
 -11 23 23
  -11 15 1
  -2 10 1
  -3 10 1
  -2 23 23
  -3 23 23
  -2 15 1
  -3 15 1
  -18 10 1
  -18 15 1
  -18 23 23
PHASE9
#
# ----------
#  PHASE 10
# ----------
  nice $MFCL skj.frq 09.par 10.par -file - <<PHASE10
  2 88 1       # Estimate age-dependent movement
  2 89 1
  1 1 200
  -10 49 500
PHASE10
#
# ----------
#  PHASE 11
# ----------
  nice $MFCL skj.frq 10.par 11.par -file - <<PHASE11
  2 73 1       # Estimate age-dependent M
  2 77 50
PHASE11
#
# ----------
#  PHASE 12
# ----------
  nice $MFCL skj.frq 11.par 12.par -file - <<PHASE12
PHASE12
#
# ----------
#  PHASE 13
# ----------
  nice $MFCL skj.frq 12.par 13.par -file - <<PHASE13
  1 182 100     # Penalty weight for negative growth increments
PHASE13
#
```

```
# ----------
#  PHASE 14
# ----------
  nice $MFCL skj.frq 13.par 14.par -file - <<PHASE14
  -999 43 1     # Estimate negative binomial variance parameter
   -4 43 0
  -12 43 0
  -17 43 0
  -1 44 1
  -2 44 2
  -3 44 3
  -4 44 4
  -5 44 5
  -6 44 6
  -7 44 7
  -8 44 8
  -9 44 8
  -10 44 9
  -11 44 10
  -12 44 11
  -13 44 12
  -14 44 13
  -15 44 14
  -16 44 14
  -17 44 15
  -18 44 16
PHASE14
# ----------
#  PHASE 15
# ----------
  nice $MFCL skj.frq 14.par 15.par -file - <<PHASE15
  1 189 1       # Write graph.frq
  2 145 1           # penalty wt. for SRR
  2 146 1           # make SRR parameters active
#  2 147 0           # no. time periods for recruitment lag
  2 147 1           # no. time periods for recruitment lag
  2 148 20
  2 155 4           # but not including last 4
  2 149 0           # yield computed in weight
  1 149 0           # turn off recruitment penalties against mean
  -999 55 1
  2 193 1
  1 50 -2
PHASE15
#
# ---------
#  PHASE 17
# ---------
  nice $MFCL skj.frq 15.par 17.par -file - <<PHASE17
#  Estimate regional distribution of recruitment
  -100000 1 1
  -100000 2 1
  -100000 3 1
  1 1 3000
  1 1 6000
  1 50 -3
PHASE17
```

12 Appendix B: ski.ini

```
# ini version number
1
# 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 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 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 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 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
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0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.52 0.52 0.5 0.5 0.5 0.5 0.5 0.44 0.44 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.52 0.52 0.5 0.5 0.5 0.5 0.5 0.44 0.44 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.52 0.52 0.5 0.5 0.5 0.5 0.5 0.44 0.44 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.52 0.52 0.5 0.5 0.5 0.5 0.5 0.44 0.44 0.5 0.5
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0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.52 0.52 0.5 0.5 0.5 0.5 0.5 0.44 0.44 0.5 0.5
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0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.52 0.52 0.5 0.5 0.5 0.5 0.5 0.44 0.44 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.52 0.52 0.5 0.5 0.5 0.5 0.5 0.44 0.44 0.5 0.5
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0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.52 0.52 0.5 0.5 0.5 0.5 0.5 0.44 0.44 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.52 0.52 0.5 0.5 0.5 0.5 0.5 0.44 0.44 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 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 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 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 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5 0.5 0.5 0.5 0.46 0.46 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.52 0.52 0.5 0.5 0.5 0.5 0.5 0.44 0.44 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
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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 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 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 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 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
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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 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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# tag_fish_rep penalty
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# maturity at age
0 0 1 1 1 1 1 1 1 1 1 1 1 1 1 1
# 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
# age_pars
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
# recruitment distribution by region
0.0348 0.4056 0.5595
```

```
# 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
```