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

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Abstract

This paper presents the 2008 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 age-classes) and spatially structured and the catch, effort, size composition and tagging data used in the model are classified by 24 fisheries and quarterly time periods from 1952 through 2007.

The catch, size and tagging data used in the assessment were updated from the 2005 assessment. A large amount of tagging data was integrated in the assessment model, although the current assessment does not include tag releases and recoveries from the recent PNG and Solomon Islands tagging programmes. For each region, a standardised effort series was calculated from a GLM analysis of catch and effort data from the Japanese distant-water pole-and-line fishery. The standardized effort series were scaled among regions by the overall CPUE from the region and the size of the region (regional weighting factors).

The assessment was conducted at two spatial scales: the entire WCPO stratified into six regions and a model restricted to the two regions encompassing the equatorial WCPO. A number of sensitivity analyses were conducted using the WCPO model.

All WCPO model options estimated a large biomass in the regions north of the equatorial area (regions 1–4), at least relative to the level of catch from these regions. This is most pronounced for regions 3 and 4 which account for 12% and 24% of the total biomass, respectively, while catches from these regions are negligible. This is attributable to the assumption of pole-and-line catchability being equivalent between all regions and the relatively high regional weighting factors associated with these two regions – despite the low catch from these regions, the overall regional pole-and-line CPUE was high and the regions are relatively large. Consequently, these two regions carry significant weight in the overall assessment.

For these northern regions (1–4), there are insufficient data included in the model to reliably estimate levels of regional stock abundance. For each region, there is little or no contrast in the time-series of CPUE data, with the possible exception of a decline in CPUE for the JPDW PL 2 fishery. Further, while there is a considerable number of tag releases and, in some regions, tag recoveries, there is no information available regarding the reporting rates for the corresponding fisheries and, consequently, the tag data are uninformative regarding stock size. In the absence of informative data at the regional level, the assessment model is gaining information on the relative stock size for these northern regions largely from the estimate of (shared) catchability from the equatorial regions, mediated by the regional scaling factors.

For the WCPO models, the current estimates of total abundance and the corresponding estimates of yield and MSY-related management quantities are extremely uncertain and may be considerably inflated by the high levels of biomass in the northern regions. The *equatorial* model, which encompasses the domain of the main fisheries within the WCPO, represents a more robust assessment given that it is not sensitive to the assumptions applied to the northern regions of the WCPO model. The large tagging data set, and associated information on tag reporting rates, is relatively informative regarding stock size in the two constituent regions of the *equatorial* model. On that basis, the *equatorial* model was adopted as the principal assessment and, consequently, the scope of the key conclusions is limited to the equatorial region of the WCPO skipjack fishery. These conclusions are essentially unchanged from the last three assessments, as follows.

1. The growth estimates are in general agreement with perceived length-at-age estimates of skipjack from the Pacific and other regions. Moreover, the model seemed to be able to make a consistent interpretation of the size data, which is crucial to a length-based approach. Discrepancies between the estimated growth curve and age-length observations for tagged skipjack might be due to the tropical surface fisheries selecting mainly the smaller, slower growing skipjack from the older age-classes.

2. Similar to other tropical tunas, estimates of natural mortality are strongly age-specific, with higher rates estimated for younger skipjack.
3. The *equatorial* 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.
4. 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 considerably 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 an historically high level, but is poorly determined due to limited observations from the fishery.
5. The biomass trends are driven largely by recruitment. 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 6). The model results suggest that the skipjack population in the equatorial region of the WCPO in recent years has been considerably higher (about 40%) than the overall average level for the model period.
6. 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. For all the principal Japanese pole-and-line fisheries, there is a significant increase in standardized CPUE in the late 1980s and early 1990s and the increase is particularly pronounced in the equatorial regions. The increase in CPUE, and the high CPUE for the subsequent period, is influential regarding the general trend in both recruitment and total biomass over the model period. For some regions, most notably region 5, there is a relatively poor fit to the observed CPUE data, particularly during the period when the CPUE series increased rapidly. This indicates a degree of conflict between the CPUE series and the other sources of data, especially the size data, within the assessment model. It remains unclear whether the standardized CPUE indices represent a reliable index of stock abundance.
7. 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. Consequently, there has been no direct information on the level of absolute biomass from the equatorial component of the stock for at least a decade. Further, the tagging programme occurred prior to the expansion of the fishery in region 6 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 6 is likely to be less well determined than for region 5. The data from recent tagging programmes within PNG and Solomon Islands waters should be integrated into the stock assessment as a matter of urgency.
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 biomass by about 40% in the western equatorial region and 20% in the eastern region.
9. 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 $B_{current}/\tilde{B}_{MSY}$ reveals 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. Recruitment variability, influenced by environmental conditions, will continue to be the primary influence on stock size and fishery performance.

10. The range of sensitivity analyses undertaken were restricted to the WCPO wide model and, therefore, are not directly relevant to the *equatorial* model. Nonetheless, the main conclusions of the assessment appeared relatively insensitive to a number of the model assumptions investigated. However, a crucial assumption is the distribution of recruitment between model regions in the broader WCPO assessment. There are insufficient data to estimate this reliably within the assessment model and many of the key model outputs of the WCPO models are likely to be strongly influenced by the values assumed.

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. 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 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 (Figure 1). 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 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, $M=0.8 \text{ mo}^{-1}$) than larger skipjack (51–70 cm FL, $M=0.12\text{--}0.15 \text{ mo}^{-1}$). Skipjack tuna reach sexual maturity at about one year of age (approximately 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 2a). 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 (Figure 2b). 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 (Figure 2c). 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 (Figure 2d–f); although a Japan offshore purse seine fleet operates in the sub-tropical 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 – log, fish aggregation device (FAD) and school sets – because the 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 subtropical (Japan-based pole-and-line and purse seine) components (Figure 3).

Skipjack tuna catches in the WCPO increased steadily since 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 1,500,000 mt in 2006 (Figure 4). Pole-and-line fleets, primarily Japanese, initially dominated the fishery, with the catch peaking at 380,000 mt in 1984, but the relative importance of this fishery has declined steadily for economic reasons. Annual skipjack tuna catches increased during the 1980s due to growth in the international purse-seine fleet, combined with increased catches by domestic fleets from the Philippines and Indonesia (which have made up to 20–25% of the total skipjack tuna catch in WCPO in recent years).

Historically, most of the catch has been taken from the western equatorial region (region 5) (Figure 3). During the 1990s, annual catches from this region fluctuated about 500,000–800,000 mt before increasing sharply to approach 1,000,000 mt in 2004–2006 (Figure 5). Since the late 1990s, there was a large increase in the purse-seine fishery in the eastern equatorial region of the WCPO (region 6), 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 2001c, Hampton 2002, Langley et al. 2003, and Langley et al. 2005). 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 (Figure 3). The assessment model area contains six spatial regions (Figure 3) as used in a previous skipjack CPUE standardization study (Ogura and Shono 1999) and enlarged to include the domestic fisheries of the Philippines and eastern Indonesia. The assessment area now 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 1972–2004. 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, 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 was further stratified by distant-water and offshore categories because of the different operational characteristics of these component fleets. Purse seine fishing activity was

aggregated over all nationalities, but stratified by region and three set types (log, FAD and school sets) in order to sufficiently capture the variability in fishing operations. 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 allow the incorporation of these data. Finally, domestic fishery categories for the Philippines and Indonesia were also included in the fishery definitions. Overall, 24 fisheries were defined in the analysis (Table 1).

2.4 Catch and effort data

Catch and effort data were compiled according to the fisheries defined above and the six-region, quarterly stratification. 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 regions (1–4) are highly seasonal as are the three domestic pole-and-line fisheries operating in the regions 5 and 6 (Figure 6). There are a number of significant trends in the fisheries that have occurred over the model period, specifically.

- The development of the Japanese off-shore purse-seine fishery in region 2 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 6;
- The development of the equatorial purse-seine log and school fisheries from the mid-1970s and the FAD fisheries in the mid-1990s and the corresponding expansion of the purse-seine fishery in region 6;
- The steady increase in catch for the domestic fisheries of Indonesia and the Philippines.

For the Japanese pole-and-line fisheries (offshore and distant-water), standardised effort time-series were estimated using the General Linear Model (GLM) analyses described in Ogura and Shono (1999). Separate analyses were conducted for the distant-water and offshore fleets. Previously, the factors included in the analyses were year, quarter, region, effect of refrigerated bait tank use, effect of bird radar use, effect of sonar use, effect of satellite imagery use and albacore CPUE. In February 2008, a meeting was held in Noumea to review inputs for the current stock assessment. At that meeting, a number of concerns were raised regarding the CPUE indices derived from a recent iteration of the GLM analysis, particularly the near identical indices derived for regions 5 and 6 (Langley & Hoyle 2008). For the current assessment, the GLM analysis was updated by National Research Institute of Far Seas Fisheries (NRIFSF) to include data from 2006; however, as information concerning fishing gear was not available for the more recent years, these variables were excluded from the analysis. The resulting GLM yielded considerably different trends in CPUE for the two equatorial pole-and-line fisheries (Figure 7).

Nominal catch rates from the Japanese pole-and-line fleet were applied to determine the relative scaling of standardised distant-water pole-and-line effort among regions. 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. 2005 and Hoyle & Langley 2007). The scaling factors were derived from the Japanese pole-and-line CPUE data from 1975–85. The specific regional weighting factors are 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.

Nominal fishing vessel days was used as the effort measurement for the domestic pole-and-line fisheries of Papua New Guinea, Solomon Islands, and Fiji. For the six equatorial purse seine fisheries, days fishing (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 (proportional to the catch) for these fisheries. CPUE plots for each fishery are shown in Figure 7.

A separate sensitivity analysis was undertaken to investigate incremental increase in fishing power for the six pole-and-line fisheries. Fishing power was assumed to increase by 2 percent per annum and the correction was applied to the GLM standardised effort for each of the six fisheries (Figure 7).

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 8.

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 an observer programme conducted for the same fleet. Since the early 1990s, port sampling and observer programmes on other purse seine fleets have provided additional data. Only data that could be classified by set type were included in the final data set.

Some fisheries have not been consistently sampled at the same levels over time (Figure 8). Also, it was not possible to discriminate samples for the Japanese offshore and distant-water fleets in regions 1, 2 and 4. 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 was 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 regions (1–3) generally catch smaller fish than the equatorial fisheries (regions 5 and 6), with the catch from region 4 generally of intermediate size fish (Figure 9). 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 and possibly region 5, while no systematic trend in the size composition was evident for the other regions (Figure 9).

Longline fisheries in regions 4–6 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 within regions 4 and 6 over the last decade (Figure 10).

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 5 and 6 (Figure 11). For region 5, there was a gradual decline in the size of fish caught by the three set types from the mid 1980s to recent, while there is no systematic trend in the size composition from the region 6 purse-seine fisheries (Figure 11).

2.6 Tagging data

A large amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. 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. Only Japanese tags released north of 15°N, an area not well covered by the SPC experiments, were used in the analysis. 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. The model does not yet include the tag release and recovery data from the 2006–08 tagging programme undertaken in PNG and Solomon Islands waters.

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 MULTIFAN-CL analysis, 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 171 tag release groups (Table 2). The returns from each size-class of each tag release group (18,102 tag returns in total) were then classified by recapture fishery and recapture time period (quarter).

Most of the tag releases occurred within regions 5 and 6 during 1977–80 and 1989–92 by tagging programmes administered by SPC (Figure 12). There were also tag releases by Japanese research programmes in the two regions during 1988–2004. Tagging in regions 1 to 4 was almost exclusively conducted by the Japanese, principally in regions 2 and 4 (Figure 12).

The total tag recoveries were dominated by recoveries from fisheries operating in regions 5 and 6, 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 5 to region 6 (Figure 13). There was also a considerable movement of tags from region 5 to region 4. Recoveries of tags released in region 4 generally occurred within that region or in region 1. The latter region also received tags from region 2 and, to a lesser extent, from region 5 (Figure 13). The tags recovered from region 2 were principally from releases in that region. Only three tags were recovered from region 3 despite a reasonable number of releases in that area (Table 2).

The length at recovery of tagged fish was broadly comparable to the length composition of the main method fishery operating in each region (Figure 14). Fish tagged in region 2 and recovered in either region 1 or region 4 were generally smaller than other recoveries in these regions, consistent with the smaller size of fish tagged in region 2. Similarly, fish tagged in region 5 and recovered in region 4 were generally smaller than fish tagged in region 4 (Figure 14).

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 15). There was a higher level of mixing of tags between regions the longer the tags were at liberty, although for some regions the initial rates of transfer of tags appears to be relatively high, for example region 5 to region 4 and region 4 to region 1 (Figure 15).

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 (2001a). The main structural assumptions used in the skipjack model are discussed below and are summarised in Table 3.

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 0.05 times the actual sample size, 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 50 fish.

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

While the model has the capacity to estimate tag-reporting rates, we provided Bayesian priors for fishery-specific reporting rates. Relatively informative priors were provided for reporting rates for the Philippines and Indonesian domestic fisheries and the purse seine fisheries, as independent estimates of reporting rates for these fisheries were available from tag-seeding experiments and other information (Hampton 1997). 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 Japanese fisheries (offshore purse-seine and pole-and-line) were assumed to be constant. All reporting rates were assumed to be stable over 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 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 areas. 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. The variance of the prior was set such that recruitments of about three times and one third of the average recruitment would occur about once every 25 years on average.

Spatially-aggregated recruitment was assumed to have a weak relationship with the 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).

Typically, fisheries data are very uninformative about SRR parameters and it is generally necessary to constrain the parameterisation in order to have stable model behaviour. We have incorporated a beta-distributed prior on the “steepness” (S) of the SRR, with S defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Francis 1992; Maunder and Watters 2001). A formal derivation of the SRR parameterization and the contribution of the steepness prior to the log-likelihood are given in Hampton and Fournier (2001b).

A moderately informative prior on steepness was used, specified by a mode = 0.90 and SD = 0.10.

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.

Length-based assessments of other tuna species have indicated that there is substantial departure from the von Bertalanffy model, particularly for juvenile age-classes. To allow for this possibility in skipjack tuna, we allowed the mean lengths of the first six quarterly age-classes to be independent parameters, with the last ten mean lengths following a von Bertalanffy growth curve.

The onset of sexual maturity was assumed to occur at age-class 3. The adult component of the population was defined as the 3–16 age classes.

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. Selectivities for all Japanese pole-and-line fisheries were constrained to be equal. 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 and was assumed to be equivalent for the six principal pole-and-line fisheries. For all other fisheries, catchability was allowed to vary slowly 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 0.1. However, for the Philippines, Indonesian and research longline fisheries, no reliable effort estimates were available. We made the assumption that effort for these fisheries was constant over time, but set the variance of the priors to be high (equivalent to a CV of about 0.7 on the log scale), thus allowing catchability changes to compensate for failure of this assumption.

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

The sensitivity of the model assumption of constant catchability of the principal pole-and-line fisheries was investigated. An alternative effort series was formulated to account for an assumed increase in the catchability of the pole-and-line fishery over the entire model period. The sensitivity analysis included an arbitrary increase in catchability of 2% per annum.

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 the Philippines, Indonesian and research longline fisheries for which reliable effort data were unavailable, 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 all other fisheries, the variance was set at a moderate level (equivalent to a CV of about 0.2 on the log scale).

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 Sensitivity analyses

At a preparatory meeting (Noumea, February 2008), a range of model sensitivity analyses were considered and agreed for the current assessment (Langley & Hoyle 2008). These analyses included alternative regional weighting schemes, weighting of the length frequency data and consideration of a model with the spatial domain limited to the equatorial region. In addition, analyses were proposed to consider the influence of assumed tag reporting rates and the assumption of constant catchability of the principal pole-and-line fisheries. Of the various options initially proposed, a number of the analyses were dropped due to technical and/or data limitations. The four sensitivity analyses included in the current assessment are described in Table 4.

4 Results

This section provides a detailed summary of the results from the base-case assessment. A general summary of the results of three of the sensitivity analyses (see Table 4) is also presented, principally highlighting the main differences from the base-case assessment. The sensitivity using iterative reweighting is not presented, although it is worth noting that the approach resulted in a further down-weighting of the size data from the pole-and-line fisheries, particularly in the first two decades of the model period.

4.1 Fit statistics and convergence

A summary of the fit statistics for the three WCPO analyses and *equatorial* model is given in Table 5. Due to differences in the tag and effort data sets the total likelihood values are not strictly comparable; however, it is worth noting that the sensitivity with increased catchability of the pole-and-line fleet resulted in a considerable improvement in the fit to the length frequency data, while the base-case analysis represents a much better fit to the tagging data set. Nonetheless, for the WCPO model runs, there were significant difficulties in obtaining a converged fit and we are not confident that the present models represent the best possible fit to the data or whether the models have converged to local minima. The same difficulties were not encountered with the *equatorial* model.

4.2 Fit of the model to the data

The fit of the model to the total catch data by fishery is very good (Figure 16), which reflects our assumption that observation errors in the total catch estimates are relatively small.

The fit to the length data is displayed in Figure 17 for length samples aggregated over time for each fishery. Figure 17 provides a convenient means of assessing the overall fit of the model to the length data for each fishery. On the whole, the model appears to have captured the main features of the data, particularly for the larger, more heavily sampled fisheries. The modal structure evident in the pole-and-line and purse seine length-frequency data is represented by the model predictions.

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 18). 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, for the fisheries within region 1 and 2 (JPOS PL 1 & 2) consistently larger fish were caught post 1990 compared to the earlier period. This temporal trend in the size of fish caught is not reflected in the model dynamics and may indicate a change in the length-based selectivity of skipjack between the two periods (Figure 18).

The length samples from the Philippines domestic fishery are variable among and within sampling periods and this variation is reflected in the model dynamics (Figure 18). The observed variation in the length composition may reflect variation in the distribution of sampling effort between the individual fisheries that constitute the Philippines domestic fishery.

The Japanese pole-and-line fisheries in regions 4 and 5 (JPOS PL 4 and JPDW PL 5) generally caught significantly larger fish from 2000 onwards compared to the preceding period. This trend is

not reflected in the predicted size composition of the catch and may represent a recent change in the selectivity of the fishery (Figure 18).

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 19). 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 20. The aggregated fit is very good, with little divergence between observed and predicted tag returns. However, some discrepancies are evident when the observed and predicted data are broken down by fishery groups (Figure 21). These discrepancies occur mainly in the Japanese pole-and-line fisheries. For these fisheries, there were periods when few tags were observed despite considerable numbers being predicted (esp. JPDW PL 2) and vice versa (esp. JPOS PL 1, JPOS PS 2, JPDW PL 4). This may indicate that the assumptions concerning temporal stability of tag-reporting rates and/or constant reporting rates for all Japanese fisheries were not appropriate.

There is also a discrepancy in the tag recoveries from the Solomon Islands pole-and-line fishery, with considerably higher numbers of recoveries compared to the model prediction (Figure 21). For the remaining fisheries that returned considerable numbers of tags, there is a good match between the observed and predicted returns.

4.3 Tag reporting rates

There is considerable variation among fisheries in the estimated tag-reporting rates (Figure 22). Reporting rates for the Japanese fisheries were assumed to be constant and the global reporting rate was estimated to approximate the mode of the prior – 0.5 (SD = 0.14). For the Solomon Island and Fiji pole-and-line fisheries, the estimated tag reporting rates were very high at 0.9 — the upper bound stipulated for all reporting rates (Figure 22). The common tag reporting rate for the equatorial purse-seine fisheries was estimated to be slightly higher than the mode of the prior (mode = 0.55, SD = 0.07). Reporting rates for the PNG and Indonesian, fisheries were also relatively high, while the reporting rate for the Philippines fishery was substantially lower than the prior (Figure 22).

4.4 Age and growth

Using the four-recruitment-per-year formulation, the model was able to detect a reasonably coherent growth signal in the size data. The estimated growth curve is shown in Figure 23. Early growth rates are comparable to growth rates determined by Tanabe et al. (2003) from daily otolith increments and indicate fish “recruit” into the model population (i.e. age class 1) at the second quarter following hatching. However, the estimated growth rate of sub-adults (age classes 3–4) is faster than that determined by Tanabe et al. (2003) and the discrepancy in length-at-age (approx. 4 cm) is maintained for older age classes (Figure 23).

Estimated growth rates also appear to be slightly higher than inferred from the length-at-release and recovery of tagged skipjack tuna (in equatorial waters) (Figure 23), although this observation could be explained by size-based selectivity of the main fisheries that recovered tags resulting in the selection of the smaller, slower growing individuals within the older age classes.

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 (see Figure 17).

The variation in length-at-age is relatively constant across age-classes (Figure 24). This is surprising, as we would expect the variation to increase with increasing age. Possibly, there was insufficient information in the data to provide a signal for changes in the variation in length-at-age.

4.5 Selectivity

Estimated selectivity functions are generally consistent with expectation (Figure 25). 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 5–7 and declining selectivity for the older age-classes. For these fisheries, the selectivity of age classes 10–16 is low. The Philippines fishery catches the smallest fish with relatively high selectivity for fish in the 1–5 age-classes, although the fishery also has a high selectivity for older age classes reflecting the presence of some larger fish in the sampled catch. The research longline fisheries have been assumed to have a monotonically increasing selectivity with age.

4.6 Catchability

Estimated catchability trends are shown in Figure 26. Seasonal variability is strong for many of the pole-and-line fisheries, particularly for the Japanese fleets in regions 1–4. This occurs despite the standardisation of the effort data from these fisheries to account for seasonal variation in catchability. Strong seasonal variation in catchability is also evident in the equatorial purse-seine fishery, particularly within region 6.

Catchability was time-invariant for all the Japanese offshore fisheries and the distant-water pole-and-line fisheries, 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, particularly the FAD fisheries in areas 5 and 6 during the 1990s (Figure 26). On the other hand, the purse seine school fisheries in regions 5 and 6 showed a downturn in catchability during the 2000s. This might have been related to the increasing deployment of FADs in the fishery during this period, which might have reduced the catchability of school fish, either because a greater proportion of the available skipjack population was FAD-associated, or because vessels may have opted to focus on FAD operations and reduced their effectiveness for fishing schools..

4.7 Effort deviations

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 many of the fisheries, including a number of the principal pole-and-line fisheries (JPDW PL 1 & 2), strong temporal trends in the effort deviates are apparent and some fisheries exhibit some relatively large effort deviates (Figure 27). This indicates a lack of fit between the pole-and-line CPUE indices and exploitable biomass in regions 1 and 2 (Figure 28), although there is a reasonable fit to CPUE indices for the other regions. The lack of fit probably indicates that the assumption of equivalent catchability and selectivity among all regions is not valid.

The variability in effort deviations is reduced for the model including the equatorial regions only (Figure 29), although some significant temporal trends in effort deviations persist. Notable, is the increase in effort deviates in the JPDW PL 5 fishery from 1985 to 1995 – the period when CPUE in the fishery increased substantially (see Figure 7). The effort deviates are also large for the purse-seine fisheries in region 6, particularly the PS SCH 6 fishery, reflecting the high variability in CPUE from this fishery (Figure 29).

4.8 Natural mortality

Natural mortality is estimated to be high for the young age classes (1–4) and declines steadily with increasing age up to age class 10 (Figure 30). There is a steady increase in estimated natural mortality for the older (10+) age-classes.

4.9 Movement

A representation of the dispersal pattern resulting from the estimated movement parameters is shown in Figure 31. This figure shows the movement of the proportion of four age groups between each region by quarter. The model estimates high (approaching 70%) movement coefficients from the northern regions (1–3) to region 4 during quarters 1, 2, and 4. These movements tend to increase with increasing age; i.e. highest movement coefficients for the older age classes. There is also a high movement coefficient from region 4 to region 5 in the third quarter and from region 1 to region 2 in the fourth quarter (Figure 31 and). Movement coefficients between the other regions are estimated to be relatively small.

The distribution of regional biomass by source region derived from a simulation using the movement coefficients is presented in Figure 32. The simulation indicates that the model estimates a high degree of mixing between regions, particularly regions 4–6, and that a significant proportion of the biomass in these regions is sourced from the northern regions (1–3). For example, the model estimates that only 30% of the biomass in region 5 is sourced from recruitment within the home region, while most of the remainder of the biomass is sourced from recruitment in the northern regions and region 4. There is a significant transfer of the biomass from region 5 to region 6 regardless of the natal region (Figure 32).

The movement of fish from the northern regions into region 4 is inconsistent with the observations from the tagging data which tend to show a general northern movement of fish from region 4 into region 1 and, likewise, a northern movement of fish into region 4 from the equatorial regions (see Section 2.6). The southern movements from region 1 and 2 are also inconsistent with the observations of peak seasonal catch and CPUE from these fisheries during the second and third quarters (see Figure 6).

For the *equatorial* model, there is considerable (15–20%) eastwards movement of fish, principally within the first and last quarter.

4.10 Recruitment

The time-series of recruitment estimates is shown in Figure 33. Overall recruitment is estimated to be relatively evenly distributed throughout the six regions, although the northern regions (1–3) exhibit high seasonal variation in recruitment. There is a strong temporal trend in recruitment in a number of the regions; for regions 1 and 5 recruitment is substantially higher post 1995, while recruitment in region 2 is high from 1990 onwards (Figure 33).

Overall, recruitment was estimated to be low during the first decade of the model period (1972–82), considerably higher (approx. 60%) during 1982–2000, and at very high levels for the last 5 years (Figure 33). The recent very high recruitment is driven by high recruitment in regions 3, 4, and 6. However, there is a high level of uncertainty associated with the model's estimates of recruitment for the last few years.

The regional trends in recruitment are comparable for the three WCPO models examined (*base-case*, *PL-incr-q*, and *low tag*) (Figure 34). However, there is a significant difference in the magnitude and trend in recruitment for region 5 from the *equatorial* model; recruitment is relatively stable from 1985 onwards at a level considerably higher than the long-term average level of recruitment from the three WCPO models. This is likely to be due to the most of the biomass being sourced from recruitment in the home region, as opposed to being augmented by the movement of fish from the northern regions in the case of the WCPO models. Recruitment estimates for region 6 from the *equatorial* model are comparable to the WCPO models (Figure 34) and are highly variable with recent peaks in recruitment occurring in 1998 and 2004–2005 and lower recruitment in 2001–2003.

4.11 Biomass

The biomass trajectories by region are presented in Figure 35. Overall, most of the total biomass is within regions 4, 5 and 6 (24%, 22% and 30% of recent biomass, respectively), although a significant proportion of the biomass is within region 3 (12%).

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 very high levels of biomass in the most recent years (Figure 35). These strong trends in WCPO total biomass are largely driven by the biomass trend in region 4, although both regions 5 and 6 show elevated levels of biomass during the last decade.

Annual trends in regional total biomass were also comparable among the three WCPO model options considered (Figure 36). However, as with the recruitment series, there was considerable difference in the trend in total biomass for region 5 from the *equatorial* model — biomass increased sharply during the 1980s, declined during the 1990s and remained relatively stable over the last decade.

4.12 Fishing mortality and the impact of fishing

Annual average fishing mortality rates for juvenile and adult age-classes are shown in Figure 37 for each region. Recent fishing mortality rates on both juvenile and adult skipjack are highest within region 5; fishing mortality rates steadily increased from 1972 to 1990 and remained at a relatively high level since then. In regions 1 and 2, fishing mortality is highly seasonal and overall exploitation rates have been moderate for at least part of the model period. Fishing mortality rates in regions 3, 4, and 6 were low for the entire model period.

These trends are reflected in the recent age-specific fishing mortality rates which are highest for age classes 3–7 within region 5 (Figure 38). By comparison, recent exploitation rates are low for the other regions. The trend is consistent for the four model options, although slightly higher exploitation rates are estimated for region 5 from the *equatorial* model (Figure 38).

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, 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 39 and the level of stock depletion is presented in Figure 40. Similarly, the impact of all fishing on the fishery-specific exploitable biomass is also calculated (Figure 41).

The impact of fishing on the total biomass is negligible for regions 1–4 and is highest in region 5 where the stock is reduced to about 60% of the unfished level in recent years (Figure 40). For region 6, fishery impacts are estimated to have reduced the total biomass by about 20%. Fishery impacts in region 5 and 6 derived from the *equatorial* model are comparable to the base-case assessment.

Within regions 5 and 6, impacts on fishery-specific exploitable biomass are generally comparable to the overall level of fishery impact (Figure 41). Impacts are slightly higher for those fisheries catching slightly older fish; for example, the purse-seine school set fisheries and the Japanese distant water pole-and-line fisheries.

4.13 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, $fmult$, the natural mortality-at-age (M_a), the mean weight-at-age (w_a) and the SRR parameters α and β . All of these parameters, apart from $fmult$, which is arbitrarily specified

over a range of 0–50 in increments of 0.1, are available from the parameter estimates of the model. The maximum yield with respect to $fmult$ can easily be determined and is equivalent to the MSY. Similarly the total 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 limit reference points (Table 6). These ratios are also determined and their confidence intervals estimated using a profile likelihood technique..

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In this assessment, we use the average over the period 2003–2006. The last year in which catch and effort data are available for all fisheries is 2007. We do not include 2007 and subsequent years 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.

The assessments indicate that recruitment over the last two decades was higher than for the preceding period. Consequently, yield estimates based on the long-term equilibrium recruitment estimated from a Beverton and Holt SRR may substantially under-estimate the yields currently available from the stock under current recruitment conditions. For this reason, a separate yield analysis was conducted based on the average level of recruitment from 1997–2006.

Biomass estimates, yield estimates, and management quantities are presented in Table 7.

The stock assessments are uninformative regarding the relationship between spawning biomass and recruitment as indicated by the broad confidence interval associated with the SRR for the base-case (Figure 42). The resulting estimates of the steepness parameter are comparable to the mode of the prior distribution for all model runs (0.86–0.90).

For the base-case, MSY is estimated to be 2.26 million mt per annum at a level of fishing effort ($fmult$) approximately 8 times the current level of effort, although the yield curve and, therefore, the estimate of MSY is highly uncertain for levels of effort substantially higher than current levels (Figure 43). Further, there is little contrast in the estimated yield across a wide range of effort levels (from $fmult$ 5 to 20) indicating F_{MSY} is poorly determined.

The portion of the yield curve near the current level of F -at-age is close to linear (Figure 43). Therefore, in the absence of a technological or economic revolution in the skipjack fishery resulting in order-of-magnitude increases in fishing mortality, it might reasonably be expected that catch, on average, would continue to change almost proportionally with fishing effort over any realistic range that might be contemplated for the foreseeable future. Recruitment variability, influenced by environmental conditions, will continue to be the primary influence on stock size and fishery performance.

For the base-case, levels of equilibrium biomass levels are estimated to be relatively low at F_{MSY} ($\tilde{S}_{MSY}/\tilde{S}_0 = 0.21$ and $\tilde{B}_{MSY}/\tilde{B}_0 = 0.32$) (Figure 43).

The two other WCPO models produce similar estimates of potential yield and current stock status to the base-case model, while the results of the equatorial model are more conservative. The estimated *equatorial* MSY of 1.28 million mt per annum is substantial lower than for the base-case and occur at levels of fishing mortality 3.8 times the current (2003–2006) level (Figure 44). Current yields from the equatorial region of the fishery (approx 1.3 million mt) are comparable to the MSY level, but are being harvested at fishing mortality rates approximately a quarter of the F_{MSY} level. This is due to current recruitment levels being substantially higher than the long-term average level of recruitment. A MSY based on the recruitment levels estimated over the period 1997-2006 is approximately 2.0 million mt per annum.

For the *equatorial* model, fishing mortality rates tended to be higher during the last decade than for the preceding period, although they remained substantially lower than the F_{MSY} level ($F_{current}/\tilde{F}_{MSY} = 0.26$) (Figure 45). Therefore, overfishing of skipjack is not occurring. Total biomass remained substantially higher than the \tilde{B}_{MSY} level throughout the model period and current total

biomass approximates the equilibrium unexploited level (\tilde{B}_0) due to the higher levels of recruitment in recent years ($B_{current}/\tilde{B}_{MSY} = 2.99$). 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 46). Nonetheless, there is a zero probability that $B_{current}/\tilde{B}_{MSY}$ is anywhere close to 1.0 and, on this basis, the stock is nowhere near to an overfished state.

5 Discussion

The equatorial region of the WCPO (regions 5 and 6) accounts for the vast majority of catch from the skipjack fishery. In contrast, the current WCPO assessment models indicate a high proportion of the total recruitment occurs from the northern regions of the stock and that recruitment from these regions contributes substantially to the biomass within the equatorial region, while a significant proportion of the biomass also remains within these northern natal regions.

While tagging data show that individual skipjack are capable of undertaking long-distance movements of several thousand kilometers, 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). In contrast, the population-level estimates of dispersal obtained from the current assessment show a relatively high level of stock mixing, particularly in the regions encompassing most of the WCPO stock biomass. These dispersal rates appear to be inconsistent with the observations from the tagging data, as well as trends in the catch and effort data. For example, the model estimates of quarterly movement of skipjack from the temperate northern regions towards the equatorial region are inconsistent with the seasonal peak in catch rates in the temperate fisheries. In contrast, the tagging data suggests 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 of the model.

The three WCPO models estimate a relatively large biomass in the regions north of the equatorial are (regions 1–4), at least relative to the level of catch from these regions. This is most pronounced for regions 3 and 4 which accounts for 12% and 24% of the total biomass, respectively, while catches are negligible. This is attributable to the assumption of pole-and-line catchability being equivalent between all regions and the relatively high regional weighting factors associated with these two regions – despite the low catch from these regions the overall regional pole-and-line CPUE was high and the regions are relatively large. Consequently, these two regions carry significant weight in the overall assessment.

For the northern regions (1–4), there are insufficient data included in the model to estimate levels of regional stock abundance. For each region, there is little or no contrast in the time-series of CPUE data, with the possible exception of a decline in CPUE for the JPDW PL 2 fishery. Further, while there is a considerable number of tag releases and, in some regions, tag recoveries, there is no information available regarding the reporting rates for the corresponding fisheries and, consequently, the tag data are uninformative regarding stock size. In the absence of informative data at the regional level, the assessment model is gaining information on the relative stock size for these northern regions largely from the estimate of (shared) catchability from the equatorial regions, mediated by the regional scaling factors.

Previous WCPO-wide assessments have been less sensitive to these model assumptions as the overall proportion of the total recruitment from each region was not estimated (Hampton 2002, Langley *et al.* 2003). Rather, the distribution of recruitment was estimated independently of the assessment model from a spatial ecosystem and populations dynamics model with most (96%) of the recruitment is assumed to occur in the two equatorial regions (SEAPODYM) (Lehodey 2004). The results of these previous assessments were highly sensitive to the assumed distribution of recruitment.

In summary, for the WCPO models, the current estimates of total abundance and the corresponding estimates of yield and *MSY*-related management quantities are extremely uncertain and may be considerably inflated by the high levels of biomass in the northern regions. The *equatorial*

model, which encompasses the domain of the main fisheries within the WCPO, represents a more robust assessment given that it is not sensitive to the assumptions applied to the northern regions of the WCPO model. The large tagging data set, and associated information on tag reporting rates, is relatively informative regarding stock size in the two constituent regions of the *equatorial* model. On that basis, it is recommended that the *equatorial* model be adopted as the principal assessment model for the formulation of management advice for the WCPO skipjack fishery.

6 Conclusions

The major conclusions of the skipjack assessment are essentially unchanged from the last three assessments (Hampton 2002, Langley et al. 2003, and Langley et al. 2005). However, for this assessment the scope of the key conclusions is limited to the equatorial region of the WCPO skipjack fishery. Their key conclusions are as follow.

1. The growth estimates are in general agreement with perceived length-at-age estimates of skipjack from the Pacific and other regions. Moreover, the model seemed to be able to make a consistent interpretation of the size data, which is crucial to a length-based approach. Discrepancies between the estimated growth curve and age-length observations for tagged skipjack might be due to the tropical surface fisheries selecting mainly the smaller, slower growing skipjack from the older age-classes.
2. Similar to other tropical tunas, estimates of natural mortality are strongly age-specific, with higher rates estimated for younger skipjack.
3. The *equatorial* 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.
4. 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 considerably 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 an historically high level, but is poorly determined due to limited observations from the fishery.
5. The biomass trends are driven largely by recruitment. 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 6). The model results suggest that the skipjack population in the equatorial region of the WCPO in recent years has been considerably higher (about 40%) than the overall average level for the model period.
6. 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. For all the principal Japanese pole-and-line fisheries, there is a significant increase in standardized CPUE in the late 1980s and early 1990s and the increase is particularly pronounced in the equatorial regions. The increase in CPUE, and the high CPUE for the subsequent period, is influential regarding the general trend in both recruitment and total biomass over the model period. For some regions, most notably region 5, there is a relatively poor fit to the observed CPUE data, particularly during the period when the CPUE series increased rapidly. This indicates a degree of conflict between the CPUE series and the other sources of data, especially the size data, within the

assessment model. It remains unclear whether the standardized CPUE indices represent a reliable index of stock abundance.

7. 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. Consequently, there has been no direct information on the level of absolute biomass from the equatorial component of the stock for at least a decade. Further, the tagging programme occurred prior to the expansion of the fishery in region 6 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 6 is likely to be less well determined than for region 5. The data from recent tagging programmes within PNG and Solomon Islands waters should be integrated into the stock assessment as soon as possible.
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 biomass by about 40% in the western equatorial region and 20% in the eastern region.
9. 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 $B_{current}/\tilde{B}_{MSY}$ reveals 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. Recruitment variability, influenced by environmental conditions, will continue to be the primary influence on stock size and fishery performance.
10. The range of sensitivity analyses undertaken were restricted to the WCPO wide model and, therefore, are not directly relevant to the *equatorial* model. Nonetheless, the main conclusions of the assessment appeared relatively insensitive to a number of the model assumptions investigated. However, a crucial assumption is the distribution of recruitment among model regions in the broader WCPO assessment. There are insufficient data to estimate this reliably within the assessment model and many of the key model outputs are strongly influenced by the values assumed.
11. Recommended research and monitoring required to improve the skipjack tuna assessment include the following:
 - Continued monitoring and improvement in fisheries statistics is required. In particular, better data generally are required for the Philippines and Indonesian fisheries.
 - Refinement of techniques to standardise catch and effort data from the key fisheries, particularly the Japanese pole-and-line fisheries.
 - New conventional tagging experiments, as recently implemented within PNG and Solomon Islands waters and in the broader equatorial WCPO, 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 regions would provide additional information to parameterize relative stock levels among model regions.
 - Information regarding the tag reporting rates, particularly for the Japanese tag releases in the northern waters.
 - Further research on environmental influences on skipjack tuna recruitment and movement are required. Environmental time series identified by such research could be incorporated into the MULTIFAN-CL model.

7 Acknowledgements

The GLM analysis of pole-and-line CPUE data was undertaken by Hiroshi Shono, National Research Institute of Far Seas Fisheries (NRIFSF). We thank the various fisheries agencies, in particular NRIFSF for the provision of the catch, effort and size composition data used in this analysis. We thank participants at the preparatory stock assessment workshop (Noumea, February 2008) for their contribution to the assessment. Pierre Kleiber provided many of the plotting functions used to generate the figures.

8 References

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

Fishery code	Gear	Flag/fleet	Region	Fishery code	Gear	Flag	Region
JPOS PL 1	PL	JP/OS	1	PS LOG 5	PS/LOG	ALL	5
JPDW PL 1	PL	JP/DW	1	PS FAD 5	PS/FAD	ALL	5
JPOS PL 2	PL	JP/OS	2	PS SCH 5	PS/SCH	ALL	5
JPDW PL 2	PL	JP/DW	2	PH DOM 5	DOM	PH	5
JPOS PS 2	PS	JP/OS	2	ID DOM 5	DOM	ID	5
JPDW PL 3	PL	JP/DW	3	JP LL 5	LL	JP/RES	5
JPOS PL 4	PL	JP/OS	4	JPDW PL 6	PL	JP/DW	6
JPDW PL 4	PL	JP/DW	4	FJ PL 6	PL	FJ	6
JP LL 4	LL	JP/RES	4	PS LOG 6	PS/LOG	ALL	6
JPDW PL 5	PL	JP/DW	5	PS FAD 6	PS/FAD	ALL	6
PG PL 5	PL	PG	5	PS SCH 6	PS/SCH	ALL	6
SB PL 5	PL	SB	5	JP LL 6	LL	JP/RES	6

Table 2. Summary of the number of tag releases and recoveries (excluding Japanese tags released in the equatorial regions) by region. Recovery data are also apportioned to the fishery of recovery.

Region	Releases	Recoveries		
		Total	Fishery	Number
1	1,136	41	JPOS PL 1	41
2	23,835	1,375	JPOS PL 2	558
			JPDW PL 2	42
			JPOS PS 2	775
3	2,123	3	JPDW PL 3	3
4	23,319	194	JPOS PL 4	74
			JPDW PL 4	120
5	105,146	12,223	JPDW PL 5	388
			PG PL 5	876
			SB PL 5	1,313
			PS ALL 5	6,541
			PH DOM 5	2,253
			ID DOM 5	852
6	72,528	4,266	JPDW PL 6	304
			FJ PL 6	2,713
			PS ALL 6	1,249
Total	228,087	18,102		

Table 3. 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 0.05 times actual sample size with a maximum effective sample size of 50.
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 purse seine fisheries (based on tag seeding), moderately informative priors for Philippines and Indonesian fisheries, 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 (beta prior for steepness with mode at 0.90 and SD of 0.10). The spatial distribution of recruitment in each quarter is allowed to vary in an unconstrained fashion. The proportion of total recruitment in each region (1-6) 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 1–6 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 six principal pole-and-line fisheries and estimated independently for all other fisheries. Seasonal variation for all fisheries apart from Philippines and Indonesian fisheries. 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 0.1 (SD is 0.7 for Philippines, Indonesian and research longline fisheries with missing effort data).
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.22 (SD is 0.7 for Philippines, Indonesian and research longline fisheries with missing effort data).
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 4. Definition of sensitivity analyses. Unless noted all other parameters are equivalent to the base-case assessment.

Analysis	Description	Details
PL-incr-q	Increasing catchability of pole-and-line fleet.	Increase in PL standardised effort series by 2% per annum.
Low-tag	Lower tag reporting rate for 1977-80 SPC tag releases.	Increase number of tag recoveries from 1977-80 release groups by 100%; equivalent to a halving of the reporting rate.
Equatorial	SA model for equatorial area only.	Restrict model domain to equatorial regions (regions 5 and 6) only.
Reweight LF	Iterative reweighting of the length frequency data from the PL fishery.	Iterative reweighting of size data by fishery and decade for the six principal pole-and-line-fisheries.

Table 5. Details of objective function components for the base-case analysis and sensitivity analyses.

Objective function component	Base-case	PL-incr-q	Low-tag	Equatorial
Total catch log-likelihood	195.70	196.34	187.09	135.15
Length frequency log-likelihood	-177,687.78	-177,822.50	-177,898.55	-118,146.63
Tag log-likelihood	10,630.99	10,908.46	11,673.88	7,014.29
Penalties	3,310.08	3,385.37	3,399.85	2,224.97
Total function value	-163,551.01	-163,332.33	-162,637.73	-108,772.22

Table 6. Description of symbols used in the yield analysis.

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2003–2006
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (<i>MSY</i>)
$\tilde{Y}_{F_{current}}$	Equilibrium yield at $F_{current}$
$\tilde{Y}_{F_{MSY}}$ (or <i>MSY</i>)	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 <i>MSY</i>
$\tilde{S}\tilde{B}_0$	Equilibrium unexploited adult biomass
$\tilde{S}\tilde{B}_{F_{current}}$	Equilibrium adult biomass at $F_{current}$
$\tilde{S}\tilde{B}_{MSY}$	Equilibrium adult biomass at <i>MSY</i>
$B_{current}$	Average current (2003–2006) total biomass
$S\tilde{B}_{current}$	Average current (2003–2006) adult biomass
$B_{current, F=0}$	Average current (2003–2006) total biomass in the absence of fishing.

Table 7. Estimates of management quantities for the base-case and three alternative analyses. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading). The equatorial model is deemed to be the most appropriate analysis for the purpose of formulating management advice for the WCPO fishery (see Section 5 for details).

Management quantity	Units	Base-case	PL-incr-q	Low-tag	Equatorial
$\tilde{Y}_{F_{current}}$	t per annum	1,021,000	1,069,000	966,000	893,000
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per annum	2,264,000	2,499,000	2,196,000	1,280,000
\tilde{B}_0	t	7,595,000	8,248,000	7,566,000	4,865,000
$\tilde{B}_{F_{current}}$	t	5,810,000	6,352,000	5,818,000	2,944,000
\tilde{B}_{MSY}	t	2,436,000	2,576,000	2,413,000	1,438,000
\tilde{SB}_0	t	6,299,000	6,760,000	6,278,000	4,252,000
$\tilde{SB}_{F_{current}}$	t	4,536,000	4,885,000	4,553,000	2,348,000
\tilde{SB}_{MSY}	t	1,323,000	1,285,000	1,318,000	894,000
$B_{current}$	t	8,051,000	8,420,000	8,574,000	4,294,000
$SB_{current}$	t	6,136,000	6,324,000	6,570,000	9,024,000
$B_{current, F=0}$	t	10,031,000	10,431,000	10,595,000	6,463,000
$B_{current} / \tilde{B}_0$		1.06	1.02	1.13	0.88
$B_{current} / \tilde{B}_{F_{current}}$		1.39	1.33	1.47	1.46
$B_{current} / \tilde{B}_{MSY}$		3.31	3.27	3.55	2.99
$B_{current} / B_{current, F=0}$		0.80	0.81	0.81	0.66
$SB_{current} / \tilde{SB}_0$		0.97	0.94	1.05	2.12
$SB_{current} / \tilde{SB}_{F_{current}}$		1.35	1.29	1.44	3.84
$SB_{current} / \tilde{SB}_{MSY}$		4.64	4.92	4.98	10.09
$\tilde{B}_{F_{current}} / \tilde{B}_0$		0.76	0.77	0.77	0.61
$\tilde{SB}_{F_{current}} / \tilde{SB}_0$		0.72	0.72	0.73	0.55
$\tilde{B}_{MSY} / \tilde{B}_0$		0.32	0.31	0.32	0.30
$\tilde{SB}_{MSY} / \tilde{SB}_0$		0.21	0.19	0.29	0.38
$F_{current} / \tilde{F}_{MSY}$		0.12	0.09	0.12	0.26
$\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$		2.39	2.47	2.41	2.05
$\tilde{SB}_{F_{current}} / \tilde{SB}_{MSY}$		3.43	3.80	3.45	2.63
$\tilde{Y}_{F_{current}} / MSY$		0.45	0.43	0.44	0.70

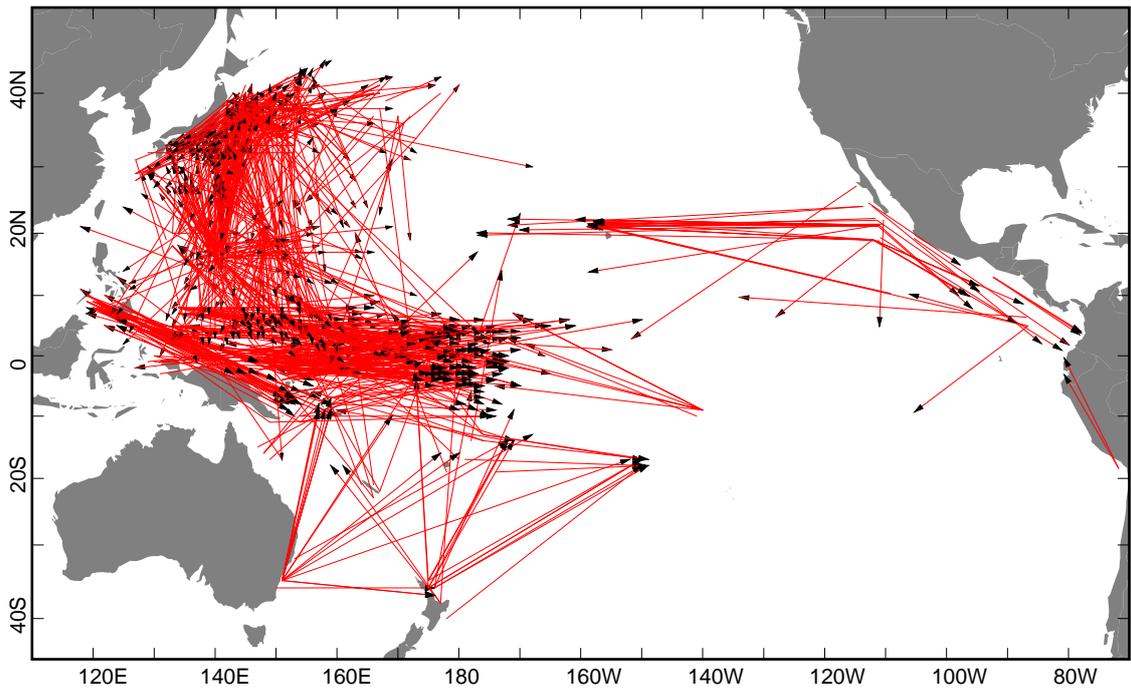


Figure 1. Long-distance (greater than 1,000 nmi) movements of tagged skipjack.

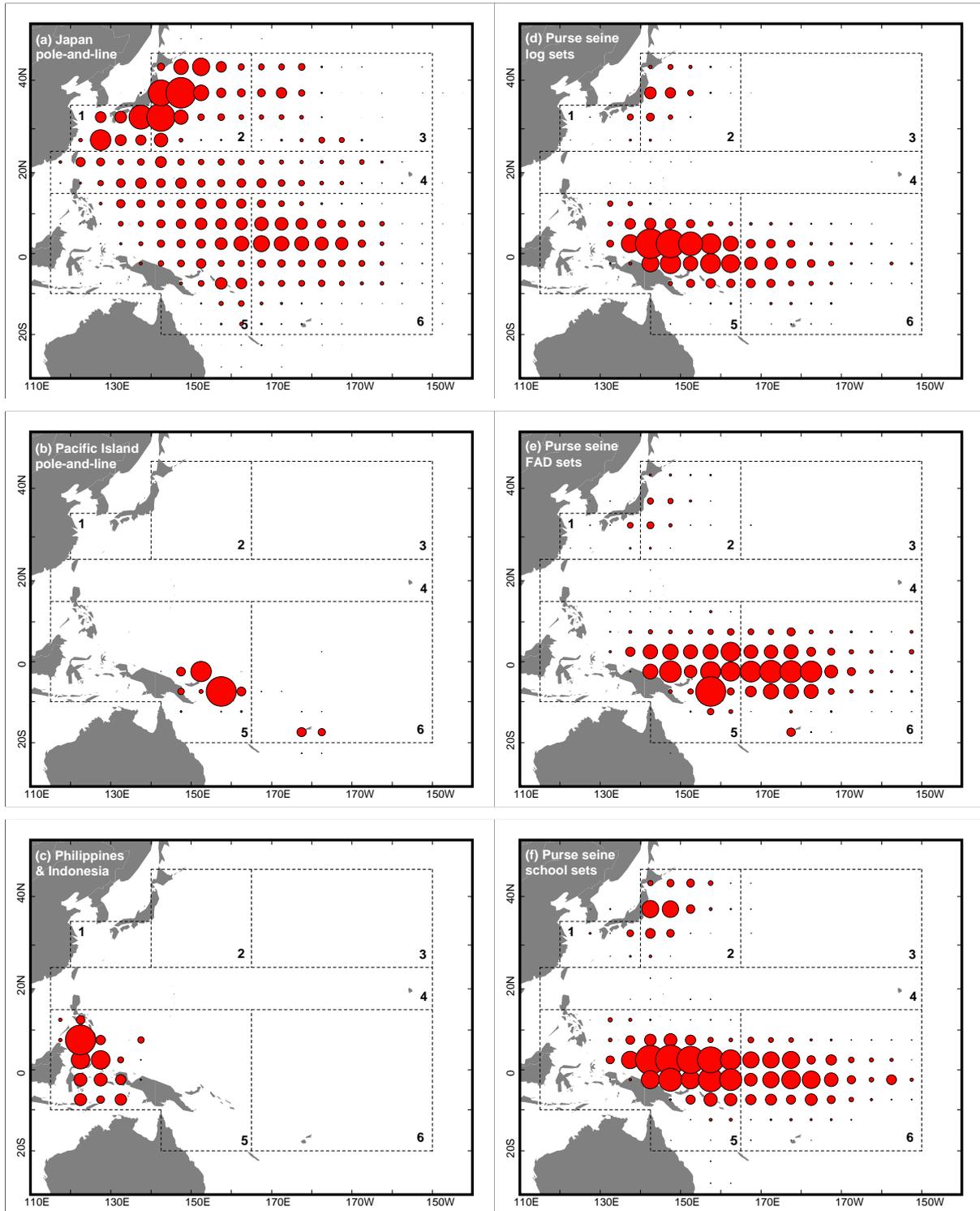


Figure 2. Distribution of skipjack catch 1972–1999 for the major fleets. The definition of the six regions used in the MULTIFAN-CL analysis is shown. Note that the size of circles reflects only spatial differences in catches within each fleet category.

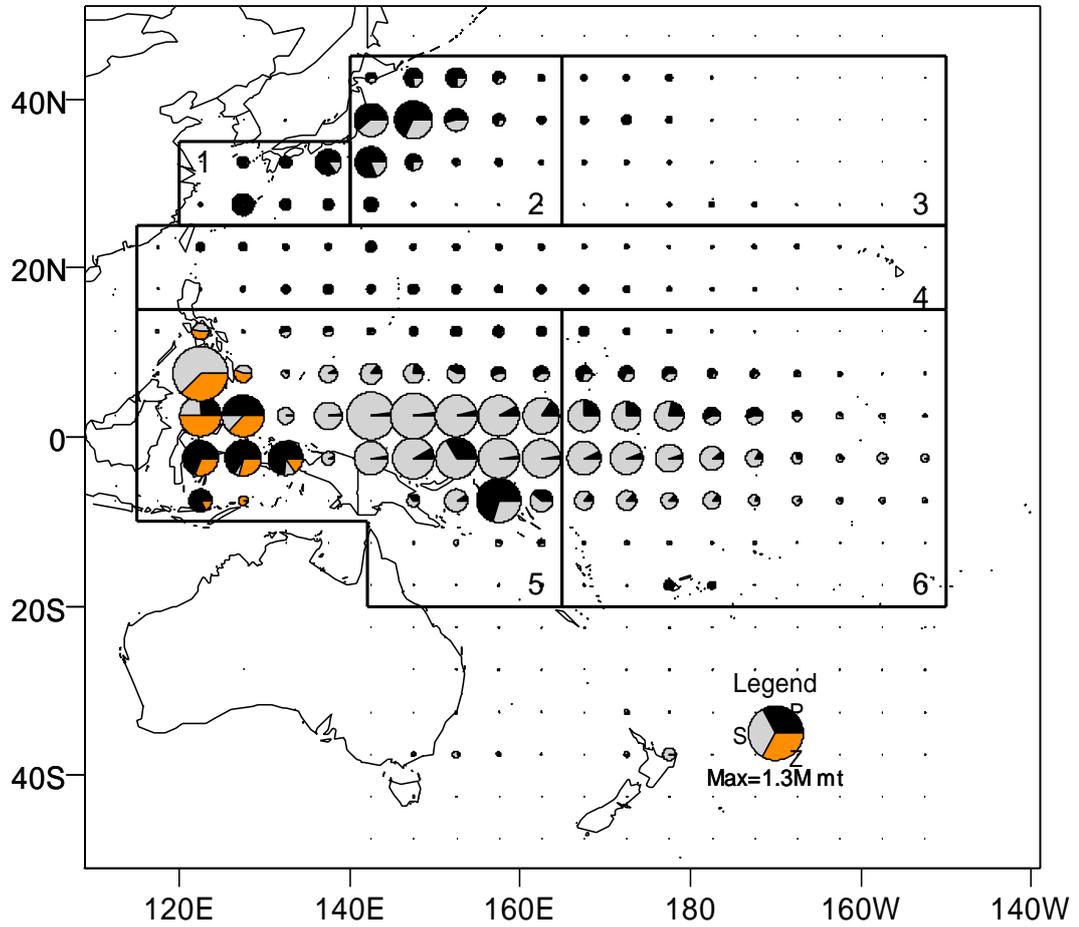


Figure 3. Distribution of total skipjack catches by method during 1972–2006 in relation to the six-region spatial stratification used in the MULTIFAN-CL analysis. Method codes: P, pole-and-line; S, purse-seine; Z, other.

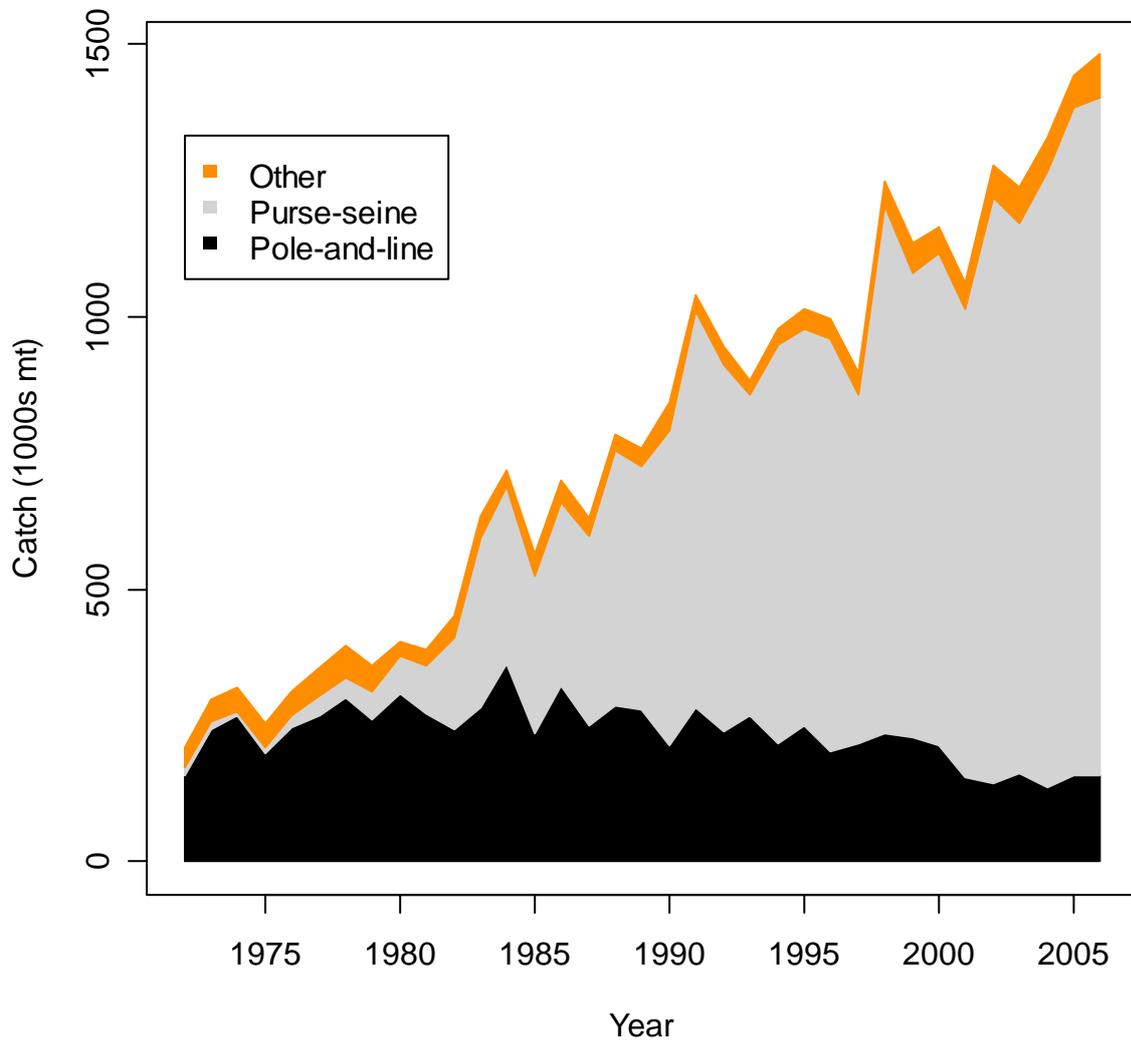


Figure 4. Annual skipjack tuna catch in the WCPO by method, 1972–2006.

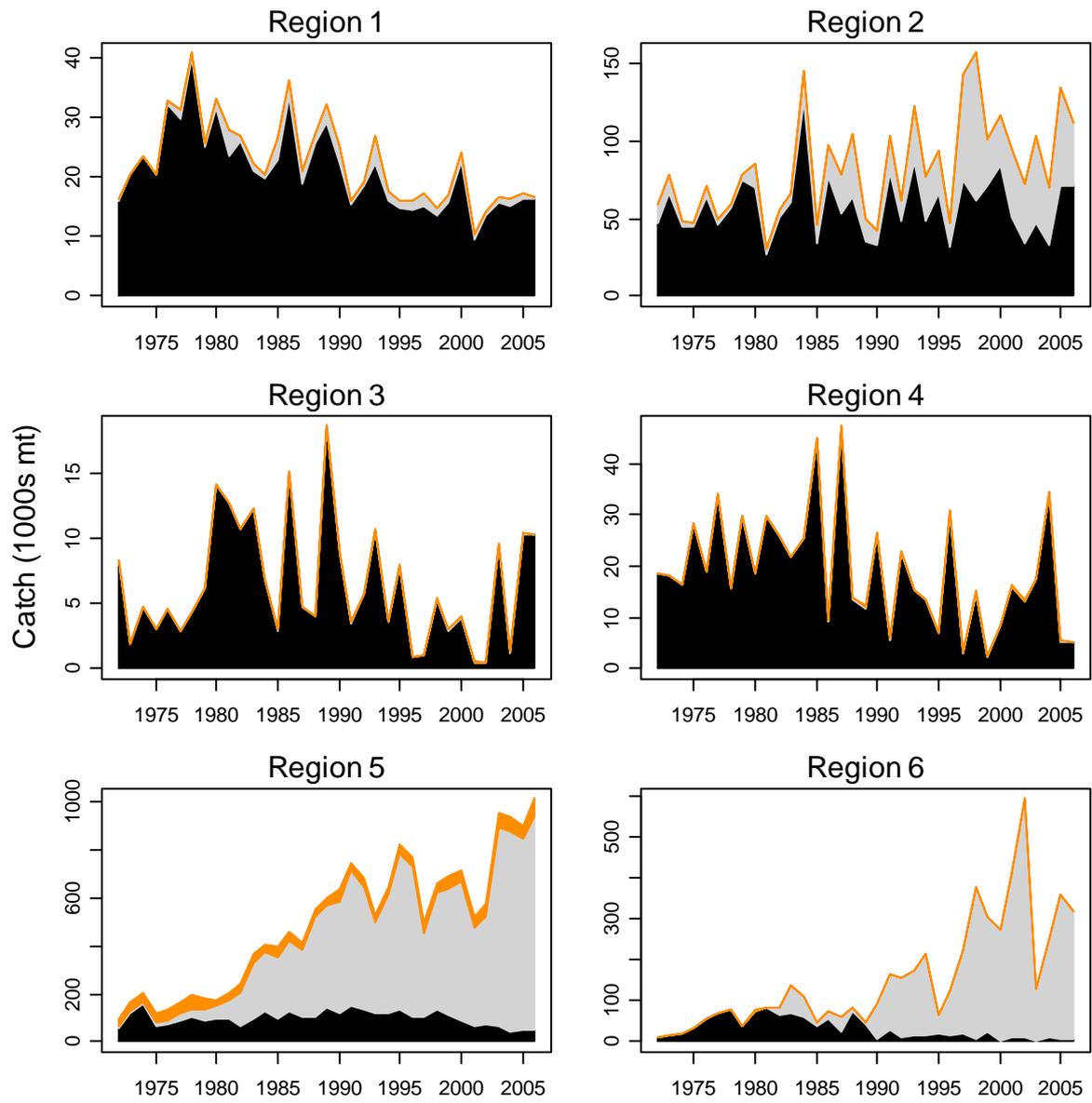


Figure 5. Annual skipjack tuna catch by region and method, 1972–2006.

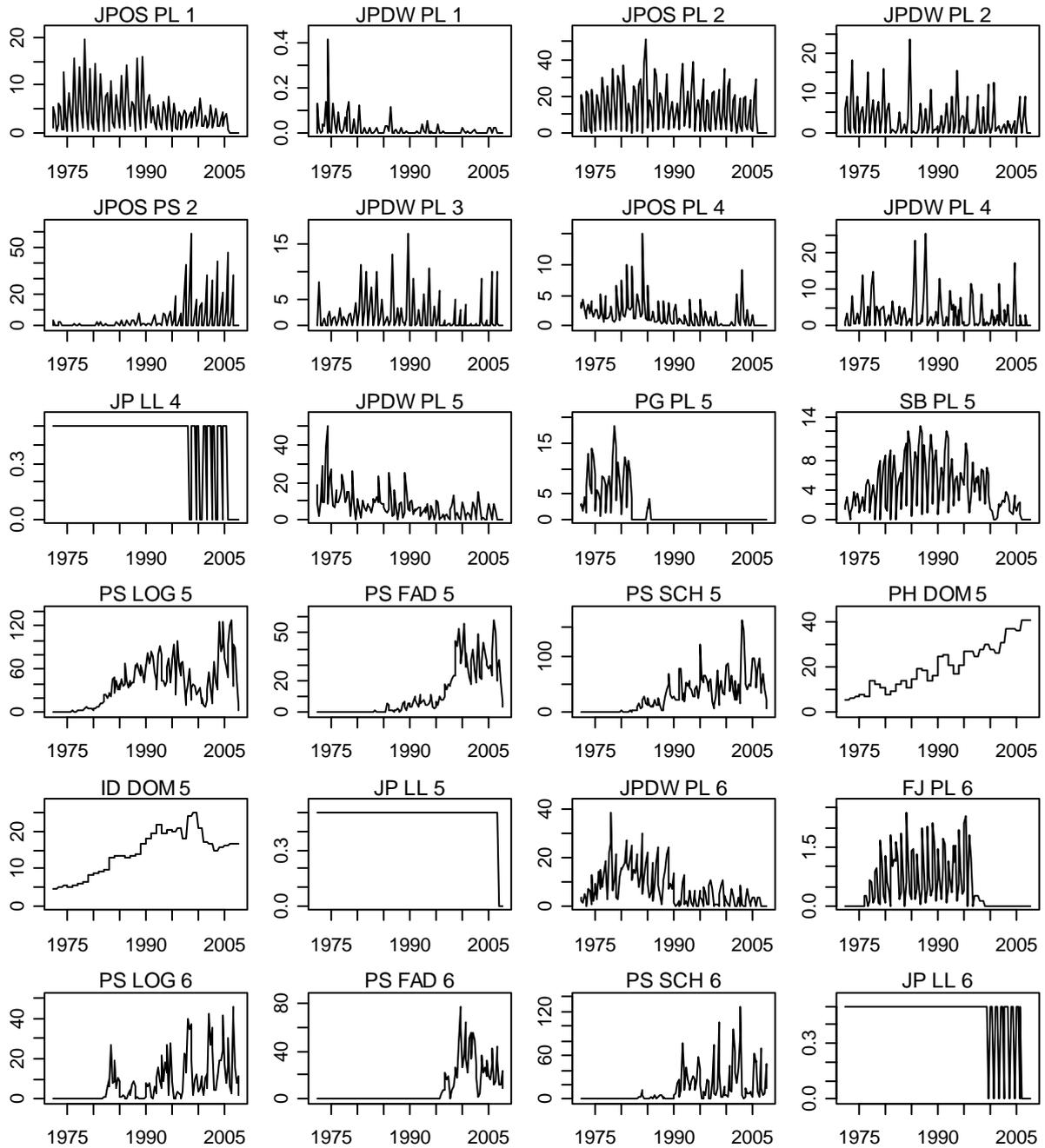


Figure 6. Quarterly catch by fishery and year. Catches are in thousands of tonnes for all fisheries except the longline (LL) fisheries, where the catches are in thousands of fish.

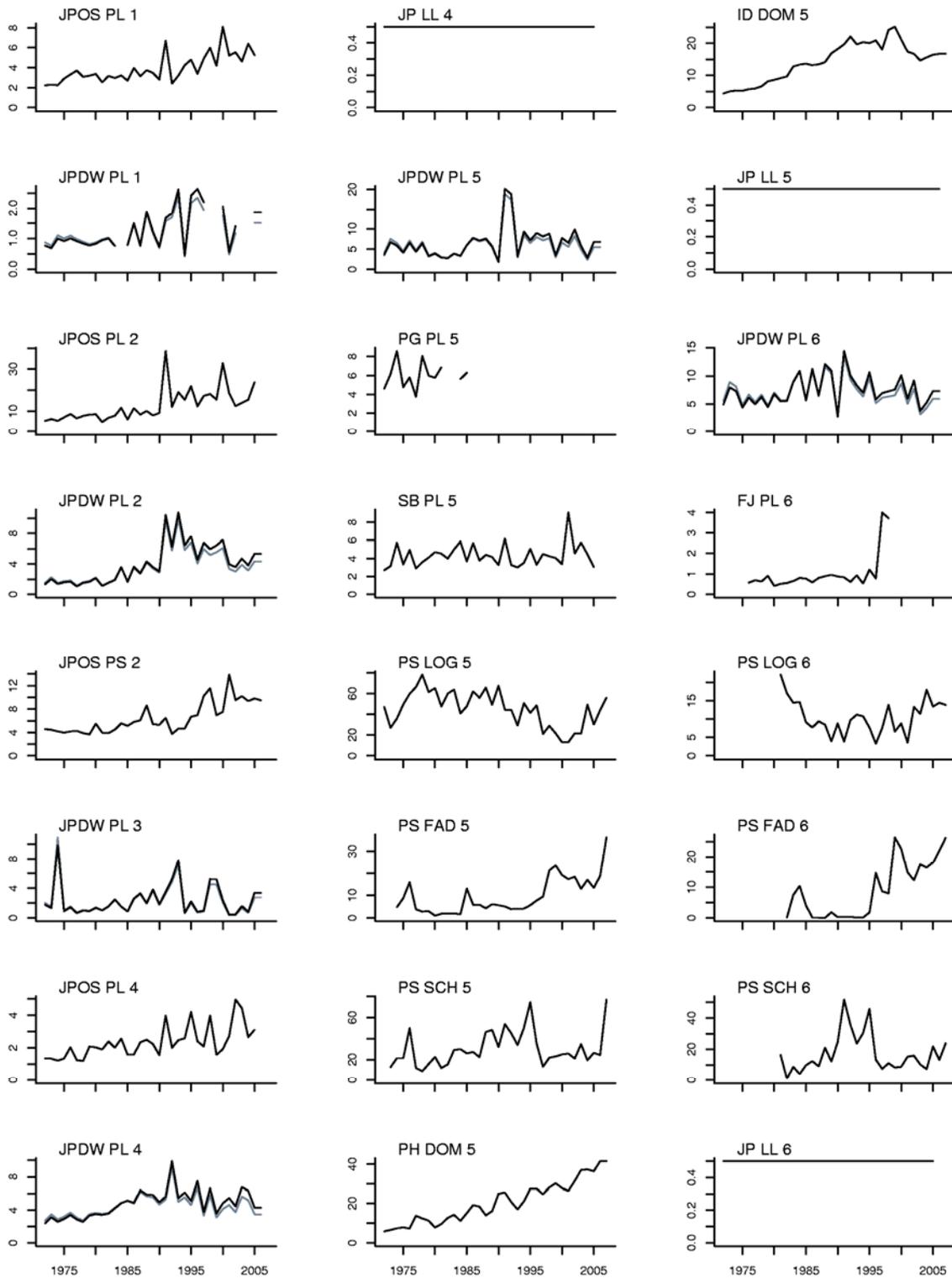


Figure 7. Annual catch per unit effort by fishery (black lines). The grey lines represent the trend in CPUE for the pole-and-line fisheries with an incremental increase in effective effort of 2% per annum (see text for details).

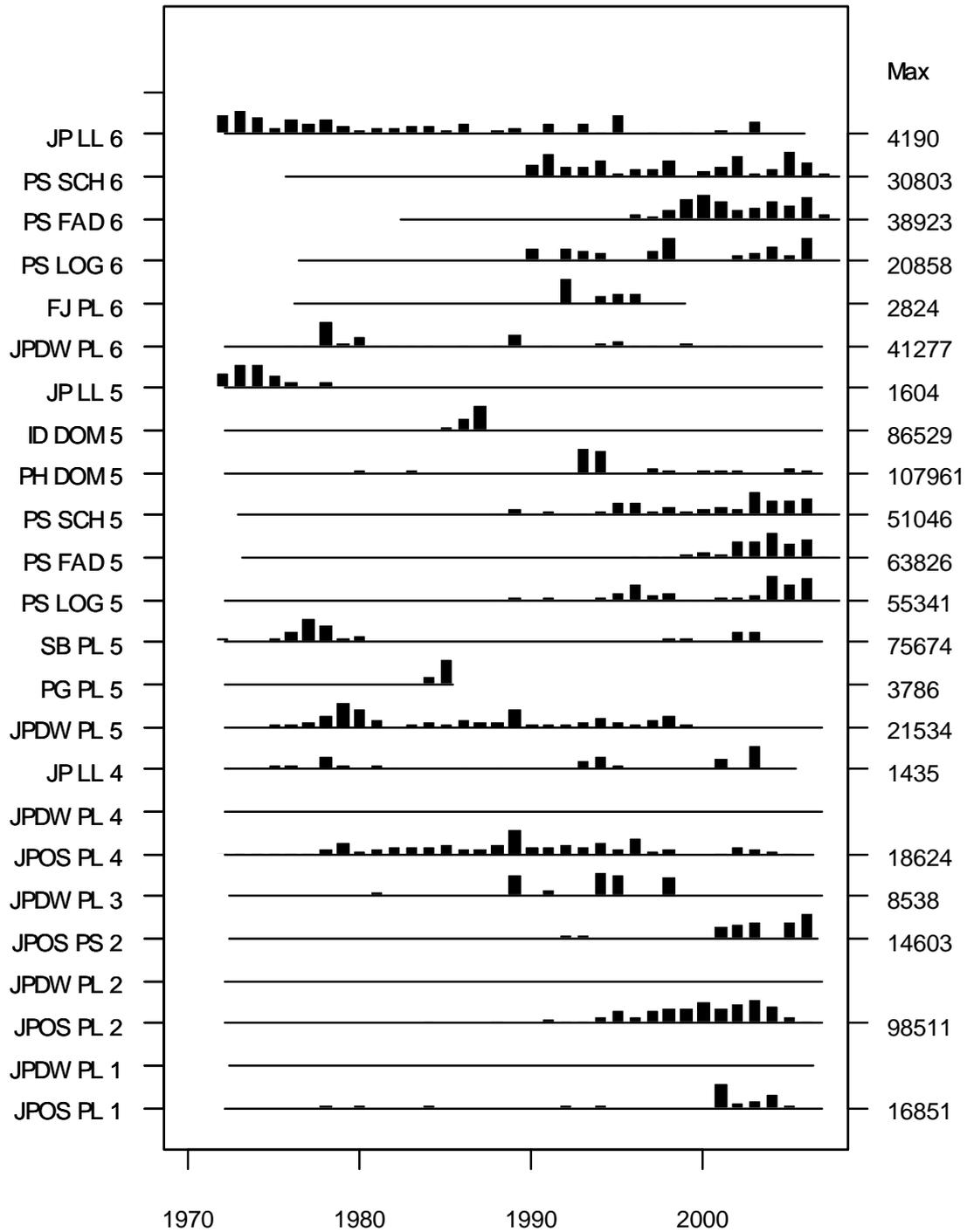


Figure 8. Number of length measurements by fishery and year. The heavy black line represents the period of operation of the fishery. The histogram bars are proportional to the maximum number of fish measured in a fishery/year (the value presented in the right hand axis).

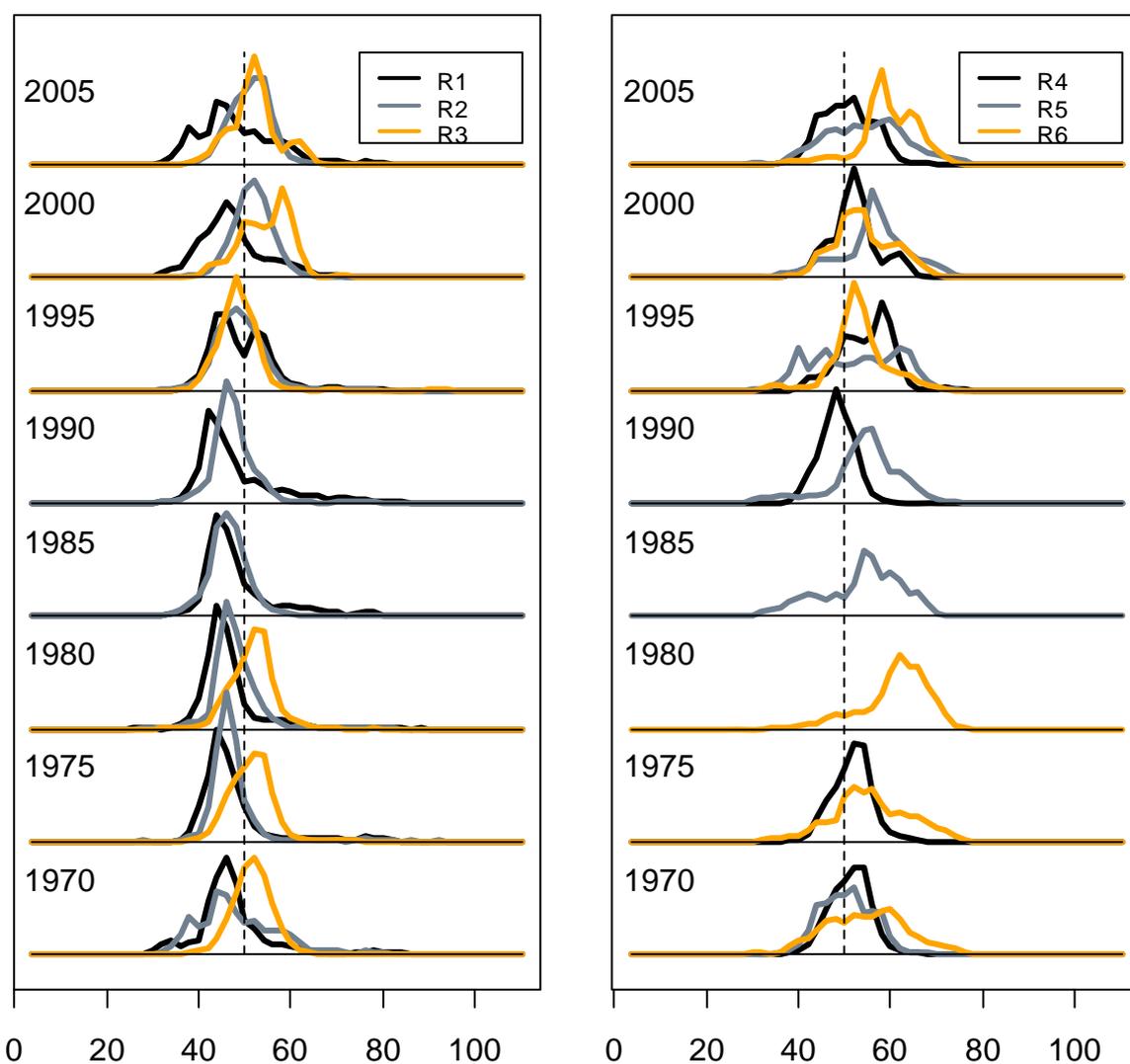


Figure 9. Proportional length compositions of skipjack from the Japanese pole-and-line fisheries operating in the six MFCL regions (R 1–6). Samples are aggregated by 5-year interval. Only region/time length compositions comprised of at least 1,000 fish are presented.

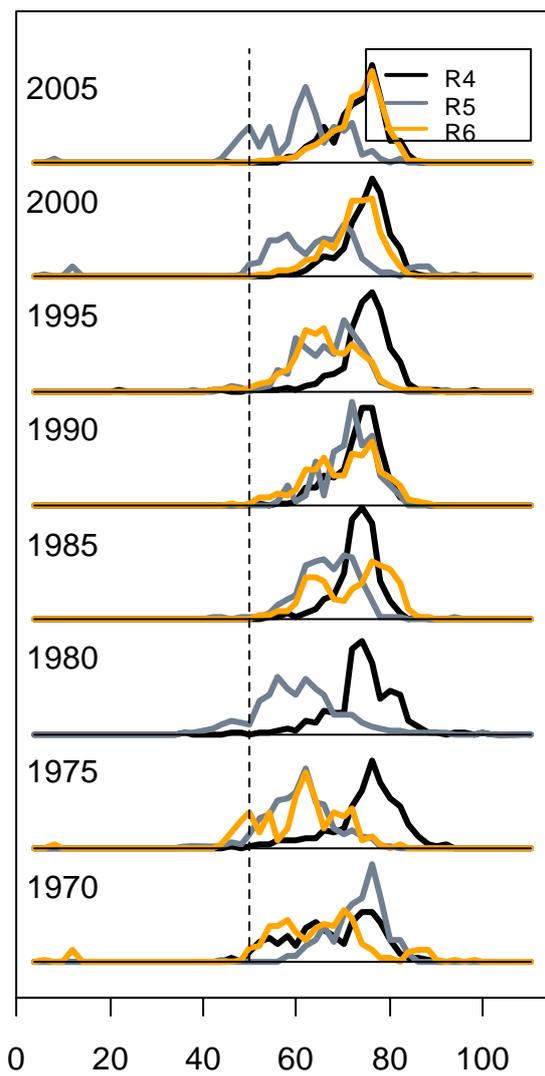


Figure 10. Proportional length compositions of skipjack from the Japanese longline fisheries operating in the MFCL regions 4–6 (R 4–6). Samples are aggregated by 5-year interval. Only region/time length compositions comprised of at least 100 fish are presented.

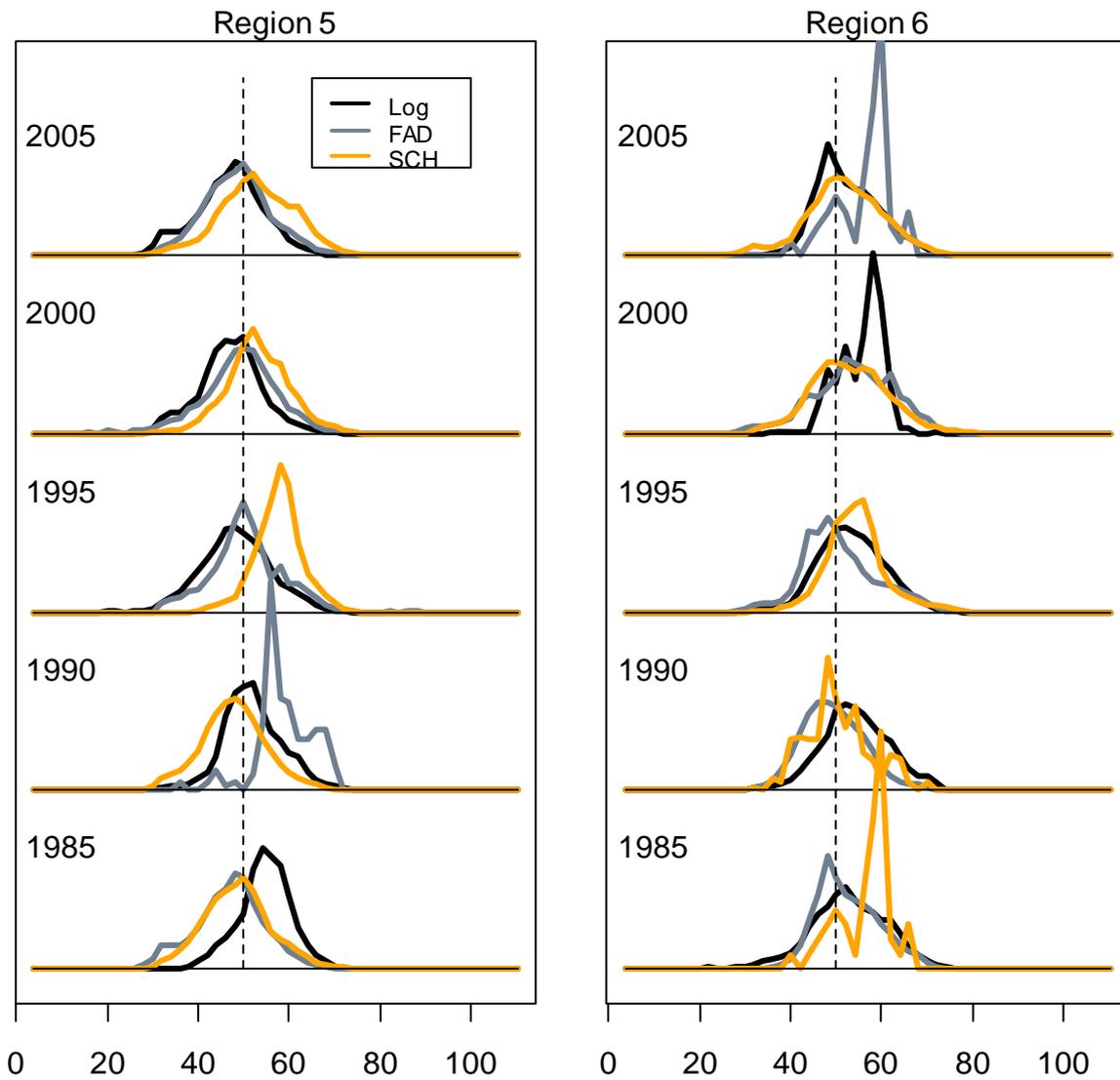


Figure 11. Proportional length compositions of skipjack from the equatorial purse-seine fisheries in the MFCL regions 5 (left panel) and 6 (right panel). Samples are aggregated by set type (log, FAD, and school) and 5-year interval.

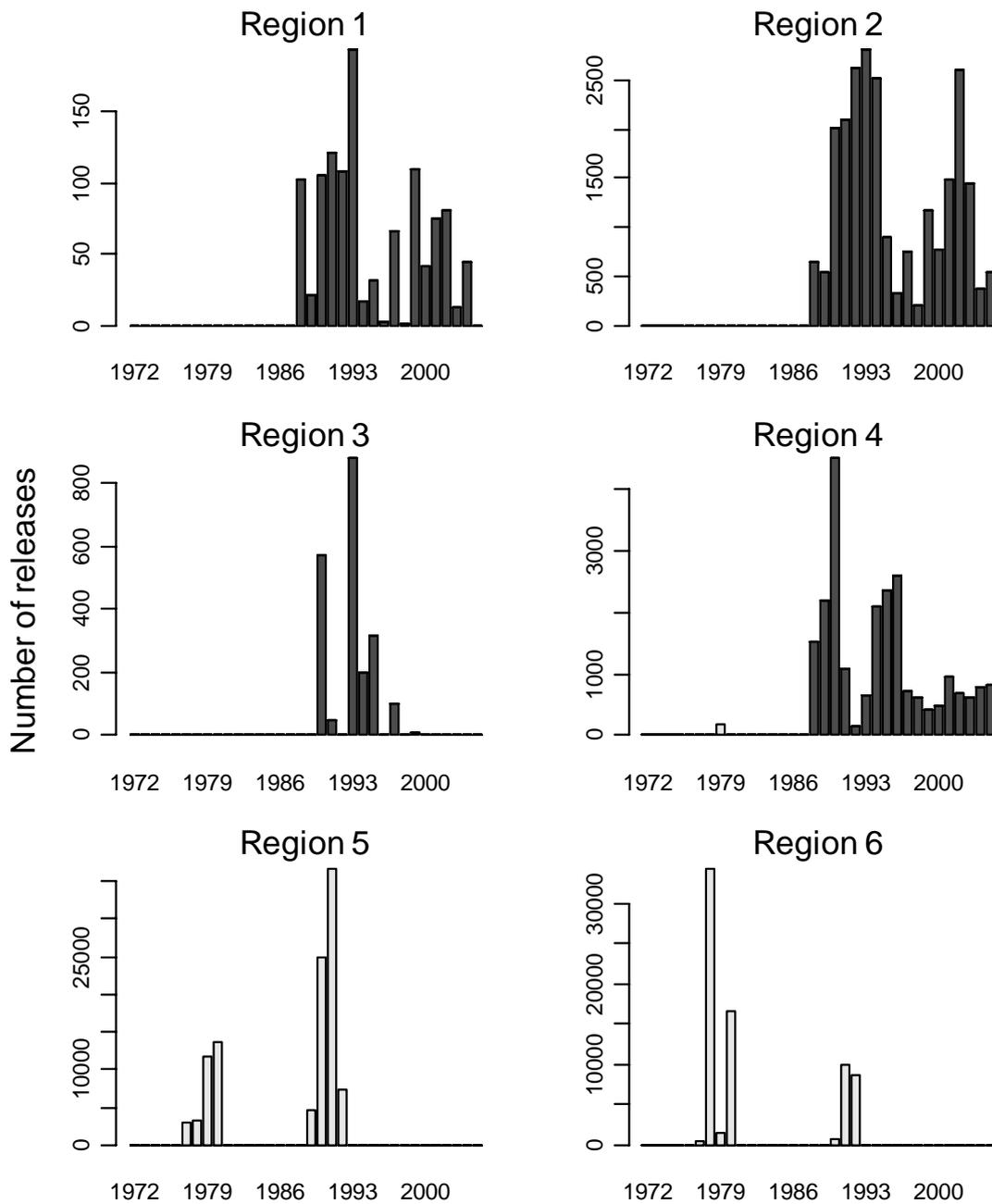


Figure 12. Number of tag releases by region, year and source of release included within the assessment model. The dark grey represents releases by Japanese research programmes; the light grey represents releases administered by SPC.

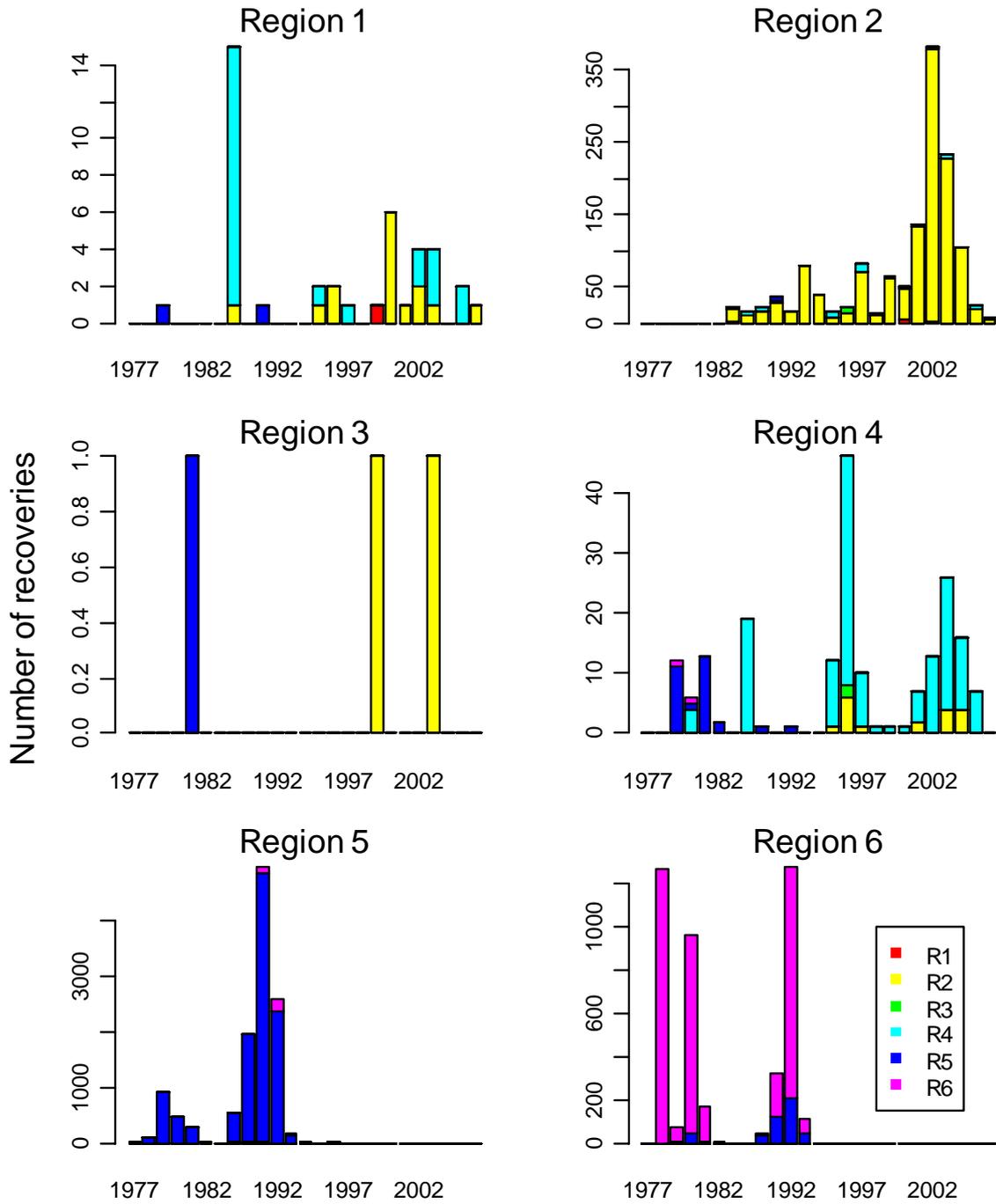


Figure 13. Annual number of tag recoveries in each region by region of release.

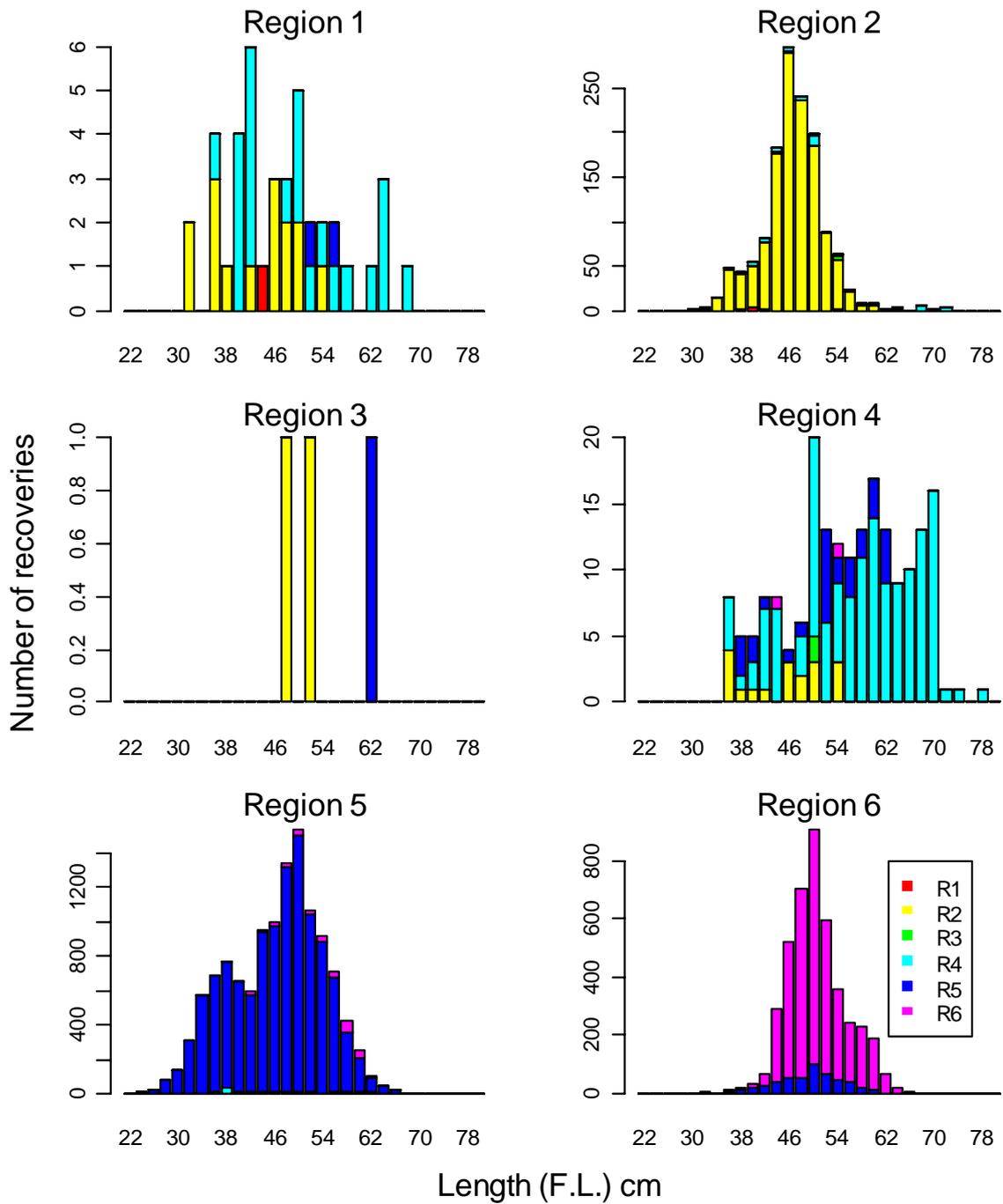


Figure 14. Number of recoveries at length for each region by region of release.

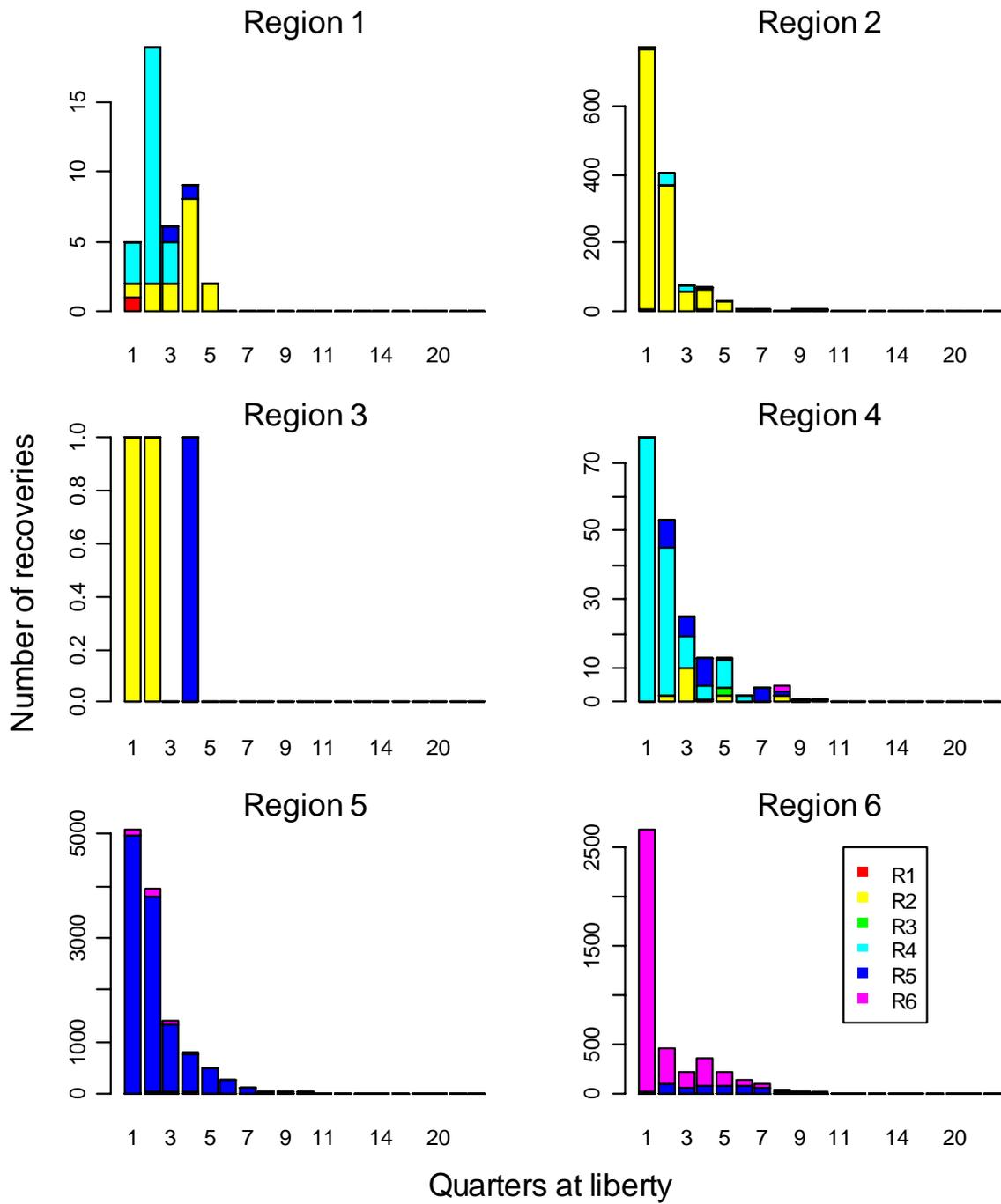


Figure 15. Number of tag recoveries by period at liberty (quarters) for each region by region of release. The first quarter represents the quarter in which the tags were released.

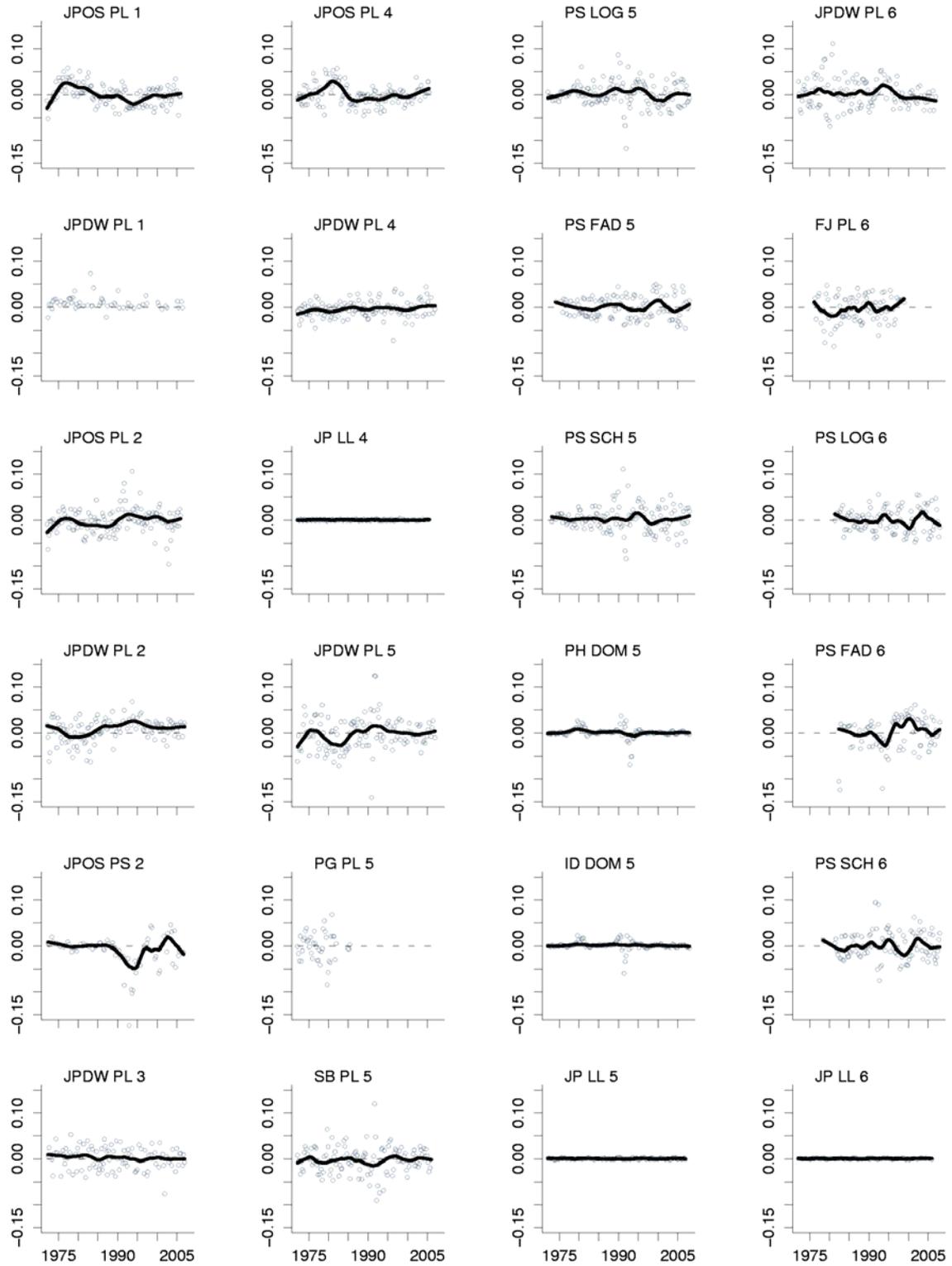


Figure 16. Residuals (observed minus predicted) of the natural logarithm of total catch for each fishery.

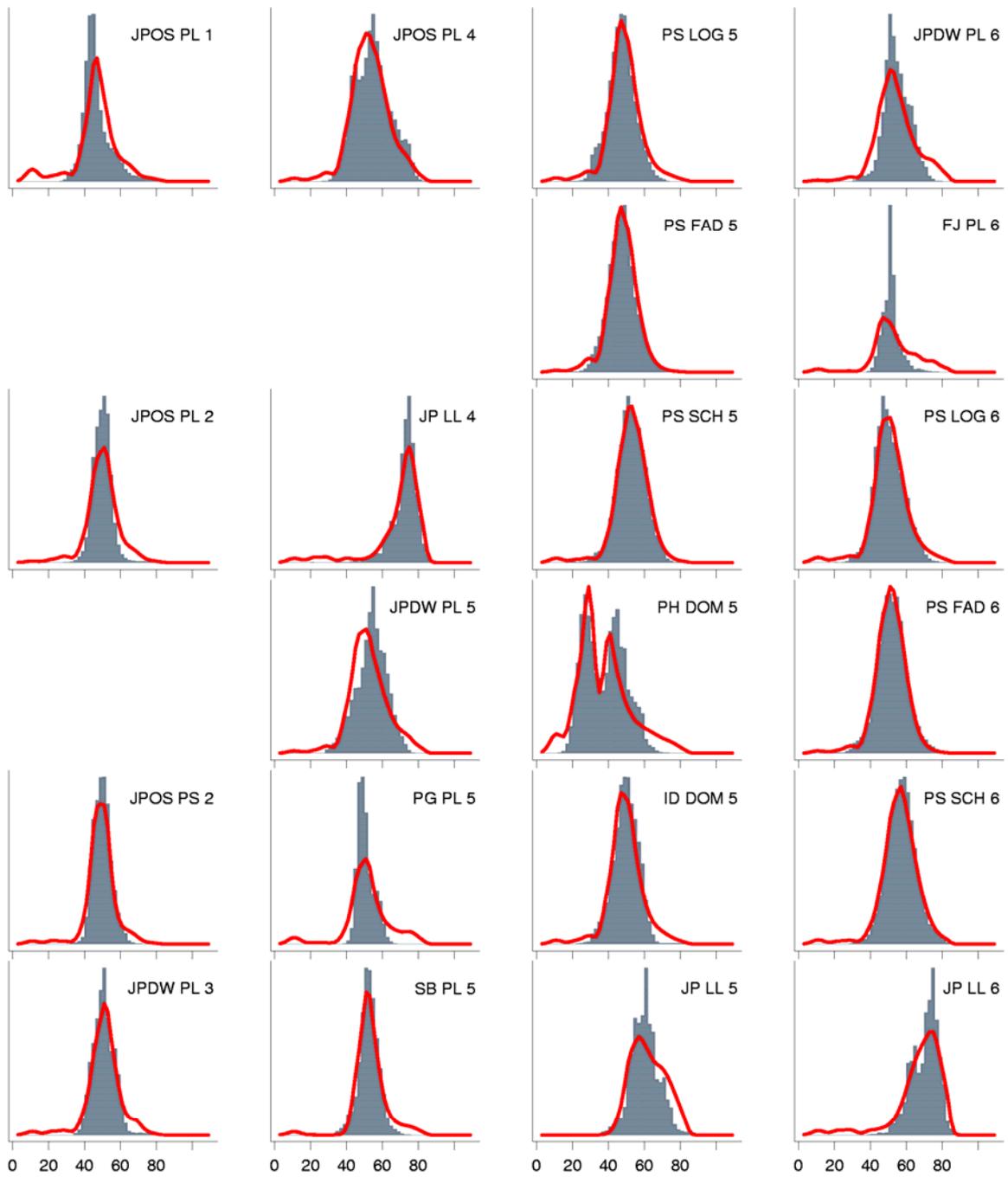


Figure 17. Observed (histograms) and predicted (line) length frequencies for each fishery aggregated over time.

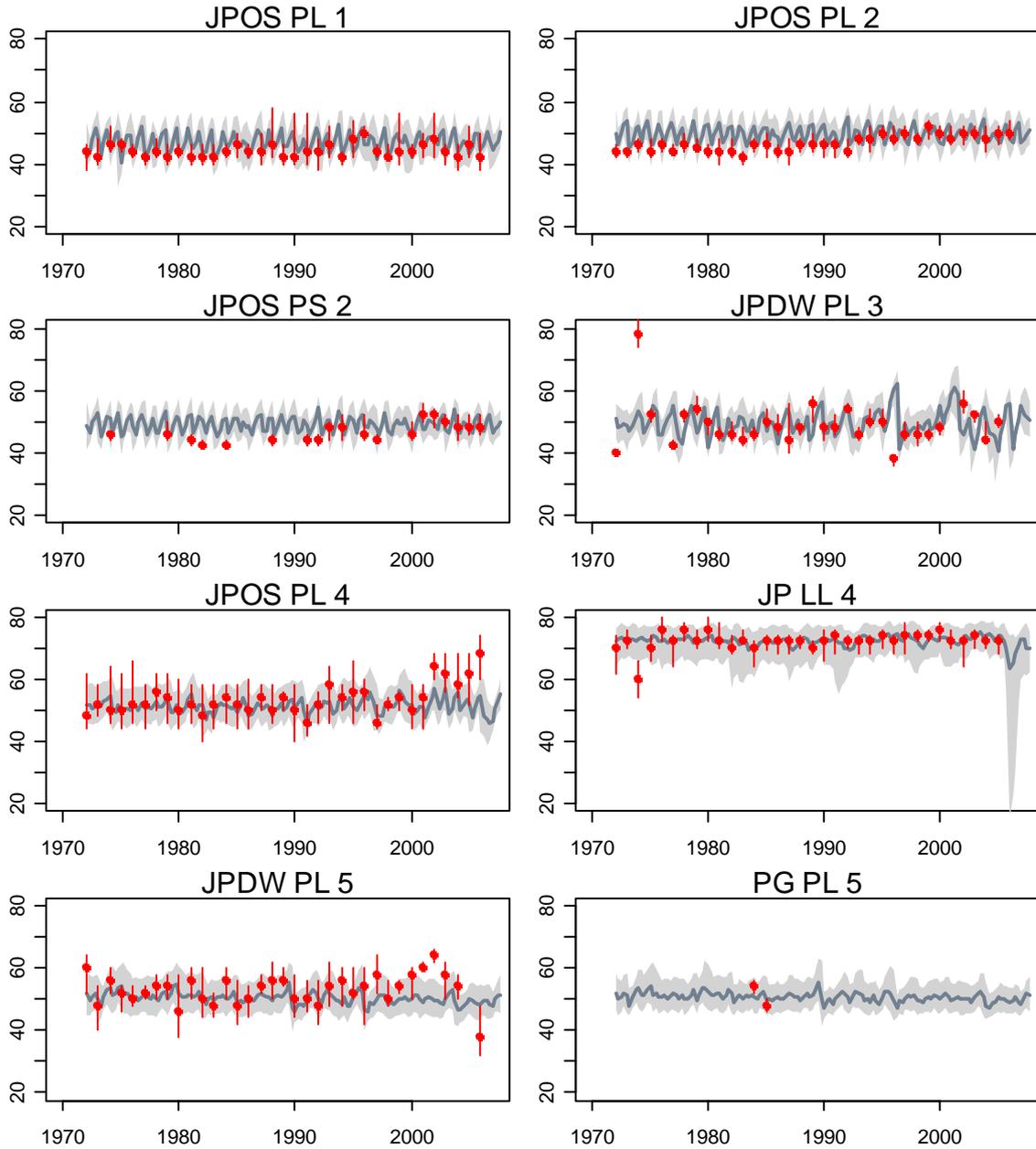


Figure 18. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of skipjack tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

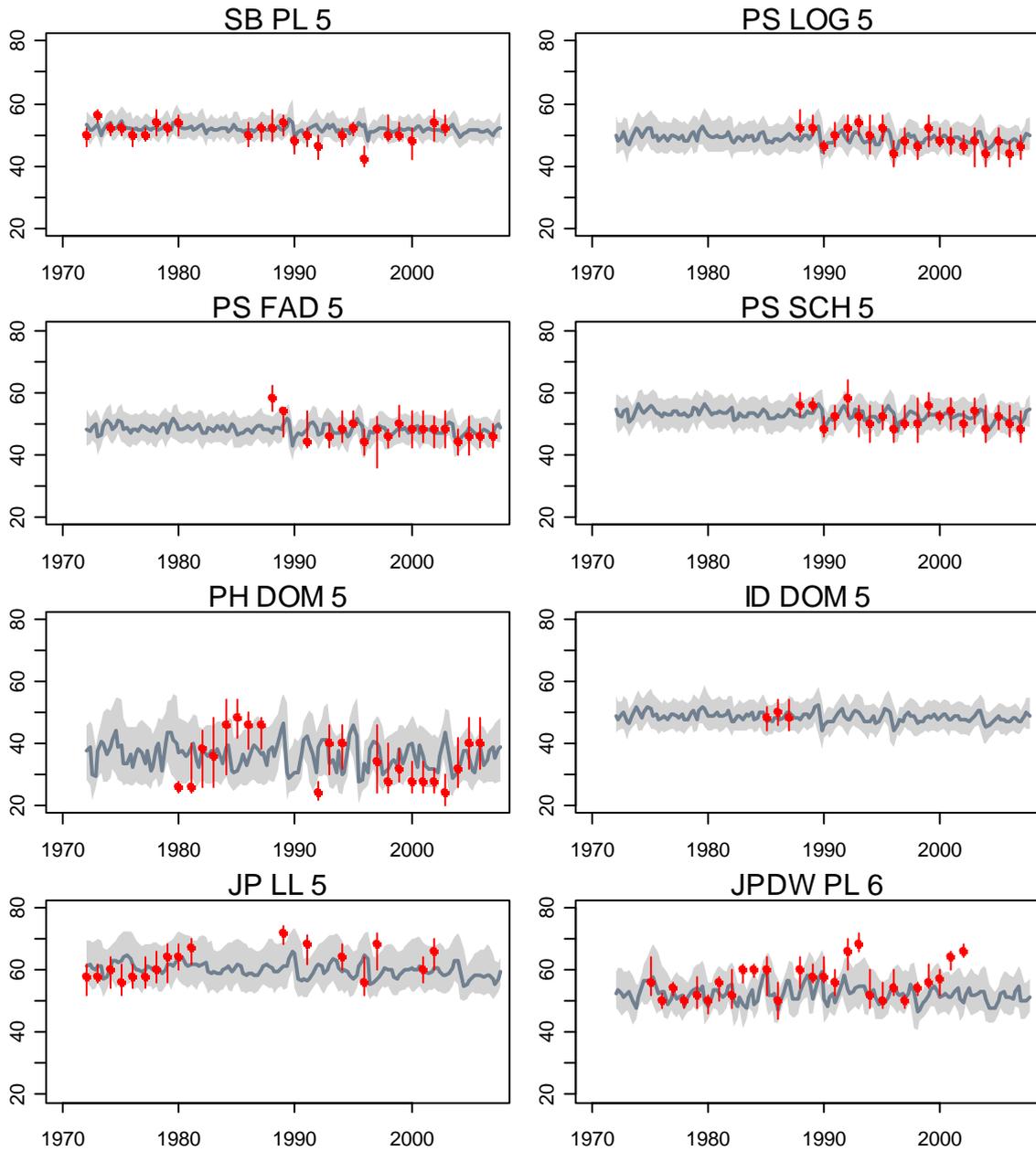


Figure 18. Continued.

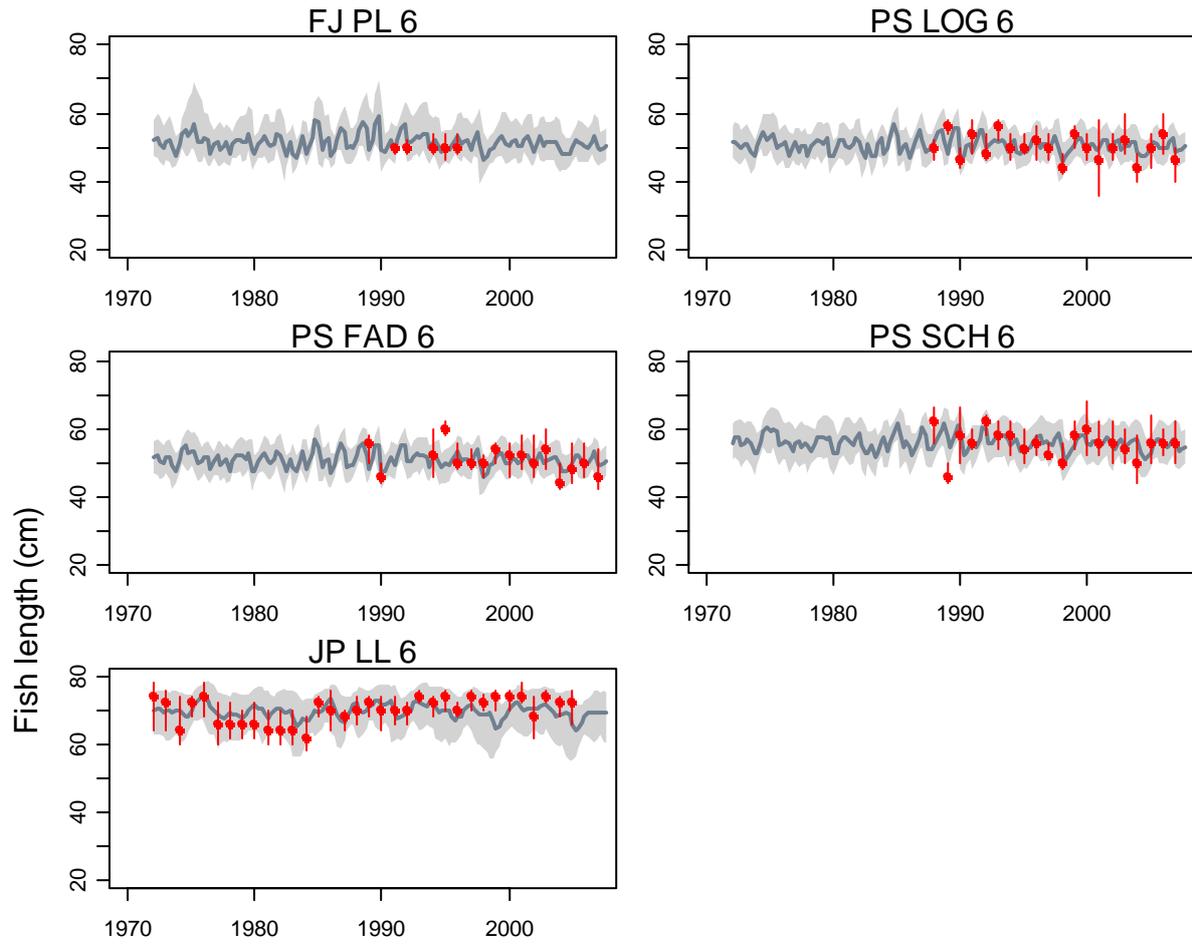


Figure 18. Continued.

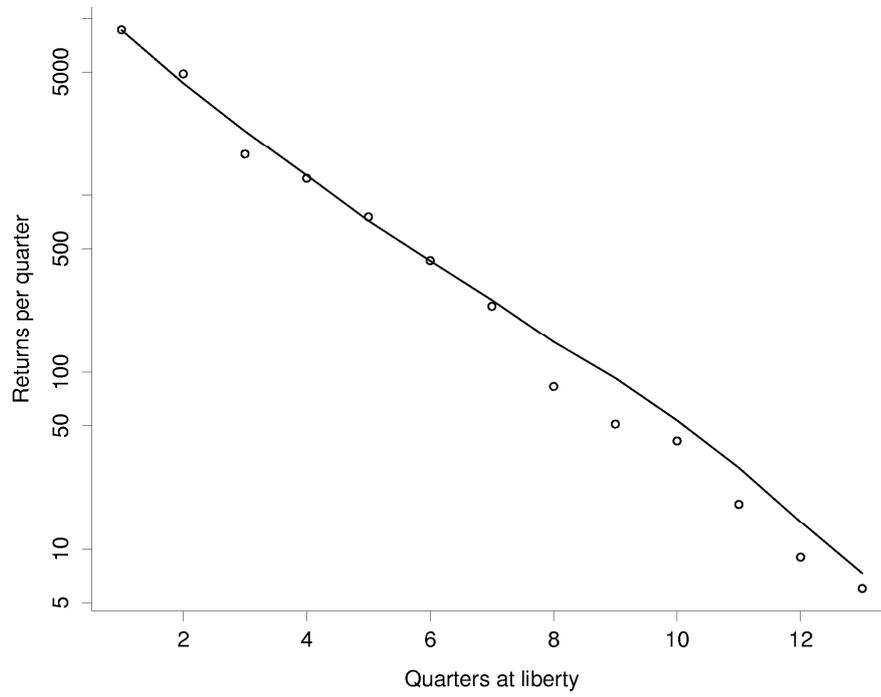


Figure 19. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters).

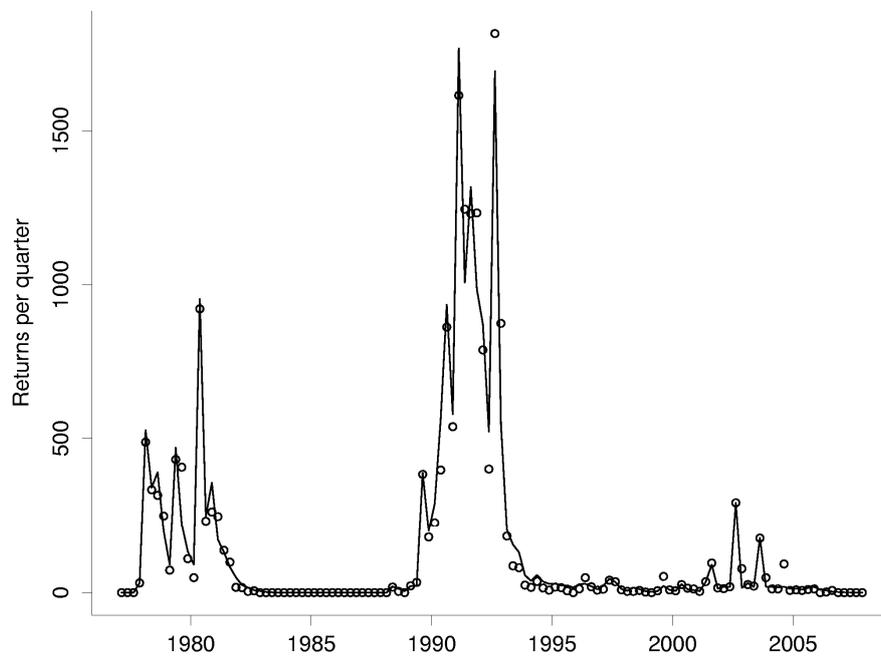


Figure 20. Number observed (circles) and predicted (lines) tag returns by recapture period (quarter).

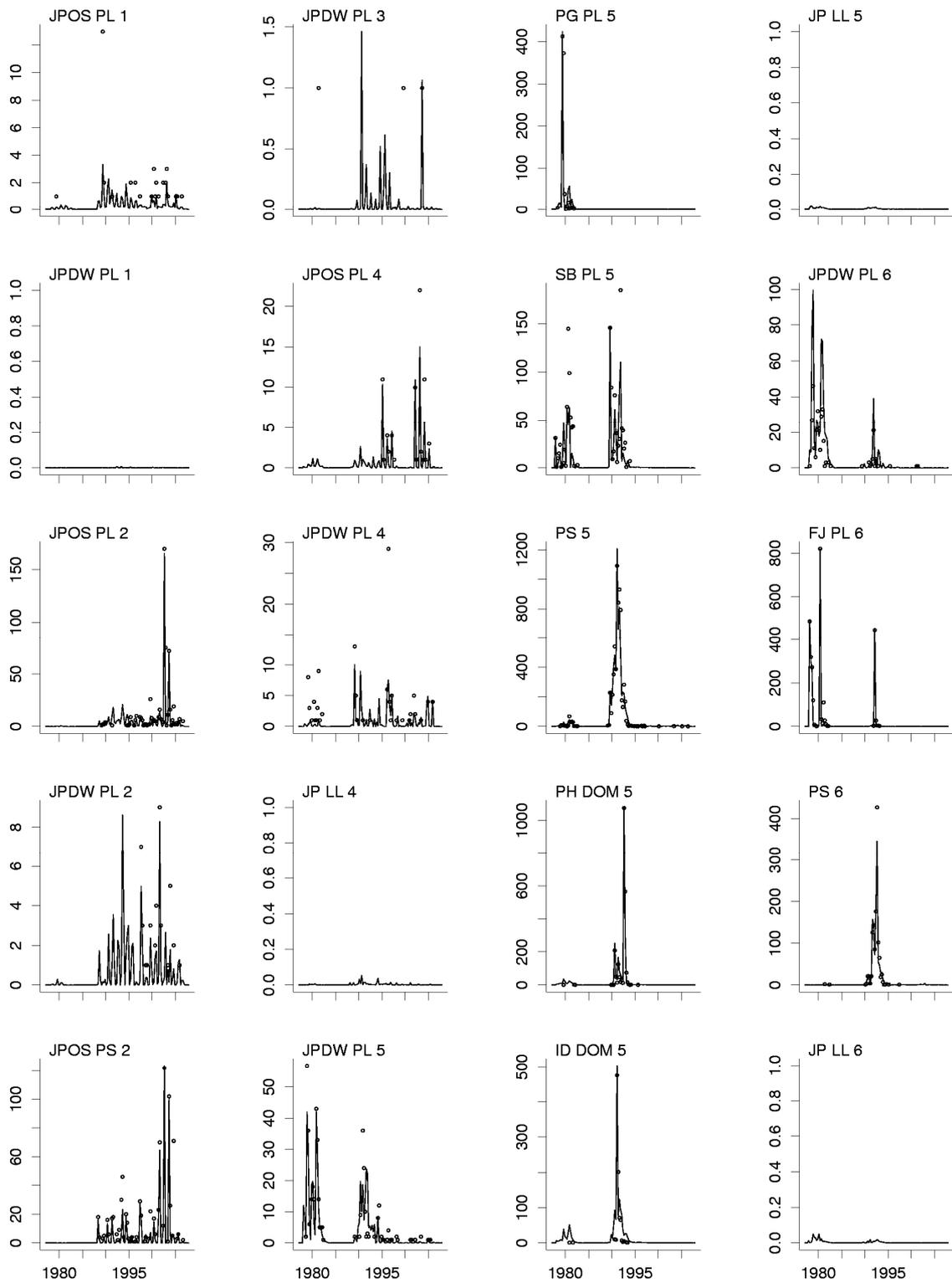


Figure 21. Observed (circles) and predicted (lines) tag returns by calendar quarter for various fisheries (tag groups).

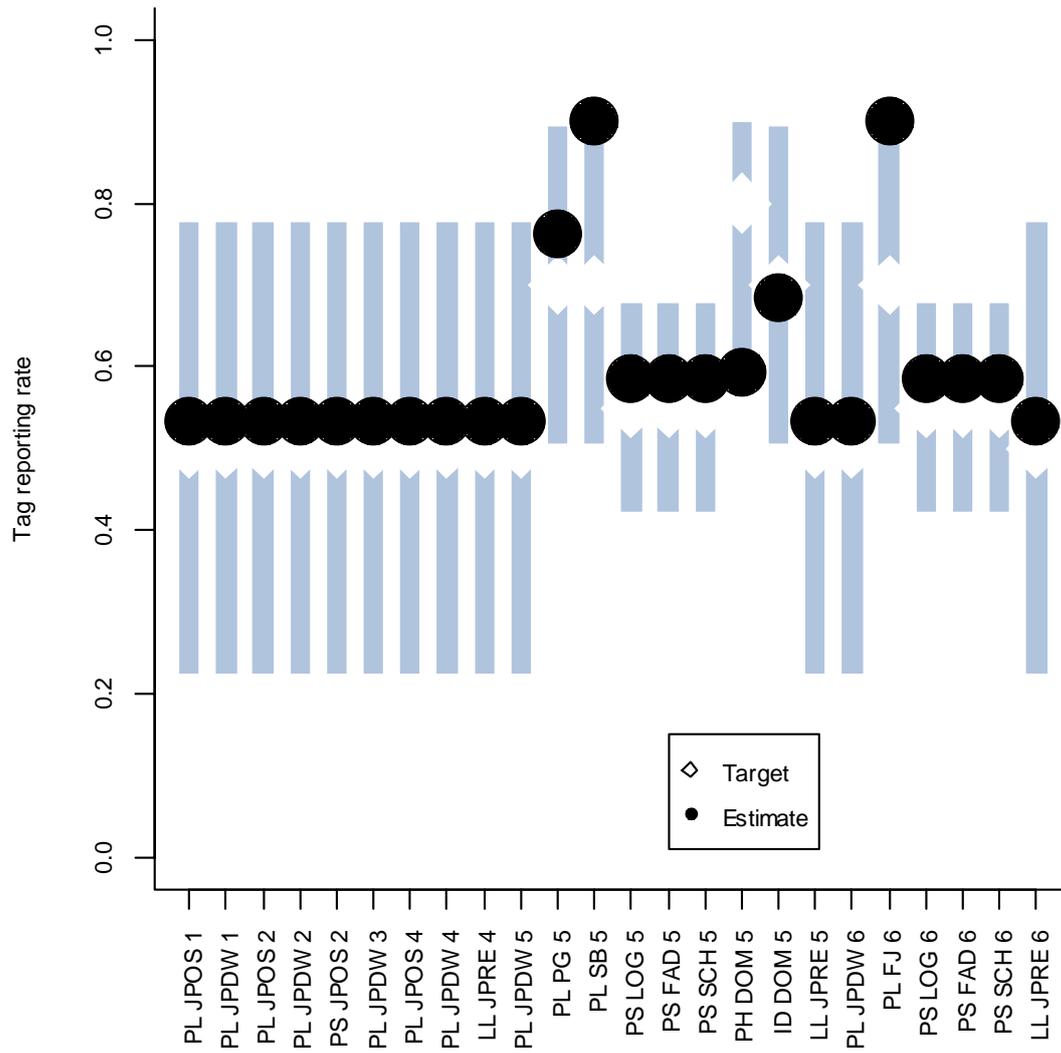


Figure 22. Estimated tag-reporting rates by fishery (histograms). The prior mean ± 1.96 SD is also shown for each fishery.

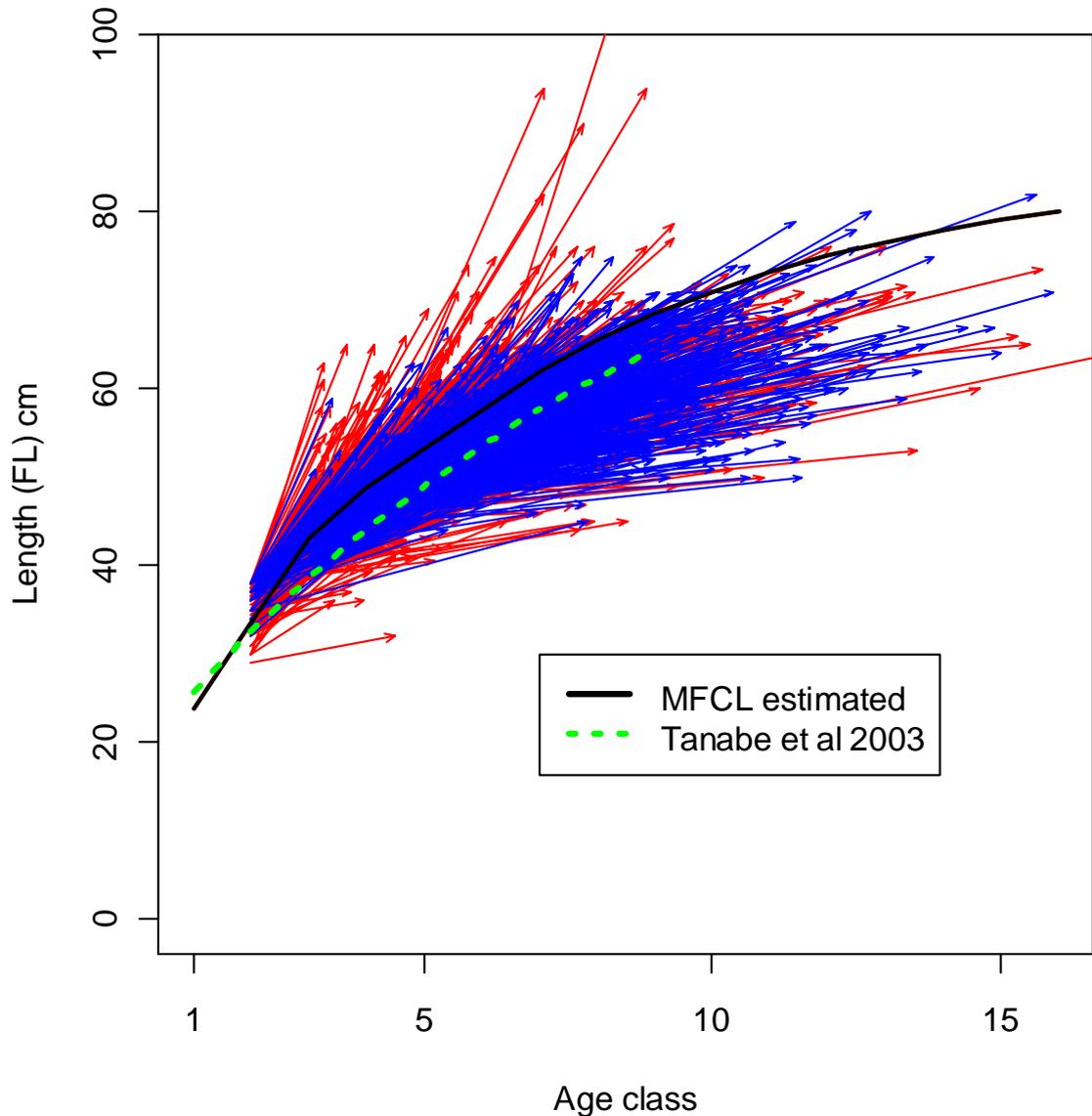


Figure 23. A comparison of the estimated mean lengths-at-age with the growth curve derived by Tanabe et al. (2003). The first age class is interpreted to represent the first quarter after hatching. For comparison, length at age estimates are presented from tag release and recapture data from the 1977–80 (blue arrows) and 1989–92 (red arrows) SPC tagging programmes. The tagging data is presented as a linear growth vector (depicted as an arrow) from length at release to length at recovery. Only fish at liberty for at least 150 days are included. Age at release is assumed from the estimated growth function.

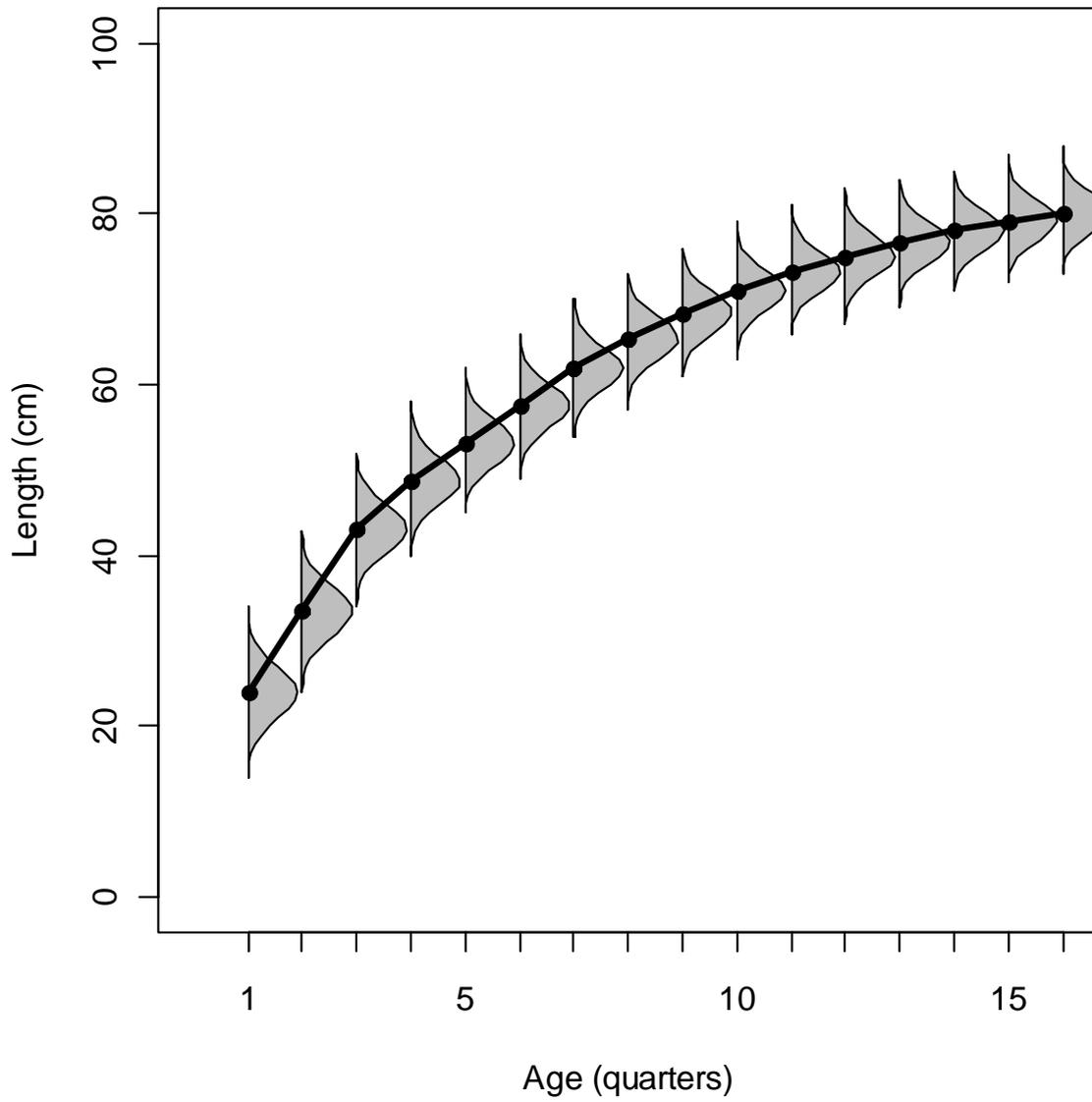


Figure 24. Estimated growth of skipjack derived from the assessment model. The black line represents the estimated length (FL, cm) at age and the grey area represents the estimated distribution of length at age.

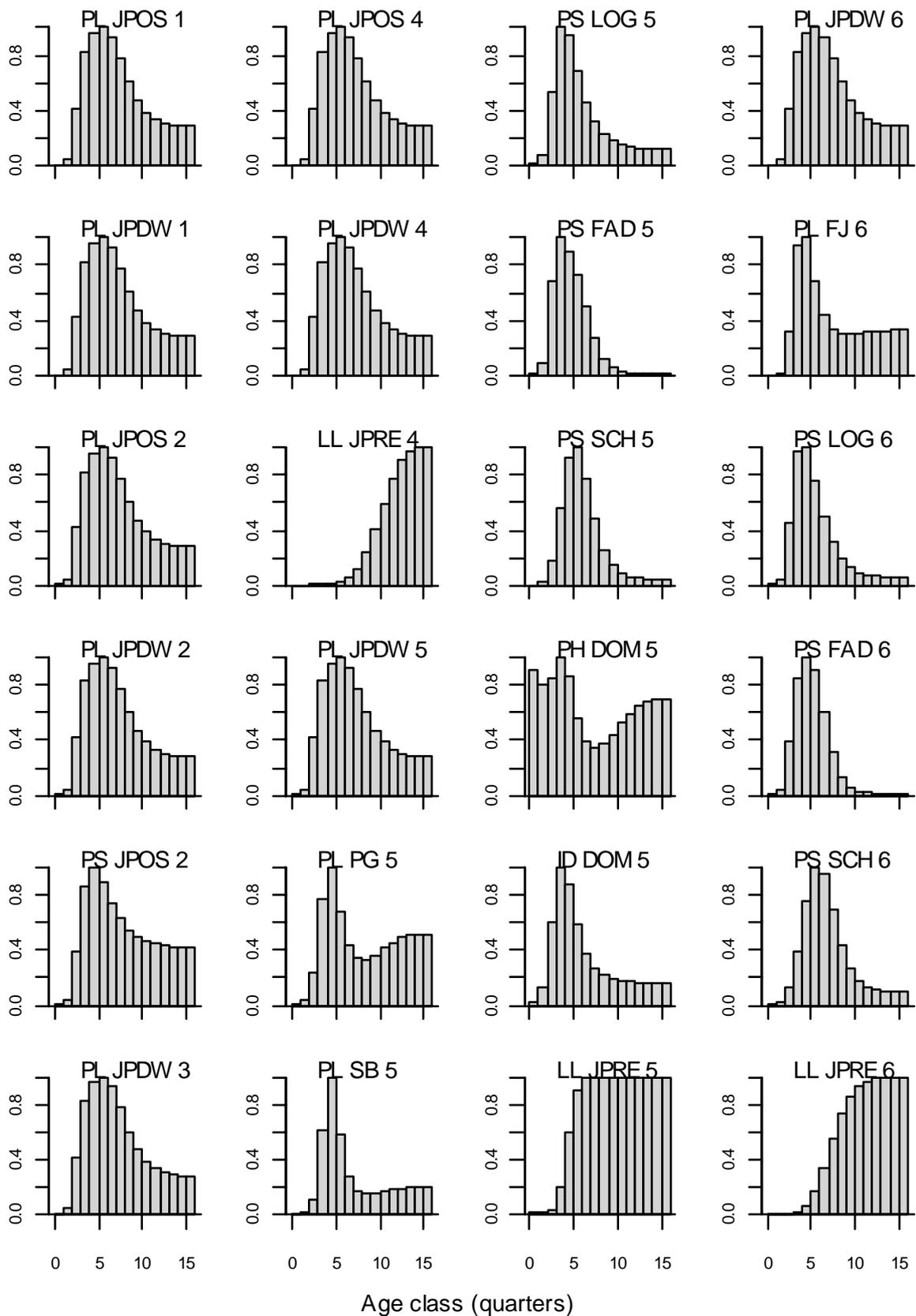


Figure 25. Selectivity coefficients, by fishery. All JP PL fisheries were assumed to have common selectivity.

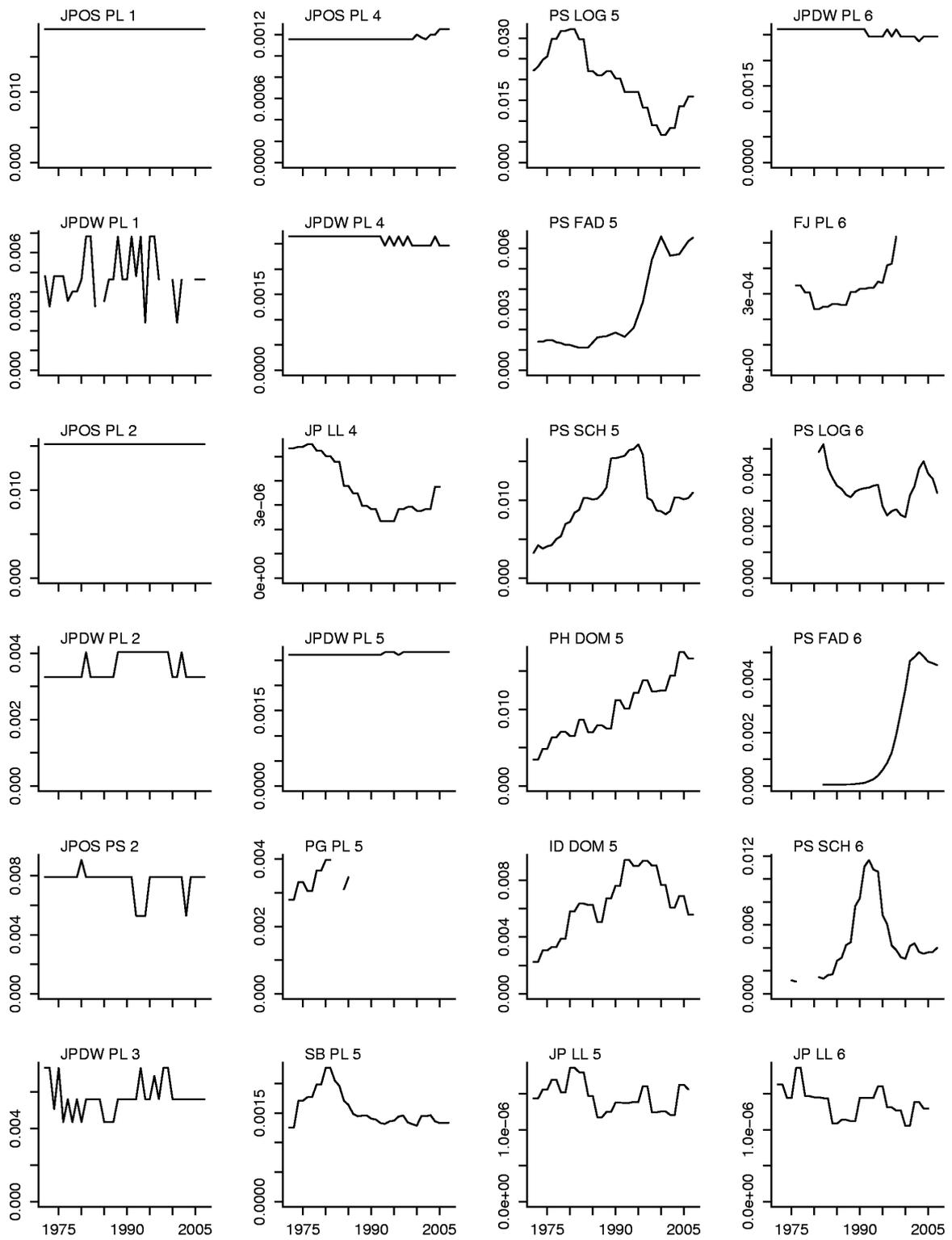


Figure 26. Estimated time-series catchability trends for each fishery.

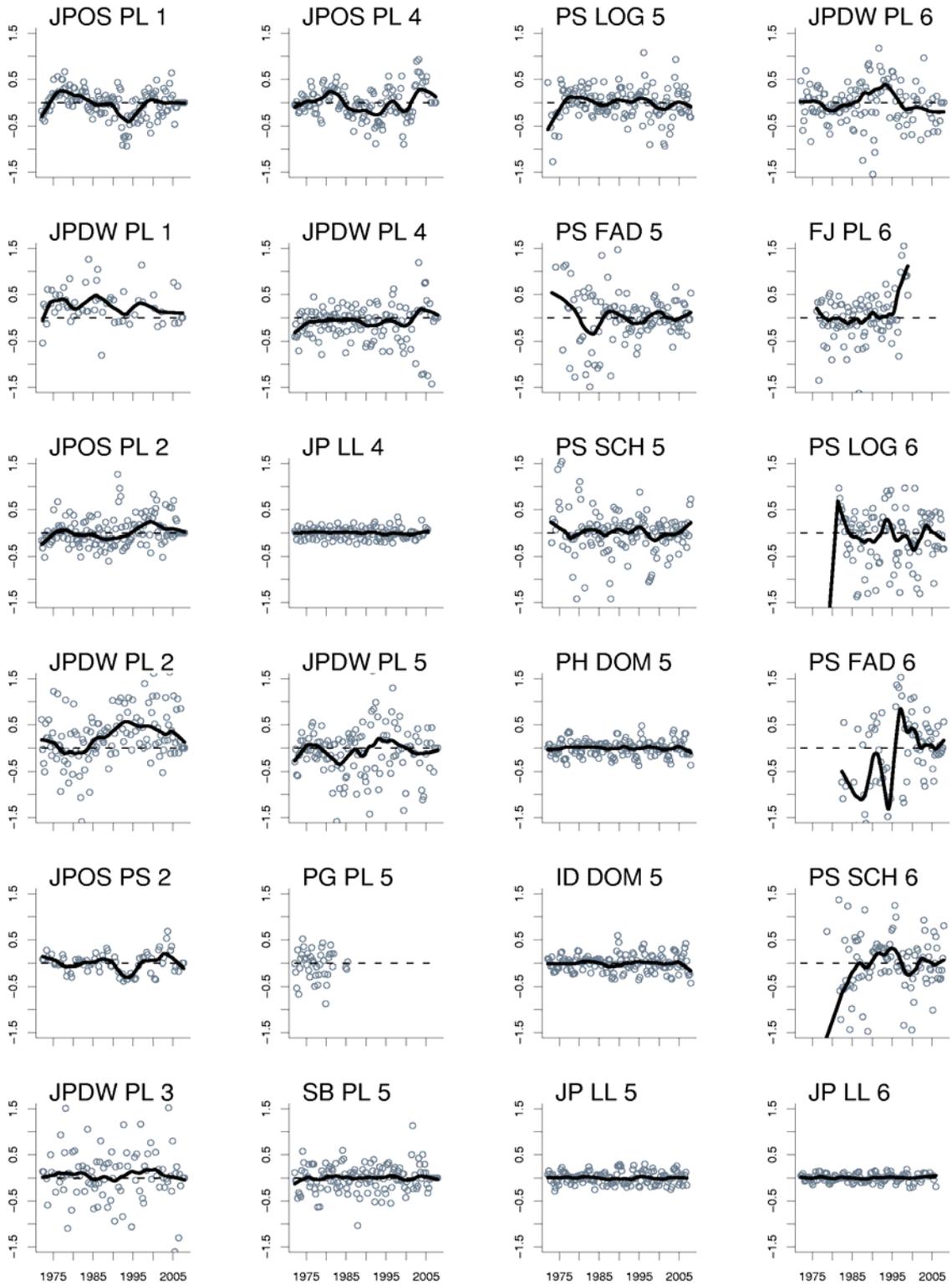


Figure 27. Effort deviations by time period for each fishery in the WCPO base-case model.

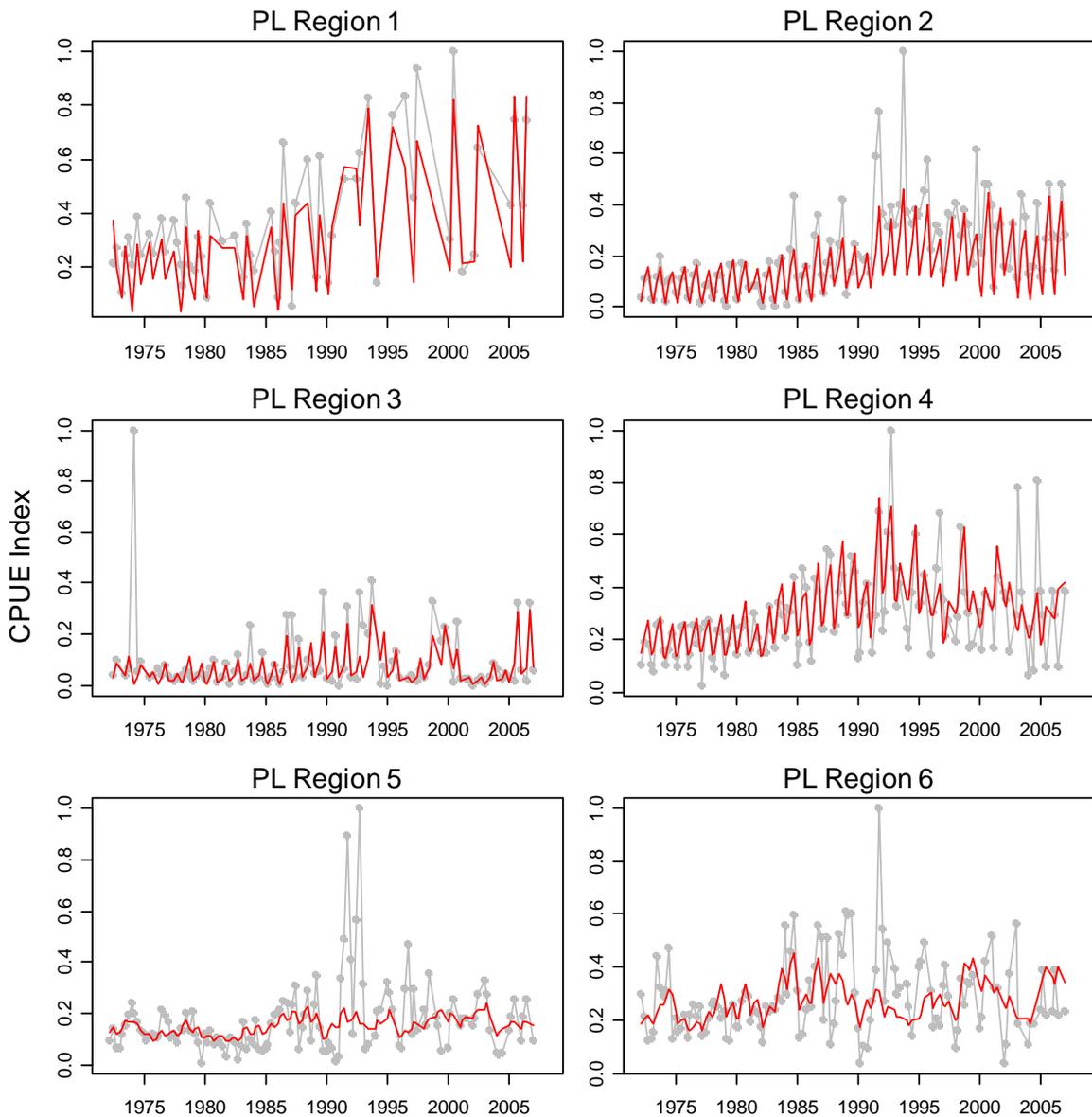


Figure 28. A comparison of pole-and-line exploitable biomass by quarter and region (red line) and the quarterly standardised CPUE indices for the fisheries.

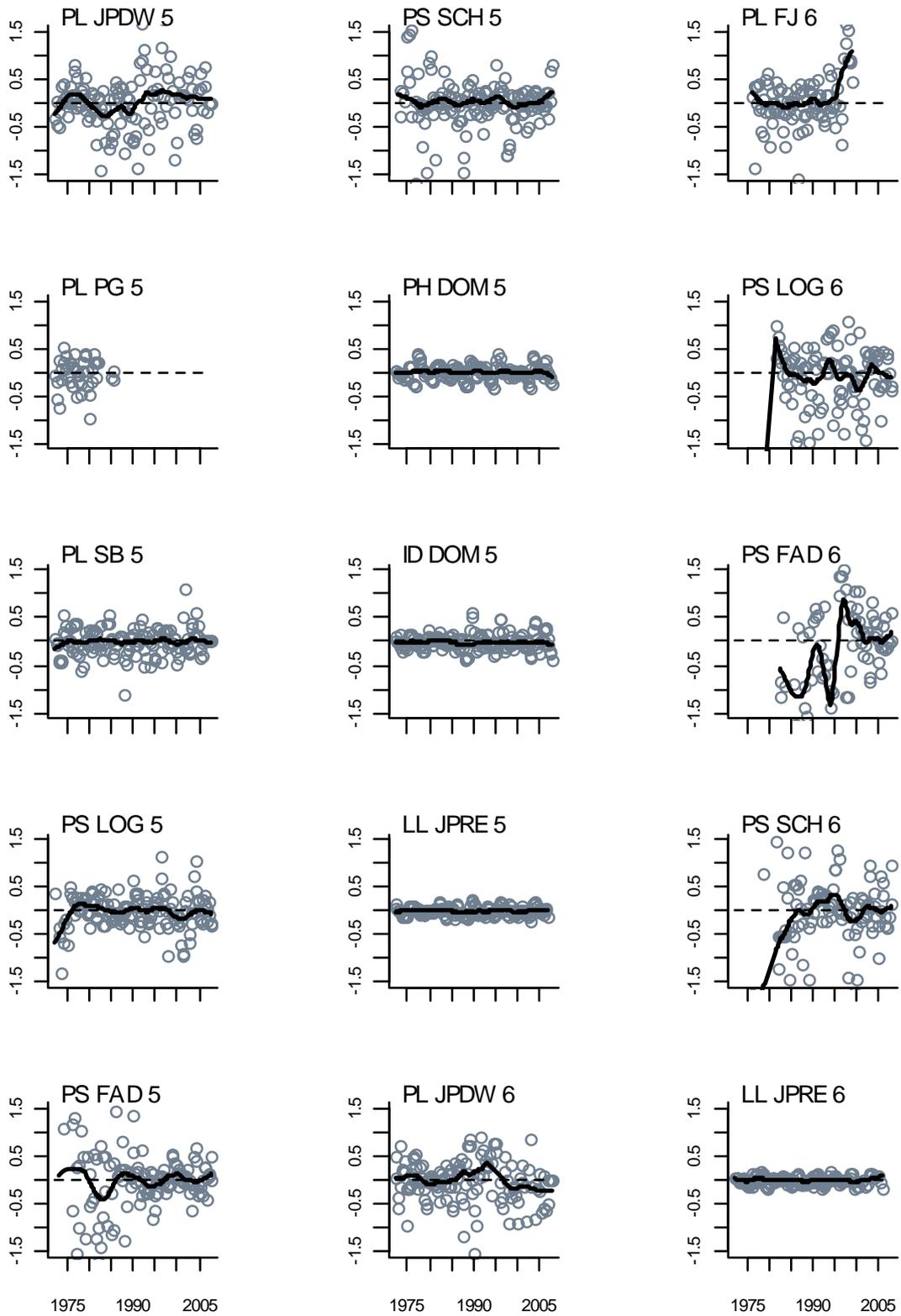


Figure 29. Effort deviations by time period for each fishery from the equatorial model.

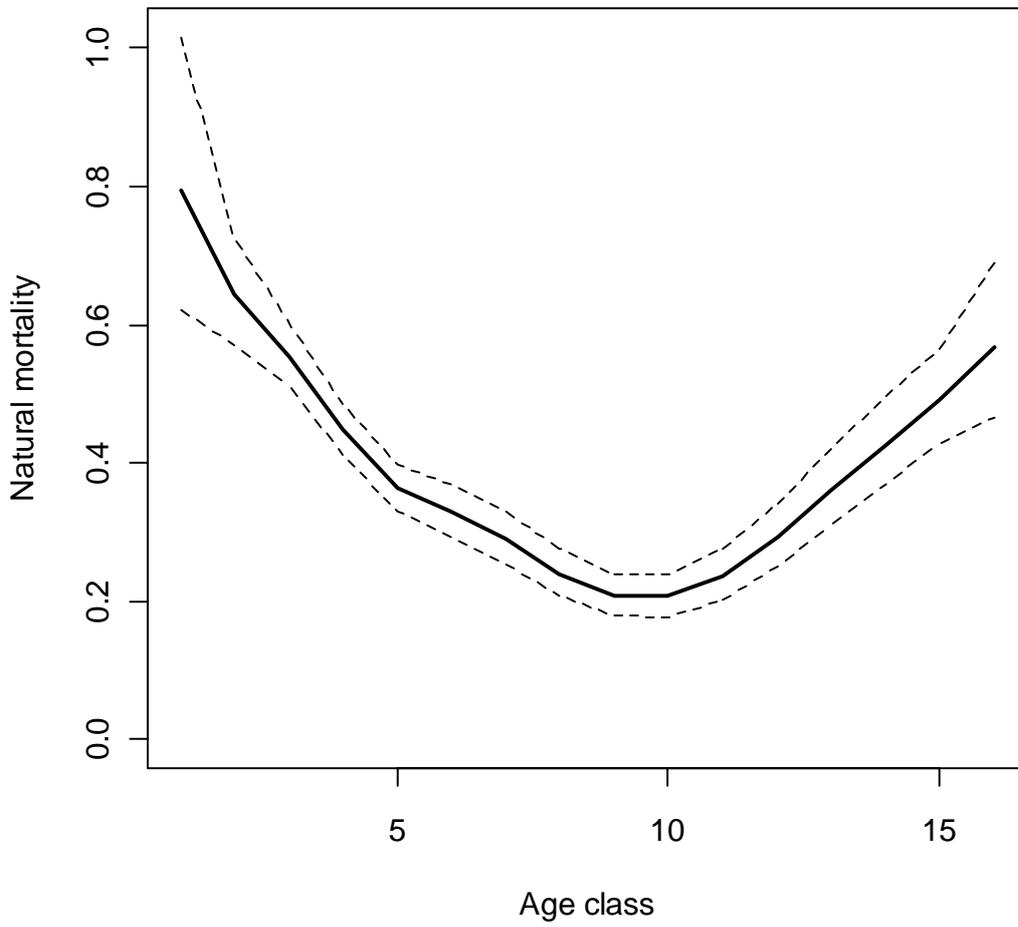


Figure 30. Estimated natural mortality rate per quarter by age-class (solid line). The dashed lines represent the 95% confidence interval.

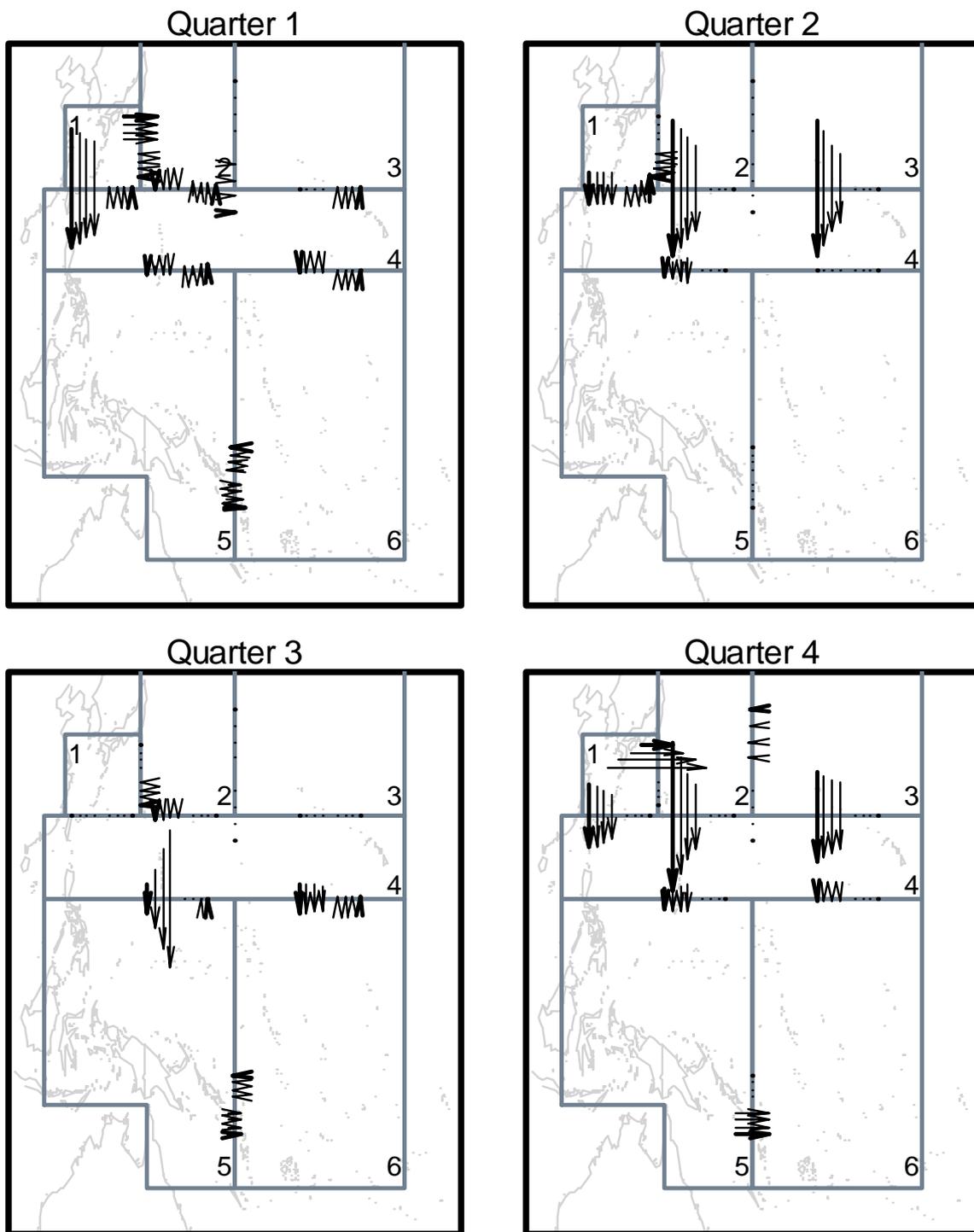


Figure 31. Graphical representation of movement coefficients among the six model regions at the beginning of each quarter. The arrows for each region boundary represent movement probabilities of 4 different age classes (1, 4, 8, and 12, thin to thick arrow) into the region into which the arrows protrude. The maximum bar length represents a quarterly movement coefficient of 0.68 (fourth quarter, region 2 to 4).

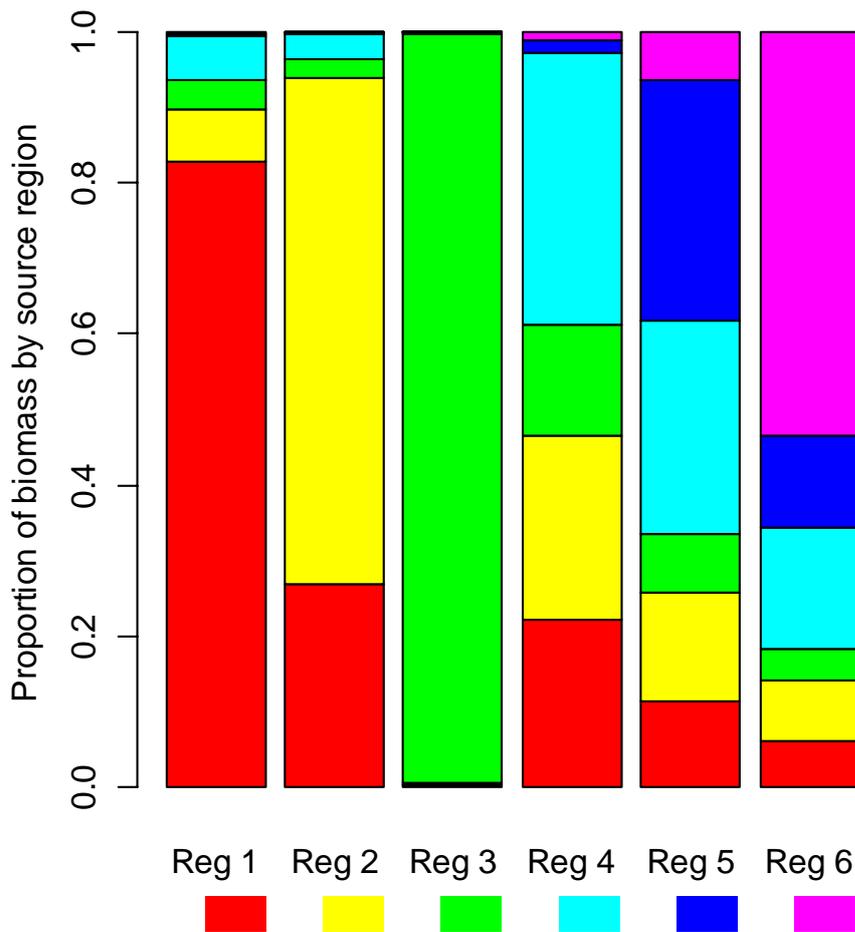


Figure 32. Proportional distribution of total biomass (by weight) in each region (Reg 1–6) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment between regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

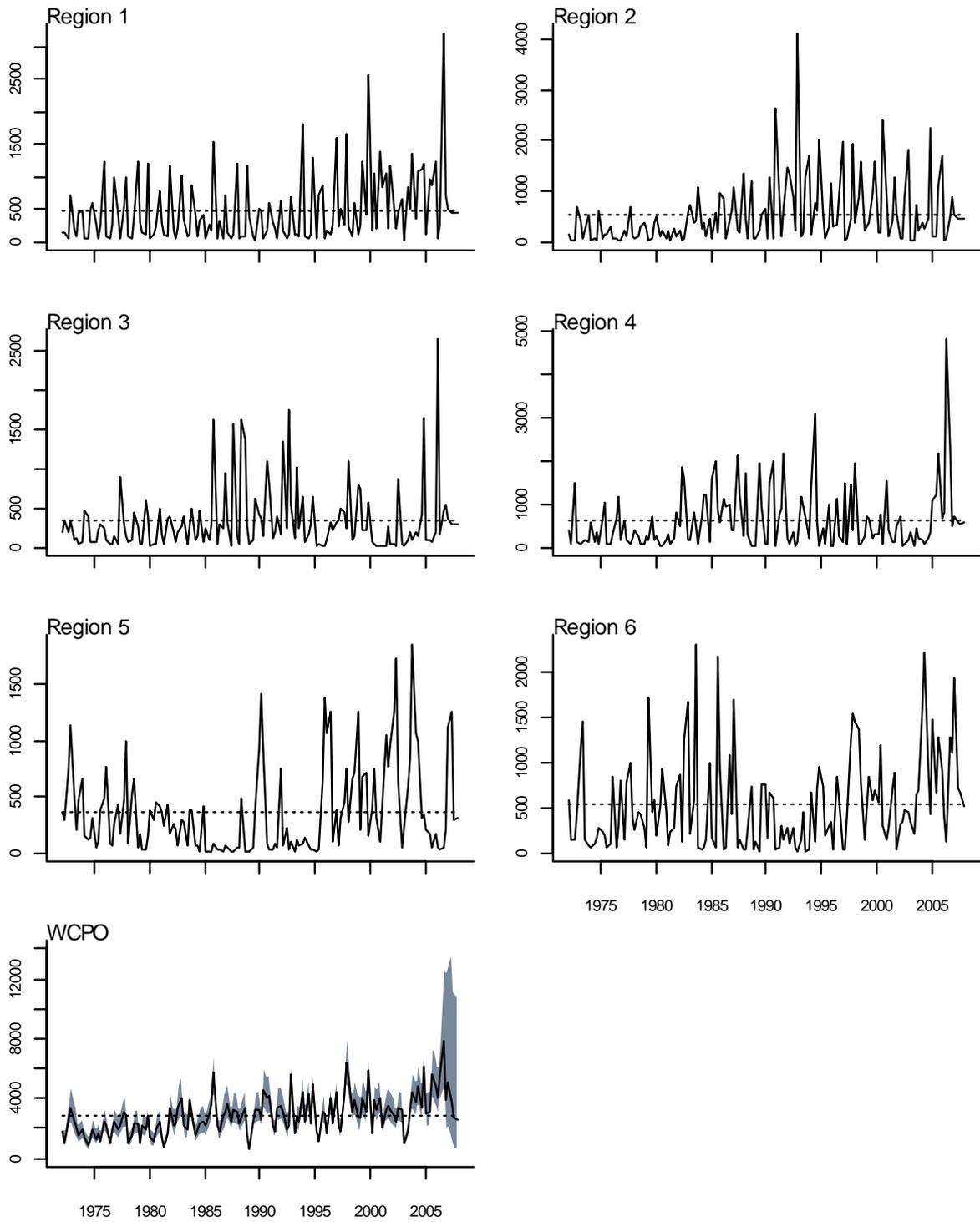


Figure 33. Estimated quarterly recruitment (millions) by region and for the WCPO for the base-case analysis. The dashed line represents the average recruitment for the entire period. The shaded area for the WCPO indicates the approximate 95% confidence intervals.

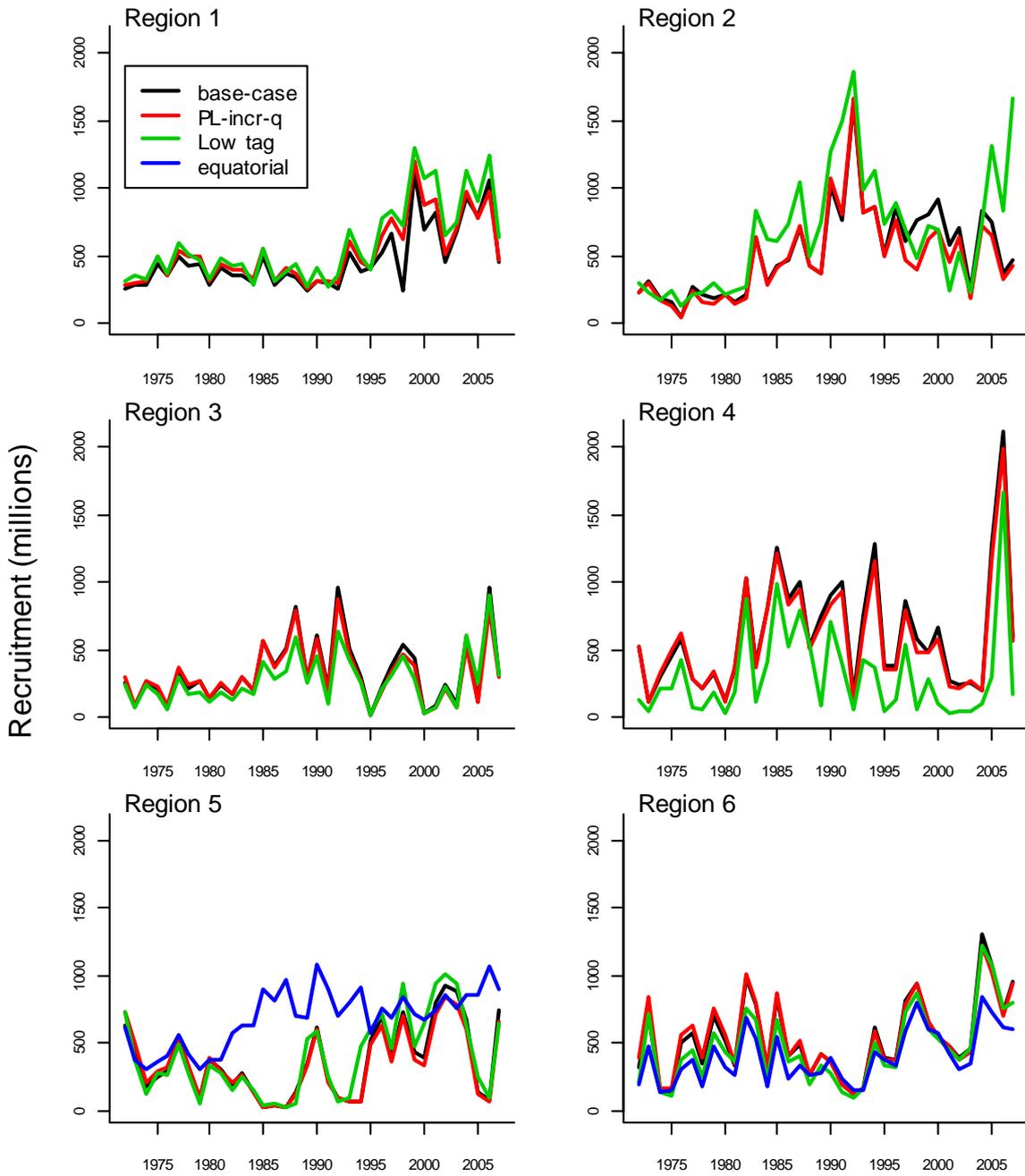


Figure 34. Comparison of annual trends in recruitment by region for the four models.

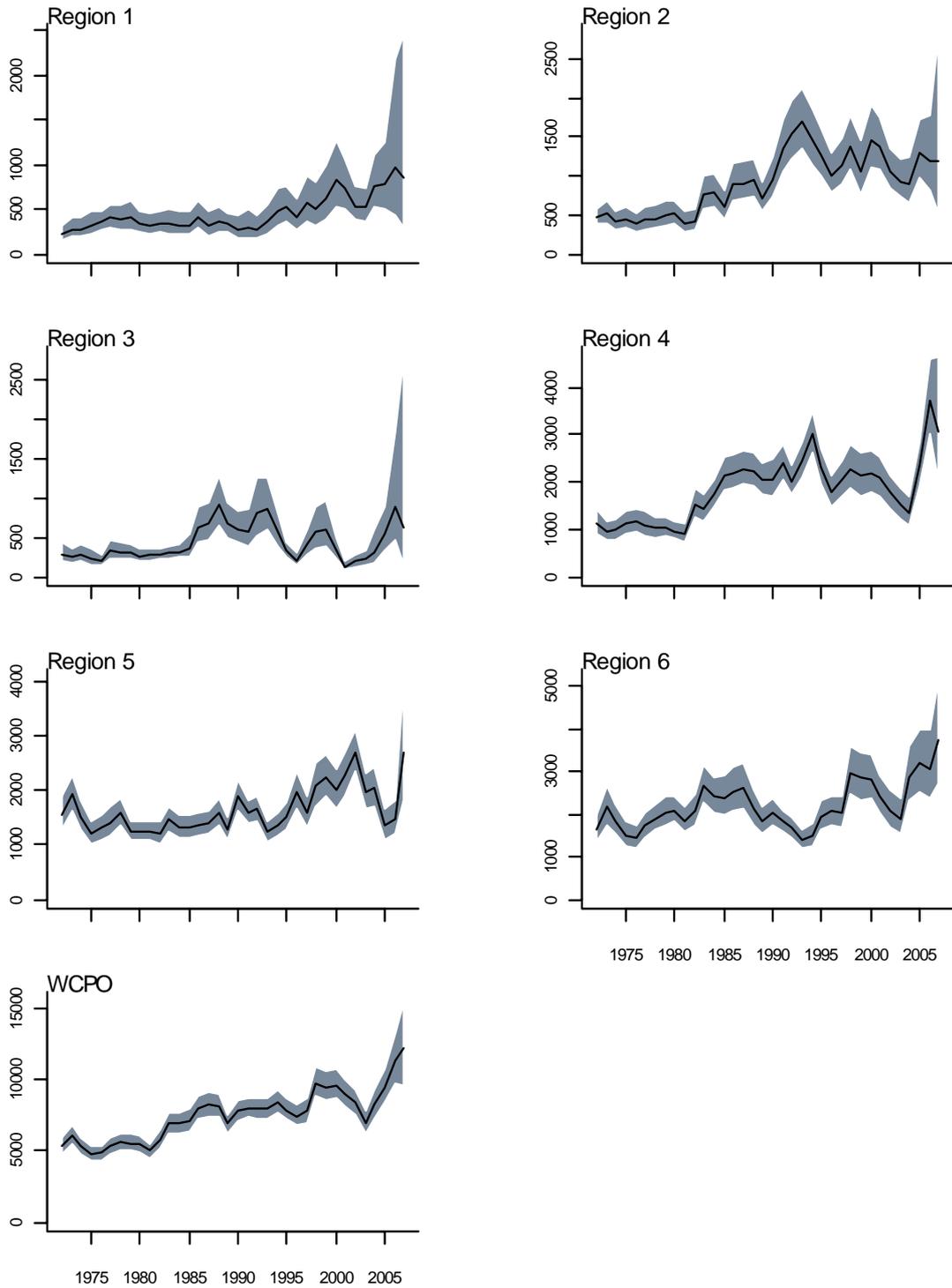


Figure 35. Estimated annual average total biomass (thousand t) by region and for the WCPO for the base-case analysis. The shaded areas indicate the approximate 95% confidence intervals.

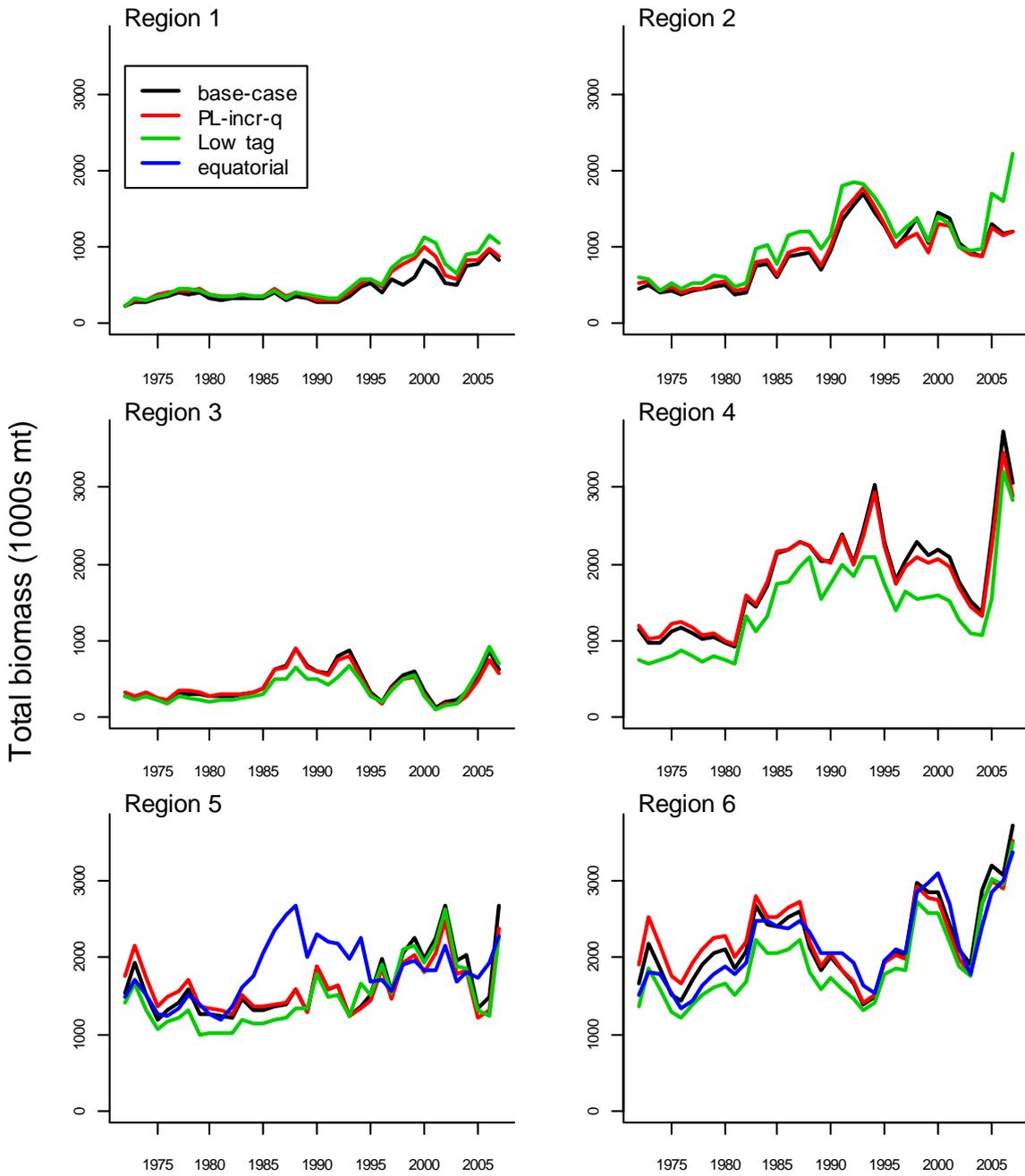


Figure 36. A comparison of trends in total biomass by region from the four models.

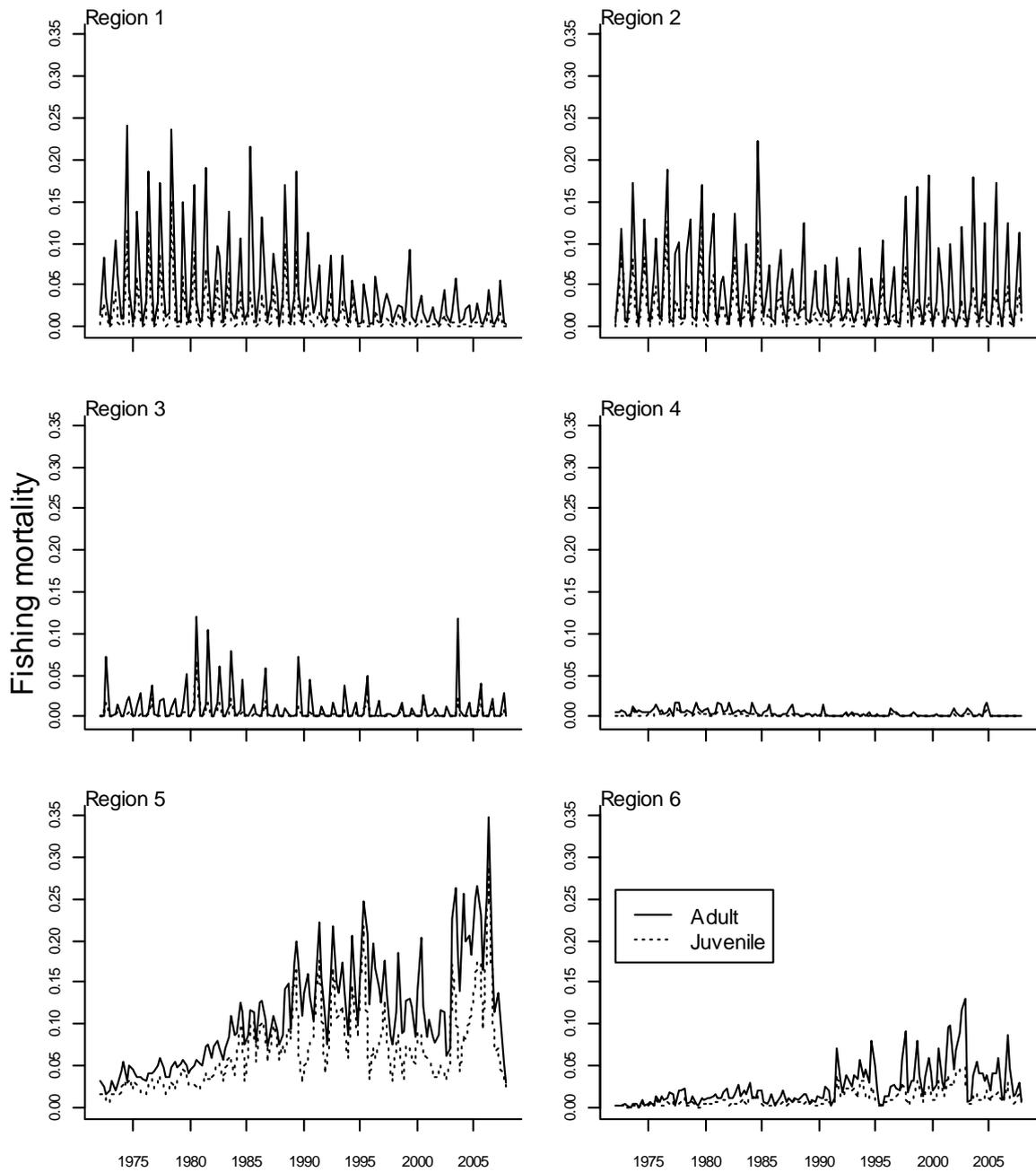


Figure 37. Estimated quarterly average fishing mortality rates for juvenile (age classes 1 and 2) (dashed line) and adult age-classes (solid line).

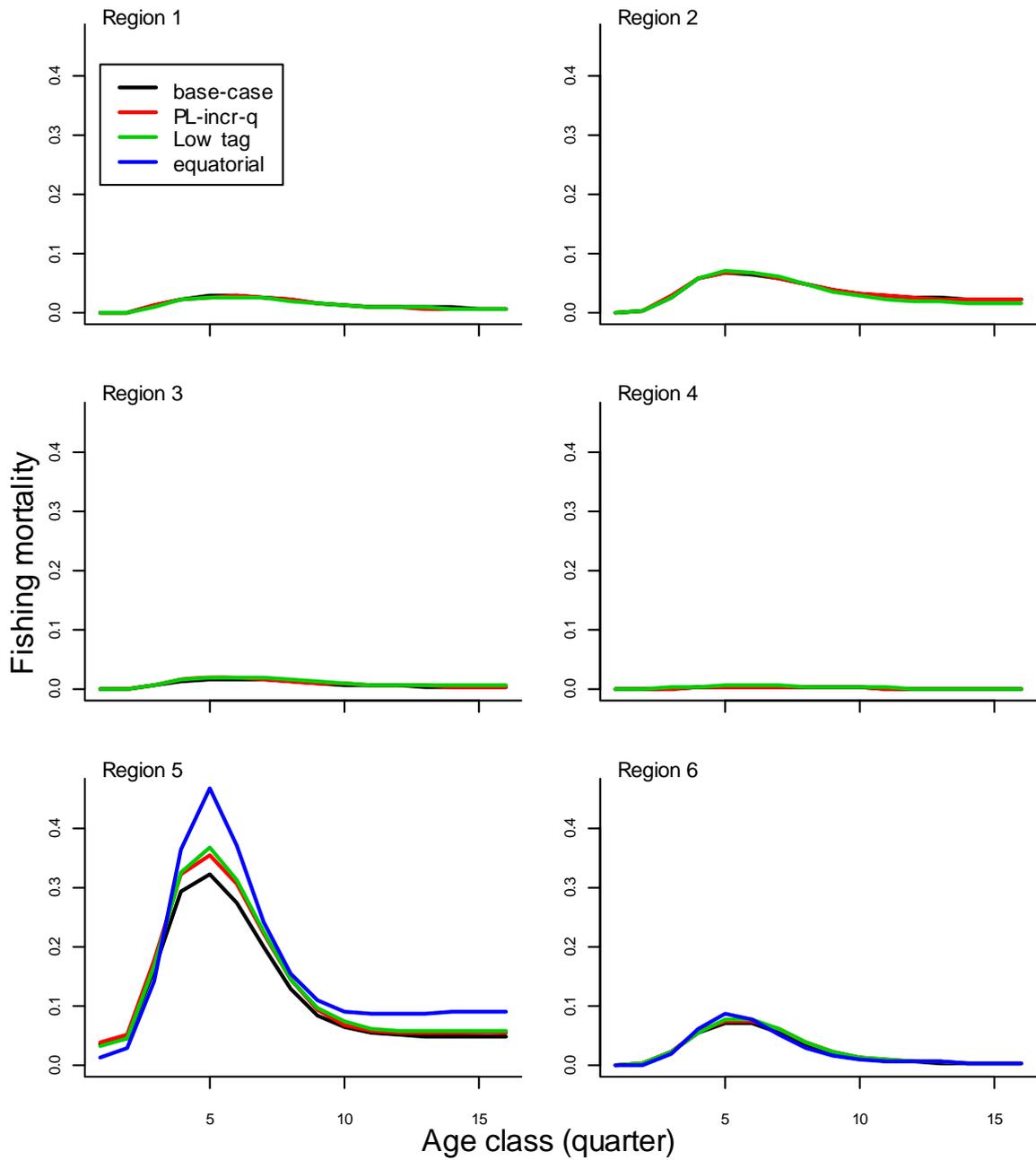


Figure 38. Fishing mortality by age class for the recent (2003-2006) period by region.

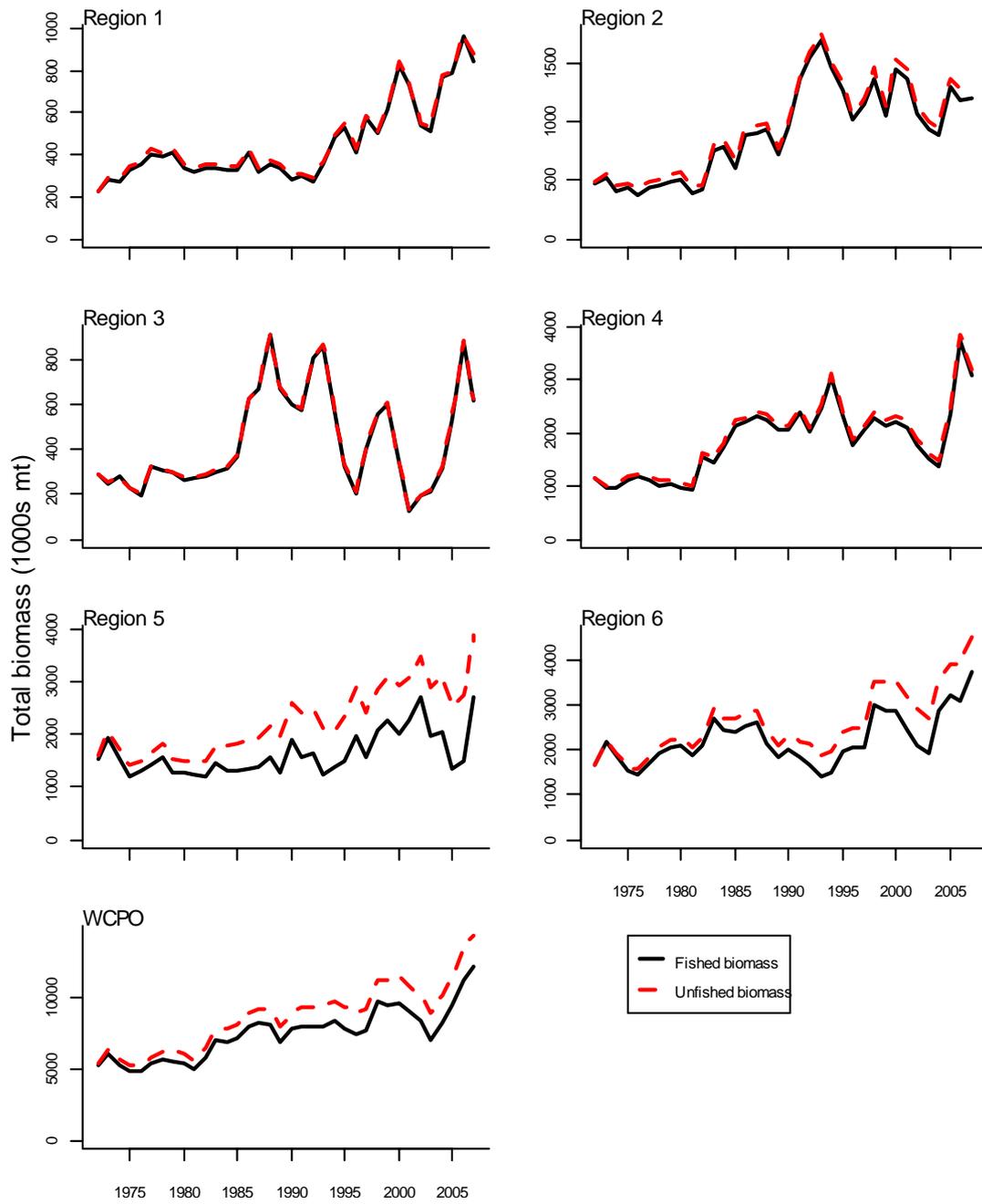


Figure 39. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (dashed lines) for the each region.

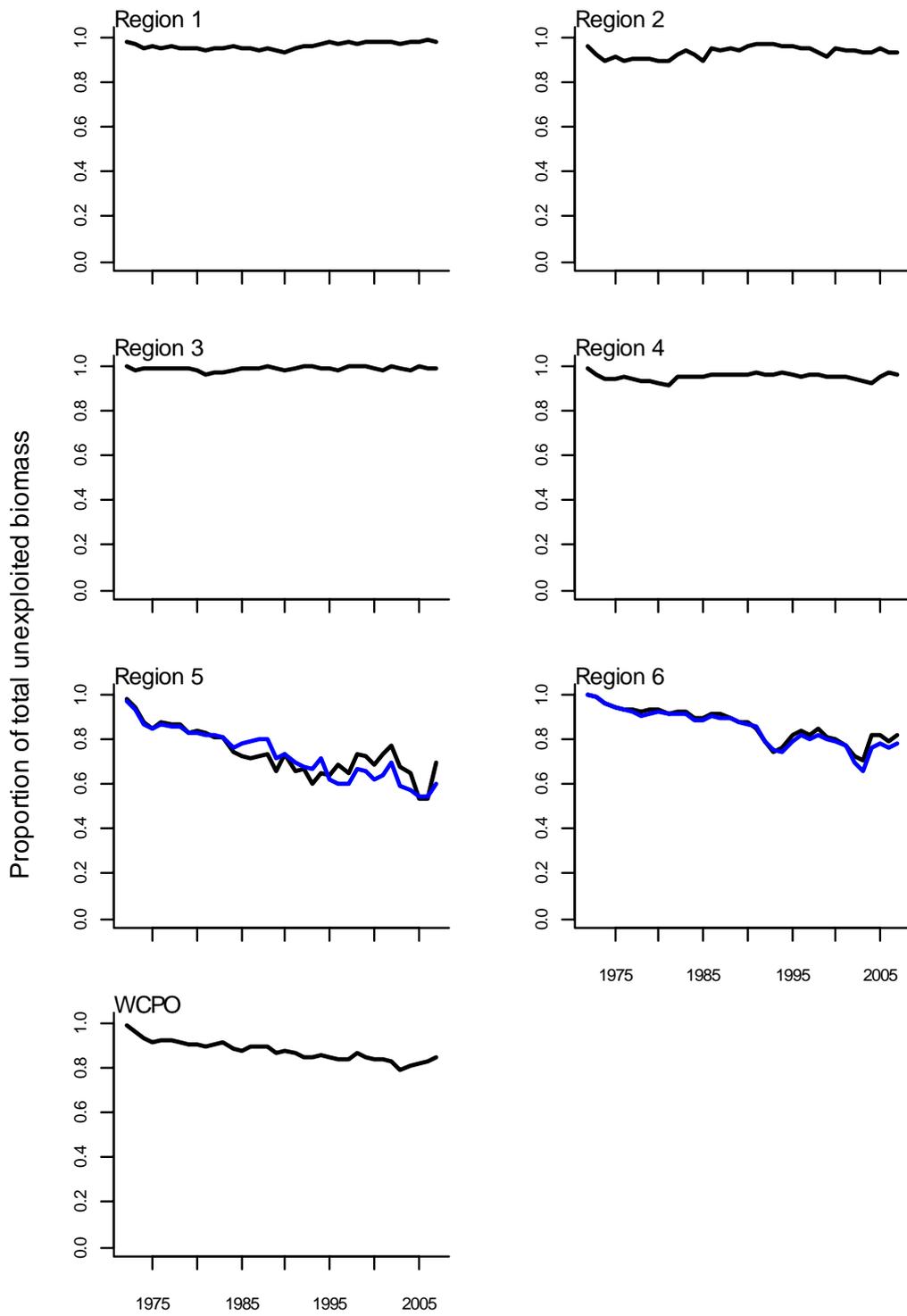


Figure 40. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the WCPO.

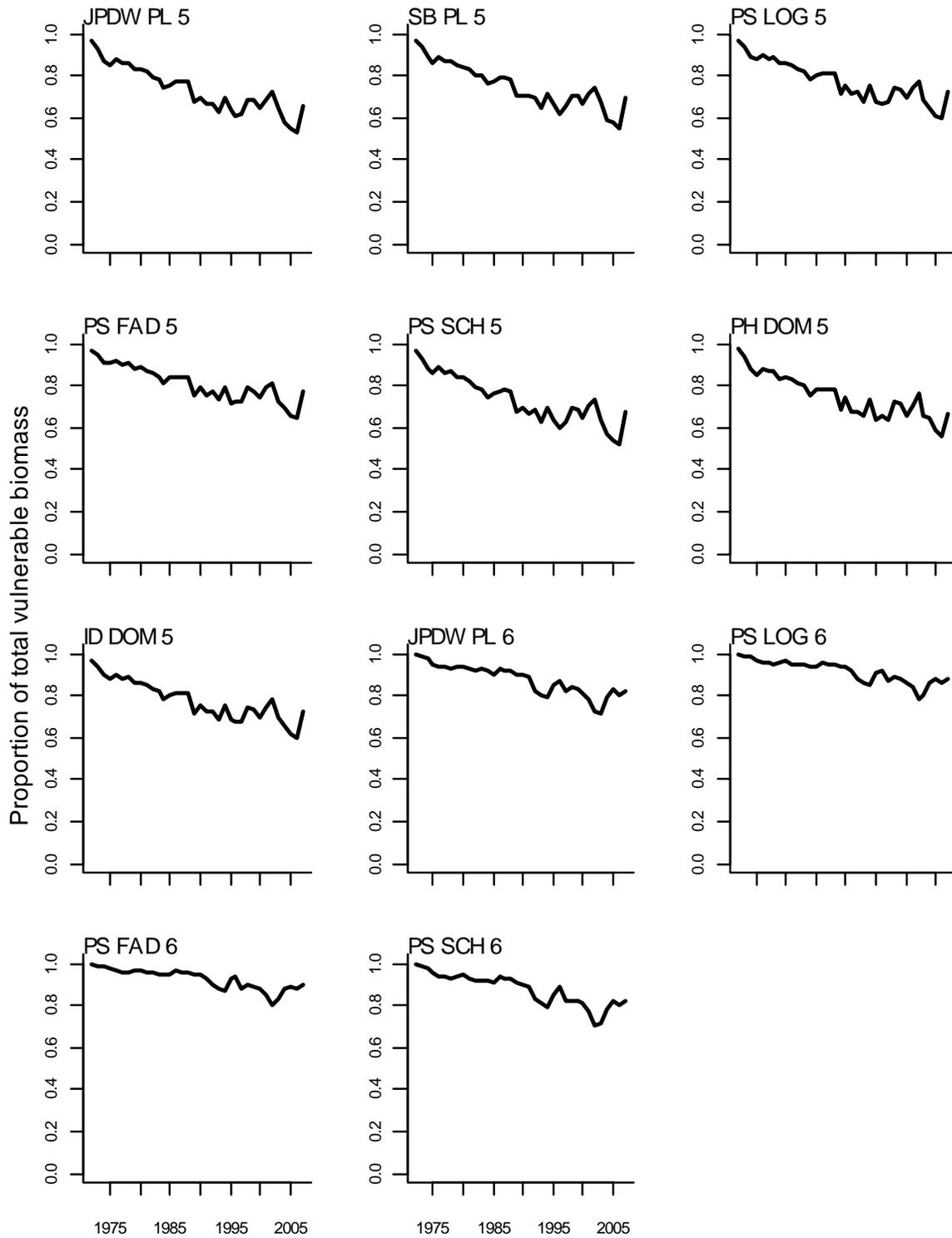


Figure 41. Proportional reduction in exploitable biomass attributable to fishing ($1 - B_t/B_{t,F=0}$) by fishery for the base-case model.

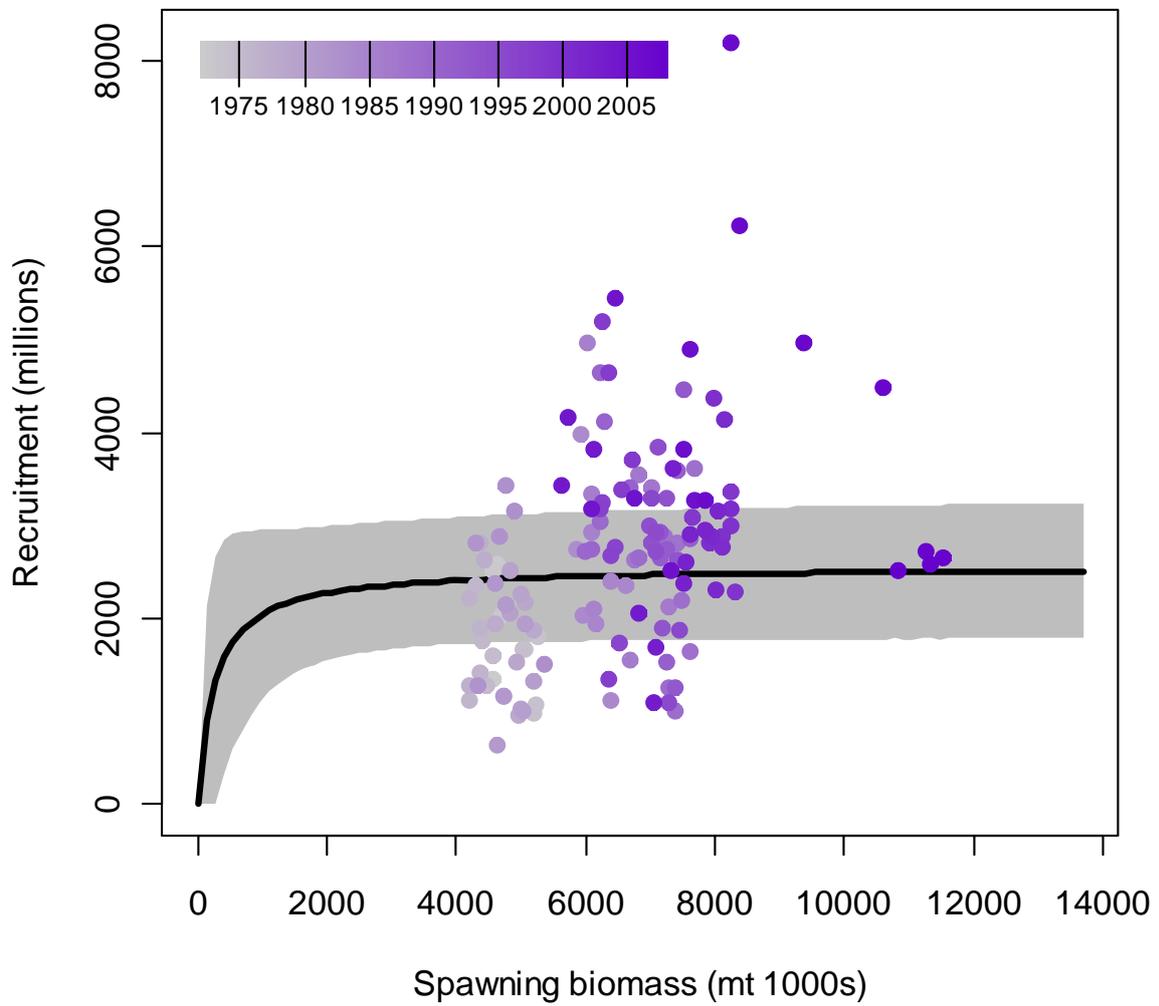


Figure 42. Spawning biomass – recruitment estimates and the fitted Beverton and Holt stock-recruitment relationship (SRR) incorporating a prior on steepness of 0.90 (SD = 0.10).

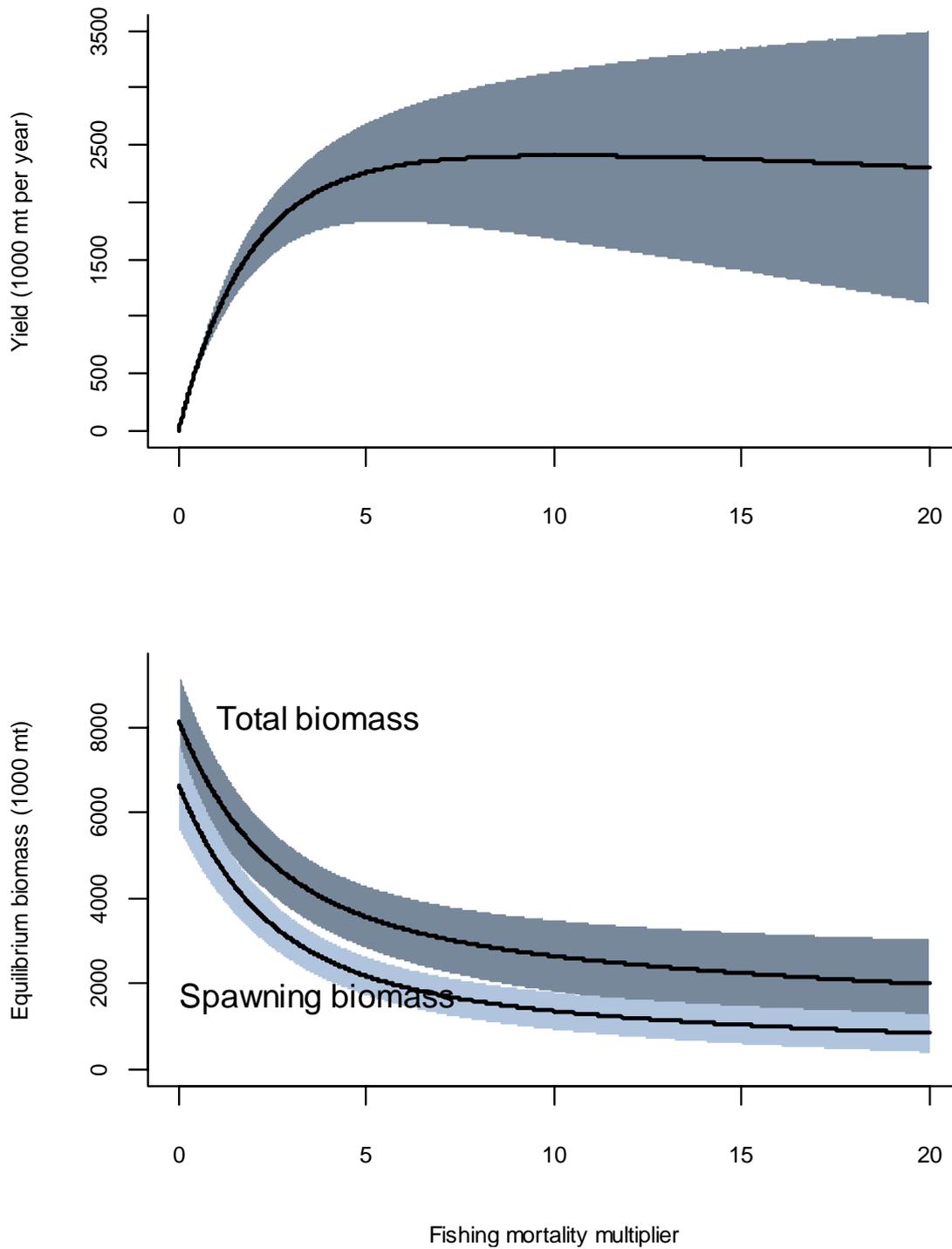


Figure 43. Predicted equilibrium yield (top) and equilibrium adult and total biomass (bottom) and 95% confidence intervals as a function of fishing mortality (base-case assessment).

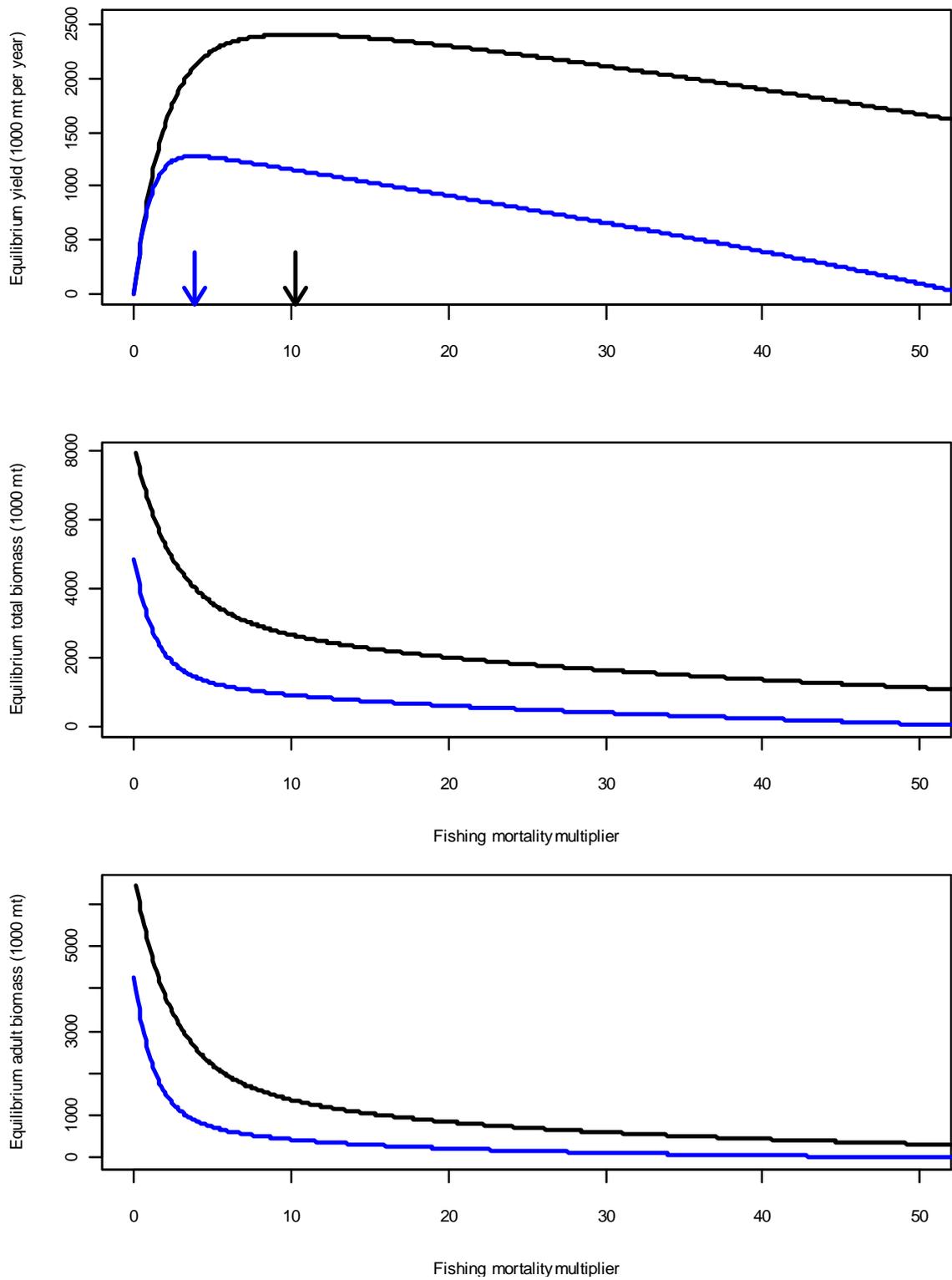


Figure 44. A comparison of equilibrium yields (top), equilibrium total biomass, and equilibrium adult biomass as a function of fishing mortality for the base-case (black line) and equatorial (blue line) models. The arrow represents the fishing mortality multiplier to achieve the MSY.

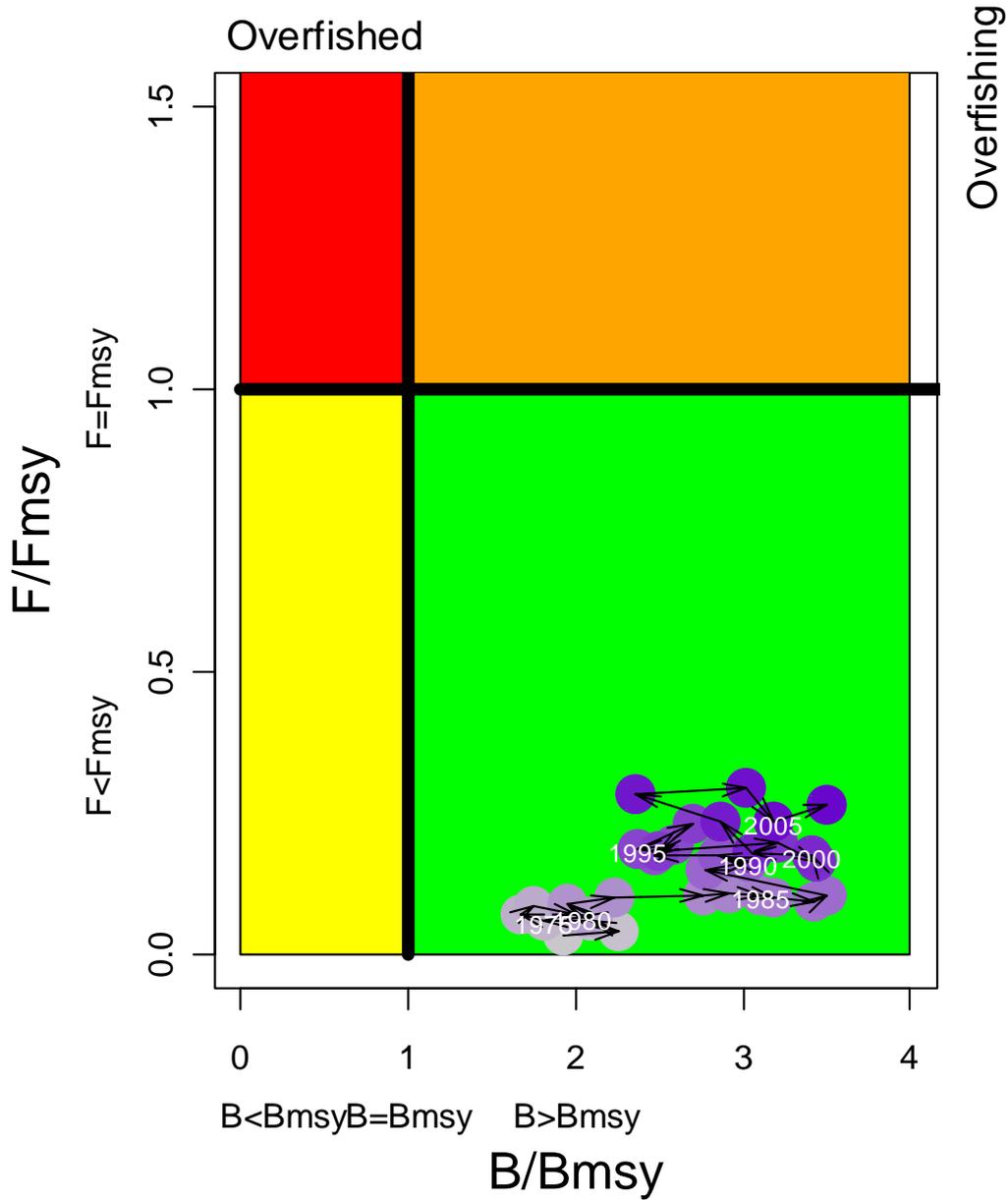


Figure 45. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1972–2006) from the *equatorial* model. The colour of the points is graduated from mauve (1972) to dark purple (2006) and the points are labeled at 5-year intervals.

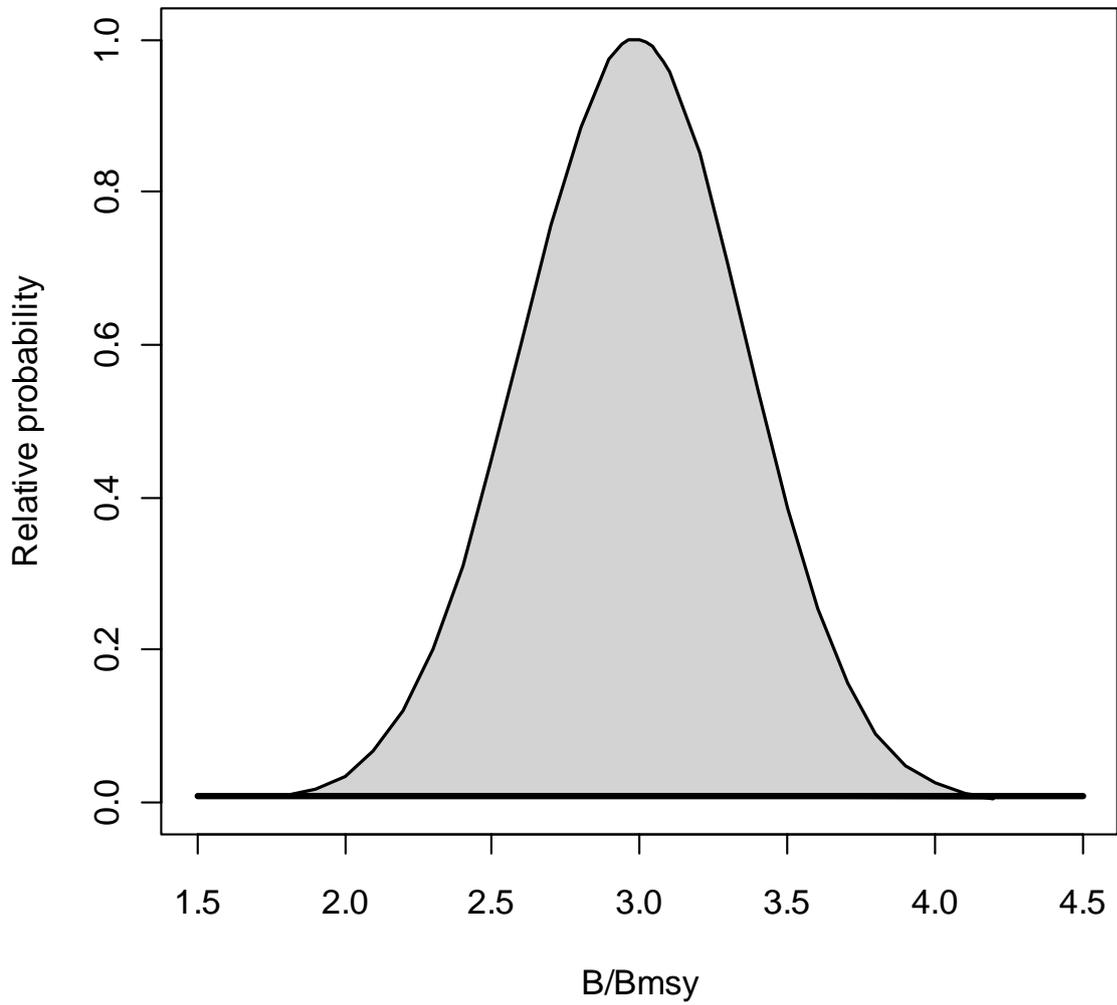


Figure 46. Likelihood profile for B/B_{MSY} from the *equatorial* model.