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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 2010 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 17 fisheries (a change from the 24 fisheries used in the 2008 assessment) and quarterly time periods from 1952 through 2009.

The current assessment incorporates a number of changes from the 2008 assessment, including:

1. Updated catch and size data;
2. Updated Japanese tagging data which now includes Japanese tags released in the southern regions. The final runs of the current assessment did not include tag releases and recoveries from the recent SPC-PTTP tagging programmes, but these data were considered during the assessment development.
3. A revised (and considerably different) standardised effort series for each region was included based on a new GLM analysis of catch and effort data from the Japanese distant-water pole-and-line fishery.
4. A new 3 region spatial structure which effectively condensed the previous multiple northern regions into a single northern region and imposed two equatorial regions that cover similar areas to the equatorial regions in the bigeye and yellowfin stock assessments (although they extend further south to 20S).

In addition to these changes, a large suite of additional models were run to aid the development of the final base model, which is considered the most plausible model and therefore the model upon which management advice should be based. The sensitivity of the base model to key assumptions (i.e. regarding the stock recruitment relationship, natural mortality, cpue time series, and purse seine catch 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. 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 declines, with greater decline in region 2. This contrasts strongly with the trends apparent in the previous assessment, and is the main reason for the somewhat different 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 stock size, mediated though growth, total mortality, and movement rates.

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

1. As with other tropical tunas, estimates of natural mortality are strongly age-specific, with higher rates estimated for younger skipjack.
2. The model estimates significant seasonal movements between all three regions. The performance of the fishery in the eastern region has been shown by other studies 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 interaction is not explicitly parameterised 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. Recruitment in the eastern equatorial region is 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. Recruitment since 2005 is estimated to have dipped and then recovered, but the most recent years are poorly determined due to limited observations from the fishery.

4. The biomass trends are driven by both fishing mortality and recruitment. The highest biomass estimates for the model period occurred in 1988-1990 and in 1998–2001, immediately following periods of high recruitment. Very high recruitment is estimated to have occurred in 2004-2006, but biomass has been constrained by higher catches. The model results suggest that recent skipjack population biomass has been lower than previously observed.

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 estimated CPUE trends are influential regarding the general trend in both recruitment and total biomass over the model period. For all regions, there is a good fit to the observed CPUE data. This indicates reasonable consistency between the CPUE series and the other sources of data within the assessment model.

6. The model also incorporates a considerable amount of tagging data that provides information concerning absolute stock size during the main tag recovery period. For the equatorial regions, the most informative data in the model are from an intensive tagging programme that ceased in the early 1990s with most tag recoveries occurring over the following 18 months. This tagging programme occurred prior to the expansion of the fishery in region 3 in the mid–late 1990s and, consequently, given the low exploitation rates, fewer tags were recovered from this region. On this basis, the level of absolute biomass in region 3 is likely to be less well determined than for region 2.

7. Data from the recent SPC-PTTP tagging program were included in preliminary runs of the current assessment model, but the data need further preparation before they can be fully integrated. Analyses of the SPC-PTTP data outside the assessment model were consistent with the conclusions of this assessment.

8. 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 (2005-2008) biomass by about 50% in the western equatorial region and 25% in the northern and eastern regions. For the entire stock, the depletion is estimated to be approximately 40%.

9. A range of sensitivity analyses undertaken indicate that the main conclusions of the assessment are relatively insensitive to most of the model assumptions investigated.

10. ***Based on estimates of*** $F_{current}/\tilde{F}_{MSY}$ ***and*** $B_{current}/\tilde{B}_{MSY}$ ***from the base 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 (2005-2008) level of exploitation is well below that which would provide the maximum sustainable yield, recent catches have increased strongly and the mean catch for 2005-2008 of 1.4 million tonnes is equivalent to the estimated MSY at the assumed steepness of 0.75. The maximum yield at the somewhat higher recruitment levels of the past ten years (1999-2008), and assuming steepness of 1, is 1.8 million tonnes. 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 2). 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).

Skipjack growth is rapid compared to yellowfin and bigeye tuna. In the Pacific, approximate age estimates from tagging and otoliths indicate fork lengths (FLs) of 48, 65, 75, and 80 cm for ages 1–4 years (Tanabe *et al.* 2003); though significant differences occur between individuals. The longest period at liberty for a tagged skipjack was 4.5 years. 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}). Skipjack tuna reach sexual maturity at about 40 cm FL.

1.2 Fisheries

Skipjack tuna 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 (Figure 1). A domestic pole-and-line fishery occurred in PNG from 1970 to 1985 and an active fishery has 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. Since 1975, purse seiners flagged in various countries (e.g. Australia, Federated States of Micronesia, Kiribati, Mexico, Papua New Guinea, Russia, Solomon Islands, and Vanuatu) have operated in the WCPO. 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 has been relatively stable during the early 1990s, approaching 1,000,000 mt per annum. Catches increased again from the late 1990s and reached almost 1,700,000 mt[3] in 2009 (Figure 3). 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

[3] Catch levels referred to in this paper are relevant to the base 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 (2010).

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 4). 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 4). Since the late 1990s, there was a large increase in the purse-seine fishery in the eastern equatorial region of the WCPO (region 3), although catches from this region were highly variable among years.

1.3 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.* 2005b; Langley and Hampton 2008). This paper updates the previous assessments and investigates a number of 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 from 45°N to 20°S and from oceanic waters adjacent to the east Asian coast to 150°W. The assessment model area has in the past contained six spatial regions. This model configuration was based on a previous skipjack CPUE standardization study (Ogura and Shono 1999), enlarged to include the domestic fisheries of the Philippines and eastern Indonesia.

In this assessment the regional structure was simplified to comprise 3 regions (Figure 2), with a single region north of 20N, and two equatorial regions 20S to 20N, with the western equatorial region from 120 to 170 degrees, and eastern equatorial from 170 to 210 degrees. The change was made in order to reduce model complexity, in view of difficulty estimating parameters for the 6 region model. An additional advantage is that the southern regions are now similar to the bigeye and yellowfin tuna regional structure, the remaining difference being the inclusion of 10S to 20S in the skipjack regions.

In this assessment, models were run using both regional structures, in order to show the effects of the change.

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 1972–2009. 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 (associated (log and FAD) sets vs other (mostly school) sets) in order to sufficiently capture the variability in fishing operations. Previous assessments have separated log and FAD sets, and the effect of combining them was examined as a sensitivity analysis.

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. Finally, domestic fishery categories for the Philippines and Indonesia were also included in the fishery definitions. Overall, 17 fisheries were defined in the analysis, down from 24 in the 2008 assessment (Table 1).

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 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.

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 6);
- 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;
- The steady increase in catch for the domestic fisheries of Indonesia and the Philippines.

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.

Effort data were not available for the Philippines domestic, Indonesia domestic and research longline fisheries (these vessels were targeting other tuna species) – effort was declared as missing for these fisheries. CPUE plots for each fishery (apart from those having missing effort, as noted) are shown in Figure 8.

2.4.2 CPUE and standardised effort time series

Revised standardised effort series 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 (Langley *et al.* 2010; Kiyofuji *et al.* 2010). Separate analyses were conducted for each region, for the distant-water and offshore fleets, for both the previous 6 region (Langley *et al.* 2010)and the new 3 region (Kiyofuji *et al.* 2010) model configurations. These analyses followed the recommendations of an April 2010 meeting held in Noumea to review inputs for the current stock assessment (Harley and Hoyle 2010). The resulting CPUE trends (Figure 7) were very different from those provided in previous years (see Langley *et al.* 2010; Kiyofuji *et al.* 2010). The effect of adding the new CPUE series is presented in the results section.

In addition, the variance of 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. This is a change from previous assessments, in which the same variance was assumed for all pole and line CPUE estimates. The effect of including these variance estimates is presented in the results section.

The GLM analyses provided 3 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 3 types of abundance indices with standard errors: the delta lognormal, the lognormal offset, 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 lognormal offset indices of abundance were exponentiated to provide indices of abundance directly. The assumed standard deviation was the reported standard deviation of the parameter estimate.

3. 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 other4 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

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

[4] 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.

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

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 base case, and the alternative indices were applied as sensitivity analyses and as part of the grid. All three sets of indices are shown in 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 in the three-region model and region 2 in the six-region model), to reflect the lack of available fish and to inform the model about relative availability.

In initial runs based on the old regional structure, relative scaling factors were applied to the CPUE values in order to constrain the relative abundances in the 6 regions. These were estimated from nominal catch rates from the Japanese pole-and-line fleet 1975–85. These scaling factors incorporated both the effective size of the region and the relative catch rate to estimate the relative level of exploitable pole-and-line biomass between regions similar to the approach applied to the longline CPUE data in the WCPO yellowfin and bigeye tuna stock assessments (see Langley *et al.* 2005a; Hoyle and Langley 2007). The specific regional weighting factors were 0.09, 0.47, 0.28, 0.66, 0.85, and 1 for regions 1–6, respectively.

The scaling factors allowed trends in pole-and-line CPUE among regions to be comparable indicators of exploitable biomass among regions. For each of the principal pole-and-line fisheries, the GLM standardised CPUE index was normalised to the mean of the GLM index from 1975–85 — the equivalent period for which the region scaling factors were derived. The normalised GLM index was then scaled by the respective regional scaling factor to account for the regional differences in the relative level of exploitable pole-and-line biomass among regions. Standardised effort was calculated by dividing the quarterly catch by the quarterly (scaled) CPUE index.

In later runs based on the new three-region structure:

a. the weight of each region was initially set to 1. This was similar to the weighting scheme for the six-region model, given the positions of the boundaries.

b. 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 (and weight) 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.

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 arbitrarily assigned to the offshore fleets 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.

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 (see 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 effective sample size of all length frequency data was reduced by 50%. The effect of this change was examined as a sensitivity analysis (model run number 29 in Table 6).

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 this appears to be due to movement of fishing location into areas with larger fish. Data from the longline fishery in region 2 before 1980 and after 2000 was removed in order to reduce the variability of fish size.

The equatorial purse-seine fisheries all catch skipjack of a similar size, although 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). 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 and sampling programs, the effective sample sizes of all purse seine data was downweighted by 80%. The effect of this change was examined as a sensitivity analysis (model run 20 in Table 6).

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 downweighted 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 avoided imposing bias on estimates of growth and total mortality. The effect of this change was examined as a sensitivity analysis (model run number 8 in Table 6).

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). Also, tagging data from regular Japanese research cruises were available for the period 1988–2005.

Japanese tags released in all regions were used in the analysis. This is in contrast to previous years, 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 this year which permitted different reporting rates to be estimated by release group and fishery. The effects of these changes were examined as a sensitivity analysis.

Tag release and recovery data from the 2006–08 PTTP tagging programme were also included in the initial models examined during the development of the base model. The effects of adding these data were examined in several sensitivity analyses. However, the data were not included in the base case or the grid, because we did not understand this complex new dataset well enough to be confident we were modelling it correctly. The reasons for its exclusion will be discussed later in more detail.

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 228,087 releases were classified into 191 tag release groups (Table 2). Release groups from 2009 and 2010 were excluded. The returns from each size-class of each tag release group (27,812 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 2006-08 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 the Japanese (Figure 12).

The total tag recoveries were dominated by recoveries from 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 2). 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 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 Structural assumptions of the model

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 mathematical specification of structural assumptions is given in Hampton and Fournier (2001b). The main structural assumptions used in the skipjack model are discussed below and are summarised in Table 5.

3.1 Observation models for the data

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

The probability distributions for the length-frequency proportions are 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 3.2 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).

3.2 Tag reporting

Tag reporting rates were estimated separately by fishery and tagging program. A new approach is introduced in this assessment.

Tags in MULTIFAN-CL are grouped into tag release groups, which represent the tags released by quarter x region x tagging program stratum. 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 release groups and fisheries, as follows:

a. Reporting rates were grouped for all Japanese fisheries, as in previous assessments. For these fisheries, separate reporting rates were estimated for a) Japanese tagging programs, b) SSAP and RTTP tagging programs, and c) the PTTP tagging program.

b. All equatorial purse seine fisheries shared reporting rates, and separate parameters were estimated for the SSAP, RTTP, PTTP, and Japanese tagging programs.

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 Papua New Guinea pole and line fishery had one parameter for SPC releases and one for Japanese releases, as did the Fiji Islands pole and line fishery. The Solomon Islands pole and line fishery had a separate parameter for each tagging program, as did the Philippines and Indonesian domestic fisheries.

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, where appropriate, PTTP) purse seine fisheries, as independent estimates of reporting rates for these fisheries were available from tag-seeding experiments and other information (Hampton 1997). 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. 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. Tag reporting rates from all tag groups were assumed to be constant through time.

3.3 Tag mixing

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

3.4 Recruitment

"Recruitment" in terms of the MULTIFAN-CL model is the appearance of age-class 1 fish (i.e. fish aged 3 months?) 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 six 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 2001a, 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 very difficult for stock assessment models to reliably estimate steepness. Steepness was therefore fixed at a value of 0.75, consistent with other WCPFC tuna stock assessments, and alternative steepness values examined as sensitivity analyses and as part of the grid.

3.5 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.

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' still refers to the biomass of adult fish, rather than changing to spawning potential as in the yellowfin, bigeye, and albacore stock assessments.

3.6 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. In this assessment, two Japanese pole-and-line selectivity curves were estimated, one for region 1 and one for the equatorial fisheries. This change was made to allow the model more flexibility to fit the size variation observed between the regions. The effect of the change is presented in the Results section. 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.

3.7 Catchability

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, Indonesian and research longline fisheries.

3.8 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.

3.9 Movement

Movement was assumed to be time invariant and to occur instantaneously at the beginning of each quarter. For age-independent movement, there would be two transfer coefficients for each boundary between the regions. 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.

3.10 Natural mortality

Natural mortality was 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.

3.11 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.

3.12 Run sequence and sensitivity analyses

At a preparatory meeting (Noumea, April 2010), a range of model changes and sensitivity analyses were considered and agreed for the current assessment (Harley and Hoyle 2010). 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; (3) inclusion of Japanese and PTTP tagging data; (4) program-specific reporting rates; (5) alternative CPUE time series; (6)

alternative fishery definitions; (7) alternative regional structures including equatorial and 6 region models; and (8) a monthly time structure.

Of the runs listed above, options 1 to 6 were considered during model development and presented in the ‘Development models’ run sequence. Option 7 is partly presented during this series, with the 6 region model considered but the equatorial model not considered. Option 8 was not examined due to lack of time. Many 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, 5, and an option addressing natural mortality were considered as formal sensitivity analyses, offset from the base case. A grid was developed based around these sensitivity analyses, in which all combinations of option values were considered.

4 Results

This section provides a detailed summary of the results from the base-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 includes references to a very large number of model runs. These models can be grouped into 3 main categories:

1. ***Development models:*** Models used to help develop the final “base” model. This set of models includes those which described the impact of each of the changes made to the 2008 assessment model(s) in transitioning to the current base model, as well as additional exploratory models used to help refine the current base model.

2. ***The base 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 base model.

It is the base model and associated sensitivity analyses models which form the basis of the conclusions regarding skipjack stock status provided in this paper.

4.2 Developmental model series

4.2.1 Transition to 3-region model

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.

Initial changes involved updating the catch and effort data from those used in 2008 (**1**) to 2010 (**2**), and adding the standardized CPUE (used in the form of standardized effort in the model) for the Japan pole and line fisheries based on the delta lognormal model (Langley *et al.* 2010). The change from an increasing to a declining CPUE time series resulted in a biomass trend that still increased, but to a lesser degree (Figure 18). Combining the FAD and LOG fisheries into a single fishery (**4**) reduced the overall biomass level slightly, and fixing steepness (**5**) had little or no effect on the biomass trend. Introducing more flexibility into the catchability deviates (**6**) (effectively removing the influence of the unstandardized effort series) resulted in a slightly more variable time series (Figure 18).

Changing to a new regional structure (**11**), adding the PTTP data (**7**), and downweighting the Philippines size data (**9**) considerably changed the time series and the biomass trend (Figure 19). The CPUE time series for these regions (Kiyofuji *et al.* 2010) was also applied at this point. The intermediate analyses are not presented here due to some last-minute problems, but the effects of adding the PTTP data are also considered elsewhere. Removing the Philippines size data did not substantially affect the biomass trend at this stage, but was necessary because the model could not be configured to fit these data appropriately. Including the updated Japanese tagging data (**12**) (new data for 2006-2008, and changes to the earlier data) lowered the average biomass estimates for the whole time series. Part of this effect is because the equatorial releases are included as well as the northern releases, whereas the earlier tagging dataset included only the Japanese releases in the northern region. Including the estimated CPUE variance in the model (**14**) resulted in lower biomass estimates post-2000 (Figure 19).

4.2.2 Investigate further changes

The following analyses were run as offsets from the 'include CPUE variance' model, in order to examine the effects of further potential changes before applying them. A random walk was introduced to the Japanese PL time series (**17**), in order to demonstrate the biomass trend being indicated by the other data in the model (tagging data and size data). The main features were low biomass before 1990, which may be driven largely by the SSAP tagging data, and a large biomass peak in about 2000, driven by size data (Figure 20). The last 4 CPUE estimates were removed (**22**) since they were implausibly low, and the most recent data are generally the least reliable and most influential. This had the effect of increasing the last part of the biomass trend (Figure 20). Removing the regional weighting (**25**) had remarkably little effect on the overall level of the biomass time series, but resulted in a slightly more declining trend (Figure 20).

Natural mortality is a generally a difficult parameter for assessment models to estimate, although the tagging data used in this model make such estimation viable. The effect of plausible alternative values was investigated by fixing the model at the values estimated in 2008, using both the exact numbers (Fix M 2008) (**18**) and the relative M at age but with the overall level estimated freely (Fix M at age 2008) (**19**). The overall biomass level did not change significantly, but recruitment varied far more in order to supply the required recruits (Figure 20). A major difference between the shapes of the 2010 and 2008 M curves was a much lower M for very small fish (which are not observed in the fishery) , and this was largely responsible for scaling the recruitment.

Two further models offset from the 'include CPUE variance' model addressed issues with the size data. Reducing the effective sample size of the size data that showed the most inconsistent temporal variability (**20**) resulted in higher average recruitment and reduced the biomass peak in 2000 (Figure 21). The higher recruitment resulted from a different growth curve and associated higher average natural mortality. Estimating the selectivity of the Japanese northern pole and line fishery separately from the other Japanese pole and line fisheries (**21**) slightly increased the biomass and recruitment trends.

All models to this point were run with S_BEST estimates of purse seine catch. Changing to spill-sampling-based catches (**23** and **24**) had very little effect on biomass trends or recruitment ().

All previous models assumed that each fishery had the same reporting rate for all tagging programs. We investigated the new approach of applying different reporting rates by tagging program (Table 3). Two different scenarios of reporting rate groups (and others not presented here) resulted in lower overall biomass levels (**26** and **27**) (Figure 22), but similar recruitment levels, indicating higher natural mortality. In each case, Japanese fisheries were estimated to have higher reporting rates for Japanese tagging programs than SPC tagging programs (SSAP, RTTP, and PTTP), and non-Japanese fisheries in the equatorial regions (apart from the Japanese purse seiners included in the aggregate purse seine fleet) were estimated to have higher reporting rates for SPC tagging programs than Japanese tagging programs.

The last model to be offset from the 'Include CPUE Variance' was a combination of the analyses considered above. This 'Combined option' model (**28**) included removal of regional weighting (**25**), downweighting size data for the variable fisheries (**20**), ungrouping PL selectivity for the northern region (**21**), removing the last 4 CPUE values (**22**), and estimating reporting rate by tagging program (**27**). As expected given the other results, the overall biomass level was lower and the time series was less variable, due to reduced influence of the size data (Figure 22). A subsequent analysis reduced the maximum effective sample size by 50% (**29**), and this had little effect on the biomass time series but raised average recruitment (Figure 22).

4.2.3 Investigate tag modelling approaches

Further diagnostic analyses were carried out, leading to changes to improve the fit to the tagging data. The following runs were offset from the 'Combined lower LF SS' model (**29**). The upper boundary on the reporting rate was increased from 0.9 to 0.99. Small fisheries operating close to the point of release (e.g. Solomon Islands pole and line recapturing RTTP tags) can return more tags than expected if mixing is not as thorough as assumed. Allowing a higher reporting rate can reduce the bias caused by a parameter estimate hitting the boundary. This change made a small difference to biomass and recruitment trends (Figure 23), as reporting rate estimates for several fisheries increased to hit the new boundary at 0.99. An alternative and more appropriate reporting rate parameter configuration (Table 4) shared reporting rates across multiple periods where there were few data, and permitted the Japanese fisheries to report PTTP tags at different rates from other SPC tagging programs (**33**). This change affected the recruitment average but had little effect on the overall biomass trend (Figure 23). A further change investigated the effect of removing priors from all reporting rate parameters except for the RTTP releases and equatorial purse seine recaptures (**36**). This resulted in slightly lower average biomass. Another offset from the 'Combined lower LF SS' model reduced the PTTP reporting rate prior mean by 50%, from 0.4 to 0.2 (**38**). This had a similar effect to the previous change (Figure 23).

Further tests involved examining the sensitivity to the linkage between purse seine selectivity in regions 2 and 3. Such linkages are often used to stabilise the model, but if the model is stable without them then it may be better to remove them. It is arguable that purse seine fisheries select the fish sizes that are available, so areas with different sized fish may have different purse seine selectivity. Unlinking these selectivities resulted in lower average biomass (Figure 24). The most recently released PTTP tag group, in the Indonesian region, had low return rates after the first quarter and very few returns away from Indonesia, suggesting that mixing was less complete than assumed. Removing this large tag group had a substantial effect on the most recent biomass estimates (Figure 24).

A series of further sensitivity analyses investigated the individual effects of the tagging programs (SSAP, RTTP, PTTP, and JP, and also the JP tags released in regions 2 and 3), by removing one group at a time (**34**). Removing the RTTP resulted in higher biomass for the whole time series (Figure 24). Removing the SSAP raised most of the biomass time series, but more during the early period when the SSAP occurred. Removing the PTTP lowered the most recent biomass estimates significantly, and had minor effects on earlier periods. Removing the Japanese tags tended to raise the earlier part of the time series and the most recent years, but lowered recruitment estimates. These results indicate the great influence of the tagging data on the model (Figure 24).

The results of these investigations led to a combined model (**39**) that included the following changes from the 'Combined lower LF SS' model: the maximum reporting rate was adjusted to 0.99; the alternative set of reporting rate parameters was used (Table 4); the poorly mixed PTTP release group was removed; no penalty was applied to the prior distribution in Japanese fishery reporting rates for the PTTP; and the zero-inflated mixed model was used for the tag return likelihood. The resulting biomass time series was similar to the previous run until the last few years, when it declined more steeply (Figure 25).

4.2.4 Transition to base case

Two final steps were taken to reach the base case. First, the PTTP data indicated increasing biomass at the end of the time series, in contrast to the CPUE data which indicated a decline. In addition, the model was not able (as it should have been) to follow the prior distribution for the PTTP reporting rates, but estimated a higher reporting rate. This suggested a possible problem modelling the number of tags returned during the mixing period, when using the new reporting rate approach. In view of the uncertainty about the effects of including the PTTP data, they were excluded (**40**). Further preparation is required before these data can be understood well enough to be included in the base case. Excluding these data resulted in a greater decline at the end of the time series (Figure 25). Secondly, the spill sampling data were use in place of the S_BEST data (**41**). Using these data was recommended by the pre-assessment workshop, and had only a minor impact on the biomass and recruitment trends (Figure 25), as seen in previous sensitivity analyses.

4.2.5 Sensitivity analyses

Four issues were investigated as part of a sensitivity analysis. These were the alternative steepness values (**42**, **43**, and **44**; Figure 26), alternative CPUE time series (**45**; Figure 26), the effects of fixing natural mortality at the level estimated in 2008 (**46** and **47**; Figure 27), and use of the S_BEST purse seine catches rather than the spill sampling purse seine catches (**48**; Figure 27). More detail on these results is given in later sections.

4.3 Base case

Results and diagnostics are presented for a single run, which represents the most plausible model selected from those explored during the model development process. Uncertainties in the base 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 base case and sensitivity analyses is given in Table 7. Due to differences in the tag and effort data sets the total likelihood values are not strictly comparable for all runs.

The fit of the model to the total catch data by fishery is very good (Figure 29), which reflects our assumption that observation errors in the total catch estimates are relatively small.

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 30). 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 after about 1995 than earlier. Similarly, the region 2 Japanese pole and line fishery and the region 3 research longline fishery caught larger fish than expected after 1995. In contrast, fish size trended smaller than expected in the western equatorial purse seine fishery 8.

These temporal trends in the size of fish caught are not reflected in the model dynamics and may indicate a change in the length-based selectivity of skipjack between the two periods (Figure 30). One possible explanation is changes through time in the locations from which samples were obtained, since skipjack sizes are quite significantly area-dependent (see Appendix 2).

The length samples from the Philippines domestic fishery were highly variable among and within sampling periods in a way that was not apparent in other fisheries (Figure 30). The observed variation in the length composition is likely to reflect variation in the distribution of sampling effort between the individual fisheries that constituent the Philippines domestic fishery.

The model accurately predicts the observed number of tag returns for tagged fish at liberty for up to two years (8 quarters) — the period accounting for 99% of all recoveries (Figure 33). However, the model over-estimated the number of tag returns expected for longer periods at liberty.

The fit of the model to the tagging data compiled by calendar date is presented in Figure 34. The aggregated fit is extremely good, with little divergence between observed and predicted tag returns. Minor discrepancies are evident when the observed and predicted data are broken down by fishery groups (Figure 35), but these are not significant.

The largest discrepancy in the tag recoveries is from the Solomon Islands pole-and-line fishery, with considerably more recoveries observed than predicted (Figure 35). This is likely to be due to poor mixing of fish released relatively close to the Solomon Islands, i.e. extended residence times in the vicinity of the archipelago (Kleiber and Hampton 1994).

4.3.2 Tag reporting rates

Where possible, reporting rates were estimated separately by fishery, and by tagging program. Results presented here for Japanese tagging programs, and for the SPC tagging programs SSAP and the RTTP (Figure 36). Note that these estimates of reporting rates incorporate those tags that were in fact returned, but with insufficient information to allow them to be classified to a fishery and time period.

There is considerable variation among fisheries in the estimated tag-reporting rates (Figure 36). The equatorial purse seine fishery reporting rates for SSAP releases were estimated close to the mode of the prior at 0.45 (SD = 0.11); for RTTP releases the estimate was somewhat higher at 0.6. Estimates for Japanese releases were considerably lower, at 0.1.

For Japanese fisheries, reporting rates for tags released by SPC (0.24) were estimated to be lower than for Japanese tags (0.5).

For the Solomon Island and Fiji pole-and-line fisheries, the estimated reporting rates for SPC tags were very high at 0.99 – the upper bound stipulated for all reporting rates (Figure 36). For Japanese tags however, their reporting rates were effectively 0.

The Philippines and Indonesian fisheries had higher reporting rates for tags released during the RTTP (0.88 and 0.35) than for the SSAP (0.12 and 0) or for Japanese tags (0 and 0).

4.3.3 Age and growth

Using the four-recruitment-per-year formulation, the model estimated the growth curve shown in Figure 37. Estimated growth rates are generally much faster than determined by Tanabe et al. (2003) from daily otolith increments. The discrepancy in length-at-age (up to 14 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 not given much weight in the assessment.

The variation in length-at-age increases across age-classes (Figure 37), as expected for most fish species.

4.3.4 Selectivity

Estimated selectivity functions are generally consistent with expectation (Figure 38). Pole-and-line and purse seine fisheries begin to select fish at 3 or 4 quarters of age. Most of the purse seine and pole-and-line fisheries have high selectivity for age-classes 4–6 and declining selectivity for the older age-classes. For these fisheries, the selectivity of age classes 8–16 is low. The Philippines fishery catches the smallest fish with relatively high selectivity for fish in the 1–5 age-classes, but also has a high selectivity for older age classes reflecting the presence of some larger fish in the sampled catch. The alternation between large and small fish in the size data has affected the results of past assessments. Reducing the size data’s weight in the likelihood allows the model to extract the fish captured, but stops the size changes influencing the biomass trajectory. 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 39.

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 a sharp recent increase in area 3 during the 2000s (Figure 39).

Seasonal variability is strong for many of the pole-and-line fisheries, particularly for the Japanese fleets in region 1. This occurs despite the standardisation of the effort data from these fisheries to account for seasonal variation in catchability. 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, as expected given the flexible estimation of catchability trends (Figure 40). 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 all regions (Figure 41).

4.3.7 Natural mortality

Natural mortality is estimated to be high for the young age classes (1–4 quarters), and declining steadily with increasing age up to age class 7 (Figure 42). There is a steady increase in estimated natural mortality for the older (9+) age-classes. The ogive differs from previous years in the lower natural mortality for quarterly age classes 1 and 2 than for 3 and 4. This results from the new growth curve including smaller fish than in previous years. It has little 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 43. This figure shows the movement of the proportion of five age groups between each region by quarter. The model estimates high (approaching 60%) 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 for younger age classes in quarter 4. There are also high movement coefficients in the first quarter from region 1 to 2, and from region 2 to 3, and smaller movements from region 1 to 3, and from region 3 to 2 (Figure 43). Movement coefficients between other regions and at other times are estimated to be small. An alternative way of looking at these movements is presented in Figure 44. Note, however, that movement rates represent the proportion of fish moving rather than the number. 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 distribution of regional biomass by source region derived from a simulation using the movement coefficients is presented in Figure 45. The simulation indicates that the model estimates a relatively high degree of mixing for all three regions. For example, the model estimates that only about 40% of the biomass in region 3 is sourced from recruitment within the home region, with another 40% sourced from region 2 and 20% 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 (Figure 45).

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 3.3). However, low tag returns and reporting rates result in very little influence of the tagging data. 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 46. Overall recruitment is estimated to be distributed throughout the three regions, with highest recruitment in the western equatorial region 2. Regions 1 and 3 show stronger seasonal variation than region 2. 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 2009. Recruitment in region 2 is variable, increasing in the early 1980's and with a large dip in the mid-1990's (Figure 46). Region 3 shows considerable medium-term variability, with 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.

Overall, recruitment was estimated to be lower during the first decade of the model period (1972–82), and higher subsequently (Figure 46). The strong recruitment variability is consistent with our understanding that environmental conditions can have large effects on recruitment. 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 47. Overall, most of the total biomass is within regions 2 and 3 (48% and 35% respectively of the biomass in 2005-2008), although a significant proportion of the biomass is within region 1 (17%).

The trend in total biomass is consistent with the trend in overall recruitment, with relatively low biomass during the early period, a higher level of biomass throughout 1982–2000 and lower biomass in the most recent years (Figure 47). 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

Annual average fishing mortality rates are shown in Figure 48 for each region. Recent fishing mortality rates on both juvenile and adult skipjack are highest within region 2; fishing mortality rates steadily increased from 1972 to 1995 and remained at that level until 2005, before increasing significantly in the last 4 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 49). By comparison, recent fishing mortality rates are low for the other regions.

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 50 and the level of stock depletion is presented in Figure 51.

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 to about 50% of the unfished level in recent years (Figure 51). For region 3, fishery impacts are estimated to have reduced the total biomass by about 25%. For the entire stock, the depletion is estimated to be approximately 40%.

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 2005–2008. The last year in which catch and effort data are available for all fisheries is 2009. We do not include 2009 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 are presented in Table 9.

The stock assessments are uninformative regarding the relationship between spawning biomass and recruitment, and a value of *h*=0.75 was assumed in the base case (Figure 52).

For the base-case, MSY is estimated to be 1.38 million mt per annum at a level of fishing effort (*Fmult*) approximately 3 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 close to the level estimated here. The maximum yield that is projected if the recent 10 year (1999-2008) average recruitment is maintained (i.e. without considering the stock recruitment relationship) is approximately 1.8 million mt per annum.

The portion of the yield curve near the current level of *F*-at-age is strongly curved (Figure 55). 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 base-case, levels of equilibrium biomass levels are estimated to be relatively low at F_{MSY} ($S\tilde{B}_{MSY} / S\tilde{B}_0$ = 0.27 and $\tilde{B}_{MSY} / \tilde{B}_0$ = 0.31) (Figure 53).

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 ($F_{current} / \tilde{F}_{MSY}$ = 0.34) (Figure 56 and Figure 57). Therefore, <u>overfishing of skipjack is not occurring</u>. Total biomass remained higher than the $\tilde{B}_{MSY}$ level throughout the model period and current total biomass is approximately 75% of the equilibrium unexploited level ($\tilde{B}_0$) due to the higher levels of recruitment in recent years ($B_{current} / \tilde{B}_{MSY}$ = 2.42). The probability distribution of $B_{current} / \tilde{B}_{MSY}$, obtained from a likelihood profile, indicates a high degree of uncertainty associated with the *MSY*-based biomass performance indicator (Figure 58). Nonetheless, there is a zero probability that $B_{current} / \tilde{B}_{MSY}$ is anywhere close to 1.0 and, on this basis, <u>the stock is not in an overfished state</u>.

4.4 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 Fcurrent / Fmsy (Figure 59), Bcurrent / Bmsy (Figure 60), and SB current / SBmsy (Figure 61).

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 10).

Fixing natural mortality at the levels estimated in the 2008 assessment resulted in slightly higher estimates of Fcurrent / Fmsy and slightly lower estimates of B/Bmsy, but there was considerable overlap between the ranges of the two alternatives.

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 lower median estimates of F current / Fmsy, and higher Bcurrent / Bmsy. 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 63 and Figure 64). 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 Fcurr/Fmsy, Bcurr/Bmsy, or SBcurr/SBmsy approach 1. The distribution of MSY ranged from approximately 1.2 million to 1.8 million metric tonnes.

5 Discussion

Large changes have been made to the structure of the skipjack assessment. 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. For the first time, however, the most recent extractions from the stock are approaching those levels.

The most significant change to the stock assessment was the addition of the new standardized CPUE time series, based on Japanese pole and line catch and effort data. These data showed a declining abundance trend, as might be expected given the large and increasing catch being taken from the fishery. The model was also able to fit these data much better. Data conflict was seen in previous assessments, indicated by strong trends in effort deviates for the standardized fisheries, but no such trends were apparent in this assessment.

A further influential change was the switch from six regions to a three region model. With this change the problem of large ‘cryptic’ biomasses occurring in regions where skipjack fisheries are not significant (e.g. the old region 4) was resolved. The new model estimates a moderate biomass in the northern region, not inconsistent with the level of catch. Model complexity was reduced, with fewer fisheries, fewer catchability and effort deviate parameters, and fewer movement parameters to estimate. Other options may be considered in future, to improve the resolution of management units and to examine movement on a smaller scale.

Another significant change was the introduction of program-specific reporting rate parameters. This change was essential for the introduction of the PTTP data, 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 programs). However, the new functionality has only recently been added to MULTIFAN-CL and more work is required to explore its implications.

The PTTP tagging data were included in the analyses presented here but were omitted from the final base case run. This was because the PTTP data were in conflict with evidence from the CPUE data, causing a trend in the effort deviates. Also, the model seemed to have difficulty fitting to the data – the predicted number of returns from the PTTP was below the number observed – which is consistent with some feature of the data causing the biomass in the last few years to be overestimated. This problem could not be resolved in the time available and so the PTTP data were removed.

There is some uncertainty about the model's estimates of growth. The estimated growth rate was faster than evidence from otolith readings (Tanabe *et al.* 2003), and the length at minimum age tended to be estimated close to or at the boundary. New evidence of spatial variation in skipjack size suggests that future models should define fisheries (but not necessarily regions) on smaller spatial scales. This is likely to improve the model's ability to estimate growth rates. In addition it would be useful to include length at age estimates directly in the model, as well as growth increment estimates from analyses of tagging data. Both options would require changes to MULTIFAN-CL.

A number of changes were made to treatment of the size data, reducing effective sample sizes where data problems were evident. Size data are very influential in length-based models. MULTIFAN-CL treats the data as representative of fish sizes in the population, filtered through the selectivity. Further work is required to ensure that the size data are truly representative of the population in the areas sampled by the fisheries, and that fishery selectivities do not change through time.

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 *et al.* 1999; Sibert and Hampton 2003). The population-level estimates of dispersal obtained from the current assessment show a relatively high 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 estimates for the RTTP (Hampton 1997) among the most influential information about overall stock size. The stock size changes suggested by the new CPUE data are, given the level of catch, consistent with these stock size estimates. However, 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 programs, and changes to include them in MULTIFAN-CL, is therefore recommended.

6 Conclusions

The major conclusions of the skipjack assessment are similar to those of the last four assessments (Hampton 2002; Langley *et al.* 2003b; Langley *et al.* 2005b; Langley and Hampton 2008). The key conclusions are as follows.

1. Similar to other tropical tunas, 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 is unlikely to 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. 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. This indicates reasonable consistency between the CPUE series and the other sources of data, especially the size data, within the assessment model. The standardized CPUE indices appear to represent a substantially more consistent index of stock abundance than the indices used in previous years.

6. The model also incorporates a considerable amount of tagging data that provides information concerning absolute stock size during the main tag recovery period. For the equatorial regions, the most recent data included in the model are from an intensive tagging programme that ceased in the early 1990s with most tag recoveries occurring over the following 18 months. Further analyses should be carried out to integrate the PTTP data into the stock assessment as soon as possible. Initial analyses of the data suggest results consistent with evidence from the CPUE time series. However, integrating the PTTP data into the model is likely to improve the accuracy and precision of estimates, particularly in the eastern equatorial region 3.

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 50% in the western equatorial region and 25% in the eastern region. For the entire stock, the depletion is estimated to be approximately 40%.

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. The main conclusions of the assessment appeared relatively insensitive to the model assumptions investigated, apart from the assumption about steepness. There are insufficient data to estimate this reliably within the assessment model and many of the key management quantities are strongly influenced by the values assumed. However, the stock is not estimated to be overfished, nor to be experiencing overfishing, over the range of steepness values investigated.

10. Recommended research and monitoring required to improve the skipjack tuna assessment include the following (in no particular order):

    - Further development of the PTTP data set for inclusion in the assessment. Critical work includes maximizing the number of returns that can be assigned to recapture fisheries with reasonable certainty and the further development of estimates of the tag reporting rates, particularly for the PTTP releases, and also Japanese tag releases in the northern waters. Incorporating more tagging data into the assessment, as it becomes available, will provide additional information on recent levels of fishing mortality, refine estimates of natural mortality and possibly allow some time-series behaviour in movement to be incorporated into the model. Additional tagging in the northern region would provide additional information to parameterize relative stock levels among model regions.

- This and recent skipjack assessments have used standardized CPUE from the Japanese pole and line fisheries as the key abundance index that drives trends in estimated abundance in the model. However, this fishery now makes up less than 4% of the total WCPO skipjack catch, and an even smaller percentage in the main equatorial zone. Future research is required to better understand the factors impacting CPUE in the purse seine fishery, which now comprises 88% of the total WCPO skipjack catch, with a view to developing an index of abundance based on this major fishery.

- The assessment model estimates of skipjack growth are not well determined by the available data. The estimation of growth would be assisted by the development of the MULTIFAN-CL software to incorporate age-length and length-increment observations, and the inclusion of such data into the assessment.

- Further research on environmental and biological influences on skipjack tuna recruitment, distribution, and movement are required. The application of fine-scale spatial models such as SEAPODYM to skipjack tuna could potentially provide a useful source of auxiliary information that could be included in MULTIFAN-CL-based assessments.

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8 References

Bigelow, K., Hampton, J., and Fournier, D. Preliminary application of the MULTIFAN-CL model to skipjack tuna in the tropical WCPO. 2000. Working Paper SKJ- 2, 13th Meeting of the Standing Committee on Tuna and Billfish, 5- 12 July 2000, Noumea, New Caledonia.

Fournier,D.A., Hampton,J., and Sibert,J.R. 1998. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, Thunnus alalunga. Can.J.Fish.Aquat.Sci. **55**: 2105-2116.

Francis,R.I.C.C. 1992. Use of risk analysis to assess fishery management strategies: A case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. Can.J.Fish.Aquat.Sci. **49**: 922-930.

Hampton,J. 1997. Estimates of tag-reporting and tag-shedding rates in a large-scale tuna tagging experiment in the western tropical Pacific Ocean. Fish.Bull. **95**: 68-79.

Hampton,J. 2000. Natural mortality rates in tropical tunas: size really does matter. Can.J.Fish.Aquat.Sci. **57**: 1002-1010.

Hampton,J. 2002. Stock assessment of skipjack tuna in the western and central Pacific Ocean. Working Paper **1**: 36.

Hampton, J. and Fournier, D. 2001a. Stock assessment of skipjack tuna in the western and central Pacific Ocean [SKJ-1]. SPC, Secretariat of the Pacific Community No. [SKJ-1].

Hampton,J. and Fournier,D. 2001b. Stock assessment of yellowfin tuna in the western and central Pacific Ocean. 14th Meeting of the Standing Committee on Tuna and Billfish, August.

Hampton,J. and Fournier,D.A. 2001c. A spatially disaggregated, length-based, age-structured population model of yellowfin tuna (Thunnus albacares) in the western and central Pacific Ocean. Mar.Freshwat.Res. **52**: 937-963.

Harley, Shelton J. and Hoyle, Simon D. Report from the pre-assessment workshop in April 2010. SA-IP-01. Scientific Committee 6. 2010. Pohnpei, WCPFC. 10-8-2010.

Hoyle, S. D. and Langley, A. 2007. Regional weighting factors for yellowfin tuna in WCP-CA stock assessments. No. WCPFC SC3/ME WP-1.

Hoyle, Simon D, Fournier, Dave, Kleiber, Pierre, Hampton, John, Bouye, Fabrice, Davies, Nick, and Harley, Shelton. Update of recent developments in MULTIFAN-CL and related software for stock assessment. WCPFC Scientific Committee. WCPFC-SC5-2009/SA- IP-06, -17. 2009. Western and Central Pacific Fisheries Commission.

Kiyofuji, H, Uosaki, K, Ogura, M, Langley, AD, and Hoyle SD 2010. Standardized CPUE for skipjack caught by Japanese offshore pole and line fishery in the northern region of western and central Pacific Ocean. No. WCPFC Scientific Committee SA-WP-09.

Kleiber,P. and Hampton,J. 1994. Modeling Effects of FADs and Islands on Movement of Skipjack Tuna (Katsuwonus pelamis): Estimating Parameters from Tagging Data. Can.J.Fish.Aquat.Sci. **51**: 2642-2653.

Langley, A., Bigelow, K., Maunder, M., and Miyabe, N. 2005a. Longline CPUE indices for bigeye and yellowfin in the Pacific Ocean using GLM and statistical habitat standardisation methods. Working paper SA WP-8, presented to the 1st Meeting of the Scientific Committee of the WCPFC. Noumea, New Caledonia. 8-19 August 2005. 40 pp. http://www. wcpfc. org/sc1/pdf/SC1_SA_WP_8. pdf No. SA WP-8.

Langley,A., Hampton,J., and Ogura,M. 2005b. Stock assessment of skipjack tuna in the western and central Pacific Ocean.

Langley, A., Ogura, M., and Hampton, J. Stock assessment of skipjack tuna in the western and central Pacific Ocean. Proceedings on Sixteenth Meeting of the Standing Committee on Tuna and Billfish.Mooloolaba, Qld, Australia . 2003a.

Langley,A., Ogura,M., and Hampton,J. 2003b. Stock assessment of skipjack tuna in the western and central Pacific Ocean. 16th Standing Committee on Tuna and Billfish. Oceanic Fisheries Program, Secretariat of the Pacific Community, Noumea, New Caledonia.

Langley, A. D. and Hampton, J. 2008. Stock assessment of skipjack tuna in the Western and Central Pacific Ocean. Western and Central Pacific Fisheries Commission (WCPFC).

Langley, AD, Uosaki, K, Hoyle, SD, Shono, H, and Ogura, M 2010. A standardized CPUE analysis of the Japanese distant-water skipjack pole-and-line fishery in the western and central Pacific Ocean (WCPO), 1972-2009. No. WCPFC Scientific Committee SA-WP-08.

Lehodey,P. 2001. The pelagic ecosystem of the tropical Pacific Ocean: dynamic spatial modelling and biological consequences of ENSO. Progress in Oceanography **49**: 439-468.

Lehodey,P., Bertignac,M., Hampton,J., Lewis,A., and Picaut,J. 1997. El Ni±o Southern Oscillation and tuna in the western Pacific. Nature **389**: 715-718.

Mace,P.M. and Doonan,I.J. 1988. Biomass and yield estimates for North Chatham Rise orange roughy. 42 p.(Draft report prepared for the Standing Committee on orange roughy.) Unpublished report held in NIWA library. PO Box **14**: 901.

Maunder,M.N., Watters,G.M., and Inter-American Tropical Tuna Commission 2003. A-SCALA: An Age-structured Statistical Catch-at-length Analysis for Assessing Tuna Stocks in the Eastern Pacific Ocean. Inter-American Tropical Tuna Commission.

Ogura, M. and Shono, H. Factors affecting the fishing effort of the Japanese distant-water poleand-line vessel and the standardization of that skipjack CPUE. 1999. Working Paper SKJ- 4, 12th Meeting of the Standing Committee on Tuna and Billfish, 16- 23 June 1999, Papeete, French Polynesia.

Sibert,J. and Hampton,J. 2003. Mobility of tropical tunas and the implications for fisheries management. Mar.Policy **27**: 87-95.

Sibert,J.R., Hampton,J., Fournier,D.A., and Bills,P.J. 1999. An advection-diffusion-reaction model for the estimation of fish movement parameters from tagging data, with application to skipjack tuna (Katsuwonus pelamis). Can.J.Fish.Aquat.Sci. **56**: 925-938.

Tanabe, T., Kayama, S., and Ogura, M. Precise age determination of young to adult skipjack tuna (*Katsuwonus pelamis*) with validation of otolith daily increment. 16th Meeting of the Standing Committee on Tuna and Billfish, 916 July 2003, Mooloolaba, Australia. Working Paper SKJ8. 2003. 2003.

Wild,A. and Hampton,J. 1994. A review of the biology and fisheries for skipjack tuna, Katsuwonus pelamis, in the Pacific Ocean. FAO Fisheries Technical Paper (FAO).

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.

New fishery definitions				2008 fishery definitions			
Fishery code	Gear	Flag/fleet	Region	Fishery code	Gear	Flag	Region
1. JPOS PL 1	PL	JP/OS	1	JPOS PL 1	PL	JP/OS	1
2. JPDW PL 1	PL	JP/DW	1	JPDW PL 1	PL	JP/DW	1
				JPOS PL 2	PL	JP/OS	2
				JPDW PL 2	PL	JP/DW	2
3. JPOS PS 1	PS	JP/OS	1	JPOS PS 2	PS	JP/OS	2
				JPDW PL 3	PL	JP/DW	3
				JPOS PL 4	PL	JP/OS	4
				JPDW PL 4	PL	JP/DW	4
4. JP LL 1	LL	JP/RES	1	JP LL 4	LL	JP/RES	4
5. JPDW PL 2	PL	JP/DW	2	JPDW PL 5	PL	JP/DW	5
6. PG PL 2	PL	PG	2	PG PL 5	PL	PG	5
7. SB PL 2	PL	SB	2	SB PL 5	PL	SB	5
8. PS LOG/FAD 2	PS/LOG+FAD	ALL	2	PS LOG 5	PS/LOG	ALL	5
			2	PS FAD 5	PS/FAD	ALL	5
9. PS SCH 2	PS/SCH	ALL	2	PS SCH 5	PS/SCH	ALL	5
10. PH DOM 2	DOM	PH	2	PH DOM 5	DOM	PH	5
11. ID DOM 2	DOM	ID	2	ID DOM 5	DOM	ID	5
12. JP LL 2	LL	JP/RES	2	JP LL 5	LL	JP/RES	5
13. JPDW PL 3	PL	JP/DW	3	JPDW PL 6	PL	JP/DW	6
14. FJ PL 3	PL	FJ	3	FJ PL 6	PL	FJ	6
15. PS LOG/FAD 3	PS/LOG+FAD	ALL	3	PS LOG 6	PS/LOG	ALL	6
				PS FAD 6	PS/FAD	ALL	6
16. PS SCH 3	PS/SCH	ALL	3	PS SCH 6	PS/SCH	ALL	6
17. JP LL 3	LL	JP/RES	3	JP LL 6	LL	JP/RES	6

Table 2. Summary of the number of tag releases and recoveries by region. Recovery data are also apportioned to the fishery of recovery.

Region	Releases	Recoveries	
		Fishery	Number
1	38,409	1. JPOS PL 1	1001
		2. JPDW PL 1	115
		3. JPOS PS 1	862
		4. JP LL 1	0
2	264,743	5. JPDW PL 2	747
		6. PG PL 2	872
		7. SB PL 2	1347
		8. FAD/LOG PS 2	5567
		9. SCH PS 2	8194
		10. PH DOM 2	2473
		11. ID DOM 2	2277
		12. JP LL 2	0
3	81,471	13. JPDW PL 3	331
		14. FJ PL 3	2631
		15. FAD/LOG PS 3	159
		16. SCH PS 3	1234
		17. JP LL 3	2
Total	228,087		27,812

Table 3: Reporting rate parameters and priors by fishery and release program

Fishery flag	Release programme	RR Parameter	Prior	SD	Penalty
JP	SSAP	1	0.45	0.71	1
JP	RTTP	1	0.45	0.71	1
JP	PTTP	2	0.55	0.05	200
JP	JP	3	0.55	0.07	100
PS	SSAP	4	0.45	0.11	40
PS	RTTP	5	0.45	0.05	200
PS	PTTP	6	0.40	0.05	200
PS	JP	7	0.45	0.71	1
PG	SSAP	8	0.45	0.71	1
PG	RTTP	9	0.45	0.71	1
PG	PTTP	10	0.45	0.71	1
PG	JP	11	0.45	0.71	1
SB	SSAP	12	0.45	0.71	1
SB	RTTP	13	0.45	0.71	1
SB	PTTP	14	0.45	0.71	1
SB	JP	15	0.45	0.71	1
PH	SSAP	16	0.45	0.71	1
PH	RTTP	17	0.45	0.71	1
PH	PTTP	18	0.45	0.71	1
PH	JP	19	0.45	0.71	1
ID	SSAP	20	0.45	0.71	1
ID	RTTP	21	0.45	0.71	1
ID	PTTP	22	0.45	0.71	1
ID	JP	23	0.45	0.71	1
FJ	SSAP	24	0.45	0.71	1
FJ	RTTP	25	0.45	0.71	1
FJ	PTTP	26	0.45	0.71	1
FJ	JP	27	0.45	0.71	1

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

Fishery flag	Release programme	RR Parameter	Prior	SD	Penalty
JP	SSAP	1	0.45	0.71	1
JP	RTTP	1	0.45	0.71	1
JP	PTTP	2	0.55	0.71	1
JP	JP	3	0.55	0.07	100
PS	SSAP	4	0.45	0.11	40
PS	RTTP	5	0.45	0.05	200
PS	PTTP	6	0.40	0.05	200
PS	JP	7	0.45	0.71	1
PG	SSAP	8	0.45	0.71	1
PG	RTTP	8	0.45	0.71	1
PG	PTTP	8	0.45	0.71	1
PG	JP	9	0.45	0.71	1
SB	SSAP	10	0.45	0.71	1
SB	RTTP	11	0.45	0.71	1
SB	PTTP	12	0.45	0.71	1
SB	JP	13	0.45	0.71	1
PH	SSAP	14	0.45	0.71	1
PH	RTTP	15	0.45	0.71	1
PH	PTTP	16	0.45	0.71	1
PH	JP	17	0.45	0.71	1
ID	SSAP	16	0.45	0.71	1
ID	RTTP	18	0.45	0.71	1
ID	PTTP	19	0.45	0.71	1
ID	JP	20	0.45	0.71	1
FJ	SSAP	21	0.45	0.71	1
FJ	RTTP	21	0.45	0.71	1
FJ	PTTP	21	0.45	0.71	1
FJ	JP	22	0.45	0.71	1

Table 5. Main structural assumptions used in the base-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 is assumed 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 (based on tag seeding), moderately informative priors for equatorial purse seine fisheries for tags released by the SSAP, and relatively uninformative priors for all other fisheries. All reporting rates constant over time. 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 0.75).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. All Japan pole-and-line fisheries share common parameters. Research longline selectivities are non-decreasing with increasing age.
Catchability	Catchability equivalent for the three principal pole-and-line fisheries and estimated independently for all other 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, including base case and sensitivity analyses. Each analysis is offset from the analysis marked ‘Offset from’, with a single change as described.

	Analysis	Offset from	Description	Details
1	**2008 analysis**			
2	**Add CE**	1	Add updated catch, effort and size data for 2010.	
3	**New CPUE**	2	Add 2010 CPUE time series to JP PL fisheries	See Langley et al (2010). Not changed to use estimated variances at this stage.
4	**FAD with LOG**	3	FAD and LOG purse seine fisheries merged.	Reduces number of fisheries from 24 to 22.
5	**Steepness 0.75**	4	Fix steepness at 0.75	Previously estimated, mode 0.9 & SD of 0.1
6	**Change q devs**	5	Catchability and effort deviates set to 0.7 for all but JP PL	Previously set to 0.1 for q deviates and 0.22 for effort deviates.
7	**Nth 0 CPUE Q1**	6	Add zero CPUE value to quarter 1 in fishery 1	
8	**Add PTTP**	7	Include new PTTP tagging data	Each fishery has same reporting rate for all releases (old approach)
9	**Downwt PH LF**	8	Reduce effective sample size of Philippines size data	ESS from N/20 to N/500, due to temporal inconsistencies in size (selectivity changes)
10	**Higher JP RR**	9	Assume higher reporting rate for Japanese fisheries	Increase assumed RR from 0.45 to 0.55.
11	**New regions**	10	Change to 3 region structure	Change regional structure, fisheries (from 22 to 17), CPUE series (Kiyofuji 2010).
12	**Add JP tags**	11	Add new JP tag releases (2006-2008) and revise old releases.	
13	**PTTP RR**	12	Change the effective PTTP reporting rate to the estimated level	This was done by reducing the number of releases in proportion to the RR change
14	**CPUE variance**	13	Include variance estimates in JP PL CPUE series	New MFCL functionality (see Hoyle *et al.* 2009).
			Using Run 15 as a base	
15	**Only one tag program**	14	Four runs, each with only one tagging program (SSAP, RTTP, PTTP, or JP)	Remove all but one tagging program to check contribution of each
16	**All tag programs but 1**	14	Five runs, removing SSAP, RTTP, PTTP, JP, or the JP equatorial tags	Remove one tagging program at a time to check contribution of each
17	**Free PL q**	14	Allow catchability trends to be estimated	Reduce the effect of the estimated CPUE series in order to check their influence.
18	**Fix M 2008**	14	Fix M at levels estimated in 2008	Check whether differences observed for small fish are important
19	**Fix Mage 2008**	14	Fix M at age with pattern estimated in 2008, but estimate average M.	As above

	Analysis	Offset from	Description	Details
20	**Downwt LF**	14	Downweight size data for fisheries with large apparent size changes to 1/5th	Fisheries with long LF time series in which significant size instability was observed. Such variation likely due to changes in sampling.
21	**Ungroup PL N selectivity**	14	Estimate JP PL 1 selectivity independently of other JP PL	Allow for the different sizes observed in the northern fisheries
22	**Last 4 CPUE**	14	Remove last 4 CPUE estimates from each JP PL series	Very low CPUE estimates that appear unrealistic
23	**Spill sampling**	14	Spill sampling PS catches instead of S_BEST	Check the effect of using spill sampling catch estimates rather than S_BEST
24	**Half spill**	14	Split the difference between spill sampling PS catches and S_BEST	To moderate the effects of spill sampling estimates
25	**No regional weighting**	14	JP PL catchability estimated independently among regions	Remove effect of effort weighting and allow model to estimate relative biomass
26	**RR by tagging program**	14	New approach using RR by tagging program.	Priors same as the old approach, but independent parameters.
27	**New priors**	14	RR by tagging program with new priors	Alternative prior distributions
28	**Combined run**	14	Run combining selected changes from the analyses above	No regional weighting, Downwt LF, Ungroup PL N sel, Last 4 CPUE, Estimate q, RR by tagging program with new priors
29	**Combined run lower LF SS**	28	Reduce maximum effective sample size to 25	Strong effect of size changes on abundance trends, but sampling consistency is uncertain.
			Tag changes	
30	**Mixing period**	29	Increase mixing period to 2	Check effect of longer mixing period and resulting lower influence of tag likelihood.
31	**RR bound**	29	Change RR bound to 0.99	For a few small fishery/tag grp combinations, tag returns are very high because releases were close.
32	**alt RR pars**	29	Change to RR parameters used in base case run	Merge RR where parameters were not estimable
33	**JP PTTP no penalty**	29	Remove penalty on Japanese fisheries for PTTP RR	Japanese PL fisheries had very low return rate for SPC tag releases, contrary to beliefs about the JP PS fleet in regions 2 and 3.
34	**Remove a tag program**	29	Five runs, removing either SSAP, RTTP, PTTP, JP, or the JP equatorial tags	Check effects of tagging programs in context of new RR parameterization
35	**Remove release group**	29	Remove release group near ID with very low RR	Largest of all release groups, near Indonesia, had remarkably low return rate. Examine sensitivity.
36	**RR not penalised**	29	All RR free to vary except RTTP	Identify RR information coming from tagging data
37	**Mixed model tag likelihood**	29	Zero inflated model for tag recoveries	Increase ability to model variable tag recoveries
38	**PTTP RR low**	29	Constrain PTTP PS RR to be low, with high penalty.	Try to assign a low value to PTTP RR

	Analysis	Offset from	Description	Details
39	**Combined tag options**	29		RR boundary to 0.99, alt RR pars, Remove release group, JP PTTP no penalty, mixed model tag likelihood
40	**Remove PTTP**	39	Remove all tags released by the PTTP	Given incompatible data sources
			Base case and sensitivity analyses	
41	**Base case**	40	Include spill sampling	Include spill sampling as recommended for the base case at the PAW
42	**Steepness 0.65**	40	Sensitivity analysis across range of steepness values	
43	**Steepness 0.65**	40	Sensitivity analysis across range of steepness values	
44	**Steepness 0.65**	40	Sensitivity analysis across range of steepness values	
45	**Fixed M**	40	Sensitivity analysis with natural mortality fixed at 2008 levels	
46	**CPUE binomial**	40	Sensitivity analysis using CPUE trends based on transformed binomial model	
47	**CPUE lognormal offset**	40	Sensitivity analysis using CPUE trends based on lognormal offset model	
48	**S_BEST**	40	Sensitivity analysis using S_BEST equatorial purse seine catches	

Table 7. Details of objective function components for the base-case analysis and sensitivity analyses.

Objective function component	Base-case	S_BEST	Fixed M	Binomial CPUE	Lognormal offset CPUE
Total catch log-likelihood	71.56	73.51	77.45	72.66	72.20
Length frequency log-likelihood	-108685.12	-108802.32	-108892.06	-108786.77	-108794.64
Tag log-likelihood	10734.59	11002.54	11516.91	11000.19	11006.96
Penalties	617.21	628.32	1464.11	571.13	893.23
Total function value	-97241.98	-97078.14	-95812.82	-97125.34	-96802.74

Table 8. Description of symbols used in the yield analysis.

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2005–2008
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 (2005–2008) total biomass
$SB_{current}$	Average current (2005–2008) adult biomass
$B_{current,F=0}$	Average current (2005–2008) total biomass in the absence of fishing.

Table 9. Estimates of management quantities for the base-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 8**.

Management quantity	Units	Base-case	Grid median	Grid 5%	Grid 95%
$\widetilde{Y}_{F_{current}}$	t per annum	1 096 000	1 147 400	1 054 400	1 231 200
$\widetilde{Y}_{F_{MSY}}$ (or MSY)	t per annum	1 375 600	1 451 200	1 200 800	1 767 600
$\widetilde{B}_0$	t	4 776 000	5 049 500	4 637 000	5 751 000
$\widetilde{B}_{F_{current}}$	t	2 661 000	2 788 000	2 541 000	3 337 750
$\widetilde{B}_{MSY}$	t	1 475 000	1 540 500	1 262 000	1 949 750
$\widetilde{SB}_0$	t	4 433 000	4 730 500	4 273 000	5249 500
$\widetilde{SB}_{F_{current}}$	t	2 343 000	2 477 000	2 235 000	2 770 250
$\widetilde{SB}_{MSY}$	t	1 197 000	1 247 500	937 800	1 633 000
$B_{current}$	t	3 567 169	3 688 971	3 351 288	4 262 752
$SB_{current}$	t	3 195 259	3 281 113	2 979 901	3 642 088
$B_{current,F=0}$	t	5 661 928	5 858 050	5 365 661	6 603 650
$B_{current} / \widetilde{B}_0$		0.75	0.71	0.67	0.77
$B_{current} / \widetilde{B}_{MSY}$		2.42	2.37	2.01	2.80
$B_{current} / B_{current,F=0}$		0.63	0.63	0.57	0.65
$SB_{current} / \widetilde{SB}_0$		0.72	0.69	0.65	0.75
$SB_{current} / \widetilde{SB}_{MSY}$		2.67	2.66	2.16	3.37
$SB_{latest} / \widetilde{SB}_{MSY}$		2.27	2.07	1.58	3.04
$\widetilde{B}_{F_{current}} / \widetilde{B}_0$		0.56	0.55	0.48	0.61
$\widetilde{SB}_{F_{current}} / \widetilde{SB}_0$		0.53	0.52	0.46	0.58
$\widetilde{B}_{MSY} / \widetilde{B}_0$		0.31	0.31	0.26	0.34
$\widetilde{SB}_{MSY} / \widetilde{SB}_0$		0.27	0.27	0.22	0.31
$F_{current} / \widetilde{F}_{MSY}$		0.34	0.36	0.11	0.61
$Fmult$		2.94	2.77	1.65	8.97
$\widetilde{B}_{F_{current}} / \widetilde{B}_{MSY}$		1.80	1.82	1.48	2.19
$\widetilde{SB}_{F_{current}} / \widetilde{SB}_{MSY}$		1.96	1.99	1.52	2.61
$\widetilde{Y}_{F_{current}} / MSY$		0.80	0.80	0.65	0.91

Table 10. Estimates of management quantities for the base-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 8**.

Management quantity	Units	Steepness 0.65	Steepness 0.75 (Base case)	Steepness 0.85	Steepness 0.95
$\tilde{Y}_{F_{current}}$	t per annum	1 055 200	1 096 000	1 120 800	1 150 400
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per annum	1 200 800	1 375 600	1 549 200	1 767 200
$\tilde{B}_0$	t	4 876 000	4 776 000	4 626 000	4 636 000
$\tilde{B}_{F_{current}}$	t	2542 000	2 661 000	2 697 000	2 806 000
$\tilde{B}_{MSY}$	t	1 645 000	1 475 000	1 314 000	1 281 000
$S\tilde{B}_0$	t	4 528 000	4 433 000	4 264 000	4 272 000
$S\tilde{B}_{F_{current}}$	t	2237 000	2 343 000	2 348 000	2 446 000
$S\tilde{B}_{MSY}$	t	1 379 000	1 197 000	999 800	937 800
$B_{current}$	t	3 547 439	3 567 169	3 513 547	3 587 575
$SB_{current}$	t	3 176 062	3 195 259	3 113 067	3 184 308
$B_{current,F=0}$	t	5 672 124	5 661 928	5 549 360	5 588 823
$B_{current}/\tilde{B}_0$		0.73	0.75	0.76	0.77
$B_{current}/\tilde{B}_{MSY}$		2.16	2.42	2.67	2.80
$B_{current}/B_{current,F=0}$		0.63	0.63	0.63	0.64
$SB_{current}/S\tilde{B}_0$		0.70	0.72	0.73	0.75
$SB_{current}/S\tilde{B}_{MSY}$		2.30	2.67	3.11	3.40
$SB_{latest}/S\tilde{B}_{MSY}$		1.92	2.27	2.27	3.05
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.52	0.56	0.58	0.61
$S\tilde{B}_{F_{current}}/S\tilde{B}_0$		0.49	0.53	0.55	0.57
$\tilde{B}_{MSY}/\tilde{B}_0$		0.34	0.31	0.28	0.28
$S\tilde{B}_{MSY}/S\tilde{B}_0$		0.30	0.27	0.23	0.22
$F_{current}/\tilde{F}_{MSY}$		0.51	0.34	0.19	0.11
$Fmult$		1.96	2.91	5.29	9.18
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.55	1.80	2.05	2.19
$S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$		1.62	1.96	2.35	2.61
$\tilde{Y}_{F_{current}}/MSY$		0.88	0.80	0.72	0.65

10 Figures

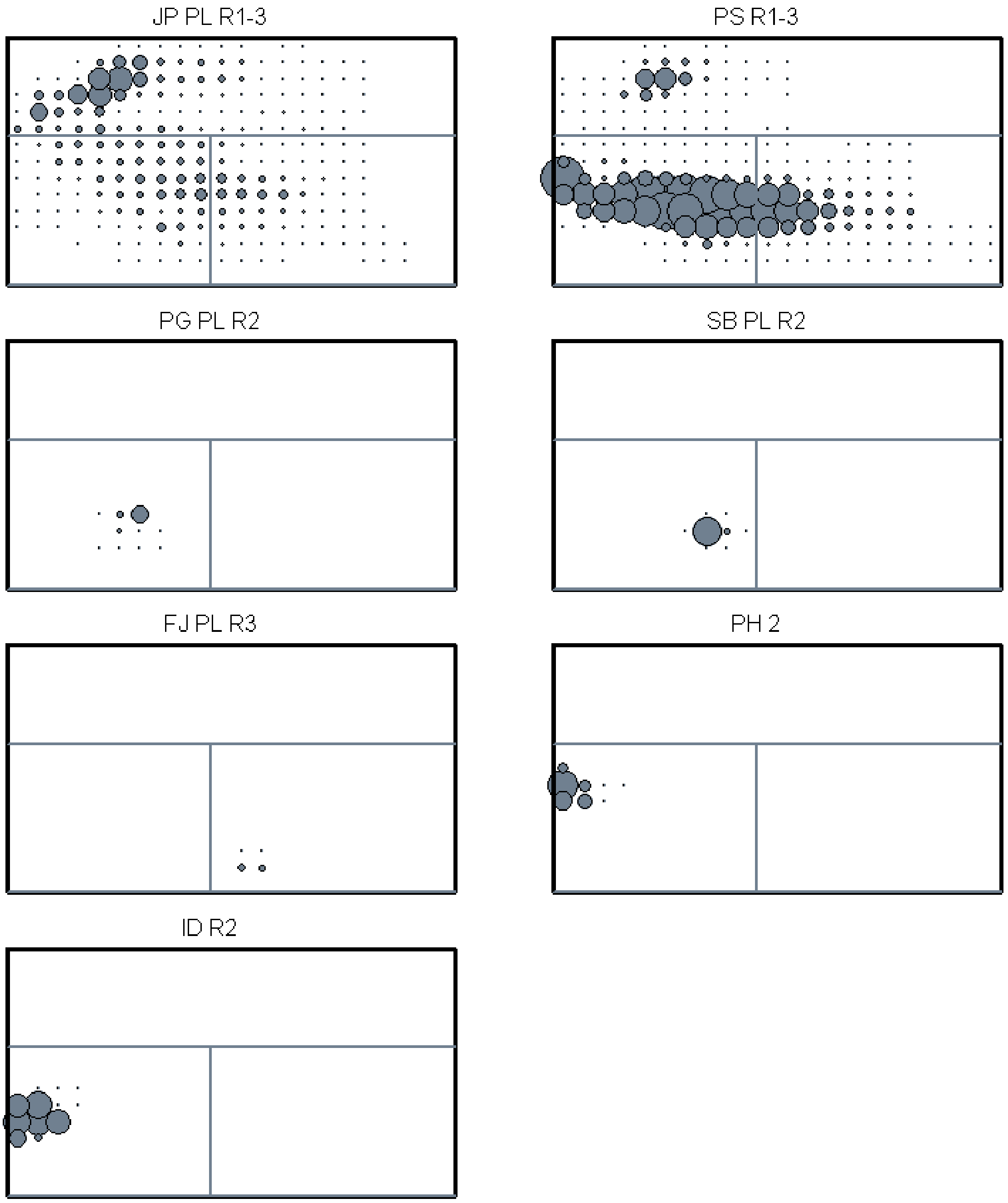

Figure 1: Location of catch by fishery and 5 degree square. Circle size is proportional to total catch 1972-2009.

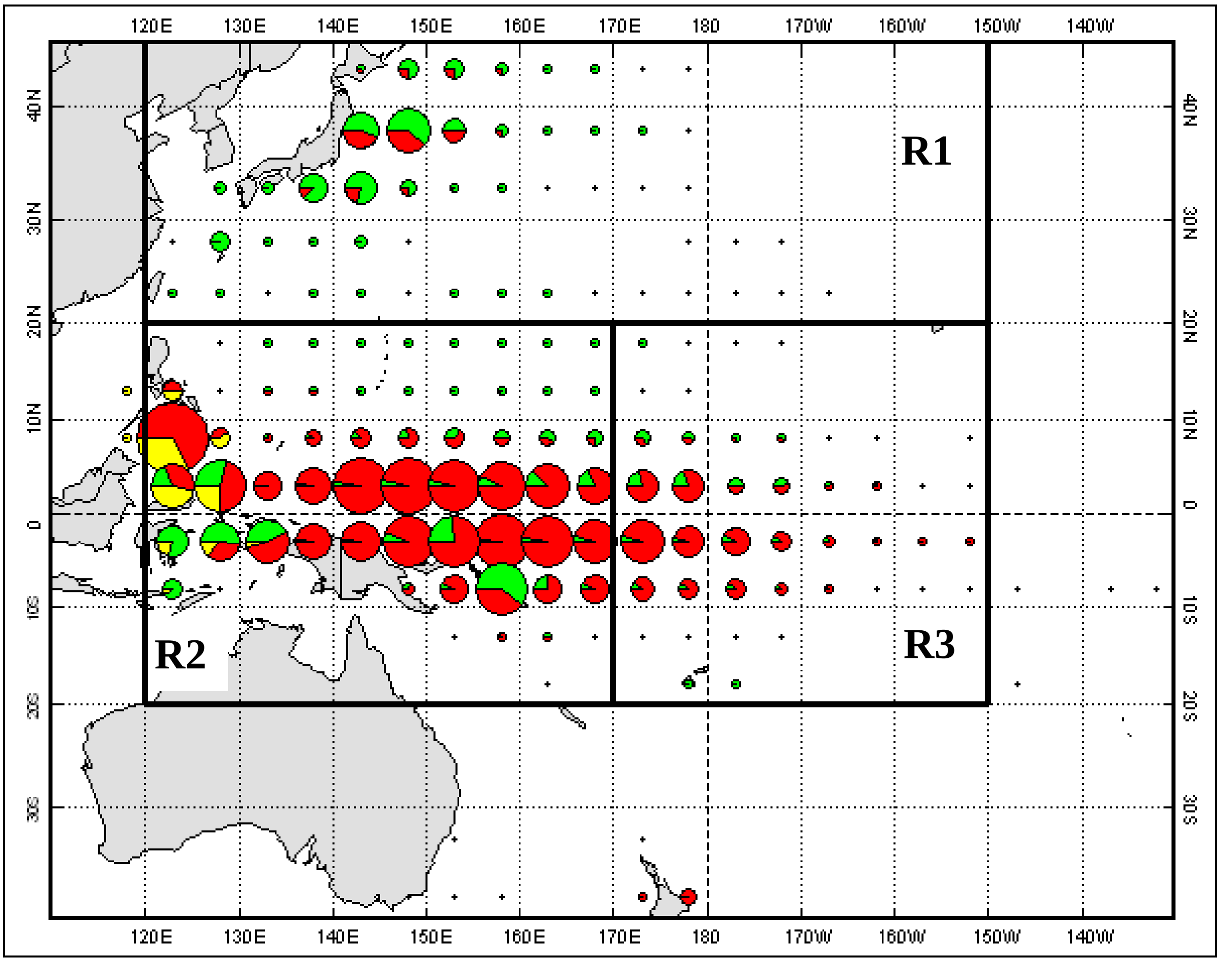

Figure 2: Distribution of total skipjack catches by method during 1972–2008 in relation to the new 3-region spatial stratification used in the MULTIFAN-CL analysis. Method colors: Green, pole-and-line; Red, purse-seine; Yellow, other.

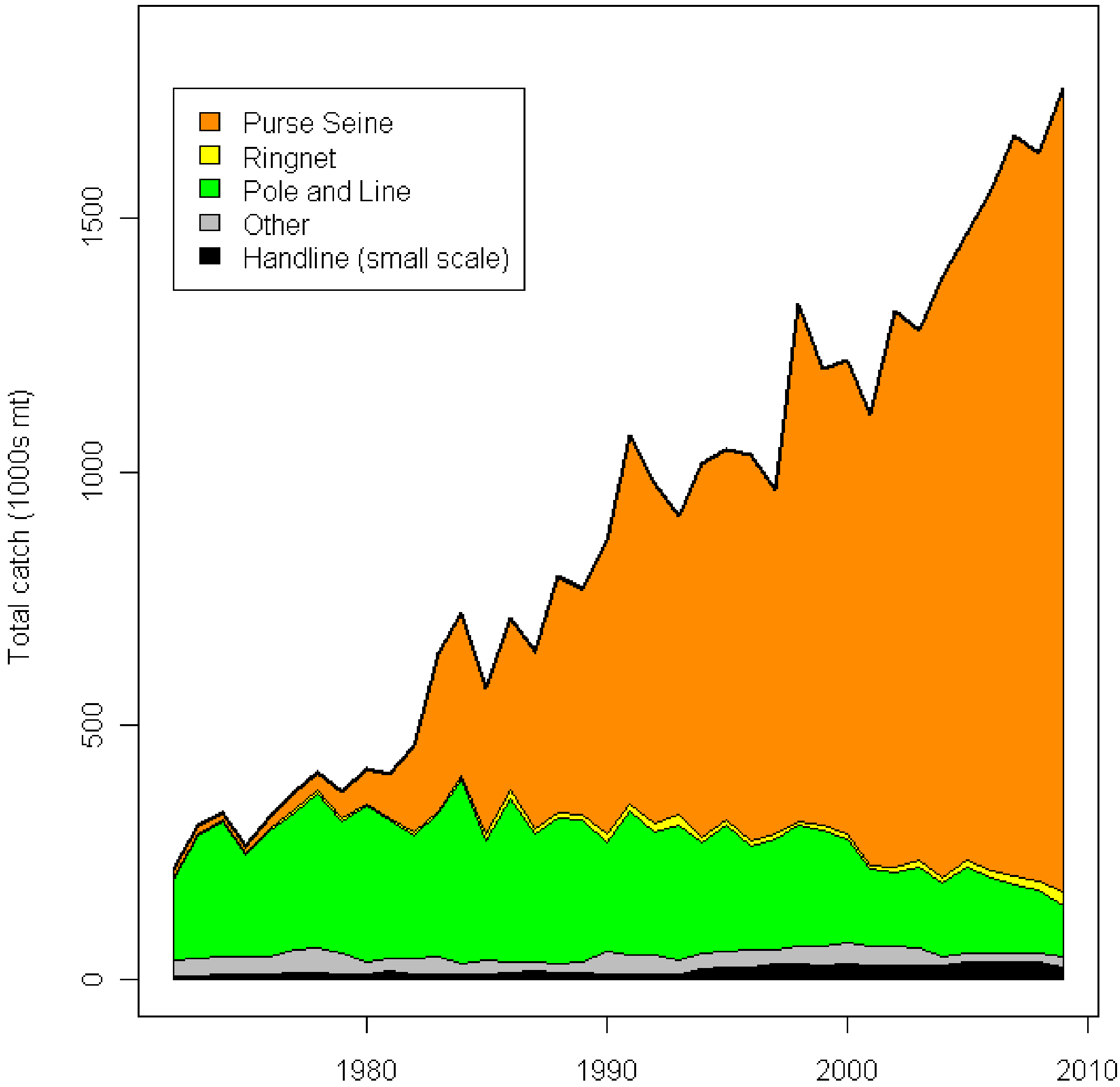

Figure 3. Annual skipjack tuna catch in the WCPO by method, 1972–2009.

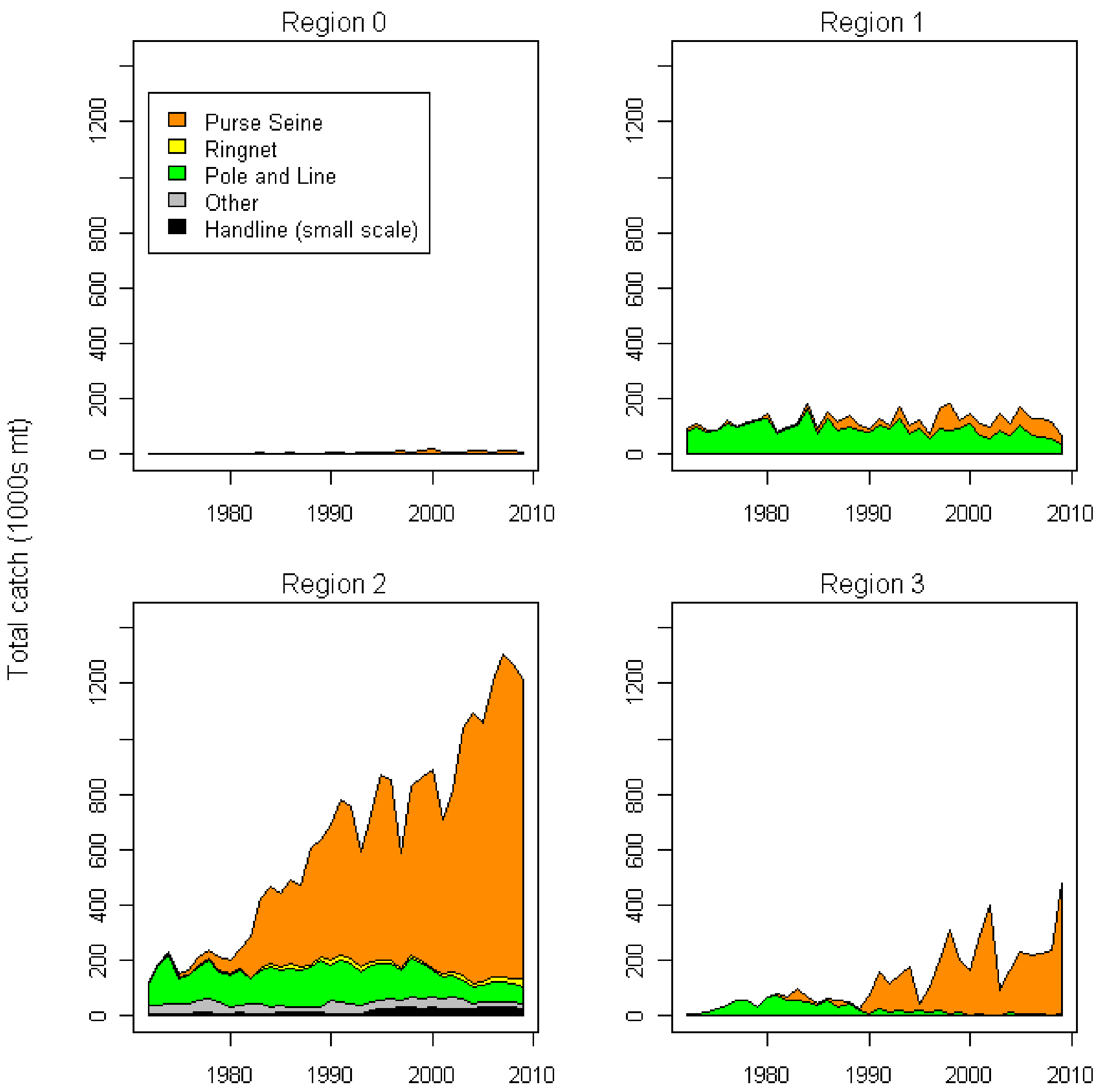

Figure 4. Annual skipjack tuna catch by region and method, 1972–2006. Region 0 represents WCPO catches outside the area included in the model.

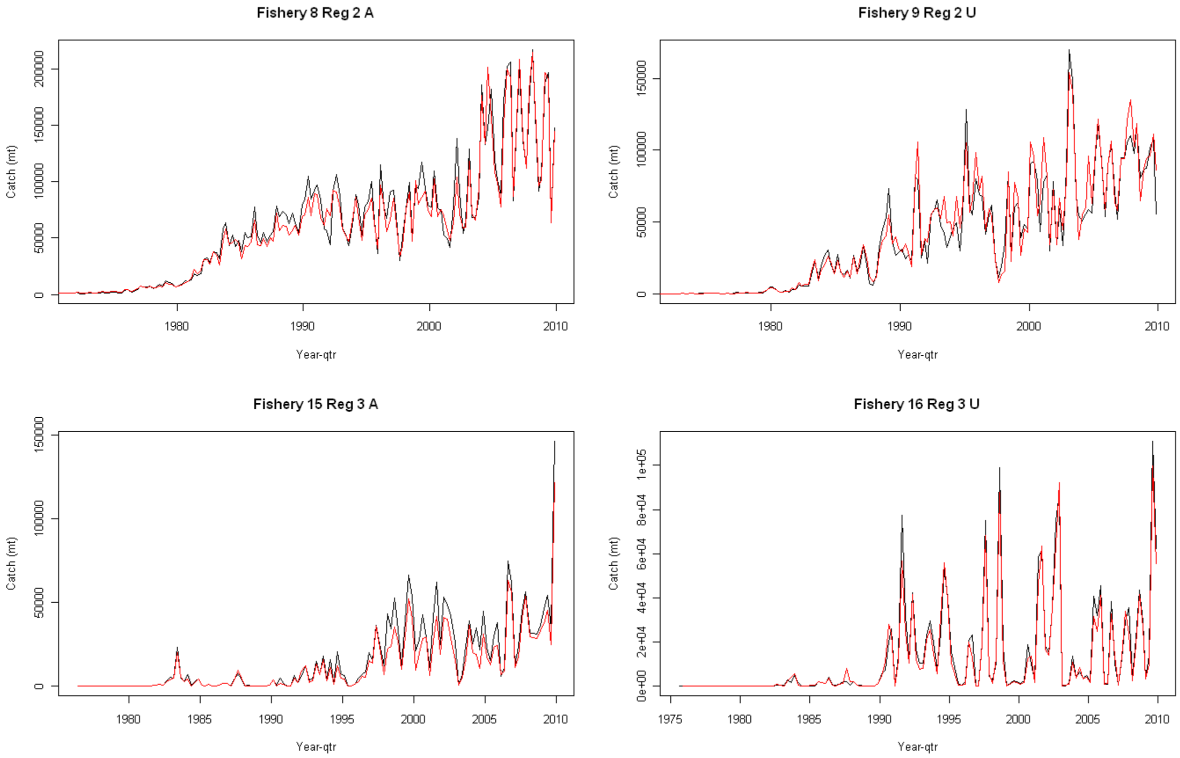

Figure 5: Comparison of S_BEST equatorial purse seine catches (black) with catches adjusted for spill sampling (red), for associated LOG/FAD (left) and unassociated (right) fisheries in regions 2 (above) and 3 (below).

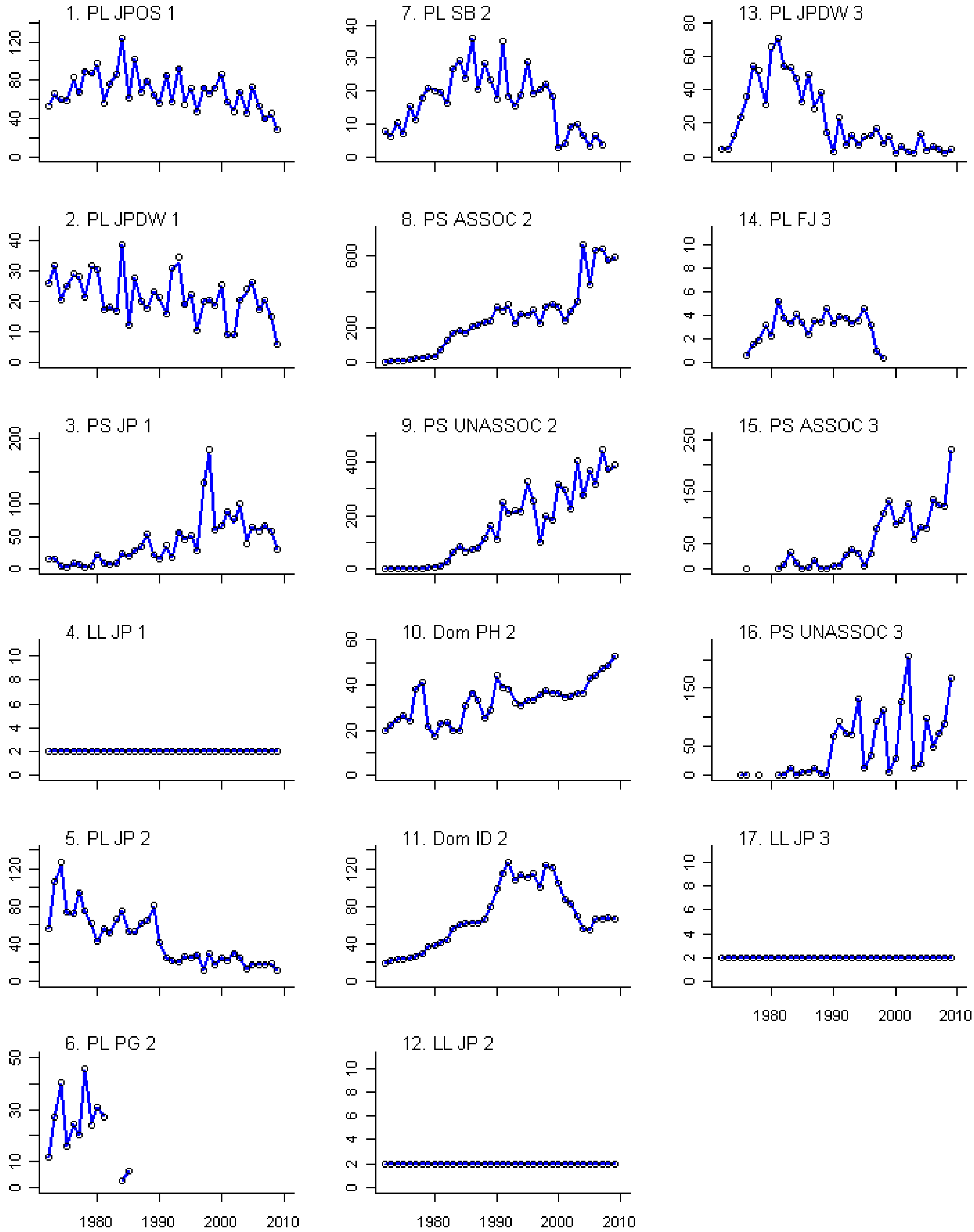

Figure 6. Annual catch by fishery and year. Catches are in thousands of tonnes for all fisheries except the longline (LL) fisheries, where the catches are in thousands of fish.

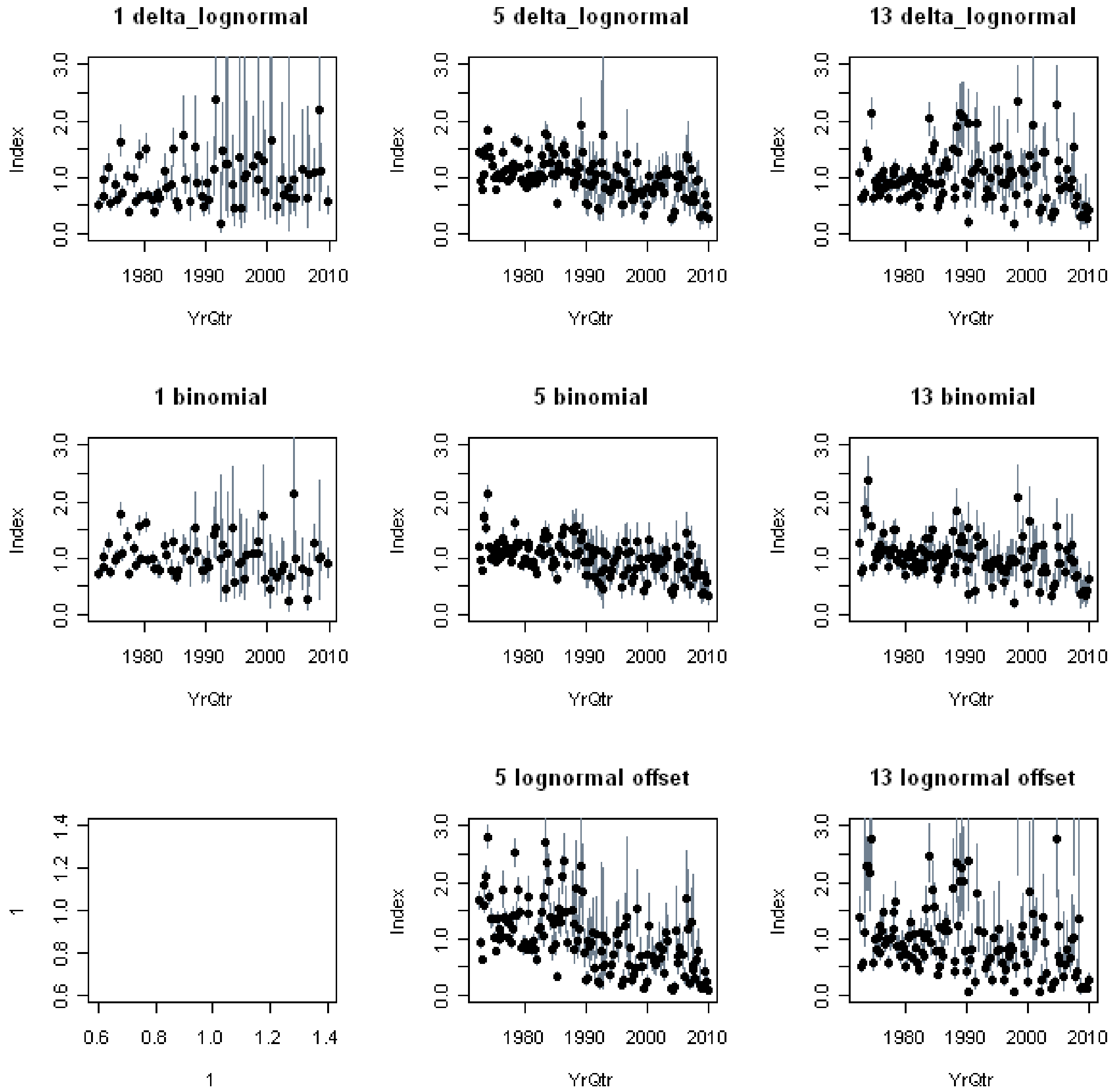

Figure 7: Catch rate time series by the three different methods (delta lognormal, transformed binomial, and lognormal offset) for the three Japanese pole and line fisheries.

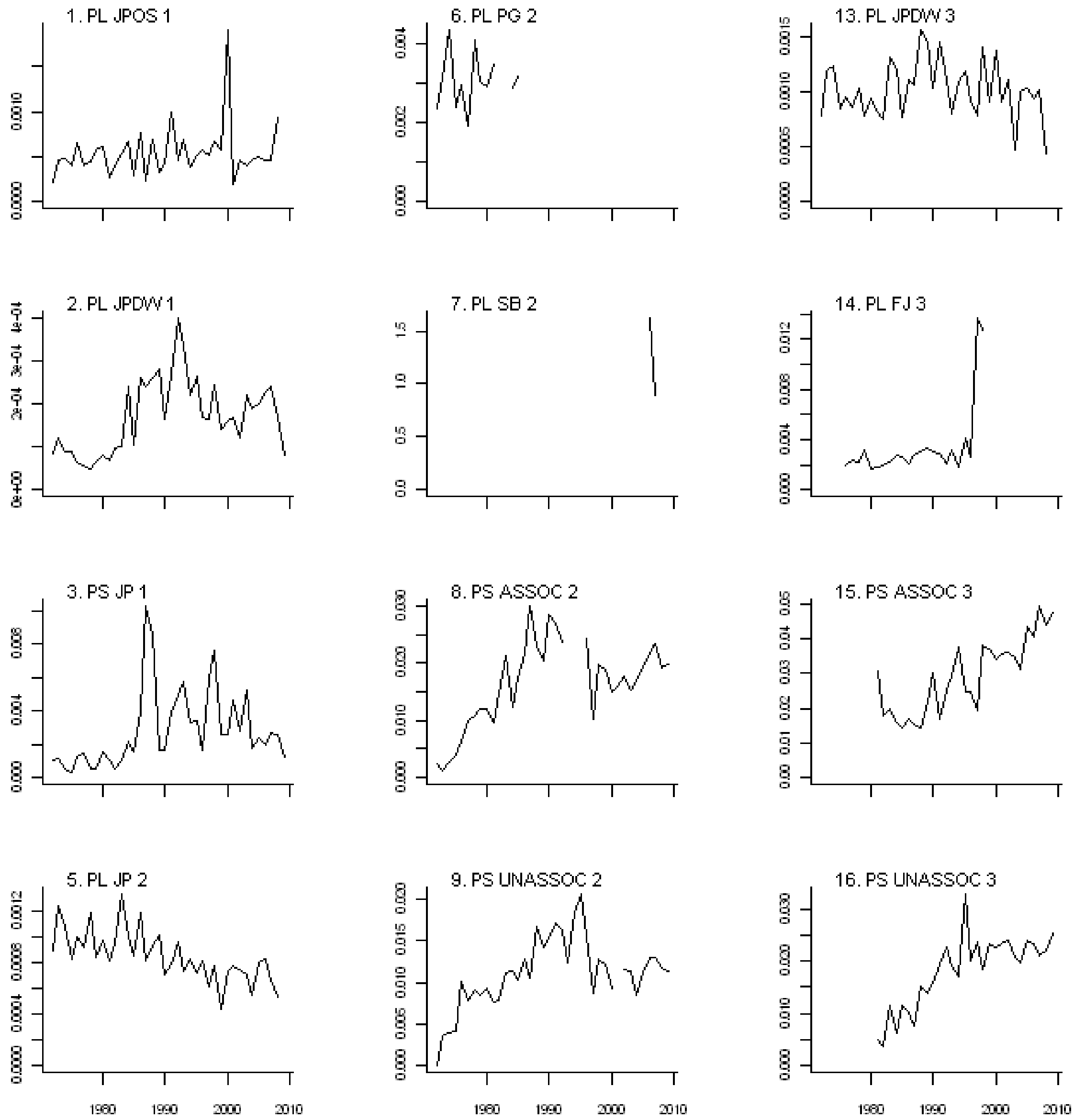

Figure 8. Annual catch per unit effort by fishery.

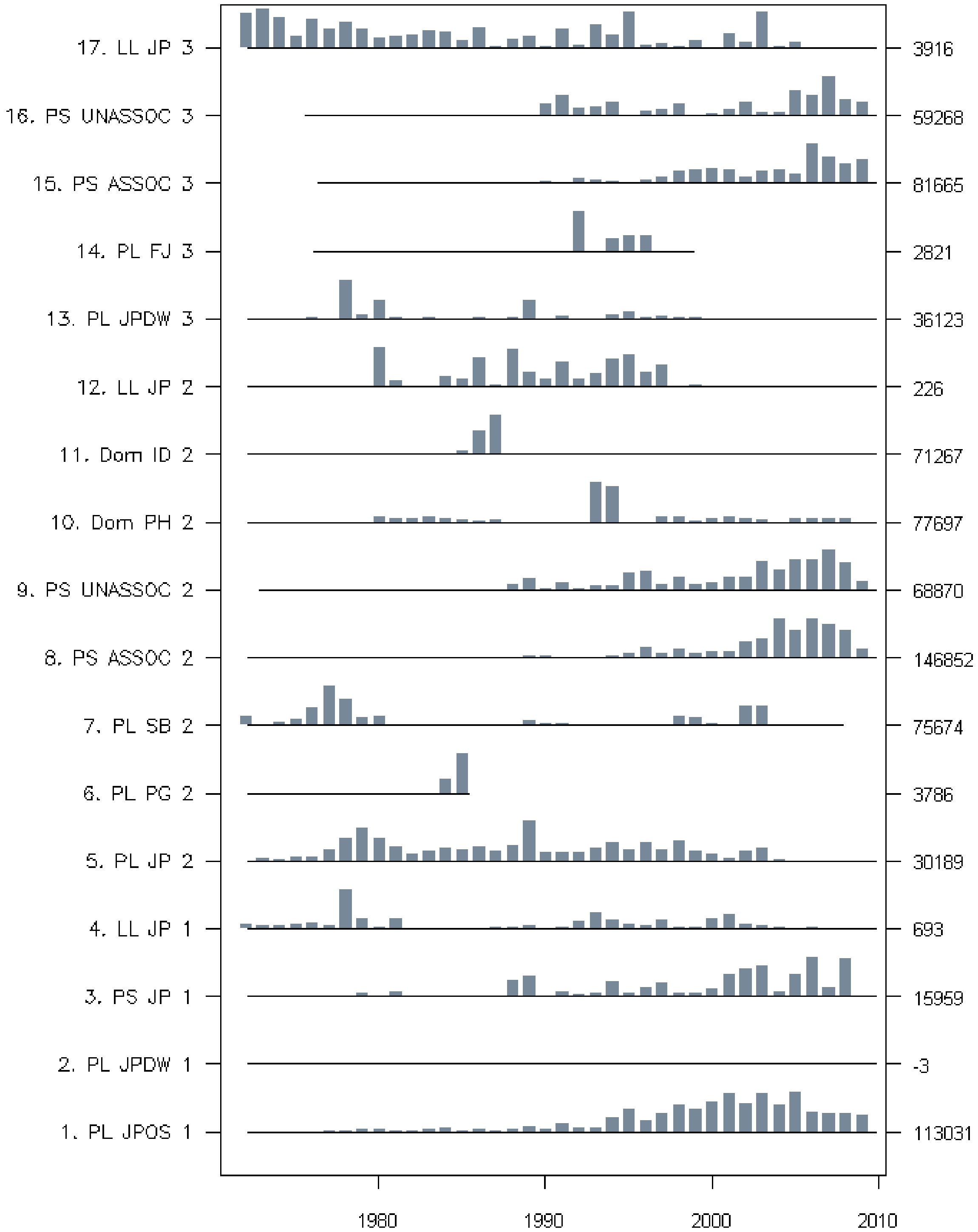

Figure 9. Number of length measurements by fishery and year. The heavy black line represents the period of operation of the fishery. The histogram bars are proportional to the maximum number of fish measured in a fishery/year (the value presented in the right hand axis).

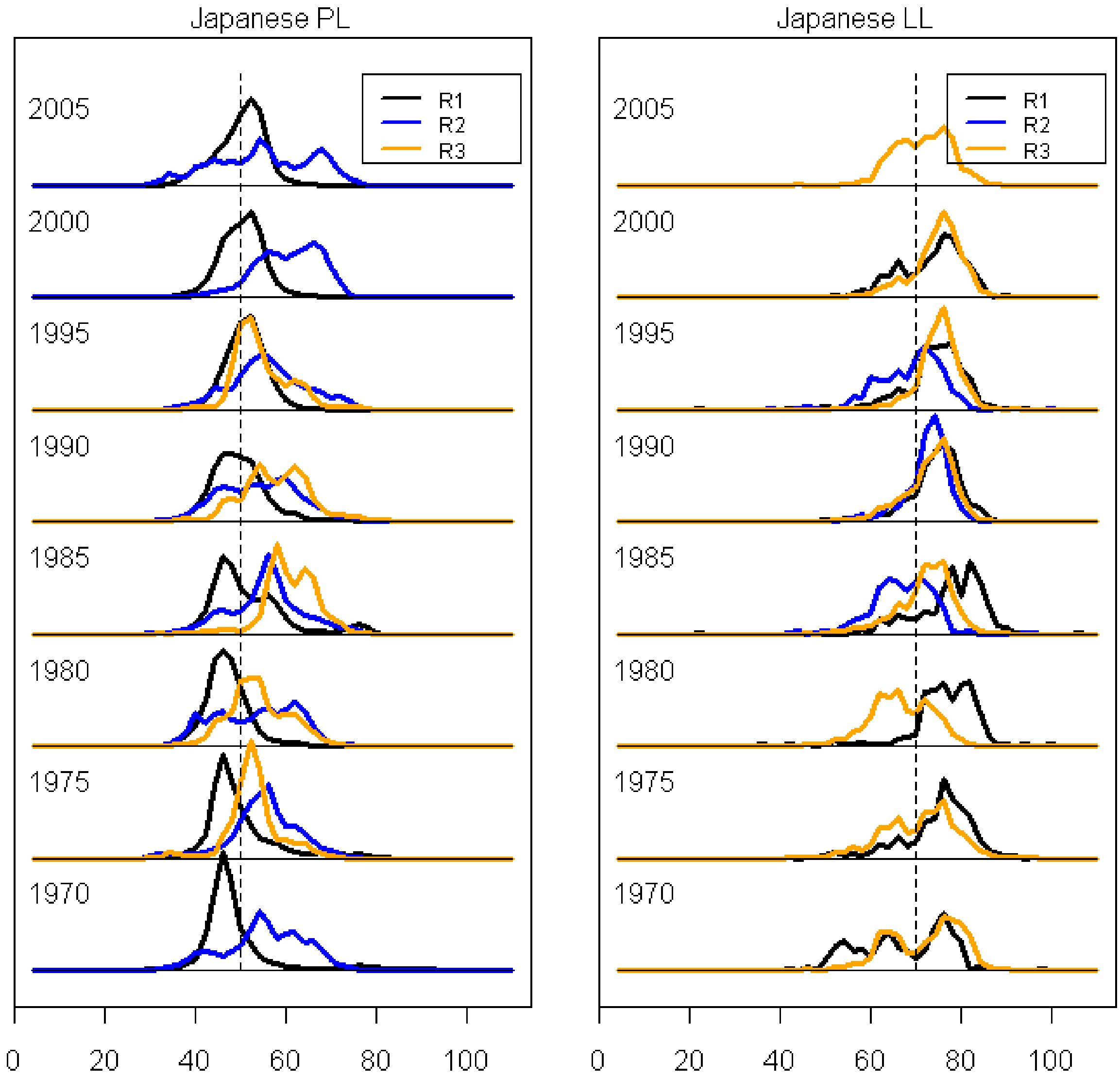

Figure 10. Proportional length compositions of skipjack from the Japanese pole-and-line and longline fisheries operating in the three MFCL regions (R 1–3). Samples are aggregated by 5-year interval. Only region/time length compositions comprised of at least 1,000 fish (PL) or 100 fish (LL) are presented.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

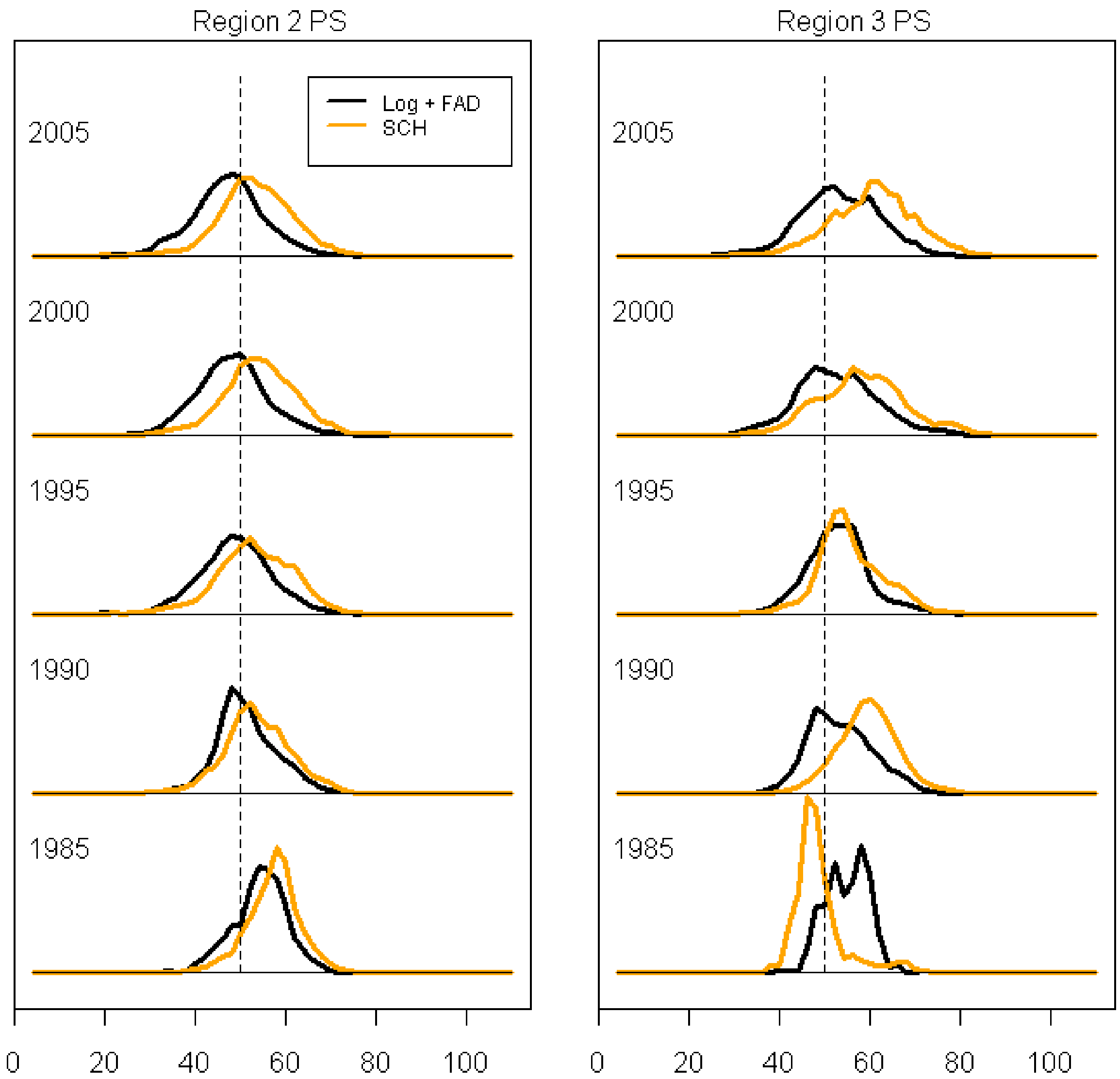

Figure 11. Proportional length compositions of skipjack from the equatorial purse-seine fisheries in the MFCL regions 5 (left panel) and 6 (right panel). Samples are aggregated by set type (log/FAD and school) and 5-year interval. Vertical dashed lines are provided to aid comparisons.

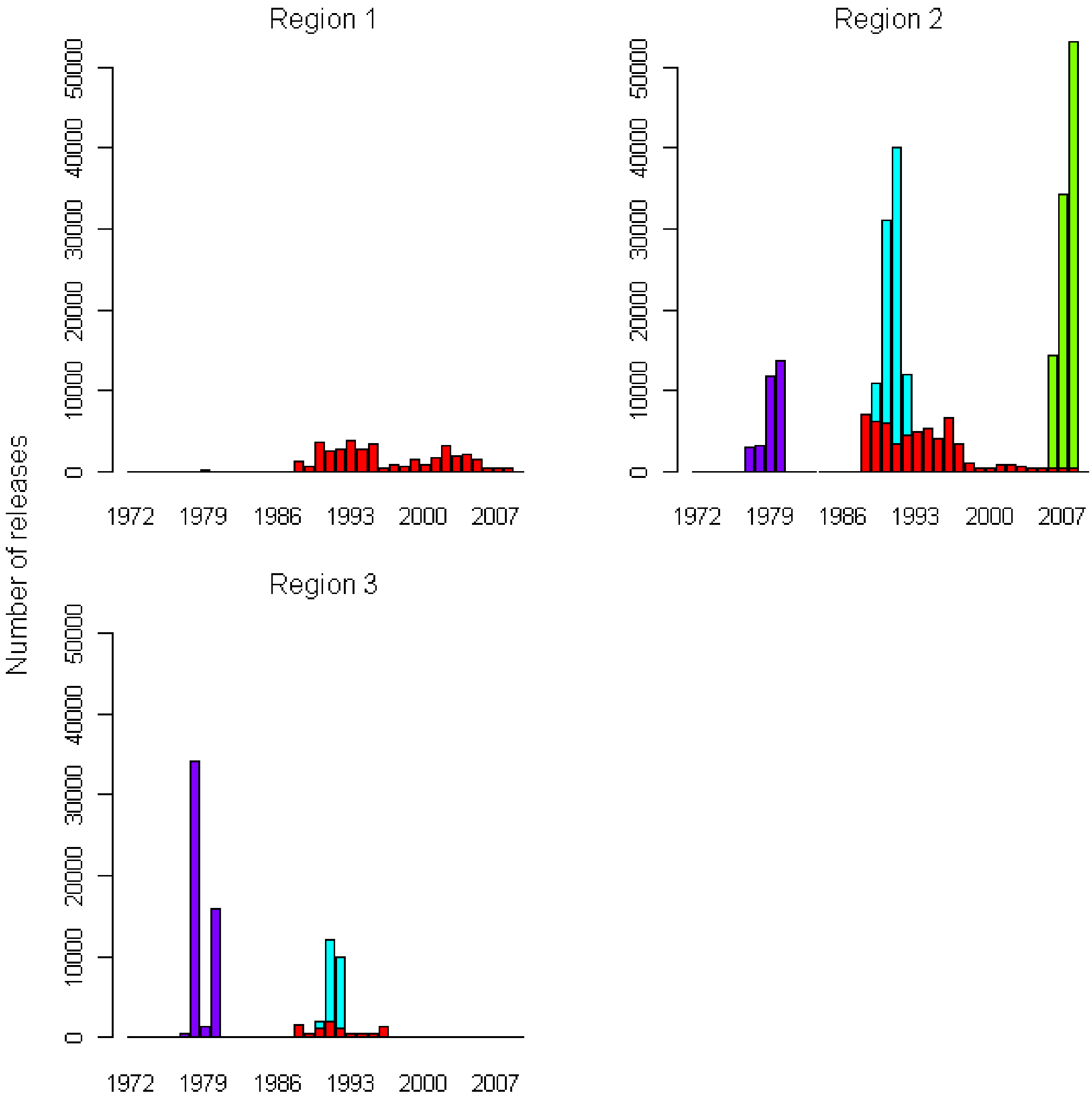

Figure 12. Number of tag releases by region, year and source of release included within the assessment model. The red represents releases by Japanese research programmes; for releases administered by SPC, the purple represents the SSAP, light blue represents the RTTP, and green represents the PTTP.

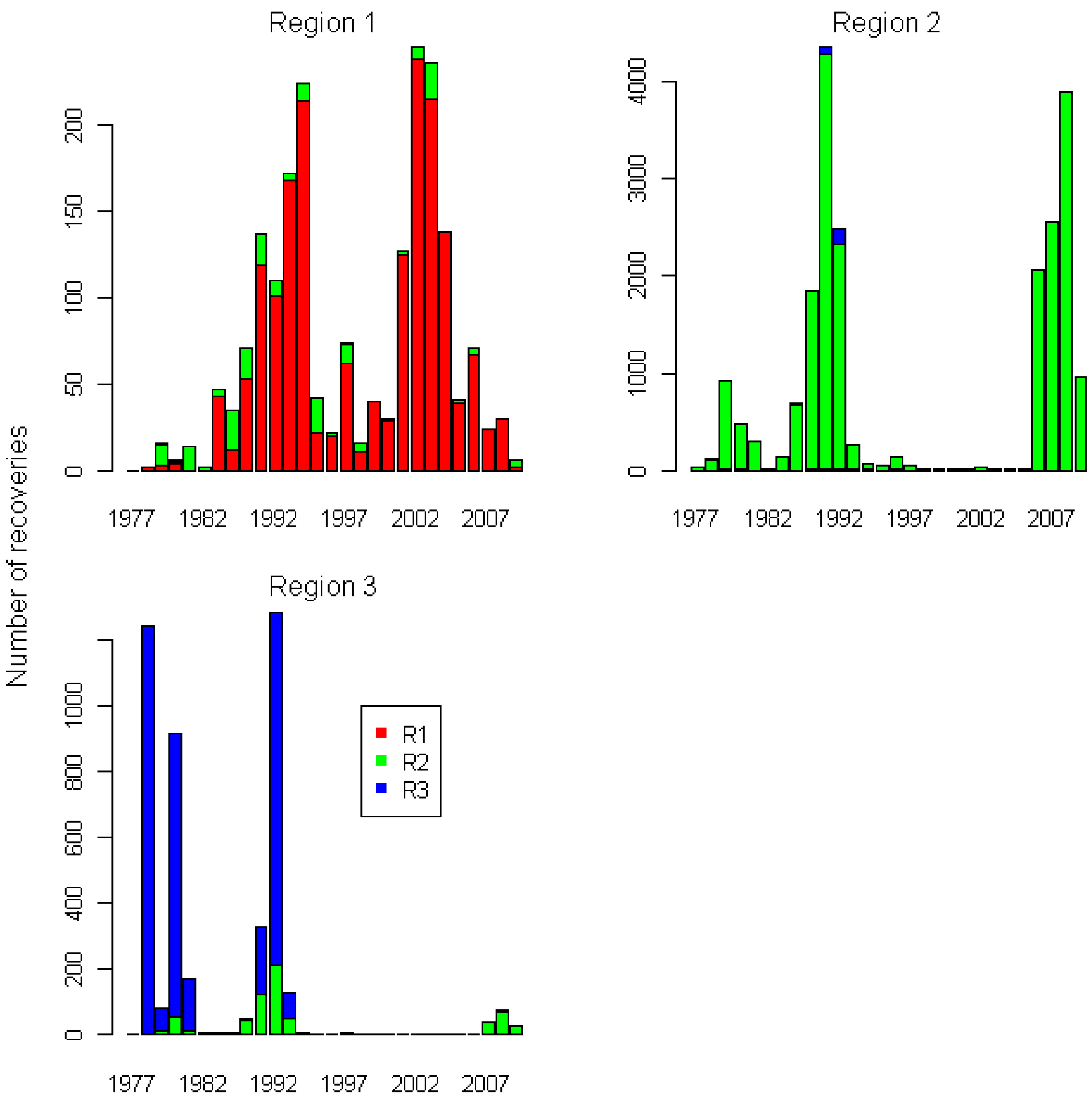

Figure 13. Annual number of tag recoveries in each region by region of release.

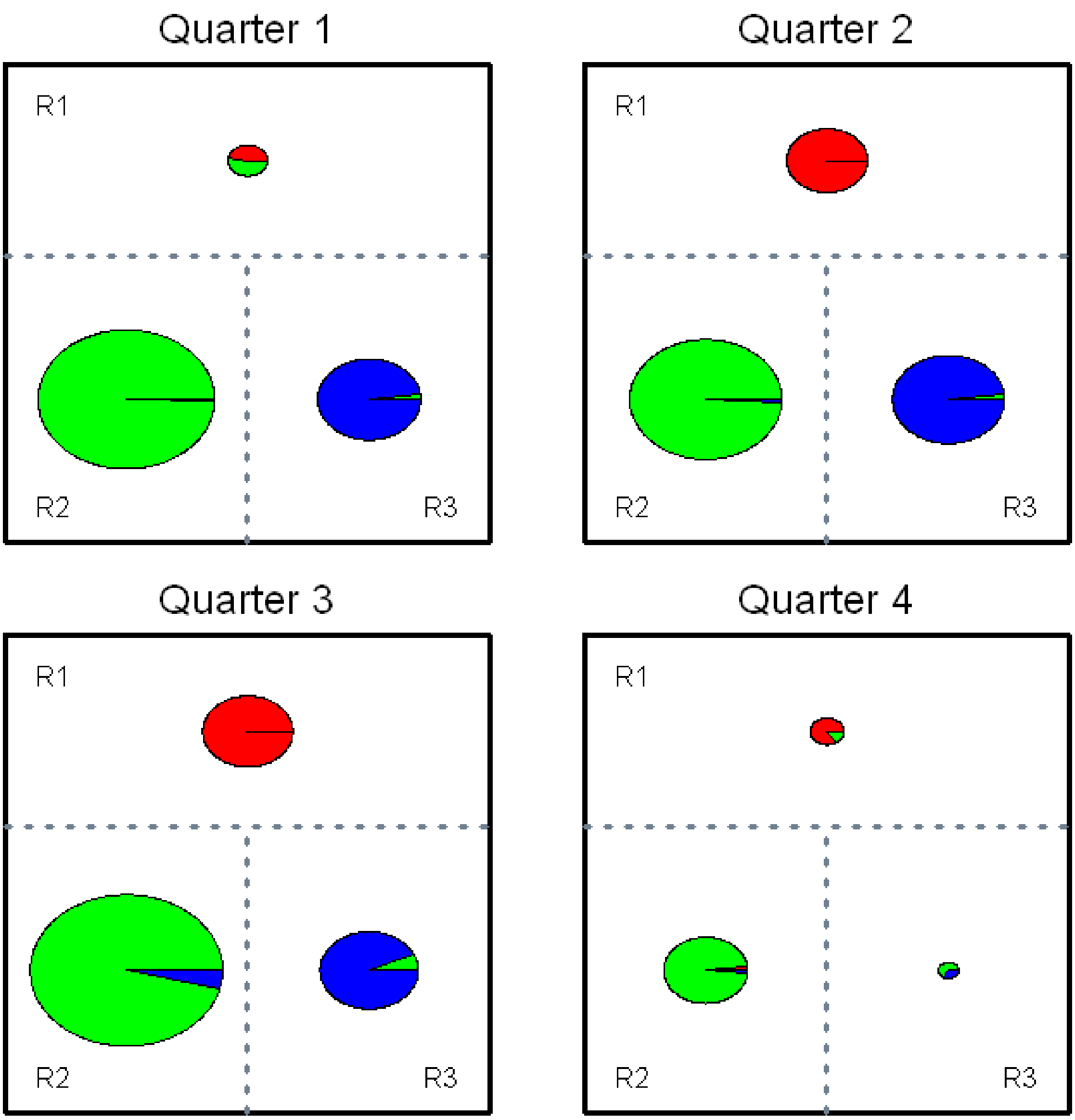

Figure 14: Number of tags recovered in each region, by quarter of recovery. The size of the pie represents the number of tags recovered, with the colour of the pie slice indicating the source region.

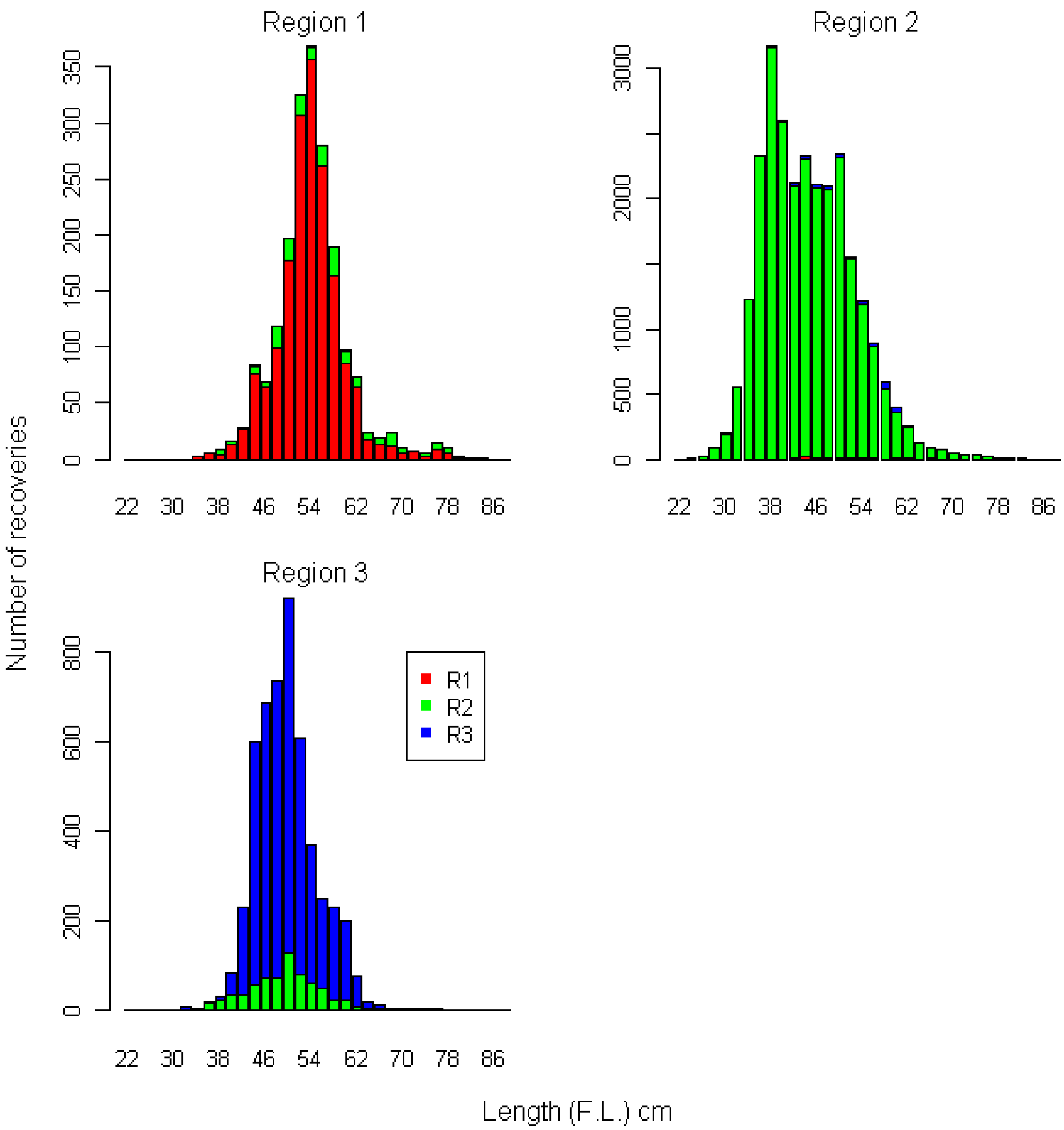

Figure 15. Number of recoveries at length for each region by region of release.

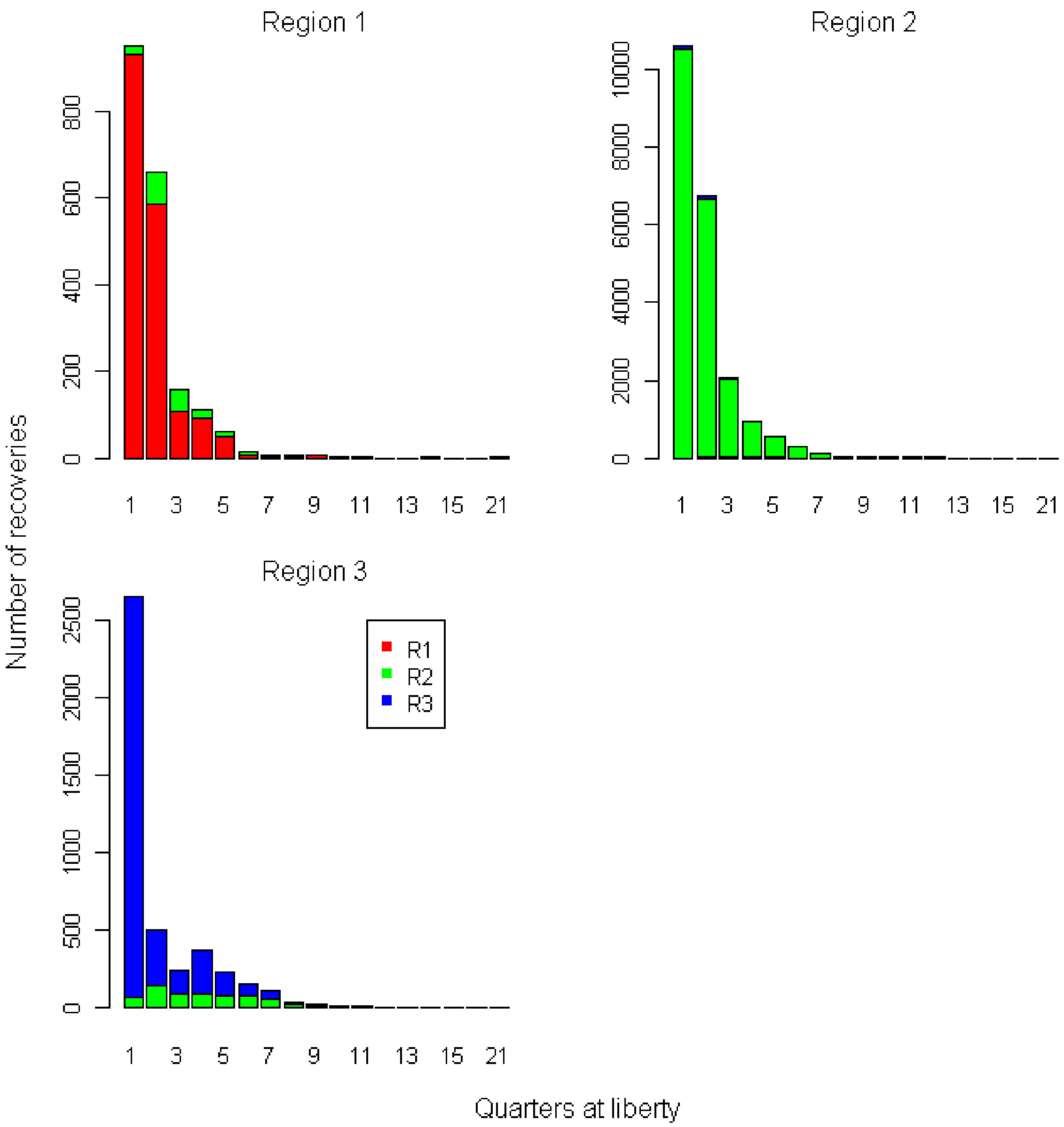

Figure 16. Number of tag recoveries by period at liberty (quarters) for each region by region of release. The first quarter represents the quarter in which the tags were released.

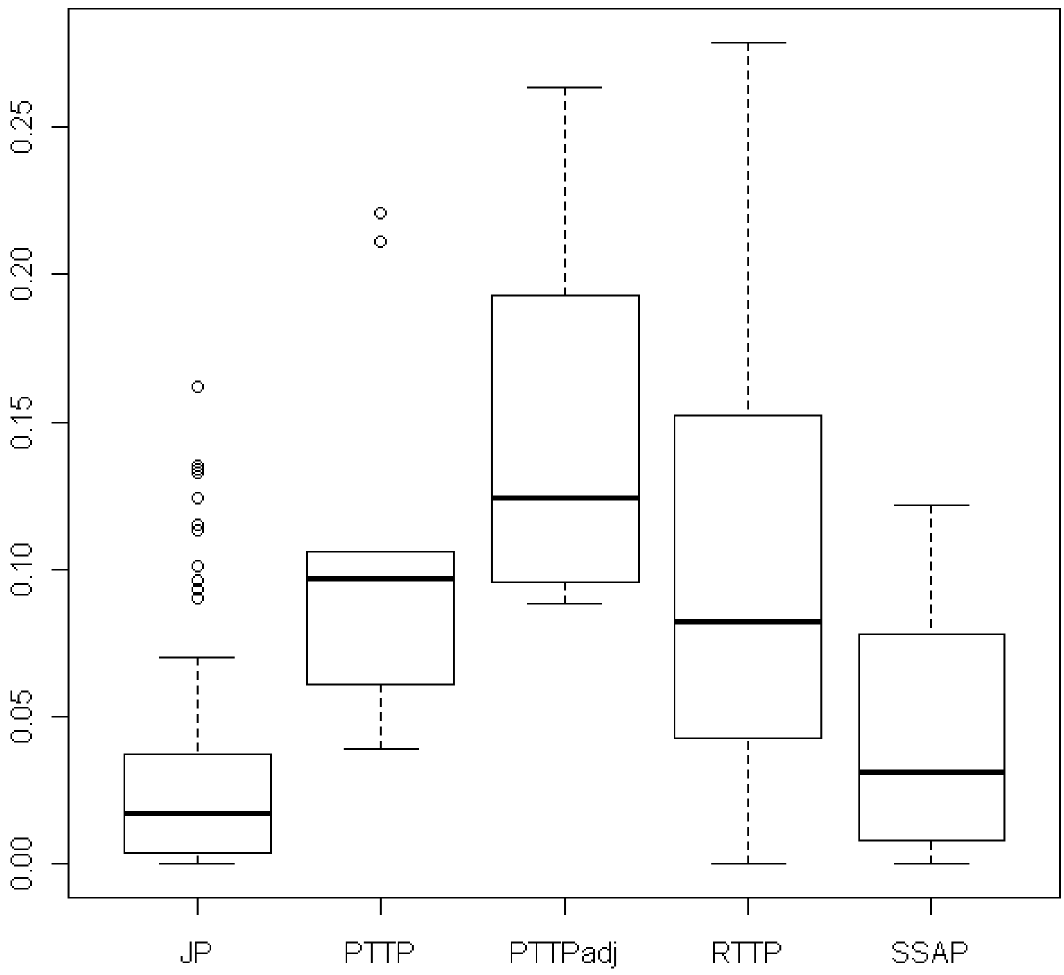

Figure 17: Boxplot of return rates per release group, by tagging program. The tagging program 'PTTPadj' represents the PTTP tagging program with a reduced number of releases, in proportion to the reduced number of recaptures (i.e. fewer than actually recaptured) in the stock assessment dataset.

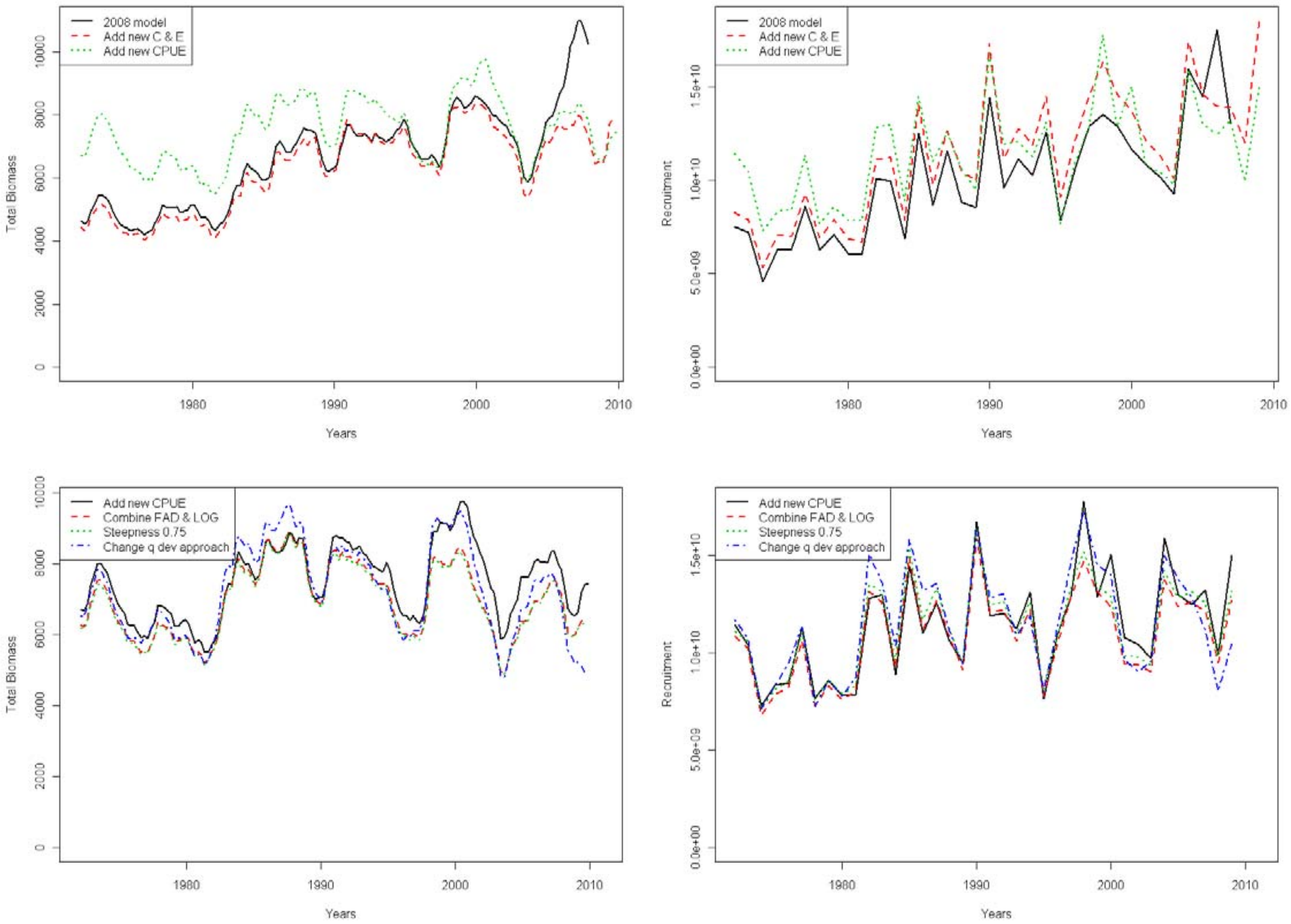

Figure 18: Effects of a series of model changes on total biomass (left) and recruitment (right). The top figures show stepwise changes from the 2008 model, adding the new catch and effort data, and including the standardized JP pole and line CPUE time series. The lower figures show stepwise changes combining the FAD and LOG purse seine into one fishery, changing steepness to 0.75, and freeing up estimation of the temporal catchability deviates.

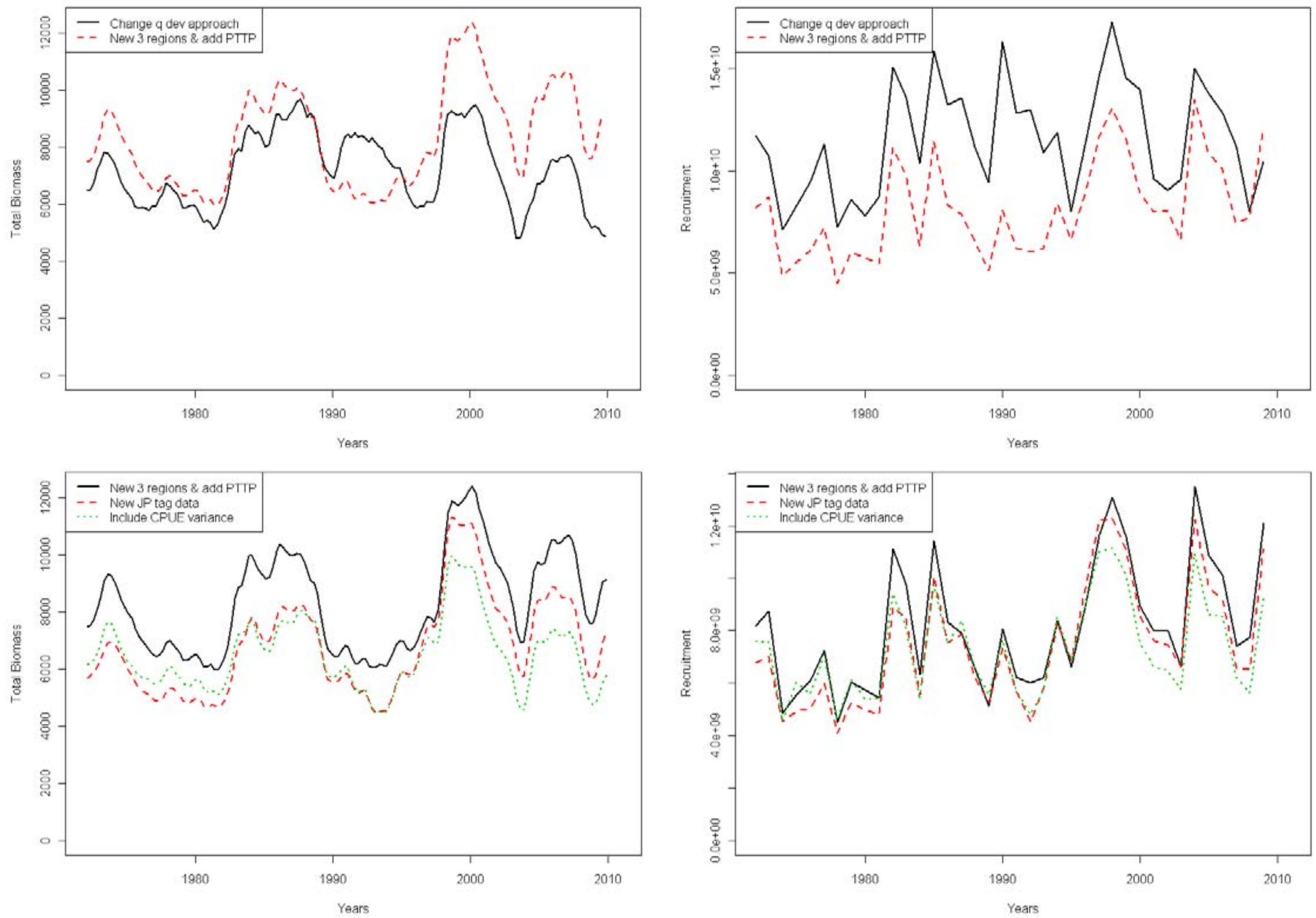

Figure 19: Effects of a series of model changes on total biomass (left) and recruitment (right). The top figures show stepwise changes from the last model above ('Change q dev approach' – see Table 6), including adding the PTTP tagging data, downweighting the Philippines length frequency data, and changing to the new regional structure. The lower figures show the stepwise effects of adding the new Japanese tagging data, and including estimated variance in the CPUE time series.

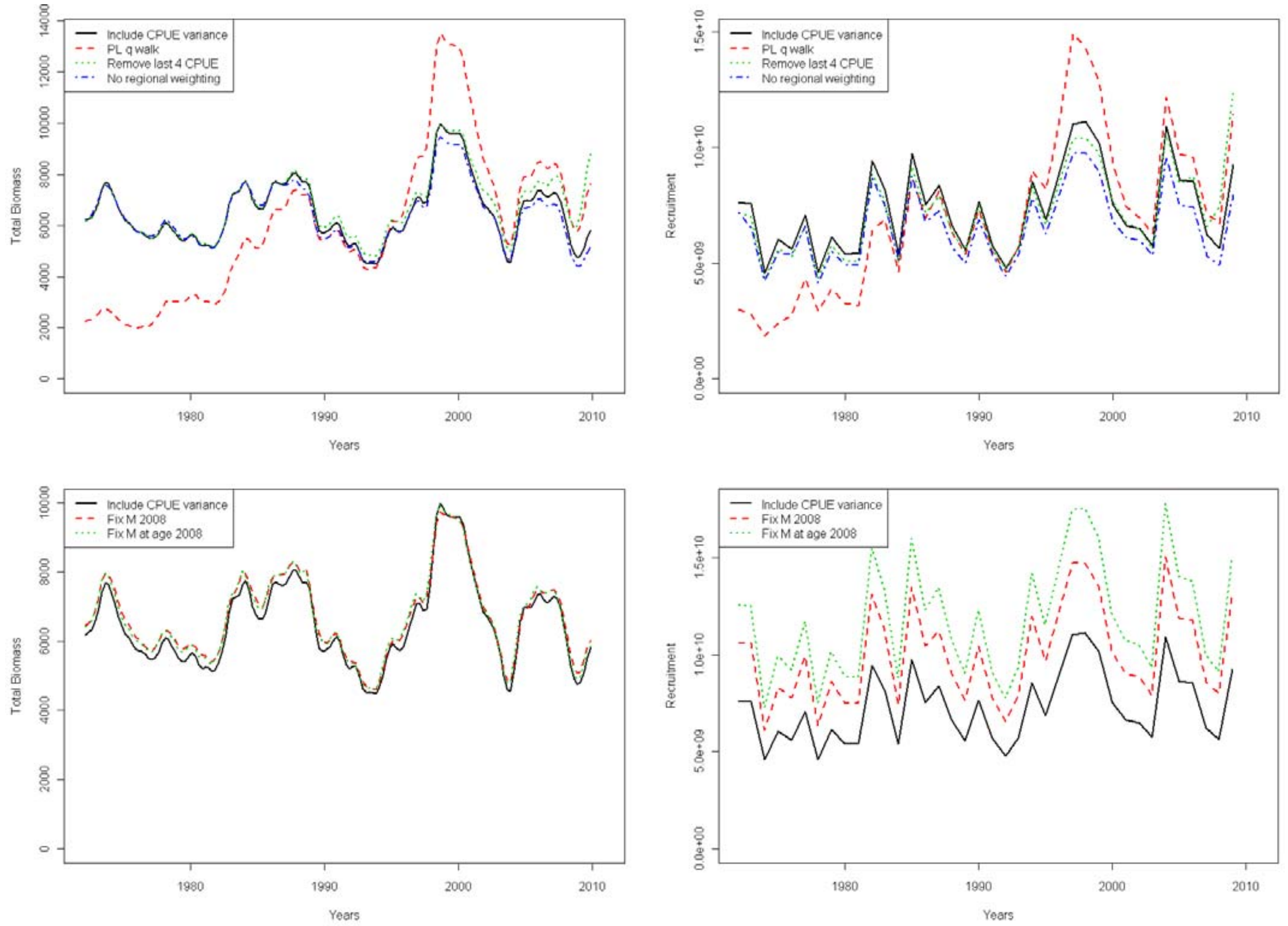

Figure 20: Effects of a series of model changes on total biomass (left) and recruitment (right). The top figures show changes offset from the 'Include CPUE variance' model (see Table 6), with a random walk in PL catchability, removal of the last 4 PL CPUE data points, and removal of regional weighting and estimation of catchability by region. The lower figures similarly show offset changes, with natural mortality (M) fixed at the 2008 estimate, and just the age-related parameters of M fixed at the 2008 level.

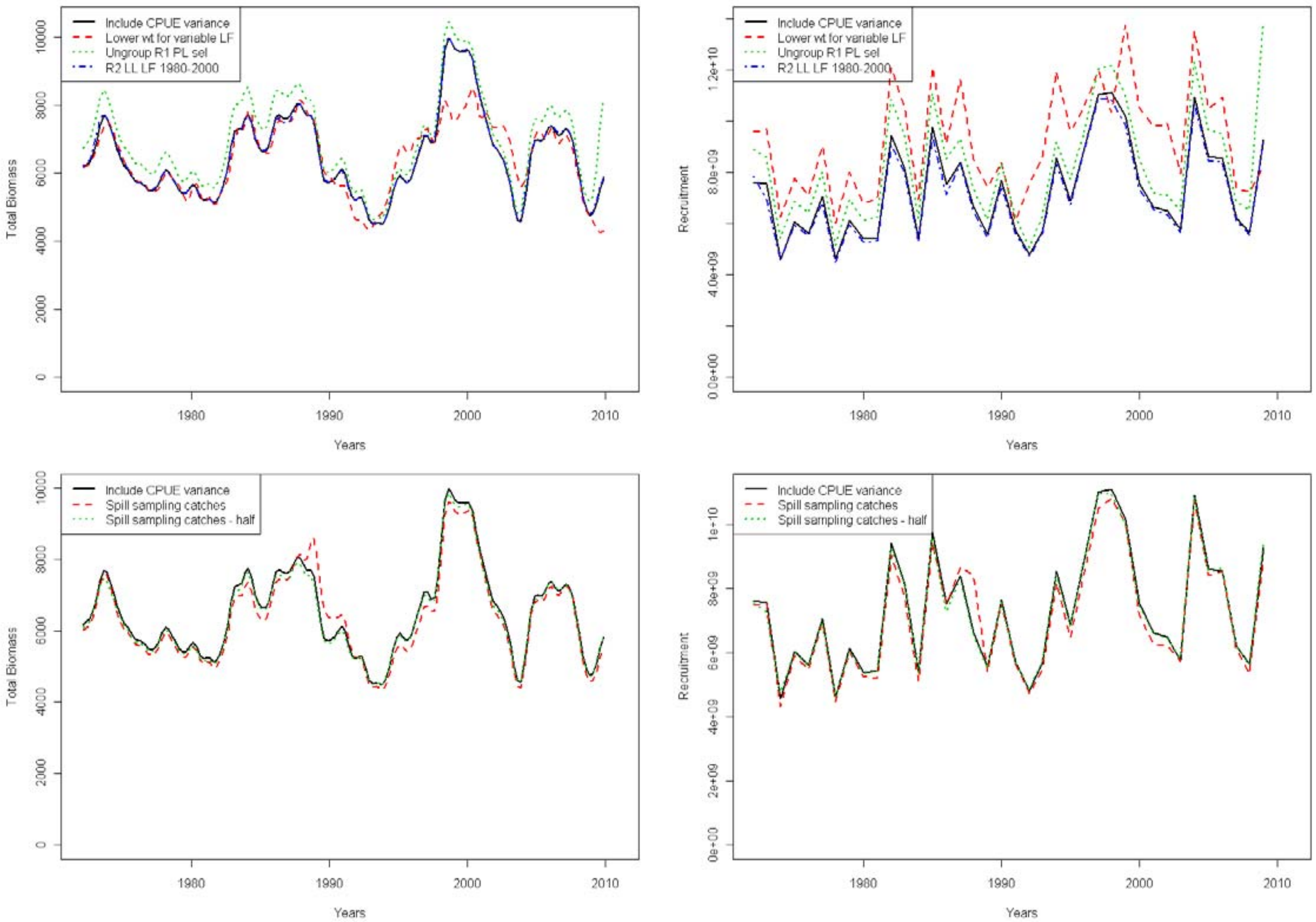

Figure 21: The top figures show changes offset from the 'Include CPUE variance' model (see Table 6), with the less consistent LF series downweighted by 80%, and PL selectivity estimated independently in region 1. The lower figures show similar offset changes, including spill sampling data rather than S_BEST data for the purse seine catches.

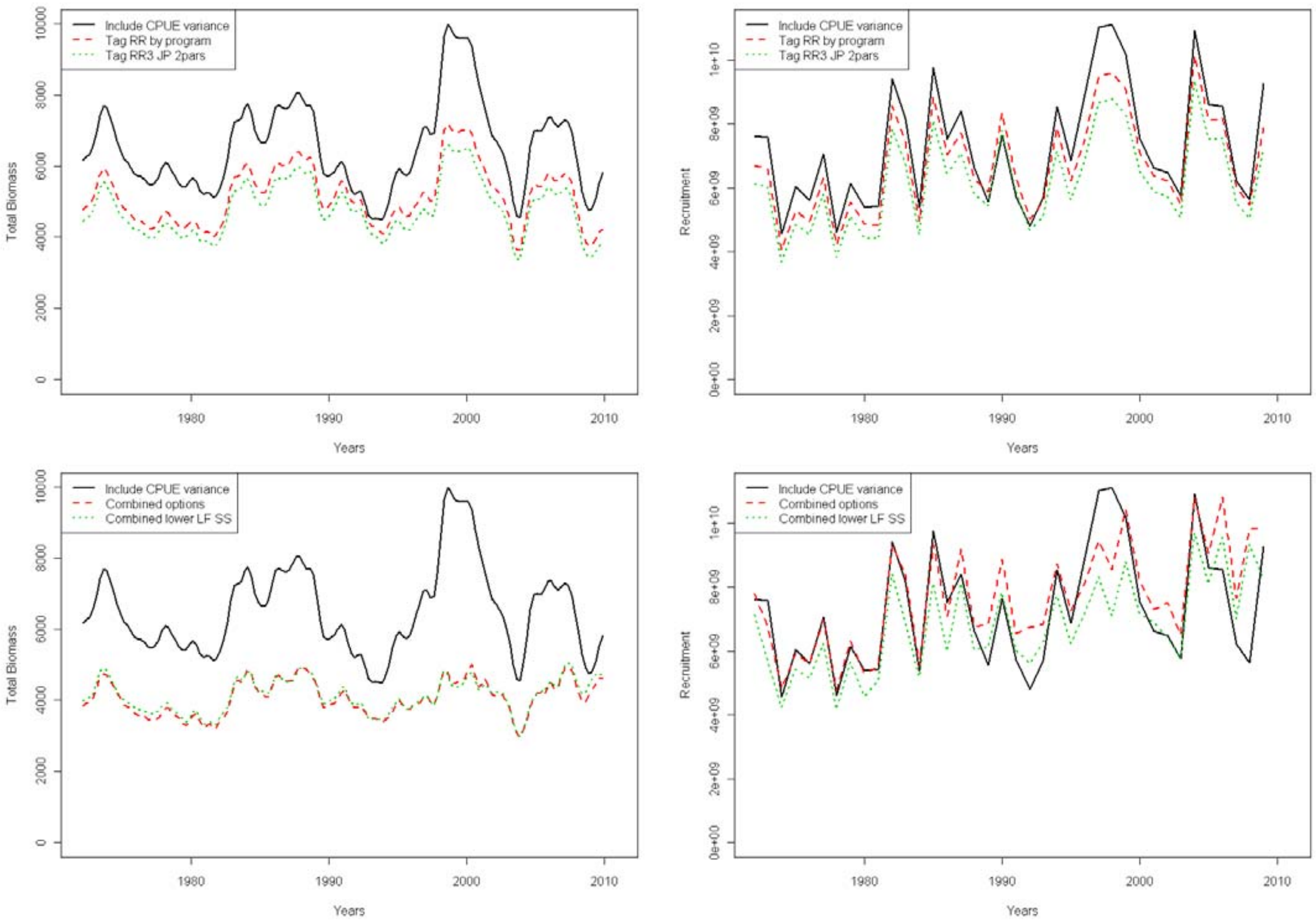

Figure 22: Effects of a series of model changes on total biomass (left) and recruitment (right). The top figures show changes offset from the 'Include CPUE variance' model (see Table 6), with 3 options for program-dependent tag reporting rates. The lower figures show an approach that combines several tag options, and a second approach that both combines those tag options and reduces the maximum sample size to 25 fish. This last approach is used as a base for further comparisons below.

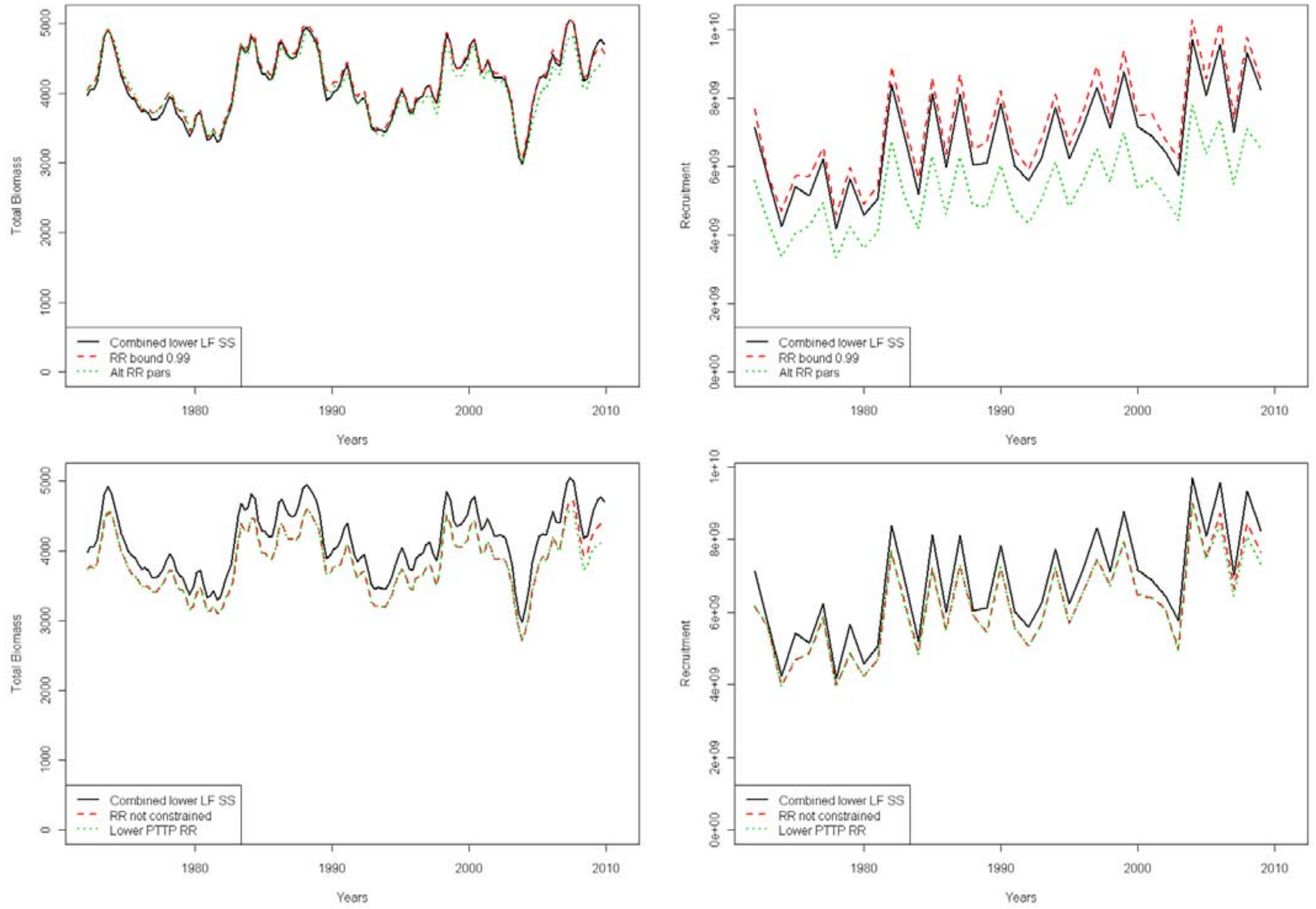

Figure 23: Effects of a series of model changes on total biomass (left) and recruitment (right). The top figures show changes offset from the 'Combined lower LF SS' model (see Table 6), with a change to the upper reporting rate boundary, alternate parameterization for reporting rates, and removal of the penalty on the Japanese reporting rates for the PTTP. The lower figures show changes offset from the 'Combined lower LF SS' model, with removal of all but the RTTP program PS fisheries prior on reporting rate, a lower prior mean on PTTP program PS fishery reporting rate.

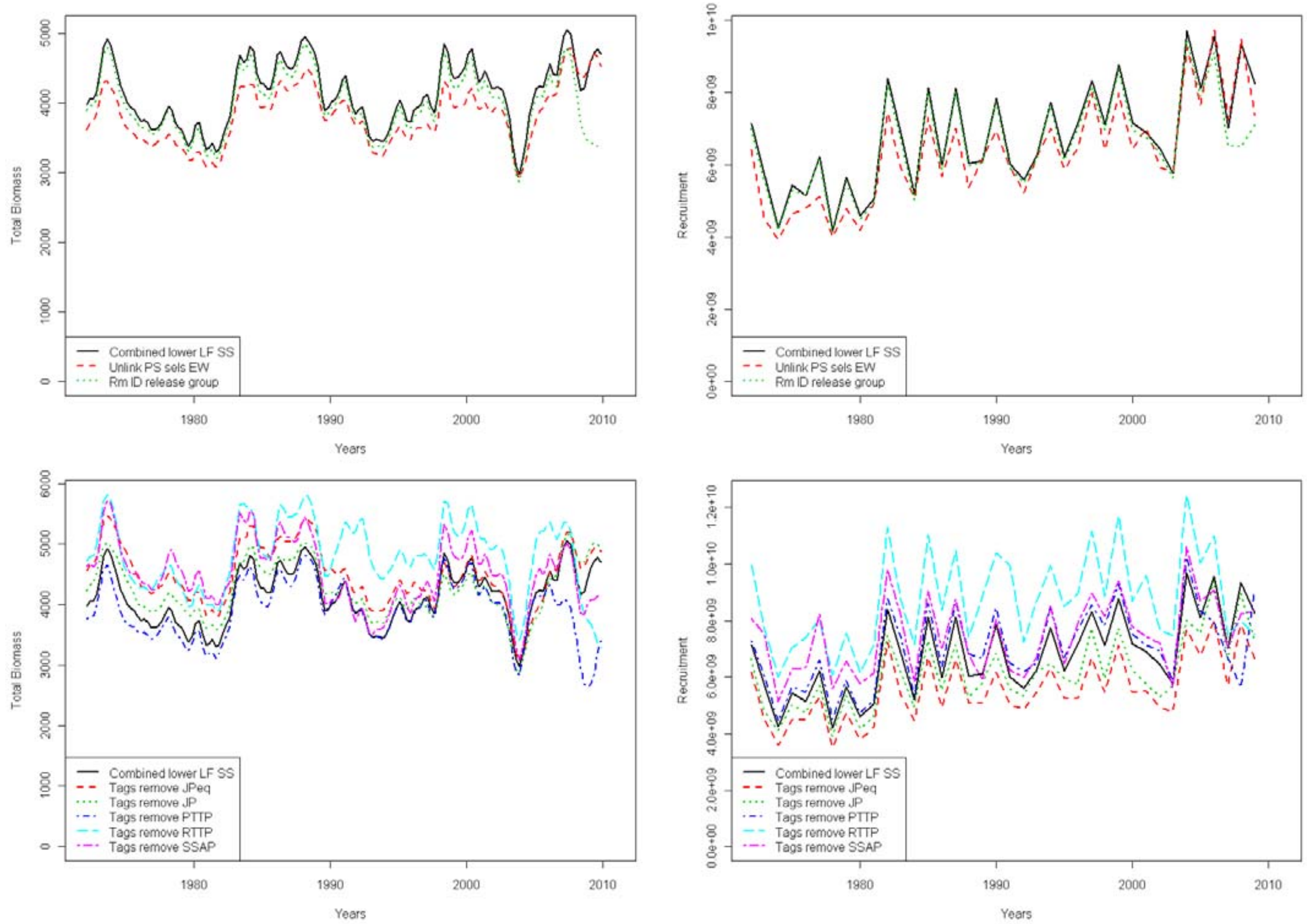

Figure 24: Effects of a series of model changes on total biomass (left) and recruitment (right). The top figures show changes offset from the ‘Combined lower LF SS’ model (see Table 6), unlinking purse seine selectivities, and removing a group of PTTP releases that were poorly mixed. The lower figures show changes offset from the ‘Combined lower LF SS’ model, with the effects of removing all tags from one tagging program at a time.

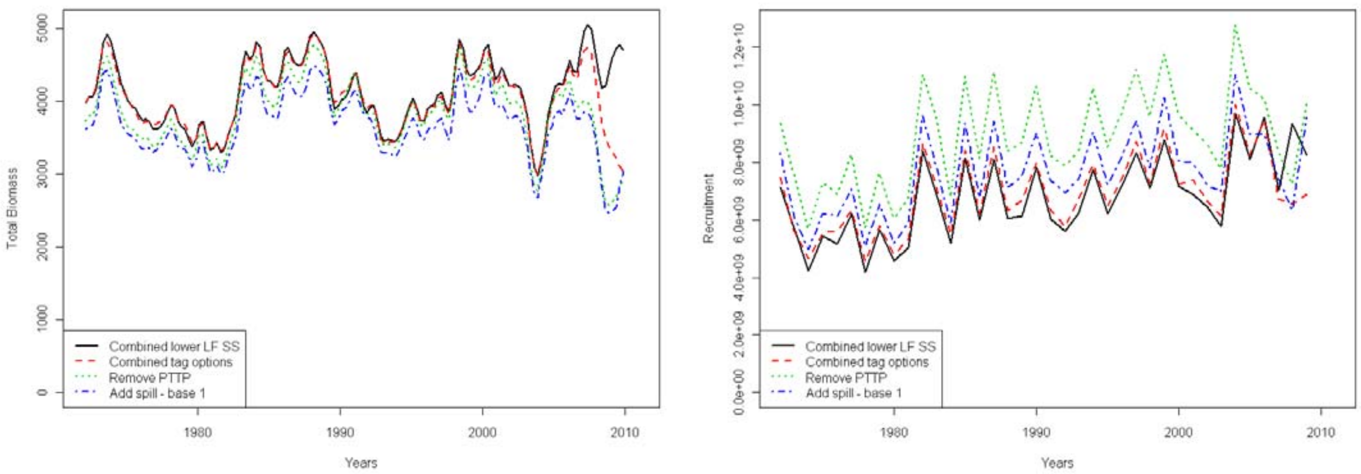

Figure 25: Effects of a series of model changes on total biomass (left) and recruitment (right). The top figures show a sequence of changes starting from the 'Combined lower LF SS' model, first combining a number of options for modeling tagging data, then removing the PTTP data, and finally including the spill sampling data. This final model is the base case.

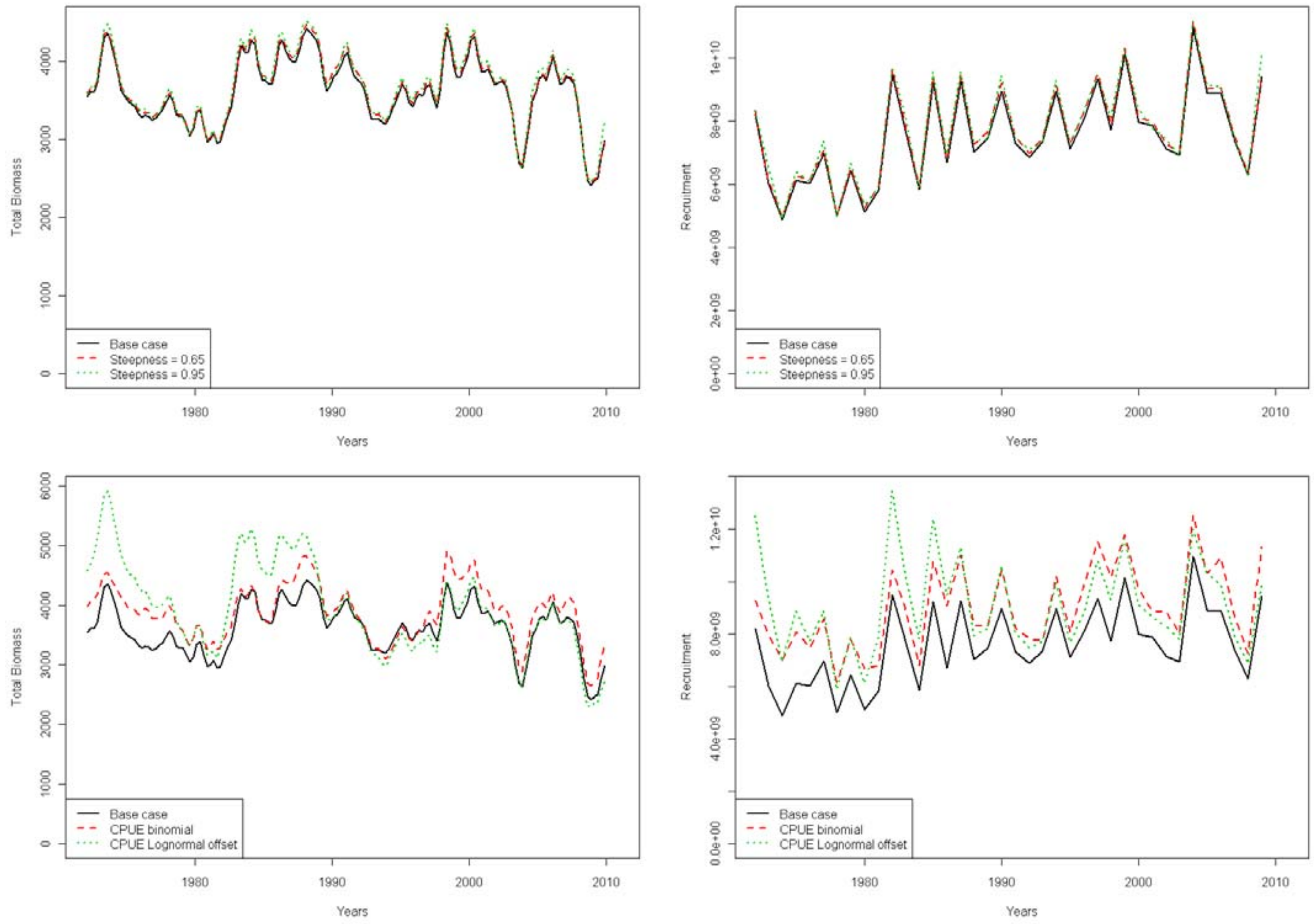

Figure 26: Sensitivity analysis effects on total biomass (left) and recruitment (right). The top figures show results with alternative steepness values. The lower figures show the results with alternative methods for producing CPUE time series.

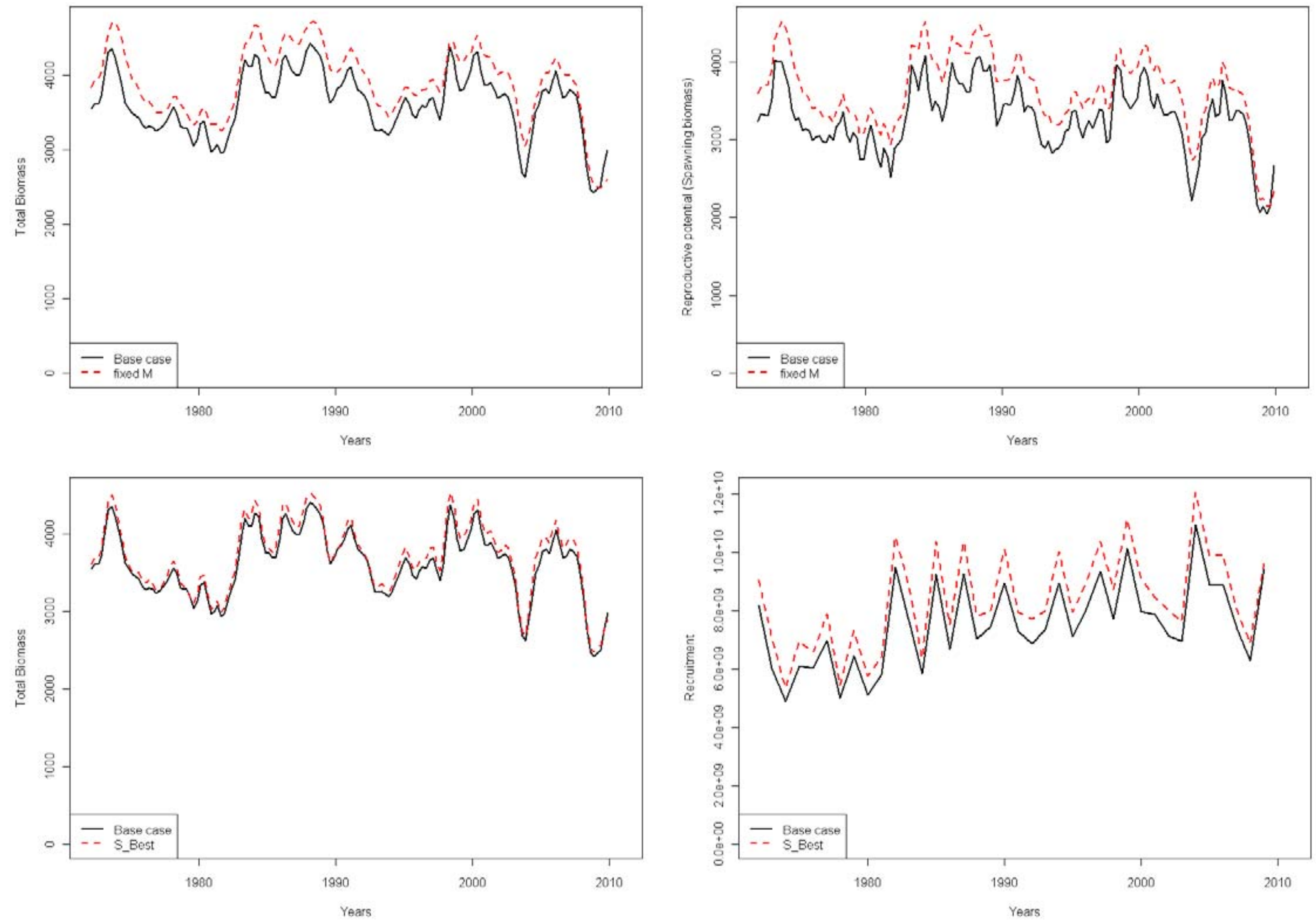

Figure 27: Sensitivity analysis effects on total biomass (left) and recruitment (right). Figure 28: Sensitivity analysis effects on total biomass (left) and recruitment (right). The top figures show the effect of fixing natural mortality. The lower figures show the results with equatorial PS catches based on S_BEST rather than spill sampling analyses.

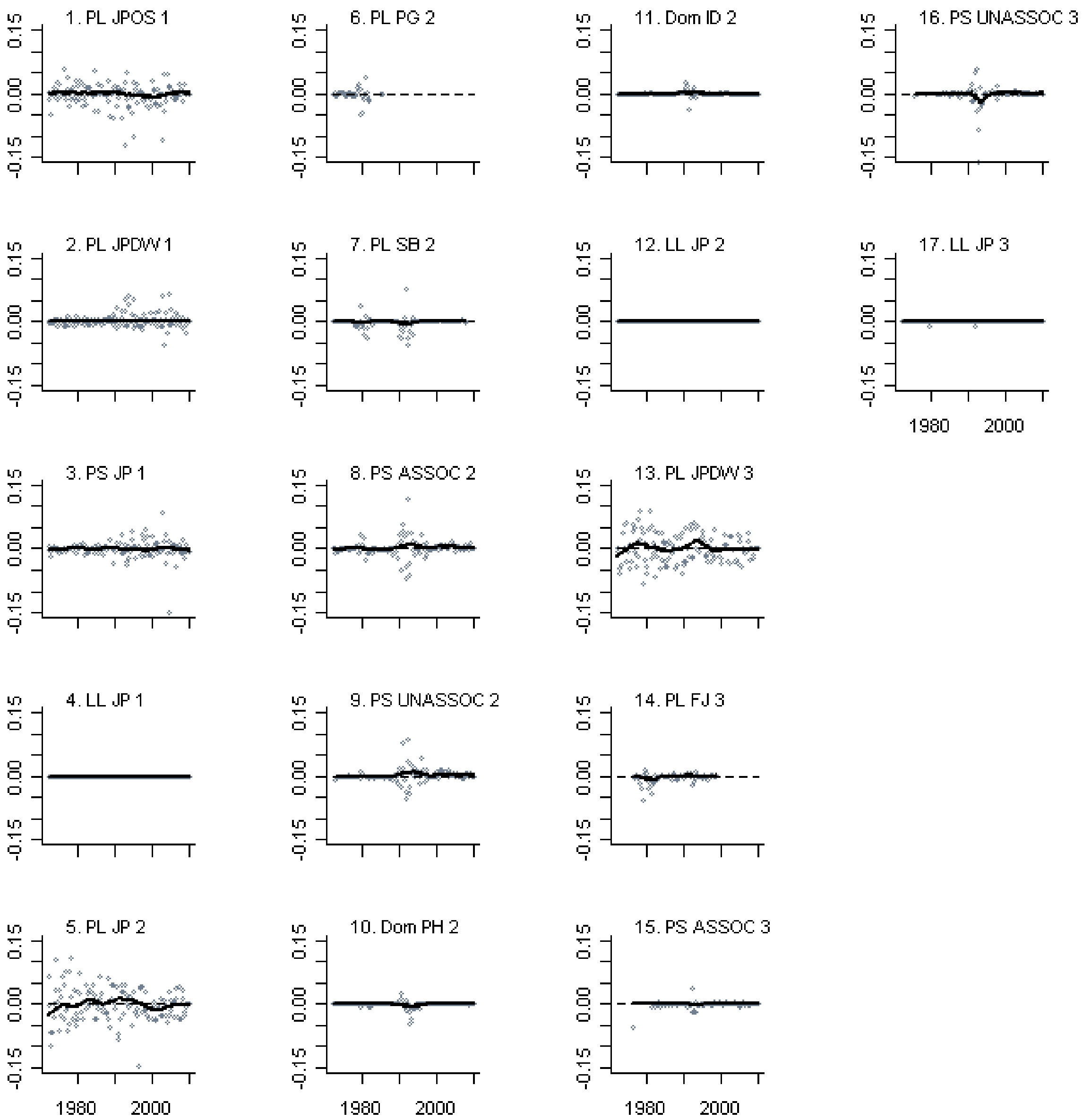

Figure 29. Residuals (observed minus predicted) of the natural logarithm of total catch for each fishery.

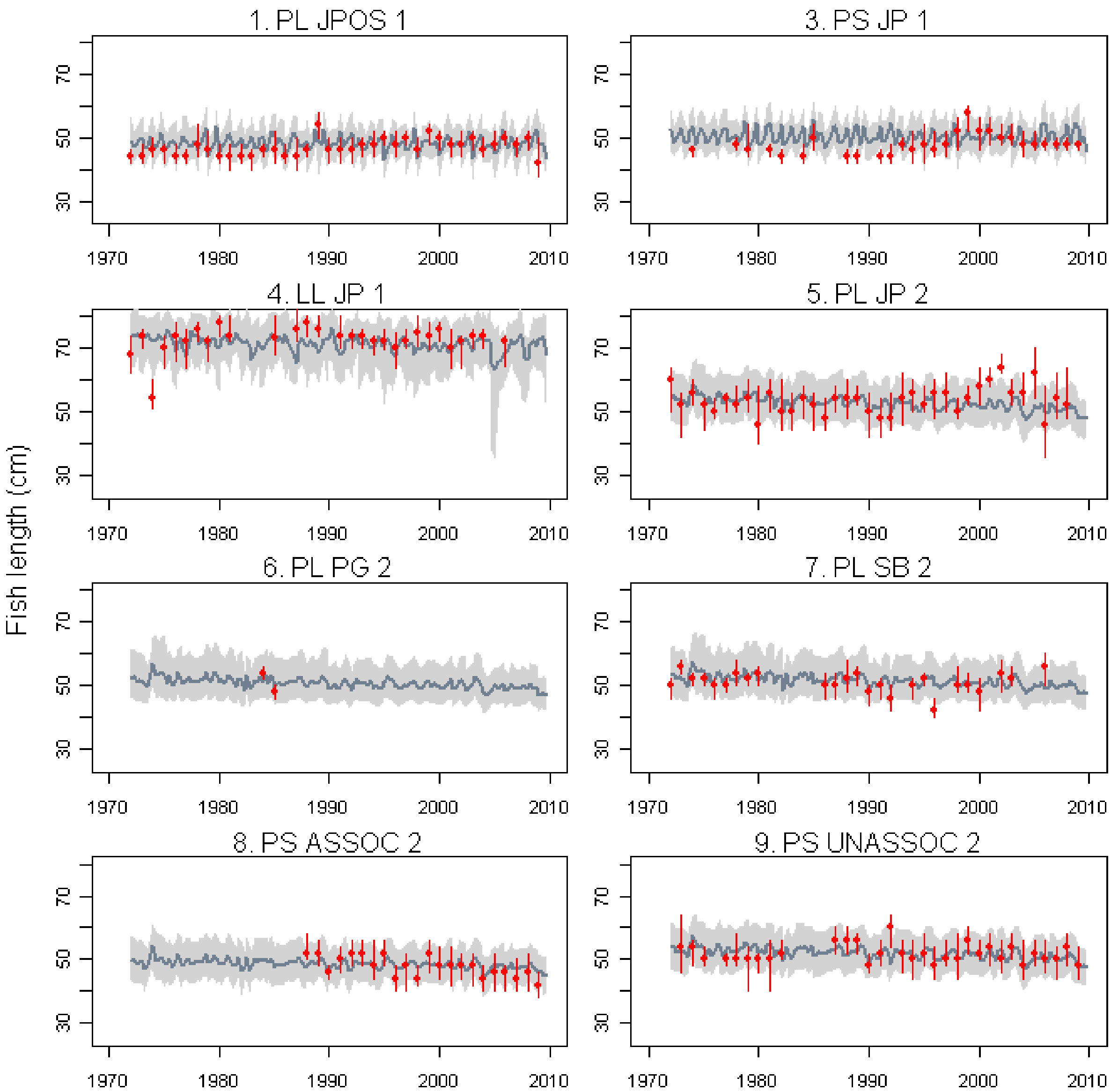

Figure 30. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of skipjack tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year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

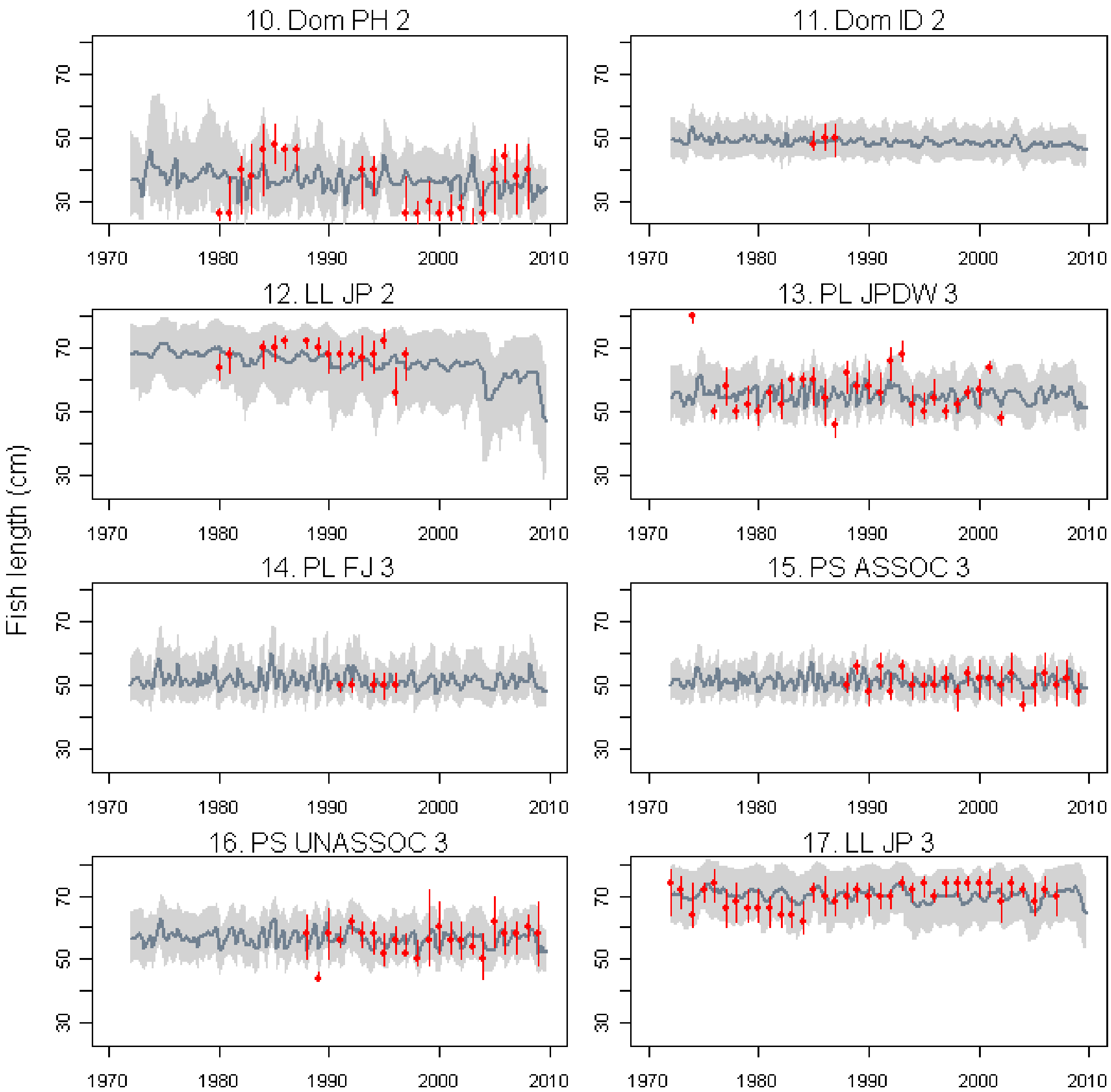

Figure 30. Continued.

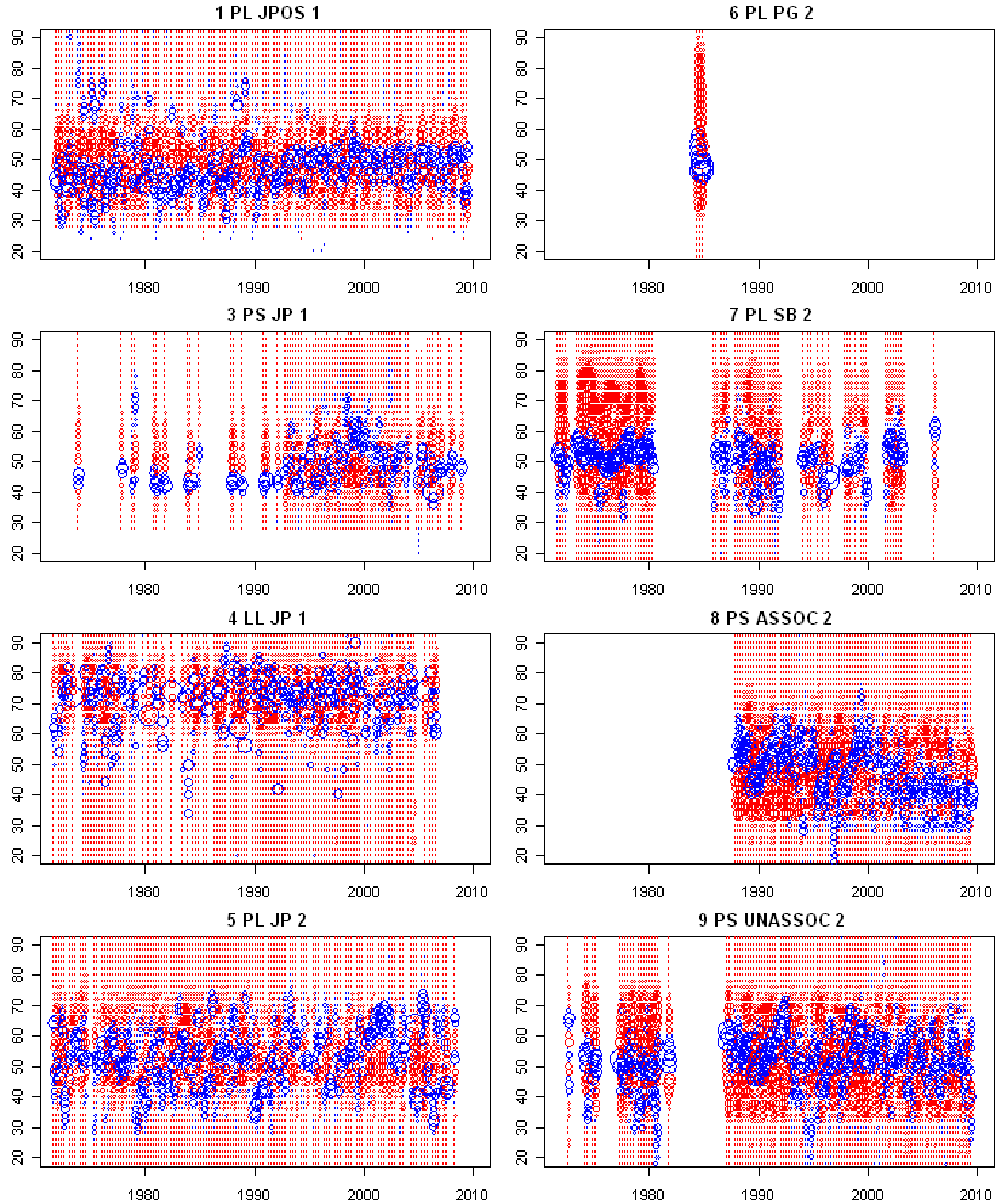
1 PL JPOS 1
6 PL PG 2
3 PS JP 1
7 PL SB 2
4 LL JP 1
8 PS ASSOC 2
5 PL JP 2
9 PS UNASSOC 2
20 30 40 50 60 70 80 90
1980 1990 2000 2010

Figure 31:

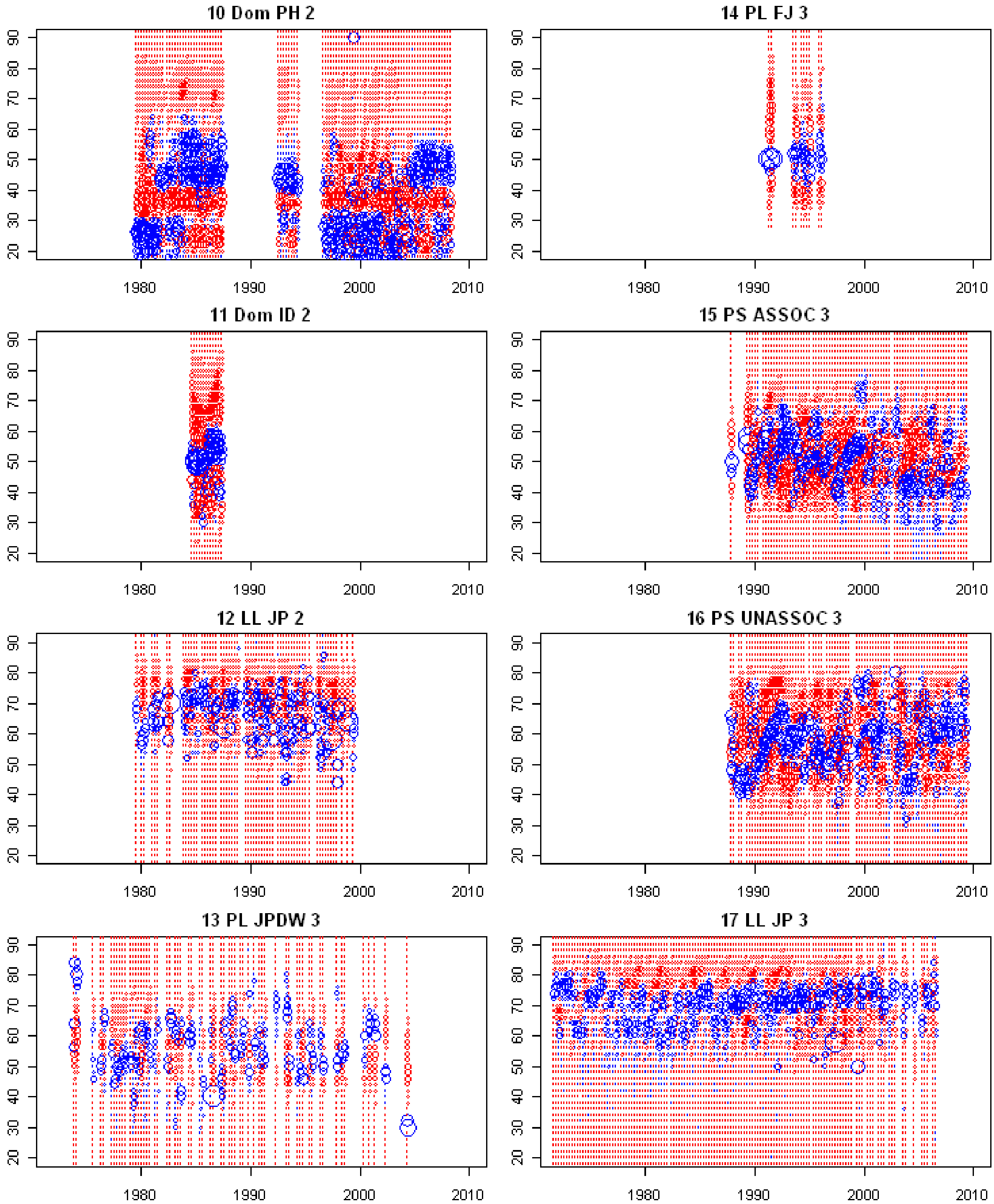

Figure 32 continued…

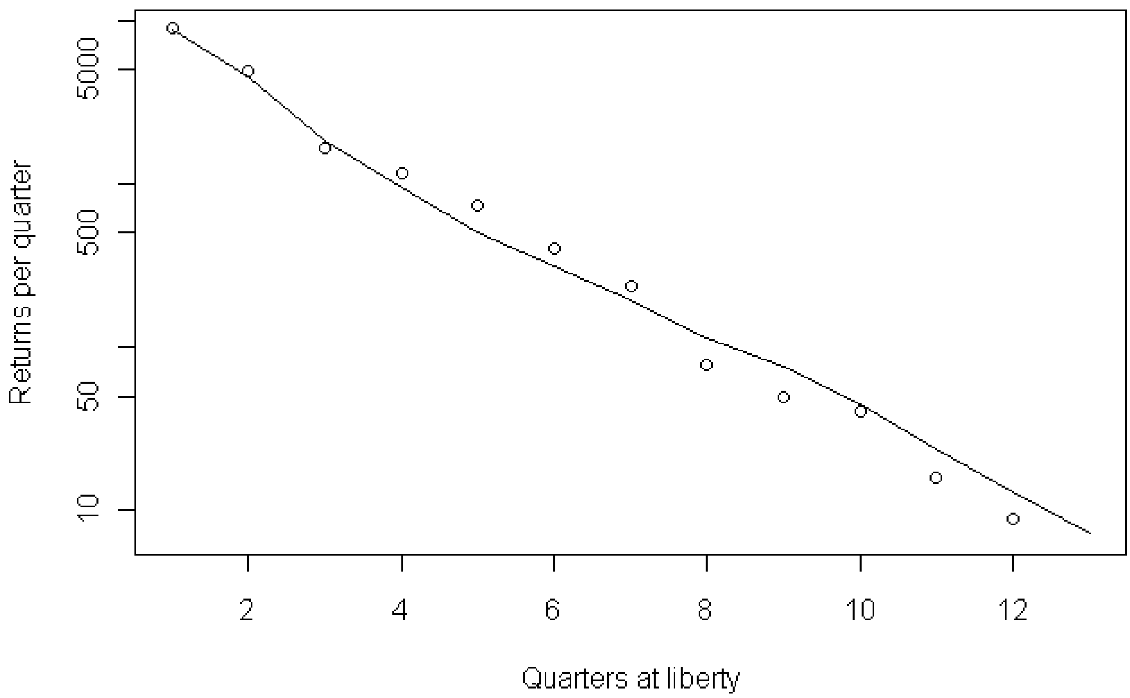

Figure 33. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters).

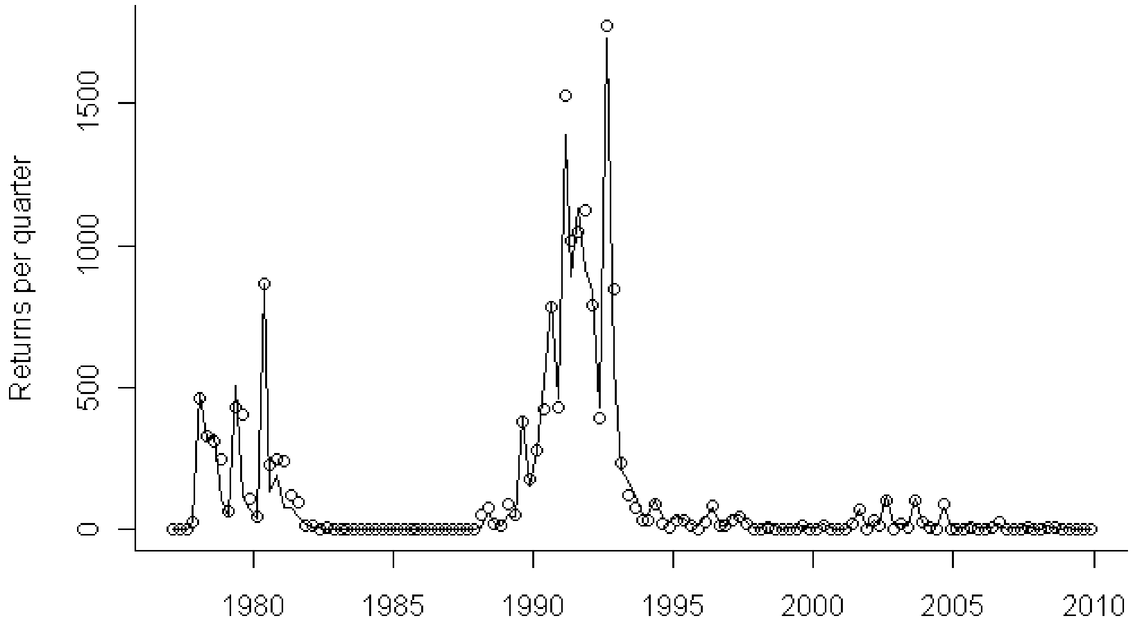

Figure 34. Number observed (circles) and predicted (lines) tag returns by recapture period (quarter).

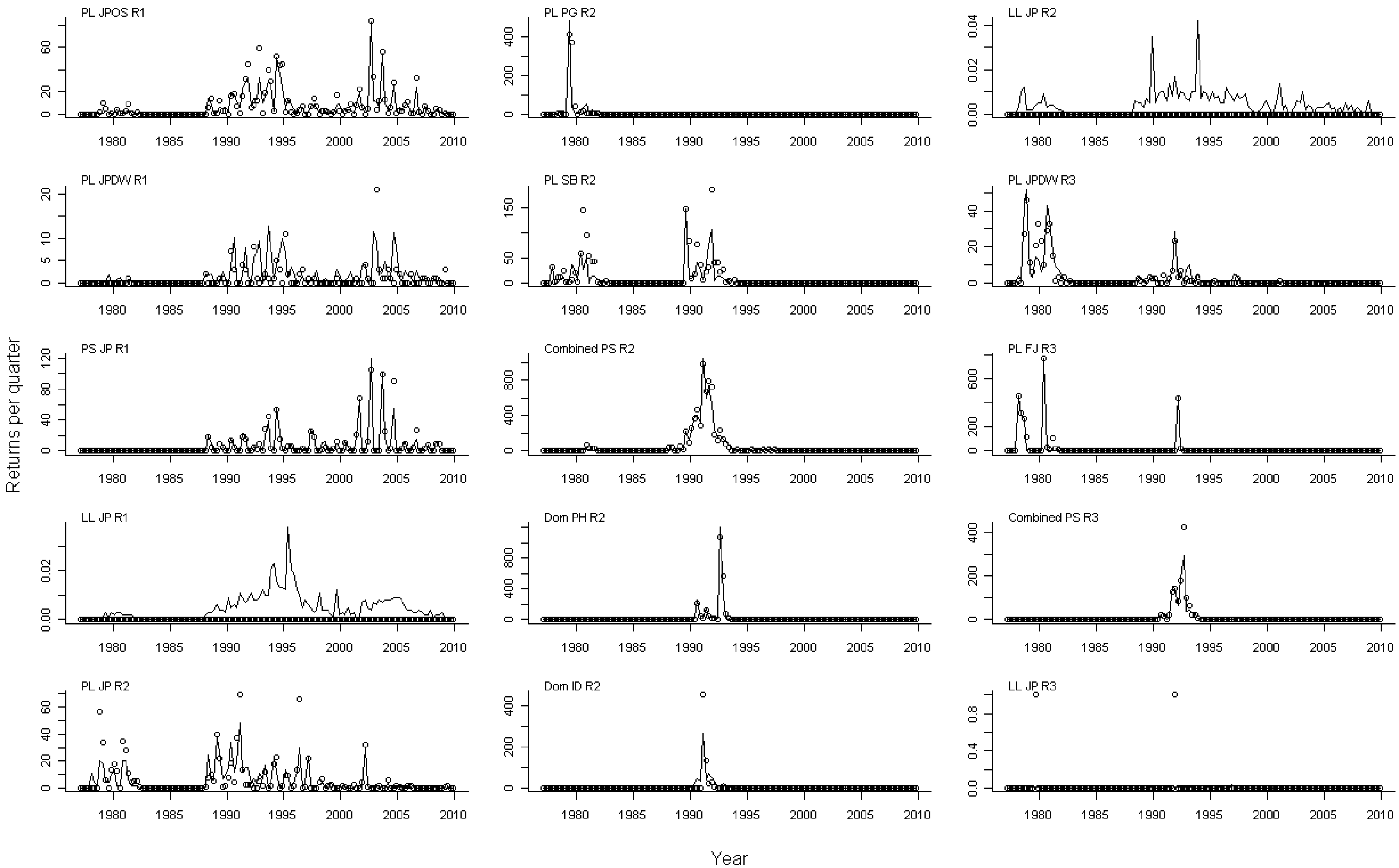

Figure 35: Number of observed (circles) and predicted (lines) tag returns by recapture period (quarter) and tag group. Tag groups are equivalent to fisheries apart from pooling of the purse seine fisheries within each region.

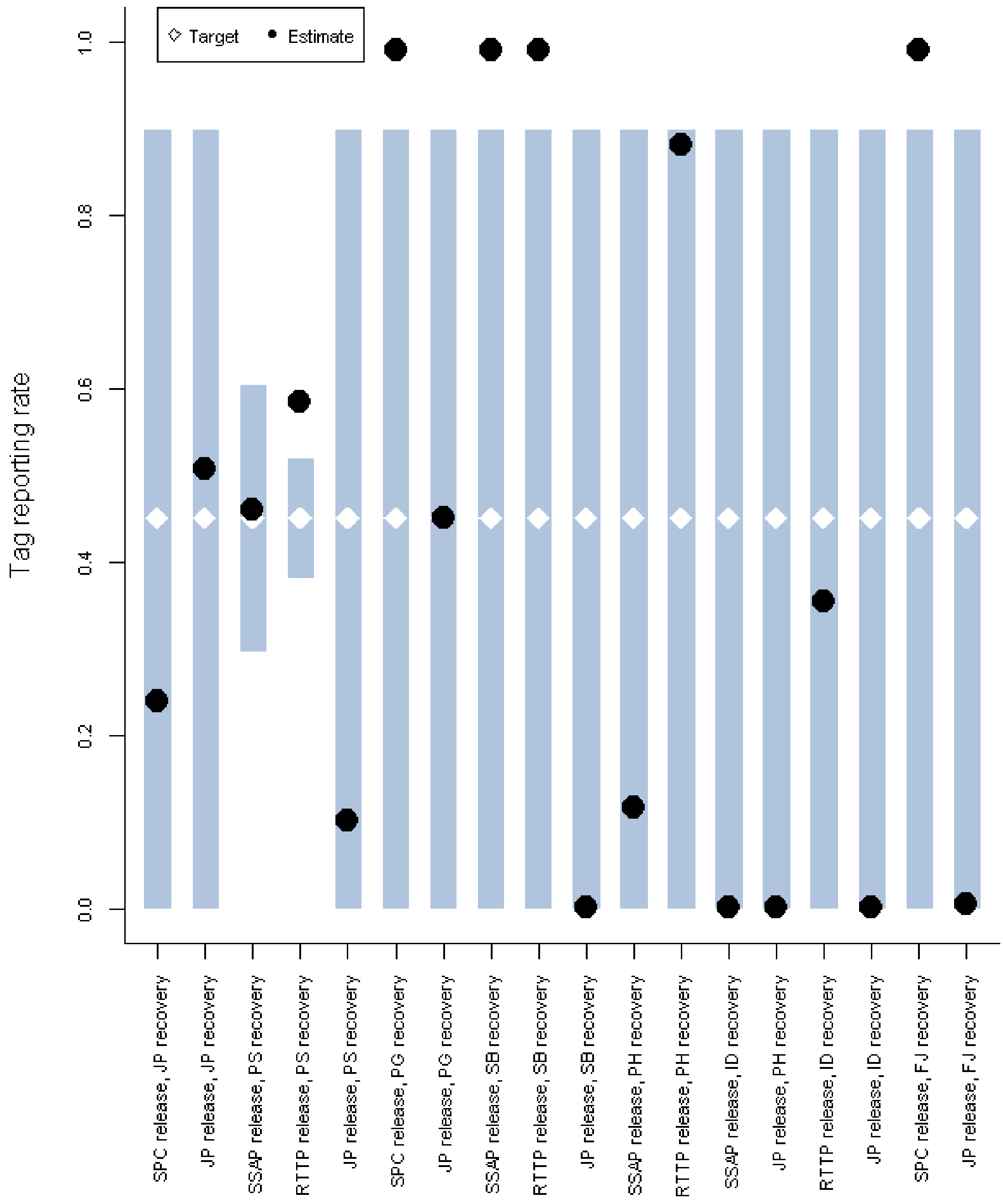

Figure 36. Estimated tag-reporting rates by fishery (histograms). The prior mean ±1.96 SD is also shown for each fishery.

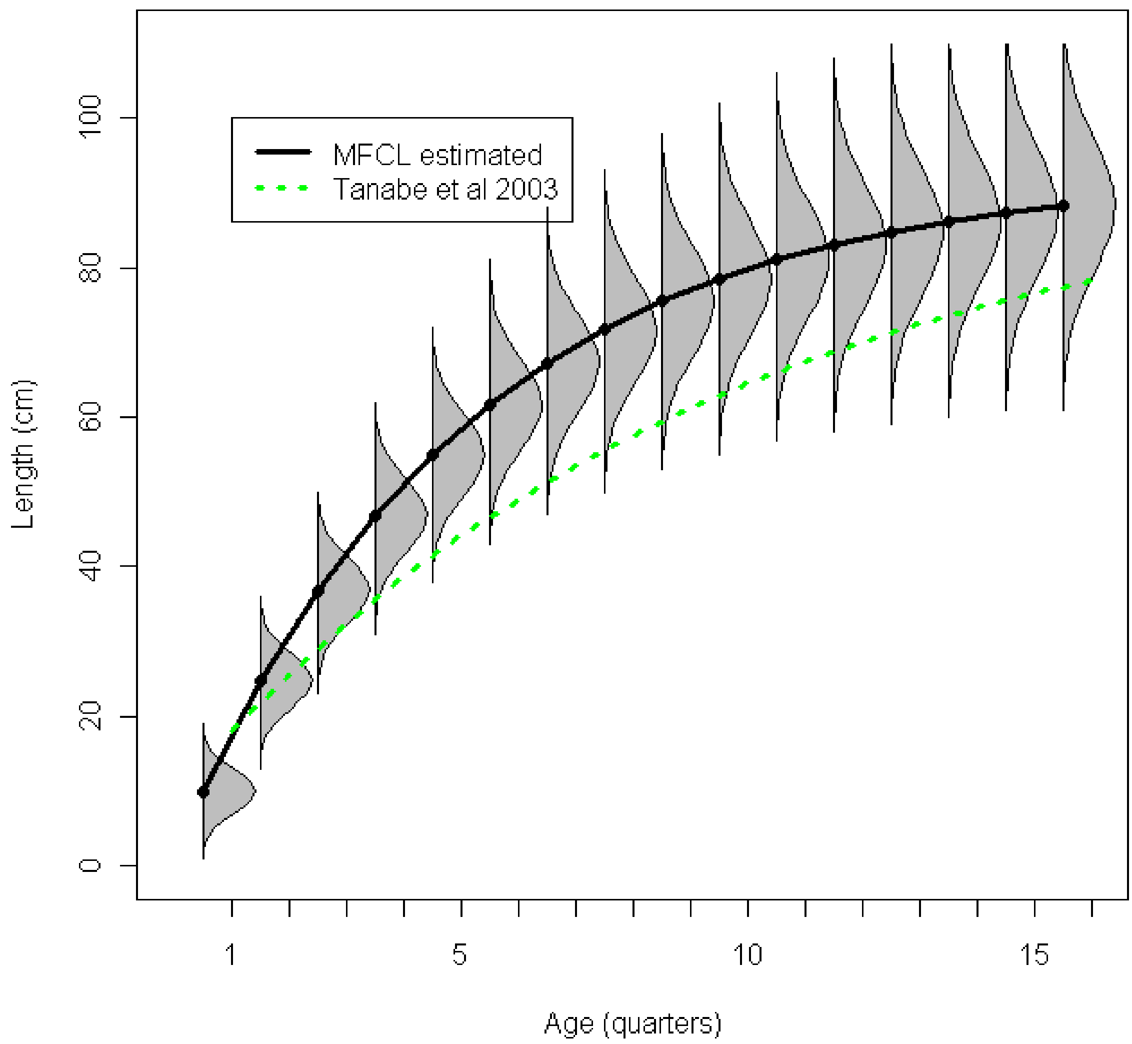

Figure 37. Estimated growth of skipjack derived from the assessment model. The black line represents the estimated length (FL, cm) at age and the grey area represents the estimated distribution of length at age.

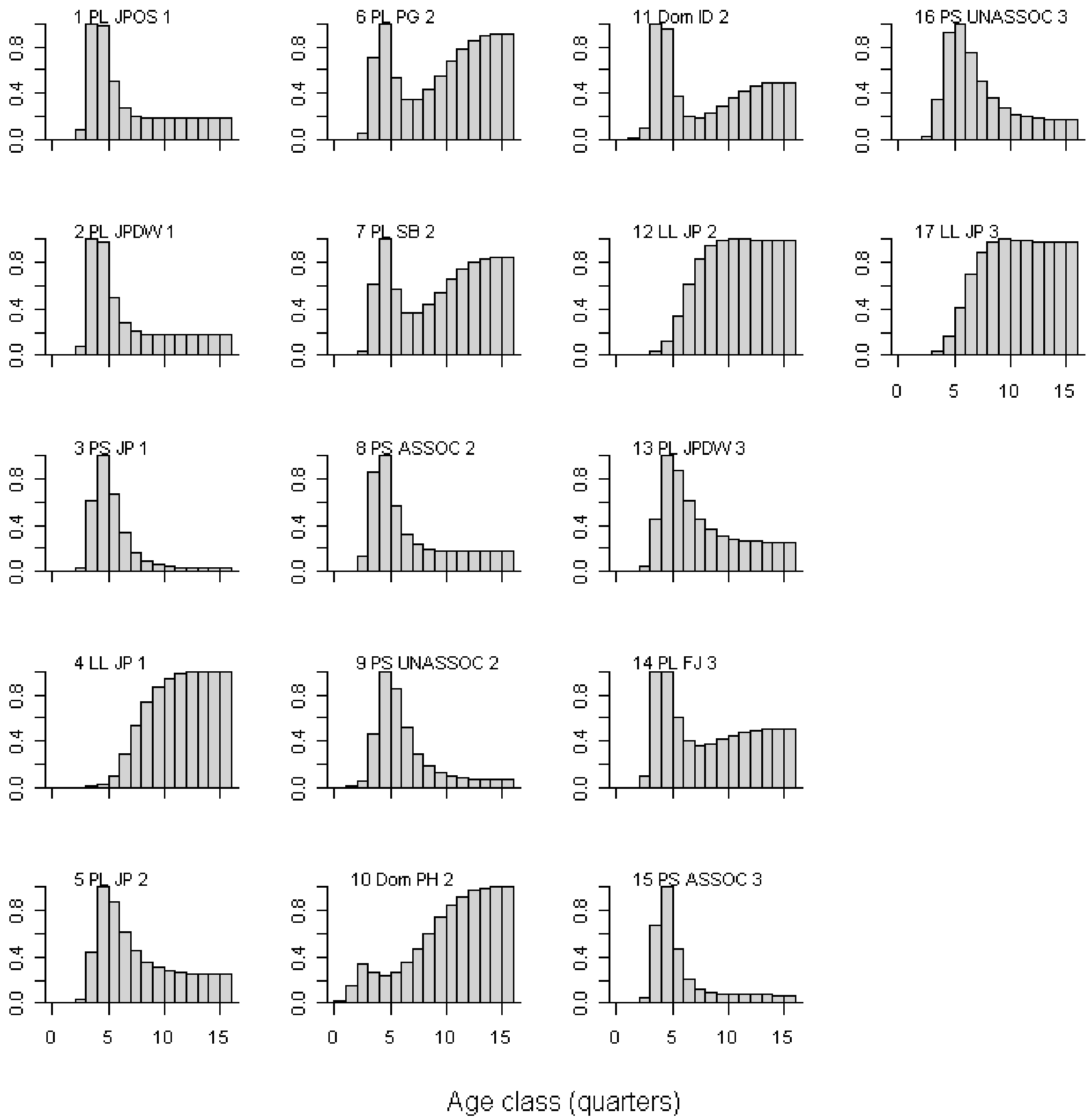

Figure 38. Selectivity coefficients, by fishery. All JP PL fisheries were assumed to have common selectivity.

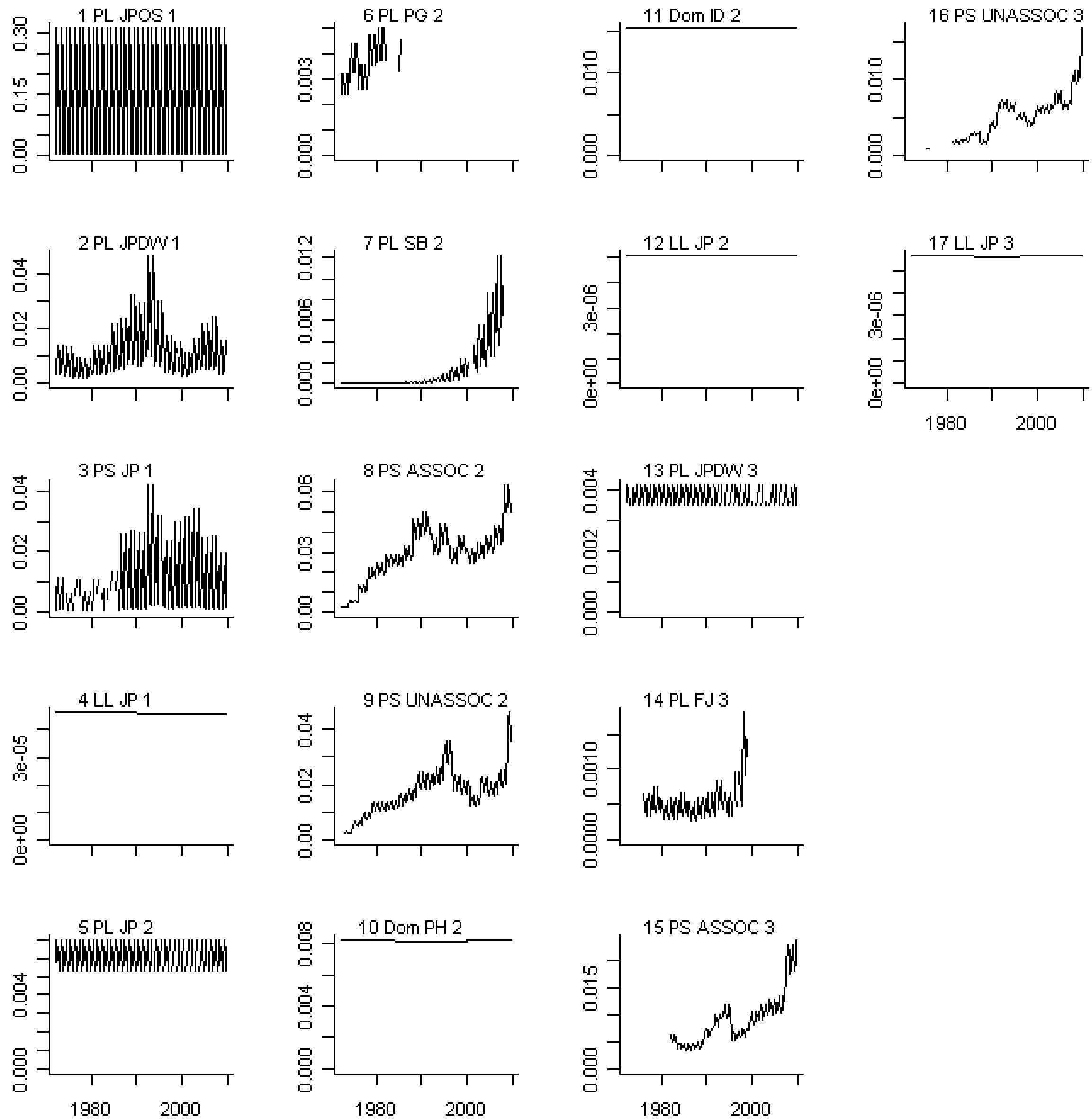

Figure 39. Estimated time-series catchability trends for each fishery.

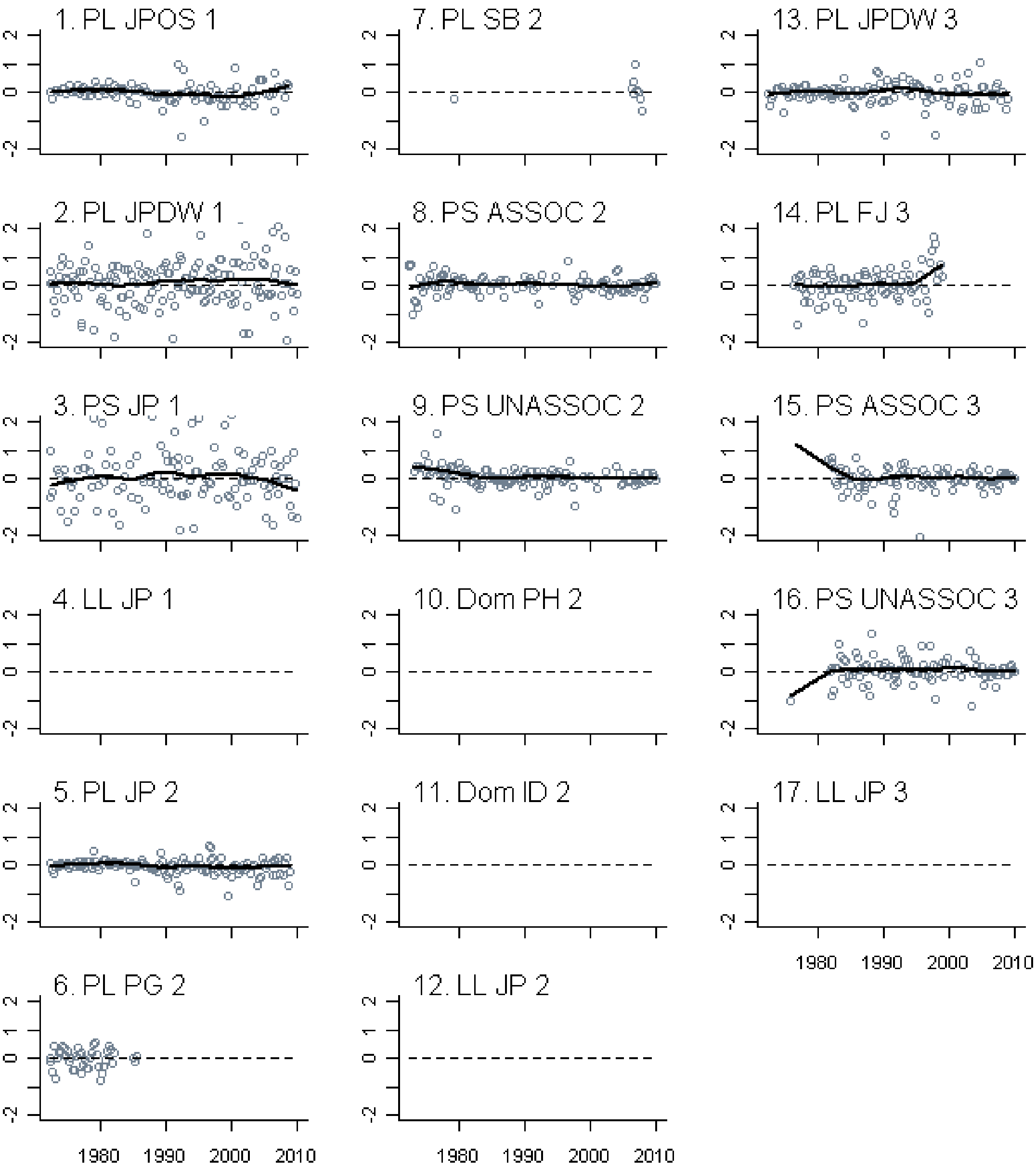

Figure 40. Effort deviations by time period for each fishery in the WCPO base-case model.

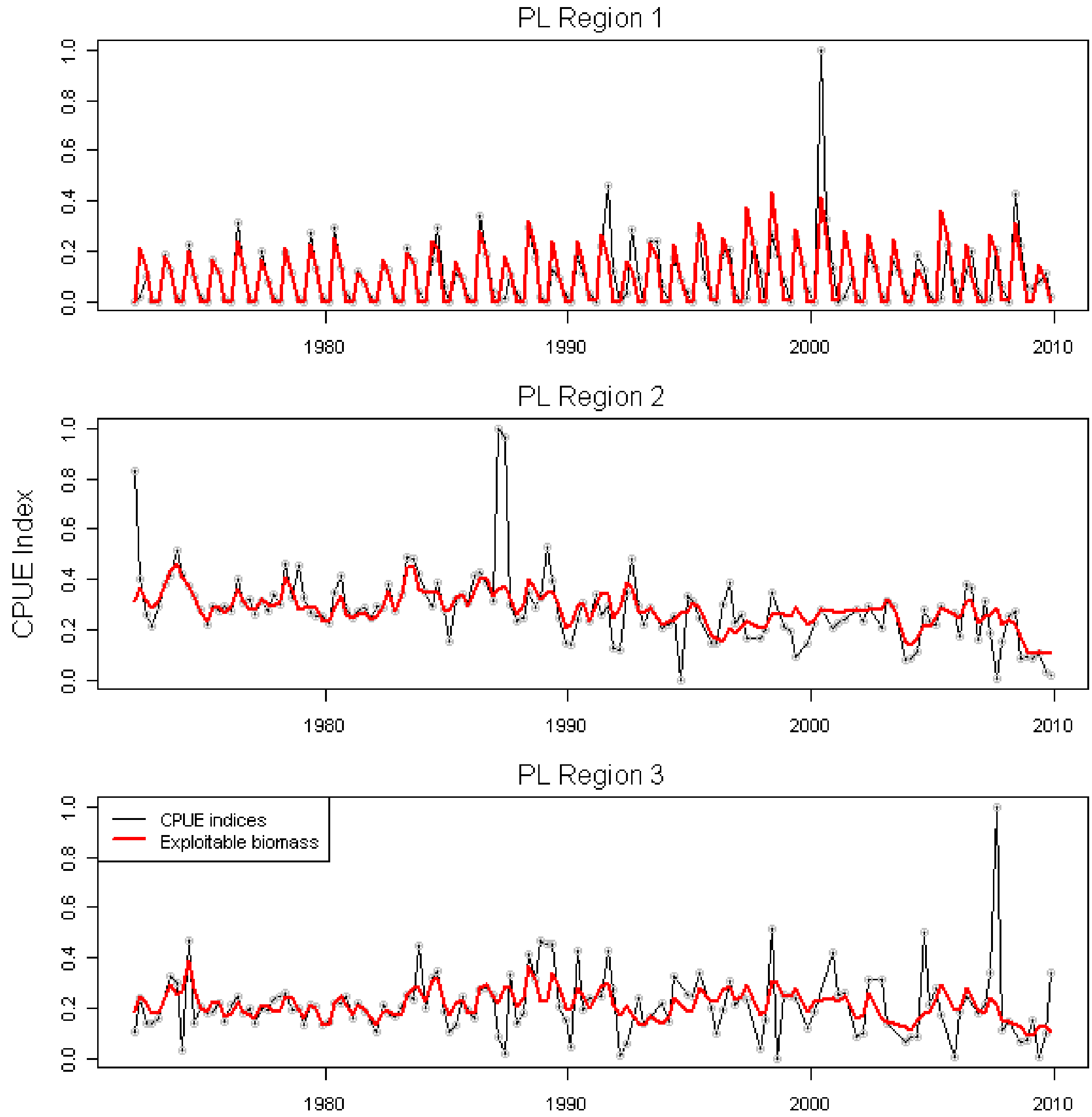

Figure 41. A comparison of pole-and-line exploitable biomass by quarter and region (red line) and the quarterly standardised CPUE indices for the fisheries.

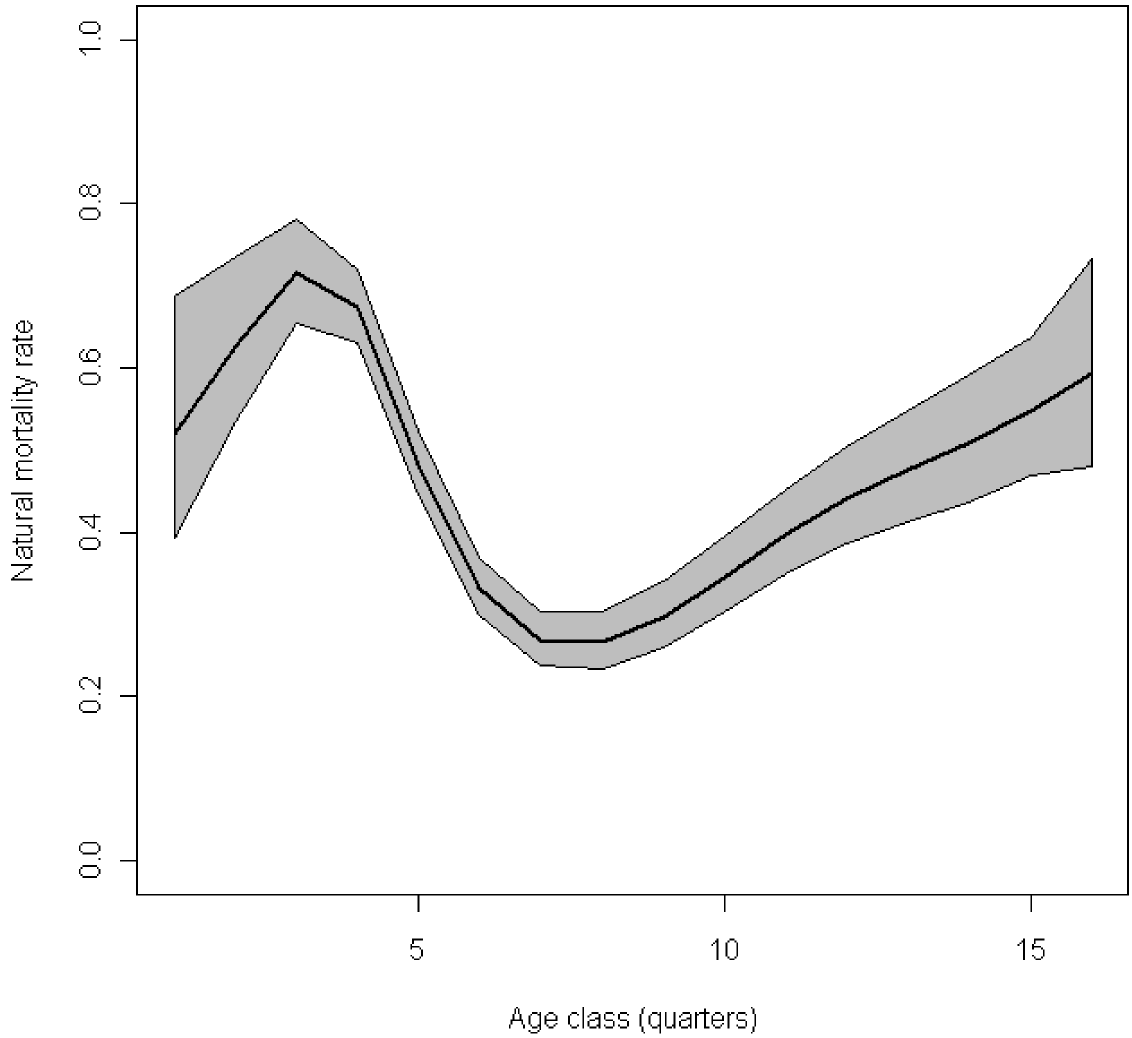

Figure 42. Estimated natural mortality rate per quarter by age-class. The dashed lines represent the 95% confidence interval.

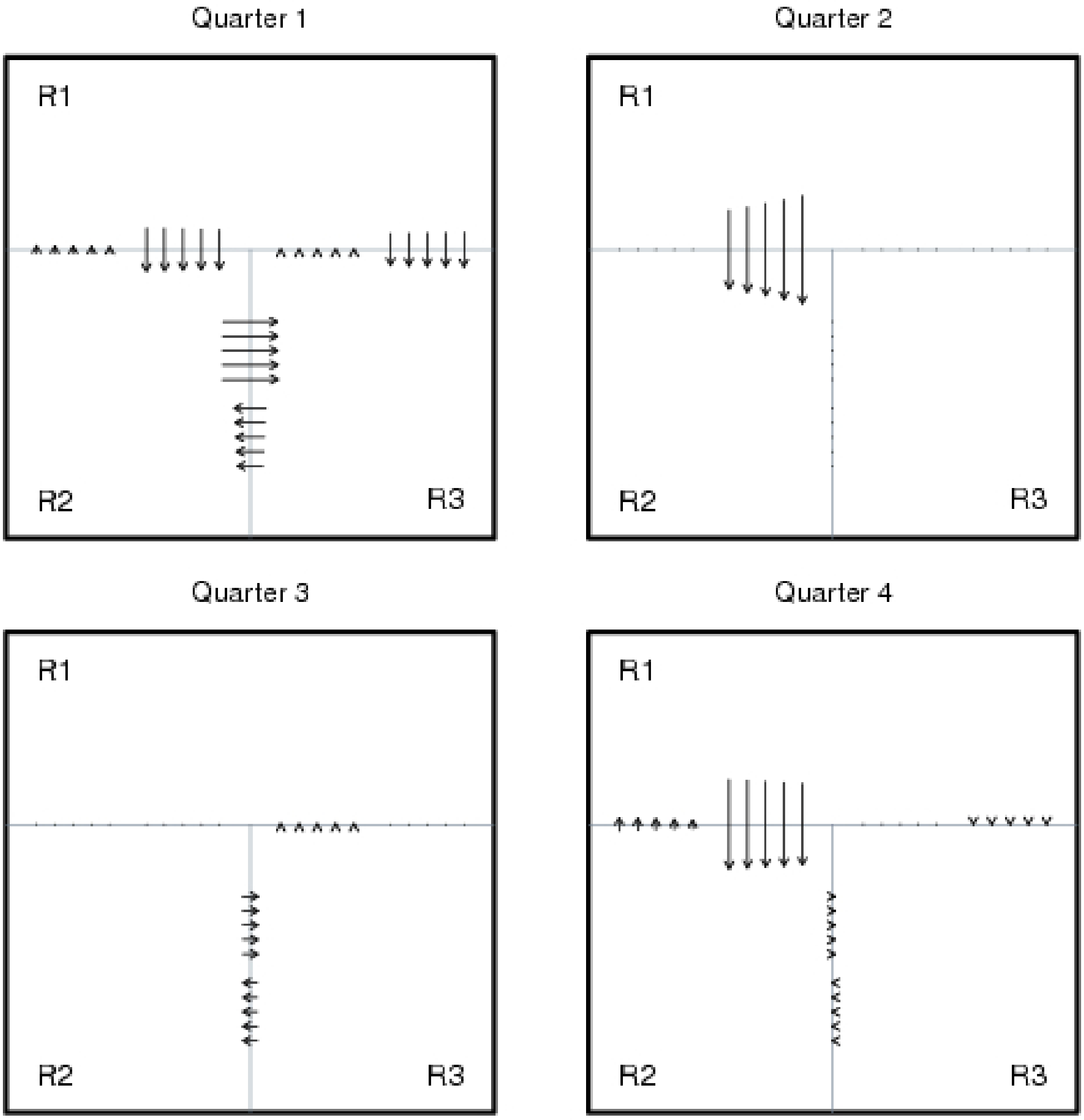

Figure 43. Graphical representation of movement coefficients among the six model regions at the beginning of each quarter. The arrows for each region boundary represent movement probabilities of 4 different age classes (1, 4, 8, and 12, with oldest age nearest the boundary edge). The maximum bar length represents a quarterly movement coefficient of 0.55 (second quarter, region 1 to 2).

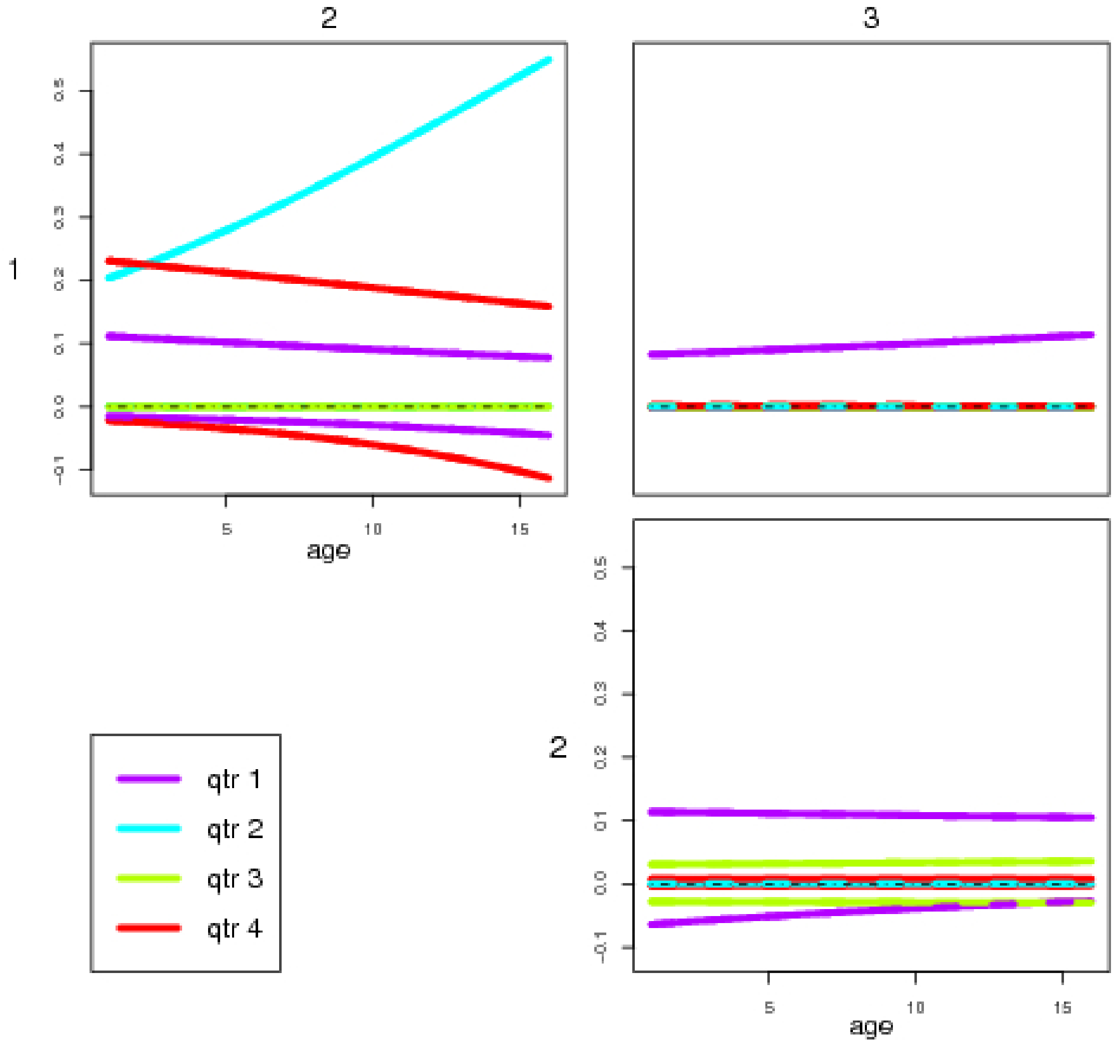

Figure 44: Estimated movements between regions. Movements from the region indicated by the row number to the region indicated by the column number are shown above the line; movements the other way are below the line. Movements by quarter are shown in different colors. The slopes of the lines represent changes with age.

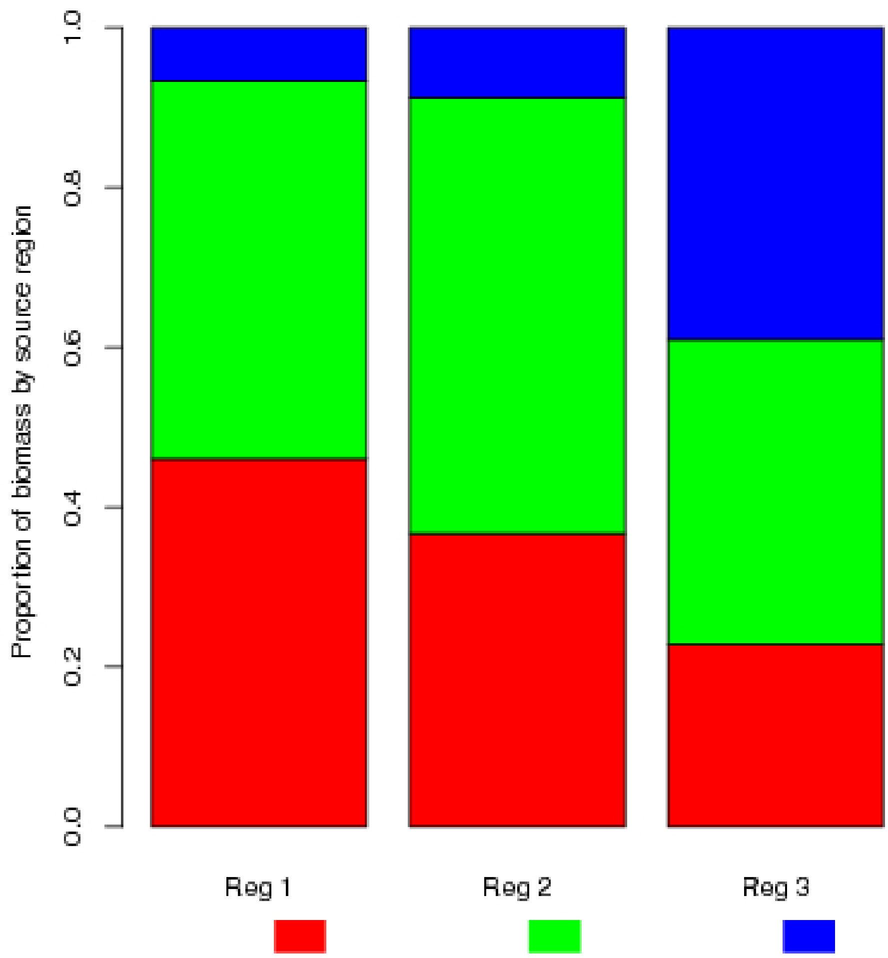

Figure 45. Proportional distribution of total biomass (by weight) in each region (Reg 1–3) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment between regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

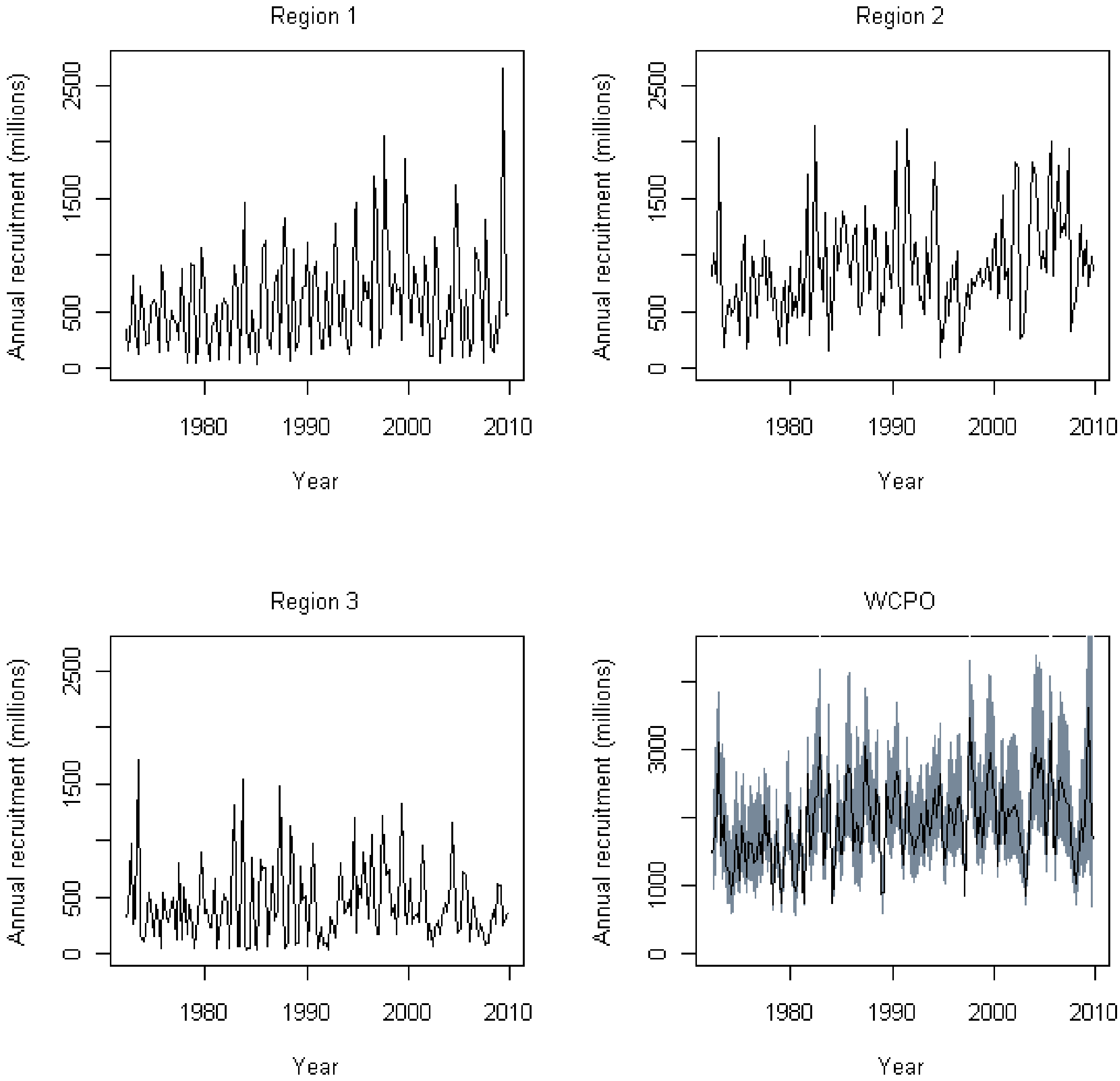

Figure 46. Estimated quarterly recruitment (millions) by region and for the WCPO for the base-case analysis. The dashed line represents the average recruitment for the entire period. The shaded area for the WCPO indicates the approximate 95% confidence intervals.

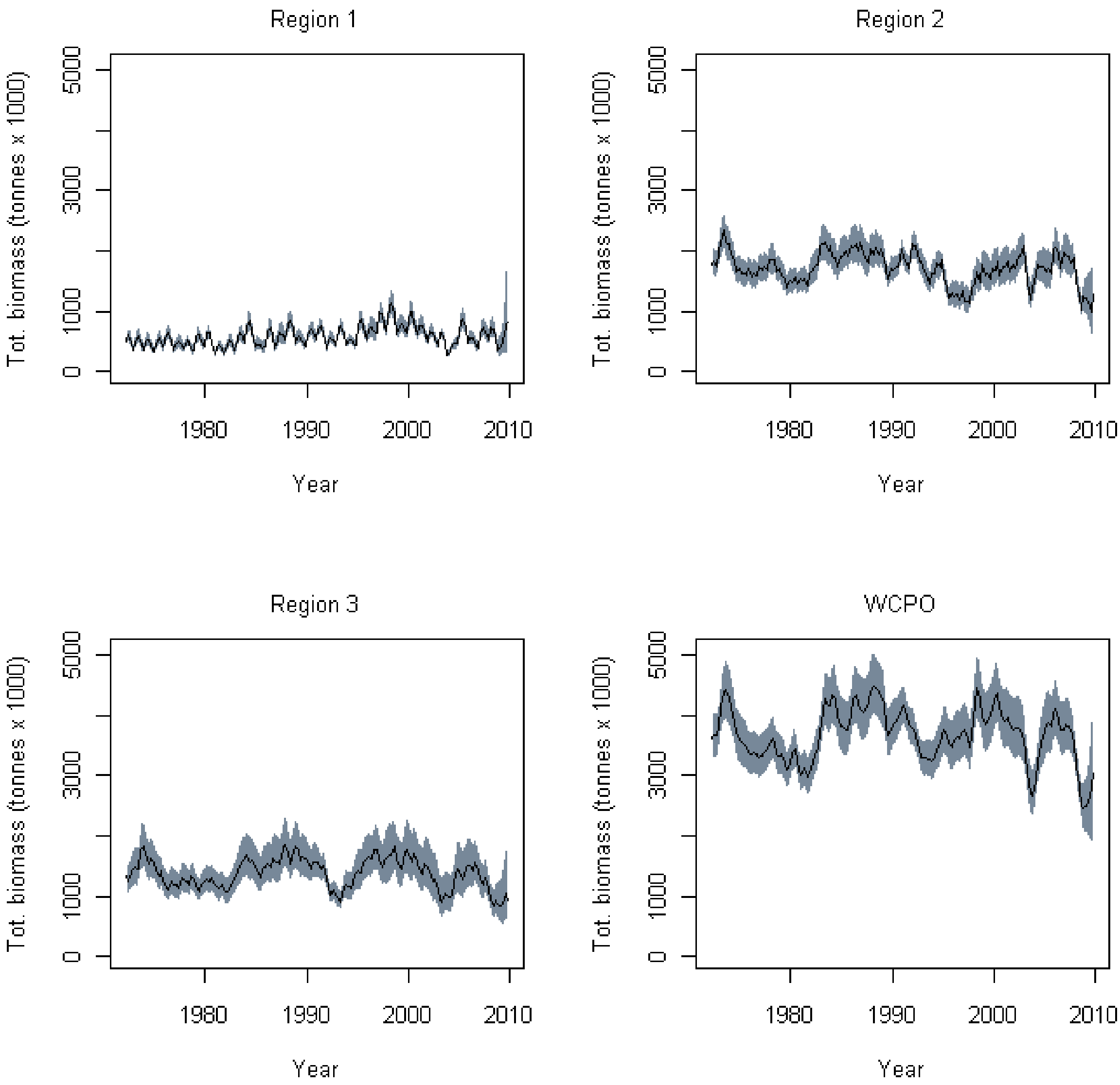

Figure 47. Estimated annual average total biomass (thousand t) by region and for the WCPO for the base-case analysis. The shaded areas indicate the approximate 95% confidence intervals.

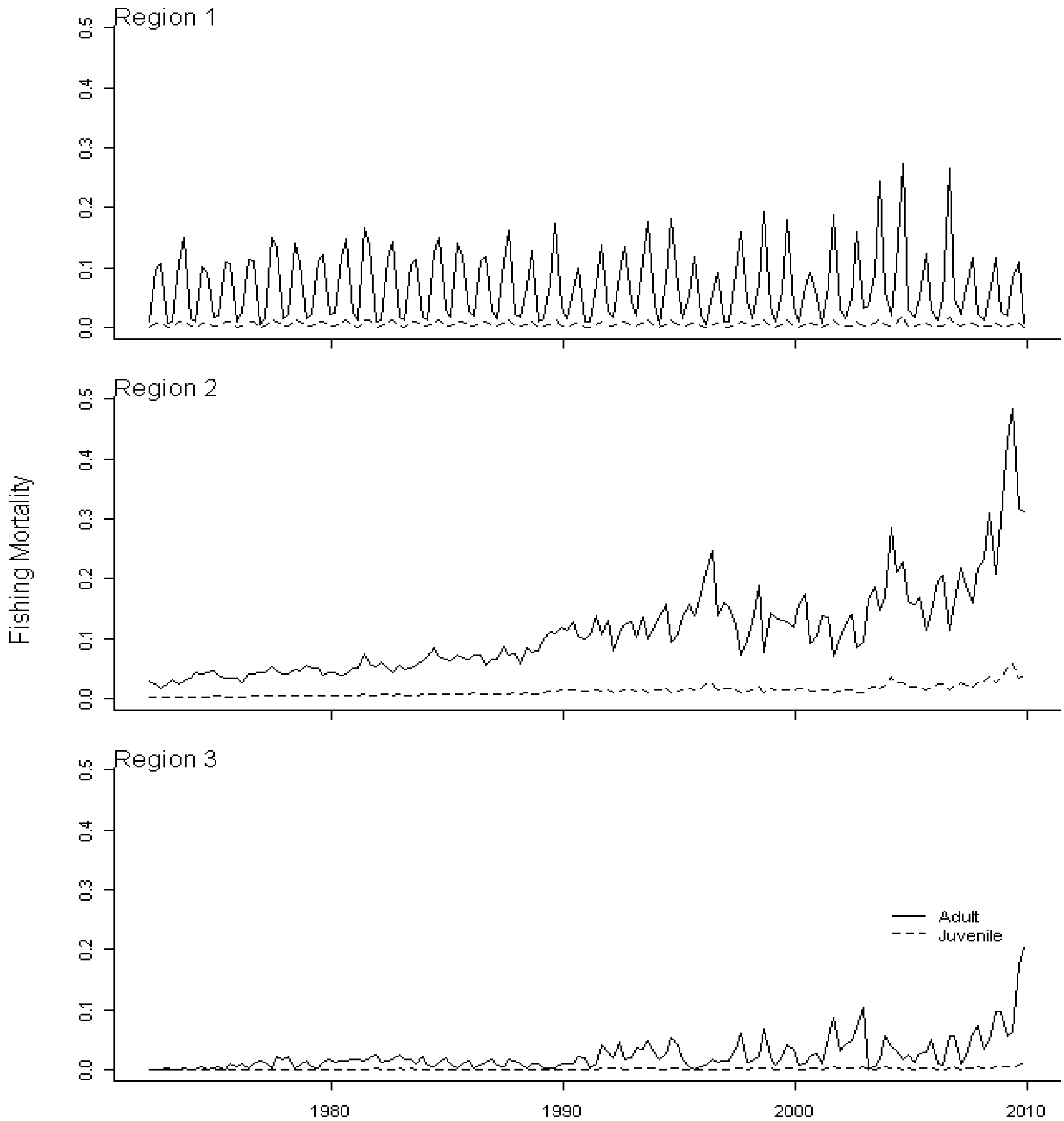

Figure 48. Estimated quarterly average fishing mortality rates for juvenile (age classes 1 and 2) (dashed line) and adult age-classes (solid line).

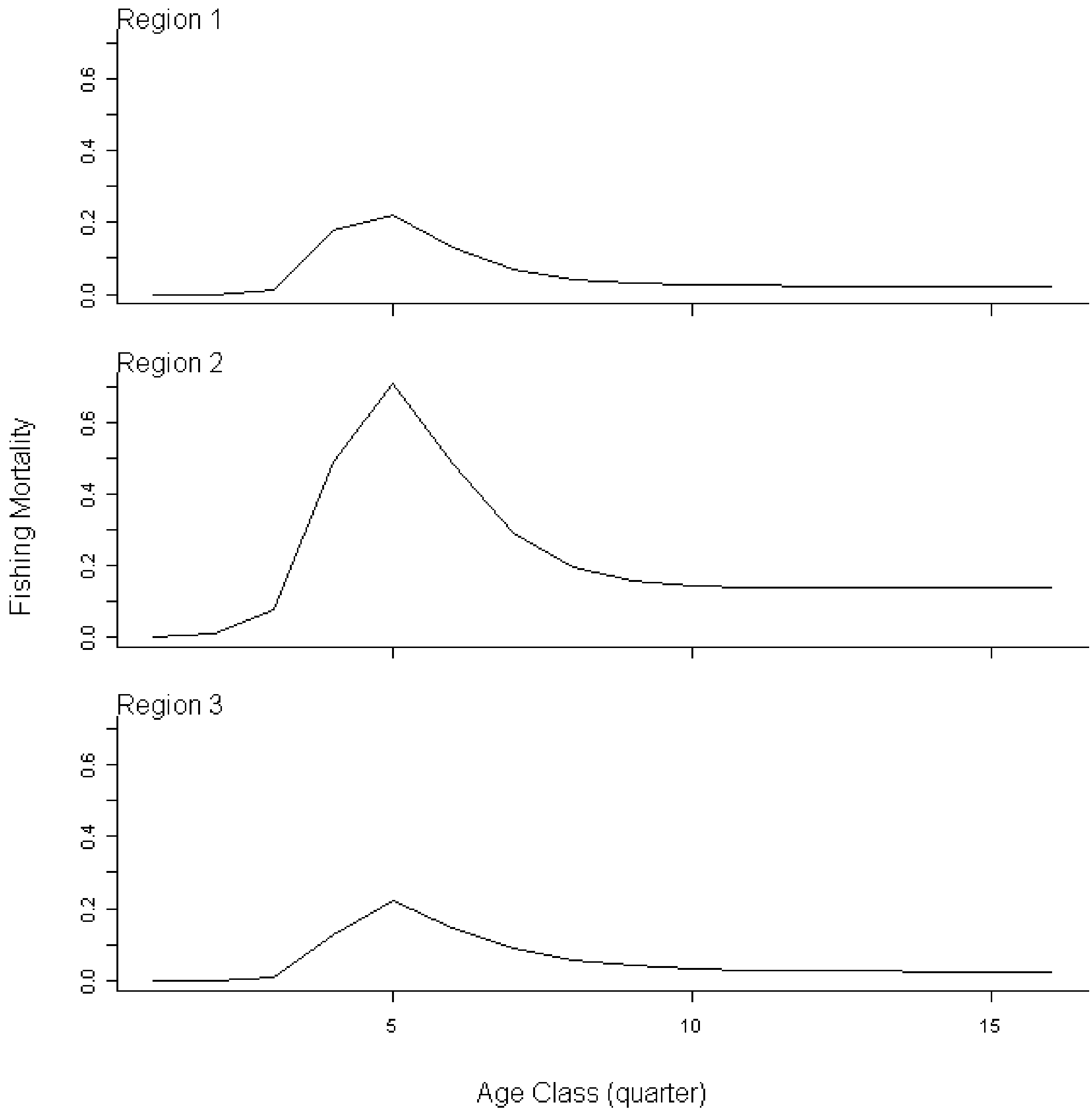

Figure 49. Fishing mortality by age class for the recent (2003-2006) period by region.

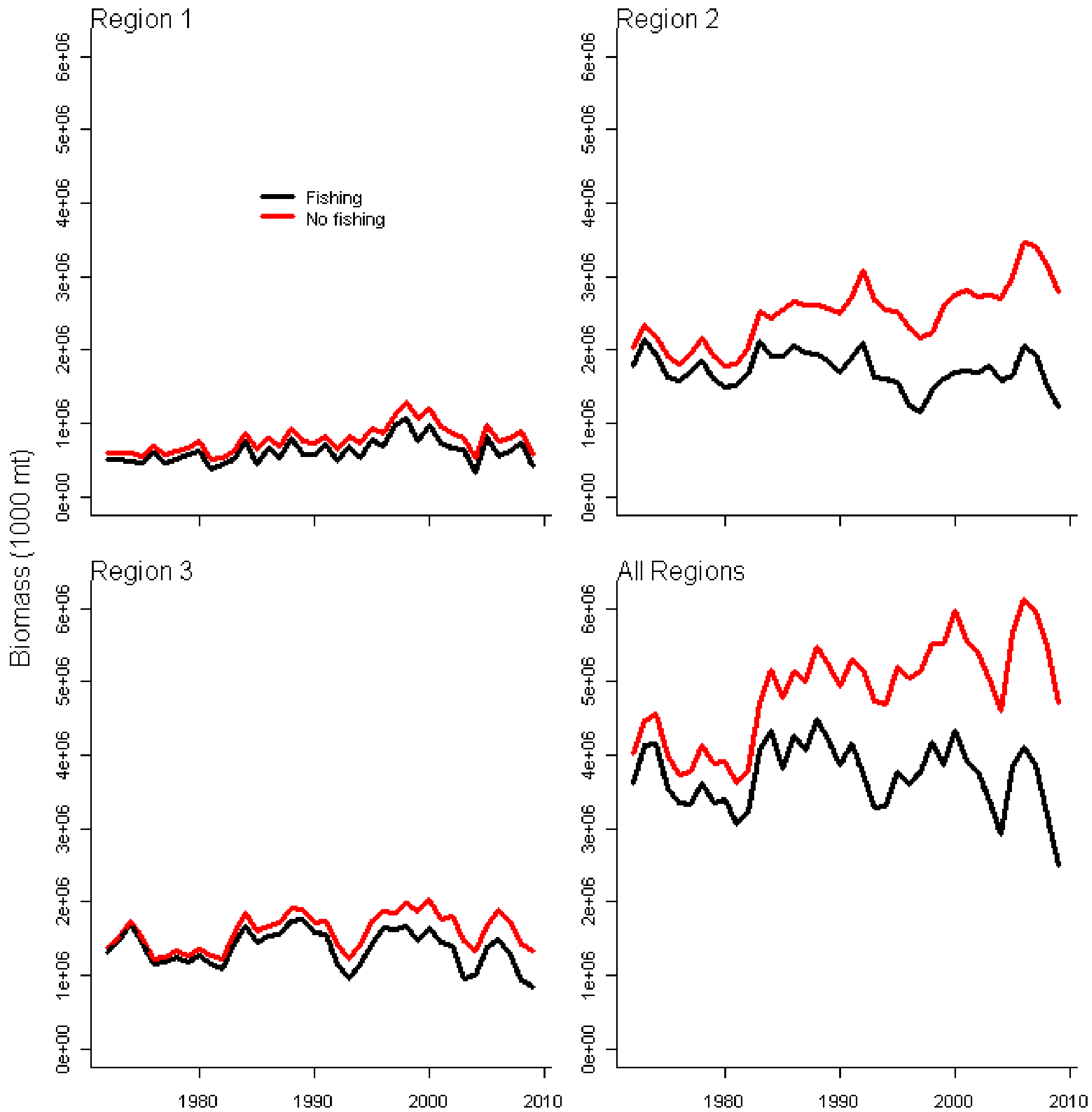

Figure 50. Comparison of the estimated biomass trajectories (lower black lines) with biomass trajectories that would have occurred in the absence of fishing (red lines) for each region and for the WCPO as a whole.

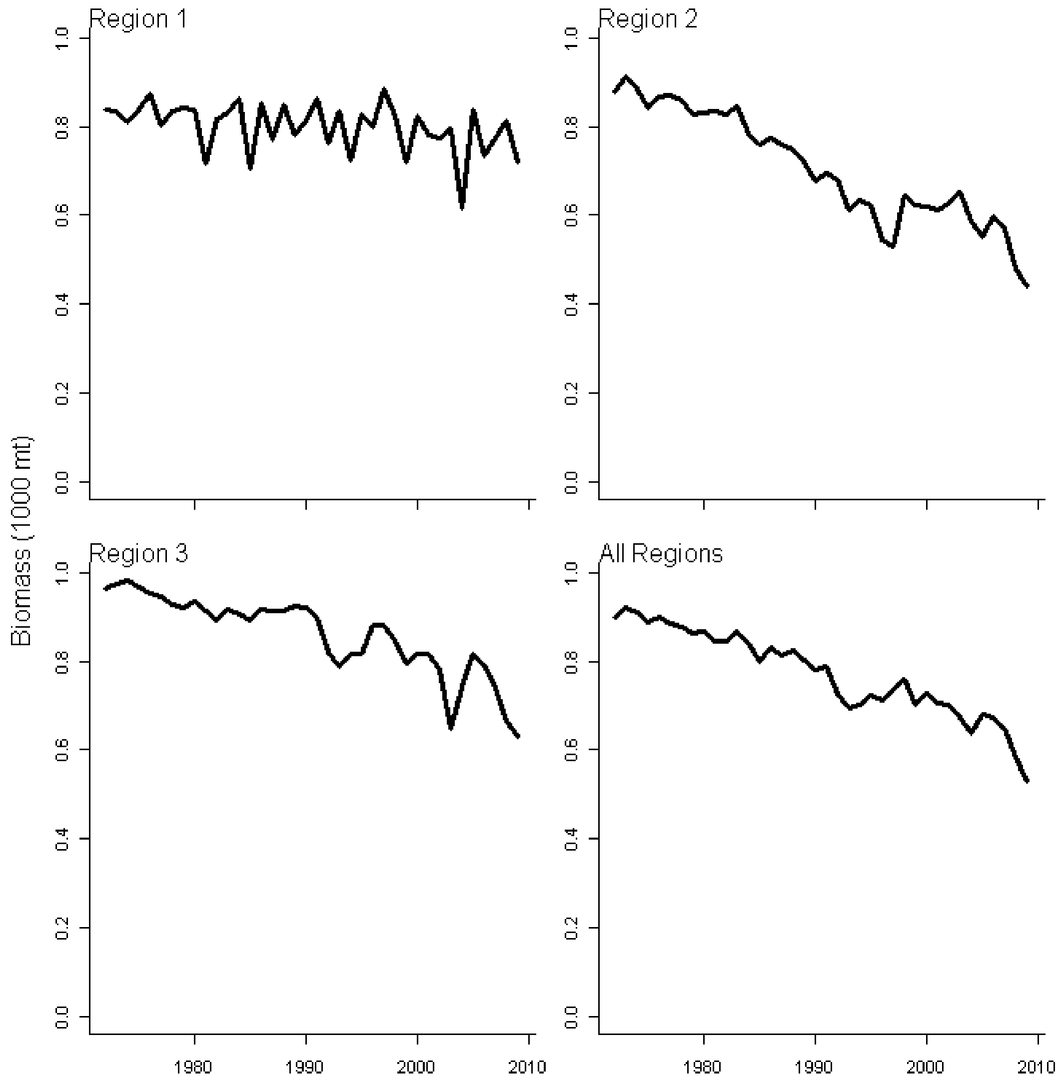

Figure 51. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the WCPO.

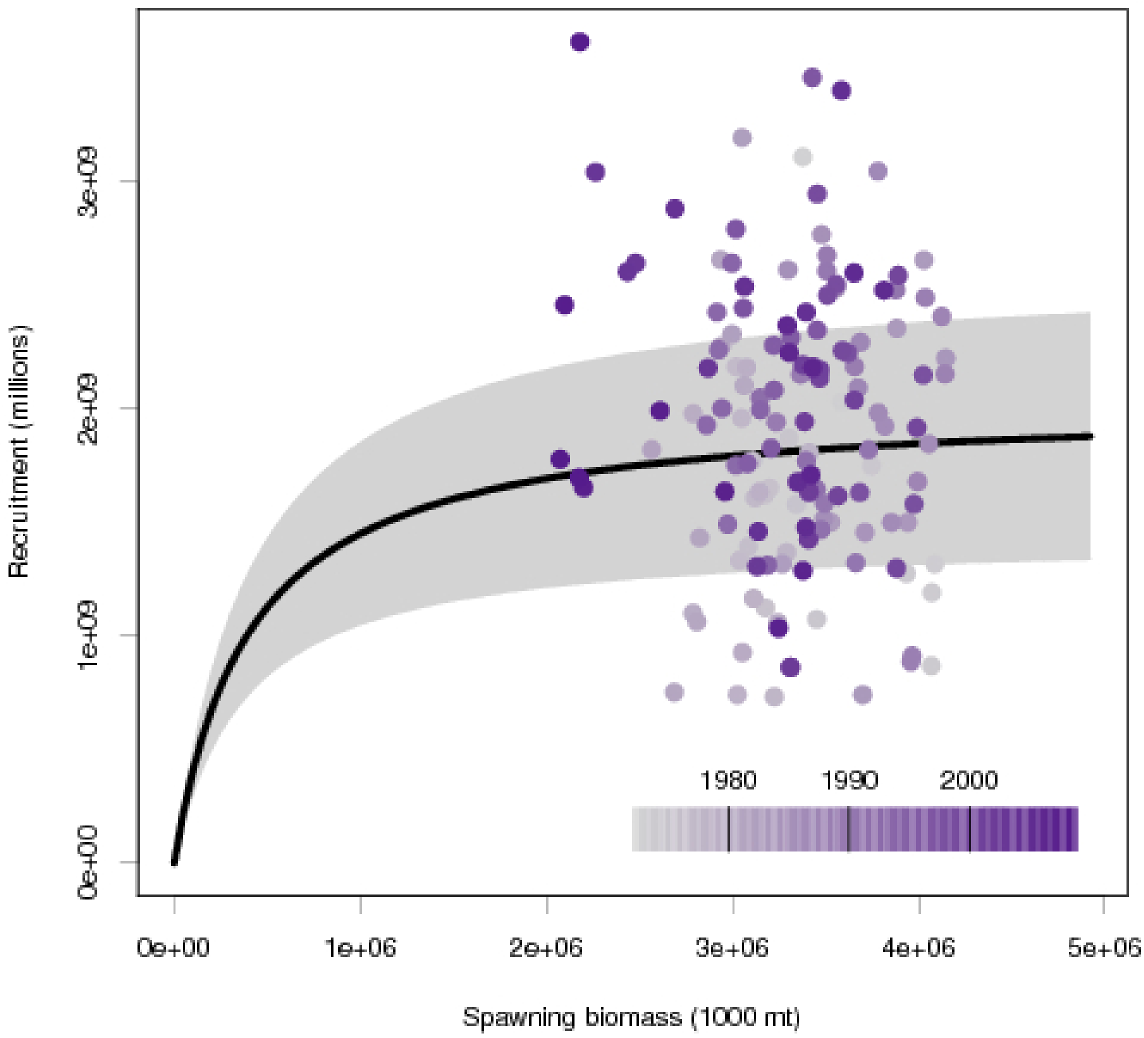

Figure 52. Spawning biomass – recruitment estimates and the assumed Beverton and Holt stock-recruitment relationship (SRR) incorporating steepness of 0.75.

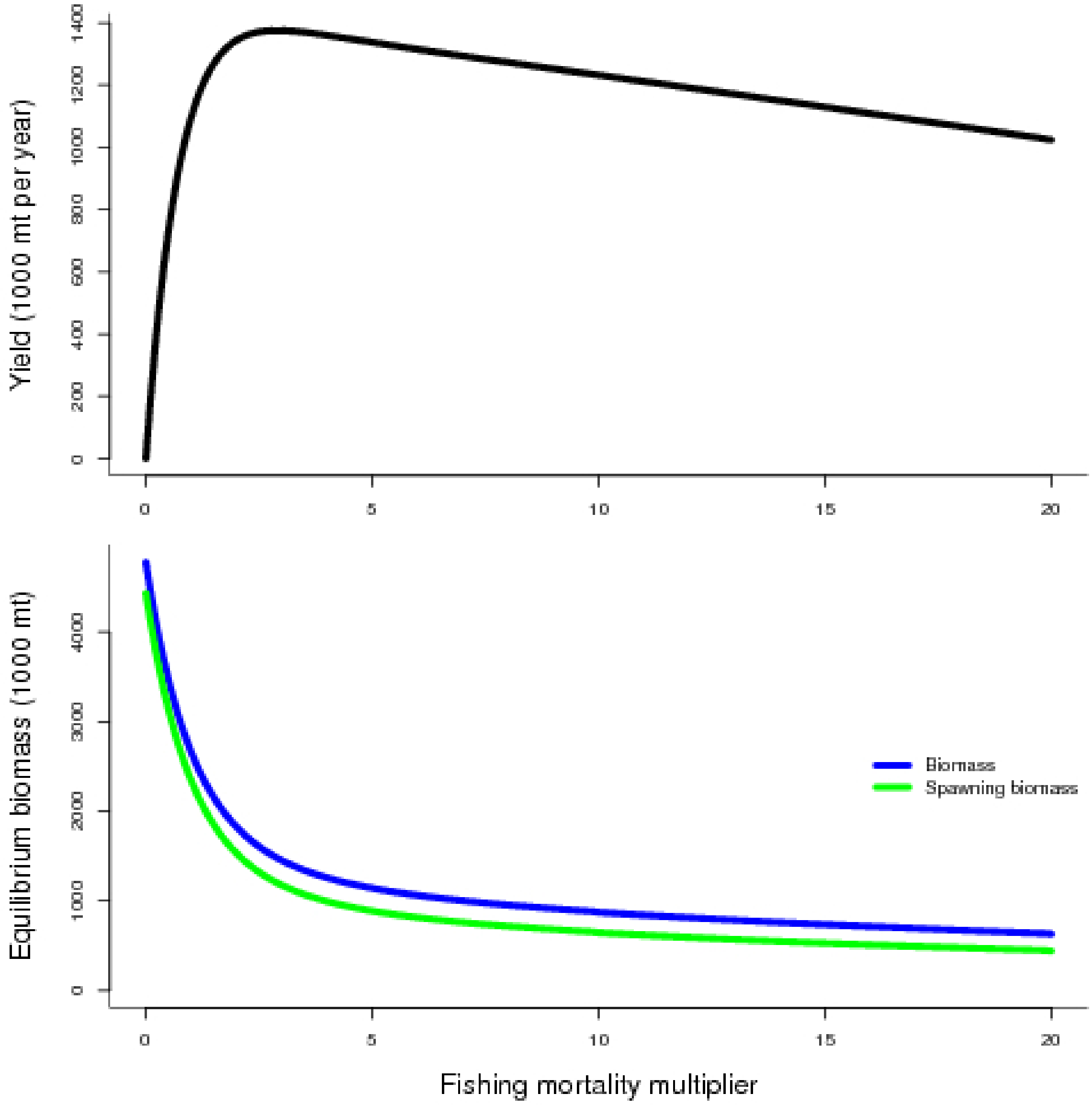

Figure 53. Predicted equilibrium yield (top) and equilibrium adult and total biomass (bottom) as a function of fishing mortality (base-case assessment).

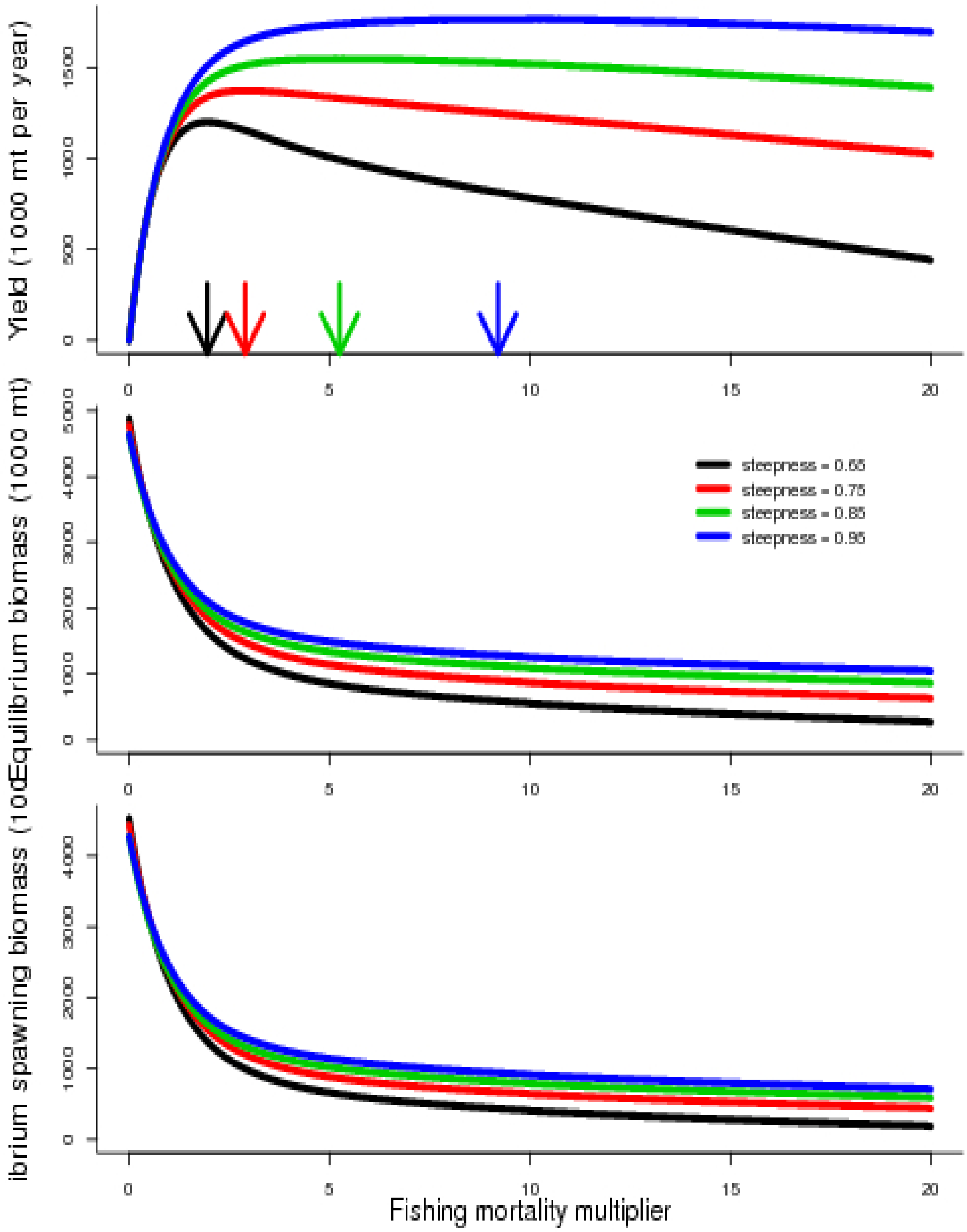

Figure 54. A comparison of equilibrium yields (top), equilibrium total biomass, and equilibrium adult biomass as a function of fishing mortality for the base-case (red line) and alternative steepness models. The arrows represent the fishing mortality multiplier to achieve the MSY.

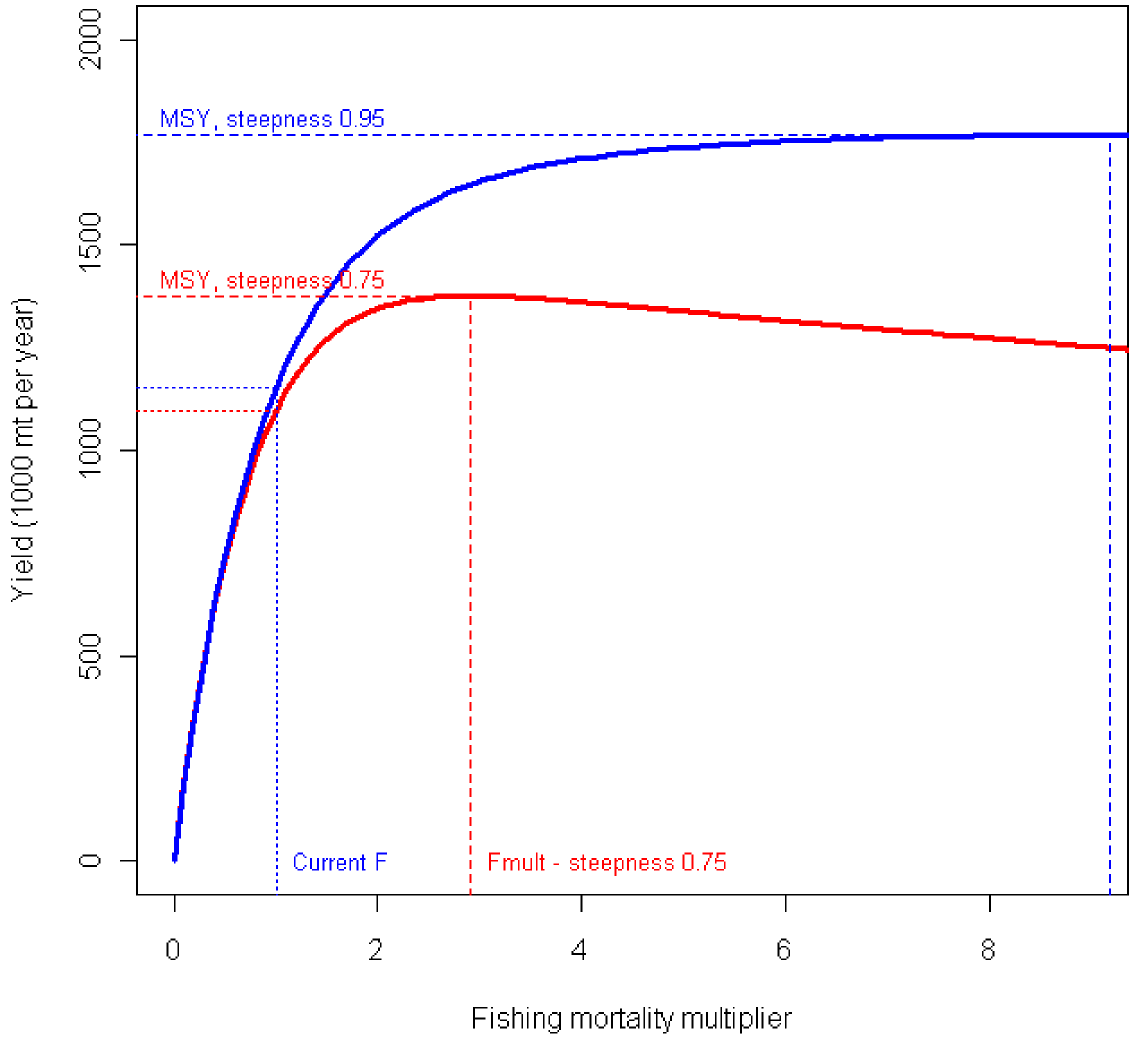

Figure 55: A comparison of equilibrium yields (top), equilibrium total biomass, and equilibrium adult biomass as a function of fishing mortality for the base-case (red line) and the model with steepness of 0.95. The lines mark the current yield and the yield at MSY, and fishing mortality multiplier to achieve the MSY, under each steepness scenario.

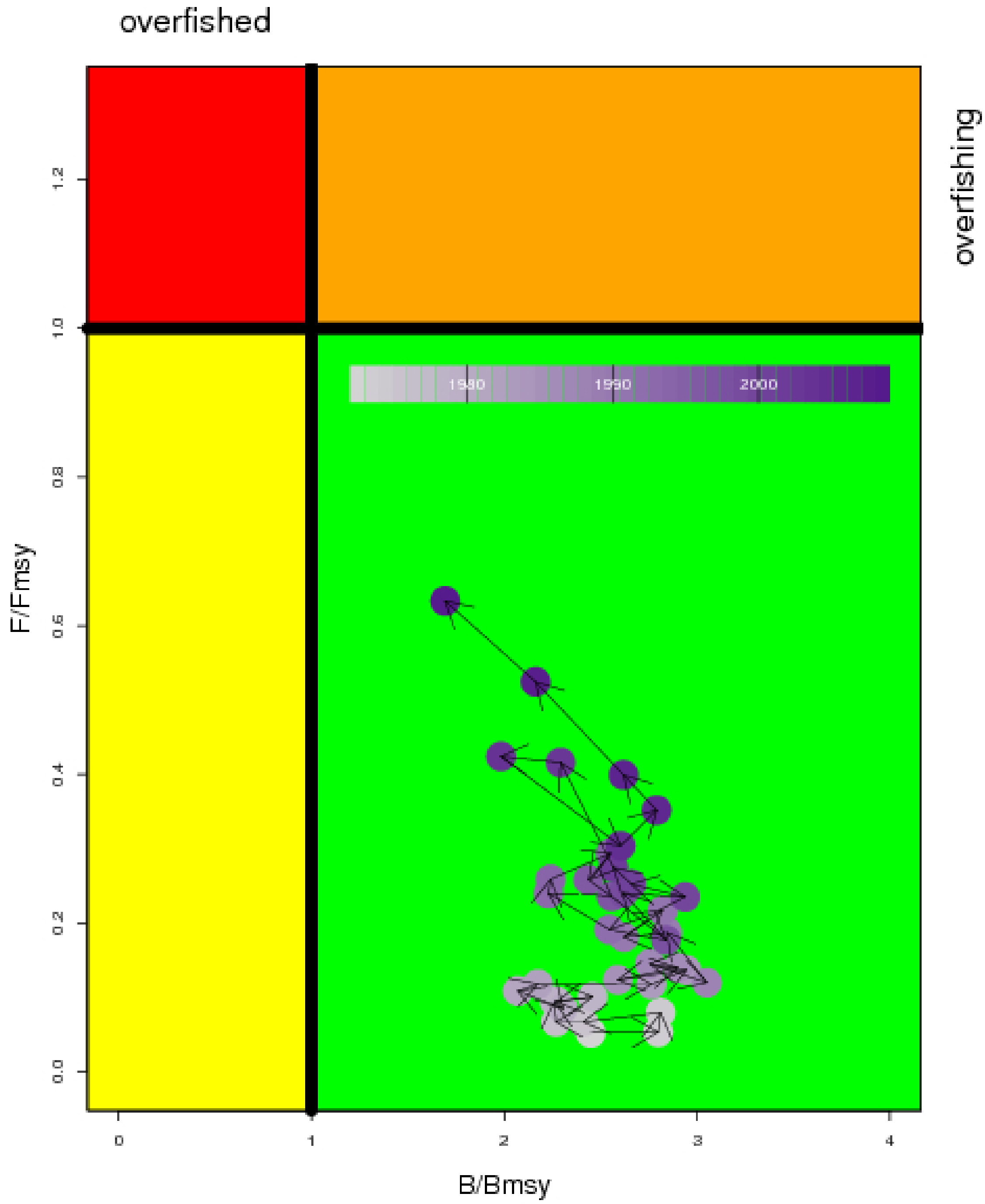

Figure 56. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1972–2009). The colour of the points is graduated from white (1972) to dark purple (2009).

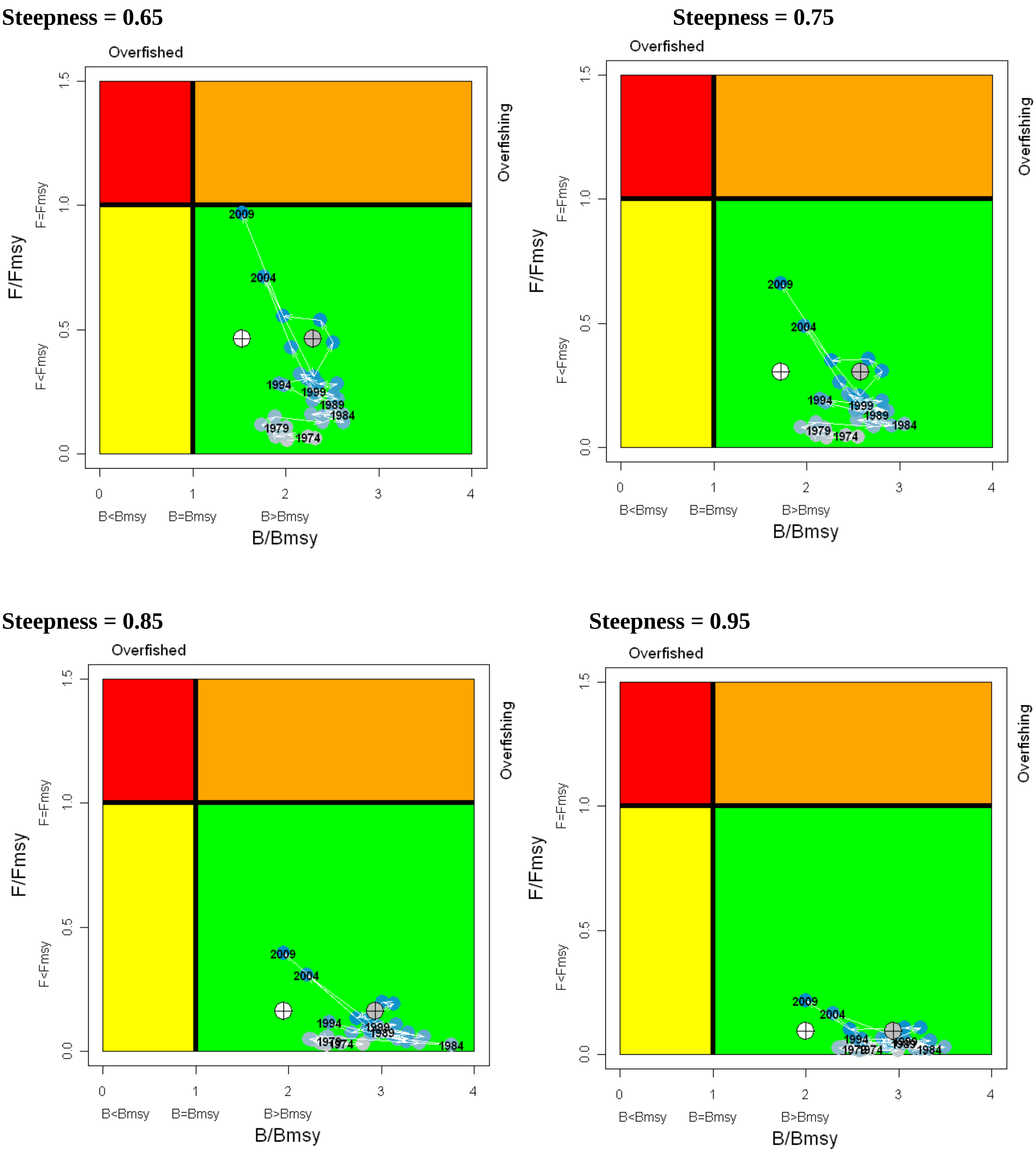

Figure 57: Temporal trend in annual stock status by assumed steepness value (0.65 to 0.95), relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1972–2009). The colour of the points is graduated from white (1972) to dark blue (2009). On each plot the white cross represents the B_{2009}/B_{MSY} and the $F_{2005\text{-}2008}$ / F_{MSY}, and the grey cross represents the $B_{2005\text{-}2008}$ / B_{MSY} and $F_{2005\text{-}2008}$ / F_{MSY}.

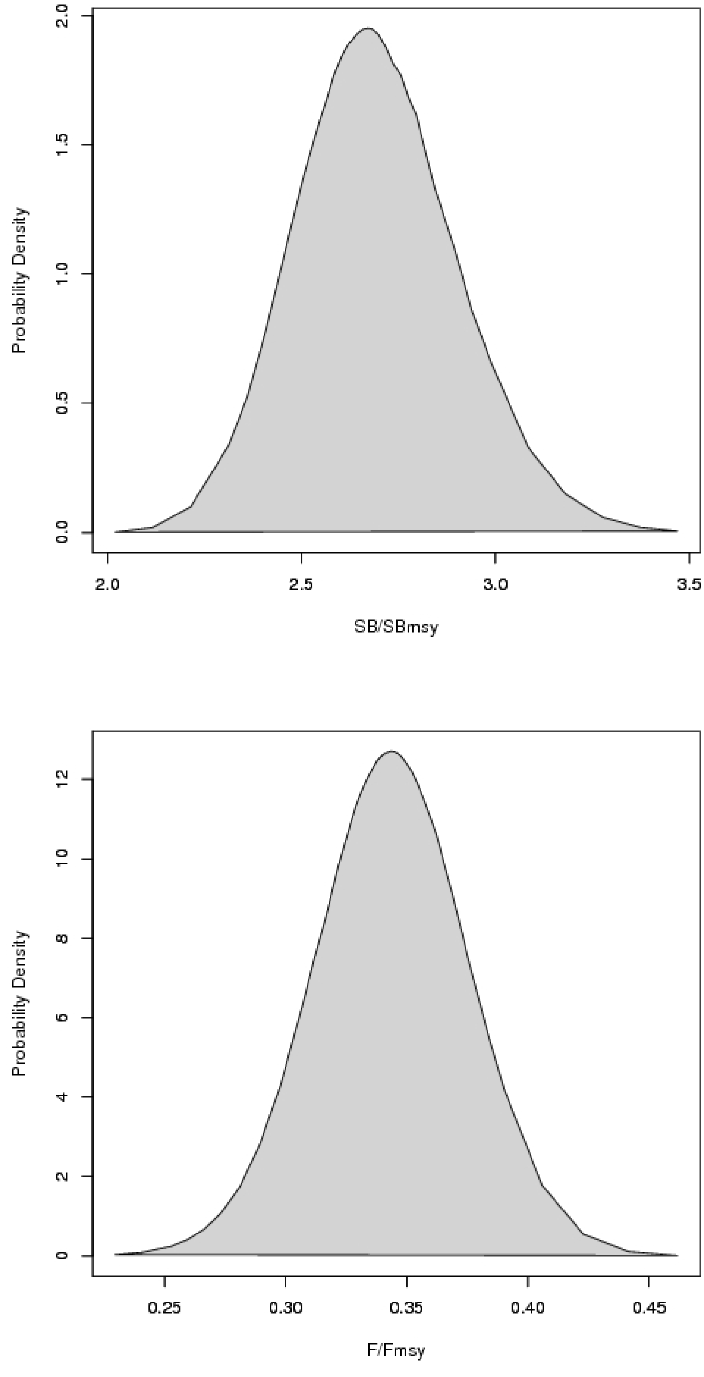

Figure 58. Likelihood profile for SB/SB$_{\mathbf{MSY}}$ (above) and F/F$_{MSY}$ (below) from the base case model.

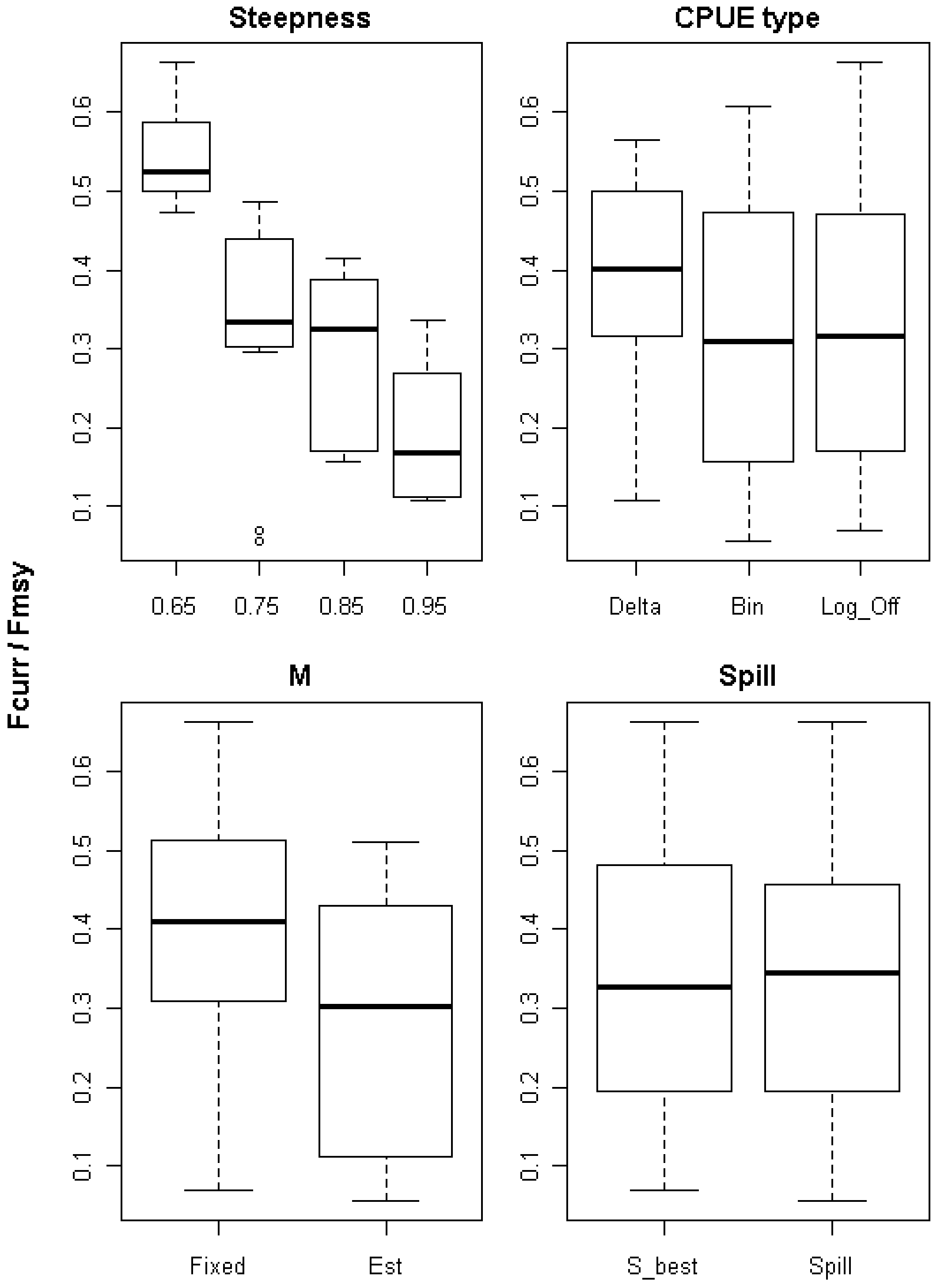

Figure 59: Box plots showing of the effects of the uncertainty grid scenarios (Steepness, CPUE type, natural mortality, and purse seine catch approach) on the management parameter Fcurrent / Fmsy.

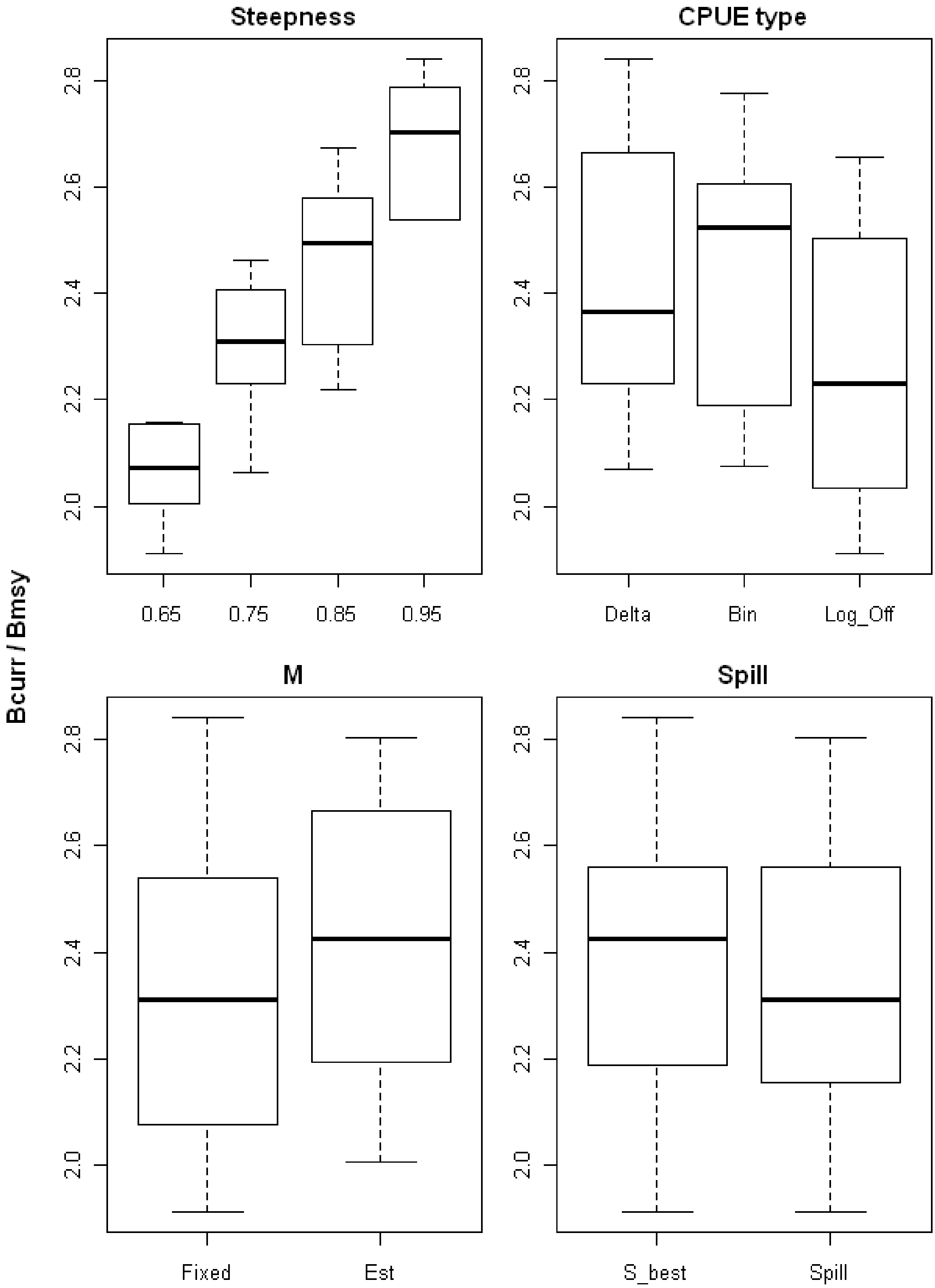

Figure 60: Box plots showing of the effects of the uncertainty grid scenarios (Steepness, CPUE type, natural mortality, and purse seine catch approach) on the management parameter Bcurrent / Bmsy.

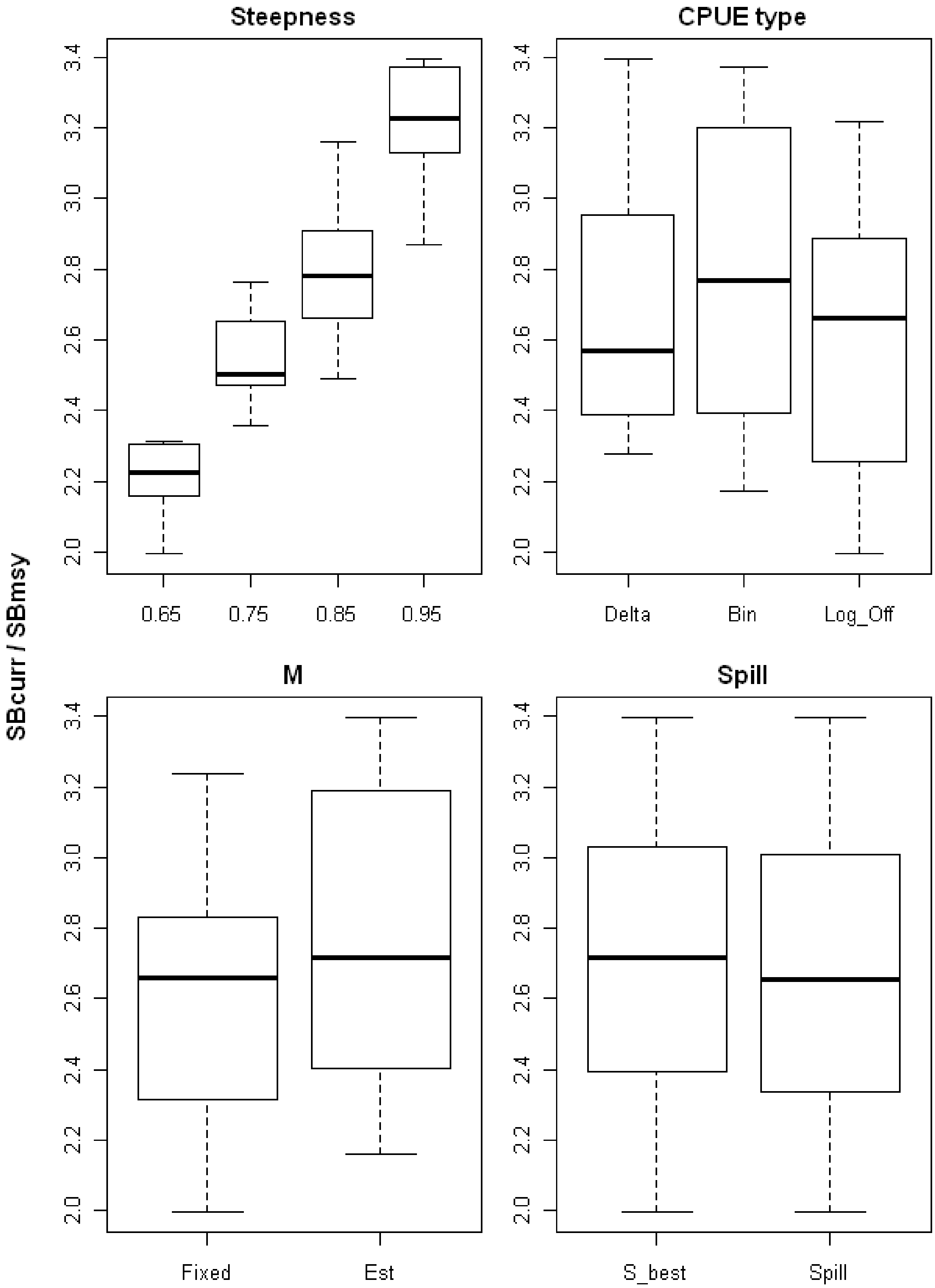

Figure 61: Box plots showing of the effects of the uncertainty grid scenarios (Steepness, CPUE type, natural mortality, and purse seine catch approach) on the management parameter Bcurrent / Bmsy.

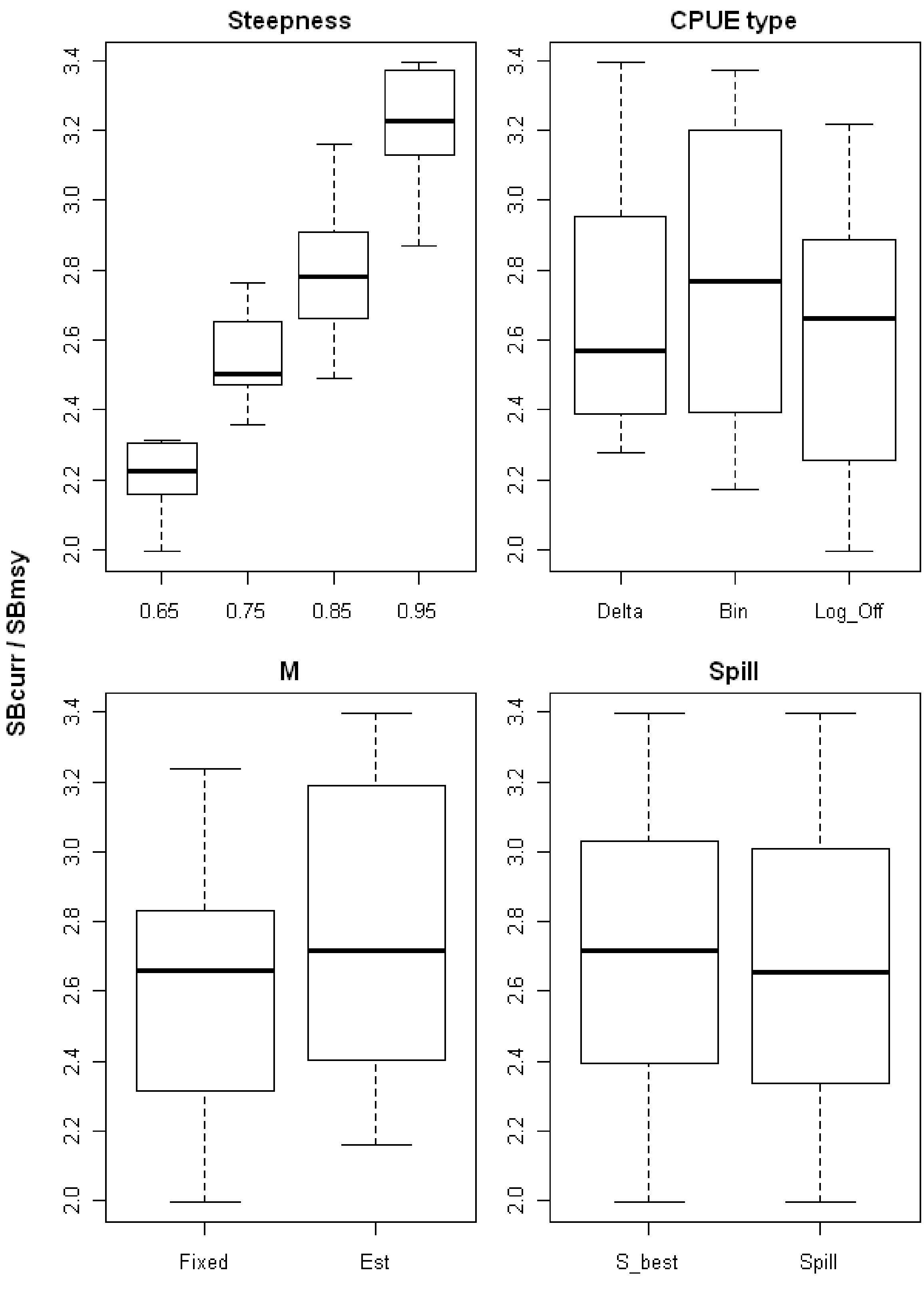

Figure 62: Box plots showing of the effects of the uncertainty grid scenarios (Steepness, CPUE type, natural mortality, and purse seine catch approach) on the management parameter SBcurrent / SBmsy.

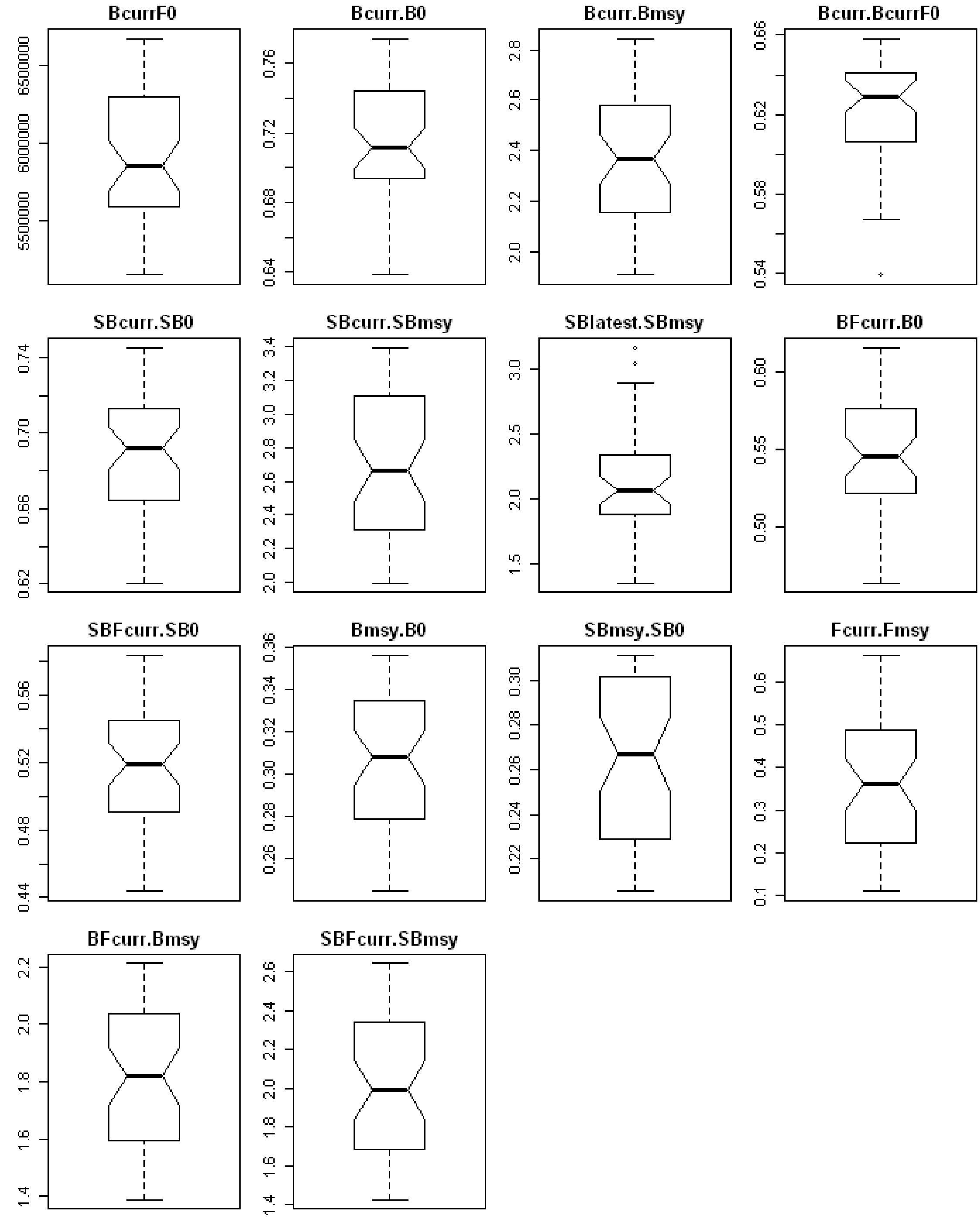

Figure 63: Box plots showing the distribution of management parameters under the range of values in the uncertainty grid.

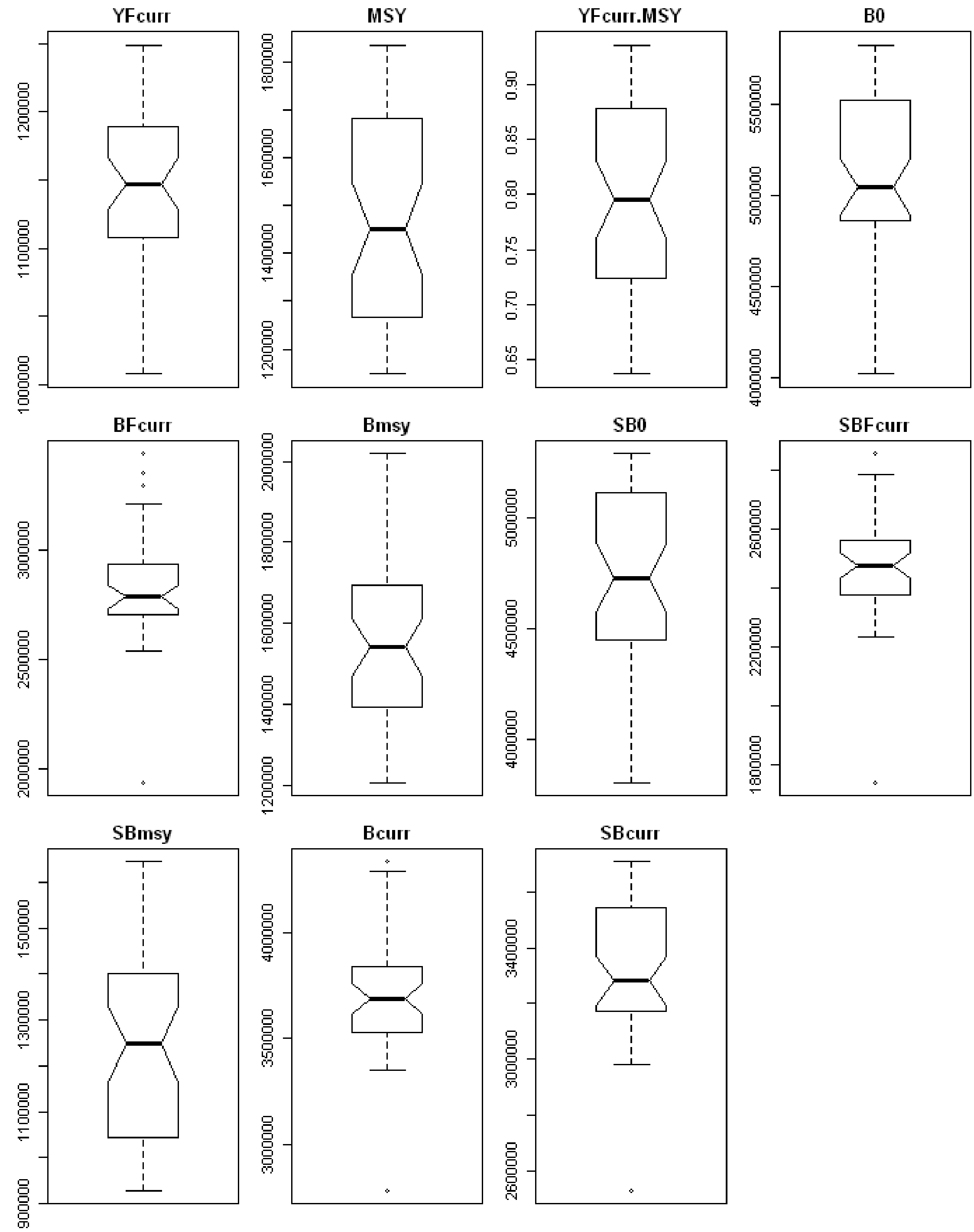

Figure 64: Box plots showing the distribution of management parameters under the range of values in the uncertainty grid.

11 Appendix 1: Tag reporting rates

11.1 Introduction

Tag reporting rates are fundamentally important to modelling tag recapture data. The tag reporting rates used in MFCL have the following components.

1. Tagging-related mortality and tag loss before storage on the vessel
2. Non-reporting of tags that are stored on the vessel

I analyzed tagging data in order to estimate these components. The first component was investigated in two stages. First, average return rates were estimated relative to a well-placed tag, by comparing the effects on return rate of tagging characteristics such as the tagger identity, fish condition, and tag placement quality. Second, 'base' rates of tag mortality and tag loss for this well-placed tag were assigned. Tag loss was estimated from double tagging experiments, in which tags were well placed by the most experienced taggers. The rate of tagging-related mortality for skipjack is unknown and was assumed.

For the second component above, reporting rates were estimated using tag seeding data.

11.2 Methods

Relative return rates were estimated for tags placed during the RTTP and the PTTP. Relative return rates were modeled by tagging event using a binomial GLM. Factors estimated in the model were fish condition on release, tag placement quality, tagging cradle, species, and individual tagger. Data for all species were combined under the assumption that tagger and fish condition affected all species equally.

The model was then used to predict the expected number of tags recovered given the observed variable states, and then to predict the expected recoveries if all fish had been released in optimal condition, by the best tagger. The ratio of the expected recoveries under these conditions was the contribution of the first component of tagging effects to overall reporting rate.

The second component of tagging effects to overall reporting rate was the tag loss and tag mortality associated with fish released by the best taggers, in good condition, and with tags that were considered well-placed.

Reporting rates for the equatorial purse seine fisheries were estimated from tag seeding data for the PTTP. Data from 47 tag seeding kits was available for analysis (Table 11). Two types of tag (steelhead and conventional) were seeded, onto vessels from a number of flags.

Reporting rates (RR) by flag were estimated using a binomial GLM, with factors tag type and vessel flag. Confidence intervals (95%) were estimated (Wilson 1927) but with a lower effective sample size (n=4 for each kit) to allow for the fact that the fates of tags within a kit were not independent, but largely determined by the trip reporting rate.

Individual flag-level reporting rates were raised to the full fishery reporting rate based on the catch of each flag. Flags with no tags seeded were allocated a reporting rate from another country, based on assumptions about similarities between countries. Catches were summed across the equatorial area by flag for 2007-2009, and the proportion taken by each flag was calculated. Catch proportions were multiplied by country-level reporting rates, and summed to give overall reporting rate.

Uncertainties in reporting rate were estimated through Monte Carlo simulation. For each flag, a reporting rate was generated from the probability distribution of the observed reporting rate. For flags without estimates, RR distribution was sampled from the distribution of the logit of the assumed reporting rate with assumed SE of 2.

Ordinary seeded tags are thought to have a lower reporting rate than actual tags due to poor retention, so reporting rate for steelhead tags were used in all cases. Uncertainty in steelhead tag reporting rate was included by sampling from the probability distribution of the tag term, and including the sample in the RR for all countries.

For 1000 samples of all variates, the total catch reporting rate was estimated.

11.3 Results

Data were analyzed for 163 980 tagged skipjack in the PTTP, for which 21 249 tags were returned. The ratio of predicted returns to predicted returns under ideal conditions was 86.4 %. For the RTTP, 74 265 releases and 9087 recoveries were analyzed, and the return ratio was 89.2%.

Tag loss for tags placed by expert taggers were estimated during the RTTP at 11% (Hampton 1997). Limited repeat experiments during the PTTP gave results that were not significantly different (John Hampton personal communication).

Tagging related mortality is unknown for skipjack or for any other tuna species. Skipjack are caught at the surface so do not suffer barotrauma. However, they are highly active and may suffer damage during the time they are kept out of the water. The fact that return rates differ substantially among taggers suggests that fish treatment can affect survival rate. I assumed a tagging-related mortality rate for expert taggers of 7%, with 95% CI from 3% to 16%.

For analyses of seeded tag reporting rates, the model with best AIC included flag and tag type (Table 12). Steel head tags were returned at a higher rate, by about 49%, but the difference was uncertain, mainly because the tag types were seeded on different trips. The 95% CI was 13% to 77% (Table 15 and Table 14).

Reporting rates varied significantly by flag, but many flags' rates were highly uncertain (Table 13). The analysis assumed constant reporting rate, but in fact steelhead tags were not seeded at the same time as conventional tags. In general they were seeded later. This adds more uncertainty to the ratio, because reporting rates vary through time.

Catches and catch proportions were calculated for all major purse seine fleets (Table 16).

The overall PTTP PS fleet reporting rate (for tags in the well) was estimated to be 54%, with 95% CI from 39-72% (Table 17).

The combined PTTP MFCL purse seine reporting rate, including tag-related mortality and tag loss, was 38%, with 95% CI 25-50%.

The combined RTTP purse seine reporting rate for MFCL was estimated as 42%, with 95% CI of 29 to 50%.

All other reporting rates were estimated in the model and given uninformative priors with mean of 0.42.

11.4 Discussion

Return rates are more likely to vary by fish processor than by vessel flag, but we currently lack comprehensive information on the fish processor from which the tags were returned. The volume of skipjack processed by each processor is also required, and the best possible information about the processor destination of the fish on each seeded vessel.

The results of the analysis were quite uncertain, and support the need for ongoing tag seeding. A power analysis would be useful to identify how much tag seeding is needed, and how it should be allocated across flags and processors.

These results directly scale all the reporting rates in the model. A 20% higher reporting rate implies a 20% higher biomass estimate (though other data in MFCL moderate this). Reporting rate is one of the most important parameters in the model.

Seeding both conventional and steelhead tags on the same trip (in the same kit) would give more accurate estimates of the relationship between tag type return rates. Double tagging individual fish with both conventional and steelhead tags would also be helpful.

Tagging mortality is unknown, but new tag types may provide a way to estimate this parameter. For example, small and relatively cheap pop-up tags are now available that are inserted like conventional tags.

I assumed that a) seeded steelhead tags were shed in the vessel at the same rate as captured conventional tags, and b) steelhead tags were not recognized as different by industry and treated differently. Some captured tags are shed on the vessel, so if steelhead tags are shed less then they would have a higher return rate than captured tags. Double tagging with steelhead tags would enable their loss rate to be estimated. Also, people notice things that are different, so may be more likely to return the unusual steelhead tags. It may be worth seeding some tags that are unusual in a different way but have the same retention as conventional tags (e.g. different head colour, different shaft material) to see if this also affects the return rate.

11.5 Tables

Table 11: Releases and recoveries by flag of standard and steelhead tags.

Flag	Steelhead releases	Steelhead recoveries	Standard releases	Standard recoveries	Total releases	Total recoveries
CN			42	1	42	1
MH			90	33	90	33
NZ			40	1	40	1
PG	120	94	254	128	374	222
PH	50	43	93	69	143	112
TW			33	10	33	10
US	180	101	124	48	304	149
Grand Total	**350**	**238**	**676**	**290**	**1026**	**528**

Table 12: Model comparisons using Akaike Information Criterion (AIC)

Model	AIC
Flag + tag type	92.74
Flag * tag type	96.18
Flag	98.08
Tag type	109.79

Table 13: Predicted terms of the binomial model for flags

flag_id	tag_type	fit.as.factor(flag_id)	se.fit(flag_id)
CN	S13	-3.28	2.18
MH	S13	-0.11	0.50
NZ	S13	-3.23	2.18
PG	S13	0.53	0.23
PH	S13	1.44	0.45
TW	S13	-0.40	0.84
US	S13	-0.18	0.28

Table 14: Estimated return rates by flag and tag type

Flag	Tag type	Estimate	Std error
CN	SteelH	0.06	0.13
MH	SteelH	0.60	0.15
NZ	SteelH	0.06	0.13
PG	SteelH	0.74	0.07
PH	SteelH	0.88	0.06
TW	SteelH	0.53	0.23
US	SteelH	0.59	0.07
CN	Conv	0.02	0.05
MH	Conv	0.37	0.11
NZ	Conv	0.03	0.06
PG	Conv	0.52	0.06
PH	Conv	0.73	0.09
TW	Conv	0.30	0.18
US	Conv	0.35	0.08

Table 15: Predicted terms of the binomial model for tag type

tag_type	fit.as.factor(tag_type)	se.fit(tag_type)
S13	0.65	0.25
Y13	-0.30	0.12

Table 16: Catches and proportion of total catch by fleet

	2007	2008	2009	Total	Catch
CN	48,182	42,217	67,196	157,595	4%
EC	6,411	5,804	4,942	17,157	0.4%
ES	12,202	24,604	19,625	56,431	1.3%
FM	11,893	15,652	15,701	43,246	1.0%
ID	138,341	149,420	144,539	432,300	10%
JP	160,909	153,744	159,856	474,509	11%
KI	4,803	4,310	16,786	25,899	1%
KR	220,854	186,333	257,365	664,552	16%
MH	53,907	26,960	39,775	120,641	3%
NZ	23,142	23,139	26,353	72,634	2%
PG	187,160	154,299	162,814	504,272	12%
PH	149,704	176,776	154,487	480,966	11%
SB	10,774	5,462	-	16,236	0.4%
SV	3,052	6,748	6,770	16,570	0.4%
TV	-	-	3,591	3,591	0.1%
TW	208,871	165,307	174,347	548,525	13%
US	77,684	167,785	247,705	493,174	12%
VU	62,958	30,408	35,878	129,244	3%

Table 17: Reporting rate estimates for the overall purse seine fleet and their probability distributions

	RTTP		PTTP	
	Reporting	Reporting, tag loss, & tag mortality	Reporting	Reporting, tag loss, and tag mortality
RR	0.59	0.45	0.55	0.40
SE	0.045	0.058	0.083	0.076
2.50%	0.50	0.30	0.40	0.25
97.50%	0.68	0.54	0.72	0.55

12 Appendix 2: Spatial size patterns in skipjack

12.1 Introduction

Changing size patterns through time have been observed in the size data sourced from skipjack fisheries. Such changes can affect size-based stock assessment models such as MULTIFAN-CL by altering the estimate of total mortality, and affecting the growth curve estimates. Factors that may contribute to these changes were investigated.

12.2 Methods

Skipjack length frequency data were extracted from the SPC size database. The data were cleaned to remove outliers, and classified by fishery, gear type, flag and fleet.

1. For each fishery, sampling locations were plotted through time by 5 year period.

2. Factors affecting size were investigated by analyzing the data with a generalized linear model. For each fishing method, length was modelled as a function of location, year, flag, fleet, and time of year. The models assumed a normal error distribution.

Length ~ year + month + latitude + longitude + flag * fleet.

12.3 Results

There was considerable spatial variation in the sources of the size data for Japanese pole and line (Figure 65), purse seine (Figure 66 and Figure 67), and Japanese research longline data (Figure 68).

There was strong spatial variation in fish sizes. The strongest pattern observed was that larger fish were found further east in all regions (Figure 69). In regions 1 and 2 there was also latitudinal variation, with the smallest fish found between 10S and the equator (Figure 70). Smaller fish were also found north of 20N, with the largest fish found between 10N and 20N.

There is also marked seasonality in the spatial distribution of fish sizes in region 1 (results not shown here).

Trends through time were apparent, after taking latitude, longitude, and flag into account. However, these trends were not consistent among gear types or regions.

12.4 Discussion

These spatial patterns of size variation, combined with the maps of sample sources, suggest that movement of sampling location may partly explain the observed patterns of fish size change in the aggregated length frequency data used in the stock assessment for the Japan pole and line, Japan research longline, and purse seine fisheries. However, even after taking location into account, some temporal variation in fish sizes remains. Contributing factors may include true changes in average fish size (due to recruitment pulses, changes in total mortality, and changes in growth rate), sampling biases (such as those associated with grab sampling, and variation among sampling programs), and possible shortcomings of the model used to estimate the year effect.

Given constant selectivity, the model interprets fish size change as reflecting change in total mortality. If fish sizes change for inappropriate reasons, such as sampling that moves into an area where fish sizes are different, the model results can be affected through failure to fit the data.

In the short term, reduction of effective sample size is appropriate, in order to reduce the influence of size data on population trends. In the longer term the following steps are recommended:

- First, fishery locations should be adjusted to cover smaller spatial subsets of each region, in order to increase the consistency of sizes available to each fishery.

- Second, size data should be carefully analyzed to ensure that fish are sampled across the distribution of the population within each fishery.
- Third, steps should be taken to ensure that future sampling covers the spatial distribution of the fisheries and the population as much as possible, following an efficient statistical design. Accurate, detailed information on all aspects of sampling is required.

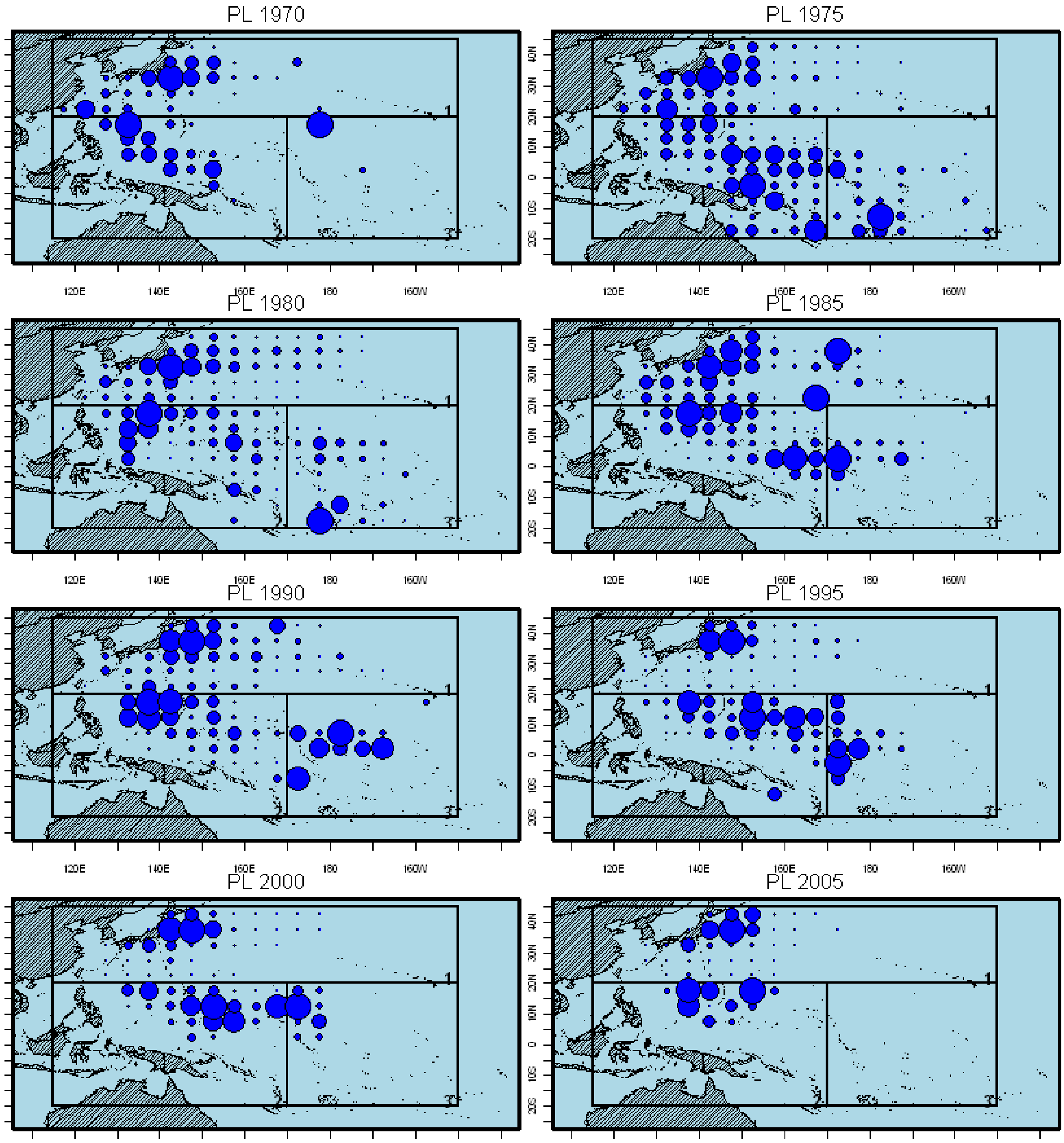

Figure 65: Sample locations through time for Japanese pole and line fisheries. Circle area represents the number of samples.

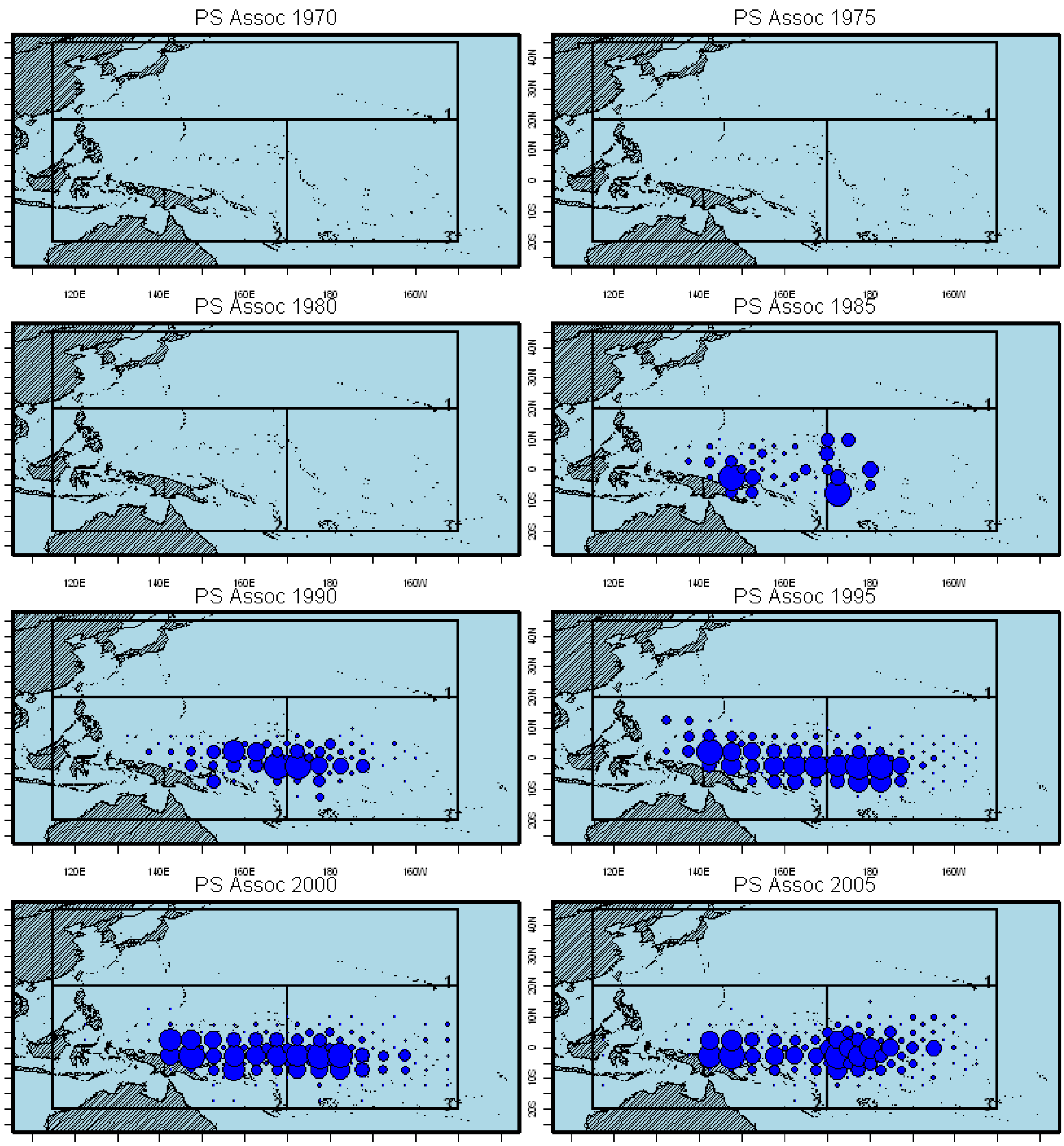

Figure 66: Sample locations through time for size data from associated sets in purse seine fisheries. Circle area represents the number of samples.

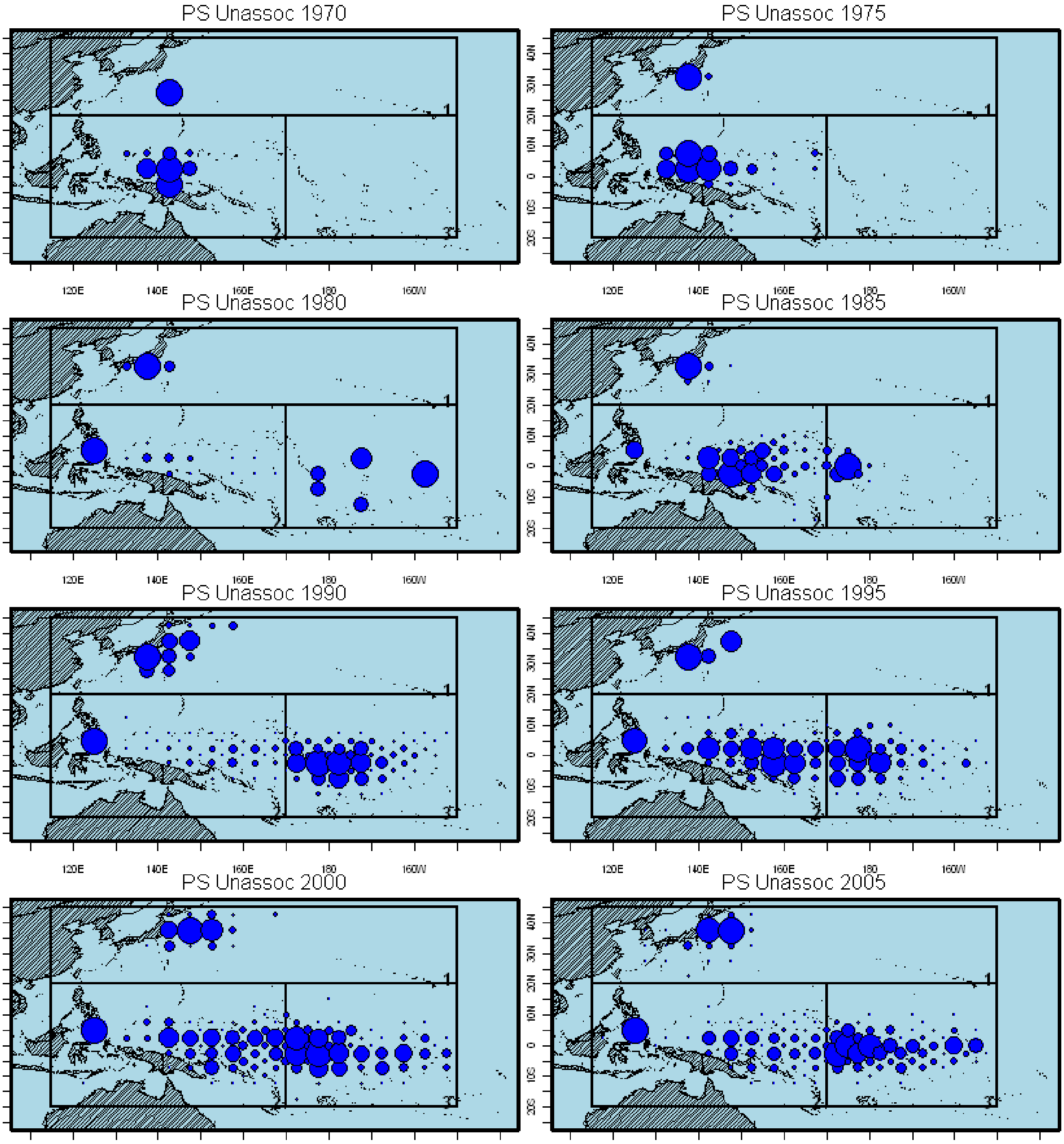

Figure 67: Sample locations through time for size data from unassociated sets in purse seine fisheries. Circle area represents the number of samples.

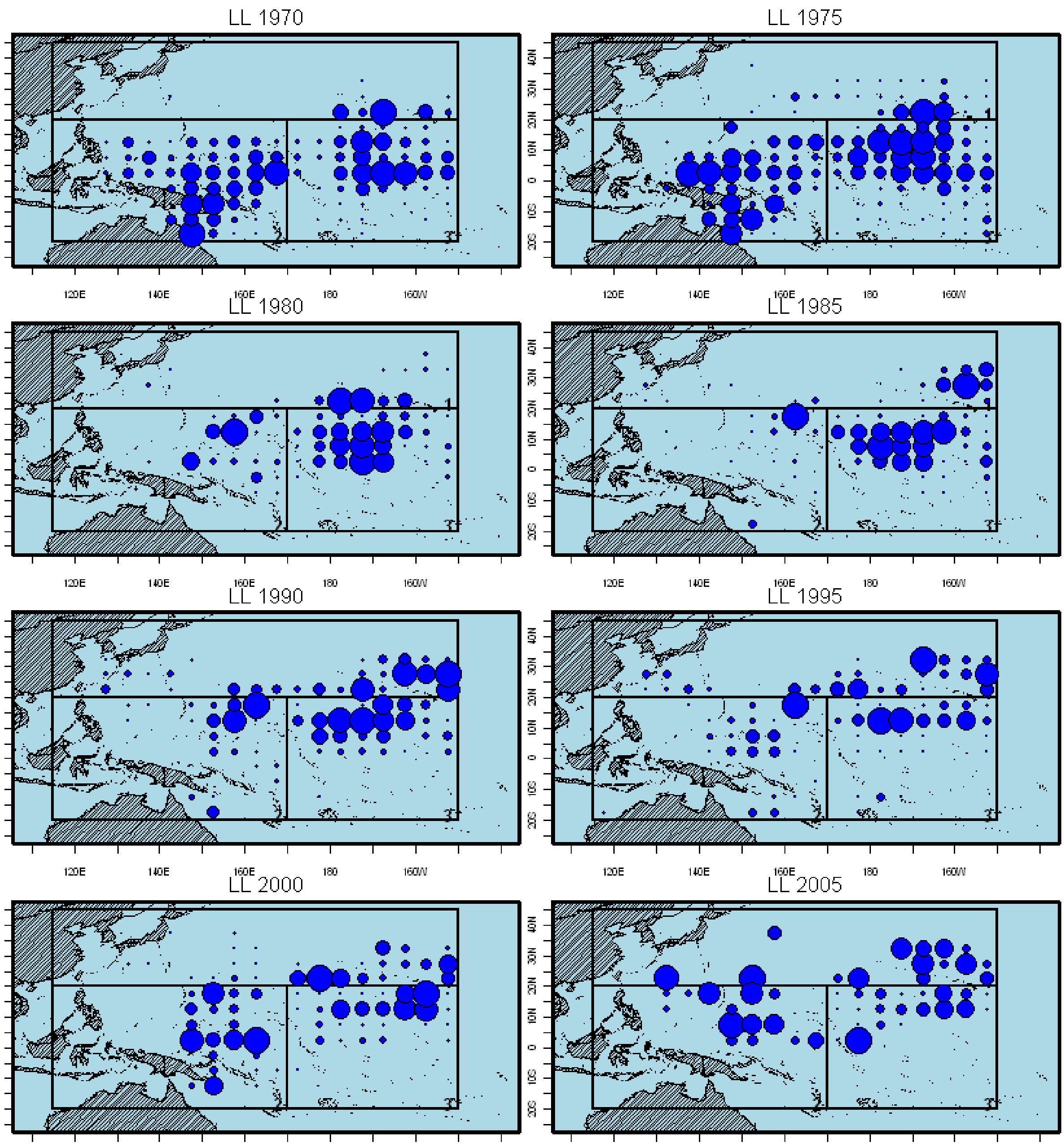

Figure 68: Sample locations through time for Japanese longline fisheries. Circle area represents the number of samples.

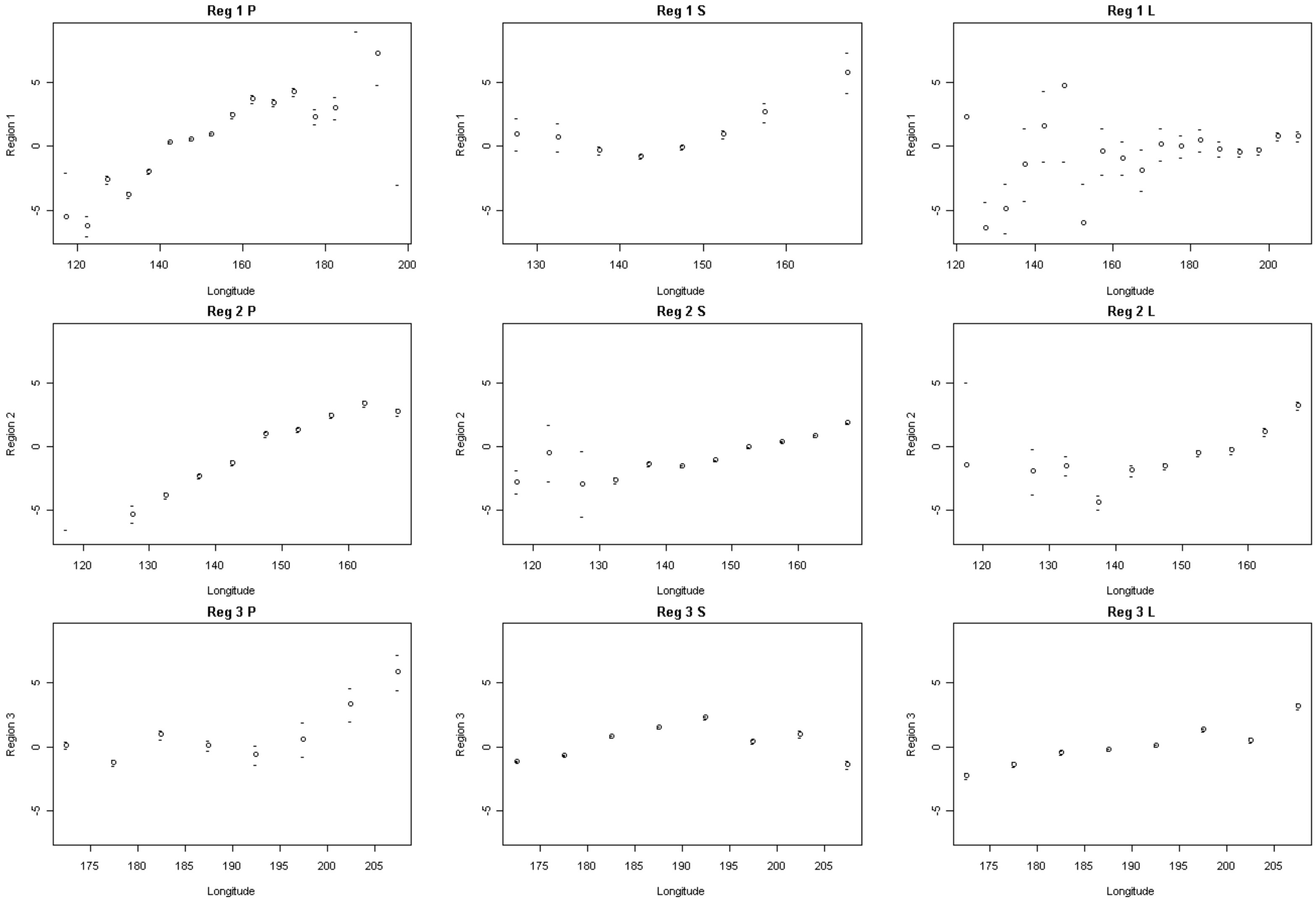

Figure 69: Contributions of longitude to variation in skipjack size in the purse seine, Japanese pole and line, and Japanese research longline fisheries, in regions 1 to 3.

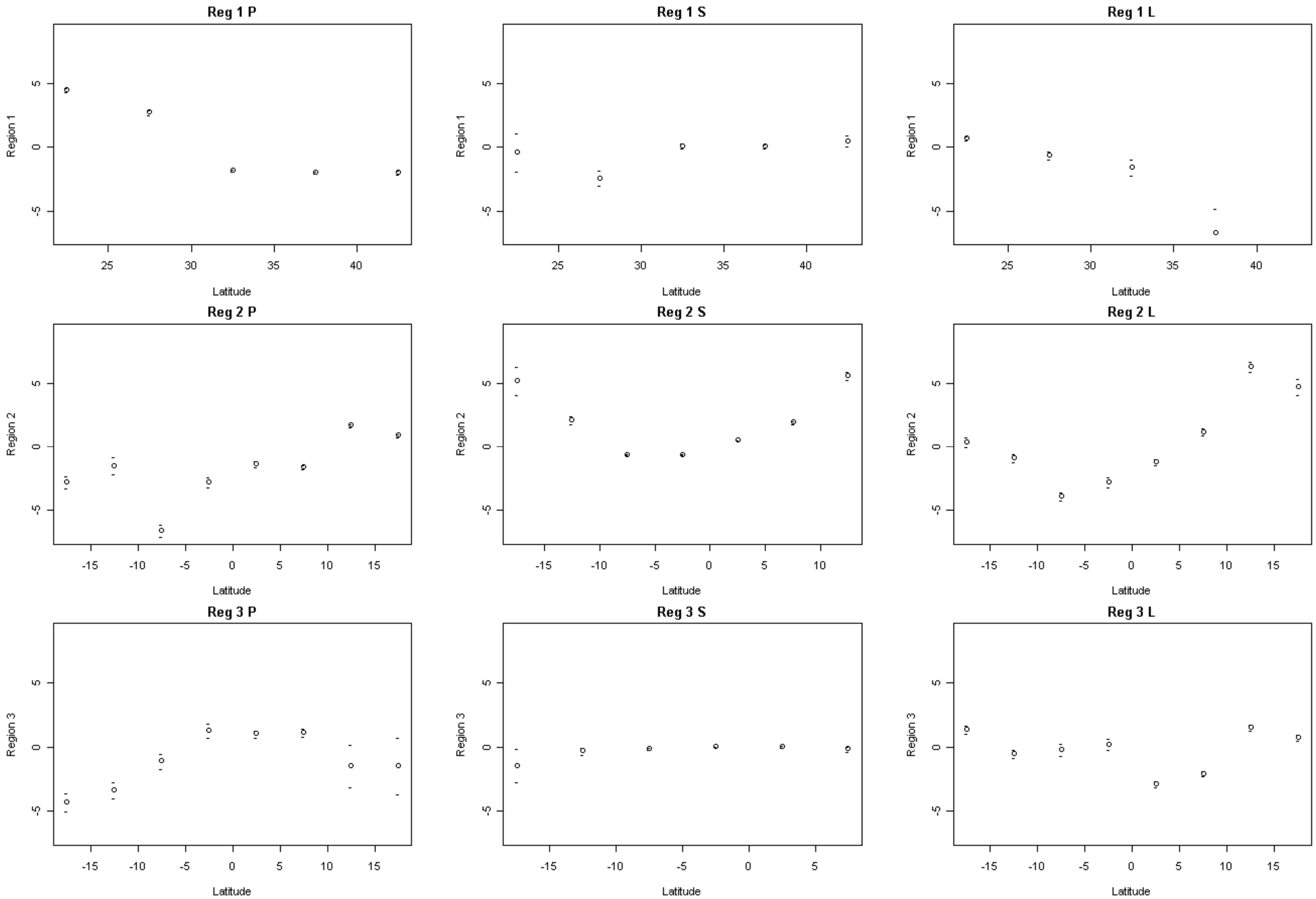

Figure 70: Contributions of latitude to variation in skipjack size in the purse seine, Japanese pole and line, and Japanese research longline fisheries, in regions 1 to 3.

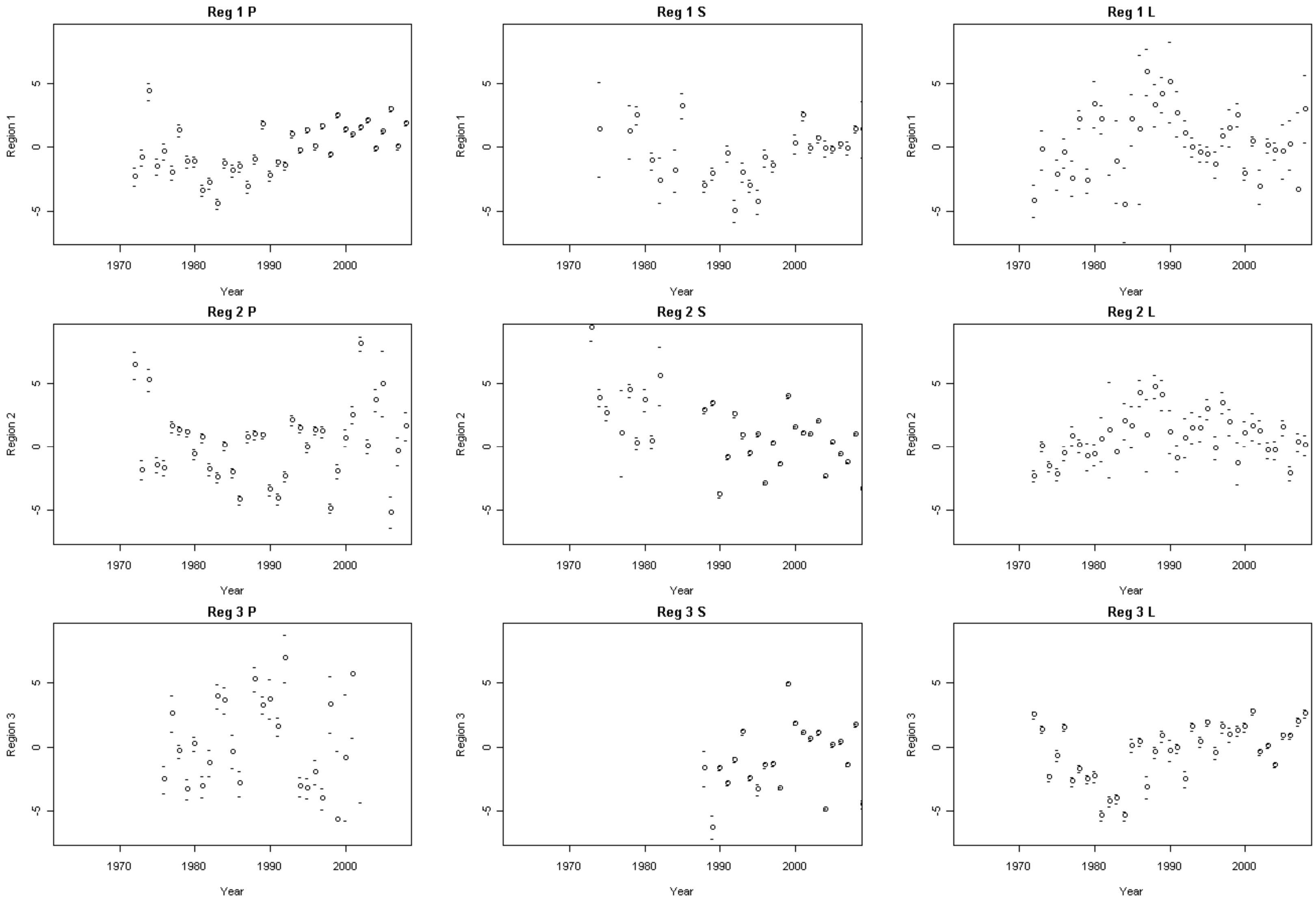

Figure 71: Contributions of year to variation in skipjack size in the purse seine, Japanese pole and line, and Japanese research longline fisheries, in regions 1 to 3.