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

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Table of Contents

Executive summary

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 2000, the total yellowfin tuna catch in the WCPO has varied between 370,000 and 440,000 mt. Purse seiners harvest the majority of the yellowfin tuna catch (53% by weight in 2007), with the longline and pole-and-line fisheries comprising 16% and 4% of the total catch, respectively (source: WCPFC 2007 Yearbook). 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 which accounted for 56% of recent (2000–2005) yellowfin purse-seine catch (by weight).

Longline catches in recent years (70,000–80,000 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. The domestic fisheries of the Philippines and eastern Indonesia catch yellowfin using a variety of gear types (e.g. pole-and-line, ringnet, gillnet, handline and seine net). Catches from these fisheries have increased over the past decade and are estimated to represent approximately 25–30% of total WCPO yellowfin tuna catches.

This paper presents the 2009 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 24 fisheries and quarterly time periods from 1952 through 2008.

The spatial and fishery structure is equivalent to that used in the 2007 assessment and the data sets have been updated to include the catch, effort, and size composition data from the last two years. However, there have been a number of significant changes to the model inputs, in particular the adoption of an alternative catch history for the purse-seine fleet that includes a substantially higher level of catch for the associated purse-seine fishery. There have also been refinements to the catch histories from the Philippines fisheries, the longline CPUE indices, and biological parameters (*M*-at-age and spawning fraction). The current assessment also investigated a range of structural assumptions related to the relative weighting of the longline CPUE indices and longline size frequency data, the consideration of an increase in the catchability of the longline fisheries (“effort creep”), and assumptions regarding the parameterisation of the spawner-recruit relationship (SRR).

For comparative purposes, the current assessment model was also configured to be equivalent to the 2007 assessment (including purse-seine catches calculated using the previous approach). The model yielded results that were very similar to the results of the 2007 base case assessment model. In general, the results from the range of current model options were considerably more optimistic than the 2007 base case model with respect to the key *MSY* based indicators of stock status. This was principally due to the assumptions regarding the steepness of the SRR, although some of the other changes in model inputs and assumptions were also influential.

The main conclusions of the current assessment are as follows.

1. For all analyses, there are strong temporal trends in the estimated recruitment series. Initial recruitment was relatively high but declined during the 1950s and 1960s. Recruitment remained relatively constant during the 1970s and 1980s and then declined steadily from the early 1990s. Recent recruitment is estimated to be considerably lower than the long-term average.
2. Trends in biomass are generally consistent with the underlying trends in recruitment. Biomass is estimated to have declined throughout the model period. Model options that incorporate an

increase in longline efficiency (catchability) were characterised by a higher initial biomass level and a stronger overall decline.

3. The biomass trends in the model are principally driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. The current assessment incorporated a revised set of longline CPUE indices and, for some model options, the indices were modified to account for an estimate increase in longline catchability. For some of the main longline fisheries (in particularly LL ALL 3), 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 somewhat different information about the relative level of fishing mortality in the region. The current assessment includes a range of model sensitivities to examine the relative influence of these two data sources. Nonetheless, further research is required to explore the relationship between longline CPUE and yellowfin abundance and the methodology applied to standardise the longline CPUE data.

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. While the various analyses have shown that the current stock status is relatively insensitive to the assumed level of catch from the Indonesian fishery, yield estimates from the fishery vary in accordance with the level of assumed Indonesian catch. Therefore, improved estimates of historical and current catch from these fisheries are important in the determination of the underlying productivity of the stock.

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 about 60% of unexploited biomass (a fishery impact of 40%) in 2004–2007. This represents a moderate level of stock-wide depletion although it is considerably higher than the equivalent equilibrium-based reference point ($\tilde{B}_{MSY} / \tilde{B}_0$ of approximately 0.35–0.40). However, depletion is considerably higher in the equatorial region 3 where recent depletion levels are approximately 0.35 and 0.30 for total and adult biomass, respectively (65% and 70% reductions from the unexploited level). Impacts are moderate in region 4 (30%), low (about 15–20%) in regions 1, 2, and 5 and minimal (5%) in region 6. If stock-wide over-fishing criteria were applied at the level of our model regions, we would conclude that region 3 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 Philippines/Indonesian domestic fisheries and associated purse-seine fishery have the highest impact, particularly in region 3, while the unassociated purse seine fishery has a moderate impact. These fisheries are also contributing significantly to the fishery impact in all other regions. Historically, the coastal Japanese pole-and-line and purse-seine fisheries have had a significant impact on biomass levels in their home region (1). In all regions, the longline fishery has a relatively small impact, less than 5%.

7. The current assessment includes a number of changes to the model assumptions, particularly related to the biological parameters (natural mortality and reproductive capacity), the relative influence of the longline CPUE and size frequency data, and changes to the input data (most notably the purse-seine catch). However, the most influential change from the previous assessment relates to the assumptions regarding the steepness of the spawner-recruit relationship. Previous assessments have determined low values of steepness in the model estimation procedure, while the current assessment has assumed a range of fixed values for steepness (0.55–0.95). Assuming a moderate value of steepness (0.75) has resulted in a considerably more optimistic assessment of the stock status (compared to 2007 base case) due to the actual value of steepness

and, to a lesser degree, the interaction between steepness and the other changes in model assumptions (especially the revised biological parameters, lower penalty on the longline effort deviations, and increasing longline catchability).

8. For a moderate value of steepness (0.75), $F_{current}/\tilde{F}_{MSY}$ is estimated to be 0.54–0.68 indicating that under equilibrium conditions the stock would remain well above the level capable of producing *MSY* ($\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$ 1.39–1.59 and $S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$ 1.50–1.79), while $B_{current}/\tilde{B}_{MSY}$ and $SB_{current}/S\tilde{B}_{MSY}$ are estimated to be well above 1.0 (1.41–1.67 and 1.46–1.88, respectively). For lower values of steepness (0.55 and 0.65), $B_{current}/\tilde{B}_{MSY}$ and $SB_{current}/S\tilde{B}_{MSY}$ were estimated to be above 1.0 for all the sensitivities considered. Most of the model options with lower values of steepness also yielded estimates of $F_{current}/\tilde{F}_{MSY}$ below 1.0; however, the F_{MSY} reference point was approached or slightly exceeded for a subset of the model options that included the lowest value of steepness (0.55) in combination with a number of other factors.

9. Sensitivity analyses were conducted to investigate the influence of a range of key model inputs, principally those relating to steepness of the SRR, the levels of catch from the Indonesian/Philippines and purse-seine fisheries, *M*-at-age, and the region 6 CPUE index. The interaction between each of these factors and the other key model assumptions (relative weighting of longline CPUE and size frequency data and increase in longline catchability) was also examined. The uncertainty associated with the point estimates of the key *MSY* based reference points was also determined using a likelihood profile approach. Both analyses revealed that most of the uncertainty in estimates of $F_{current}/\tilde{F}_{MSY}$, $B_{current}/\tilde{B}_{MSY}$ and $SB_{current}/S\tilde{B}_{MSY}$ was attributable to the value of steepness for the SRR. Overall, the full range of model options yielded estimates of current biomass that were well above $S\tilde{B}_{MSY}$ and, with the exception of a subset of the model options that incorporated the lowest value of steepness (0.55), estimates of fishing mortality were well below F_{MSY}. The probability distributions derived from the likelihood profiles were generally consistent with these observations.

10. The estimates of *MSY* for the four principal models are 552,000–637,000 mt and considerably higher than recent catches estimates for yellowfin (430,000 mt, source WCPFC Yearbook 2007). The large difference between the *MSY* and recent catches is partly attributable to the stock assessment model incorporating the higher (preliminary) purse-seine catch estimates (representing an additional catch of approximately 100,000 mt per annum in recent years). The more optimistic models suggest that the stock could potentially support long-term average yields above the recent levels of catch. However, it is important to note that recent (1998–2007) levels of estimated recruitment are considerably lower (80%) than the long-term average level of recruitment used to calculate the estimates of *MSY*. If recruitment remains at recent levels, then the overall yield from the fishery will be lower than the *MSY* estimates.

11. While estimates of current fishing mortality are generally well below F_{MSY}, any increase in fishing mortality would most likely occur within region 3 — the region that accounts for most of the catch. This would exacerbate the already high levels of depletion that are occurring within the region. Further, the computation of *MSY*-based metrics assumes that the relationship between spawning biomass and recruitment occurs at the global level of the stock and, therefore, does not consider the differential levels of impact on spawning biomass between regions. The spawning biomass in region 3 is estimated to have been reduced to approximately 30% of the unexploited level; however, due to the lower overall depletion of the entire WCPO stock, the model assumes that there has been no significant reduction in the spawning capacity of the stock. A more conservative approach would be to consider the spawning capacity at the regional level and define reference points accordingly.

12. The current assessment has undertaken a more comprehensive analysis of model uncertainty than previous assessments. The analysis indicates that the assumptions regarding the spawner-recruit

relationship represent the most significant source of uncertainty. For tuna species, there are no strong empirical data available to inform the model regarding the likely range of values of steepness of the SRR that underpin the *MSY* based stock indicators. On that basis, it may be more appropriate to adopt alternative fishing mortality and biomass based reference points that are not reliant on the *MSY* concept, although inevitably some assumption regarding the SRR is necessary, implicitly or explicitly, in the formulation of other alternative stock indicators.

13. The structural uncertainty analysis investigated the impact of a range of sources of uncertainty in the current model and the interaction between these assumptions. Nonetheless, there remains a range of other assumptions in the model that should be investigated either internally or through directed research. Further studies are required: to refine our estimates of growth, natural mortality and reproductive potential, incorporating consideration of spatio-temporal variation and sexual dimorphism; to examine in detail the time-series of size frequency data from the fisheries, which may lead to refinement in the structure of the fisheries included in the model; to consider size-based selectivity processes in the assessment model; to collect age frequency data from the commercial catch in order to improve current estimates of the population age structure; to improve the accuracy of the catch estimates from a number of key fisheries, particularly those catching large quantities of small yellowfin; to refine the methodology and data sets used to derive CPUE abundance indices from the longline fishery; and to refine approaches to integrate the recent tag release/recapture data into the assessment model.

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). The first assessment was conducted in 1999 and assessments were conducted annually until 2007. The most recent assessments are documented in Hampton and Kleiber (2003), Hampton et al. (2004, 2005 and 2006) and Langley et al. (2007). The current assessment incorporates the most recent data from the yellowfin fishery and maintains the model structure of the recent assessments. The sensitivity of the key results of assessment to a range of model assumptions, principally related to uncertainty in the various input data sets, is also examined.

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 ($B_{current}/\tilde{B}_{MSY}$ and $SB_{current}/S\tilde{B}_{MSY}$) and recent fishing mortality to the fishing mortality at MSY ($F_{current}/\tilde{F}_{MSY}$). Likelihood profiles of these ratios are used to describe their uncertainty.

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).

There is some indication that young yellowfin may grow more slowly in the waters of Indonesia and the Philippines than in the wider area of the WCPO (Yamanaka 1990). This is further supported by the comparison between the growth rates derived from WCPO yellowfin stock assessment (Hampton et al. 2006) and the growth rates derived from a MFCL model that included only the single western, equatorial region (region 3) (Langley et al. 2007) (Figure 2). The growth rates from the western equatorial region alone were considerably lower than from the WCPO, with the former growth rates more consistent with the growth of yellowfin in the southern Philippines waters (Yamanaka 1990) (Figure 2) and growth increments from tag release/recovery data (Figure 3). On the other hand, the growth rates from the WCPO MFCL model are more consistent with the growth rates determined from daily growth increments from a collection of otoliths collected from a broad area of the equatorial WCPO (Lehodey and Leroy 1999) (Figure 2).

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 wide 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 2000, the total yellowfin tuna catch in the WCPO has varied between 370,000 and 440,000 mt (Figure 4). Purse seiners harvest the majority of the yellowfin tuna catch (53% by weight in 2007), with the longline and pole-and-line fisheries comprising 16% and 4% of the total catch, respectively (source: WCPFC 2007 Yearbook). 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 which accounted for 56% of recent (2000–2005) yellowfin purse-seine catch (by weight).

Longline catches in recent years (70,000–80,000 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. The domestic fisheries of the Philippines and eastern Indonesia catch yellowfin using a variety of gear types (e.g. pole-and-line, ringnet, gillnet, handline and seine net). Catches from these fisheries have increased over the past decade and are estimated to represent approximately 25–30% of total WCPO yellowfin tuna catches.

Figure 5 shows the spatial distribution of yellowfin tuna catch in the WCPO for the past 10 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 6).

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 5). 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 spatial stratification is also designed to minimise the spatial heterogeneity in the magnitude and trend in longline CPUE (Langley 2006b) and the size composition of the longline catch (Langley 2006c). The stratification for the assessment is equivalent to that used in the 2007 assessment.

3.2 Temporal stratification

The time period covered by the assessment is 1952–2008. 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). Twenty four fisheries have been defined for this analysis on the basis of region, gear type, nationality and, in the case of purse seine, set type (Table 1).

There is a single principal 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).

A spatio-temporal analysis of size data from the Japanese longline fishery revealed that yellowfin caught within PNG waters, principally the Bismarck Sea, were consistently smaller than the fish caught in the remainder of Region 3 (Langley 2006c). Historically, this area accounted for a significant component of the total longline catch from Region 3 and, given the apparent difference in size selectivity, it was decided to separate this component of the fishery (LL BMK 3) from the principal longline fishery in Region 3 (LL ALL 3).

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 western equatorial region also includes a pole-and-line fishery that includes the catch and effort data from the Japanese distant-water pole-and-line fleet and the domestic pole-and-line fisheries (Solomon Islands and, historically, PNG) (PL ALL 3). Catches of yellowfin from this fishery peaked in the late 1970s–early 1980s (at about 8,000 mt per annum) but have been negligible since 2000.

The domestic fisheries of the Philippines were grouped into two separate fisheries largely based on the size of fish caught: a hand-line fishery catching large fish (PH HL 3) and a surface fishery (ring net, small-scale purse-seine, etc) catching smaller fish (PH MISC 3). In previous assessments, the Indonesian domestic fishery was combined with the Philippines surface fishery. However, there is considerably greater uncertainty associated with the recent catch from the Indonesian fishery and it was decided to disaggregate the composite fishery to enable a more comprehensive investigation of the uncertainty related to the Indonesian catch. The Indonesian surface fishery includes catch by pole-and-line, purse-seine, ring net, and other methods (ID MISC 3).

The assessment includes the yellowfin catch from the seasonal purse-seine (PS JP 1) and pole-and-line (PL JP 1) fisheries operated by the Japanese coastal fleet within MFCL region 1. 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.

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 8). This is consistent with the form in which the catch data are recorded for these fisheries.

Total catches included in the model are lower than the summation of total reported catches from the WCPFC (Figure 4) due to the difficulties in spatially separating some of the aggregated catch estimates. For 1990–2007, model catches represent about 95% of the total WCPFC reported catch, with most of the discrepancy due to the catches from the "other" fisheries and longline fisheries. Historical (pre 1970) catches for all gears other than longline were not available for inclusion in the model data set (Figure 4).

Two alternative sets of purse-seine catch data were used in the assessment. The first set consisted of data extracted from the OFP database of catches aggregated by 1° latitude, 1° longitude, month and flag. These data are equivalent to the catch history used in previous assessments. Recent studies have shown that these catch estimates are likely to substantially under-estimate the actual catch of yellowfin due to inaccurate reporting of the species catch composition on logsheets and biases in the observer sampling procedures (grab sampling) (Lawson 2009). To address this bias, the catch data were corrected using the results of a limited number of paired grab and spill samples. This resulted in considerably higher estimates of yellowfin catch from associated sets (Figure 7). There remains a high level of uncertainty associated with these new estimates; however, on balance, the corrected catches were considered to be more reliable than the uncorrected catches. The corrected catches were used as the principal catch series in the assessment, while the uncorrected catches were incorporated in a sensitivity analysis (see below).

Effort data for the Philippines and Indonesian surface fisheries were unavailable. Where effort data are absent, the model assumes a constant value of effort and the model predicts the catch using the effort and catchability deviations. The low penalty weight specified for the deviations means that the assumed effort data for these fisheries do not influence the estimates of stock biomass.

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. Similarly, effort data for the pole-and-line fisheries were defined as days fishing and/or searching.

For the principal longline fisheries (LL ALL 1–6), effective (or standardised) effort was derived using generalized linear models (GLM) refining the approach used in recent assessments (Hoyle 2009).

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 (Hoyle & Langley 2007).

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.

An analysis of longline logsheet data from the region 3 fishery has provided a minimum estimate of the increase in longline catchability (efficiency) associated with the introduction of new vessels into the fishery during 1980–2008 (Hoyle 2009). The catchability of yellowfin tuna by the Japanese longline fleet in region 3 was estimated to have increased by 1.4% per annum over the period. This estimate was applied to the entire period of the LL ALL 3 standardised effort series to account for the increase in efficiency of new vessels entering the fishery – this factor is not incorporated in the GLMs of the aggregated catch and effort data used to derive the principal CPUE indices. For the other regions, yellowfin tuna is a lesser component of the longline catch and, given the lower level of targeting of the species, it was considered that historical trends in catchability would be lower (than the estimated value). On that basis, an annual increase in longline catchability of 0.5% per annum was assumed for the other principal longline fisheries. The two alternative longline effort series (with and without increasing catchability) were included in separate stock assessment models.

For the other longline fisheries, the effort units were defined as the total number of hooks set.

Time-series of catch-per-unit-effort (CPUE) for all fisheries are shown in Figure 9. The GLM standardised CPUE for the principal longline fisheries (with and without increasing catchability) are presented in Figure 10.

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 among 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 11. 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 1995. In addition, data collected during 1997–2008 from the Philippines hand-line (PH HL 3) and surface fisheries (PH 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.

Purse seine: Length-frequency samples from purse seiners have been collected from a variety of port sampling and observer programmes since the mid-1980s. Most of the early data is sourced from the U.S. National Marine Fisheries Service (NMFS) port sampling programme for U.S. purse seiners in Pago Pago, American Samoa and an observer programme conducted for the same fleet. Since the early 1990s, port sampling and observer programmes on other purse seine fleets have provided additional data. Only data that could be classified by set type were included in the final data set.

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. For each temporal stratum, the composite length distribution for the fishery was derived following the approach described below. In recent years, length data from other longline fleets have been collected by OFP and national port sampling and observer programmes in the WCPO.

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

Pole and line: For the equatorial pole-and line fishery, length data were available from the Japanese distant-water fleet (sourced from NRIFS) and from the domestic fleets (Solomon Islands and PNG). Since the late 1990s, most of the length data were collected by observers covering the Solomon Islands pole-and-line fleet.

For the current assessment, quarterly length frequency distributions were computed for the principal longline fisheries weighted by the spatial distribution of the quarterly catch from the individual fishery. Length data from the Japanese distant-water and offshore longline fleets were principally available aggregated in spatial strata of 10 degrees of latitude by 20 degrees of longitude. The following procedure was applied to generate an aggregated length distribution for the region-specific fisheries.

i. The catch (in numbers of fish) for the fishery/quarter was aggregated to a spatial resolution equivalent to the spatial resolution of the length data (usually 10*20 lat/long).

ii. The spatial strata that accounted for most (at least 70%) of the catch in the quarter were identified.

iii. Each of the main spatial strata (ii) was required to include a minimum of 15 fish sampled for length. Otherwise, the length composition for the quarter was not computed.

iv. Fish lengths sampled from each stratum were combined, weighted in proportion to the catch in each stratum. The resulting length distribution was scaled to represent the total number of fish measured in the quarter.

These protocols resulted in the exclusion of a large proportion of the length samples collected from the principal longline fisheries from 1970 onwards. In particular, LL ALL 1 and LL ALL 2, virtually all length samples collected during that period were rejected from the model data set (Langley et al. 2007).

For the other fisheries, length data from each fishery/quarter were simply aggregated assuming that the collection of samples was broadly representative of the operation of the fishery in each quarter.

3.6 Weight-frequency data

A large data set of individual fish weights from the Japanese longline fisheries are available for inclusion in the assessment. 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. Weights samples from the Japanese coastal purse-seine fishery were also provided by NRIFSF.

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. For the principal longline fisheries, the weight data was aggregated in proportion to the spatial distribution of the catch, as described for the length data (see above).

The time-series distribution of available weight samples is shown in Figure 11. The same protocol for the aggregation of the length data was also applied to the calculation of the fishery/quarter weight frequency data for the principal longline fisheries. The protocol reduced the number of weight frequency samples included for a number of fisheries, particularly LL ALL 5 during the last two decades (Langley et al. 2007).

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).

The model does not yet include the tag release and recovery data from the 2006–09 tagging programme undertaken in PNG waters and the wider western and central Pacific Ocean.

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, 4,170 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. 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 model partitions the population into six 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 1952–2008. 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) with a fixed value of steepness (*h*). Steepness is defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Francis 1992; Maunder and Watters 2001).

The SRR was incorporated mainly so that yield analysis could be undertaken for stock assessment purposes, particularly the determination of equilibrium based reference points. 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 the steepness parameter of the SRR parameters; hence, the steepness parameter was fixed at a moderate value (0.75) and the sensitivity of the model results to the value of steepness was explored via a range of model sensitivities with lower (0.55, 0.65) and higher (0.85, 0.95) values of steepness. This differs from the approach used in the 2007 stock assessment which, for the base case, estimated the value of steepness internally in the model. For comparison with the current assessment, the 2007 model was rerun with the equivalent model assumptions. In this case, a beta-distributed prior was assumed on steepness of the SRR with a lower bound at 0.2, a mode = 0.85, and standard deviation = 0.16 (Figure 12).

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). These processes are assumed to be regionally invariant.

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. 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.

4.1.5 Reproductive potential

Reproductive output at age, which is used to derive spawning biomass, was recalculated for this assessment (Hoyle et al. 2009). The calculations were based on data collected in the WCPO, and based on relative reproductive potential rather than (as previously) the relative biomass of both sexes above the age of female maturity. The calculations used an approach previously applied to albacore (Hoyle 2008) and bigeye (Hoyle & Nicol 2008) tunas in the WCPO. The reproductive potential of each age class was assumed to be the product of the proportion female at age, the proportion of females mature at age, the spawning frequency at age of mature females, and the fecundity at age per spawning of mature females (Figure 13). Overall, this results in a slight shift in the age of first maturity and a substantial reduction in the reproductive potential for older age classes relative to the values used in the 2007 assessment.

4.1.6 Natural mortality

Natural mortality (*M*) was held fixed at pre-determined age-specific levels. Natural mortality at age was recalculated for this assessment using an approach previously applied to bigeye (Watters and Maunder 2001; Harley and Maunder 2003) and yellowfin (Maunder and Watters 2001) tunas in the EPO, and to albacore (Hoyle 2008) and bigeye (Hoyle and Nicol 2008) tunas in the WCPO. The increasing proportion of males in the catch with increasing size is assumed to be due to an increase in the natural mortality of females, associated with sexual maturity and the onset of reproduction. Details of the calculations are provided in Hoyle et al. (2009).

Previous WCPO yellowfin assessments have applied a natural mortality ogive calculated using EPO data (Maunder and Watters 2001). The revised schedule has a slightly lower level of natural mortality for the 11–14 age classes. The externally-estimated *M*-at-age is shown in Figure 14.

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.

The Chinese/Taiwanese longline fisheries (LL TW-CH 3 and 4) have caught consistently larger fish than the other longline fleets in a comparable time period. There are operational differences between the longline fleets that may account for a higher selectivity of larger fish by the Chinese/Taiwanese fleet. These differences in size composition, which were consistent across length- and weight-frequency data, implied that the selectivity of older yellowfin by the LL ALL fisheries was less than 100%. On this basis, the selectivity of the Chinese/Taiwanese longline fisheries was constrained to have full selectivity for the oldest age classes, while the selectivity of the other longline fisheries (including the principal LL ALL fisheries) was allowed to have declining selectivity for the older age classes.

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 (LL PNG 3 & LL BMK 3) 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 (PH MISC 3 and ID MISC 3), no effort estimates were available. In the absence of effort data, MFCL assumes a notional value for the effort. For these fisheries, the variance on the catchability deviations was high (approximating a CV of about 0.7), thereby, allowing catchability changes (as well as effort deviations) to predict the observed effort without the assumed effort series influencing the trend in stock abundance. 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 handline fishery, the 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).

In previous assessments, the assumed variance of the effort deviates for the main longline fisheries (LL ALL 1–6) was set at a low level (approximating a CV of 0.1) on the basis that the effort had been standardised in prior analyses and these longline fisheries provide wide spatial coverage of the respective areas in which they occur. However, the standard errors associated with the region-specific GLM indices indicate that the overall level of variance in the CPUE indices is considerably higher than the assumed level and that the variance is not uniform over the time period – the variance is generally higher during the 1950s reflecting a higher variation in the observed catch rates. On this basis, the penalty on the effort deviates for each region was set at a level that corresponded to an average CV of 0.2 over the entire model period and allowing for temporal variation in the CV (in proportion to the standard error of the individual indices).

This approach down-weighted the overall influence of the LL CPUE indices compared to previous assessments by allowing the model more freedom to predict the longline catches via the effort deviate parameters, particularly during the early model period.

The GLM analysis also reveals that there are marked differences in the variance associated with the CPUE indices among regions. The average standard error for the region specific indices are 0.26, 0.66, 0.16, 0.30, 0.65, and 0.63 for LL ALL 1–6, respectively. An alternative approach using iterative reweighting of the longline CPUE indices (following McAllister & Ianelli 1997) was applied to determine the variance of the effort deviates that was more consistent with the region specific variability in the CPUE indices, while maintaining the temporal variability within a region. This approach substantially increased the average CV (from the assumed level of 0.2) for the peripheral regions of the fishery (LL ALL 1, 2, 4 and 5) (Table 4). Model runs using lower effort deviate penalties derived from the iterative reweighting of the CPUE indices were denoted "CPUE low", while model runs with an assumed CV of 0.2 were denoted "CPUE high".

For comparison with previous assessments, a model run was conducted with the LL ALL 1–6 effort deviates penalties set at the higher level (approximating a CV of 0.1).

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.

Nevertheless, compared to earlier assessments, the size distributions constructed using the protocols described in Section 3.5 are likely to be much more representative of the catch from the principal fisheries. On this basis, the size data were considered to be moderately informative and were given an according weighting in the likelihood function; individual length and weight frequency distributions were assigned an effective sample size of 0.2 times the actual sample size, with a maximum effective sample size of 50. This was lower than the effective sample size assumed in the 2007 stock assessment (0.1 times the actual sample size with a maximum effective sample size of 100).

An alternative approach to determining the effective sample size of the length and weight frequency samples from the principal longline fisheries using an iterative reweighting approach (following McAllister & Ianelli 1997). This resulted in the effective sample size for the length and weight frequency data being reduced; for example, the effective sample size for LL ALL 3 was reduced to approximately 12 and 5 for weight- and length frequency samples, respectively (Table 5 and Table 6). On this basis, model runs using iterative reweighting to determine sample size were denoted “LL sample low”, whereas, the base sample size of 0.2 times the actual sample size was denoted “LL sample high”.

For comparison with the 2007 stock assessment, the model was also run with the effective sample size of 0.1 times the actual sample size, with a maximum effective sample size of 100.

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 Principal model runs

The previous assessments have highlighted a lack of fit to the principal longline CPUE index in the main region of the fishery (LL ALL 3), with the CPUE index showing a less significant decline since 1990 than predicted by the stock assessment model (Langley et al. 2007). This suggests a conflict between the CPUE index and the other principal source of data from the fishery – the length- and weight frequency data from the LL ALL 3 fishery. This was confirmed during preliminary analyses that revealed an improved fit to the CPUE index when the size frequency data were down-weighted.

It was concluded that the recent CPUE and size frequency data were giving somewhat different signals regarding recent levels of fishing mortality, with the CPUE index indicating that fishing mortality was lower than indicated by the size frequency data. It is also worth noting that the opposite trends were evident in the stock assessment model for bigeye tuna; for region 3 the bigeye stock assessment model predicted a higher level of biomass in recent years than predicted by the CPUE time-series.

The current assessment contrasts the two data sets in a range of model runs that either give a higher relative weighting to the longline CPUE indices (“CPUE high, LL sample low”) or a higher relative weight to the longline (LL ALL 1–6) size frequency data (“CPUE low, LL sample high”). The two model options were then compared with and without an increase in the catchability (fishing efficiency) of the longline fleet (“LL q incr”). The details of the four base model runs are specified in Table 3.

4.6 Parameter estimation and uncertainty

The parameters of the model were estimated by maximizing the log-likelihoods of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. The maximization was performed by an efficient optimization using exact derivatives with respect to the model parameters. Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters. A bash shell script, *doitall.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 $F_{current} / \tilde{F}_{MSY}$, $B_{current} / \tilde{B}_{MSY}$ and $SB_{current} / \tilde{SB}_{MSY}$. Likelihood profiles were generated by undertaking model runs with $F_{current} / \tilde{F}_{MSY}$, $B_{current} / \tilde{B}_{MSY}$ or $SB_{current} / \tilde{SB}_{MSY}$ 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.

4.7 Stock assessment interpretation methods

Several ancillary analyses are conducted in order to interpret the results of the model for stock assessment purposes. The methods involved are summarized below and the details can be found in Kleiber et al. (2003). Note that, in each case, these ancillary analyses are completely integrated into the model, and therefore confidence intervals for quantities of interest are available using the Hessian-Delta approach (or likelihood profile approach in the case of yield analysis results).

4.7.1 Fishery impact

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

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

4.7.2 Yield analysis

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

[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).

for the principal assessment model with alternative values of steepness assumed for the SRR. The confidence intervals of these metrics were estimated using a likelihood profile technique.

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In this assessment, we use the average over the period 2004–2007. The last year in which a complete set of catch and effort data is available for all fisheries is 2007. We do not include 2008 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).

The MSY based reference points were also computed using the average annual F_a from each year included in the model (1952–2007). This enabled temporal trends in the reference points to be assessed and a consideration of the differences in MSY levels under historical patterns of age-specific exploitation.

4.8 Comparison with the 2007 assessment

There are five main differences in the input data and structural assumptions of the current assessment compared to the 2007 assessment.

i. Fixing the steepness parameter (*h*) of the SRR at a specified level rather than estimating steepness within the model.
ii. A down-weighting of the effective sample size of the length- and weight- frequency data for all fisheries from 0.1 to 0.2 times the actual sample size.
iii. A revision of the age specific natural mortality and maturity schedules (Hoyle et al. 2009).
iv. A revision of the catch history of the purse-seine fishery (Lawson 2009).
v. A revision of the principal longline CPUE indices (Hoyle 2009).
vi. A reduction in the penalty on the effort deviations for the principal longline fisheries (from an assumed CV of 0.1 to a CV of 0.2 with temporal variation in the CV of individual observations) and a further reduction in the penalty on the effort deviations via iterative reweighting.
vii. The modification of the standardised effort series of the principal longline fisheries to account for the increase in the catchability (fishing efficiency) of the longline fleet.

For comparison to the 2007 stock assessment, a model was run that essentially replicated the structural assumptions and data inputs of the 2007 base case model with the inclusion of the most recent data (2007 and 2008) ("base 2007"). Each of the key changes specified above were then made to the "base 2007" model in a step-wise manner resulting in a final model that was equivalent to the "CPUE low, LL sample high, LL q incr" model. The biomass trajectories and principal stock status indicators of each model step-wise change were compared.

4.9 Sensitivity analyses

The sensitivity analyses focussed on a number of key uncertainties, principally related to uncertainties in the key input data sets. Initially, the sensitivities were examined as a single change to the base model ("CPUE low, LL sample high, LL q incr") although a more comprehensive analysis of the range of sensitivities was undertaken across all four principal models that encompassed the interactions between the various sensitivities (see below).

The key uncertainties identified in the current assessment were the assumed level of steepness of the SRR, catch history of the purse-seine fisheries, the magnitude of the catch from the Philippines and Indonesia domestic fisheries, the reliability of the CPUE index from the LL ALL 6 fishery, and the level of natural mortality for the youngest age classes.

The base model assumed a value of 0.75 for the steepness of the SRR. Alternative values of 0.55, 0.65, 0.85 and 0.95 were considered as equally plausible alternative values.

As noted above, historical catches from the purse-seine fisheries (PS ASS, PS UNA 3 & 4) have been revised based on the results of recent sampling (Lawson 2009) yielding catch estimates that are substantially higher than previously reported, principally for the associated fisheries. However, the current estimates are based on limited sampling data and are considered indicative only. The sensitivity of the model results to the assumed level of purse-seine catch was examined by comparing the base model results to a model with the purse-seine catches determined using the previous methodology ("Low PS catch"). The overall level of purse-seine catch in the alternative catch history is approximately 50% of the recent level of catch from the associated fisheries, while the unassociated catch is comparable between the two data sets (Figure 7).

Recent initiatives in the Philippines and, to a lesser extent in Indonesia, have increased the level of understanding of the magnitude of the recent catches from the various sectors that comprise these fisheries. The Philippines domestic fishery (PH MISC 3) is comprised of three main components: purse-seine, ring net, and a large unclassified municipal catch. There is reasonable confidence in the magnitude of the estimates of catch for the purse-seine and ring net components of the fishery, although it is suspected that the actual unclassified catch estimates are substantially lower than the reported values. An alternative catch history was constructed for the PH MISC 3 fishery based on the catch estimates from the purse-seine and ring net fisheries and reducing the municipal catch to approximately 25% of the reported level. This resulted in a 50% reduction to the total catch from the PH MISC 3 fishery and is considered to be a lower boundary of the plausible catch level (Figure 15).

Annual catches from the Indonesian domestic fishery (ID MISC 3) are highly uncertain. The catch is assumed to have increased steadily from 1980 to 2000 and then to have dropped sharply in the early 2000s. An alternative catch history was constructed that reaches a plateau at the level of catch attained in 1990 (10,000 mt per quarter) (Figure 15).

The alternative (lower) catch histories for the Indonesian and Philippines domestic fisheries were combined in a single sensitivity analysis ("IDPH low catch").

The stock assessment relies on the longline CPUE indices to provide an index of relative abundance in each of the model regions. However, the CPUE index in region 6 is highly uncertain due to low levels of fishing effort by the Japanese longline fleet, particularly over the last two decades. An alternative CPUE index was derived using catch and effort data from the Taiwanese fleet operating within region 6 during 1967–2008 (Chang et al. 2009). The indices were less variable than the LL ALL 6 indices derived from the Japanese catch and effort data and exhibited a steeper decline from 1985 onwards (Figure 16). The Taiwanese CPUE index was included in an alternative index for the region 6 longline fishery ("TW CPUE").

Natural mortality at age is assumed to be known (without error) in the principal assessment models. However, there is limited information available to determine natural mortality, particularly for the youngest age classes. An alternative age-specific natural mortality schedule was configured with a higher natural mortality for the youngest age classes (1–4 quarters) (Figure 14). This was treated as a single change sensitivity ("High M"); however, because of the strong interaction between a higher natural mortality for the youngest age classes and the level of catch of those age classes, an interaction between the lower ID/PH catch and the higher juvenile M was also explicitly considered ("IDPH low catch, high M").

The interactions between the each of the principal models and the various model sensitivities were assessed by conducting a range of sensitivities that combined the various model options. This represented a grid of 128 combinations of the following factors: weighting of the LL CPUE and size frequency data ("CPUE low, LL sample high" or "CPUE high, LL sample low"), assumptions regarding longline catchability ("increasing catchability" or "constant catchability"), steepness of the SRR (0.55, 0.68, 0.82, or 0.95), the longline CPUE index for region 6 (Japanese or Taiwanese), purse-seine catch history (high or low catch), and recent Indonesian and Philippines catch (low or high). A separate model was run for each of the combinations in the grid. The model results were screened to ensure model convergence and reasonable values of key parameters (principally related to the estimation of growth).

5 Results

5.1 Comparison with 2007 assessment

A range of preliminary model runs were conducted to examine the impact of the key changes in the 2009 assessment compared to the 2007 assessment (as described in Section 4.8). The magnitude and trends in total biomass are sensitive to a number of these assumptions; decreasing the effective sample size of the size frequency data from all fisheries resulted in the reduction in the biomass level from the 2007 base model; the addition of the new purse-seine catch history resulted in a considerable increase in the biomass level; reducing the penalty on the longline effort deviations reduced the overall level of biomass and moderated the declining trend in biomass; including an increasing trend in longline catchability results in a substantial increase in the historical biomass level.

The “base 2007” model is not directly comparable to the 2007 base case assessment due to some differences in the size frequency data for some fisheries (especially LL TW-CH 3 and LL PI 6) and the inclusion of two additional years of catch, effort, and size frequency data. The period for computing the MSY-based reference points was also advanced two years (from 2002–05 to 2004–07). Nonetheless, the “base 2007” model yielded comparable MSY-based fishing mortality and biomass based reference points to the base-case model from the 2007 assessment: $B_{current}/\tilde{B}_{MSY}$ of 1.23 compared to 1.17, $SB_{current}/S\tilde{B}_{MSY}$ of 1.28 vs. 1.25, and $F_{current}/\tilde{F}_{MSY}$ of 0.93 vs. 0.95, while the estimate of *MSY* was slightly lower (371,000 mt compared to 400,000 mt).

The MSY-based reference points changed markedly from the “base 2007” model when steepness of the SRR was fixed at 0.75 resulting in $F_{current}/\tilde{F}_{MSY}$ decreasing from 0.93 to 0.59 and a corresponding increase in $SB_{current}/S\tilde{B}_{MSY}$, $B_{current}/\tilde{B}_{MSY}$ and *MSY* (see Appendix 3). Reducing the effective sample size of the size frequency data resulted in a relatively small increase in $F_{current}/\tilde{F}_{MSY}$ as was the case when the new purse-seine catch history was incorporated in the model. The adoption of the revised biological parameters, the lower penalty on the longline effort deviates, and the inclusion of the temporal increase in the catchability of the longline fleet each resulted in a relatively small decrease in $F_{current}/\tilde{F}_{MSY}$. The changes in the $F_{current}/\tilde{F}_{MSY}$ metric were generally reversed for the $SB_{current}/S\tilde{B}_{MSY}$ and $B_{current}/\tilde{B}_{MSY}$ metrics.

The inclusion of the revised purse-seine catch, the fixing steepness of the SRR (0.75), and the temporal increase in the catchability of the longline fleet had a positive effect on the *MSY*. This was partially countered by the lower penalty on the longline effort deviates (Appendix 3).

5.2 Current assessment

As noted in the previous section, there are marked differences in the results of some the model options compared to 2007 “base case” assessment. These differences are essentially driven by changes in the underlying model assumptions rather than the input data. The current assessment represents a more comprehensive exploration of a number of key assumptions of the model and, to that end, a range of model options are presented. Summary results are presented for all model options; however, a single model option “CPUE low, LL sample high, LL Q incr” was selected for a more detailed analysis in preference to other model options (and denoted “base case 2009”). The rationale for the selection of this option was as follows:

i. the model incorporated a level of variability in the longline CPUE indices that was comparable with the standard error of the indices derived from the GLM;
ii. the longline size frequency data were down-weighted compared to the 2007 assessment, although the data is given sufficient weight to influence the model estimates if there is a significant trend in these data; and
iii. the model incorporated an allowance for an increase in the longline catchability based on the results of a quantitative analysis (Hoyle 2009).

The main stock assessment-related results are summarised for all analyses in the relevant sections (below).

5.3 Fit statistics and convergence

A summary of the fit statistics for the three analyses is given in Table 7. The lower penalty on the effort deviates for the longline fisheries results in a significant improvement in the fit to the catch data compared to the "Base 2007" models. The fit statistics are not directly comparable among most of the principal model runs and sensitivities due to differences in the structural assumptions and input data. Consequently, the fit statistics alone do not provide a criterion for selecting an individual model or set of models in preference to other models.

5.4 Fit diagnostics ("CPUE low, LL sample high, LL Q incr" i.e. base case 2009)

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 18. The residuals are relatively small and, for most fisheries, generally show even distributions about zero. The very small residuals associated with the LL ALL 1, 2, 5 and 6 fisheries are due to the lower penalties on the effort deviations for these fisheries, enabling the catch to be fitted almost exactly. There is a trend in the catch deviates from the LL ALL 3 fishery, with catches slightly over-estimated prior to 1990 and under-estimated in the subsequent period; catches from the LL ALL 1 and 2 fisheries are over-estimated during the last decade. Catch residuals for the purse-seine fisheries (PS ASS 3, PS UNS 3, PS ASS 4, and PS UNS 4) are more variable from 1990 onwards, although there is no systematic lack of fit to the observed catch.
- 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 19). For some of the longline fisheries (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.
- There is a lack of fit to the length data from the LL ALL 2 fishery (Figure 19). Very few length samples are included in the model data set from this fishery and the size data from the fishery are dominated by the weight frequency data. There is an apparent inconsistency in the size data from the two sources.
- For the Philippines and Indonesian surface fisheries (PH MISC 3 and ID MISC 3) and Japanese pole-and-line fishery (PL JP 1), 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 mode at about 50 cm FL is consistently under-represented in the predicted size composition of the two fisheries (Figure 19).
- 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 somewhat smaller fish during the 1960s than for the remainder of the model period (Figure 20). For this fishery, there are strong temporal trends in the residuals from the fit to the length data with a persistent pattern of positive residuals for the smaller length classes (70–100 cm FL) during the 1950s and 1960s (Figure 21).
- A number of fisheries that principally catch small fish also intermittently include some large fish in the length frequency samples, most notably fisheries PL JP 1, PH MISC 3 and ID MISC 3. Consequently, for these fisheries there are small modes of larger fish in the predicted length distributions (Figure 19). The corresponding selectivity functions also result in considerable

variation in the temporal trends in the predicted size distribution of the vulnerable population (Figure 20).

- There is a marked shift from large to small fish in the length composition of the catch from the Japanese purse-seine fishery in the mid 1980s. The model is unable to fit this abrupt change and it is likely to represent a substantial change in the size selectivity of the fishery at that time (Figure 20).

- For most of the longline fisheries, there is a very good fit to the aggregated weight frequency data (Figure 22). 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 BMK 3, LL PG 3 and LL AU 5 for which the model tends to consistently under-estimates the proportion of fish in the mode of the weight frequency distribution (at about 20–25 kg).

- There are no strong temporal trends in the weight frequency data from the principal longline fisheries within regions 3–5 and the model predictions are consistent with this observation; i.e., the model predicts that the size composition of the longline exploitable biomass has remained relatively constant throughout the model period (Figure 23). However, there are a number of discrepancies, most notably for the LL ALL 3 and LL BMK 3 fisheries with the observed fish weights being generally lower than predicted by the model during the 1960s and 1970s (Figure 24). The consistency in the trends between the length- and weight-frequency data from these fisheries may indicate a temporal trend in the selectivity of these fisheries.

- The model generally fits the observed decline in the LL ALL 1 and 2 weight frequency data, with the exception of the very small fish observed in the catch from LL ALL 2 in the 1990s (Figure 23). However, the assessment model is not predicting the magnitude of the decline in fish weights that has been observed in a number of fisheries over the last 10 years, in particularly from LL ALL 2, LL ALL 3 and LL TW-CH 3 (Figure 23).

- While many of the problems evident in the fit to the size data (particularly length data) in the earlier assessments have been resolved, there remain some inconsistencies in the fit to the region 4 Chinese/Taiwanese (LL TW-CH 4) length- and weight-frequency data (Figure 22). The 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 25 and Figure 26. 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 main tag recovery period (1993–94) (Figure 25). This is also evident in the over-estimation of tag returns for about 6–13 quarters at liberty (Figure 26). The model under-estimates the recovery of fish at liberty for long periods (greater than 20 quarters), although the number of observations is small and this is an inevitable result on this type of plot when the expected number of returns per time step falls to less than 1. The fits for individual fishery groups are shown in Figure 27. 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 pole-and-line fisheries and the Philippines and 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 27). For most of these fisheries, the tagging data are uninformative. Of the longline fisheries, most recoveries have been made from the Australian fishery and the composite LL ALL 5 fishery. However, the model tends to under-estimate the number of tag returns from these fisheries (Figure 27). 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. Similarly, there are a modest number of tag recoveries from the HW LL 4 fishery from releases by the Hawaiian handline fishery (in region 2), whereas, the model does not predict the recapture of these tags in the HW LL 4 fishery.

- 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 28). 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) (Figure 29).
- The effort deviations for the LL ALL 1, 2 and 6 fisheries are considerably more variable than the other fisheries. This is consistent with the lower penalty on the effort deviations for these fisheries. Most of the longline fisheries exhibit some degree of temporal variation in the pattern of the effort deviations indicating a systematic lack of fit to the longline CPUE indices over the model period. These trends are most pronounced in LL ALL 1, 2, and 5 (Figure 29).
- For the LL ALL 3 fishery, effort deviates tended to be positive since 1995 indicating that the estimated decline in biomass from the model is greater than predicted from the CPUE index. This has been evident in previous assessments and was a characteristic of the four main model options, although the trend was more pronounced for models that assigned a higher relative weight to the longline size frequency data and for model options without an allowance for a temporal increase in longline catchability.
- Effort deviates for those fisheries without effort data – the Philippines and Indonesian fisheries (PH MISC 3, PH HL 3, ID MISC 3) – reveal a strong temporal trend in the effort deviates over the period of the fishery (Figure 28). In the absence of effort data, the model assumes a constant level of effort and the model uses the effort deviates to predict the observed level of catch. For these fisheries, the effort deviates are not included in the model likelihood and, therefore, do not influence the trend in stock abundance.

5.5 Model parameter estimates (base-case 2009 unless otherwise stated)

5.5.1 Growth

The estimated growth curve is shown in Figure 30. The non-von Bertalanffy growth of juvenile yellowfin is clearly evident, with near-linear growth in the 50–100 cm size range. The estimated growth pattern from the base-case model is similar to that observed in the otolith length-increment data (Figure 31) (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 31).

As previously noted, the 2007 stock assessment also conducted a model for region 3 only which estimated growth rates for the 2–7 age classes that were substantially lower than the growth rates estimated for the WCPO model. The current assessment attempted to replicate the region 3 model; however, while lower growth rates were once again derived, the model estimates were variable between model runs and the model growth parameters were poorly determined.

5.5.2 Natural mortality

Unlike earlier assessments, natural mortality was not estimated in any of the analyses and a fixed age-specific mortality function was applied (see Figure 14). This issue may be re-visited in future assessments using biologically reasonable functional forms for M-at-age.

5.5.3 Movement

The model estimates very large movements of fish southward from region 1 to region 3 in the first quarter (35% of all fish moving) and second quarter (28%) of the year (Figure 32). A further southward movement is estimated to occur in the fourth quarter, representing 15% of all fish. There is an estimated movement of 10% of the fish from region 2 to region 4 in the third quarter. Movement rates between all other adjacent regions are low by comparison, about 3–6%, or negligible. However, it is important to note that even low movement rates from regions of high abundance can result in considerable stock mixing in the recipient region.

Note that the lack of substantial movement between 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 33. The simulation indicates that most biomass within a region is sourced from recruitment within the region, particularly for regions 1, 2, 5 and 6. The high movement rates from region 1 to region 3 results in a substantial proportion (about 25%) of the region 3 biomass originating from recruitment in region 1. Recruitment in region 1 is also estimated to contribute to the biomass in region 4, sourced via region 3.

The mixing between the equatorial regions results in a significant proportion of biomass (30%) in the eastern region (region 4) being sourced from recruitment in the western region (region 3) (Figure 33).

5.5.4 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 34). Unassociated purse-seine sets generally catch substantially larger fish than associated sets. Limited size data are available for the Indonesian surface fishery (ID MISC 3) and the model estimates that catches from this fishery are comprised of young fish (the 2–3 age classes).

The Philippines surface fishery (PH MISC 3), the Japanese coastal pole-and-line fishery (PL JP 1) and the equatorial pole-and-line fishery (PL ALL 3) 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 Japanese purse-seine fishery (PS JP 1), there is an apparent shift in the size composition of the catch from large fish to small fish in the late 1980s (see Figure 20). The current model assumes a single selectivity for the entire period with a high selectivity for older fish. For future assessments, it would be more appropriate to estimate separate selectivities for the two time periods.

For the principal longline fisheries LL ALL 3–6, selectivity is estimated to be highest for age-classes 7–10 with lower selectivity of older fish. 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. The historical distant-water longline fishery in PNG waters (LL BMK 3) has a higher selectivity for younger fish (age classes 6–8) than the principal longline fishery in the region (LL ALL 3).

5.5.5 Catchability

Time-series changes in catchability are evident for several fisheries (Figure 35). Catchability in the principal longline fisheries (LL ALL 1–6) has been assumed to be constant over time. There is evidence of a strong increase in catchability in the purse seine fisheries up to the early 2000s, although catchability for the purse-seine fisheries in region 4 is predicted to have declined somewhat over the more recent years.

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. Similarly, the catchability of the Japanese purse-seine and pole-and-line fisheries (PS JP 1 and PL JP 1) declined from the mid 1980s onwards.

Catchability for the Philippines and Indonesian domestic fisheries (PH MISC 3 and ID MISC 3) is estimated to have declined slightly throughout the model period. This is an artefact of the model's interpretation of the "missing" effort data and the increase in catch is fitted through the strong positive trend in the effort deviations for these two fisheries. This is also the case for the PH HL fishery prior to the late 1990s (Figure 35).

5.5.6 Tag-reporting rates

Estimated tag-reporting rates by fishery are shown in Figure 36. The estimates for the purse seine fisheries in region 3 deviated from the mode of their prior distributions and were estimated to be considerably higher than the reporting rates from the region 4 purse seine fishery. The estimates for the Philippines domestic fisheries deviate considerably from 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.

The reporting rate for the equatorial pole-and-line fishery (PL ALL 3), a fishery that accounted for a moderate number of tag recoveries, is estimated at the upper bound on the reporting rate (0.9).

5.6 Stock assessment results

5.6.1 Recruitment

The base-case recruitment estimates (aggregated by year for ease of display) for each region and the WCPO are shown in Figure 37. Overall recruitment is highest within region 3, while moderate levels of recruitment also occur within regions 1, 4 and 5. The regional estimates display large interannual variability and variation on longer time scales. Recruitment is estimated to be high in most regions during the late 1950s with large peaks in recruitment estimated for regions 4–6 during the mid 1950s. Recruitment in region 3 remains high during the 1960s and 1970s, declines through the 1980s and remains low through the 1990s. This trend is countered by a marked increase in the level of recruitment in region 1 during the same period (Figure 37). The increase in recruitment in region 1 may be partially attributable to the apparent change in the size composition of the JP PS 1 fishery in the late 1980s.

The recruitment trends for regions 1 and 3 strongly influence the trend in the aggregate WCPO recruitment estimates; total recruitment was very high during the late 1950s and declined steadily over the remainder of the model period. Recent (2000–05) WCPO recruitment is estimated to be 80% of the long-term average (Figure 37).

A comparison of WCPO recruitment estimates for the four principal model options and the "base 2007" model is provided in Figure 38a. The analyses all reveal the same general trend in overall recruitment with very high recruitment in the 1950s, relatively stable recruitment in the 1960s, 1970s and 1980s and the declining recruitment from 1990 onwards. The peak in recruitment in the 1950s is much more pronounced in the models that assign a relatively high (low) weight to the longline size frequency (CPUE) data. Model options that include an increase in longline catchability ("LL q incr") also estimate a higher level of recruitment during the early model period, up to the mid 1970s. Recruitment levels for the "base 2007" model are generally comparable to the four principal model options.

The sensitivities to the "CPUE low, LL sample high, LL Q incr" model yield comparable trends in overall WCPO recruitment, with the exception of the substantially higher level of recruitment for the "High M" model option (Figure 38b). In contrast, recruitment levels for the "Low PS catch" sensitivity are slightly lower than for the base model option.

5.6.2 Biomass

The estimated biomass time-series for each region and for the WCPO are shown in Figure 39 for the base-case analysis. The trends are variable between regions, generally reflecting the differences in the CPUE trends from the main longline fisheries (LL ALL 1–6) (Figure 40). Nevertheless, some discrepancies do exist between the CPUE trends from the longline fisheries and the temporal trend in the longline exploitable biomass, most notably regions 1 and 2 during the last decade. There is also a lack of fit to the CPUE indices for the LL ALL 3 fishery during the same period with the estimated biomass exhibiting a higher decline than the CPUE index (Figure 40).

However, overall the model estimates of exploitable abundance show very similar scaling among regions as the CPUE data (Figure 41). This indicates that model estimates are generally consistent with the CPUE data in terms of both time-series and spatial variability. Historically, the highest proportion of the total biomass was within region 3, although there has been a steady decline in biomass in this region since about 1980 (Figure 39), while the total biomass in region 4 has also declined over the same period. Biomass trends are variable among the other regions and overall levels of biomass are considerably lower in regions 1, 2, and 6.

The trend in total biomass for the WCPO is largely driven by the composite biomass trends from regions 3–5 (Figure 39). There was a peak in the biomass during the late 1950s following the very high recruitments estimated during the preceding period. Biomass levels subsequently declined throughout the model period with the rate of the decline in biomass increasing from 1980 onwards, largely driven by the decline in biomass in region 3 and, to a lesser extent, region 4.

The comparison of biomass trends for the principal model options and the "Base 2007" model is shown in Figure 42a. The trends in biomass are generally comparable for the five model options, although the level of initial (1950s) peak in biomass and the overall level of decline in biomass are higher for the options that include an increase in longline catchability ("LL q incr"). The two options without an increase in longline catchability have similar biomass trajectories to the "Base 2007" model.

The sensitivities to the "CPUE low, LL sample high, LL Q incr" model yield comparable trends in total biomass for WCPO, with the exception of the lower level of biomass for the scenario with the lower purse-seine catch ("Low PS catch") (Figure 42b).

5.6.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase strongly from 1970 for all the model options and are at the highest level in the most recent years (Figure 43). The principal model options and the "Base 2007" models all estimate comparable levels of fishing mortality for juvenile and adult age-classes throughout the model period.

For the base-case model, recent exploitation rates are high on the youngest age classes due to the impact of the associated purse-seine fishery and the Philippines and Indonesian fisheries in region 3 (PS ASS 3, PH MISC 3 and ID MISC 3) (Figure 44 and Figure 45). There is also a high exploitation rate on the older age classes (6–16 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 44). Amongst the regions, recent exploitation rates were highest in region 3 and comparatively low in all other regions (Figure 45).

5.6.4 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 46. It is evident that the impact has been substantial in region 3 and moderate in region 4, with the impact increasing steadily from the early 1980s. Impacts are relatively low (about 15–20%) in regions 1, 2, and 5 and minimal (5%) in region 6.

Overall, the impact of fishing has reduced the current total biomass in region 3 to about 35% of the unexploited level, while the current total WCPO biomass is at about 60% of unexploited levels (Figure 47) sustained by the lower impacts outside of the equatorial regions. Fishery impacts have reduced the total biomass in region 4 to about 70% of unexploited levels.

A comparison of relative impact of fishing on the entire WCPO biomass from the various model options is presented in Figure 48. Overall fishery impacts are comparable for all model options with the exception of "Base 2007" model which estimates slightly higher impacts in the most recent years.

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 spawning biomass (Figure 49) and total biomass (Figure 50). Within each region, the relative impacts of specific fisheries on spawning and total biomass are comparable. In region 3, the Philippines/Indonesian domestic fisheries and the associated purse-seine fishery have the greatest impact. The unassociated purse seine fishery (PS UNS 3) has a moderate impact.

In region 4, the purse seine fishery is responsible for most of the impact, while the Philippines/Indonesian fisheries accounts for about 25% of the impact due to the direct movement of fish from region 3 to region 4. Similarly, while the direct fishery impacts are moderately low in regions 1, 2 and 5, the high impacts on the stock in region 3 are reducing the movement of fish to these adjacent regions. Within region 1, there are the additional impacts of the pole-and-line and purse-seine fisheries (PL JP 1 & PS JP 1) which were highest during the 1980s.

It is noteworthy that in all regions, the longline fishery has a relatively small impact, less than 5%. In the sub-equatorial regions, the longline fishery tends to have a larger share of the impact, but overall impacts are much smaller.

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 (4%), moderate impact from the unassociated purse-seine fishery (7%) and highest impacts from the associated purse-seine (15%) and Philippines/Indonesian (15%) domestic fisheries.

5.6.5 Yield analysis

Symbols used in the following discussion are defined in Table 8. The yield analyses conducted in this assessment incorporate the SRR (Figure 51) into the equilibrium biomass and yield computations. Unlike previous assessments, when the steepness of the SRR was estimated, the steepness coefficient was fixed at a value of 0.75 which implies a moderate relationship between spawning stock biomass and recruitment; average recruitment is assumed to decline to 75% of the equilibrium unexploited recruitment when the level of spawning biomass is reduced to 20% of the unexploited level. However, there is limited information available to define an appropriate value of steepness for tuna species and, consequently, a range of other lower (0.55 and 0.65) and higher (0.85 and 0.95) plausible values were examined through sensitivity analyses. For comparison with the 2007 assessment, steepness was also estimated for the "Base 2007" model run, yielding an estimate of 0.52 (lower than the previous estimate of 0.62).

Equilibrium yield and biomass (spawning and total) are computed as a function of multiples of the 2004–2007 average fishing mortality-at-age (Figure 52). For the "CPUE low, LL sample high, LL Q incr" model, a maximum yield (*MSY*) of 637,000 mt per annum is achieved at *fmult* = 1.71; i.e. at 171% of the current level of fishing effort. This represents that the ratio of $F_{current}/\tilde{F}_{MSY}$ is equal to 0.584 (approximately 1/1.71) (Table 9a). On this basis, current exploitation rates are approximately 58% of the exploitation rates to produce the *MSY*. However, the form of the yield curve is highly uncertain as it is derived from estimates of fishing mortality at levels considerably less than the F_{MSY} level and is highly dependent on the assumed value of steepness in the SRR.

Further, the *MSY* computation assumes recruitment at the level of the long-term average, mediated by the SRR. For the current assessment, recruitment is estimated to have declined steadily over the model period and recent recruitment levels have been substantially lower than the long-term average. If future recruitments remain at about the current level then substantially lower yields can be anticipated from the stock.

Estimates of yield are considerably higher from the four principal models than from the "base 2007" assessment. This is largely due to the higher value of steepness (0.75) than that estimated (0.52) and the inclusion of the high levels of catch from the purse-seine fishery in the four principal models. For the "base 2007" model the estimate of $F_{current}/\tilde{F}_{MSY}$ is 0.928, substantially higher than the value for $F_{current}/\tilde{F}_{MSY}$ (0.588) from the comparable model that fixed steepness at 0.75 ("2007 steepness 0.75") (Table 9a).

For the "CPUE low, LL sample high, LL Q incr"model (base case 2009), lower yields and higher values of $F_{current}/\tilde{F}_{MSY}$ are estimated when values of steepness lower than 0.75 are assumed. Conversely, higher yields and lower values of $F_{current}/\tilde{F}_{MSY}$ are estimated for higher values of steepness (Table 9b). A comparison of the yield and equilibrium biomass curves for the four assumed values of steepness illustrates the sensitivity of the *MSY* based reference points to this variable (Figure 53).

Models that assigned a lower weight to the longline CPUE indices and a correspondingly higher relative weight to the longline size data ("CPUE low, LL sample high") tended to yield a slightly higher estimate of *MSY* and lower value of $F_{current}/\tilde{F}_{MSY}$ than the models that assigned the alternative weighting of the data sets ("CPUE high, LL sample low"). There is also a significant difference between the models that include or exclude an allowance for an increase in the catchability of the longline fleet ("LL Q incr"). The former models have a higher estimate of *MSY* and lower value of $F_{current}/\tilde{F}_{MSY}$ principally due to the higher value (approximately 115%) of long-term average recruitment estimated for these models.

For the base-case 2009 model, the reference points $F_t/\tilde{F}_{MSY}$, $B_t/\tilde{B}_{MSY}$ and $SB_t/S\tilde{B}_{MSY}$ were computed for each year (*t*) included in the model (1952–2008). 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 54 and Figure 55). Prior to 1980, exploitation rates and total and adult biomass remained at high levels relative to $\tilde{B}_{MSY}$ and $S\tilde{B}_{MSY}$. Over the next 25 years, fishing mortality rates steadily increased and the biomass level declined relative to $\tilde{B}_{MSY}$ and $S\tilde{B}_{MSY}$. Nonetheless, throughout the model period, including the most recent years, the biomass level is estimated to have remained well above the $\tilde{B}_{MSY}$ and $S\tilde{B}_{MSY}$ levels, while fishing mortality rates have remained well below $F_t/\tilde{F}_{MSY}$ (Table 9).

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 56). 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* compared to that estimated for the fishery based on the recent age-specific fishing mortality pattern. The decline in the *MSY* over time follows the increased development of those fisheries that catch smaller yellowfin, principally the surface fisheries (Figure 56).

The estimates of *MSY*-based stock status indicators were less variable among the single change sensitivities to the "CPUE low, LL sample high, LL Q incr" model than across the four principal model runs (Table 9). For the five sensitivities, the estimates of $F_{current}/\tilde{F}_{MSY}$, $B_{current}/\tilde{B}_{MSY}$ and $SB_{current}/S\tilde{B}_{MSY}$ were comparable to the base case. The estimates of *MSY* varied considerably between the sensitivities with the lower purse-seine and Indonesian/Philippines catch scenarios resulting in lower estimates of *MSY*.

The full grid of model sensitivities, encompassing the combinations of data assumptions and sensitivities, attempts to encompass the uncertainty associated with the stock assessment model. The distribution of the fishing mortality ($F_{current}/\tilde{F}_{MSY}$) and biomass ($SB_{current}/S\tilde{B}_{MSY}$) based reference points occupies a broad domain, with steepness being the most influential factor in the range of assumptions considered (Figure 57). For the entire range of combinations, higher levels of purse-seine catch and a lower/higher relative weighting of the CPUE/size frequency data tended to result in higher levels of fishing mortality relative to F_{MSY} (Figure 57). Model options with the lowest value of steepness (0.55) estimated values of $F_{current}/\tilde{F}_{MSY}$ that either approached or slightly exceeded 1.0 with the most pessimistic options combining low steepness and a higher relative weighting to the CPUE indices. Nonetheless, for all model options, estimates of current biomass were above the $S\tilde{B}_{MSY}$ reference point biomass ($SB_{current}/S\tilde{B}_{MSY}$ > 1.0) (Figure 57).

5.6.6 Key Reference Points

A number of quantities of potential management interest associated with the yield analyses are provided in Table 9. 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 $B_{current}/\tilde{B}_{MSY}$, $SB_{current}/S\tilde{B}_{MSY}$ 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 $B_{current}/\tilde{B}_{MSY}$, $SB_{current}/S\tilde{B}_{MSY}$ 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 $B_{current}/\tilde{B}_{MSY}$, $SB_{current}/S\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ were calculated for this purpose.

The profile likelihood distributions were computed for the "CPUE low, LL sample high, LL Q incr" model separately for each of the assumed values of steepness. For an individual value of steepness, the posterior probability distribution occupied a relatively narrow range for the three metrics of stock status ($B_{current}/\tilde{B}_{MSY}$, $SB_{current}/S\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$) (Figure 58, Figure 59, and Figure 60). However, the individual distributions are highly constrained given that the *MSY*-based metrics are largely determined by the fact that steepness is known without error. Given that most of the uncertainty in the stock assessment is related to the assumed value of steepness, it was thought that a more appropriate measure of uncertainty was obtained by integrating the posterior probability distributions over the range of likely values for steepness (0.55 to 0.95). The resulting probability distributions reveal that there is no probability that either $B_{current}/\tilde{B}_{MSY}$ (Figure 58) or $SB_{current}/S\tilde{B}_{MSY}$ (Figure 59) are below 1.0, while there is no probability that $F_{current}/\tilde{F}_{MSY}$ exceeds 1.0 (Figure 60).

As noted above, the determination of the *MSY*-based reference points is highly dependent on the assumed relationship between recruitment and spawning biomass. The four principal assessment models, including "CPUE low, LL sample high, LL Q incr", estimated that recent recruitment was substantially lower than the long-term average, indicating that the *MSY*-based reference points may not be appropriate indicators of the current stock status. Further, the formulation of the *MSY*-based reference points assumes that the relationship between recruitment and spawning biomass is a stock-wide (WCPO) process; i.e., recruitment in a specific region is a function of the total spawning biomass and the overall average recruitment distribution rather than the spawning biomass in the specific region. Under this set of assumptions, the calculation of *MSY*-based reference points is not influenced by differential levels of depletion of regional stock biomass — it is assumed that a region where the spawning biomass is heavily depleted can be sustained by the recruitment from the total spawning biomass in the wider stock area. This assumption warrants further consideration for a stock that occupies a geographic area as large as the WCPO.

There are considerable differences in the estimated levels of depletion of the spawning biomass among the six regions of the WCPO, with the highest level of depletion occurring in region 3 and relatively low impacts in the other regions. On that basis, a more conservative approach to formulate *MSY* based reference points is to compute them at a regional level assuming that the level of recruitment to a region would be dependent on the spawning biomass within the region. Such an analysis was undertaken using the “CPUE low, LL sample high, LL Q incr” model with an assumed steepness of 0.75. The region specific analysis yielded a $F_{current}/\tilde{F}_{MSY}$ of 0.87 for region 3 and substantially lower values for the other regions. The combined region specific *MSY*s was approximately 446,000 mt (with 364,000 mt from region 3). These values are considerably less optimistic than the corresponding WCPO wide values ($F_{current}/\tilde{F}_{MSY}$ of 0.584 and *MSY* of 637,000 mt).

6 Discussion and conclusions

This assessment of yellowfin tuna for the WCPO applied a similar modelling approach to that used in the 2007 assessment. The model’s data structure was equivalent to the previous assessment and the principal data sets were similar, with a number of notable exceptions:

- The revision of purse-seine catches resulting in the substantial increase in catch estimates for the catch from the associated purse-seine fisheries, particularly in region 3;
- The revision of the historical catch estimates from the Philippines domestic fisheries (PH MISC 2, PH HL 3);
- A revised series of CPUE indices for the principal longline fisheries; and
- The addition of recent catch, effort, and size frequency data from most fisheries.

The results of preliminary modelling revealed that these changes in the input data set were inconsequential in relation to the model estimates of the key stock status indicators ($B_{current}/\tilde{B}_{MSY}$, $SB_{current}/S\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$).

Of more significance, were a number of changes to the structural assumptions of the model that were included in the four principal model options. The model assumptions that differ from the 2007 base case assessment are as follow.

- A lower overall penalty on the effort deviations for the longline standardised effort series, including a lower penalty for indices that are highly uncertain (particularly in the first decade of the model).
- A reduction in the effective sample size of the length- and weight- frequency data for all fisheries.
- Revised parameters for natural mortality and reproductive potential.
- The allowance for an increase in the catchability of the longline fleet in the standardised effort series for the principal fisheries.

- A change in the approach used to determine the value of steepness for the SRR. In the 2007 base case assessment, steepness was estimated, whereas, the current assessment assumed a range of values for steepness.
- In addition, a large number of model sensitivities were conducted that investigated the uncertainty of catches from specific fisheries, *M*-at-age for juvenile age classes, and an alternative CPUE index for region 6.

The influence of the individual changes in model assumptions was examined in a range of preliminary model runs. Most of the changes had a relatively minor influence on the magnitude and trend in total biomass. Nonetheless, the changes in these individual assumptions, with the exception of the assumptions relating to steepness, did not result in a substantial change in the key stock status indicators ($B_{current}/\tilde{B}_{MSY}$, $SB_{current}/S\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$) relative to the 2007 assessment.

However, the *MSY* based stock indictors are highly sensitive to the assumed value of steepness. The 2007 assessment yielded a low estimated value of steepness (0.61) and a similar value was attained when the model was rerun using the current data set. Fixing the value of steepness at 0.75 reduced the $F_{current}/\tilde{F}_{MSY}$ from 0.93 ("Base 2007") to 0.59 (see Appendix 3), while the cumulative effect of the additional changes in model assumptions ("CPUE low, LL sample high, LL Q incr") resulted in a slight reduction in the $F_{current}/\tilde{F}_{MSY}$ from 0.59 to 0.58. Nonetheless, there are likely to be significant interactions between the various new model assumptions that will influence the final conclusions and the influence of a particular assumption is likely to vary depending on the value of steepness assumed. Consequently, at the lowest fixed value of steepness (0.55) the estimate of $F_{current}/\tilde{F}_{MSY}$ was lower than the estimate from the "Base 2007" model (0.85 compared to 0.92) (Table 9b).

The current stock assessment investigated a wide range of potential model options and sensitivities. These models 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. Overall, the model diagnostics indicate a reasonable fit to the various sources of data; however, they also highlight some inconsistencies among the various sets of input data and model assumptions.

- For the model options that down-weight the CPUE indices ("CPUE low"), there is a marked divergence in the recent (from 2000) trends between the longline CPUE indices and the trend in the longline exploitable biomass in regions 1 and 2. In contrast, the strong decline in CPUE in both regions is fitted by the models that assign a higher relative weight to the longline standardised effort series and a low weight to the longline size data ("CPUE high, LL sample low"). It is worth noting that size data are relatively limited from these two fisheries for the last decade.
- For all model options examined, there is a positive trend in the effort deviates for the LL ALL 3 fishery from the mid 1990s indicating that the model predicts a stronger decline in the longline exploitable biomass than is evident in the CPUE index. This trend was more pronounced in the model options that assigned a higher weighting to the size frequency data and those options that did not include a temporal increase in longline catchability. The trend in the effort deviates is evidence of a conflict between the size frequency data and the CPUE indices. A range of trials were conducted to determine the main source of this conflict; however, the down-weighting of each set of size frequency data could not attribute the effect to an individual fishery. The trend in the effort deviations was only removed when the size frequency data from all the principal longline fisheries was down-weighted. This indicates that a complex interaction exists among the region specific fisheries due, in part, to the assumptions regarding the linkage of longline selectivity and catchability among regions.
- 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. The previous

assessment indicated that initial growth rates in the core region of the fishery (region 3) may be substantially over-estimated in the WCPO model (Langley et al. 2007). Spatial variation in growth can not be easily accommodated in the assessment model and further research is required to fully elucidate the degree of spatial heterogeneity in growth.

- Residuals in the tag return data for the Australian and Hawaiian longline fisheries suggest 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 both fisheries.
- There remains a lack of fit to the size data for some of the fisheries. Some of these changes may be explained by a strong temporal trend in size selectivity, for example the large change in the size of fish caught by the Hawaiian longline fishery (LL HW 4). However, of more significance is the inability of the model to fit the full extent of the observed decline in fish weights evident in a number of fisheries over the last 10 years, in particularly from LL ALL 2, LL ALL 3, and LL TW-CH 3.
- Another diagnostic, albeit not directly related to the fit to the various data sets, is the observed trend in recruitment from the various model options. Most of the principal model options revealed a declining trend in the recruitment series, particularly for the first 30 years of the model period. This was most pronounced for the models with the increase in longline catchability ("LL q incr.") and indicates that the models are endeavouring to fit the larger decline in longline CPUE via the decline in overall recruitment rather than estimating an increase in fishing mortality rates.

From the range of diagnostics examined, no single model emerges as a most preferred candidate. However, the "CPUE low, LL sample high, LL Q incr" model is preferred from the perspective that there is less conflict in the longline CPUE series within region 3 and the model attempts to incorporate an increase in the efficiency of the longline fleet. The model also exhibits a somewhat weaker temporal trend in recruitment compared to the model with a higher relative weighting assigned to the CPUE indices ("CPUE high, LL sample low, LL Q incr").

Clearly, all the assessment models exhibit a degree of conflict between the longline CPUE indices and the size frequency data. The range of models considered in this assessment has endeavoured to encompass a reasonable range of options that give differential weighting to these two principal data sources. The range of model sensitivities, including the interaction between all the key sensitivities, provides an indication of the extent of the uncertainty associated with the assessment. The level of uncertainty associated with key stock indicators inferred from the structural sensitivity analysis is somewhat higher than the estimates of uncertainty of the key stock status indicators from the composite likelihood profiles. However, in both cases the estimates of uncertainty are constrained by the range of the structural assumptions considered and, consequently, should be treated as minimum levels of uncertainty.

The key source of uncertainty is attributable to the assumptions regarding the steepness parameter of the stock recruitment relationship, while the conclusions of the assessment are relatively insensitive to the other assumptions investigated. For a moderate value of steepness (0.75), $F_{current}/\tilde{F}_{MSY}$ is estimated to be 0.54–0.68 and $B_{current}/\tilde{B}_{MSY}$ and $SB_{current}/\widetilde{SB}_{MSY}$ are estimated to be well above 1.0 (1.41–1.67 and 1.46–1.88, respectively). For lower values of steepness (0.55 and 0.65), $B_{current}/\tilde{B}_{MSY}$ and $SB_{current}/\widetilde{SB}_{MSY}$ were estimated to be above 1.0 for all the sensitivities considered. Most of the model options with lower values of steepness also yielded estimates of $F_{current}/\tilde{F}_{MSY}$ below 1.0; however, the F_{MSY} reference point was approached or slightly exceeded for a subset of the model options that included the lowest value of steepness (0.55) in combination with a number of other factors.

The estimates of *MSY* for the four principal models are 552,000–637,000 mt and considerably higher than recent catches estimates for yellowfin (430,000 mt, source WCPFC Yearbook 2007). The large difference between the *MSY* and recent catches is partly attributable to the stock assessment model incorporating the higher (preliminary) purse-seine catch estimates (representing an additional catch of approximately 100,000 mt per annum in recent years). The more optimistic models suggest that the stock could potentially support long-term average yields above the recent levels of catch. However, it is important to note that recent (1998–2007) levels of estimated recruitment are considerably lower (80%) than the long-term average level of recruitment used to calculate the estimates of *MSY*. If recruitment remains at recent levels, then the overall yield from the fishery will be lower than the *MSY* estimates.

Further, as discussed in the previous section, the computation of *MSY* assumes that the relationship between recruitment and spawning biomass operates at the scale of the entire stock (i.e. WCPO). The current assessment reveals that the core region (region 3) of the fishery is considerably more depleted than other regions. In reality, recruitment processes are unlikely to occur at geographic scale of the WCPO and it may be more appropriate to define separate recruitment processes at the regional scale of the assessment model. Such a region-specific yield analysis (assuming a steepness of 0.75) resulted in a more conservative interpretation of current stock status. $F_{current}/\tilde{F}_{MSY}$ was estimated to be 0.87 for region 3 (i.e. approaching the F_{MSY} level) but was considerably lower for all other regions. The combined region specific *MSY*s was approximately 446,000 mt (with 364,000 mt attributable to region 3).

The main conclusions of the current assessment are as follows.

1. For all analyses, there are strong temporal trends in the estimated recruitment series. Initial recruitment was relatively high but declined during the 1950s and 1960s. Recruitment remained relatively constant during the 1970s and 1980s and then declined steadily from the early 1990s. Recent recruitment is estimated to be considerably lower than the long-term average.
2. Trends in biomass are generally consistent with the underlying trends in recruitment. Biomass is estimated to have declined throughout the model period. Model options that incorporate an increase in longline efficiency (catchability) were characterised by a higher initial biomass level and a stronger overall decline.
3. The biomass trends in the model are principally driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. The current assessment incorporated a revised set of longline CPUE indices and, for some model options, the indices were modified to account for an estimated increase in longline catchability (Hoyle 2009). For some of the main longline fisheries (in particularly LL ALL 3), 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 somewhat different information about the relative level of fishing mortality in the region. The current assessment includes a range of model sensitivities to examine the relative influence of these two data sources. Nonetheless, further research is required to explore the relationship between longline CPUE and yellowfin abundance and the methodology applied to standardise the longline CPUE data.
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. While the various analyses have shown that the current stock status is relatively insensitive to the assumed level of catch from the Indonesian fishery, yield estimates from the fishery vary in accordance with the level of assumed Indonesian catch. Therefore, improved estimates of historical and current catch from these fisheries are important in the determination of the underlying productivity of the stock.

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 about 60% of unexploited biomass (a fishery impact of 40%) in 2004–2007. This represents a moderate level of stock-wide depletion although it is considerably higher than the equivalent equilibrium-based reference point ($\tilde{B}_{MSY} / \tilde{B}_0$ of approximately 0.35–0.40). However, depletion is considerably higher in the equatorial region 3 where recent depletion levels are approximately 0.35 and 0.30 for total and adult biomass, respectively (65% and 70% reductions from the unexploited level). Impacts are moderate in region 4 (30%), low (about 15–20%) in regions 1, 2, and 5 and minimal (5%) in region 6. If stock-wide over-fishing criteria were applied at the level of our model regions, we would conclude that region 3 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 Philippines/Indonesian domestic fisheries and associated purse-seine fishery have the highest impact, particularly in region 3, while the unassociated purse seine fishery has a moderate impact. These fisheries are also contributing significantly to the fishery impact in all other regions. Historically, the coastal Japanese pole-and-line and purse-seine fisheries have had a significant impact on biomass levels in their home region (1). In all regions, the longline fishery has a relatively small impact, less than 5%.

7. The current assessment includes a number of changes to the model assumptions, particularly related to the biological parameters (natural mortality and reproductive capacity), the relative influence of the longline CPUE and size frequency data, and changes to the input data (most notably the purse-seine catch). However, the most influential change from the previous assessment relates to the assumptions regarding the steepness of the spawner-recruit relationship. Previous assessments have determined low values of steepness in the model estimation procedure, while the current assessment has assumed a range of fixed values for steepness (0.55–0.95). Assuming a moderate value of steepness (0.75) has resulted in a considerably more optimistic assessment of the stock status (compared to 2007 base case) due to the actual value of steepness and the interaction between steepness and the other changes in model assumptions (especially the revised biological parameters, lower penalty on the longline effort deviations, and increasing longline catchability).

8. For a moderate value of steepness (0.75), $F_{current} / \tilde{F}_{MSY}$ is estimated to be 0.54–0.68 indicating that under equilibrium conditions the stock would remain well above the level capable of producing MSY ($\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$ 1.39–1.59 and $S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$ 1.50–1.79), while $B_{current} / \tilde{B}_{MSY}$ and $SB_{current} / S\tilde{B}_{MSY}$ are estimated to be well above 1.0 (1.41–1.67 and 1.46–1.88, respectively). For lower values of steepness (0.55 and 0.65), $B_{current} / \tilde{B}_{MSY}$ and $SB_{current} / S\tilde{B}_{MSY}$ were estimated to be above 1.0 for all the sensitivities considered. Most of the model options with lower values of steepness also yielded estimates of $F_{current} / \tilde{F}_{MSY}$ below 1.0; however, the F_{MSY} reference point was approached or slightly exceeded for a subset of the model options that included the lowest value of steepness (0.55) in combination with a number of other factors.

9. Sensitivity analyses were conducted to investigate the influence of a range of key model inputs, principally those relating to steepness of the SRR, the levels of catch from the Indonesian/Philippines and purse-seine fisheries, *M*-at-age, and the region 6 CPUE index. The interaction between each of these factors and the other key model assumptions (relative weighting of longline CPUE and size frequency data and increase in longline catchability) was also examined. The uncertainty associated with the point estimates of the key *MSY* based reference points was also determined using a likelihood profile approach. Both analyses revealed that most of the uncertainty in estimates of $F_{current} / \tilde{F}_{MSY}$, $B_{current} / \tilde{B}_{MSY}$ and $SB_{current} / S\tilde{B}_{MSY}$ was attributable to the value of steepness for the SRR. Overall, the full range of model options yielded estimates of current biomass that were well above $S\tilde{B}_{MSY}$ and, with the exception of a subset of

the model options that incorporated the lowest value of steepness (0.55), estimates of fishing mortality were well below F_{MSY} . The probability distributions derived from the likelihood profiles were generally consistent with these observations.

10. The estimates of *MSY* for the four principal models are 552,000–637,000 mt and considerably higher than recent catches estimates for yellowfin (430,000 mt, source WCPFC Yearbook 2007). The large difference between the *MSY* and recent catches is partly attributable to the stock assessment model incorporating the higher (preliminary) purse-seine catch estimates (representing an additional catch of approximately 100,000 mt per annum in recent years). The more optimistic models suggest that the stock could potentially support long-term average yields above the recent levels of catch. However, it is important to note that recent (1998–2007) levels of estimated recruitment are considerably lower (80%) than the long-term average level of recruitment used to calculate the estimates of *MSY*. If recruitment remains at recent levels, then the overall yield from the fishery will be lower than the *MSY* estimates.

11. While estimates of current fishing mortality are generally well below F_{MSY} , any increase in fishing mortality would most likely occur within region 3 — the region that accounts for most of the catch). This would exacerbate the already high levels of depletion that are occurring within that region. Further, the computation of *MSY*-based metrics assumes that the relationship between spawning biomass and recruitment occurs at the global level of the stock and, therefore, does not consider the differential levels of impact on spawning biomass between regions. The spawning biomass in region 3 is estimated to have been reduced to approximately 30% of the unexploited level; however, due to the lower overall depletion of the entire WCPO stock, the model assumes that there has been no significant reduction in the spawning capacity of the stock. A more conservative approach would be to consider the spawning capacity at the regional level and define reference points accordingly.

12. The current assessment has undertaken a more comprehensive analysis of model uncertainty than previous assessments. The analysis indicates that the assumptions regarding the spawner-recruit relationship represent the most significant source of uncertainty. For tuna species, there are no strong empirical data available to inform the model regarding the likely range of values of steepness of the SRR that underpin the *MSY* based stock indicators. On that basis, it may be more appropriate to adopt alternative fishing mortality and biomass based reference points that are not reliant on the *MSY* concept, although inevitably some assumption regarding the SRR is necessary, implicitly or explicitly, in the formulation of other alternative stock indicators.

13. The structural uncertainty analysis investigated the impact of a range of sources of uncertainty in the current model and the interaction between these assumptions. Nonetheless, there remains a range of other assumptions in the model that should be investigated either internally or through directed research. Further studies are required to refine our estimates of growth, natural mortality and reproductive potential, incorporating consideration of spatio-temporal variation and sexual dimorphism; to examine in detail the time-series of size frequency data from the fisheries, which may lead to refinement in the structure of the fisheries included in the model; to consider size-based selectivity processes in the assessment model; to collect age frequency data from the commercial catch in order to improve current estimates of the population age structure; to continue to improve the accuracy of the catch estimates from a number of key fisheries, particularly those catching large quantities of small yellowfin; to refine the methodology and data sets used to derive CPUE abundance indices from the longline fishery; and to refine approaches to integrate the recent tag release/recapture data into the assessment model.

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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 (excluding PNG waters)	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. PH MISC 3	Philippines	Miscellaneous (small fish)	3
19. PH HL 3	Philippines, Indonesia	Handline (large fish)	3
20. PS JP 1	Japan	Purse seine, all sets	1
21. PL JP 1	Japan	Pole-and-line	1
22. PL ALL 3	All, except Indonesia	Pole-and-line	3
23. LL BMK 3	All excl. PNG, Chinese Taipei & China within PNG waters	Longline	3
24. ID MISC 3	Indonesia	Miscellaneous (small fish)	3

Table 2. Main structural assumptions of the yellowfin tuna assessment model(s) 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 dependent on the individual model option (see Table 3).	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 dependent on the individual model option (see Table 3).	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. All reporting rates constant over time.	LL 1–6, CH/TW LL, PNG LL, PI LL, LL BMK 3, PL 3, PL JP 1, PS JP 1	13	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	3	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 (fixed value of steepness) .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)	228	SRR	0.7	-20	20
		Average spatial distribution of recruitment	5	-	-	0	1
		Time series deviations from average spatial distribution (ln)	1,130	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)	92	-	-	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, Taiwanese/Chinese, and LL BMK 3 longline fisheries have structural time-series variation, with random steps (catchability deviations) taken every 2 years.	Average catchability coefficients (ln)	19	-	-	-15	1
		Seasonality amplitude (ln)	21	0	2.2	-	-
		Seasonality phase	21	-	-	-	-
		Catchability deviations PH/ID (ln)	57	0	0.7	-0.8	0.8
		Catchability deviations other (ln)	230	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 average SD determined by iterative reweighting (or fixed at 0.2) for LL ALL 1–6 with temporal variation in SD. 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)	1,334	0	0.16	-6	6
		Effort deviations PH, ID (ln)	464	0	0.22	-6	6
		Effort deviations other (ln)	1,764	0	0.22	-6	6
Natural mortality	Age-dependent but constant over time and among regions. All parameters are specified (see Figure 14).	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.	None	Na	na	na	0	1

Table 3. Summary of the range of model options investigated.

Scenario	LL CPUE indices	LL catchability	LL sample size	Biol. parameters	Purse-seine catch	Steepness SRR
Base 2007	CV = 0.10	constant	0.1 times actual sample size, max = 100.	2007	2007	Estimated
Base 2007, steepness 0.75	CV = 0.10	constant	As above.	2007	2007	Fixed, 0.75
CPUE low, LL sample high, LL q incr	Temporal variation in CV, average CV determined by iterative reweighting.	Catchability increase	0.2 times actual sample size, max = 50.	2009	Lawson 2009	Fixed, 0.75
CPUE low, LL sample high	As above.	constant	As above.	2009	Lawson 2009	Fixed, 0.75
CPUE high, LL sample low	Temporal variation in CV, average CV = 0.20 (per region).	constant	Iterative reweighting	2009	Lawson 2009	Fixed, 0.75
CPUE high, LL sample low, LL q incr	As above.	Catchability increase	Iterative reweighting	2009	Lawson 2009	Fixed, 0.75
High M	As per "CPUE low, LL sample high, LL q incr" with a higher natural mortality for the youngest age classes.					
IDPH low catch	As per "CPUE low, LL sample high, LL q incr" with a lower recent catch from the Philippines and Indonesian domestic fisheries.					
Low PS catch	As per "CPUE low, LL sample high, LL q incr" with the purse seine catch history comparable to the 2007 assessment.					
TW CPUE region 6	As per "CPUE low, LL sample high, LL q incr" with an alternative standardised effort series for the LL ALL 6 fishery derived from Taiwanese catch and effort data.					

Table 4. Average assumed CV for the effort deviations for the principal longline fishery in each region for each of the principal model options.

Model option	Region					
	1	2	3	4	5	6
CPUE low, LL sample high, LL q incr	0.71	0.85	0.28	0.42	0.62	1.23
CPUE low, LL sample high	0.69	0.84	0.30	0.40	0.60	1.22
CPUE high, LL sample low	0.20	0.20	0.20	0.20	0.20	0.20
CPUE high, LL sample low, LL q incr	0.20	0.20	0.20	0.20	0.20	0.20

Table 5. The number of length frequency samples and the average effective sample size for the length frequency data for the principal longline fishery in each region for each of the principal model options.

	Region					
	1	2	3	4	5	6
Number of samples	41	14	82	80	65	48
Model option						
CPUE low, LL sample high, LL q incr	39.4	18.9	48.8	42.9	43.1	25.4
CPUE low, LL sample high	39.4	18.9	48.8	42.9	43.1	25.4
CPUE high, LL sample low	4.6	1.4	5.7	6.6	5.8	3.5
CPUE high, LL sample low, LL q incr	4.6	1.4	5.7	6.6	5.8	3.5

Table 6. The number of weight frequency samples and the average effective sample size for the weight frequency data for the principal longline fishery in each region for each of the principal model options.

	Region					
	1	2	3	4	5	6
Number of samples	103	100	154	123	80	42
Model option						
CPUE low, LL sample high, LL q incr	41.5	32	49.7	48.9	40.3	31.8
CPUE low, LL sample high	41.5	32	49.7	48.9	40.3	31.8
CPUE high, LL sample low	6.9	7.8	12.0	16.6	10.1	6.5
CPUE high, LL sample low, LL q incr	6.9	7.8	12.0	16.6	10.1	6.5

Table 7. Details of objective function components for various model options.

Objective function component	**CPUE low, LL sample high, LL q incr**	**CPUE high, LL sample low, LL q incr**	**CPUE low, LL sample high**	**CPUE high, LL sample low**	**Base 2007**	**Base 2007, steepness 0.75**
Length frequency log-likelihood	-372,200.20	-344,431.70	-372,206.00	-344,424.90	-410,082.70	-410,082.20
Principal LL fisheries	-89,221.58	-61,168.68	-89,220.20	-61,165.51	-97,652.02	-97,652.35
Other fisheries	-282,978.60	-283,263.00	-282,985.80	-283,259.40	-312,430.70	-312,429.80
Weight frequency log-likelihood	-670,570.30	-592,920.70	-670,564.10	-592,909.40	-735,160.80	-735,160.40
Principal LL fisheries	-402,445.10	-324,736.20	-402,442.00	-324,735.70	-440,745.90	-440,745.90
Other fisheries	-268,125.30	-268,184.50	-268,122.20	-268,173.70	-294,414.90	-294,414.60
Tag log-likelihood	2,598.64	2,608.71	2,594.68	2,600.83	2,640.06	2,639.57
Total catch log-likelihood	89.65	172.80	89.61	172.15	486.18	486.24
Penalties	2,485.21	3,641.19	2,485.81	3,627.23	5,953.26	5,949.79
Total function value	-1,037,597.00	-930,929.70	-1,037,600.00	-930,934.10	-1,136,164.00	-1,136,167.00
gradient	0.00081	0.02958	0.07894	0.01785	0.00092	0.00084

	High M	**IDPH low catch**	**IDPH catch, high M**	**Low PS catch**	**TW CPUE region6**
Length frequency log-likelihood	-372,178.50	-372,185.20	-372,168.30	-372,198.30	-372,200.90
Principal LL fisheries	-89,221.78	-89,220.48	-89,220.57	-89,229.65	-89,218.98
Other fisheries	-282,956.70	-282,964.70	-282,947.80	-282,968.70	-282,981.90
Weight frequency log-likelihood	-670,552.00	-670,557.20	-670,544.00	-670,571.20	-670,549.90
Principal LL fisheries	-402,443.50	-402,440.80	-402,442.00	-402,443.70	-402,426.80
Other fisheries	-268,108.50	-268,116.40	-268,101.90	-268,127.50	-268,123.10
Tag log-likelihood	2,621.24	2,610.19	2,631.62	2,566.39	2,601.10
Total catch log-likelihood	89.97	89.40	89.69	111.79	114.88
Penalties	2,490.29	2,471.81	2,480.99	2,782.33	3,080.82
Total function value	-1,037,529.00	-1,037,571.00	-1,037,510.00	-1,037,309.00	-1,036,954.00
gradient	0.03653	0.06948	0.09683	0.09538	0.04389

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

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2004–2007
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 (2004–2007) total biomass
$SB_{current}$	Average current (2004–2007) adult biomass
B_{1998}	Average total biomass in 1998
SB_{1998}	Average adult biomass in 1998
SB_{2007}	Average adult biomass in 2007
$B_{current,F=0}$	Average current (2004–2007) total biomass in the absence of fishing.

Table 9a. Estimates of management quantities for the four principal stock assessment models and the models comparable to the 2007 base case. 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	CPUE low, LL sample high, LL q incr	CPUE high, LL sample low, LL q incr	CPUE low, LL sample high	CPUE high, LL sample low	Base 2007	Base 2007, steepness 0.75
$\tilde{Y}_{F_{current}}$	mt per year	555,600	648,400	496,400	571,200	369,000	445,600
$\tilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	636,800	704,000	552,000	614,800	370,520	509,600
$\tilde{B}_0$	mt	5,283,000	5,976,000	4,499,000	5,103,000	4,523,000	4,385,000
$\tilde{B}_{F_{current}}$	mt	2,991,000	3,120,000	2,452,000	2,633,000	2,106,000	2,531,000
$\tilde{B}_{MSY}$	mt	1,979,000	2,233,000	1,695,000	1,920,000	1,962,000	1,704,000
$\tilde{SB}_0$	mt	2,850,000	3,200,000	2,441,000	2,732,000	2,654,000	2,573,000
$\tilde{SB}_{F_{current}}$	mt	1,437,000	1,466,000	1,174,000	1,230,000	1,052,000	1,263,000
$\tilde{SB}_{MSY}$	mt	855,300	965,200	736,900	827,000	967,200	750,300
$B_{current}$	mt	3,099,135	2,883,346	2,826,518	2,731,251	2,415,538	2,402,778
$SB_{current}$	mt	1,522,039	1,415,684	1,386,464	1,334,711	1,239,312	1,231,167
SB_{2007}		1,526,249	1,324,075	1,378,534	1,241,625	1,205,386	1,198,091
$B_{current,F=0}$	mt	5,246,194	4,993,169	4,955,395	4,806,548	4,628,455	3,989,080
$B_{current}/\tilde{B}_0$		0.587	0.482	0.628	0.535	0.534	0.548
$B_{current}/\tilde{B}_{F_{current}}$		1.036	0.924	1.153	1.037	1.147	0.949
$B_{current}/\tilde{B}_{MSY}$		1.568	1.288	1.669	1.419	1.231	1.410
$B_{current}/B_{current,F=0}$		0.591	0.577	0.570	0.568	0.522	0.602
$SB_{current}/\tilde{SB}_0$		0.534	0.442	0.568	0.489	0.467	0.478
$SB_{2007}/\tilde{SB}_0$		0.536	0.414	0.565	0.454	0.454	0.466
$SB_{current}/\tilde{SB}_{F_{current}}$		1.059	0.966	1.181	1.085	1.178	0.975
$SB_{current}/\tilde{SB}_{MSY}$		1.784	1.464	1.885	1.611	1.281	1.641
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.566	0.522	0.545	0.516	0.466	0.577
$\tilde{SB}_{F_{current}}/\tilde{SB}_0$		0.504	0.458	0.481	0.450	0.396	0.491
$\tilde{B}_{MSY}/\tilde{B}_0$		0.375	0.374	0.377	0.376	0.434	0.389
$\tilde{SB}_{MSY}/\tilde{SB}_0$		0.300	0.302	0.302	0.303	0.364	0.292
$F_{current}/\tilde{F}_{MSY}$		0.584	0.666	0.625	0.682	0.928	0.588
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.511	1.397	1.447	1.371	1.073	1.485
$\tilde{SB}_{F_{current}}/\tilde{SB}_{MSY}$		1.680	1.519	1.593	1.487	1.088	1.683
$\tilde{Y}_{F_{current}}/MSY$		0.872	0.921	0.899	0.929	0.996	0.874
$B_{current}/B_{1998}$		0.838	0.678	0.840	0.693	0.747	0.748
SB_{2007}/SB_{1998}		0.752	0.557	0.754	0.570	0.637	0.638

Table 9b. Estimates of management quantities for the “CPUE low, LL sample high, LL q incr” model with the five assumed values of steepness for the SRR.

Management quantity	Units	*h* 0.55	*h* 0.65	*h* 0.75	*h* 0.85	*h* 0.95
$\tilde{Y}_{F_{current}}$	mt per year	485,200	529,200	555,600	572,400	584,000
$\tilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	493,600	569,200	636,800	701,200	767,200
$\tilde{B}_0$	mt	5,431,000	5,347,000	5,283,000	5,231,000	5,191,000
$\tilde{B}_{F_{current}}$	mt	2,618,000	2,852,000	2,991,000	3,081,000	3,145,000
$\tilde{B}_{MSY}$	mt	2,263,000	2,118,000	1,979,000	1,831,000	1,649,000
$S\tilde{B}_0$	mt	2,929,000	2,884,000	2,850,000	2,822,000	2,801,000
$S\tilde{B}_{F_{current}}$	mt	1,259,000	1,371,000	1,437,000	1,481,000	1,511,000
$S\tilde{B}_{MSY}$	mt	1,062,000	956,100	855,300	750,500	626,300
$B_{current}$	mt	3,107,639	3,101,552	3,099,135	3,097,367	3,097,439
$SB_{current}$	mt	1,527,743	1,523,819	1,522,039	1,520,788	1,520,557
SB_{2007}		1,529,487	1,526,860	1,526,249	1,525,890	1,526,350
$B_{current,F=0}$	mt	5,905,599	5,504,164	5,246,194	5,066,349	4,935,454
$B_{current}/\tilde{B}_0$		0.572	0.580	0.587	0.592	0.597
$B_{current}/\tilde{B}_{F_{current}}$		1.187	1.088	1.036	1.005	0.985
$B_{current}/\tilde{B}_{MSY}$		1.375	1.466	1.568	1.694	1.880
$B_{current}/B_{current,F=0}$		0.526	0.563	0.591	0.611	0.628
$SB_{current}/S\tilde{B}_0$		0.522	0.528	0.534	0.539	0.543
$SB_{2007}/S\tilde{B}_0$		0.522	0.529	0.536	0.541	0.545
$SB_{current}/S\tilde{B}_{F_{current}}$		1.213	1.111	1.059	1.027	1.006
$SB_{current}/S\tilde{B}_{MSY}$		1.442	1.598	1.784	2.032	2.434
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.482	0.533	0.566	0.589	0.606
$S\tilde{B}_{F_{current}}/S\tilde{B}_0$		0.430	0.475	0.504	0.525	0.539
$\tilde{B}_{MSY}/\tilde{B}_0$		0.417	0.396	0.375	0.350	0.318
$S\tilde{B}_{MSY}/S\tilde{B}_0$		0.363	0.332	0.300	0.266	0.224
$F_{current}/\tilde{F}_{MSY}$		0.853	0.696	0.584	0.493	0.407
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.157	1.347	1.511	1.683	1.907
$S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$		1.185	1.434	1.680	1.973	2.413
$\tilde{Y}_{F_{current}}/MSY$		0.983	0.930	0.872	0.816	0.761
$B_{current}/B_{1998}$		0.835	0.836	0.838	0.839	0.840
SB_{2007}/SB_{1998}		0.748	0.750	0.752	0.753	0.754

Table 9c. Estimates of management quantities for the main sensitivities to the "CPUE low, LL sample high, LL q incr" model.

Management quantity	Units	base	High M	IDPH low catch	IDPH low catch, high M	Low PS catch	TW CPUE region 6
$\tilde{Y}_{F_{current}}$	mt per year	555,600	549,200	504,800	501,600	426,000	554,000
$\tilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	636,800	632,800	583,600	582,400	504,400	622,000
$\tilde{B}_0$	mt	5,283,000	4,940,000	4,716,000	4,470,000	4,195,000	5,151,000
$\tilde{B}_{F_{current}}$	mt	2,991,000	2,828,000	2,689,000	2,579,000	2,493,000	2,836,000
$\tilde{B}_{MSY}$	mt	1,979,000	1,880,000	1,762,000	1,701,000	1,596,000	1,930,000
$S\tilde{B}_0$	mt	2,850,000	2,585,000	2,541,000	2,336,000	2,266,000	2,781,000
$S\tilde{B}_{F_{current}}$	mt	1,437,000	1,288,000	1,283,000	1,166,000	1,222,000	1,355,000
$S\tilde{B}_{MSY}$	mt	855,300	749,600	749,600	666,700	702,800	834,900
$B_{current}$	mt	3,099,135	2,950,267	2,787,749	2,680,869	2,416,182	2,948,762
$SB_{current}$	mt	1,522,039	1,377,734	1,357,737	1,242,197	1,179,653	1,449,870
SB_{2007}		1,526,249	1,389,136	1,365,777	1,252,896	1,235,024	1,444,089
$B_{current,F=0}$	mt	5,246,194	4,974,744	4,595,379	4,404,451	4,024,443	5,098,263
$B_{current}/\tilde{B}_0$		0.587	0.597	0.591	0.600	0.576	0.572
$B_{current}/\tilde{B}_{F_{current}}$		1.036	1.043	1.037	1.040	0.969	1.040
$B_{current}/\tilde{B}_{MSY}$		1.568	1.573	1.584	1.580	1.519	1.528
$B_{current}/B_{current,F=0}$		0.591	0.593	0.607	0.609	0.600	0.578
$SB_{current}/S\tilde{B}_0$		0.534	0.533	0.534	0.532	0.521	0.521
$SB_{2007}/S\tilde{B}_0$		0.536	0.537	0.537	0.536	0.545	0.519
$SB_{current}/S\tilde{B}_{F_{current}}$		1.059	1.070	1.058	1.065	0.965	1.070
$SB_{current}/S\tilde{B}_{MSY}$		1.784	1.844	1.817	1.869	1.687	1.739
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.566	0.572	0.570	0.577	0.594	0.551
$S\tilde{B}_{F_{current}}/S\tilde{B}_0$		0.504	0.498	0.505	0.499	0.539	0.487
$\tilde{B}_{MSY}/\tilde{B}_0$		0.375	0.381	0.374	0.381	0.380	0.375
$S\tilde{B}_{MSY}/S\tilde{B}_0$		0.300	0.290	0.295	0.285	0.310	0.300
$F_{current}/\tilde{F}_{MSY}$		0.584	0.577	0.575	0.569	0.541	0.613
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.511	1.504	1.526	1.516	1.562	1.469
$S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$		1.680	1.718	1.712	1.749	1.739	1.623
$\tilde{Y}_{F_{current}}/MSY$		0.872	0.868	0.865	0.861	0.845	0.891
$B_{current}/B_{1998}$		0.838	0.848	0.839	0.846	0.870	0.806
SB_{2007}/SB_{1998}		0.752	0.759	0.749	0.752	0.806	0.719

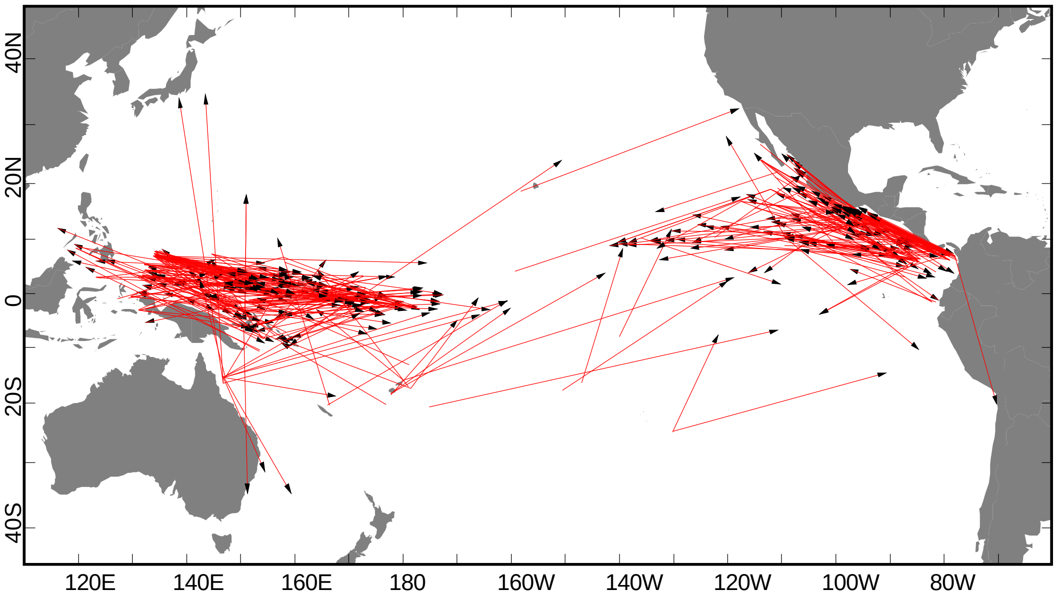

Figure 1. Long-distance (greater than 1,000 nmi) movements of tagged yellowfin tuna.

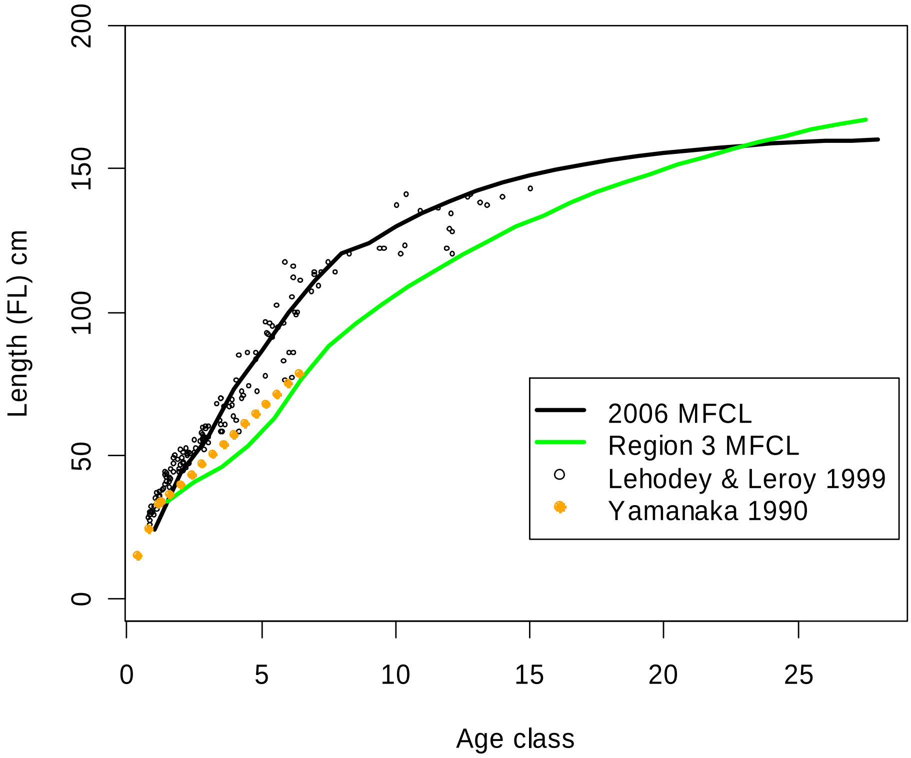

Figure 2. A comparison of yellowfin growth estimated from WCPO and 2007 region 3 MFCL models and the results from ageing studies using otolith daily increments.

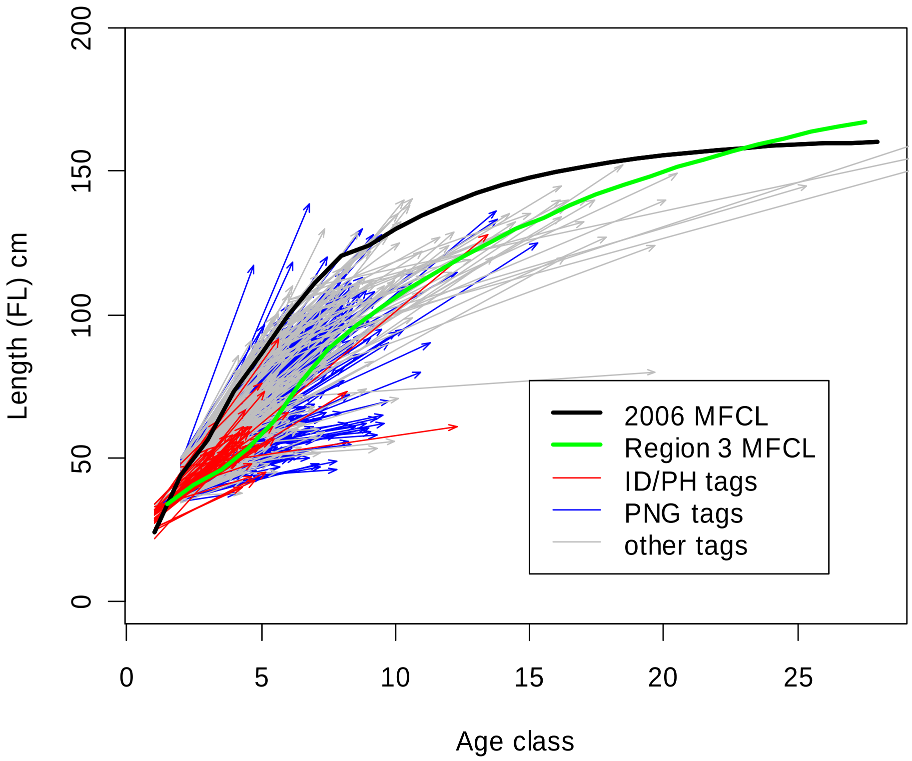

Figure 3. A comparison of yellowfin growth estimated from WCPO and region 3 (2007) MFCL models with growth increments from tagged fish released in Indonesian/Philippines waters, PNG waters, and other areas.

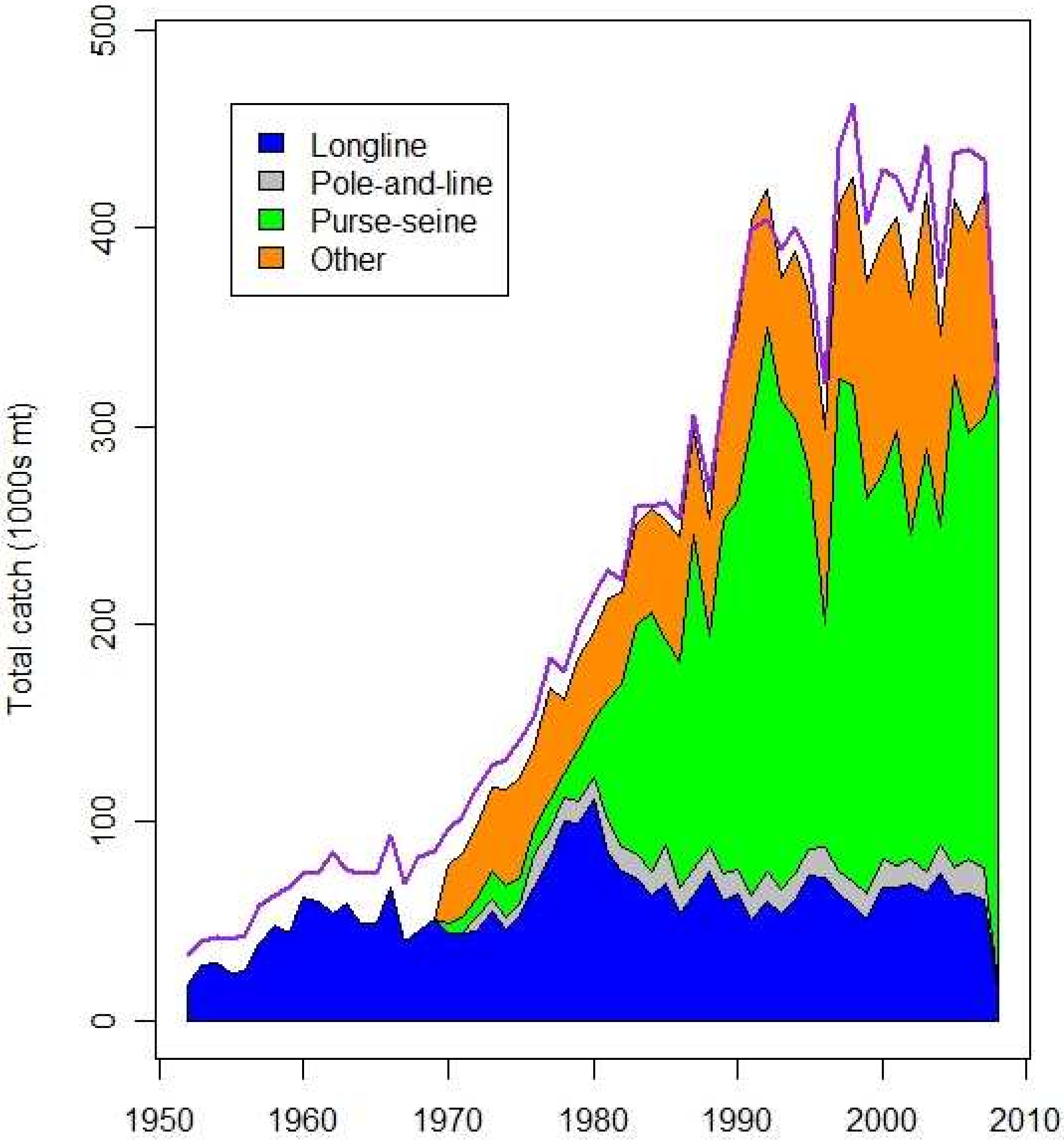

Figure 4. Total annual catches (1000s mt) of yellowfin from the WCPO by fishing method from 1952 to 2008. The "Other" category represents catches from the domestic fisheries of Indonesia and the Philippines. Data from 2008 are incomplete. The purple line represents the total annual catch estimates for the WCPFC, including some reported catch that could not be reliably ascribed to a fishery defined in the model.

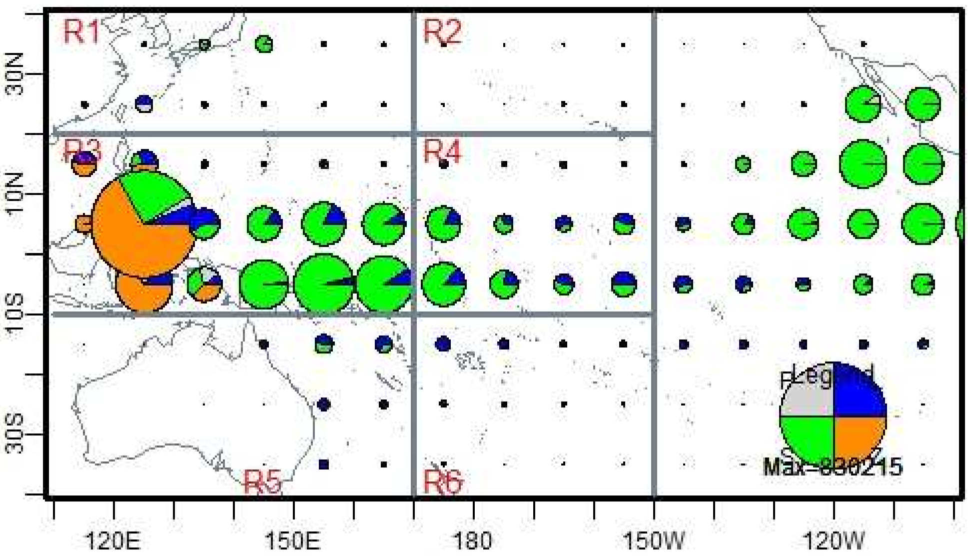

Figure 5. Distribution of cumulative yellowfin tuna catch from 1998–2007 by 5 degree squares of latitude and longitude and fishing gear; longline (L, blue), purse-seine (S, green), pole-and-line (P, grey) and other (Z, dark orange). The grey lines indicate the spatial stratification.

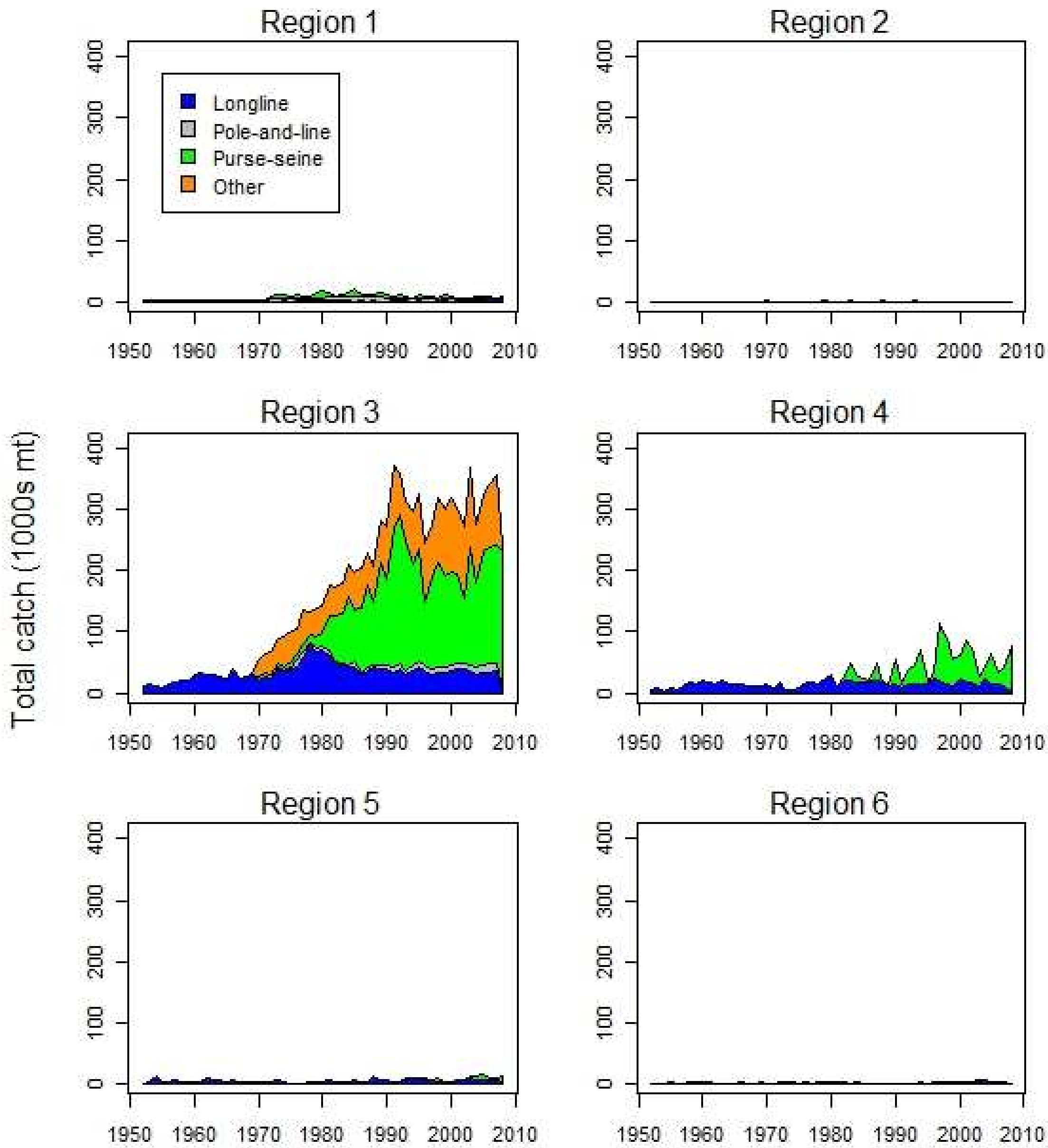

Figure 6. Total annual catch (1000s mt) of yellowfin by fishing method and MFCL region from 1952 to 2008. The "Other" category represents catches from the domestic fisheries of Indonesia and the Philippines. Data from 2008 are incomplete.

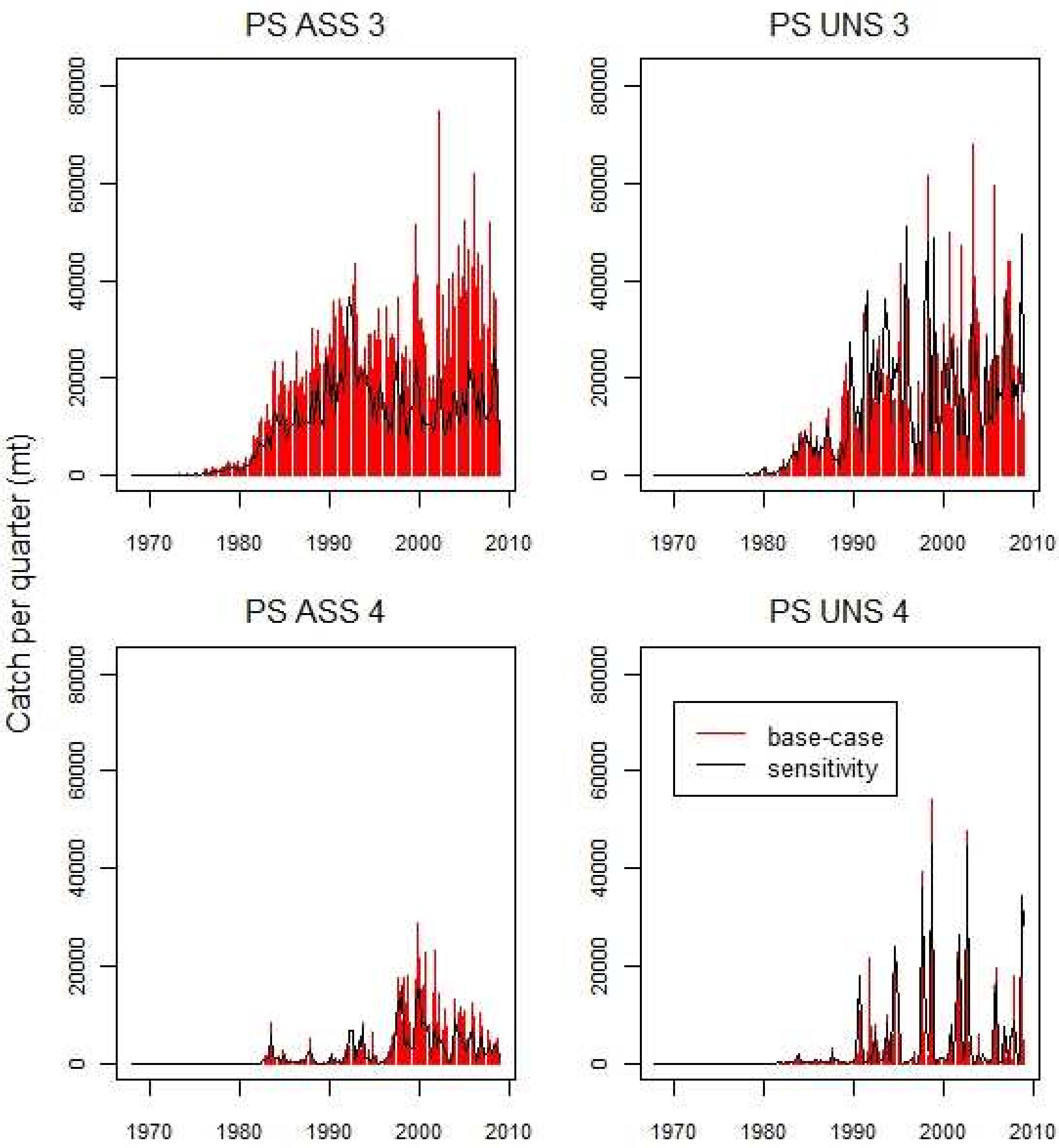

Figure 7. A comparison of the quarterly purse-seine catch by fishery derived from observer sampling (red bars) and from the previous methodology (black line). The catch history derived from observer sampling was included in the principal model runs, while the alternative catch history was included in a range of sensitivity analyses.

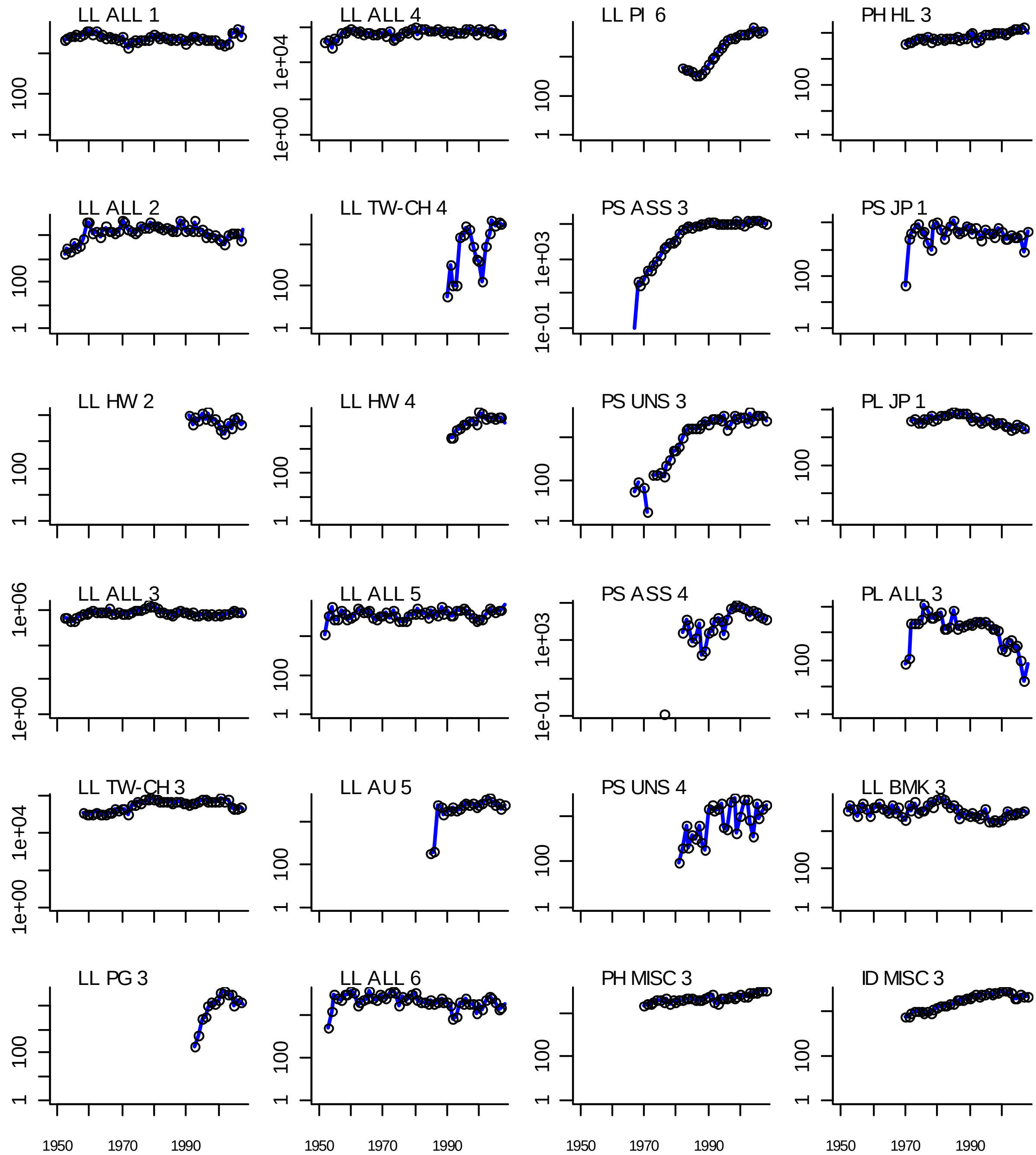

Figure 8. Annual catches, by fishery. Circles are observed and the lines are model predictions. Units are catch number in thousands for the longline fisheries and thousand metric tonnes for all other fisheries.

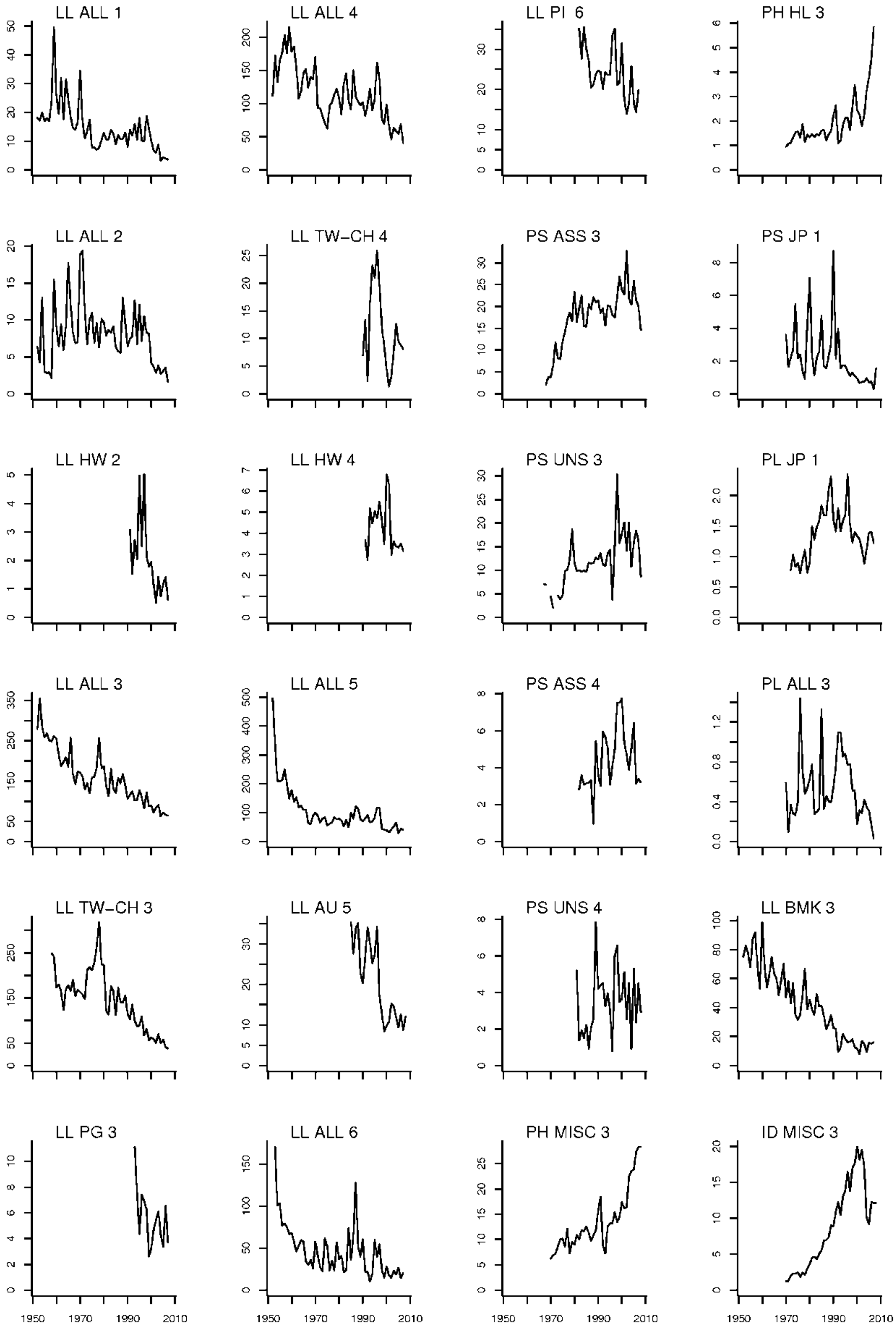

Figure 9. Catch-per-unit-effort (CPUE) by fishery. Units are catch number per GLM-standardised effort (with increasing catchability) (fisheries LL ALL 1–LL ALL 6), catch number per 100 nominal hooks (LL HW, CH/TW LL, LL PI, LL PG, LL BMK) and catch (mt) per day fished/searched (all PS and PL fisheries). Note that CPUE for PH and ID MISC 3 is arbitrary and not based on data (see discussion on catchability and effort deviation constraints for these fisheries).

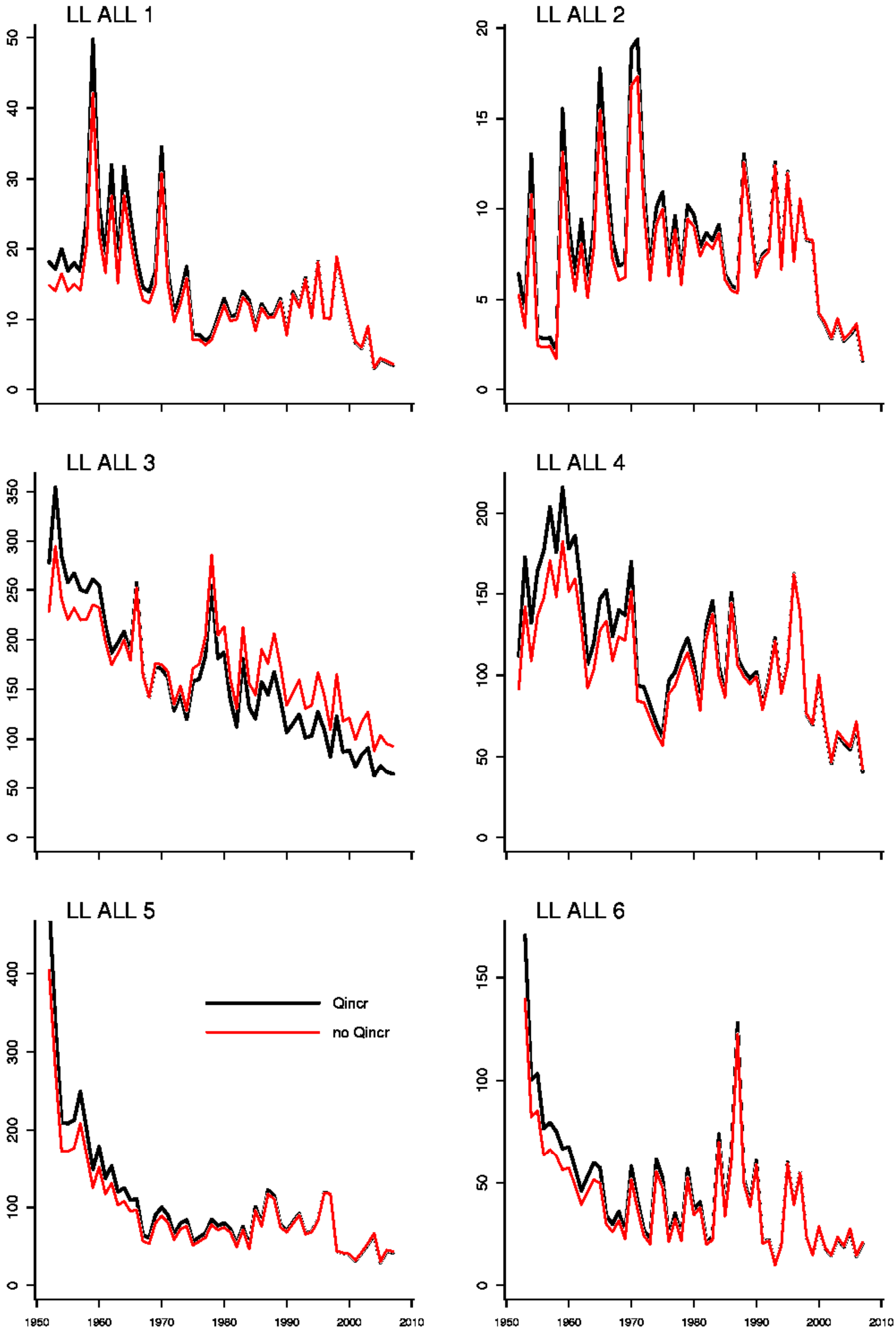

Figure 10. GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL ALL 1–6), with and without an increase in longline catchability (Qincr), scaled by the respective region scalars.

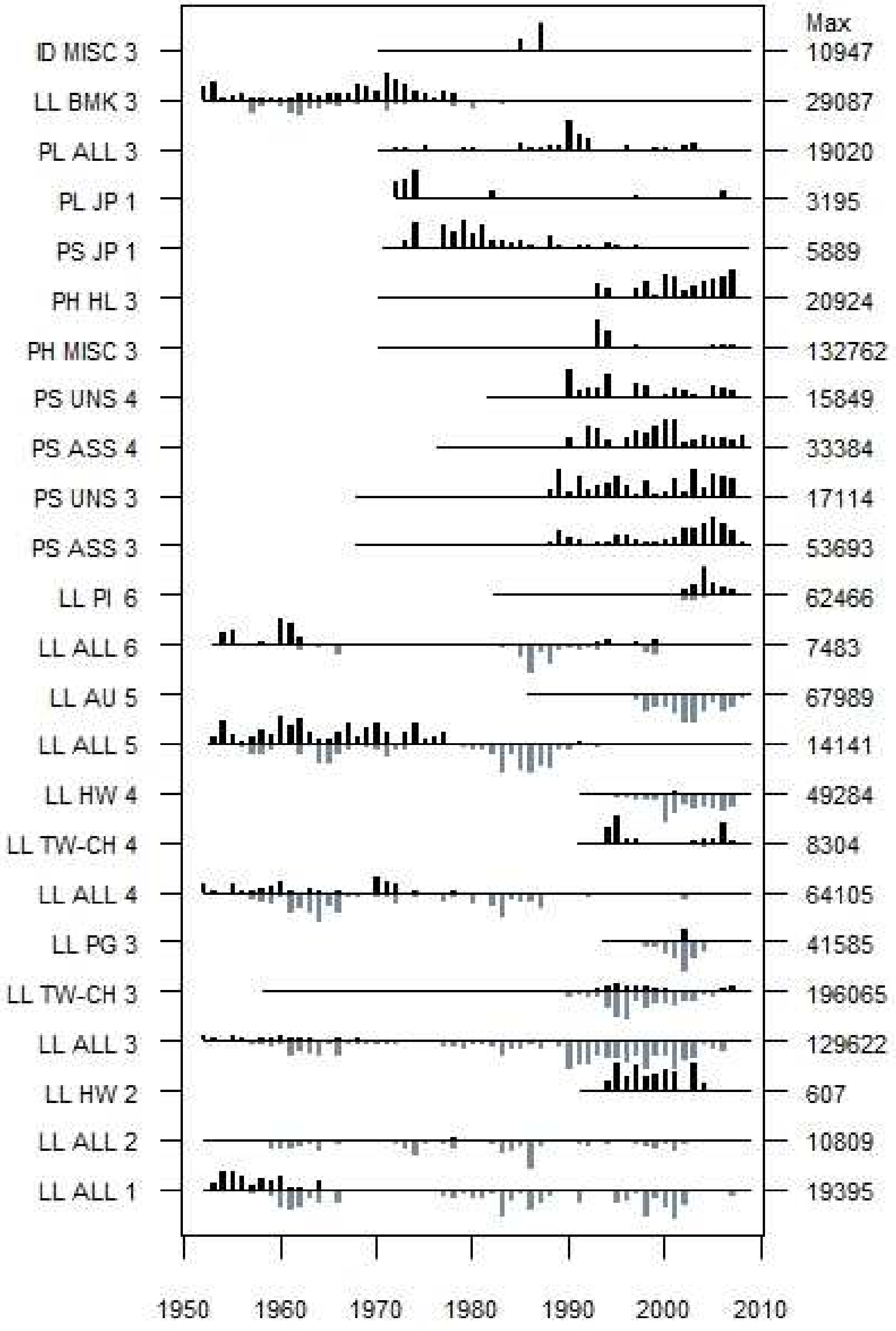

Figure 11. Number of fish size measurements by year for each fishery. The upper black bars represent length measurements and the lower grey bars represent weight measurements. The maximum bar length for each fishery is given on the right-hand side. The extent of the horizontal lines indicates the period over which each fishery occurred.

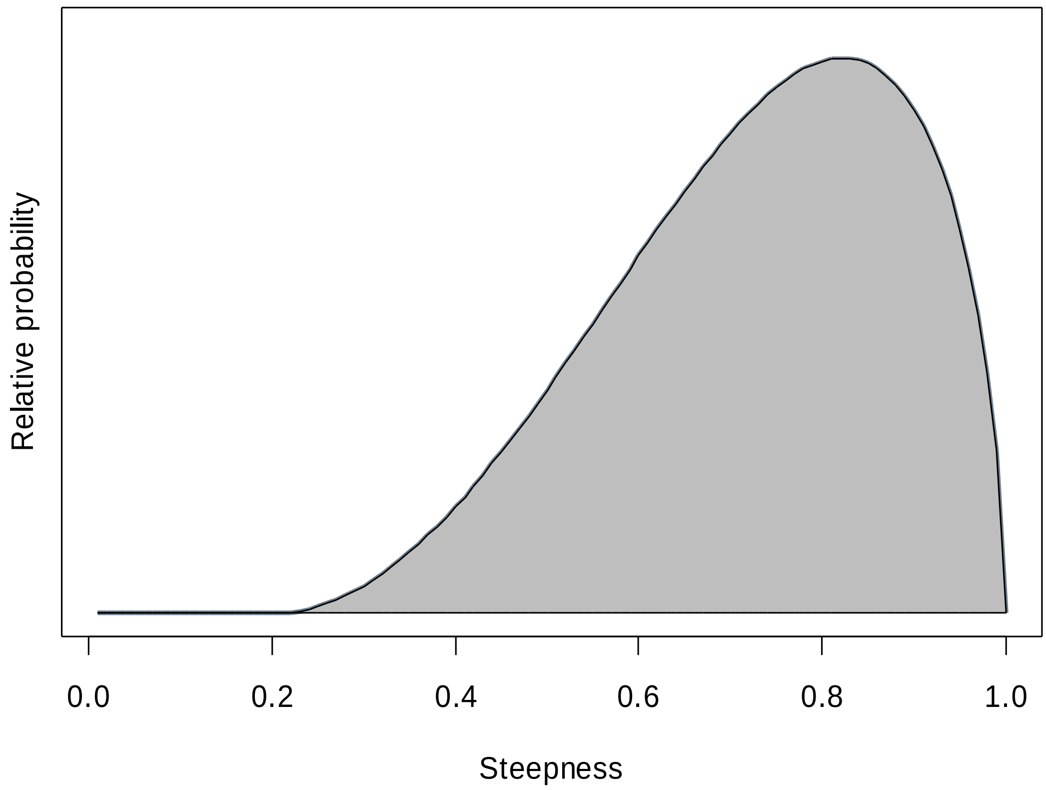

Figure 12. Prior for the steepness parameter of the relationship between spawning biomass and recruitment (SSR) (mode = 0.85, standard deviation = 0.16).

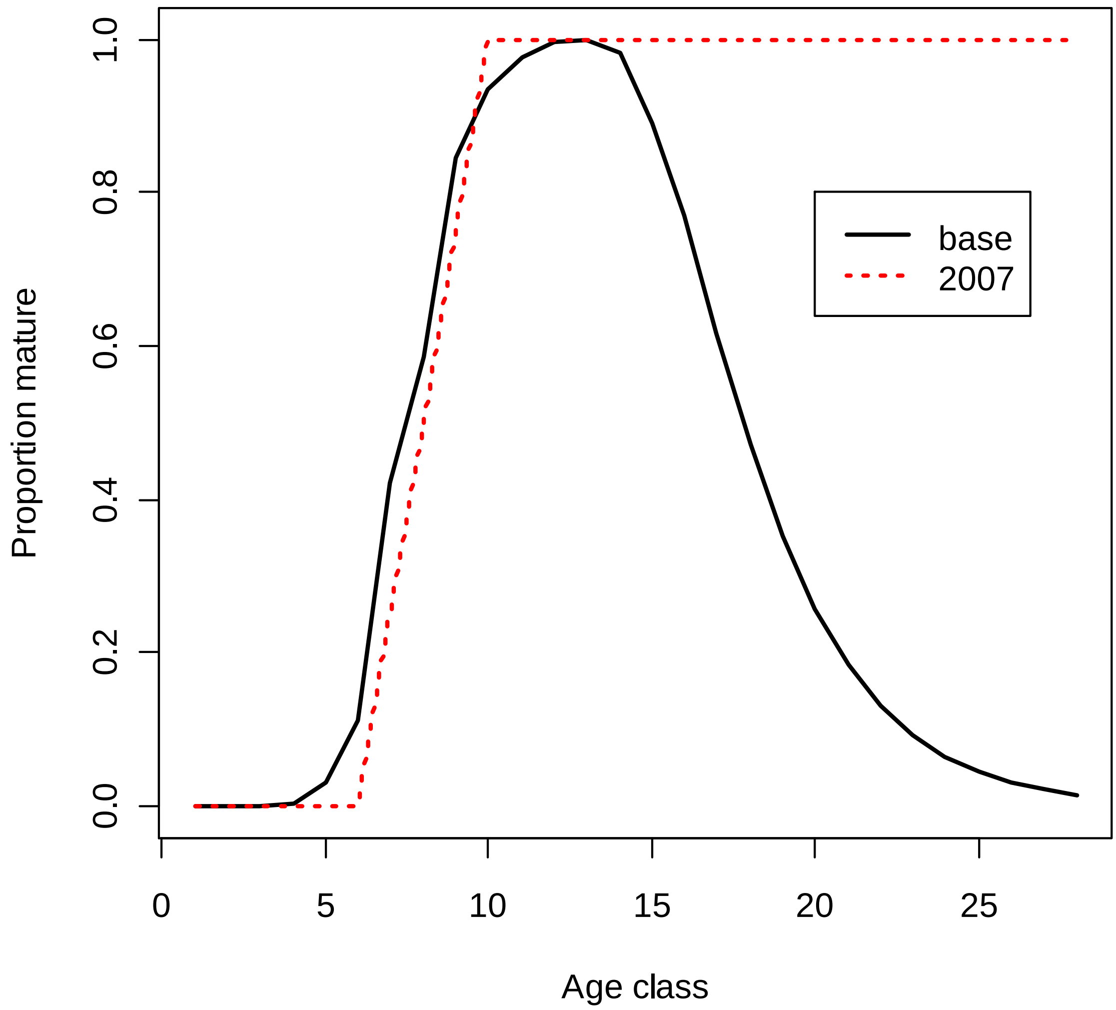

Figure 13. Proportion mature (reproductive potential) by age class for the current assessment (base) and the values assumed in the 2007 stock assessment.

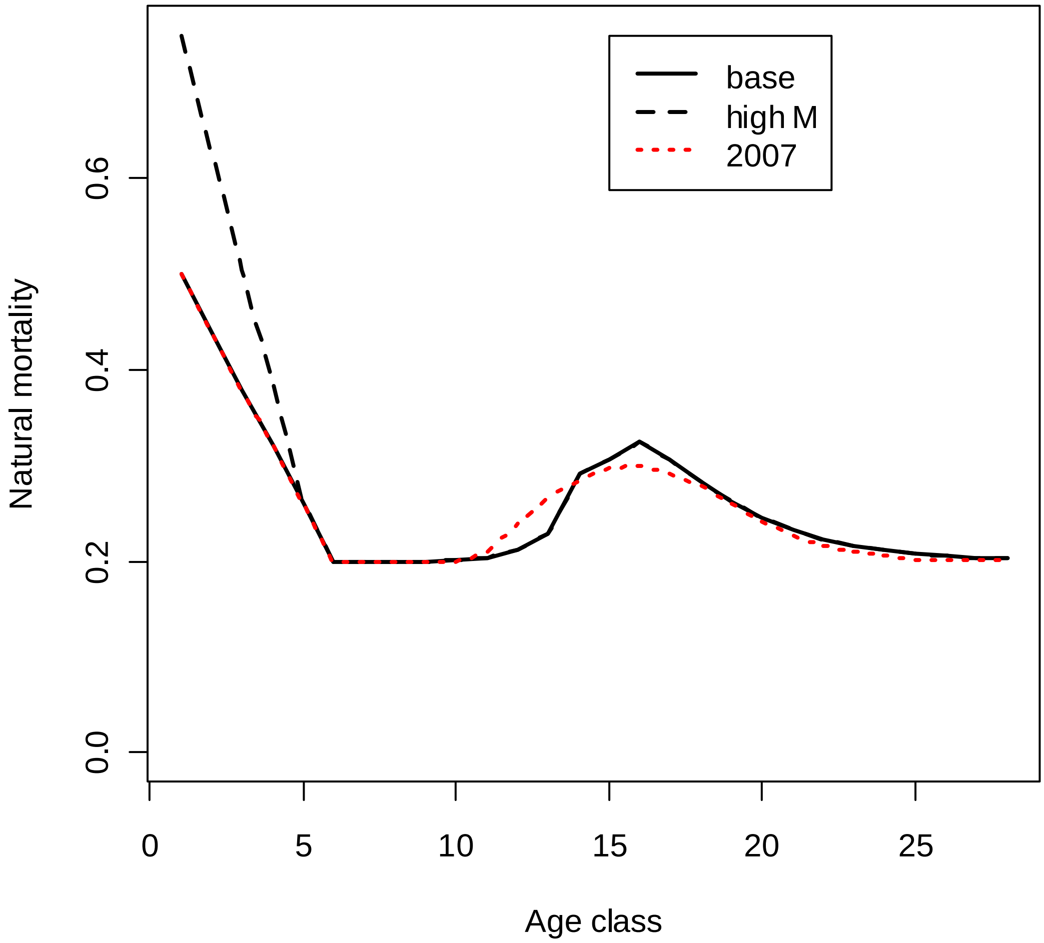

Figure 14. Age-specific natural mortality assumed for the assessment (solid line) and the alternative natural mortality used for high M sensitivity analyses (dashed line). The age-specific natural mortality assumed in the 2007 stock assessment is also presented.

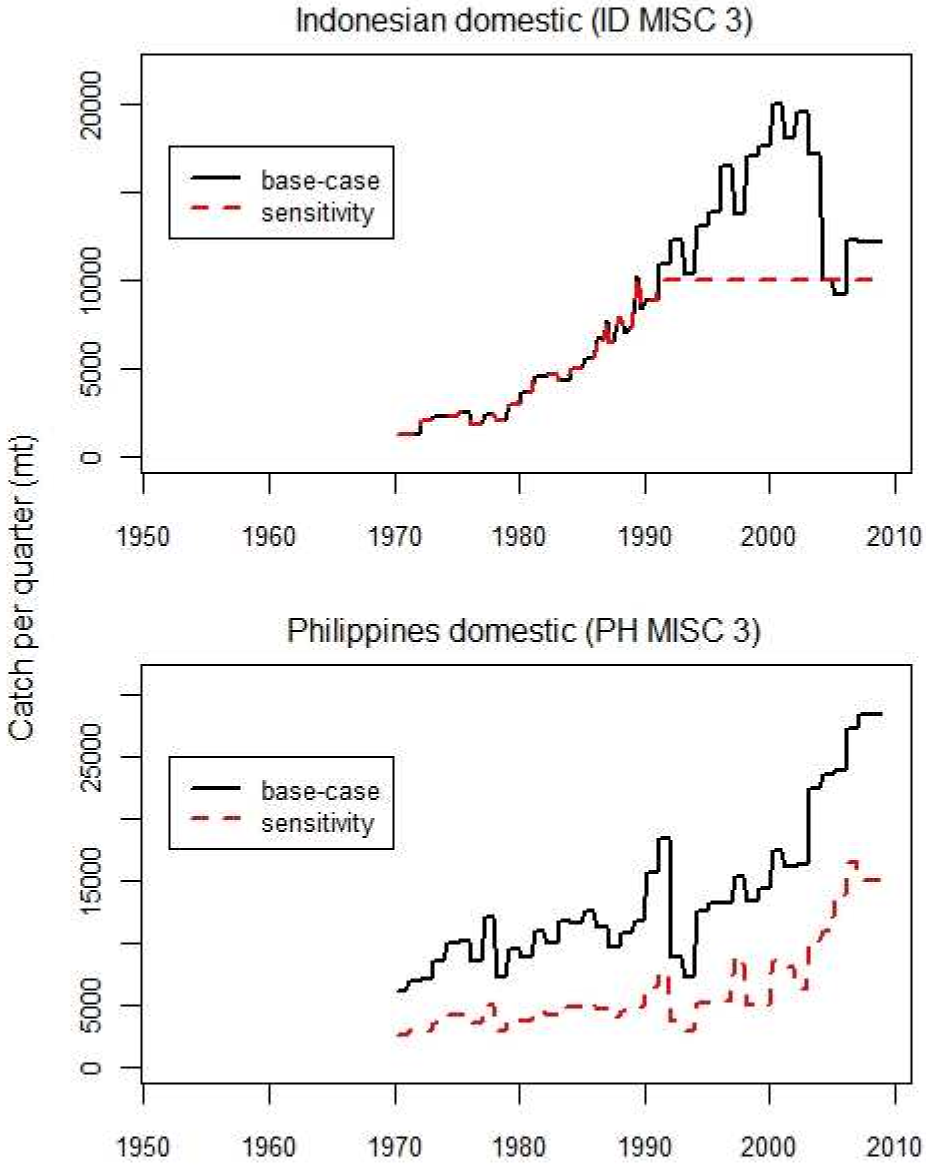

Figure 15. A comparison of the yellowfin tuna catch (mt per quarter) from the Indonesian (ID MISC 3) and Philippines (PH MISC 3) fisheries incorporated in the base-case model and the ID/PH sensitivity analyses.

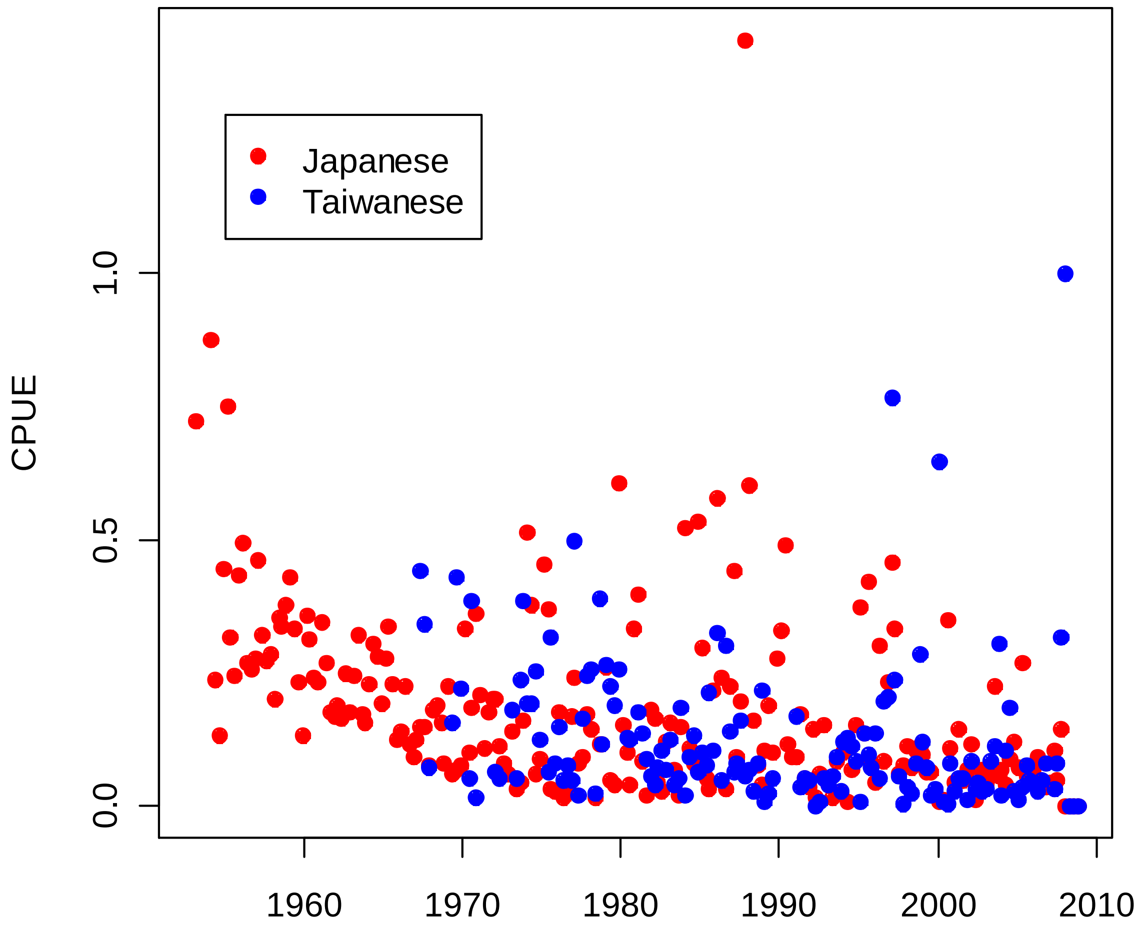

Figure 16. Quarterly region 6 CPUE indices derived from catch and effort data from the Japanese and Taiwanese longline fleets.

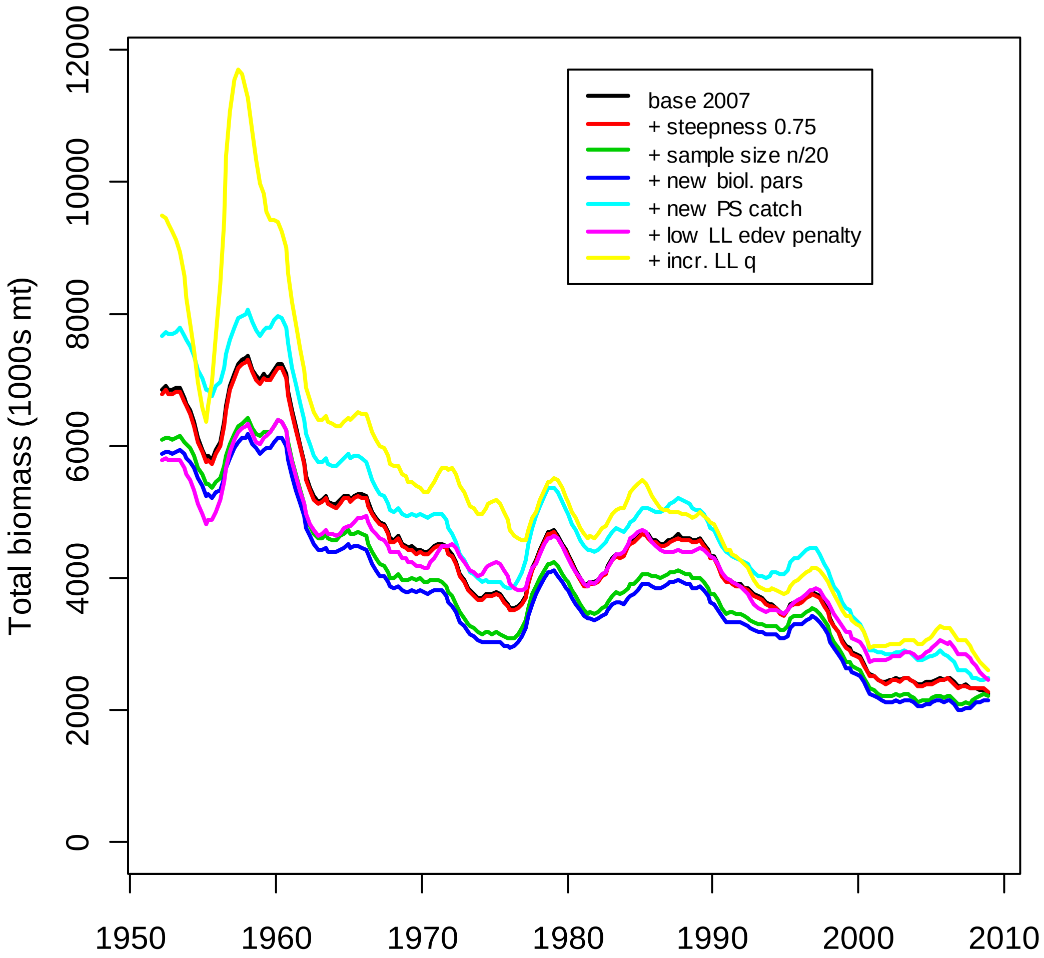

Figure 17. Total biomass (mt) from successive model runs with step-wise changes in key data sets and model assumptions from the "base 2007" model (black line) to replicate the "CPUE low, LL sample high, LL q incr" model (yellow line).

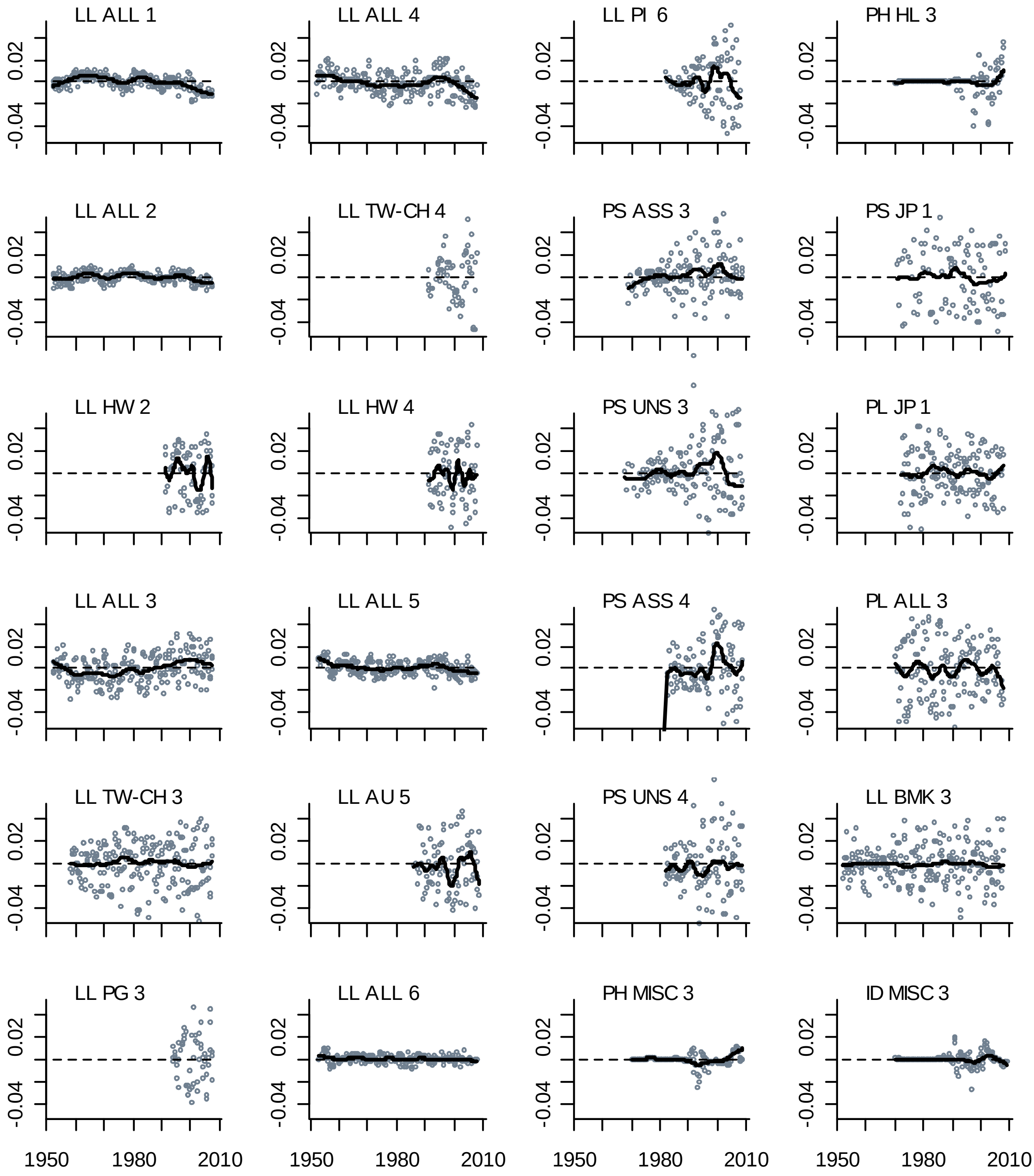

Figure 18. Residuals of ln (total catch) for each fishery.

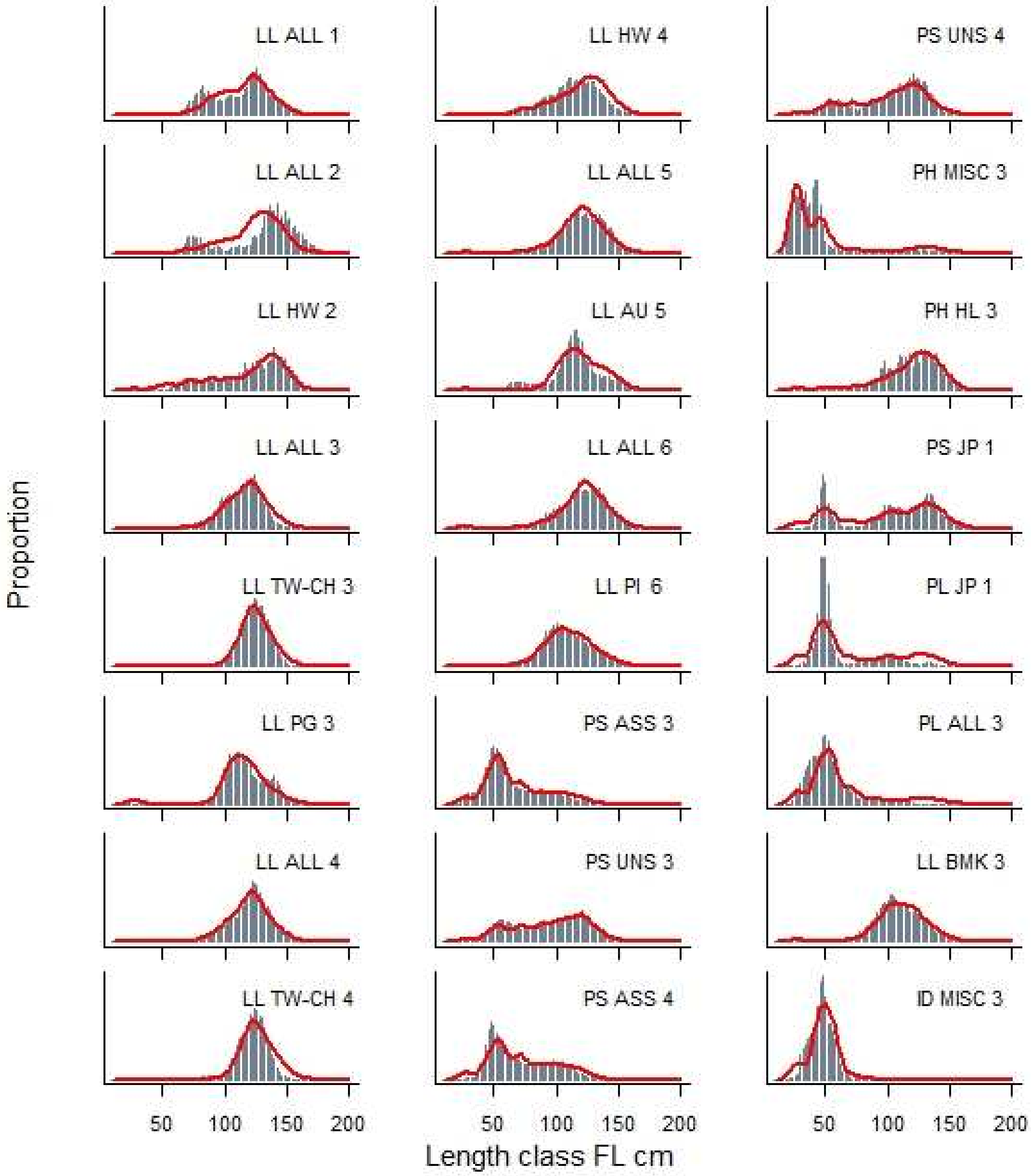

Figure 19. Observed (histograms) and predicted (line) length frequencies (in cm) for each fishery aggregated over time.

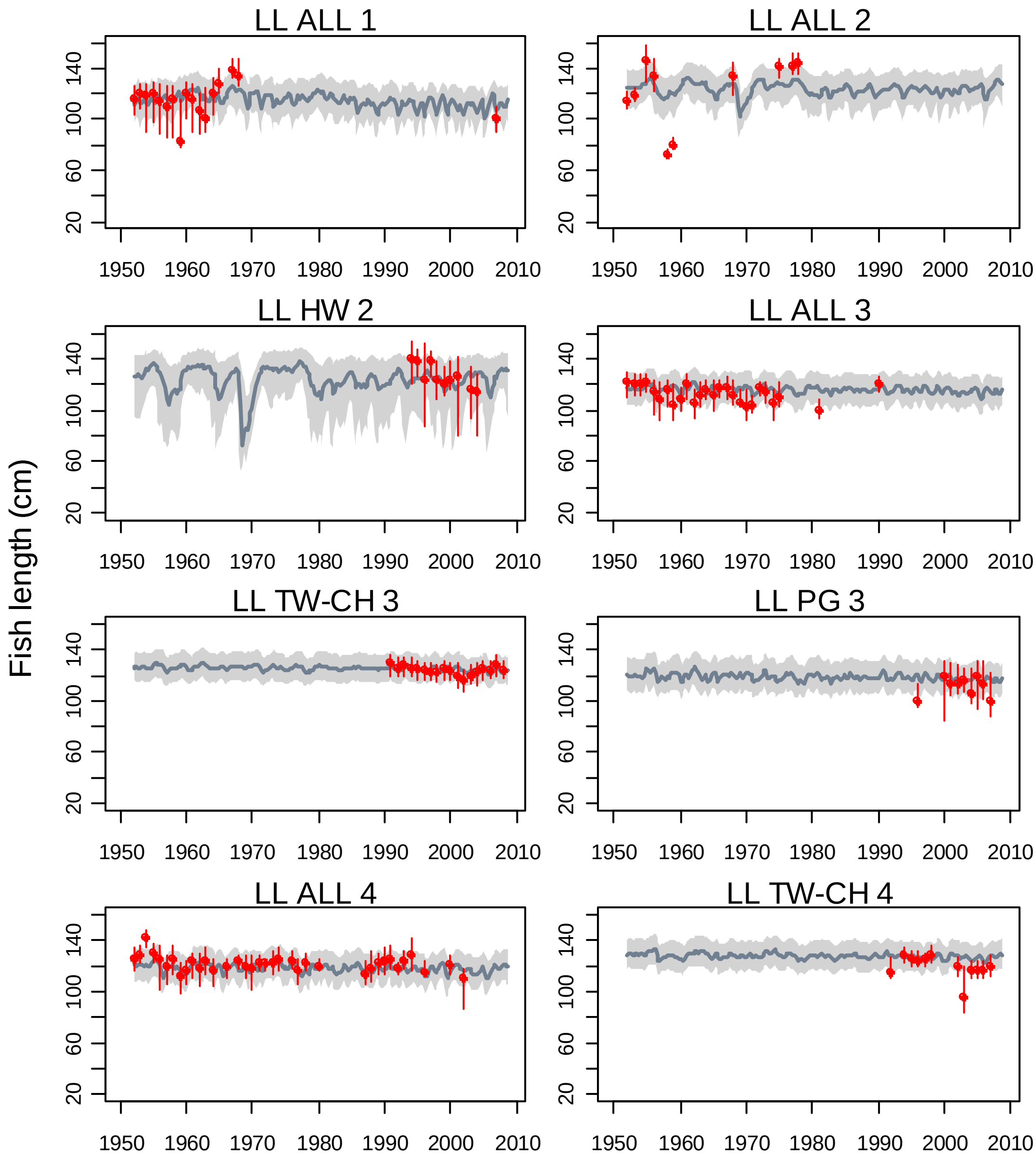

Figure 20. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of yellowfin tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year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

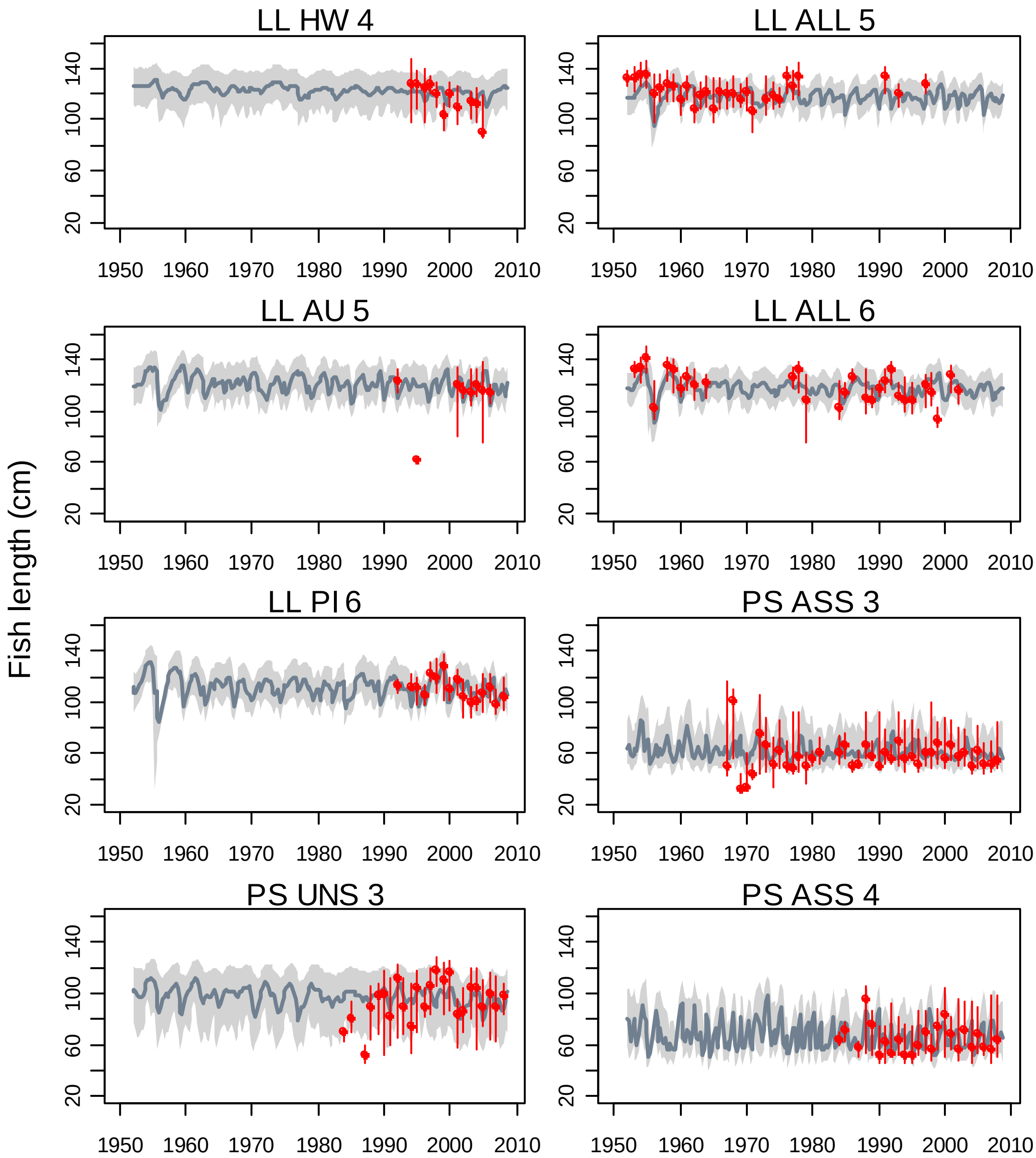

Figure 20 (continued).

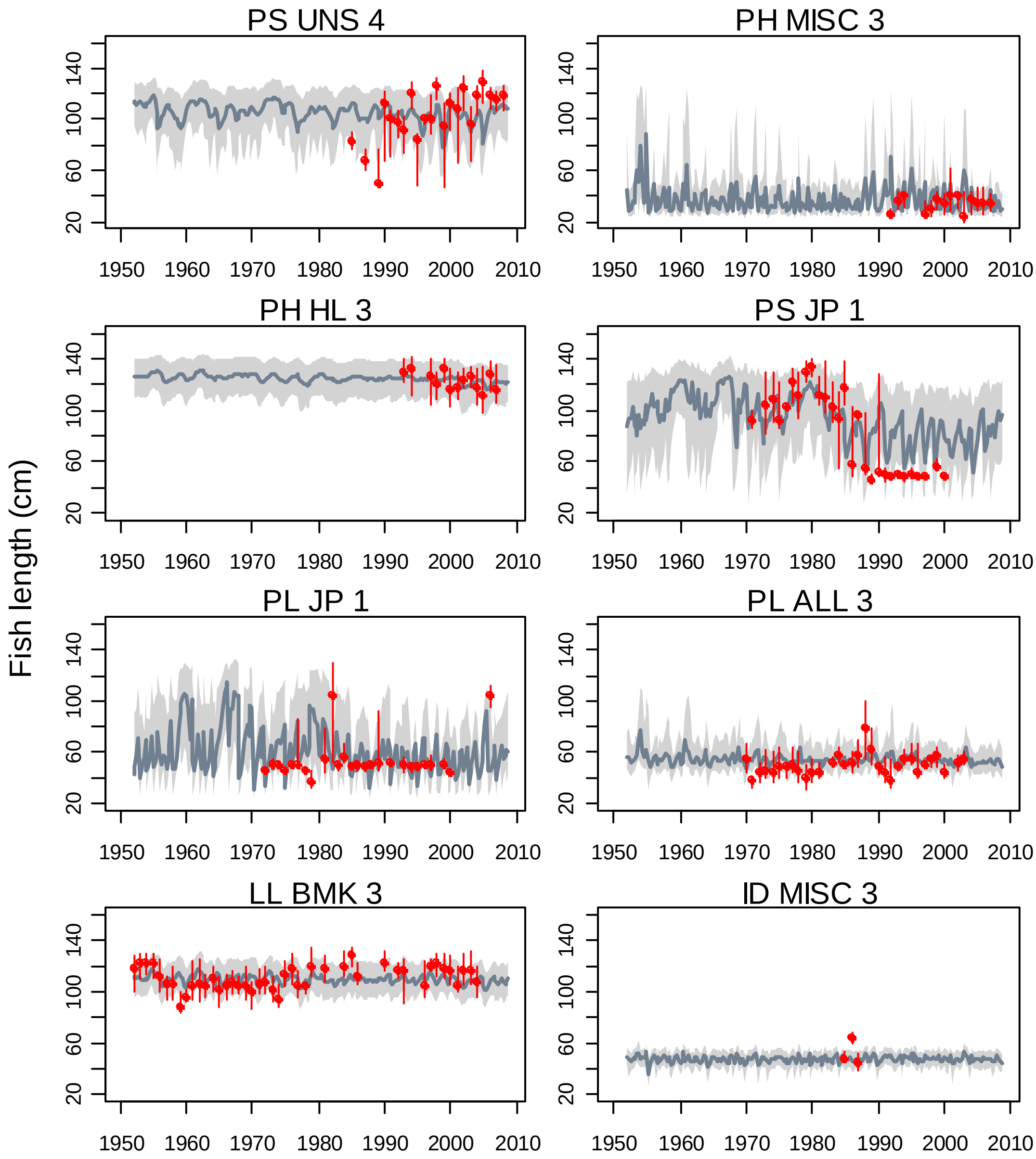

Figure 20 (continued).

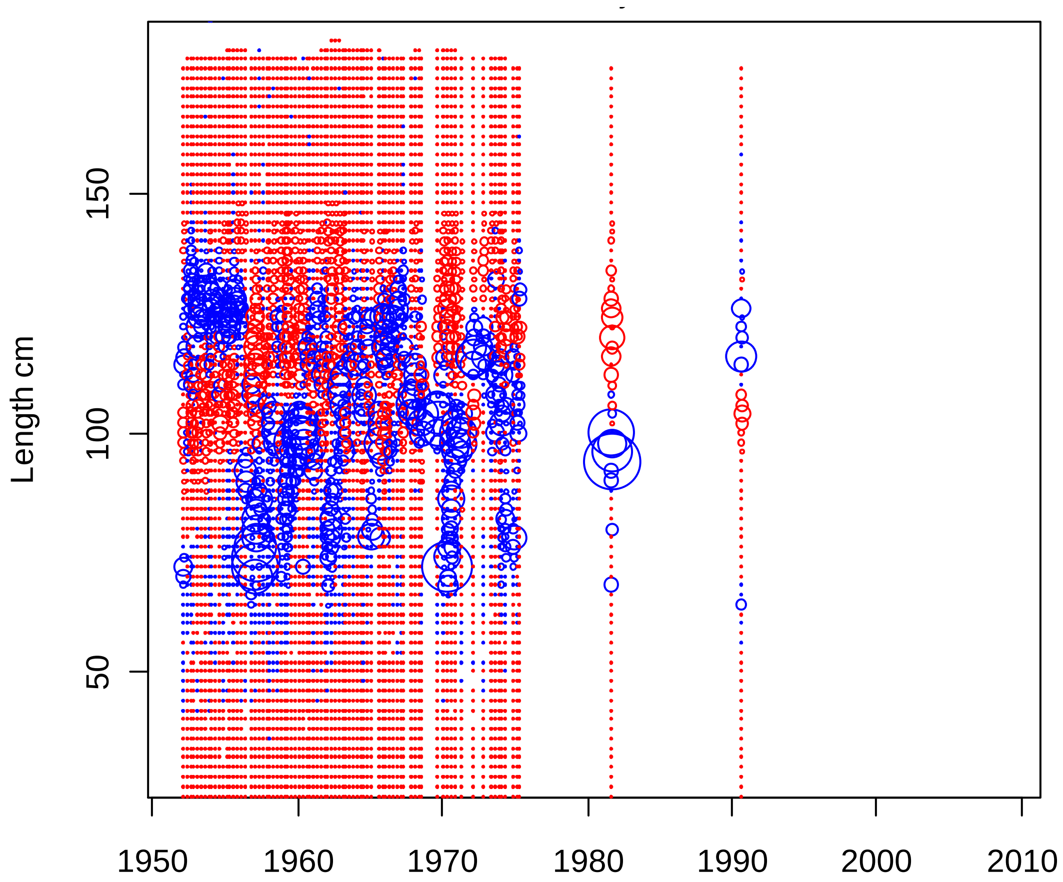

Figure 21. Residuals (observed – predicted proportions) of the fit to the length frequency data from the LL ALL 3 fishery. The size of the circle is proportional to the residual; blue circles are positive residuals, red circles negative residuals. The maximum residual is 0.1069.

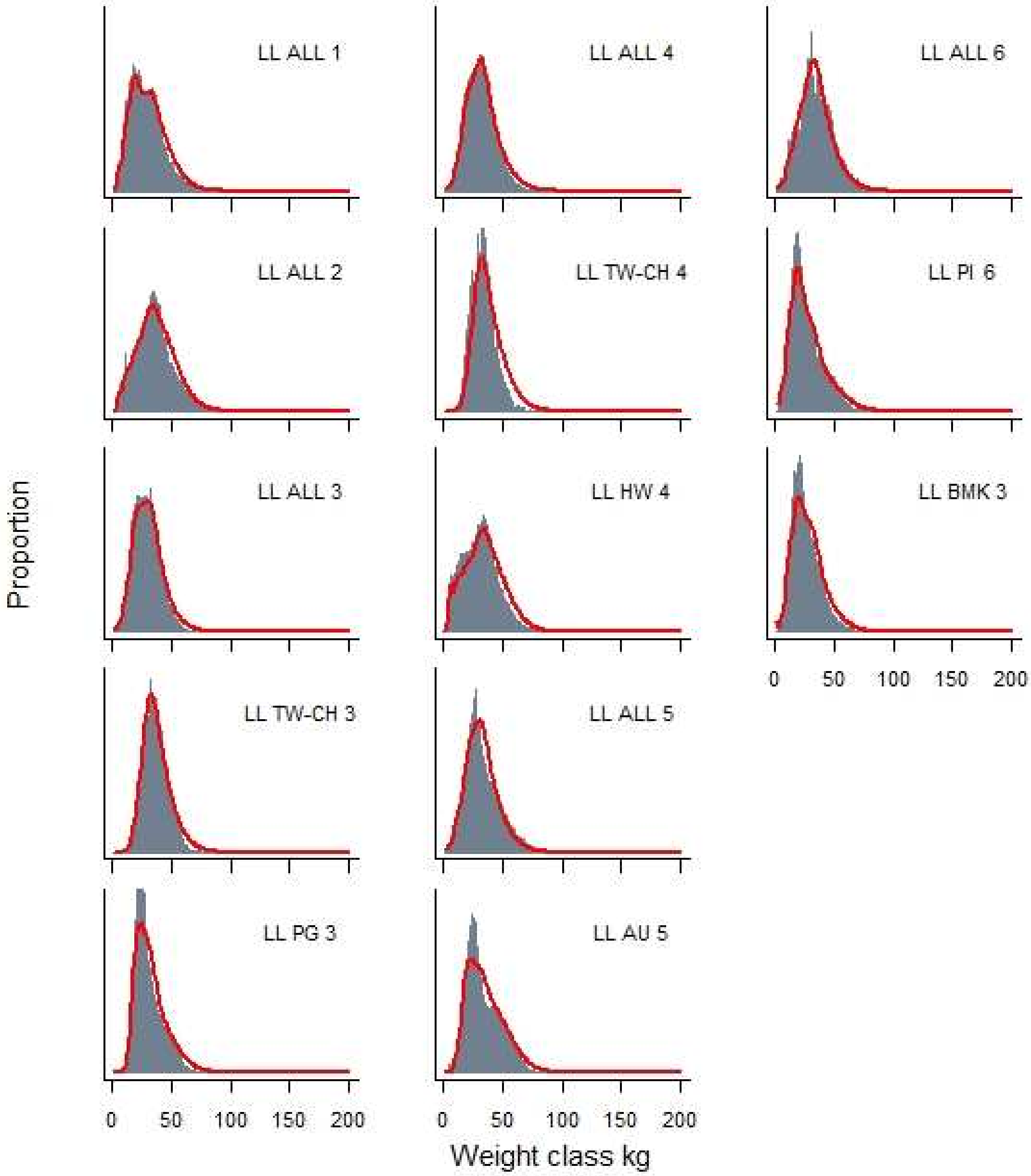

Figure 22. Observed (histograms) and predicted (line) weight frequencies (in kg) for each fishery aggregated over time.

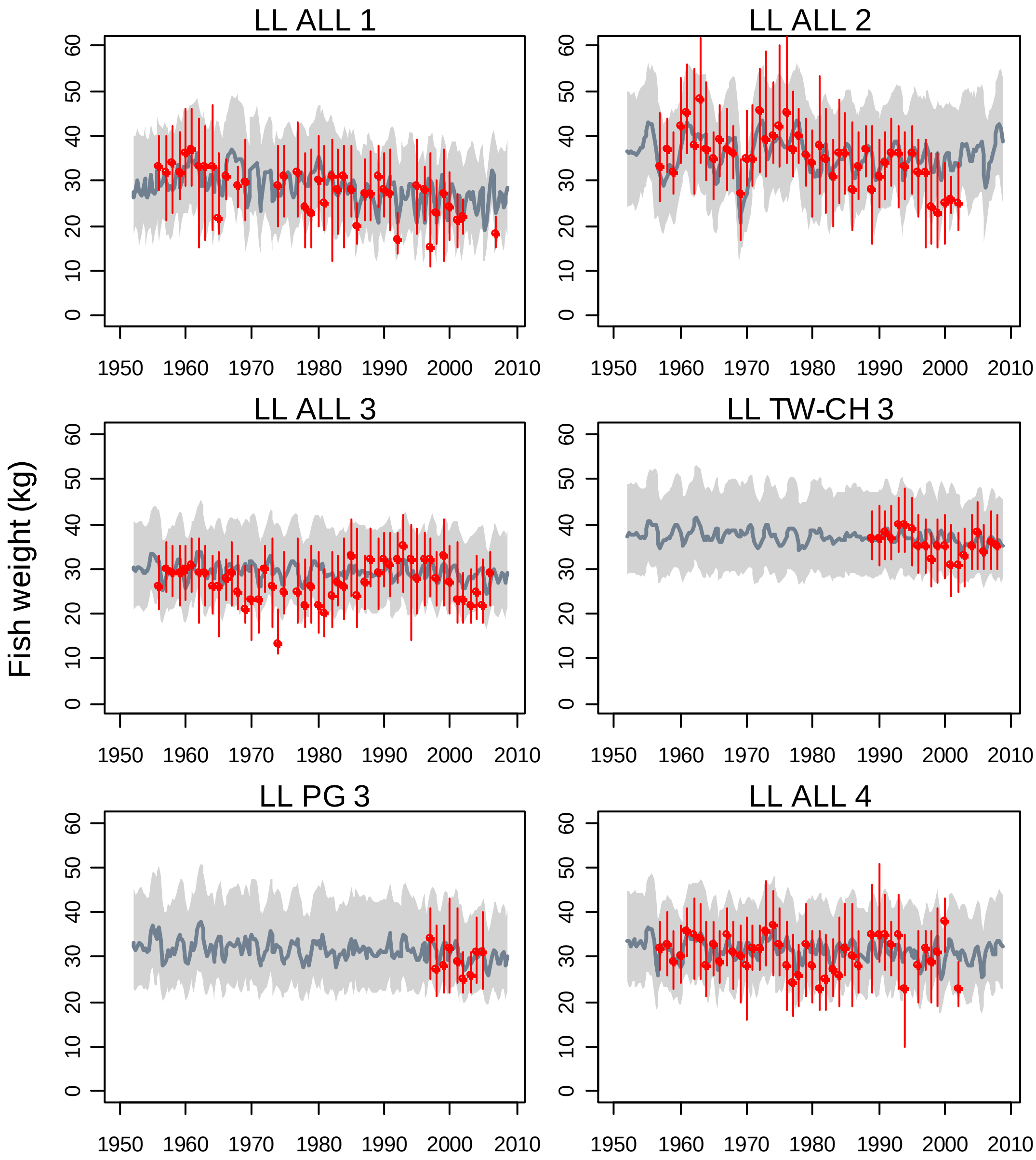

Figure 23. A comparison of the observed (red points) and predicted (grey line) median fish weight (whole weight, kg) of yellowfin tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only weight samples with a minimum of 30 fish per year are plotted.

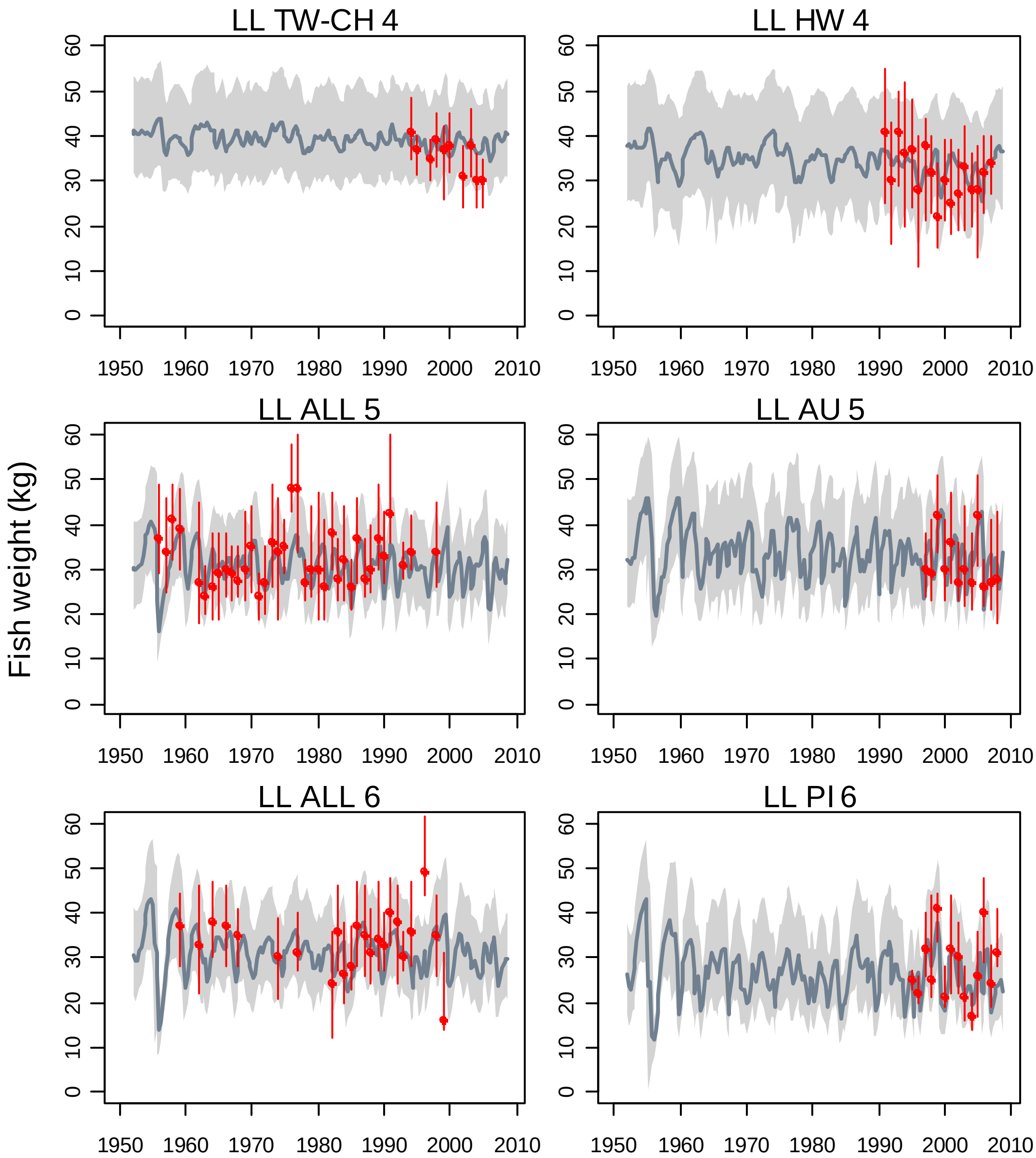

Figure 23 (continued).

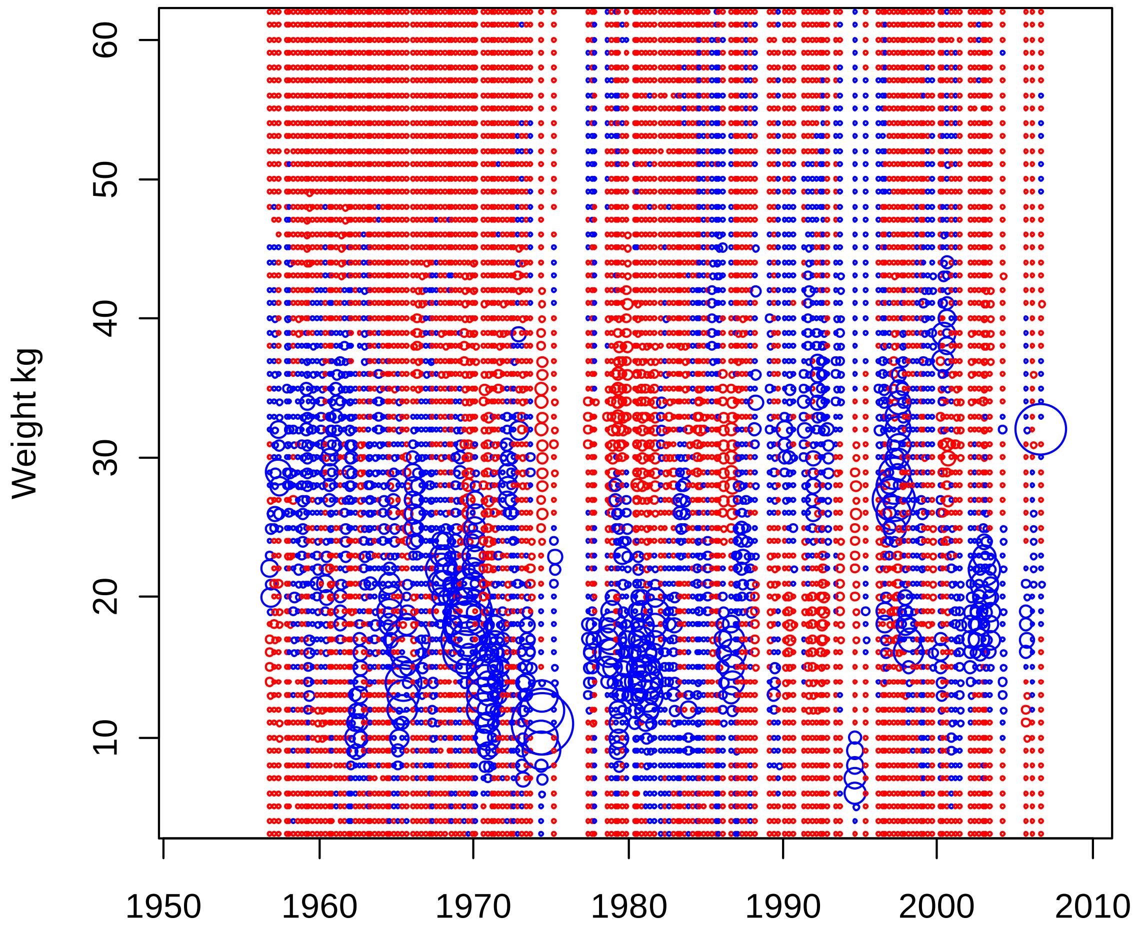

Figure 24. Residuals (observed – predicted proportions) of the fit to the weight frequency data from the LL ALL 3 fishery. The size of the circle is proportional to the residual; blue circles are positive residuals, red circles negative residuals. The maximum residual is 0.1155.

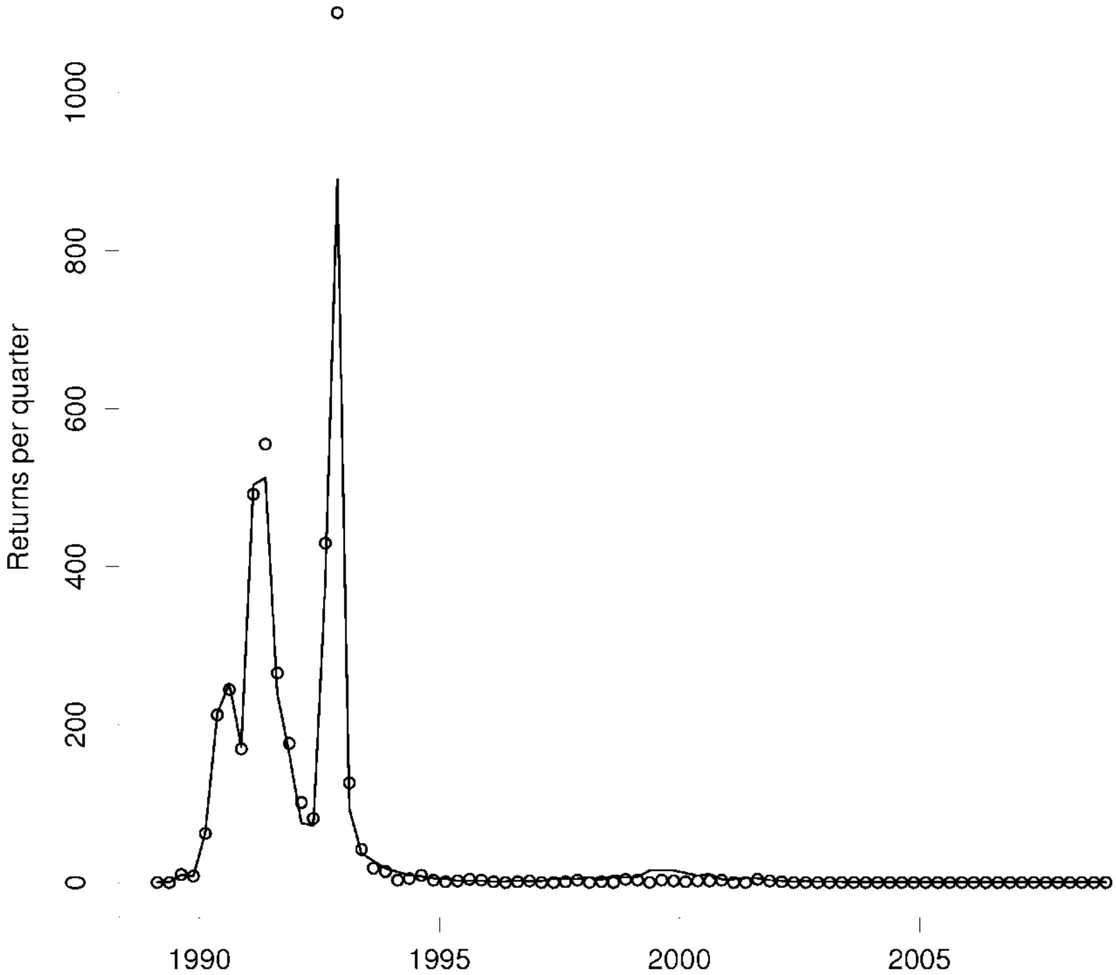

Figure 25. Number of observed (points) and predicted (line) tag returns by recapture period (quarter).

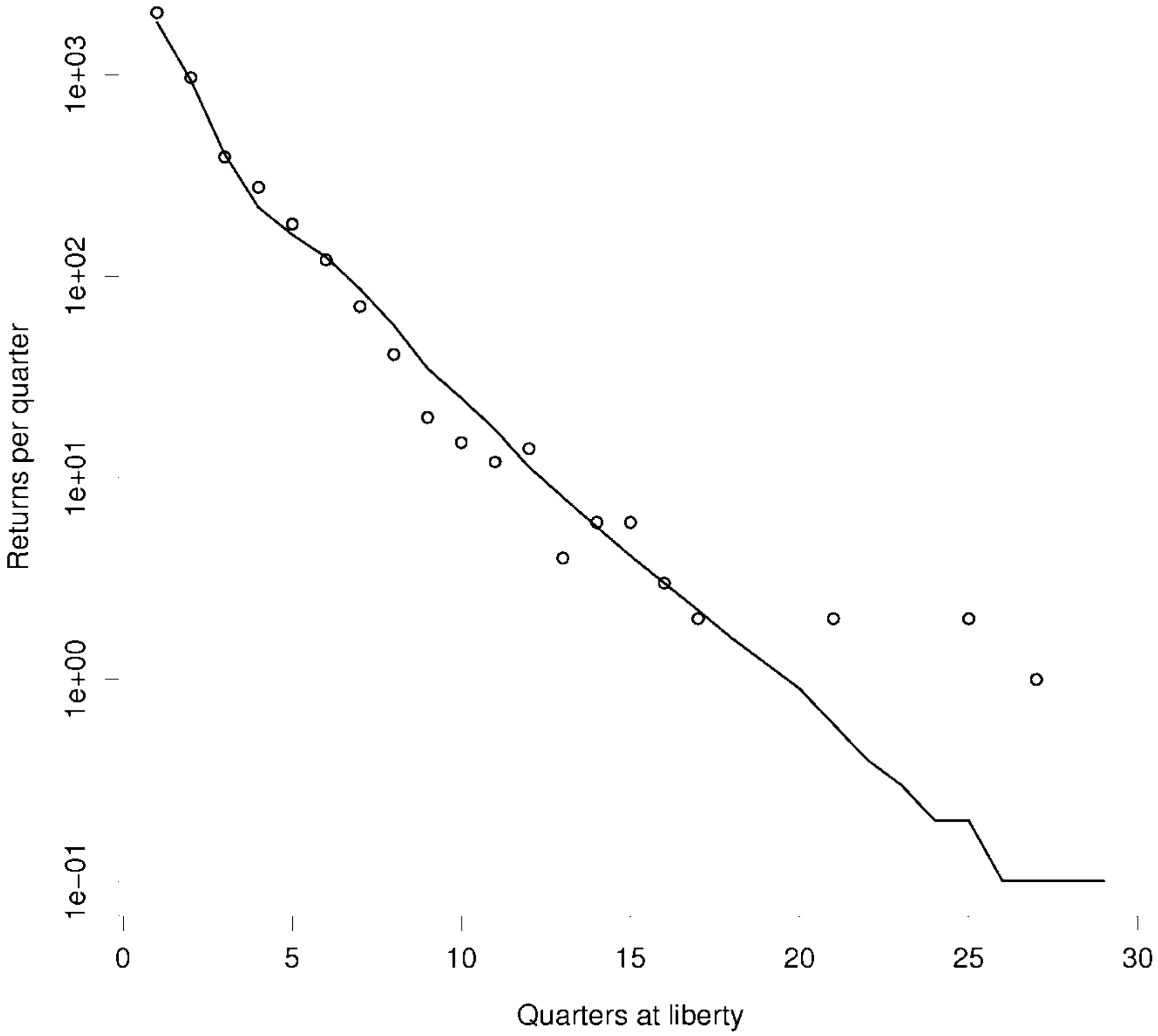

Figure 26. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters).

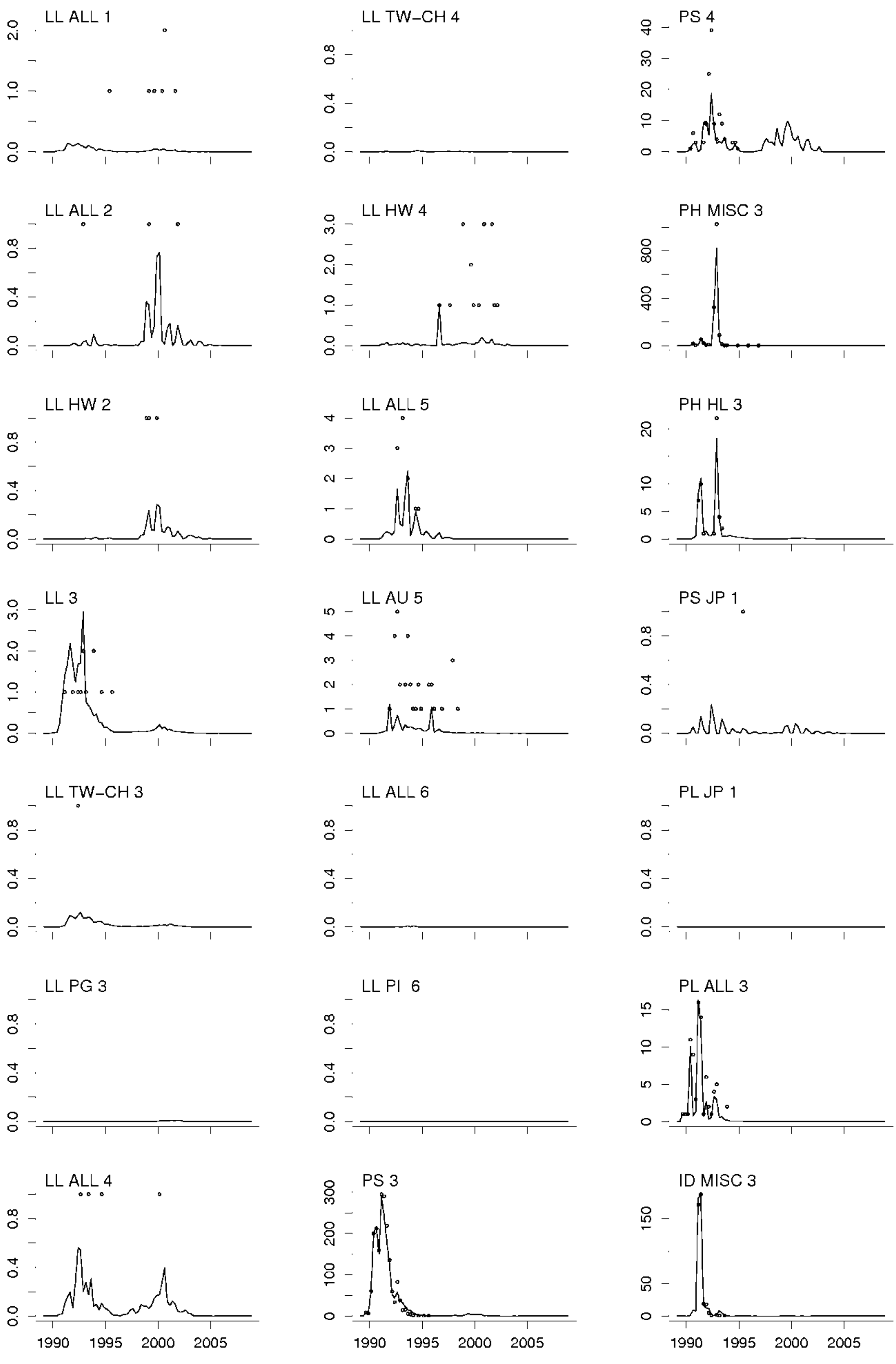

Figure 27. Number of observed (points) and predicted (line) tag returns by recapture period (quarter) for the various fisheries (or groups of fisheries) defined in the model.

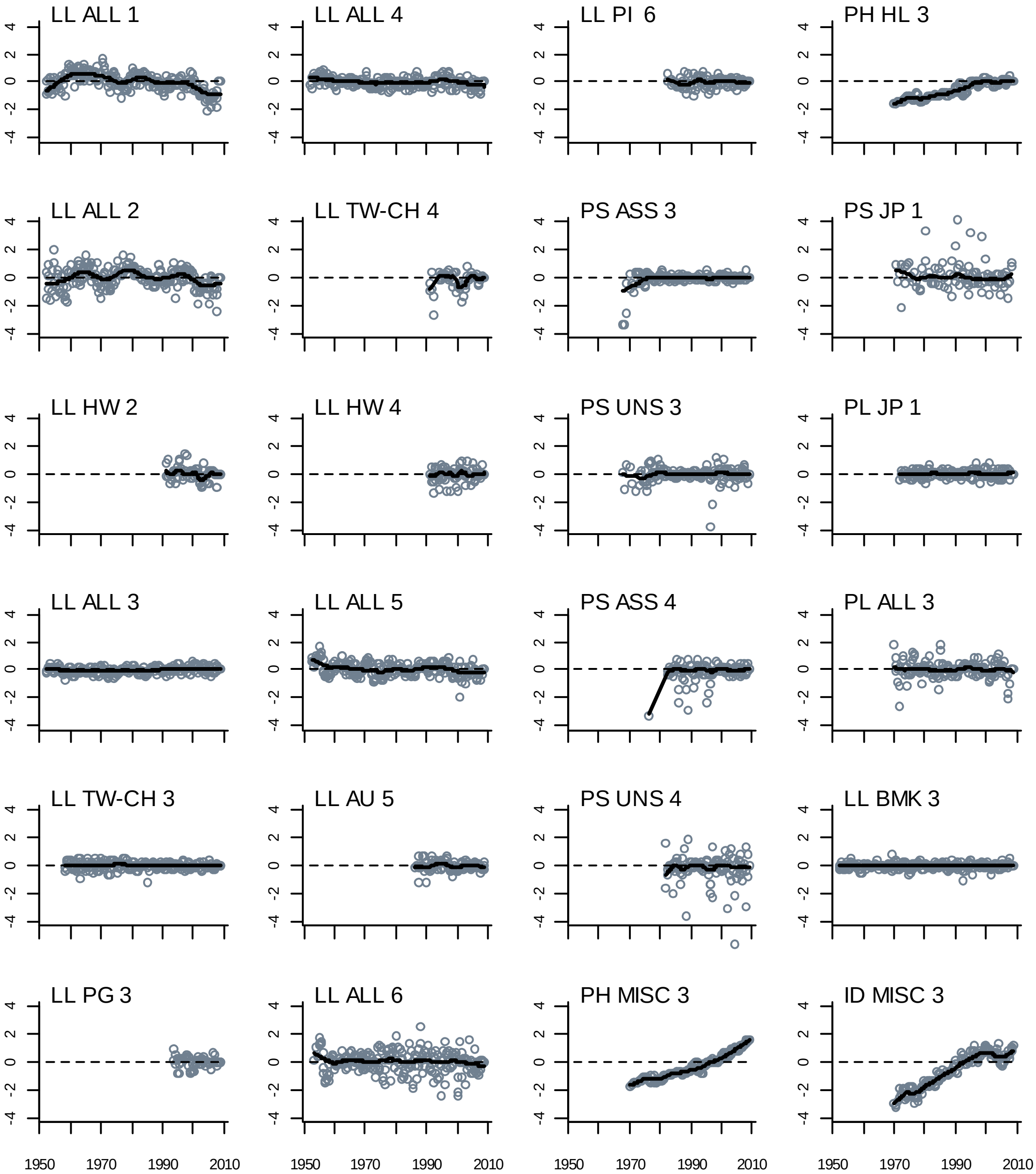

Figure 28. Effort deviations by time period for each fishery. The solid black line represents the lowess smoothed trend of the data.

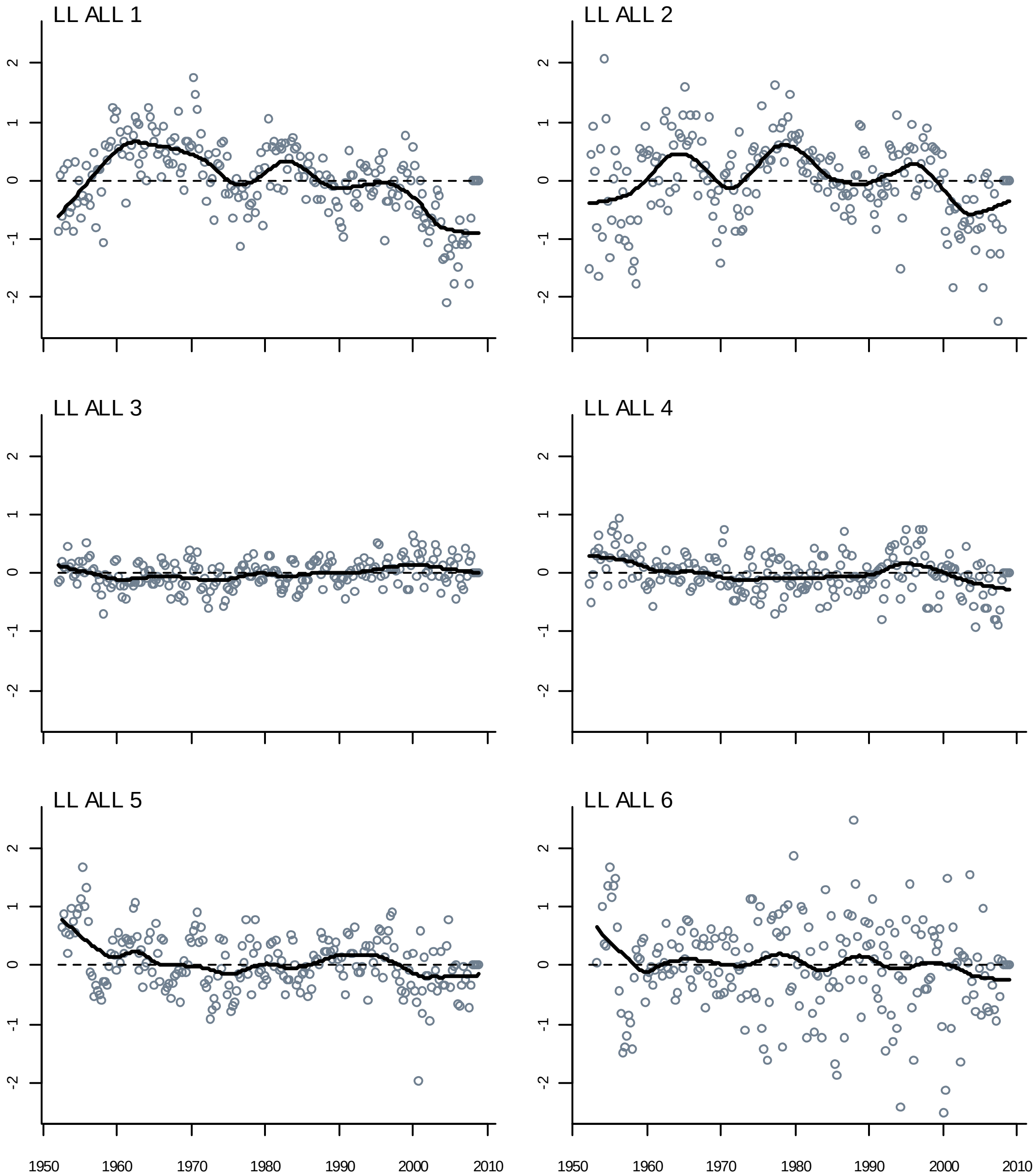

Figure 29. Effort deviations for the principal longline fisheries. The solid black line represents the lowess smoothed trend of the data.

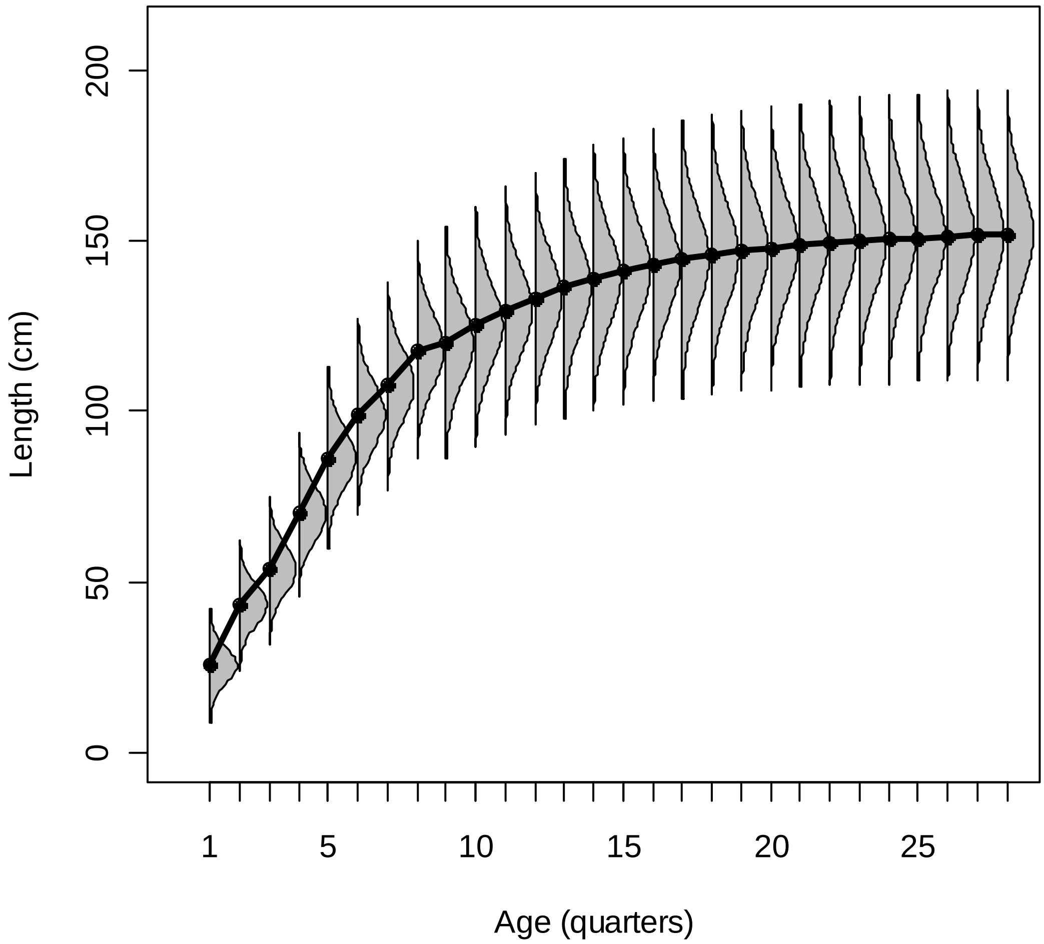

Figure 30. Estimated growth of yellowfin derived from the base-case assessment model. The black line represents the estimated mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age.

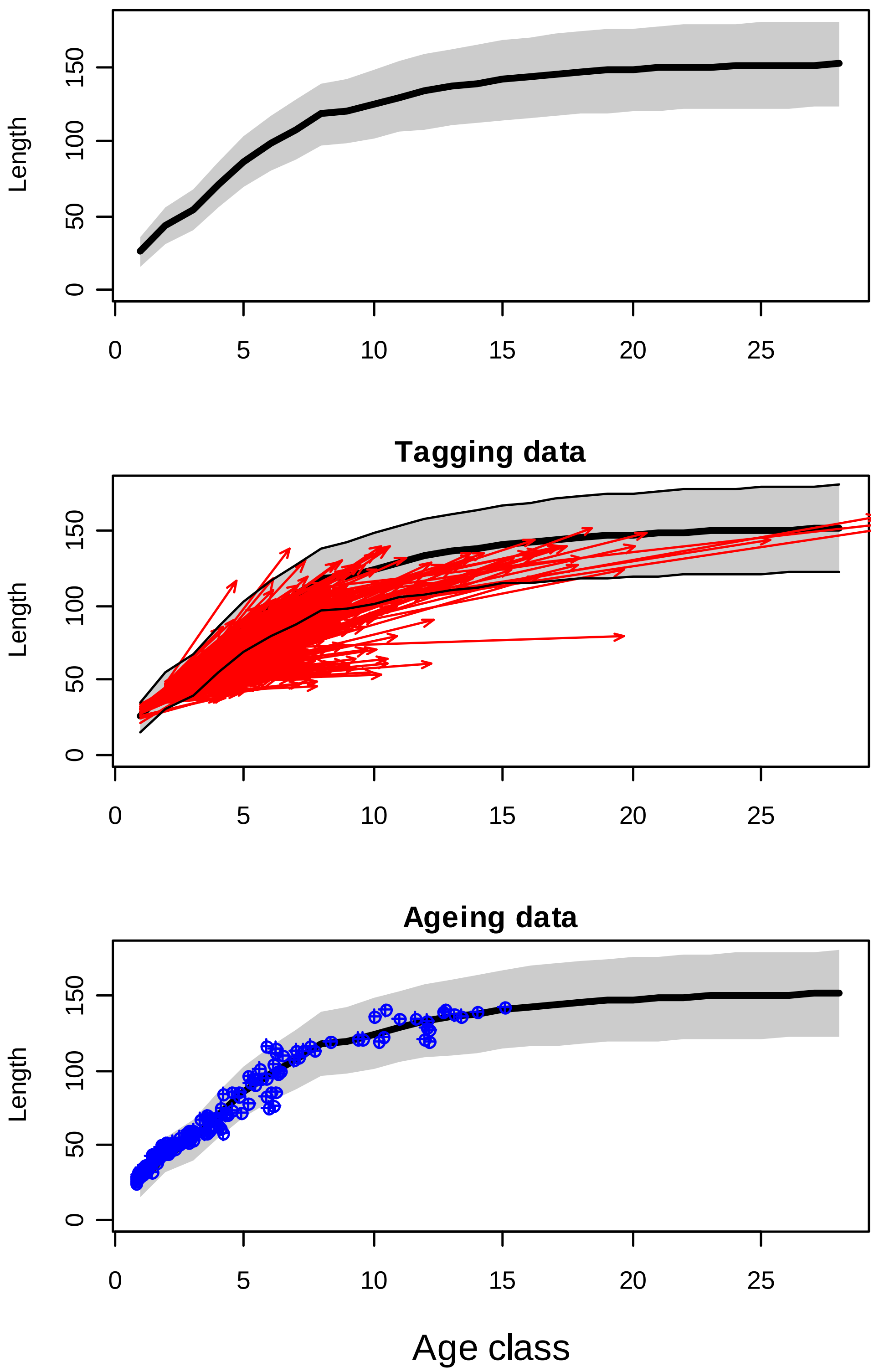

Figure 31. Estimated mean lengths-at-age (heavy line) and the variability of length-at-age (shaded area represents ± 2 SD). Age is in quarters and length is in cm (top figure). For comparison, length at age estimates are presented from tag release and recapture data (middle figure) and empirical age 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.

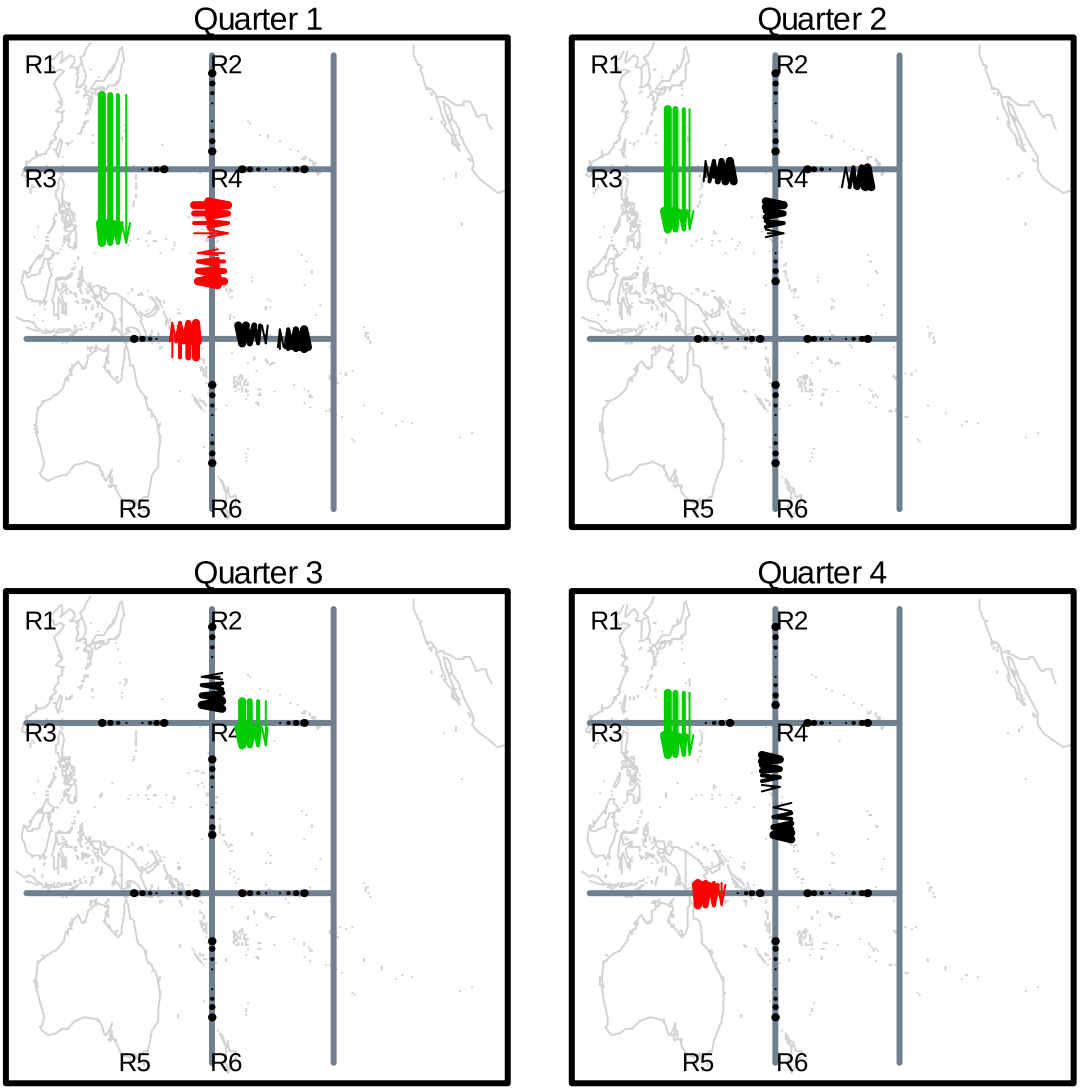

Figure 32. Estimated quarterly movement coefficients at age (1, 7, 15, 25 quarters) from the base-case model. The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age. The maximum movement (quarter 1, region 1 to region 3) represents movement of 35% of the fish at the start of the quarter. Movement rates are colour coded: black, 0.5–5%; red 5–10%; green >10%.

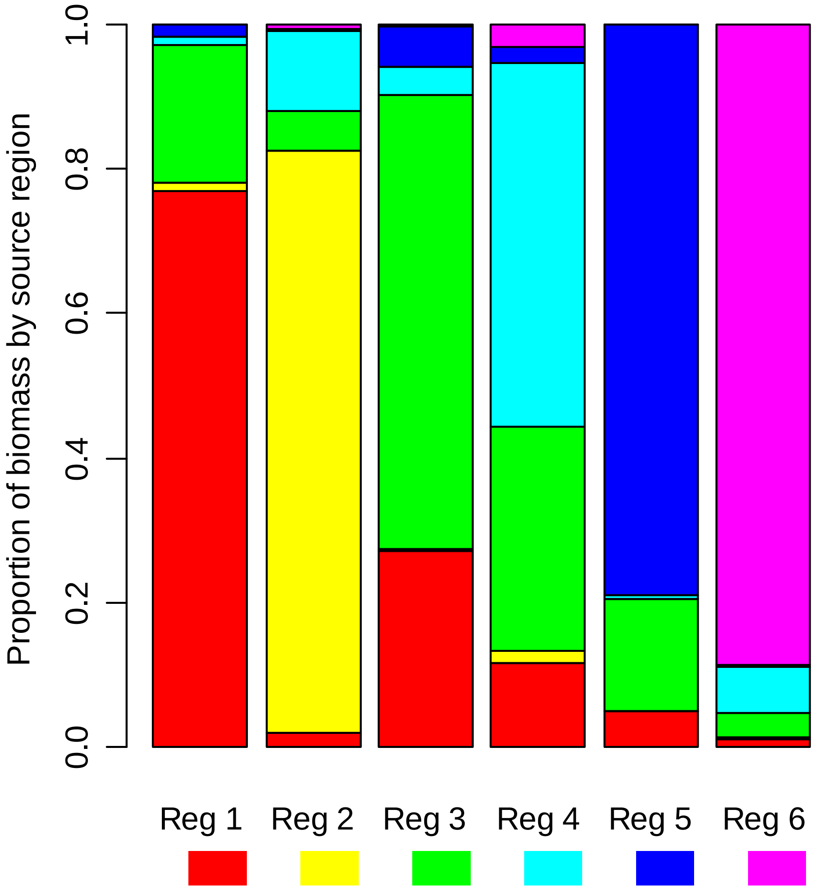

Figure 33. Proportional distribution of total biomass (by weight) in each region (Reg 1–6) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment among regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

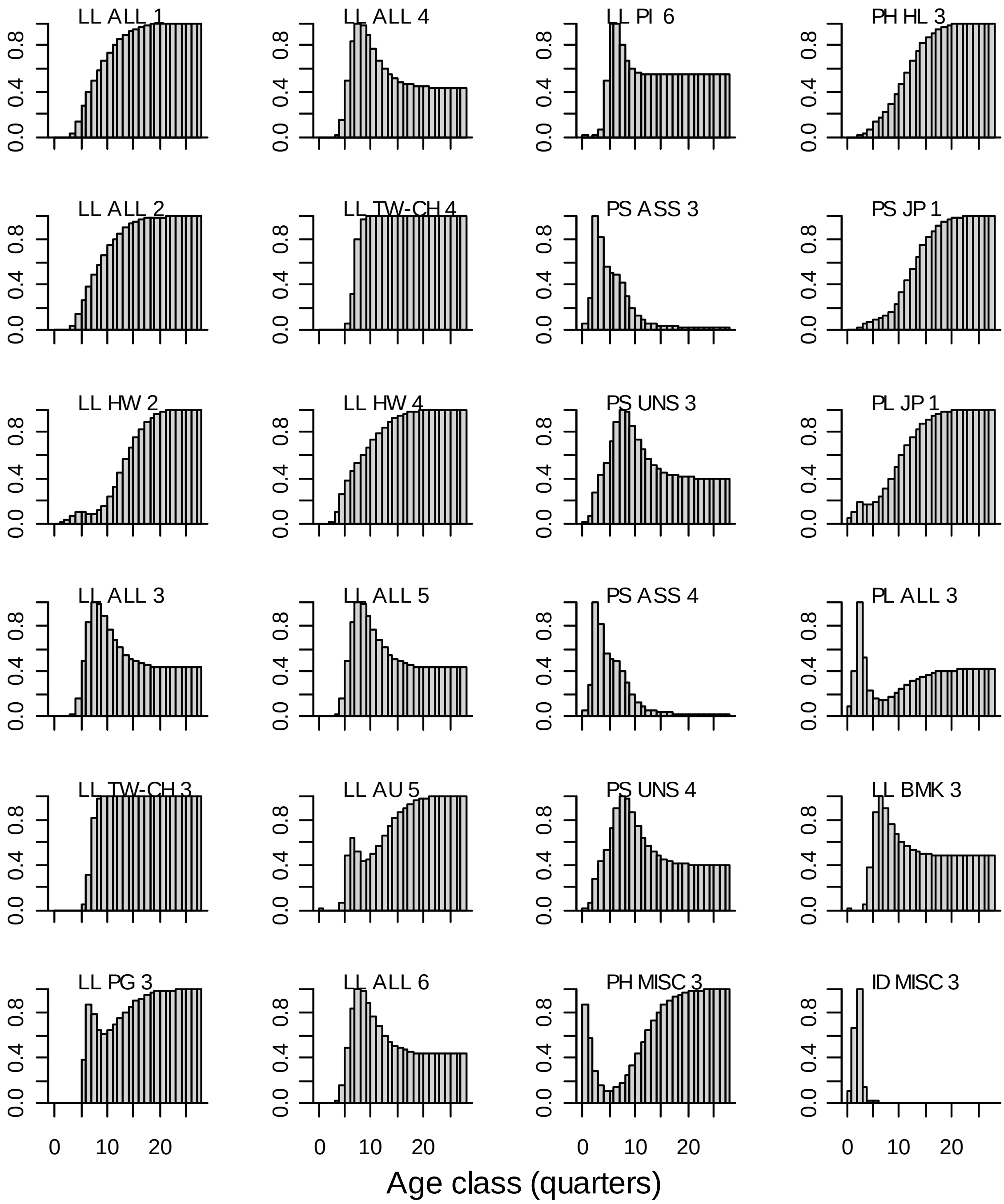

Figure 34. Selectivity coefficients, by fishery.

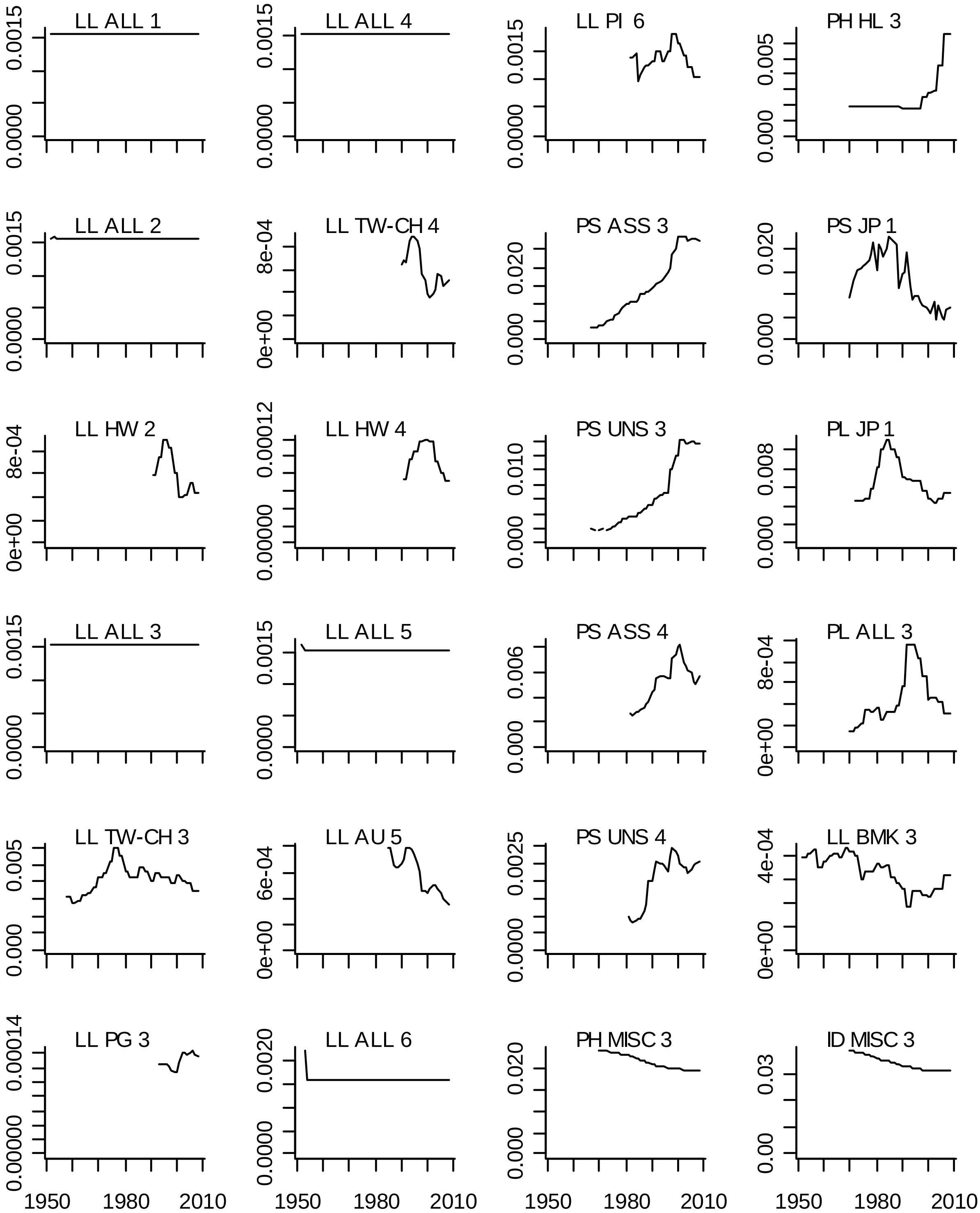

Figure 35. Average annual catchability time series, by fishery.

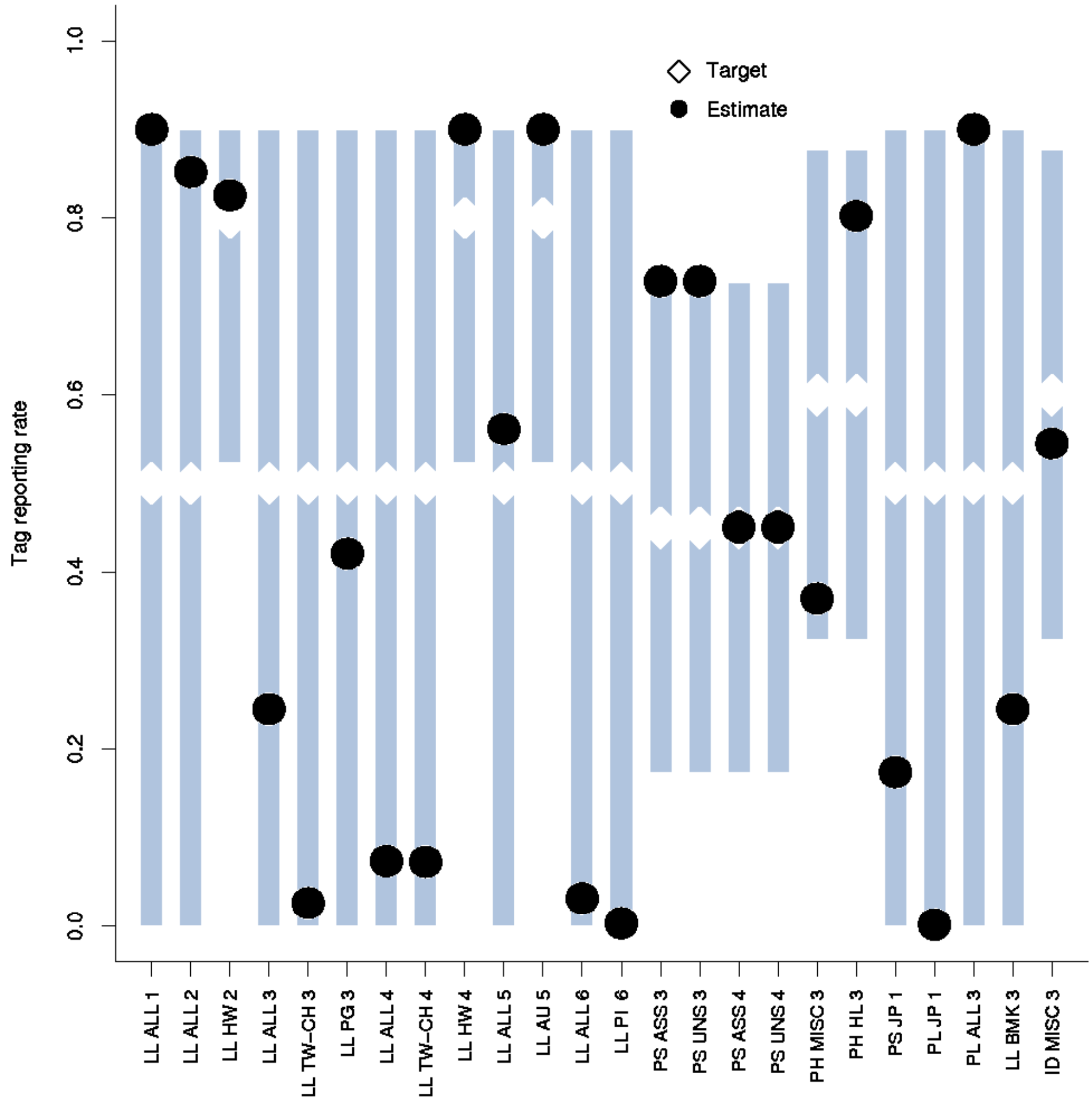

Figure 36. Estimated tag-reporting rates by fishery (black circles). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars indicate a range of ±1 SD.

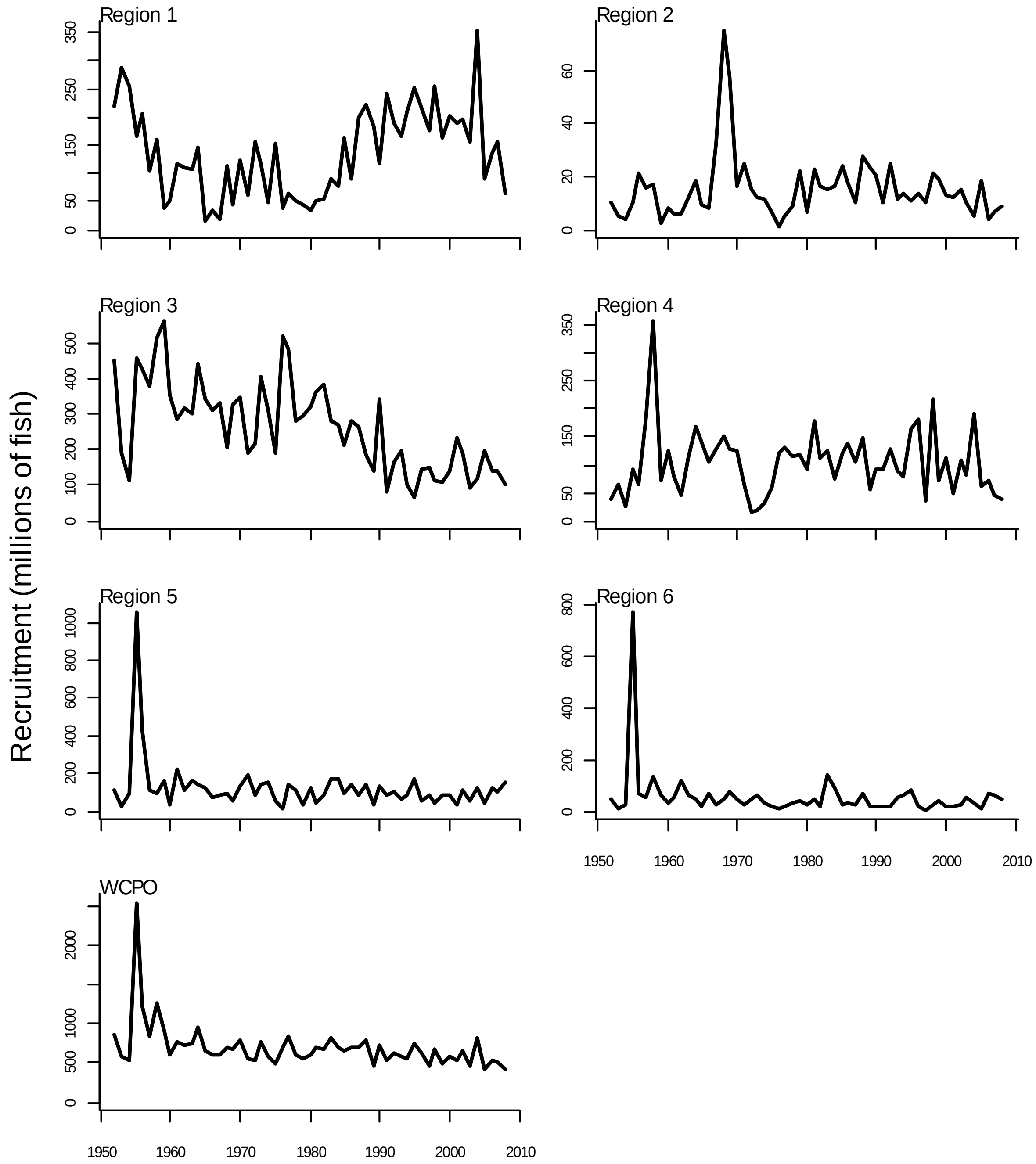

Figure 37. Estimated annual recruitment (millions of fish) by region and for the WCPO.

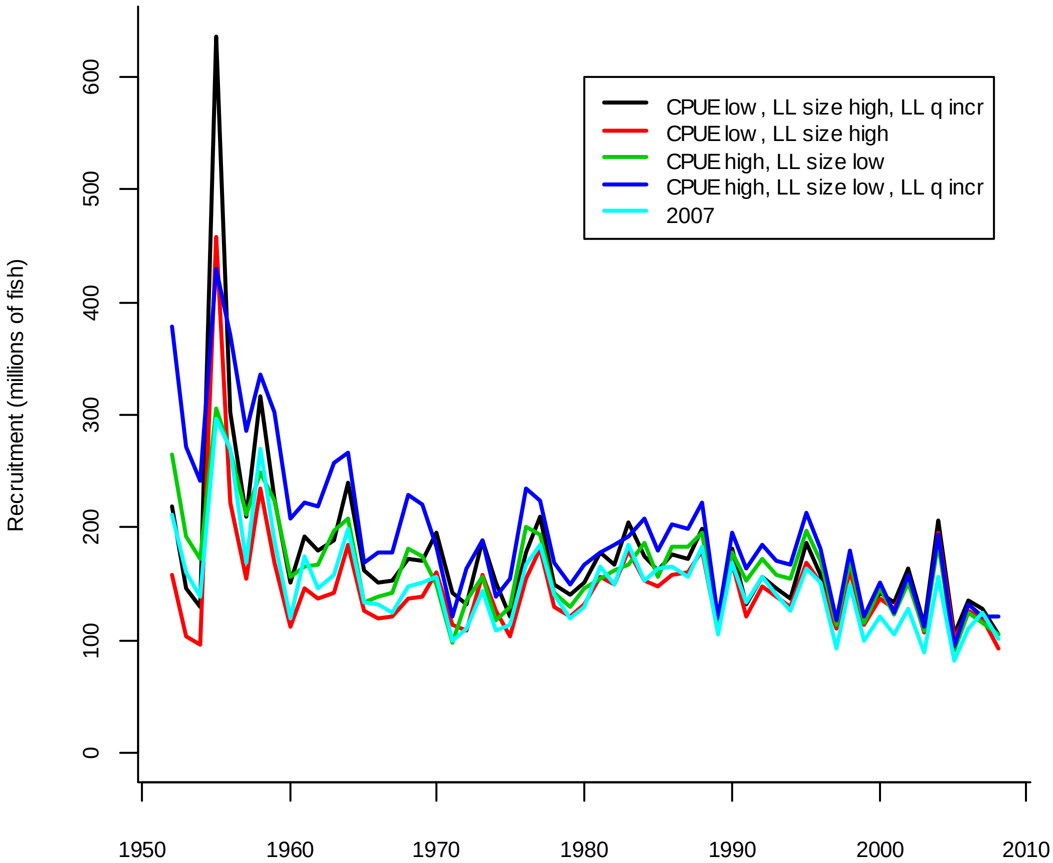

Figure 38a. Estimated annual recruitment (millions of fish) for the WCPO obtained from the different model options.

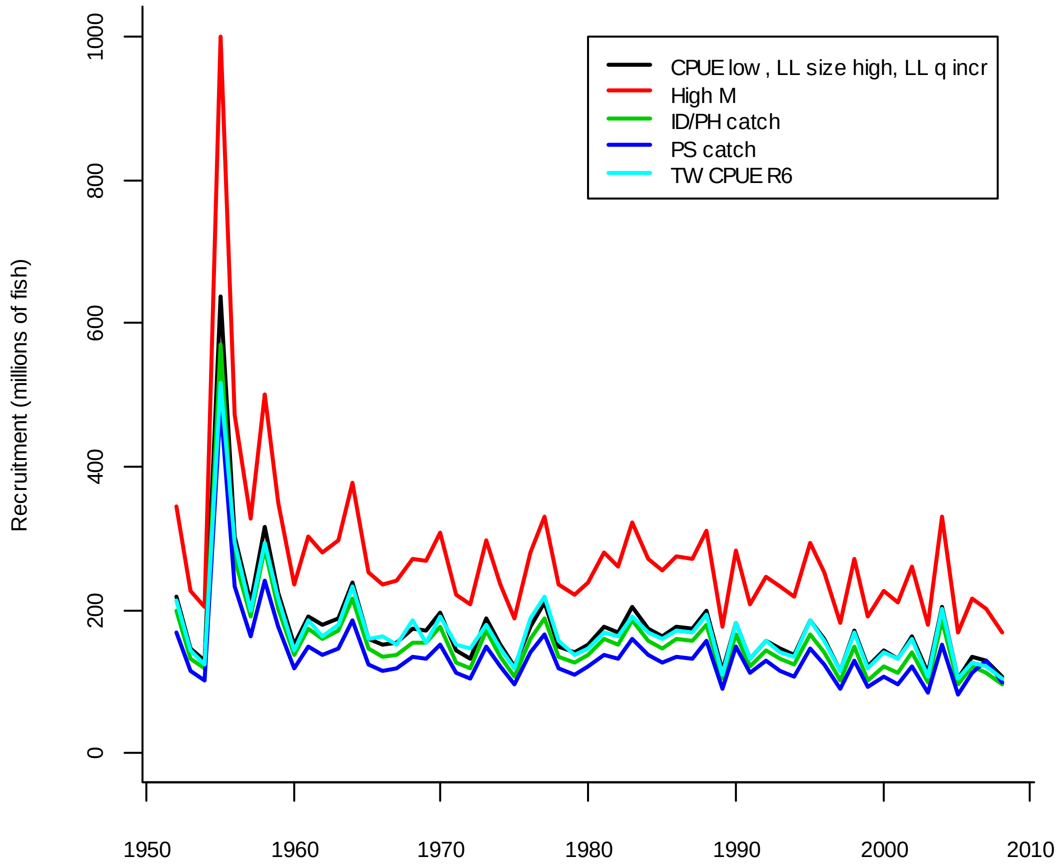

Figure 38b. Estimated annual recruitment (millions of fish) for the WCPO obtained from the different model options.

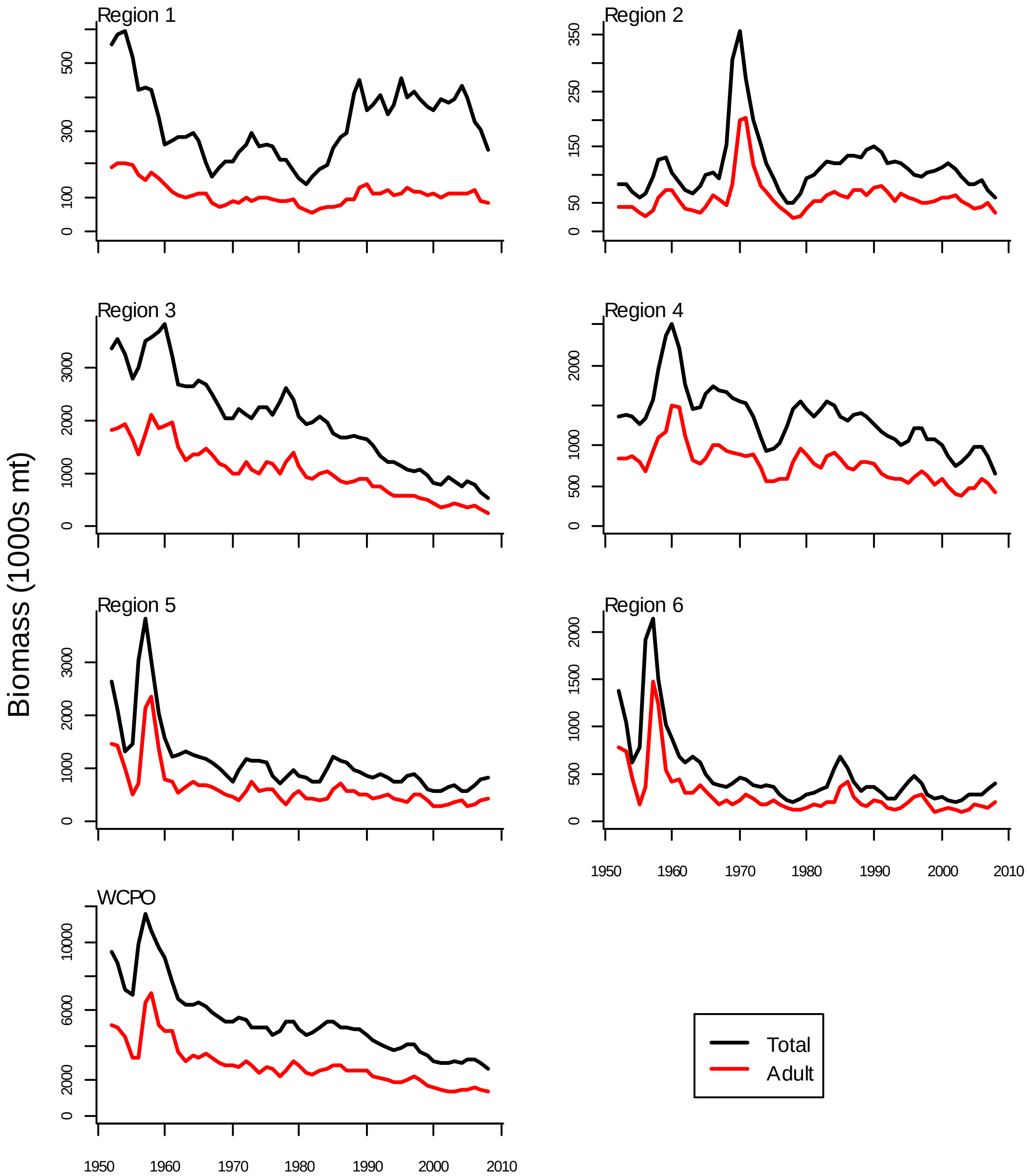

Figure 39. Estimated annual average total biomass and adult biomass (thousand mt) by region and for the WCPO for the base-case analysis.

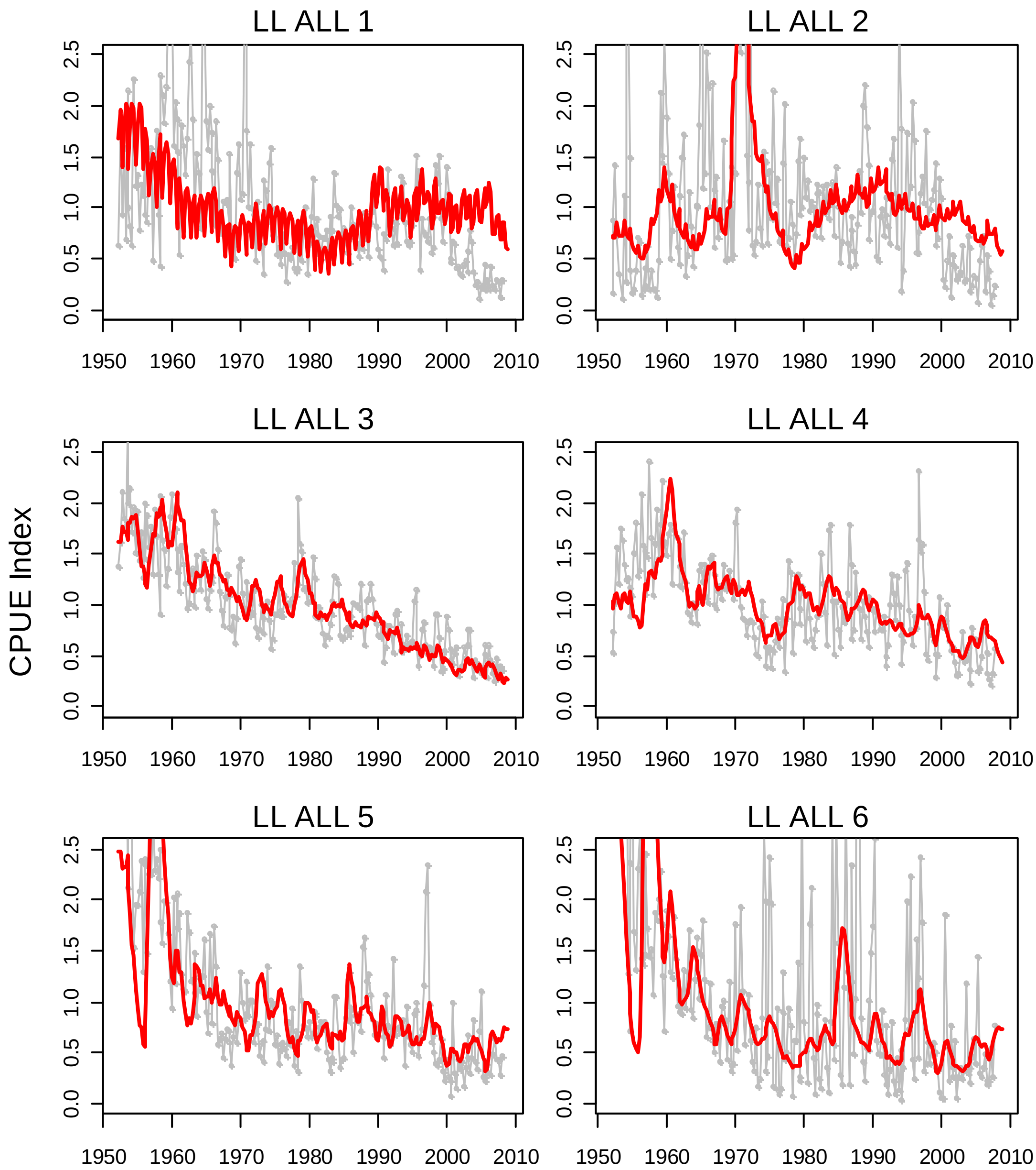

Figure 40. A comparison of longline exploitable biomass by quarter and region (red line) and the quarterly standardised CPUE indices for the fisheries. For comparison, both series are scaled to the average of the series.

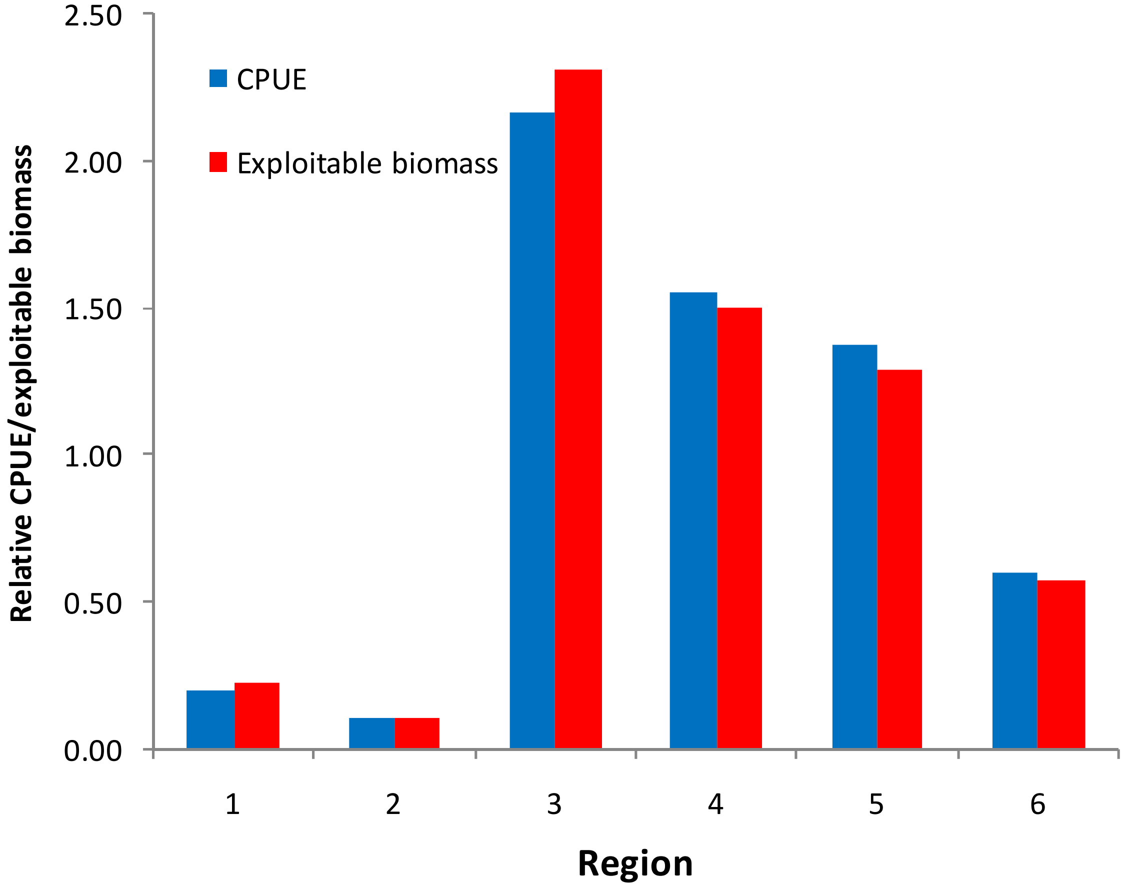

Figure 41. CPUE and exploitable abundance for LL ALL 1–6 averaged over all time periods. Values for each region are scaled relative to their averages across all regions.

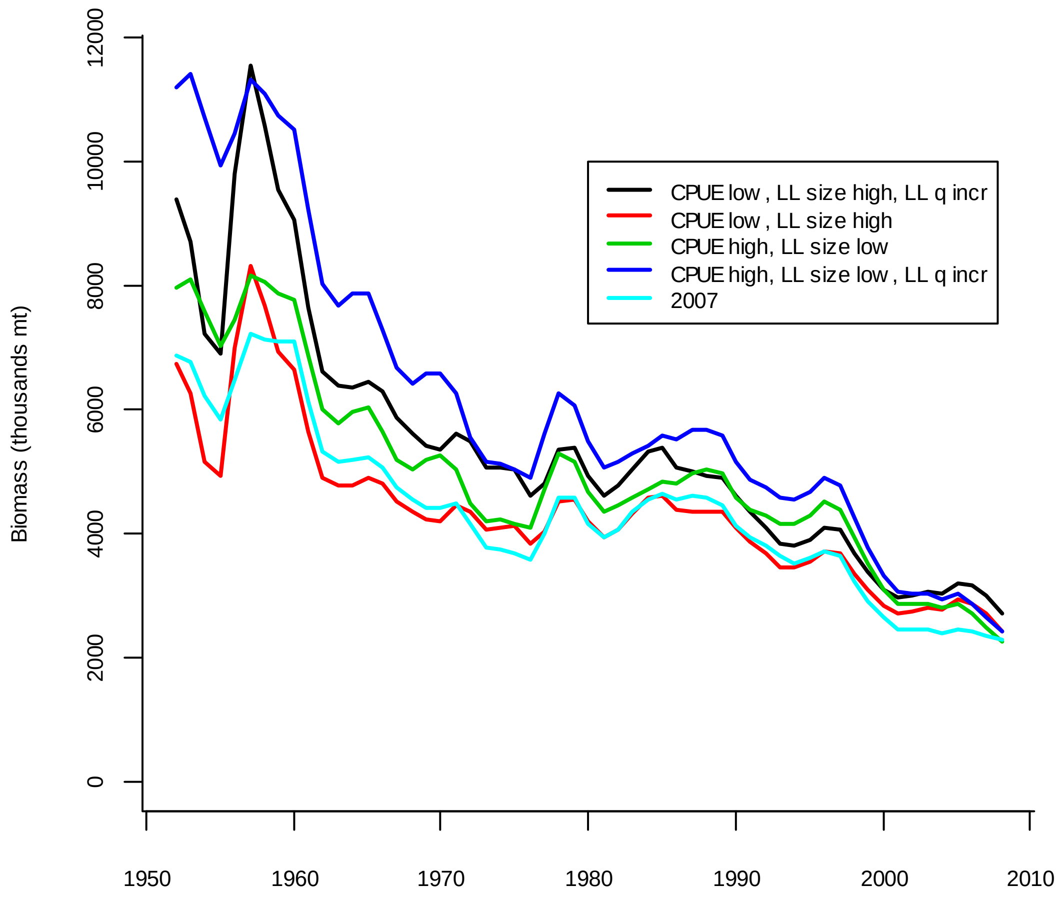

Figure 42a. Estimated annual average total biomass (thousands mt) for the WCPO obtained from a range of different model options.

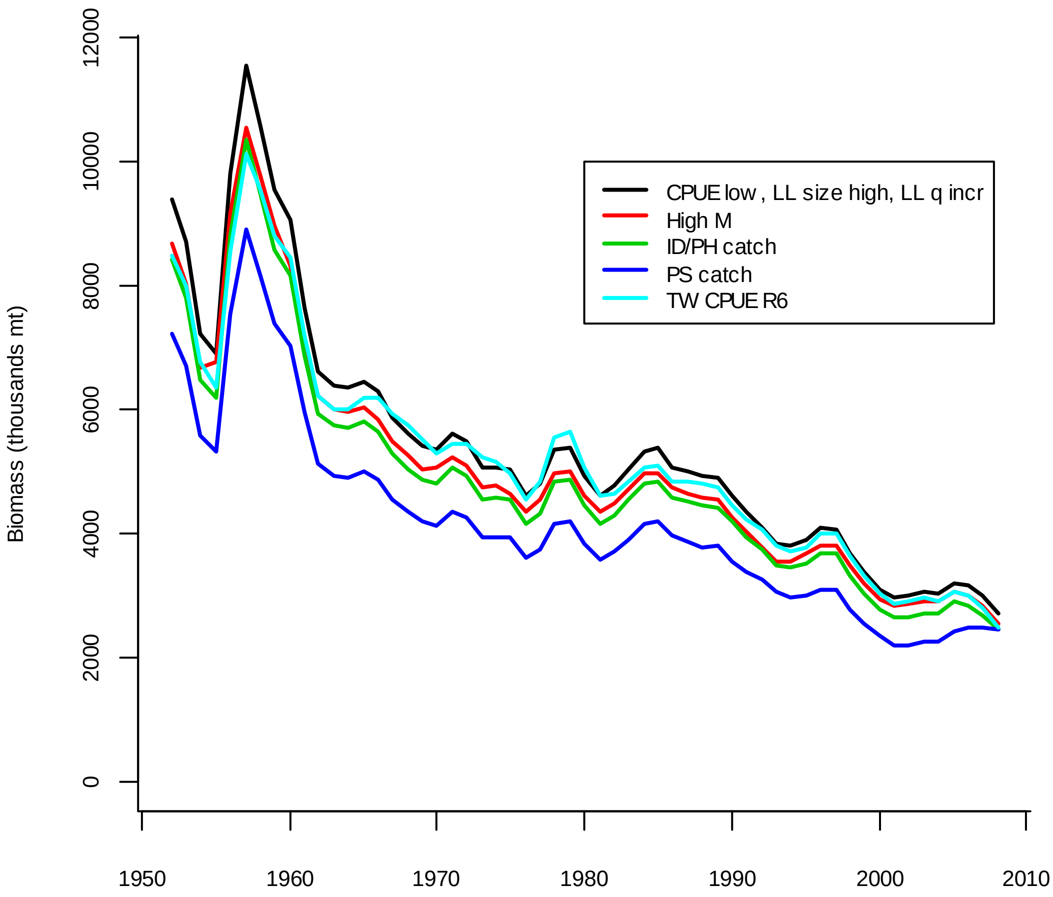

Figure 42b. Estimated annual average total biomass (thousands mt) for the WCPO obtained from a range of different model options.

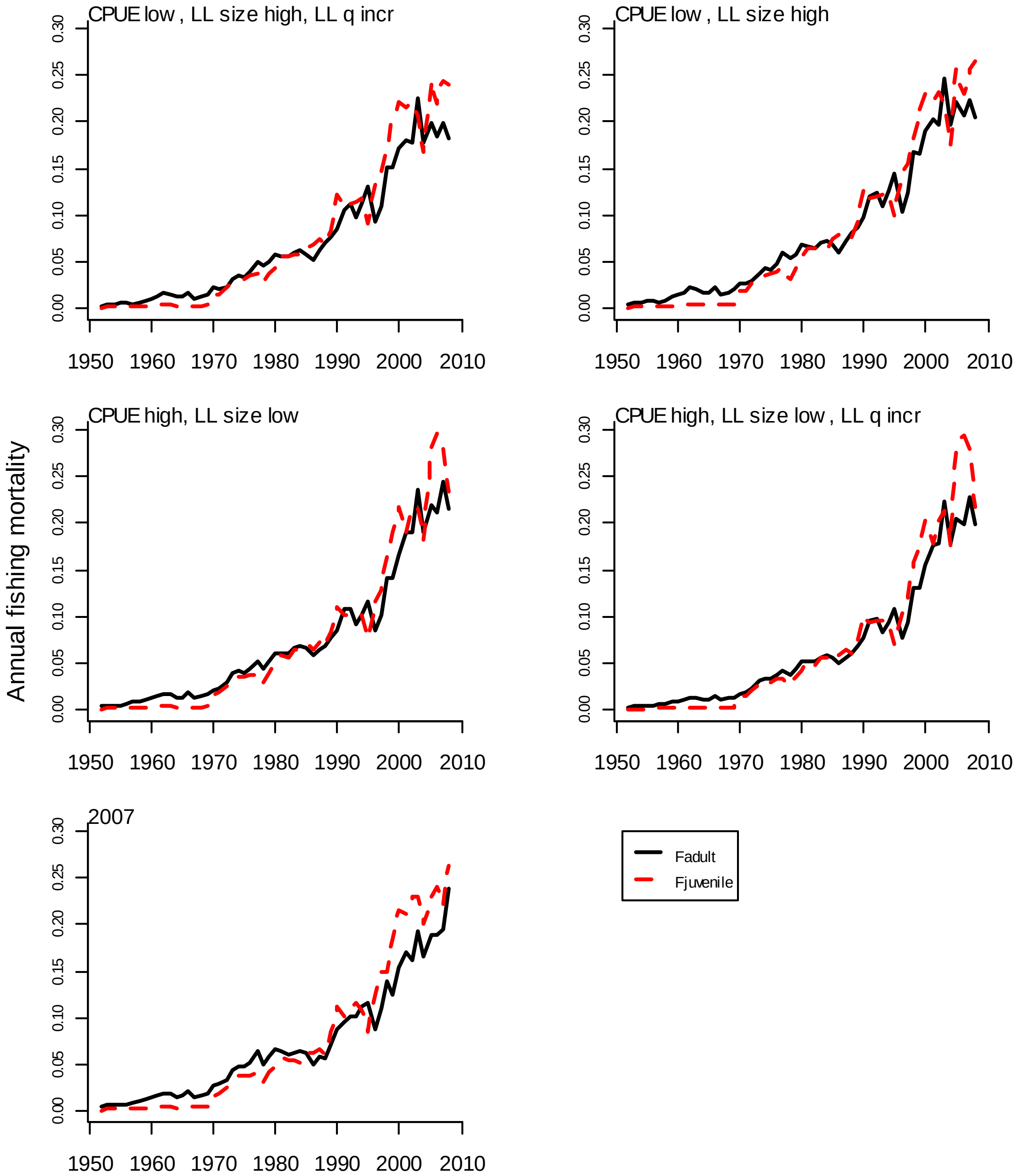

Figure 43. Estimated annual average juvenile and adult fishing mortality for the WCPO obtained from the four principal model options and the "Base 2007" model.

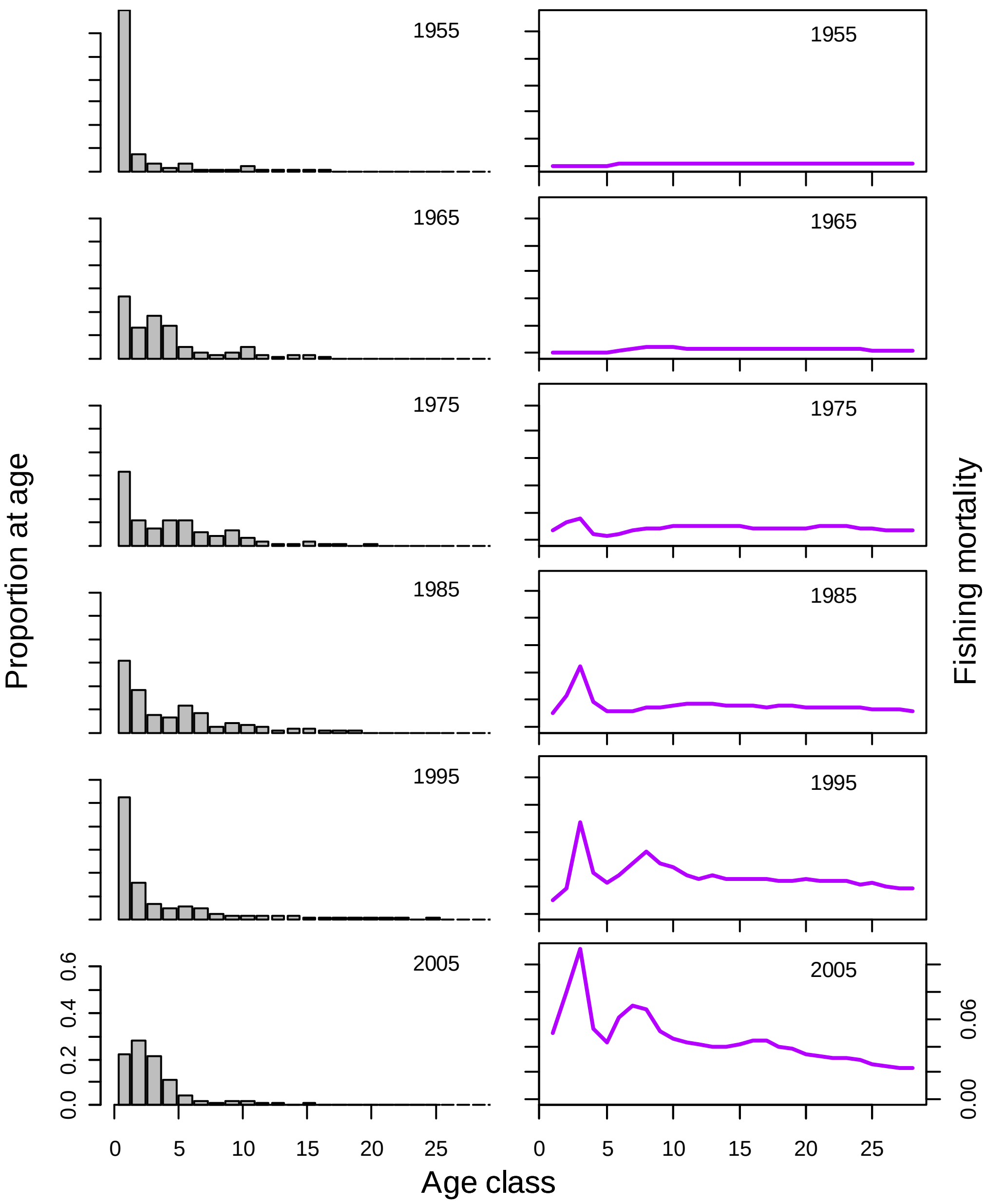

Figure 44. Estimated proportion at age (quarters) for the WCPO yellowfin population (left) and fishing mortality at age (right) by year at decade intervals.

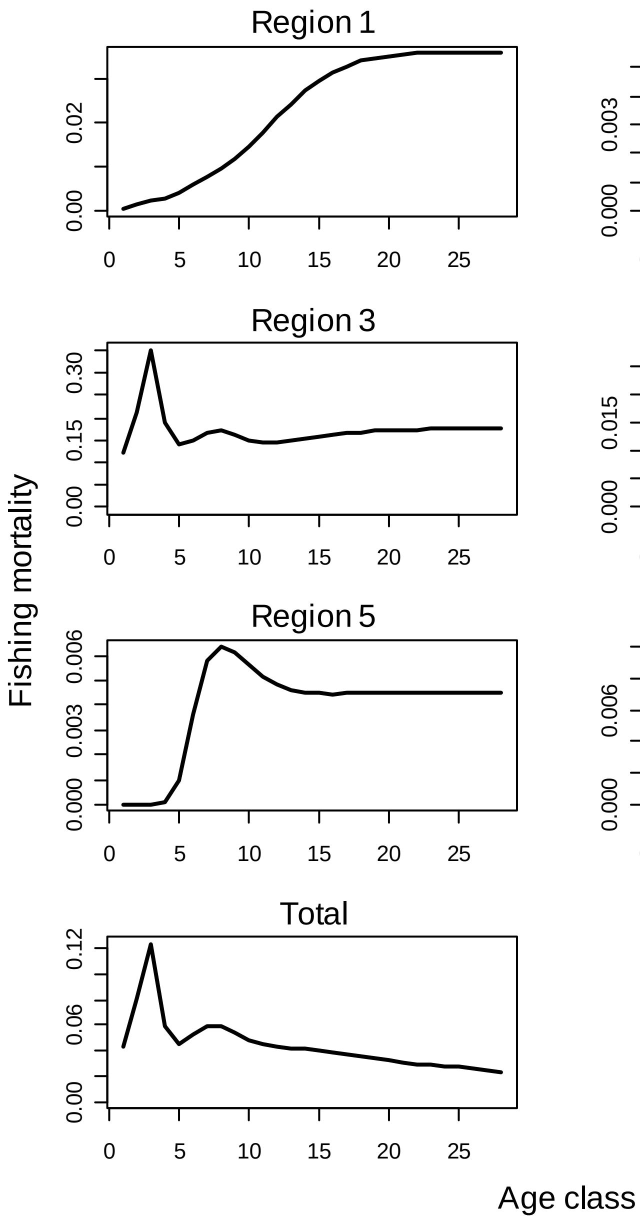

Figure 45. Fishing mortality by age class and region for the period used to determine the total F-at-age included in the calculation of MSY based reference points (2004–07). Note that the y-axis varies between plots.

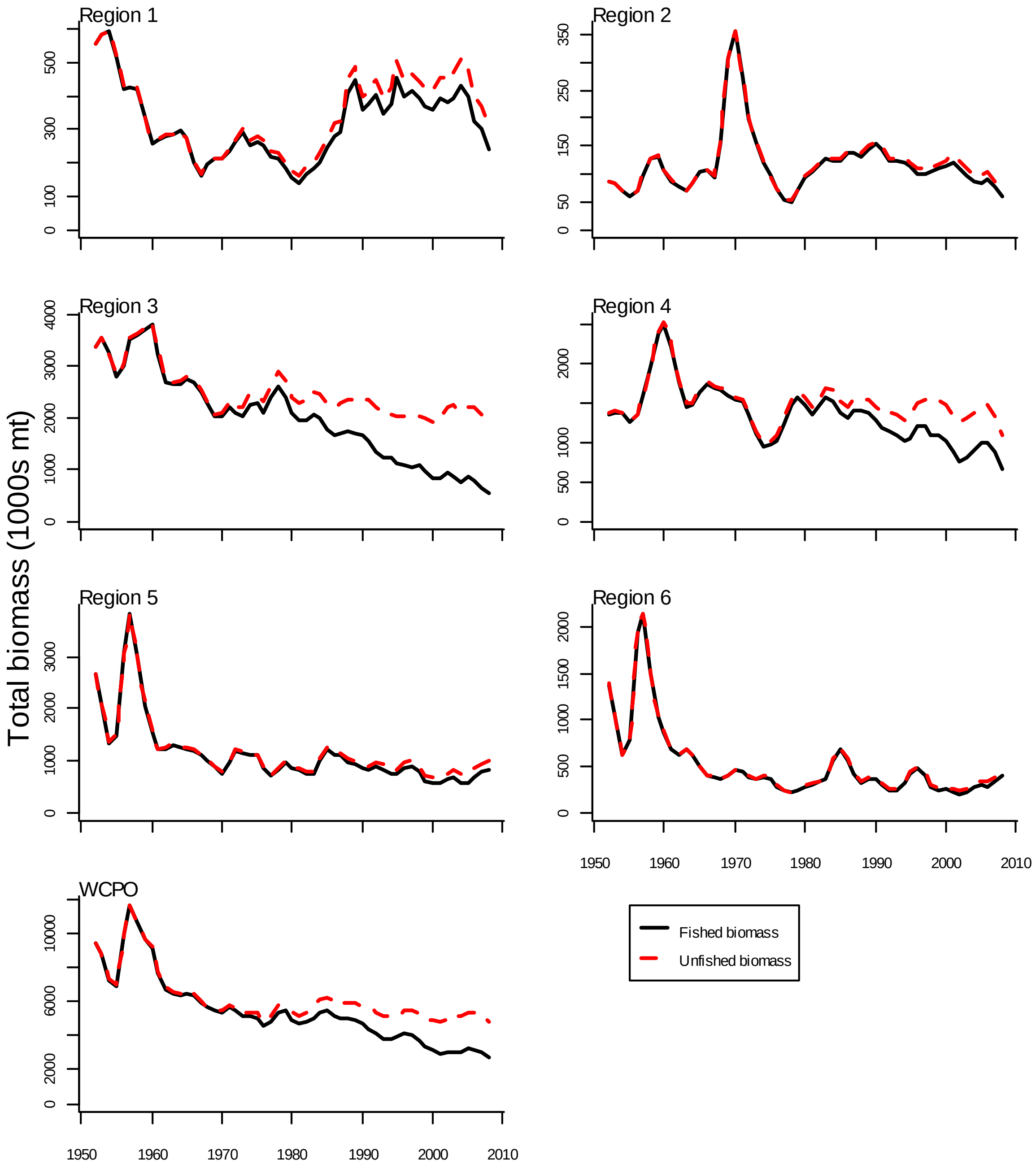

Figure 46. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper dashed lines) for the base-case model for each region and for the WCPO.

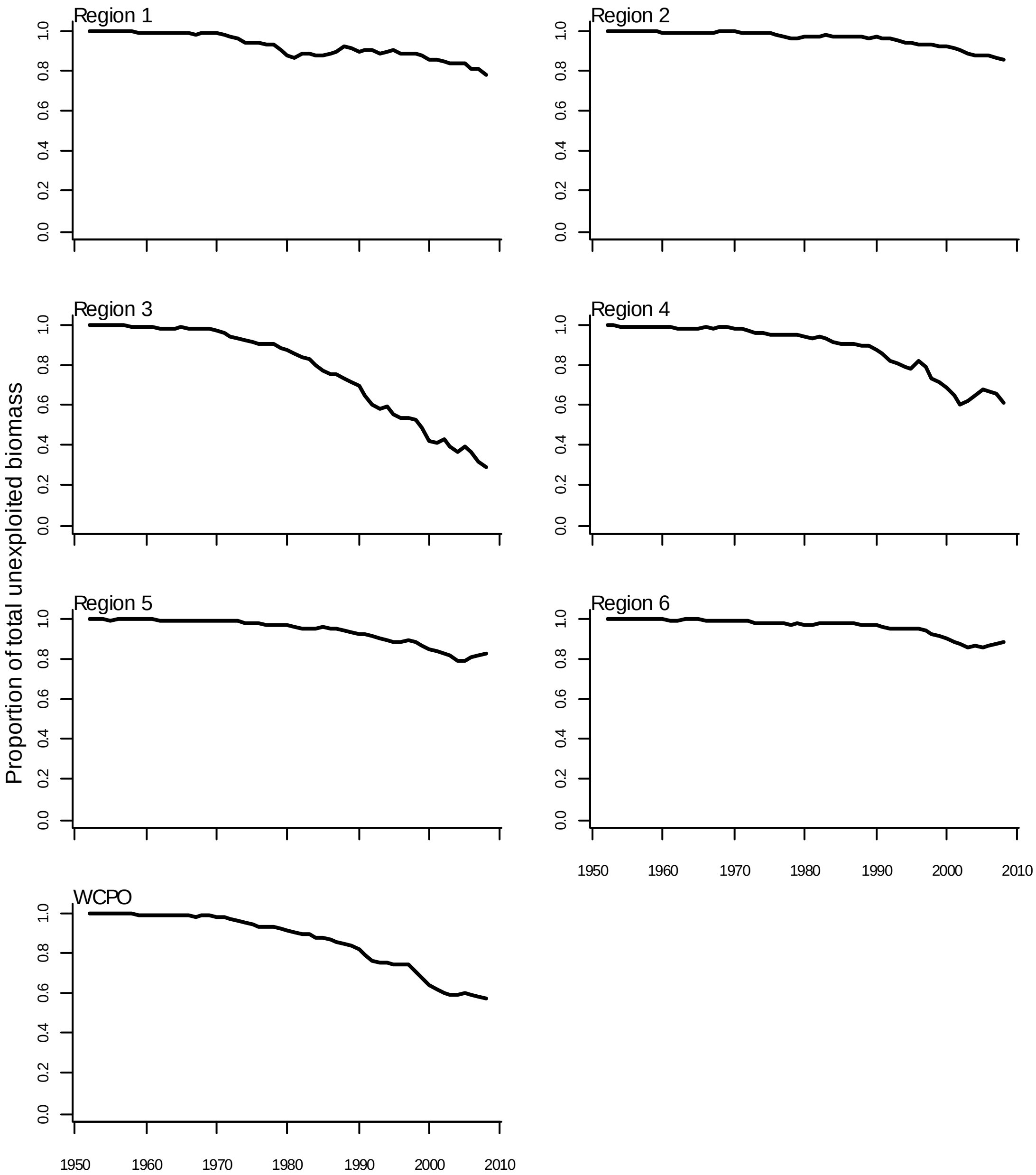

Figure 47. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the WCPO.

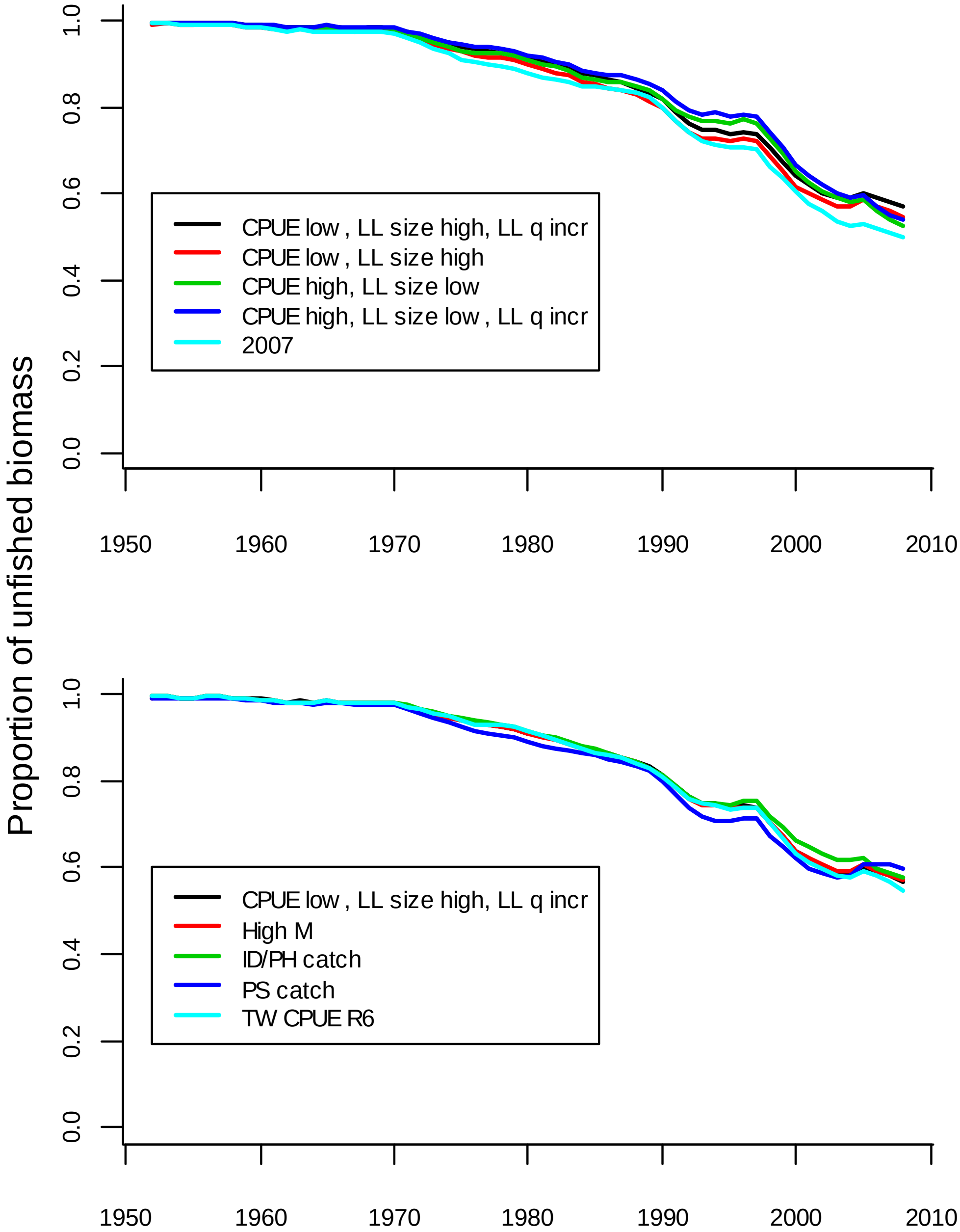

Figure 48. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for the WCPO obtained from the separate analyses.

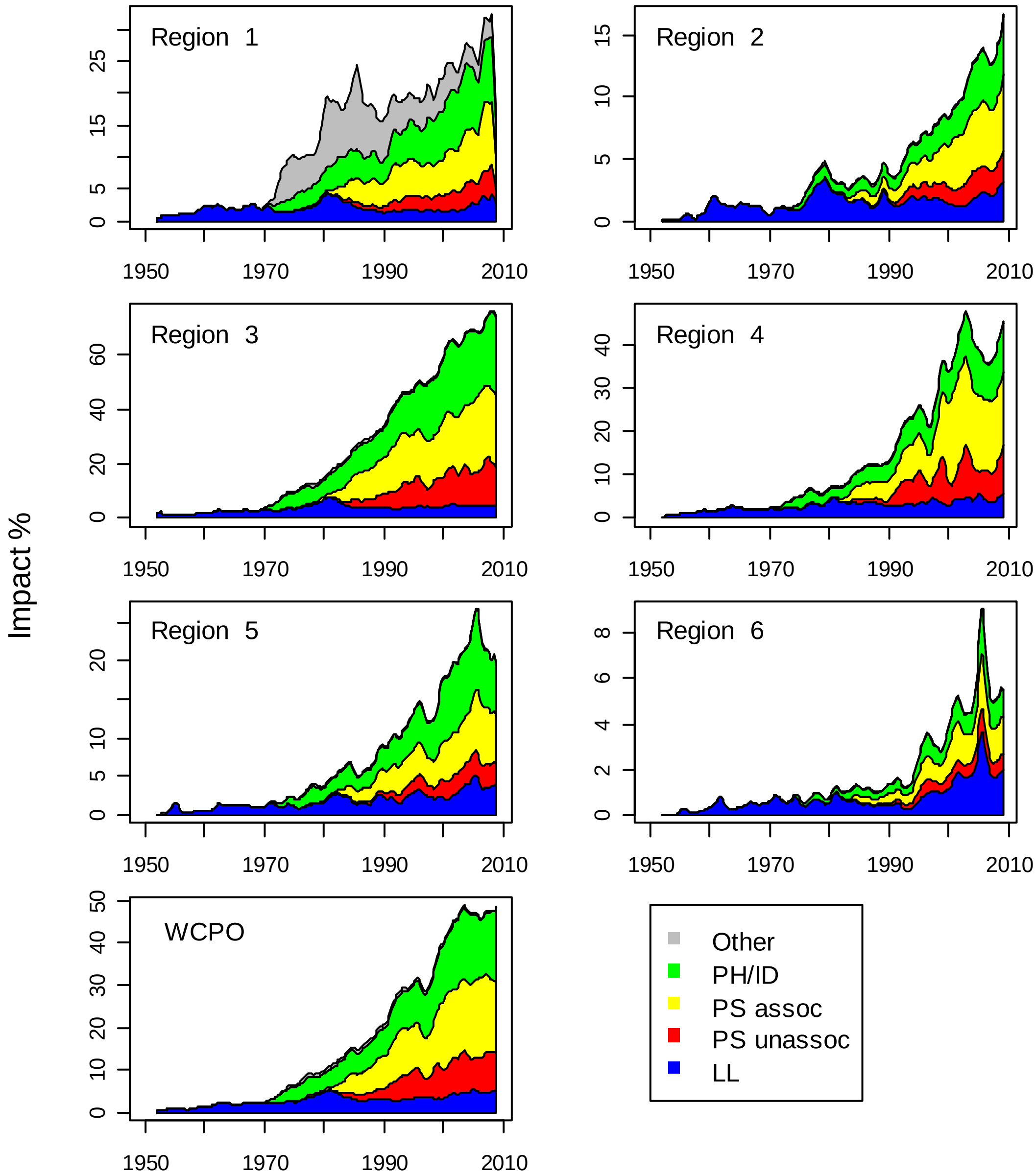

Figure 49. Estimates of reduction in spawning biomass due to fishing (fishery impact = 1-$SB_t/SB_{0,t}$) by region and for the WCPO attributed to various fishery groups. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine FAD and log sets; PS unassoc = purse seine school sets; Other = JP coastal PL & PL and equatorial PL.

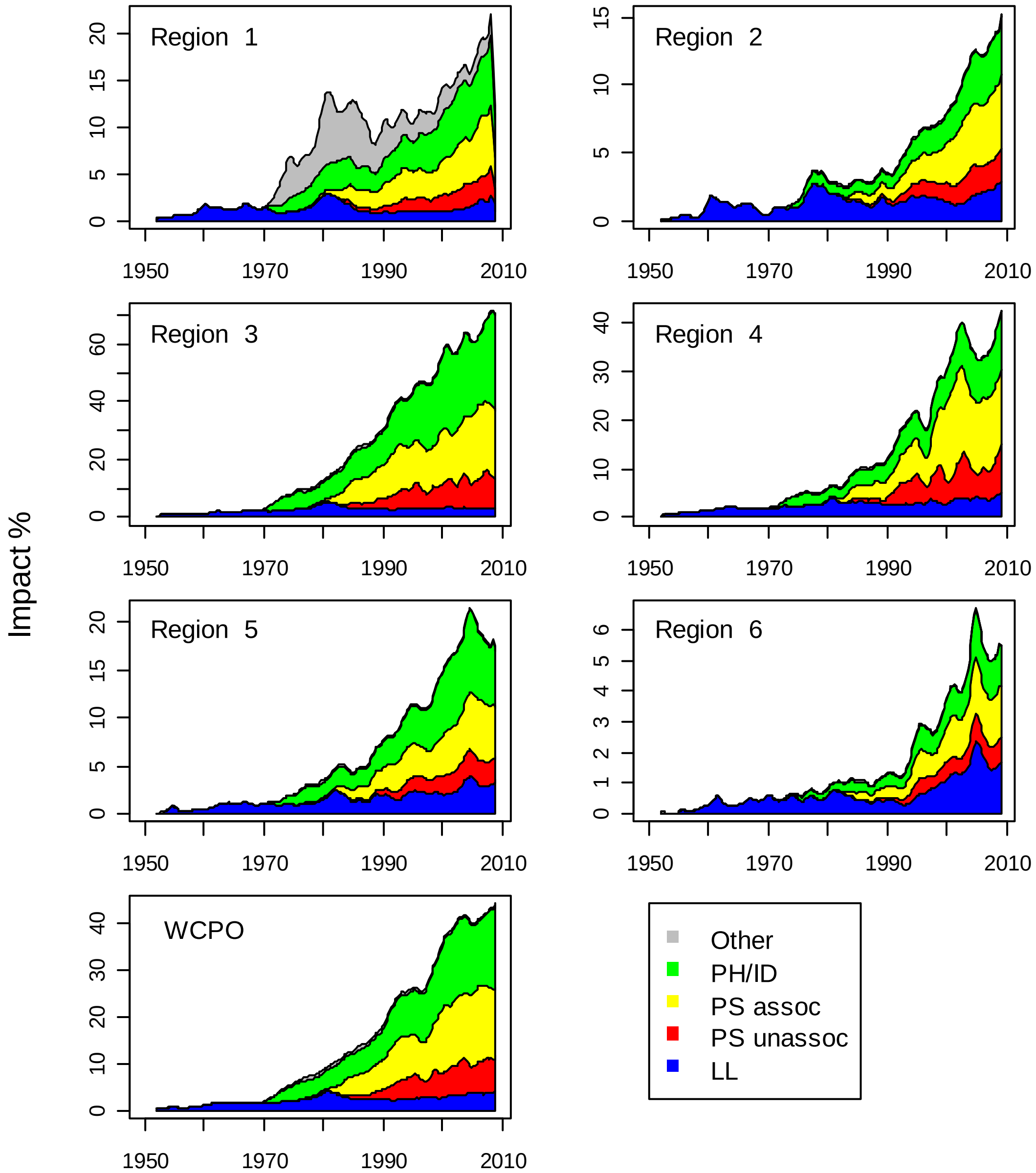

Figure 50. Estimates of reduction in total biomass due to fishing (fishery impact = 1-$B_t/B_{0,t}$) by region and for the WCPO attributed to various fishery groups. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine FAD and log sets; PS unassoc = purse seine school sets; Other = JP coastal PL & PL and equatorial PL.

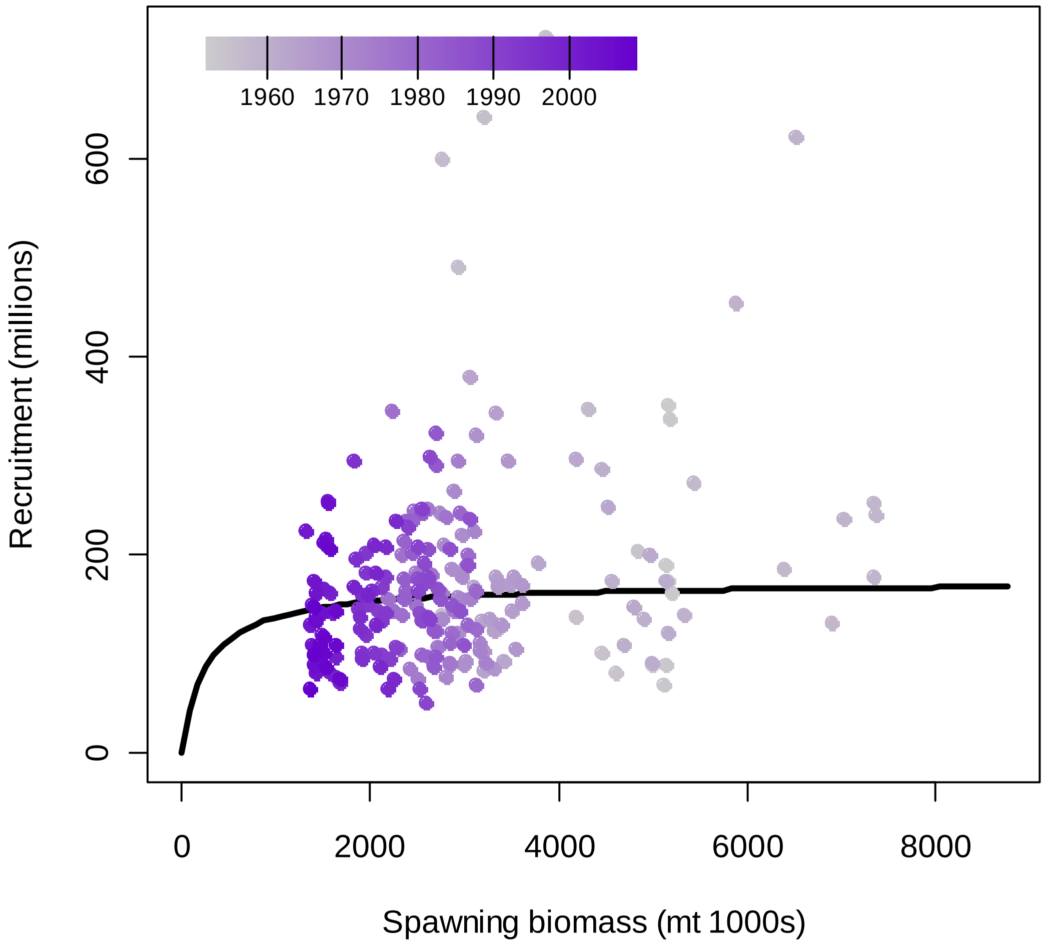

Figure 51. Estimated relationship between equilibrium recruitment and equilibrium spawning biomass. The points represent the estimated recruitment-spawning biomass and the colour of the points denotes the time period from which the estimate was obtained (see legend).

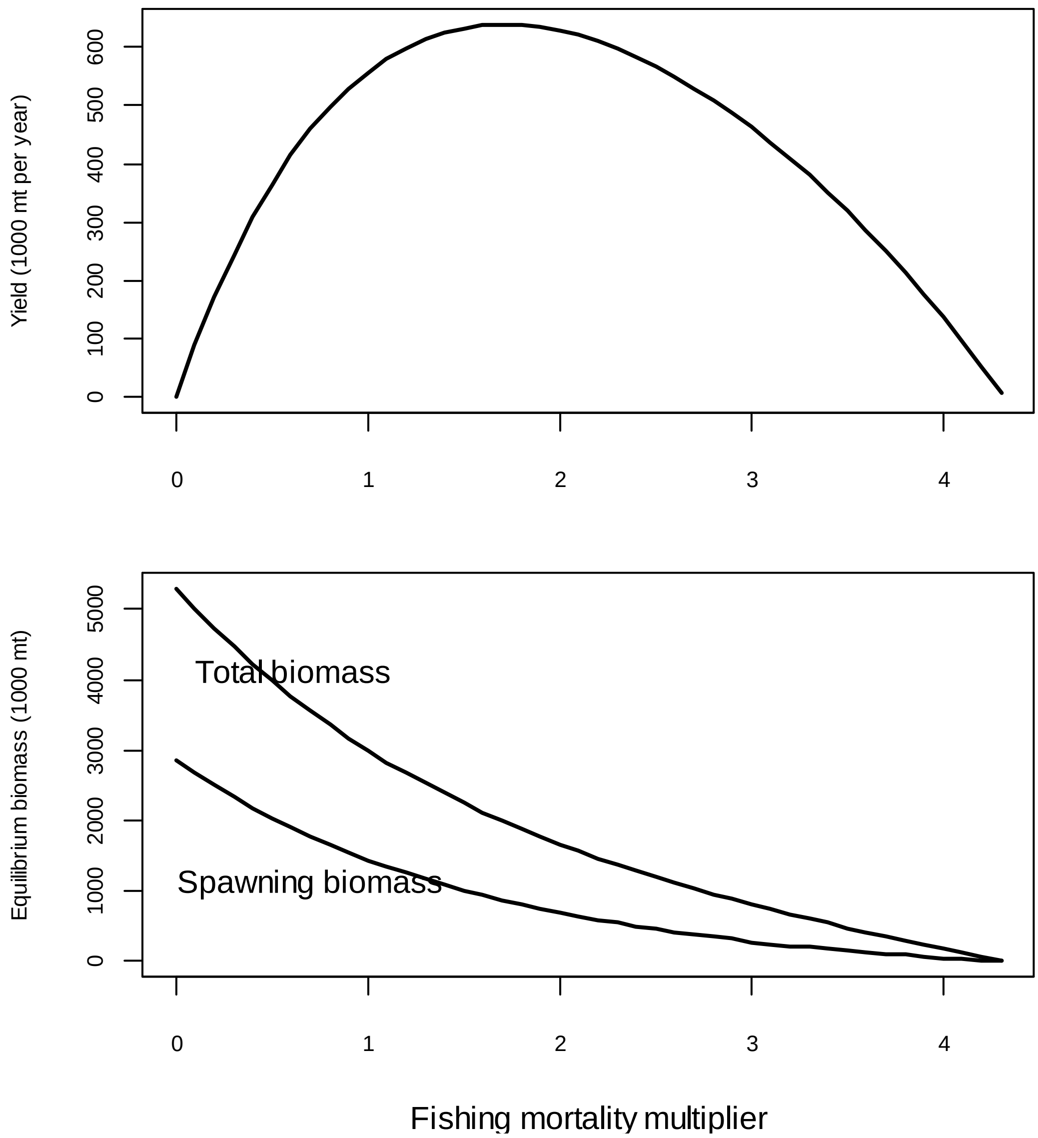

Figure 52. Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier for the base case model "CPUE low, LL sample high, LL q incr".

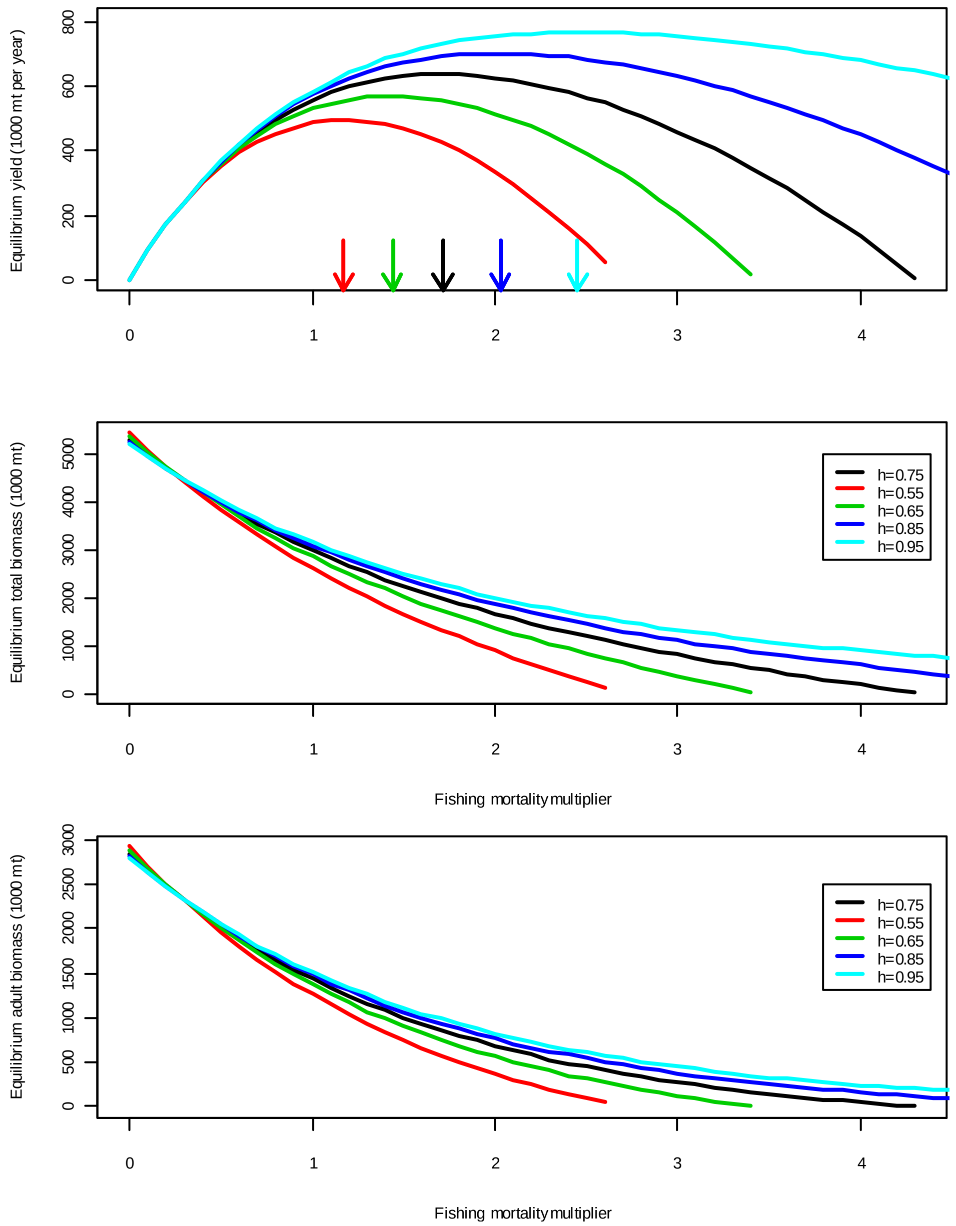

Figure 53. Yield (top), equilibrium total biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier for different assumed levels of the base case model “CPUE low, LL sample high, LL q incr”. In the top panel, the arrows indicate the value of the fishing mortality multiplier at maximum yield.

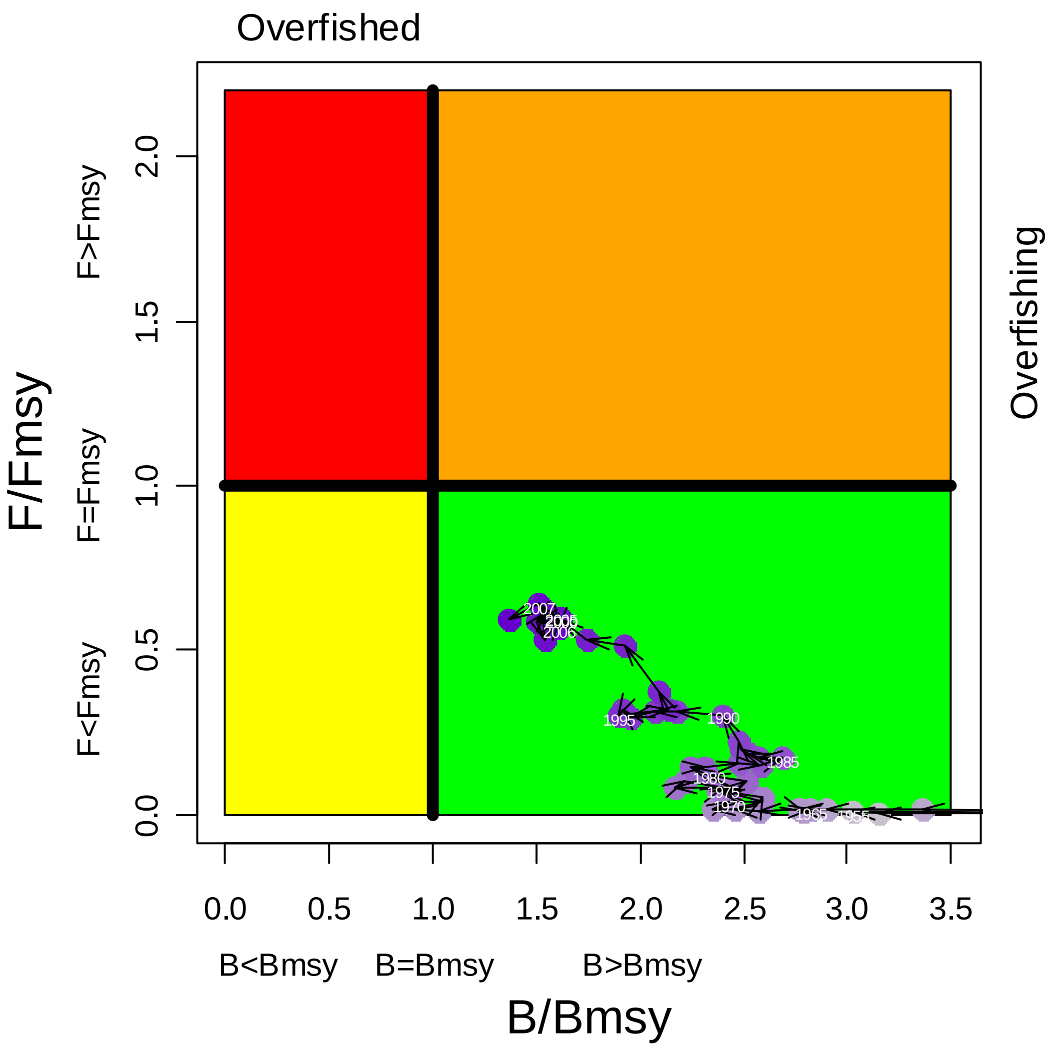

Figure 54. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1952–2008). The colour of the points is graduated from mauve (1952) to dark purple (2008) and the points are labelled at 5-year intervals.

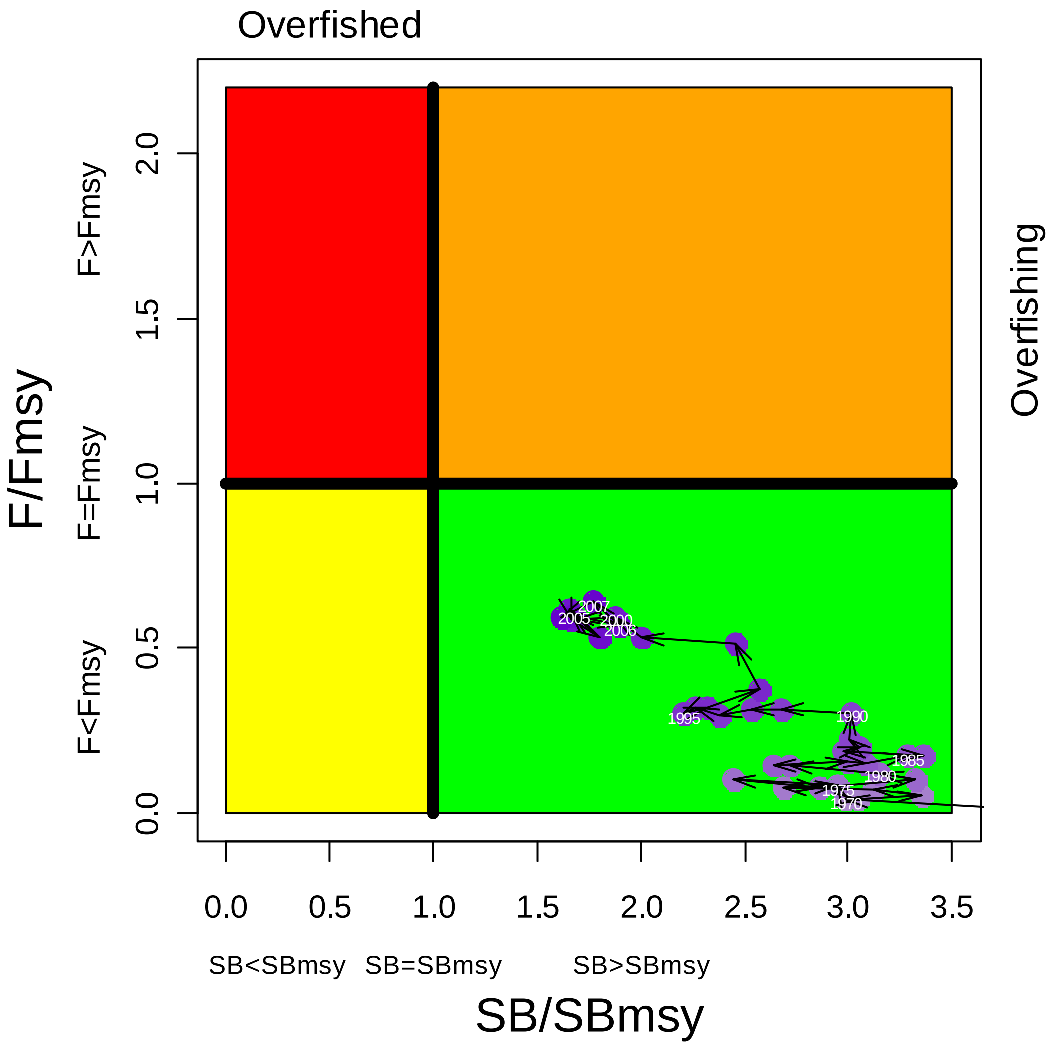

Figure 55. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1952–2008). The colour of the points is graduated from mauve (1952) to dark purple (2008) and the points are labelled at 5-year intervals.

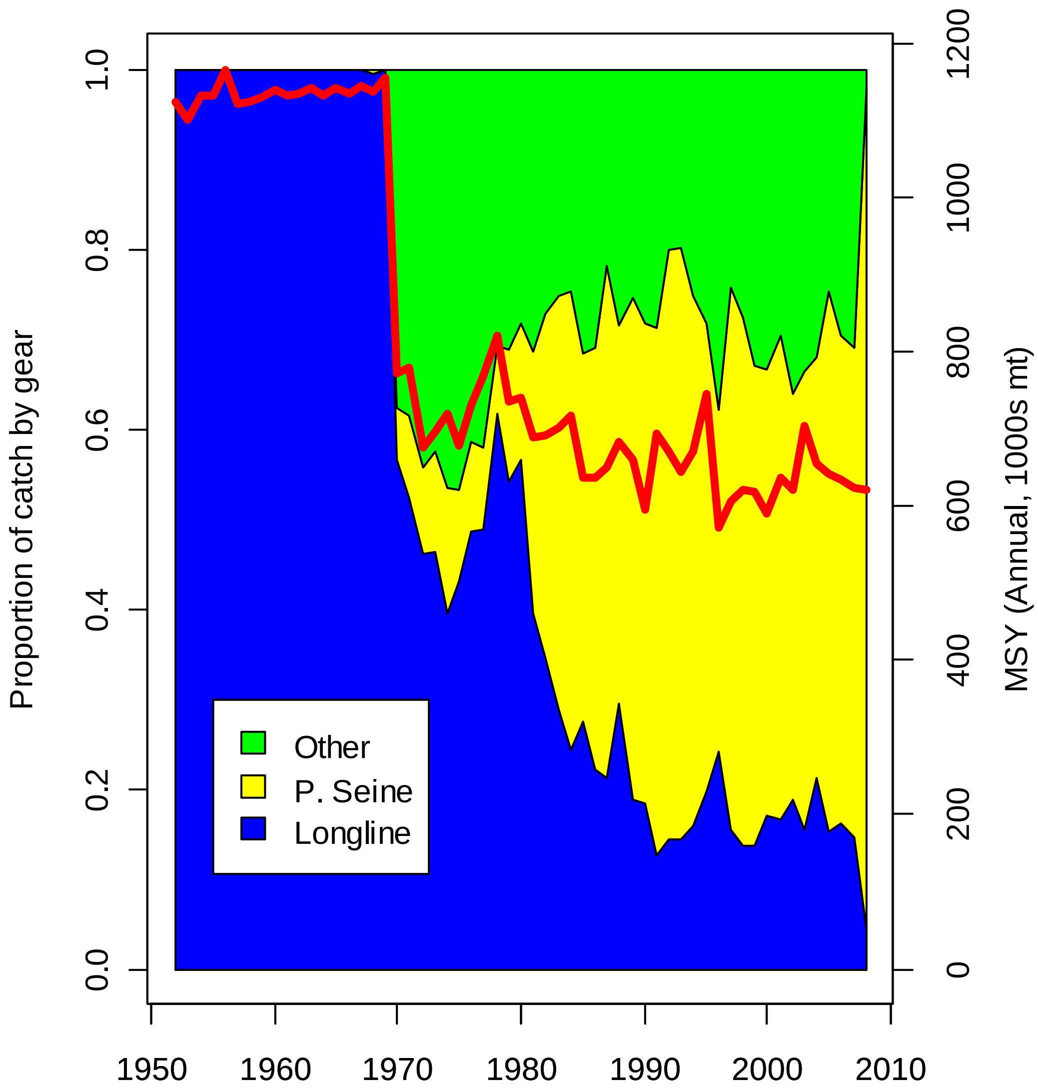

Figure 56. Temporal trend in annual Maximum Sustainable Yield (MSY) (red line) estimated for each year included in the yellowfin stock assessment model. This is compared to the proportional distribution in the annual yellowfin catch by main gear type for the entire WCPO. The “other” fishery is principally the Indonesia and Philippines domestic fisheries combined (PH MISC and ID MISC).

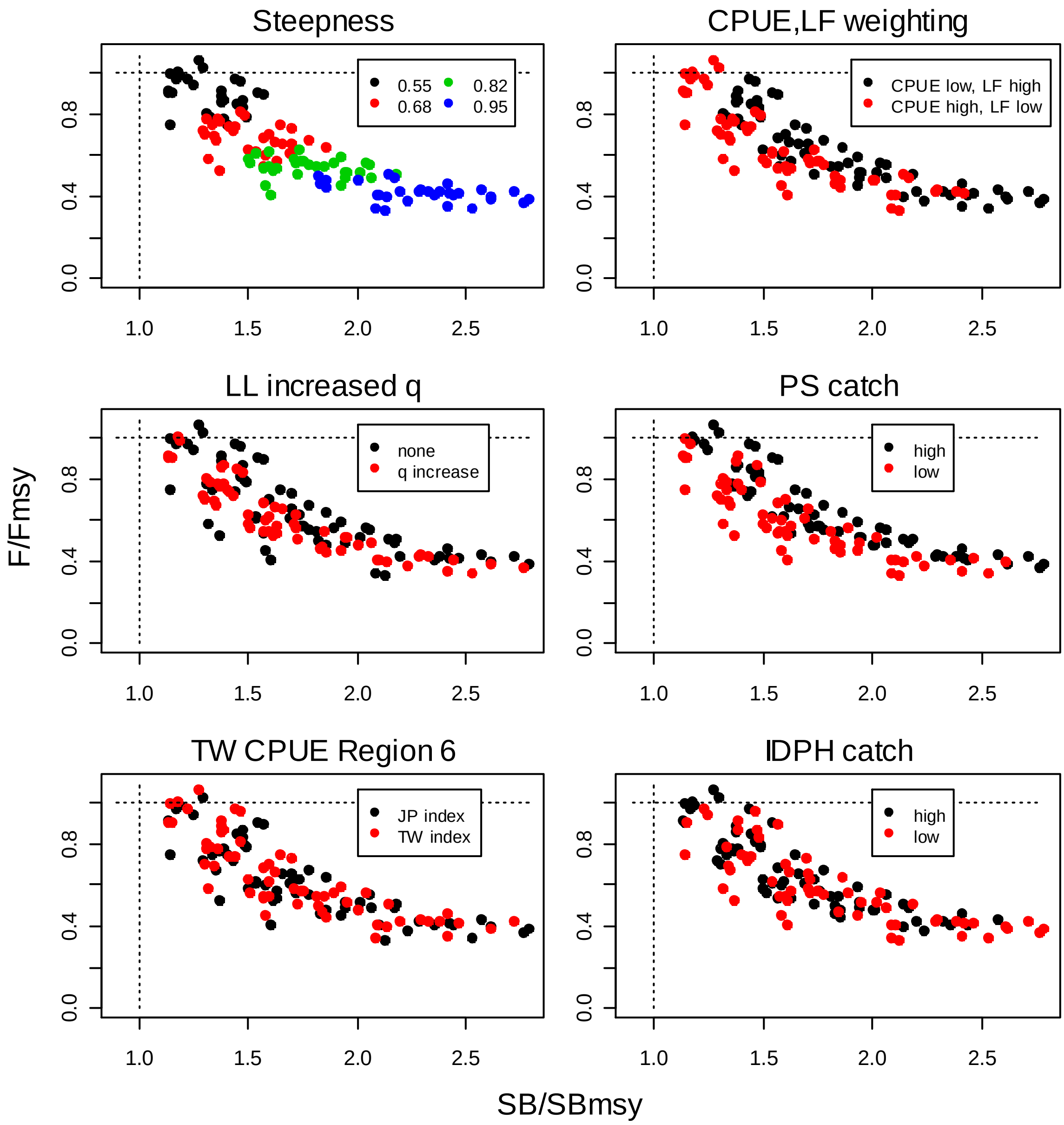

Figure 57. Comparison of F/Fmsy and SB/SBmsy reference points derived from the combinations of model sensitivities. Each panel represents the entire set of qualifying model runs plotted by the individual factor.

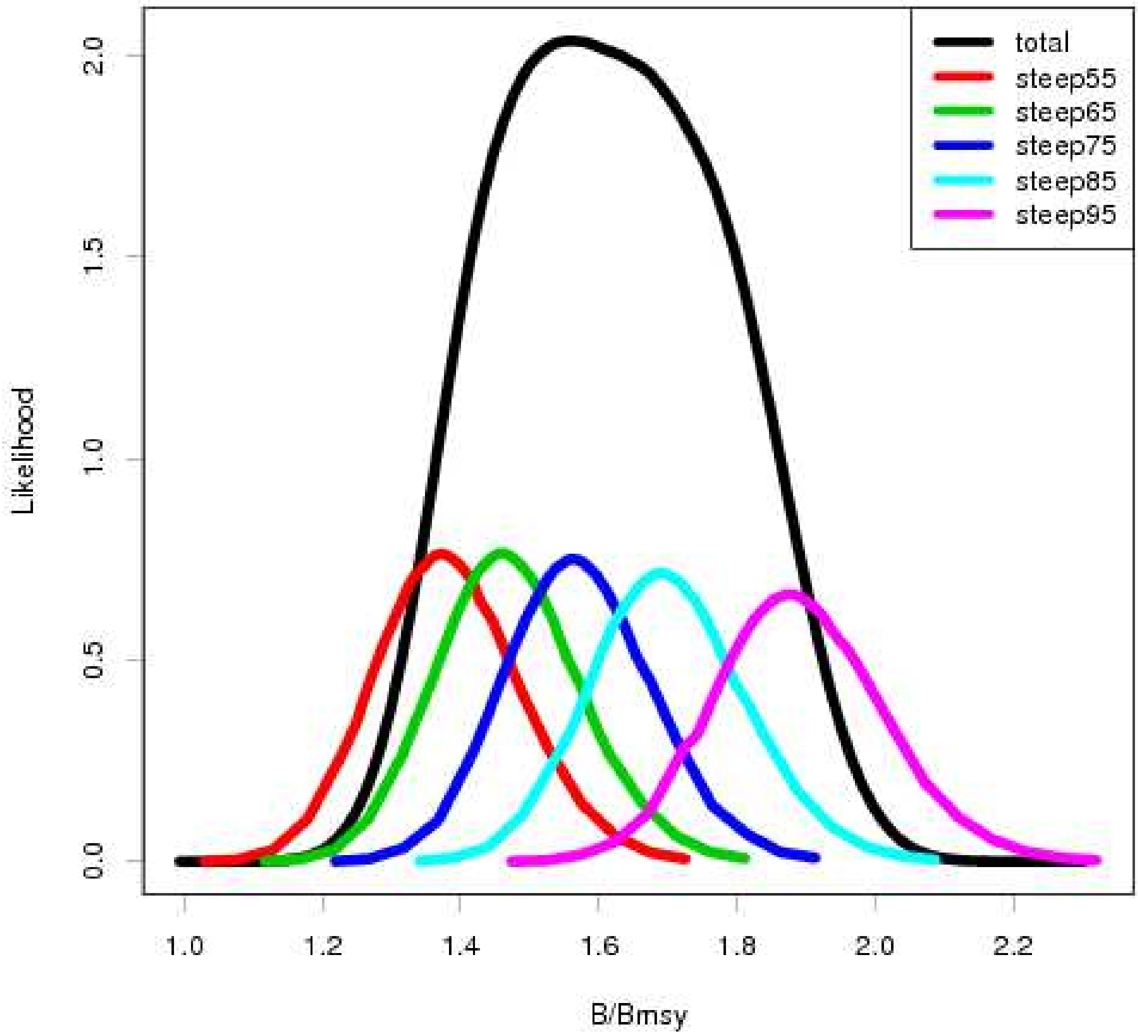

Figure 58. Likelihood profile for $B_{current}/\widetilde{B}_{MSY}$ from the "CPUE low, LL sample high, LL q incr" model with the five different values of steepness (0.55, 0.65, 0.75, 0.85, 0.95) and a composite distribution derived from the five separate profiles.

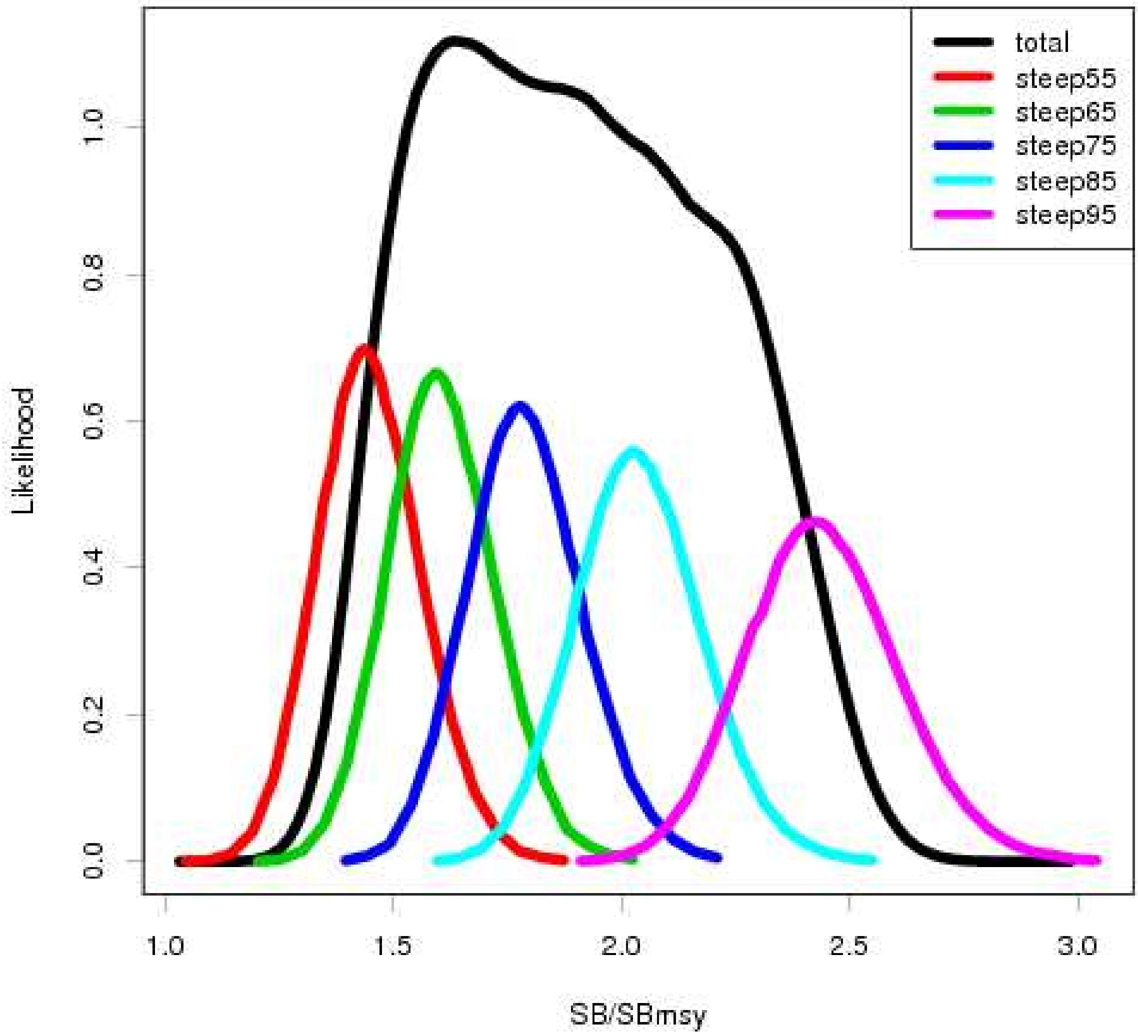

Figure 59. Likelihood profile for $SB_{current} / S\widetilde{B}_{MSY}$ from the "CPUE low, LL sample high, LL q incr" model with the five different values of steepness (0.55, 0.65, 0.75, 0.85, 0.95) and a composite distribution derived from the five separate profiles.

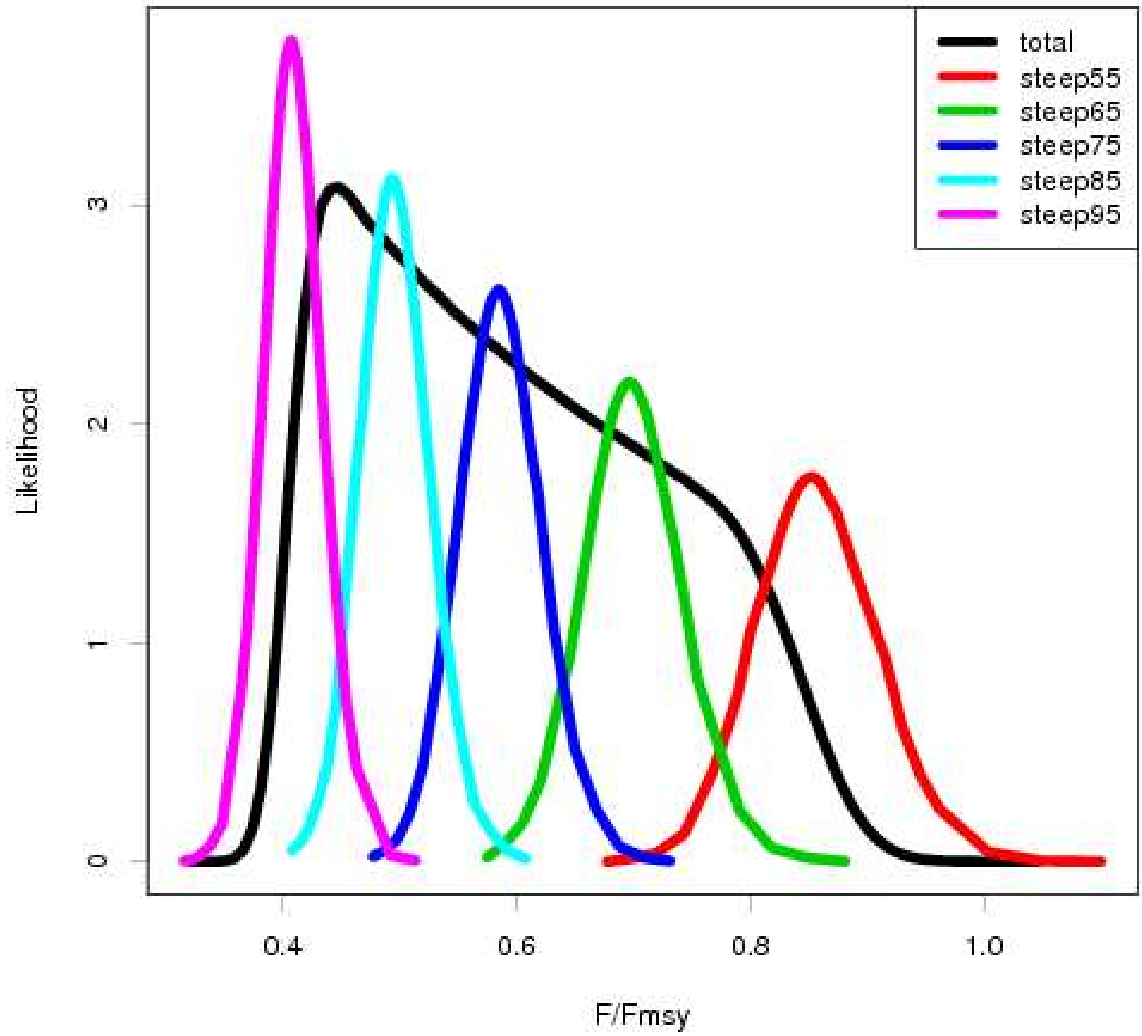

Figure 60. Likelihood profiles for $F_{current}/\tilde{F}_{MSY}$ from the "CPUE low, LL sample high, LL q incr" model with the five different values of steepness (0.55, 0.65, 0.75, 0.85, 0.95) and a composite distribution derived from the five separate profiles.

Appendix 1 *doitall.yft*

```
#  ------------------------
#  PHASE 0 - create initial par file
#  ------------------------
#
if [ ! -f 00.par ]; then
  mfclo32 yft.frq yft.ini 00.par -makepar
fi
#  ------------------------
#  PHASE 1 - initial par
#  ------------------------
#
if [ ! -f 01.par ]; then
  mfclo32 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 20      # divide LL LF sample sizes by 20 (default)
  -999 50 20      # divide LL WF sample sizes by 20 (default=10)
  -20 50 20       # except for PS in area 1 - lower confidence in these weight data
  1 32 2          # sets control
  1 111 4         # sets likelihood function for tags to negative binomial
  1 141 3         # sets likelihood function for LF data to normal
  1 173 8         # 1st n lengths are independent pars
  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
# 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 13
  -21 24 14
  -22 24 15
  -23 24 16            # separate LL selectivity for smaller fish in PNG waters
```

```
  -24 24 17
# 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 15
  -21 29 16
  -22 29 17
  -23 29 18
  -24 29 19
  -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 15
  -21 60 16
  -22 60 17
  -23 60 18
  -24 60 19
# 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 17
  -20 32 18
  -21 32 19
  -22 32 20
  -23 32 4
  -24 32 21
# 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 17
  -20 34 18
  -21 34 19
  -22 34 20
  -23 34 4
  -24 34 21
# 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
   -22 35 1
   -23 35 1
   -24 35 50
# 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
   -22 36 50
   -23 36 50
   -24 36 60
# effort dev bpoundary
  2 35 10
# sets penalties for effort deviations (negative penalties force effort devs
# to be zero when catch is unknown)
   -999 13 -10
   -1 13 1
   -2 13 1
   -4 13 1
   -7 13 1
  -10 13 1
  -12 13 1
  -18 13 10
   -999 66 0
   -1 66 1
   -2 66 1
   -4 66 1
   -7 66 1
  -10 66 1
  -12 66 1
# sets penalties for catchability deviations
   -18 15 1       # low penalty for PH.ID MISC.
   -24 15 1
  -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
```

```
  mfclo32 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
  mfclo32 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
PHASE3
fi
#  ---------
#   PHASE 4
#  ---------
if [ ! -f 04.par ]; then
  mfclo32 yft.frq 03.par 04.par -file - <<PHASE4
  2 68 1          # estimate movement coefficients
PHASE4
fi
#  ---------
#   PHASE 5
#  ---------
if [ ! -f 05.par ]; then
  mfclo32 yft.frq 04.par 05.par -file - <<PHASE5
  1 16 1          # estimate length dependent SD
PHASE5
fi
#  ---------
#   PHASE 6
#  ---------
if [ ! -f 06.par ]; then
  mfclo32 yft.frq 05.par 06.par -file - <<PHASE6
  1 173 8         # estimate independent mean lengths for 1st 8 age classes
  1 182 10
  1 184 1
PHASE6
fi
#  ---------
#   PHASE 7
#  ---------
if [ ! -f 07.par ]; then
  mfclo32 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
  -24 27 0
PHASE7
fi
#  ---------
#   PHASE 8
```

```
#  ---------
if [ ! -f 08.par ]; then
  mfclo32 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
  -20 10 1
  -21 10 1
  -22 10 1
  -23 10 1
  -24 10 1
  -999 23 23      # and do a random-walk step every 23+1 months
PHASE8
fi
#  ---------
#   PHASE 9
#  ---------
if [ ! -f 09.par ]; then
  mfclo32 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
  mfclo32 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
```

```
  -22 44 2
  -23 44 1
  -24 44 3
 -999 43 1       # estimate a for all fisheries
PHASE10
fi
#  ---------
#   PHASE 11
#  ---------
if [ ! -f 11.par ]; then
  mfclo32 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
PHASE11
fi
#  ---------
#   PHASE 12
#  ---------
if [ ! -f 12.par ]; then
  mfclo32 yft.frq 11.par 12.par -file - <<PHASE12
  2 145 1
  1 149 0
  2 146 1
  2 162 0
  2 163 0
  2 147 1
  2 148 20       # Current is defined as 2004-2007
  2 155 4
  2 153 31
  2 154 16
  1 1 2000
  1 50 -3
  -999 14 0
  -999 55 1 # fishery impact
  2 193 1  # initial impact for depletion
PHASE12
fi
```

Appendix 2 *yft.ini*

```
# number of age classes
  28
# MATURITY AT AGE
0.000000000000 0.000000000000 0.000000000000 0.003112633000 0.031087873000 0.112437021000
0.423024369000 0.585775860000 0.844926311000 0.934591096000 0.975401043000 0.995264883000
1.000000000000 0.981462405000 0.890010382000 0.771445490000 0.617121988000 0.472944161000
0.352073537000 0.256720297000 0.184325598000 0.130839012000 0.092100132000 0.064441996000
0.044896017000 0.031182966000 0.021611419000 0.014954788000
# natural mortality
0.250298600000
# 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
# 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
0.691953490000 0.564120120000 0.417516650000 0.245666390000 0.038027030000 -0.224337240000 -
0.224337240000 -0.224168900000 -0.223805020000 -0.221483170000 -0.210353690000 -0.171575700000 -
0.088868250000 0.154243450000 0.199631840000 0.259333920000 0.199468890000 0.118825250000
0.041481990000 -0.024338360000 -0.077188400000 -0.117954550000 -0.148447860000 -0.170734480000 -
0.186748780000 -0.198114760000 -0.206111030000 -0.211701590000
  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 0.40 0.35 0.05 0.09
# 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             15.0
      0.40         -1.00             1.00
# The number of mean constraints
  0
```

Appendix 3. Estimates of management quantities from each of the models in a step-wise process to account for the main differences between the "Base 2007" model and the "CPUE low, LL sample high, LL q incr" (base case 2009) model.

Management quantity	Units	Base 2007	Base 2007, steepness 0.75 Step 1	Sample size n/20 Step 2	New biological parameters Step 3	New PS catch Step 4	Lower LL Edev penalty Step 5	Increase LL q Step 6
$\tilde{Y}_{F_{current}}$	**mt per year**	369,000	445,600	438,800	440,800	573,200	493,200	555,600
$\tilde{Y}_{F_{MSY}}$ **(or *MSY*)**	**mt per year**	370,520	509,600	483,200	489,600	625,200	555,200	636,800
$\tilde{B}_0$	**mt**	4,523,000	4,385,000	4,079,000	3,962,000	5,046,000	4,506,000	5,283,000
$\tilde{B}_{MSY}$	**mt**	1,962,000	1,704,000	1,589,000	1,508,000	1,894,000	1,699,000	1,979,000
$\tilde{SB}_0$	**mt**	2,654,000	2,573,000	2,381,000	2,147,000	2,725,000	2,433,000	2,850,000
$\tilde{SB}_{MSY}$	**mt**	967,200	750,300	690,200	659,200	810,300	731,100	855,300
$B_{current}$	mt	2,415,538	2,402,778	2,160,236	2,089,348	2,739,203	2,904,457	3,099,135
$SB_{current}$	mt	1,239,312	1,231,167	1,079,178	1,025,287	1,338,408	1,415,108	1,522,039
$B_{current}/\tilde{B}_0$		0.534	0.548	0.530	0.527	0.543	0.645	0.587
$B_{current}/\tilde{B}_{MSY}$		1.231	1.410	1.359	1.384	1.444	1.711	1.568
$SB_{current}/\tilde{SB}_0$		0.467	0.478	0.453	0.478	0.491	0.581	0.536
$SB_{current}/\tilde{SB}_{F_{current}}$		1.178	0.975	0.992	0.983	1.073	1.187	1.059
$SB_{current}/\tilde{SB}_{MSY}$		1.281	1.641	1.563	1.554	1.649	1.940	1.784
$\tilde{SB}_{F_{current}}/\tilde{SB}_0$		0.396	0.491	0.457	0.486	0.458	0.490	0.504
$\tilde{B}_{MSY}/\tilde{B}_0$		0.434	0.389	0.390	0.381	0.375	0.377	0.375
$\tilde{SB}_{MSY}/\tilde{SB}_0$		0.364	0.292	0.290	0.307	0.297	0.300	0.300
$F_{current}/\tilde{F}_{MSY}$		0.928	0.588	0.644	0.625	0.659	0.608	0.584