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STOCK ASSESSMENT OF YELLOWFIN TUNA IN THE WESTERN AND CENTRAL PACIFIC OCEAN, INCLUDING AN ANALYSIS OF MANAGEMENT OPTIONS

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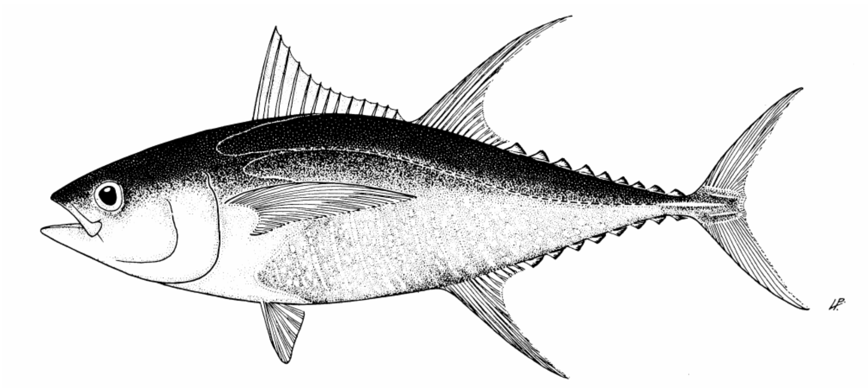

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Executive summary

This paper presents the 2006 assessment of yellowfin tuna in the western and central Pacific Ocean. The assessment uses the stock assessment model and computer software known as MULTIFAN-CL. The yellowfin tuna model is age (28 age-classes) and spatially structured (6 regions) and the catch, effort, size composition and tagging data used in the model are classified by 19 fisheries and quarterly time periods from 1952 through 2005.

The catch, size and tagging data used in the assessment were the same as those used last year, with the exception that additional recent fishery data (2004 for longline, 2004 for Philippines and Indonesia, 2005 for purse seine) were included. It should be noted that 2005 data are not complete for some fisheries. The estimation of standardised effort for the main longline fisheries used the GLM approach similar to the 2005 assessment, with a minor refinement to the method for scaling indices of abundance among regions. Other refinements to the conversion of length to weight and processed weight to whole weight were included in the assessment.

The sensitivity of the assessment model to the relative weighting applied to size-frequency data was investigated through changing the effective sample size applied to the size-frequency data. The impact of a key structural assumption in the model was investigated through a reconfiguration of the spatial stratification of the model with the inclusion of an additional region (seven-region model).

In summary, the sensitivity analyses carried out were:

LOWSAMP	Six-region spatial stratification, general linear model standardised effort for "main" longline fisheries, *M*-at-age assumed at fixed levels, lower effective sample size applied to the length and weight frequency samples.
HIGHSAMP	Six-region spatial stratification, general linear model standardised effort for "main" longline fisheries, *M*-at-age assumed at fixed levels, higher effective sample size applied to the length and weight frequency samples. This analysis approximates the base-case model run (GLM-MFIX) from the 2005 assessment. The only significant difference is the parameterisation of the selectivity functions for the principal longline fisheries — allowing a decline in the selectivity for the oldest age classes.
7REGION	Seven-region spatial stratification, general linear model standardised effort for "main" longline fisheries, *M*-at-age assumed at fixed levels, lower effective sample size applied to the length and weight frequency samples.

The main conclusions of the current assessment are as follows:

1. For the three analyses, there was a strong temporal trend in recruitment. Initial recruitment was relatively high but declined to a lower level during the early 1970s. Recruitment subsequently increased during the late-1970s and remained relatively high during the 1980s and 1990s. This is a similar, albeit weaker, pattern to that obtained in previous assessments and is largely attributable to the trends in the principal longline CPUE indices, particularly from regions 3 and 4.
2. For all analyses, the trends in biomass are generally comparable prior to the mid-1980s and were consistent with the underlying trends in recruitment, with biomass declining during the initial period to a low level in the early–mid 1970s, before increasing in the mid-1970s. Biomass levels remained relatively stable during the 1980s. For all model options, biomass is estimated to have declined steadily since 1990, largely due to the decline in the biomass within region 3 but also evident in most other regions.
3. The biomass trends in the model are strongly driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. For some of the main longline fisheries, there is an apparent inconsistency between the trends in the size-frequency data and the trends in longline catch and effort; i.e., the two types of data are providing inconsistent information about the relative level of fishing mortality in the region. The LOWSAMP model was adopted as the

base case because it was considered that the catch and effort data are more informative than the size-frequency data in the estimation of trends in fishing mortality.

4. Fishing mortality for adult and juvenile yellowfin tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. A significant component of the increase in juvenile fishing mortality is attributable to the Philippines and Indonesian surface fisheries, which have the weakest catch, effort and size data. There has been recent progress made in the acquisition of a large amount of historical length frequency data from the Philippines and these data were incorporated in the assessment. However, there is an ongoing need to improve estimates of recent and historical catch from these fisheries and maintain the current fishery monitoring programme within the Philippines. Many of the key conclusions of the assessment are strongly influenced by the current assumptions regarding historical and current catches from these fisheries.

5. The ratios $B_t / B_{t,F=0}$ provide a time-series index of population depletion by the fisheries. Depletion has increased steadily over time, reaching a level of 50% of unexploited biomass (a fishery impact of 50%) in 2004. This represents a moderate level of stock-wide depletion that is approaching the equivalent equilibrium-based limit reference point ($\tilde{B}_{MSY} / \tilde{B}_0$ = 0.42). Further, depletion is somewhat greater for some individual model regions, notably in the equatorial region 3 where recent depletion levels are approximately 0.3 (a 70% reduction from the unexploited level). Other regions are less depleted, with indices of 0.8 or greater for all other regions except for region 4 (0.5). If stock-wide over-fishing criteria were applied at the level of our model regions, we would conclude that region 3 is over-exploited, region 4 is fully exploited, and the remaining regions are under-exploited.

6. The attribution of depletion to various fisheries or groups of fisheries indicates that the Indonesian fishery has the greatest impact, particularly in its home region (3) and is contributing significantly to the impact in adjacent regions 1, 4 and 5. The purse seine fishery also has a high impact in regions 3 and 4 and accounts for a significant component of the recent impacts in all other regions, except region 6. It is notable that the composite longline fishery is responsible for biomass depletion of only 10% in the WCPO during recent years.

7. The reference points that predict the status of the stock under equilibrium conditions are $\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$ (0.91) and $S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$ (0.87), which indicate that the long-term average biomass would approximate or fall below that capable of producing *MSY* at 2001–2004 average fishing mortality. Overall, current biomass exceeds the biomass yielding *MSY* ($B_{current} / \tilde{B}_{MSY}$ > 1.0); i.e. **<u>the yellowfin stock in the WCPO is not in an overfished state</u>**. However, biomass levels in recent years have been declining under increasing levels of fishing mortality, and the probability of the stock becoming overfished is increasing over time.

8. The estimate of $F_{current} / \tilde{F}_{MSY}$ reveals that **<u>overfishing of yellowfin is likely to be occurring in the WCPO</u>**. While the stock is not yet in an overfished state ($B_{current} / \tilde{B}_{MSY}$ > 1), further biomass decline is likely to occur at 2001–2004 levels of fishing mortality.

9. Stock projections for 2006–2010 — that attempt to simulate the conservation and management measures adopted at WCPFC2 — indicate that the point estimate of $B_t / \tilde{B}_{MSY}$ remains above 1.0 throughout the projection period. However, the increasing uncertainty in the future projections results in a greater probability of the biomass declining below $\tilde{B}_{MSY}$ by the end of the projection period. The projections indicate a strong shift in the spatial distribution of biomass with continued depletion occurring in the equatorial regions.

10. The 7REGION model provides a slightly more optimistic assessment of the status of the stock than the base-case model, although the probability of $F_{current} / \tilde{F}_{MSY}$ > 1 (overfishing) is still significant (49%). However, because of the lack of a reliable index of abundance since the late-

1980s and weak data generally for the additional region (western tropical Pacific incorporating Philippines and Indonesia), we do not have sufficient confidence in the 7REGION model to use it as the main management advisory model at this time. Subject to further model testing and the incorporation of improved data from the western tropical region, it may be possible in the future to adopt the 7REGION model structure for the assessment.

1 Introduction

This paper presents the current stock assessment of yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean (WCPO, west of 150°W). Since 1999, the assessment has been conducted annually and the most recent assessments are documented in Hampton and Kleiber (2003) and Hampton et al. (2004 and 2005). The current assessment incorporates the most recent data from the yellowfin fishery and, essentially, represents an update of the assessment undertaken in 2005. In addition, a range of sensitivity analyses are presented, including consideration of an alternative regional stratification of the model.

The overall objectives of the assessment are to estimate population parameters, such as time series of recruitment, biomass and fishing mortality, that indicate the status of the stock and impacts of fishing. We also summarise stock status in terms of well-known reference points, such as the ratios of recent stock biomass to the biomass at maximum sustainable yield ($B_{current} / \widetilde{B}_{MSY}$) and recent fishing mortality to the fishing mortality at MSY ($F_{current} / \widetilde{F}_{MSY}$). Likelihood profiles of these ratios are used to describe their uncertainty. The effects of the continuation of the current management arrangements for yellowfin tuna are further investigated through stock projections.

The methodology used for the assessment is that commonly known as MULTIFAN-CL (Fournier et al. 1998; Hampton and Fournier 2001; Kleiber et al. 2003; http://www.multifan-cl.org), which is software that implements a size-based, age- and spatially-structured population model. Parameters of the model are estimated by maximizing an objective function consisting both of likelihood (data) and prior information components.

2 Background

2.1 Biology

Yellowfin tuna are distributed throughout the tropical and sub-tropical waters of the Pacific Ocean. However, there is some indication of restricted mixing between the western and eastern Pacific based on analysis of genetic samples (Ward et al. 1994) and tagging data (Figure 1). Adults (larger than about 100 cm) spawn, probably opportunistically, in waters warmer than 26°C (Itano 2000), while juvenile yellowfin are first encountered in commercial fisheries (mainly surface fisheries in Philippines and eastern Indonesia) at several months of age.

Yellowfin tuna are relatively fast growing, and have a maximum fork length (FL) of about 180 cm. The growth of juveniles departs from von Bertalanffy type growth with the growth rate slowing between about 40 and 70 cm FL (Lehodey and Leroy 1999). The natural mortality rate is strongly variable with size, with the lowest rate of around 0.6–0.8 yr^{-1} being for pre-adult yellowfin 50–80 cm FL (Hampton 2000). Tag recapture data indicate that significant numbers of yellowfin reach four years of age. The longest period at liberty for a recaptured yellowfin, tagged in the western Pacific at about 1 year of age, is currently 6 years.

2.2 Fisheries

Yellowfin tuna, an important component of tuna fisheries throughout the WCPO, are harvested with a diverse variety of gear types, from small-scale artisanal fisheries in Pacific Island and southeast Asian waters to large, distant-water longliners and purse seiners that operate widely in equatorial and tropical waters. Purse seiners catch a wide size range of yellowfin tuna, whereas the longline fishery takes mostly adult fish.

Since 1990, the yellowfin tuna catch in the WCPO has varied between 300,000 and 400,000 mt (Figure 2). Purse seiners harvest the majority of the yellowfin tuna catch (47% by weight in 1998–2002), with the longline and pole-and-line fisheries comprising 15% and 3% of the total catch, respectively. Yellowfin tuna usually represent approximately 20–25% of the overall purse-seine catch and may contribute higher percentages of the catch in individual sets. Yellowfin tuna is often directly targeted by purse seiners, especially as unassociated schools.

Longline catches in recent years (60,000–70,000 mt) are well below catches in the late 1970s to early 1980s (which peaked at about 110,000 mt), presumably related to changes in targeting practices by some of the larger fleets. Catches in the 'Other' category in Figure 2 are largely composed of yellowfin tuna from the Philippines and eastern Indonesia. These catches come from a variety of gear types (e.g. pole-and-line, ringnet, gillnet, handline and seine net) and have increased steadily over the past decade. Based on catch data provided by those countries, recent catches represent approximately 35% of total WCPO yellowfin tuna catches.

Figure 3 shows the spatial distribution of yellowfin tuna catch in the WCPO for the past 15 years. Most of the catch is taken in western equatorial areas, with declines in both purse-seine and longline catch towards the east. The east-west distribution of catch is strongly influenced by ENSO events, with larger catches taken east of 160°E during *El Niño* episodes. Catches from outside the equatorial region are relatively minor (5%) and are dominated by longline catches south of the equator and purse-seine and pole-and-line catches in the north-western area of the WCPO (Figure 4).

3 Data compilation

The data used in the yellowfin tuna assessment consist of catch, effort, length-frequency and weight-frequency data for the fisheries defined in the analysis, and tag release-recapture data. The details of these data and their stratification are described below.

3.1 Spatial stratification

The geographic area considered in the assessment is the WCPO, defined by the coordinates 40°N–40°S, 120°E–150°W. Within this overall area, a six-region spatial stratification was adopted for the assessment (Figure 3). The rationale for this stratification was to separate the tropical area, where both surface and longline fisheries occur year-round, from the higher latitudes, where the longline fisheries occur more seasonally. The stratification for the base-case assessment is equivalent to that used in the 2005 assessment.

For the current assessment, an alternative regional stratification was also investigated. This analysis included seven regions, essentially creating a new region in the western equatorial region encompassing the waters around Indonesia and the Philippines and extending northward to include the South China Sea and the Philippine Sea (Figure 3). In addition, the northern latitude of the equatorial regions (3 and 4) was changed from 20°N to 10°N. The rationale and supporting analyses for the seven region stratification are presented in Langley (2006a), principally:

- To spatially segregate the area (fisheries) that includes the main uncertainty in the catch history, i.e. the surface fisheries of Indonesia and the Philippines.
- To restrict the equatorial fisheries to the area of operation of the main purse-seine fisheries. These areas could be expected to have a different rate of exploitation to areas where the purse-seine fishery does not operate (i.e. north of 10°N).
- To formulate individual regions that have consistent historical trends in longline catch rates (see Langley 2006b) and a relatively homogeneous size composition of fish in the longline catch (see Langley 2006c).

The other main structural assumptions of the seven-region model are equivalent to those described for the six-region model. The key difference between the two models is the requirement to restructure the fisheries in accordance to the alteration of the fishery boundaries with the inclusion of two additional fisheries in the model; a Japanese longline fishery and a Chinese/Taiwanese longline fishery within the western equatorial region (region 7).

3.2 Temporal stratification

The time period covered by the assessment is 1952–2005. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec). The 2004 assessment was extended back to 1950. However, data prior to 1952 are limited and pre-date the expansion of the fishery in the southern regions; consequently, the two earlier years were excluded from the current analysis. The time period covered by the assessment includes almost all the significant post-war tuna fishing in the WCPO.

3.3 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). Nineteen fisheries have been defined for this analysis on the basis of region, gear type and, in the case of purse seine, set type (Table 1).

There is a single general longline fishery in each region (LL ALL 1–6) and two additional Chinese/Taiwanese longline fisheries (LL TW-CH) fishing in regions 3 and 4. The separation of these fisheries from the general longline fisheries in those regions was required because of the different size composition of yellowfin tuna (and hence different selectivity) taken by the Chinese/Taiwanese fleet. This difference is thought to be related to operational characteristics (shallow night sets, as opposed to deep day sets).

Similarly, the Papua New Guinea longline fishery (LL PG 3), the eastern Australian longline (LL AU 5) fishery, Hawaiian longline fishery (LL HW 2, 4), and an aggregate of the Pacific Island domestic longline fisheries (LL PI 6) were included as separate fisheries in the model (Table 1).

In the two equatorial regions, the purse-seine catch and effort (days searching and fishing) data were apportioned into two separate fisheries: effort on associated schools of tuna (log, anchored FAD, and drifting FAD sets) (PS ASS) and effort on unassociated schools (free schools) (PS UNS).

The domestic fisheries of Indonesia and the Philippines were grouped into two separate fisheries largely based on the size of fish caught: a Philippines hand-line fishery catching large fish (PH HL 3) and a composite Indonesia and Philippines fishery, including surface gears (ring net, small-scale purse-seine, etc) catching smaller fish (PHID MISC 3).

The purse-seine and pole-and-line fisheries within model region 1 were not included in the assessment model. Catches of yellowfin by the Japanese coastal surface fleet peaked at about 15,000 mt in the mid 1980s and steadily decline over the subsequent period to about 5,000 mt in recent years.

As mentioned in the previous section, the alternative seven-region structure adopted very similar fishery definitions, except for the inclusion of two additional longline fisheries within the western equatorial region (LL ALL 7 and LL TW-CH 7). However, limited data are available from the LL ALL 7 fishery from the late 1980s onwards and, consequently, it was not possible to derive a standardised effort series extending through the latter period of the model (see Langley 2006a).

3.4 Catch and effort data

Catch and effort data were compiled according to the fisheries defined above. Catches by the longline fisheries were expressed in numbers of fish, and catches for all other fisheries expressed in weight (Figure 5). This is consistent with the form in which the catch data are recorded for these fisheries.

Effort data for the Philippines and Indonesian fisheries were unavailable – instead a proxy effort series was constructed that was directly proportional to the catch. A low penalty weight was specified for effort and catchability deviations to minimise the influence of these effort data on the model results.

Effort data units for purse seine fisheries are defined as days fishing and/or searching, allocated to set types based on the proportion of total sets attributed to a specified set type (associated or unassociated sets) in logbook data. For the principal longline fisheries (LL ALL 1–6 or LL ALL 1–7), effective (or standardised) effort was derived using generalized linear models (GLM) (Langley et al. 2005). Time-series of catch-per-unit-effort (CPUE) for all fisheries are shown in Figure 6. The GLM standardised CPUE for the principal longline fisheries, for both the six- and seven-region models, are presented in Figure 7.

The technique for standardising longline effort was also applied to determine the relative scaling of longline effort between regions. These scaling factors incorporated both the size of the region and the relative catch rate to estimate the relative level of exploitable longline biomass between regions (see Langley et al. 2005). The scaling factors were derived from the Japanese longline CPUE data from 1960–86.

The scaling factors allowed trends in longline CPUE among regions to be comparable indicators of exploitable biomass among regions. For each of the principal longline fisheries, the GLM standardised CPUE index was normalised to the mean of the GLM index from 1960–86 — the equivalent period for which the region scaling factors were derived. The normalised GLM index was then scaled by the respective regional scaling factor to account for the regional differences in the relative level of exploitable longline biomass between regions. Standardised effort was calculated by dividing the quarterly catch by the quarterly (scaled) CPUE index.

This approach was comparable to that applied in the 2005 assessment, except for the period used to normalise the individual CPUE series. In last year's assessment, the GLM CPUE index was normalised to the mean of the entire CPUE series, while in the current assessment the series was normalised to the mean of 1960–86; i.e. equivalent to the period used to derive the regional scaling factors. The difference in approach resulted in some changes in the relative biomass levels between regions due to the differing trends in the CPUE indices between regions.

Within the model, effort for each fishery was normalised to an average of 1.0 to assist numerical stability. The principal longline fisheries were grouped to share common catchability parameters in the various analyses. For such grouped fisheries, the normalisation occurred over the group rather than for the individual fisheries so as to preserve the relative levels of effort between the fisheries.

3.5 Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 95 2-cm size classes (10–12 cm to 198–200 cm). Each length-frequency observation consisted of the actual number of yellowfin tuna measured. A graphical representation of the availability of length (and weight) samples is provided in Figure 8. The data were collected from a variety of sampling programmes, which can be summarized as follows:

Philippines: Size composition data for the Philippines domestic fisheries derived from a sampling programme conducted in the Philippines in 1993–94 were augmented with data from the 1980s and for 1995. In addition, data collected during 1997–2004 from the Philippines hand-line (PH HL 3) and surface fisheries (PHID MISC 3) under the National Stock Assessment Project (NSAP) were included in the current assessment.

Indonesia: Limited size data were obtained for the Indonesian domestic fisheries from the former IPTP database. Note that the miscellaneous Indonesian fishery has been combined with the

Philippines small-fish fishery in this assessment, and therefore the size composition of the catch is assumed to be represented by the combined data.

Purse seine: Length-frequency samples from purse seiners have been collected from a variety of port sampling programmes since the mid-1980s. Most of the early data is sourced from the U.S. National Marine Fisheries Service (NMFS) port sampling programme for U.S. purse seiners in Pago Pago, American Samoa and an observer programme conducted for the same fleet. Since the early 1990s, port sampling and observer programmes on other purse seine fleets have provided additional data. Only data that could be classified by set type were included in the final data set. For each purse seine fishery, size samples were aggregated without weighting within temporal strata.

Longline: The majority of the historical data were collected by port sampling programmes for Japanese longliners unloading in Japan and from sampling aboard Japanese research and training vessels. It is assumed that these data are representative of the sizes of longline-caught yellowfin in the various model regions. In recent years, data have also been collected by OFP and national port sampling and observer programmes in the WCPO.

3.6 Weight-frequency data

Individual weight data for the Japanese longline fisheries previously converted to lengths and aggregated with length measurement data were available and included in this assessment in their original form. For many other longline fleets, "packing list" data are available from export documentation, and these data are progressively being processed and incorporated into the assessment database. For this assessment, the available weight data (apart from those provided by Japan) originated from vessels unloading in various ports around the region from where tuna are exported, including Guam, Palau, FSM, Marshall Islands, Fiji, Papua New Guinea, Hawai'i, and eastern Australian ports.

All weight data were recorded as processed weights (usually recorded to the nearest kg). Processing methods varied among fleets requiring the application of fishery-specific conversion factors to standardise the processed weight data to whole fish weights. Details of the conversion to whole weight are described in Langley et al (2006).

For each fishery, quarterly weight frequency data were compiled by 1 kg weight intervals over a range of 1–200 kg. The time-series distribution of available weight samples is shown in Figure 8.

3.7 Tagging data

A considerable amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. The data used consisted of yellowfin tuna tag releases and returns from the OFP's Regional Tuna Tagging Project conducted during 1989–1992 and recent tag releases in the Hawaiian handline fishery (1996–2001). Tags were released using standard tuna tagging equipment and techniques by trained scientists and technicians. The tag release effort was spread throughout the tropical western Pacific, between approximately 120°E and 170°W (see Kaltongga 1998 for further details).

For incorporation into the MULTIFAN-CL analyses, tag releases were stratified by release region (all yellowfin tuna releases occurred in regions 2–6), time period of release (quarter) and the same length classes used to stratify the length-frequency data. A total of 48,043 releases were classified into 56 tag release groups in this way. Of the 4,952 tag returns in total, 4,130 could be assigned to the fisheries included in the model. Tag returns that could not be so assigned were included in the non-reported category and appropriate adjustments made to the tag-reporting rate priors and bounds. The returns from each size class of each tag release group were then classified by recapture fishery and recapture time period (quarter). Because tag returns by purse seiners were often not accompanied by information concerning the set type, tag-return data were aggregated across set types for the purse seine fisheries in each region. The population dynamics model was in turn configured to predict equivalent estimated tag recaptures by these grouped fisheries.

4 Model description – structural assumptions, parameterisation, and priors

The model can be considered to consist of several components, (i) the dynamics of the fish population; (ii) the fishery dynamics; (iii) the dynamics of tagged fish; (iv) observation models for the data; (v) parameter estimation procedure; and (vi) stock assessment interpretations. Detailed technical descriptions of components (i) – (iv) are given in Hampton and Fournier (2001) and Kleiber et al (2003) and are not repeated here. Rather, brief descriptions of the various processes are given, including information on structural assumptions, estimated parameters, priors and other types of penalties used to constrain the parameterisation. For convenience, these descriptions are summarized in Table 2. In addition, we describe the procedures followed for estimating the parameters of the model and the way in which stock assessment conclusions are drawn using a series of reference points.

4.1 Population dynamics

The six-region model partitions the population into 6 spatial regions and 28 quarterly age-classes. The first age-class has a mean fork length of around 25 cm and is approximately three months of age according to analysis of daily structures on otoliths (Lehodey and Leroy 1999). The last age-class comprises a "plus group" in which mortality and other characteristics are assumed to be constant. For the purpose of computing the spawning biomass, we assume a fixed maturity schedule (Table 2) consistent with the observations of Itano (2000). The population is "monitored" in the model at quarterly time steps, extending through a time window of 1952–2005. The main population dynamics processes are as follows:

4.1.1 Recruitment

Recruitment is the appearance of age-class 1 fish in the population. Yellowfin tuna spawning does not follow a clear seasonal pattern in the tropics but occurs sporadically when food supplies are plentiful (Itano 2000). We have assumed that recruitment occurs instantaneously at the beginning of each quarter. This is a discrete approximation to continuous recruitment, but provides sufficient flexibility to allow a range of variability to be incorporated into the estimates as appropriate.

The distribution of recruitment among the six model regions was estimated within the model and allowed to vary over time in a relatively unconstrained fashion. Stronger constraints were placed on the variation of the spatial distribution of recruitment in the initial 5 years of the time series. 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 spawning biomass via a Beverton and Holt stock-recruitment relationship (SRR). The SRR was incorporated mainly so that yield analysis and stock projections 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 2001, Appendix D).

Typically, fisheries data are not very informative about SRR parameters and it is generally necessary to constrain the parameterisation in order to have stable model behaviour. We 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). The beta-distribution of the prior has a lower bound at 0.2, a mode = 0.85, and standard deviation = 0.16 (Figure 9).

4.1.2 Initial population

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

4.1.3 Growth

The standard assumptions made concerning age and growth are (i) the lengths-at-age are normally distributed for each age-class; (ii) the mean lengths-at-age follow a von Bertalanffy growth curve; (iii) the standard deviations of length for each age-class are a log-linear function of the mean lengths-at-age; and (iv) the probability distributions of weights-at-age are a deterministic function of the lengths-at-age and a specified weight-length relationship (see Table 2).

As noted above, the population is partitioned into 28 quarterly age-classes. The number of older age classes allows for the possibility of significantly older and possibly larger fish in the early years of the fishery when exploitation rates were very low.

Previous analyses assuming a standard von Bertalanffy growth pattern indicated that there was substantial departure from the model, particularly for sizes up to about 80 cm. Similar observations have been made on yellowfin growth patterns determined from daily otolith increments and tagging data (Lehodey and Leroy 1999). We therefore modelled growth by allowing the mean lengths of the first eight quarterly age-classes to be independent parameters, with the remaining mean lengths following a von Bertalanffy growth curve. These deviations attract a small penalty to avoid over-fitting the size data.

4.1.4 Movement

Movement was assumed to occur instantaneously at the beginning of each quarter through movement coefficients connecting regions sharing a common boundary. Note however that fish can move between non-contiguous regions in a single time step due to the "implicit transition" computational algorithm employed (see Hampton and Fournier 2001; Kleiber et al. 2003 for details). Movement is parameterised as the proportion of fish in a given region that move to the adjacent region. For the six-region model, there are seven inter-regional boundaries in the model with movement possible across each in both directions. Four seasonal movements were allowed, each with their own movement coefficients. Thus there is a need for $2 \times 7 \times 4 = 56$ movement parameters. The seasonal pattern of movement persists from year to year with no allowance for longer-term variation in movement. A previous (2004) assessment had included the estimation of age-specific movement. However, there are limited data available to estimate these parameters and for the current assessment movement coefficients were invariant with respect to age.

The seven-region model estimates additional movement coefficients between regions 1 and 7 and regions 3 and 7, increasing the total number of movement parameters to 72.

4.1.5 Natural mortality

Natural mortality (*M*) was held fixed at pre-determined age-specific levels as applied in the 2005 assessment (MFIX model options). *M*-at-age was determined outside of the MULTIFAN-CL model using yellowfin sex-ratio data and the assumed maturity-at-age schedule. An identical procedure is used to determine fixed *M*-at-age for assessments in the EPO (Maunder 2005). Essentially, this method reflects the hypothesis that the higher proportion of males in sex-ratio samples with increasing length is due to the higher natural mortality of females after they reach maturity. The externally-estimated *M*-at-age is shown in Figure 10.

We did not estimate *M*-at-age in these assessments because trial fits estimating *M*-at-age produced biologically unreasonable results.

4.2 Fishery dynamics

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

4.2.1 Selectivity

In many stock assessment models, selectivity is modelled as a functional relationship with age, e.g. using a logistic curve to model monotonically increasing selectivity and various dome-shaped curves to model fisheries that select neither the youngest nor oldest fish. In previous assessments, we have modelled selectivity with separate age-specific coefficients (with a range of 0–1), but constraining the parameterisation with smoothing penalties. This has the disadvantage of requiring a large number of parameters to describe selectivity. In this assessment, we have used a method based on a cubic spline interpolation to estimate age-specific selectivity. This is a form of smoothing, but the number of parameters for each fishery is the number of cubic spline "nodes" that are deemed to be sufficient to characterise selectivity over the age range. We chose five nodes, which seems to be sufficient to allow for reasonably complex selectivity patterns.

Selectivity is assumed to be fishery-specific and time-invariant. Selectivity coefficients for "main" longline fisheries LL ALL 1 and LL ALL 2 (northern fisheries) were constrained to be equal, as were LL ALL 3–6 (equatorial and southern fisheries) and the Chinese/Taiwanese fisheries (LL TW-CH 3 and 4). For the two latter fisheries, selectivity was parameterised using a logistic functional form rather than the cubic spline method. For all fisheries, the selectivity for the last four age-classes, for which the mean lengths are very similar, was constrained to be equal.

In the 2005 assessment, the selectivity of the longline fisheries (which catch mainly adult yellowfin) was assumed to increase with age and to remain at the maximum once attained. However, this assumption was relaxed in the current assessment for all longline fisheries, except for the fisheries Chinese/Taiwanese fisheries (LL TW-CH 3 and 4), thereby, allowing selectivity to decline for the older age classes. This is because the Chinese/Taiwanese fleet caught consistently larger fish than the other longline fleets in a comparable time period. These differences in size composition, which were consistent across length- and weight-frequency data, implied less than 100% selectivity for older yellowfin by the LL ALL fisheries. There are operational differences between the longline fleets that may account for a higher selectivity of larger fish by the Chinese/Taiwanese fleet.

4.2.2 Catchability

Catchability was allowed to vary slowly over time (akin to a random walk) for all purse seine fisheries, the Philippines and Indonesian fisheries, the Australian, Taiwanese/Chinese, Hawaii, PNG and other Pacific-Island longline fisheries, using a structural time-series approach. Random walk steps were taken every two years, and the deviations were constrained by prior distributions of mean zero and variance specified for the different fisheries according to our prior belief regarding the extent to which catchability may have changed. For the Philippines and Indonesian surface fisheries (PHID MISC 3), no effort estimates were available. We made the prior assumption that effort for these fisheries was proportional to catch, but set the variance of the priors to be high (approximating a CV of about 0.7), thus allowing catchability changes to compensate for failure of this assumption. For the other fisheries with time-series variability in catchability, the catchability deviation priors were assigned a variance approximating a CV of 0.10.

The "main" longline fisheries were grouped for the purpose of initial catchability, and time-series variation was assumed not to occur in this group. As noted earlier, this assumption is similar to assuming that the CPUE for these fisheries indexes the exploitable abundance both among areas and over time.

Catchability for all fisheries apart from the Philippines and Indonesian fisheries (in which the data were based on annual estimates) was allowed to vary seasonally.

4.2.3 Effort deviations

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 and Indonesian fisheries, purse seine fisheries and the Australian, Hawaii and Taiwanese-Chinese longline fisheries, the variance was set at a moderate level (approximating a CV of 0.2). For the main longline fisheries (LL ALL 1-6), the variance was set at a lower level (approximating a CV of 0.1) because the effort had been standardised in prior analyses and these longline fisheries provide wide spatial coverage of the respective areas in which they occur.

4.3 Dynamics of tagged fish

4.3.1 Tag mixing

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

We assumed that tagged yellowfin mix fairly quickly with the untagged population at the region level and that this mixing process is complete by the end of the second quarter after release.

4.3.2 Tag reporting

In principal, tag-reporting rates can be estimated internally within the model. In practice, experience has shown that independent information on tag-reporting rates for at least some fisheries tends to be required for reasonably precise estimates to be obtained. We provided reporting rate priors for all fisheries that reflect our prior opinion regarding the reporting rate and the confidence we have in that opinion. 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 longline fisheries, we have no auxiliary information with which to estimate reporting rates, so relatively uninformative priors were used for those fisheries. All reporting rates were assumed to be stable over time. The proportions of tag returns rejected from the analysis because of insufficient data were incorporated into the reporting rate priors.

4.4 Observation models for the data

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

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

The size frequency data is assigned an effective sample size lower than the actual number of fish sampled. Reduction of the effective sample size recognises that (i) length- and weight-frequency samples are not truly random (because of clumping in the population with respect to size) and would have higher variance as a result; and (ii) the model does not include all possible process error, resulting in further under-estimation of variances. The influence of the size frequency data in the model was examined by varying the effective sample size in the model. A higher weighting on the size data (HIGHSAMP), equivalent to the 2005 assessment, assumed an effective sample size of 0.1 times the actual sample size, with a maximum effective sample size of 100. This was compared to a lower weighting on the sampling data (LOWSAMP); effective sample size of 0.02 times the actual sample size, with a maximum effective sample size of 20.

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 parameterisation of the variance parameters such that as they approach infinity, the negative binomial approaches the Poisson. Therefore, if the tag return data show high variability (for example, due to contagion or non-independence of tags), then the negative binomial is able to recognise this. This should then provide a more realistic weighting of the tag return data in the overall log-likelihood and allow the variability to impact the confidence intervals of estimated parameters. A complete derivation and description of the negative binomial likelihood function for tagging data is provided in Hampton and Fournier (2001) (Appendix C).

4.5 Parameter estimation and uncertainty

The parameters of the model were estimated by maximizing the log-likelihoods of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. The maximization was performed by an efficient optimization using exact derivatives with respect to the model parameters. Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters. A bash shell script, *doitall.yft*, documenting the phased procedure is provided in Appendix A. Some parameters were assigned specified starting values consistent with available biological information. The values of these parameters are provided in the *yft.ini* file (Appendix B)[1].

The Hessian matrix computed at the mode of the posterior distribution was used to obtain estimates of the covariance matrix, which was used in combination with the Delta method to compute approximate confidence intervals for parameters of interest. In addition, the likelihood profile method was used to generate probability distributions for the critical reference points $F_{current}/\widetilde{F}_{MSY}$ and $B_{current}/\widetilde{B}_{MSY}$. Likelihood profiles were generated by undertaking model runs with either $F_{current}/\widetilde{F}_{MSY}$ or $B_{current}/\widetilde{B}_{MSY}$ set at various levels (by applying a penalty to the likelihood function for deviations from the target ratio) over the range of possible values. The likelihood function values resulting from these runs were then used to construct a probability distribution for each ratio.

4.6 Stock assessment interpretation methods

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

[1] Details of elements of the *doitall* and *.ini* files as well as other input files that structure a MULTIFAN-CL run are given in Kleiber et al. (2003).

Kleiber et al. (2003). Note that, in each case, these ancillary analyses are completely integrated into the model, and therefore confidence intervals for quantities of interest are available using the Hessian-Delta approach (or likelihood profile approach in the case of yield analysis results).

4.6.1 Fishery impact

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

We approach this problem by computing biomass time series (at the region level) using the estimated model parameters, but assuming that fishing mortality was zero. Because both the *real* biomass B_t and the *unexploited* biomass B_{0t} incorporate recruitment variability, their ratio at each time step of the analysis $\frac{B_t}{B_{0t}}$ can be interpreted as an index of fishery depletion. The computation of unexploited biomass includes an adjustment in recruitment to acknowledge the possibility of reduction of recruitment in exploited populations through stock-recruitment effects.

4.6.2 Yield analysis

The yield analysis consists of computing equilibrium catch (or yield) and biomass, conditional on a specified basal level of age-specific fishing mortality (F_a) for the entire model domain, a series of fishing mortality multipliers, *fmult*, the natural mortality-at-age (M_a), the mean weight-at-age (w_a) and the SRR parameters α and β. All of these parameters, apart from *fmult*, which is arbitrarily specified over a range of 0–50 in increments of 0.1, are available from the parameter estimates of the model. The maximum yield with respect to *fmult* can easily be determined and is equivalent to the MSY. Similarly the total and adult biomass at MSY can also be determined. The ratios of the current (or recent average) levels of fishing mortality and biomass to their respective levels at MSY are of interest as limit reference points. These ratios are also determined and their confidence intervals estimated using a profile likelihood technique.

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In this assessment, we use the average over the period 2001–2004. The last year in which catch and effort data are available for all fisheries is 2005. We do not include 2005 in the average as fishing mortality tends to have high uncertainty for the terminal data year of the analysis and the catch and effort data for this terminal year are usually incomplete (see Langley 2006a).

5 Sensitivity analyses

As outlined above, the sensitivity of the assessment model to the relative weighting applied to size-frequency data was investigated through changing the effective sample size applied to the size-frequency data. The impact of a key structural assumption in the model was investigated through a reconfiguration of the spatial stratification of the model with the inclusion of an additional region (seven-region model).

In summary, the analyses carried out are:

LOWSAMP	Six-region spatial stratification, general linear model standardised effort for "main" longline fisheries, *M*-at-age assumed at fixed levels, lower effective sample size applied to the length and weight frequency samples.
HIGHSAMP	Six-region spatial stratification, general linear model standardised effort for "main" longline fisheries, *M*-at-age assumed at fixed levels, higher effective sample size applied to the length and weight frequency samples. This analysis approximates the base-case model run (GLM-MFIX) from the 2005 assessment. The only significant difference is the parameterisation of the

selectivity functions for the principal longline fisheries — allowing a decline in the selectivity for the oldest age classes.

7REGION Seven-region spatial stratification, general linear model standardised effort for "main" longline fisheries, *M*-at-age assumed at fixed levels, lower effective sample size applied to the length and weight frequency samples.

Other sensitivities included in the 2005 assessment were not repeated; principally the examination of the effect of an expansion in fishing power and the estimation of natural mortality (invariant with respect to age). Nevertheless, the results of the 2005 assessment are still pertinent when considering the relative influence that such factors may have on the 2006 assessment conclusions.

6 Results

The results from the three analyses are presented below. In the interests of brevity, some categories of results are presented for the LOWSAMP analysis only, which is designated the base-case analysis due to superior performance with respect to effort deviation diagnostics (see Section 6.4). Significant differences between the base case and the two sensitivity analyses are summarised in Section 6.4. The main stock assessment-related results are also summarised for all analyses.

6.1 Fit statistics and convergence

A summary of the fit statistics for the three analyses is given in Table 3. Due to differences in the relative weighting of the size frequency data it is not possible to directly compare the fit between the two six-region models. Note the higher contribution of the size frequency data to the total likelihood for the model with the higher effective sample size (HIGHSAMP). Similarly, the differences in model structure for the seven-region model (additional region and two additional fisheries) means that the total likelihood values are not statistically comparable.

6.2 Fit diagnostics (LOWSAMP)

We can assess the fit of the model to the four predicted data classes – the total catch data, the length frequency data, the weight frequency data and the tagging data. In addition, the estimated effort deviations provide an indication of the consistency of the model with the effort data. The following observations are made concerning the various fit diagnostics:

- The log total catch residuals by fishery are shown in Figure 11. The residuals are all relatively small and, for most fisheries, generally show even distributions about zero. However, some patterns are worthy of comment. First, there appears to be some autocorrelation in residuals for fisheries LL ALL 1 and LL ALL 3, which could be evidence of minor time-series changes in catchability (catchability was constrained to be constant among years for LL ALL 1–6 fisheries). Secondly, the purse-seine fisheries (PS ASS 3, PS UNS 3, PS ASS 4, and PS UNS 4) show a very tight distribution of residuals up to about 1990 and are considerably more variable in the subsequent years.

- There is some systematic lack of fit to the length data for the longline fisheries as revealed from a comparison of the observed and predicted length data aggregated over time (Figure 12). For some of the longline fisheries (LL ALL 3, LL TW-CH 4, and LL HW 4) the model over-estimates the proportion of fish in the larger length classes and, correspondingly, under-estimates the proportion of fish in the smaller length classes. However, the fit to these data is much superior to the previous assessment (Hampton et al. 2005) largely due to the refinement of the treatment of the weight-frequency data and a change in the length-weight relationship included in the model (see Langley 2006a for details). These changes resolved much of the apparent conflict between the length- and weight-frequency data included in the model.

- Some of the outstanding discrepancies between the observed and predicted length data appear to be due to temporal trends in the fit to the size data over time. For example, the LL ALL 3 fishery length samples were comprised of significantly smaller fish during the 1960s and 1970s than for the remainder of the model period (Figure 13). Similarly, there is a marked shift in the observed length-composition in the LL ALL 1 fishery in the late 1970s–early 1980s with significantly smaller fish sampled in the latter period. Such changes are indicative of temporal changes in the selectivity of individual fisheries and may be, at least partly, explained by temporal trends in the spatial distribution of fishing and sampling effort within a sub-region that exhibits spatial heterogeneity in size structure (see Langley 2006c).
- For the surface fisheries (the purse-seine fisheries and PHID MISC 3), there is a strong modal structure in the size data. This modal structure in the aggregated length data is not well predicted by the model, in particular the second and third age classes (about 40–60 cm FL) are consistently under-represented in the predicted size composition of the PS ASS 3 and PS ASS 4 fisheries (Figure 12). This lack of fit is attributable to the growth function estimated for the base-case model (see Section 6.3.1). Nevertheless, in general, the model predicts the temporal trends in the size composition of the catch from the surface fisheries (Figure 13), in particular for the PS ASS fisheries indicating that the size data from these fisheries are informative in the model estimates of recruitment.
- For most of the longline fisheries, there is a good fit to the aggregated weight frequency data (Figure 14). However, there are several fisheries with a strong modal structure in the weight distribution for which the model does not reliably predict the size composition. These fisheries include LL ALL 1, LL ALL 3, LL PG 3, and LL AU 5 for which the model tends to consistently under-estimate the proportion of the size composition in the 5–6 age classes. There is also a relatively poor fit to the weight data from those fisheries with limited data (LL TW-CH 4, LL ALL 6) (Figure 14).
- The temporal trends in the fit to the weight data are similar to those described for the length data, most notably for LL ALL 1 and LL ALL 3 (Figure 15). The consistency in the trends between the length- and weight-frequency data further supports the presumption of a temporal trend in the selectivity of these fisheries.
- While many of the problems evident in the fit to the size data (particularly length data) in the 2005 assessment have been resolved, there remain considerable inconsistencies in the fit to the region 4 Chinese/Taiwanese (LL TW-CH 4) and Hawaiian longline (LL HW 4) length- and weight-frequency data (Figure 14). The latter fishery appears to have exhibited a strong shift in the size of fish caught from the fishery over the last decade that may represent a change in selectivity by the fleet. The selectivity of the LL TW-CH 4 is equivalent to the comparable fishery in region 3 (LL TW-CH 3) and the estimation of selectivity is dominated by the size data from the LL TW-CH 3. The assumption of a common selectivity for these two fisheries may not be appropriate.
- The fits of the model to the tagging data compiled by calendar time and by time at liberty are shown in Figure 16 and Figure 17. The model generally approximates the observed number of tag returns by time interval, although there is a systematic over-estimation of tag-return numbers towards the end of the tag recovery period (1993–94). This is also evident in the over-estimation of tag returns for about 6–13 quarters at liberty (Figure 17). The model under-estimates the recovery of fish at liberty for long periods (greater than 20 quarters), although the number of observations is small). The fits for individual fishery groups are shown in Figure 18. There is a very good fit to the observed number of returns for those fisheries that returned large numbers of tags: the equatorial purse-seine and Philippines/Indonesian fisheries.
- Observed and predicted tag recovery rates for the longline fisheries are very low due to the relatively low total catch and the emphasis on the tagging of smaller yellowfin (Figure 18). For most of these fisheries, the tagging data are uninformative. Of the longline fisheries, most recoveries have been made from the Australian fishery. However, there is some considerable

discrepancy in the number of observed and predicted returns from the fishery (Figure 18). This is possibly related to the coarse resolution of spatial structure in the model, estimation of movement parameters, and a lack of adequate mixing of tagged fish with the wider population of region 5.

- The overall consistency of the model with the observed effort data can be examined in plots of effort deviations against time for each fishery (Figure 19). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. On the other hand, if there was an obvious trend in the effort deviations with time, this may indicate that a trend in catchability had occurred and that this had not been sufficiently captured by the model. Of particular interest are the effort deviations for the LL ALL 1–6 longline fisheries, which were constrained to have the same average catchability and to have no year-to-year variation (i.e., catchability deviations were assumed to be zero). For these fisheries, there is no strong trend in the effort deviations and, in most cases, effort deviates are relatively small indicating a consistency between the predicted fishery-specific exploitable biomass and the corresponding standardised effort series for the fishery (Figure 19). Nevertheless, it is worth noting the positive effort deviations for LL ALL 5 at the beginning of the time series. These deviations correspond to very high CPUE observations during the development of the fisheries (Figure 7). The converse is evident in the early period of the LL ALL 2 fishery which had negative effort deviations.
- Effort deviates are substantially higher for the purse-seine fisheries than the principal longline fisheries (Figure 19). This can be interpreted as a high degree of variation in the effective effort of the purse-seine fleet which is to be expected given the differences in the style of fishing operation.

6.3 Model parameter estimates (LOWSAMP unless otherwise stated)

6.3.1 Growth

The estimated growth curve is shown in Figure 20. The non-von Bertalanffy growth of juvenile yellowfin is clearly evident, with near-linear growth in the 50–100 cm size range. This growth pattern is similar to that observed in the otolith length-increment data (Figure 21) (Lehodey and Leroy 1999). However, growth increments derived from tag data are generally lower than predicted by the estimated growth curve, particularly for shorter-term release periods (Figure 21).

There are significant differences in estimated growth from the three model options (Figure 20). Initial growth is considerably lower for the HIGHSAMP model compared to the LOWSAMP model, while initial growth is slightly higher for the 7REGION model although L_∞ is lower and attained at a younger age.

The difference in estimated growth between the LOWSAMP and HIGHSAMP models may be attributable to the influence of the strong length mode at about 50 cm evident in the length data from the PS ASSOC fisheries (Figure 22). For the HIGHSAMP model this mode is estimated to correspond to fish at age 3 quarters, while for the LOWSAMP model it is estimated to be a composite of age 2 and 3 fish.

6.3.2 Natural mortality

Unlike previous assessments, natural mortality was not estimated in any of the analyses and a fixed age-specific mortality function was applied (see Figure 10). This issue may be re-visited in future assessments using biologically reasonable functional forms for *M*-at-age.

6.3.3 Movement

The model estimates a very large movement of fish (39%) southward from region 1 to region 3 in the second quarter of the year (Figure 23). A further southward movement is estimated to occur in the fourth quarter, representing 13% of all fish. Movements between all other adjacent regions are relatively low, about 3–6%, or negligible. Movement is estimated to occur between regions 3 and 4 and between regions 3 and 5 in all quarters.

Note that the lack of substantial movement for some regions could be due to limited data on movement. In the model, a small penalty is placed on movement coefficients different to zero. This is done for reasons of stability, but it would tend to promote low movement rates in the absence of data that are informative about movement. An alternative model formulation would be to have high movement rates, rather than zero movement, as the “null hypothesis”. This is a topic for further research.

The distribution of regional biomass by source region derived from a simulation using the movement coefficients is presented in Figure 24. The simulation indicates that most biomass within a region is sourced from recruitment within the region, particularly for regions 1–3 and 6. The mixing between the equatorial regions results in a significant proportion of biomass (25%) in the eastern region (region 4) being sourced from the western region (region 3). Regional fidelity is lowest in region 5 with a substantial proportion of the biomass sourced from region 3 (Figure 24).

6.3.4 Selectivity

Estimated selectivity coefficients are generally consistent with expectation with longline fisheries principally selecting larger, older fish and the associated purse-seine sets (FAD and log sets) catching smaller yellowfin (Figure 25). Unassociated purse-seine sets generally catch substantially larger fish than from associated sets. The composite Philippines/Indonesia surface fisheries principally catch small fish; however, there are also some observations of larger fish in the catch that explain the high selectivity of older fish also.

For the principal longline fisheries LL ALL 3−6, selectivity is estimated to decline for the older age classes and the catch is predicted to be principally comprised of age-classes 5−9 and selectivity of older fish is relatively low. This is consistent with the slightly smaller size of fish caught by these fisheries compared to the corresponding TW-CH fisheries. The functional form of the (common) selectivity of the latter fisheries is constrained to have full selectivity for the oldest age classes.

Selectivity functions are temporally invariant. However, for a number of fisheries there is a clear temporal change in the size-frequency data and an associated lack of fit to the predicted size composition (see Section 6.2). This is particularly evident for the LL ALL 1 fishery with a substantial change in size composition in the late 1970s. For this fishery, a considerable improvement in the fit to the size frequency data was achieved when separate selectivities were estimated for the two time periods (Figure 26 compared to Figure 13 and Figure 15).

6.3.5 Catchability

Time-series changes in catchability are evident for several fisheries (Figure 27). Catchability in the principal longline fisheries (LL ALL 1−6) has been assumed to be constant over time. There is evidence of a general increasing catchability in the unassociated purse seine fisheries and some of the domestic longline fisheries (LL PG 3, LL HW 4, and LL PI 6). Since the early 1990s, the model estimates a strong increase in the catchability from the Philippines and Indonesian domestic fisheries (PHID MISC 3 and PH HL 3). There is limited effort data for the PHID MISC 3 fishery and the model assumes catches are proportional to effort throughout the history of the fishery. During a period of declining stock biomass, the model has attempted to account for the catches from the fisheries by increasing the catchability inversely proportional to the trend in exploitable biomass. Catchability for the Australian longline fishery is estimated to have declined over time — this is consistent with the shift in targeting activity to bigeye during the 1990s.

6.3.6 Tag-reporting rates

Estimated tag-reporting rates by fishery are shown in Figure 28. The estimates for the purse seine fisheries deviated from the mode of their prior distributions and reporting rates from the purse-seine fisheries in region 3 were estimated to be about 50% of the reporting rates from region 4. The estimates for the Philippine/Indonesia domestic fisheries are significantly below their prior mode, indicating that the model has used information contained in the data to estimate this reporting rate. The estimates for the longline fisheries are highly variable, ranging from near zero to the upper limit allowed (0.9). However, the estimated reporting rates from the longline fisheries are based on a very small number of tag recoveries and, consequently, the tag recovery data from these fisheries are not very informative.

6.4 Sensitivity analyses

This section summarises the key differences in the main parameters between the base-case (LOWSAMP) model and the two sensitivity analyses. The HIGHSAMP model, with higher weighting to the size frequency data, differs from the base case assessment in respect to the following:

i. Initial growth is considerably lower for the HIGHSAMP model.
ii. Differences in the movement parameterisation; the HIGHSAMP model estimates that a large proportion of fish move from region 1 to region 3 in the first, second and fourth quarters of the year.
iii. Fishery-specific selectivities were comparable for the main fisheries, except that the selectivity was shifted by one age class to older fish to reflect the difference in the growth estimates between the LOWSAMP and HIGHSAMP models.
iv. Recruitment was estimated to be substantially higher in region 1, particularly since the early 1980s (compared to the LOWSAMP model). There was a corresponding reduction in the recruitment in region 3. The magnitude and trend in recruitment was comparable for the other four regions.
v. Overall, there is a substantial improvement in the fit to the size-frequency data, particularly the modal structure of the surface fisheries (purse-seine and Indonesia/Philippines).
vi. For the main longline fisheries, effort deviations are more variable and reveal stronger temporal trends than for the LOWSAMP model. Most notable is a general trend in LL ALL 4 (region 3) from predominantly negative effort deviations in the first half of the model period to predominantly positive effort deviations in the second half of the model period (Figure 29). Regions 1 and 2 exhibit high positive effort deviations in the first 20 years (1950s and 1960s).

The difference in regional structure between the six- and seven-region models makes comparisons between the two models less clear at a regional scale, although there is enough similarity between the spatial stratification (and fishery definitions) to enable general comparisons. The key differences between the 7REGION and the six-region model with similar weighting to the size-frequency data (LOWSAMP, base case model) are as follows:

i. Initial growth is slightly higher for the 7REGION model although L_∞ is lower and attained at a younger age.
ii. There are significant differences in the movement parameterisation. For the 7REGION model, there is no direct movement from region 1 to region 3. Instead, the model estimates a substantial movement of fish from region 1 to region 7 in the fourth quarter and high movements from region 7 to region 3 in quarters 1–3.
iii. The common selectivity of the main longline fisheries in regions 3–6 (LL ALL 3–6) is similar to the LOWSAMP model except for a shift to fish one age class younger. This is consistent with the difference in growth estimates between the two models. For the 7REGION model, selectivity of the principal longline fisheries in the northern regions declines for the older age classes, while for the LOWSAMP model selectivity increases steadily with age.
iv. The selectivity of the purse-seine fisheries is similar between the two models, albeit that the selectivity for the 7REGION model is shifted slightly to younger age classes to account for the difference in growth. The principal difference in selectivity between the two models is for the PHID MISC 3 fishery. In the seven-region model, the highest selectivity occurs for the two youngest age classes and selectivity decreases sharply with increasing age, although there is still some selectivity for old age classes. In contrast, the six-region model estimates a selectivity function with relatively low selectivity for the young age classes and high selectivity for old age classes.
v. The 7REGION model estimates substantially higher tag reporting rates from the purse-seine fisheries (PS ASSOC/UNASSOC) compared to the LOWSAMP model.

vi. The magnitude and trends in regional recruitment (regions 1–6) are very similar between the 7REGION and LOWSAMP model. However, total recruitment is considerably higher for the 7REGION model as region 7 accounts for a significant proportion of total recruitment (13% for the entire time period), particularly in the last decade (28%).

vii. A qualitative examination of the 7REGION model fit to the size data indicates a marginal improvement relative to the LOWSAMP model. However, there remains an inconsistency in the fit to length frequency data from those fisheries exhibiting a strong modal structure in the length distribution.

viii. For the 7REGION model, the variation in effort deviations for the principal longline fisheries in regions 1, 2, and 3 (LL ALL 1–3) is considerably lower than for the base case (LOWSAMP) model. There is also no temporal trend in the effort deviations evident for any of the principal longline fisheries. This may indicate an improvement in the standardisation of the longline CPUE data achieved through the adoption of a spatial structure that represents a more consistent trend in abundance within each region (see Langley 2006a).

For the three models, differences in the stock assessment results, at the WCPO region scale, are summarised in the following section.

6.5 Stock assessment results

6.5.1 Recruitment

The LOWSAMP recruitment estimates (aggregated by year for ease of display) for each region and the WCPO are shown in Figure 30. Recruitment is highest within region 3, while moderate levels of recruitment also occur within regions 4 and 5. The regional estimates display large interannual variability and variation on longer time scales. Recruitment in region 3 was relatively low between the late 1950s and early 1970s, while recruitment was low in region 4 and 5 during the 1970s. The recruitments from regions 3 and, to a lesser extent regions 4 and 5, strongly influence the trend in the aggregate WCPO recruitment estimates and overall recruitment from the mid 1980s to 2000 was considerably higher than during the late 1960s and early 1970s.

The increase in recruitment estimates during the mid 1970s is consistent with the increase in CPUE from the equatorial longline fisheries (LL ALL 3 & 4) during that time (Figure 7), as well as the sustained increase in catches from the mid 1970s to 1990. The model also explains the high initial CPUE observed in a number of the main longline fisheries (LL ALL 4–6) by high estimates of recruitment during the early period (Figure 30).

The confidence intervals associated with the combined WCPO annual recruitment estimates reveal a substantially higher level of uncertainty associated with recruitment estimates prior to the mid 1980s (Figure 30). Confidence intervals for recruitment estimated from the HIGHSAMP analysis are somewhat smaller than those from the LOWSAMP analysis (Figure 31), as well as the point estimates of recruitment being higher overall.

A comparison of WCPO recruitment estimates for the various model options is provided in Figure 32. All analyses reveal the same trend in overall recruitment with recruitment declining from 1950 to 1970 and then increasing during the late 1970s to plateau at a higher level. The overall magnitude of recruitment varied between analyses; the analysis with increased weighting on the size-frequency data (higher effective sample size, HIGHSAMP) had a consistently higher recruitment level compared to the base case (LOWSAMP). Similarly, the seven-region (7REGION) model estimated a similar magnitude of recruitment to the HIGHSAMP model (Figure 32).

6.5.2 Biomass

Estimated biomass time-series for each region and for the WCPO are shown in Figure 33 for the LOWSAMP analysis. The trends are variable between regions, reflecting the CPUE trends from the main longline fisheries (LL ALL 1–6) (Figure 34). Also, the model estimates of exploitable abundance show very similar scaling among regions as the CPUE data (Figure 35). This indicates that model estimates are consistent with the CPUE data in terms of both time-series and spatial variability.

Overall, a higher proportion of the biomass is within region 3, although there has been a steady decline in this region throughout the model period. For regions 4–6, the biomass is estimated to have declined sharply in the early model period to a low level during the 1970s and then subsequently increased to a higher level during the 1980s and 1990s. These historical trends are an effect of long-term trends in recruitment rather than attributable to the impacts of fishing. Similarly, the biomass trends from regions 1 and 2 are consistent with the trends in longline CPUE (Figure 34) and are essentially driven by the estimated trends in recruitment.

The trend in biomass for the WCPO is largely driven by the biomass trend from region 3 (Figure 33). Biomass declines steadily during the early model period, remains relatively stable from the mid 1970s to mid 1990s, and then declines sharply (by about 40%) during the last decade.

The comparison of biomass trends for the three model options is shown in Figure 36. For the two six-region models, the total biomass trajectory is comparable, although the HIGHSAMP model estimates slightly higher levels of total biomass throughout the model period. Overall biomass levels are substantially higher for the 7REGION model, particularly prior to the mid 1970s, although the model exhibits a substantially greater decline in overall biomass.

6.5.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase strongly throughout the time series, particularly during the last decade (Figure 37). There are differences among the analyses, with the highest recent exploitation rates evident in the six-region LOWSAMP model. The fishing mortality rates on adult yellowfin are substantially lower for the seven-region (7REGION) model compared to the two six-region models (LOWSAMP and HIGHSAMP).

Recent exploitation rates are high on the youngest age classes due to the impact of the PHID MISC 3 fishery (Figure 38). There is also a high exploitation rate on the older age classes (7–14 age classes), largely attributable to the equatorial purse-seine fisheries. Overall, there has been a substantial decline in the proportion of old (greater than age class 10) fish in the population since the mid 1970s (Figure 38).

6.5.4 Fishery impact

We measure fishery impact at each time step as the ratio of the estimated biomass to the biomass that would have occurred in the historical absence of fishing. This is a useful variable to monitor, as it can be computed both at the region level and for the WCPO as a whole. The two trajectories are plotted in Figure 39. It is immediately evident that the impact has been substantial in region 3 and significant impact has also occurred in region 4. Impacts are slight in the four sub-equatorial regions.

Overall, the impact of fishing has reduced the WCPO biomass to about 50% of unexploited levels (Figure 40), largely driven by the impact in regions 3 and 4. Fishery impacts in region 3 have steadily increased over time and are currently reducing the biomass to about 30% of the unexploited level. By comparison, fishery impacts are relatively low in regions 1, 2, 5 and 6; less than 20% over the entire time period, i.e. total biomass maintained at above 80% of unexploited levels.

A comparison of relative impact of fishing on the entire WCPO biomass from the various model options is presented in Figure 41. Recent levels of fishery impact range form about 40% for the seven-region model to 50% for the six-region LOWSAMP model. The HIGH SAMP model estimates an intermediate level of recent impact.

It is possible to classify the fishery impact on the spawning biomass ($1 - SB_t / SB_{0t}$) or total biomass ($1 - B_t / B_{0t}$) to specific fishery components in order to see which types of fishing activity have the largest impact on biomass (Figure 42 and Figure 43). Within each region, the relative impacts of specific fisheries on spawning and total biomass are comparable. In region 3 (of the six-region model), the Philippines/Indonesian domestic fisheries have by far the greatest impact. The purse seine fishery (PS ASS 3 and PS UNS 3) had the greatest impact in the early to mid-1990s, but has since declined.

In region 4, the purse seine fishery is responsible for about half of the impact, while the Philippines/Indonesian fisheries accounts for about 25% due to the direct movement of fish from region 3 to region 4. Similarly, while the direct fishery impacts are low in region 1 and region 5, the high impacts on the stock in region 3 are reducing the movement of fish to these adjacent regions.

It is noteworthy that in both regions 3 and 4, the longline fishery has a relatively small impact, generally less than 10%. In the sub-equatorial regions, the longline fishery has a larger share of the impact, but overall impacts are much smaller. In these regions, the longline fishery is estimated to have depleted population biomass by no more than about 10%.

The recent overall fishery-specific impacts on total biomass in the WCPO are broadly consistent with the proportional impacts within region 3; low impact from the longline fishery (7%), moderate impact from the associated (12%) and unassociated (7%) purse-seine fisheries, and highest (25%) and increasing impacts from the Philippines/Indonesian domestic fisheries.

6.5.5 Yield analysis

Symbols used in the following discussion are defined in Table 4. The yield analyses conducted in this assessment incorporate the SRR (Figure 44) into the equilibrium biomass and yield computations. The estimated SRR steepness coefficient for the base-case is 0.74, close to the prior mode of 0.85. This represents a moderate value of steepness and means that average recruitment is predicted to decline to 74% of the equilibrium unexploited recruitment when the level of spawning biomass is reduced to 20% of the unexploited level.

Equilibrium yield and biomass (spawning and total) are computed as a function of multiples of the 2001–2004 average fishing mortality-at-age (Figure 45). For the LOWSAMP model, a maximum yield (*MSY*) of 329,600 mt per annum (82,400 mt per quarter) is achieved at *fmult* = 0.9; i.e. at 90% of the current level of fishing effort. This represents that the ratio of $F_{current}/\tilde{F}_{MSY}$ is equal to 1.11 (approximately 1/0.9); current exploitation rates are higher than the exploitation rates to produce the *MSY*. The equilibrium biomass at *MSY* is estimated at 960,500 mt, approximately 42% of the equilibrium unexploited biomass (Table 5).

There is considerable uncertainty regarding the equilibrium yields at and above the current level of fishing effort (*fmult*) (Figure 45). For the LOWSAMP model, the 95% confidence interval for *MSY* is 208,000–450,000 mt. Levels of uncertainty increase rapidly with increasing levels of *fmult*, largely attributable to uncertainty associated with the recruitment levels predicted from the SRR at low levels of spawning biomass (Figure 44). The confidence interval associated with *MSY* was similar for the HIGHSAMP model.

For the LOWSAMP model, the reference points $F_t/\tilde{F}_{MSY}$ and $B_t/\tilde{B}_{MSY}$ were computed for each year (*t*) included in the model (1952–2005). These computations incorporated the overall fishery selectivity in year *t*. This enables trends in the status of the stock relative to these two reference points to be followed over the model period (Figure 46). From 1952 to 1970, exploitation rates were low while total biomass declined rapidly relative to $\tilde{B}_{MSY}$. Over the subsequent 25 years, the biomass level ($B_t/\tilde{B}_{MSY}$) remained relatively constant while $F_t/\tilde{F}_{MSY}$ steadily increased. The increase in $F_t/\tilde{F}_{MSY}$ accelerated from the mid 1990s to recent years, exceeding 1.0 in 2001 and remaining slightly above 1.0 in the subsequent years. During the same period, there was a rapid decline in $B_t/\tilde{B}_{MSY}$ and total biomass has approached the overfished threshold ($\tilde{B}_{MSY}$) in recent years (Figure 46). For the LOWSAMP model, current (2001–04) total biomass is estimated to be 17% higher than $\tilde{B}_{MSY}$ ($B_{current}/\tilde{B}_{MSY}$ = 1.17) (Table 5).

For the LOWSAMP model, the maximum equilibrium yield (MSY_t) was also computed for each year (*t*) in the model. This analysis enables an assessment of the *MSY* level that would be theoretically achievable under the different patterns of age-specific fishing mortality observed through the history of the fishery (Figure 47). Prior to 1970, the WCPO yellowfin fishery was almost exclusively conducted by the longline method, with a low exploitation of small yellowfin. The associated age-specific selectivity resulted in a substantially higher level of *MSY* (440,000 mt per annum) compared to that estimated for the fishery based on the recent age-specific fishing mortality pattern (329,600 mt). The decline in the *MSY* over time follows the increased development of those fisheries that catch smaller yellowfin, principally the surface fisheries (Figure 47). An additional demonstration of the impact of fishery composition on *MSY* is shown in Table 6, which shows the estimated *MSY*, *fmult* and $\tilde{B}_{MSY}$ for different hypothetical fisheries. *MSY* ranges from 436,092 mt per year for a situation where all current longline fisheries operate alone, to 248,960 mt if the fishery were composed only of the purse seine FAD/log set fishing operation.

A comparison of the yield and equilibrium biomass curves for the three model options is shown in Figure 48. For the three model options, maximum equilibrium yield was achieved at levels of *fmult* between 0.9 and 1.1 (equivalent to $F_{current}/\tilde{F}_{MSY}$ ratios of 0.91–1.11). *MSY* estimates were comparable between the two six-region models (about 83,000 mt per quarter), with current exploitation rates from the HIGHSAMP model approximating F_{MSY}. The seven-region model is more optimistic with a higher *MSY* (97,000 mt per quarter) and *fmult* of 1.1 ($F_{current}/\tilde{F}_{MSY}$ = 0.91). Equilibrium spawning and total biomass at F_{MSY} are estimated to be substantially higher for the seven-region model.

The *MSY* estimates for the three analyses range from about 82,400 mt to 97,000 mt per quarter (329,600 mt to 388,000 mt per year). These estimates of equilibrium yield are lower than recent catches, which have been of the order of 400,000–450,000 mt annually. Recent (1994–2004) recruitment has been at or slightly less than long-term recruitment levels. Consequently, the recent high catches have been sustained by the removal of the accumulated biomass, rather than higher recent recruitment levels. This is evident from the recent accelerated fishery impacts on the stock and levels of current and total biomass are approximately 60–70% of the corresponding biomass level in 1995 (Table 5).

A number of quantities of potential management interest associated with the yield analyses are provided in Table 5. In the top half of the table, absolute quantities are provided, while the bottom half of the table contains ratios of various biomass and fishing mortality measures that might be useful for stock monitoring purposes. It is useful to distinguish three different types of ratio: (i) ratios comparing a measure for a particular time period with the corresponding equilibrium measure; (ii) ratios comparing two equilibrium measures (rows shaded grey); and (iii) ratios comparing two measures pertaining to the same time period (row shaded black). Several commonly used reference points, such as $B_{current}/\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ fall into the first category. These ratios are usually subject to greater variability than the second category of ratios because recruitment variability is present in the numerator but not in the denominator. Indeed, the range of values observed over the various analyses conducted in recent assessments suggests that the category (ii) ratios are considerably more robust than those in category (i).

However, it is likely that $B_{current}/\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ will continue to be used as indicators of stock status and overfishing, respectively. This being the case, we need to pay particular attention to quantifying uncertainty in these ratios. Profile likelihood-based estimates of the posterior probability distribution of $B_{current}/\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ were calculated for this purpose. The profile likelihood distribution for the six-region LOWSAMP model reveals that there is a low probability that $B_{current}/\tilde{B}_{MSY}$ is below 1.0 (5%) and that the highest probability is at about the level of the point estimate from the model (1.17) — there is a 52% probability that $B_{current}/\tilde{B}_{MSY}$ is within 1.1–1.3 (Figure 49 and Table 7). The posterior probability distribution of $F_{current}/\tilde{F}_{MSY}$ is skewed with the mode of the distribution at about the point estimate of 1.10 and a 73% probability of $F_{current}/\tilde{F}_{MSY}$ exceeding 1.0 (Figure 50). The broad upper tail of the distribution includes a 21%

probability that $F_{current} / \widetilde{F}_{MSY}$ exceeds 1.5 (Table 7). The lower tail of the distribution is truncated at about 0.7, i.e., there is only a low probability that $F_{current} / \widetilde{F}_{MSY}$ is substantially less than 1.0. Somewhat more optimistic outcomes resulted from the other model options (Table 8).

6.6 Analyses of management options

At WCPFC-2, the Commission requested advice from the Scientific Committee on a number of issues relating to the assessment and management of yellowfin tuna. Subsequent discussions with the Acting Chair of SC-2 and the Executive Director identified the following analyses for inclusion in the yellowfin tuna stock assessment report for 2006:

1. Estimation of levels of fishing effort to ensure that the stock will remain at an agreed level above B_{MSY}; and
2. Stock projections to estimate:
   a. the effects of the WCPFC-2 conservation and management arrangements (CMAs) on the yellowfin tuna stock; and
   b. the effects of closures of the purse seine fishery, similar to those agreed by the IATTC for the eastern Pacific Ocean, on the yellowfin tuna stock.

For these analyses, we have used the base-case assessment (6-region, down-weighted size data – LOWSAMP).

6.6.1 Fishing Effort and B_{MSY}

To investigate this question, we consider the equilibrium biomass in relation to B_{MSY} so that the effects of variable recruitment on future biomass need not be considered. This is appropriate as we are simply interested in a long-term average indicator of the relationship between fishing effort, resulting biomass and B_{MSY}. The yield analysis described above provides a basis for estimating levels of equilibrium biomass that would result at different levels of relative fishing effort, assuming maintenance of the 2001–2004 overall fishery selectivity and constant catchability. The former assumption means, *inter alia*, that the relative fishing effort of each fishery defined in the assessment model remains the same as the 2001–2004 average.

Table 9 provides estimates of fishing effort scalars (relative to the 2001–2004 average) that result in equilibrium total biomass at various levels above B_{MSY}. The fishing effort scalar consistent with B_{MSY} is 0.92. In other words, fishing effort would need to be reduced across the board by 8% to obtain an equilibrium biomass equal to B_{MSY}. Progressively lower fishing effort is required to achieve higher equilibrium biomass relative to B_{MSY}.

6.6.2 Stock Projections

a. Effects of WCPFC-2 Conservation and Management Arrangements

Projections were constructed to simulate the application of the WCPFC-2 conservation and management arrangements as they apply to yellowfin tuna. The CMAs with respect to yellowfin tuna are contained in Attachment D of the WCPFC-2 report[2], and the pertinent paragraphs are:

> *1. Through the adoption of necessary measures, the total level of fishing effort for bigeye and yellowfin tuna in the Convention Area shall not be increased beyond current levels.*
>
> *8. CCMs shall take necessary measures to ensure that purse seine effort levels do not exceed either 2004 levels, or the average of 2001 to 2004 levels, in waters under their national jurisdiction, beginning in 2006.*

[2] http://www.wcpfc.org/wcpfc2/pdf/WCPFC2_Records_D.pdf

To take account of the above, the projection was designed as follows:

- o Purse seine effort levels for 2004 were assumed for the five-year projection period (2006–2010). The distribution of effort among regions, quarters and set types was specified according to the average distributions for the period 2001–2004. The use of a multi-year average distribution reduces the risk of anomalous results arising from unusually high or low effort occurring in one of these strata in an individual year.
- o Longline effort levels averaged over 2001–2004 were assumed for the projection period.
- o Relative effort levels for the Philippines and Indonesian domestic fisheries were assumed to continue through the projection period at 2004 levels (due to increases in estimated effective effort for those fisheries during 2001–2004).
- o For fisheries with estimated time-series variation in catchability, the estimated catchability for the last data year (2005) was assumed to continue through the projection period.
- o Recruitment during the projection period was predicted using the estimated SRR and distributed among regions based on the long-term average distribution of recruitment.

The results of the projection were expressed as the ratio of total biomass to $\widetilde{B}_{MSY}$ where the latter was computed using the *F*-at-age for the final year of the projection (2010). $\widetilde{B}_{MSY}$ at the end of the projection period is estimated to be 851,800 mt (compared to 960,500 mt at $F_{current}$). $B_t/\widetilde{B}_{MSY}$ for the final years of the assessment (2001–2005) and the five-year projection period is shown in Figure 51. Projected biomass and $B_t/\widetilde{B}_{MSY}$ decline initially due to low recruitments estimated towards the end of the assessment time period, but increase to near the levels at the start of the projection period by year 5.

During the projection period, there is a considerable shift in the regional distribution of total biomass with an increase in the proportion of biomass in regions 5 and 6 and a decline in biomass in the equatorial regions (regions 3 and 4) (Figure 52). The change in biomass distribution is due to the assumption that future recruitment is distributed according to the long-term distribution, thereby, increasing the level of recruitment in regions 5 and 6 compared to more recent years. Exploitation rates are lower in these two regions and, therefore, stock-wide *F*-at-age decreases through the projection period. This explains the reason for $B_t/\widetilde{B}_{MSY}$ remaining above 1.0 throughout the projection period despite $F_{current}/\widetilde{F}_{MSY}$ being above 1.0.

A profile likelihood for the biomass ratio in the final year of the projection ($B_{final}/\widetilde{B}_{MSY}$) was computed in order to characterize the uncertainty (Figure 53). While the mode of the probability distribution is not substantially different to that for the $B_{current}/\widetilde{B}_{MSY}$ profile, the variance is much greater, as expected, due to propagation of uncertainty in recruitment and other parameters through the projection period. Due to this increased uncertainty, the probability of $B_{final} < \widetilde{B}_{MSY}$ is approximately 29%, compared to 4.9% for $B_{current} < \widetilde{B}_{MSY}$.

The stock projections are highly sensitive to the underlying assumptions described above, particularly regarding the magnitude and distribution of future recruitments. For this reason, the profile likelihood underestimates the magnitude of the uncertainty associated with the stock projections. For example, if recruitment remained distributed among regions in accordance to the recent pattern of recruitment then the probability of the stock size falling below the $\widetilde{B}_{MSY}$ level would be greatly increased.

b. The effects of closures of the purse seine fishery

As $B_t/\widetilde{B}_{MSY}$ remains above 1.0 for the duration of the projection period, we have not tested purse seine closure scenarios for yellowfin tuna in this report. However, should the SC wish to investigate the effects of specific closure scenarios, these can be run during the meeting and the results presented.

7 Discussion and conclusions

This assessment of yellowfin tuna for the WCPO applied a similar modelling approach to that used in last year's assessment, although there were a number of important changes, notably:

- The weight frequency sample data were reprocessed to account for temporal and fishery-specific changes in the conversion factors used to convert processed weights (usually gilled-and-gutted) to whole fish weights. The principal effect of this change was to reduce the weight (in whole weight) of yellowfin sampled by the Japanese longline fisheries prior to 1973 (see Langley et al. 2006) and, thereby, reduce the magnitude of the decline in fish size from the longline fishery over the model period.
- A change in the yellowfin length-weight relationship was included in the model, applying a relationship more consistent with established values for the species. The relationship predicts a marginally higher weight-at-length compared to the relationship applied in the 2005 assessment.
- Selectivity was parameterised to allow declining selectivity of older fish for the principal (LL ALL 1–6) fisheries. In the previous assessment, all longline fisheries were constrained to be non-decreasing with increasing age and, thereby, have full selectivity for the oldest age classes.
- The base-case assessment (LOWSAMP) applied a lower effective sample size to the length- and weight-frequency data compared to the 2005 assessment. This gives greater influence to the effort data included in the model, resulting in trends in exploitable biomass for the principal longline fisheries being more consistent with the catch and effort series. The HIGHSAMP model applies effective sample sizes that are equivalent to those used in all of the 2005 yellowfin tuna assessment runs.
- Only the general linear modelling (GLM) approach was applied to the standardization of the longline effort series. The alternative statistical habitat based standardisation (SHBS) approach used in the 2005 assessment was not used in the current assessment.
- There was a change in the application of the regional scaling effects in the calculation of the standardised effort series for the principal longline fisheries. This resulted in an increased weighting to the LL ALL 5 longline CPUE index and, consequently, a higher total biomass estimated for this region (by approximately 50%).
- A sensitivity analysis was undertaken to investigate the effect of a substantial change in the regional structure of the model with the inclusion of an additional region in the western equatorial region encompassing the fisheries in Indonesian and Philippines waters.
- The addition of recent catch, effort, and size frequency data from most fisheries as well as the inclusion of a significant time-series of length frequency data (and some effort data) from the Philippines domestic fisheries.

The assessment integrated catch, effort, length-frequency, weight-frequency and tagging data into a coherent analysis that is broadly consistent with other information on the biology and fisheries. The model diagnostics did not indicate any serious failure of model assumptions, although inevitably, departures from the model's assumptions were identified in several areas:

- Lack of fit to the size data for some fisheries is indicative of temporal changes in selectivity. Some of these changes may be accommodated in future assessments by temporal stratification of certain fisheries. For example, we were able to demonstrate a substantial improvement in fit to the size data for LL ALL 1 by separating the fishery into two pre- and post-1978 fisheries. Lack of fit may also result from changes in the distribution of sampling programmes in relation to the distribution of catch and effort. Improved methods for aggregating samples in some fisheries may result in size data that are more representative of the total catch.

- The lack of fit to the juvenile modes in the size frequency data from some fisheries may indicate a bias in the model estimates of growth for the youngest age classes. There is also considerable divergence between the model estimates of initial growth and length-at-age derived from otolith readings. Further, more detailed, analysis of the modal structure of the size frequency data is required to understand this apparent discrepancy in the growth estimates from the model.
- Residuals in the tag return data for the Australian longline fishery suggested that yellowfin tuna may have patterns of residency that cannot be captured by the spatial resolution of this model. However, the excess in observed tag returns over those predicted was relatively minor in this case.

While not a failure of the model *per se*, the model did have some difficulty in interpreting the very strong declines in longline CPUE in regions 5 and 6 during the early 1950s. The model attempted to explain these CPUE trends by estimating very high initial recruitments in those regions. While high recruitment in the early 1950s is a possibility (and is in fact suggested by SEAPODYM simulations – see Lehodey 2005), there may be other explanations for the high initial longline CPUE, including short-term targeting of "hot-spots", higher initial catchability by longline due to higher competition for food, and others. This is the subject of ongoing research.

Approximate confidence intervals for many model parameters and other quantities of interest have been provided in the assessment. We would stress that these confidence intervals (both Hessian- and profile-likelihood-based) are conditional on the assumed model structure being correct. Estimated confidence intervals are also potentially impacted by priors, smoothing penalties and other constraints on the parameterisation. For these reasons, the confidence intervals presented in the assessment should be treated as minimum levels of uncertainty.

The HIGHSAMP (six-region, high effective sampling size) model most closely approximates the base case assessment from 2005. However, these assessments are not directly comparable due to a number of changes in the assessment from last year (Hampton et al. 2005). These changes are outlined above and represent refinements to the model rather than substantive changes to model structure. These changes have resulted in a slightly more optimistic assessment than last year, with a lower overall level of depletion (depletion to 45% of unexploited biomass in the HIGHSAMP assessment compared to 60% in the equivalent 2005 assessment) and lower levels of current fishing mortality ($F_{current}/\widetilde{F}_{MSY}$ of 1.0 compared to 1.22 from the 2005 assessment). Biomass based reference points are similar between the two assessments; $B_{current}/\widetilde{B}_{MSY}$ of 1.27 from the current (HIGHSAMP) assessment and 1.32 from the 2005 base case.

For the current assessment, preference was given to the model with a lower weighting given to the size frequency data and the LOWSAMP model was designated to be the base-case assessment. This decision was based on the observation of a temporal trend in the effort deviations for key longline fisheries in the HIGHSAMP model; essentially the model was unable to adequately fit the observed catch without the increasing the effective level of fishing effort through the model period. This indicates a degree of conflict between the catch and effort data and size-frequency data from these longline fisheries. It was considered that the catch and effort data are more informative about trends in stock size (exploitable biomass) than the size-frequency data and, on that basis, the influence of the size frequency data in the overall likelihood should be reduced (LOWSAMP model).

The LOWSAMP model is slightly more pessimistic than the HIGHSAMP model; biomass based reference points are lower ($B_{current}/\widetilde{B}_{MSY}$ of 1.17 compared to 1.27), levels of depletion are marginally higher, and fishing mortality based reference points are higher ($F_{current}/\widetilde{F}_{MSY}$ of 1.11 compared to 1.00). Recent declines in biomass have also been higher for the LOWSAMP model ($B_{current}/B_{1995}$ of 0.65 compared to 0.76 for the HIGHSAMP model). The difference in the summary reference points from the two models are consistent with the lower overall levels of recruitment and biomass estimated for the LOWSAMP model.

An alternative spatial stratification was also investigated in the current assessment. The primary reason for developing a seven-region model was to spatially isolate the domestic fisheries of Indonesia and Philippines. The historical and, in the case of the Indonesia fishery, recent levels of catch from these fisheries are highly uncertain and, given the magnitude of these assumed catches, represent the greatest source of uncertainty in the assessment. It was considered that by compartmentalising these fisheries in a separate region the impact of this source of uncertainty in the overall model would be reduced. The revised regional stratification also attempted to minimise the heterogeniety in the population dynamics within each of the individual regions of the model (see Langley 2006a).

On this basis, it is likely that, in principle, the seven-region model is an improvement over the current six-region model. For the equatorial regions of the model (regions 3 and 4), the change in regional structure adopted in the seven-region model may represent an increase in the precision of the model for those two regions – the key regions for the management of the industrial purse-seine fisheries. The trend and magnitude of total biomass for these regions is comparable between the six- and seven region models, albeit for a substantially reduced area in the latter model — regions 3 and 4 of the seven-region model do not include the western region of the Philippine Sea and the South China Sea and the northern boundary of two regions is retracted to 10°N.

Nevertheless, the seven-region model does not address the main deficiency of the current six-region assessment; rather, the uncertainty is partitioned into another region. The western equatorial region (region 7) is estimated to account for a substantial proportion of the total WCPO yellowfin biomass (about 13%). Trends in longline CPUE for this region differ from other areas within the western equatorial waters, hence, the rationale for partitioning this area. However, changes in the spatial distribution and targeting practices of the longline fishery in region 7 mean that there is no reliable index of stock abundance from the late 1980s onward.

In the absence of a strong index of abundance, the model accounts for the large and increasing catches from the Indonesia/Philippines domestic fisheries through a large increase in recruitment from region 7, particularly in the last decade. There are limited data to support this observation from the model beyond the assumed increase in catch and, consequently, less credence should be given to the results from the seven-region model. Further development of a model incorporating a similar spatial stratification will be dependent on developing a reliable (fishery-dependent) index of abundance for this region.

The main conclusions of the current assessment, largely based on the six-region model, are as follows.

1. For the three analyses, there was a strong temporal trend in recruitment. Initial recruitment was relatively high but declined to a lower level during the early 1970s. Recruitment subsequently increased during the late-1970s and remained relatively high during the 1980s and 1990s. This is a similar, albeit weaker, pattern to that obtained in previous assessments and is largely attributable to the trends in the principal longline CPUE indices, particularly from regions 3 and 4.
2. For all analyses, the trends in biomass are generally comparable prior to the mid-1980s and were consistent with the underlying trends in recruitment, with biomass declining during the initial period to a low level in the early–mid 1970s, before increasing in the mid-1970s. Biomass levels remained relatively stable during the 1980s. For all model options, biomass is estimated to have declined steadily since 1990, largely due to the decline in the biomass within region 3 but also evident in most other regions.
3. The biomass trends in the model are strongly driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. For some of the main longline fisheries, there is an apparent inconsistency between the trends in the size-frequency data and the trends in longline catch and effort; i.e., the two types of data are providing inconsistent information about the relative level of fishing mortality in the region. The LOWSAMP model was adopted as the

base case because it was considered that the catch and effort data are more informative than the size-frequency data in the estimation of trends in fishing mortality. However, further research is required to explore the relationship between longline CPUE and yellowfin abundance and the methodology applied to standardise the longline CPUE data, particularly to account for temporal trends in fishing efficiency. The latter issue was examined by way of a sensitivity analysis in the 2005 assessment and shown to be highly influential in the conclusions of the assessment.

4. Fishing mortality for adult and juvenile yellowfin tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. A significant component of the increase in juvenile fishing mortality is attributable to the Philippines and Indonesian surface fisheries, which have the weakest catch, effort and size data. There has been recent progress made in the acquisition of a large amount of historical length frequency data from the Philippines and these data were incorporated in the assessment. However, there is an ongoing need to improve estimates of recent and historical catch from these fisheries and maintain the current fishery monitoring programme within the Philippines. Many of the key conclusions of the assessment are strongly influenced by the current assumptions regarding historical and current catches from these fisheries.

5. The ratios $B_t / B_{t,F=0}$ provide a time-series index of population depletion by the fisheries. Depletion has increased steadily over time, reaching a level of 50% of unexploited biomass (a fishery impact of 50%) in 2004. This represents a moderate level of stock-wide depletion that is approaching the equivalent equilibrium-based limit reference point ($\widetilde{B}_{MSY} / \widetilde{B}_0$ = 0.42). Further, depletion is somewhat greater for some individual model regions, notably in the equatorial region 3 where recent depletion levels are approximately 0.3 (a 70% reduction from the unexploited level). Other regions are less depleted, with indices of 0.8 or greater for all other regions except for region 4 (0.5). If stock-wide over-fishing criteria were applied at the level of our model regions, we would conclude that region 3 is over-exploited, region 4 is fully exploited, and the remaining regions are under-exploited.

6. The attribution of depletion to various fisheries or groups of fisheries indicates that the Indonesian fishery has the greatest impact, particularly in its home region (3) and is contributing significantly to the impact in adjacent regions 1, 4 and 5. The purse seine fishery also has a high impact in regions 3 and 4 and accounts for a significant component of the recent impacts in all other regions, except region 6. It is notable that the composite longline fishery is responsible for biomass depletion of about 10% in the WCPO during recent years.

7. The reference points that predict the status of the stock under equilibrium conditions are $\widetilde{B}_{F_{current}} / \widetilde{B}_{MSY}$ (0.91) and $S\widetilde{B}_{F_{current}} / S\widetilde{B}_{MSY}$ (0.87), which indicate that the long-term average biomass would approximate or fall below that capable of producing *MSY* at 2001–2004 average fishing mortality. Overall, current biomass exceeds the biomass yielding *MSY* ($B_{current} / \widetilde{B}_{MSY}$ > 1.0); i.e. **the yellowfin stock in the WCPO is not in an overfished state**. However, biomass levels in recent years have been declining under increasing levels of fishing mortality, and the probability of the stock becoming overfished is increasing over time.

8. The estimate of $F_{current} / \widetilde{F}_{MSY}$ reveals that **overfishing of yellowfin is likely to be occurring in the WCPO**. While the stock is not yet in an overfished state ($B_{current} / \widetilde{B}_{MSY}$ > 1), further biomass decline is likely to occur at 2001–2004 levels of fishing mortality.

9. Stock projections for 2006–2010 — that attempt to simulate the conservation and management measures adopted at WCPFC2 — indicate that the point estimate of $B_t / \widetilde{B}_{MSY}$ remains above 1.0 throughout the projection period. However, the increasing uncertainty in the future projections results in a greater probability of the biomass declining below $\widetilde{B}_{MSY}$ by the end of the projection period. The projections indicate a strong shift in the spatial distribution of biomass with continued depletion occurring in the equatorial regions. This change in the spatial distribution of biomass

results in a reduction in the aggregated F-at-age, thereby, explaining why $B_t / \widetilde{B}_{MSY}$ remains above 1.0 throughout the projection period despite $F_{current} / \widetilde{F}_{MSY}$ exceeding 1.0.

10. The 7REGION model provides a slightly more optimistic assessment of the status of the stock than the base-case model, although the probability of $F_{current} / \widetilde{F}_{MSY} > 1$ (overfishing) is still significant (49%). However, because of the lack of a reliable index of abundance since the late-1980s and weak data generally for the additional region (western tropical Pacific incorporating Philippines and Indonesia), we do not have sufficient confidence in the 7REGION model to use it as the main management advisory model at this time. Subject to further model testing and the incorporation of improved data from the western tropical region, it may be possible in the future to adopt the 7REGION model structure for the assessment.

8 Acknowledgements

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Table 1. Definition of fisheries for the six-region MULTIFAN-CL analysis of yellowfin tuna.

Fishery	Nationality	Gear	Region
1. LL ALL 1	Japan, Korea, Chinese Taipei	Longline	1
2. LL ALL 2	Japan, Korea, Chinese Taipei	Longline	2
3. LL HW 2	United States (Hawaii)	Longline	2
4. LL ALL 3	All excl. Chinese Taipei & China	Longline	3
5. LL TW-CH 3	Chinese Taipei and China	Longline	3
6. LL PG 3	Papua New Guinea	Longline	4
7. LL ALL 4	Japan, Korea	Longline	4
8. LL TW-CH 4	Chinese Taipei and China	Longline	4
9. LL HW 4	United States (Hawaii)	Longline	4
10. LL ALL 5	All excl. Australia	Longline	5
11. LL AU 5	Australia	Longline	5
12. LL ALL 6	Japan, Korea, Chinese Taipei	Longline	6
13. LL PI 6	Pacific Island Countries/Territories	Longline	6
14. PS ASS 3	All	Purse seine, log/FAD sets	3
15. PS UNS 3	All	Purse seine, school sets	3
16. PS ASS 4	All	Purse seine, log/FAD sets	4
17. PS UNS 4	All	Purse seine, school sets	4
18. PHID MISC 3	Philippines, Indonesia	Miscellaneous (small fish)	3
19. PH HL 3	Philippines, Indonesia	Handline (large fish)	3

Table 2. Main structural assumptions of the yellowfin tuna six-region base-case analysis (LOWSAMP) and details of estimated parameters, priors and bounds. Note that the number of estimated parameters shown is substantially greater than the effective number of parameters in a statistical sense because of the effects of priors, bounds and smoothing penalties.

Category	**Assumptions**	**Estimated parameters** (ln = log transformed parameter)	**No.**	**Prior**		**Bounds**	
				μ	**σ**	**Low**	**High**
Observation model for total catch data	Observation errors small, equivalent to a residual SD on the log scale of 0.07.	None	na	na	na	na	na
Observation model for length-frequency data	Normal probability distribution of frequencies with variance determined by effective sample size and observed frequency. Effective sample size assumed to be 0.02 times actual sample size for all fisheries with a maximum effective sample size of 20.	None	na	na	na	na	na
Observation model for weight-frequency data	Normal probability distribution of frequencies, variance determined by effective sample size and observed frequency. Effective sample size assumed to be equal to 0.02 times the actual sample size for all fisheries with a maximum effective sample size of 20.	None	na	na	Na	na	na
Observation model for tagging data	Tag numbers in a stratum have negative binomial probability distribution, with estimated variance parameters for fishery groups.	Variance parameters	3	-	-	0	100
Tag reporting	Purse seine reporting rates constrained to be equal within regions. PH /ID fishery reporting rates constrained to be equal. All reporting rates constant over time.	LL 1–LL6, CH/TW LL, PNG LL, PI LL	10	0.5	0.7	0.001	0.9
		AU LL, HW LL	3	0.8	0.7	0.001	0.9
		PS	2	0.45	0.05	0.001	0.9
		PH, ID fisheries	1	0.6	0.05	0.001	0.9
Tag mixing	Tags assumed to be randomly mixed at the model region level two quarters following the quarter of release.	None	na	na	na	na	na
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, lower bound 0.2) .The spatial distribution of recruitment in each quarter is allowed to vary with a small penalty on deviations from the average spatial distribution.	Average spatially aggregated recruitment (ln)	1	-	-	-20	20
		Spatially aggregated recruitment deviations (ln)	216	SRR	0.7	-20	20
		Average spatial distribution of recruitment	5	-	-	0	1
		Time series deviations from average spatial distribution (ln)	1,070	0	1	-3	3

Initial population	A function of the initial recruitment and equilibrium age structure in each region, which is in turn assumed to arise from the total mortality estimated for 1952–56 and movement rates.	Initial recruitment scaling (ln)	1	-	-	-8	8
Age and growth	28 quarterly age-classes, with the last representing a plus group. Juvenile age-classes 1-8 have independent mean lengths constrained by a small penalty for deviation from the von Bertalanffy growth curve; adult age-class mean lengths constrained by VB curve. SD of length-at-age are log-linearly related to the mean length-at-age. 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= 2.512e-05, b= 2.9396, source N. Miyabe, NRIFSF).	Mean length age class 1	1	-	-	20	40
		Mean length age class 28	1	-	-	140	200
		von Bertalanffy *K*	1	-	-	0	0.3
		Independent mean lengths	7	0	0.7		
		Length-at-age SD	1	-	-	3	8
		Dependency on mean length (ln)	1	-	-	-1.00	1.00
Selectivity	Constant over time. Coefficients for the last 4 age-classes are constrained to be equal. Longline fisheries LL ALL 1–2 and LL ALL 3–6 share selectivity parameters. Purse-seine fisheries share selectivity among regions. For all fisheries, selectivity parameterised with 5-node cubic spline, except Taiwanese/Chinese longline selectivities with logistic function (non decreasing with age).	Selectivity coefficients (5 cubic spline nodes or 2 logistic parameters per fishery)	57	-	-	0	1
Catchability	Constant over years and among regions for longline fisheries (effort data are scaled to reflect different region sizes). Seasonal variation for all fisheries apart from Philippines and Indonesian fisheries. Non-longline fisheries and the Australian and Taiwanese/Chinese longline fisheries have structural time-series variation, with random steps (catchability deviations) taken every 2 years.	Average catchability coefficients (ln)	14	-	-	-15	1
		Seasonality amplitude (ln)	17	0	2.2	-	-
		Seasonality phase	17	-	-	-	-
		Catchability deviations PH/ID (ln)	34	0	0.7	-0.8	0.8
		Catchability deviations other (ln)	141	0	0.1	-0.8	0.8
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.1 for LL ALL 1–6 and SD 0.22 for other fisheries at the average level of effort for each fishery. SD inversely proportional to the square root of effort.	Effort deviations LL 1, 2, 4, 7, 10, 12 (ln)	1262	0	0.16	-6	6
		Effort deviations PH, ID (ln)	288	0	0.22	-6	6
		Effort deviations other (ln)	1078	0	0.22	-6	6
Natural mortality	Age-dependent but constant over time and among regions. All parameters are specified (see Figure 10).	Average natural mortality (ln)	0	-	-	-	-
		Age-specific deviations (ln)	0	-	-	-	-
Movement	Age-independent and variant by quarter but constant among years. No age-dependent variation.	Movement coefficients	56	0	0.32	0	3
		Age-dependent component (ln)	0	0	0.32	-4	4
Maturity	Age-dependent and specified – age-class 0-6: 0; 7: 0.25; 8: 0.5; 9: 0.75; 10-28: 1.0	None	na	na	na	0	1

Table 3. Details of objective function components for the three analyses using alternative likelihood weightings for size data (LOWSAMP, HIGHSAMP) and an alternative seven-region spatial structure (7REGION).

Objective function component	LOWSAMP	HIGHSAMP	7REGION
Total catch log-likelihood	469.56	538.90	494.88
Length frequency log-likelihood	-316,905.49	-427,887.32	-371,090.85
Weight frequency log-likelihood	-656,026.14	-842,348.96	-770,070.41
Tag log-likelihood	2,239.57	2,408.90	2,039.98
Penalties	4,906.23	6,252.58	5,119.05
Total function value	-965,316.27	-1,261,035.90	-1,133,507.35

Table 4. Description of symbols used in the yield analysis.

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2001–2004
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 (2001–2004) total biomass
$SB_{current}$	Average current (2001–2004) adult biomass
B_{1995}	Average total biomass in 1995
SB_{1995}	Average adult biomass in 1995
$B_{current,F=0}$	Average current (2001–2004) total biomass in the absence of fishing.

Table 5. Estimates of management quantities for the three stock assessment models. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading).

Management quantity	Units	LOWSAMP	HIGHSAMP	7REGION
$\tilde{Y}_{F_{current}}$	mt per year	328,320	330,040	385,120
$\tilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	329,680	330,040	388,120
$\tilde{B}_0$	mt	2,275,000	2,463,000	3,741,000
$\tilde{B}_{F_{current}}$	mt	869,700	1,050,000	1,731,000
$\tilde{B}_{MSY}$	mt	960,500	1,050,000	1,584,000
$\tilde{SB}_0$	mt	1,338,000	1,579,000	1,954,000
$\tilde{SB}_{F_{current}}$	mt	336,900	497,900	716,700
$\tilde{SB}_{MSY}$	mt	389,200	497,900	639,300
$B_{current}$	mt	1,120,690	1,337,468	1,951,174
$SB_{current}$	mt	468,097	643,500	836,511
$B_{current,F=0}$	mt	2,181,576	2,403,546	3,222,139
$B_{current}/\tilde{B}_0$		0.49	0.54	0.52
$B_{current}/\tilde{B}_{F_{current}}$		1.29	1.27	1.13
$B_{current}/\tilde{B}_{MSY}$		1.17	1.27	1.23
$B_{current}/B_{current,F=0}$		0.51	0.56	0.61
$SB_{current}/\tilde{SB}_0$		0.35	0.41	0.43
$SB_{current}/\tilde{SB}_{F_{current}}$		1.39	1.29	1.17
$SB_{current}/\tilde{SB}_{MSY}$		1.20	1.29	1.31
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.38	0.43	0.46
$\tilde{SB}_{F_{current}}/\tilde{SB}_0$		0.25	0.32	0.37
$\tilde{B}_{MSY}/\tilde{B}_0$		0.42	0.43	0.42
$\tilde{SB}_{MSY}/\tilde{SB}_0$		0.29	0.32	0.33
$F_{current}/\tilde{F}_{MSY}$		1.11	1.00	0.91
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		0.91	1.00	1.09
$\tilde{SB}_{F_{current}}/\tilde{SB}_{MSY}$		0.87	1.00	1.12
$\tilde{Y}_{F_{current}}/MSY$		1.00	1.00	0.99
$B_{current}/B_{1995}$		0.65	0.76	0.69
$SB_{current}/SB_{1995}$		0.58	0.68	0.68

Table 6. Estimates of MSY, the fishing effort required to achieve MSY (relative to the 2004 level of effort) and the biomass at MSY for hypothetical fisheries consisting of individual gear or set type components.

Gear type / fishery group	MSY (mt per year)	Relative fishing effort to achieve MSY	B_{MSY} (mt)
Longline only	436,092	5.07	991,700
Purse seine only	294,344	2.62	859,500
Purse seine log/FAD sets only	248,960	4.46	783,700
Purse seine school sets only	365,516	6.26	927,200
Philippines/Indonesia only	297,276	2.38	940,000

Table 7. Percentage probability that $B_{current}/\widetilde{B}_{MSY}$ and $F_{current}/\widetilde{F}_{MSY}$ exceed the reference value based on the likelihood profile of the six-region LOWSAMP model.

Reference level	Probability (%) of exceeding reference level	
	$B_{current}/\widetilde{B}_{MSY}$	$F_{current}/\widetilde{F}_{MSY}$
0.5	100.0	100.0
0.6	100.0	100.0
0.7	100.0	100.0
0.8	100.0	94.1
0.9	100.0	84.7
1.0	95.1	73.5
1.1	80.1	61.3
1.2	54.1	49.3
1.3	28.4	38.4
1.4	10.6	28.9
1.5	1.7	21.2
1.6	0.0	15.1
1.7	0.0	10.5
1.8	0.0	6.9
1.9	0.0	4.5
2.0	0.0	2.7
2.1	0.0	1.8
2.2	0.0	0.8
2.3	0.0	0.5
2.4	0.0	0.2
2.5	0.0	0.0

Table 8. Probabilities of exceeding reference points for each of the model structures investigated in the assessment.

Reference point	LOWSAMP	HIGHSAMP	7REGION
$P(F_{current}/\widetilde{F}_{MSY} > 1)$	73.5%	62.9%	49.4%
$P(B_{current}/\widetilde{B}_{MSY} < 1)$	4.9%	1.0%	2.5%

Table 9. Fishing effort scalars relative to the 2001-2004 average required to produce equilibrium total biomass at various levels above B_{MSY}.

Equilibrium biomass relative to B_{MSY}	Equilibrium biomass relative to $\widetilde{B}_0$	Fishing Effort Scalar relative to 2001-2004 average
1.00	0.41	0.92
1.05	0.43	0.87
1.10	0.45	0.83
1.15	0.47	0.78
1.20	0.49	0.74
1.25	0.51	0.70
1.30	0.53	0.66
1.35	0.55	0.62
1.40	0.57	0.58

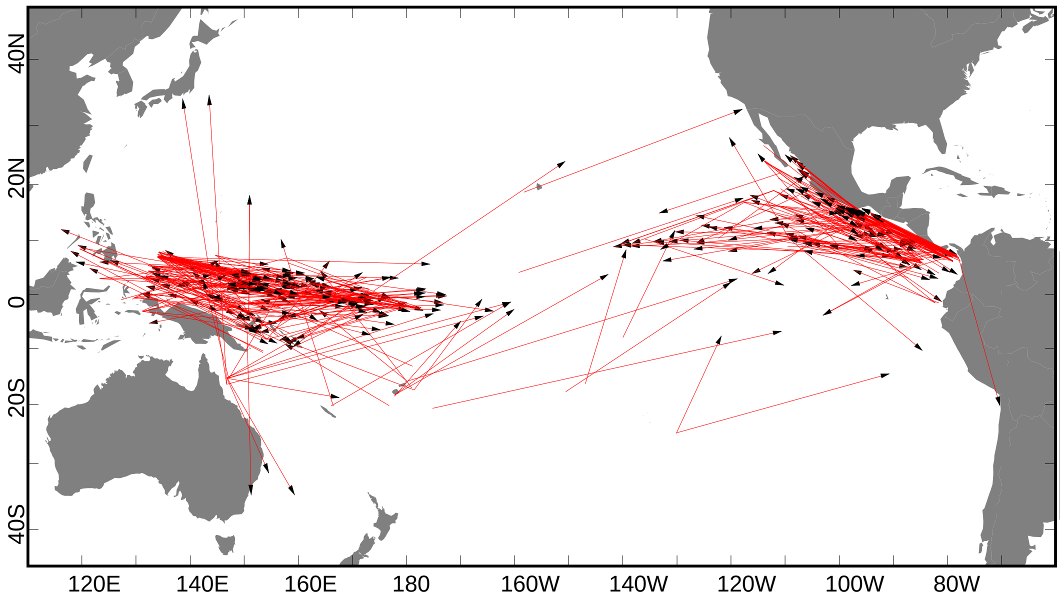


Figure 1. Long-distance (greater than 1,000 nmi) movements of tagged yellowfin tuna.

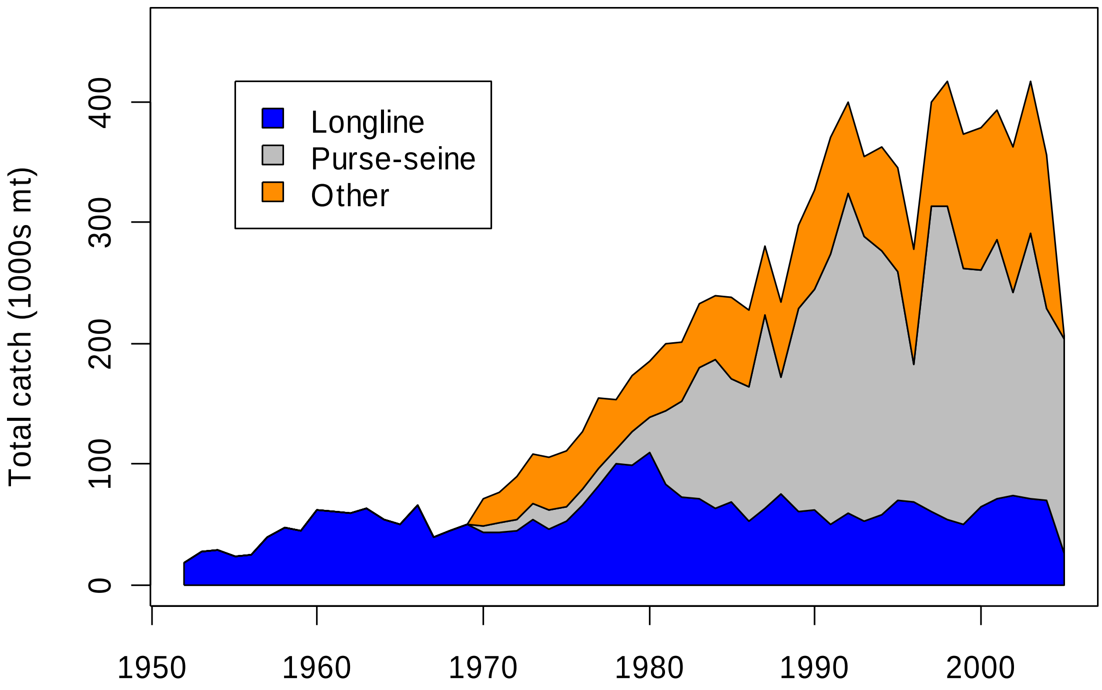
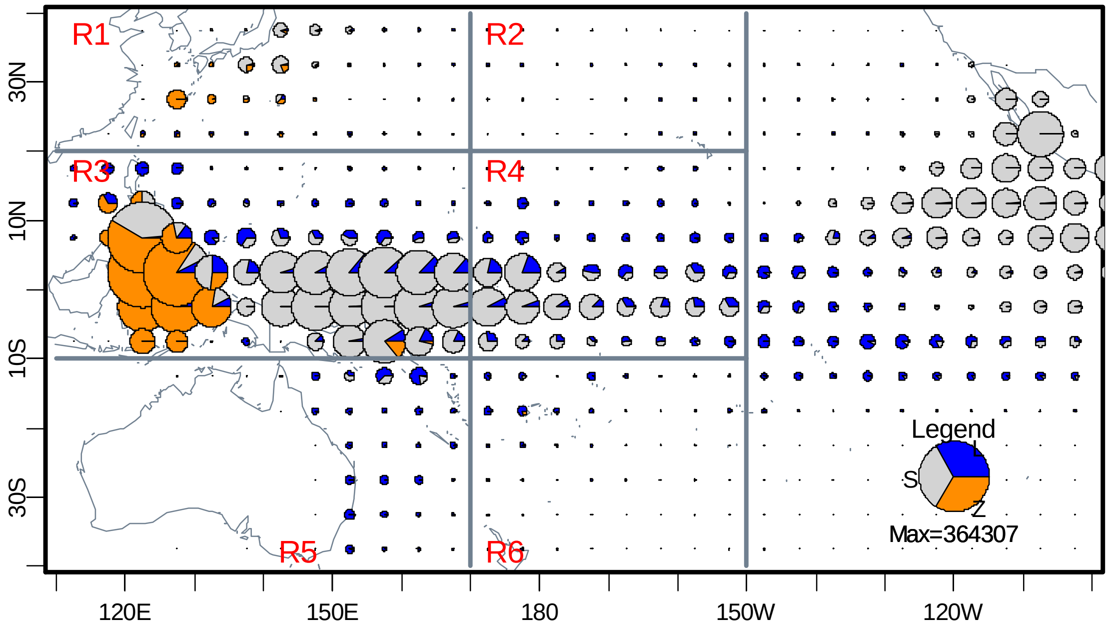


Figure 2. Total annual catch (1000s mt) of yellowfin from the WCPO by fishing method from 1952 to 2005. Data from 2005 are incomplete.

(a) Six-region spatial stratification



(b) Seven-region spatial stratification

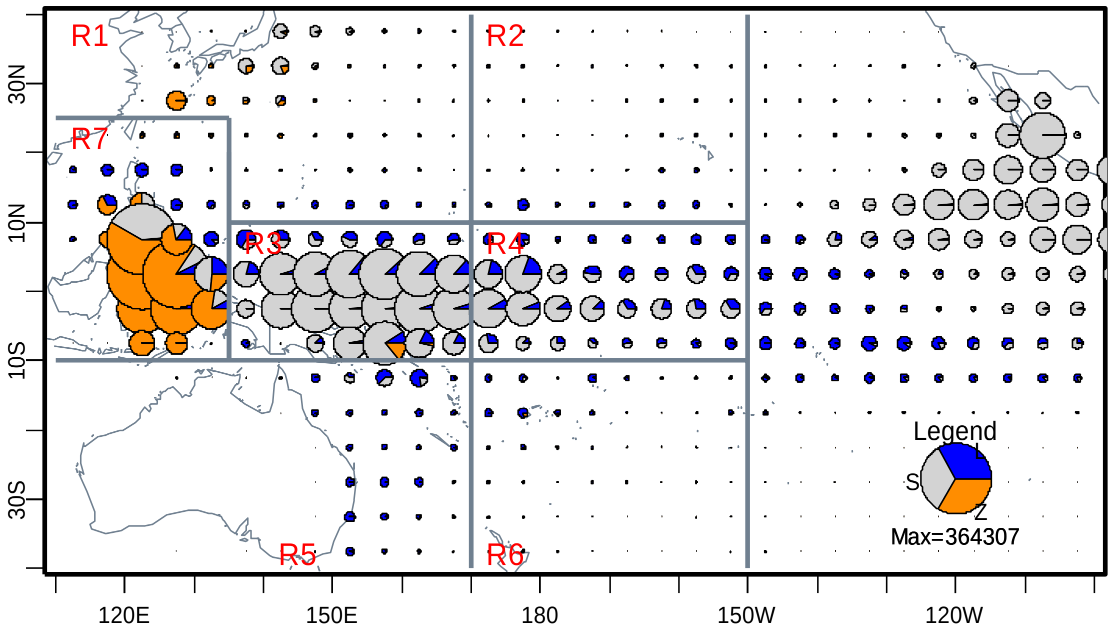


Figure 3. Distribution of cumulative yellowfin tuna catch from 1990–2004 by 5 degree squares of latitude and longitude and fishing gear; longline (blue), purse-seine (grey), and other (dark orange). The grey lines indicate the spatial stratification in the (a) six-region model (upper panel) and (b) the seven-region model (lower panel).

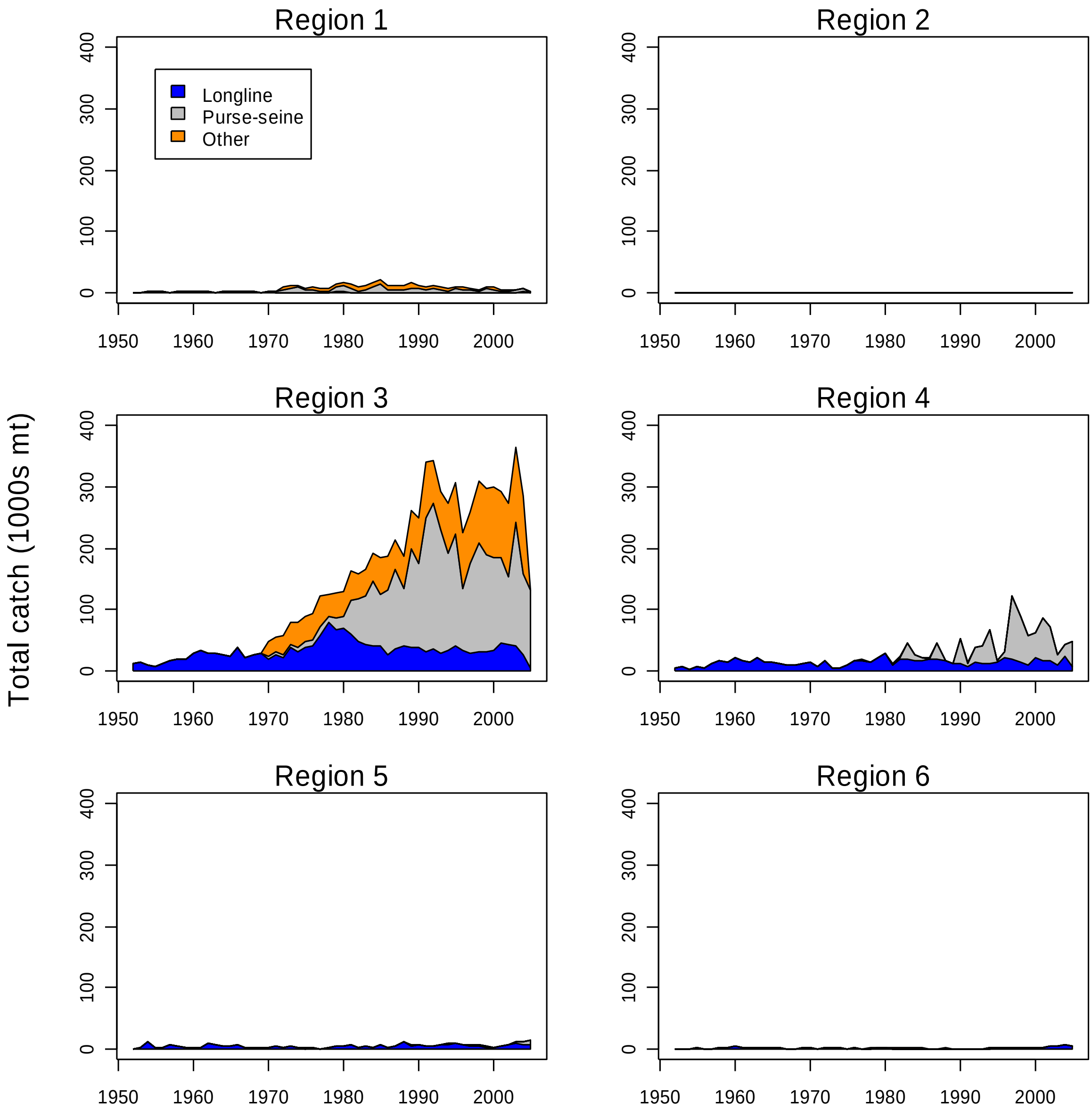


Figure 4. Total annual catch (1000s mt) of yellowfin by fishing method and MFCL region from 1952 to 2005. Data from 2005 are incomplete.

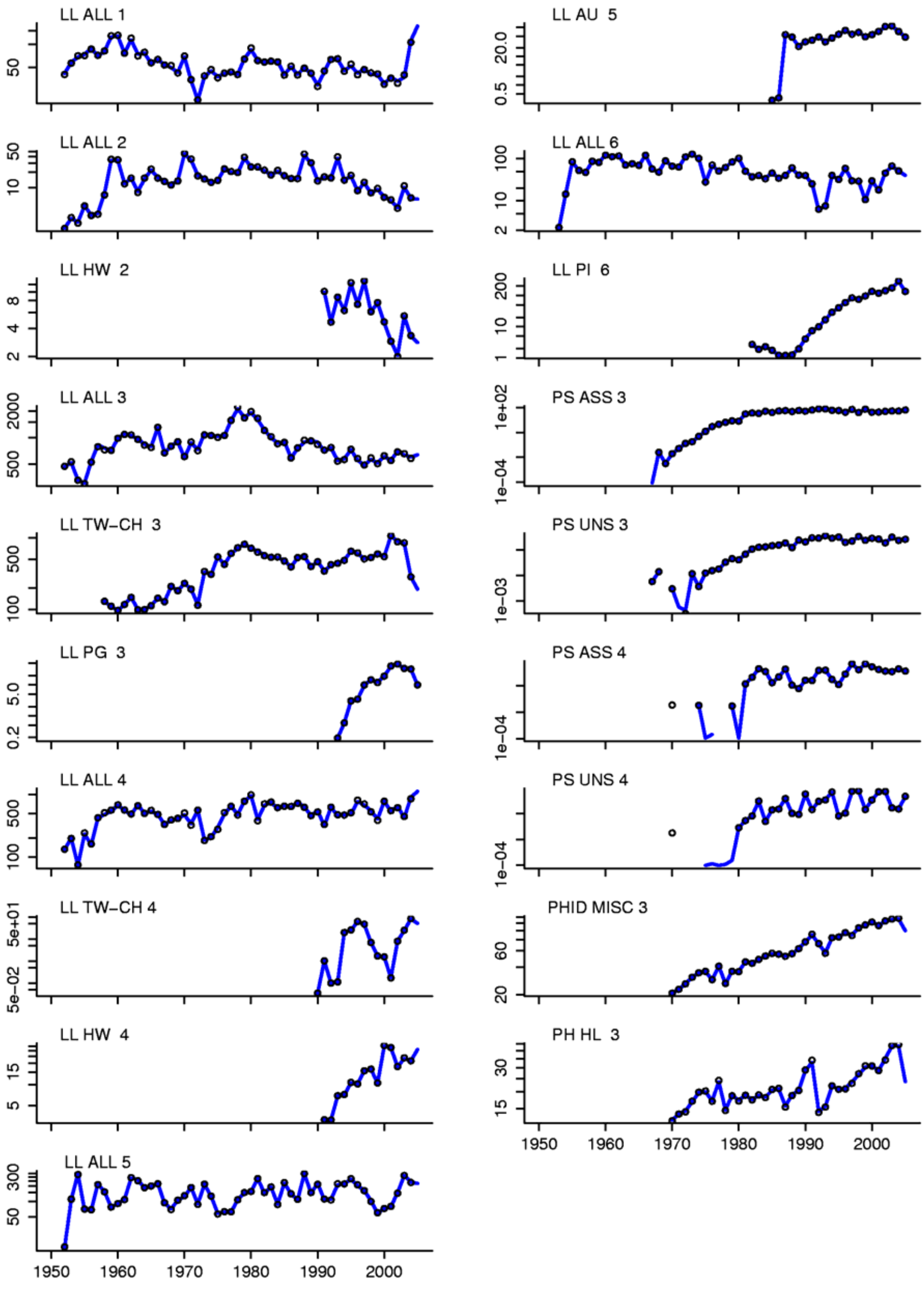


Figure 5. Annual catches, by fishery. Circles are observed and the lines are model predictions. Units are catch number in thousands for the longline fisheries and thousand metric tonnes for all other fisheries.

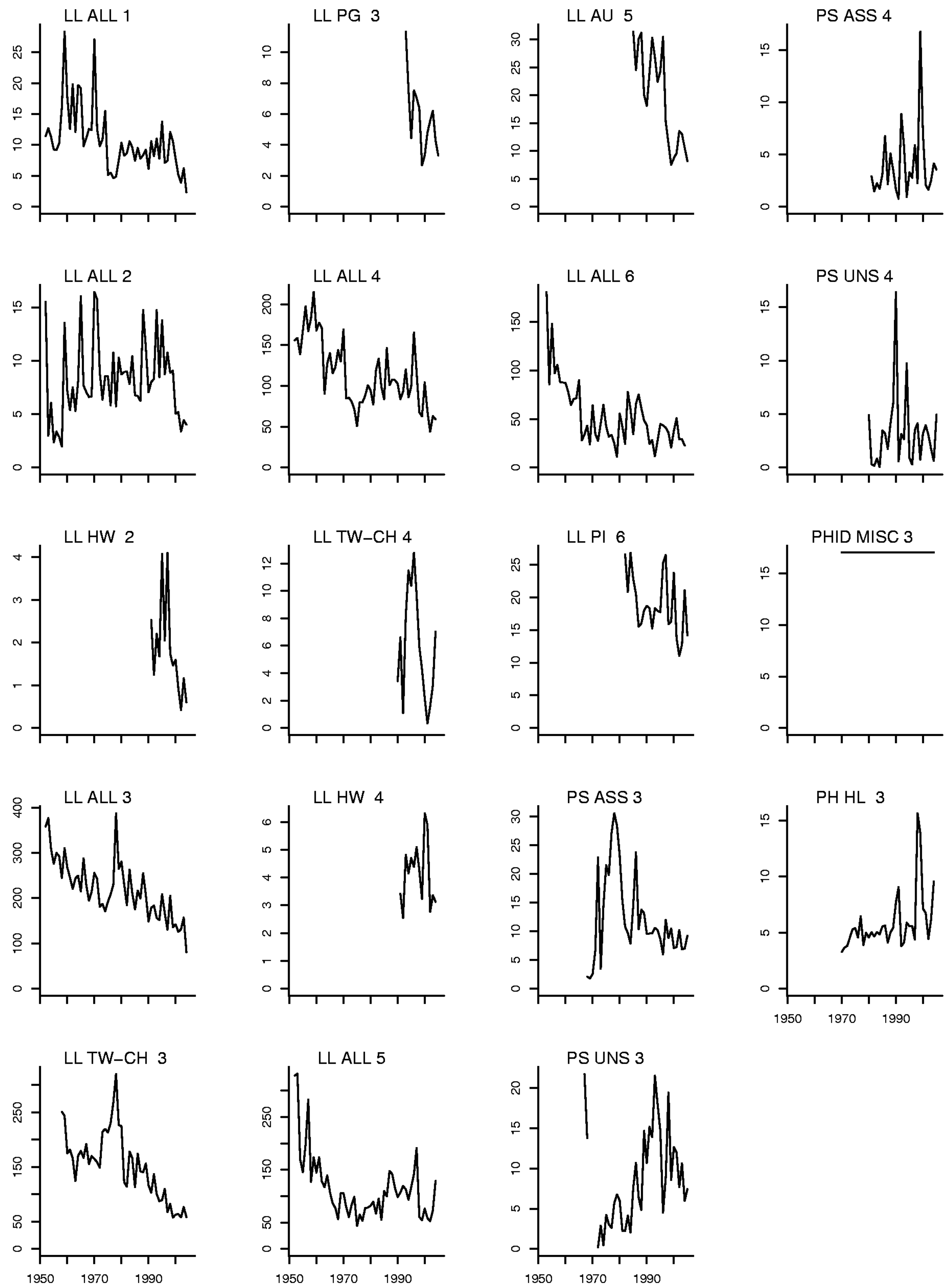


Figure 6. Catch-per-unit-effort (CPUE) by fishery. Units are catch number per GLM-standardised effort (fisheries LL ALL 1–LL ALL 6), catch number per 100 nominal hooks (LL HW, CH/TW LL, LL PI, LL PG) and catch (mt) per day fished/searched (all PS fisheries). Note that CPUE for PHID MISC 3 is arbitrary and not based on data (see discussion on catchability and effort deviation constraints for these fisheries).

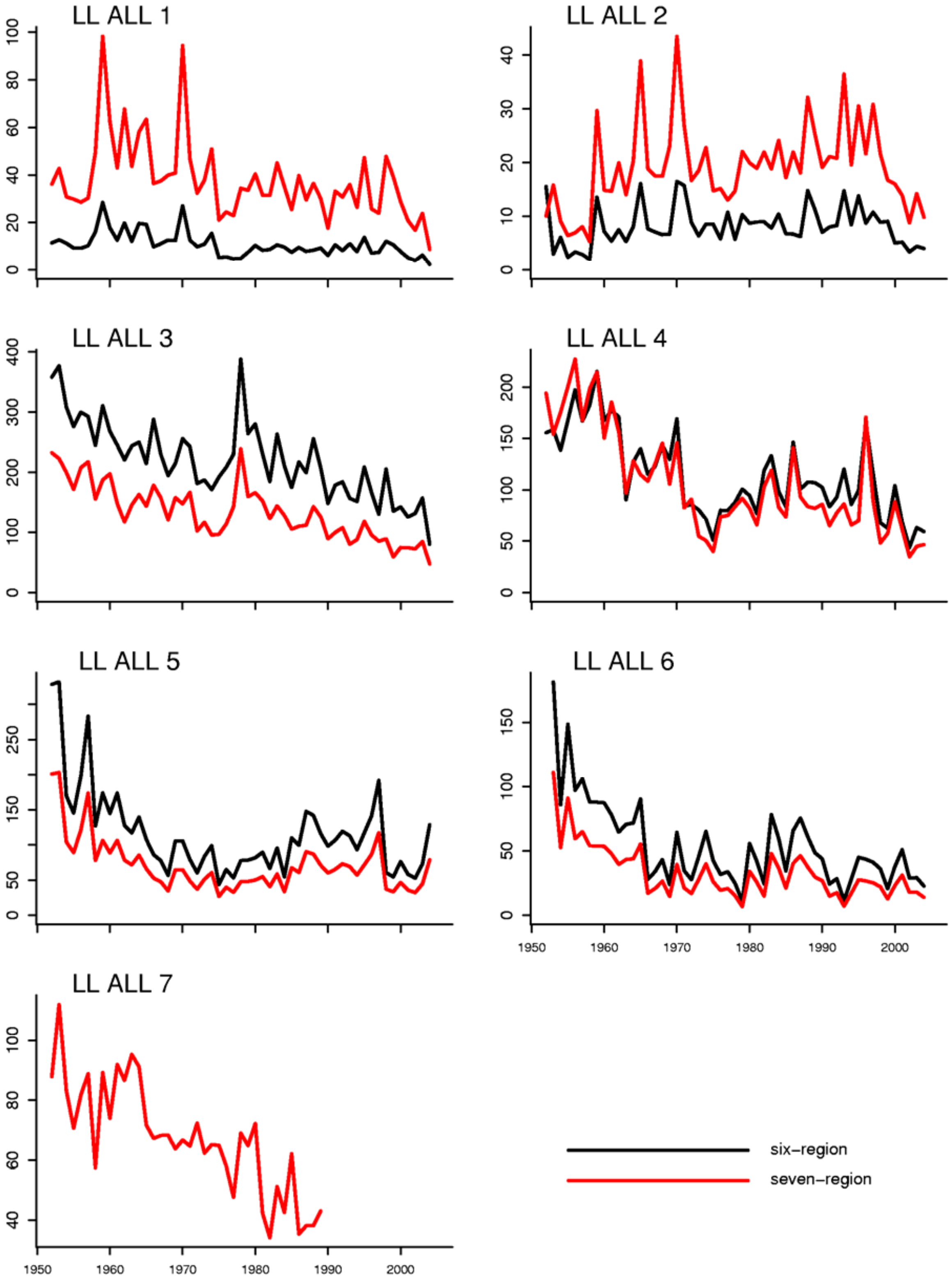


Figure 7. GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL ALL 1–6 and LL ALL 1–7) for the six-region and seven-region models and scaled by the respective region scalars. The LL ALL 7 index extends to 1990 only.

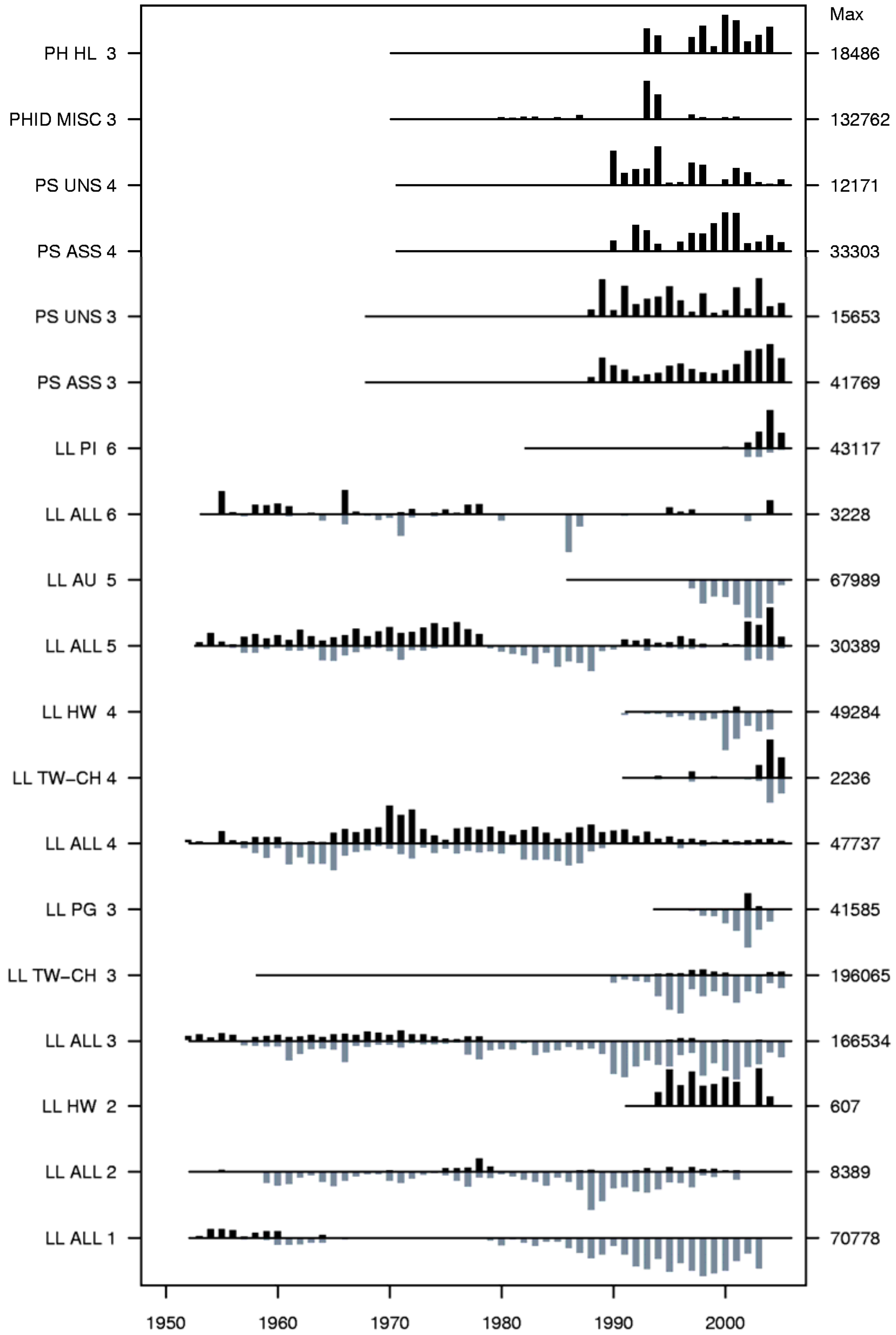


Figure 8. Number of fish size measurements by year for each fishery. The upper black bars represent length measurements and the lower grey bars represent weight measurements. The maximum bar length for each fishery is given on the right-hand side. The extent of the horizontal lines indicates the period over which each fishery occurred.

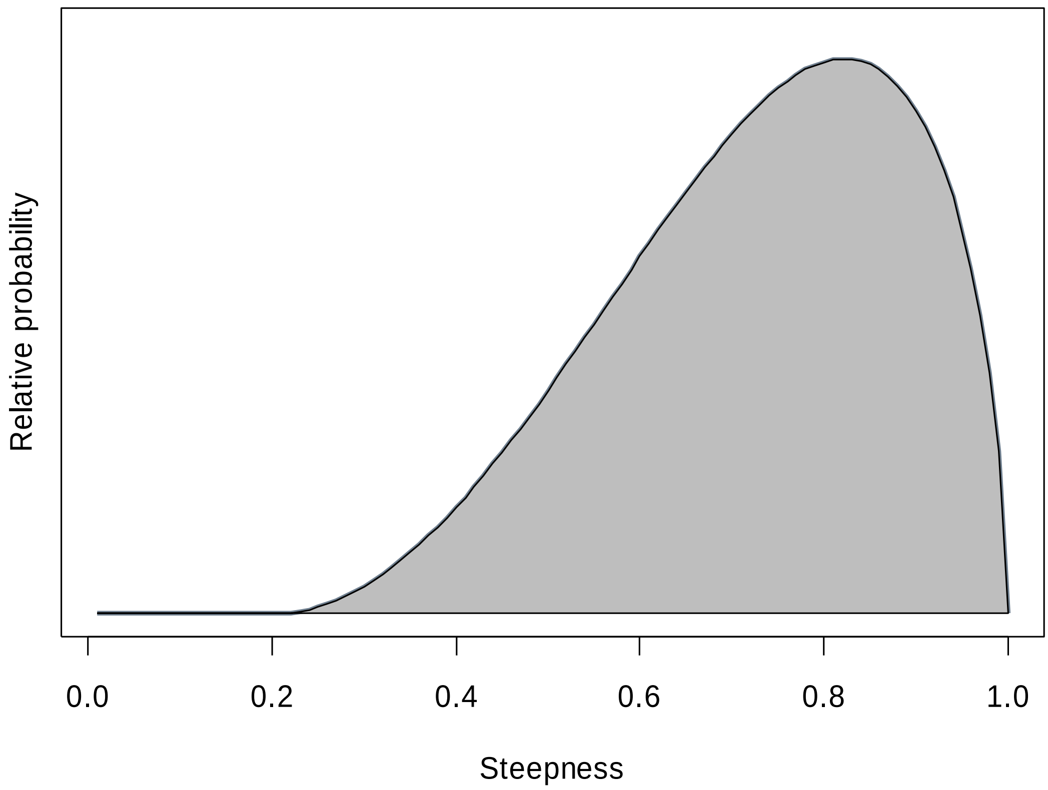


Figure 9. Prior for the steepness parameter of the relationship between spawning biomass and recruitment (SSR) (mode = 0.85, standard deviation = 0.16).

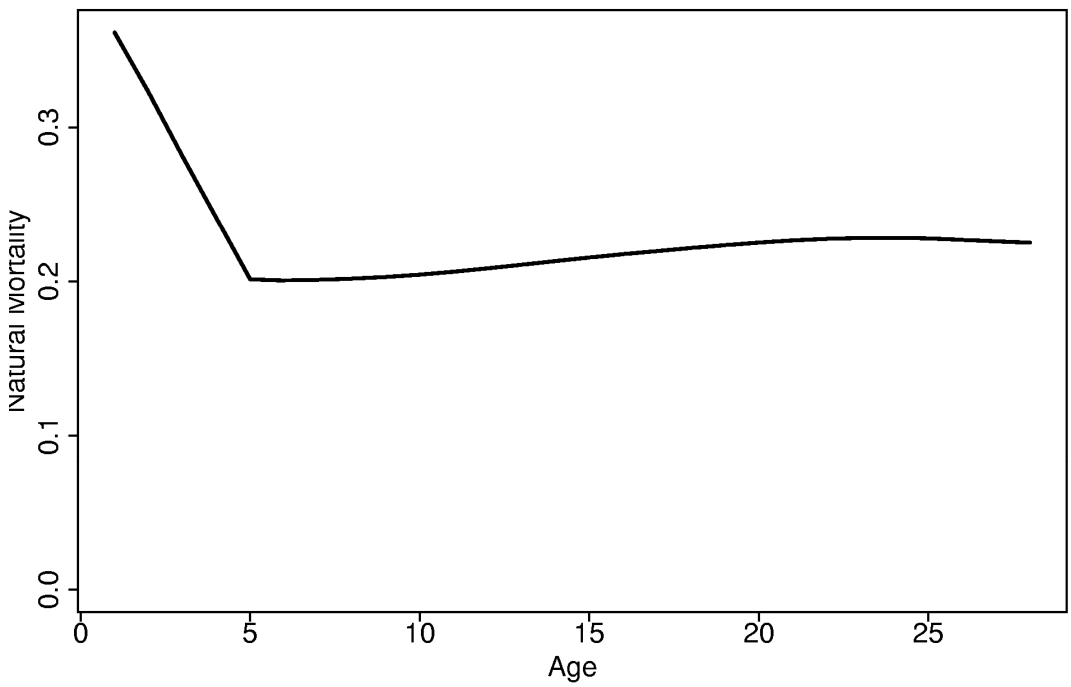


Figure 10. Age-specific natural mortality assumed for the sensitivity analyses using a fixed natural mortality from Maunder and Harley (2004).

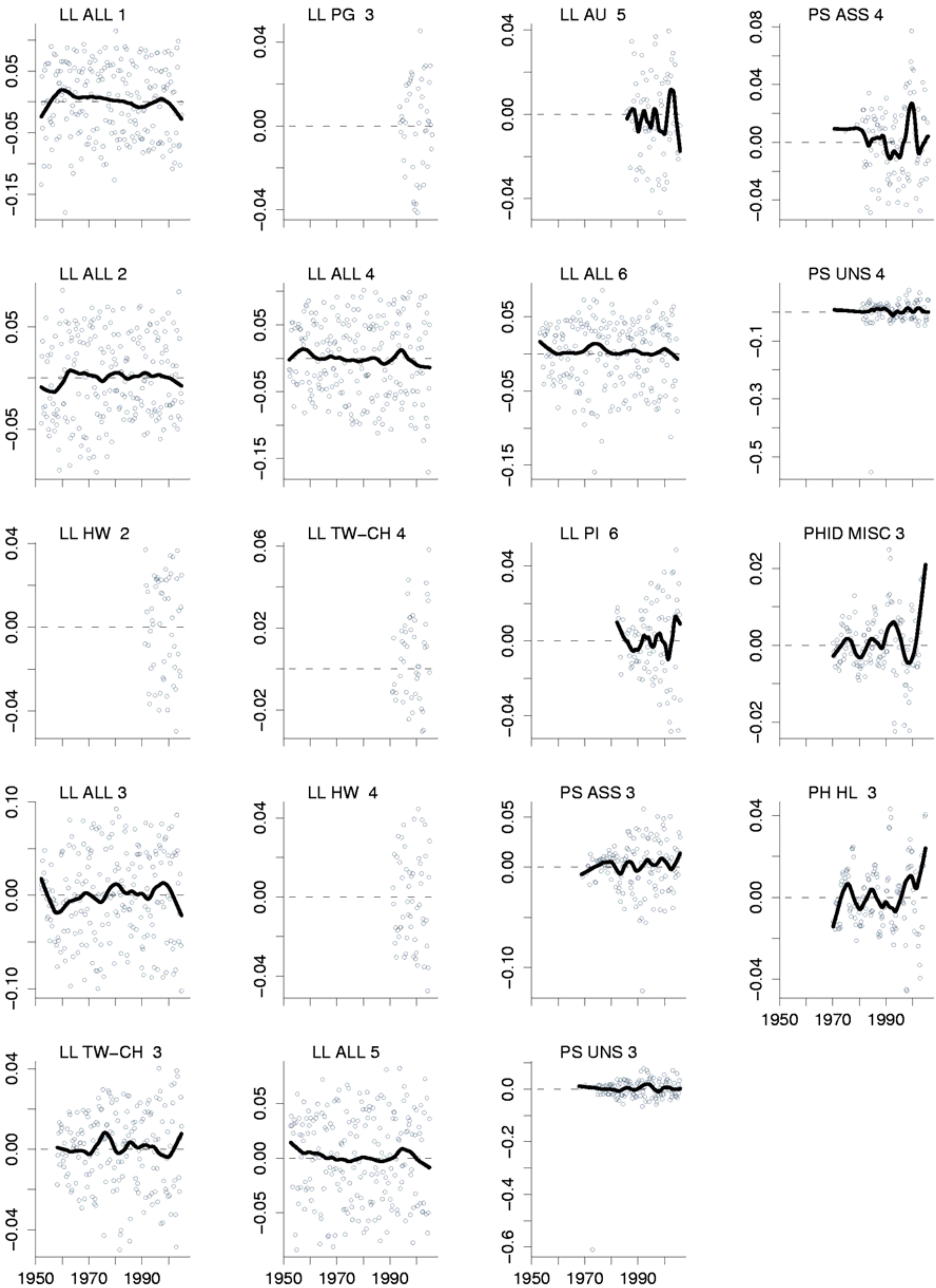


Figure 11. Residuals of ln (total catch) for each fishery (six-region LOWSAMP model). The solid line represents a lowess fit to the data.

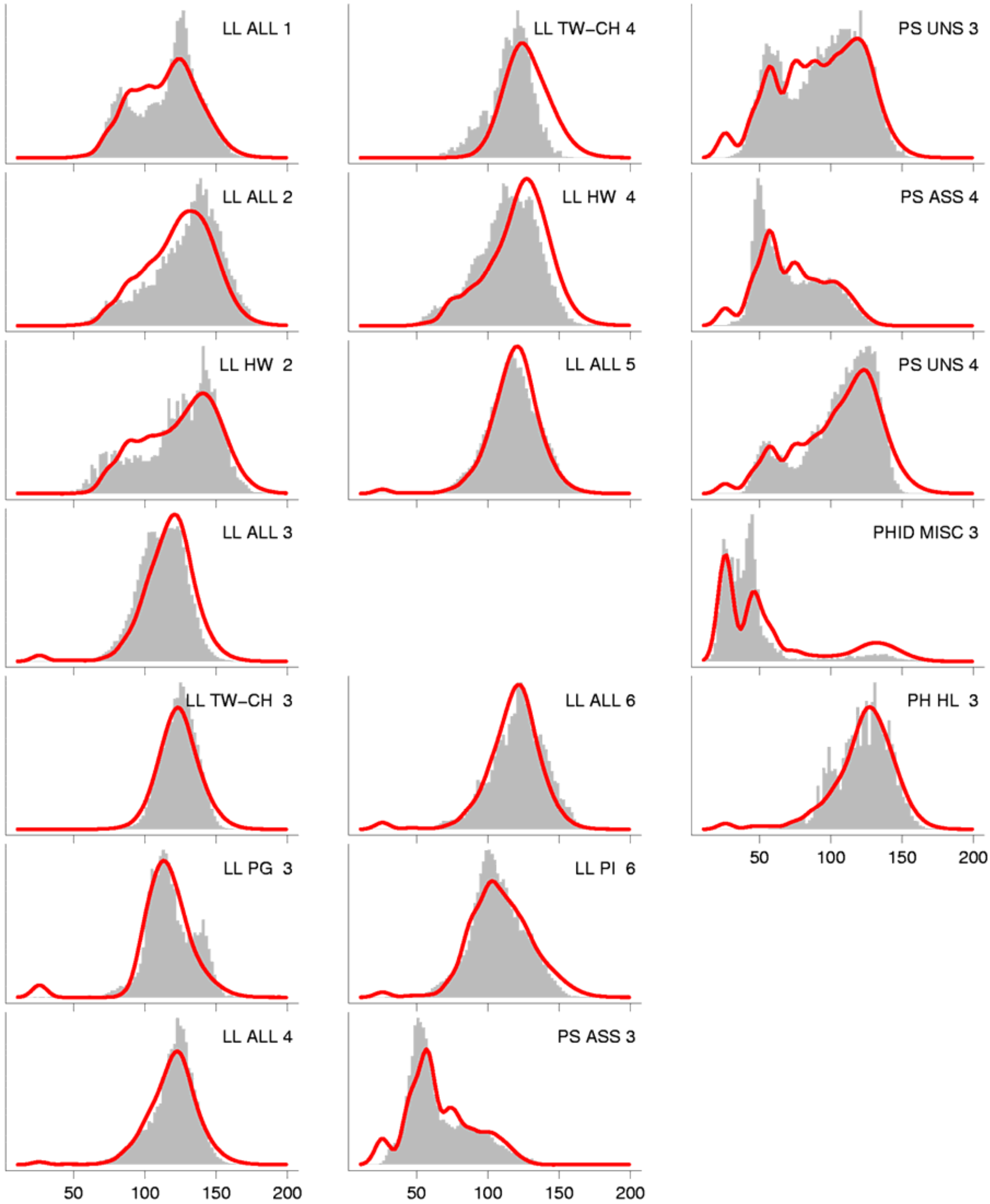


Figure 12. Observed (histograms) and predicted (line) length frequencies (in cm) for each fishery aggregated over time.

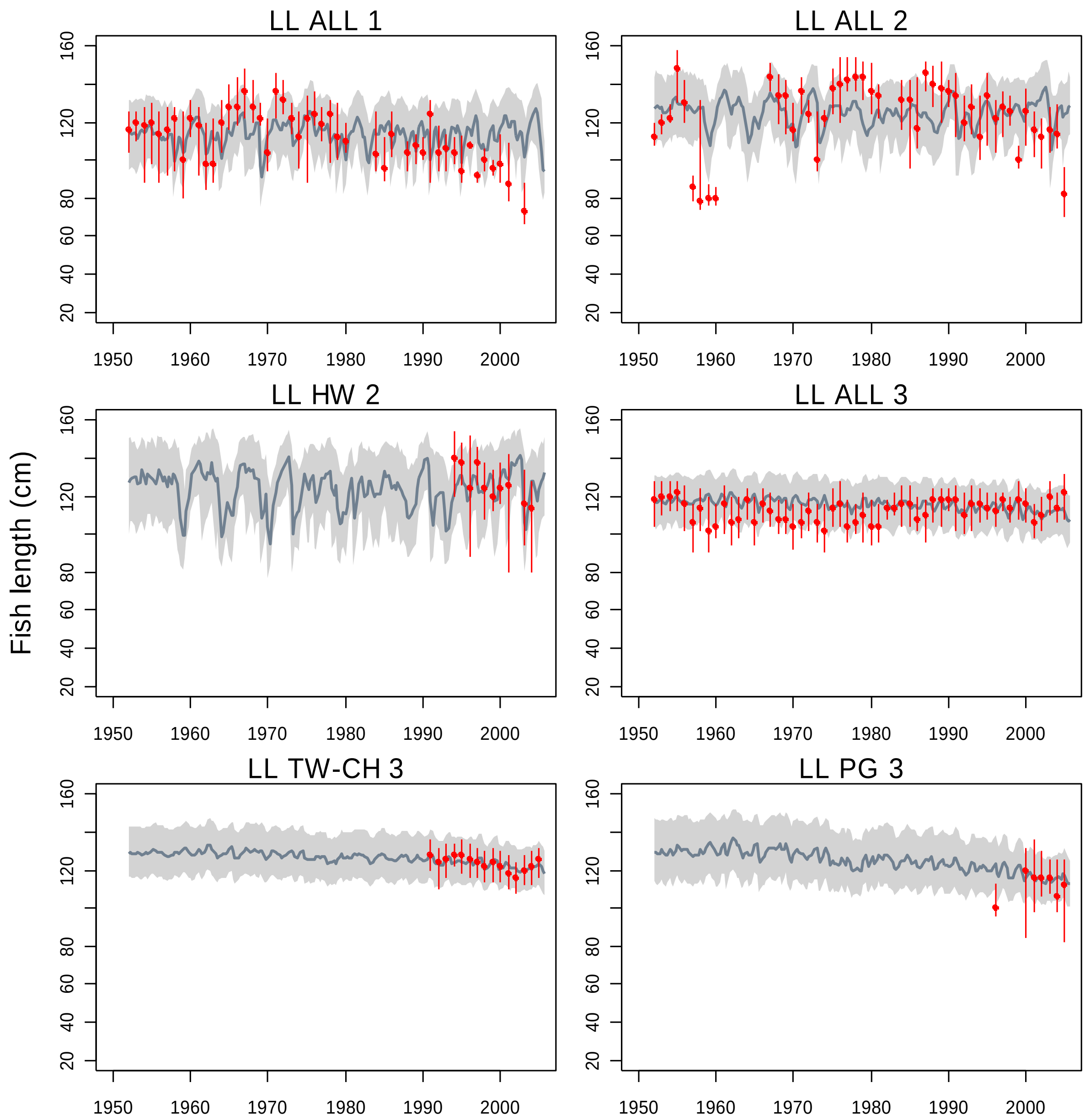


Figure 13. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of yellowfin tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

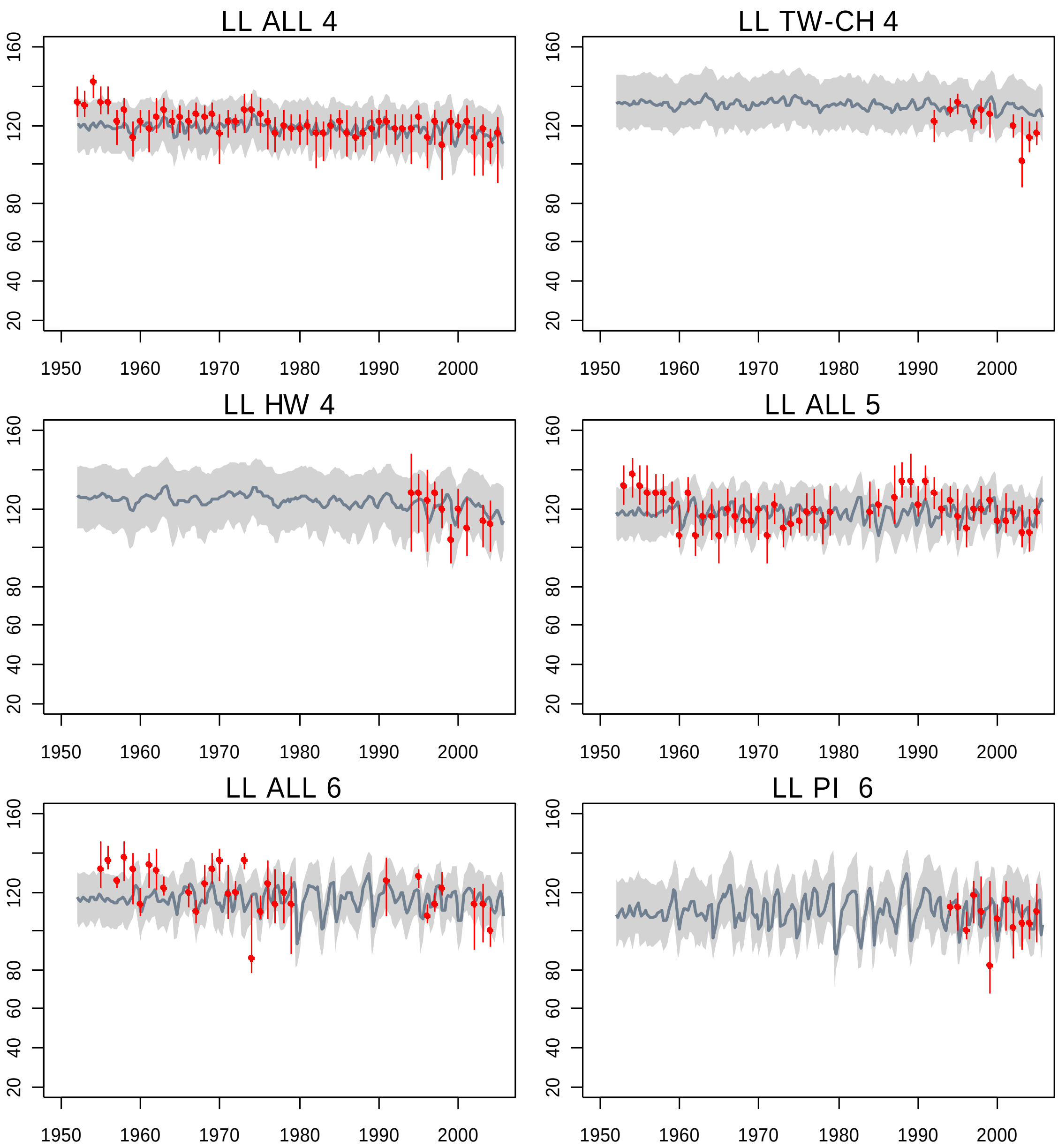


Figure 13 (continued).

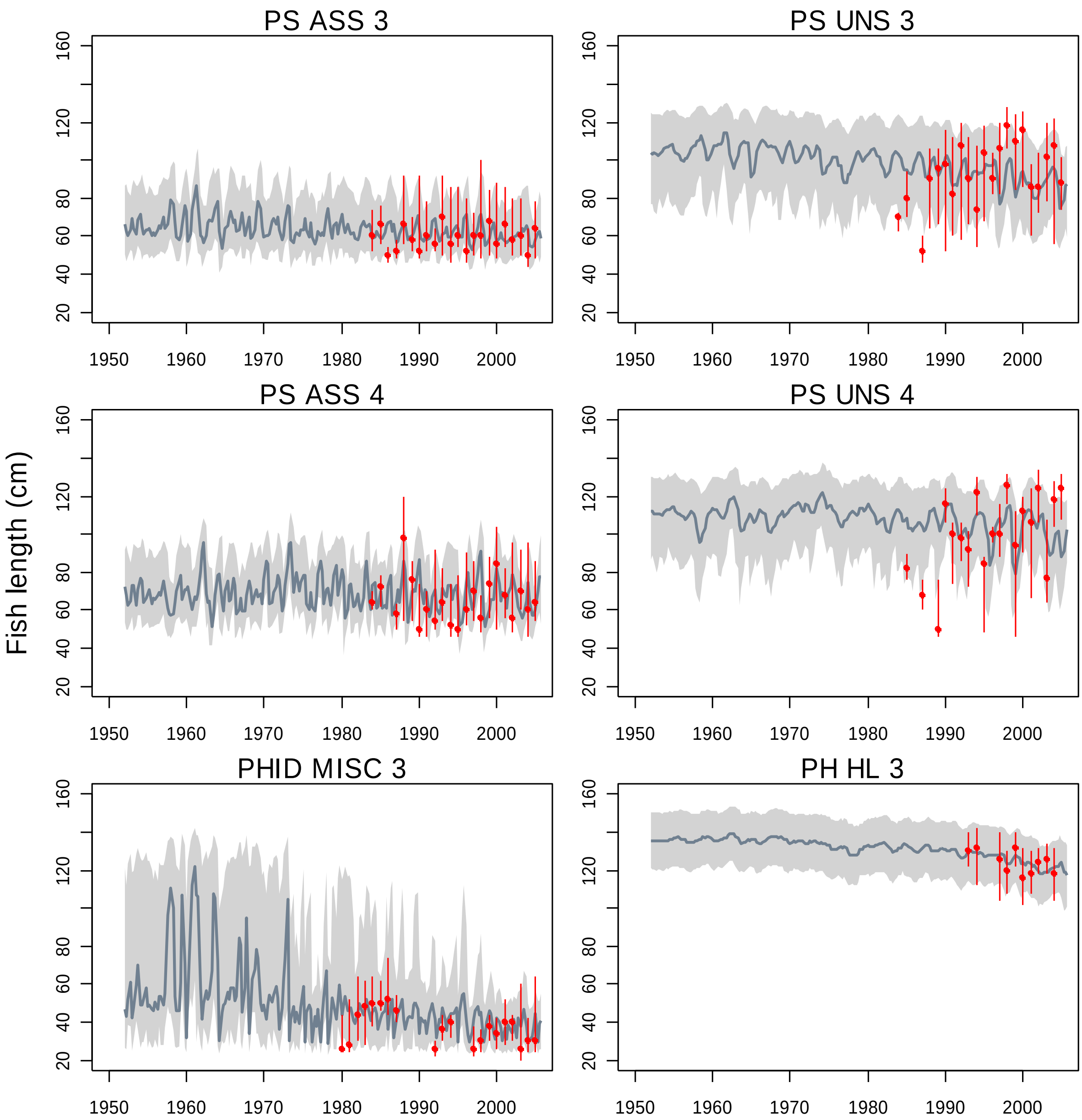


Figure 13 (continued).

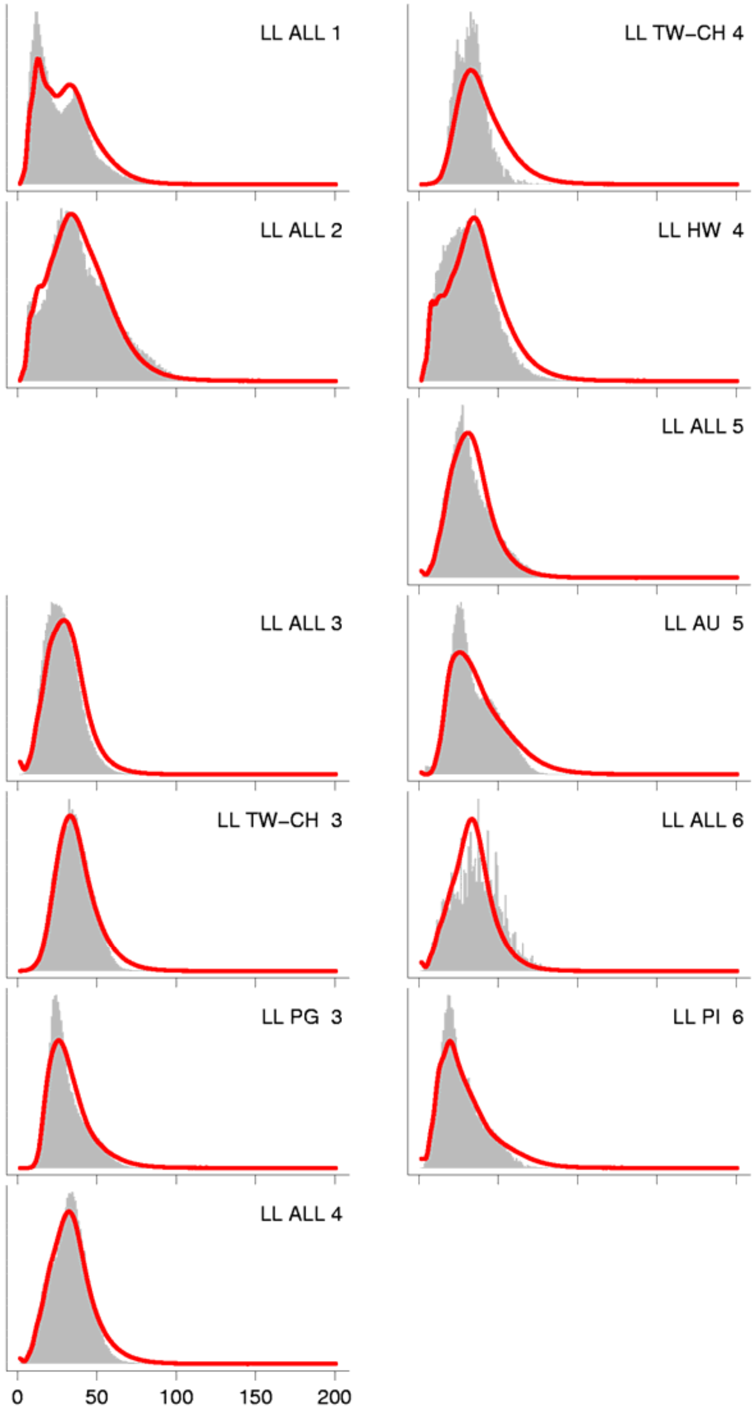


Figure 14. Observed (histograms) and predicted (line) weight frequencies (in kg) for each fishery aggregated over time (six-region LOWSAMP model).

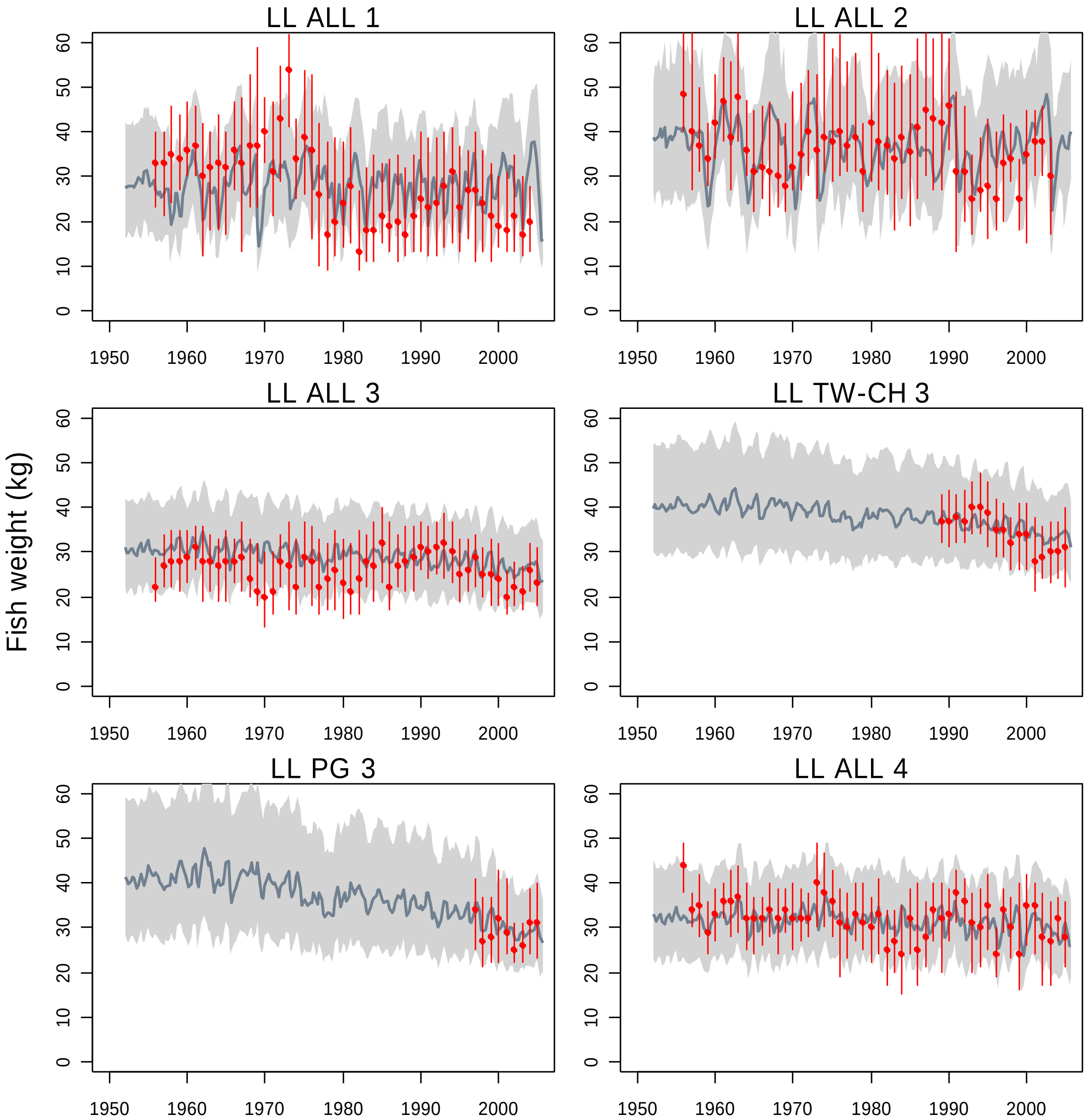


Figure 15. A comparison of the observed (red points) and predicted (grey line) median fish weight (whole weight, kg) of yellowfin tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only weight samples with a minimum of 30 fish per year are plotted.

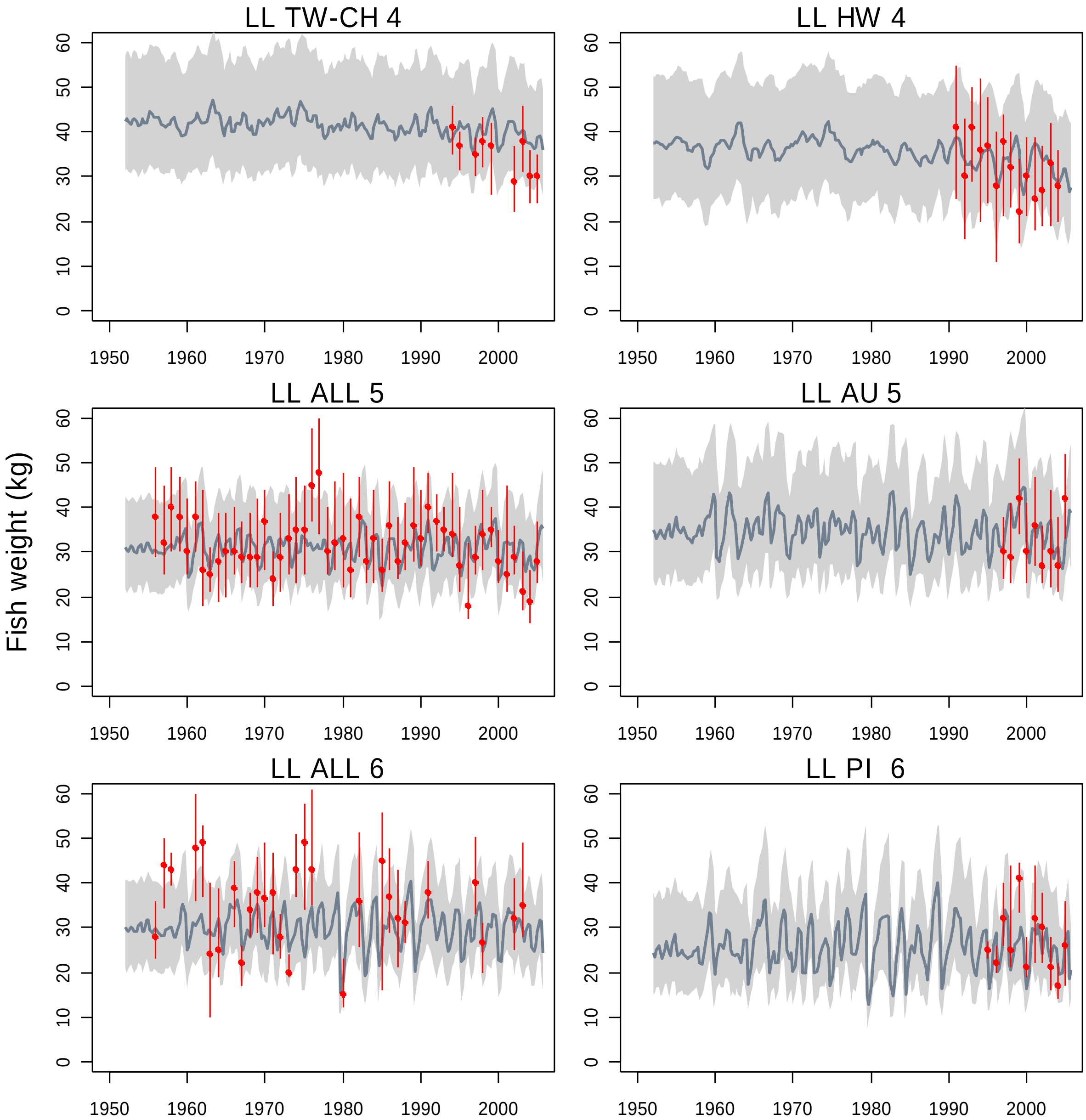


Figure 15 (continued).

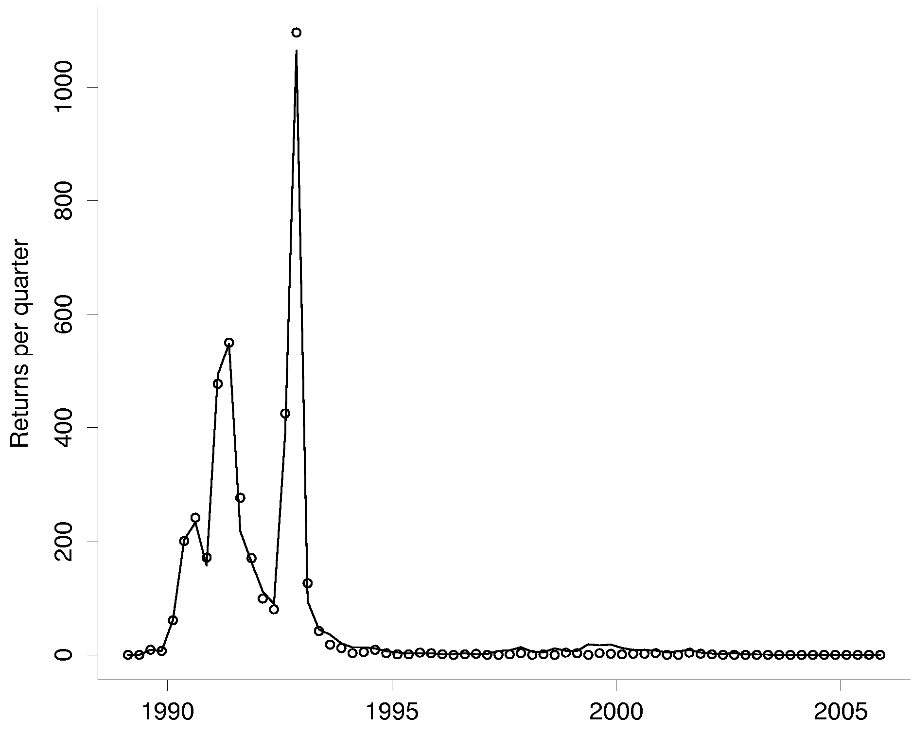


Figure 16. Number of observed (points) and predicted (line) tag returns by recapture period (quarter).

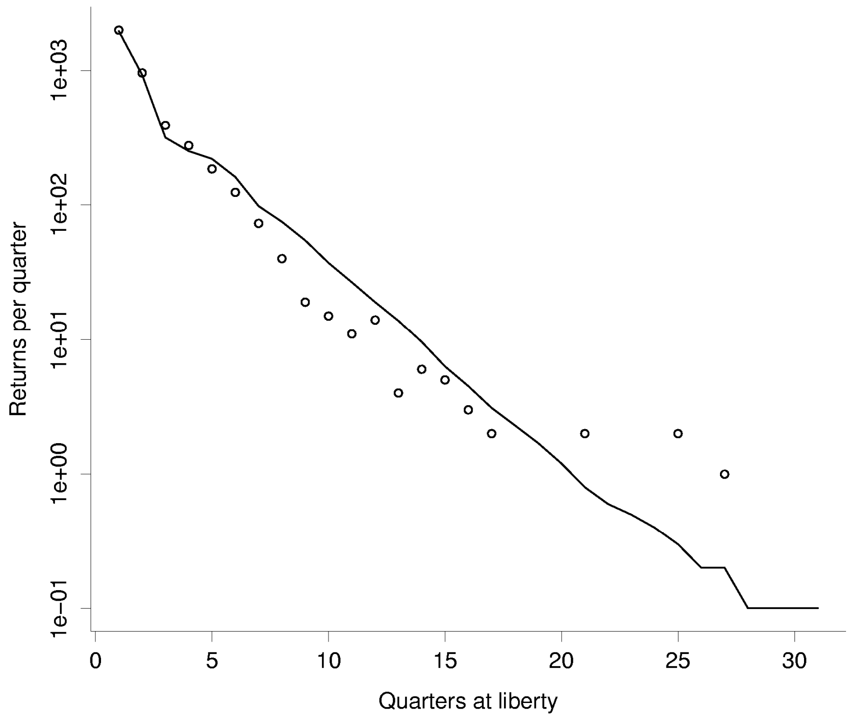


Figure 17. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters).

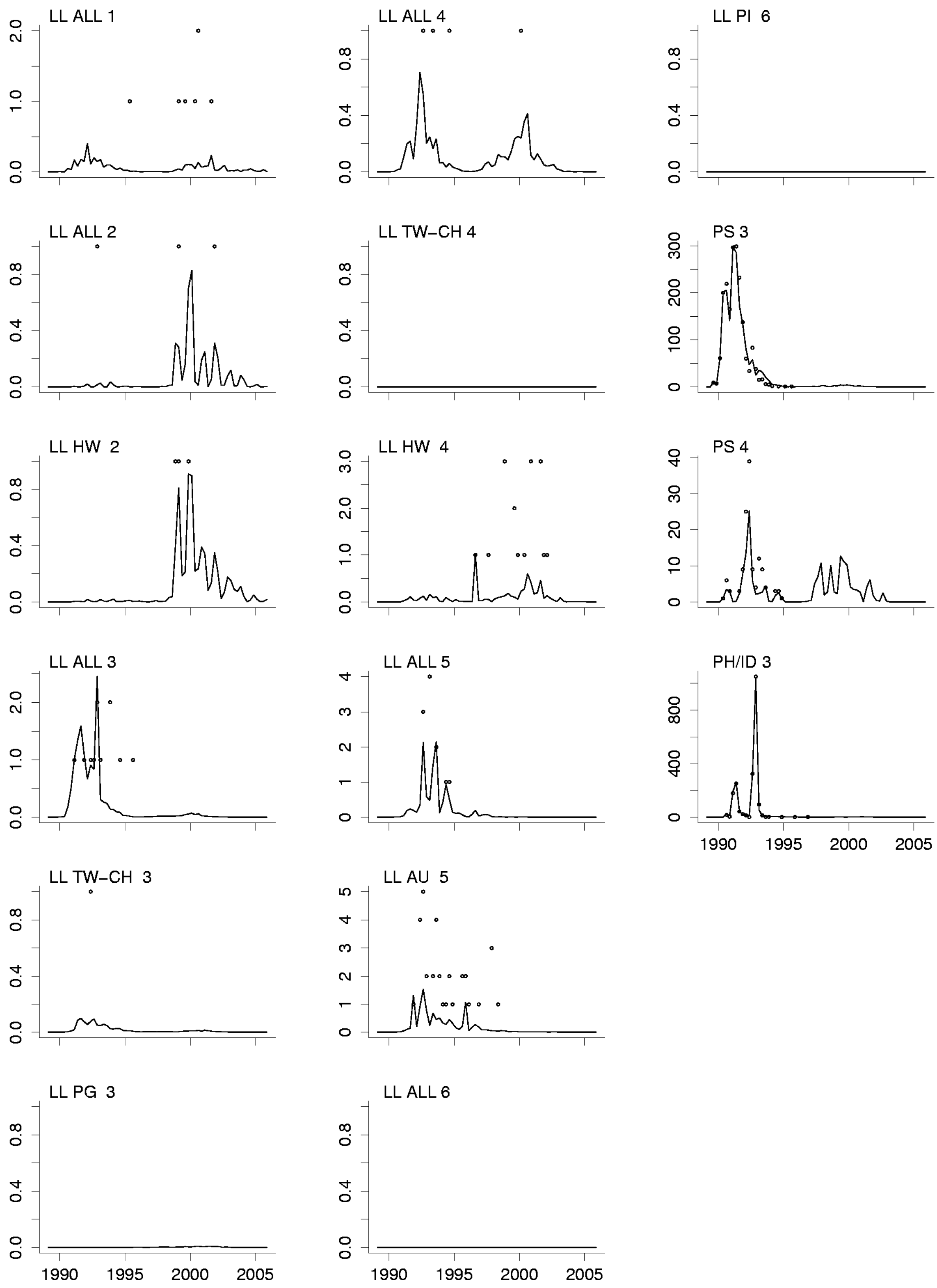


Figure 18. Number of observed (points) and predicted (line) tag returns by recapture period (quarter) for the various fisheries (or groups of fisheries) defined in the model.

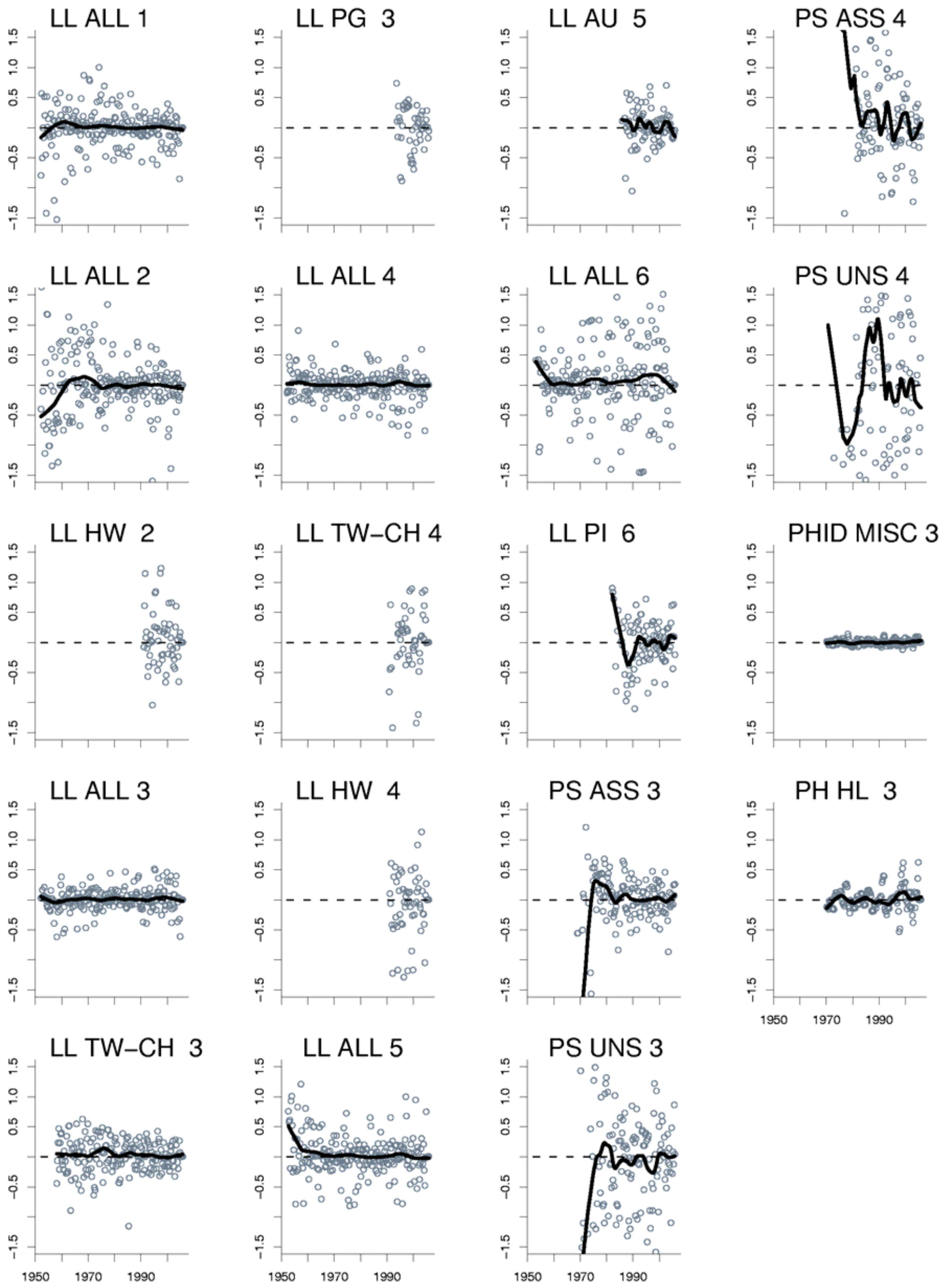


Figure 19. Effort deviations by time period for each fishery. The solid line represents a lowess fit to the data.

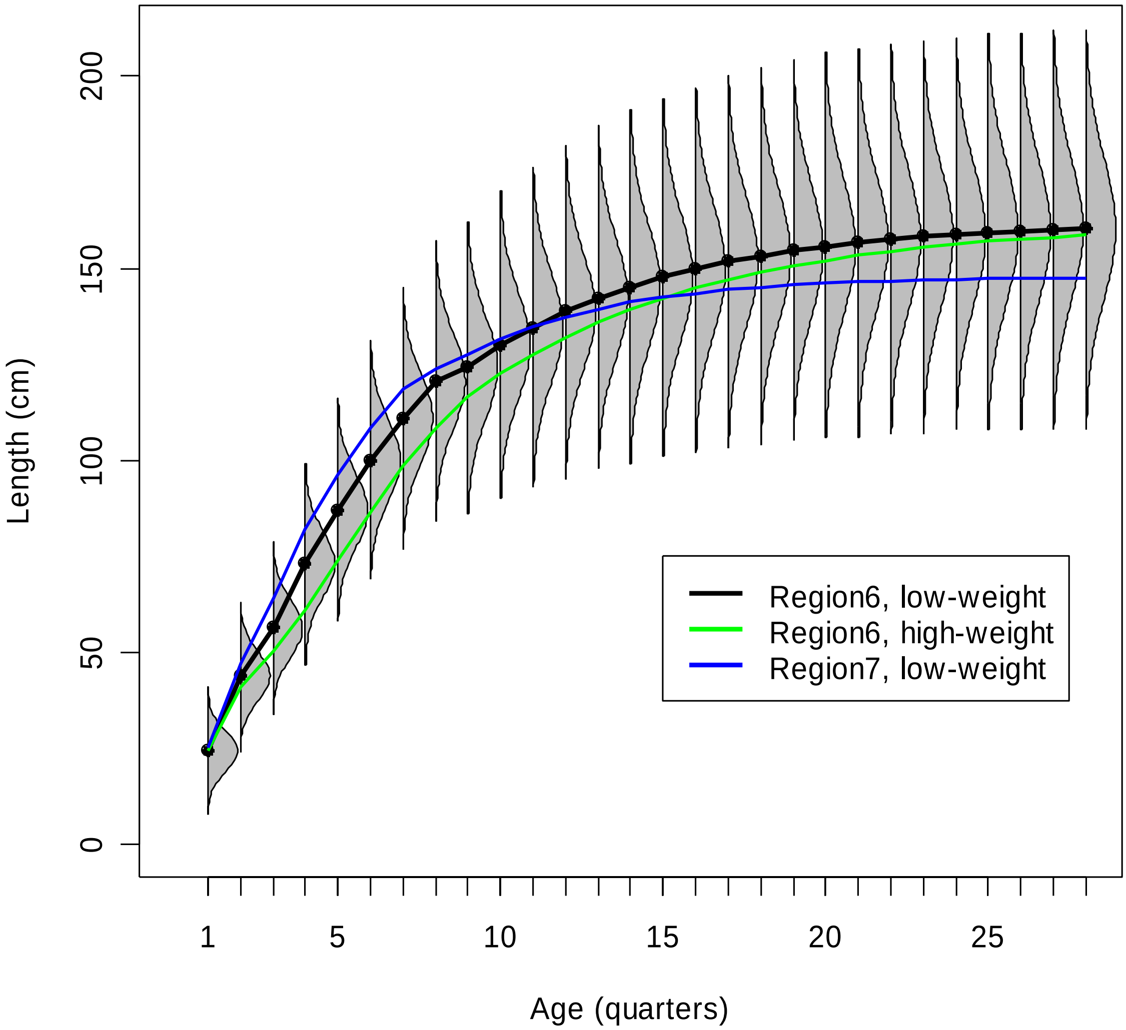


Figure 20. Estimated growth of yellowfin derived from the base case assessment model (LOWSAMP: Region 6, low-weight). The black line represents the estimated mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age. The estimated mean length at age is also plotted for the two sensitivity analyses.

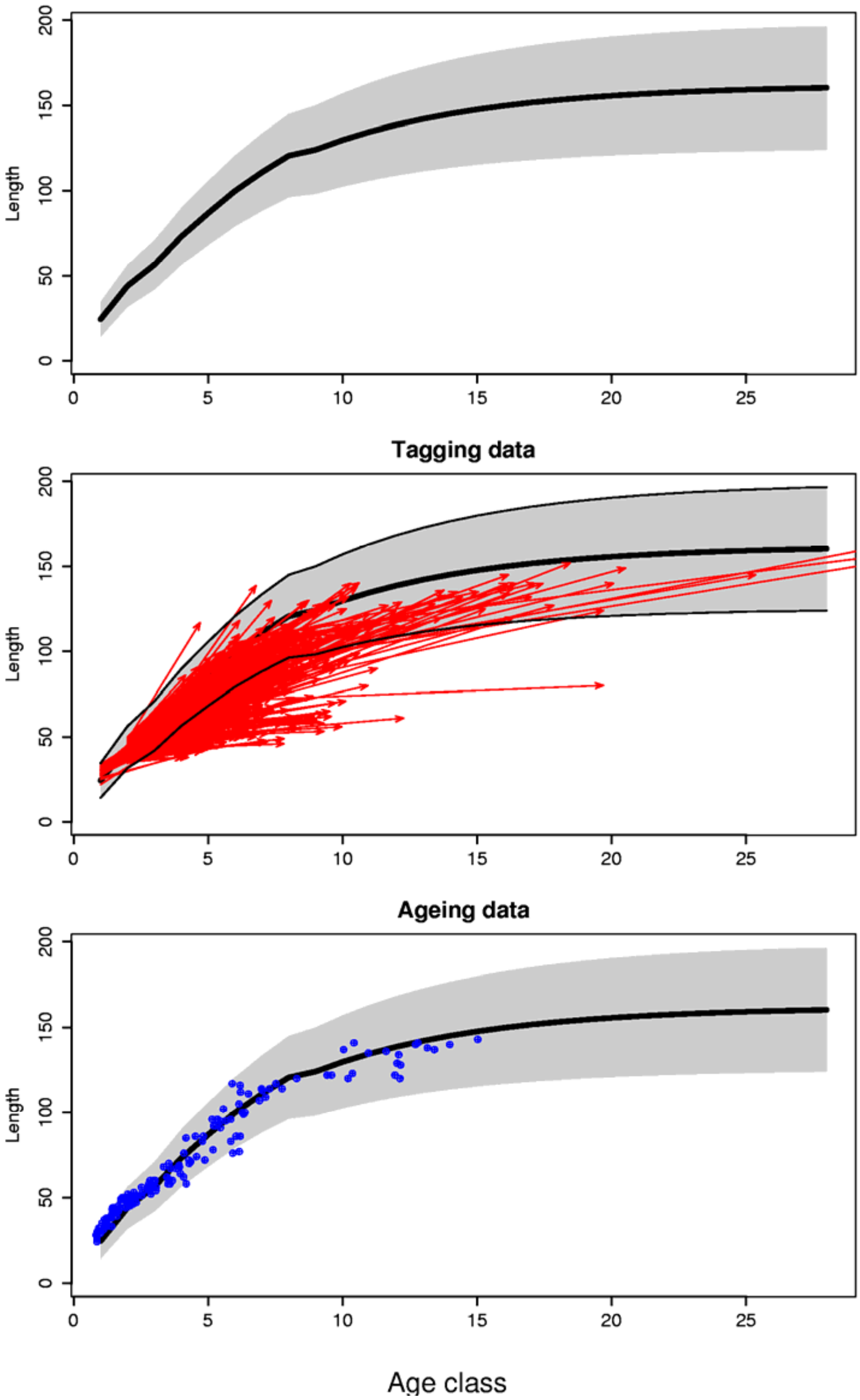


Figure 21. Estimated mean lengths-at-age (heavy line) and the variability of length-at-age (shaded area represents ± 2 SD). Age is in quarters and length is in cm (top figure). For comparison, length at age estimates are presented from tag release and recapture data (middle figure) and empirical age determination from otolith readings (bottom figure). The tagging data is presented as a linear growth vector (depicted as an arrow) from length at release to length at recovery. Only fish at liberty for at least 150 days are included (813 records). Age at release is assumed from the estimated growth function.

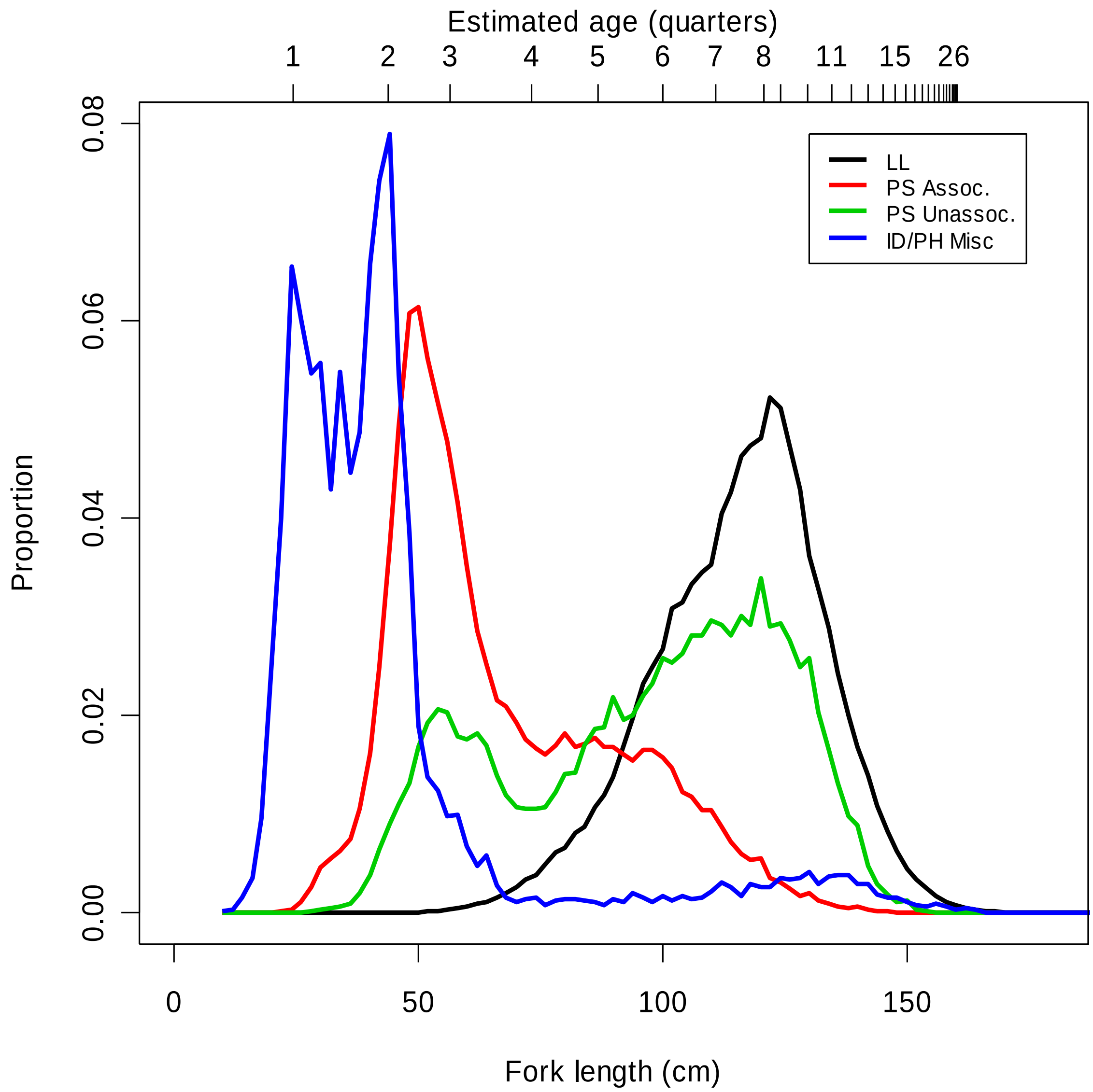


Figure 22. Aggregated length compositions for the main fishery method groups included in the WCPO yellowfin assessment (all time periods combined) compared to the estimated mean length at age from the base case assessment (six-region LOWSAMP) (top axis).

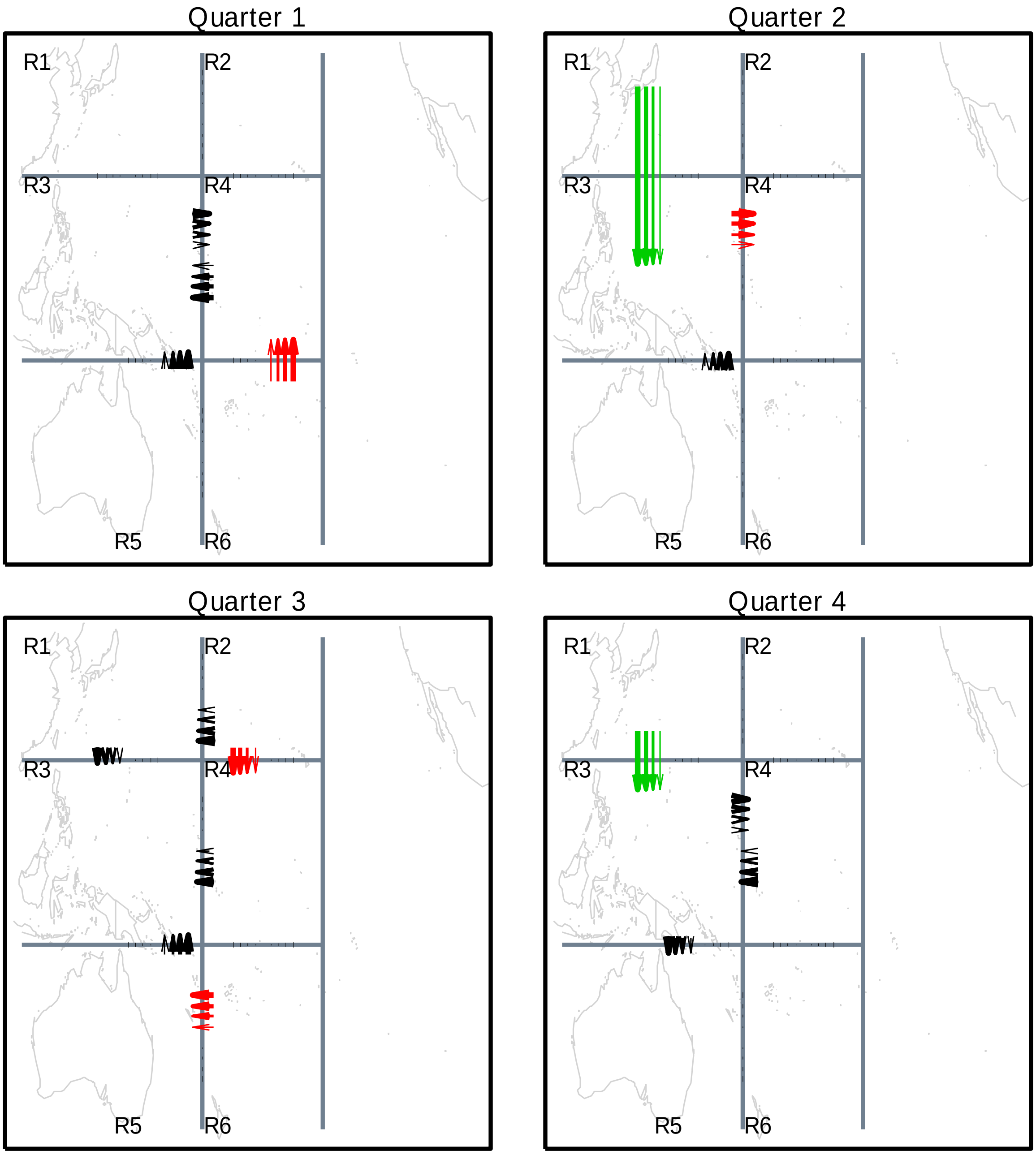


Figure 23. Estimated quarterly movement coefficients at age (1, 7, 15, 25 quarters) from the base case model. The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age. The maximum movement (quarter 2, region 1 to region 3) represents movement of 39% of the fish at the start of the quarter. Movement rates are colour coded: black, 0.5–5%; red 5–10%; green >10%.

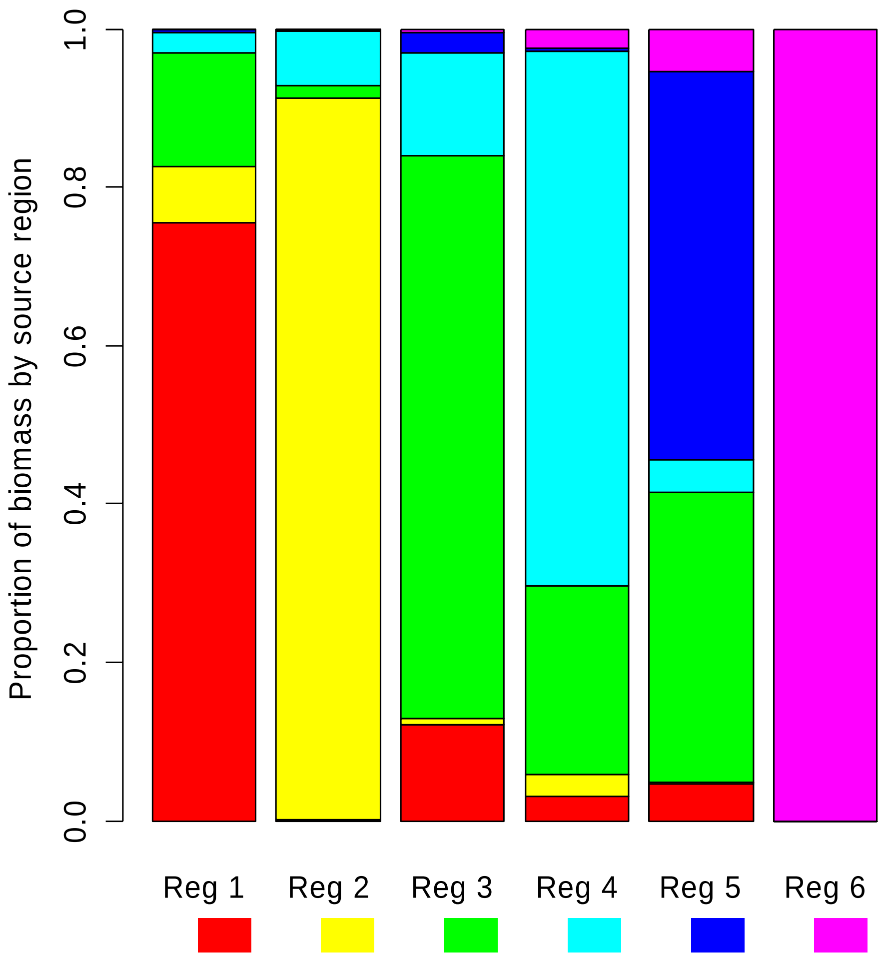


Figure 24. Proportional distribution of total biomass (by weight) in each region (Reg 1–6) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment among regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

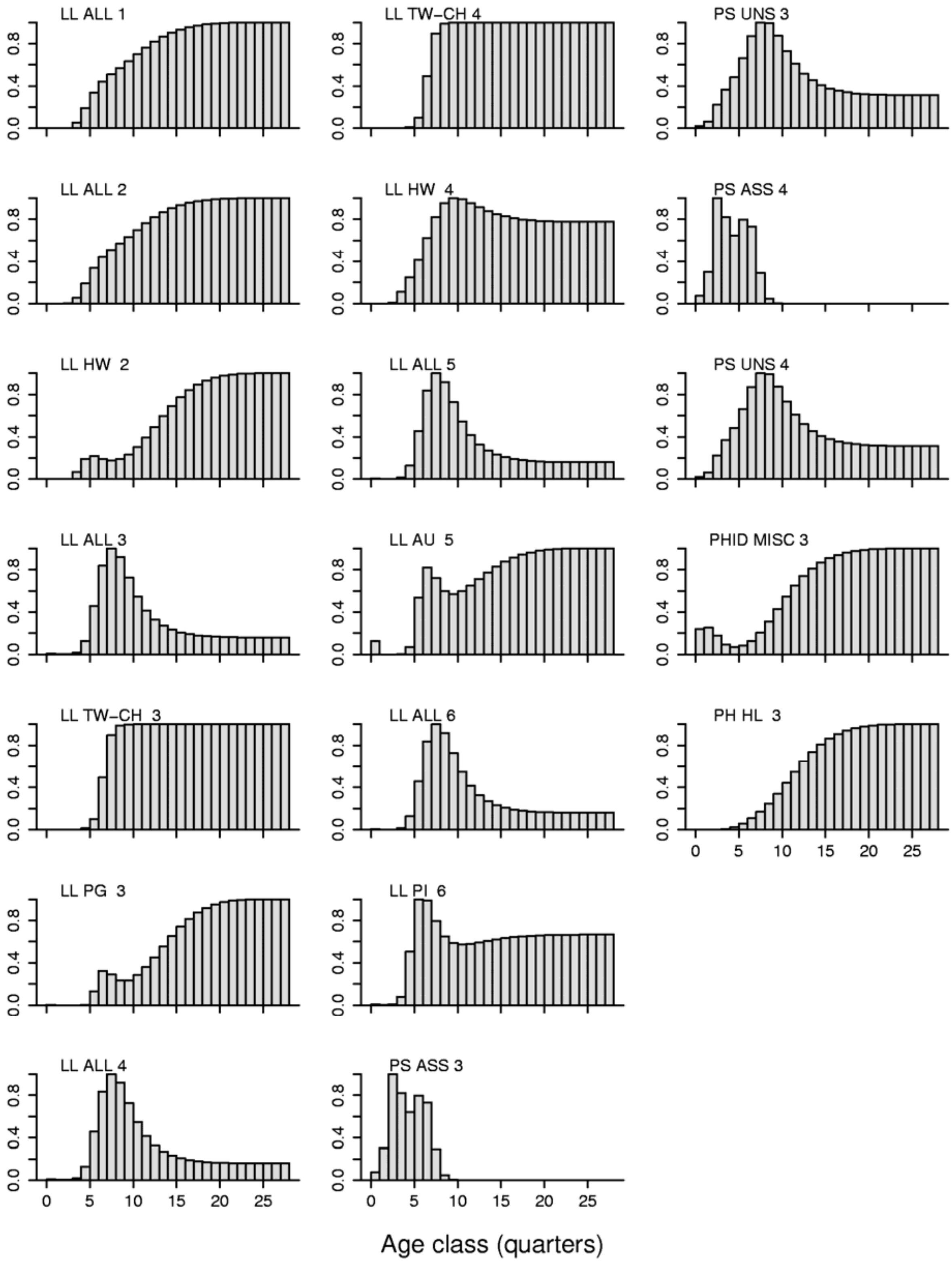


Figure 25. Selectivity coefficients, by fishery.

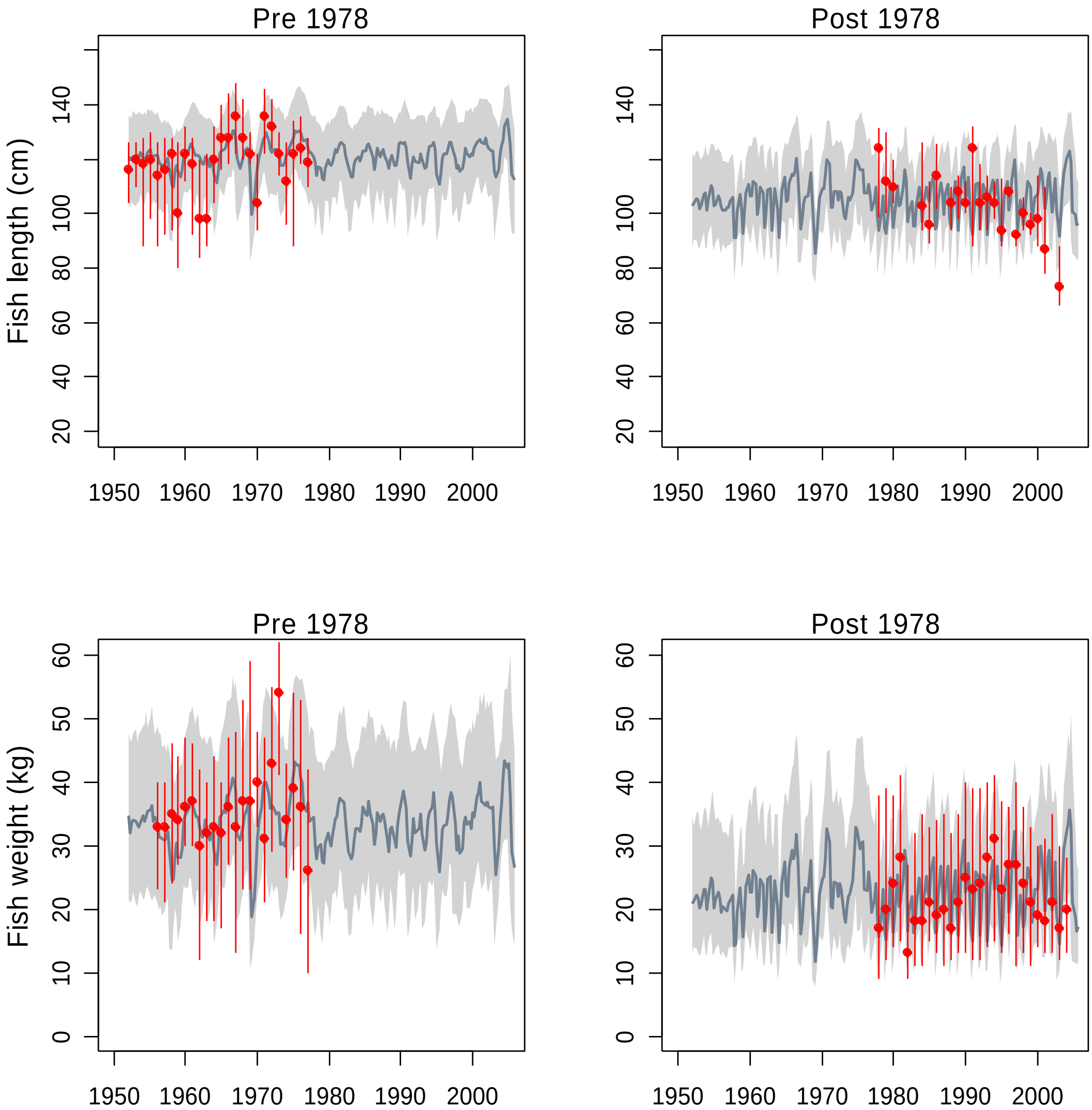


Figure 26. A comparison of the observed (red points) and predicted (grey line) median fish length (top) and median fish weight (bottom) of yellowfin tuna for the LL ALL 1 fishery with separate selectivities estimated for the period pre- and post-1978. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

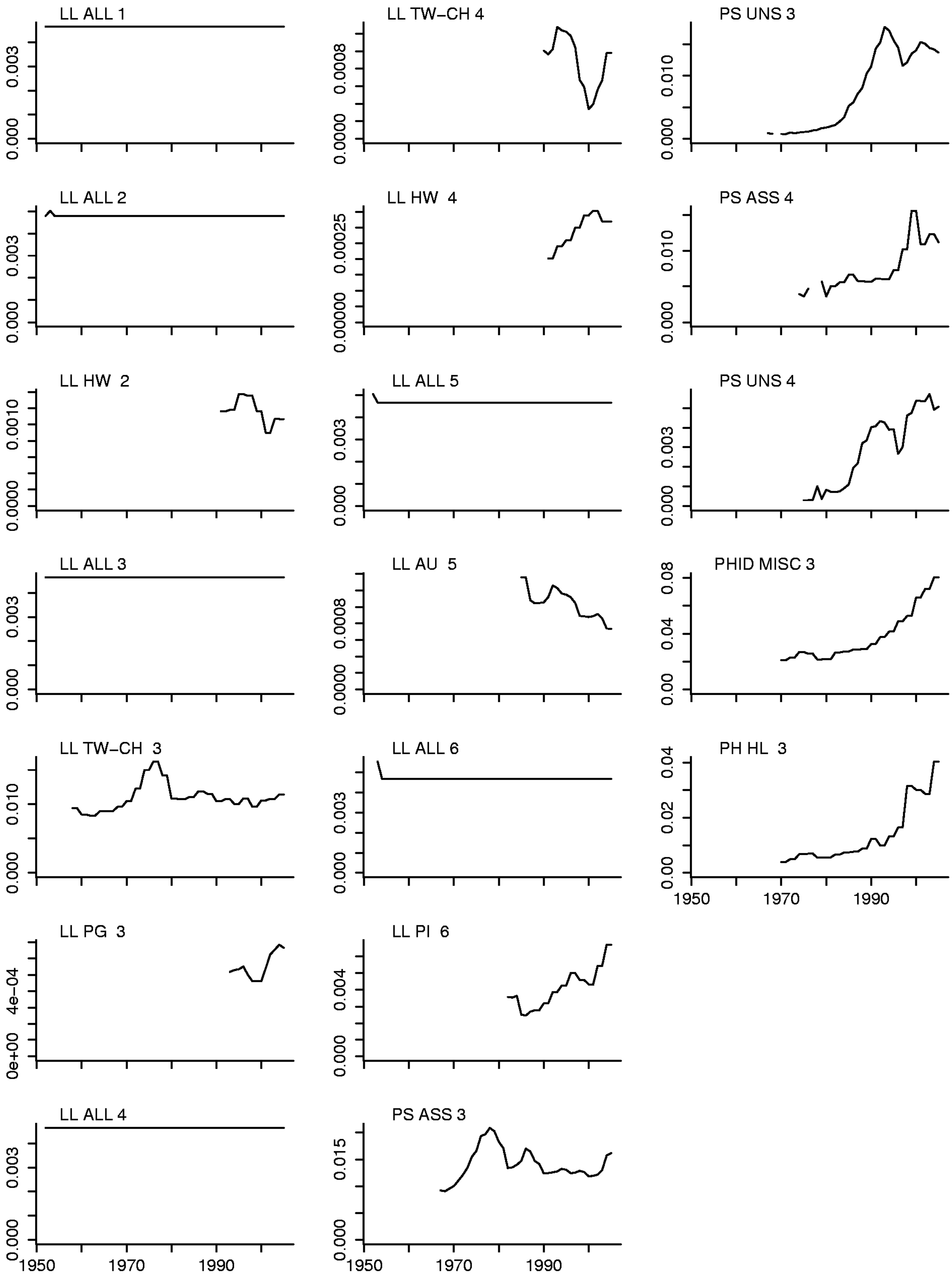


Figure 27. Average annual catchability time series, by fishery from the six-region LOWSAMP model.

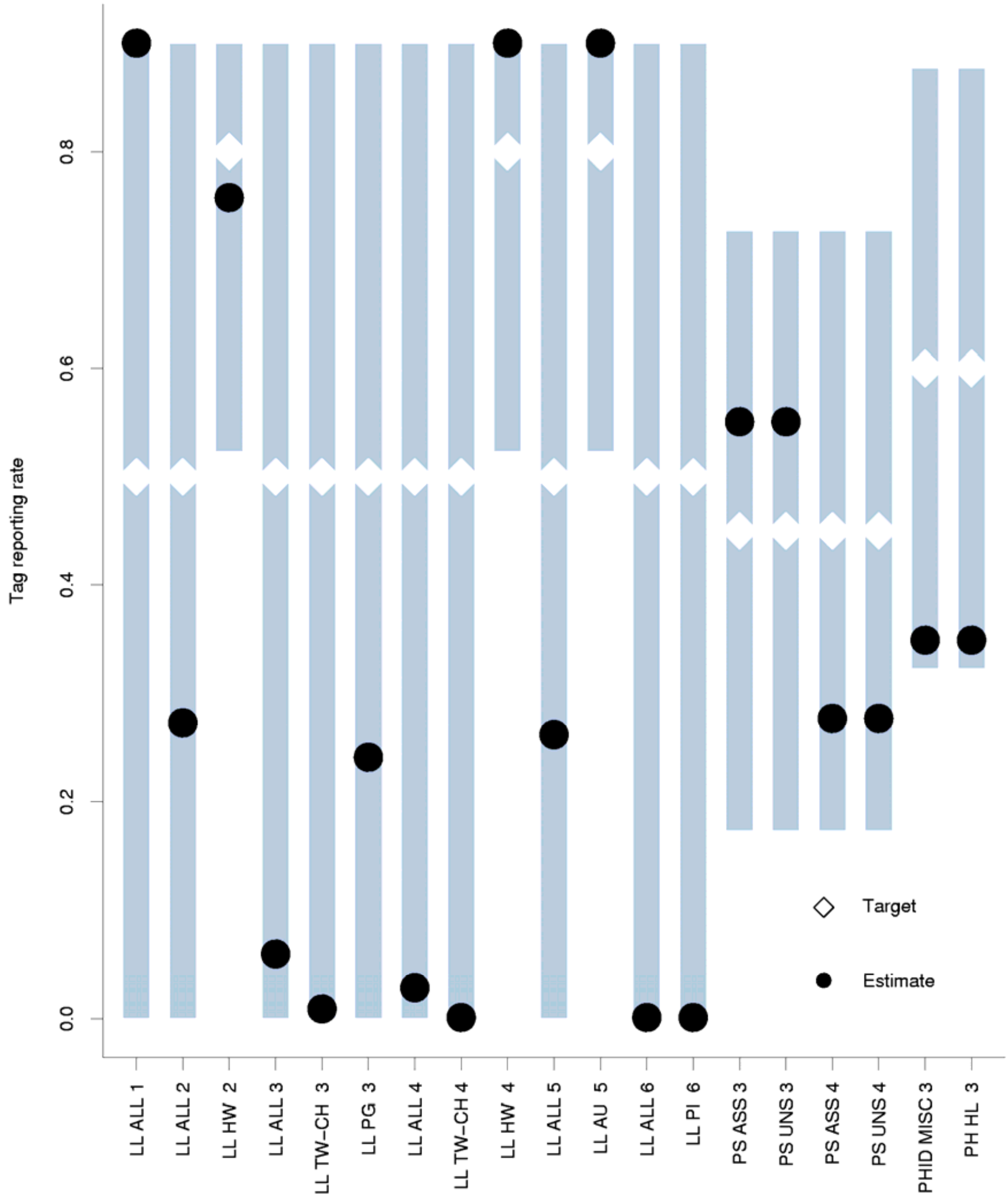


Figure 28. Estimated tag-reporting rates by fishery (black circles). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars indicate a range of ±1 SD.

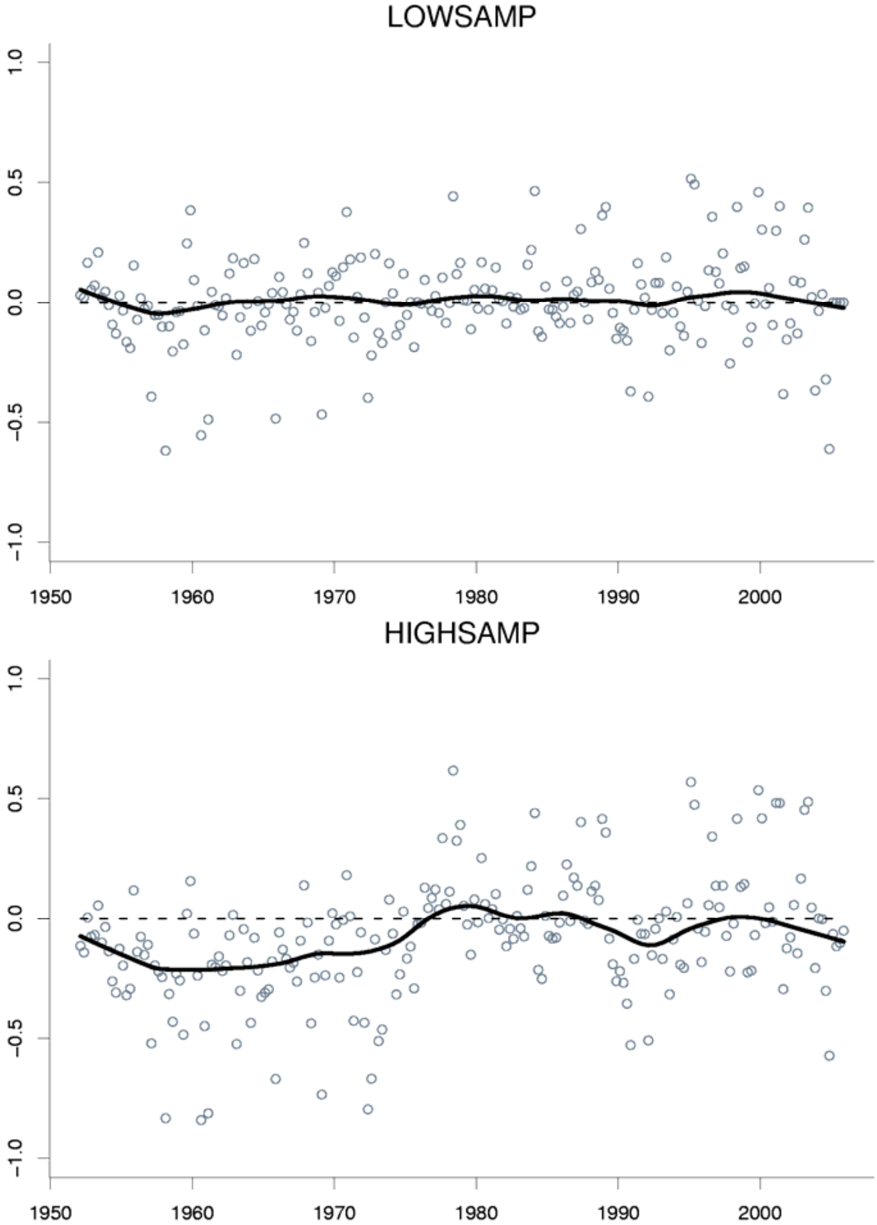


Figure 29. A comparison of the trends in the effort deviations for the LL ALL 4 fishery from the six-region LOWSAMP (top) and HIGHSAMP (bottom) models. The line represents the lowess smoothed fit to the data points.

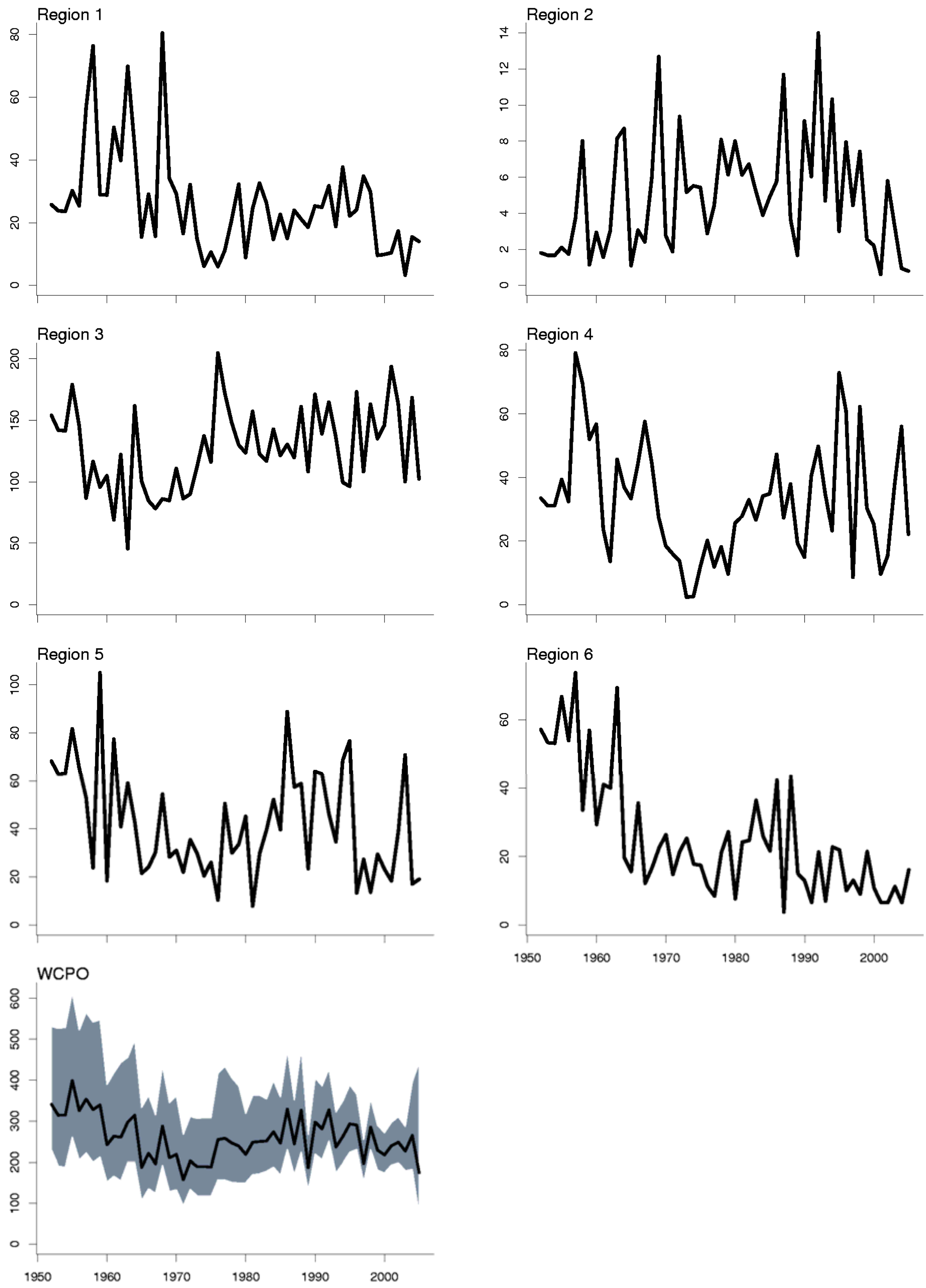


Figure 30. Estimated annual recruitment (millions of fish) by region and for the WCPO. The shaded area for the WCPO indicates the approximate 95% confidence intervals.

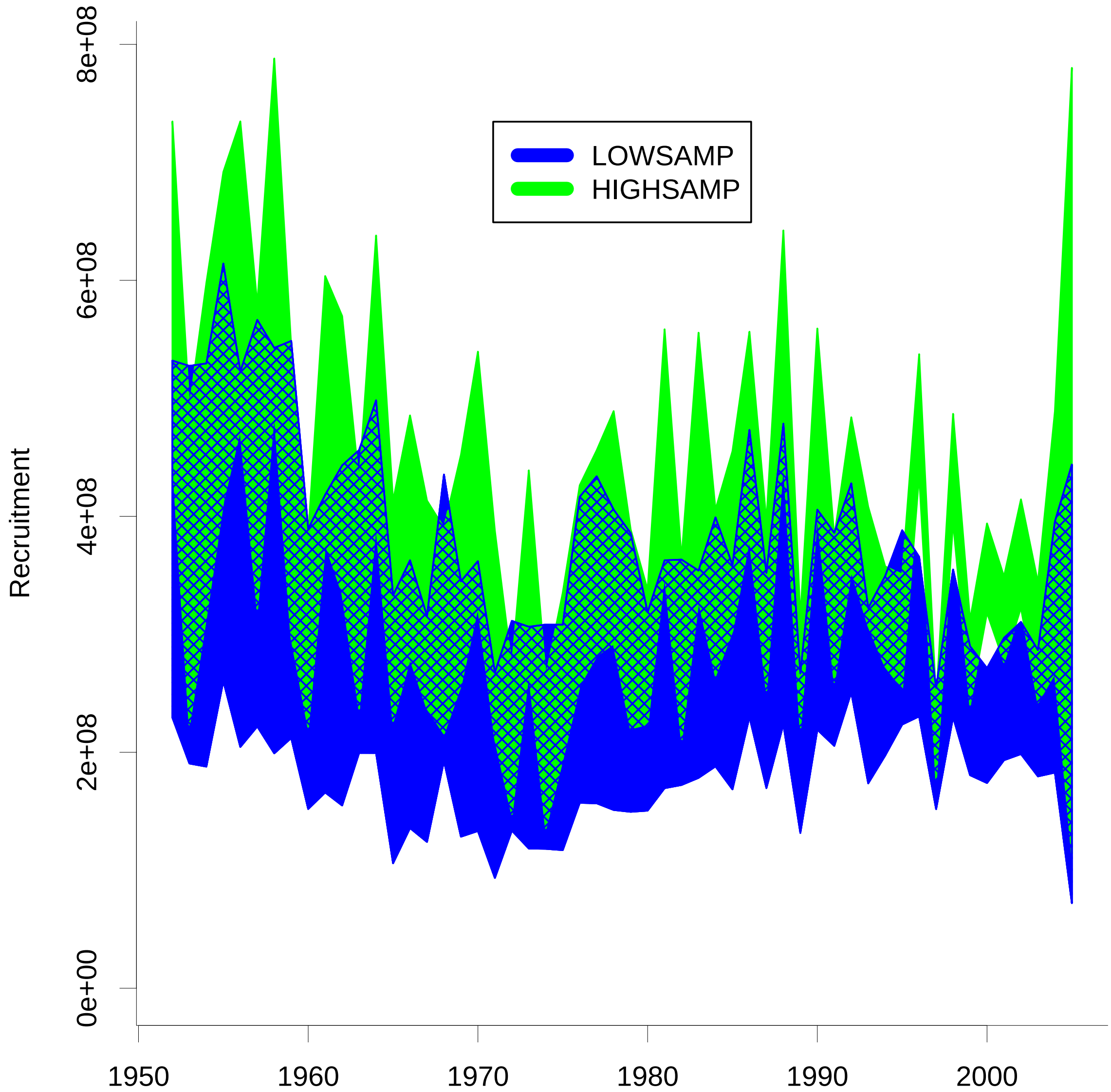


Figure 31. A comparison of 95% confidence intervals for total recruitment estimated for the LOWSAMP and HIGHSAMP models. The hatched area indicates the region of overlap of 95% confidence intervals.

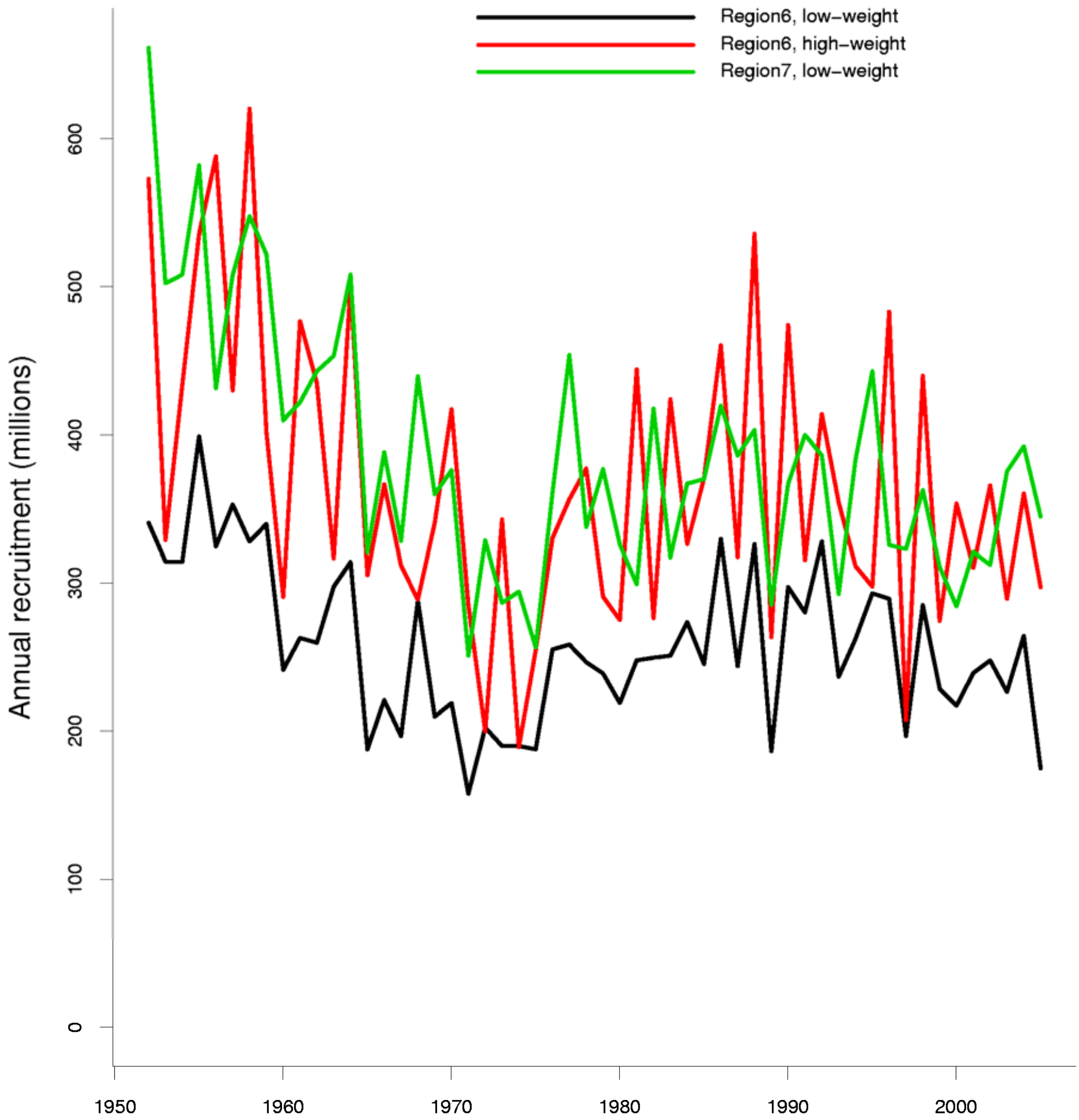


Figure 32. Estimated annual recruitment (millions of fish) for the WCPO obtained from the three different model options.

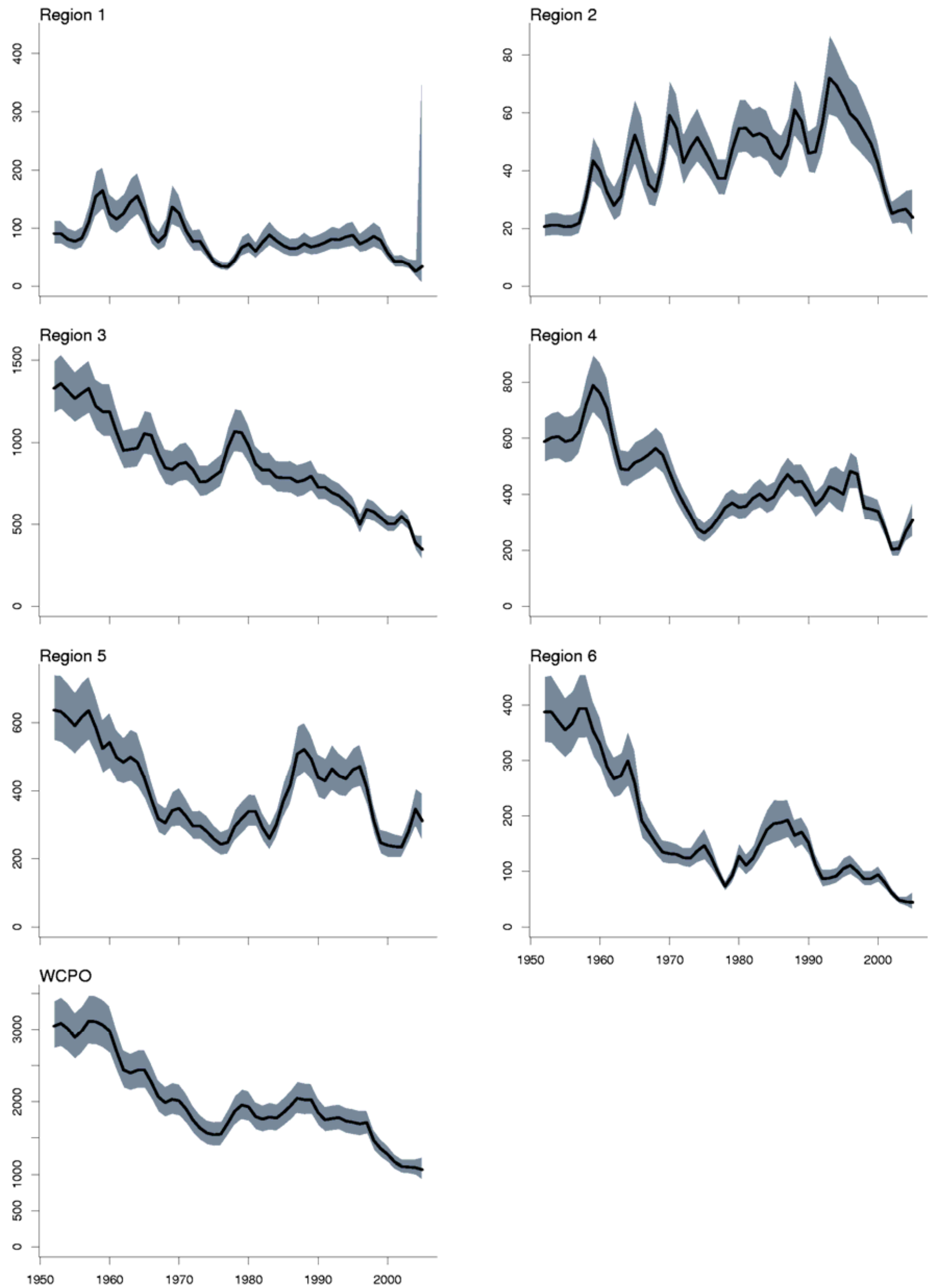


Figure 33. Estimated annual average total biomass (thousand mt) by region and for the WCPO for the base-case analysis. The shaded areas indicate the approximate 95% confidence intervals.

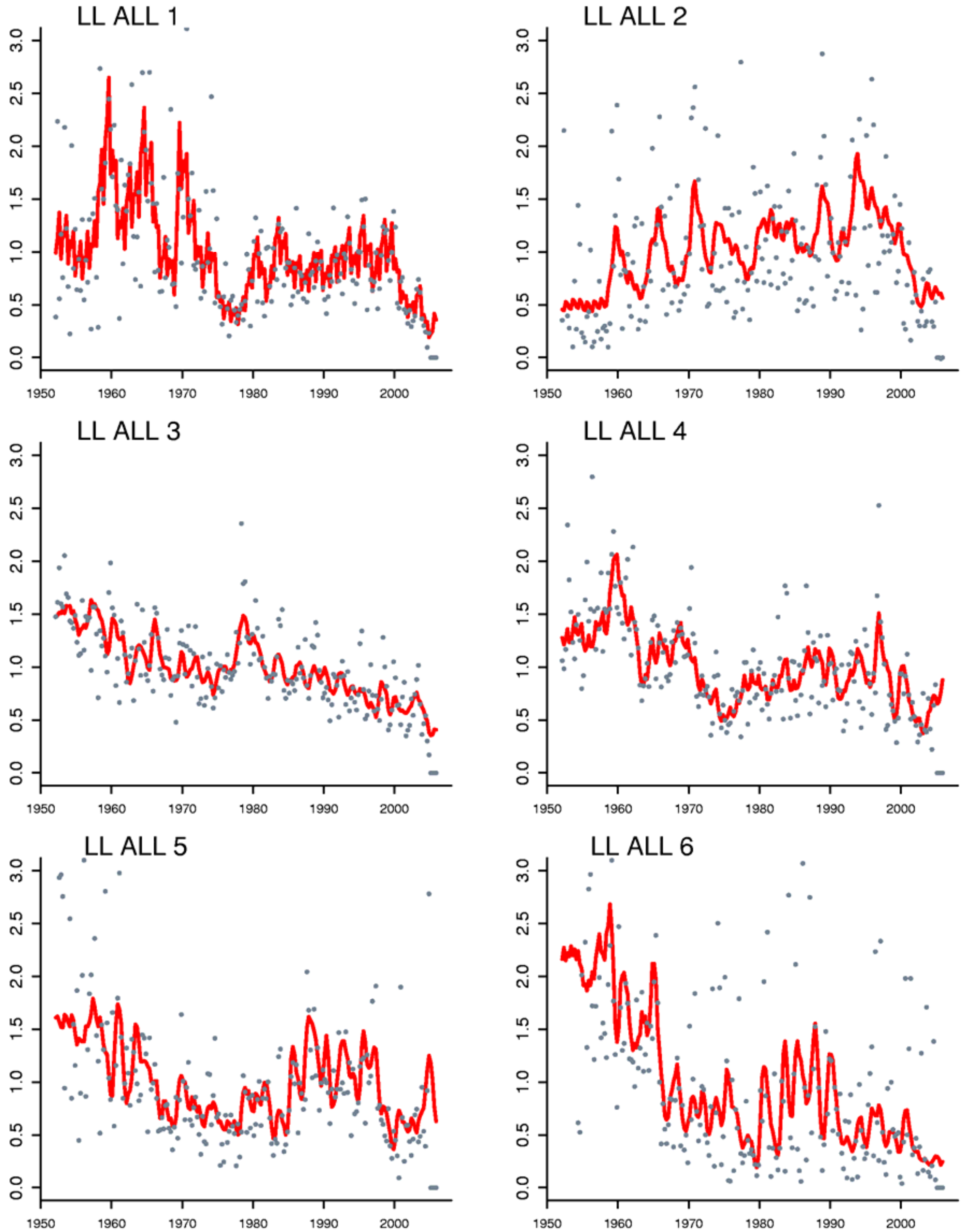


Figure 34. A comparison of longline exploitable biomass by quarter and region (red line) and the quarterly standardised CPUE indices for the fisheries. For comparison, both series are scaled to the average of the series.

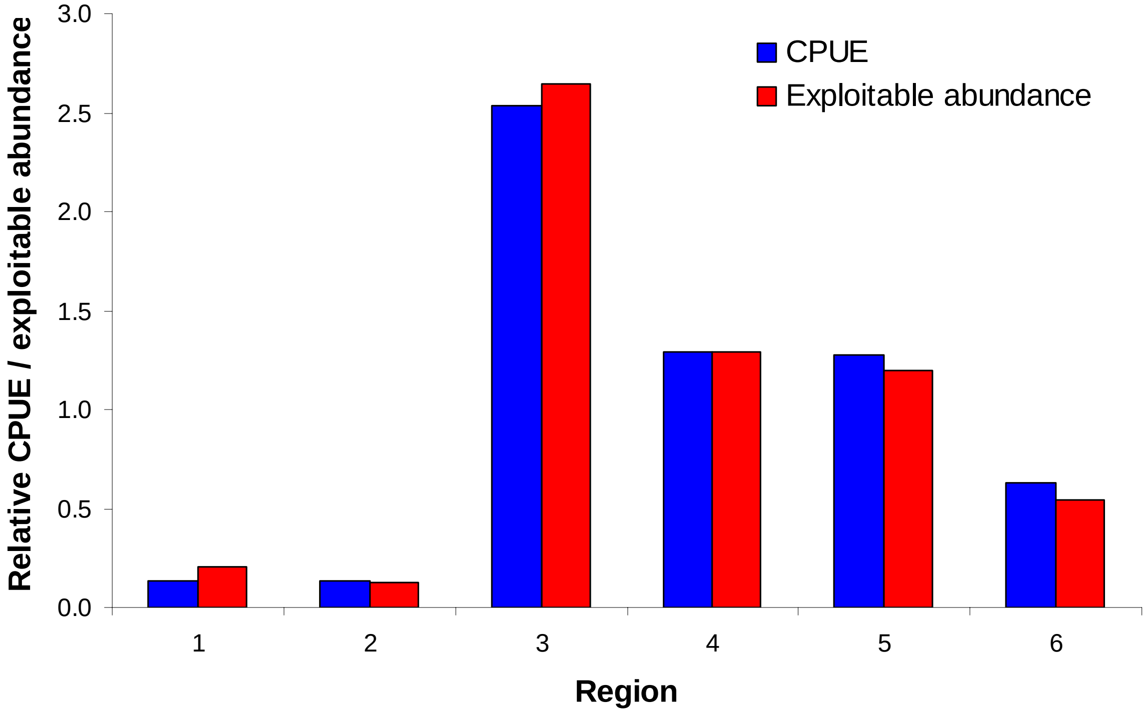


Figure 35. CPUE and exploitable abundance for LL ALL 1–6 averaged over all time periods. Values for each region are scaled relative to their averages across all regions.

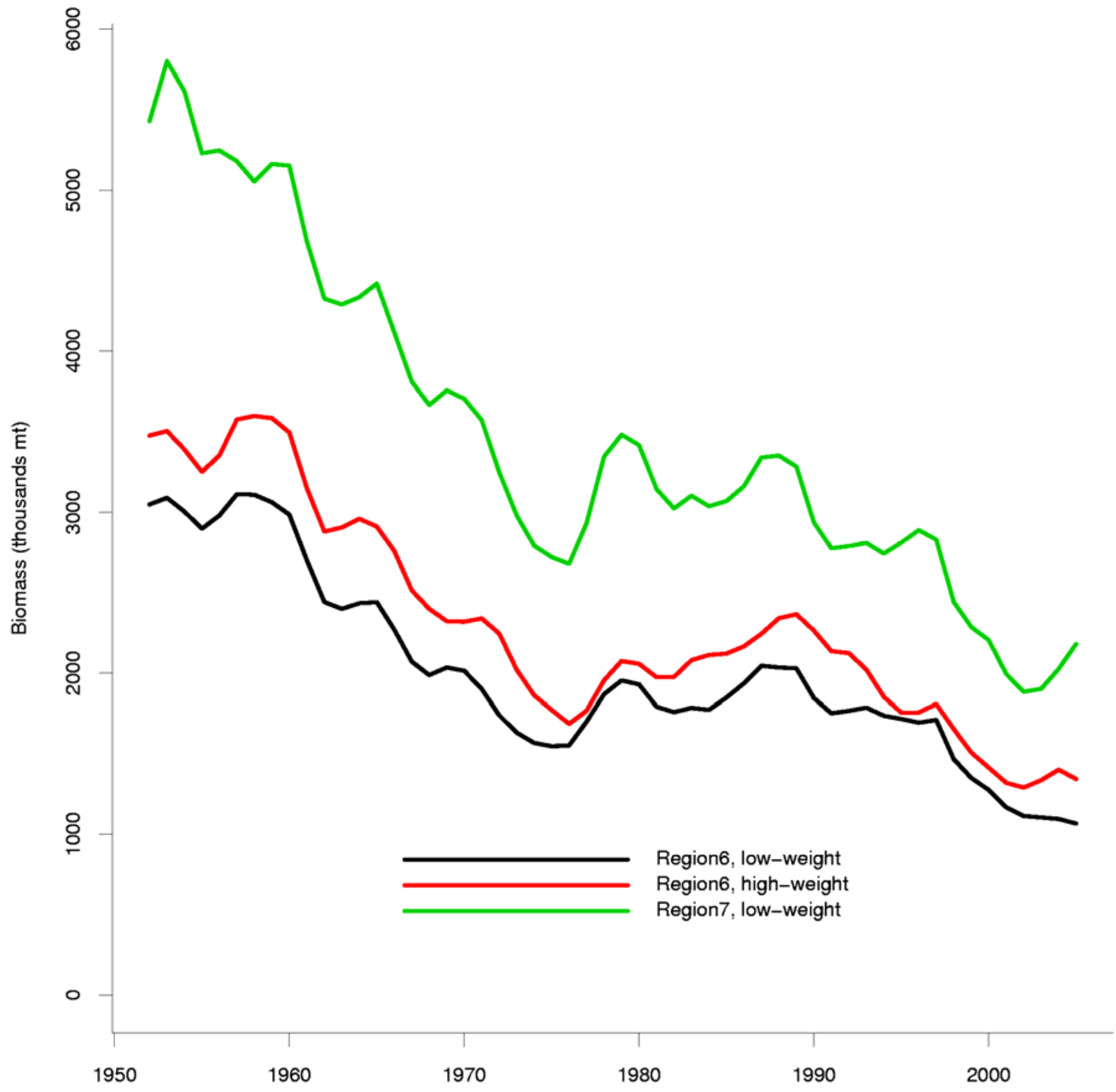


Figure 36. Estimated annual average total biomass (thousands mt) for the WCPO obtained from the three different model options.

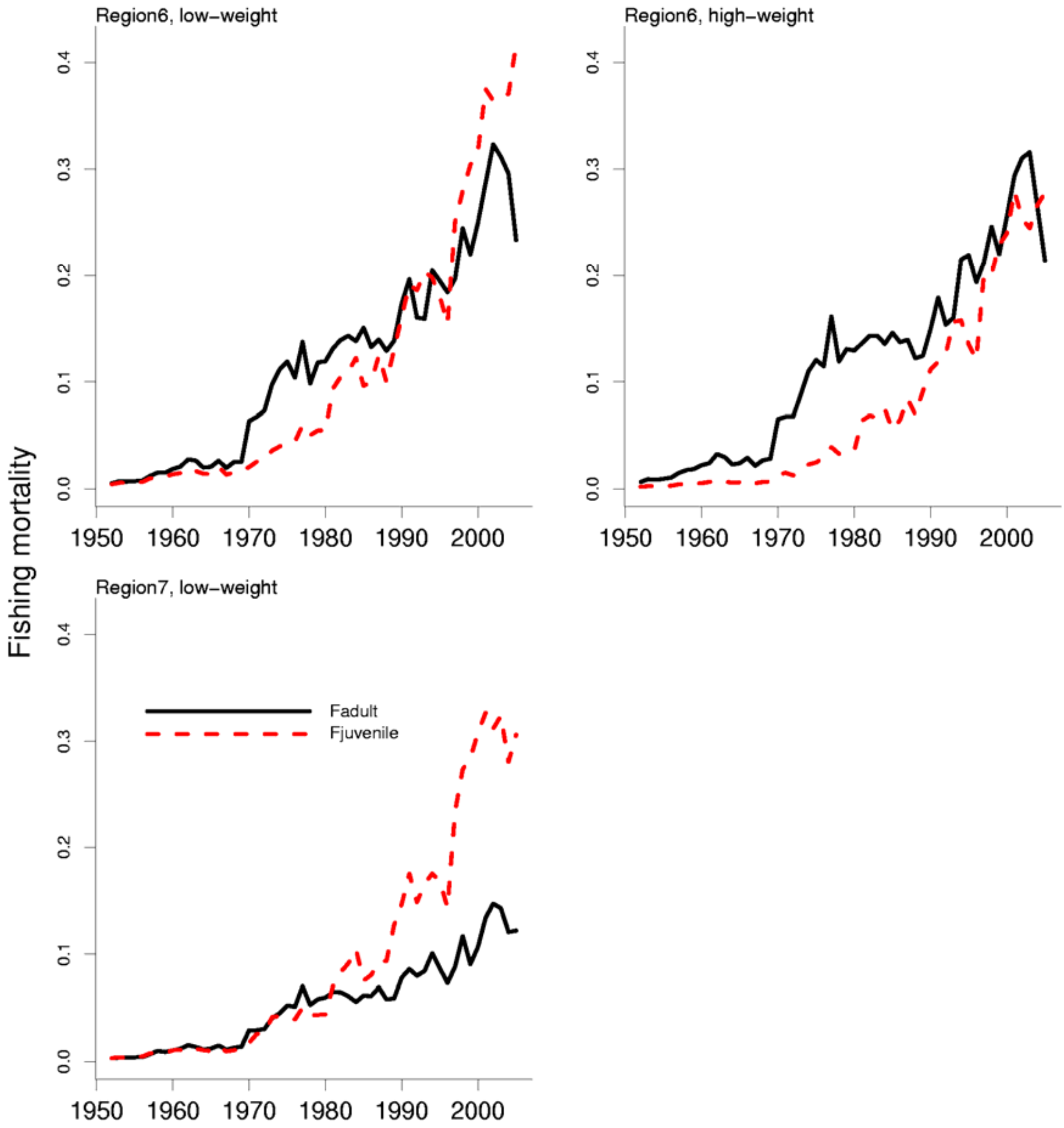


Figure 37. Estimated annual average juvenile and adult fishing mortality for the WCPO obtained from the three separate model options.

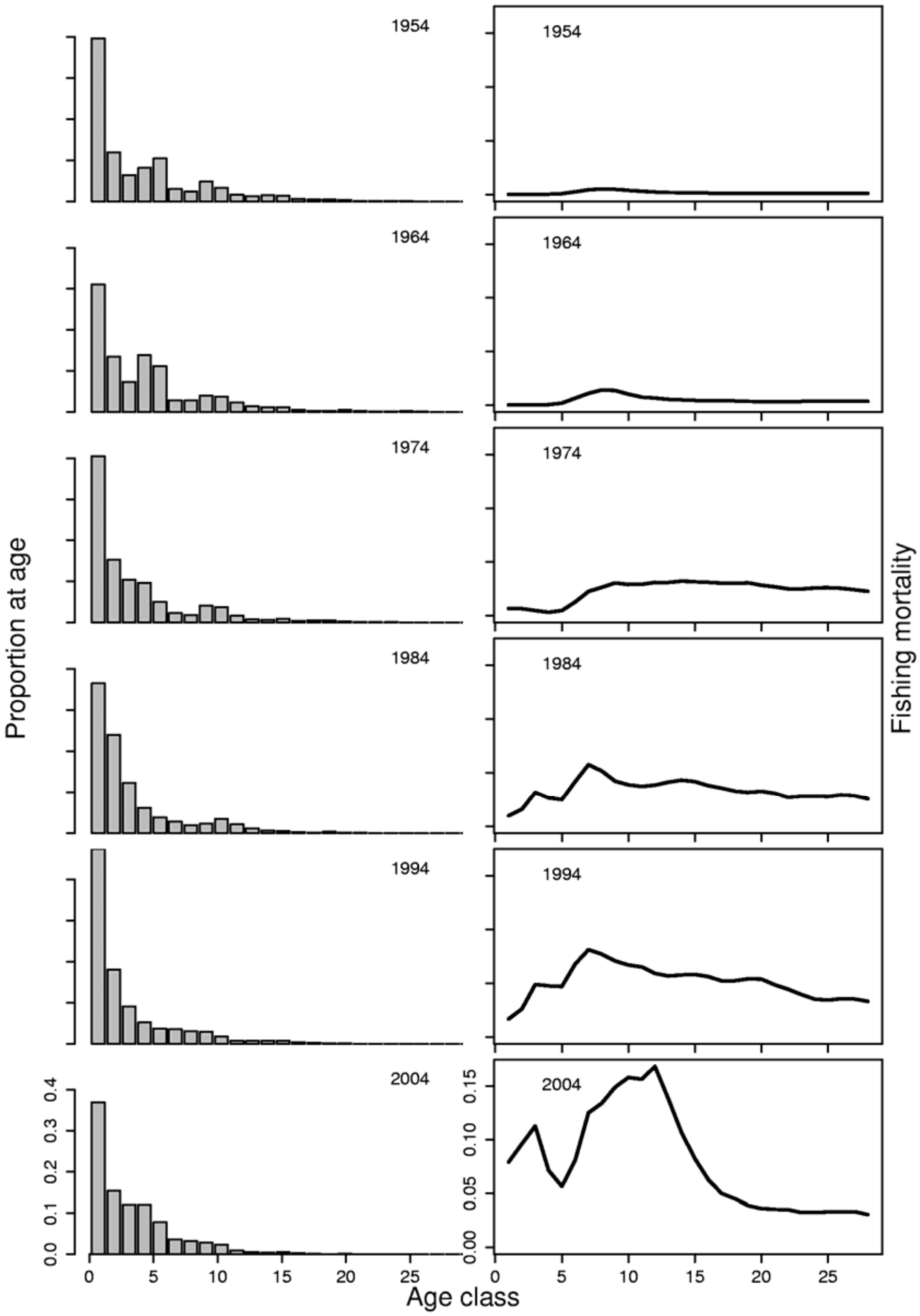


Figure 38. Estimated proportion at age (quarters) for the WCPO yellowfin population (left) and fishing mortality at age (right) by year at decade intervals.

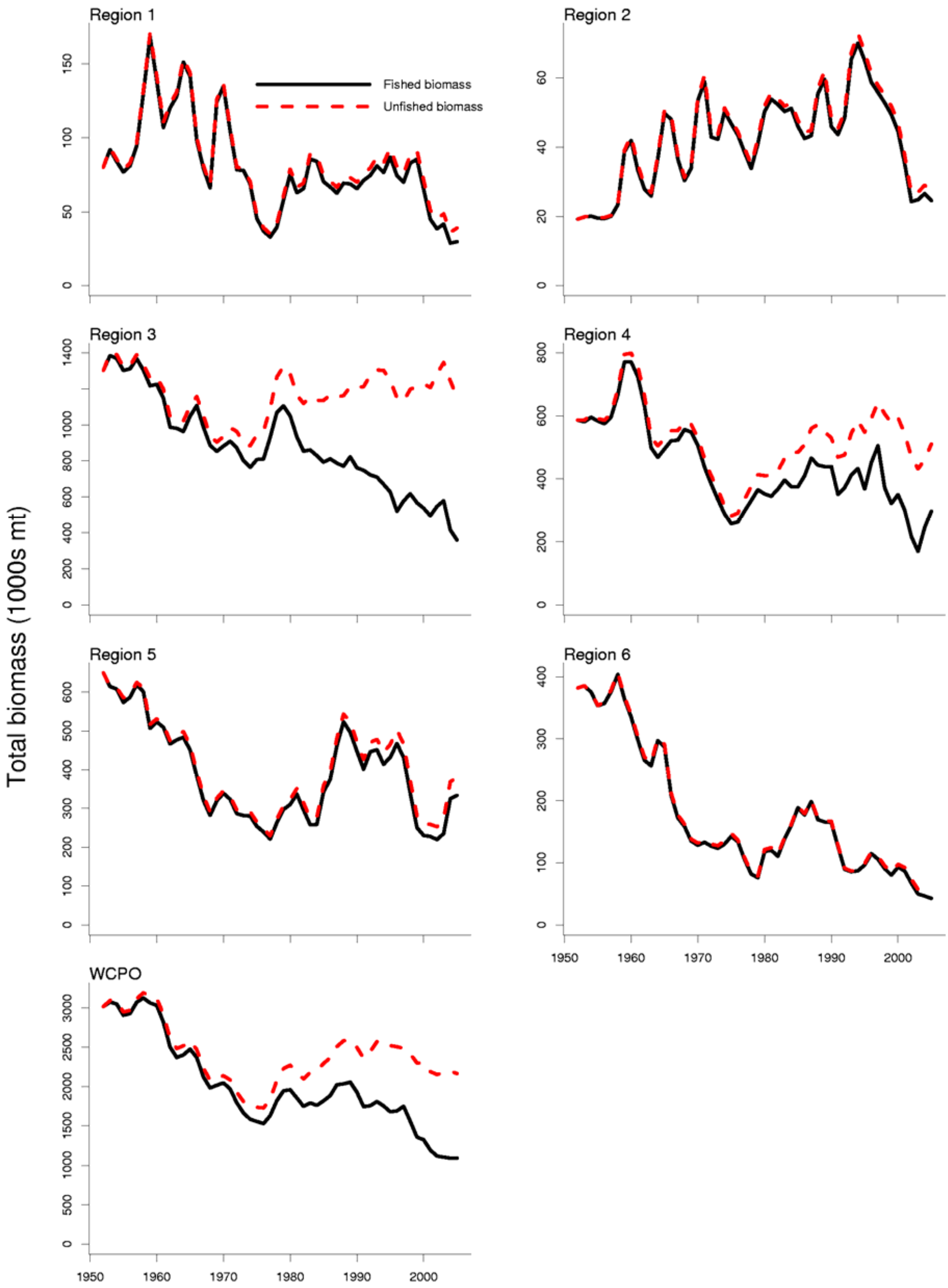


Figure 39. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper thin lines) for the base case model for each region and for the WCPO.

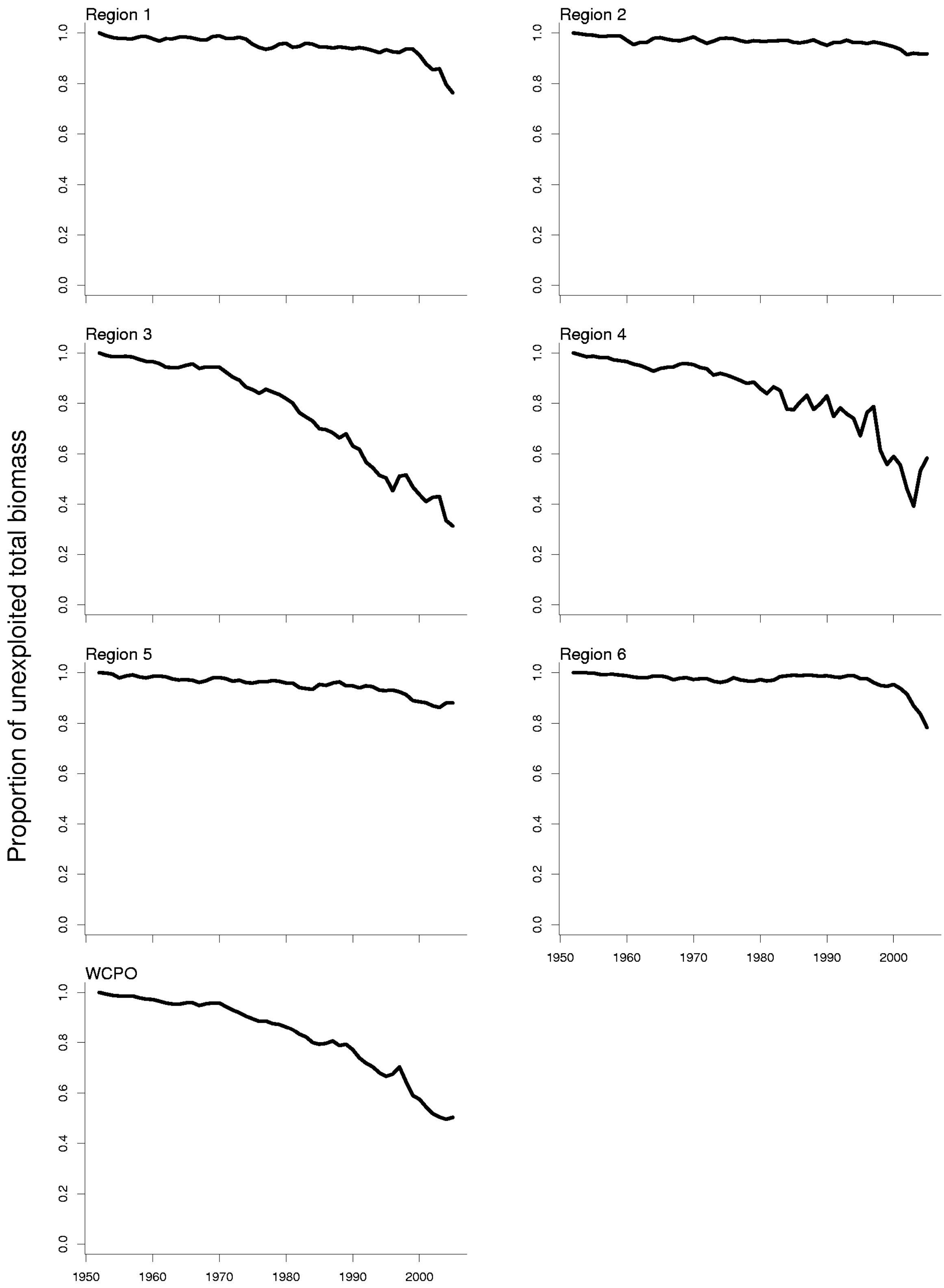


Figure 40. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the WCPO.

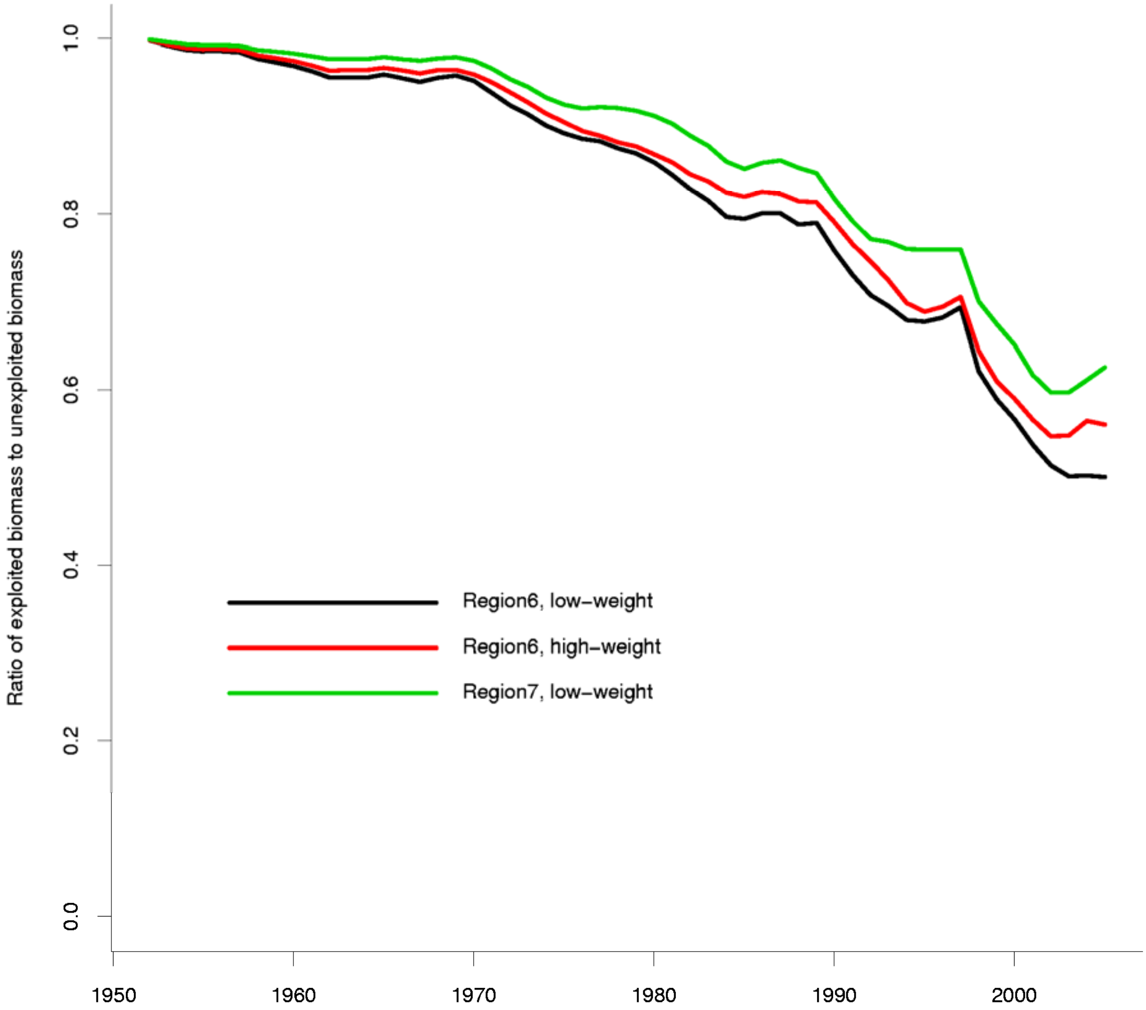


Figure 41. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for the WCPO obtained from the separate analyses.

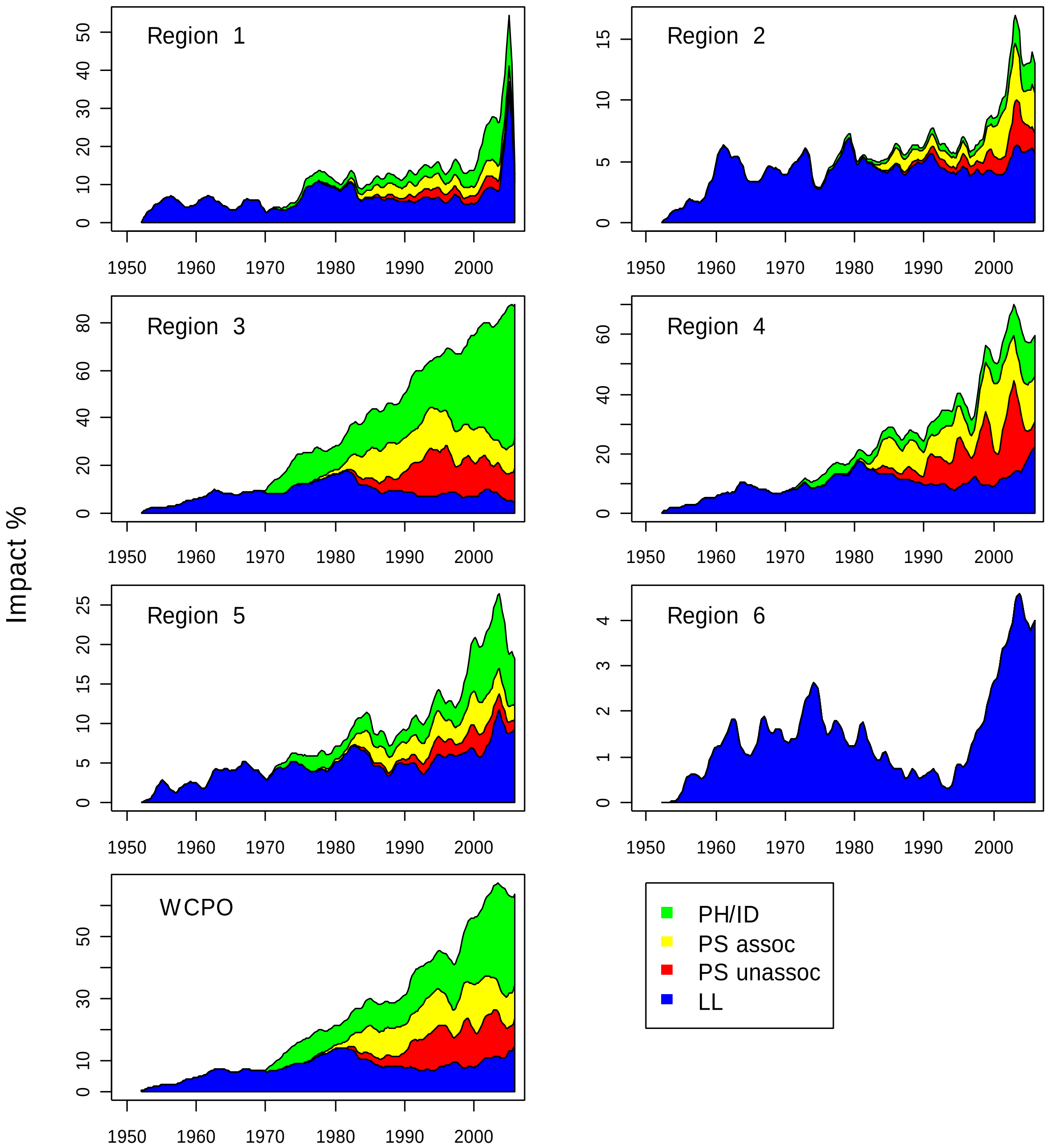


Figure 42. Estimates of reduction in spawning biomass due to fishing (fishery impact = 1-$SB_t/SB_{0,t}$) by region and for the WCPO attributed to various fishery groups. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine FAD and log sets; PS unassoc = purse seine school sets.

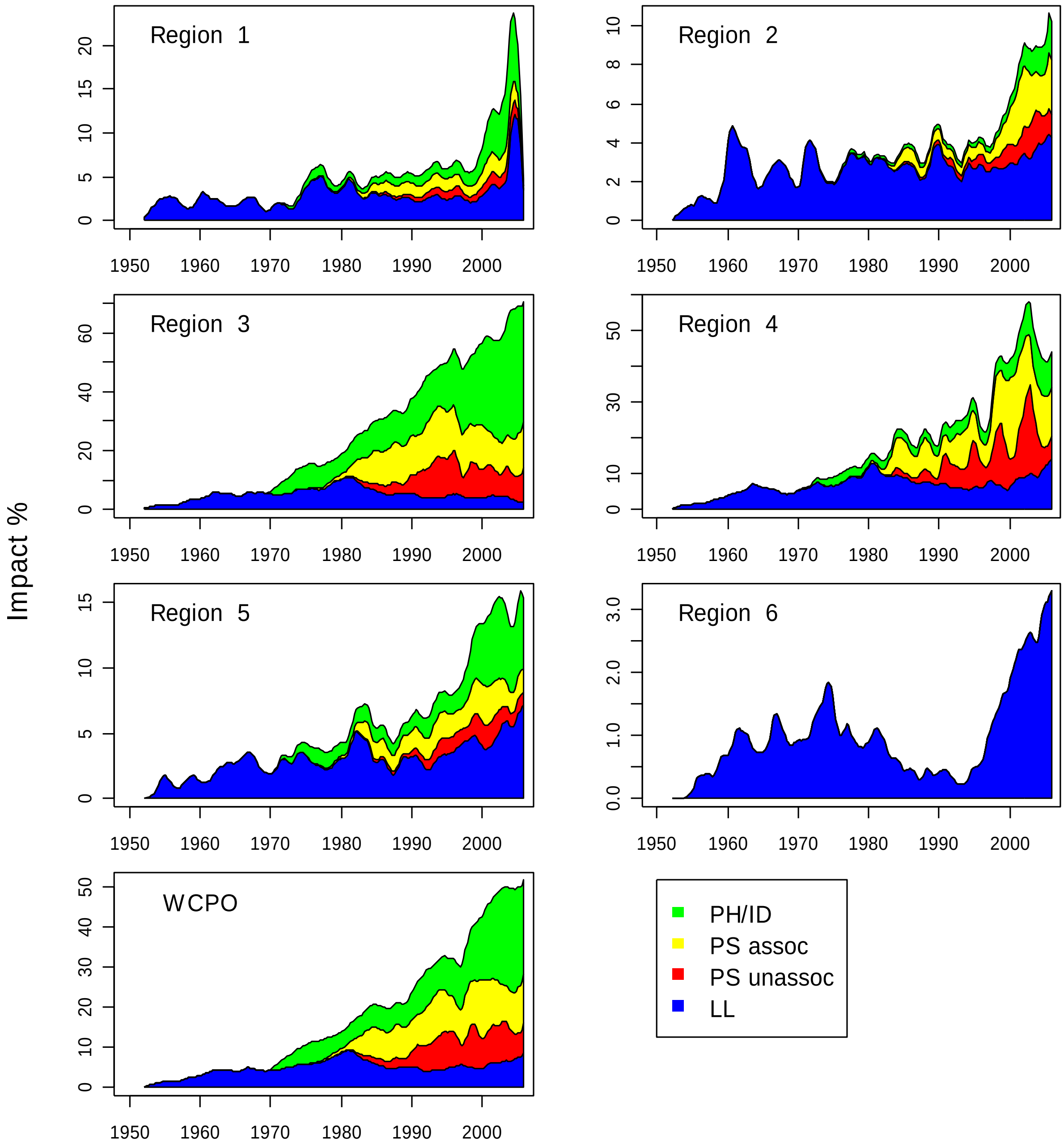


Figure 43. Estimates of reduction in total biomass due to fishing (fishery impact = $1\text{-}B_t/B_{0,t}$) by region and for the WCPO attributed to various fishery groups. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine FAD and log sets; PS unassoc = purse seine school sets.

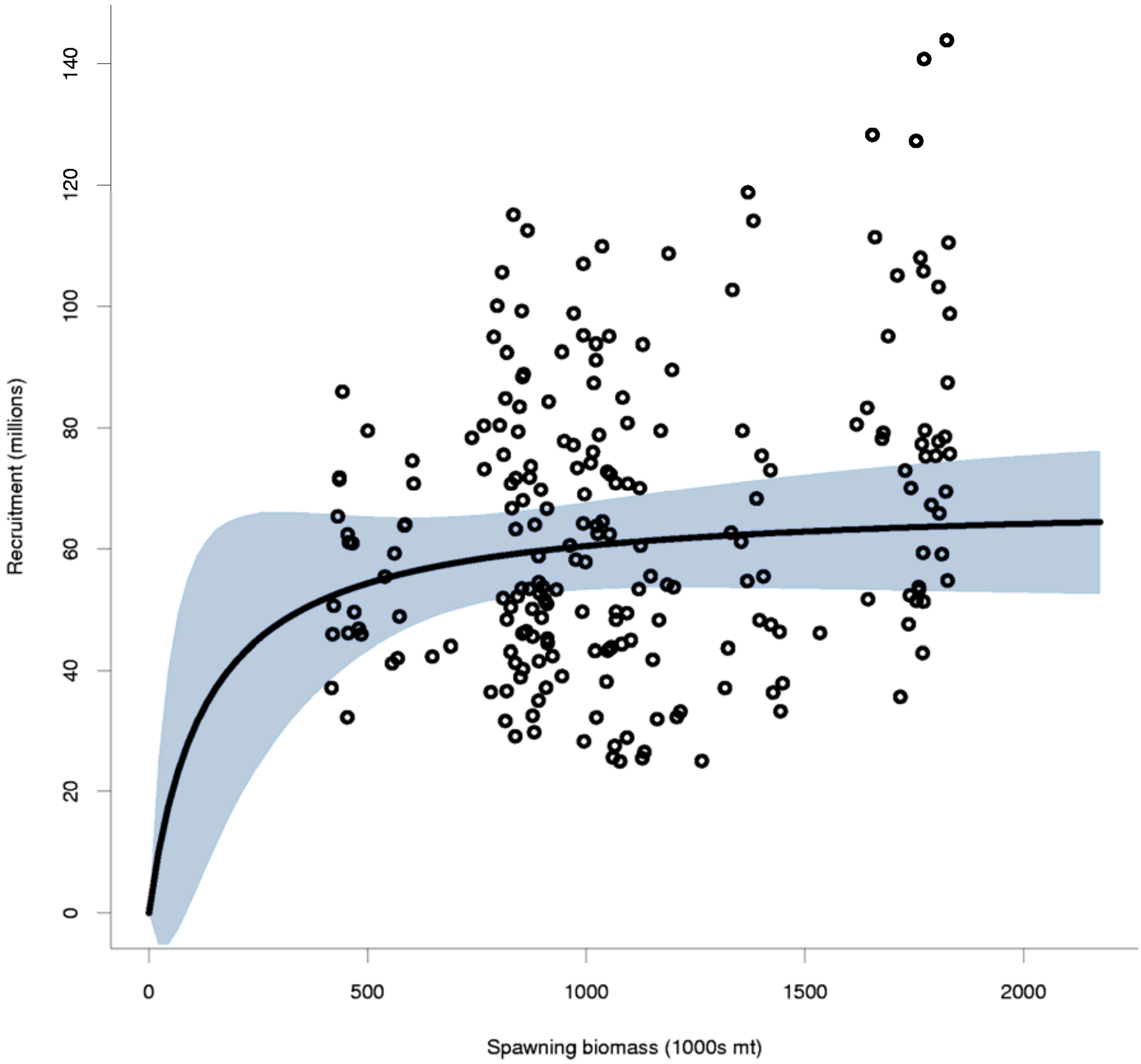


Figure 44. Estimated relationship between equilibrium recruitment and equilibrium spawning biomass. The grey area indicates the 95% confidence region. Estimated recruitment-spawning biomass points are plotted as open circles.

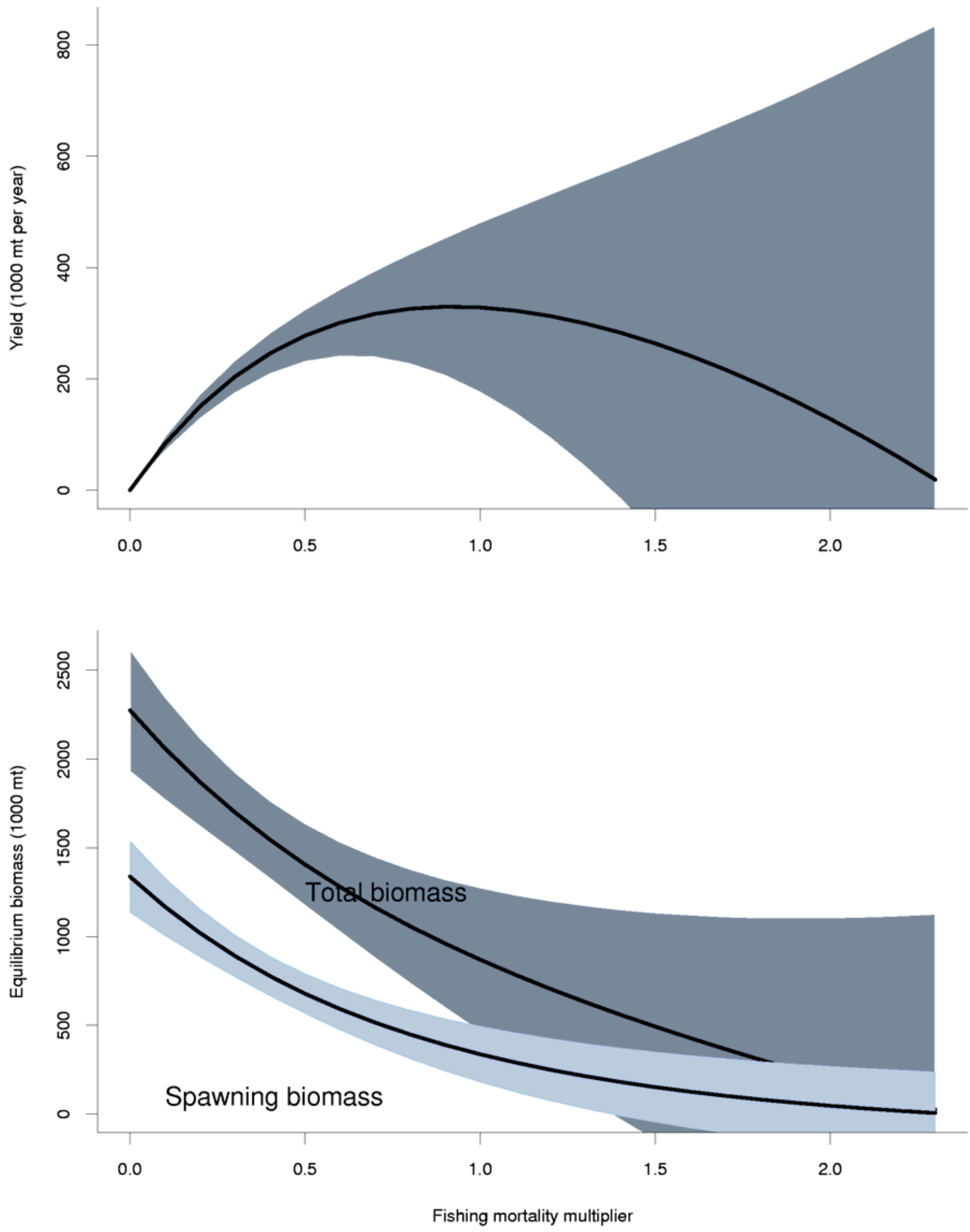


Figure 45. Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier. The shaded areas represent approximate 95% confidence intervals.

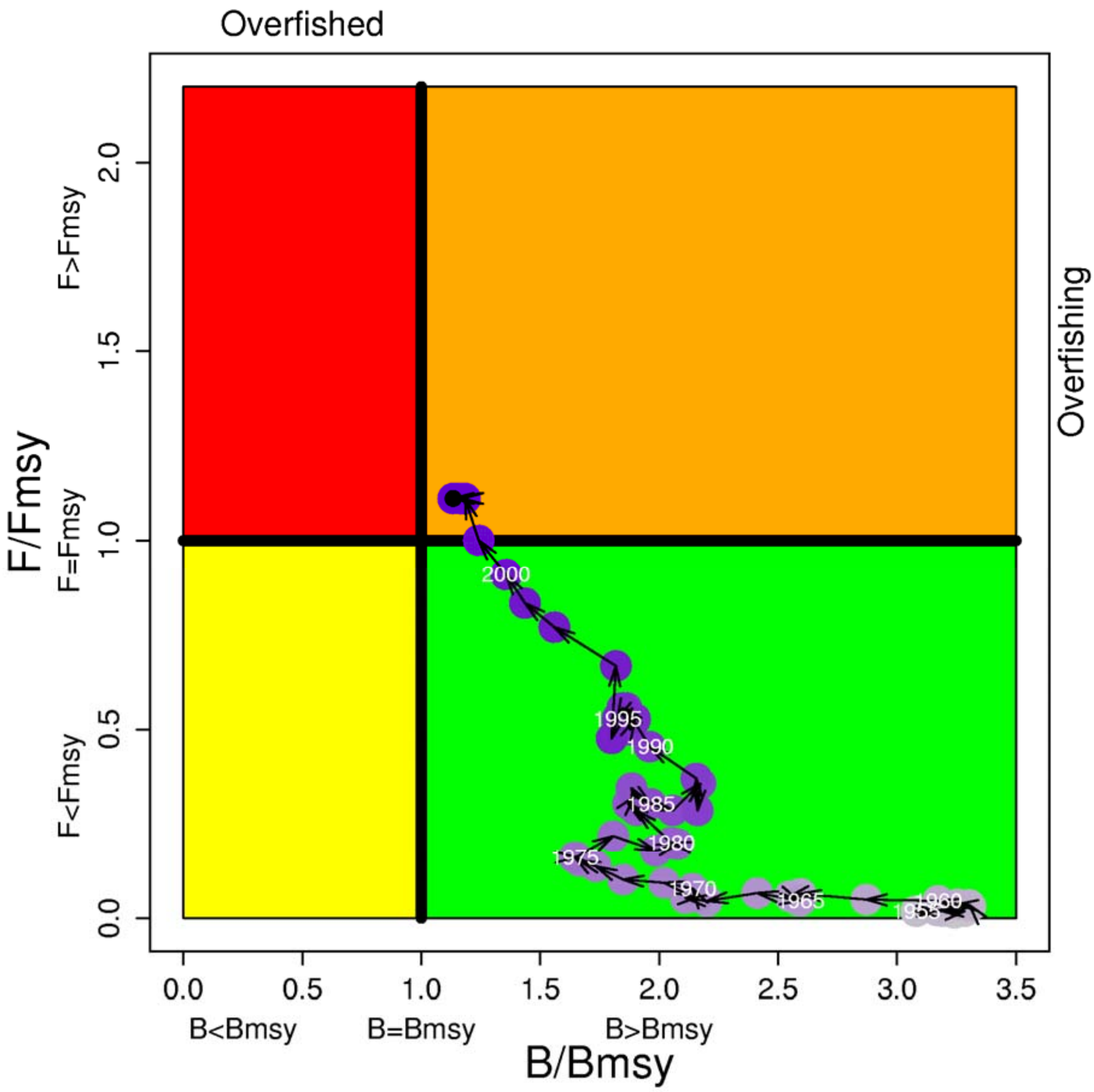


Figure 46. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1952–2005). The colour of the points is graduated from mauve (1952) to dark purple (2005) and the points are labelled at 5-year intervals.

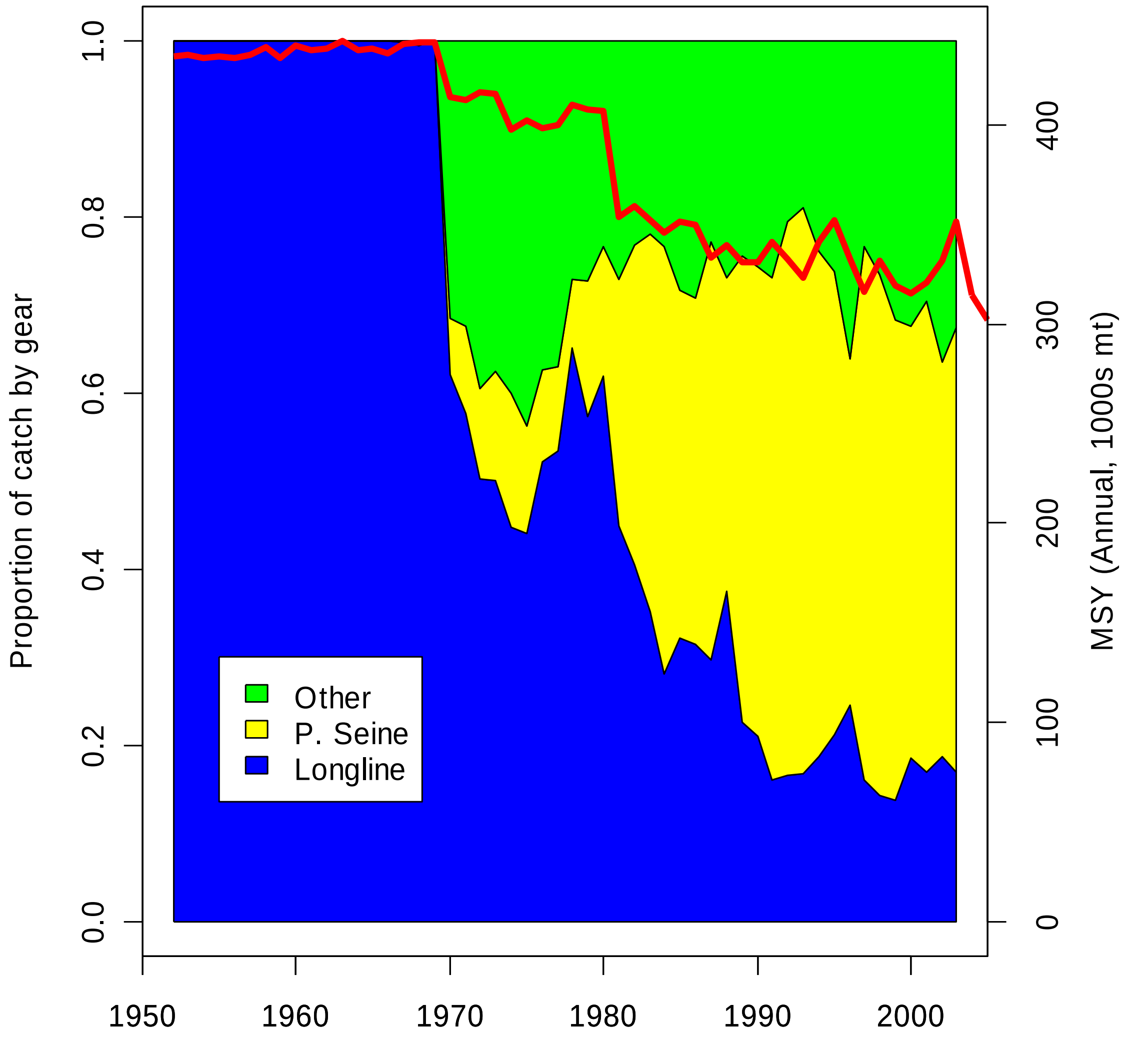


Figure 47. Temporal trend in annual Maximum Sustainable Yield (MSY) (red line) estimated for each year included in the yellowfin stock assessment model. This is compared to the proportional distribution in the annual yellowfin catch by main gear type for the entire WCPO. The "other" fishery is principally the Indonesia/Philippines domestic fishery (PH/ID MISC).

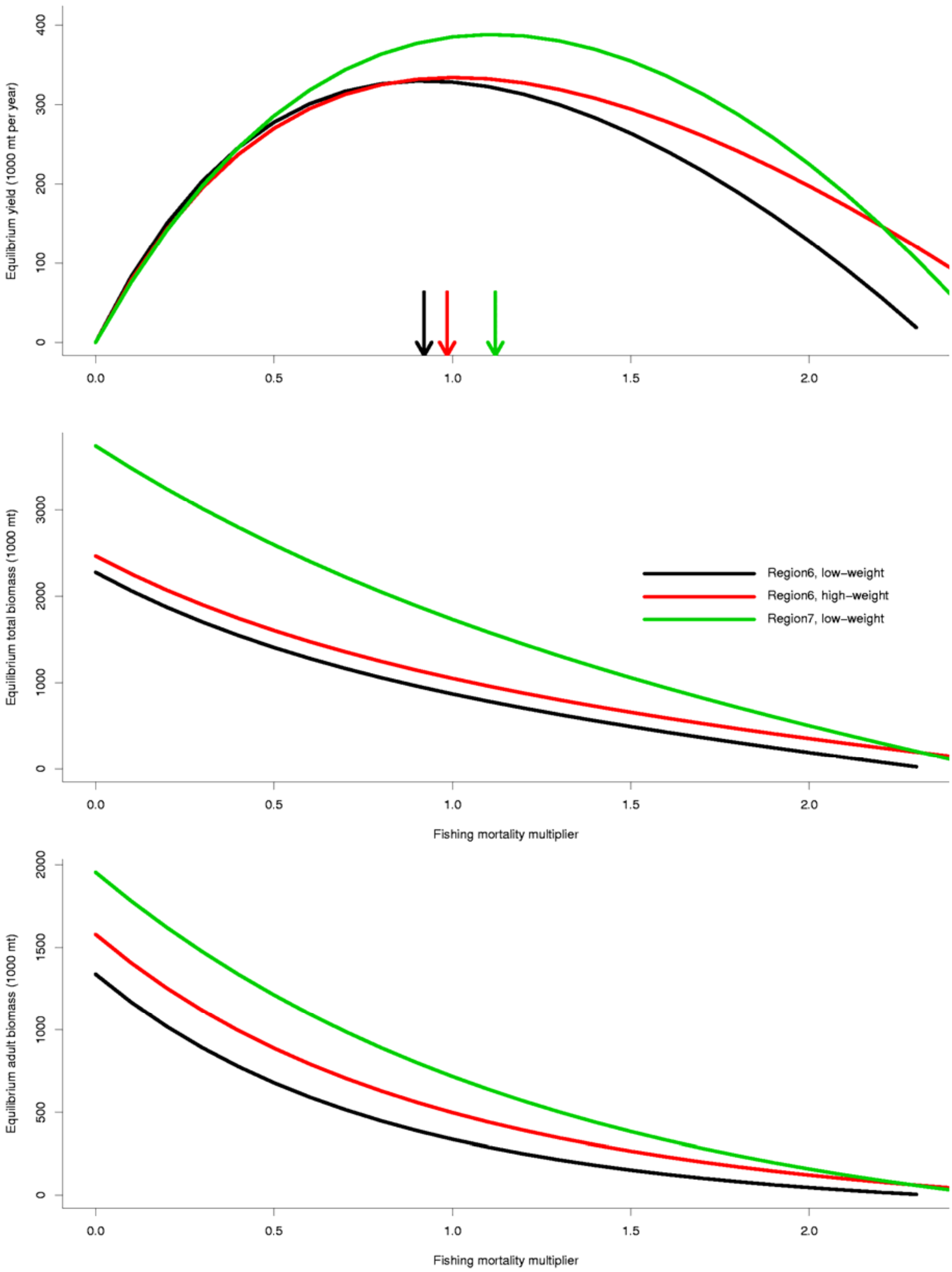


Figure 48. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier obtained from the separate model options. In the upper panel, the arrows indicate the value of the fishing mortality multiplier at maximum yield.

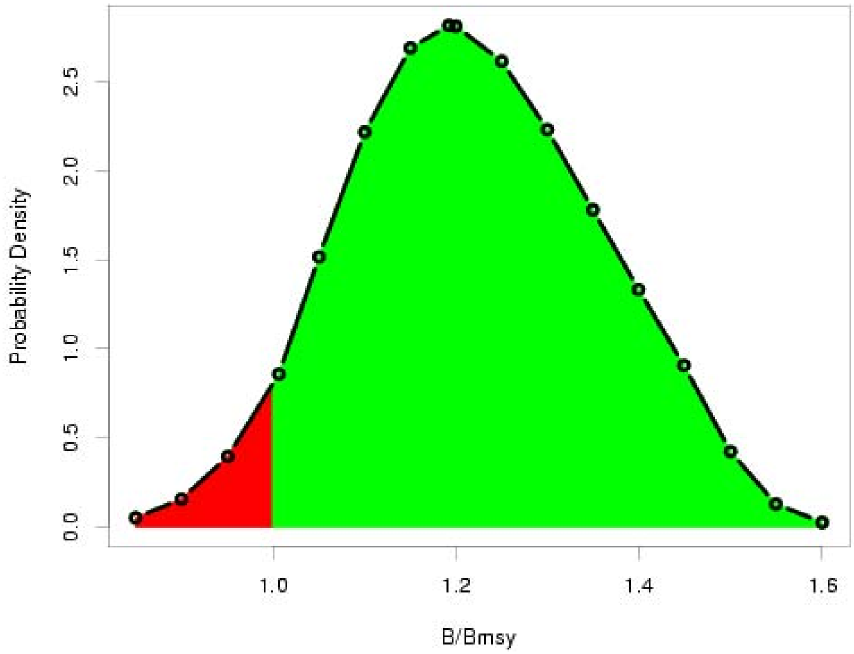


Figure 49. Likelihood profile for $B_{current}/\widetilde{B}_{MSY}$ from the six-region LOWSAMP model. The probability of $B_{current}/\widetilde{B}_{MSY} < 1$ (red region) is approximately 4.9%.

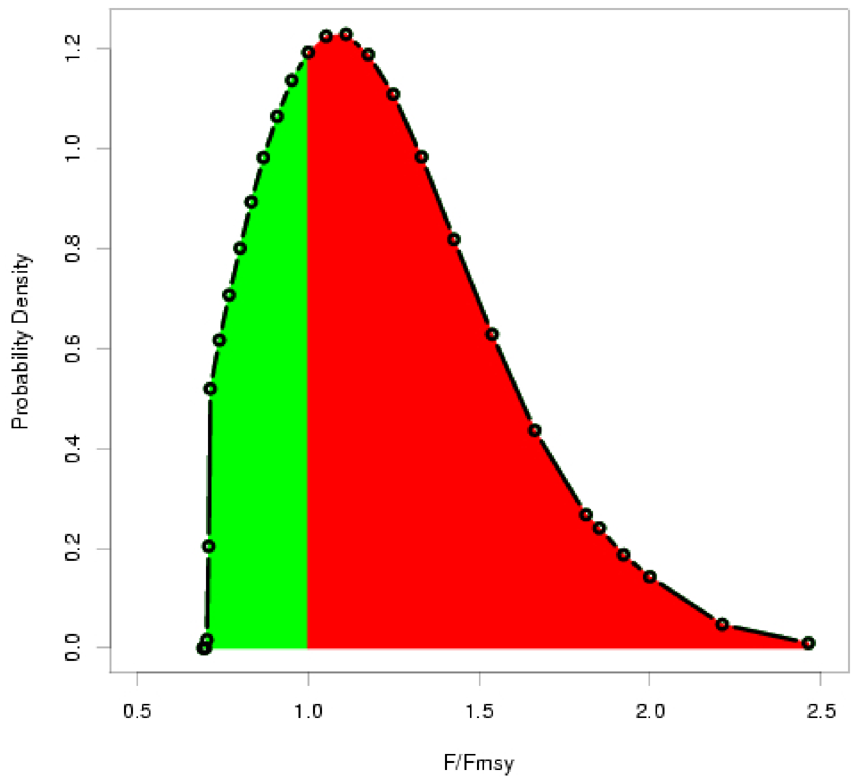


Figure 50. Likelihood profile for $F_{current}/\widetilde{F}_{MSY}$ from the six-region LOWSAMP model. The probability of $F_{current}/\widetilde{F}_{MSY} > 1$ (red region) is approximately 73.5%.

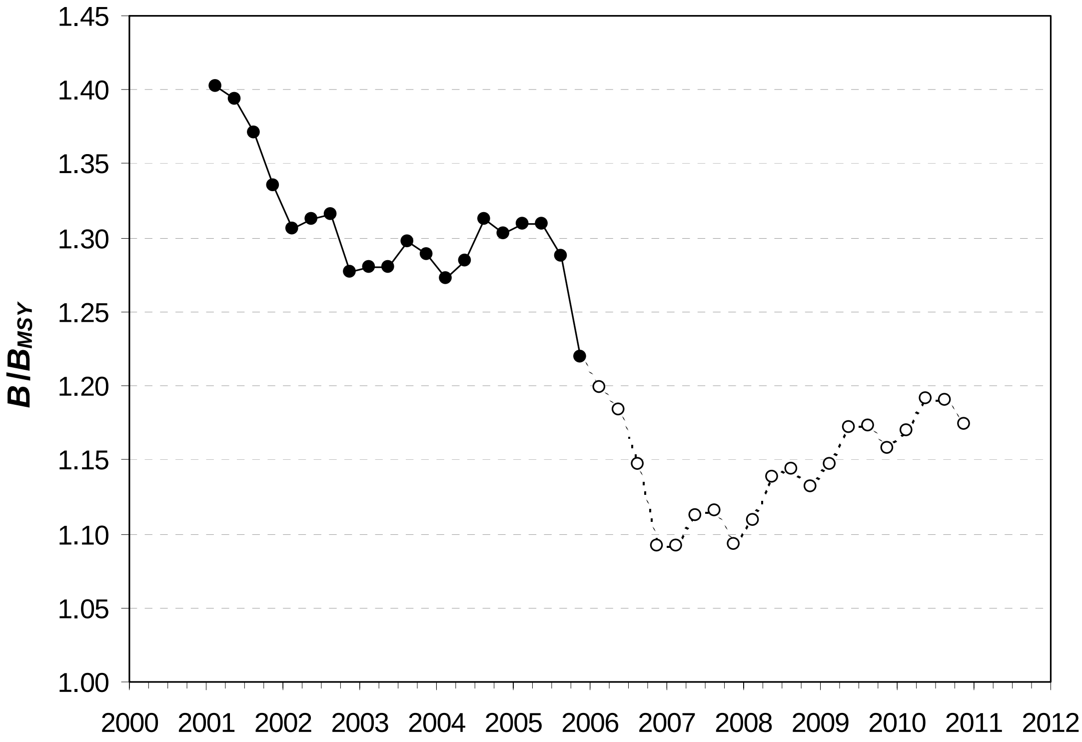


Figure 51. Projected ratio of $B_t / \widetilde{B}_{MSY}$ where $\widetilde{B}_{MSY}$ is computed based on the average *F*-at-age in the final year (5) of the projection (851,800 mt). The black circles and solid line are estimates from the stock assessment; the open circles and dashed line are the projection.

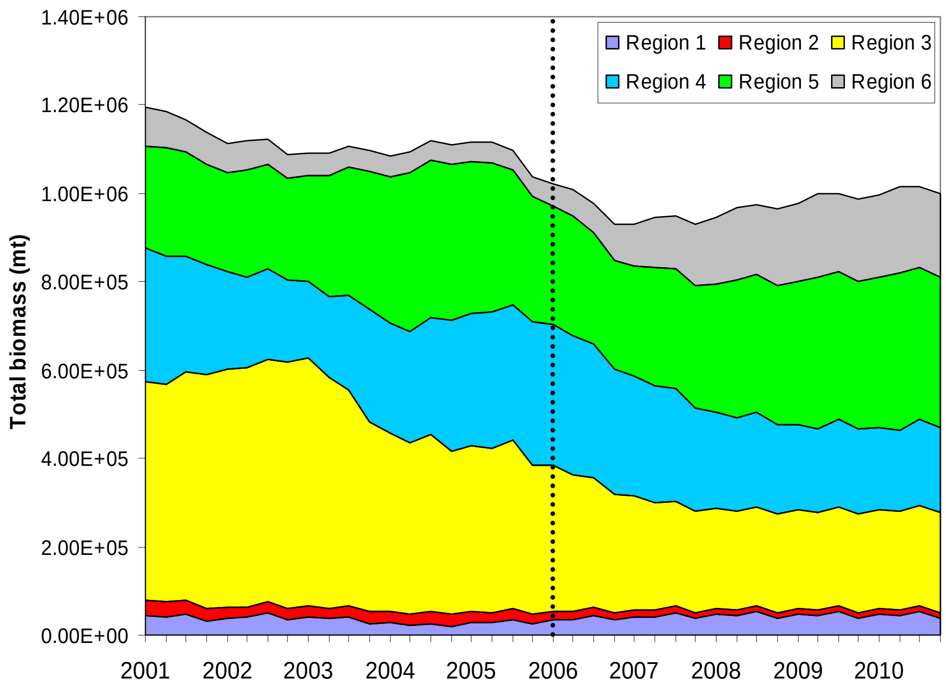


Figure 52. Recent and projected total biomass (mt) by region. The vertical dotted line represents the start of the five-year projection period.

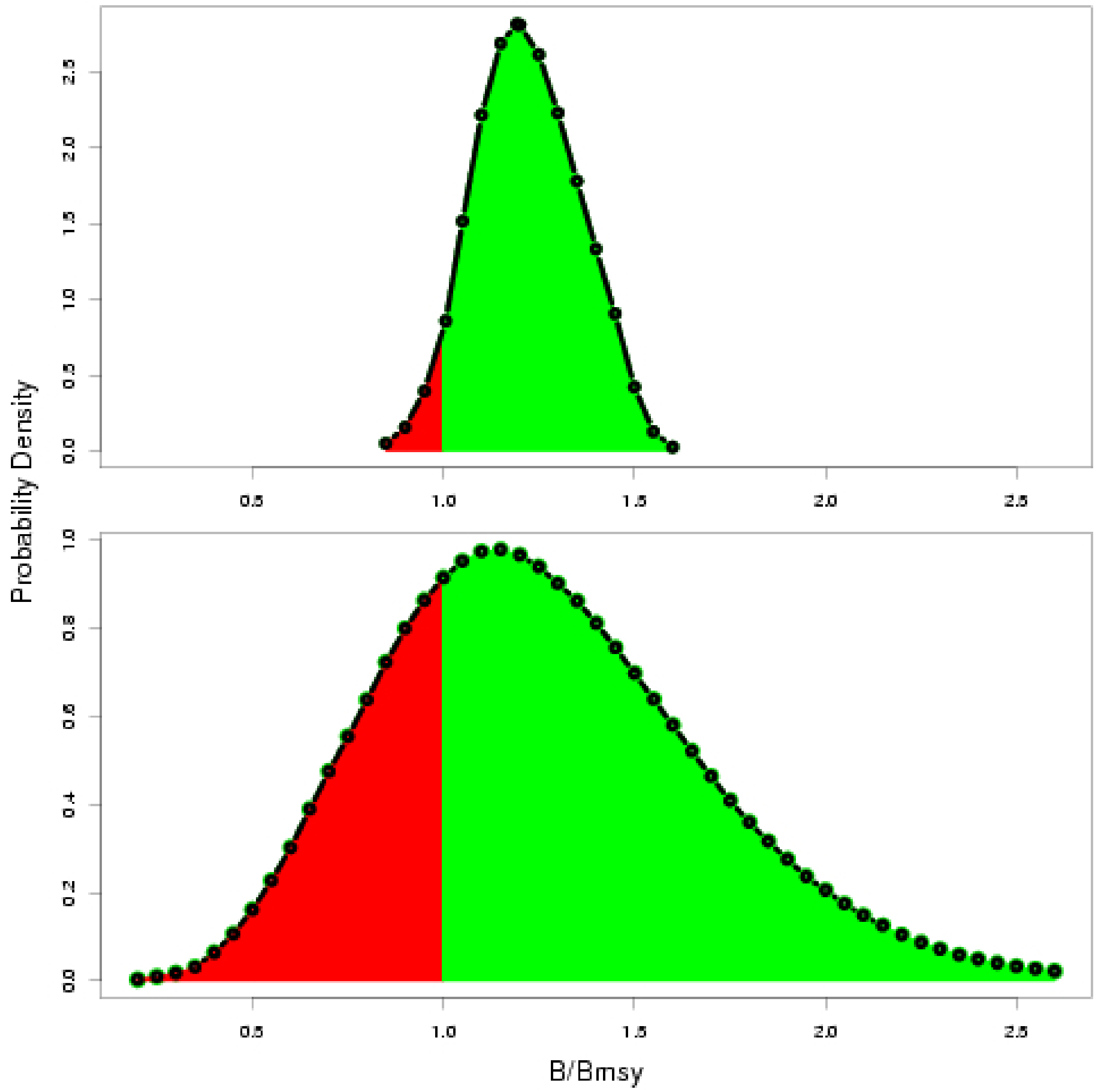


Figure 53. Profile likelihood for $B_{final}/\widetilde{B}_{MSY}$, i.e., the biomass ratio for the final year (5) of the projection (lower panel). The $B_{current}/\widetilde{B}_{MSY}$ profile likelihood based on 2001–2004 average *F*-at-age is shown on the same scale in the upper panel for comparison. The probability that $B_{current}/\widetilde{B}_{MSY} < 1$ is approximately 4.9%; the probability that $B_{final}/\widetilde{B}_{MSY} < 1$ is approximately 29%. $\widetilde{B}_{MSY}$ at the end of the projection period is estimated to be 851,800 mt (compared to 960,500 mt at $F_{current}$).

Appendix 1 ***doitall.yft***

```
#  ------------------------
#  PHASE 0 - create initial par file
#  ------------------------
#
if [ ! -f 00.par ]; then
  mfclopt yft.frq yft.ini 00.par -makepar
fi
#
#  ------------------------
#  PHASE 1 - initial par
#  ------------------------
#
if [ ! -f 01.par ]; then
  mfclopt yft.frq 00.par 01.par -file - <<PHASE1
  1 149 100      # recruitment penalties
  2 113 1        # estimate initpop/totpop scaling parameter
  2 177 1        # use old totpop scaling method
  2 32 1         # and estimate the totpop parameter
  -999 49 10     # divide LL LF sample sizes by 10 (default)
  -999 50 10     # divide LL WF sample sizes by 5 (default=10)
  1 32 2         # sets standard control
  1 111 4        # sets likelihood function for tags to negative binomial
  1 141 3        # sets likelihood function for LF data to normal
  2 57 4         # sets no. of recruitments per year to 4
  2 69 1         # sets generic movement option (now default)
  2 93 4         # sets no. of recruitments per year to 4 (is this used?)
  2 94 2 2 95 20  # initial age structure based on Z for 1st 20 periods
  -999 26 2      # sets length-dependent selectivity option
  -9999 1 2      # sets no. mixing periods for all tag release groups to 2
# sets non-decreasing selectivity for longline fisheries
 -999 57 3       # uses cubic spline selectivity
 -999 61 3       # with 3 nodes for cubic spline
   -5 57 1       # logistic selectivity for 3 TWCH fisheries
   -8 57 1
  -21 57 1
# grouping of fisheries with common selectivity
   -1 24 1       # Longline fisheries have common selectivity in reg. 1, 2, 7
   -2 24 1
   -3 24 2       # Longline fisheries have common selectivity in reg. 3, 4, 5, 6, 8
   -4 24 3
   -5 24 4       # TW/CH longliners use night sets -> generally bigger fish
   -6 24 5
   -7 24 3
   -8 24 4
   -9 24 6
  -10 24 3
  -11 24 7
  -12 24 3
  -13 24 8
  -14 24 9
  -15 24 10
  -16 24 9
  -17 24 10
  -18 24 11
  -19 24 12
  -20 24 3 #LL in ID/PH
  -21 24 4
# grouping of fisheries with common catchability
```

```
  -1 29 1      # Longline fisheries grouped
  -2 29 1
  -3 29 2      # HI LL fishery different
  -4 29 1
  -5 29 3      # TW/CH LL fishery different
  -6 29 4
  -7 29 1      # AU LL fishery different
  -8 29 5      # JP LL in Aust. region 5 are targeting SBT in the south
  -9 29 6      # AU LL fishery different
 -10 29 1
 -11 29 7
 -12 29 1
 -13 29 8
 -14 29 9
 -15 29 10
 -16 29 11
 -17 29 12
 -18 29 13
 -19 29 14
 -20 29 1
 -21 29 15
 -1 60 1      # Longline fisheries grouped
  -2 60 1
  -3 60 2      # HI LL fishery different
  -4 60 1
  -5 60 3      # TW/CH LL fishery different
  -6 60 4
  -7 60 1      # AU LL fishery different
  -8 60 5      # JP LL in Aust. region 5 are targeting SBT in the south
  -9 60 6      # AU LL fishery different
 -10 60 1
 -11 60 7
 -12 60 1
 -13 60 8
 -14 60 9
 -15 60 10
 -16 60 11
 -17 60 12
 -18 60 13
 -19 60 14
 -20 60 1
 -21 60 15
# grouping of fisheries for tag return data
   -1 32 1
   -2 32 2
   -3 32 3
   -4 32 4
   -5 32 5
   -6 32 6
   -7 32 7
   -8 32 8
   -9 32 9
  -10 32 10
  -11 32 11
  -12 32 12
  -13 32 13
  -14 32 14      # PS assoc. and unassoc. returns are grouped
  -15 32 14
  -16 32 15
  -17 32 15
```

```
   -18 32 16        # PH/ID returns returns are grouped
   -19 32 16
   -20 32 17
   -21 32 18
# grouping of fisheries with common tag-reporting rates - as for tag grouping
    -1 34 1
    -2 34 2
    -3 34 3
    -4 34 4
    -5 34 5
    -6 34 6
    -7 34 7
    -8 34 8
    -9 34 9
   -10 34 10
   -11 34 11
   -12 34 12
   -13 34 13
   -14 34 14        # PS assoc. and unassoc. returns are grouped
   -15 34 14
   -16 34 15
   -17 34 15
   -18 34 16        # PH/ID returns returns are grouped
   -19 34 16
   -20 34 17
   -21 34 18
# sets penalties on tag-reporting rate priors
    -1 35 1        # The penalties are set to be small for LL fisheries
    -2 35 1
    -3 35 50       # HI LL fishery thought to be high rep. rate
    -4 35 1
    -5 35 1
    -6 35 1
    -7 35 1
    -8 35 1
    -9 35 50
   -10 35 1
   -11 35 50        # AU LL region 4 thought to be high rep. rate
   -12 35 1
   -13 35 1
   -14 35 50        # WTP PS based on tag seeding
   -15 35 50
   -16 35 50
   -17 35 50
   -18 35 50        # PH/ID based on high recovery rate
   -19 35 50
   -20 35 1
   -21 35 1
# sets prior means for tag-reporting rates
    -1 36 50       # Mean of 0.5 and penalty of 1 -> uninformative prior
    -2 36 50
    -3 36 80       # HI LL
    -4 36 50
    -5 36 50
    -6 36 50
    -7 36 50
    -8 36 50
    -9 36 80
   -10 36 50
   -11 36 80        # AU LL region 4
```

```
   -12 36 50
   -13 36 50
   -14 36 45        # WTP PS based on tag seeding and discounted for unable returns
   -15 36 45
   -16 36 45
   -17 36 45
   -18 36 60        # PH/ID
   -19 36 60        # PH HL
   -20 36 50
   -21 36 50
# sets penalties for effort deviations (negative penalties force effort devs
# to be zero when catch is unknown)
 -999 13 -10      # higher for longline fisheries where effort is standardized
   -1 13 -50
   -2 13 -50
   -4 13 -50
   -7 13 -50
  -10 13 -50
  -12 13 -50
  -18 13 10
  -20 13 -50
# sets penalties for catchability deviations
   -18 15 1       # low penalty for PH.ID MISC.
  -999 33 1       # estimate tag-reporting rates
  1 33 90         # maximum tag reporting rate for all fisheries is 0.9
PHASE1
fi
#  ---------
#   PHASE 2
#  ---------
if [ ! -f 02.par ]; then
  mfclopt yft.frq 01.par 02.par -file - <<PHASE2
  -999 3 25       # all selectivities equal for age class 25 and older
  -999 4 4        # possibly not needed
  -999 21 4       # possibly not needed
  1 189 1         # write graph.frq (obs. and pred. LF data)
  1 190 1         # write plot.rep
  1 1 200         # set max. number of function evaluations per phase to 100
  1 50 -2         # set convergence criterion to 1E+01
  -999 14 10      # Penalties to stop F blowing out
  -999 62 2       # add more nodes to cubic spline
PHASE2
fi
#  ---------
#   PHASE 3
#  ---------
if [ ! -f 03.par ]; then
  mfclopt yft.frq 02.par 03.par -file - <<PHASE3
  2 70 1          # activate parameters and turn on
  2 71 1          # estimation of temporal changes in recruitment distribution
  1 183 20        # penalties on devs for first 20 time periods
  -100001 1 1000  # pen wt on region rec diffs in region 1
  -100001 2 1000  # pen wt on region rec diffs in region 2
  -100001 3 1000  # pen wt on region rec diffs in region 3
  -100001 4 1000  # pen wt on region rec diffs in region 4
  -100001 5 1000  # pen wt on region rec diffs in region 5
  -100001 6 1000  # pen wt on region rec diffs in region 6
  -100001 7 1000  # pen wt on region rec diffs in region 7
PHASE3
fi
```

```
#  ---------
#   PHASE 4
#  ---------
if [ ! -f 04.par ]; then
  mfclopt yft.frq 03.par 04.par -file - <<PHASE4
  2 68 1          # estimate movement coefficients
PHASE4
fi
#  ---------
#   PHASE 5
#  ---------
if [ ! -f 05.par ]; then
  mfclopt yft.frq 04.par 05.par -file - <<PHASE5
  1 16 1          # estimate length dependent SD
PHASE5
fi
#  ---------
#   PHASE 6
#  ---------
if [ ! -f 06.par ]; then
  mfclopt yft.frq 05.par 06.par -file - <<PHASE6
  1 173 8         # estimate independent mean lengths for 1st 8 age classes
  1 182 10
PHASE6
fi
#  ---------
#   PHASE 7
#  ---------
if [ ! -f 07.par ]; then
  mfclopt yft.frq 06.par 07.par -file - <<PHASE7
  -999 27 1       # estimate seasonal catchability for all fisheries
  -18 27 0        # except those where
  -19 27 0        # only annual catches
PHASE7
fi
#  ---------
#   PHASE 8
#  ---------
if [ ! -f 08.par ]; then
  mfclopt yft.frq 07.par 08.par -file - <<PHASE8
  -3 10 1         # estimate
  -5 10 1         # catchability
  -6 10 1         # time-series
  -8 10 1         # for all
  -9 10 1         # non-longline
  -11 10 1        # fisheries
  -13 10 1
  -14 10 1
  -15 10 1
  -16 10 1
  -17 10 1
  -18 10 1
  -19 10 1
  -21 10 1
  -999 23 23      # and do a random-walk step every 23+1 months
PHASE8
fi
#  ---------
#   PHASE 9
#  ---------
```

```
if [ ! -f 09.par ]; then
  mfclopt yft.frq 08.par 09.par -file - <<PHASE9
  1 14 1        # estimate von Bertalanffy K
  1 12 1        # and mean length of age 1
PHASE9
fi
#  ---------
#   PHASE 10
#  ---------
if [ ! -f 10.par ]; then
  mfclopt yft.frq 09.par 10.par -file - <<PHASE10
# grouping of fisheries for estimation of negative binomial parameter a
   -1 44 1
   -2 44 1
   -3 44 1
   -4 44 1
   -5 44 1
   -6 44 1
   -7 44 1
   -8 44 1
   -9 44 1
  -10 44 1
  -11 44 1
  -12 44 1
  -13 44 1
  -14 44 2
  -15 44 2
  -16 44 2
  -17 44 2
  -18 44 3
  -19 44 3
  -20 44 1
  -21 44 1
 -999 43 1       # estimate a for all fisheries
PHASE10
fi
#  ---------
#   PHASE 11
#  ---------
if [ ! -f 11.par ]; then
  mfclopt yft.frq 10.par 11.par -file - <<PHASE11
  -100000 1 1    # estimate
  -100000 2 1    # time-invariant
  -100000 3 1    # distribution
  -100000 4 1    # of
  -100000 5 1    # recruitment
  -100000 6 1
  -100000 7 1
PHASE11
fi
#  ---------
#   PHASE 12
#  ---------
if [ ! -f 12.par ]; then
  mfclopt yft.frq 11.par 12.par -file - <<PHASE12
  2 145 1
  1 149 0
  2 146 1
  2 147 1
  2 148 20      # Current is defined as 2001-2004
```

```
  2 155 4
  2 153 31
  2 154 16
  1 1 1000
  1 50 -3
  -999 14 0
PHASE12
fi
cp plot.rep plot-12.rep
cp length.fit length-12.fit
cp weight.fit weight-12.fit
#  ---------
#   PHASE 13
#  ---------
if [ ! -f 13.par ]; then
  mfclopt yft.frq 12.par 13.par -file - <<PHASE13
  -999 49 50
  -999 50 50
PHASE13
fi
```

Appendix 2 *yft.ini*

```
# number of age classes
  28
# MATURITY AT AGE
  0 0 0 0 0 0 0.25 0.50 0.75 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
# natural mortality
0.249404147000
# movemap
  1 2 3 4
# diffusion coffs
   0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
   0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
   0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
   0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
# age_pars
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0.695533437000  0.567700066000  0.421096592000  0.249246335000  0.041606970000  -0.220757290000  -
0.220757290000  -0.220757290000  -0.220757290000  -0.220757290000  -0.171967130000  -0.041774192000
0.061062580000   0.133805664000   0.174460761000   0.182064874000   0.157959023000   0.107378580000
0.040072948000  -0.031368892000  -0.095330229000  -0.144824574000  -0.178525605000  -0.199049425000  -
0.210388972000 -0.216136835000 -0.218830926000 -0.220004603000
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
# recruitment distribution among regions
   0.05 0.06 0.25 0.35 0.05 0.09 0.15
# The von Bertalanffy parameters (mean length 1, mean length nage, K)
# Initial value   Lower bound      Upper bound
      25.0          20.0           40.0
     150.0         140.0           200.0
      0.15          0.0            0.3
# Weight-length parameters
#  FAR Seas values
   2.512e-05  2.9396
# Variance parameters (Average SD by age class, SD dependency on mean length)
# Initial value   Lower bound      Upper bound
       6.0          3.0           10.0
       0.40        -1.00           1.00
# The number of mean constraints
  0
```