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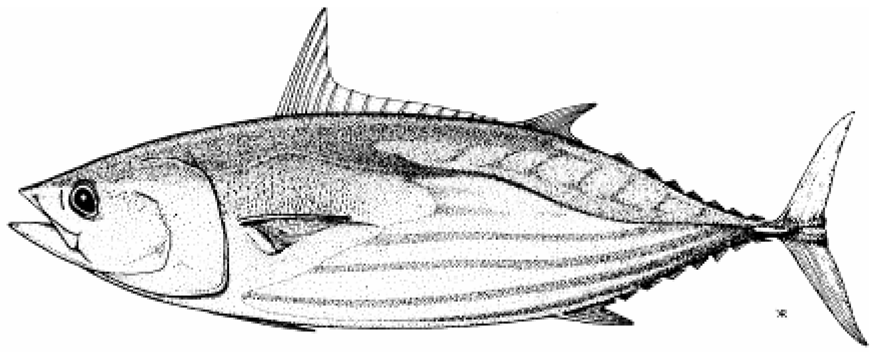
Stock assessment of skipjack tuna in the western and central Pacific Ocean



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1 Background

1.1 Biology

Surface-schooling, adult skipjack tuna (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 (Tanabe et al. 2003); though significant differences occur between individuals. The longest period at liberty for a tagged skipjack was 4.5 years. Estimates of natural mortality rate have been obtained using a size-structured tag attrition model (Hampton 2000), which indicated that natural mortality was substantially larger for small skipjack (21–30 cm FL, M=0.8 mo^{-1}) than larger skipjack (51–70 cm FL, M=0.12–0.15 mo^{-1}).

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 have 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 in the late 1990s and averaged about 1,200,000 mt during 1998–2003 (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). Since the late 1980s, annual catches from this region have fluctuated in the 500,000–

800,000 mt range (Figure 5). The increase in catch during the late 1990s has been largely attributable to the expansion of the purse-seine fishery in the eastern equatorial region of the WCPO (region 6).

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). 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;
- 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 General Linear Model (GLM) analyses (Ogura and Shono 1999). Separate analyses were conducted for the distant-water and offshore fleets. 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. Similarly, a standardised effort series was developed for the Japanese offshore purse-seine fishery operating in region 2 (JPOS PS 2). For this fishery, the GLM included the variables year, quarter, area, and bluefin tuna CPUE.

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, standardised effort series were estimated using a GLM approach. The dependent variable in the GLM was the natural logarithm of the skipjack CPUE for the set type (i.e. skipjack catch divided by the number of vessel days apportioned to the specific set type). Potential explanatory variables included in a step-wise fitting procedure were year/quarter, vessel flag, latitude, longitude, and yellowfin catch and interactions between a number of these variables (latitude/longitude, latitude/quarter, and longitude/quarter). The standardised effort series was determined by dividing the catch in the year/quarter by the year/quarter indices derived from the GLM.

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 equatorial purse-seine fisheries. Fishing power was assumed to increase by 5 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.

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.

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 1988–2004. 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.

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 226,329 releases were classified into 163 tag release groups (Table 2). The returns from each size-class of each tag release group (18,042 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 fished 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 0.1 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 100 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 set relative to the variation in recruitment predictions from Lehodey (2001). Preliminary model runs estimated the recruitment proportion in the later phases of the fitting procedure. However, this resulted in implausible distributions of biomass (esp. very high biomass in region 4) and, consequently, these parameters were not estimated in the final models.

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 relatively uninformative prior on steepness was used, specified by a mode = 0.85 and SD = 0.16. A sensitivity analysis was also conducted on the steepness parameter using a more influential prior (mode =0.91, SD = 0.05). The latter prior was comparable to the prior used in the 2003 assessment.

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. 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.

Various schemes for assigning common catchability patterns among fisheries were tested during the 2002 stock assessment. It was initially considered appropriate for the Japanese distant-water pole-and-line fisheries and the Japanese offshore pole-and-line fisheries to have common catchability among the different regions in which those fleets operate because of the way in which the effort data were pre-standardized using the GLM analyses. However, such grouping of parameters resulted in distributions of effort deviations (or residuals) that showed time-series trends and/or uneven distributions about zero, indicating that the assumptions regarding common catchability were not valid. Therefore, the base-case results reported here are from a model in which catchability parameters are independently estimated for each fishery.

The model assumptions regarding catchability were varied for two of the sensitivity analyses undertaken. The first analysis investigated the impact of increasing the relative fishing power of all the equatorial purse-seine fisheries by 5% per annum (*PS fpower*) and, for this sensitivity, the temporal catchability of these fisheries was held constant. Another sensitivity analysis was undertaken to investigate the impact of assuming a common catchability for the two equatorial distant-water pole-and-line fisheries (*PL56-fixq*).

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.

4 Results

This section provides a detailed summary of the results from the base-case assessment. A general summary of the results of the three sensitivity analyses (see Table 4) is also presented, principally highlighting the main differences from the base-case assessment. The results of the base-case assessment are also compared with the 2003 assessment (Langley et al. 2003).

4.1 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.

While the model provides a good overall fit to the aggregated length data from each fishery, there is considerable variability in the fits when the data are disaggregated by time period. This was assessed by comparing the observed and predicted proportion of large fish in the catch from each fishery at each time interval (Figure 18). Large fish were defined by the length classes greater than the modal length; i.e. the 70–90 cm length range for the longline fisheries and 50–70 cm for all other fisheries.

There are some persistent temporal trends in the fit to the length frequency data. Since the mid 1980s, there has been a general increase in the residuals from the Japanese distant-water pole-and-line fisheries in regions 5 and 6 indicating more large fish in the length samples than otherwise predicted from the model (Figure 18). The converse trend is evident from the purse-seine fisheries operating in regions 5 and 6, with a general decline in residuals from the early 1990s indicating the model is over-estimating the proportion of large fish in the sampled catch and, vice versa, under-estimating the proportion of small fish in the catch (Figure 18). These contrasting trends in the residuals indicate a conflict in the length frequency data from the two main fishing methods operating in the equatorial region (see Section 2.5). This may suggest that the assumptions regarding constant fishery-specific selectivity are not appropriate for the equatorial fisheries and/or the assumption of common selectivity between all Japanese pole-and-line fisheries should be relaxed.

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 (e.g. JPDW PL 2, JPDW PL 3) and vice versa (e.g. JPOS PL 1, 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.

4.2 Tag reporting rates

There is considerable variation among fisheries in 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 be lower than 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). Similarly, the common tag reporting rate for the equatorial purse-seine fisheries was higher than the mode of the prior (mode = 0.55, SD = 0.07). Reporting rates for the PNG, Indonesian, and Philippines fisheries were also relatively high (Figure 22).

4.3 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. The estimated growth curve is consistent with a recent ageing study (Tanabe et al. 2003); approximately 30 cm at 6 months, 42 cm at 1 year, and 60 cm at 2 years old. The comparable model estimates of length at age were 28 cm, 45 cm, and 63 cm, respectively (Figure 23). On this basis, fish are considered to “recruit” into the model population (i.e. age class 1) at the second quarter following hatching.

Limited length data are included in the model from the younger age classes in the population, with only the Philippines fishery catching significant numbers of fish in the 20–30 cm length range and no observations of smaller fish in the sampled catches (see Figure 17)

The variation in length-at-age is relatively constant across age-classes (Figure 23). 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.

4.4 Selectivity

Estimated selectivity functions are generally consistent with expectation (Figure 24). The Philippines fishery catches the smallest fish with relatively high selectivity for fish in the 1–5 age-classes. 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. Only the research longline fisheries have been assumed to have a monotonically increasing selectivity with age.

4.5 Catchability

Estimated catchability trends are shown in Figure 25. 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 (Figure 25).

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 in recent years (Figure 25). Nevertheless, over the time-series of these fisheries the overall rate of annual increase in catchability is slight (less than 1% per annum).

4.6 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. The effort deviation plots for the skipjack model display these characteristics (Figure 26). Most of the fisheries exhibit relatively small effort deviates. The exceptions are longline fisheries (LL JPRE 4, 5, and 6) that were given low penalties on the effort deviates in order to fit the variable and uninformative catch and effort data. 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 26).

4.7 Natural mortality

Natural mortality is estimated to be high for the young age classes (1–4), averaging about 2.0 per annum (Figure 27). Natural mortality is relatively constant for age classes 5–12, at about 0.37 per quarter and slightly lower than the initial value of 0.4 per quarter. There is a steady increase in estimated natural mortality for the older (12+) age-classes.

4.8 Movement

A representation of the dispersal pattern resulting from the estimated movement parameters is shown in Figure 28. This figure shows the movement of the proportion of four age groups between each region by quarter. These movements have also been expressed in terms of the number of fish moving by applying the movement parameters to the recent age structure of the population (Figure 30). The movement parameters reveal the largest movements occur from the northern regions (1–3) into region 4 during quarters 1–3. These movements tend to increase with increasing age; i.e. highest movement coefficients for the older age classes.

There is also movement estimated from region 1 to region 2 in the third quarter (Figure 28 and Figure 30). Movements between the other regions are estimated to be small.

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).

One plausible explanation for the high movement south into region 4 is that the model is attempting to compensate for the low fixed proportion of the overall recruitment assigned to this region (see Table 3). This presumably results in a better fit to the other observations from the region.

4.9 Recruitment

The time-series of recruitment estimates is shown in Figure 30. Total recruitment is dominated by the equatorial regions (5 and 6) and, to a lesser extent region 4. Recruitment is comparatively low in the northern regions (1–3), while exhibiting high seasonal variation (Figure 30).

Overall recruitment has been higher since the mid-1980s, principally dominated by trends in recruitment from the equatorial regions (regions 5 and 6). Recruitment was estimated to be high in 1982, 1985, 1990, and 1998 principally dominated by recruitment in region 6 (Figure 30). These recruitment events generally coincide with *El Niño* conditions, which are thought to enhance skipjack recruitment, particularly in the eastern area of the equatorial WCPO. For region 6, the very high recruitment estimates for the mid-1980s appear to be largely driven by the observation of increased catch rates from the Japanese equatorial pole-and-line fisheries in the late 1980s, while there was also an increase in the size of fish in the sampled catch from the pole-and-line fishery during the same period (see Figure 9).

Recent recruitment is estimated to be exceptionally high in both region 5 and region 6, although there is a high level of uncertainty associated with these estimates (Figure 30). These high recruitment estimates are the model's interpretation of the higher proportion of small fish observed from the equatorial purse-seine fisheries during 2004.

4.10 Biomass

The biomass trajectories by region are presented in Figure 31. Most of the population occurs in regions 5 and 6 (31% and 49% of recent biomass, respectively), with the majority of the remainder of the current biomass in region 4 (16%).

Total biomass increased firstly in the mid-1980s in response to the increase in recruitment and increased again in the late 1990s and has been sustained by strong recruitment throughout 1997–2001 (Figure 31). The high current biomass is attributable to the exceptionally high recruitment in 2004.

The trend in total biomass is largely driven by the high variation in biomass from region 6, with the large peaks in biomass during the mid-1980s and late 1990s. In contrast, the biomass level in region 5 was relatively constant over the model period with the exception of a steady increase in biomass since the mid-1990s (Figure 31).

4.11 Fishing mortality and the impact of fishing

Annual average fishing mortality rates for juvenile and adult age-classes are shown in Figure 32 for each region. Fishing mortality for the juvenile skipjack is very low in all regions, although it has tended to increase slightly over time within region 5 mainly due to the steady increase in catch from the Philippines fishery.

For adult skipjack, fishing mortality rates vary considerably between regions. Fishing mortality rates in the northern regions, particularly regions 1 and 2, were high during the 1970s and 1980s but were generally lower in the latter period (Figure 32). For region 5, fishing mortality rates for adult skipjack have steadily increased over the model period consistent with the increase in total catch (see Figure 5). Since the early 1990s, there has also been a general increase in fishing mortality rates in region 6, although exploitation rates are much lower than region 5 due to the higher overall level of biomass in region 6 (see Figure 31). Fishing mortality rates in region 4 are exceptionally low reflecting the low level of catch taken in the region (see Figure 5).

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 33. Similarly, the impact of fishing on the exploitable biomass is also calculated for each fishery (Figure 34).

The impact of fishing varies considerably between regions. For region 1, the impact on the total biomass is negligible (Figure 33), while the impact on the exploitable biomass for the two fisheries in the region is relatively high (20–40% reduction in biomass), particularly prior to 1990 (Figure 34). For region 2, fishery impacts on total biomass and exploitable biomass are both relatively high, while impacts in region 3 are considerably lower, particularly in recent years (Figure 33 and Figure 34). Fishery impacts in region 4 are negligible.

For region 5, the fishery impact on the total biomass increased over the model period and was about 25% during recent years (Figure 33), similar to the level of impact on the exploitable biomass for the purse-seine fisheries in the region (Figure 34). Fishery impacts on total and exploitable biomass have been lower in region 6, approaching about 10% in recent years. Overall, the impact of fishing on the total WCPO biomass is about 15% in recent years, with the low fishery impacts in regions 4 and 6 buffering the higher impact in region 5.

4.12 Sensitivity analyses

For the 2003 assessment, a number of sensitivity analyses were undertaken to assess various model assumptions (Langley et al. 2003). The main sensitivities considered were as follows.

a) Declining selectivity for the older age classes in the equatorial purse-seine fisheries with a selectivity of zero for ages 15 and 16.
b) Inclusion of the Japanese tag data for MULTIFANCL regions 5 and 6.
c) Limited temporal change in catchability of the Japanese pole-and-line fisheries in all regions (via a heavy penalty on the catchability deviations).

These sensitivities were not repeated in the current assessment as the results were either not significantly difference from the 2003 base-case (a) or not considered plausible (b) due to known differences in the tag reporting rates depending on the agency of release. The current assessment assumes constant temporal catchability for all the Japanese pole-and-line fisheries negating the need to repeat sensitivity (c).

For the current assessment, three additional sensitivity analyses were undertaken (see Table 4). The sensitivity of the model to the assumptions regarding the prior distribution on steepness is described in Section 4.14.

The effect of increasing the efficiency of the equatorial purse-seine fleet was examined by increasing the standardised effort series by 5% per annum (compounded) over the entire period of the fishery (“*PS_fpower*”). The *PS_fpower* sensitivity represented an improved fit to the total data set compared to the base-case due to the substantially lower value for the length frequency likelihood component (Table 5).

For the equatorial regions, the increased purse-seine efficiency resulted in an increase in biomass early in the model period and a depression of the biomass level from the 1990s onward (Figure 35). The effect was greatest within region 5, negating most of the recent large increase in biomass observed from the base-case assessment. There was a corresponding increase in the level of fishery impact in this region; about 30% in recent years compared to about 25% for the base-case (Figure 36).

Overall, the lower current biomass in region 5 and, to a lesser extent in region 6, resulted in a lower total current biomass, in both absolute terms and as a proportion of the equilibrium biomass level, compared to the base-case assessment (Table 7). However, all other performance indicators for the stock were comparable and the results of the *PS_fpower* sensitivity do not differ from the overall conclusions of the base-case.

A further sensitivity analysis was undertaken whereby the catchability of the Japanese distant-water pole-and-line fisheries in the two equatorial regions was equivalent (*PL56-fixq*). The purpose of this sensitivity was to attempt to constrain the magnitude and degree of inter-annual variability in biomass estimated for region 6 (see Figure 31). This was undertaken on the basis that there is very limited abundance information from the region in terms of tagging data and a relatively short history of high catches from the region.

The *PL56-fixq* sensitivity actually resulted in a significantly higher level of current and reference biomass compared to the base-case assessment (Table 7). This was mainly attributable to a higher overall level of biomass in regions 4–6, particularly in the last decade. However, overall yields were estimated to be lower than the base-case due to a lower estimate of the steepness parameter of the SSR and lower estimates of natural mortality for the main vulnerable age-classes.

While not reported in detail in this paper, several other model options were investigated prior to finalising the current assessment. These results provided some other insights into the assessment, the most significant being the high level of uncertainty regarding the overall level of biomass in region 4. Several model runs were undertaken whereby the proportion of the total recruitment in each region was estimated; however, these runs resulted in implausibly high levels of biomass in region 4 compared to the equatorial regions and relative to the overall level of catch from this region. Consequently, these runs were rejected and the final models assumed the recruitment distribution was fixed at the initial values (see Section 3.4). Nevertheless, this observation indicates that there is very limited data included in the model that provides any information concerning the level of absolute biomass for the region and, consequently, model estimates of biomass for this region should be considered highly uncertain.

4.13 Comparison with 2003 assessment

For the base-case assessment, the main differences in the model data sets and structural assumptions used in the previous (2003) assessment are as follow.

- The inclusion of two years of additional catch, effort, and length data from each of the fisheries.
- Additional tagging release/recovery data in the four northern regions.
- The standardisation of the effort series for the equatorial purse-seine fisheries using a GLM approach.
- The assumption of constant catchability for the Japanese offshore purse-seine fishery and all the Japanese pole-and-line fisheries.
- Technical improvements to the MULTIFANCL software allowing alternative parameterisation of the selectivity functions.
- The assumption of constant tag reporting rates for all Japanese fisheries.
- The fixing of the proportion of the total recruitment that occurs in each region (estimated in the 2003 assessment).
- A less informative prior on the steepness parameter of the SSR.

There are substantial differences in the magnitude and distribution of total biomass between the current and previous (2002 and 2003) assessments (Figure 37). These are most evident in regions 4, 5, and 6 — the areas that include the vast majority of the total biomass. For the current assessment, the level of biomass in region 4 is substantially (3–4 times) larger than estimated from the previous two assessments. For region 6, the level of total biomass from the current assessment is approximately twice the level from previous assessments over most of the model period and much greater during the two periods of peak abundance (mid–late 1980s and late 1990s) (Figure 37).

In contrast, for region 5 the level of biomass estimated from the current assessment is generally lower than for the previous two assessments and does not exhibit the peaks in the mid–late 1980s and late 1990s (Figure 37). Overall, the cumulative biomass from the equatorial regions (5 and 6) from the current assessment was about 20% higher than for the 2003 assessment throughout most of the model period and higher (30–40%) during the two periods of peak abundance.

The current assessment also yields higher overall estimates of biomass for the three northern regions (1–3), although the small biomass in these regions has a trivial influence in the entire WCPO assessment (Figure 37).

The higher overall biomass level from the current assessment, translated into a considerably lower overall fishery impact on the WCPO stock in recent years about — approximately 15% compared to 20–25% from the previous assessment. Similarly, the impact on the exploitable purse-seine biomass in the equatorial regions was slightly lower than for the previous assessment: 25% and 10% in region 5 and region 6, respectively, compared to 30–35% and 15–20% from the previous assessment.

The maximum sustainable yield (MSY) estimate from the current assessment is approximately 25% higher than for the 2003 assessment (approximately 500,000 mt per quarter compared to 400,000 mt) and all reference biomass levels are considerably higher in the current assessment.

For these complex models, it is difficult to diagnose the main differences in the model parameterisation that may explain the results between the recent assessments. Between the 2003 and current assessments, there are clear differences in the estimates of the proportion of total recruitment between regions, natural mortality at age, and the age-specific movement coefficients. However, there are strong interactions between all these variables and the model observations are clearly explained by a range of values for these parameters.

Further, there have been a number of changes in the underlying model assumptions. While these changes may appear minor, it is not clear how influential these changes are on the overall results of the model without undertaking a number of additional sensitivity analyses. In addition, the current model includes a further two years of fishery and tagging data. All of the additional tagging data is from the northern areas of the WCPO (regions 1–4) and, therefore, unlikely to be influential on the results from the equatorial regions (5 and 6).

Nevertheless, region 6 has only supported large catches of skipjack since the late 1990s and recent (2001 and 2002) catches from the region were the highest on record (see Figure 5). These recent catches may be influential in scaling the overall biomass level in the region. There is also potential that the large and lightly exploited biomass in this region may be a model artefact ("cryptic biomass"), buffering the overall stock and resulting in an overly optimistic assessment of the fishery.

This scenario was investigated through a further sensitivity analysis whereby the two equatorial regions (5 and 6) were amalgamated while maintaining the equivalent fishery definitions. In this scenario, the time-series of recruitment and overall exploitation rates are equivalent throughout the entire equatorial region and there is no estimation of longitudinal movement; essentially it is a single population exploited by all the equatorial fisheries. The other model assumptions were equivalent to the base-case model.

The resulting single equatorial region model yielded recruitment estimates that were generally lower and less variable than the cumulative recruitment from the two equatorial regions of the base-case model. The recruitment series exhibited similar inter-annual variation in recruitment, although there was no strong temporal trend of increasing recruitment as evident in the base-case model and the extremely high recruitment in the mid–late 1980s and late 1990s was not evident in the single equatorial region model.

The differences in recruitment between the two models were also evident in the adult biomass trajectories. Overall, the level of adult biomass in the equatorial area was broadly comparable between the two models, with the exception that the extremely high biomass in region 6 during the mid late 1980s and late 1990s from the base-case model was not evident in the single equatorial region model. There was also increasing divergence in the biomass trajectories during the time-series, with higher biomass from the base-case model since the mid-1980s attributable to the increasing trend in recruitment. The difference in biomass levels was also evident in the slightly higher impacts of fishing on adult biomass estimated from the single equatorial region model.

However, despite the differences between the two models described above, the overall yields, reference biomass, and management quantities derived from the two models were comparable (see following section). On this basis, it was concluded that the regional structure applied to the equatorial area of the WCPO was not introducing undue sources of bias that were impacting on the overall conclusions of the assessment.

4.14 Yield and reference point analysis

The use of reference points provides a framework for quantitatively determining the status of the stock and its exploitation level. Two types of reference points are often now required for fisheries management: the fishing mortality at maximum sustainable yield (F_{MSY}) is used as an indicator of overfishing; and the biomass at MSY ($\tilde{B}_{MSY}$) is used as an indicator of an overfished state (Table 6). It is possible for overfishing to be occurring, but for the stock to not yet be in an overfished state. Conversely, it is possible for the stock to be in an overfished state but for the current level of fishing to be within the overfishing reference point. In this case, the stock has presumably been depressed by past overfishing and would recover to a non-overfished state if the current level of fishing was maintained. It is likely that these reference points, or something similar, will be used for stock status determinations in the new WCPO tuna commission. We have therefore developed a reference point analysis within the MULTIFAN-CL model framework as an example of how this might be applied in WCPO tuna fisheries.

The reference point analysis has been carried out as follows:

- Estimate population model parameters, including the parameters of a Beverton and Holt stock-recruitment relationship (SRR).
- Estimate a "base" age-specific fishing mortality vector, F_{age}, various multiples of which are assumed to maintained into the future; for the skipjack tuna assessment, the average F_{age} over 1999–2003 was used.
- For various multiples of F_{age} compute the equilibrium population-at-age, and equilibrium yield using the estimated SRR, natural mortality and other parameters.
- Compute the equilibrium total biomass, equilibrium adult biomass and equilibrium fishing mortality (averaged over age classes) at MSY. These equilibrium quantities are the reference points.
- Compare the actual estimated biomass and fishing mortality levels at time *t* with these reference points. This is done by computing the ratios $B_{current} / \tilde{B}_{MSY}$, $SB_{current} / S\tilde{B}_{MSY}$, $F_{current} / \tilde{F}_{MSY}$ and their 95% confidence intervals and comparing them with 1.0. Values of $F_{current} / \tilde{F}_{MSY}$ significantly greater than 1.0 would indicate overfishing, while values of $B_{current} / \tilde{B}_{MSY}$ and/or $SB_{current} / S\tilde{B}_{MSY}$ or less than 1.0 would indicate an overfished state.

Note that these somewhat simplistic notions make assumptions about equilibrium behaviour of the populations. This aspect of reference points and in particular those based on equilibrium models has been roundly criticised (with some justification) in some fisheries circles. One criticism is that long-term changes in recruitment might occur through environmental or ecosystem changes that have little or nothing to do with the fisheries. More generally, it is not unreasonable to view many fish populations as being in a continual state of flux with an equilibrium condition never being reached or maintained for any length of time. In reality, therefore, MSY, F_{MSY} and $\tilde{B}_{MSY}$ are "moving targets" and not static quantities. At best, they should be considered as averages over time, and additional analyses undertaken in cases where it is suspected that important non-fishery-induced changes in productivity may have occurred.

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

Two different prior distributions for the value steepness were considered in the current assessment; a broad prior distribution with a mode of 0.85 and a tight prior distribution with a mode of 0.91 (Figure 38). The latter prior distribution was very similar to the prior used in the 2003 assessment. The assumption regarding the prior distribution was influential in the estimated SRR. The broad prior distribution resulted in an estimate of steepness of 0.66 (Figure 38 and Figure 39). This represents a low value of steepness for a species such as skipjack and the estimate appears to be driven by the lower values of recruitment that were estimated for 1972–1983 when adult biomass was also estimated to be low (see Figure 30 and Figure 31). Nevertheless, it is important to note that this was a period when the dynamics of the fishery were considerably different from the current fishery; i.e. it was prior to the development of the equatorial purse-seine fishery.

The high constraint on the prior distribution (mode = 0.91, SD = 0.05) resulted in a model estimate very close to the mode of the prior (Figure 38) and, thereby, a SRR that exhibited a very weak relationship between spawning biomass and recruitment (Figure 39). However, as the estimated spawning biomass has rarely been below 60% of the equilibrium adult biomass ($\tilde{SB}_0$) there is very little information on how recruitment might respond to very low biomass levels and, therefore, limited basis for choosing between the two point estimates of steepness.

The two values for steepness yielded different estimates of yields and reference biomass (Table 7). Nevertheless, the estimated equilibrium yield, using a base *F*-at-age given by the 1999–2003 average, is comparable for both values of steepness as the spawning biomass has not been significantly reduced below the equilibrium, unexploited level (i.e. $SB_{current}/\tilde{SB}_0$ about 1.0)(Figure 40). This analysis indicates that, for this average *F*-at-age (i.e. a fishing mortality multiplier of 1.0), the equilibrium yield is approximately 920,000 mt per year (Table 7). This is lower than the actual catches that occurred during 1999–2003, which averaged about 1.2 million t per year. This is because the yield analysis is based on an equilibrium model in which equilibrium recruitment is predicted on the basis of the SRR shown in Figure 39. However, recruitment during the late 1990s was at a relatively high level which enabled the recent high catches to occur.

For the lower value of steepness, the maximum equilibrium yield (equivalent to MSY) is about 2.0 million mt per annum and is achieved at a F-multiplier of about six (5.9) i.e. six-times the average level of effort in 1999–2003 (Table 7). The higher value of steepness results in a MSY of 2.7 million mt at a F-multiplier of about 12.5.

The portion of the yield curve near the current level of *F*-at-age is close to linear (Figure 39). 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 lower value of steepness, the maximum equilibrium yield would be taken at 27% and 33% of the level of the current spawning and total biomass, respectively (Table 7 and Figure 41).

The ratios of $F_{current}/\tilde{F}_{MSY}$ and $B_{current}/\tilde{B}_{MSY}$ reveal that overfishing of skipjack is not occurring in the WCPO, nor is the stock in an overfished state (Figure 42).

5 Conclusions

The major conclusions of the skipjack assessment are essentially unchanged from the last two assessments (Hampton 2002, Langley et al. 2003). They 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. While tagging data show that individual skipjack are capable of undertaking long-distance movements of several thousand kilometers, the population-level estimates of dispersal obtained from this model are in fact consistent with some degree of regional fidelity. The contribution of local recruitment to the regional sub-populations is generally 70% or greater.

4. Nevertheless, some of the population-level estimates of dispersal appear to be inconsistent with the other observations from the fishery and the tagging 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, albeit limited, reveals 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, e.g. the fixed proportion of the total recruitment in each of the model regions.

5. Similarly, the model estimates relatively modest 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.

6. Recruitment showed an upward shift in the mid-1980s and is estimated to have remained at a higher level since that time. Recruitment was also estimated to have been very high during the late 1990s. The strong *El Niño* at around that time and the high frequency of such events during the 1990s is suspected to have had a positive effect on skipjack recruitment. Recent recruitment is estimated to be exceptionally high, but is poorly determined due to limited observations from the fishery.

7. Most (96%) of the recruitment is assumed to occur in the two equatorial regions. This proportion is estimated independently of the assessment model from a spatial ecosystem and populations dynamics model (SEAPODYM) (Lehodey 2004). The results of the assessment are relatively sensitive to the assumed distribution of recruitment and, consequently, the values should be revised following future developments of SEAPODYM. Estimates of recruitment from the current assessment model are also sensitive to the current regional structure of the equatorial region; a sensitivity analysis revealed that the extremely high levels of recruitment in region 6 during the mid late 1980s and late 1990s were moderated by the amalgamation of the two equatorial regions.

8. The biomass trends are driven largely by recruitment. The highest biomass estimates for the model period occurred in 1983–88 and 1998–2000, immediately following periods of sustained high recruitment. The model results suggest that the skipjack population in the WCPO in recent years has been considerably higher (about 20%) than the overall average level for the model period.

9. 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 standardisation of the effort series. The general increase in standardised CPUE from the Japanese equatorial pole-and-line fisheries and high CPUE in the late 1980s, therefore, provides an explanation for the general trend in both recruitment and total biomass over the model period. However, given the general increase in

pole-and-line catch rates over time, it remains unclear whether the standardised effort series provides a reliable index of stock abundance.

10. The model also incorporates a considerable amount of tagging data that provides information concerning absolute stock size during the main tag recovery period. However, for the equatorial regions, the last intensive tagging programme 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 level of biomass in region 4 is also poorly determined. This current assessment estimates that the region accounts for about 20% of the total biomass, although catches from the region are trivial, representing only 1–2% of the total. A comparison of previous model results indicates that the level of biomass estimated in this region is highly sensitive to the underlying model assumptions.

11. Fishing mortality has increased throughout most of the time-series, stabilising to some extent in recent years. The impact of fishing is predicted to have reduced recent biomass by about 15%, with the higher impacts in region 5 (about 25%) buffered by lower impacts in region 6 (10%) and negligible impacts in region 4. The impacts of fishing are higher in the northern sub-tropical regions (1–3) that account for a small proportion of the total biomass.

12. A range of sensitivity analyses were undertaken to address some of the uncertainty in the assessment described above. However, the general stock assessment conclusions from the various sensitivity analyses were comparable to the base-case analysis. The principal conclusions are that skipjack is currently exploited at a modest 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. Recruitment variability, influenced by environmental conditions, will continue to be the primary influence on stock size and fishery performance.

13. 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, undertaken regularly, would 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.
    - 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.

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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 (including 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	1,092	42	JPOS PL 1	42
2	23,289	1,362	JPOS PL 2	558
			JPDW PL 2	40
			JPOS PS 2	764
3	2,123	3	JPDW PL 3	3
4	22,151	260	JPOS PL 4	99
			JPDW PL 4	161
5	144,890	13,325	JPDW PL 5	636
			PG PL 5	876
			SB PL 5	1,316
			PS ALL 5	7,380
			PH DOM 5	2,264
			ID DOM 5	853
6	83,928	4,414	JPDW PL 6	393
			FJ PL 6	2,713
			PS ALL 6	1,308
Total	277,473	19,406		

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 0.1 times actual sample size with a maximum effective sample size of 100.
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 0.85 and SD of 0.16).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 assumed to be 0.0065, 0.0013, 0.0004, 0.0266, 0.4056, and 0.5595.
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 estimated independently for all 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	Parameter	Fisheries/areas	Details
PS fpower	Effort data	PS LOG, FAD, SCH MFCL areas 5 & 6.	Increase in effective fishing effort of the equatorial purse-seine fisheries by 5% per annum.
			Constant catchability for these fisheries.
High steepness	Steepness		Beta prior for steepness with mode at 0.91 and SD of 0.05.
PL56-fixq	Catchability	JP DW PL5 & 6	Catchability for the two fisheries constant at the same level.

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

Objective function component	Base-case	PS-fpower	High steepness	PL56-fixq
Total catch log-likelihood	179.57	190.74	179.55	183.35
Length frequency log-likelihood	-175229.54	-175416.98	-175229.71	-175629.99
Tag log-likelihood	10612.06	10653.5	10612.15	10832.04
Penalties	3239.17	3241.77	3238.37	3486.68
Total function value	-161198.74	-161330.97	-161199.64	-161127.92

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

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 1999–2003
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (*MSY*)
$\tilde{Y}_{F_{current}}$	Equilibrium yield at $F_{current}$
$\tilde{Y}_{F_{MSY}}$ (or *MSY*)	Equilibrium yield at F_{MSY} , or maximum sustainable yield
$\tilde{B}_0$	Equilibrium unexploited total biomass
$\tilde{B}_{F_{current}}$	Equilibrium total biomass at $F_{current}$
$\tilde{B}_{MSY}$	Equilibrium total biomass at MSY
$S\tilde{B}_0$	Equilibrium unexploited adult biomass
$S\tilde{B}_{F_{current}}$	Equilibrium adult biomass at $F_{current}$
$S\tilde{B}_{MSY}$	Equilibrium adult biomass at MSY
$B_{current}$	Average current (1999–2003) total biomass
$SB_{current}$	Average current (1999–2003) adult biomass
$B_{current,F=0}$	Average current (1999–2003) total biomass in the absence of fishing.

Table 7. Estimates of management quantities for the base-case and three sensitivity analyses. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (gray shading).

Management quantity	Units	Base-case	High steepness	PS_fpower	PL56-fixq
$\tilde{Y}_{F_{current}}$	t per quarter	227,000	231,000	229,000	207,000
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per quarter	499,000	664,000	482,000	326,000
$\tilde{B}_0$	t	7,401,000	7,261,000	7,436,000	8,958,000
$\tilde{B}_{F_{current}}$	t	5,989,000	6,060,000	5,589,000	6,628,000
$\tilde{B}_{MSY}$	t	2,907,000	2,576,000	2,636,000	3,694,000
$\tilde{SB}_0$	t	6,025,000	5,912,000	6,130,000	7,486,000
$\tilde{SB}_{F_{current}}$	t	4,669,000	4,723,000	4,337,000	5,317,000
$\tilde{SB}_{MSY}$	t	1,865,000	1,381,000	1,618,000	2,726,000
$B_{current}$	t	8,744,000	8,720,000	7,772,000	10,764,000
$SB_{current}$	t	6,929,000	6,910,000	6,186,000	8,742,000
$B_{current,F=0}$	t	10,113,000	10,088,000	9,481,000	12,601,000
$B_{current}/\tilde{B}_0$		1.18	1.20	1.05	1.20
$B_{current}/\tilde{B}_{F_{current}}$		1.46	1.44	1.39	1.62
$B_{current}/\tilde{B}_{MSY}$		3.01	3.38	2.95	2.91
$B_{current}/B_{current,F=0}$		0.86	0.86	0.82	0.85
$SB_{current}/\tilde{SB}_0$		1.15	1.17	1.01	3.21
$SB_{current}/\tilde{SB}_{F_{current}}$		1.48	1.46	1.43	1.64
$SB_{current}/\tilde{SB}_{MSY}$		3.72	5.00	3.82	3.21
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.81	0.83	0.75	0.74
$\tilde{SB}_{F_{current}}/\tilde{SB}_0$		0.77	0.80	0.71	1.95
$\tilde{B}_{MSY}/\tilde{B}_0$		0.39	0.35	0.35	0.41
$\tilde{SB}_{MSY}/\tilde{SB}_0$		0.31	0.23	0.37	0.51
$F_{current}/\tilde{F}_{MSY}$		0.17	0.08	0.20	0.34
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		2.06	2.35	2.12	1.79
$\tilde{SB}_{F_{current}}/\tilde{SB}_{MSY}$		2.50	3.42	2.68	1.95
$\tilde{Y}_{F_{current}}/MSY$		0.46	0.35	0.47	0.63

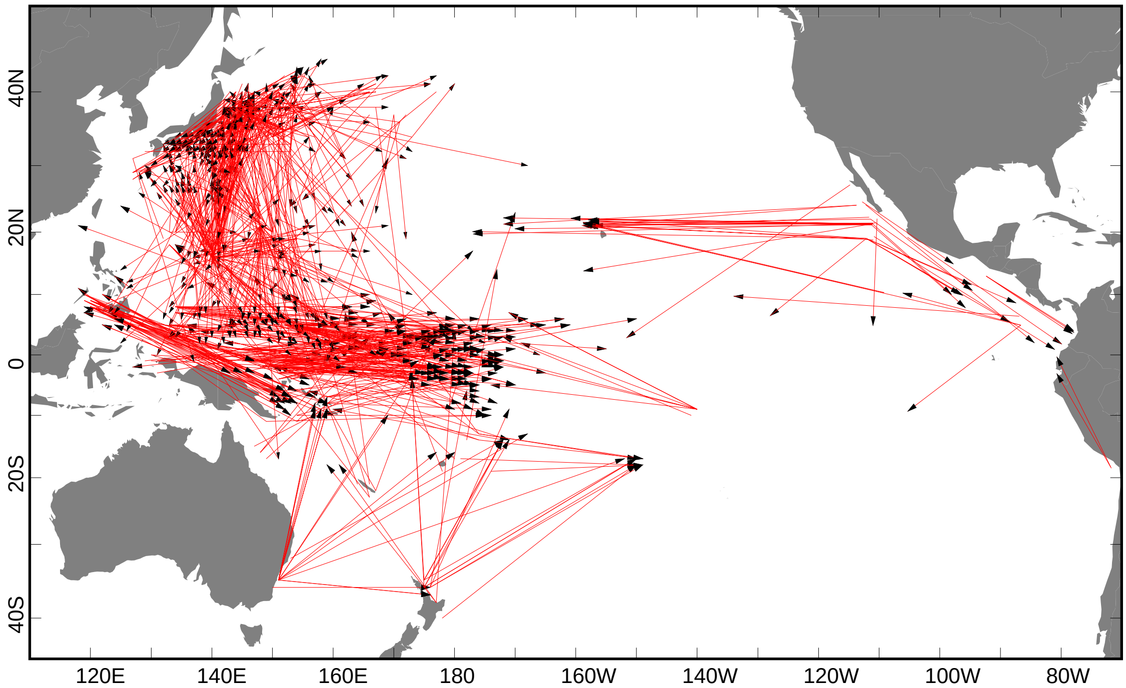

Figure 1. Long-distance (greater than 1,000 nmi) movements of tagged skipjack.

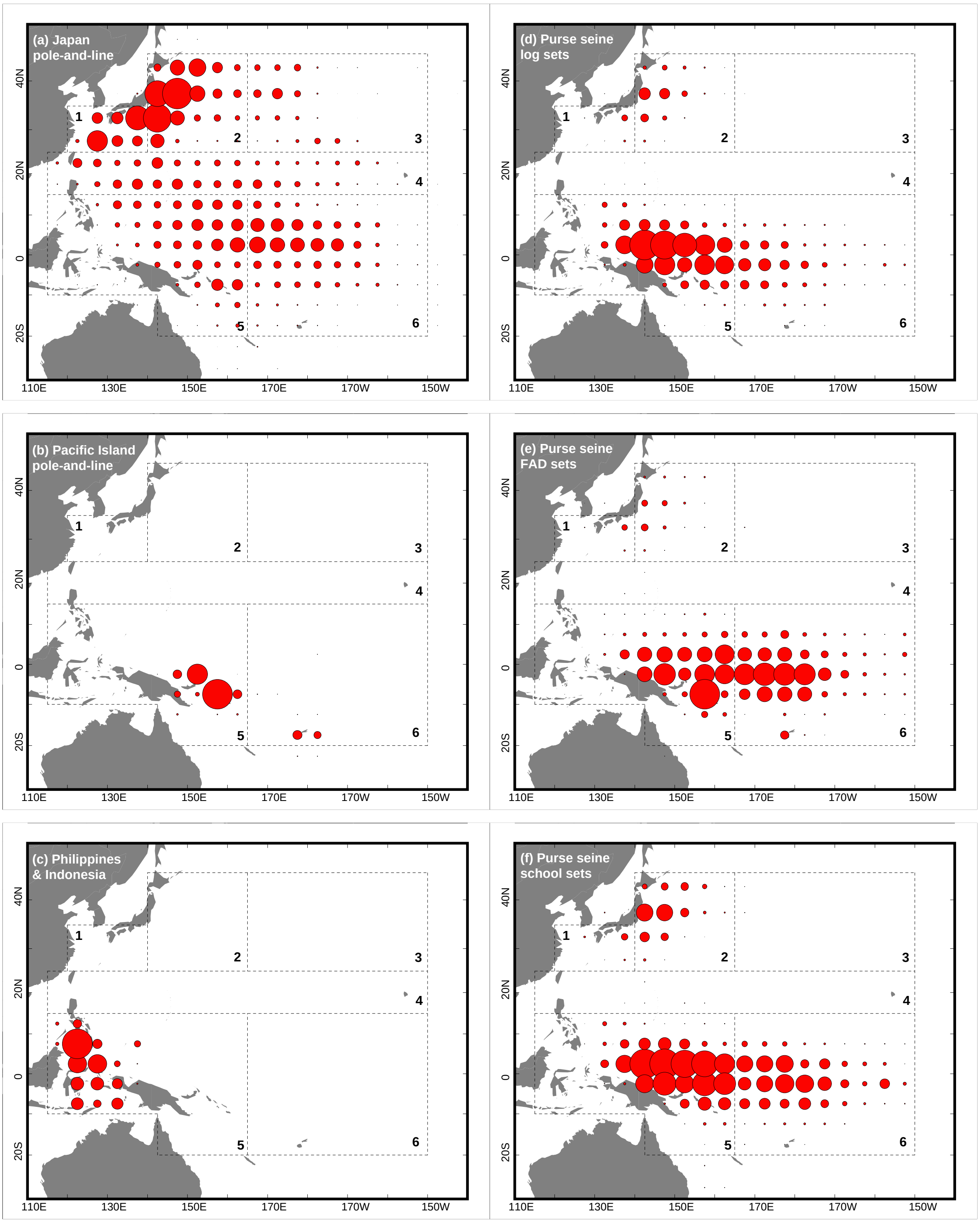

Figure 2. Distribution of skipjack catch 1972–1999 for the major fleets. The definition of the six regions used in the MULTIFAN-CL analysis is shown. Note that the size of circles reflects only spatial differences in catches within each fleet category.

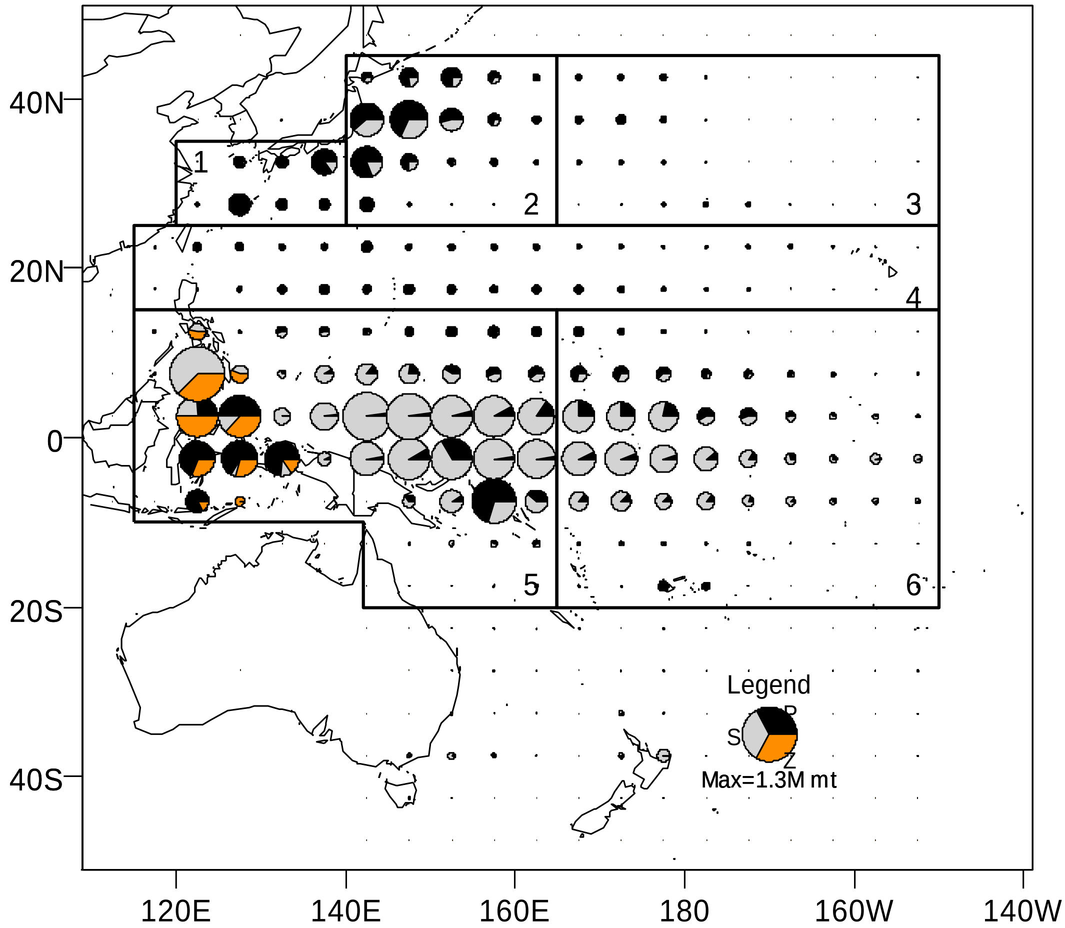

Figure 3. Distribution of total skipjack catches by method during 1972–2004 in relation to the six-region spatial stratification used in the MULTIFAN-CL analysis. Method codes: P, pole-and-line; S, purse-seine; Z, other.

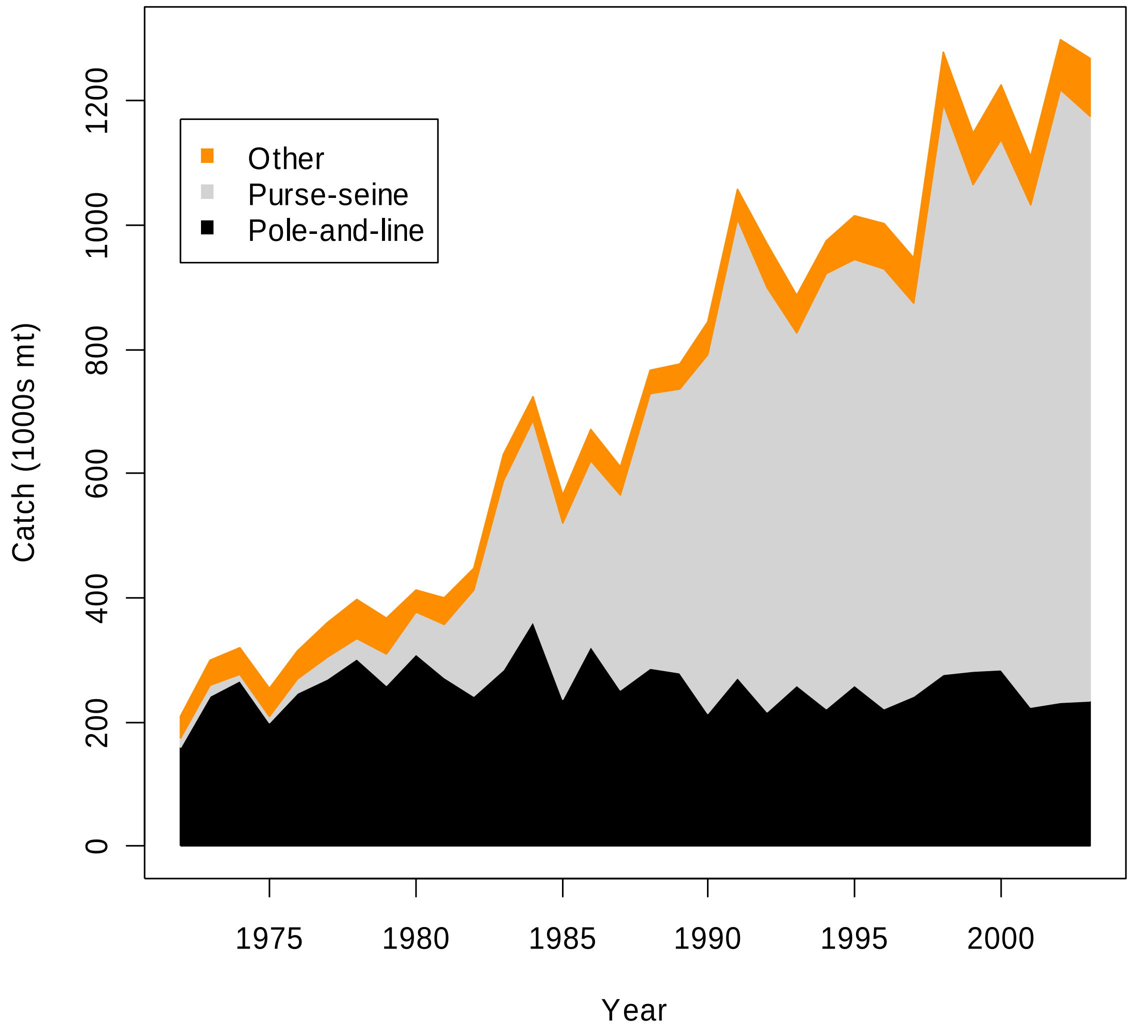

Figure 4. Annual skipjack tuna catch in the WCPO by method, 1972–2003.

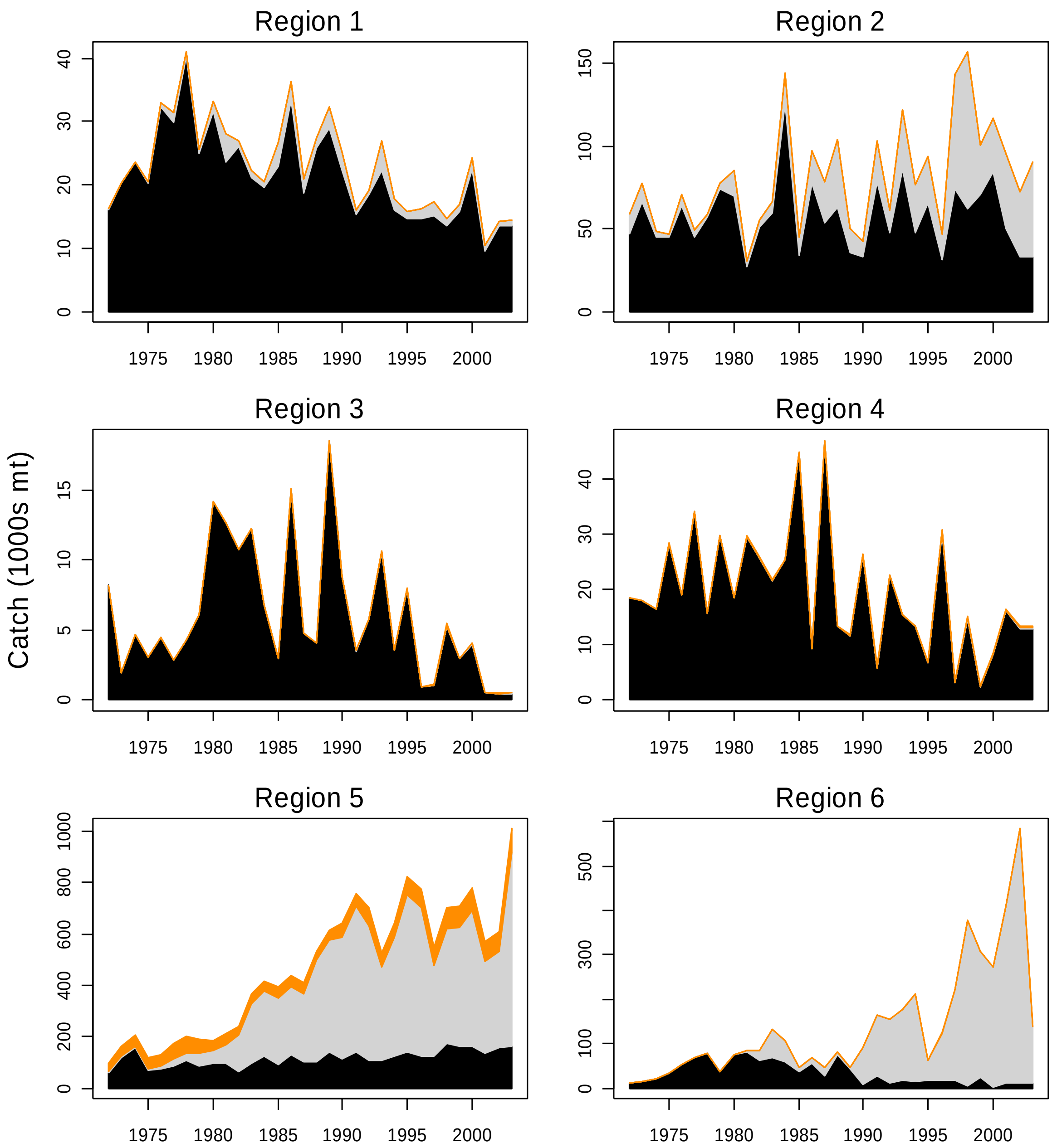

Figure 5. Annual skipjack tuna catch by region and method, 1972–2003.

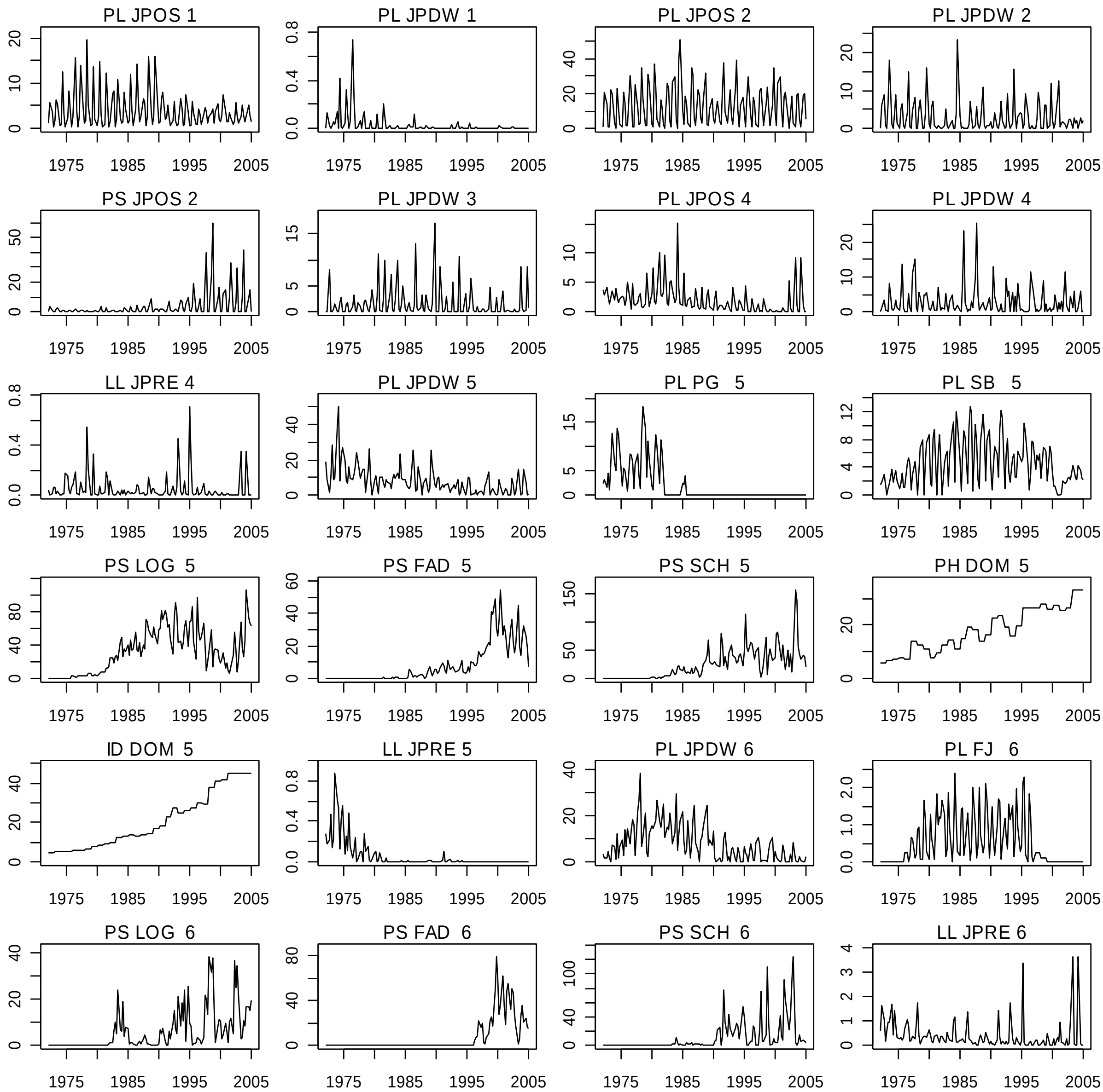

Figure 6. Quarterly catch by fishery and year. Catches are in thousands of tonnes for all fisheries except the longline (LL) fisheries, where the catches are in thousands of fish.

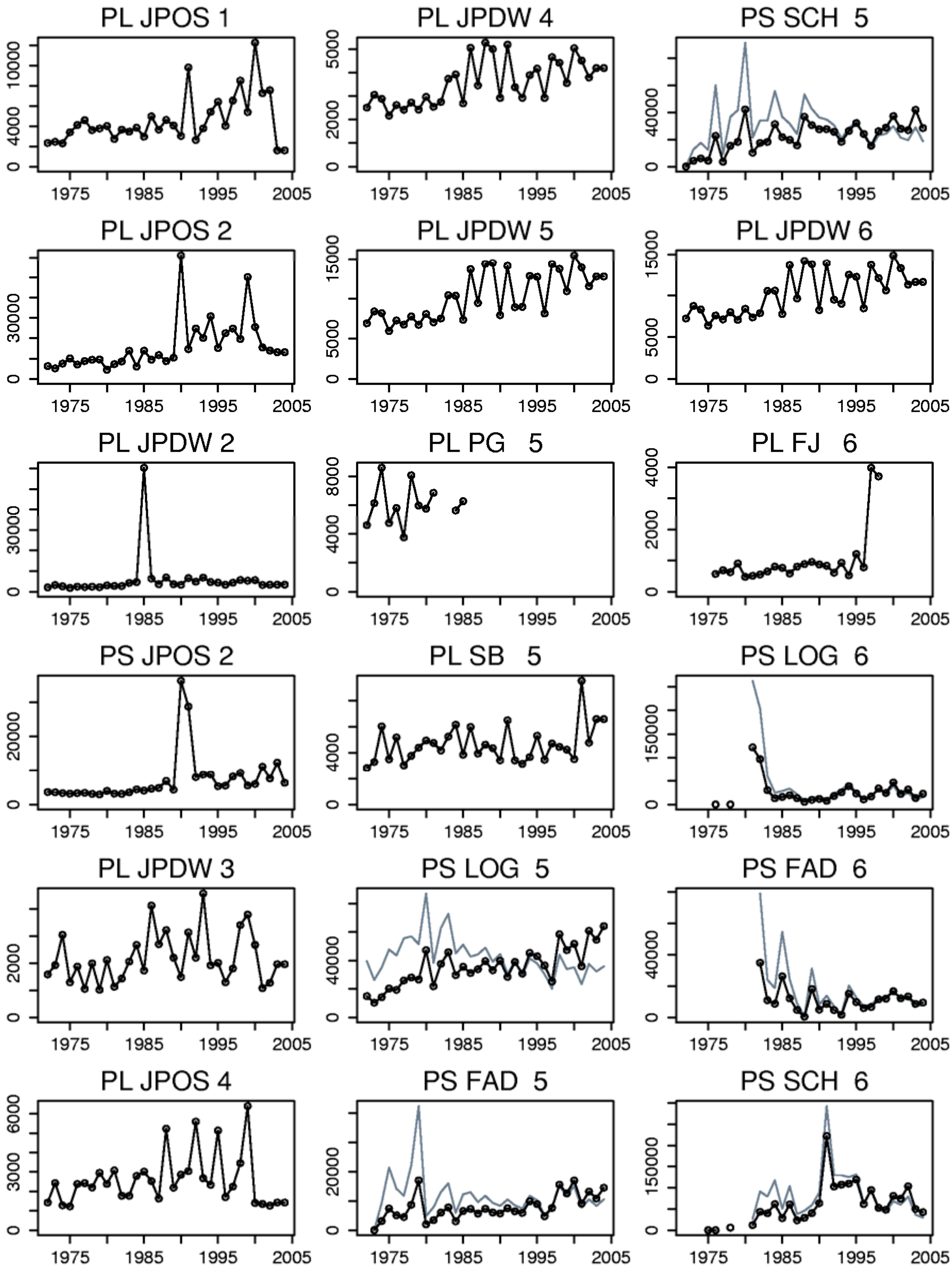

Figure 7. Annual catch per unit effort by fishery (black lines). The grey lines represent the trend in CPUE for the purse-seine fishery with an incremental increase in effective effort of 5% per annum (see text for details).

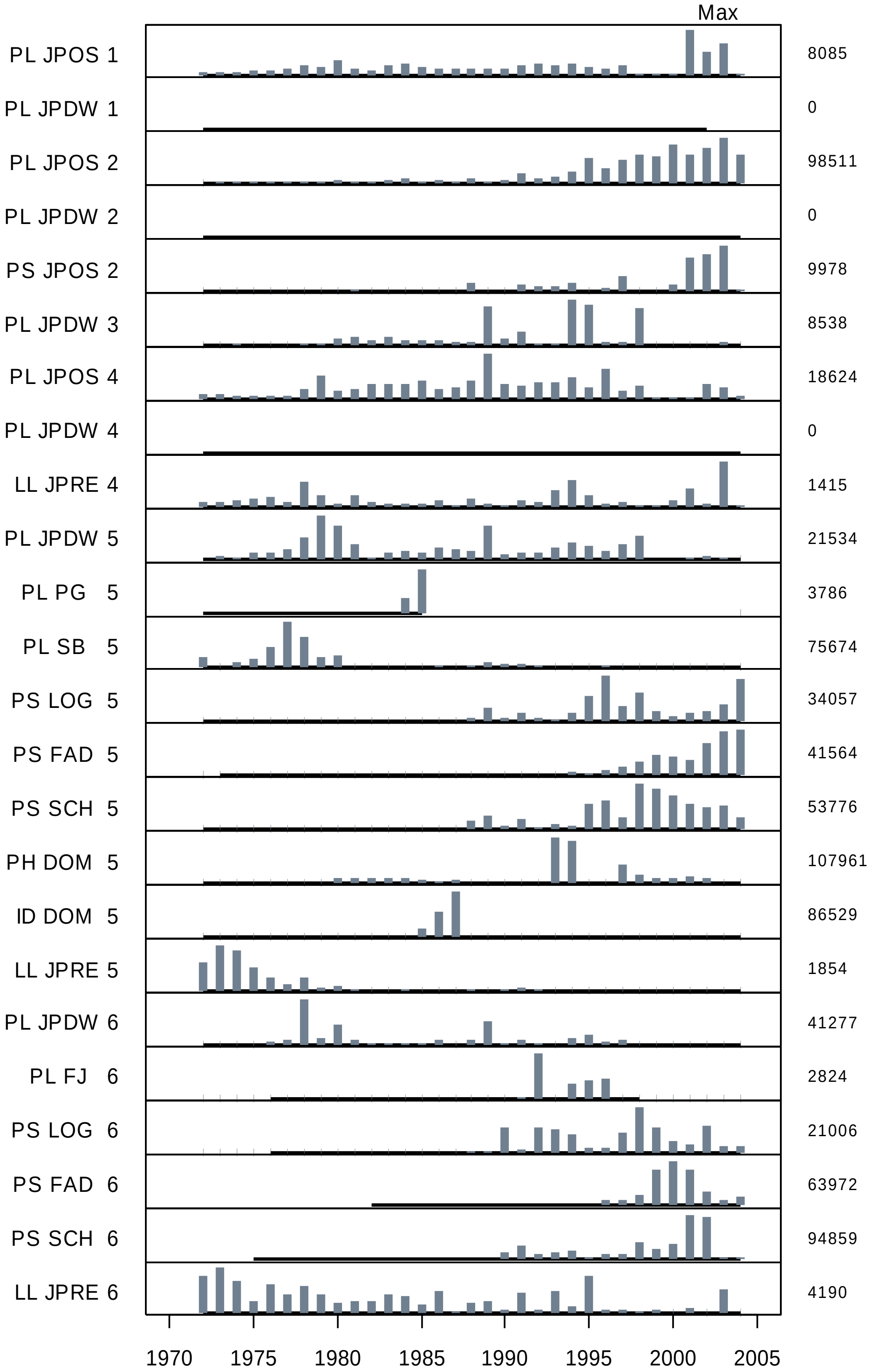

Figure 8: Number of length measurements by fishery and year. The heavy black line represents the period of operation of the fishery. The histogram bars are proportional to the maximum number of fish measured in a fishery/year (the value presented in the right hand axis).

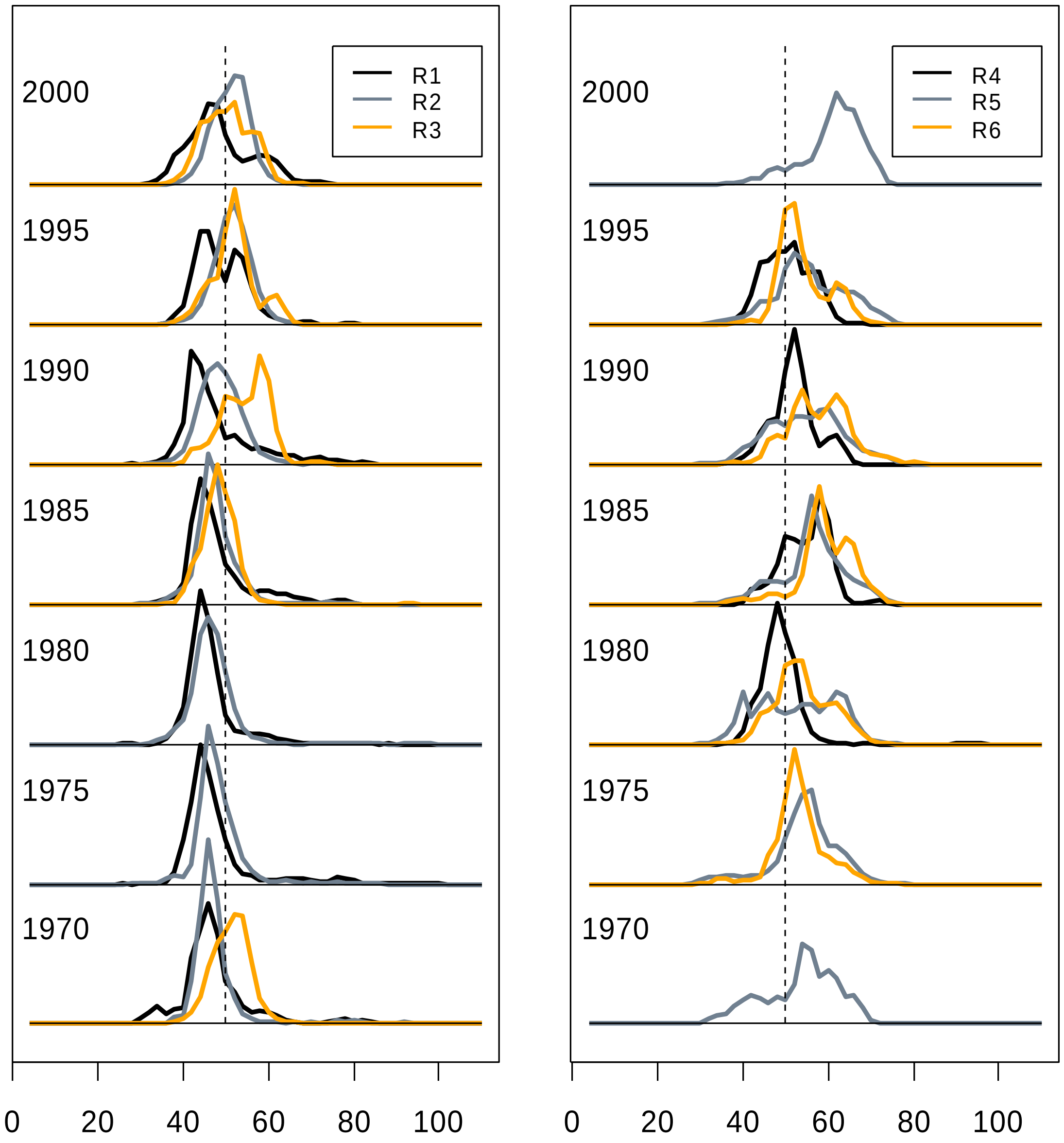

Figure 9: Proportional length compositions of skipjack from the Japanese pole-and-line fisheries operating in the six MFCL regions (R 1–6). Samples are aggregated by 5-year interval. Only region/time length compositions comprised of at least 1,000 fish are presented.

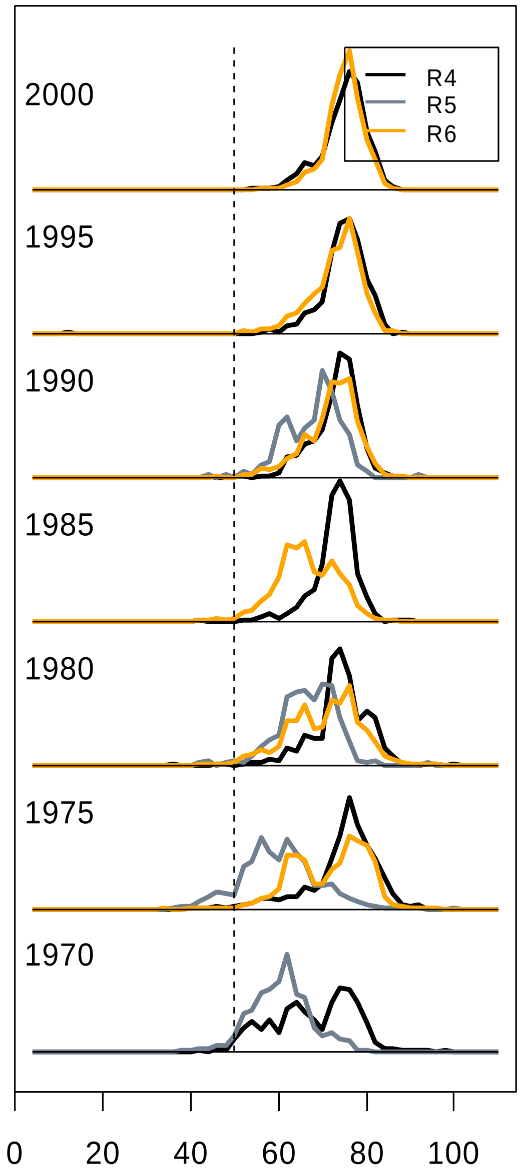

Figure 10: Proportional length compositions of skipjack from the Japanese longline fisheries operating in the MFCL regions 4–6 (R 4–6). Samples are aggregated by 5-year interval. Only region/time length compositions comprised of at least 100 fish are presented.

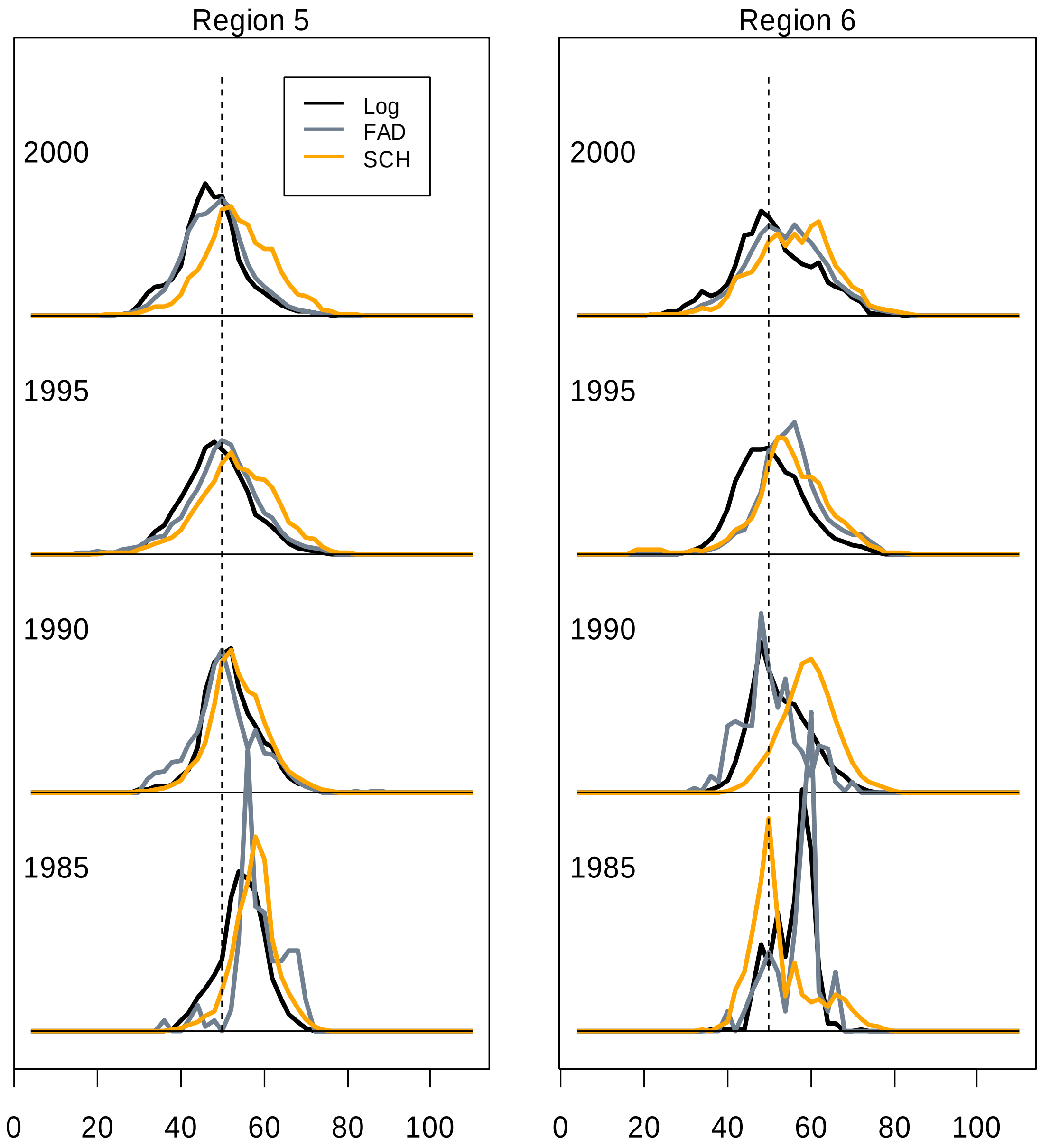

Figure 11: Proportional length compositions of skipjack from the equatorial purse-seine fisheries in the MFCL regions 5 (left panel) and 6 (right panel). Samples are aggregated by set type (log, FAD, and school) and 5-year interval.

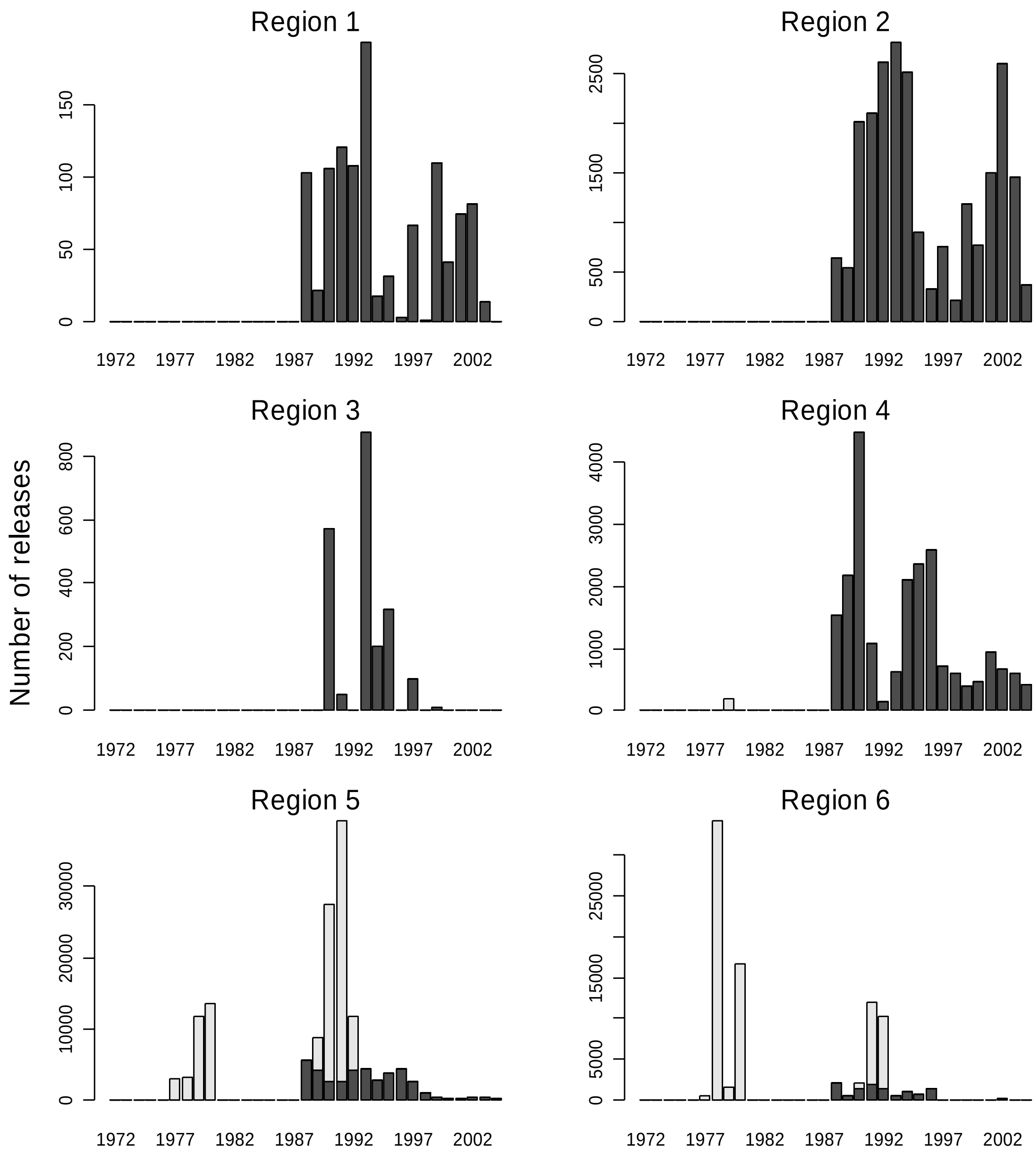

Figure 12: Number of tag releases by region, year and source of release. The dark grey represents releases by Japanese research programmes, the light grey represents releases administered by SPC.

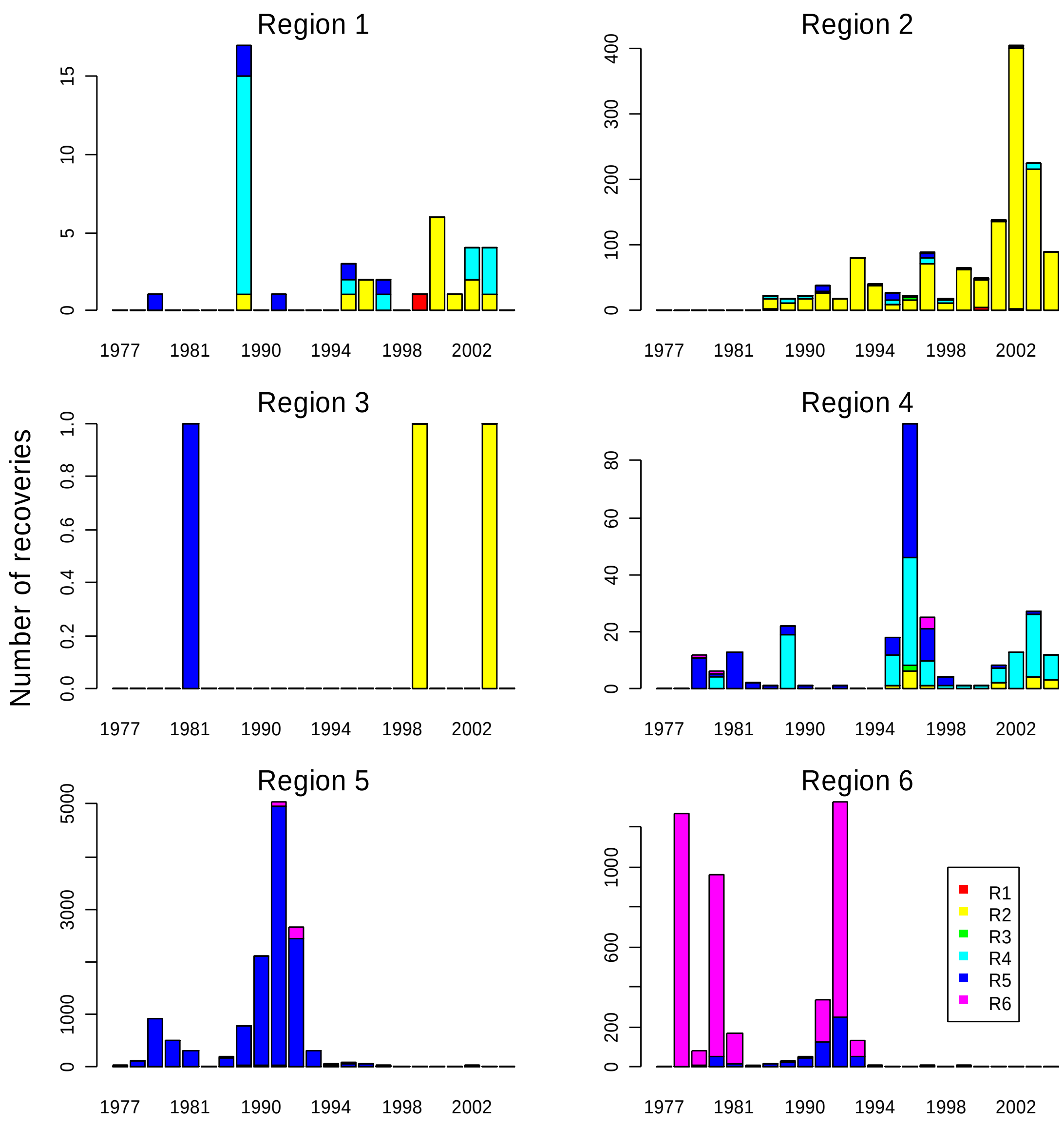

Figure 13: Annual number of tag recoveries in each region by region of release.

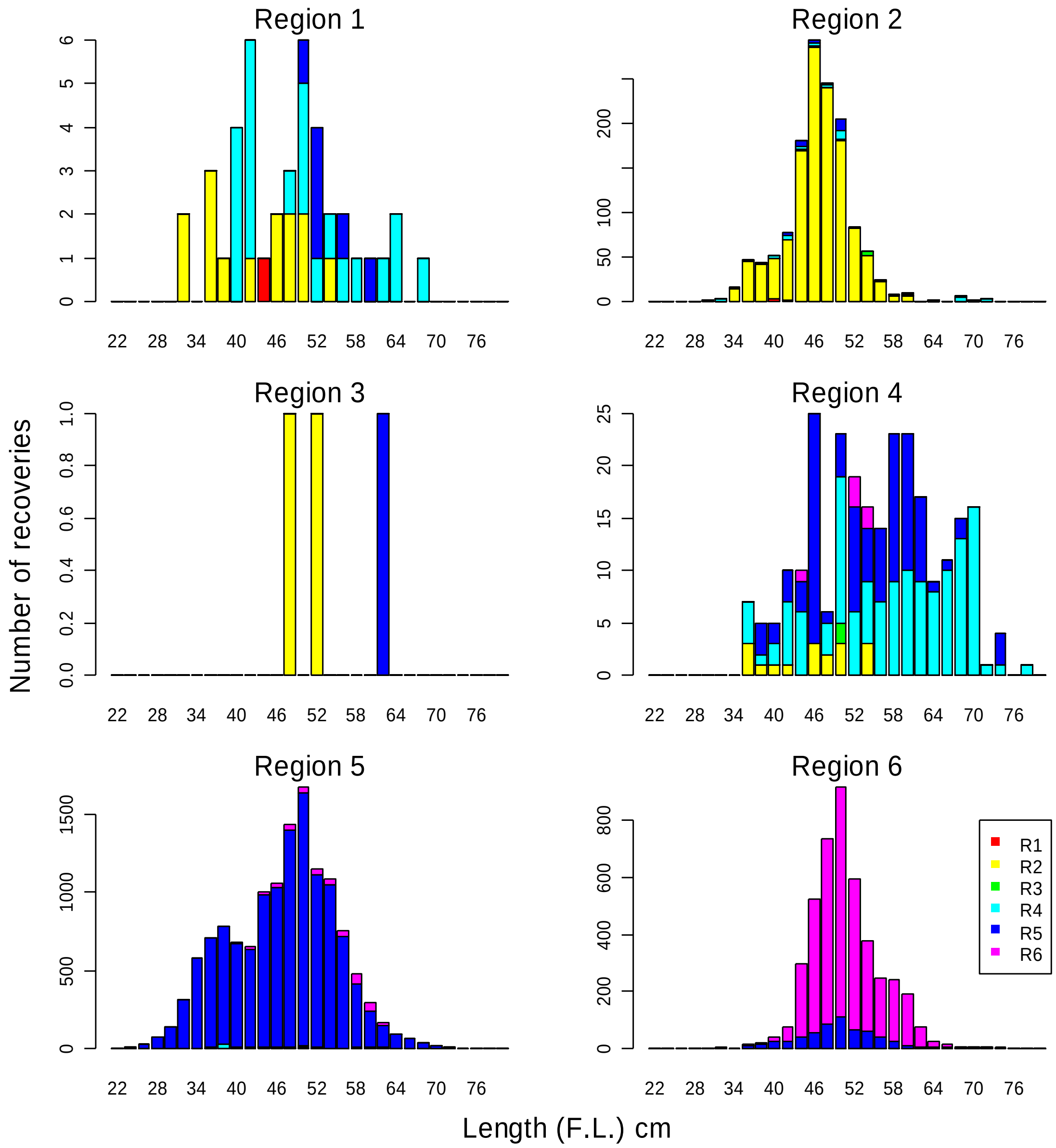

Figure 14: Number of recoveries at length for each region by region of release.

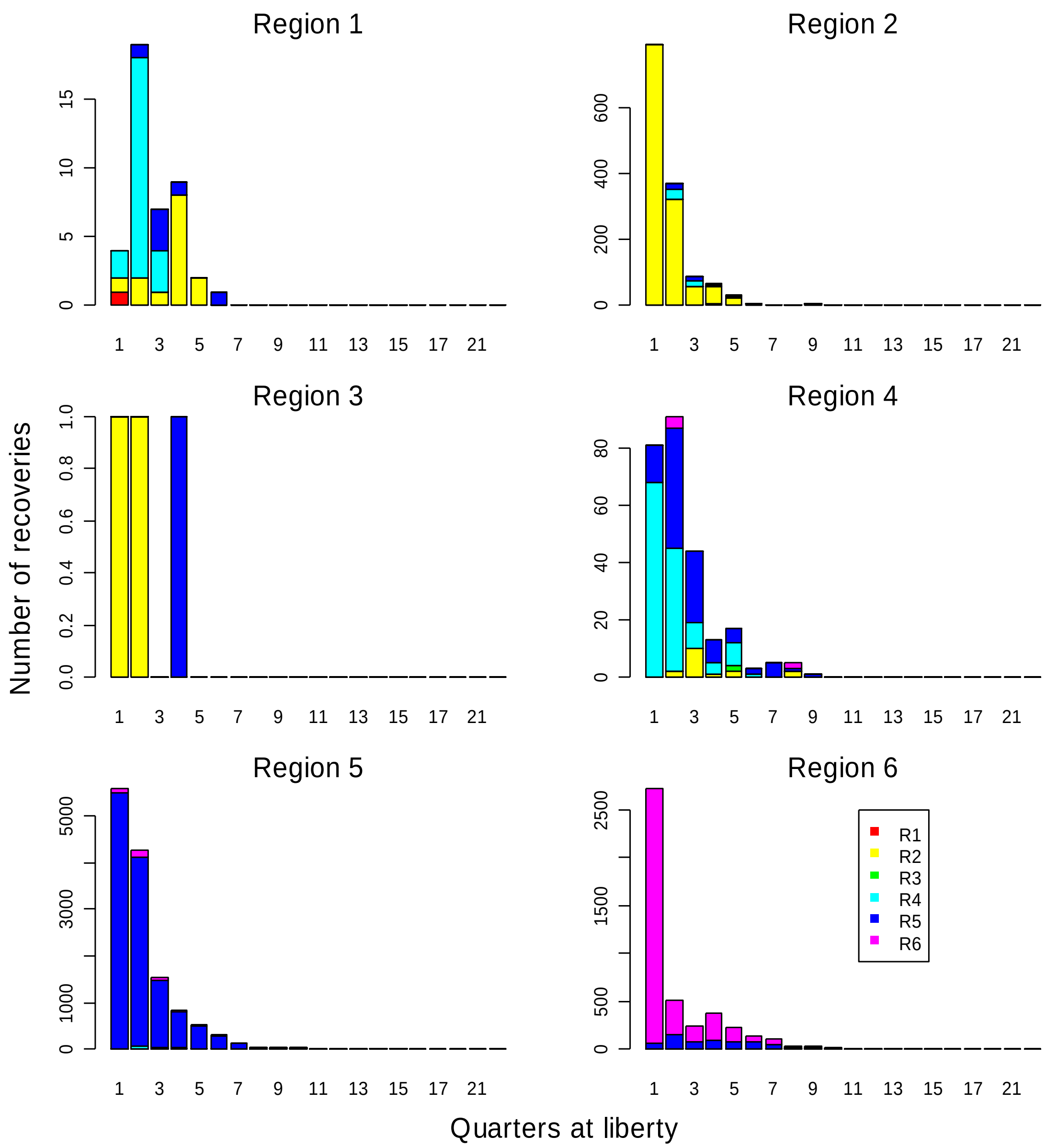

Figure 15: Number of tag recoveries by period at liberty (quarters) for each region by region of release. The first quarter represents the quarter in which the tags were released.

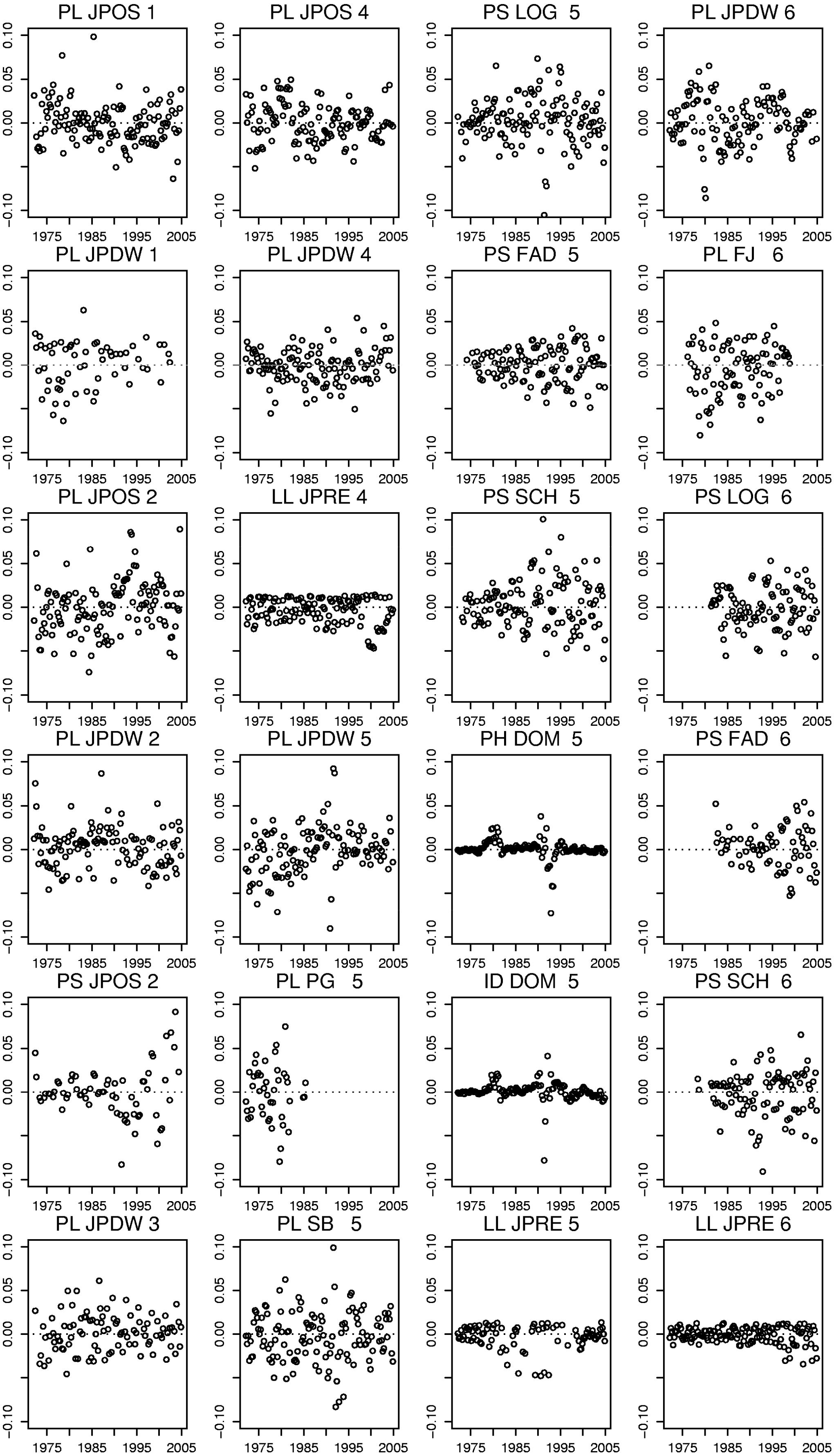

Figure 16: Residuals (observed minus predicted) of the natural logarithm of total catch for each fishery.

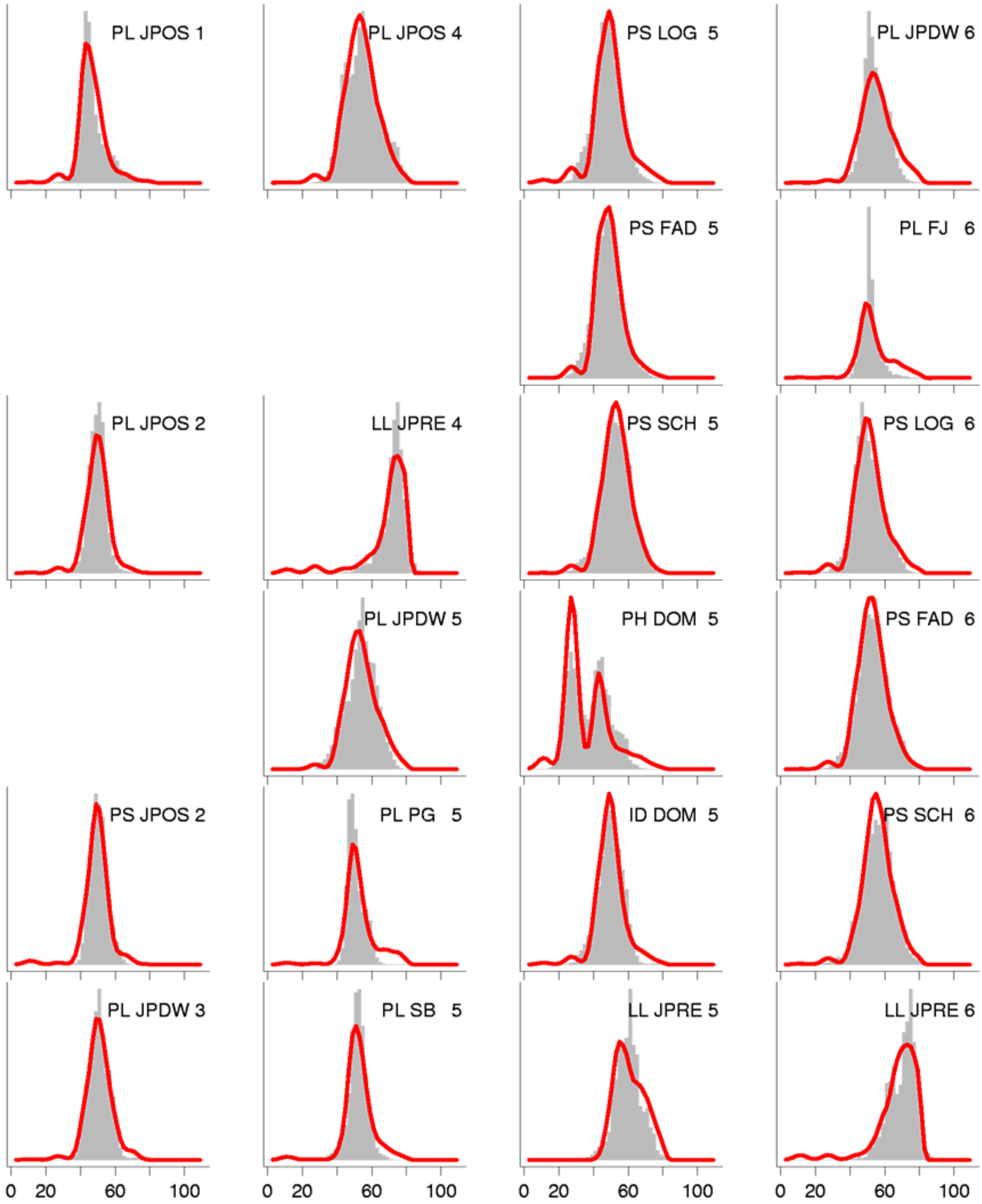

Figure 17. Observed (histograms) and predicted (line) length frequencies for each fishery aggregated over time.

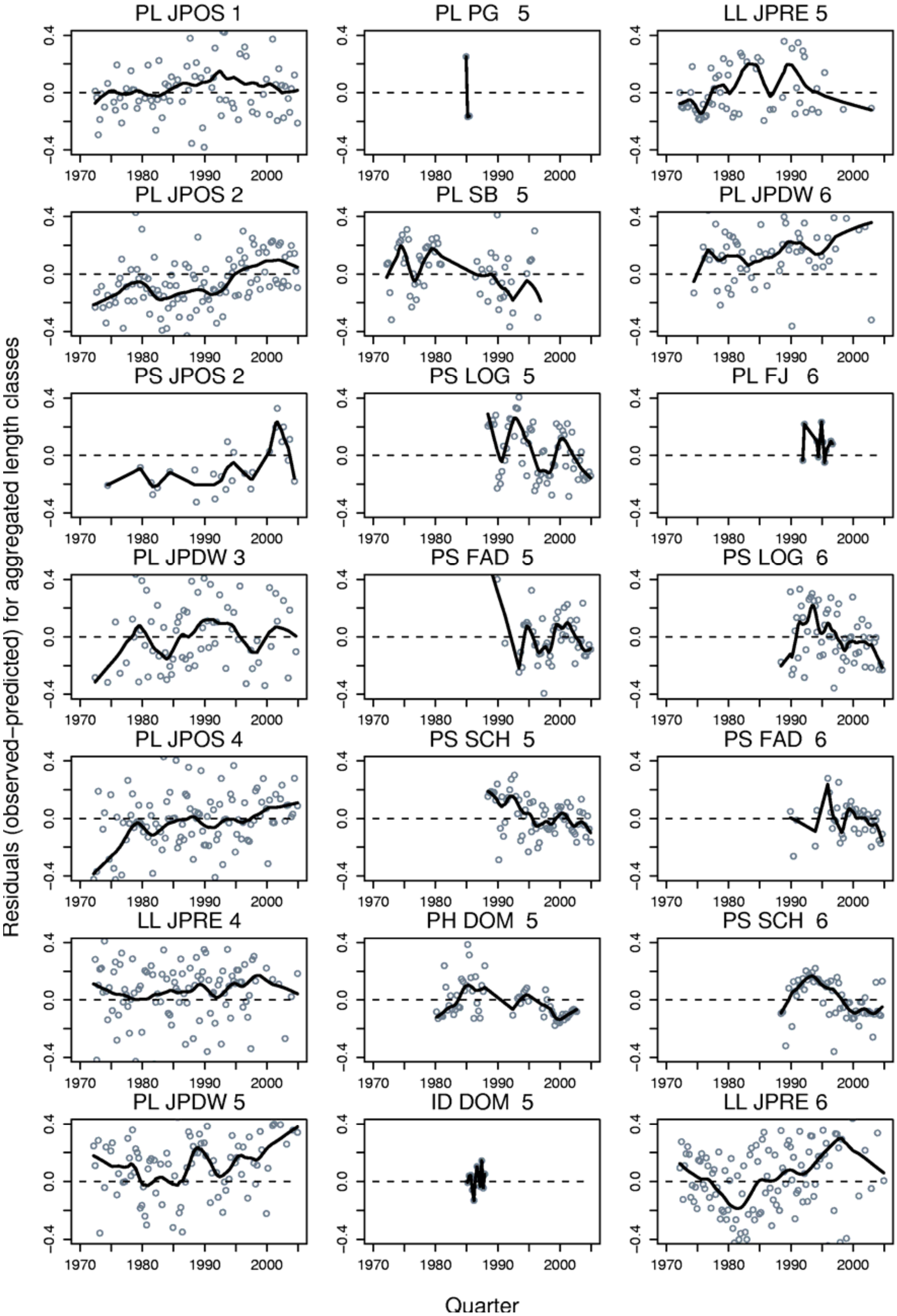

Figure 18. Residuals (observed minus predicted) of the aggregated proportion of fish in the larger length classes from sampled and predicted catches by fishery and sample period. The aggregated length range is 70–90 cm for all the longline fisheries and 50–70 cm for all other fisheries. The line represents a lowess smoothed fit to the data.

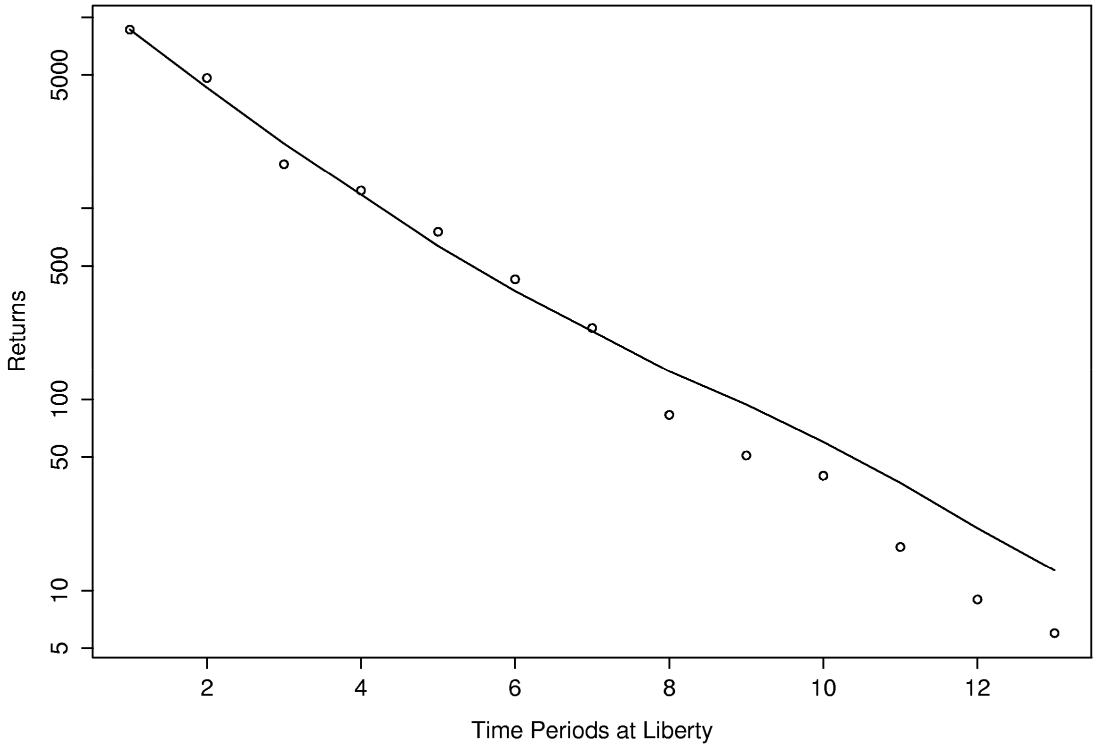

Figure 19. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters).

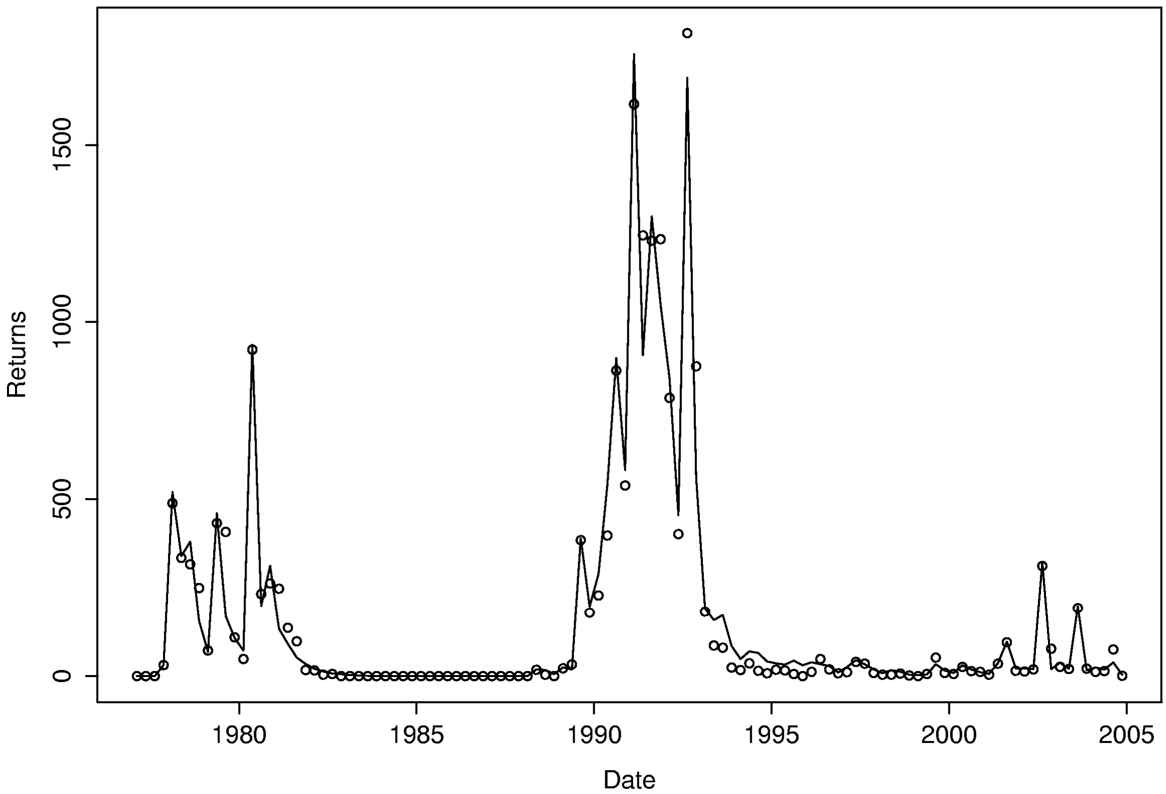

Figure 20. Number observed (circles) and predicted (lines) tag returns by recapture period (quarter).

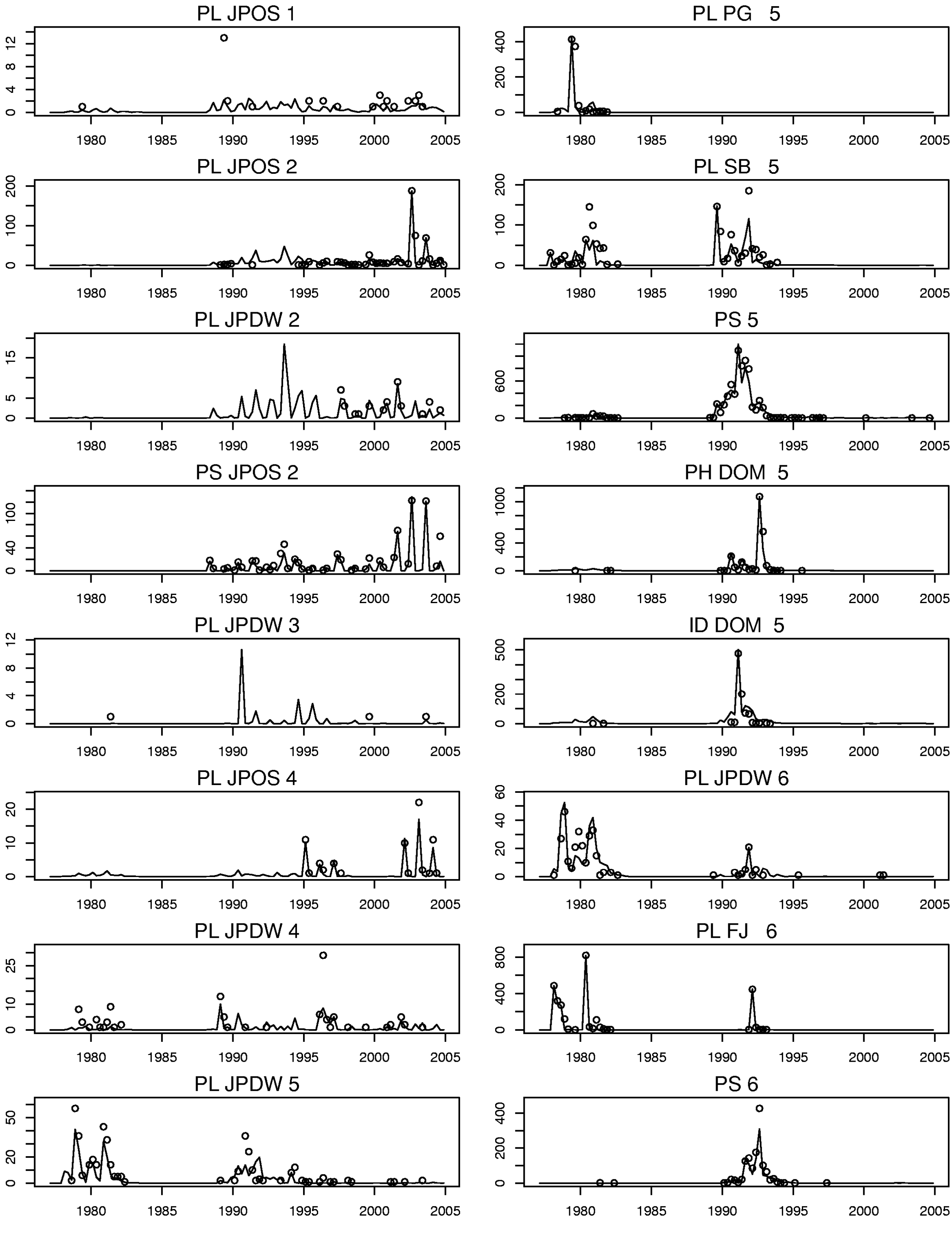

Figure 21. Observed (circles) and predicted (lines) tag returns by calendar quarter for various fisheries (tag groups).

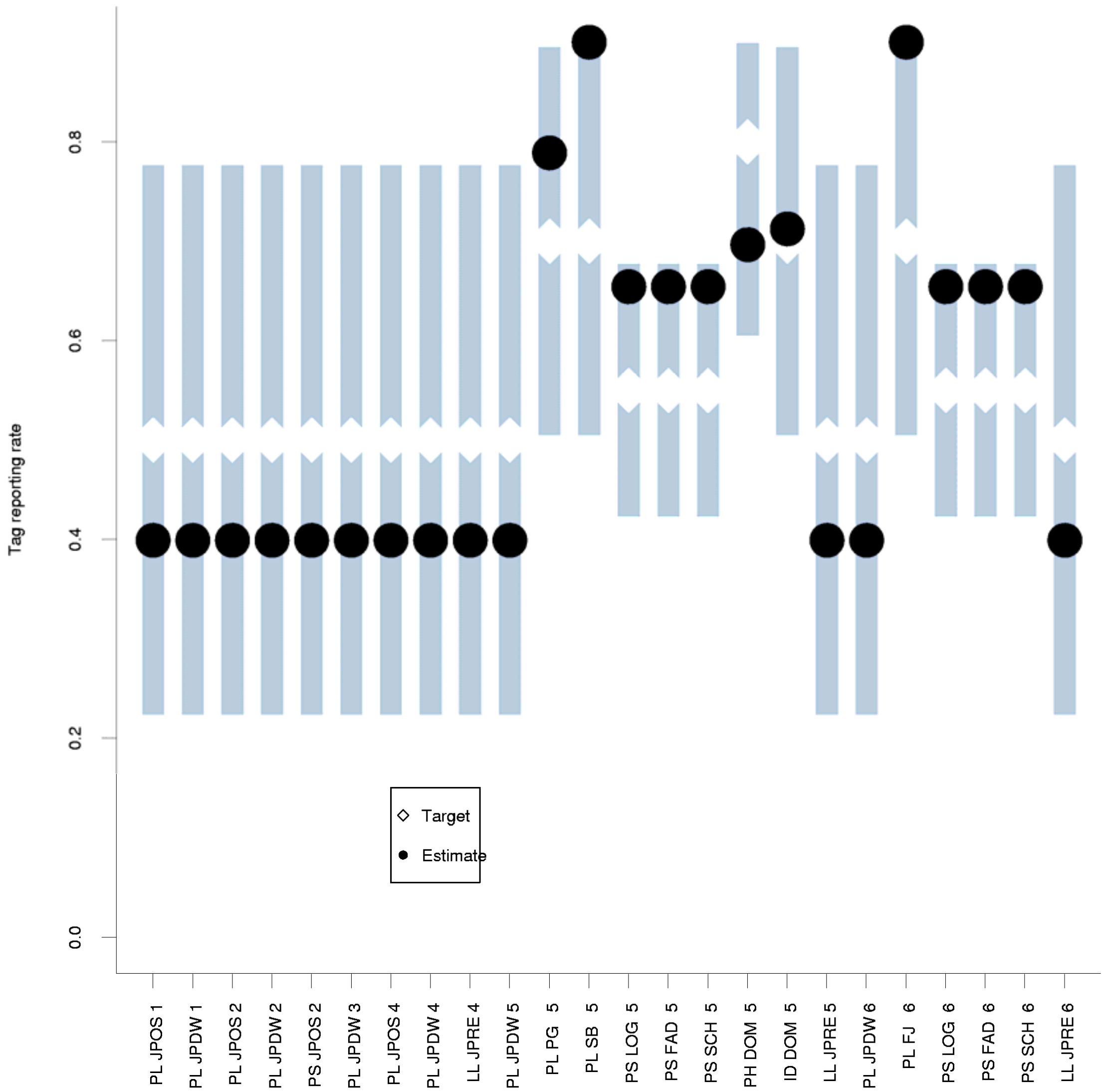

Figure 22. Estimated tag-reporting rates by fishery (histograms). The prior mean ±1.96 SD is also shown for each fishery.

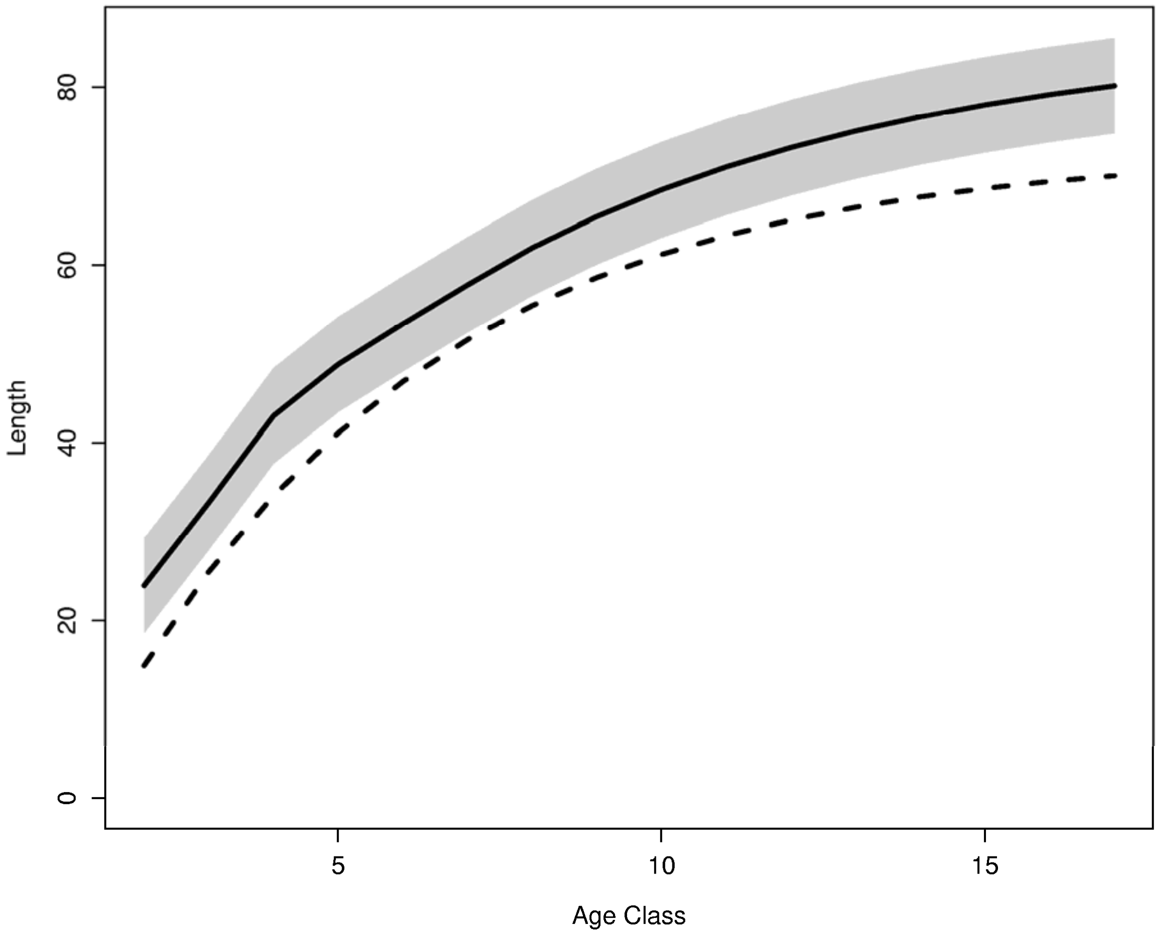

Figure 23. Estimated mean lengths-at-age, ± 2 SD of length-at-age. The dashed line represents the initial starting values for the growth parameters. The first age class is interpreted to represent the second quarter after hatching.

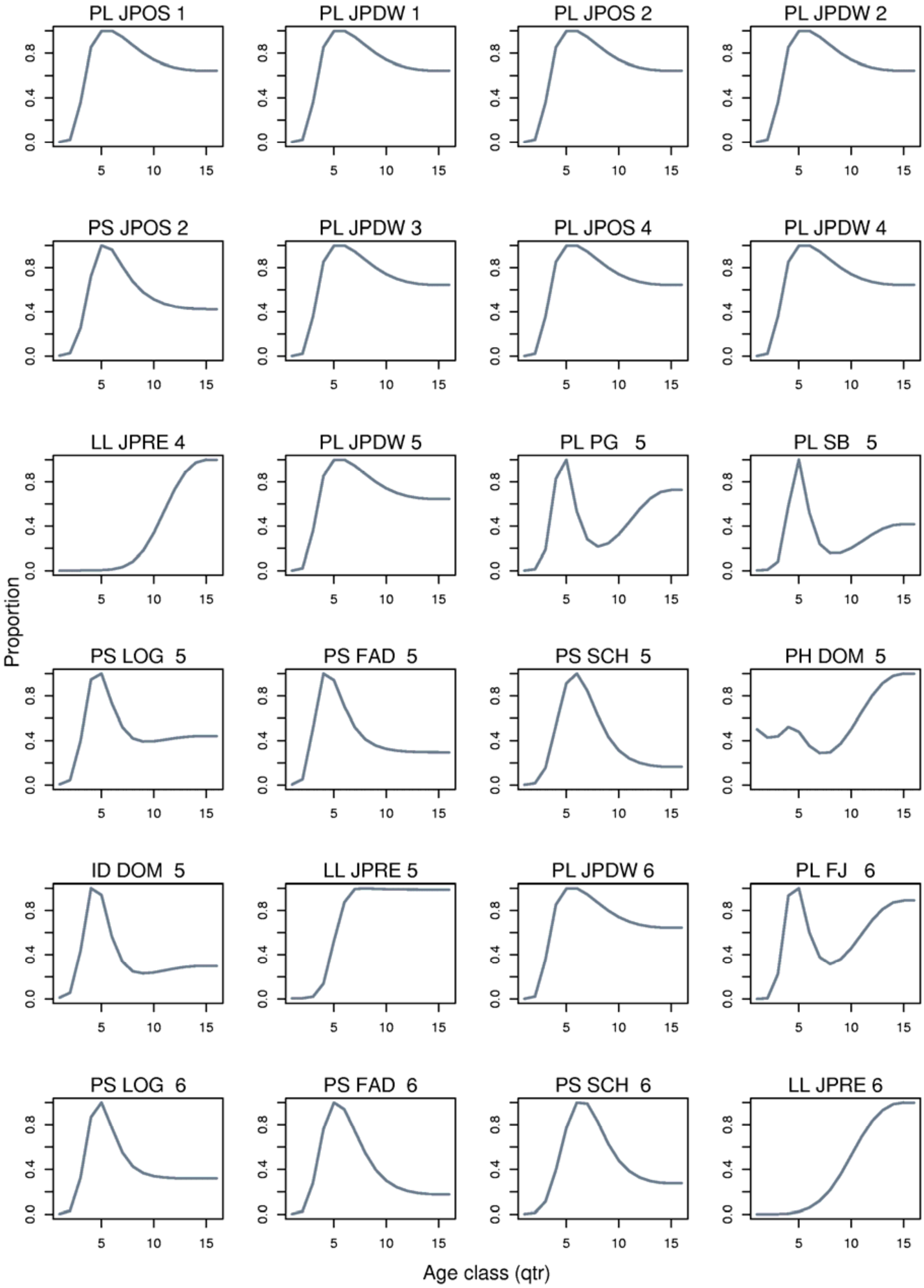

Figure 24. Selectivity coefficients, by fishery. All JP PL fisheries were assumed to have common selectivity.

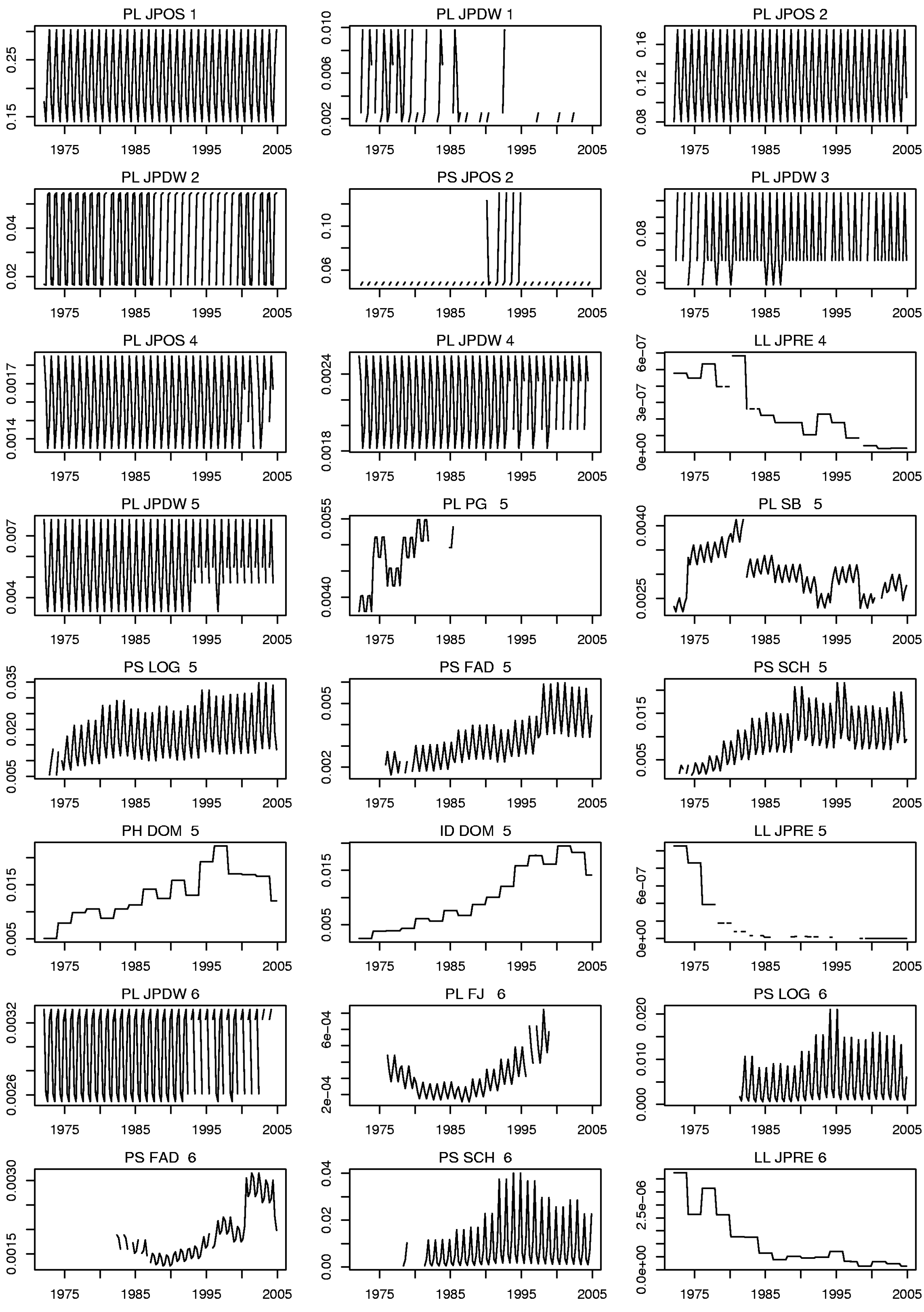

Figure 25. Estimated time-series catchability trends for each fishery.

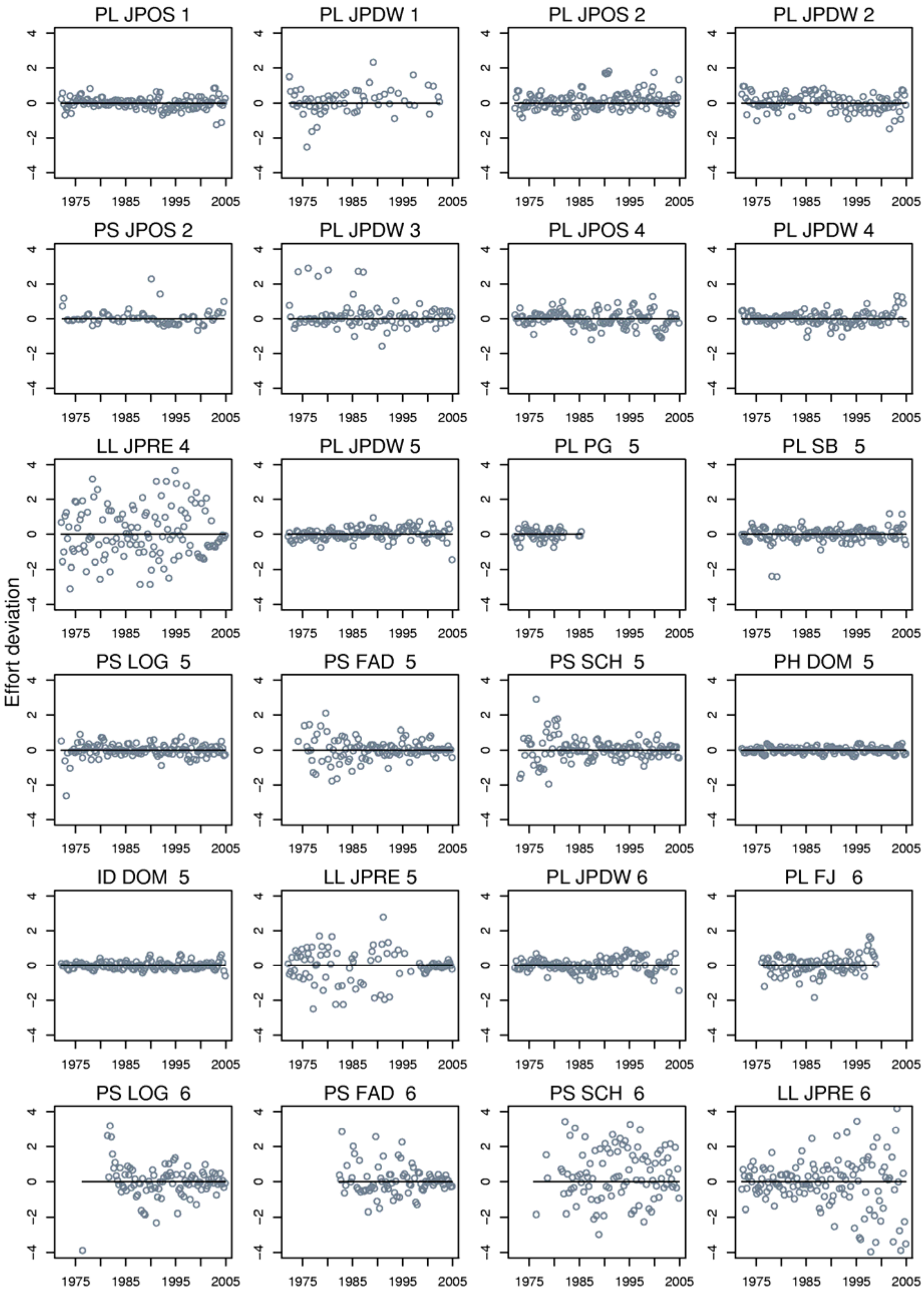

Figure 26. Effort deviations by time period for each fishery.

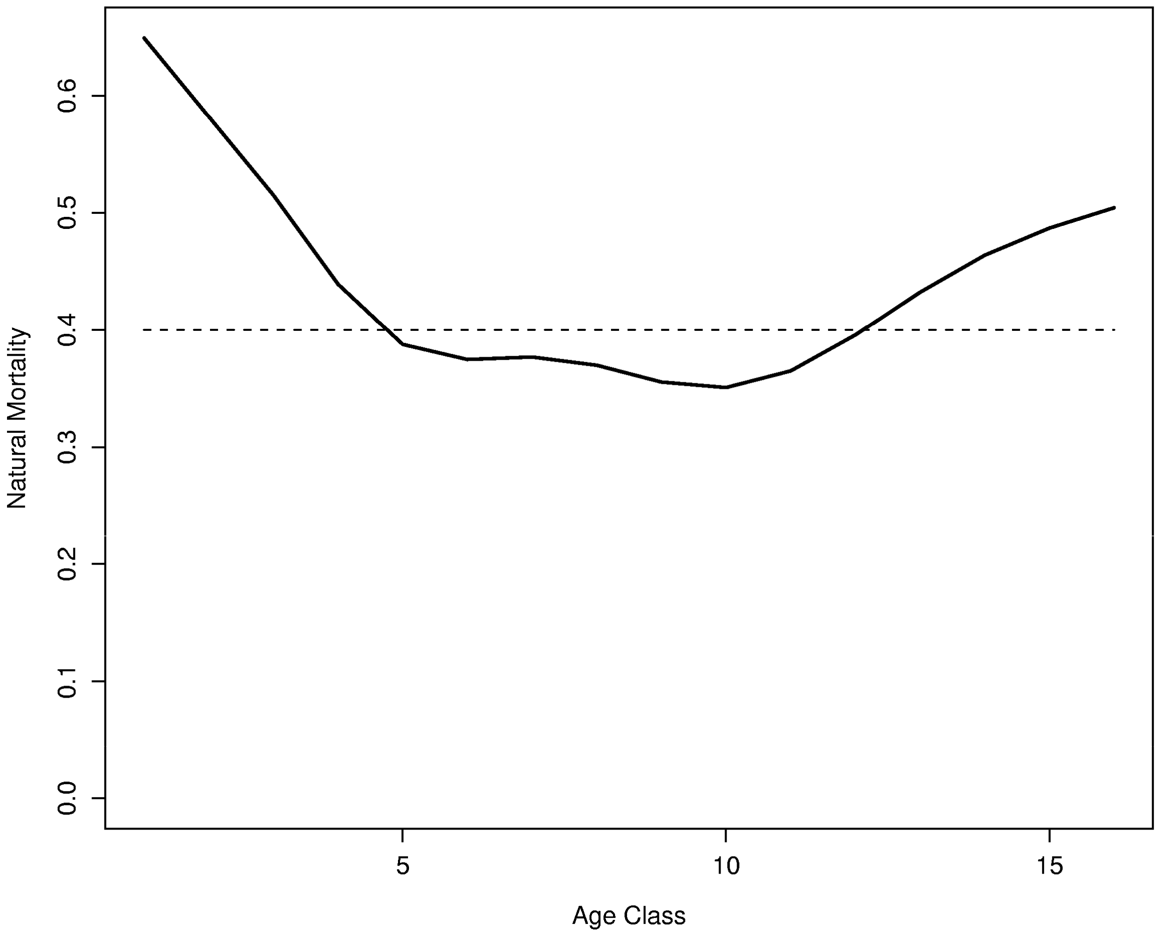

Figure 27. Estimated natural mortality rate per quarter by age-class (solid line). The dashed line represents the initial values for the model.

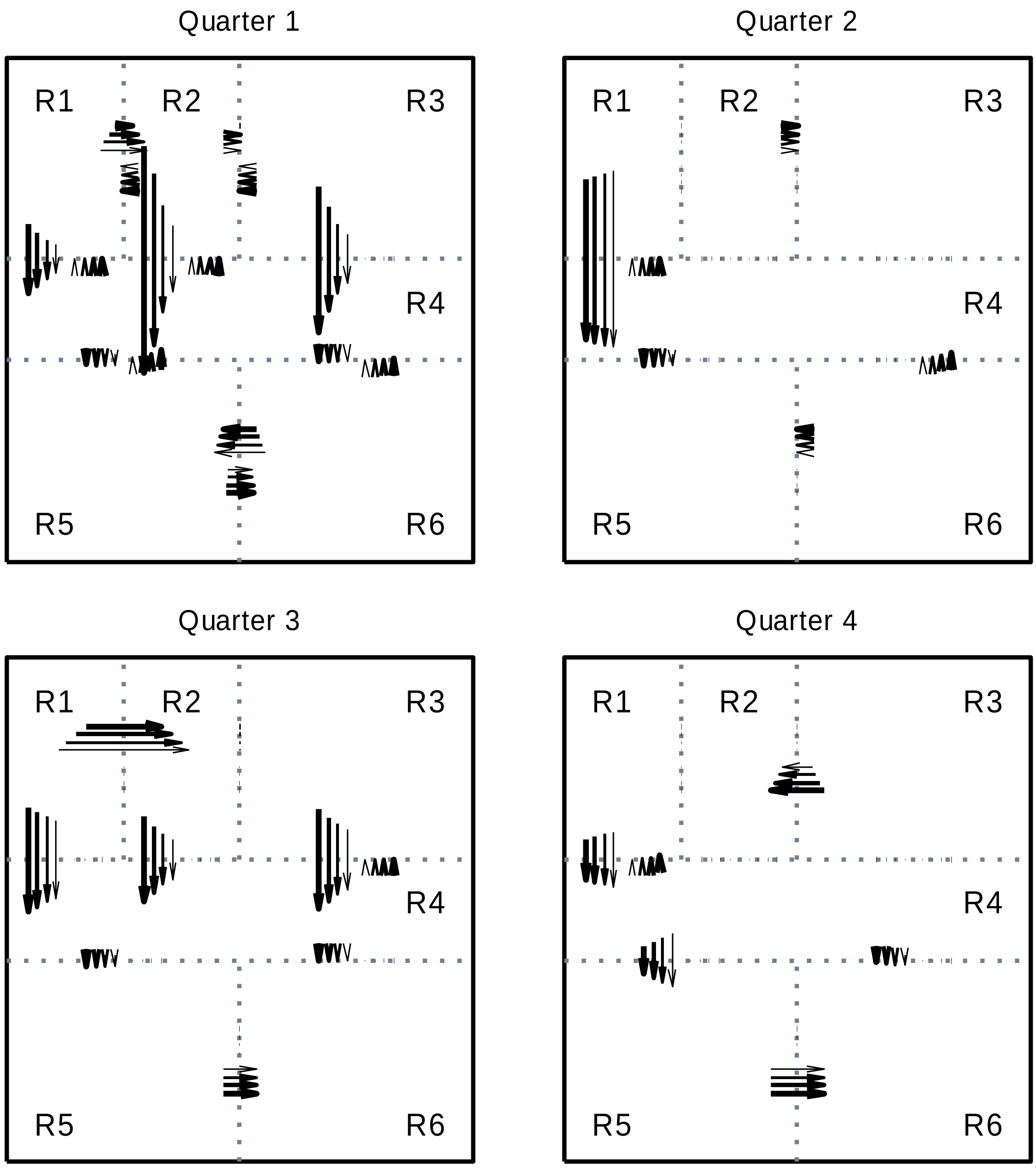

Figure 28: Graphical representation of movement probabilities among the five model regions at the beginning of each quarter. The five individual bars for each region boundary represent movement probabilities of 4 different age classes (1, 4, 8, 12 and 15, thin to thick arrow) into the region into which the bars protrude. The maximum bar length represents a quarterly movement probability of approximately 0.75 (first quarter, region 2 to 4).

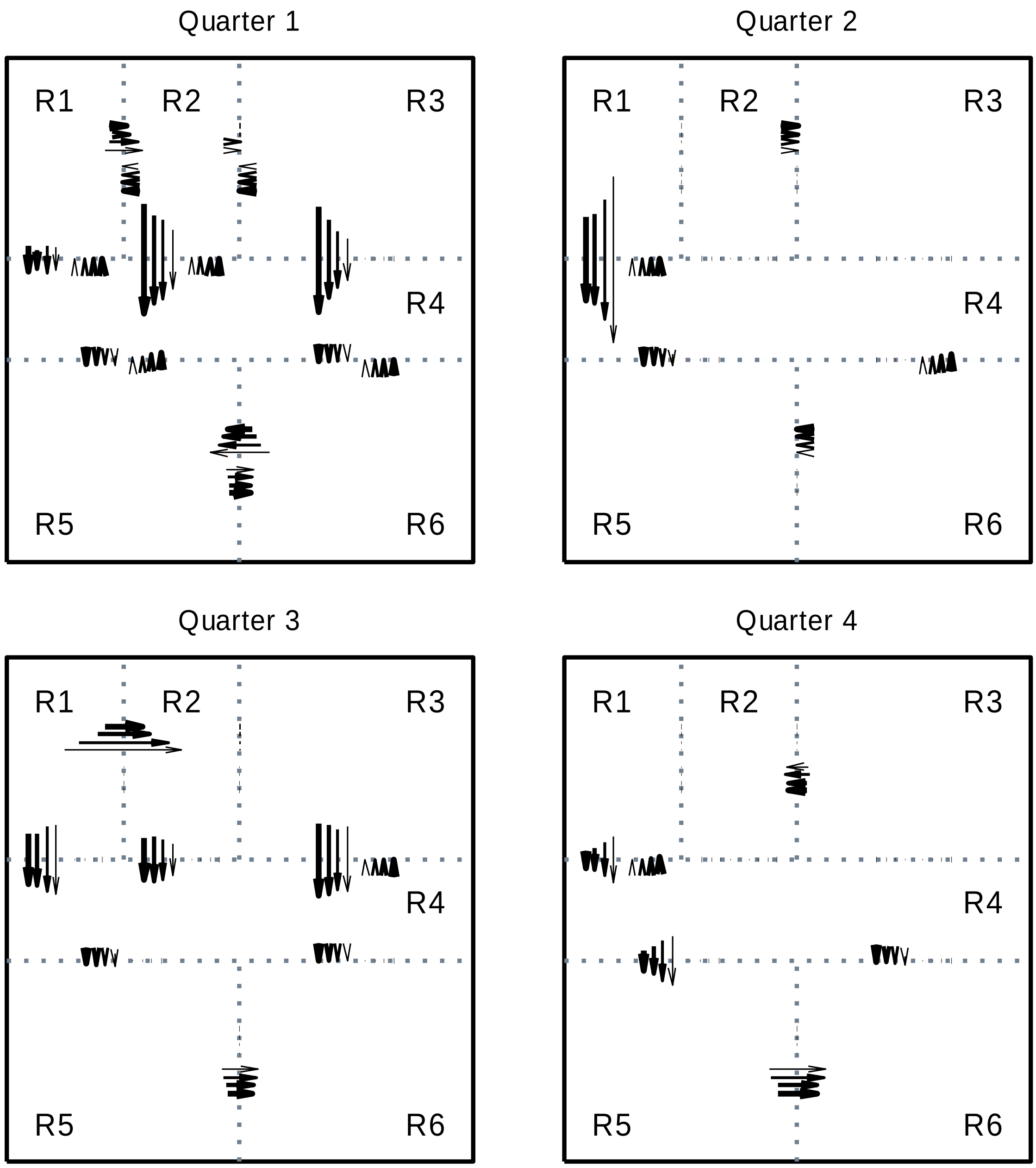

Figure 29: Graphical representation of estimate movement (numbers of fish) among the five model regions at the beginning of each quarter. The five individual bars for each region boundary represent the movement of 4 different age classes (1, 4, 8, 12 and 15, thin to thick arrow) into the region into which the bars protrude. Movements have been calculated based on the age composition in 2003 and the numbers of fish are represented on a logarithmic scale. The maximum bar length represents a quarterly movement of approximately 300,000 fish (second quarter, region 1 to 4).

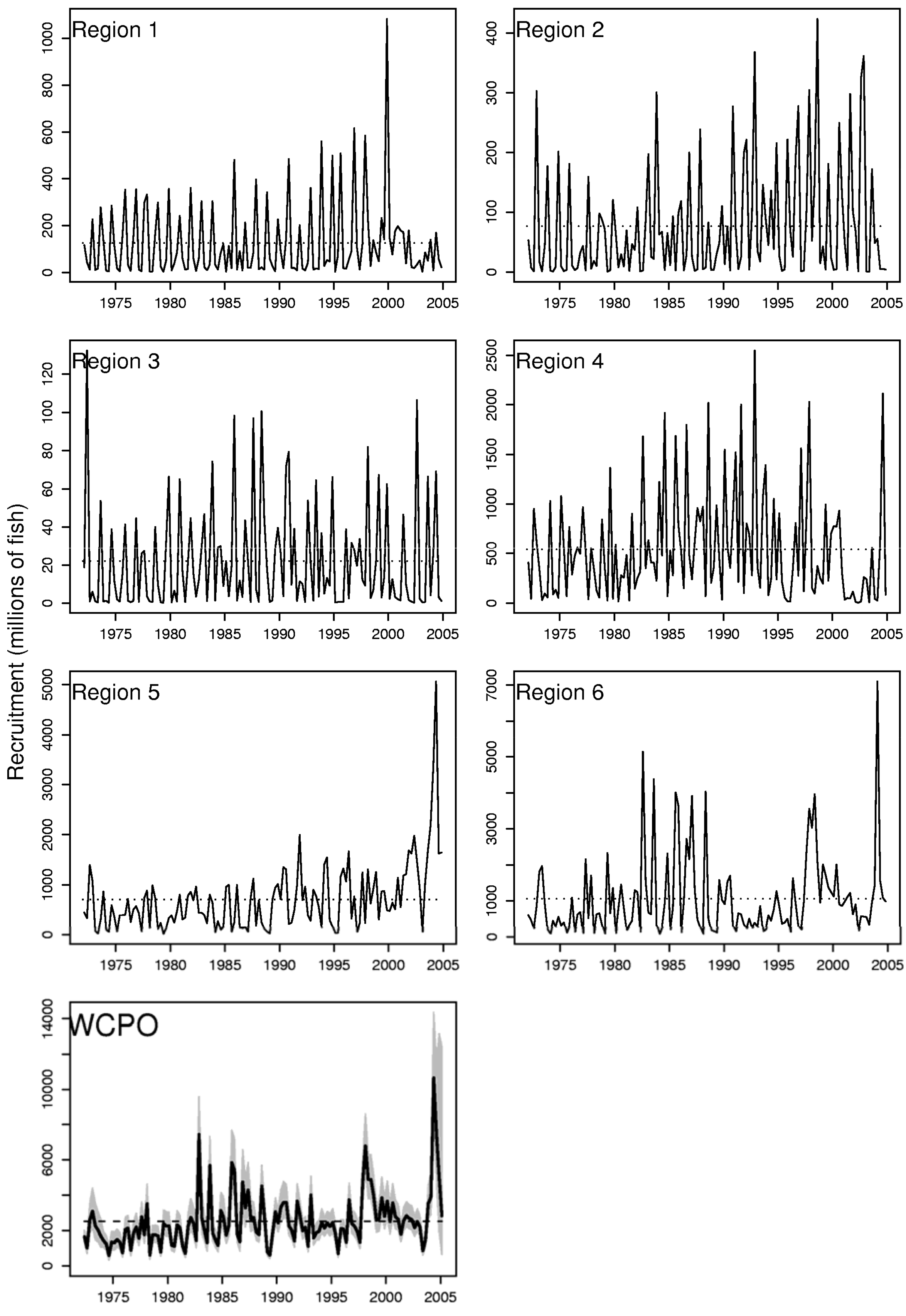

Figure 30. Estimated quarterly recruitment (millions) by region and for the WCPO for the basecase analysis. The dashed line represents the average recruitment for the entire period. The shaded area for the WCPO indicates the approximate 95% confidence intervals.

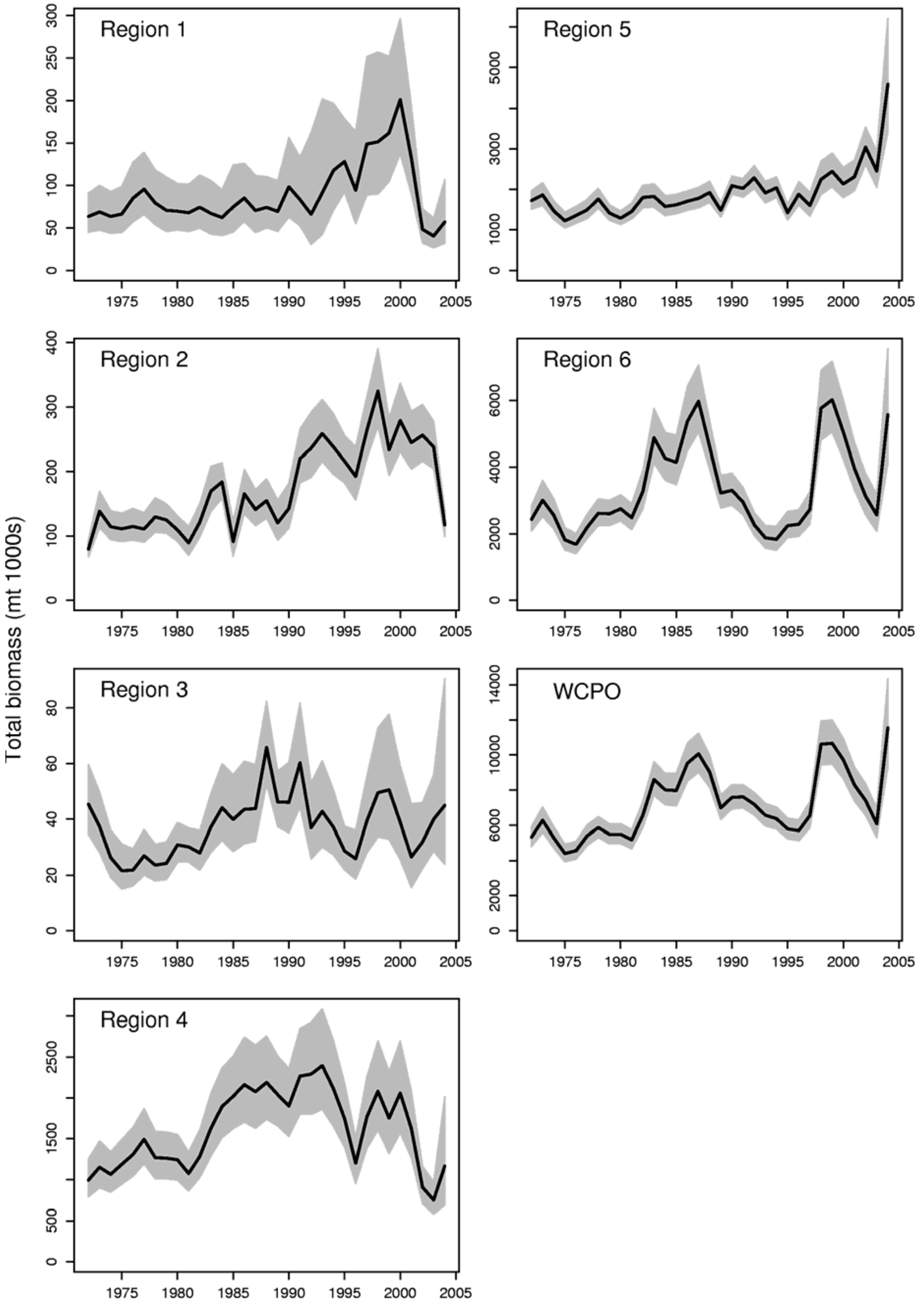

Figure 31. Estimated annual average total biomass (thousand t) by region and for the WCPO for the base-case analysis. The shaded areas indicate the approximate 95% confidence intervals.

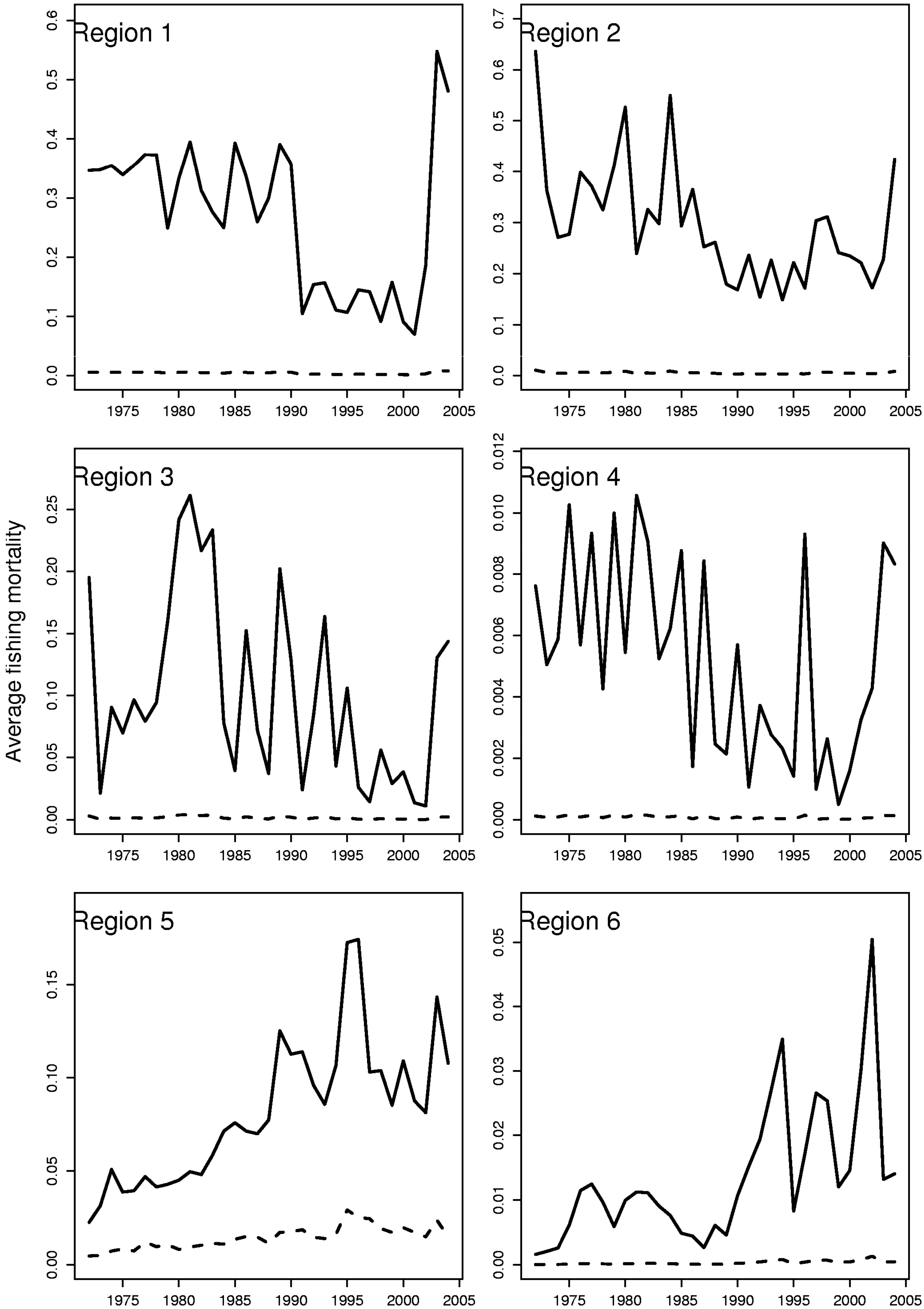

Figure 32. Estimated quarterly average fishing mortality rates for juvenile (age classes 1 and 2) (dashed line) and adult age-classes (solid line).

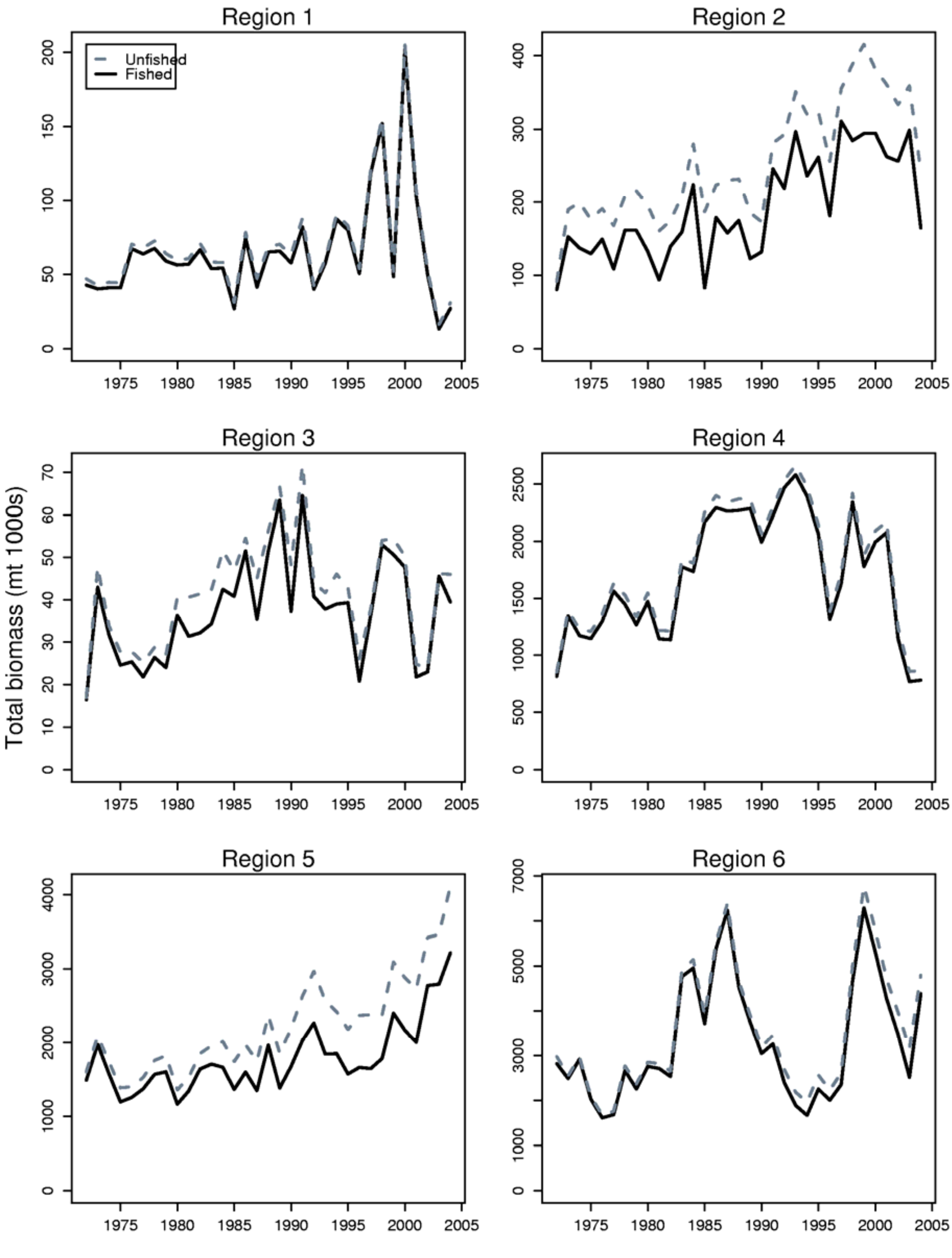

Figure 33. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (dashed lines) for the each region.

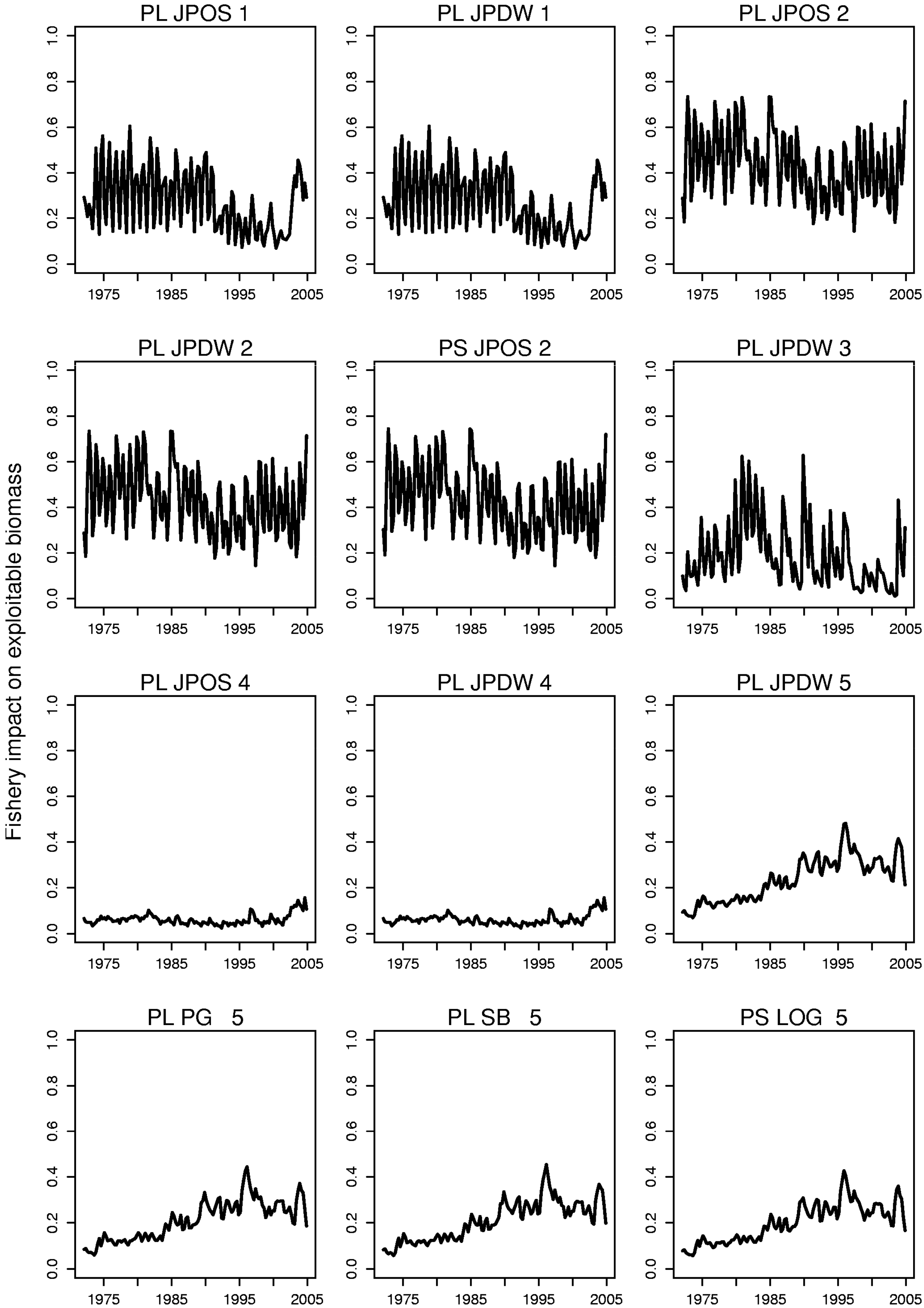

Figure 34a. Proportional reduction in exploitable biomass attributable to fishing ($1 - B_t/B_{t, F=0}$) by fishery for the base-case model.

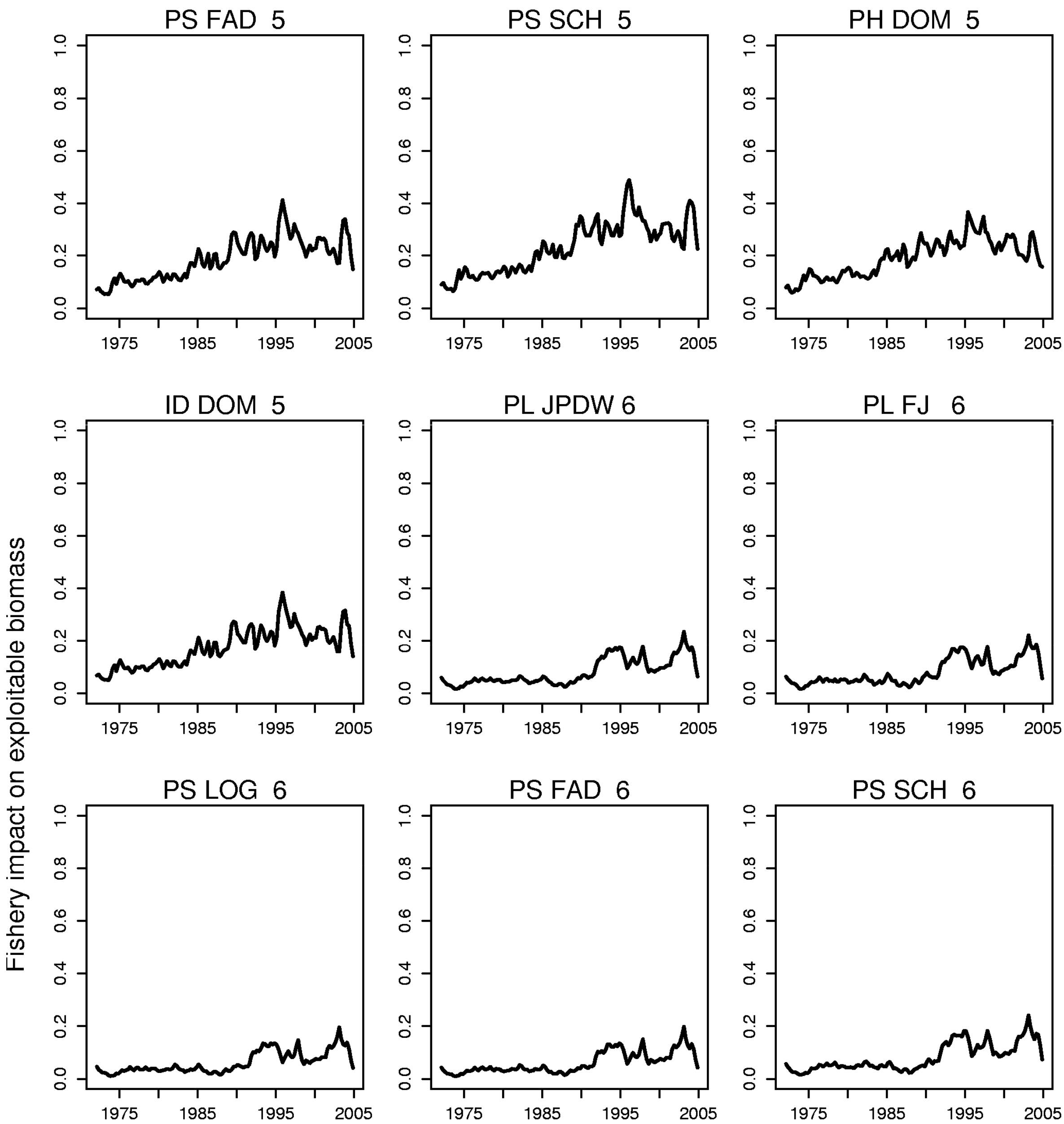

Figure 34b continued.

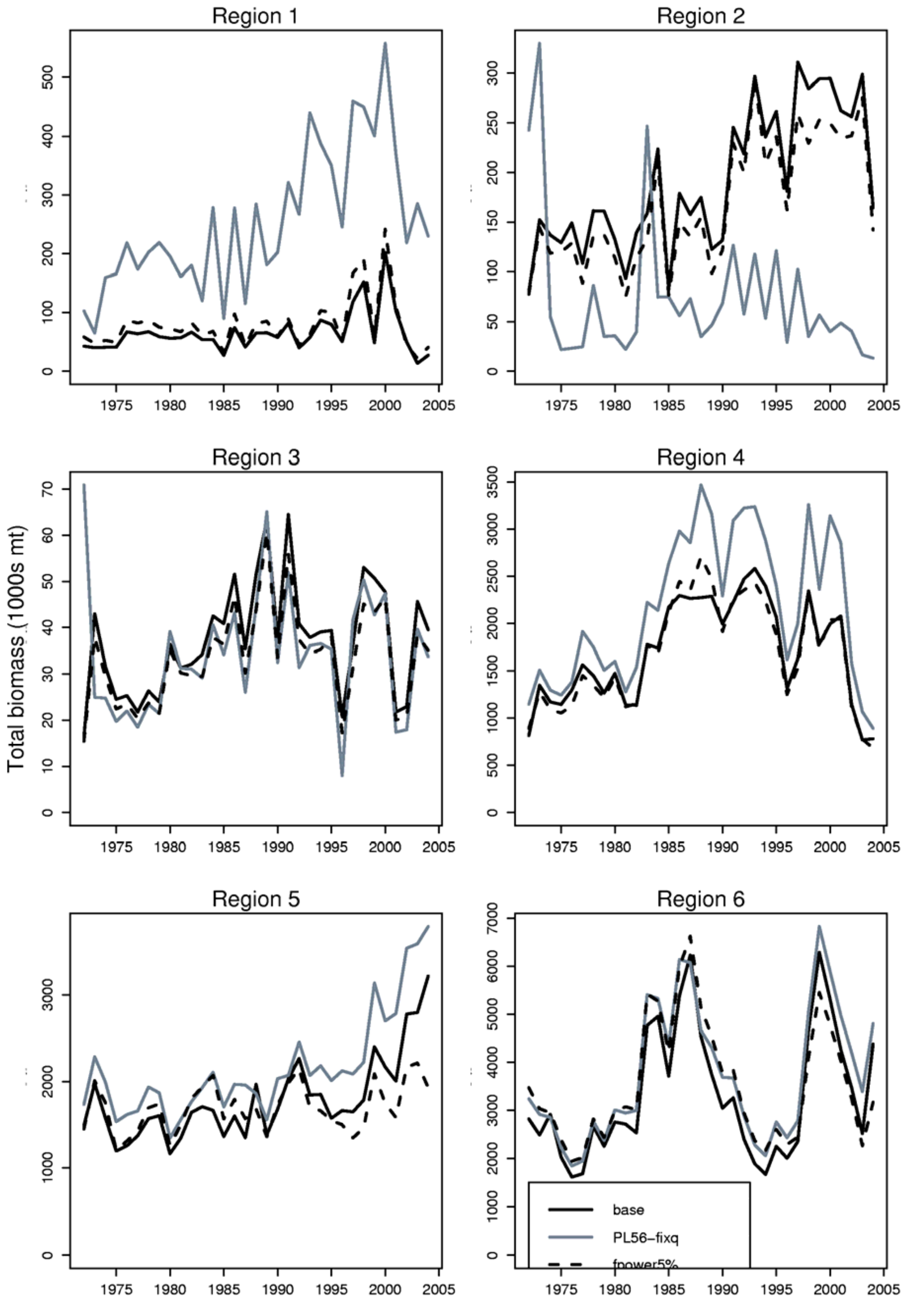

Figure 35. Comparison of the total region biomass trajectory for the base-case assessment, the PL56-fixq sensitivity analysis, and the inclusion of a 5% increase in purse-seine fishing power in the equatorial regions.

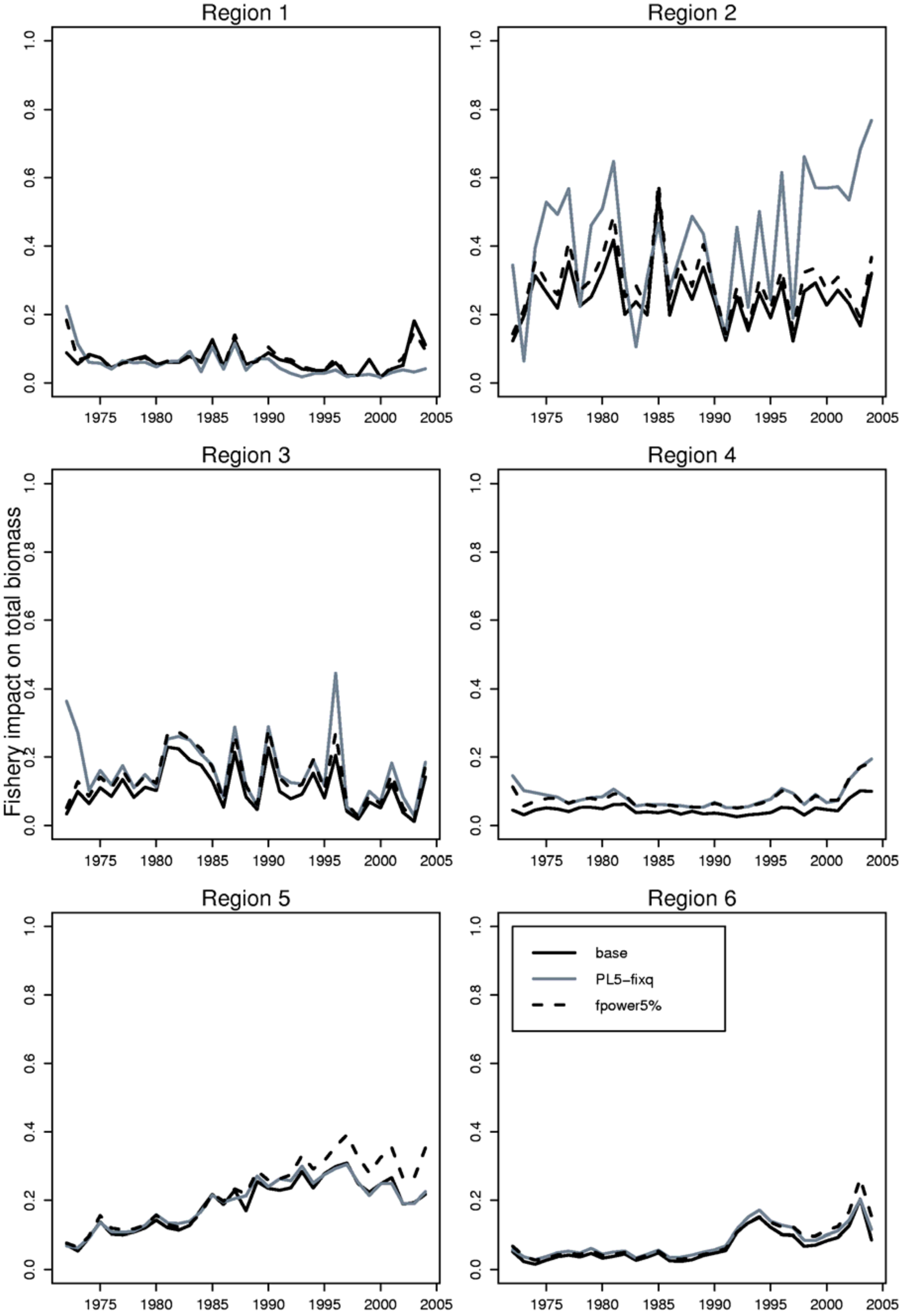

Figure 36. Comparison of the proportional reduction in total region biomass attributable to fishing (1 - $B_t/B_{t,\,F=0}$) for the base-case assessment, the PL56-fixq sensitivity analysis, and the inclusion of a 5% increase in purse-seine fishing power in the equatorial regions.

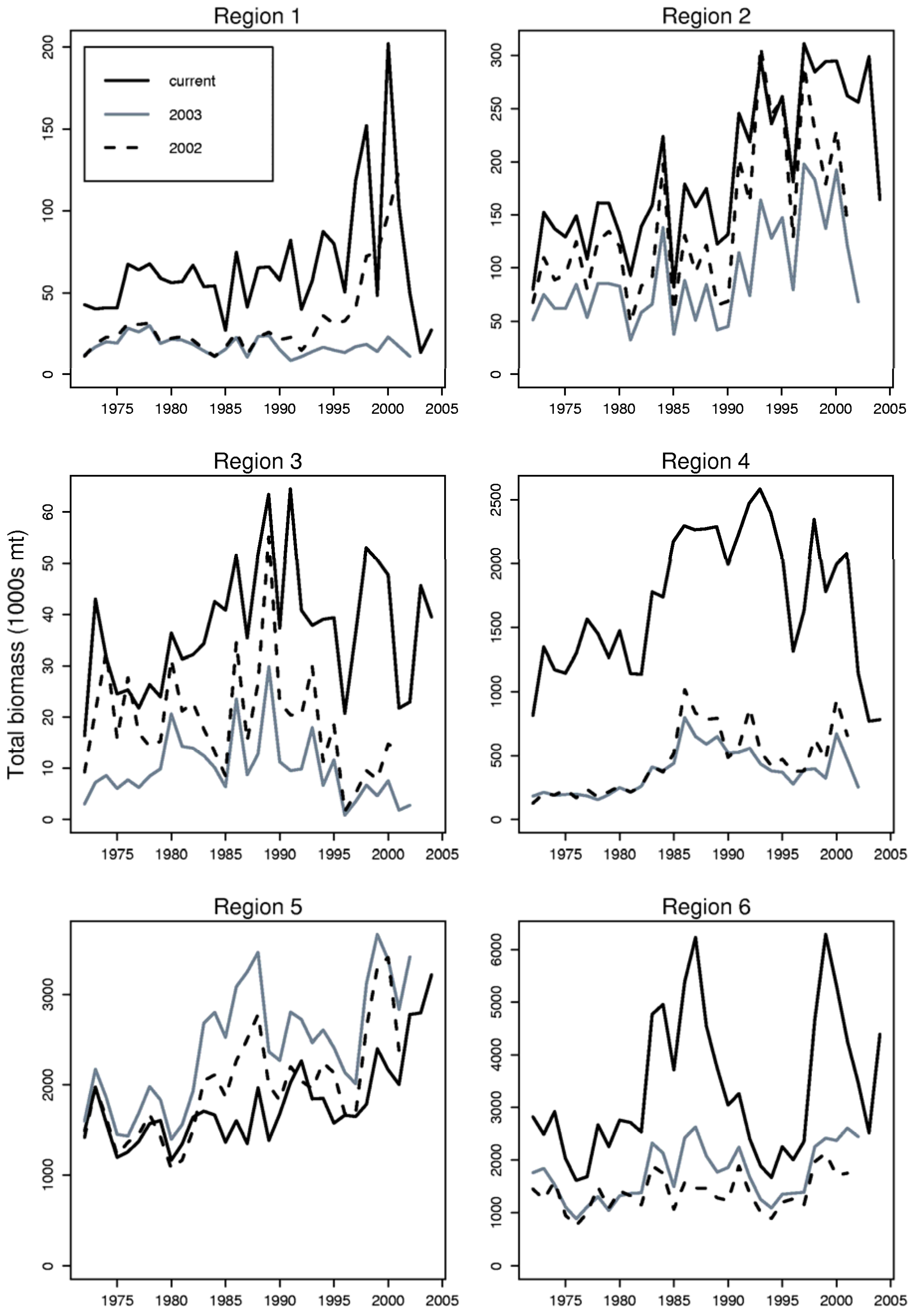

Figure 37. A comparison of the total biomass trajectories for each region from the 2002 (Hampton 2002), 2003 (Langley et al. 2003), and the current base-case assessments.

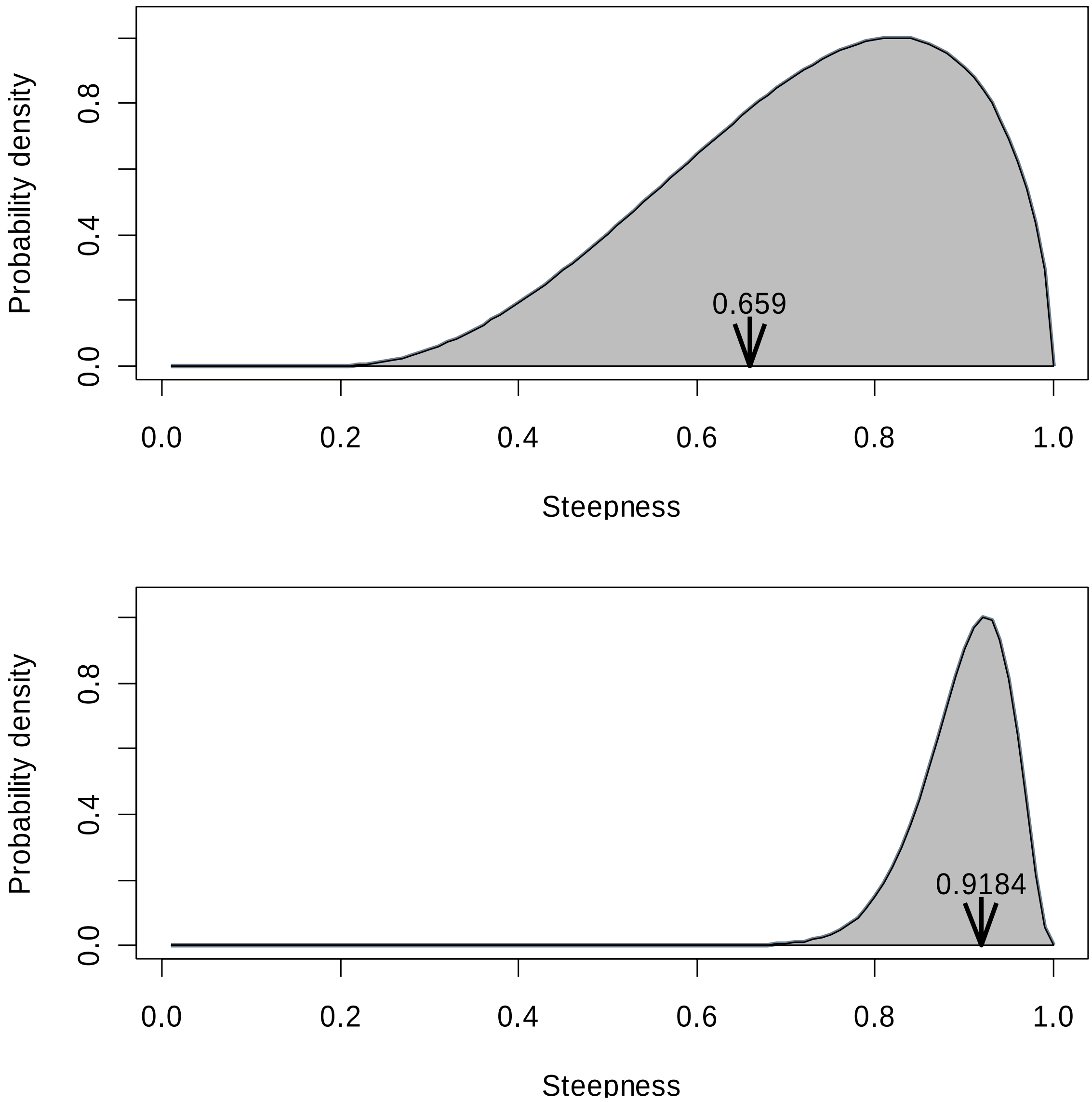

Figure 38. A comparison of the alternative probability density distributions for the prior on steepness and the resulting model point estimate of steepness; prior distributions mode = 0.85, SD = 0.16 (top), mode = 0.91, SD = 0.05 (bottom).

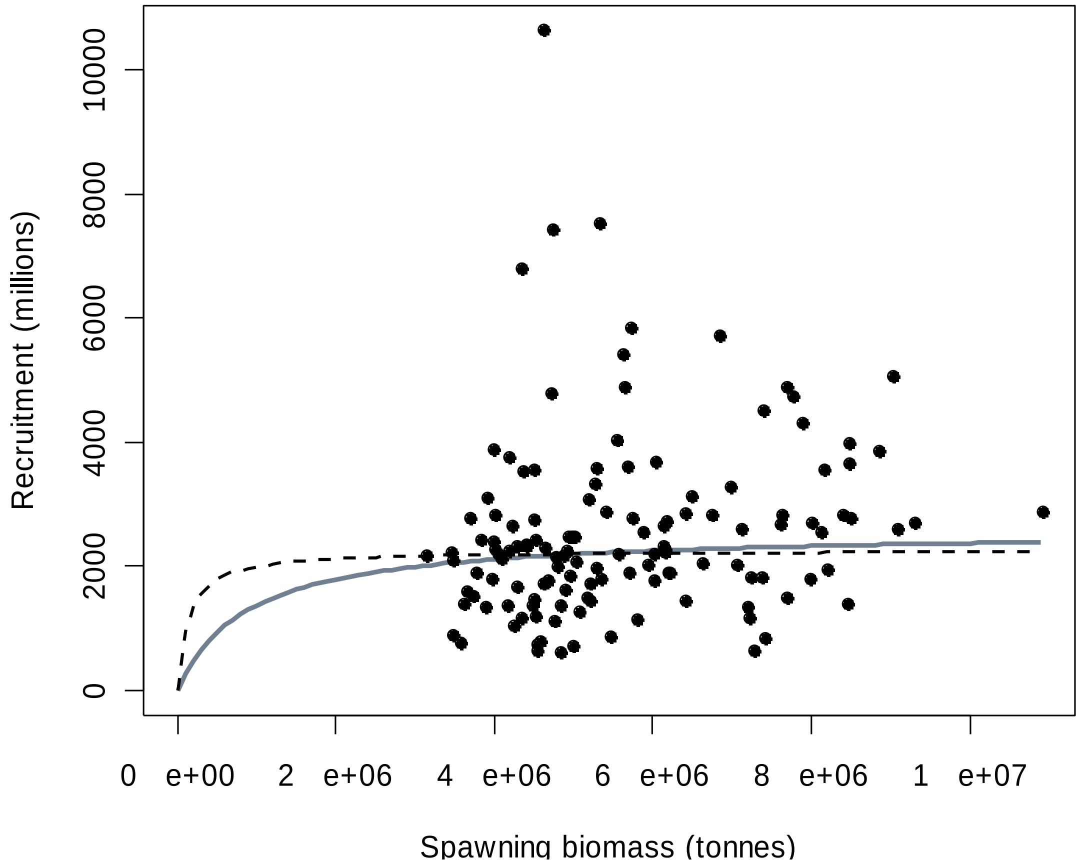

Figure 39. Spawning biomass – recruitment estimates and the fitted Beverton and Holt stock-recruitment relationship (SRR) incorporating a prior on steepness of 0.85 (SD = 0.16) (grey line). The dashed line is the SRR derived from the model using the alternative prior distribution (mode = 0.91, SD = 0.05).

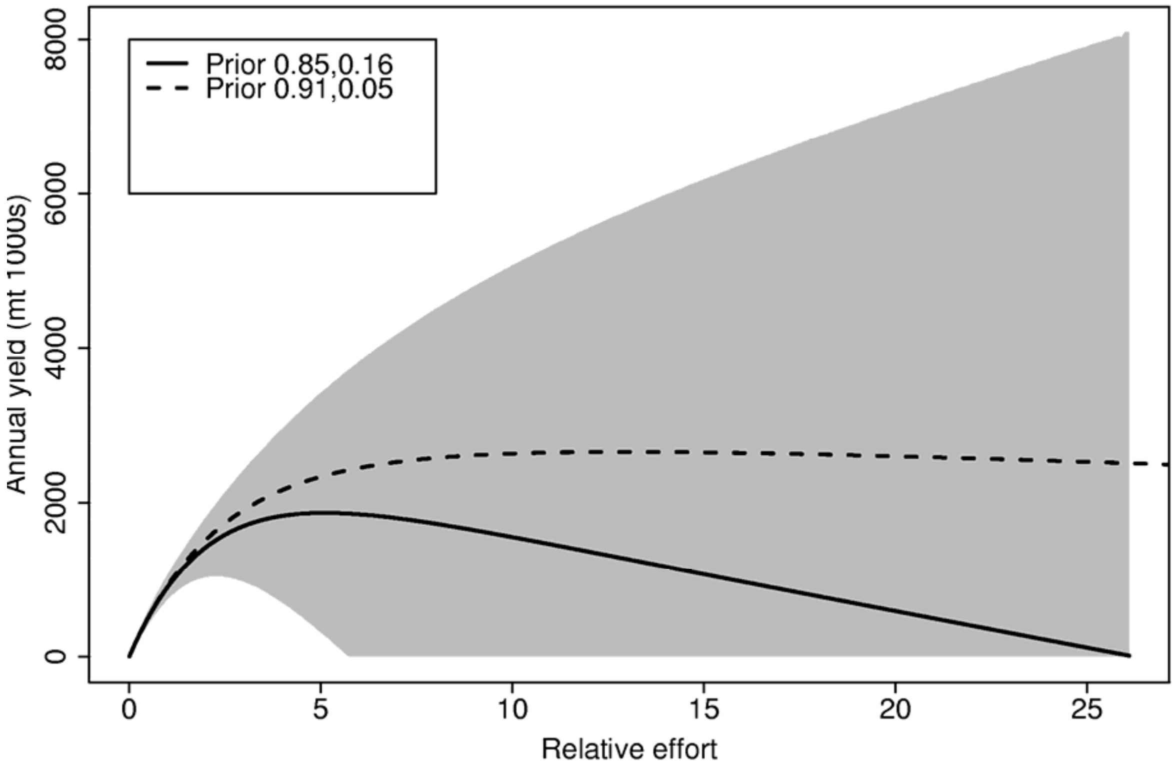

Figure 40. Predicted equilibrium yield and 95% confidence intervals as a function of fishing mortality for the base-case assessment (prior on steepness mode = 0.85, sd = 0.16) (relative to the average fishing mortality-at-age during 1999-2003). For comparison, the yield is also presented for the alternative steepness prior (mode = 0.91, sd = 0.05).

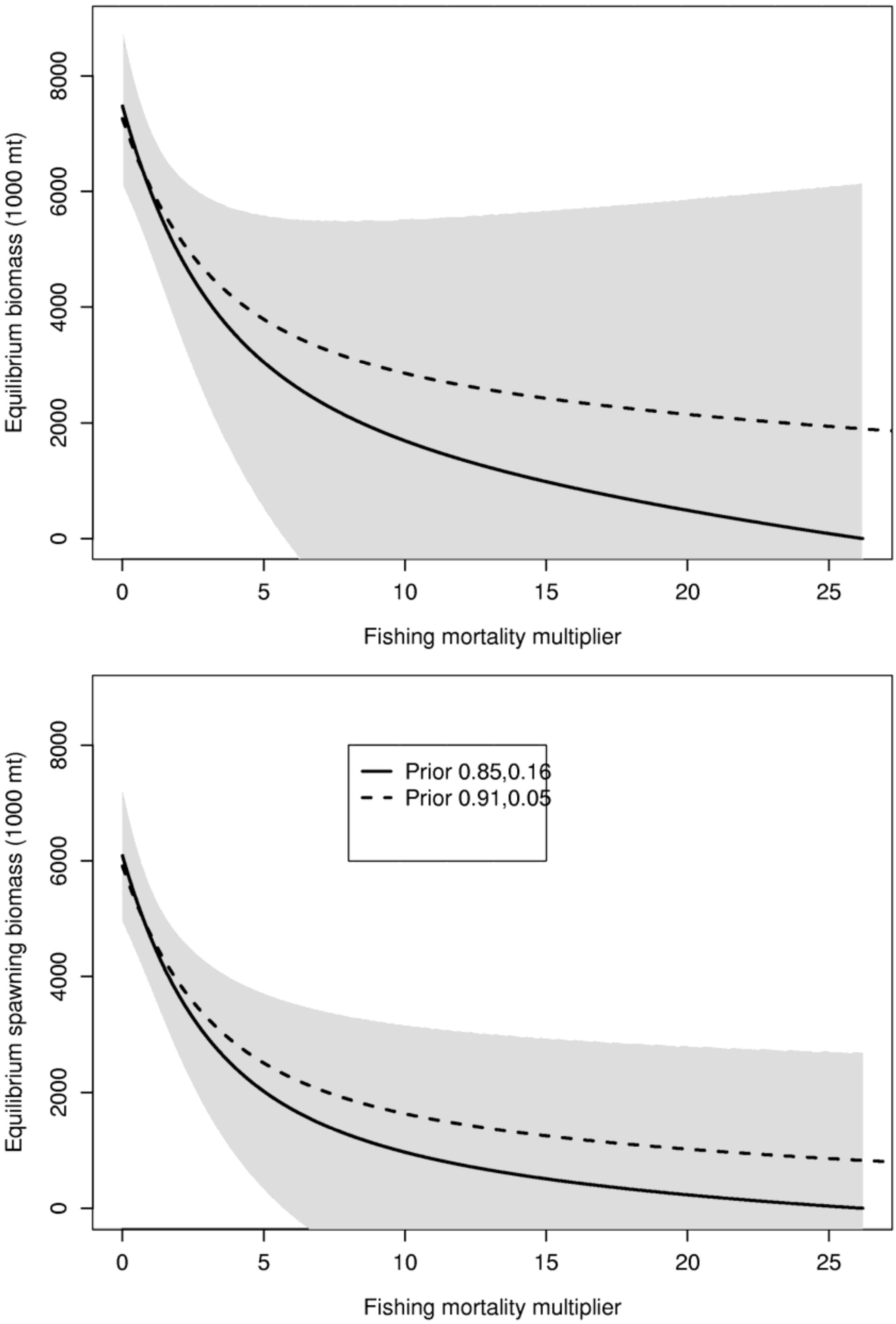

Figure 41: Equilibrium total biomass (top) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier (*F*-mult) for the base-case assessment (prior on steepness mode = 0.85, sd = 0.16). The shaded areas represent approximate 95% confidence intervals. For comparison, the equilibrium biomass is also presented for the alternative steepness prior (mode = 0.91, sd = 0.05) (dashed line).

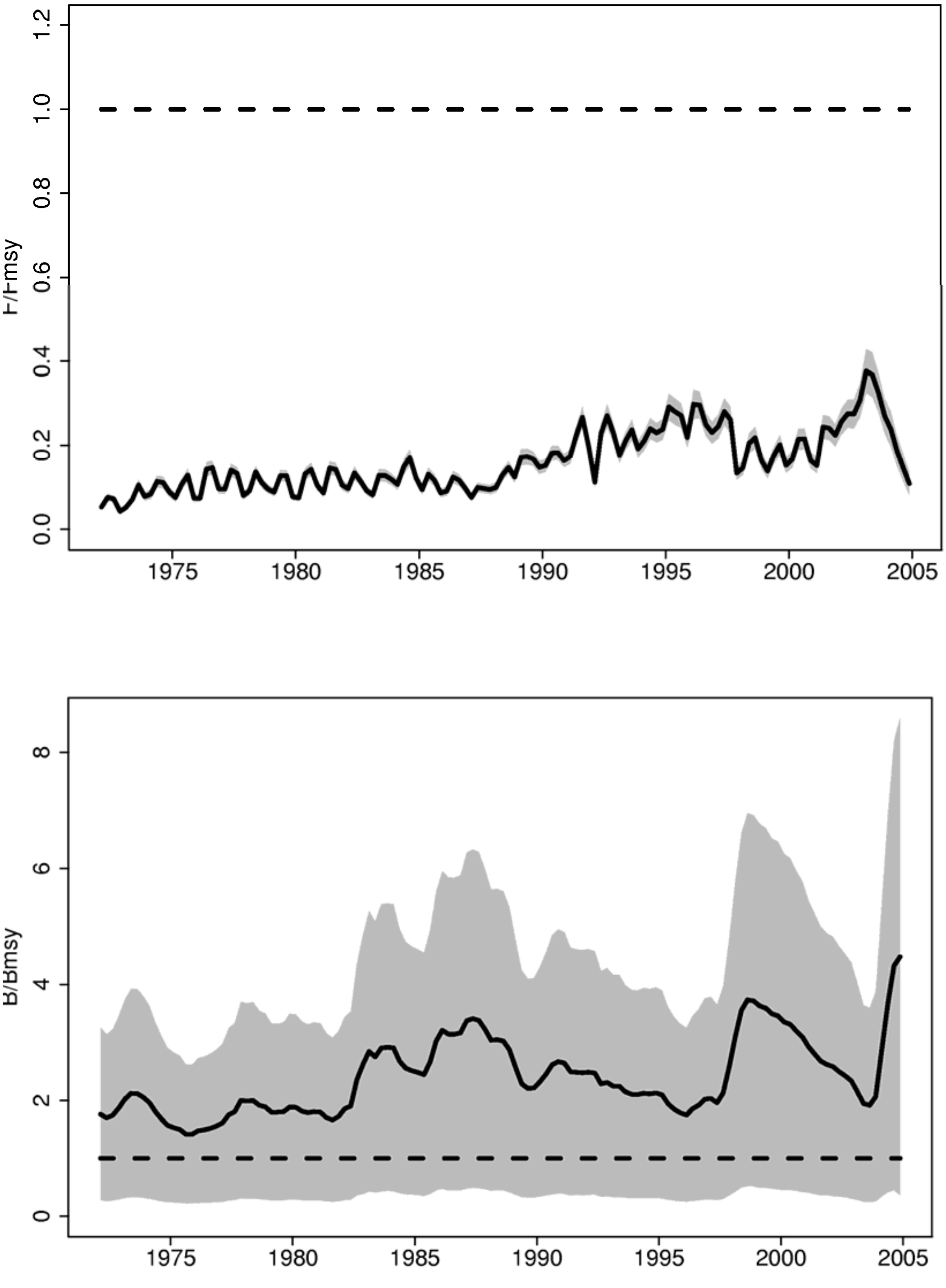

Figure 42. Ratios of $F_t / \tilde{F}_{MSY}$ (top) and $B_t / \tilde{B}_{MSY}$ (bottom) with 95% confidence intervals for the base-case assessment (prior on steepness mode = 0.85, sd = 0.16). The horizontal lines at 1.0 in each case indicate the overfishing (a) and overfished state (b) reference points.