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Stock assessment of yellowfin tuna in the western and central Pacific Ocean, including an analysis of management options

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Adam Langley[1], John Hampton[1], Pierre Kleiber[2] and Simon Hoyle[1]

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[1] Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia
[2] Pacific Islands Fishery Science Center, National Marine Fisheries Service, Honolulu, Hawaii, USA.

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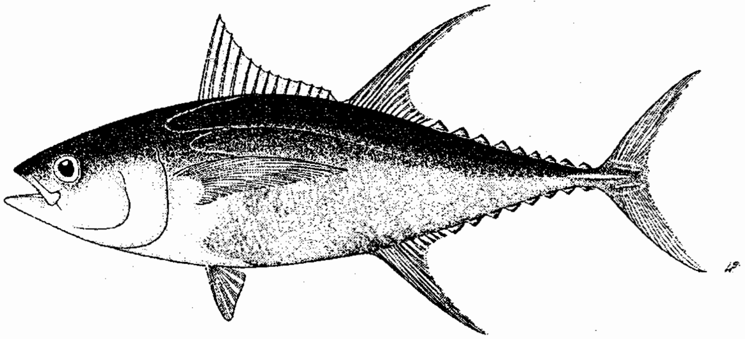

Adam Langley[1], John Hampton[1], Pierre Kleiber[2] and Simon Hoyle[1]

[1]Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia.
[2]Pacific Islands Fishery Science Center, National Marine Fisheries Service, Honolulu, Hawaii, USA.

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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 1997, the total yellowfin tuna catch in the WCPO has varied between 350,000 and 450,000 mt. Purse seiners harvest the majority of the yellowfin tuna catch (54% by weight in 2005), with the longline and pole-and-line fisheries comprising 15% and 3% of the total catch, respectively. Yellowfin tuna usually represent approximately 20–25% of the overall purse-seine catch and may contribute higher percentages of the catch in individual sets. Yellowfin tuna is often directly targeted by purse seiners, especially as unassociated schools which accounted for 56% of recent (2000–2005) yellowfin purse-seine catch (by weight).

Longline catches in recent years (60,000–80,000 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 30% of total WCPO yellowfin tuna catches.

This paper presents the 2007 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 2006.

The catch, size and tagging data used in the assessment were similar those used last year, although there were a number of significant changes to the configuration of the fisheries and associated size-frequency data; the main changes were the inclusion of three new fisheries (an equatorial pole-and-line fishery and Japanese coastal pole-and-line and purse-seine fisheries), separation of the Philippines and Indonesian domestic fisheries, the subdivision of the principal longline fishery in region 3 (LL ALL 3), and the treatment of the length- and weight-frequency data collected from the main longline and purse-seine fisheries. The model also includes that additional recent fishery data (2005 for longline, 2005 for Philippines and Indonesia, and 2006 for purse seine) were included. It should be noted that 2006 data are not complete for some fisheries. The estimation of standardised effort for the main longline fisheries used the GLM approach similar to recent assessments.

The current assessment included a range of sensitivity analyses, mainly assessing the implications of the assumed level of catch from the Indonesian fishery, the potential for spatial heterogeneity in growth, and the effect of various changes in the model data structure. The sensitivity of the model to assumptions regarding the steepness parameter of the SRR was also investigated. In addition, a separate model was constructed based on a single-region encompassing the western equatorial region (MFCL region 3) — the core region of the fishery.

The main conclusions of the current assessment are as follows:

1. For all analyses, there was a strong temporal trend in recruitment. Initial recruitment was relatively high but declined to a lower level during the early 1970s. Recruitment subsequently increased during the late-1970s and remained relatively high during the 1980s before declining in the 1990s. This pattern is similar to the results of previous assessments and is largely driven by the trends in the principal longline CPUE indices, particularly from regions 3 and 4. For the most recent years, recruitment is predicted to have increased, although recent recruitment estimates are poorly determined. Nevertheless, the estimates of stronger recruitment in recent years are

generally consistent with recruitment estimates derived from a model relating yellowfin recruitment to the oceanographic conditions of the WCPO.

2. For all analyses, the trends in biomass are generally comparable prior to the mid-1980s and were consistent with the underlying trends in recruitment, with biomass declining during the initial period to a low level in the early–mid 1970s, before increasing in the mid-1970s. Biomass levels remained relatively stable during the 1980s. For all model options, biomass is estimated to have declined steadily during the 1990s, largely due to the decline in the biomass within region 3 but also evident in most other regions. The recent estimates of strong recruitment result in a predicted increase in total biomass during the most recent years in the model; again, there is considerable uncertainty associated with the recent recruitment estimates and, therefore, recent trends in total biomass.

3. The biomass trends in the model are strongly driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. For some of the main longline fisheries (for example, 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 inconsistent information about the relative level of fishing mortality in the region. Further research is required to explore the relationship between longline CPUE and yellowfin abundance and the methodology applied to standardise the longline CPUE data, particularly to account for temporal trends in fishing efficiency. The latter issue was examined by way of a sensitivity analysis in the 2005 assessment and shown to be highly influential in the conclusions of the assessment. There is also the potential that the size selectivity of some fisheries may have changed over time in response to changes in targeting behaviour of the longline fleet, although the stock assessment assumes selectivity is temporally invariant.

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 51% of unexploited biomass (a fishery impact of 49%) in 2002–2005. This represents a moderate level of stock-wide depletion that is approaching the equivalent equilibrium-based limit reference point ($\widetilde{B}_{MSY} / \widetilde{B}_0$ = 0.42). Further, depletion is somewhat greater for some individual model regions, notably in the equatorial region 3 where recent depletion levels are approximately 0.4 (a 60% reduction from the unexploited level). Other regions are less depleted, with indices of 0.8 or greater for all other regions except for region 4 (0.65). If stock-wide over-fishing criteria were applied at the level of our model regions, we would conclude that region 3 is fully exploited, region 4 is approaching full exploitation, and the remaining regions are under-exploited. The results of the single region 3 model are generally consistent with the conclusions regarding the stock status of region 3 from the entire WCPO model.

6. The attribution of depletion to various fisheries or groups of fisheries indicates that the Indonesian and Philippines domestic fisheries have the greatest impact, particularly in its home region (3) and is contributing significantly to the impact in adjacent regions 1, 4 and 5. The purse seine fishery also has a high impact in regions 3 and 4 and accounts for a significant component

of the recent impacts in all other regions, except region 6. Historically, the coastal Japanese pole-and-line and purse-seine fisheries have had a significant impact on biomass levels in their home region (1). It is notable that the composite longline fishery is responsible for biomass depletion of about 10% in the WCPO during recent years.

7. The reference points that predict the status of the stock under equilibrium conditions are $\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$ (1.10) and $\widetilde{SB}_{F_{current}} / \widetilde{SB}_{MSY}$ (1.12), which indicate that the long-term average biomass would remain slightly above the level capable of producing *MSY* at 2002–2005 average fishing mortality. Overall, current biomass exceeds the biomass yielding *MSY* ($B_{current} / \tilde{B}_{MSY} >$ 1.0); i.e. **the yellowfin stock in the WCPO is not in an overfished state**.

8. While the point estimate of $F_{current} / \tilde{F}_{MSY}$ remains slightly less than 1 (0.95), the probability distribution associated with fishing mortality based reference point is about the threshold level, with virtually equal probability that the value of $F_{current} / \tilde{F}_{MSY}$ is less than or greater than the reference point. Therefore, it is not possible to make a definitive statement as to whether or not overfishing of yellowfin is occurring in the WCPO. Nonetheless, **current exploitation rates are likely to be, at least, approaching the F_{MSY} level and any further increase in exploitation rates will not result in an increase in equilibrium yields from the stock** under the current age specific pattern of exploitation (i.e, $\tilde{Y}_{F_{current}}$ is approximately equal to *MSY).* On that basis, the WCPO yellowfin tuna fishery can be considered to be fully exploited, with a substantial (47%) probability that overfishing is occurring.

9. The stock assessment conclusions differ slightly from the 2006 assessment, particularly in relation to the $F_{current} / \tilde{F}_{MSY}$ threshold with the current assessment being slightly more optimistic than the 2006 assessment. This change is largely due to the changes in the configuration of the fisheries and their associated size data in the model. However, the stock assessment results are also highly sensitive to the assumptions relating to the steepness of the stock-recruitment relationship. The base-case assessment yields a relatively low value for steepness (which is partly constrained by an informative prior), although considerably higher values of steepness are also plausible which would result in more optimistic conclusions regarding the current stock status. On the other hand, more pessimistic conclusions ($F_{current} / \tilde{F}_{MSY} = 1.08$; $B_{current} / \tilde{B}_{MSY} = 1.20$) are obtained when an uninformative steepness prior is used. In this case, the estimate of steepness is based only on evidence from the data and approaches the lower limit of values considered to be plausible for tropical tunas.

10. Stock projections for 2007–2011 — that attempt to simulate the conservation and management measures adopted at WCPFC2 and WCPFC3 — indicate that the point estimate of $B_t / \tilde{B}_{MSY}$ remains above 1.0 throughout the projection period. However, the increasing uncertainty in the future projections is likely to result in a greater probability of the biomass declining below $\tilde{B}_{MSY}$ by the end of the projection period.

1 Introduction

This paper presents the current stock assessment of yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean (WCPO, west of 150°W). Since 1999, the assessment has been conducted annually and the most recent assessments are documented in Hampton and Kleiber (2003) and Hampton et al. (2004, 2005 and 2006). The current assessment incorporates the most recent data from the yellowfin fishery and, essentially, represents an update of the assessment undertaken in 2006. In addition, a range of sensitivity analyses are presented, including consideration of a single-region model in encompassing the western equatorial region (MFCL region 3) — the core region of the fishery.

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

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

2 Background

2.1 Biology

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

Yellowfin tuna are relatively fast growing, and have a maximum fork length (FL) of about 180 cm. The growth of juveniles departs from von Bertalanffy type growth with the growth rate slowing between about 40 and 70 cm FL (Lehodey and Leroy 1999).

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 unpublished) (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 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 1997, the total yellowfin tuna catch in the WCPO has varied between 350,000 and 450,000 mt (Figure 4). Purse seiners harvest the majority of the yellowfin tuna catch (54% by weight in 2005), with the longline and pole-and-line fisheries comprising 15% and 3% of the total catch, respectively. Yellowfin tuna usually represent approximately 20–25% of the overall purse-seine catch and may contribute higher percentages of the catch in individual sets. Yellowfin tuna is often directly targeted by purse seiners, especially as unassociated schools which accounted for 56% of recent (2000–2005) yellowfin purse-seine catch (by weight).

Longline catches in recent years (60,000–80,000 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 30% of total WCPO yellowfin tuna catches.

Figure 5 shows the spatial distribution of yellowfin tuna catch in the WCPO for the past 15 years. Most of the catch is taken in western equatorial areas, with declines in both purse-seine and longline catch towards the east. The east-west distribution of catch is strongly influenced by ENSO events, with larger catches taken east of 160°E during *El Niño* episodes. Catches from outside the equatorial region are relatively minor (5%) and are dominated by longline catches south of the equator and purse-seine and pole-and-line catches in the north-western area of the WCPO (Figure 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 base-case assessment is equivalent to that used in the 2006 assessment.

3.2 Temporal stratification

The time period covered by the assessment is 1952–2006. 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 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).

Previous assessments have not included the yellowfin catch from the seasonal purse-seine and pole-and-line 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. These fisheries were included separately in the current assessment (PS JP 1 and PL JP 1).

Further, an additional pole-and-line fishery was included within MFCL region 3 to incorporate 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).

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 7). 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 WCPO (Figure 4) due to the difficulties in spatially separating some of the aggregated catch estimates. For 1990–2005, model catches represent 95% of the total WCPO 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).

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

Effort data units for purse seine fisheries are defined as days fishing and/or searching, allocated to set types based on the proportion of total sets attributed to a specified set type (associated or unassociated sets) in logbook data. 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 or LL ALL 1–7), effective (or standardised) effort was derived using generalized linear models (GLM) (Langley et al. 2005). Time-series of catch-per-unit-effort (CPUE) for all fisheries are shown in Figure 8. The GLM standardised CPUE for the principal longline fisheries are presented in Figure 9.

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 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.

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

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 10. The data were collected from a variety of sampling programmes, which can be summarized as follows:

Philippines: Size composition data for the Philippines domestic fisheries derived from a sampling programme conducted in the Philippines in 1993–94 were augmented with data from the 1980s and for 1995. In addition, data collected during 1997–2006 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. For each purse seine fishery, size samples were combined within temporal strata weighted by the spatial distribution of the catch (see below).

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.

In previous assessments, length (and weight) 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. For the current assessment, quarterly length frequency distributions were computed for the principal longline fisheries and the equatorial purse-seine 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, while purse-seine size data were generally aggregated by 5 degrees of latitude and 5 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 or 5*5 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 (Table 2).

3.6 Weight-frequency data

A large data set of individual fish weights are available 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 10. The same protocol for the aggregation of the length data were 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 (Table 3).

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 include the tag release and recovery data from the 2006–07 tagging programme undertaken in PNG waters.

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 4. In addition, we describe the procedures followed for estimating the parameters of the model and the way in which stock assessment conclusions are drawn using a series of reference points.

4.1 Population dynamics

The six-region model partitions the population into 6 spatial regions and 28 quarterly age-classes. The first age-class has a mean fork length of around 25 cm and is approximately three months of age according to analysis of daily structures on otoliths (Lehodey and Leroy 1999). The last age-class comprises a "plus group" in which mortality and other characteristics are assumed to be constant. For the purpose of computing the spawning biomass, we assume a fixed maturity schedule (Table 4) consistent with the observations of Itano (2000). The population is "monitored" in the model at quarterly time steps, extending through a time window of 1952–2006. The main population dynamics processes are as follows:

4.1.1 Recruitment

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

The distribution of recruitment among the six model regions was estimated within the model and allowed to vary over time in a relatively unconstrained fashion. Stronger constraints were placed on the variation of the spatial distribution of recruitment in the initial 5 years of the time series. The time-series variation in spatially-aggregated recruitment was somewhat constrained by a lognormal prior. The variance of the prior was set such that recruitments of about three times and one third of the average recruitment would occur about once every 25 years on average.

Spatially-aggregated recruitment was assumed to have a weak relationship with the spawning biomass via a Beverton and Holt stock-recruitment relationship (SRR). The SRR was incorporated mainly so that yield analysis and stock projections could be undertaken for stock assessment purposes. We therefore opted to apply a relatively weak penalty for deviation from the SRR so that it would have only a slight effect on the recruitment and other model estimates (see Hampton and Fournier 2001, Appendix D).

Typically, fisheries data are not very informative about SRR parameters and it is generally necessary to constrain the parameterisation in order to have stable model behaviour. We incorporated a beta-distributed prior on the "steepness" (S) of the SRR, with S defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Francis 1992; Maunder and Watters 2001). The beta-distribution of the prior has a lower bound at 0.2, a mode = 0.85, and standard deviation = 0.16 (Figure 11).

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 4). 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.

In addition, an alternative growth model was included as a sensitivity analysis (see Section 5). The growth model was derived from a MFCL model that included only the single western, equatorial region (region 3) with the growth parameters estimated in an equivalent manner to that described above. The resulting growth model exhibited slower growth than the growth model estimated by Hampton et al. (2006) but was more consistent with the growth of yellowfin in the southern Philippines waters (Yamanaka 1990) and with the results of tagging studies.

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 $2\times7\times4 = 56$ 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 Natural mortality

Natural mortality (M) was held fixed at pre-determined age-specific levels as applied in the 2006 assessment. M-at-age was determined externally of the MULTIFAN-CL model using estimates of M by length category from tagging data, sex-ratio data and the assumed maturity-at-age schedule. An identical procedure is used to determine fixed M-at-age for assessments in the EPO (Maunder 2005). Essentially, this method reflects the hypothesis that the higher proportion of males in sex-ratio samples with increasing length is due to the higher natural mortality of females after they reach maturity. The externally-estimated M-at-age is shown in Figure 12.

A separate M-at-age schedule was determined for the sensitivity analysis using growth estimated for MFCL Region 3 only (Figure 12). The changes in M-at-age simply reflect the differences in the two growth functions, given that estimates of M-at-age are derived from length-based data.

The M-at-age has been estimated in previous yellowfin stock assessments. However, the resulting estimates were inconsistent with the biology of the species and, consequently, the estimates were considered implausible.

4.2 Fishery dynamics

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

4.2.1 Selectivity

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

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

In the 2005 assessment, the selectivity of the longline fisheries (which catch mainly adult yellowfin) was assumed to increase with age and to remain at the maximum once attained. However, this assumption was relaxed in the 2006 and the current assessment for all longline fisheries, except for the fisheries Chinese/Taiwanese fisheries (LL TW-CH 3 and 4), thereby, allowing selectivity to decline for the older age classes. This is because the Chinese/Taiwanese fleet caught consistently larger fish than the other longline fleets in a comparable time period. These differences in size composition, which were consistent across length- and weight-frequency data, implied less than 100% selectivity for older yellowfin by the LL ALL fisheries. There are operational differences between the longline fleets that may account for a higher selectivity of larger fish by the Chinese/Taiwanese fleet.

4.2.2 Catchability

Catchability was allowed to vary slowly over time (akin to a random walk) for all purse seine fisheries, the Philippines and Indonesian fisheries, the Australian, Taiwanese/Chinese, Hawaii, PNG (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. We made the prior assumption that effort for these fisheries was proportional to catch, but set the variance of the priors to be high (approximating a CV of about 0.7), thus allowing catchability changes to compensate for failure of this assumption. For the other fisheries with time-series variability in catchability, the catchability deviation priors were assigned a variance approximating a CV of 0.10.

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

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

4.2.3 Effort deviations

Effort deviations, constrained by prior distributions of zero mean, were used to model the random variation in the effort – fishing mortality relationship. For the Philippines and Indonesian fisheries, purse seine fisheries and the Australian, Hawaii and Taiwanese-Chinese longline fisheries, the variance was set at a moderate level (approximating a CV of 0.2). For the main longline fisheries (LL ALL 1–6), the variance was set at a lower level (approximating a CV of 0.1) because the effort had been standardised in prior analyses and these longline fisheries provide wide spatial coverage of the respective areas in which they occur.

4.3 Dynamics of tagged fish

4.3.1 Tag mixing

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

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

4.3.2 Tag reporting

In principal, tag-reporting rates can be estimated internally within the model. In practice, experience has shown that independent information on tag-reporting rates for at least some fisheries tends to be required for reasonably precise estimates to be obtained. We provided reporting rate priors for all fisheries that reflect our prior opinion regarding the reporting rate and the confidence we have in that opinion. Relatively informative priors were provided for reporting rates for the Philippines and Indonesian domestic fisheries and the purse seine fisheries, as independent estimates of reporting rates for these fisheries were available from tag seeding experiments and other information (Hampton 1997). For the longline fisheries, we have no auxiliary information with which to estimate reporting rates, so relatively uninformative priors were used for those fisheries. All reporting rates were assumed to be stable over time. The proportions of tag returns rejected from the analysis because of insufficient data were incorporated into the reporting rate priors.

4.4 Observation models for the data

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

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

The size frequency data is assigned an effective sample size lower than the actual number of fish sampled. Reduction of the effective sample size recognises that (i) length- and weight-frequency samples are not truly random (because of clumping in the population with respect to size) and would have higher variance as a result; and (ii) the model does not include all possible process error, resulting in further under-estimation of variances.

Nevertheless, compared to previous 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 0.1 times the actual sample size, with a maximum effective sample size of 100 (equivalent to the HIGHSAMP sensitivity in the 2006 assessment).

A log-likelihood component for the tag data was computed using a negative binomial distribution in which fishery-specific variance parameters were estimated from the data. The negative binomial is preferred over the more commonly used Poisson distribution because tagging data often exhibit more variability than can be attributed by the Poisson. We have employed a parameterisation of the variance parameters such that as they approach infinity, the negative binomial approaches the Poisson. Therefore, if the tag return data show high variability (for example, due to contagion or non-independence of tags), then the negative binomial is able to recognise this. This should then provide a more realistic weighting of the tag return data in the overall log-likelihood and allow the variability to impact the confidence intervals of estimated parameters. A complete derivation and description of the negative binomial likelihood function for tagging data is provided in Hampton and Fournier (2001) (Appendix C).

4.5 Parameter estimation and uncertainty

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

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

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[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).

4.6 Stock assessment interpretation methods

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

4.6.1 Fishery impact

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

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

4.6.2 Yield analysis

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

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In this assessment, we use the average over the period 2002–2005. The last year in which a complete set of catch and effort data is available for all fisheries is 2005. We do not include 2006 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 (1952–2006). 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.

Further, theoretical MSY values were computed assuming exploitation was applied to each individual age class. The resulting theoretical MSY values from each age class were compared to determine the optimal age of harvest for yellowfin; i.e. the age class of harvest that yields the highest theoretical MSY. While it is implausible that a fishery can effectively select a single age class, such an analysis is useful to identify fisheries that are responsible for significantly reducing the total yields that could be available from the stock.

5 Sensitivity analyses

There are five main differences in the configuration of the data set included in the current "base-case" assessment compared to the 2006 assessment.

i. The inclusion of three new fisheries that were previously unaccounted in the model: the Japanese coastal pole-and-line and purse-seine fisheries in region 1 and the composite pole-and-line fishery in region 3.

ii. The separation of the composite Philippines and Indonesia domestic fishery (PHID MISC 3) into two separate national fisheries (PH MISC 3 and ID MISC 3).

iii. The separation of the LL ALL 3 fishery, the principal longline fishery in region 3, to include an additional historical distant-water longline fishery within an area approximating PNG national waters (LL BMK 3).

iv. The computation of length- and weight frequency distributions for key fisheries that are representative of the spatial distribution of the catch from the fisheries. The protocols used in aggregating the size data resulted in the exclusion of a considerable proportion of the data from some fisheries.

v. The revision of the recent (2004 onwards) annual catch estimates from the Indonesian domestic fisheries.

The sensitivity analyses were structured to assess the impact of these changes in the data and model structure. Additional sensitivities were conducted to assess the effect of individual model assumptions (Table 5).

As noted above, there is a high level of uncertainty regarding historical and recent catches from the Indonesian domestic fishery (ID MISC 3). The recent (2004) catches included in the model were revised downwards following the provision of catch estimates by Indonesia; the recent catch estimate is approximately 50% of the level assumed for 2004–05 in the 2006 assessment. The sensitivity of the current assessment to the change in the catch level was investigated by running the model with the two different levels of recent catch (for 2004–06) (Figure 13).

Two additional sensitivities to the past and recent levels of Indonesian catch were investigated: a catch history that was 50% higher than the assumed level of catch throughout the model period (including the higher level of 2004–06 catch) ("id-high-catch") and an overall lower level of catch configured as a steady increase in catch from the 1970 level to the level of the recent (lower) catch estimate ("id-low-catch") (Figure 13).

A number of the sensitivities involved reconfiguration of the input data set to be more consistent with the 2006 assessment (scenarios "old-size", "ex-newfish", "recombine-LL3"; see Table 5). The results from these sensitivities are most comparable with the results from the HIGHSAMP sensitivity from the 2006 assessment, given the higher weightings applied to the size frequency data.

The "base-case" model revealed a relatively poor fit to the early catch and effort data from the principal longline fishery in region 3 (see Section 6.5.2). The catch and effort data from this fishery are assumed to provide the principal index of stock abundance in the region that accounts for the majority of the catch. To improve the fit to these data the penalty weight on the effort deviates was increased for this fishery (scenario "region3-edevs"; see Table 5).

Given the significance of region 3 in the entire stock assessment, a separate model was formulated for that region only principally to assess the influence that information from the more peripheral regions may be having on the underlying stock assessment conclusions. The single region model included the 10 fisheries located within region 3 and tag data from 13 separate release periods within region 3 (scenario "region3"; see Table 5).

An earlier assessment model constructed for region 3 only revealed a significant difference in the estimated growth rates between the entire WCPO (6 region model) and region 3 only (see Figure

2). The region 3 growth parameters were applied to the WCPO model, with the corresponding change in the *M*-at-age (see Section 4.1.5), to investigate the sensitivity of the base-case model to different growth assumptions (scenario "region3-growth"; see Table 5).

The sensitivity to steepness of the SRR was investigated by comparing the stock assessment conclusions from the base-case model with a model with a steepness fixed at a higher value ("high-steepness") (0.912 compared to 0.62 from the base-case). A further sensitivity was undertaken by relaxing the prior on the distribution of steepness that was assumed for the base-case (replaced with a non-informative, uniform prior) (scenario "steepness-no-prior").

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

6 Results

The results from the three analyses are presented below. In the interests of brevity, some categories of results are presented for the model that is designated as the "base-case" analysis (Table 5). The selection of this analysis as the base-case is due to the overall superior fit of the model to most of the components of the objective function (Table 6). Significant differences between the base-case and the sensitivity analyses are summarised in Section 6.4. The main stock assessment-related results are also summarised for all analyses.

6.1 Fit statistics and convergence

A summary of the fit statistics for the three analyses is given in Table 6. The base-case model has a superior fit to the overall data set, although there is only a marginal difference between the base-case and the model with a higher level of catch from the Indonesian fishery (ID-high-catch). The latter model actually provides a considerably improved fit to the length- and weight-frequency data, but a poorer fit to the tag data. The model that includes a lower catch from the Indonesian fishery (ID-low-catch) has a better fit to the tag data but a poorer fit the length-frequency data.

The model with growth fixed at the growth parameters determined for the western equatorial region (region3-growth) has a poorer overall fit to the data, particularly the weight-frequency data (Table 6). However, there is a significant improvement in the fit to the length data most of which is collected from the fisheries within region 3. The relative contribution of the fishery-specific components of the length-frequency data to the overall likelihood is discussed in more detail in Section 6.1.

Information of the fit to some of the other sensitivity analyses is not presented as the differences in the data structure mean that the fit criteria are not comparable.

6.2 Fit diagnostics (base-case)

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

- There is some systematic lack of fit to the length data for the longline fisheries as revealed from a comparison of the observed and predicted length data aggregated over time (Figure 15). 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. However, the fit to these data is much superior to the previous assessments (Hampton et al. 2005) largely due to the refinement of the treatment of the weight-frequency data and a change in the length-weight relationship in the 2006 assessment (see Langley 2006a for details). These changes resolved much of the apparent conflict between the length- and weight-frequency data included in the model.
- There is a lack of fit to the length data from the LL ALL 2 fishery (Figure 15). Very few length samples are included in the model data set from this fishery (see Table 2) 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.
- 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 16). However, in the case of this fishery, the separation of the longline fishery in PNG waters (LL BMK 3) to account for spatial heterogeneity in size structure (see Langley 2006c) has resulted in an improved fit to the length frequency data compared to the 2006 assessment (Hampton et al. 2006). More generally, the exclusion of length data from some of the fisheries on the basis that it was unrepresentative of the catch has also resulted in an improved fit to the remaining size data compared to 2006 (most notably in the LL ALL 1 fishery).
- For the Philippines and Indonesian surface fisheries (PH MISC 3 and ID MISC 3), there is a strong modal structure in the size data. This modal structure in the aggregated length data is not well predicted by the model, in particular the second age class (about 40–50 cm FL) are consistently under-represented in the predicted size composition of the two fisheries (Figure 15). This lack of fit may be attributable to the growth function estimated for the base-case model (see Section 6.3.1), although limited samples are available from these fisheries.
- 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 15). The corresponding selectivity functions also result in considerable variation in the temporal trends in the predicted size distribution of the vulnerable population (Figure 16).
- For most of the longline fisheries, there is a very good fit to the aggregated weight frequency data (Figure 17). The improvement in the fit to these data from the 2006 assessment is largely due to the protocols applied to the size frequency data (both weight and length) in the current assessment. 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-estimate the proportion of the size composition in the 5–6 age classes. There is also a relatively poor fit to the weight data from PS JP 1 fishery (Figure 17).
- Despite the overall improvement in the fit to the weight data, there are a number of temporal trends in the fit to the weight data, most notably for LL ALL 3 and LL BMK 3 with the predicted fish weights being higher/lower than the observations during 1960–70/1970–80 (Figure 18). 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 assessment model is also not predicting 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, LL TW-CH 3, and PS JP 1 (Figure 18).

- While many of the problems evident in the fit to the size data (particularly length data) in the 2005 and 2006 assessments have been resolved, there remain considerable inconsistencies in the fit to the region 4 Chinese/Taiwanese (LL TW-CH 4) and Hawaiian longline (LL HW 4) length- and weight-frequency data (Figure 17). The latter fishery appears to have exhibited a strong shift in the size of fish caught from the fishery over the last decade that may represent a change in selectivity by the fleet. The selectivity of the LL TW-CH 4 is equivalent to the comparable fishery in region 3 (LL TW-CH 3) and the estimation of selectivity is dominated by the size data from the LL TW-CH 3. The assumption of a common selectivity for these two fisheries may not be appropriate.

- The fits of the model to the tagging data compiled by calendar time and by time at liberty are shown in Figure 19 and Figure 20. The model generally approximates the observed number of tag returns by time interval, although there is a systematic over-estimation of tag-return numbers towards the end of the tag recovery period (1993–94). This is also evident in the over-estimation of tag returns for about 6–13 quarters at liberty (Figure 20). The model under-estimates the recovery of fish at liberty for long periods (greater than 20 quarters), although the number of observations is small). The fits for individual fishery groups are shown in Figure 21. 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 21). For most of these fisheries, the tagging data are uninformative. Of the longline fisheries, most recoveries have been made from the Australian fishery. However, there is some considerable discrepancy in the number of observed and predicted returns from the fishery (Figure 21). This is possibly related to the coarse resolution of spatial structure in the model, estimation of movement parameters, and a lack of adequate mixing of tagged fish with the wider population of region 5.

- The overall consistency of the model with the observed effort data can be examined in plots of effort deviations against time for each fishery (Figure 22). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. On the other hand, if there was an obvious trend in the effort deviations with time, this may indicate that a trend in catchability had occurred and that this had not been sufficiently captured by the model. Of particular interest are the effort deviations for the LL ALL 1–6 longline fisheries, which were constrained to have the same average catchability and to have no year-to-year variation (i.e., catchability deviations were assumed to be zero). For a number of these fisheries, there is strong trend in the effort deviations during the early period of the fishery that indicates an inconsistency between the predicted fishery-specific exploitable biomass and the corresponding standardised effort series for the fishery (Figure 22). For LL ALL 1 and LL ALL 2, effort deviates are negative during the earlier period revealing that the predicted exploitable biomass is higher than indexed by the standardised effort series. The converse is evident for LL ALL 5 and LL ALL 6 corresponding to the very high CPUE observations during the development of the fisheries (Figure 9). Nevertheless, for the remainder of the model period, effort deviates are relatively small for all fisheries indicating a consistency between the standardised effort series and the trend in longline exploitable biomass.

- Effort deviates are substantially higher for the purse-seine fisheries than the principal longline fisheries, with the exception of the PS ASS 3 fishery (Figure 22). This can be interpreted as a high degree of variation in the effective effort of the purse-seine fleet which is to be expected given the differences in the style of fishing operation.

6.3 Model parameter estimates (base-case unless otherwise stated)

6.3.1 Growth

The estimated growth curve is shown in Figure 23. The non-von Bertalanffy growth of juvenile yellowfin is clearly evident, with near-linear growth in the 50–100 cm size range. The 2007 growth parameters indicate higher initial growth than estimated from the 2006 stock assessment. As previously noted, growth estimated from the entire WCPO model yields substantially higher growth rate for age classes 2–7 compare to growth estimates for region 3 only (Figure 23).

The estimated growth pattern from the base-case model is similar to that observed in the otolith length-increment data (Figure 24) (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 24). The growth rates of tagged fish are more consistent with the growth pattern from the region 3 model (see Figure 3).

A sensitivity of the assessment to the assumptions regarding growth was explored by applying the region 3 growth parameters to the WCPO model (region3-growth sensitivity). Overall, the region 3 growth parameters resulted in a poorer fit to the data, particularly the size data. However, when the fishery-specific components of the length- and weight- likelihood were examined is was evident that the region3-growth parameters resulted in a much improved fit to the length data for those fisheries that predominantly catch small fish (PS ASS 3 & 4, PH MISC 3, PL ALL 3, and PL JP 1) (Figure 25).

Conversely, for most of the fisheries principally catching larger fish there was a deterioration in the fit to the length data with the fixed region 3 growth parameters, particularly for the principal distant-water longline fisheries (LL ALL 1, 3–6) (Figure 25). Conversely, there was a slight improvement in the fit to the length data for the LL BMK 3 fishery. The change to the region 3 growth parameters also resulted in a much poorer fit to the weight frequency data, particularly from the longline fisheries in regions 1, 2, and 4 (LL ALL 1, LL ALL 2, LL ALL 4, and LL HW 4) and the purse-seine fishery in region 1 (PS JP 1) (Figure 25 and Figure 26).

Overall, the comparison in the fits to the size data between the two model runs confirms the apparent large differences in the growth rates of juvenile yellowfin between the western equatorial region and the wider WCPO. A cursory analysis suggests that the growth estimates from the base-case model are largely driven by the strong modal structure in the size data from the region 1 fisheries, particularly the longline fishery (LL ALL 1). The apparent faster growth of juvenile fish in this region appears to be positively biasing the growth of juvenile yellowfin in the core area of the fishery. This may explain why the modal structure in the progress of the modes in the size composition of the small fish fisheries deviates from the estimated growth in the base-case model (Figure 26 and Figure 27).

6.3.2 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 12). This issue may be re-visited in future assessments using biologically reasonable functional forms for M-at-age.

6.3.3 Movement

The model estimates a very large movement of fish (51%) southward from region 1 to region 3 in the second quarter of the year (Figure 28). A further southward movement is estimated to occur in the fourth quarter, representing 28% of all fish. Movement rates between all other adjacent regions are relatively low, about 3–6%, or negligible.

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 29. The simulation indicates that most biomass within a region is sourced from recruitment within the region, particularly for regions 1, 2 and 6. The high movement rates from region 1 to region 3 results in a substantial proportion of the region 3 recruitment estimated to have been sourced from region 1. Recruitment in region 1 is also estimated to contribute significantly to the biomass in regions 4 and 5, sourced via region 3.

The mixing between the equatorial regions results in a significant proportion of biomass (25%) in the eastern region (region 4) being sourced from recruitment in the western region (region 3). Similarly, recruitment in region 3 also contributes to the biomass in region 5 (Figure 29).

6.3.4 Selectivity

Estimated selectivity coefficients are generally consistent with expectation with longline fisheries principally selecting larger, older fish and the associated purse-seine sets (FAD and log sets) catching smaller yellowfin (Figure 30). Unassociated purse-seine sets generally catch substantially larger fish than from associated sets. The Japanese purse-seine fishery (PS JP 1) catches large fish in a region where the abundance of large fish is estimated to be low and, consequently, selectivity is high for the older age classes.

The Philippines and Indonesia surface fisheries (PH MISC 3 and ID MISC 3) and the Japanese pole-and-line fishery (PL JP 1) principally catch small fish; however, there are also some observations of larger fish in the catch that explain the high selectivity of older fish also.

For the principal longline fisheries LL ALL 3–6, selectivity is estimated to decline for the older age classes and the catch is predicted to be principally comprised of age-classes 7–10 and selectivity of older fish is relatively low. This is consistent with the slightly smaller size of fish caught by these fisheries compared to the corresponding TW-CH fisheries. The functional form of the (common) selectivity of the latter fisheries is constrained to have full selectivity for the oldest age classes. 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).

6.3.5 Catchability

Time-series changes in catchability are evident for several fisheries (Figure 31). Catchability in the principal longline fisheries (LL ALL 1–6) has been assumed to be constant over time. There is evidence of a general increasing catchability in the unassociated purse seine fisheries, pole-and-line fisheries, and some of the domestic longline fisheries (LL PG 3, LL HW 4, and LL PI 6). In contrast, 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 fishery (PS JP 1) declined from the mid 1980s onwards.

Since the early 1990s, the model estimates a strong increase in the catchability from the Philippines and Indonesian domestic fisheries (PHID MISC 3 and PH HL 3). There is limited effort data for the PHID MISC 3 fishery and the model assumes catches are proportional to effort throughout the history of the fishery. During a period of declining stock biomass, the model has attempted to account for the catches from the fisheries by increasing the catchability inversely proportional to the trend in exploitable biomass.

6.3.6 Tag-reporting rates

Estimated tag-reporting rates by fishery are shown in Figure 32. The estimates for the purse seine fisheries deviated from the mode of their prior distributions and reporting rates from the purse-seine fisheries in region 4 were estimated to be about 50% of the reporting rates from region 3. The estimates for the Philippine and Indonesia domestic fisheries are significantly below their prior mode, indicating that the model has used information contained in the data to estimate this reporting rate. The estimates for the longline fisheries are highly variable, ranging from near zero to the upper limit allowed (0.9). However, the estimated reporting rates from the longline fisheries are based on a very small number of tag recoveries and, consequently, the tag recovery data from these fisheries are not very informative.

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).

6.4 Sensitivity analyses

This section summarises the key differences in the main parameters between the base-case model and a number of key sensitivity analyses. Only those sensitivities that are likely to result in a substantial change in the underlying population dynamics are examined in this section. Those sensitivity analyses are region3-growth, id-low-catch, and id-high-catch. The main differences between these model runs and the base-case assessment are, as follows.

i. The main difference is the parameterisation is the shift in the selectivities between the base-case and the region3-growth model in accordance with the difference in the growth rate. The two sensitivities with different levels of Indonesian catch have fishery specific selectivities that are virtually identical to the base-case model.
ii. Temporal trends in catchability are very similar between all fisheries although the magnitude of the catchability coefficients varies between sensitivities depending on the relative levels of recruitment and, therefore, exploitable biomass (see below). The increase/decrease in catch from the Indonesian fishery was partly accounted for by a stronger/weaker temporal trend in the catchability coefficients for the fishery.
iii. Differences in the movement parameterisation; the region3-growth model differed from the other three models in that high rates of movement from region 1 to region 3 were limited to the fourth quarter of the year.
iv. For the Indonesian low/high catch sensitivities, the level of recruitment in region 3 and, to a lesser extent, in region 1 was estimated to decrease/increase over time relative to the base-case model while maintaining the same short-term temporal variation. For the region3-growth model, overall levels of recruitment were much higher than for the base-case consistent with the slower initial growth and correspondingly higher initial levels of M (see Figure 12). The broader temporal trends in recruitment were very similar between the two models, although there was a lag in the recruitment series of three quarters between the two series, in line with the difference in initial growth rates.
v. For the model with growth fixed at parameters estimated for region 3 only (region3-growth), there is a substantial improvement in the fit to the length-frequency data for the fisheries principally catching smaller fish (purse-seine and Indonesia/Philippines), while there was a decline in the fit to the size data for the longline fisheries, especially those in areas outside of region 3 (as discussed above).

For all model sensitivities, differences in the stock assessment results, at the WCPO region scale, are summarised in the following section.

6.5 Stock assessment results

6.5.1 Recruitment

The base-case recruitment estimates (aggregated by year for ease of display) for each region and the WCPO are shown in Figure 33. 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 and high in regions 1, 4, and 5 during the 1980s and early 1990s. Recruitment was relatively low in regions 4 and 5 during the 1960s and 1970s and recruitment in regions 1 and 3 has been relatively low since the mid 1990s (Figure 33).

These trends strongly influence the trend in the aggregate WCPO recruitment estimates; total recruitment was very high during the late 1950s, relatively low from the mid 1960s to the mid 1970s, high from the late 1970s to late 1980s, and relatively low over the last decade. Recent WCPO recruitment is estimated to be relatively high largely due to strong recruitment in region3 and 5 during 2003 (Figure 33).

The increase in recruitment estimates during the mid 1970s is consistent with the increase in CPUE from the equatorial longline fisheries (LL ALL 3 & 4) during that time (Figure 9), as well as the sustained increase in catches from the mid 1970s to 1990. The model also explains the high initial CPUE observed in a number of the main longline fisheries (LL ALL 4–6) by high estimates of recruitment during the early period (Figure 33).

The confidence intervals associated with the combined WCPO annual recruitment estimates reveal a substantially higher level of uncertainty associated with recruitment estimates prior to the mid 1980s (Figure 33). There is also a high level of uncertainty associated with the most recent recruitment estimates (2005 and 2006).

A comparison of WCPO recruitment estimates for the various model options is provided in Figure 34. All analyses reveal the same trend in overall recruitment with recruitment generally declining from the late 1950s to the early 1970s and then increasing during the late 1970s to plateau at a higher level. The overall magnitude of recruitment varied slightly between the analyses exploring different assumptions regarding the catch from the Indonesian fishery (ID MISC 3); overall recruitment levels varied in accordance to the assumed level of catch (Figure 34). The region3-growth sensitivity yielded a much higher level of overall recruitment due to the combination of the effects of slower initial growth and higher initial M-at-age for the younger age classes.

There is a large difference in the level of recruitment estimated for the current base-case assessment compared to the 2006 base-case model (Hampton et al. 2006). This issue is discussed in more detail in Section 6.6.

6.5.2 Biomass

Estimated biomass time-series for each region and for the WCPO are shown in Figure 35 for the base-case analysis. The trends are variable between regions, reflecting the CPUE trends from the main longline fisheries (LL ALL 1–6) (Figure 36). Nevertheless, some discrepancies do exist between the CPUE trends from the longline fisheries and the temporal trend in the longline exploitable biomass, particularly the deviation in the trend for the LL ALL 3 fishery in the late 1950s and early 1960s. The increase in the exploitable biomass during this period is attributable to the preceding peak in recruitment evident in most regions, including region 3. The increase in recruitment appears to be largely driven by an increase in the size of fish caught many of the longline fisheries during the late 1950s and early 1960s and a corresponding increase in CPUE. However, the predicted associated increase in CPUE is not evident for the LL ALL 3 fishery (Figure 36).

However, overall the model estimates of exploitable abundance show very similar scaling among regions as the CPUE data (Figure 37). 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 total biomass in this region throughout the model period (Figure 35).

Most other regions exhibit a general decline in total biomass from the late 1950s to mid 1970s followed by an increase in the level of total biomass that persisted through the 1980s and early 1990s (Figure 35). During the mid–late 1990s, the level of total biomass declined in all regions, subsequently recovering in region 5 only.

The trend in total biomass for the WCPO is largely driven by the composite biomass trends from regions 3–5 (Figure 35). Biomass declines steadily during the early model period, remains relatively stable from the mid 1970s to the early 1990s, and then declines sharply (by about 40%) during the last decade.

The comparison of biomass trends for various model options is shown in Figure 38. For the sensitivities to the Indonesian catch level and region 3 growth, the total biomass trajectories are very similar to the base-case model. This is a large difference in the overall biomass level between the current base-case model and the 2006 assessment (see Section 6.6).

A comparison of the trends in total biomass for region 3 from the base-case model and the single region model (region3 sensitivity) reveals a comparable level of biomass prior to 1970 (Figure 39). The biomass trajectories deviate in the early 1970s with the region3 model biomass increasing sharply in response to very strong increase in recruitment through the 1970s. From the late 1970s, both models reveal a comparable rate of decline in total biomass within region 3.

Overall, the region3 model provides a better fit to the principal longline CPUE trend for the region (LL ALL 3) than the base-case model. This is probably due to the assumptions of common catchability and selectivity among most of the principal longline fisheries in the entire WCPO model.

6.5.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase strongly throughout the time series, particularly during the last decade (Figure 40). The adult exploitation rates are virtually identical between the base-case and the low and high alternative Indonesian catch scenarios, while the juvenile fishing mortality rates decrease and increase for the two scenarios, respectively.

For the region3-growth scenario, exploitation rates for the juvenile component of the stock are lower than for the base-case, while adult exploitation rates are higher. This may partly relate to the difference in the assumed recruitment OGIVE between the two models (changed to account for slower growth) and/or be due to the higher overall level of recruitment for the region3-growth model resulting in a lower overall exploitation rate on the juvenile component of the stock.

For the base-case model, recent exploitation rates are high on the youngest age classes due to the impact of the PH MISC 3 and ID MISC 3 fisheries (Figure 41 and Figure 42). 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 41).

Amongst regions, exploitation rates are highest in region 3 and comparatively low in all other regions (Figure 42), with the exception of the high exploitation rates on the oldest age classes in region 1; however, this exploitation rate is applied to a very small component of the total WCPO population and has little influence on the overall exploitation rate. The recent reduction in the reported level of catch from the Indonesian fishery has resulted in a corresponding reduction in the exploitation rate on the 2–16 age classes (compare Figure 41 and Figure 42).

6.5.4 Fishery impact

We measure fishery impact at each time step as the ratio of the estimated biomass to the biomass that would have occurred in the historical absence of fishing. This is a useful variable to monitor, as it can be computed both at the region level and for the WCPO as a whole. The two trajectories are plotted in Figure 43. It is evident that the impact has been substantial in region 3 and significant impact has also occurred in region 4, with the impact increasing steadily from the early 1980s. Impacts are slight in the four sub-equatorial regions.

Overall, the impact of fishing has reduced the WCPO total biomass to about 40% of unexploited levels (Figure 44), largely driven by the impact in regions 3 and 4. Fishery impacts in region 3 have steadily increased over time and are currently reducing the biomass to about 35% of the unexploited level. By comparison, fishery impacts are relatively low in regions 1, 2, 5 and 6; less than about 20% for most of the time period, i.e. total biomass maintained at above 80% of unexploited levels.

A comparison of relative impact of fishing on the entire WCPO biomass from the various model options is presented in Figure 45. Overall fishery impacts are comparable between the scenarios presented with only the lower Indonesian catch scenario (id-low-catch) yielding a slightly more optimistic scenario during the latter period. The overall impact is considerably lower than estimated from the 2006 assessment.

It is possible to classify the fishery impact on the spawning biomass ($1-SB_t/SB_{0t}$) or total biomass ($1-B_t/B_{0t}$) to specific fishery components in order to see which types of fishing activity have the largest impact on biomass (Figure 46 and Figure 47). Within each region, the relative impacts of specific fisheries on spawning and total biomass are comparable. In region 3, the Philippines/Indonesian domestic fisheries have the greatest impact. The purse seine fishery (PS ASS 3 and PS UNS 3) had the greatest impact in the early to mid-1990s, but has since declined.

In region 4, the purse seine fishery is responsible for about half of the impact, while the Philippines/Indonesian fisheries accounts for about 25% due to the direct movement of fish from region 3 to region 4. Similarly, while the direct fishery impacts are moderately low in region 1 and region 5, the high impacts on the stock in region 3 are reducing the movement of fish to these adjacent regions. Within region1 there are the additional impacts of the pole-and-line and purse-seine fisheries (PL JP 1 & PS JP 1).

It is noteworthy that in both regions 3 and 4, the longline fishery has a relatively small impact, generally less than 10%. In the sub-equatorial regions, the longline fishery has a larger share of the impact, but overall impacts are much smaller. In these regions, the longline fishery is estimated to have depleted population biomass by no more than about 5%.

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 (5%), moderate impact from the associated (10%) and unassociated (6%) purse-seine fisheries, and highest (20%) and increasing impacts from the Philippines/Indonesian domestic fisheries.

Fishery impact can also be considered in the context of the reduction in the level of biomass available to a specific fishery (vulnerable or exploitable biomass). Trends in fishery-specific exploitable biomass, under fished and unfished conditions, were computed for four key fisheries within region 3: the distant-water longline fishery (LL ALL 3), the domestic PNG longline fishery (LL PG 3) and the associated (PS ASS 3) and unassociated (PS UNS 3) purse-seine fisheries (Figure 48). The cumulative impact of all fisheries is estimated to have substantially reduced the exploitable biomass available to the two longline fisheries and in recent years the level of exploitable biomass is only 30–40% the level that is estimated unfished biomass level. The biomass vulnerable to the unassociated purse-seine fishery is also estimated to have been impacted to a similar extent, while the impact on the associated purse-seine fishery vulnerable biomass is considerably lower (60% of the unexploited level) (Figure 48).

6.5.5 Yield analysis

Symbols used in the following discussion are defined in Table 7. The yield analyses conducted in this assessment incorporate the SRR (Figure 49) into the equilibrium biomass and yield computations. The estimated SRR steepness coefficient for the base-case is 0.62 — considerably lower than the prior mode of 0.85. This represents a moderate value of steepness and means that average recruitment is predicted to decline to 62% of the equilibrium unexploited recruitment when the level of spawning biomass is reduced to 20% of the unexploited level. However, steepness is poorly determined as indicated by the broad confidence intervals about the SRR at low levels of spawning biomass (Figure 49).

A likelihood profile of the value for steepness from the analysis using the uninformative prior (steepness-no-prior) is presented in Figure 50. The posterior probability distribution occupies a relatively broad range of values for steepness (from 0.35 to approaching 1.0) indicating the model data are relatively uninformative about the true value of steepness. Nevertheless, the mode of the distribution is at 0.53, lower than the value estimated for the base-case model. This indicates that the prior used in the base-case is somewhat constraining the model estimate of steepness. This is evident from the likelihood profile for steepness from the base-case model which occupies the range of values between the prior on steepness and the profile using the uninformative prior (Figure 50).

Equilibrium yield and biomass (spawning and total) are computed as a function of multiples of the 2002–2005 average fishing mortality-at-age (Figure 51). For the base-case model, a maximum yield (*MSY*) of 400,000 mt per annum is achieved at *fmult* = 1.05; i.e. at 1.05% of the current level of fishing effort. This represents that the ratio of $F_{current}/\widetilde{F}_{MSY}$ is equal to 0.95 (approximately 1/1.05); current exploitation rates are slightly lower than the exploitation rates to produce the *MSY*. However, the increase in yield achieved by increasing exploitation rates from $F_{current}$ to F_{MSY} is negligible (<< 1%) and, consequently, "current" exploitation rates should be viewed as equivalent to F_{MSY}. The equilibrium biomass at *MSY* is estimated at 1,489,000 mt, approximately 41% of the equilibrium unexploited biomass (Table 8).

There is considerable uncertainty regarding the equilibrium yields at and above the current level of fishing effort (*fmult*) (Figure 51). For the base-case model, the 95% confidence interval for *MSY* is 201,000–602,000 mt. Levels of uncertainty increase rapidly with increasing levels of *fmult*, largely attributable to uncertainty associated with the recruitment levels predicted from the SRR at low levels of spawning biomass (Figure 49).

For the base-case model, the reference points $F_t/\widetilde{F}_{MSY}$ and $B_t/\widetilde{B}_{MSY}$ were computed for each year (*t*) included in the model (1952–2006). 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 52). From 1952 to 1970, exploitation rates were low while total biomass declined rapidly relative to $\widetilde{B}_{MSY}$ due to a general decline in recruitment levels. Over the subsequent 25 years, the biomass level ($B_t/\widetilde{B}_{MSY}$) remained relatively constant while $F_t/\widetilde{F}_{MSY}$ steadily increased. The increase in $F_t/\widetilde{F}_{MSY}$ accelerated from the mid 1990s to recent years, reaching 1.0 in 2001 and remaining slightly below 1.0 in the subsequent years (up to 2005). During the same period, there was a rapid decline in $B_t/\widetilde{B}_{MSY}$ and total biomass has approached the overfished threshold ($\widetilde{B}_{MSY}$) in recent years (Figure 52). For the base-case model, current (2002–05) total biomass is estimated to be 10% higher than $\widetilde{B}_{MSY}$ ($B_{current}/\widetilde{B}_{MSY} = 1.10$) (Table 8).

For 2006, the last year included in the assessment model, there was an apparent improvement in the status of the stock relative to the two reference points ($F_t/\widetilde{F}_{MSY}$ and $B_t/\widetilde{B}_{MSY}$) (Figure 52). However, the improved stock status in 2006 is attributable to recent high levels of recruitment which are poorly determined and the reported decline in the yellowfin catch from the Indonesian domestic fishery. Consequently, the stock status for the 2006 year is highly uncertain and not included in the computation of "current" stock status.

For the base-case model, the maximum equilibrium yield (MSY_t) was also computed for each year (*t*) in the model. This analysis enables an assessment of the *MSY* level that would be theoretically achievable under the different patterns of age-specific fishing mortality observed through the history of the fishery (Figure 53). 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* (about 600,000 mt per annum) compared to that estimated for the fishery based on the recent age-specific fishing mortality pattern (400,000 mt). The decline in the *MSY* over time follows the increased development of those fisheries that catch smaller yellowfin, principally the surface fisheries (Figure 53).

A comparison of the yield and equilibrium biomass curves for the three model options is shown in Figure 54. For the low and high Indonesian catch scenarios and the single region model, maximum equilibrium yield was achieved at levels of *fmult* between 1.0 and 1.1 (equivalent to $F_{current}/\widetilde{F}_{MSY}$ ratios of 0.91–1.00) — comparable to the base-case model (Table 8). For the region3-growth model, *MSY* is achieved at an *fmult* of 1.3 ($F_{current}/\widetilde{F}_{MSY} = 0.77$).

For the WCPO model options, *MSY* estimates range between 377,000 and 452,000 mt per annum which is comparable with recent catch levels from the WCPO which have been of the order of 380,000–440,000 mt annually (1997–2005 average catch 408,000 mt). The only model option that estimates a significantly higher *MSY* is the sensitivity with a high steepness for the SRR (high-steepness) — a yield of 550,000 mt at an *fmult* of 1.8 (Figure 54 and Figure 55).

For the single western equatorial region (region3 model), the estimated *MSY* (268,200 mt per annum), achieved at the current level of fishing effort (i.e. *fmult* = 1.1), is lower than the recent average catch of about 320,000 mt from the region. The higher catches have been sustained by recent recruitment levels which are higher than predicted from the SRR for the region (Table 8). Nevertheless, the single region model indicates that there is no potential to expand the current yields from the core region of the entire WCPO fishery.

Hypothetical *MSY*s were computed using a single fishery selectivity based on an individual age class and the other biological parameters from the base-case assessment (natural mortality, growth, maturity OGIVE and the SRR). For each age class (1–28), the theoretical *MSY* and the associated exploitation rate were calculated (Figure 56). The peak in yield occurred when fish were harvested at age class 11 and the resulting theoretical yield was virtually double the estimate of *MSY* from the current base-case assessment. However, to achieve that yield would require an exceptionally high exploitation rate on the individual age class.

Nevertheless, the analysis shows that a smaller increase in the age of harvest, from the current average of about age class 5, could result in a considerable increase in yield from the stock without a significant increase in the level of exploitation on the individual age classes (Figure 56). The fisheries with an average age of capture less than 5 quarters include the Philippines and Indonesian domestic fisheries (PH MISC 3 & ID MISC 3), the pole-and-line fisheries (PL ALL 3 & PL JP 1), and the associated purse-seine fisheries (Figure 57).

6.5.6 Key Reference Points

A number of quantities of potential management interest associated with the yield analyses are provided in Table 8. In the top half of the table, absolute quantities are provided, while the bottom half of the table contains ratios of various biomass and fishing mortality measures that might be useful for stock monitoring purposes. It is useful to distinguish three different types of ratio: (i) ratios comparing a measure for a particular time period with the corresponding equilibrium measure; (ii) ratios comparing two equilibrium measures (rows shaded grey); and (iii) ratios comparing two measures pertaining to the same time period (row shaded black). Several commonly used reference points, such as $B_{current}/\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ fall into the first category. These ratios are usually subject to greater variability than the second category of ratios because recruitment variability is present in the numerator but not in the denominator. Indeed, the range of values observed over the various analyses conducted in recent assessments suggests that the category (ii) ratios are considerably more robust than those in category (i).

However, it is likely that $B_{current}/\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ will continue to be used as indicators of stock status and overfishing, respectively. This being the case, we need to pay particular attention to quantifying uncertainty in these ratios. Profile likelihood-based estimates of the posterior probability distribution of $B_{current}/\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ were calculated for this purpose. The profile likelihood distribution for the base-case model reveals that there is a low probability that $B_{current}/\tilde{B}_{MSY}$ is below 1.0 (6%) and that the highest probability is at about the level of the point estimate from the model (1.17) — there is a 49% probability that $B_{current}/\tilde{B}_{MSY}$ is within 1.1–1.3 (Figure 58 and Table 9). The posterior probability distribution of $F_{current}/\tilde{F}_{MSY}$ is slightly skewed with the mode of the distribution at about the point estimate of 0.95 and a 47% probability of $F_{current}/\tilde{F}_{MSY}$ exceeding 1.0 (Figure 59). Conversely, there is a similar probability (53%) that $F_{current}/\tilde{F}_{MSY}$ is less than 1.0 (Table 9) and the distribution is relatively symmetrical about the threshold level (probability $F_{current}/\widetilde{F}_{MSY}$ 0.8–1.0 equals 29.3%; probability $F_{current}/\widetilde{F}_{MSY}$ 1.0–1.2 equals 25.1%).

The comparable likelihood profiles for the sensitivity to the steepness prior (steepness-no-prior) are more pessimistic, particularly for the fishing mortality based reference point $F_{current}/\widetilde{F}_{MSY}$ (Figure 60 and Figure 61). This result is consistent with the lower mode for the likelihood profile of steepness relative to the estimate from the base-case model (Figure 50). The probability that $B_{current}/\widetilde{B}_{MSY}$ exceeds 1.0 increases to 15% (compared to 6% for the base-case) and the mode of the distribution decreases to 1.09 (compared to 1.17) (Figure 60). The mode of the posterior probability distribution of $F_{current}/\widetilde{F}_{MSY}$ is shifted to an overfishing state (1.17), while the probability that $F_{current}/\widetilde{F}_{MSY}$ exceeds 1.0 is approximately 76% (Figure 61). The lower bound of the distribution is truncated at approximately $F_{current}/\widetilde{F}_{MSY} = 0.5$ corresponding to the approximate upper bound of steepness (1.0). The truncation at the upper bound is due to numerical instability of the model as steepness values approach the lower limit of 0.2 (equivalent to a linear relationship between spawning biomass and recruitment).

6.6 Comparisons with the 2006 assessment

As noted above, there are considerable differences between the current assessment and the results of the 2006 assessment, particularly with respect to the magnitude of the recruitment and biomass levels. These differences are due to the changes in the structural assumptions of the model, principally the reconfiguration of some fisheries and size frequency data and the inclusion of additional fisheries (and catch). To explore the relative impact of each of these changes (detailed in Section 5) the current data set was reconfigured in a step-wise manner to have an equivalent configuration to the data set used in the 2006 assessment.

Overall the total biomass level from the 2006 assessment was about 67% the level of the current base-case (Figure 62). Recombining the two distant-water longline fisheries in region 3 (LL ALL 3 and LL BMK 3) reduced the overall level of biomass by about 18%. The additional combination of the PH MISC 3 and ID MISC 3 reduced the total biomass by a further 6%, while the subsequent removal of the three new fisheries in the model (PL JP 1, PS JP 1 and PL ALL 3) had very little impact. The next step of reverting to the old size data (i.e. the inclusion of all size data without rescaling based on catch distribution) resulted in a reduction in the total biomass level to that of the equivalent model run from the 2006 assessment (HIGHSAMP) and in particularly substantially lowered the peak in biomass in the late 1950s/early 1960s (Figure 62).

While the total biomass and recruitment series (not shown) between the 2007 and 2006 assessments converged by reconfigurating the data, there remain significant differences in the estimates of *MSY* and the associated *MSY*-based reference points. These are attributable to differences in the steepness parameter of the SRR between the two models; the 2006 assessment had a steepness of 0.694 compared to a steepness of 0.819 for the reconfigured 2007 assessment. Consequently, the 2006 assessment was considerably more pessimistic (lower *MSY*, higher $\widetilde{B}_{MSY}$, higher current exploitation rate relative to F_{MSY}). This result serves to illustrate that while steepness is a critical parameter in the determination of *MSY*-based reference points it is poorly determined in the assessments.

6.7 Analyses of management options

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

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

These analyses were undertaken for the 2006 assessment and repeated for the current assessment using the base-case model. Consideration of issues relating to area closures, principally with respect to bigeye tuna, is presented in a separate paper. The results of stock projections that attempt to replicate the effects of area closures applied to the purse-seine fishery are documented in other papers tabled at the Scientific Committee and Commission meetings.

6.7.1 Fishing Effort and B_{MSY}

To investigate this question, we consider the equilibrium biomass in relation to B_{MSY} so that the effects of variable recruitment on future biomass need not be considered. This is appropriate as we are simply interested in a long-term average indicator of the relationship between fishing effort, resulting biomass and B_{MSY}. The yield analysis described above provides a basis for estimating levels of equilibrium biomass that would result at different levels of relative fishing effort, assuming maintenance of the 2002–2005 overall fishery selectivity and constant catchability. The former assumption means, *inter alia*, that the relative fishing effort of each fishery defined in the assessment model remains the same as the 2002–2005 average.

Table 10 provides estimates of fishing effort scalars (relative to the 2002–2005 average) that result in equilibrium total biomass at various levels above B_{MSY}. The fishing effort scalar consistent with B_{MSY} is 1.05. In other words, the "current" level fishing effort will maintain the equilibrium biomass at a level approximately 5% higher than B_{MSY}. Progressively lower levels of fishing effort would achieve a higher equilibrium biomass relative to B_{MSY}.

6.7.2 Stock Projections

a. Effects of WCPFC-2 Conservation and Management Measures

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

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

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

- Purse seine effort levels for 2004 were assumed for the five-year projection period (2007–2011). The distribution of effort among regions, quarters and set types was specified according to the average distributions for the period 2001–2004. The use of a multi-year average distribution reduces the risk of anomalous results arising from unusually high or low effort occurring in one of these strata in an individual year.
- Longline effort levels averaged over 2001–2004 were assumed for the projection period.

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

- Relative effort levels for the Philippines and Indonesian domestic fisheries were assumed to continue through the projection period at 2006 levels (due to increases in estimated effective effort for those fisheries during 2001–2004).
- For fisheries with estimated time-series variation in catchability, the estimated catchability for the last data year (2006) was assumed to continue through the projection period.
- Recruitment during the projection period was predicted using the estimated SRR and distributed among regions based on the long-term average distribution of recruitment.

The results of the projection were expressed as the ratio of total biomass to $\widetilde{B}_{MSY}$ where the latter was computed using the F-at-age for the final year of the projection (2011). $\widetilde{B}_{MSY}$ at the end of the projection period is estimated to be 1,582,000 mt (compared to 1,631,000 mt at $F_{current}$). $B_t/\widetilde{B}_{MSY}$ for the final years of the assessment (2000–2006) and the five-year projection period is shown in Figure 63. Projected biomass and $B_t/\widetilde{B}_{MSY}$ increases towards the end of the assessment time period due to high recruitments estimated in recent years, principally for region 4 (Figure 64).

During the projection period, the total biomass is predicted to decline slightly in response to a return to long-term average recruitment and approaches equilibrium conditions above the $\widetilde{B}_{MSY}$ level at the end of the projection period ($B_{final}/\widetilde{B}_{MSY} = 1.21$) (Figure 63).

Based on the results of the 2006 assessment, specifically the profile likelihood for the biomass ratio in the final year of the projection ($B_{final}/\widetilde{B}_{MSY}$), it is likely that the variance of the probability distribution of the $B_{final}/\widetilde{B}_{MSY}$ profile will be considerably greater than that of $B_{current}/\widetilde{B}_{MSY}$ due to propagation of uncertainty in recruitment and other parameters through the projection period. Consequently, while not determined for this year's assessment, the probability of $B_{final} < \widetilde{B}_{MSY}$ is likely to be greater than for $B_{current} < \widetilde{B}_{MSY}$ (6%).

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

7 Discussion and conclusions

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

- The computation of length- and weight-frequency distributions for key fisheries (longline and equatorial purse-seine) that are representative of the spatial distribution of the catch from the fisheries. The protocols used in aggregating the size data resulted in the exclusion of a considerable proportion of the data from some fisheries. 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, for LL ALL 1 and LL ALL 2, virtually all length samples collected during that period were rejected from the model data set, while a high proportion of the weight samples collected from LL ALL 5 in the last two decades were also rejected.
- The separation of the LL ALL 3 fishery, the principal longline fishery in region 3, to include an additional historical distant-water longline fishery within an area approximating PNG

national waters (LL BMK 3). A previous analysis revealed that the historical distant-water longline fishery in PNG waters caught considerably smaller fish than the fishery operating in other areas of region 3 (Langley 2006c). Up to the 1980s, the PNG area averaged approximately 20% of the distant-water longline catch from region 3; however, the proportion of the total catch was higher during the 1950s (exceeding 50% in some quarters). The selectivity of the PNG component of the fishery was estimated independently of the other principal longline fisheries.

- The inclusion of three new fisheries that were previously unaccounted in the model: the Japanese coastal pole-and-line and purse-seine fisheries in region 1 and the composite pole-and-line fishery in region 3 (excluding Indonesia). These fisheries collectively accounted for an average catch of 15,000 mt per annum during the 1970s and 1980s, although since about 1990 catches from all three fisheries have steadily declined to a cumulative total of about 5,000 mt in recent years.
- The separation of the composite Philippines and Indonesia domestic fishery (PHID MISC 3) into two separate national fisheries (PH MISC 3 and ID MISC 3). This was undertaken on the basis that, at least for recent years, the catch estimates from the Philippines domestic fisheries are considered to be more reliable than for the comparable Indonesian fisheries. The separation of the fisheries enabled a more comprehensive examination of the sensitivity to the model to the assumed magnitude of catch from the Indonesian fishery. However, in separating the fisheries, the paucity of size data from the Indonesian fishery is highlighted and, consequently, the selectivity for the fishery is likely to be poorly determined.
- The revision of the recent (2004 onwards) annual catch estimates from the Indonesian domestic fisheries.
- The addition of recent catch, effort, and size frequency data from most fisheries.
- The current assessment included a range of sensitivity analyses, mainly assessing the implications of the assumed level of catch from the Indonesian fishery, the potential for spatial heterogeneity in growth (discussed above), and the effect of various changes in the model data structure. In addition, the sensitivity of the model to assumptions regarding the steepness parameter of the SRR was also investigated.

For the 2006 assessment, an alternative seven-region spatial stratification was also investigated. The rationale for the alternative regional stratification was to reduce the spatial heterogeneity in the CPUE and size data within each of the individual regions of the model, while also spatially segregating the Indonesian and Philippines fisheries from the other regions. However, the utility of the model was limited due to the lack of a reliable (fishery-dependent) index of abundance for this region during the latter period of the model. Some attempts were made to investigate potential sources of CPUE data for this region; however, no new data were forthcoming and, consequently, there was no opportunity to further develop the seven-region model.

The current stock assessment integrated catch, effort, length-frequency, weight-frequency and tagging data into a coherent analysis that is broadly consistent with other information on the biology and fisheries. Compared to previous assessments, there was a substantial improvement in the fit to the size (length and weight) data included in the model through the revision of the length-weight relationship and processed- to whole weight conversion factors (2006 assessment) and the application of protocols to assure the size data are representative of the catch from the fisheries (current assessment). The subdivision of the distant-water longline fishery in region 3 is also likely to have resulted in an improved fit to the longline size data from the principal fisheries (LL ALL 3–6).

Overall, the model diagnostics do not indicate any serious failure of model assumptions, although inevitably, departures from the model's assumptions were identified in several areas:

- There is a divergence in the early period (late 1950s–early 1960s) between the catch and effort data from the principal longline fishery in region 3 (LL ALL 3) and the trend in the longline exploitable biomass from the model. This is evident from the paucity of the fit to the catch data during that period. The model estimates a series of strong recruitments during that period interpreting and increase in both the observed fish size and CPUE in most of the principal longline fisheries, with the exception of the LL ALL 3 fishery. Increasing the penalty weight for the effort deviations for the LL ALL 3 fishery (region3-edevs sensitivity) resulted in an improved fit to the catch and effort data from this fishery without significantly changing the stock assessment conclusions.

- The lack of fit to the juvenile modes in the size frequency data from some fisheries may indicate a bias in the model estimates of growth for the youngest age classes. There is evidence to indicate that growth rates in the western equatorial region differ from other areas of the WCPO, particular for juvenile fish. 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. However, given that initial growth rates in the core region of the fishery (region 3) appear to be substantially over-estimated in the WCPO model, it is necessary to undertaken routine sensitivity analyses using the alternative growth parameters.
- Residuals in the tag return data for the Australian longline fishery suggested that yellowfin tuna may have patterns of residency that cannot be captured by the spatial resolution of this model. However, the excess in observed tag returns over those predicted was relatively minor in this case.
- 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.

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

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

The changes in fishery structure, particularly the subdivision of LL ALL 3, and the treatment of the size frequency data resulted in considerable differences between the current assessment and last year's (base-case) assessment (Hampton et al. 2006). These changes have influenced the underlying model population dynamics; the overall level of recruitment and, consequently, total biomass have increased although the relative trend in biomass is comparable between assessments, except for the early period of the model. For the current base-case assessment, the results are slightly more optimistic than last year, with a lower level of current fishing mortality ($F_{current}/\widetilde{F}_{MSY}$ of 0.95 compared to 1.11 from the 2006 LOWSAMP assessment and 1.00 from the 2006 HIGHSAMP assessment), while the overall levels of depletion are similar (current biomass 51% of the unexploited level). Biomass based reference points are also equivalent between the two assessments; $B_{current}/\widetilde{B}_{MSY}$ of 1.17 from the current assessment and 1.17 from the 2005 base-case. Estimates of *MSY* are considerably higher from the current assessment (400,000 mt per annum) compared to last year's assessment (328,300 mt).

From a management perspective, the most significant change between the two assessments is a shift in the point estimate of in the fishing mortality based reference point from an overfishing condition ($F_{current}/\widetilde{F}_{MSY} > 1.0$) in last year's assessment to being marginally below the overfishing threshold in the current assessment ($F_{current}/\widetilde{F}_{MSY} = 0.95$). This change is largely due to the change in the structure of the fisheries data included in the model. However, it is important to note the substantial overlap in the confidence intervals associated with the point estimates from the two assessments, particularly through the range including the F_{MSY} level ($F_{current}/\widetilde{F}_{MSY}$ between 0.8 and 1.2). This is also evident from the shape of the yield curve, which estimates yields to be within 10% of the *MSY* estimate over a range in *fmults* from 0.7 to 1.5.

The $F_{current}/\widetilde{F}_{MSY}$ and $B_{current}/\widetilde{B}_{MSY}$ reference points are relatively insensitive to large differences in the assumed historical and recent levels of catch from the Indonesian fishery. The model essentially accounts for the different levels of catch by scaling the overall level of recruitment for the stock and, consequently, varying the estimate of *MSY* accordingly. Key reference points are also comparable between the entire WCPO model and the model encompassing the core region of the fishery — the western equatorial region which accounts for over 80% of the catch.

The assumptions related to the steepness parameter of the SRR were the most crucial of the range of sensitivities investigated. The base-case assessment yields a relatively low value for steepness (0.62) largely due to the relatively high recruitment estimates from early in the model period. However, the likelihood profile indicates steepness is poorly determined and a considerably higher value of steepness is also plausible; a higher steepness results in a considerably more optimistic view of the current stock status and indicates the stock could sustain considerably higher yields. Conversely, the mode of the steepness PDF in the absence of an informative prior (0.53) is slightly lower than the estimate for the base-case assessment, in which the steepness estimate was to some extent influenced by a prior with a mode at 0.85. This unconstrained estimate of steepness is toward the lower bound of values considered plausible for tropical tunas.

The main conclusions of the current assessment are as follows.

1. For all analyses, there was a strong temporal trend in recruitment. Initial recruitment was relatively high but declined to a lower level during the early 1970s. Recruitment subsequently increased during the late-1970s and remained relatively high during the 1980s before declining in the 1990s. This pattern is similar to the results of previous assessments and is largely driven by the trends in the principal longline CPUE indices, particularly from regions 3 and 4. For the most recent years, recruitment is predicted to have increased, although recent recruitment estimates are poorly determined. Nevertheless, the estimates of stronger recruitment in recent years are generally consistent with recruitment estimates derived from a model relating yellowfin recruitment to the oceanographic conditions of the WCPO (Langley et al. in press).
2. For all analyses, the trends in biomass are generally comparable prior to the mid-1980s and were consistent with the underlying trends in recruitment, with biomass declining during the initial period to a low level in the early–mid 1970s, before increasing in the mid-1970s. Biomass levels remained relatively stable during the 1980s. For all model options, biomass is estimated to have declined steadily during the 1990s, largely due to the decline in the biomass within region 3 but also evident in most other regions. The recent estimates of strong recruitment result in a predicted increase in total biomass during the most recent years in the model; again, there is considerable uncertainty associated with the recent recruitment estimates and, therefore, recent trends in total biomass.
3. The biomass trends in the model are strongly driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. For some of the main longline fisheries (for example, 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 inconsistent information about the relative level of fishing mortality in the region. Further research is required to explore the relationship between longline CPUE and yellowfin abundance

and the methodology applied to standardise the longline CPUE data, particularly to account for temporal trends in fishing efficiency. The latter issue was examined by way of a sensitivity analysis in the 2005 assessment and shown to be highly influential in the conclusions of the assessment. There is also the potential that the size selectivity of some fisheries may have changed over time in response to changes in targeting behaviour of the longline fleet, although the stock assessment assumes selectivity is temporally invariant.

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 51% of unexploited biomass (a fishery impact of 49%) in 2002–2005. This represents a moderate level of stock-wide depletion that is approaching the equivalent equilibrium-based limit reference point ($\tilde{B}_{MSY} / \tilde{B}_0 = 0.42$). Further, depletion is somewhat greater for some individual model regions, notably in the equatorial region 3 where recent depletion levels are approximately 0.4 (a 60% reduction from the unexploited level). Other regions are less depleted, with indices of 0.8 or greater for all other regions except for region 4 (0.65). If stock-wide over-fishing criteria were applied at the level of our model regions, we would conclude that region 3 is fully exploited, region 4 is approaching full exploitation, and the remaining regions are under-exploited. The results of the single region 3 model are generally consistent with the conclusions regarding the stock status of region 3 from the entire WCPO model.

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

7. The reference points that predict the status of the stock under equilibrium conditions are $\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$ (1.10) and $S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$ (1.12), which indicate that the long-term average biomass would remain slightly above the level capable of producing MSY at 2002–2005 average fishing mortality. Overall, current biomass exceeds the biomass yielding MSY ($B_{current} / \tilde{B}_{MSY} > 1.0$); i.e. **the yellowfin stock in the WCPO is not in an overfished state**.

8. While the point estimate of $F_{current} / \tilde{F}_{MSY}$ remains slightly less than 1 (0.95), the probability distribution associated with fishing mortality based reference point is about the threshold level, with virtually equal probability that the value of $F_{current} / \tilde{F}_{MSY}$ is less than or greater than the reference point. Therefore, it is not possible to make a definitive statement as to whether or not overfishing of yellowfin is occurring in the WCPO. Nonetheless, **current exploitation rates are likely to be, at least, approaching the F_{MSY} level and any further increase in exploitation**

rates will not result in an increase in equilibrium yields from the stock under the current age specific pattern of exploitation (i.e, $\widetilde{Y}_{F_{current}}$ is approximately equal to *MSY)*. On that basis, the WCPO yellowfin tuna fishery can be considered to be fully exploited, with a substantial (47%) probability that overfishing is occurring.

9. The stock assessment conclusions differ slightly from the 2006 assessment, particularly in relation to the $F_{current}/\widetilde{F}_{MSY}$ threshold with the current assessment being slightly more optimistic than the 2006 assessment. This change is largely due to the changes in the configuration of the fisheries and their associated size data in the model. However, the stock assessment results are also highly sensitive to the assumptions relating to the steepness of the stock-recruitment relationship. The base-case assessment yields a relatively low value for steepness (which is partly constrained by an informative prior), although considerably higher values of steepness are also plausible which would result in more optimistic conclusions regarding the current stock status. On the other hand, more pessimistic conclusions ($F_{current}/\widetilde{F}_{MSY}$ =1.08; $B_{current}/\widetilde{B}_{MSY}$ =1.20) are obtained when an uninformative steepness prior is used. In this case, the estimate of steepness is based only on evidence from the data and approaches the lower limit of values considered to be plausible for tropical tunas.
10. Stock projections for 2007–2011 — that attempt to simulate the conservation and management measures adopted at WCPFC2 and WCPFC3 — indicate that the point estimate of $B_t/\widetilde{B}_{MSY}$ remains above 1.0 throughout the projection period. However, the increasing uncertainty in the future projections is likely to result in a greater probability of the biomass declining below $\widetilde{B}_{MSY}$ by the end of the projection period.

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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. Number of length frequency samples included in the 2006 and the current (2007) assessment data set for each of the key longline fisheries, by decade.

2006	Number of samples					
	LL ALL 1	LL ALL 2	LL ALL 3	LL ALL 4	LL ALL 5	LL ALL 6
1950	32	18	32	31	23	10
1960	39	14	40	37	40	17
1970	34	34	40	40	32	22
1980	26	28	37	40	13	3
1990	38	35	40	40	37	15
2000	15	17	24	24	24	12

2007	Number of samples					
	LL ALL 1	LL ALL 2	LL ALL 3	LL ALL 4	LL ALL 5	LL ALL 6
1950	24	8	31	28	20	10
1960	13	1	34	21	29	9
1970	0	5	15	18	13	4
1980	0	0	1	6	0	7
1990	0	0	1	8	3	16
2000	0	0	4	2	0	2

Table 3. Number of weight frequency samples included in the 2006 and the current (2007) assessment data set for each of the key longline fisheries, by decade.

2006	Number of samples					
	LL ALL 1	LL ALL 2	LL ALL 3	LL ALL 4	LL ALL 5	LL ALL 6
1950	14	13	13	13	10	3
1960	38	38	40	40	36	15
1970	39	28	40	40	35	16
1980	40	33	40	40	38	14
1990	40	40	40	38	30	5
2000	19	17	24	18	21	5

2007	Number of samples					
	LL ALL 1	LL ALL 2	LL ALL 3	LL ALL 4	LL ALL 5	LL ALL 6
1950	12	6	12	11	8	2
1960	25	24	39	34	19	7
1970	11	24	25	29	17	1
1980	24	21	33	29	27	18
1990	18	18	29	12	4	12
2000	13	9	22	7	0	0

Table 4. Main structural assumptions of the yellowfin tuna base-case analysis and details of estimated parameters, priors and bounds. Note that the number of estimated parameters shown is substantially greater than the effective number of parameters in a statistical sense because of the effects of priors, bounds and smoothing penalties.

Category	Assumptions	Estimated parameters (ln = log transformed parameter)	No.	Prior		Bounds	
				μ	σ	Low	High
Observation model for total catch data	Observation errors small, equivalent to a residual SD on the log scale of 0.07.	None	na	na	na	na	na
Observation model for length-frequency data	Normal probability distribution of frequencies with variance determined by effective sample size and observed frequency. Effective sample size assumed to be 0.1 times actual sample size for all fisheries with a maximum effective sample size of 100.	None	na	na	na	na	na
Observation model for weight-frequency data	Normal probability distribution of frequencies, variance determined by effective sample size and observed frequency. Effective sample size assumed to be equal to 0.02 times the actual sample size for all fisheries with a maximum effective sample size of 20.	None	na	na	Na	na	na
Observation model for tagging data	Tag numbers in a stratum have negative binomial probability distribution, with estimated variance parameters for fishery groups.	Variance parameters	3	-	-	0	100
Tag reporting	Purse seine reporting rates constrained to be equal within regions. 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 (beta prior for steepness with mode at 0.85 and SD of 0.16, lower bound 0.2) .The spatial distribution of recruitment in each quarter is allowed to vary with a small penalty on deviations from the average spatial distribution.	Average spatially aggregated recruitment (ln)	1	-	-	-20	20
		Spatially aggregated recruitment deviations (ln)	220	SRR	0.7	-20	20
		Average spatial distribution of recruitment	5	-	-	0	1
		Time series deviations from average spatial distribution (ln)	1,090	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)	54	0	0.7	-0.8	0.8
		Catchability deviations other (ln)	218	0	0.1	-0.8	0.8
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.1 for LL ALL 1–6 & LL BMK 3 and SD 0.22 for other fisheries at the average level of effort for each fishery. SD inversely proportional to the square root of effort.	Effort deviations LL 1, 2, 4, 7, 10, 12 (ln)	1286	0	0.16	-6	6
		Effort deviations PH, ID (ln)	444	0	0.22	-6	6
		Effort deviations other (ln)	1687	0	0.22	-6	6
Natural mortality	Age-dependent but constant over time and among regions. All parameters are specified (see Figure 12).	Average natural mortality (ln)	0	-	-	-	-
		Age-specific deviations (ln)	0	-	-	-	-
Movement	Age-independent and variant by quarter but constant among years. No age-dependent variation.	Movement coefficients	56	0	0.32	0	3
		Age-dependent component (ln)	0	0	0.32	-4	4
Maturity	Age-dependent and specified – age-class 0-6: 0; 7: 0.25; 8: 0.5; 9: 0.75; 10-28: 1.0	None	na	na	na	0	1

Table 5. Summary of the range of model options investigated.

Scenario	Description	Rationale
base-case	24 fisheries, new size data aggregation, new ID catch, separate LL 3 fishery (Bismarck Sea), JP PL 1, JP PS 1, PL 3.	
region3-growth	Base-case data set with growth and M fixed based on growth estimated from single region 3 MFCL model.	Sensitivity to growth.
old-size	Determine LL size distributions as per 2006 assessment.	Sensitivity to new methodology of combining size data weighted by spatial distribution of the catch.
id-old-catch	Compare effect of change in ID MISC 3 catch from 2006 assessment.	Sensitivity to uncertainty regarding ID catch.
id-low-catch	Approx. 50% decrease in ID MISC 3 catch throughout catch history.	Sensitivity to uncertainty regarding ID catch.
id-high-catch	50% increase in ID MISC 3 catch throughout catch history.	Sensitivity to uncertainty regarding ID catch.
region3-edevs	Increase penalty weight on effort deviates for LL 3 fishery (from -50 to 200).	Improve fit to the catch/effort data from the principal LL index (LL ALL 3).
ex-newfish	Exclude JP PL 1, JP PS 1, and PL 3 from base-case data set.	Assess impact on inclusion of additional catch.
recombine-LL3	Recombine LL ALL 3 and LL BMK 3 fisheries (23 fisheries).	Assess impact of splitting LL ALL 3 fishery.
recombine-LL3&PHID	Recombine LL ALL 3 & LL BMK 3 fisheries and ID MISC 3 & PH MISC 3 fisheries (22 fisheries).	Assess impact of splitting LL ALL 3 fishery and PHID MISC 3 fishery.
region3	Single region model encompassing MFCL region 3 only. 10 fisheries and 13 tag release groups.	Assess the influence of data from the peripheral regions of the WCPO on the key stock assessment conclusions for the main region of the fishery.
high-steepness	Steepness of the SRR of 0.913 (compared to the estimated value of 0.6215).	Examine the influence of steepness on the biological reference points.
steepness-no-prior	Replace the beta-distribution prior on steepness used in the base-case with a uniform, uninformative prior.	Examine the influence of steepness on the biological reference points.

Table 6. Details of objective function components for the base-case model and three of the sensitivity analyses.

Objective function component	**base-case**	**ID-low-catch**	**ID-high-catch**	**region3-growth**
Total catch log-likelihood	598.80	595.90	600.18	638.50
Length frequency log-likelihood	-349,920.62	-349,876.45	-349,936.53	-350,030.85
Weight frequency log-likelihood	-760,710.15	-760,709.29	-760,713.94	-759,670.09
Tag log-likelihood	2,618.91	2,606.04	2,632.90	3,118.94
Penalties	7,152.87	7,148.73	7,157.87	7,331.48
Total function value	-1,100,260.19	-1,100,235.07	-1,100,259.52	-1,098,612.02

Table 7. Description of symbols used in the yield analysis.

Symbol	**Description**
$F_{current}$	Average fishing mortality-at-age for 2002–2005
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 (2002–2005) total biomass
$SB_{current}$	Average current (2002–2005) adult biomass
B_{1995}	Average total biomass in 1995
SB_{1995}	Average adult biomass in 1995
$B_{current,F=0}$	Average current (2002–2005) total biomass in the absence of fishing.

Table 8. Estimates of management quantities for the three stock assessment models. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading).

Management quantity	Units	base-case	ID-low-catch	ID-high-catch	region3-growth	high-steepness	Steepness-no-prior	region3
$\tilde{Y}_{F_{current}}$	mt per year	399,960	376,760	449,200	406,800	481,200	337,400	268,120
$\tilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	400,000	376,760	452,400	422,000	549,200	344,520	268,200
$\tilde{B}_0$	mt	3,665,000	3,420,000	4,002,000	3,440,000	3,528,000	3,735,000	1,881,000
$\tilde{B}_{F_{current}}$	mt	1,631,000	1,536,000	1,773,000	1,762,000	1,945,000	1,372,000	850,200
$\tilde{B}_{MSY}$	mt	1,489,000	1,536,000	1,626,000	1,476,000	1,275,000	1,203,000	802,600
$\tilde{SB}_0$	mt	2,171,000	2,017,000	2,372,000	2,306,000	2,086,000	2,209,000	1,261,000
$\tilde{SB}_{F_{current}}$	mt	763,600	713,700	830,600	956,900	907,700	641,200	420,800
$\tilde{SB}_{MSY}$	mt	679,800	713,700	742,600	750,700	482,000	548,000	386,700
$B_{current}$	mt	1,821,671	1,728,256	2,010,322	1,884,754	1,805,380	1,815,953	1,028,022
$SB_{current}$	mt	850,210	797,860	935,146	1,011,554	839,100	846,622	511,528
$B_{current,F=0}$	mt	3,594,445	3,253,999	3,938,575	3,480,678	3,109,349	3,910,865	2,195,727
$B_{current}/\tilde{B}_0$		0.50	0.51	0.50	0.55	0.51	0.49	0.55
$B_{current}/\tilde{B}_{F_{current}}$		1.12	1.13	1.13	1.07	0.93	1.32	1.21
$B_{current}/\tilde{B}_{MSY}$		1.17	1.13	1.24	1.28	1.42	1.20	1.28
$B_{current}/B_{current,F=0}$		0.51	0.53	0.51	0.54	0.58		0.47
$SB_{current}/\tilde{SB}_0$		0.39	0.40	0.39	0.44	0.40	0.38	0.41
$SB_{current}/\tilde{SB}_{F_{current}}$		1.11	1.12	1.13	1.06	0.92	1.32	1.22
$SB_{current}/\tilde{SB}_{MSY}$		1.25	1.12	1.26	1.35	1.74	1.54	1.32
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.45	0.45	0.44	0.51	0.55	0.37	0.45
$\tilde{SB}_{F_{current}}/\tilde{SB}_0$		0.35	0.35	0.35	0.41	0.44	0.29	0.33
$\tilde{B}_{MSY}/\tilde{B}_0$		0.41	0.45	0.41	0.43	0.36	0.32	0.43
$\tilde{SB}_{MSY}/\tilde{SB}_0$		0.31	0.35	0.31	0.33	0.23	0.25	0.31
$F_{current}/\tilde{F}_{MSY}$		0.95	1.00	0.91	0.77	0.56	0.92	0.91
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.10	1.00	1.09	1.19	1.53	1.14	1.06
$\tilde{SB}_{F_{current}}/\tilde{SB}_{MSY}$		1.12	1.00	1.12	1.27	1.88	1.17	1.09
$\tilde{Y}_{F_{current}}/MSY$		1.00	1.00	0.99	0.96	0.88	0.98	1.00
$B_{current}/B_{1995}$		0.65	0.66	0.66	0.73	0.65	0.65	0.82
$SB_{current}/SB_{1995}$		0.58	0.59	0.59	0.64	0.58	0.58	0.72

Table 9. Percentage probability that $B_{current}/\widetilde{B}_{MSY}$ and $F_{current}/\widetilde{F}_{MSY}$ exceed the reference value based on the likelihood profile of the base-case model.

Reference level	Probability (%) of exceeding reference level	
	$B_{current}/\widetilde{B}_{MSY}$	$F_{current}/\widetilde{F}_{MSY}$
0.5	100.0	99.7
0.6	100.0	95.5
0.7	100.0	87.5
0.8	100.0	76.1
0.9	98.9	62.2
1.0	92.7	46.8
1.1	74.6	33.0
1.2	48.8	21.7
1.3	25.7	13.5
1.4	12.3	8.3
1.5	5.2	5.2
1.6	2.0	3.3
1.7	0.7	2.3
1.8	0.2	1.5
1.9	0.0	1.0
2.0	0.0	0.7
2.1	0.0	0.6
2.2	0.0	0.5
2.3	0.0	0.4
2.4	0.0	0.3
2.5	0.0	0.3

Table 10. Fishing effort scalars relative to the 2002-2005 average required to produce equilibrium total and spawning biomass at various levels above B_{MSY}.

Equilibrium biomass relative to B_{MSY}	**Equilibrium biomass relative to $\widetilde{B}_0$**	**Equilibrium biomass relative to $\widetilde{SB}_0$**	**Fishing Effort Scalar relative to 2002-2005 average**
1.00	0.42	0.33	1.05
1.05	0.44	0.35	1.00
1.10	0.47	0.38	0.94
1.15	0.49	0.40	0.89
1.20	0.51	0.42	0.84
1.25	0.53	0.44	0.79
1.30	0.55	0.46	0.75
1.35	0.57	0.49	0.70
1.40	0.59	0.51	0.66

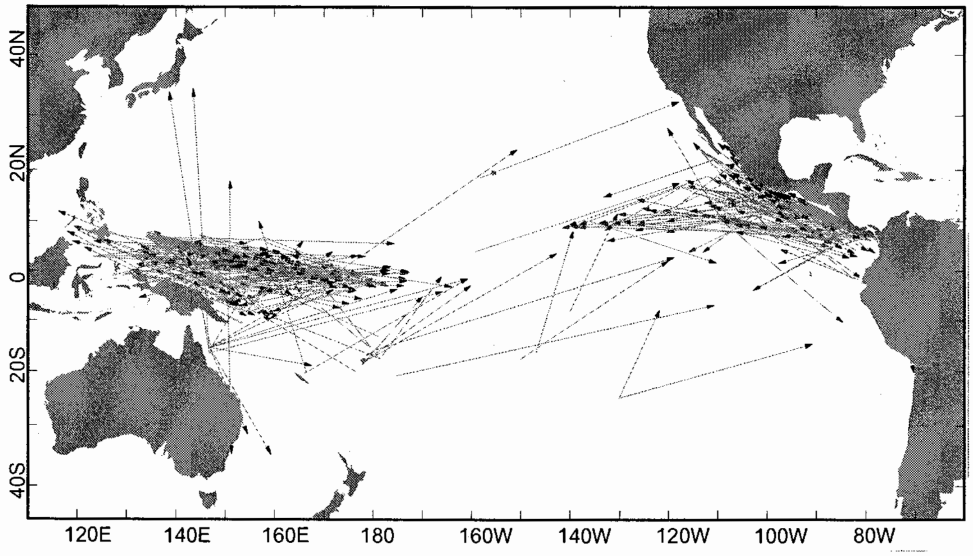


Figure 1. Long-distance (greater than 1,000 nmi) movements of tagged yellowfin tuna.

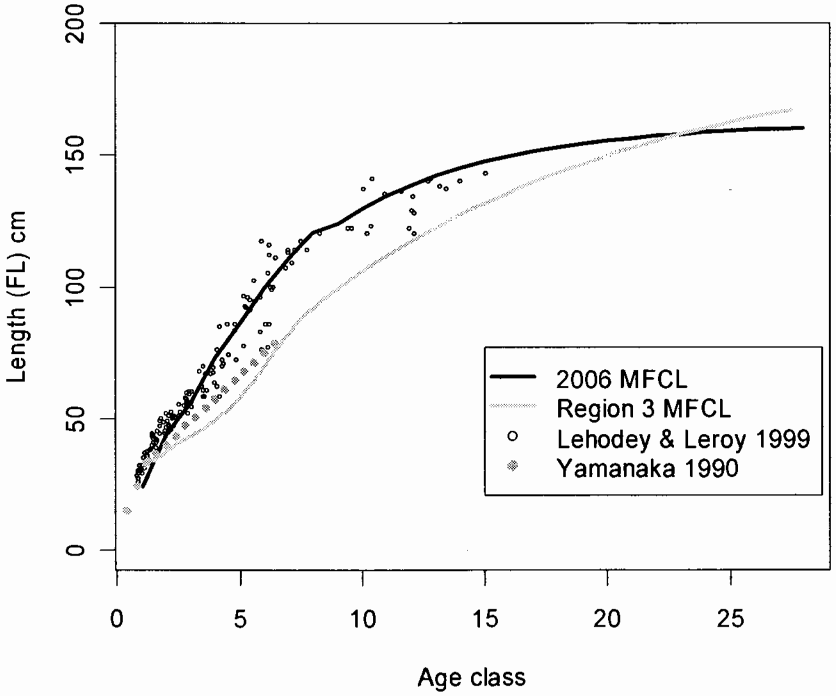


Figure 2. A comparison of yellowfin growth estimated from WCPO and region 3 MFCL models and the results from ageing studies using otolith daily increments.

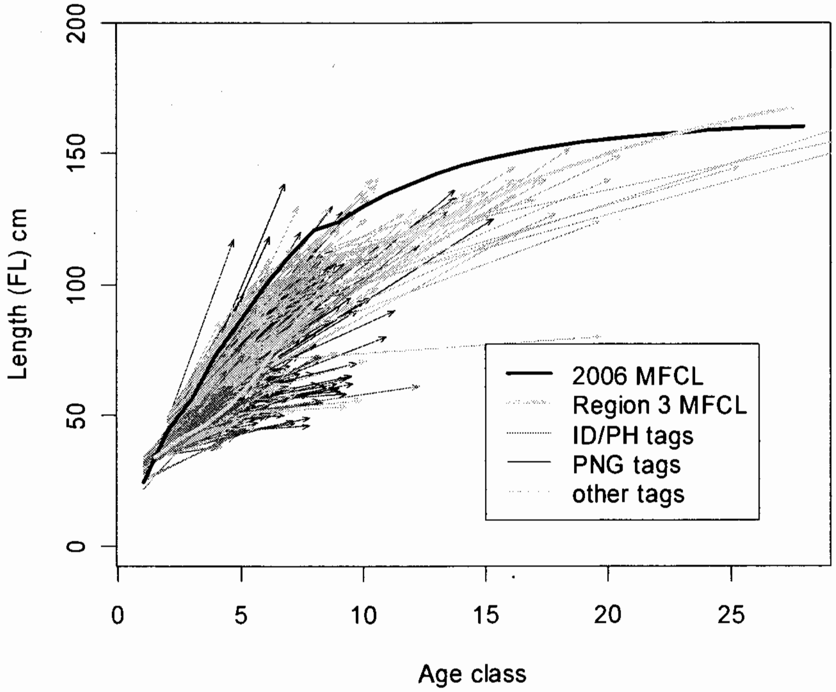


Figure 3. A comparison of yellowfin growth estimated from WCPO and region 3 MFCL models with growth increments from tagged fish released in Indonesian/Philippines waters, PNG waters, and other areas.

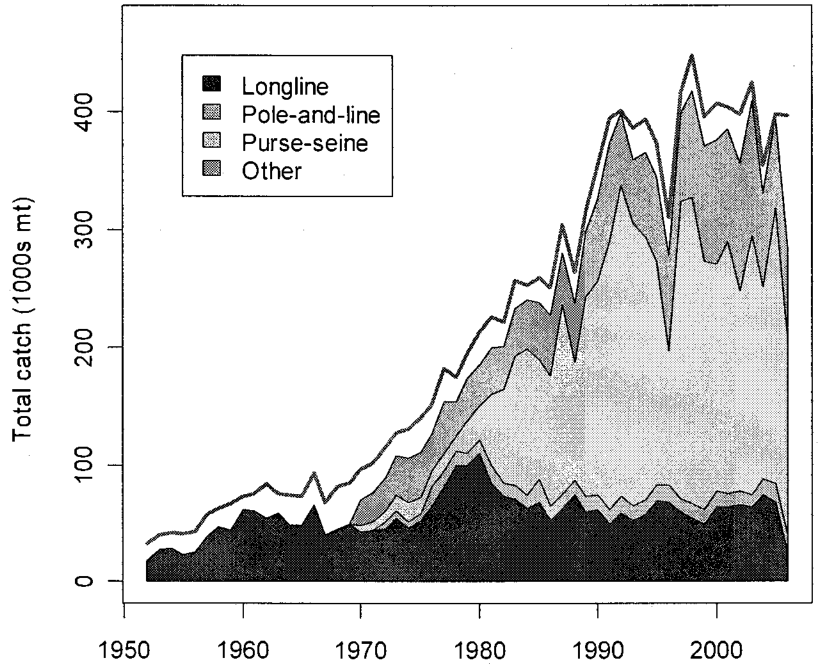


Figure 4. Total annual catches (1000s mt) of yellowfin from the WCPO by fishing method from 1952 to 2006. The "Other" category represents catches from the domestic fisheries of Indonesia and the Philippines. Data from 2006 are incomplete. The purple line represents the total annual catch estimates for the WCPO.

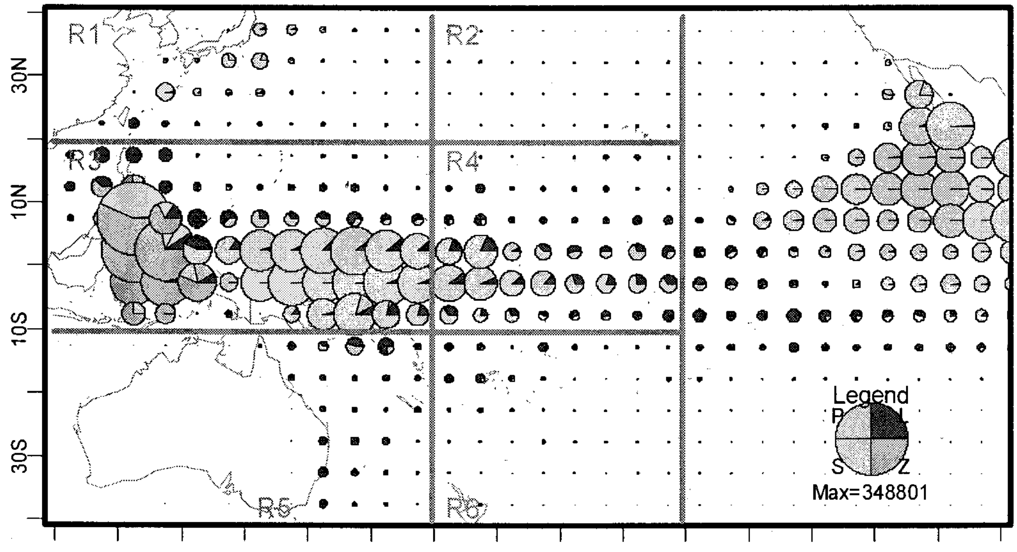


Figure 5. Distribution of cumulative yellowfin tuna catch from 1990–2005 by 5 degree squares of latitude and longitude and fishing gear; longline (L, blue), purse-seine (S, green), pole-and-line (P, grey) and other (Z, dark orange). The grey lines indicate the spatial stratification.

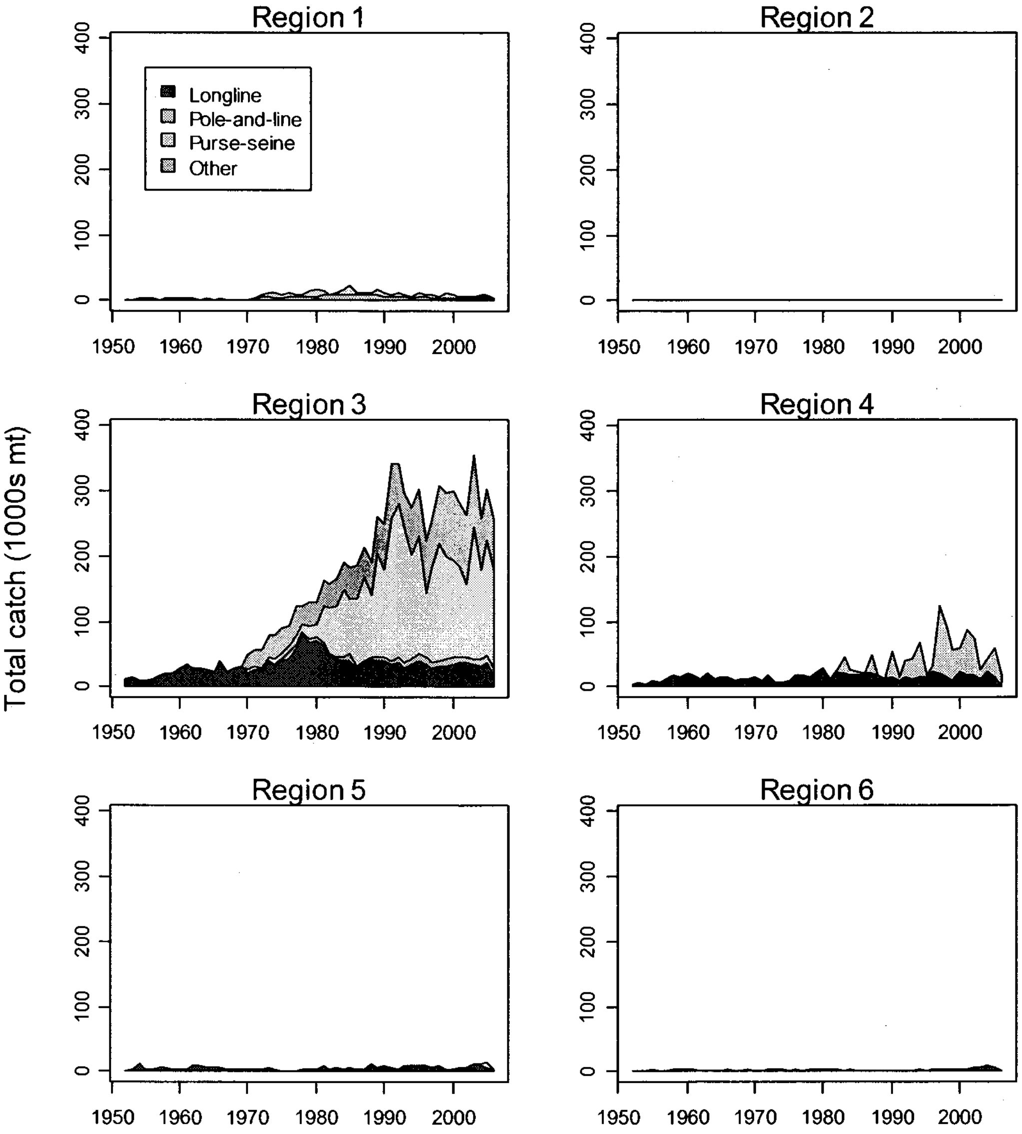
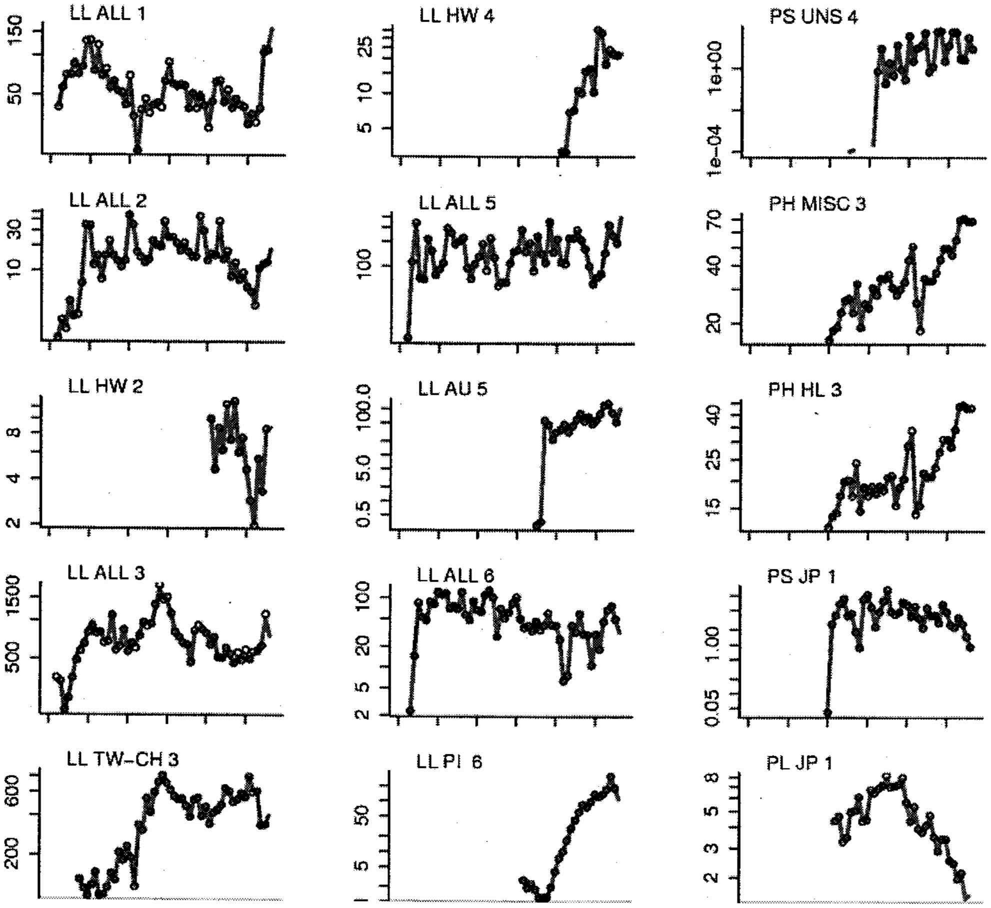


Figure 6. Total annual catch (1000s mt) of yellowfin by fishing method and MFCL region from 1952 to 2006. The "Other" category represents catches from the domestic fisheries of Indonesia and the Philippines. Data from 2006 are incomplete.



LL ALL 1
150
50
LL HW 4
25
10
5
PS UNS 4
1e+00
1e−04
LL ALL 2
30
10
LL ALL 5
100
PH MISC 3
70
40
20
LL HW 2
8
4
2
LL AU 5
100.0
5.0
0.5
PH HL 3
40
25
15
LL ALL 3
1500
500
LL ALL 6
100
20
5
2
PS JP 1
1.00
0.05
LL TW−CH 3
600
200
LL PI 6
50
5
1
PL JP 1
8
5
3
2

SCIENTIFIC COMMITTEE
THIRD REGULAR SESSION

13-24 August 2007
Honolulu, United States of America

Stock assessment of yellowfin tuna in the western and central Pacific Ocean, including an analysis of management options

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WCPFC-SC3-SA SWG/WP-01

Adam Langley[1], John Hampton[1], Pierre Kleiber[2] and Simon Hoyle[1]

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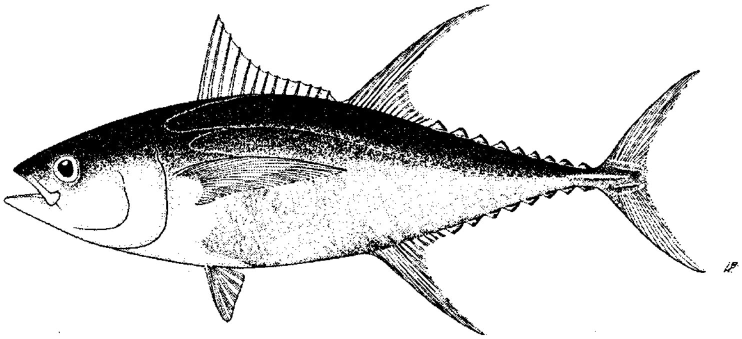
[1] Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia
[2] Pacific Islands Fishery Science Center, National Marine Fisheries Service, Honolulu, Hawaii, USA.

WCPFC–SC3 **SA WP–1**

Stock assessment of yellowfin tuna in the western and central Pacific Ocean, including an analysis of management options



Adam Langley[1], John Hampton[1], Pierre Kleiber[2] and Simon Hoyle[1]

[1]Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia.
[2]Pacific Islands Fishery Science Center, National Marine Fisheries Service, Honolulu, Hawaii, USA.

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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 1997, the total yellowfin tuna catch in the WCPO has varied between 350,000 and 450,000 mt. Purse seiners harvest the majority of the yellowfin tuna catch (54% by weight in 2005), with the longline and pole-and-line fisheries comprising 15% and 3% of the total catch, respectively. Yellowfin tuna usually represent approximately 20–25% of the overall purse-seine catch and may contribute higher percentages of the catch in individual sets. Yellowfin tuna is often directly targeted by purse seiners, especially as unassociated schools which accounted for 56% of recent (2000–2005) yellowfin purse-seine catch (by weight).

Longline catches in recent years (60,000–80,000 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 30% of total WCPO yellowfin tuna catches.

This paper presents the 2007 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 2006.

The catch, size and tagging data used in the assessment were similar those used last year, although there were a number of significant changes to the configuration of the fisheries and associated size-frequency data; the main changes were the inclusion of three new fisheries (an equatorial pole-and-line fishery and Japanese coastal pole-and-line and purse-seine fisheries), separation of the Philippines and Indonesian domestic fisheries, the subdivision of the principal longline fishery in region 3 (LL ALL 3), and the treatment of the length- and weight-frequency data collected from the main longline and purse-seine fisheries. The model also includes that additional recent fishery data (2005 for longline, 2005 for Philippines and Indonesia, and 2006 for purse seine) were included. It should be noted that 2006 data are not complete for some fisheries. The estimation of standardised effort for the main longline fisheries used the GLM approach similar to recent assessments.

The current assessment included a range of sensitivity analyses, mainly assessing the implications of the assumed level of catch from the Indonesian fishery, the potential for spatial heterogeneity in growth, and the effect of various changes in the model data structure. The sensitivity of the model to assumptions regarding the steepness parameter of the SRR was also investigated. In addition, a separate model was constructed based on a single-region encompassing the western equatorial region (MFCL region 3) — the core region of the fishery.

The main conclusions of the current assessment are as follows:

1. For all analyses, there was a strong temporal trend in recruitment. Initial recruitment was relatively high but declined to a lower level during the early 1970s. Recruitment subsequently increased during the late-1970s and remained relatively high during the 1980s before declining in the 1990s. This pattern is similar to the results of previous assessments and is largely driven by the trends in the principal longline CPUE indices, particularly from regions 3 and 4. For the most recent years, recruitment is predicted to have increased, although recent recruitment estimates are poorly determined. Nevertheless, the estimates of stronger recruitment in recent years are

generally consistent with recruitment estimates derived from a model relating yellowfin recruitment to the oceanographic conditions of the WCPO.

2. For all analyses, the trends in biomass are generally comparable prior to the mid-1980s and were consistent with the underlying trends in recruitment, with biomass declining during the initial period to a low level in the early–mid 1970s, before increasing in the mid-1970s. Biomass levels remained relatively stable during the 1980s. For all model options, biomass is estimated to have declined steadily during the 1990s, largely due to the decline in the biomass within region 3 but also evident in most other regions. The recent estimates of strong recruitment result in a predicted increase in total biomass during the most recent years in the model; again, there is considerable uncertainty associated with the recent recruitment estimates and, therefore, recent trends in total biomass.

3. The biomass trends in the model are strongly driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. For some of the main longline fisheries (for example, 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 inconsistent information about the relative level of fishing mortality in the region. Further research is required to explore the relationship between longline CPUE and yellowfin abundance and the methodology applied to standardise the longline CPUE data, particularly to account for temporal trends in fishing efficiency. The latter issue was examined by way of a sensitivity analysis in the 2005 assessment and shown to be highly influential in the conclusions of the assessment. There is also the potential that the size selectivity of some fisheries may have changed over time in response to changes in targeting behaviour of the longline fleet, although the stock assessment assumes selectivity is temporally invariant.

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 51% of unexploited biomass (a fishery impact of 49%) in 2002–2005. This represents a moderate level of stock-wide depletion that is approaching the equivalent equilibrium-based limit reference point ($\widetilde{B}_{MSY} / \widetilde{B}_0$ = 0.42). Further, depletion is somewhat greater for some individual model regions, notably in the equatorial region 3 where recent depletion levels are approximately 0.4 (a 60% reduction from the unexploited level). Other regions are less depleted, with indices of 0.8 or greater for all other regions except for region 4 (0.65). If stock-wide over-fishing criteria were applied at the level of our model regions, we would conclude that region 3 is fully exploited, region 4 is approaching full exploitation, and the remaining regions are under-exploited. The results of the single region 3 model are generally consistent with the conclusions regarding the stock status of region 3 from the entire WCPO model.

6. The attribution of depletion to various fisheries or groups of fisheries indicates that the Indonesian and Philippines domestic fisheries have the greatest impact, particularly in its home region (3) and is contributing significantly to the impact in adjacent regions 1, 4 and 5. The purse seine fishery also has a high impact in regions 3 and 4 and accounts for a significant component

of the recent impacts in all other regions, except region 6. Historically, the coastal Japanese pole-and-line and purse-seine fisheries have had a significant impact on biomass levels in their home region (1). It is notable that the composite longline fishery is responsible for biomass depletion of about 10% in the WCPO during recent years.

7. The reference points that predict the status of the stock under equilibrium conditions are $\widetilde{B}_{F_{current}}/\widetilde{B}_{MSY}$ (1.10) and $\widetilde{SB}_{F_{current}}/\widetilde{SB}_{MSY}$ (1.12), which indicate that the long-term average biomass would remain slightly above the level capable of producing *MSY* at 2002–2005 average fishing mortality. Overall, current biomass exceeds the biomass yielding *MSY* ($B_{current}/\widetilde{B}_{MSY} > 1.0$); i.e. **the yellowfin stock in the WCPO is not in an overfished state**.

8. While the point estimate of $F_{current}/\widetilde{F}_{MSY}$ remains slightly less than 1 (0.95), the probability distribution associated with fishing mortality based reference point is about the threshold level, with virtually equal probability that the value of $F_{current}/\widetilde{F}_{MSY}$ is less than or greater than the reference point. Therefore, it is not possible to make a definitive statement as to whether or not overfishing of yellowfin is occurring in the WCPO. Nonetheless, **current exploitation rates are likely to be, at least, approaching the F_{MSY} level and any further increase in exploitation rates will not result in an increase in equilibrium yields from the stock** under the current age specific pattern of exploitation (i.e, $\widetilde{Y}_{F_{current}}$ is approximately equal to *MSY)*. On that basis, the WCPO yellowfin tuna fishery can be considered to be fully exploited, with a substantial (47%) probability that overfishing is occurring.

9. The stock assessment conclusions differ slightly from the 2006 assessment, particularly in relation to the $F_{current}/\widetilde{F}_{MSY}$ threshold with the current assessment being slightly more optimistic than the 2006 assessment. This change is largely due to the changes in the configuration of the fisheries and their associated size data in the model. However, the stock assessment results are also highly sensitive to the assumptions relating to the steepness of the stock-recruitment relationship. The base-case assessment yields a relatively low value for steepness (which is partly constrained by an informative prior), although considerably higher values of steepness are also plausible which would result in more optimistic conclusions regarding the current stock status. On the other hand, more pessimistic conclusions ($F_{current}/\widetilde{F}_{MSY} = 1.08$; $B_{current}/\widetilde{B}_{MSY} = 1.20$) are obtained when an uninformative steepness prior is used. In this case, the estimate of steepness is based only on evidence from the data and approaches the lower limit of values considered to be plausible for tropical tunas.

10. Stock projections for 2007–2011 — that attempt to simulate the conservation and management measures adopted at WCPFC2 and WCPFC3 — indicate that the point estimate of $B_t/\widetilde{B}_{MSY}$ remains above 1.0 throughout the projection period. However, the increasing uncertainty in the future projections is likely to result in a greater probability of the biomass declining below $\widetilde{B}_{MSY}$ by the end of the projection period.

1 Introduction

This paper presents the current stock assessment of yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean (WCPO, west of 150°W). Since 1999, the assessment has been conducted annually and the most recent assessments are documented in Hampton and Kleiber (2003) and Hampton et al. (2004, 2005 and 2006). The current assessment incorporates the most recent data from the yellowfin fishery and, essentially, represents an update of the assessment undertaken in 2006. In addition, a range of sensitivity analyses are presented, including consideration of a single-region model in encompassing the western equatorial region (MFCL region 3) — the core region of the fishery.

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

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

2 Background

2.1 Biology

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

Yellowfin tuna are relatively fast growing, and have a maximum fork length (FL) of about 180 cm. The growth of juveniles departs from von Bertalanffy type growth with the growth rate slowing between about 40 and 70 cm FL (Lehodey and Leroy 1999).

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 unpublished) (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 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 1997, the total yellowfin tuna catch in the WCPO has varied between 350,000 and 450,000 mt (Figure 4). Purse seiners harvest the majority of the yellowfin tuna catch (54% by weight in 2005), with the longline and pole-and-line fisheries comprising 15% and 3% of the total catch, respectively. Yellowfin tuna usually represent approximately 20–25% of the overall purse-seine catch and may contribute higher percentages of the catch in individual sets. Yellowfin tuna is often directly targeted by purse seiners, especially as unassociated schools which accounted for 56% of recent (2000–2005) yellowfin purse-seine catch (by weight).

Longline catches in recent years (60,000–80,000 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 30% of total WCPO yellowfin tuna catches.

Figure 5 shows the spatial distribution of yellowfin tuna catch in the WCPO for the past 15 years. Most of the catch is taken in western equatorial areas, with declines in both purse-seine and longline catch towards the east. The east-west distribution of catch is strongly influenced by ENSO events, with larger catches taken east of 160°E during *El Niño* episodes. Catches from outside the equatorial region are relatively minor (5%) and are dominated by longline catches south of the equator and purse-seine and pole-and-line catches in the north-western area of the WCPO (Figure 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 base-case assessment is equivalent to that used in the 2006 assessment.

3.2 Temporal stratification

The time period covered by the assessment is 1952–2006. 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 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).

Previous assessments have not included the yellowfin catch from the seasonal purse-seine and pole-and-line 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. These fisheries were included separately in the current assessment (PS JP 1 and PL JP 1).

Further, an additional pole-and-line fishery was included within MFCL region 3 to incorporate 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).

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 7). 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 WCPO (Figure 4) due to the difficulties in spatially separating some of the aggregated catch estimates. For 1990–2005, model catches represent 95% of the total WCPO 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).

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

Effort data units for purse seine fisheries are defined as days fishing and/or searching, allocated to set types based on the proportion of total sets attributed to a specified set type (associated or unassociated sets) in logbook data. 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 or LL ALL 1–7), effective (or standardised) effort was derived using generalized linear models (GLM) (Langley et al. 2005). Time-series of catch-per-unit-effort (CPUE) for all fisheries are shown in Figure 8. The GLM standardised CPUE for the principal longline fisheries are presented in Figure 9.

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 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.

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

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 10. The data were collected from a variety of sampling programmes, which can be summarized as follows:

<u>Philippines:</u> Size composition data for the Philippines domestic fisheries derived from a sampling programme conducted in the Philippines in 1993–94 were augmented with data from the 1980s and for 1995. In addition, data collected during 1997–2006 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. For each purse seine fishery, size samples were combined within temporal strata weighted by the spatial distribution of the catch (see below).

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.

In previous assessments, length (and weight) 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. For the current assessment, quarterly length frequency distributions were computed for the principal longline fisheries and the equatorial purse-seine 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, while purse-seine size data were generally aggregated by 5 degrees of latitude and 5 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 or 5*5 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 (Table 2).

3.6 Weight-frequency data

A large data set of individual fish weights are available 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 10. The same protocol for the aggregation of the length data were 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 (Table 3).

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 include the tag release and recovery data from the 2006–07 tagging programme undertaken in PNG waters.

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 4. In addition, we describe the procedures followed for estimating the parameters of the model and the way in which stock assessment conclusions are drawn using a series of reference points.

4.1 Population dynamics

The six-region model partitions the population into 6 spatial regions and 28 quarterly age-classes. The first age-class has a mean fork length of around 25 cm and is approximately three months of age according to analysis of daily structures on otoliths (Lehodey and Leroy 1999). The last age-class comprises a "plus group" in which mortality and other characteristics are assumed to be constant. For the purpose of computing the spawning biomass, we assume a fixed maturity schedule (Table 4) consistent with the observations of Itano (2000). The population is "monitored" in the model at quarterly time steps, extending through a time window of 1952–2006. The main population dynamics processes are as follows:

4.1.1 Recruitment

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

The distribution of recruitment among the six model regions was estimated within the model and allowed to vary over time in a relatively unconstrained fashion. Stronger constraints were placed on the variation of the spatial distribution of recruitment in the initial 5 years of the time series. The time-series variation in spatially-aggregated recruitment was somewhat constrained by a lognormal prior. The variance of the prior was set such that recruitments of about three times and one third of the average recruitment would occur about once every 25 years on average.

Spatially-aggregated recruitment was assumed to have a weak relationship with the spawning biomass via a Beverton and Holt stock-recruitment relationship (SRR). The SRR was incorporated mainly so that yield analysis and stock projections could be undertaken for stock assessment purposes. We therefore opted to apply a relatively weak penalty for deviation from the SRR so that it would have only a slight effect on the recruitment and other model estimates (see Hampton and Fournier 2001, Appendix D).

Typically, fisheries data are not very informative about SRR parameters and it is generally necessary to constrain the parameterisation in order to have stable model behaviour. We incorporated a beta-distributed prior on the "steepness" (S) of the SRR, with S defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Francis 1992; Maunder and Watters 2001). The beta-distribution of the prior has a lower bound at 0.2, a mode = 0.85, and standard deviation = 0.16 (Figure 11).

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 4). 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.

In addition, an alternative growth model was included as a sensitivity analysis (see Section 5). The growth model was derived from a MFCL model that included only the single western, equatorial region (region 3) with the growth parameters estimated in an equivalent manner to that described above. The resulting growth model exhibited slower growth than the growth model estimated by Hampton et al. (2006) but was more consistent with the growth of yellowfin in the southern Philippines waters (Yamanaka 1990) and with the results of tagging studies.

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 2×7×4 = 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 Natural mortality

Natural mortality (*M*) was held fixed at pre-determined age-specific levels as applied in the 2006 assessment. *M*-at-age was determined externally of the MULTIFAN-CL model using estimates of *M* by length category from tagging data, sex-ratio data and the assumed maturity-at-age schedule. An identical procedure is used to determine fixed *M*-at-age for assessments in the EPO (Maunder 2005). Essentially, this method reflects the hypothesis that the higher proportion of males in sex-ratio samples with increasing length is due to the higher natural mortality of females after they reach maturity. The externally-estimated *M*-at-age is shown in Figure 12.

A separate *M*-at-age schedule was determined for the sensitivity analysis using growth estimated for MFCL Region 3 only (Figure 12). The changes in *M*-at-age simply reflect the differences in the two growth functions, given that estimates of M-at-age are derived from length-based data.

The *M*-at-age has been estimated in previous yellowfin stock assessments. However, the resulting estimates were inconsistent with the biology of the species and, consequently, the estimates were considered implausible.

4.2 Fishery dynamics

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

4.2.1 Selectivity

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

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

In the 2005 assessment, the selectivity of the longline fisheries (which catch mainly adult yellowfin) was assumed to increase with age and to remain at the maximum once attained. However, this assumption was relaxed in the 2006 and the current assessment for all longline fisheries, except for the fisheries Chinese/Taiwanese fisheries (LL TW-CH 3 and 4), thereby, allowing selectivity to decline for the older age classes. This is because the Chinese/Taiwanese fleet caught consistently larger fish than the other longline fleets in a comparable time period. These differences in size composition, which were consistent across length- and weight-frequency data, implied less than 100% selectivity for older yellowfin by the LL ALL fisheries. There are operational differences between the longline fleets that may account for a higher selectivity of larger fish by the Chinese/Taiwanese fleet.

4.2.2 Catchability

Catchability was allowed to vary slowly over time (akin to a random walk) for all purse seine fisheries, the Philippines and Indonesian fisheries, the Australian, Taiwanese/Chinese, Hawaii, PNG (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. We made the prior assumption that effort for these fisheries was proportional to catch, but set the variance of the priors to be high (approximating a CV of about 0.7), thus allowing catchability changes to compensate for failure of this assumption. For the other fisheries with time-series variability in catchability, the catchability deviation priors were assigned a variance approximating a CV of 0.10.

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

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

4.2.3 Effort deviations

Effort deviations, constrained by prior distributions of zero mean, were used to model the random variation in the effort – fishing mortality relationship. For the Philippines and Indonesian fisheries, purse seine fisheries and the Australian, Hawaii and Taiwanese-Chinese longline fisheries, the variance was set at a moderate level (approximating a CV of 0.2). For the main longline fisheries (LL ALL 1–6), the variance was set at a lower level (approximating a CV of 0.1) because the effort had been standardised in prior analyses and these longline fisheries provide wide spatial coverage of the respective areas in which they occur.

4.3 Dynamics of tagged fish

4.3.1 Tag mixing

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

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

4.3.2 Tag reporting

In principal, tag-reporting rates can be estimated internally within the model. In practice, experience has shown that independent information on tag-reporting rates for at least some fisheries tends to be required for reasonably precise estimates to be obtained. We provided reporting rate priors for all fisheries that reflect our prior opinion regarding the reporting rate and the confidence we have in that opinion. Relatively informative priors were provided for reporting rates for the Philippines and Indonesian domestic fisheries and the purse seine fisheries, as independent estimates of reporting rates for these fisheries were available from tag seeding experiments and other information (Hampton 1997). For the longline fisheries, we have no auxiliary information with which to estimate reporting rates, so relatively uninformative priors were used for those fisheries. All reporting rates were assumed to be stable over time. The proportions of tag returns rejected from the analysis because of insufficient data were incorporated into the reporting rate priors.

4.4 Observation models for the data

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

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

The size frequency data is assigned an effective sample size lower than the actual number of fish sampled. Reduction of the effective sample size recognises that (i) length- and weight-frequency samples are not truly random (because of clumping in the population with respect to size) and would have higher variance as a result; and (ii) the model does not include all possible process error, resulting in further under-estimation of variances.

Nevertheless, compared to previous 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 0.1 times the actual sample size, with a maximum effective sample size of 100 (equivalent to the HIGHSAMP sensitivity in the 2006 assessment).

A log-likelihood component for the tag data was computed using a negative binomial distribution in which fishery-specific variance parameters were estimated from the data. The negative binomial is preferred over the more commonly used Poisson distribution because tagging data often exhibit more variability than can be attributed by the Poisson. We have employed a parameterisation of the variance parameters such that as they approach infinity, the negative binomial approaches the Poisson. Therefore, if the tag return data show high variability (for example, due to contagion or non-independence of tags), then the negative binomial is able to recognise this. This should then provide a more realistic weighting of the tag return data in the overall log-likelihood and allow the variability to impact the confidence intervals of estimated parameters. A complete derivation and description of the negative binomial likelihood function for tagging data is provided in Hampton and Fournier (2001) (Appendix C).

4.5 Parameter estimation and uncertainty

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

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

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[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).

4.6 Stock assessment interpretation methods

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

4.6.1 Fishery impact

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

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

4.6.2 Yield analysis

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

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In this assessment, we use the average over the period 2002–2005. The last year in which a complete set of catch and effort data is available for all fisheries is 2005. We do not include 2006 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 (1952–2006). 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.

Further, theoretical MSY values were computed assuming exploitation was applied to each individual age class. The resulting theoretical MSY values from each age class were compared to determine the optimal age of harvest for yellowfin; i.e. the age class of harvest that yields the highest theoretical MSY. While it is implausible that a fishery can effectively select a single age class, such an analysis is useful to identify fisheries that are responsible for significantly reducing the total yields that could be available from the stock.

5 Sensitivity analyses

There are five main differences in the configuration of the data set included in the current "base-case" assessment compared to the 2006 assessment.

i. The inclusion of three new fisheries that were previously unaccounted in the model: the Japanese coastal pole-and-line and purse-seine fisheries in region 1 and the composite pole-and-line fishery in region 3.

ii. The separation of the composite Philippines and Indonesia domestic fishery (PHID MISC 3) into two separate national fisheries (PH MISC 3 and ID MISC 3).

iii. The separation of the LL ALL 3 fishery, the principal longline fishery in region 3, to include an additional historical distant-water longline fishery within an area approximating PNG national waters (LL BMK 3).

iv. The computation of length- and weight frequency distributions for key fisheries that are representative of the spatial distribution of the catch from the fisheries. The protocols used in aggregating the size data resulted in the exclusion of a considerable proportion of the data from some fisheries.

v. The revision of the recent (2004 onwards) annual catch estimates from the Indonesian domestic fisheries.

The sensitivity analyses were structured to assess the impact of these changes in the data and model structure. Additional sensitivities were conducted to assess the effect of individual model assumptions (Table 5).

As noted above, there is a high level of uncertainty regarding historical and recent catches from the Indonesian domestic fishery (ID MISC 3). The recent (2004) catches included in the model were revised downwards following the provision of catch estimates by Indonesia; the recent catch estimate is approximately 50% of the level assumed for 2004–05 in the 2006 assessment. The sensitivity of the current assessment to the change in the catch level was investigated by running the model with the two different levels of recent catch (for 2004–06) (Figure 13).

Two additional sensitivities to the past and recent levels of Indonesian catch were investigated: a catch history that was 50% higher than the assumed level of catch throughout the model period (including the higher level of 2004–06 catch) ("id-high-catch") and an overall lower level of catch configured as a steady increase in catch from the 1970 level to the level of the recent (lower) catch estimate ("id-low-catch") (Figure 13).

A number of the sensitivities involved reconfiguration of the input data set to be more consistent with the 2006 assessment (scenarios "old-size", "ex-newfish", "recombine-LL3"; see Table 5). The results from these sensitivities are most comparable with the results from the HIGHSAMP sensitivity from the 2006 assessment, given the higher weightings applied to the size frequency data.

The "base-case" model revealed a relatively poor fit to the early catch and effort data from the principal longline fishery in region 3 (see Section 6.5.2). The catch and effort data from this fishery are assumed to provide the principal index of stock abundance in the region that accounts for the majority of the catch. To improve the fit to these data the penalty weight on the effort deviates was increased for this fishery (scenario "region3-edevs"; see Table 5).

Given the significance of region 3 in the entire stock assessment, a separate model was formulated for that region only principally to assess the influence that information from the more peripheral regions may be having on the underlying stock assessment conclusions. The single region model included the 10 fisheries located within region 3 and tag data from 13 separate release periods within region 3 (scenario "region3"; see Table 5).

An earlier assessment model constructed for region 3 only revealed a significant difference in the estimated growth rates between the entire WCPO (6 region model) and region 3 only (see Figure

2). The region 3 growth parameters were applied to the WCPO model, with the corresponding change in the *M*-at-age (see Section 4.1.5), to investigate the sensitivity of the base-case model to different growth assumptions (scenario "region3-growth"; see Table 5).

The sensitivity to steepness of the SRR was investigated by comparing the stock assessment conclusions from the base-case model with a model with a steepness fixed at a higher value ("high-steepness") (0.912 compared to 0.62 from the base-case). A further sensitivity was undertaken by relaxing the prior on the distribution of steepness that was assumed for the base-case (replaced with a non-informative, uniform prior) (scenario "steepness-no-prior").

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

6 Results

The results from the three analyses are presented below. In the interests of brevity, some categories of results are presented for the model that is designated as the "base-case" analysis (Table 5). The selection of this analysis as the base-case is due to the overall superior fit of the model to most of the components of the objective function (Table 6). Significant differences between the base-case and the sensitivity analyses are summarised in Section 6.4. The main stock assessment-related results are also summarised for all analyses.

6.1 Fit statistics and convergence

A summary of the fit statistics for the three analyses is given in Table 6. The base-case model has a superior fit to the overall data set, although there is only a marginal difference between the base-case and the model with a higher level of catch from the Indonesian fishery (ID-high-catch). The latter model actually provides a considerably improved fit to the length- and weight-frequency data, but a poorer fit to the tag data. The model that includes a lower catch from the Indonesian fishery (ID-low-catch) has a better fit to the tag data but a poorer fit the length-frequency data.

The model with growth fixed at the growth parameters determined for the western equatorial region (region3-growth) has a poorer overall fit to the data, particularly the weight-frequency data (Table 6). However, there is a significant improvement in the fit to the length data most of which is collected from the fisheries within region 3. The relative contribution of the fishery-specific components of the length-frequency data to the overall likelihood is discussed in more detail in Section 6.1.

Information of the fit to some of the other sensitivity analyses is not presented as the differences in the data structure mean that the fit criteria are not comparable.

6.2 Fit diagnostics (base-case)

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

- There is some systematic lack of fit to the length data for the longline fisheries as revealed from a comparison of the observed and predicted length data aggregated over time (Figure 15). 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. However, the fit to these data is much superior to the previous assessments (Hampton et al. 2005) largely due to the refinement of the treatment of the weight-frequency data and a change in the length-weight relationship in the 2006 assessment (see Langley 2006a for details). These changes resolved much of the apparent conflict between the length- and weight-frequency data included in the model.
- There is a lack of fit to the length data from the LL ALL 2 fishery (Figure 15). Very few length samples are included in the model data set from this fishery (see Table 2) 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.
- 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 16). However, in the case of this fishery, the separation of the longline fishery in PNG waters (LL BMK 3) to account for spatial heterogeneity in size structure (see Langley 2006c) has resulted in an improved fit to the length frequency data compared to the 2006 assessment (Hampton et al. 2006). More generally, the exclusion of length data from some of the fisheries on the basis that it was unrepresentative of the catch has also resulted in an improved fit to the remaining size data compared to 2006 (most notably in the LL ALL 1 fishery).
- For the Philippines and Indonesian surface fisheries (PH MISC 3 and ID MISC 3), there is a strong modal structure in the size data. This modal structure in the aggregated length data is not well predicted by the model, in particular the second age class (about 40–50 cm FL) are consistently under-represented in the predicted size composition of the two fisheries (Figure 15). This lack of fit may be attributable to the growth function estimated for the base-case model (see Section 6.3.1), although limited samples are available from these fisheries.
- 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 15). The corresponding selectivity functions also result in considerable variation in the temporal trends in the predicted size distribution of the vulnerable population (Figure 16).
- For most of the longline fisheries, there is a very good fit to the aggregated weight frequency data (Figure 17). The improvement in the fit to these data from the 2006 assessment is largely due to the protocols applied to the size frequency data (both weight and length) in the current assessment. 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-estimate the proportion of the size composition in the 5–6 age classes. There is also a relatively poor fit to the weight data from PS JP 1 fishery (Figure 17).
- Despite the overall improvement in the fit to the weight data, there are a number of temporal trends in the fit to the weight data, most notably for LL ALL 3 and LL BMK 3 with the predicted fish weights being higher/lower than the observations during 1960–70/1970–80 (Figure 18). 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 assessment model is also not predicting 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, LL TW-CH 3, and PS JP 1 (Figure 18).

- While many of the problems evident in the fit to the size data (particularly length data) in the 2005 and 2006 assessments have been resolved, there remain considerable inconsistencies in the fit to the region 4 Chinese/Taiwanese (LL TW-CH 4) and Hawaiian longline (LL HW 4) length- and weight-frequency data (Figure 17). The latter fishery appears to have exhibited a strong shift in the size of fish caught from the fishery over the last decade that may represent a change in selectivity by the fleet. The selectivity of the LL TW-CH 4 is equivalent to the comparable fishery in region 3 (LL TW-CH 3) and the estimation of selectivity is dominated by the size data from the LL TW-CH 3. The assumption of a common selectivity for these two fisheries may not be appropriate.

- The fits of the model to the tagging data compiled by calendar time and by time at liberty are shown in Figure 19 and Figure 20. The model generally approximates the observed number of tag returns by time interval, although there is a systematic over-estimation of tag-return numbers towards the end of the tag recovery period (1993–94). This is also evident in the over-estimation of tag returns for about 6–13 quarters at liberty (Figure 20). The model under-estimates the recovery of fish at liberty for long periods (greater than 20 quarters), although the number of observations is small). The fits for individual fishery groups are shown in Figure 21. 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 21). For most of these fisheries, the tagging data are uninformative. Of the longline fisheries, most recoveries have been made from the Australian fishery. However, there is some considerable discrepancy in the number of observed and predicted returns from the fishery (Figure 21). This is possibly related to the coarse resolution of spatial structure in the model, estimation of movement parameters, and a lack of adequate mixing of tagged fish with the wider population of region 5.

- The overall consistency of the model with the observed effort data can be examined in plots of effort deviations against time for each fishery (Figure 22). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. On the other hand, if there was an obvious trend in the effort deviations with time, this may indicate that a trend in catchability had occurred and that this had not been sufficiently captured by the model. Of particular interest are the effort deviations for the LL ALL 1–6 longline fisheries, which were constrained to have the same average catchability and to have no year-to-year variation (i.e., catchability deviations were assumed to be zero). For a number of these fisheries, there is strong trend in the effort deviations during the early period of the fishery that indicates an inconsistency between the predicted fishery-specific exploitable biomass and the corresponding standardised effort series for the fishery (Figure 22). For LL ALL 1 and LL ALL 2, effort deviates are negative during the earlier period revealing that the predicted exploitable biomass is higher than indexed by the standardised effort series. The converse is evident for LL ALL 5 and LL ALL 6 corresponding to the very high CPUE observations during the development of the fisheries (Figure 9). Nevertheless, for the remainder of the model period, effort deviates are relatively small for all fisheries indicating a consistency between the standardised effort series and the trend in longline exploitable biomass.

- Effort deviates are substantially higher for the purse-seine fisheries than the principal longline fisheries, with the exception of the PS ASS 3 fishery (Figure 22). This can be interpreted as a high degree of variation in the effective effort of the purse-seine fleet which is to be expected given the differences in the style of fishing operation.

6.3 Model parameter estimates (base-case unless otherwise stated)

6.3.1 Growth

The estimated growth curve is shown in Figure 23. The non-von Bertalanffy growth of juvenile yellowfin is clearly evident, with near-linear growth in the 50–100 cm size range. The 2007 growth parameters indicate higher initial growth than estimated from the 2006 stock assessment. As previously noted, growth estimated from the entire WCPO model yields substantially higher growth rate for age classes 2–7 compare to growth estimates for region 3 only (Figure 23).

The estimated growth pattern from the base-case model is similar to that observed in the otolith length-increment data (Figure 24) (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 24). The growth rates of tagged fish are more consistent with the growth pattern from the region 3 model (see Figure 3).

A sensitivity of the assessment to the assumptions regarding growth was explored by applying the region 3 growth parameters to the WCPO model (region3-growth sensitivity). Overall, the region 3 growth parameters resulted in a poorer fit to the data, particularly the size data. However, when the fishery-specific components of the length- and weight- likelihood were examined is was evident that the region3-growth parameters resulted in a much improved fit to the length data for those fisheries that predominantly catch small fish (PS ASS 3 & 4, PH MISC 3, PL ALL 3, and PL JP 1) (Figure 25).

Conversely, for most of the fisheries principally catching larger fish there was a deterioration in the fit to the length data with the fixed region 3 growth parameters, particularly for the principal distant-water longline fisheries (LL ALL 1, 3–6) (Figure 25). Conversely, there was a slight improvement in the fit to the length data for the LL BMK 3 fishery. The change to the region 3 growth parameters also resulted in a much poorer fit to the weight frequency data, particularly from the longline fisheries in regions 1, 2, and 4 (LL ALL 1, LL ALL 2, LL ALL 4, and LL HW 4) and the purse-seine fishery in region 1 (PS JP 1) (Figure 25 and Figure 26).

Overall, the comparison in the fits to the size data between the two model runs confirms the apparent large differences in the growth rates of juvenile yellowfin between the western equatorial region and the wider WCPO. A cursory analysis suggests that the growth estimates from the base-case model are largely driven by the strong modal structure in the size data from the region 1 fisheries, particularly the longline fishery (LL ALL 1). The apparent faster growth of juvenile fish in this region appears to be positively biasing the growth of juvenile yellowfin in the core area of the fishery. This may explain why the modal structure in the progress of the modes in the size composition of the small fish fisheries deviates from the estimated growth in the base-case model (Figure 26 and Figure 27).

6.3.2 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 12). This issue may be re-visited in future assessments using biologically reasonable functional forms for M-at-age.

6.3.3 Movement

The model estimates a very large movement of fish (51%) southward from region 1 to region 3 in the second quarter of the year (Figure 28). A further southward movement is estimated to occur in the fourth quarter, representing 28% of all fish. Movement rates between all other adjacent regions are relatively low, about 3–6%, or negligible.

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 29. The simulation indicates that most biomass within a region is sourced from recruitment within the region, particularly for regions 1, 2 and 6. The high movement rates from region 1 to region 3 results in a substantial proportion of the region 3 recruitment estimated to have been sourced from region 1. Recruitment in region 1 is also estimated to contribute significantly to the biomass in regions 4 and 5, sourced via region 3.

The mixing between the equatorial regions results in a significant proportion of biomass (25%) in the eastern region (region 4) being sourced from recruitment in the western region (region 3). Similarly, recruitment in region 3 also contributes to the biomass in region 5 (Figure 29).

6.3.4 Selectivity

Estimated selectivity coefficients are generally consistent with expectation with longline fisheries principally selecting larger, older fish and the associated purse-seine sets (FAD and log sets) catching smaller yellowfin (Figure 30). Unassociated purse-seine sets generally catch substantially larger fish than from associated sets. The Japanese purse-seine fishery (PS JP 1) catches large fish in a region where the abundance of large fish is estimated to be low and, consequently, selectivity is high for the older age classes.

The Philippines and Indonesia surface fisheries (PH MISC 3 and ID MISC 3) and the Japanese pole-and-line fishery (PL JP 1) principally catch small fish; however, there are also some observations of larger fish in the catch that explain the high selectivity of older fish also.

For the principal longline fisheries LL ALL 3–6, selectivity is estimated to decline for the older age classes and the catch is predicted to be principally comprised of age-classes 7–10 and selectivity of older fish is relatively low. This is consistent with the slightly smaller size of fish caught by these fisheries compared to the corresponding TW-CH fisheries. The functional form of the (common) selectivity of the latter fisheries is constrained to have full selectivity for the oldest age classes. 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).

6.3.5 Catchability

Time-series changes in catchability are evident for several fisheries (Figure 31). Catchability in the principal longline fisheries (LL ALL 1–6) has been assumed to be constant over time. There is evidence of a general increasing catchability in the unassociated purse seine fisheries, pole-and-line fisheries, and some of the domestic longline fisheries (LL PG 3, LL HW 4, and LL PI 6). In contrast, 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 fishery (PS JP 1) declined from the mid 1980s onwards.

Since the early 1990s, the model estimates a strong increase in the catchability from the Philippines and Indonesian domestic fisheries (PHID MISC 3 and PH HL 3). There is limited effort data for the PHID MISC 3 fishery and the model assumes catches are proportional to effort throughout the history of the fishery. During a period of declining stock biomass, the model has attempted to account for the catches from the fisheries by increasing the catchability inversely proportional to the trend in exploitable biomass.

6.3.6 Tag-reporting rates

Estimated tag-reporting rates by fishery are shown in Figure 32. The estimates for the purse seine fisheries deviated from the mode of their prior distributions and reporting rates from the purse-seine fisheries in region 4 were estimated to be about 50% of the reporting rates from region 3. The estimates for the Philippine and Indonesia domestic fisheries are significantly below their prior mode, indicating that the model has used information contained in the data to estimate this reporting rate. The estimates for the longline fisheries are highly variable, ranging from near zero to the upper limit allowed (0.9). However, the estimated reporting rates from the longline fisheries are based on a very small number of tag recoveries and, consequently, the tag recovery data from these fisheries are not very informative.

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).

6.4 Sensitivity analyses

This section summarises the key differences in the main parameters between the base-case model and a number of key sensitivity analyses. Only those sensitivities that are likely to result in a substantial change in the underlying population dynamics are examined in this section. Those sensitivity analyses are region3-growth, id-low-catch, and id-high-catch. The main differences between these model runs and the base-case assessment are, as follows.

i. The main difference is the parameterisation is the shift in the selectivities between the base-case and the region3-growth model in accordance with the difference in the growth rate. The two sensitivities with different levels of Indonesian catch have fishery specific selectivities that are virtually identical to the base-case model.
ii. Temporal trends in catchability are very similar between all fisheries although the magnitude of the catchability coefficients varies between sensitivities depending on the relative levels of recruitment and, therefore, exploitable biomass (see below). The increase/decrease in catch from the Indonesian fishery was partly accounted for by a stronger/weaker temporal trend in the catchability coefficients for the fishery.
iii. Differences in the movement parameterisation; the region3-growth model differed from the other three models in that high rates of movement from region 1 to region 3 were limited to the fourth quarter of the year.
iv. For the Indonesian low/high catch sensitivities, the level of recruitment in region 3 and, to a lesser extent, in region 1 was estimated to decrease/increase over time relative to the base-case model while maintaining the same short-term temporal variation. For the region3-growth model, overall levels of recruitment were much higher than for the base-case consistent with the slower initial growth and correspondingly higher initial levels of M (see Figure 12). The broader temporal trends in recruitment were very similar between the two models, although there was a lag in the recruitment series of three quarters between the two series, in line with the difference in initial growth rates.
v. For the model with growth fixed at parameters estimated for region 3 only (region3-growth), there is a substantial improvement in the fit to the length-frequency data for the fisheries principally catching smaller fish (purse-seine and Indonesia/Philippines), while there was a decline in the fit to the size data for the longline fisheries, especially those in areas outside of region 3 (as discussed above).

For all model sensitivities, differences in the stock assessment results, at the WCPO region scale, are summarised in the following section.

6.5 Stock assessment results

6.5.1 Recruitment

The base-case recruitment estimates (aggregated by year for ease of display) for each region and the WCPO are shown in Figure 33. 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 and high in regions 1, 4, and 5 during the 1980s and early 1990s. Recruitment was relatively low in regions 4 and 5 during the 1960s and 1970s and recruitment in regions 1 and 3 has been relatively low since the mid 1990s (Figure 33).

These trends strongly influence the trend in the aggregate WCPO recruitment estimates; total recruitment was very high during the late 1950s, relatively low from the mid 1960s to the mid 1970s, high from the late 1970s to late 1980s, and relatively low over the last decade. Recent WCPO recruitment is estimated to be relatively high largely due to strong recruitment in region3 and 5 during 2003 (Figure 33).

The increase in recruitment estimates during the mid 1970s is consistent with the increase in CPUE from the equatorial longline fisheries (LL ALL 3 & 4) during that time (Figure 9), as well as the sustained increase in catches from the mid 1970s to 1990. The model also explains the high initial CPUE observed in a number of the main longline fisheries (LL ALL 4–6) by high estimates of recruitment during the early period (Figure 33).

The confidence intervals associated with the combined WCPO annual recruitment estimates reveal a substantially higher level of uncertainty associated with recruitment estimates prior to the mid 1980s (Figure 33). There is also a high level of uncertainty associated with the most recent recruitment estimates (2005 and 2006).

A comparison of WCPO recruitment estimates for the various model options is provided in Figure 34. All analyses reveal the same trend in overall recruitment with recruitment generally declining from the late 1950s to the early 1970s and then increasing during the late 1970s to plateau at a higher level. The overall magnitude of recruitment varied slightly between the analyses exploring different assumptions regarding the catch from the Indonesian fishery (ID MISC 3); overall recruitment levels varied in accordance to the assumed level of catch (Figure 34). The region3-growth sensitivity yielded a much higher level of overall recruitment due to the combination of the effects of slower initial growth and higher initial M-at-age for the younger age classes.

There is a large difference in the level of recruitment estimated for the current base-case assessment compared to the 2006 base-case model (Hampton et al. 2006). This issue is discussed in more detail in Section 6.6.

6.5.2 Biomass

Estimated biomass time-series for each region and for the WCPO are shown in Figure 35 for the base-case analysis. The trends are variable between regions, reflecting the CPUE trends from the main longline fisheries (LL ALL 1–6) (Figure 36). Nevertheless, some discrepancies do exist between the CPUE trends from the longline fisheries and the temporal trend in the longline exploitable biomass, particularly the deviation in the trend for the LL ALL 3 fishery in the late 1950s and early 1960s. The increase in the exploitable biomass during this period is attributable to the preceding peak in recruitment evident in most regions, including region 3. The increase in recruitment appears to be largely driven by an increase in the size of fish caught many of the longline fisheries during the late 1950s and early 1960s and a corresponding increase in CPUE. However, the predicted associated increase in CPUE is not evident for the LL ALL 3 fishery (Figure 36).

However, overall the model estimates of exploitable abundance show very similar scaling among regions as the CPUE data (Figure 37). 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 total biomass in this region throughout the model period (Figure 35).

Most other regions exhibit a general decline in total biomass from the late 1950s to mid 1970s followed by an increase in the level of total biomass that persisted through the 1980s and early 1990s (Figure 35). During the mid–late 1990s, the level of total biomass declined in all regions, subsequently recovering in region 5 only.

The trend in total biomass for the WCPO is largely driven by the composite biomass trends from regions 3–5 (Figure 35). Biomass declines steadily during the early model period, remains relatively stable from the mid 1970s to the early 1990s, and then declines sharply (by about 40%) during the last decade.

The comparison of biomass trends for various model options is shown in Figure 38. For the sensitivities to the Indonesian catch level and region 3 growth, the total biomass trajectories are very similar to the base-case model. This is a large difference in the overall biomass level between the current base-case model and the 2006 assessment (see Section 6.6).

A comparison of the trends in total biomass for region 3 from the base-case model and the single region model (region3 sensitivity) reveals a comparable level of biomass prior to 1970 (Figure 39). The biomass trajectories deviate in the early 1970s with the region3 model biomass increasing sharply in response to very strong increase in recruitment through the 1970s. From the late 1970s, both models reveal a comparable rate of decline in total biomass within region 3.

Overall, the region3 model provides a better fit to the principal longline CPUE trend for the region (LL ALL 3) than the base-case model. This is probably due to the assumptions of common catchability and selectivity among most of the principal longline fisheries in the entire WCPO model.

6.5.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase strongly throughout the time series, particularly during the last decade (Figure 40). The adult exploitation rates are virtually identical between the base-case and the low and high alternative Indonesian catch scenarios, while the juvenile fishing mortality rates decrease and increase for the two scenarios, respectively.

For the region3-growth scenario, exploitation rates for the juvenile component of the stock are lower than for the base-case, while adult exploitation rates are higher. This may partly relate to the difference in the assumed recruitment OGIVE between the two models (changed to account for slower growth) and/or be due to the higher overall level of recruitment for the region3-growth model resulting in a lower overall exploitation rate on the juvenile component of the stock.

For the base-case model, recent exploitation rates are high on the youngest age classes due to the impact of the PH MISC 3 and ID MISC 3 fisheries (Figure 41 and Figure 42). 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 41).

Amongst regions, exploitation rates are highest in region 3 and comparatively low in all other regions (Figure 42), with the exception of the high exploitation rates on the oldest age classes in region 1; however, this exploitation rate is applied to a very small component of the total WCPO population and has little influence on the overall exploitation rate. The recent reduction in the reported level of catch from the Indonesian fishery has resulted in a corresponding reduction in the exploitation rate on the 2–16 age classes (compare Figure 41 and Figure 42).

6.5.4 Fishery impact

We measure fishery impact at each time step as the ratio of the estimated biomass to the biomass that would have occurred in the historical absence of fishing. This is a useful variable to monitor, as it can be computed both at the region level and for the WCPO as a whole. The two trajectories are plotted in Figure 43. It is evident that the impact has been substantial in region 3 and significant impact has also occurred in region 4, with the impact increasing steadily from the early 1980s. Impacts are slight in the four sub-equatorial regions.

Overall, the impact of fishing has reduced the WCPO total biomass to about 40% of unexploited levels (Figure 44), largely driven by the impact in regions 3 and 4. Fishery impacts in region 3 have steadily increased over time and are currently reducing the biomass to about 35% of the unexploited level. By comparison, fishery impacts are relatively low in regions 1, 2, 5 and 6; less than about 20% for most of the time period, i.e. total biomass maintained at above 80% of unexploited levels.

A comparison of relative impact of fishing on the entire WCPO biomass from the various model options is presented in Figure 45. Overall fishery impacts are comparable between the scenarios presented with only the lower Indonesian catch scenario (id-low-catch) yielding a slightly more optimistic scenario during the latter period. The overall impact is considerably lower than estimated from the 2006 assessment.

It is possible to classify the fishery impact on the spawning biomass ($1 - SB_t / SB_{0t}$) or total biomass ($1 - B_t / B_{0t}$) to specific fishery components in order to see which types of fishing activity have the largest impact on biomass (Figure 46 and Figure 47). Within each region, the relative impacts of specific fisheries on spawning and total biomass are comparable. In region 3, the Philippines/Indonesian domestic fisheries have the greatest impact. The purse seine fishery (PS ASS 3 and PS UNS 3) had the greatest impact in the early to mid-1990s, but has since declined.

In region 4, the purse seine fishery is responsible for about half of the impact, while the Philippines/Indonesian fisheries accounts for about 25% due to the direct movement of fish from region 3 to region 4. Similarly, while the direct fishery impacts are moderately low in region 1 and region 5, the high impacts on the stock in region 3 are reducing the movement of fish to these adjacent regions. Within region1 there are the additional impacts of the pole-and-line and purse-seine fisheries (PL JP 1 & PS JP 1).

It is noteworthy that in both regions 3 and 4, the longline fishery has a relatively small impact, generally less than 10%. In the sub-equatorial regions, the longline fishery has a larger share of the impact, but overall impacts are much smaller. In these regions, the longline fishery is estimated to have depleted population biomass by no more than about 5%.

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 (5%), moderate impact from the associated (10%) and unassociated (6%) purse-seine fisheries, and highest (20%) and increasing impacts from the Philippines/Indonesian domestic fisheries.

Fishery impact can also be considered in the context of the reduction in the level of biomass available to a specific fishery (vulnerable or exploitable biomass). Trends in fishery-specific exploitable biomass, under fished and unfished conditions, were computed for four key fisheries within region 3: the distant-water longline fishery (LL ALL 3), the domestic PNG longline fishery (LL PG 3) and the associated (PS ASS 3) and unassociated (PS UNS 3) purse-seine fisheries (Figure 48). The cumulative impact of all fisheries is estimated to have substantially reduced the exploitable biomass available to the two longline fisheries and in recent years the level of exploitable biomass is only 30–40% the level that is estimated unfished biomass level. The biomass vulnerable to the unassociated purse-seine fishery is also estimated to have been impacted to a similar extent, while the impact on the associated purse-seine fishery vulnerable biomass is considerably lower (60% of the unexploited level) (Figure 48).

6.5.5 Yield analysis

Symbols used in the following discussion are defined in Table 7. The yield analyses conducted in this assessment incorporate the SRR (Figure 49) into the equilibrium biomass and yield computations. The estimated SRR steepness coefficient for the base-case is 0.62 — considerably lower than the prior mode of 0.85. This represents a moderate value of steepness and means that average recruitment is predicted to decline to 62% of the equilibrium unexploited recruitment when the level of spawning biomass is reduced to 20% of the unexploited level. However, steepness is poorly determined as indicated by the broad confidence intervals about the SRR at low levels of spawning biomass (Figure 49).

A likelihood profile of the value for steepness from the analysis using the uninformative prior (steepness-no-prior) is presented in Figure 50. The posterior probability distribution occupies a relatively broad range of values for steepness (from 0.35 to approaching 1.0) indicating the model data are relatively uninformative about the true value of steepness. Nevertheless, the mode of the distribution is at 0.53, lower than the value estimated for the base-case model. This indicates that the prior used in the base-case is somewhat constraining the model estimate of steepness. This is evident from the likelihood profile for steepness from the base-case model which occupies the range of values between the prior on steepness and the profile using the uninformative prior (Figure 50).

Equilibrium yield and biomass (spawning and total) are computed as a function of multiples of the 2002–2005 average fishing mortality-at-age (Figure 51). For the base-case model, a maximum yield (*MSY*) of 400,000 mt per annum is achieved at *fmult* = 1.05; i.e. at 1.05% of the current level of fishing effort. This represents that the ratio of $F_{current}/\tilde{F}_{MSY}$ is equal to 0.95 (approximately 1/1.05); current exploitation rates are slightly lower than the exploitation rates to produce the *MSY*. However, the increase in yield achieved by increasing exploitation rates from $F_{current}$ to F_{MSY} is negligible (<< 1%) and, consequently, "current" exploitation rates should be viewed as equivalent to F_{MSY}. The equilibrium biomass at *MSY* is estimated at 1,489,000 mt, approximately 41% of the equilibrium unexploited biomass (Table 8).

There is considerable uncertainty regarding the equilibrium yields at and above the current level of fishing effort (*fmult*) (Figure 51). For the base-case model, the 95% confidence interval for *MSY* is 201,000–602,000 mt. Levels of uncertainty increase rapidly with increasing levels of *fmult*, largely attributable to uncertainty associated with the recruitment levels predicted from the SRR at low levels of spawning biomass (Figure 49).

For the base-case model, the reference points $F_t/\tilde{F}_{MSY}$ and $B_t/\tilde{B}_{MSY}$ were computed for each year (*t*) included in the model (1952–2006). 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 52). From 1952 to 1970, exploitation rates were low while total biomass declined rapidly relative to $\tilde{B}_{MSY}$ due to a general decline in recruitment levels. Over the subsequent 25 years, the biomass level ($B_t/\tilde{B}_{MSY}$) remained relatively constant while $F_t/\tilde{F}_{MSY}$ steadily increased. The increase in $F_t/\tilde{F}_{MSY}$ accelerated from the mid 1990s to recent years, reaching 1.0 in 2001 and remaining slightly below 1.0 in the subsequent years (up to 2005). During the same period, there was a rapid decline in $B_t/\tilde{B}_{MSY}$ and total biomass has approached the overfished threshold ($\tilde{B}_{MSY}$) in recent years (Figure 52). For the base-case model, current (2002–05) total biomass is estimated to be 10% higher than $\tilde{B}_{MSY}$ ($B_{current}/\tilde{B}_{MSY}$ = 1.10) (Table 8).

For 2006, the last year included in the assessment model, there was an apparent improvement in the status of the stock relative to the two reference points ($F_t/\tilde{F}_{MSY}$ and $B_t/\tilde{B}_{MSY}$) (Figure 52). However, the improved stock status in 2006 is attributable to recent high levels of recruitment which are poorly determined and the reported decline in the yellowfin catch from the Indonesian domestic fishery. Consequently, the stock status for the 2006 year is highly uncertain and not included in the computation of "current" stock status.

For the base-case model, the maximum equilibrium yield (MSY_t) was also computed for each year (*t*) in the model. This analysis enables an assessment of the *MSY* level that would be theoretically achievable under the different patterns of age-specific fishing mortality observed through the history of the fishery (Figure 53). 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* (about 600,000 mt per annum) compared to that estimated for the fishery based on the recent age-specific fishing mortality pattern (400,000 mt). The decline in the *MSY* over time follows the increased development of those fisheries that catch smaller yellowfin, principally the surface fisheries (Figure 53).

A comparison of the yield and equilibrium biomass curves for the three model options is shown in Figure 54. For the low and high Indonesian catch scenarios and the single region model, maximum equilibrium yield was achieved at levels of *fmult* between 1.0 and 1.1 (equivalent to $F_{current}/\tilde{F}_{MSY}$ ratios of 0.91–1.00) — comparable to the base-case model (Table 8). For the region3-growth model, *MSY* is achieved at an *fmult* of 1.3 ($F_{current}/\tilde{F}_{MSY}$ = 0.77).

For the WCPO model options, *MSY* estimates range between 377,000 and 452,000 mt per annum which is comparable with recent catch levels from the WCPO which have been of the order of 380,000–440,000 mt annually (1997–2005 average catch 408,000 mt). The only model option that estimates a significantly higher *MSY* is the sensitivity with a high steepness for the SRR (high-steepness) — a yield of 550,000 mt at an *fmult* of 1.8 (Figure 54 and Figure 55).

For the single western equatorial region (region3 model), the estimated *MSY* (268,200 mt per annum), achieved at the current level of fishing effort (i.e. *fmult* = 1.1), is lower than the recent average catch of about 320,000 mt from the region. The higher catches have been sustained by recent recruitment levels which are higher than predicted from the SRR for the region (Table 8). Nevertheless, the single region model indicates that there is no potential to expand the current yields from the core region of the entire WCPO fishery.

Hypothetical *MSY*s were computed using a single fishery selectivity based on an individual age class and the other biological parameters from the base-case assessment (natural mortality, growth, maturity OGIVE and the SRR). For each age class (1–28), the theoretical *MSY* and the associated exploitation rate were calculated (Figure 56). The peak in yield occurred when fish were harvested at age class 11 and the resulting theoretical yield was virtually double the estimate of *MSY* from the current base-case assessment. However, to achieve that yield would require an exceptionally high exploitation rate on the individual age class.

Nevertheless, the analysis shows that a smaller increase in the age of harvest, from the current average of about age class 5, could result in a considerable increase in yield from the stock without a significant increase in the level of exploitation on the individual age classes (Figure 56). The fisheries with an average age of capture less than 5 quarters include the Philippines and Indonesian domestic fisheries (PH MISC 3 & ID MISC 3), the pole-and-line fisheries (PL ALL 3 & PL JP 1), and the associated purse-seine fisheries (Figure 57).

6.5.6 Key Reference Points

A number of quantities of potential management interest associated with the yield analyses are provided in Table 8. 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 $B_{current}/\widetilde{B}_{MSY}$ and $F_{current}/\widetilde{F}_{MSY}$ 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 $B_{current}/\widetilde{B}_{MSY}$ and $F_{current}/\widetilde{F}_{MSY}$ 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 $B_{current}/\widetilde{B}_{MSY}$ and $F_{current}/\widetilde{F}_{MSY}$ were calculated for this purpose. The profile likelihood distribution for the base-case model reveals that there is a low probability that $B_{current}/\widetilde{B}_{MSY}$ is below 1.0 (6%) and that the highest probability is at about the level of the point estimate from the model (1.17) — there is a 49% probability that $B_{current}/\widetilde{B}_{MSY}$ is within 1.1–1.3 (Figure 58 and Table 9). The posterior probability distribution of $F_{current}/\widetilde{F}_{MSY}$ is slightly skewed with the mode of the distribution at about the point estimate of 0.95 and a 47% probability of $F_{current}/\widetilde{F}_{MSY}$ exceeding 1.0 (Figure 59). Conversely, there is a similar probability (53%) that $F_{current}/\widetilde{F}_{MSY}$ is less than 1.0 (Table 9) and the distribution is relatively symmetrical about the threshold level (probability $F_{current}/\widetilde{F}_{MSY}$ 0.8–1.0 equals 29.3%; probability $F_{current}/\widetilde{F}_{MSY}$ 1.0–1.2 equals 25.1%).

The comparable likelihood profiles for the sensitivity to the steepness prior (steepness-no-prior) are more pessimistic, particularly for the fishing mortality based reference point $F_{current}/\widetilde{F}_{MSY}$ (Figure 60 and Figure 61). This result is consistent with the lower mode for the likelihood profile of steepness relative to the estimate from the base-case model (Figure 50). The probability that $B_{current}/\widetilde{B}_{MSY}$ exceeds 1.0 increases to 15% (compared to 6% for the base-case) and the mode of the distribution decreases to 1.09 (compared to 1.17) (Figure 60). The mode of the posterior probability distribution of $F_{current}/\widetilde{F}_{MSY}$ is shifted to an overfishing state (1.17), while the probability that $F_{current}/\widetilde{F}_{MSY}$ exceeds 1.0 is approximately 76% (Figure 61). The lower bound of the distribution is truncated at approximately $F_{current}/\widetilde{F}_{MSY} = 0.5$ corresponding to the approximate upper bound of steepness (1.0). The truncation at the upper bound is due to numerical instability of the model as steepness values approach the lower limit of 0.2 (equivalent to a linear relationship between spawning biomass and recruitment).

6.6 Comparisons with the 2006 assessment

As noted above, there are considerable differences between the current assessment and the results of the 2006 assessment, particularly with respect to the magnitude of the recruitment and biomass levels. These differences are due to the changes in the structural assumptions of the model, principally the reconfiguration of some fisheries and size frequency data and the inclusion of additional fisheries (and catch). To explore the relative impact of each of these changes (detailed in Section 5) the current data set was reconfigured in a step-wise manner to have an equivalent configuration to the data set used in the 2006 assessment.

Overall the total biomass level from the 2006 assessment was about 67% the level of the current base-case (Figure 62). Recombining the two distant-water longline fisheries in region 3 (LL ALL 3 and LL BMK 3) reduced the overall level of biomass by about 18%. The additional combination of the PH MISC 3 and ID MISC 3 reduced the total biomass by a further 6%, while the subsequent removal of the three new fisheries in the model (PL JP 1, PS JP 1 and PL ALL 3) had very little impact. The next step of reverting to the old size data (i.e. the inclusion of all size data without rescaling based on catch distribution) resulted in a reduction in the total biomass level to that of the equivalent model run from the 2006 assessment (HIGHSAMP) and in particularly substantially lowered the peak in biomass in the late 1950s/early 1960s (Figure 62).

While the total biomass and recruitment series (not shown) between the 2007 and 2006 assessments converged by reconfigurating the data, there remain significant differences in the estimates of *MSY* and the associated *MSY*-based reference points. These are attributable to differences in the steepness parameter of the SRR between the two models; the 2006 assessment had a steepness of 0.694 compared to a steepness of 0.819 for the reconfigured 2007 assessment. Consequently, the 2006 assessment was considerably more pessimistic (lower *MSY*, higher $\widetilde{B}_{MSY}$, higher current exploitation rate relative to F_{MSY}). This result serves to illustrate that while steepness is a critical parameter in the determination of *MSY*-based reference points it is poorly determined in the assessments.

6.7 Analyses of management options

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

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

These analyses were undertaken for the 2006 assessment and repeated for the current assessment using the base-case model. Consideration of issues relating to area closures, principally with respect to bigeye tuna, is presented in a separate paper. The results of stock projections that attempt to replicate the effects of area closures applied to the purse-seine fishery are documented in other papers tabled at the Scientific Committee and Commission meetings.

6.7.1 Fishing Effort and B_{MSY}

To investigate this question, we consider the equilibrium biomass in relation to B_{MSY} so that the effects of variable recruitment on future biomass need not be considered. This is appropriate as we are simply interested in a long-term average indicator of the relationship between fishing effort, resulting biomass and B_{MSY}. The yield analysis described above provides a basis for estimating levels of equilibrium biomass that would result at different levels of relative fishing effort, assuming maintenance of the 2002–2005 overall fishery selectivity and constant catchability. The former assumption means, *inter alia*, that the relative fishing effort of each fishery defined in the assessment model remains the same as the 2002–2005 average.

Table 10 provides estimates of fishing effort scalars (relative to the 2002–2005 average) that result in equilibrium total biomass at various levels above B_{MSY}. The fishing effort scalar consistent with B_{MSY} is 1.05. In other words, the "current" level fishing effort will maintain the equilibrium biomass at a level approximately 5% higher than B_{MSY}. Progressively lower levels of fishing effort would achieve a higher equilibrium biomass relative to B_{MSY}.

6.7.2 Stock Projections

a. Effects of WCPFC-2 Conservation and Management Measures

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

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

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

- Purse seine effort levels for 2004 were assumed for the five-year projection period (2007–2011). The distribution of effort among regions, quarters and set types was specified according to the average distributions for the period 2001–2004. The use of a multi-year average distribution reduces the risk of anomalous results arising from unusually high or low effort occurring in one of these strata in an individual year.
- Longline effort levels averaged over 2001–2004 were assumed for the projection period.

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

- Relative effort levels for the Philippines and Indonesian domestic fisheries were assumed to continue through the projection period at 2006 levels (due to increases in estimated effective effort for those fisheries during 2001–2004).
- For fisheries with estimated time-series variation in catchability, the estimated catchability for the last data year (2006) was assumed to continue through the projection period.
- Recruitment during the projection period was predicted using the estimated SRR and distributed among regions based on the long-term average distribution of recruitment.

The results of the projection were expressed as the ratio of total biomass to $\widetilde{B}_{MSY}$ where the latter was computed using the *F*-at-age for the final year of the projection (2011). $\widetilde{B}_{MSY}$ at the end of the projection period is estimated to be 1,582,000 mt (compared to 1,631,000 mt at $F_{current}$). $B_t/\widetilde{B}_{MSY}$ for the final years of the assessment (2000–2006) and the five-year projection period is shown in Figure 63. Projected biomass and $B_t/\widetilde{B}_{MSY}$ increases towards the end of the assessment time period due to high recruitments estimated in recent years, principally for region 4 (Figure 64)..

During the projection period, the total biomass is predicted to decline slightly in response to a return to long-term average recruitment and approaches equilibrium conditions above the $\widetilde{B}_{MSY}$ level at the end of the projection period ($B_{final}/\widetilde{B}_{MSY}$ = 1.21) (Figure 63).

Based on the results of the 2006 assessment, specifically the profile likelihood for the biomass ratio in the final year of the projection ($B_{final}/\widetilde{B}_{MSY}$), it is likely that the variance of the probability distribution of the $B_{final}/\widetilde{B}_{MSY}$ profile will be considerably greater than that of $B_{current}/\widetilde{B}_{MSY}$ due to propagation of uncertainty in recruitment and other parameters through the projection period. Consequently, while not determined for this year's assessment, the probability of $B_{final} < \widetilde{B}_{MSY}$ is likely to be greater than for $B_{current} < \widetilde{B}_{MSY}$ (6%).

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

7 Discussion and conclusions

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

- The computation of length- and weight-frequency distributions for key fisheries (longline and equatorial purse-seine) that are representative of the spatial distribution of the catch from the fisheries. The protocols used in aggregating the size data resulted in the exclusion of a considerable proportion of the data from some fisheries. 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, for LL ALL 1 and LL ALL 2, virtually all length samples collected during that period were rejected from the model data set, while a high proportion of the weight samples collected from LL ALL 5 in the last two decades were also rejected.
- The separation of the LL ALL 3 fishery, the principal longline fishery in region 3, to include an additional historical distant-water longline fishery within an area approximating PNG

national waters (LL BMK 3). A previous analysis revealed that the historical distant-water longline fishery in PNG waters caught considerably smaller fish than the fishery operating in other areas of region 3 (Langley 2006c). Up to the 1980s, the PNG area averaged approximately 20% of the distant-water longline catch from region 3; however, the proportion of the total catch was higher during the 1950s (exceeding 50% in some quarters). The selectivity of the PNG component of the fishery was estimated independently of the other principal longline fisheries.

- The inclusion of three new fisheries that were previously unaccounted in the model: the Japanese coastal pole-and-line and purse-seine fisheries in region 1 and the composite pole-and-line fishery in region 3 (excluding Indonesia). These fisheries collectively accounted for an average catch of 15,000 mt per annum during the 1970s and 1980s, although since about 1990 catches from all three fisheries have steadily declined to a cumulative total of about 5,000 mt in recent years.
- The separation of the composite Philippines and Indonesia domestic fishery (PHID MISC 3) into two separate national fisheries (PH MISC 3 and ID MISC 3). This was undertaken on the basis that, at least for recent years, the catch estimates from the Philippines domestic fisheries are considered to be more reliable than for the comparable Indonesian fisheries. The separation of the fisheries enabled a more comprehensive examination of the sensitivity to the model to the assumed magnitude of catch from the Indonesian fishery. However, in separating the fisheries, the paucity of size data from the Indonesian fishery is highlighted and, consequently, the selectivity for the fishery is likely to be poorly determined.
- The revision of the recent (2004 onwards) annual catch estimates from the Indonesian domestic fisheries.
- The addition of recent catch, effort, and size frequency data from most fisheries.
- The current assessment included a range of sensitivity analyses, mainly assessing the implications of the assumed level of catch from the Indonesian fishery, the potential for spatial heterogeneity in growth (discussed above), and the effect of various changes in the model data structure. In addition, the sensitivity of the model to assumptions regarding the steepness parameter of the SRR was also investigated.

For the 2006 assessment, an alternative seven-region spatial stratification was also investigated. The rationale for the alternative regional stratification was to reduce the spatial heterogeneity in the CPUE and size data within each of the individual regions of the model, while also spatially segregating the Indonesian and Philippines fisheries from the other regions. However, the utility of the model was limited due to the lack of a reliable (fishery-dependent) index of abundance for this region during the latter period of the model. Some attempts were made to investigate potential sources of CPUE data for this region; however, no new data were forthcoming and, consequently, there was no opportunity to further develop the seven-region model.

The current stock assessment integrated catch, effort, length-frequency, weight-frequency and tagging data into a coherent analysis that is broadly consistent with other information on the biology and fisheries. Compared to previous assessments, there was a substantial improvement in the fit to the size (length and weight) data included in the model through the revision of the length-weight relationship and processed- to whole weight conversion factors (2006 assessment) and the application of protocols to assure the size data are representative of the catch from the fisheries (current assessment). The subdivision of the distant-water longline fishery in region 3 is also likely to have resulted in an improved fit to the longline size data from the principal fisheries (LL ALL 3–6).

Overall, the model diagnostics do not indicate any serious failure of model assumptions, although inevitably, departures from the model's assumptions were identified in several areas:

- There is a divergence in the early period (late 1950s–early 1960s) between the catch and effort data from the principal longline fishery in region 3 (LL ALL 3) and the trend in the longline exploitable biomass from the model. This is evident from the paucity of the fit to the catch data during that period. The model estimates a series of strong recruitments during that period interpreting and increase in both the observed fish size and CPUE in most of the principal longline fisheries, with the exception of the LL ALL 3 fishery. Increasing the penalty weight for the effort deviations for the LL ALL 3 fishery (region3-edevs sensitivity) resulted in an improved fit to the catch and effort data from this fishery without significantly changing the stock assessment conclusions.

- The lack of fit to the juvenile modes in the size frequency data from some fisheries may indicate a bias in the model estimates of growth for the youngest age classes. There is evidence to indicate that growth rates in the western equatorial region differ from other areas of the WCPO, particular for juvenile fish. 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. However, given that initial growth rates in the core region of the fishery (region 3) appear to be substantially over-estimated in the WCPO model, it is necessary to undertaken routine sensitivity analyses using the alternative growth parameters.
- Residuals in the tag return data for the Australian longline fishery suggested that yellowfin tuna may have patterns of residency that cannot be captured by the spatial resolution of this model. However, the excess in observed tag returns over those predicted was relatively minor in this case.
- 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.

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

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

The changes in fishery structure, particularly the subdivision of LL ALL 3, and the treatment of the size frequency data resulted in considerable differences between the current assessment and last year's (base-case) assessment (Hampton et al. 2006). These changes have influenced the underlying model population dynamics; the overall level of recruitment and, consequently, total biomass have increased although the relative trend in biomass is comparable between assessments, except for the early period of the model. For the current base-case assessment, the results are slightly more optimistic than last year, with a lower level of current fishing mortality ($F_{current}/\tilde{F}_{MSY}$ of 0.95 compared to 1.11 from the 2006 LOWSAMP assessment and 1.00 from the 2006 HIGHSAMP assessment), while the overall levels of depletion are similar (current biomass 51% of the unexploited level). Biomass based reference points are also equivalent between the two assessments; $B_{current}/\tilde{B}_{MSY}$ of 1.17 from the current assessment and 1.17 from the 2005 base-case. Estimates of *MSY* are considerably higher from the current assessment (400,000 mt per annum) compared to last year's assessment (328,300 mt).

From a management perspective, the most significant change between the two assessments is a shift in the point estimate of in the fishing mortality based reference point from an overfishing condition ($F_{current}/\widetilde{F}_{MSY}$ > 1.0) in last year's assessment to being marginally below the overfishing threshold in the current assessment ($F_{current}/\widetilde{F}_{MSY}$ = 0.95). This change is largely due to the change in the structure of the fisheries data included in the model. However, it is important to note the substantial overlap in the confidence intervals associated with the point estimates from the two assessments, particularly through the range including the F_{MSY} level ($F_{current}/\widetilde{F}_{MSY}$ between 0.8 and 1.2). This is also evident from the shape of the yield curve, which estimates yields to be within 10% of the *MSY* estimate over a range in *fmult*s from 0.7 to 1.5.

The $F_{current}/\widetilde{F}_{MSY}$ and $B_{current}/\widetilde{B}_{MSY}$ reference points are relatively insensitive to large differences in the assumed historical and recent levels of catch from the Indonesian fishery. The model essentially accounts for the different levels of catch by scaling the overall level of recruitment for the stock and, consequently, varying the estimate of *MSY* accordingly. Key reference points are also comparable between the entire WCPO model and the model encompassing the core region of the fishery — the western equatorial region which accounts for over 80% of the catch.

The assumptions related to the steepness parameter of the SRR were the most crucial of the range of sensitivities investigated. The base-case assessment yields a relatively low value for steepness (0.62) largely due to the relatively high recruitment estimates from early in the model period. However, the likelihood profile indicates steepness is poorly determined and a considerably higher value of steepness is also plausible; a higher steepness results in a considerably more optimistic view of the current stock status and indicates the stock could sustain considerably higher yields. Conversely, the mode of the steepness PDF in the absence of an informative prior (0.53) is slightly lower than the estimate for the base-case assessment, in which the steepness estimate was to some extent influenced by a prior with a mode at 0.85. This unconstrained estimate of steepness is toward the lower bound of values considered plausible for tropical tunas.

The main conclusions of the current assessment are as follows.

1. For all analyses, there was a strong temporal trend in recruitment. Initial recruitment was relatively high but declined to a lower level during the early 1970s. Recruitment subsequently increased during the late-1970s and remained relatively high during the 1980s before declining in the 1990s. This pattern is similar to the results of previous assessments and is largely driven by the trends in the principal longline CPUE indices, particularly from regions 3 and 4. For the most recent years, recruitment is predicted to have increased, although recent recruitment estimates are poorly determined. Nevertheless, the estimates of stronger recruitment in recent years are generally consistent with recruitment estimates derived from a model relating yellowfin recruitment to the oceanographic conditions of the WCPO (Langley et al. in press).
2. For all analyses, the trends in biomass are generally comparable prior to the mid-1980s and were consistent with the underlying trends in recruitment, with biomass declining during the initial period to a low level in the early–mid 1970s, before increasing in the mid-1970s. Biomass levels remained relatively stable during the 1980s. For all model options, biomass is estimated to have declined steadily during the 1990s, largely due to the decline in the biomass within region 3 but also evident in most other regions. The recent estimates of strong recruitment result in a predicted increase in total biomass during the most recent years in the model; again, there is considerable uncertainty associated with the recent recruitment estimates and, therefore, recent trends in total biomass.
3. The biomass trends in the model are strongly driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. For some of the main longline fisheries (for example, 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 inconsistent information about the relative level of fishing mortality in the region. Further research is required to explore the relationship between longline CPUE and yellowfin abundance

and the methodology applied to standardise the longline CPUE data, particularly to account for temporal trends in fishing efficiency. The latter issue was examined by way of a sensitivity analysis in the 2005 assessment and shown to be highly influential in the conclusions of the assessment. There is also the potential that the size selectivity of some fisheries may have changed over time in response to changes in targeting behaviour of the longline fleet, although the stock assessment assumes selectivity is temporally invariant.

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 51% of unexploited biomass (a fishery impact of 49%) in 2002–2005. This represents a moderate level of stock-wide depletion that is approaching the equivalent equilibrium-based limit reference point ($\tilde{B}_{MSY} / \tilde{B}_0 = 0.42$). Further, depletion is somewhat greater for some individual model regions, notably in the equatorial region 3 where recent depletion levels are approximately 0.4 (a 60% reduction from the unexploited level). Other regions are less depleted, with indices of 0.8 or greater for all other regions except for region 4 (0.65). If stock-wide over-fishing criteria were applied at the level of our model regions, we would conclude that region 3 is fully exploited, region 4 is approaching full exploitation, and the remaining regions are under-exploited. The results of the single region 3 model are generally consistent with the conclusions regarding the stock status of region 3 from the entire WCPO model.

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

7. The reference points that predict the status of the stock under equilibrium conditions are $\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$ (1.10) and $S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$ (1.12), which indicate that the long-term average biomass would remain slightly above the level capable of producing *MSY* at 2002–2005 average fishing mortality. Overall, current biomass exceeds the biomass yielding *MSY* ($B_{current} / \tilde{B}_{MSY} >$ 1.0); i.e. **the yellowfin stock in the WCPO is not in an overfished state**.

8. While the point estimate of $F_{current} / \tilde{F}_{MSY}$ remains slightly less than 1 (0.95), the probability distribution associated with fishing mortality based reference point is about the threshold level, with virtually equal probability that the value of $F_{current} / \tilde{F}_{MSY}$ is less than or greater than the reference point. Therefore, it is not possible to make a definitive statement as to whether or not overfishing of yellowfin is occurring in the WCPO. Nonetheless, **current exploitation rates are likely to be, at least, approaching the F_{MSY} level and any further increase in exploitation**

rates will not result in an increase in equilibrium yields from the stock under the current age specific pattern of exploitation (i.e, $\tilde{Y}_{F_{current}}$ is approximately equal to *MSY).* On that basis, the WCPO yellowfin tuna fishery can be considered to be fully exploited, with a substantial (47%) probability that overfishing is occurring.

9. The stock assessment conclusions differ slightly from the 2006 assessment, particularly in relation to the $F_{current}/\tilde{F}_{MSY}$ threshold with the current assessment being slightly more optimistic than the 2006 assessment. This change is largely due to the changes in the configuration of the fisheries and their associated size data in the model. However, the stock assessment results are also highly sensitive to the assumptions relating to the steepness of the stock-recruitment relationship. The base-case assessment yields a relatively low value for steepness (which is partly constrained by an informative prior), although considerably higher values of steepness are also plausible which would result in more optimistic conclusions regarding the current stock status. On the other hand, more pessimistic conclusions ($F_{current}/\tilde{F}_{MSY}$ =1.08; $B_{current}/\tilde{B}_{MSY}$ =1.20) are obtained when an uninformative steepness prior is used. In this case, the estimate of steepness is based only on evidence from the data and approaches the lower limit of values considered to be plausible for tropical tunas.
10. Stock projections for 2007–2011 — that attempt to simulate the conservation and management measures adopted at WCPFC2 and WCPFC3 — indicate that the point estimate of $B_t/\tilde{B}_{MSY}$ remains above 1.0 throughout the projection period. However, the increasing uncertainty in the future projections is likely to result in a greater probability of the biomass declining below $\tilde{B}_{MSY}$ by the end of the projection period.

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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. Number of length frequency samples included in the 2006 and the current (2007) assessment data set for each of the key longline fisheries, by decade.

2006	Number of samples					
	LL ALL 1	LL ALL 2	LL ALL 3	LL ALL 4	LL ALL 5	LL ALL 6
1950	32	18	32	31	23	10
1960	39	14	40	37	40	17
1970	34	34	40	40	32	22
1980	26	28	37	40	13	3
1990	38	35	40	40	37	15
2000	15	17	24	24	24	12

2007	Number of samples					
	LL ALL 1	LL ALL 2	LL ALL 3	LL ALL 4	LL ALL 5	LL ALL 6
1950	24	8	31	28	20	10
1960	13	1	34	21	29	9
1970	0	5	15	18	13	4
1980	0	0	1	6	0	7
1990	0	0	1	8	3	16
2000	0	0	4	2	0	2

Table 3. Number of weight frequency samples included in the 2006 and the current (2007) assessment data set for each of the key longline fisheries, by decade.

2006	Number of samples					
	LL ALL 1	LL ALL 2	LL ALL 3	LL ALL 4	LL ALL 5	LL ALL 6
1950	14	13	13	13	10	3
1960	38	38	40	40	36	15
1970	39	28	40	40	35	16
1980	40	33	40	40	38	14
1990	40	40	40	38	30	5
2000	19	17	24	18	21	5

2007	Number of samples					
	LL ALL 1	LL ALL 2	LL ALL 3	LL ALL 4	LL ALL 5	LL ALL 6
1950	12	6	12	11	8	2
1960	25	24	39	34	19	7
1970	11	24	25	29	17	1
1980	24	21	33	29	27	18
1990	18	18	29	12	4	12
2000	13	9	22	7	0	0

Table 4. Main structural assumptions of the yellowfin tuna base-case analysis and details of estimated parameters, priors and bounds. Note that the number of estimated parameters shown is substantially greater than the effective number of parameters in a statistical sense because of the effects of priors, bounds and smoothing penalties.

Category	Assumptions	Estimated parameters (ln = log transformed parameter)	No.	Prior		Bounds	
				μ	σ	Low	High
Observation model for total catch data	Observation errors small, equivalent to a residual SD on the log scale of 0.07.	None	na	na	na	na	na
Observation model for length-frequency data	Normal probability distribution of frequencies with variance determined by effective sample size and observed frequency. Effective sample size assumed to be 0.1 times actual sample size for all fisheries with a maximum effective sample size of 100.	None	na	na	na	na	na
Observation model for weight-frequency data	Normal probability distribution of frequencies, variance determined by effective sample size and observed frequency. Effective sample size assumed to be equal to 0.02 times the actual sample size for all fisheries with a maximum effective sample size of 20.	None	na	na	Na	na	na
Observation model for tagging data	Tag numbers in a stratum have negative binomial probability distribution, with estimated variance parameters for fishery groups.	Variance parameters	3	-	-	0	100
Tag reporting	Purse seine reporting rates constrained to be equal within regions. 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 (beta prior for steepness with mode at 0.85 and SD of 0.16, lower bound 0.2) .The spatial distribution of recruitment in each quarter is allowed to vary with a small penalty on deviations from the average spatial distribution.	Average spatially aggregated recruitment (ln)	1	-	-	-20	20
		Spatially aggregated recruitment deviations (ln)	220	SRR	0.7	-20	20
		Average spatial distribution of recruitment	5	-	-	0	1
		Time series deviations from average spatial distribution (ln)	1,090	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 Mean length age class 28 von Bertalanffy *K* Independent mean lengths Length-at-age SD Dependency on mean length (ln)	1 1 1 7 1 1	- - - 0 - -	- - - 0.7 - -	20 140 0 3 -1.00	40 200 0.3 8 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) Seasonality amplitude (ln) Seasonality phase Catchability deviations PH/ID (ln) Catchability deviations other (ln)	19 21 21 54 218	- 0 - 0 0	- 2.2 - 0.7 0.1	-15 - - -0.8 -0.8	1 - - 0.8 0.8
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.1 for LL ALL 1–6 & LL BMK 3 and SD 0.22 for other fisheries at the average level of effort for each fishery. SD inversely proportional to the square root of effort.	Effort deviations LL 1, 2, 4, 7, 10, 12 (ln) Effort deviations PH, ID (ln) Effort deviations other (ln)	1286 444 1687	0 0 0	0.16 0.22 0.22	-6 -6 -6	6 6 6
Natural mortality	Age-dependent but constant over time and among regions. All parameters are specified (see Figure 12).	Average natural mortality (ln) Age-specific deviations (ln)	0 0	- -	- -	- -	- -
Movement	Age-independent and variant by quarter but constant among years. No age-dependent variation.	Movement coefficients Age-dependent component (ln)	56 0	0 0	0.32 0.32	0 -4	3 4
Maturity	Age-dependent and specified – age-class 0-6: 0; 7: 0.25; 8: 0.5; 9: 0.75; 10-28: 1.0	None	na	na	na	0	1

Table 5. Summary of the range of model options investigated.

Scenario	Description	Rationale
base-case	24 fisheries, new size data aggregation, new ID catch, separate LL 3 fishery (Bismarck Sea), JP PL 1, JP PS 1, PL 3.	
region3-growth	Base-case data set with growth and M fixed based on growth estimated from single region 3 MFCL model.	Sensitivity to growth.
old-size	Determine LL size distributions as per 2006 assessment.	Sensitivity to new methodology of combining size data weighted by spatial distribution of the catch.
id-old-catch	Compare effect of change in ID MISC 3 catch from 2006 assessment.	Sensitivity to uncertainty regarding ID catch.
id-low-catch	Approx. 50% decrease in ID MISC 3 catch throughout catch history.	Sensitivity to uncertainty regarding ID catch.
id-high-catch	50% increase in ID MISC 3 catch throughout catch history.	Sensitivity to uncertainty regarding ID catch.
region3-edevs	Increase penalty weight on effort deviates for LL 3 fishery (from -50 to 200).	Improve fit to the catch/effort data from the principal LL index (LL ALL 3).
ex-newfish	Exclude JP PL 1, JP PS 1, and PL 3 from base-case data set.	Assess impact on inclusion of additional catch.
recombine-LL3	Recombine LL ALL 3 and LL BMK 3 fisheries (23 fisheries).	Assess impact of splitting LL ALL 3 fishery.
recombine-LL3&PHID	Recombine LL ALL 3 & LL BMK 3 fisheries and ID MISC 3 & PH MISC 3 fisheries (22 fisheries).	Assess impact of splitting LL ALL 3 fishery and PHID MISC 3 fishery.
region3	Single region model encompassing MFCL region 3 only. 10 fisheries and 13 tag release groups.	Assess the influence of data from the peripheral regions of the WCPO on the key stock assessment conclusions for the main region of the fishery.
high-steepness	Steepness of the SRR of 0.913 (compared to the estimated value of 0.6215).	Examine the influence of steepness on the biological reference points.
steepness-no-prior	Replace the beta-distribution prior on steepness used in the base-case with a uniform, uninformative prior.	Examine the influence of steepness on the biological reference points.

Table 6. Details of objective function components for the base-case model and three of the sensitivity analyses.

Objective function component	base-case	ID-low-catch	ID-high-catch	region3-growth
Total catch log-likelihood	598.80	595.90	600.18	638.50
Length frequency log-likelihood	-349,920.62	-349,876.45	-349,936.53	-350,030.85
Weight frequency log-likelihood	-760,710.15	-760,709.29	-760,713.94	-759,670.09
Tag log-likelihood	2,618.91	2,606.04	2,632.90	3,118.94
Penalties	7,152.87	7,148.73	7,157.87	7,331.48
Total function value	-1,100,260.19	-1,100,235.07	-1,100,259.52	-1,098,612.02

Table 7. Description of symbols used in the yield analysis.

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2002–2005
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 (2002–2005) total biomass
$SB_{current}$	Average current (2002–2005) adult biomass
B_{1995}	Average total biomass in 1995
SB_{1995}	Average adult biomass in 1995
$B_{current,F=0}$	Average current (2002–2005) total biomass in the absence of fishing.

Table 8. Estimates of management quantities for the three stock assessment models. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading).

Management quantity	**Units**	**base-case**	**ID-low-catch**	**ID-high-catch**	**region3-growth**	**high-steepness**	**Steepness-no-prior**	**region3**
$\widetilde{Y}_{F_{current}}$	mt per year	399,960	376,760	449,200	406,800	481,200	337,400	268,120
$\widetilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	400,000	376,760	452,400	422,000	549,200	344,520	268,200
$\widetilde{B}_0$	mt	3,665,000	3,420,000	4,002,000	3,440,000	3,528,000	3,735,000	1,881,000
$\widetilde{B}_{F_{current}}$	mt	1,631,000	1,536,000	1,773,000	1,762,000	1,945,000	1,372,000	850,200
$\widetilde{B}_{MSY}$	mt	1,489,000	1,536,000	1,626,000	1,476,000	1,275,000	1,203,000	802,600
$S\widetilde{B}_0$	mt	2,171,000	2,017,000	2,372,000	2,306,000	2,086,000	2,209,000	1,261,000
$S\widetilde{B}_{F_{current}}$	mt	763,600	713,700	830,600	956,900	907,700	641,200	420,800
$S\widetilde{B}_{MSY}$	mt	679,800	713,700	742,600	750,700	482,000	548,000	386,700
$B_{current}$	mt	1,821,671	1,728,256	2,010,322	1,884,754	1,805,380	1,815,953	1,028,022
$SB_{current}$	mt	850,210	797,860	935,146	1,011,554	839,100	846,622	511,528
$B_{current,F=0}$	mt	3,594,445	3,253,999	3,938,575	3,480,678	3,109,349	3,910,865	2,195,727
$B_{current} / \widetilde{B}_0$		0.50	0.51	0.50	0.55	0.51	0.49	0.55
$B_{current} / \widetilde{B}_{F_{current}}$		1.12	1.13	1.13	1.07	0.93	1.32	1.21
$B_{current} / \widetilde{B}_{MSY}$		1.17	1.13	1.24	1.28	1.42	1.20	1.28
$B_{current} / B_{current,F=0}$		0.51	0.53	0.51	0.54	0.58		0.47
$SB_{current} / S\widetilde{B}_0$		0.39	0.40	0.39	0.44	0.40	0.38	0.41
$SB_{current} / S\widetilde{B}_{F_{current}}$		1.11	1.12	1.13	1.06	0.92	1.32	1.22
$SB_{current} / S\widetilde{B}_{MSY}$		1.25	1.12	1.26	1.35	1.74	1.54	1.32
$\widetilde{B}_{F_{current}} / \widetilde{B}_0$		0.45	0.45	0.44	0.51	0.55	0.37	0.45
$S\widetilde{B}_{F_{current}} / S\widetilde{B}_0$		0.35	0.35	0.35	0.41	0.44	0.29	0.33
$\widetilde{B}_{MSY} / \widetilde{B}_0$		0.41	0.45	0.41	0.43	0.36	0.32	0.43
$S\widetilde{B}_{MSY} / S\widetilde{B}_0$		0.31	0.35	0.31	0.33	0.23	0.25	0.31
$F_{current} / \widetilde{F}_{MSY}$		0.95	1.00	0.91	0.77	0.56	0.92	0.91
$\widetilde{B}_{F_{current}} / \widetilde{B}_{MSY}$		1.10	1.00	1.09	1.19	1.53	1.14	1.06
$S\widetilde{B}_{F_{current}} / S\widetilde{B}_{MSY}$		1.12	1.00	1.12	1.27	1.88	1.17	1.09
$\widetilde{Y}_{F_{current}} / MSY$		1.00	1.00	0.99	0.96	0.88	0.98	1.00
$B_{current} / B_{1995}$		0.65	0.66	0.66	0.73	0.65	0.65	0.82
$SB_{current} / SB_{1995}$		0.58	0.59	0.59	0.64	0.58	0.58	0.72

Table 9. Percentage probability that $B_{current}/\widetilde{B}_{MSY}$ and $F_{current}/\widetilde{F}_{MSY}$ exceed the reference value based on the likelihood profile of the base-case model.

Reference level	**Probability (%) of exceeding reference level**	
	$B_{current}/\widetilde{B}_{MSY}$	$F_{current}/\widetilde{F}_{MSY}$
0.5	100.0	99.7
0.6	100.0	95.5
0.7	100.0	87.5
0.8	100.0	76.1
0.9	98.9	62.2
1.0	92.7	46.8
1.1	74.6	33.0
1.2	48.8	21.7
1.3	25.7	13.5
1.4	12.3	8.3
1.5	5.2	5.2
1.6	2.0	3.3
1.7	0.7	2.3
1.8	0.2	1.5
1.9	0.0	1.0
2.0	0.0	0.7
2.1	0.0	0.6
2.2	0.0	0.5
2.3	0.0	0.4
2.4	0.0	0.3
2.5	0.0	0.3

Table 10. Fishing effort scalars relative to the 2002-2005 average required to produce equilibrium total and spawning biomass at various levels above B_{MSY}.

Equilibrium biomass relative to B_{MSY}	Equilibrium biomass relative to $\widetilde{B}_0$	Equilibrium biomass relative to $\widetilde{SB}_0$	Fishing Effort Scalar relative to 2002-2005 average
1.00	0.42	0.33	1.05
1.05	0.44	0.35	1.00
1.10	0.47	0.38	0.94
1.15	0.49	0.40	0.89
1.20	0.51	0.42	0.84
1.25	0.53	0.44	0.79
1.30	0.55	0.46	0.75
1.35	0.57	0.49	0.70
1.40	0.59	0.51	0.66

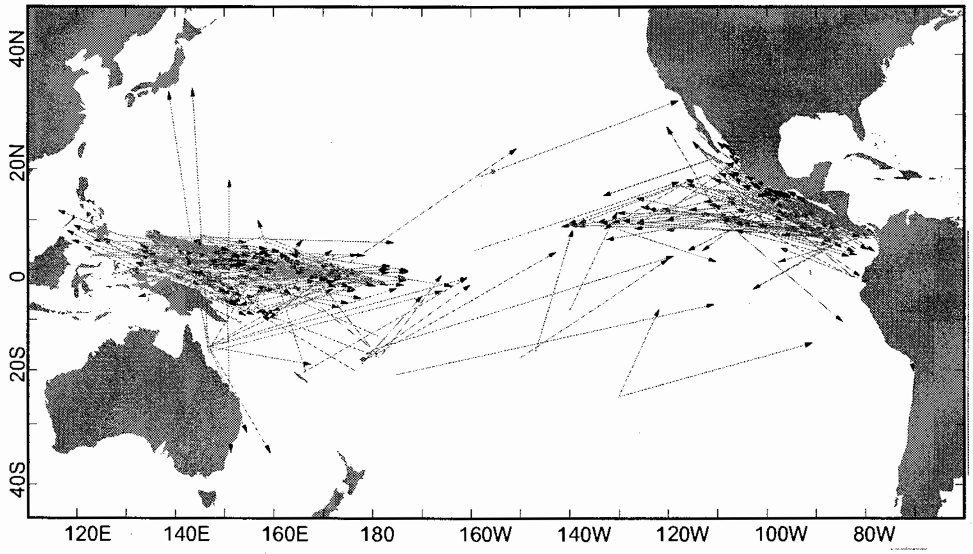

Figure 1. Long-distance (greater than 1,000 nmi) movements of tagged yellowfin tuna.

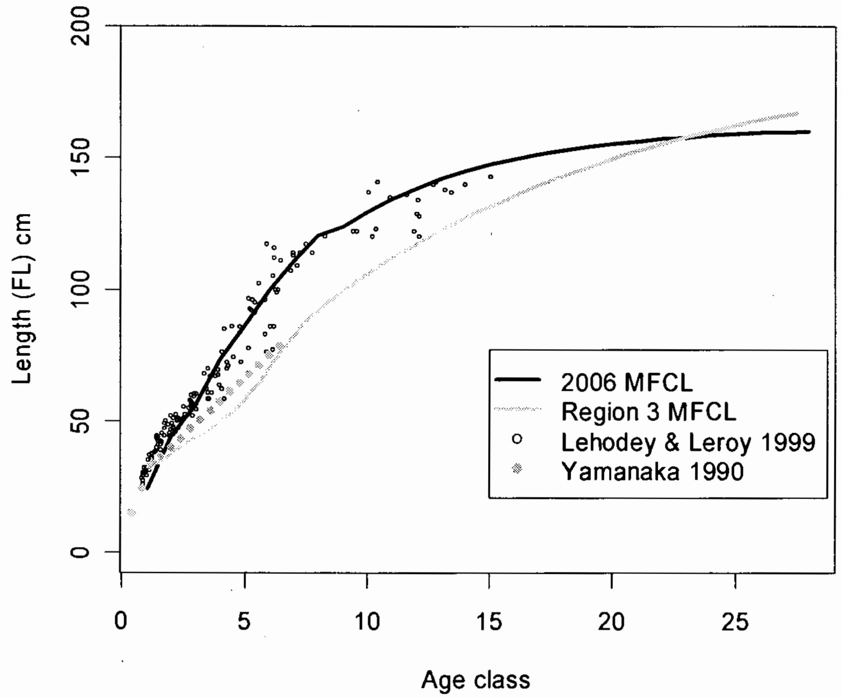

Figure 2. A comparison of yellowfin growth estimated from WCPO and region 3 MFCL models and the results from ageing studies using otolith daily increments.

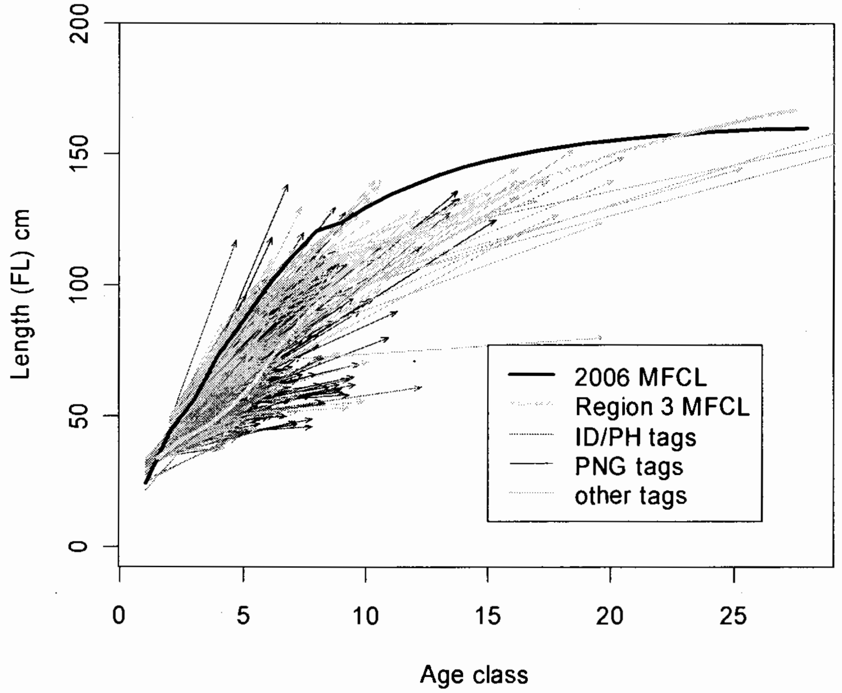

Figure 3. A comparison of yellowfin growth estimated from WCPO and region 3 MFCL models with growth increments from tagged fish released in Indonesian/Philippines waters, PNG waters, and other areas.

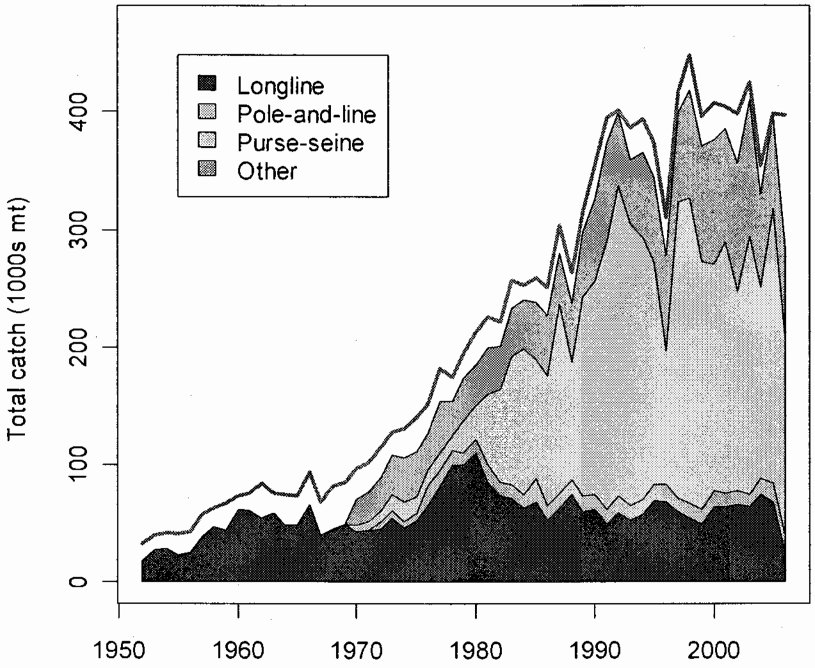

Figure 4. Total annual catches (1000s mt) of yellowfin from the WCPO by fishing method from 1952 to 2006. The "Other" category represents catches from the domestic fisheries of Indonesia and the Philippines. Data from 2006 are incomplete. The purple line represents the total annual catch estimates for the WCPO.

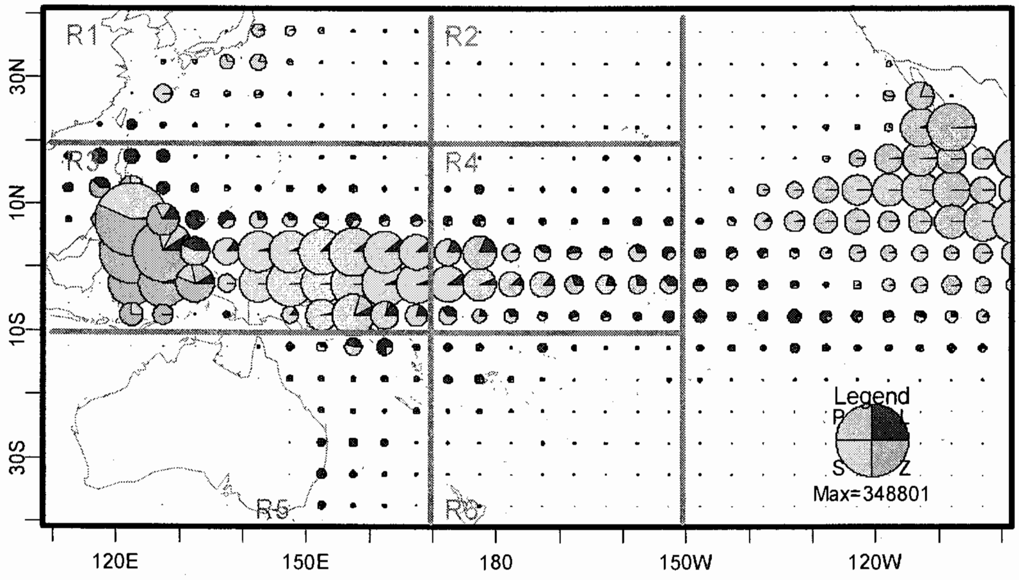

Figure 5. Distribution of cumulative yellowfin tuna catch from 1990–2005 by 5 degree squares of latitude and longitude and fishing gear; longline (L, blue), purse-seine (S, green), pole-and-line (P, grey) and other (Z, dark orange). The grey lines indicate the spatial stratification.

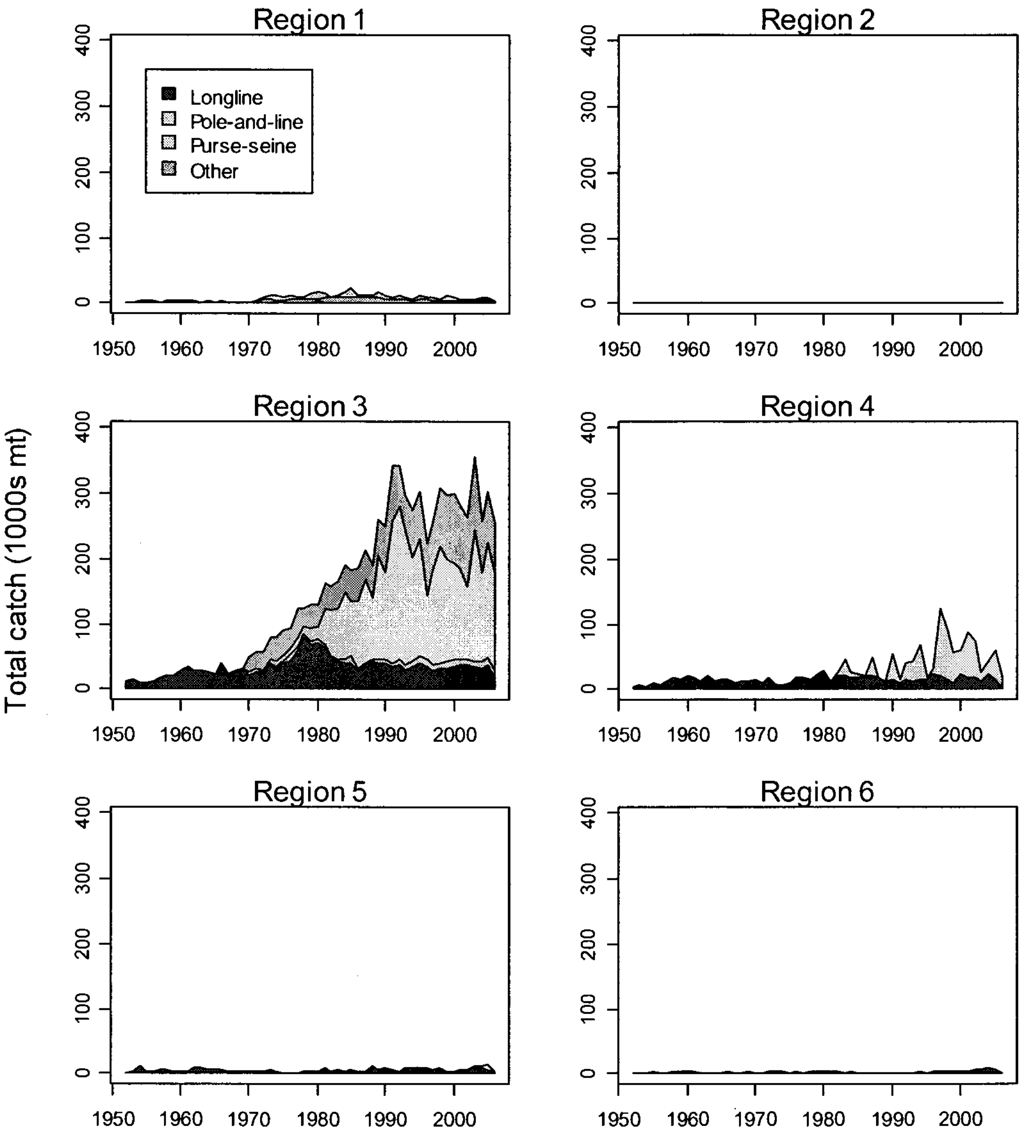

Figure 6. Total annual catch (1000s mt) of yellowfin by fishing method and MFCL region from 1952 to 2006. The "Other" category represents catches from the domestic fisheries of Indonesia and the Philippines. Data from 2006 are incomplete.

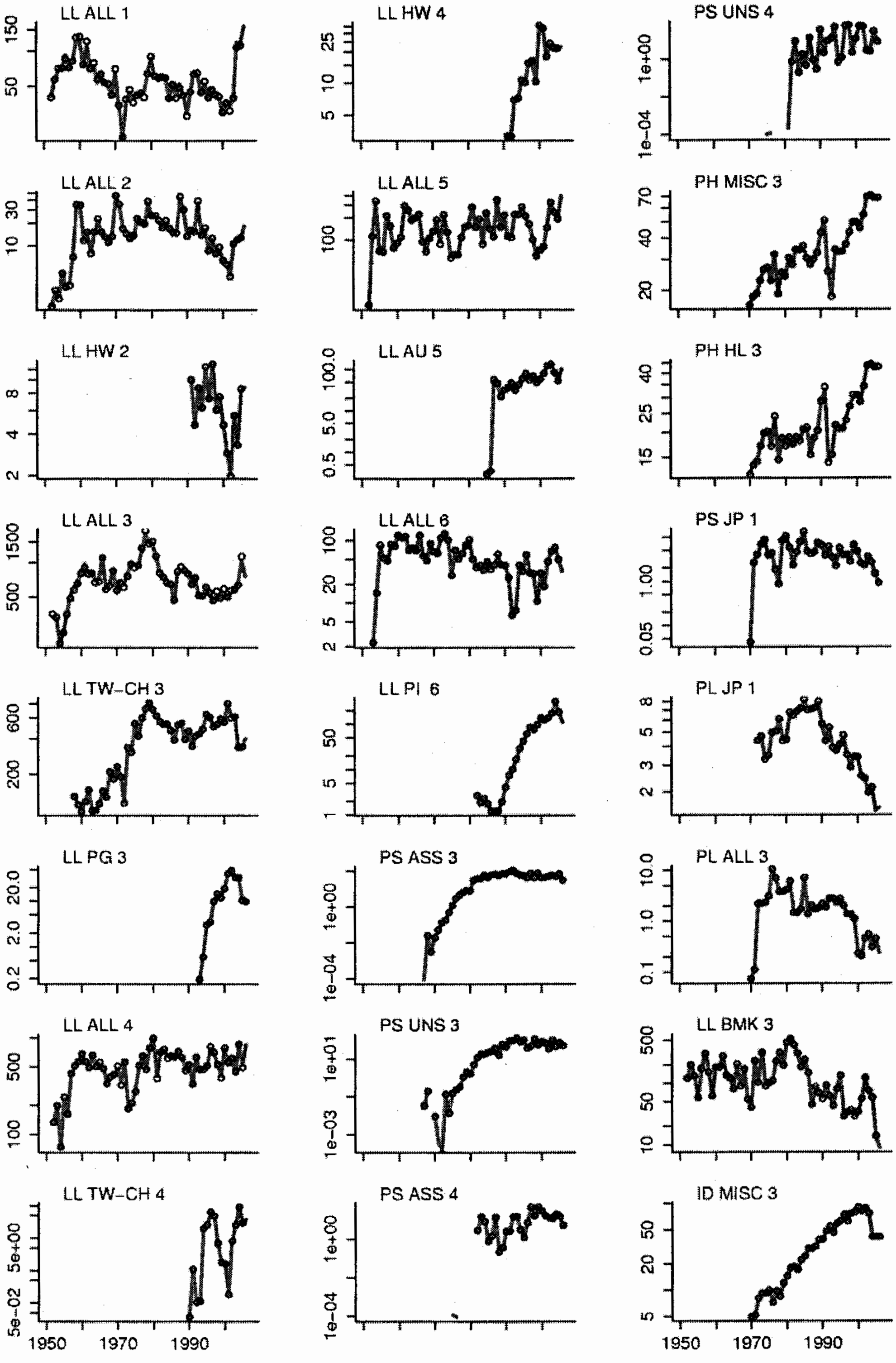

Figure 7. Annual catches, by fishery. Circles are observed and the lines are model predictions. Units are catch number in thousands for the longline fisheries and thousand metric tonnes for all other fisheries.

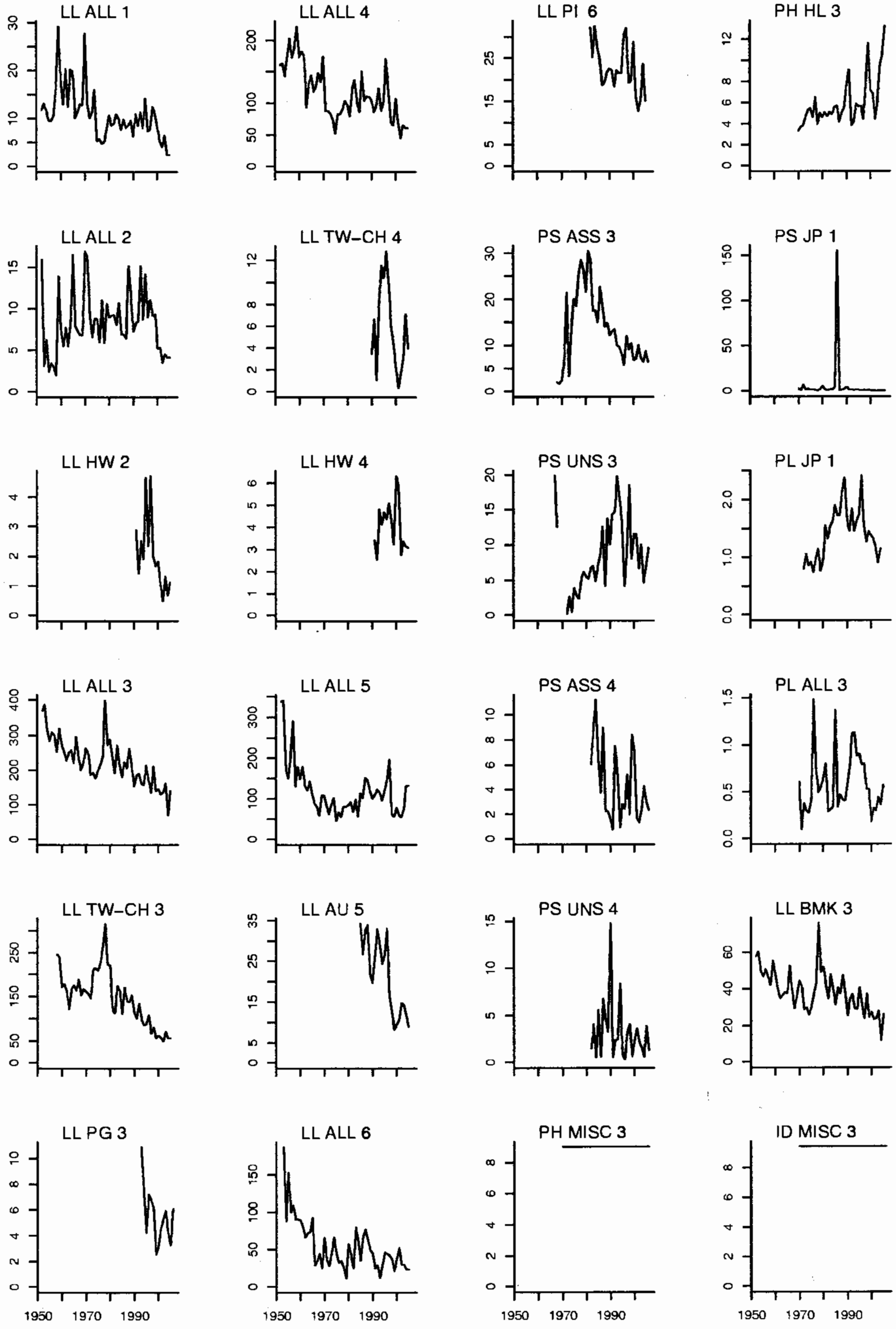

Figure 8. Catch-per-unit-effort (CPUE) by fishery. Units are catch number per GLM-standardised effort (fisheries LL ALL 1–LL ALL 6), catch number per 100 nominal hooks (LL HW, CH/TW LL, LL PI, LL PG, LL BMK) and catch (mt) per day fished/searched (all PS and PL fisheries). Note that CPUE for PH and ID MISC 3 is arbitrary and not based on data (see discussion on catchability and effort deviation constraints for these fisheries).

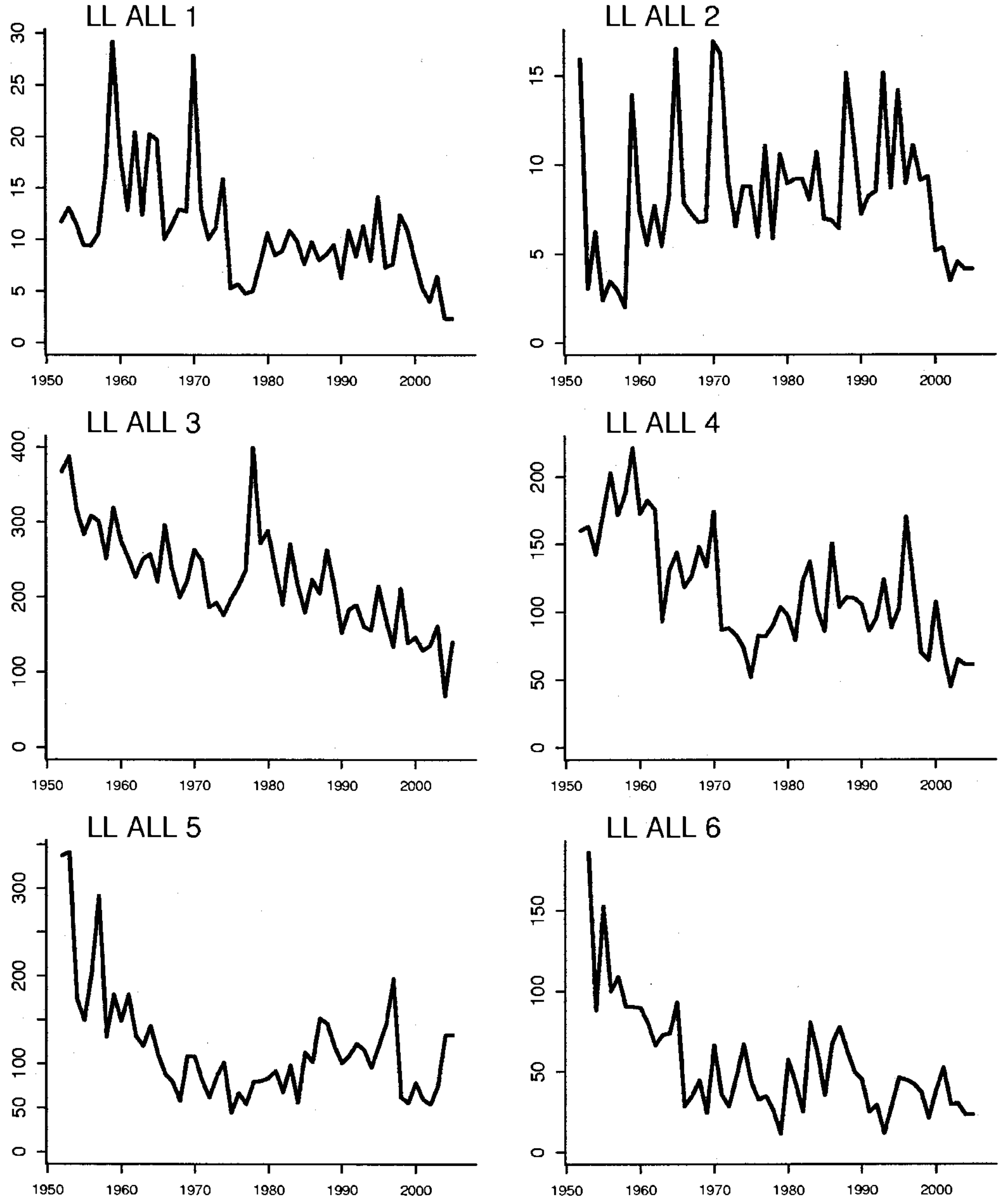

Figure 9. GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL ALL 1–6) scaled by the respective region scalars.

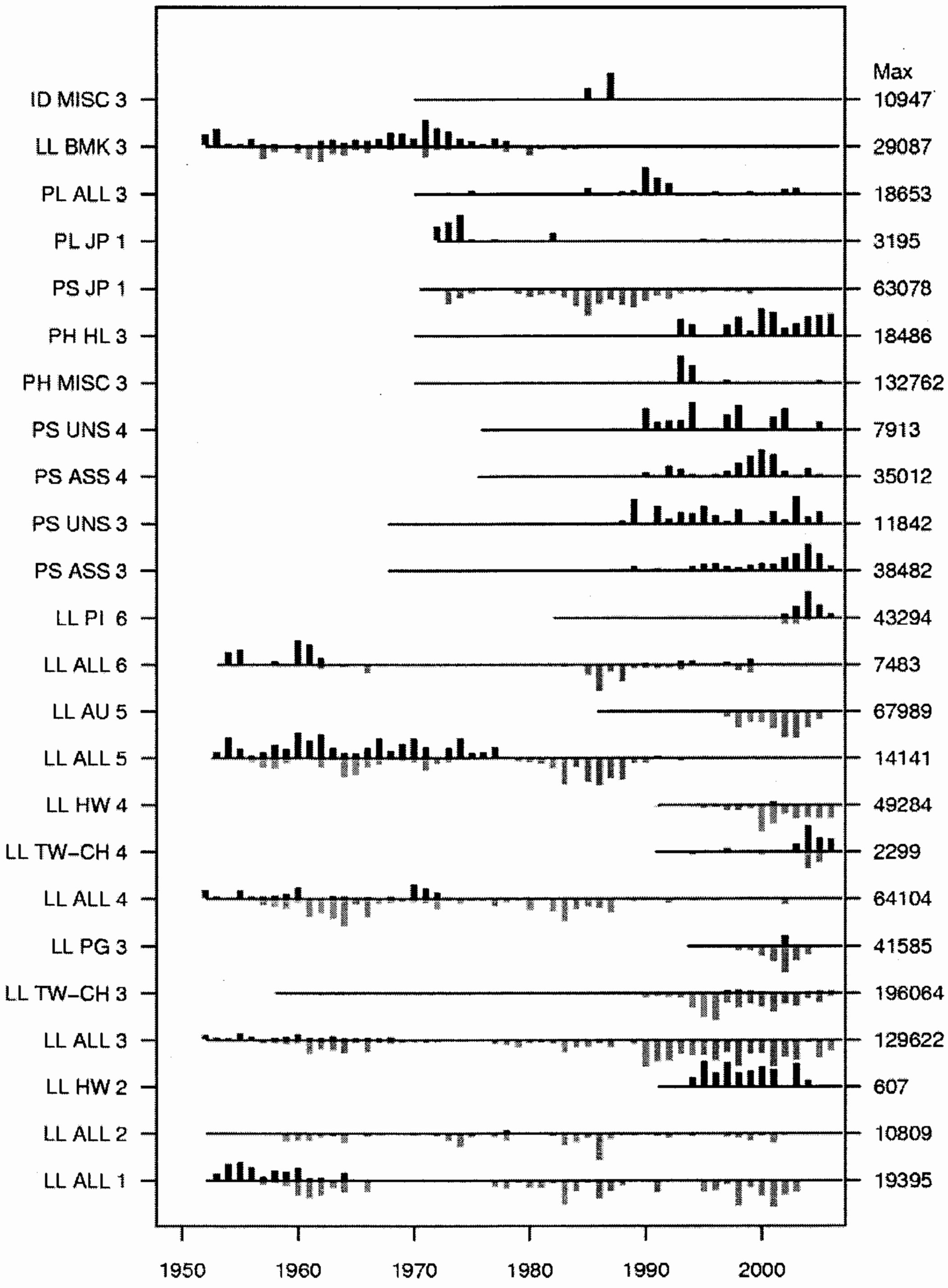

Figure 10. Number of fish size measurements by year for each fishery. The upper black bars represent length measurements and the lower grey bars represent weight measurements. The maximum bar length for each fishery is given on the right-hand side. The extent of the horizontal lines indicates the period over which each fishery occurred.

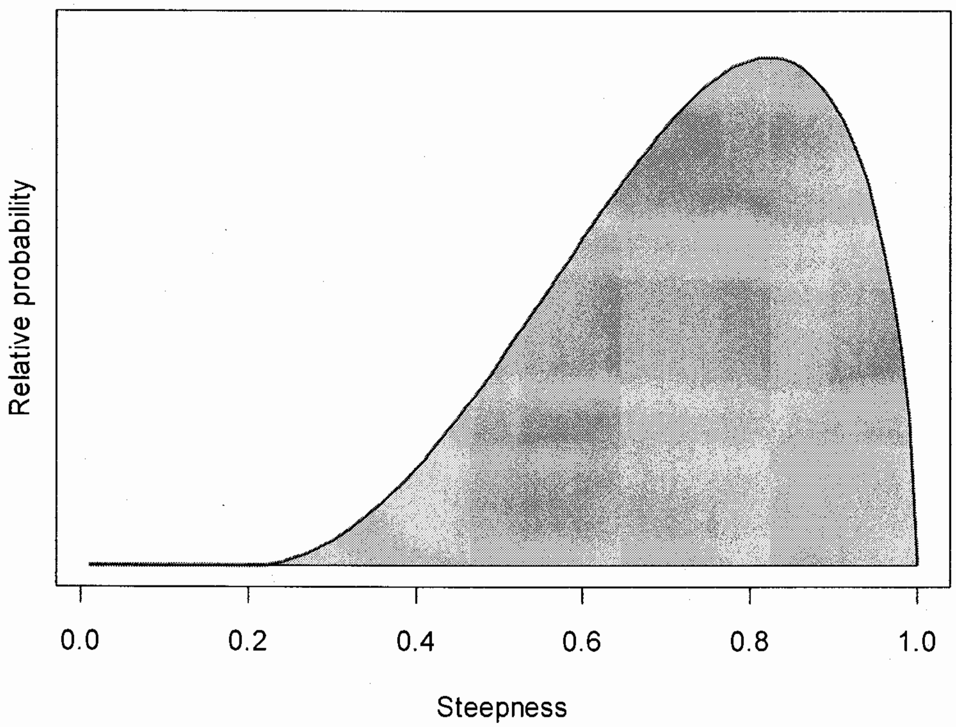

Figure 11. Prior for the steepness parameter of the relationship between spawning biomass and recruitment (SSR) (mode = 0.85, standard deviation = 0.16).

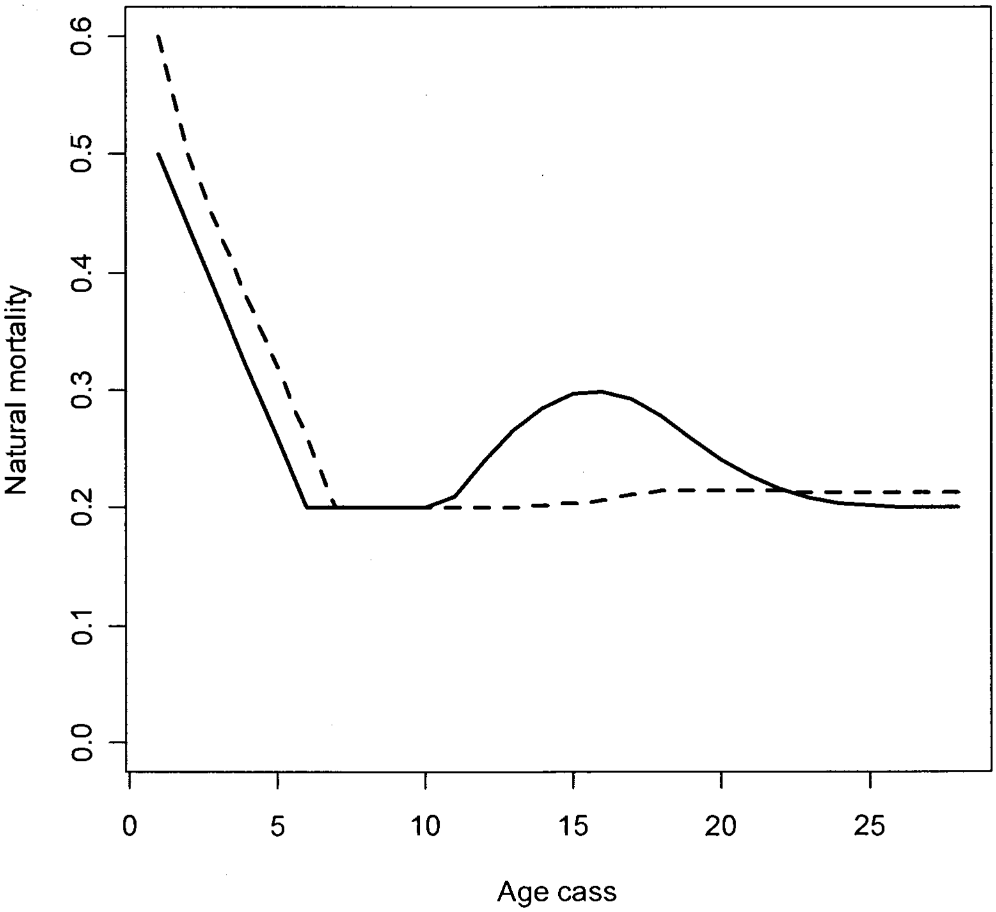

Figure 12. Age-specific natural mortality assumed for the assessment (from Maunder and Harley 2004) (solid line) and the alternative natural mortality used for sensitivity analyses using growth parameters derived from MFCL region 3 (dashed line).

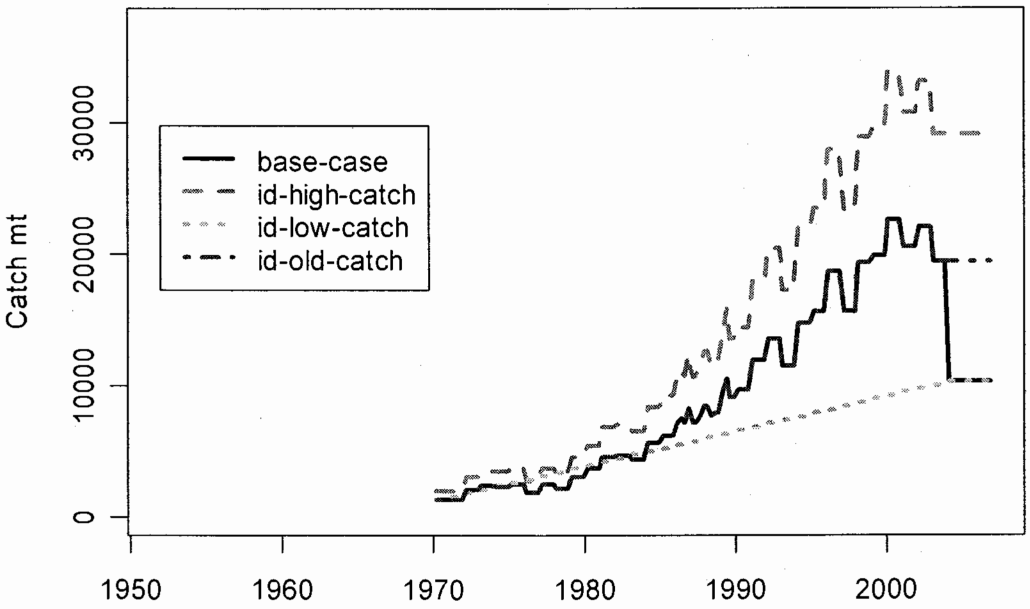

Figure 13. A comparison of the yellowfin tuna catch (mt per quarter) from the Indonesian fishery (ID MISC 3) incorporated in the base-case model and the three sensitivity analyses.

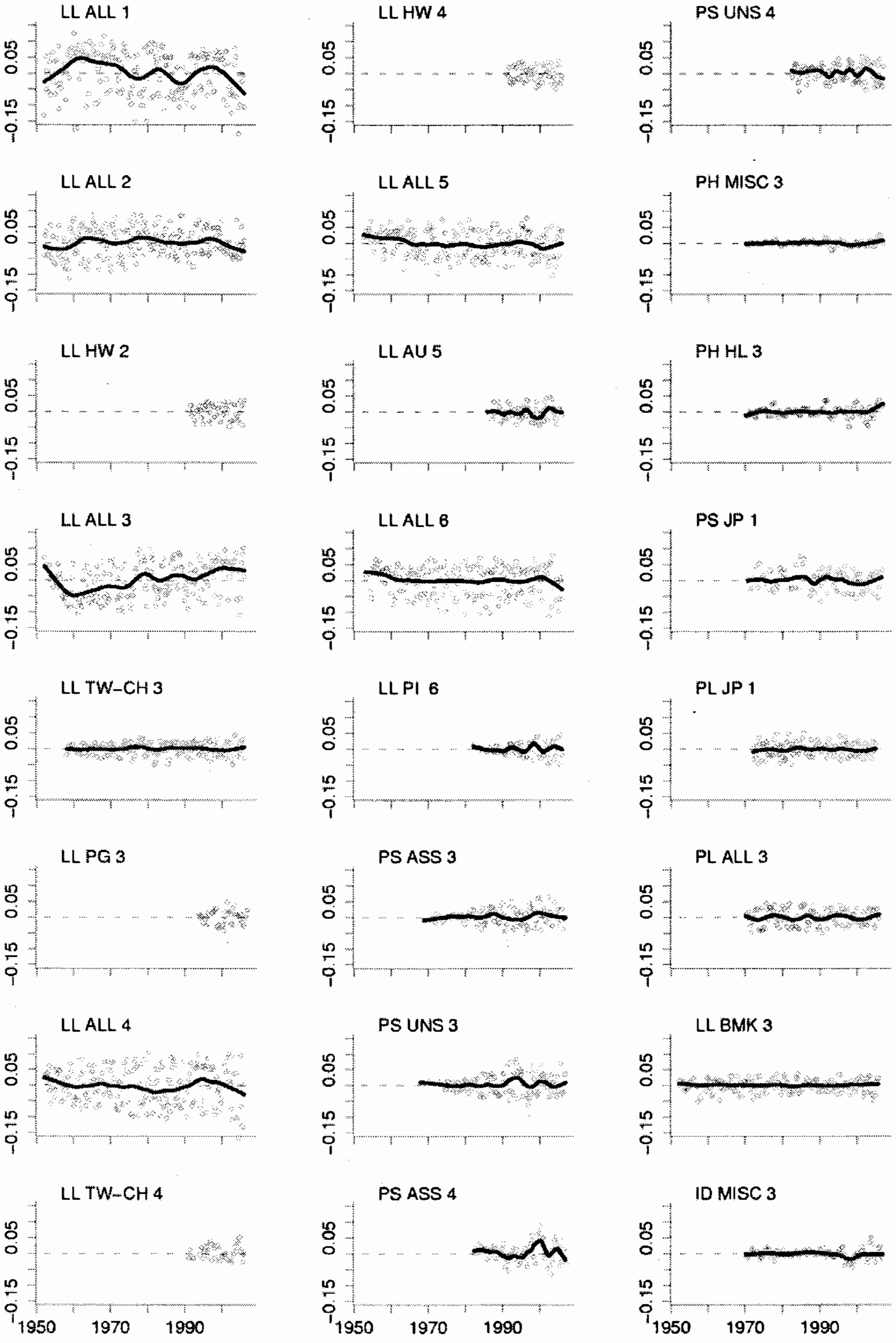

Figure 14. Residuals of ln (total catch) for each fishery. The solid line represents a lowess fit to the data.

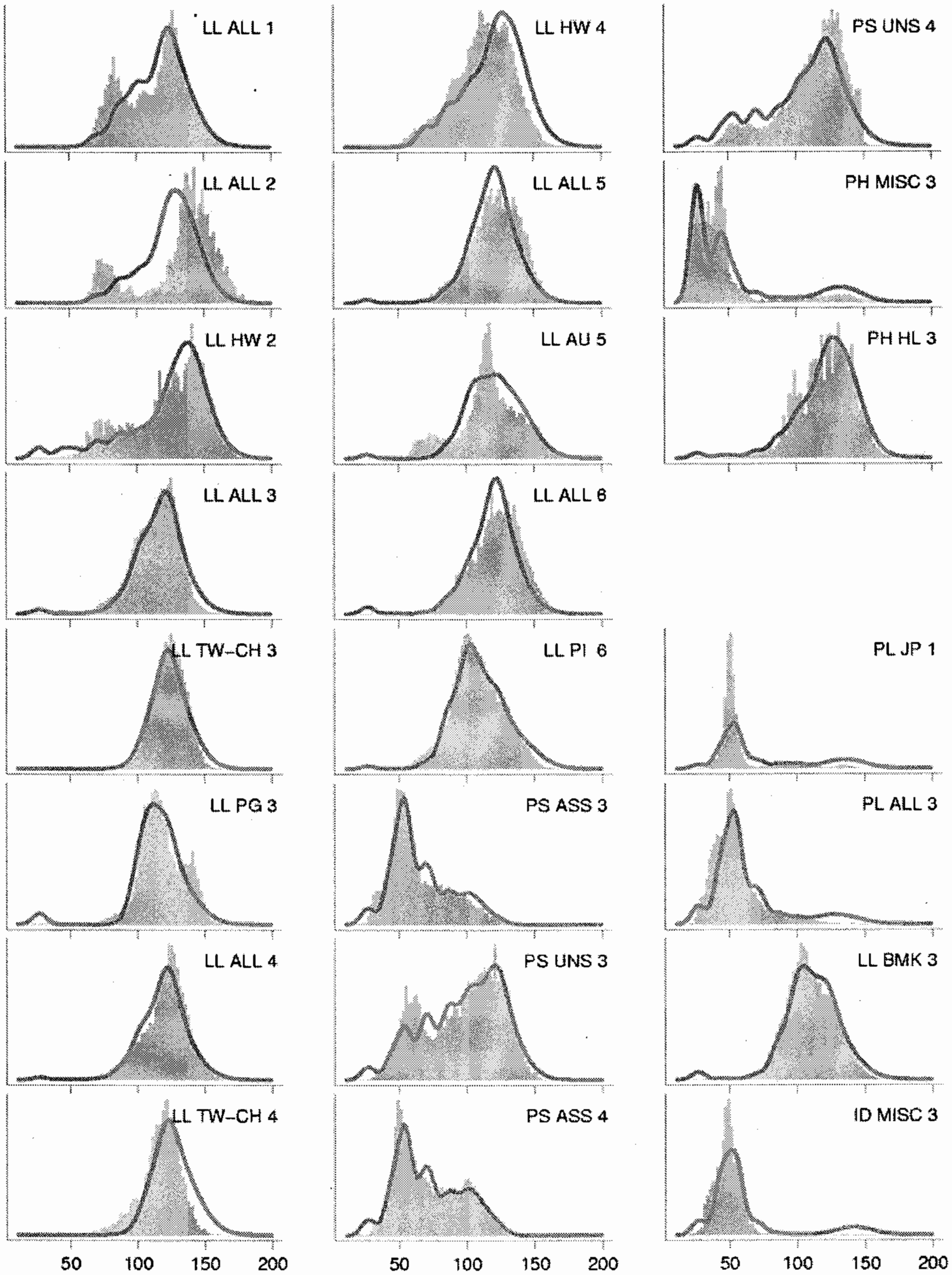

Figure 15. Observed (histograms) and predicted (line) length frequencies (in cm) for each fishery aggregated over time.

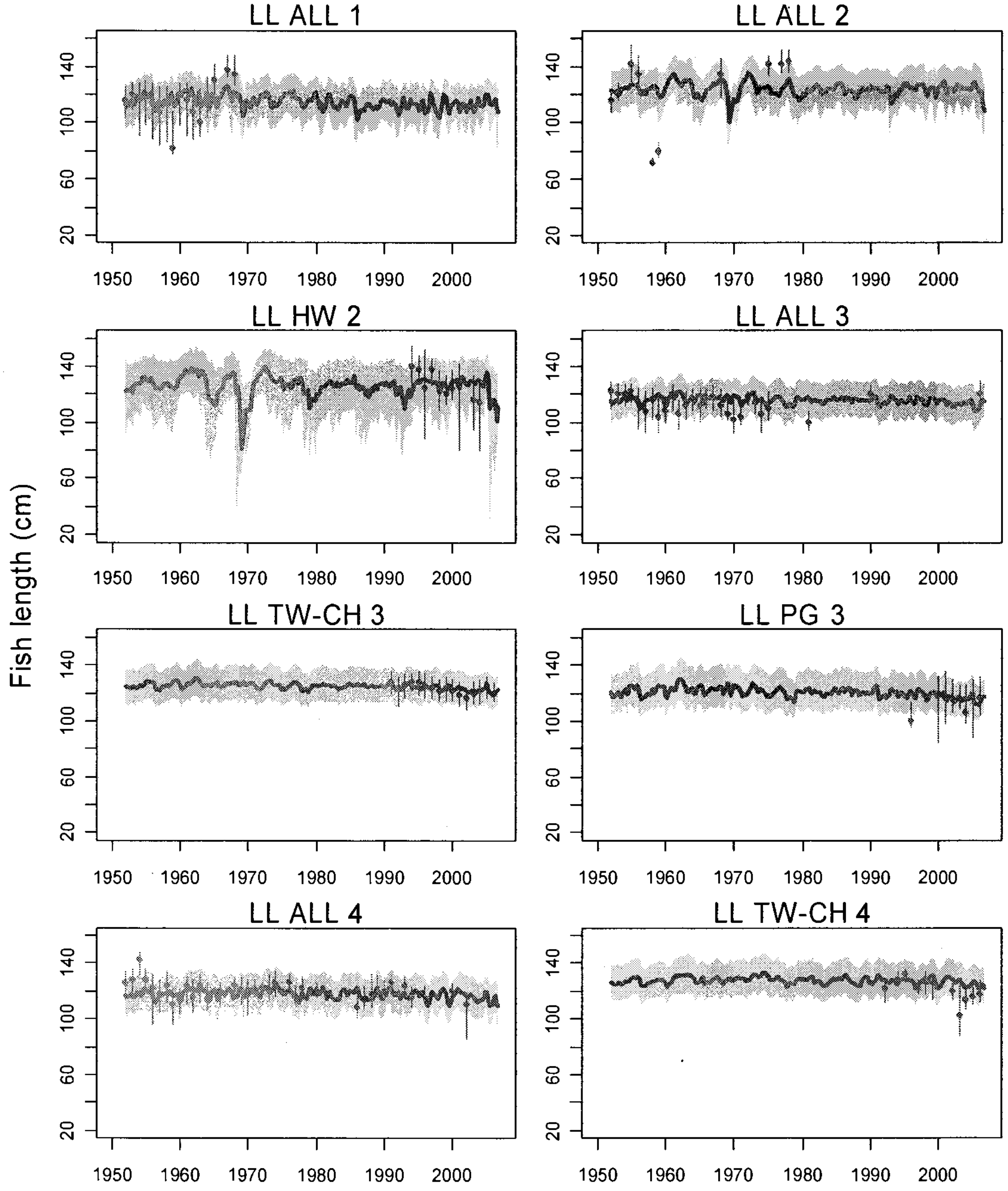

Figure 16. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of yellowfin tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

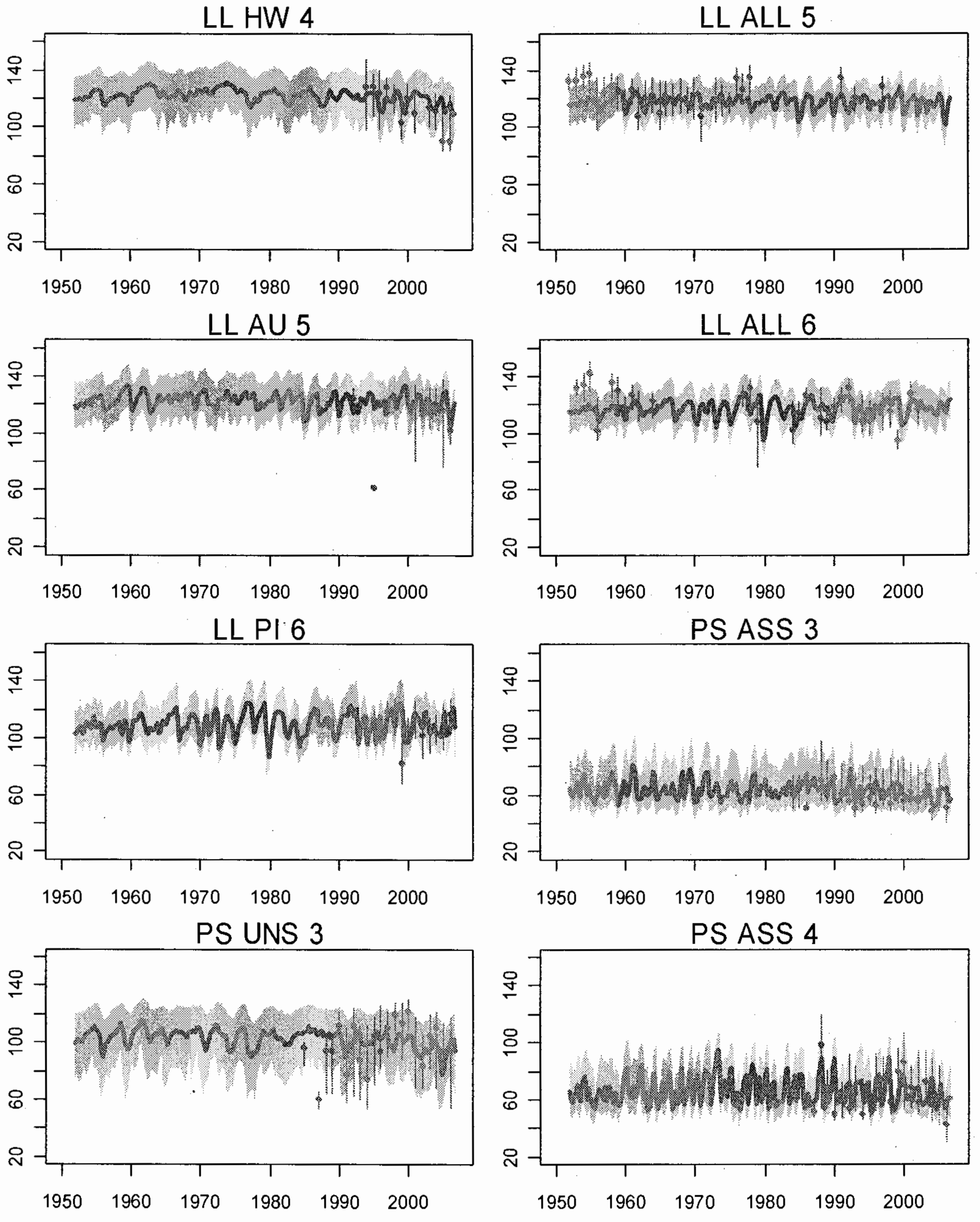

Figure 16 (continued).

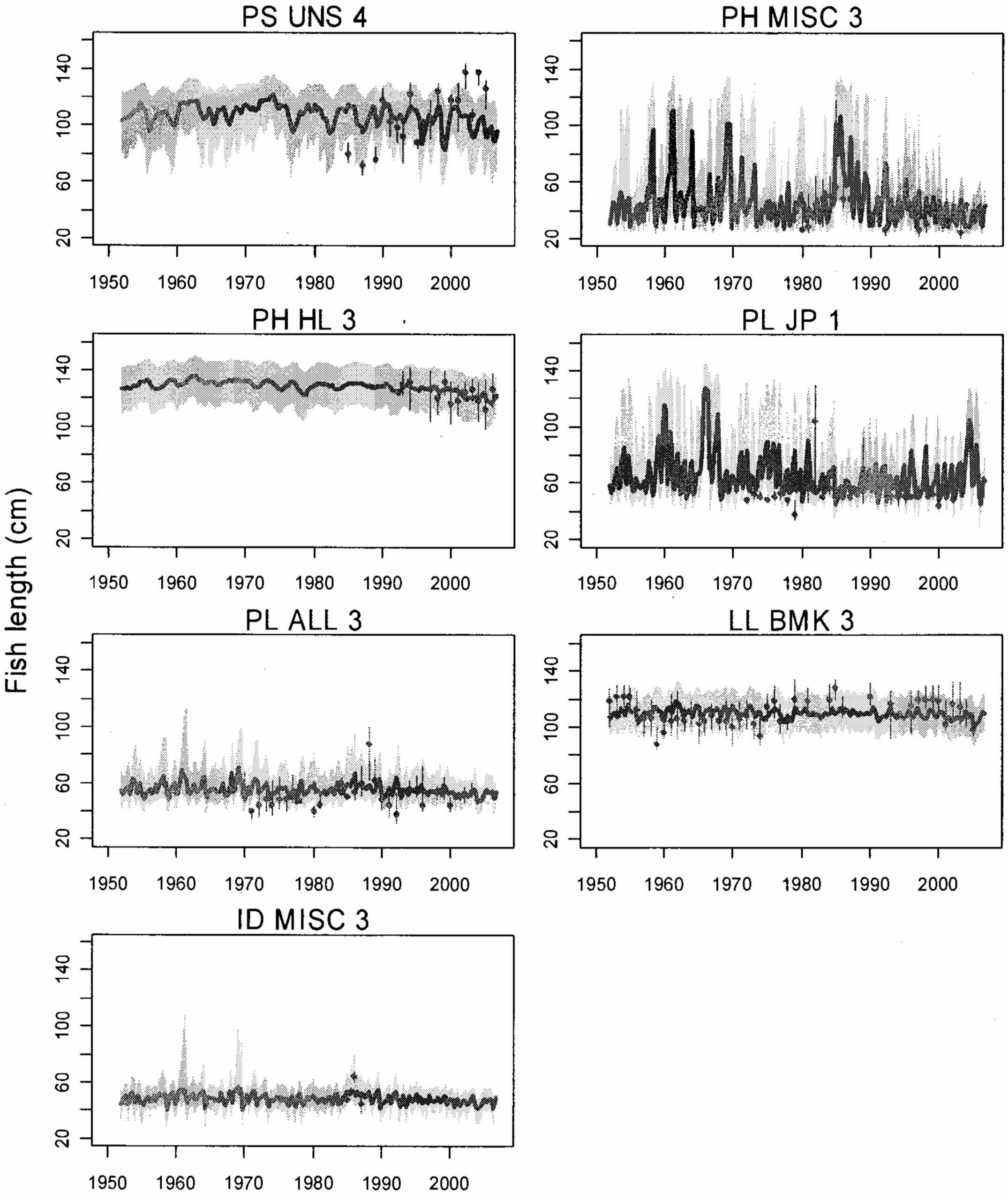

Figure 16 (continued).

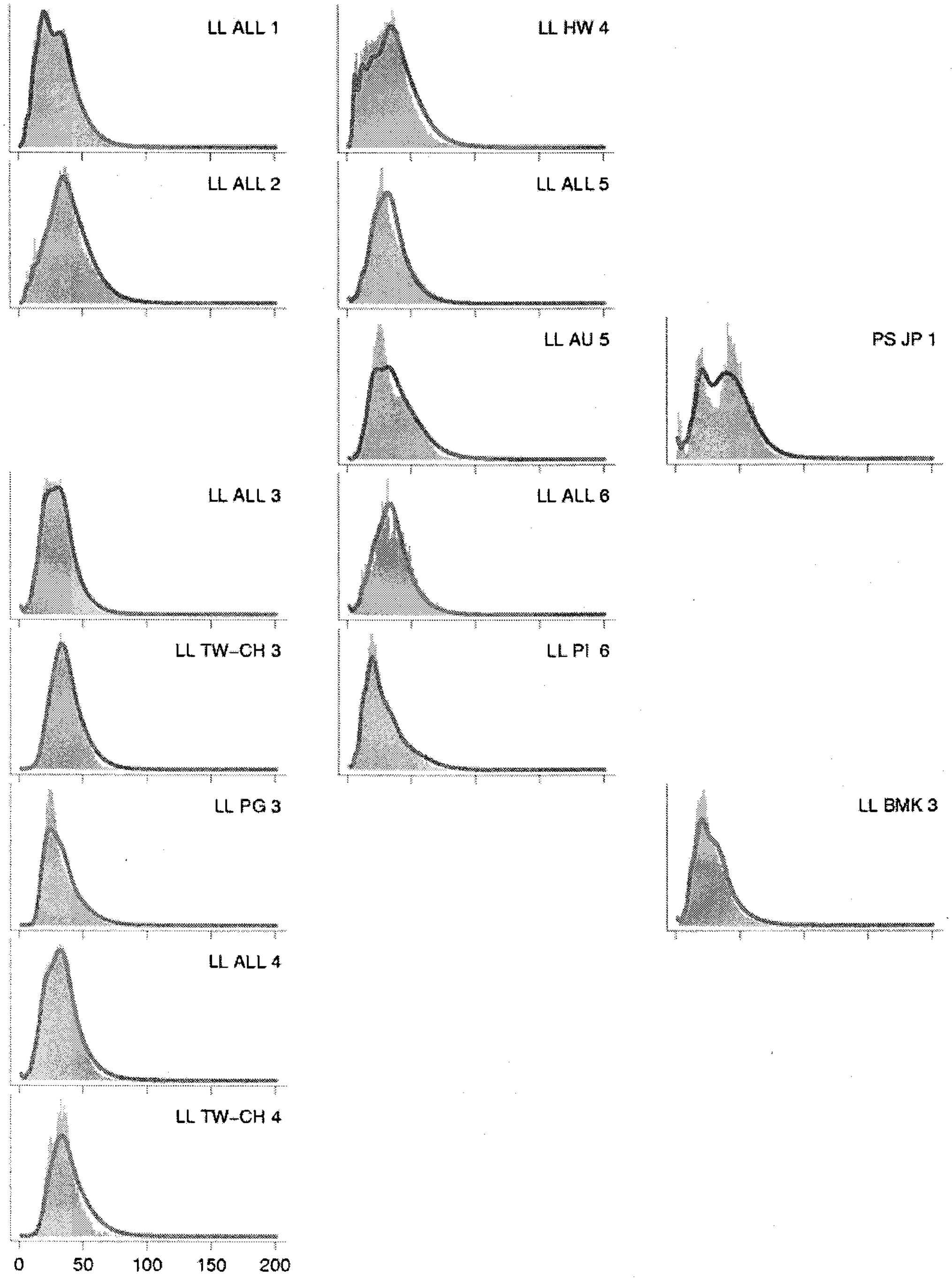

Figure 17. Observed (histograms) and predicted (line) weight frequencies (in kg) for each fishery aggregated over time.

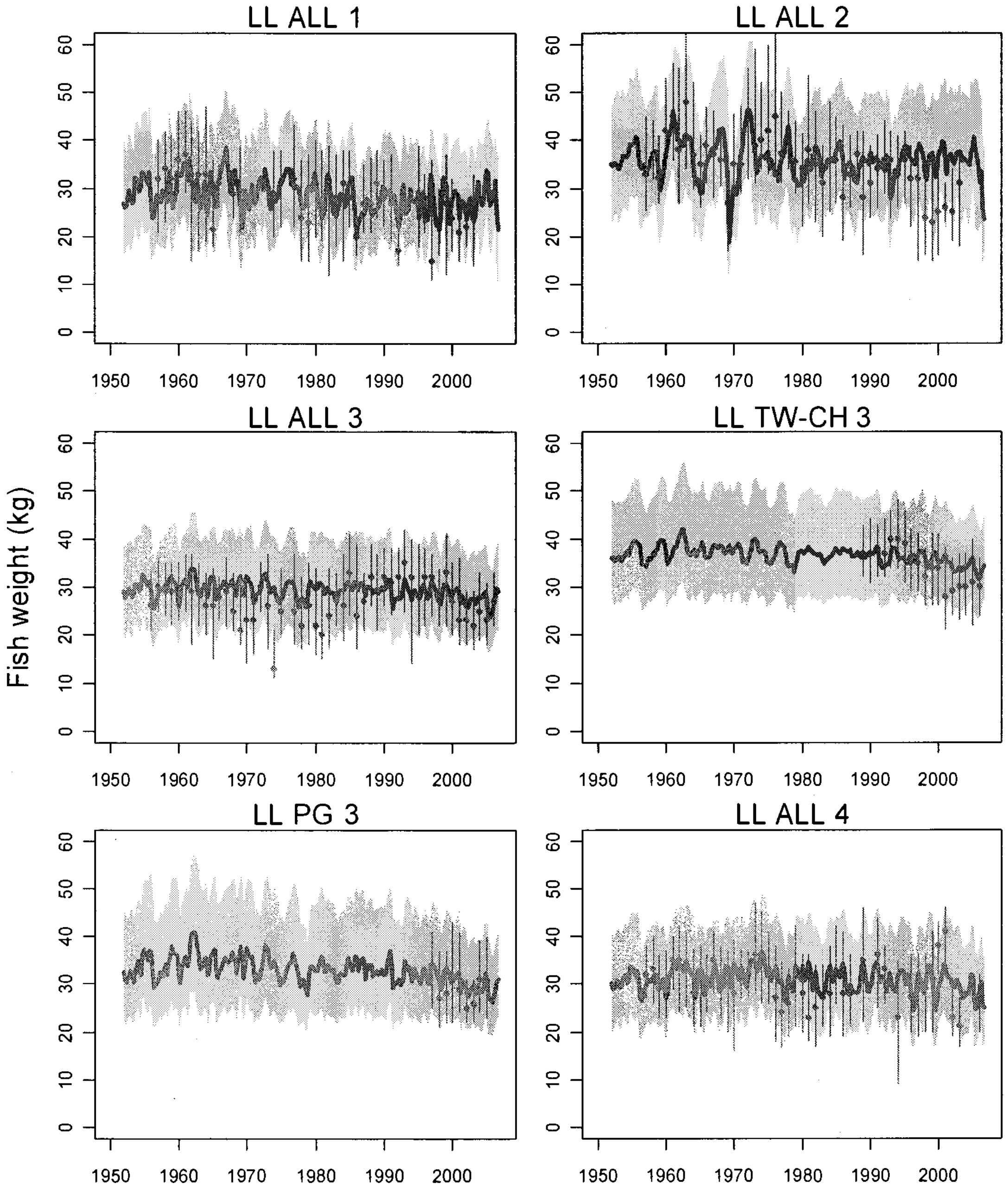

Figure 18. A comparison of the observed (red points) and predicted (grey line) median fish weight (whole weight, kg) of yellowfin tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated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

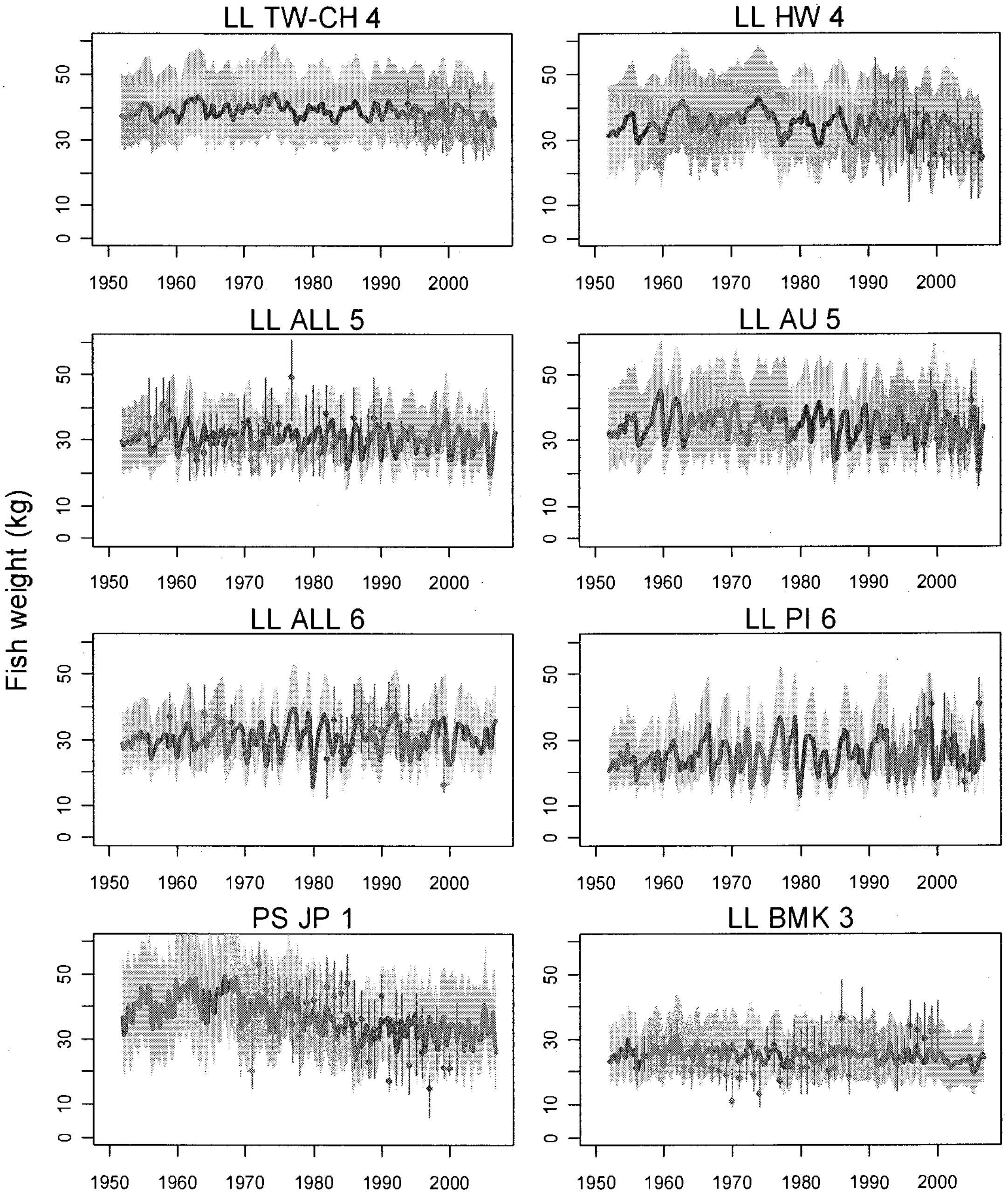

Figure 18 (continued).

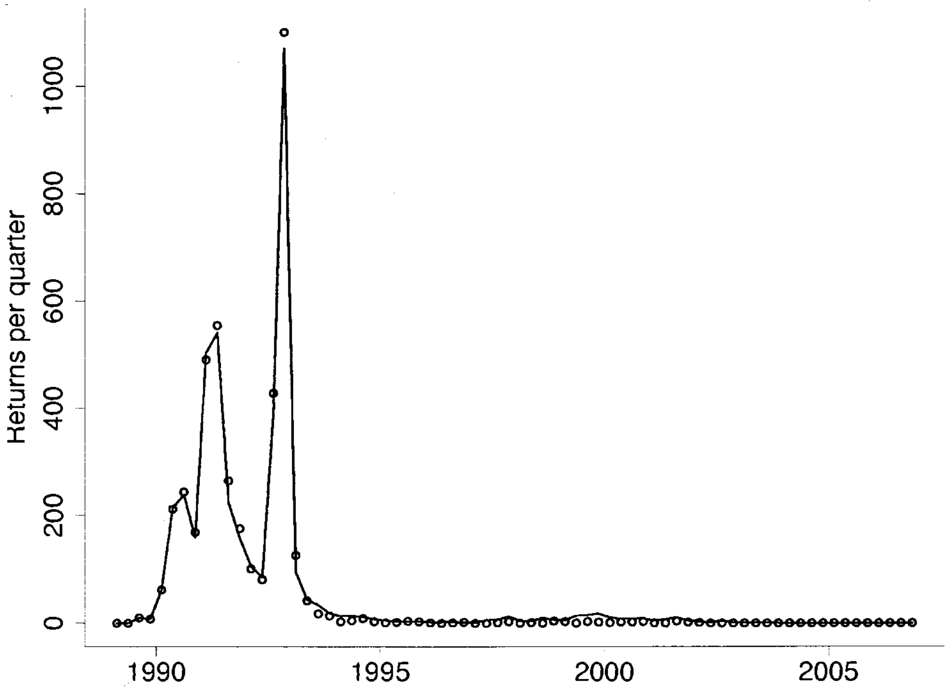

Figure 19. Number of observed (points) and predicted (line) tag returns by recapture period (quarter).

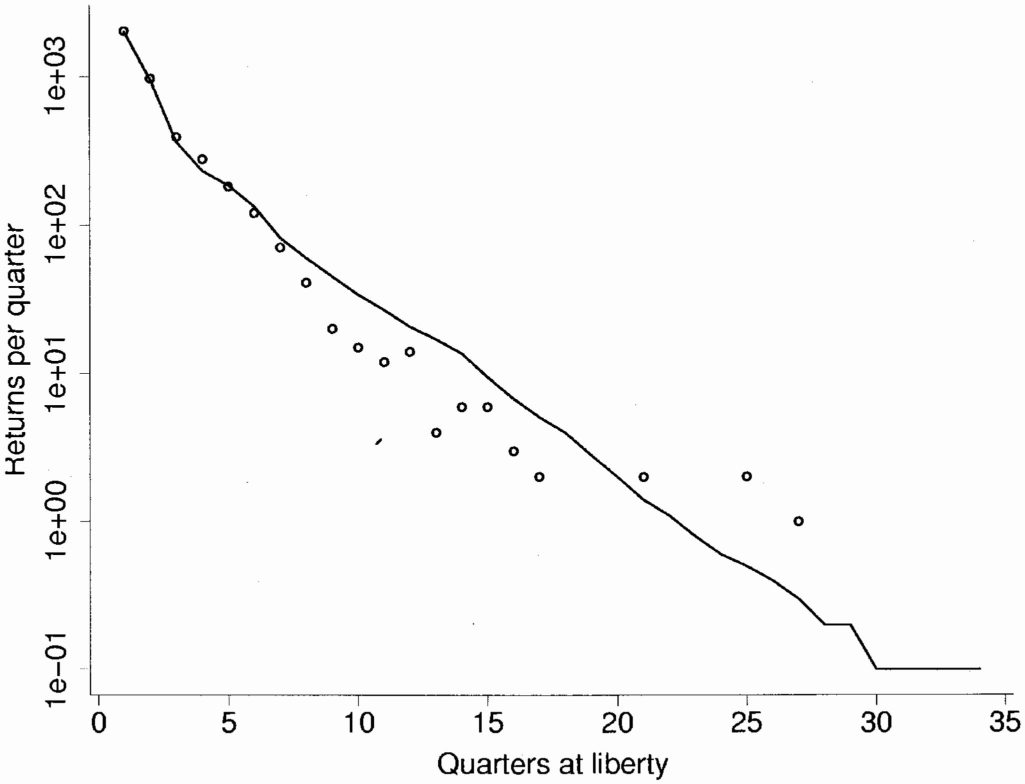

Figure 20. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters).

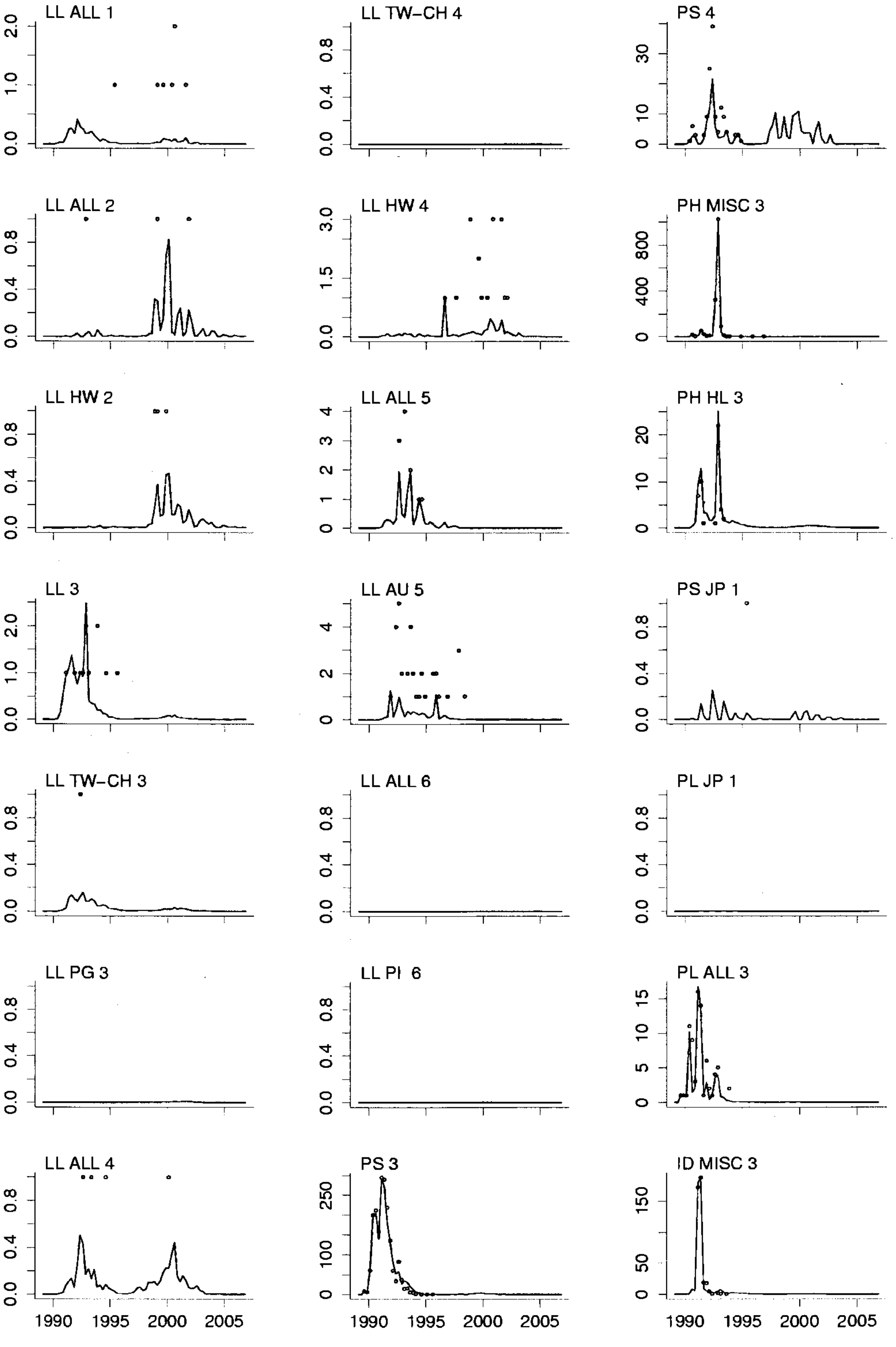

Figure 21. Number of observed (points) and predicted (line) tag returns by recapture period (quarter) for the various fisheries (or groups of fisheries) defined in the model.

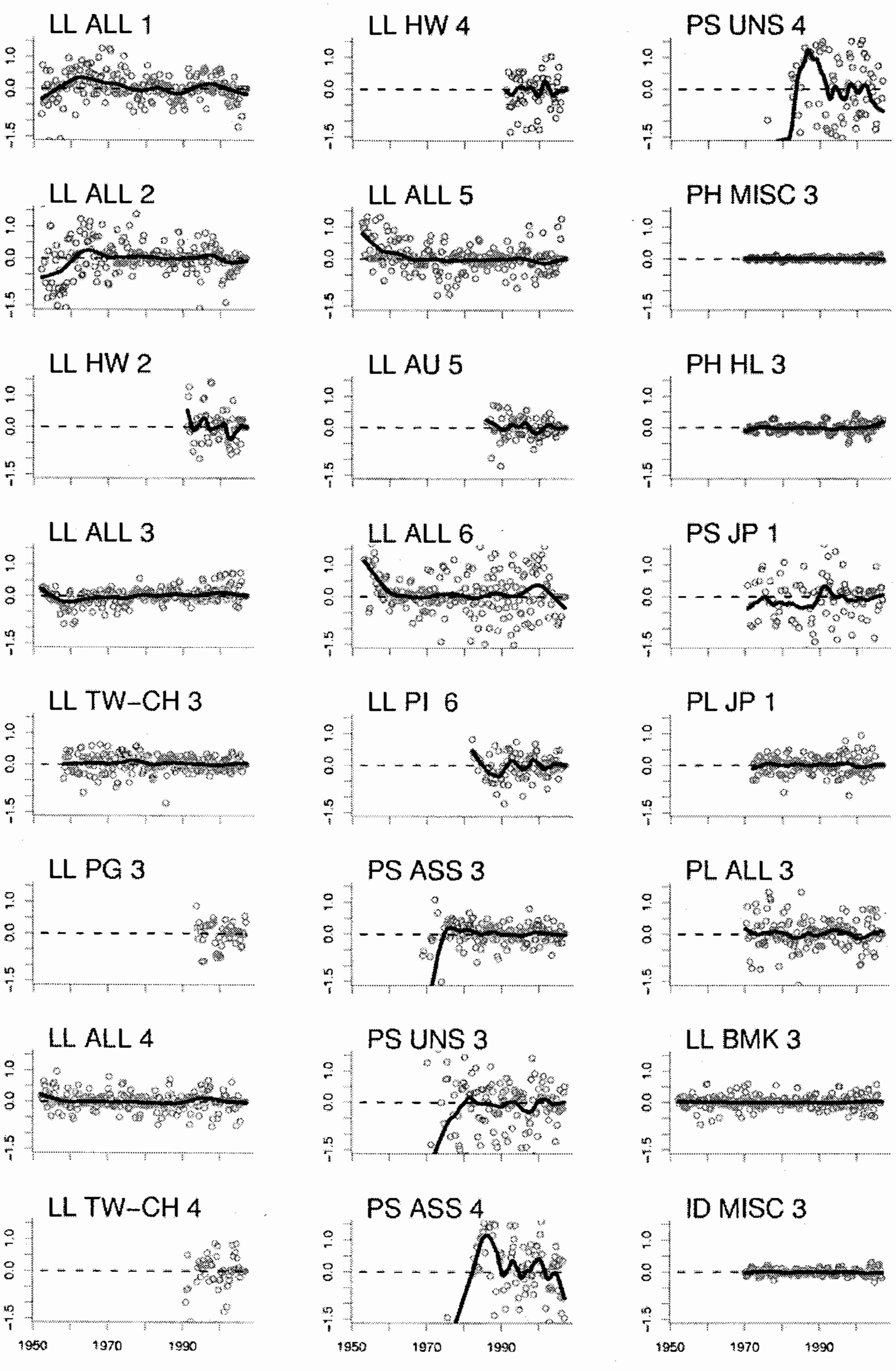

Figure 22. Effort deviations by time period for each fishery. The solid line represents a lowess fit to the data.

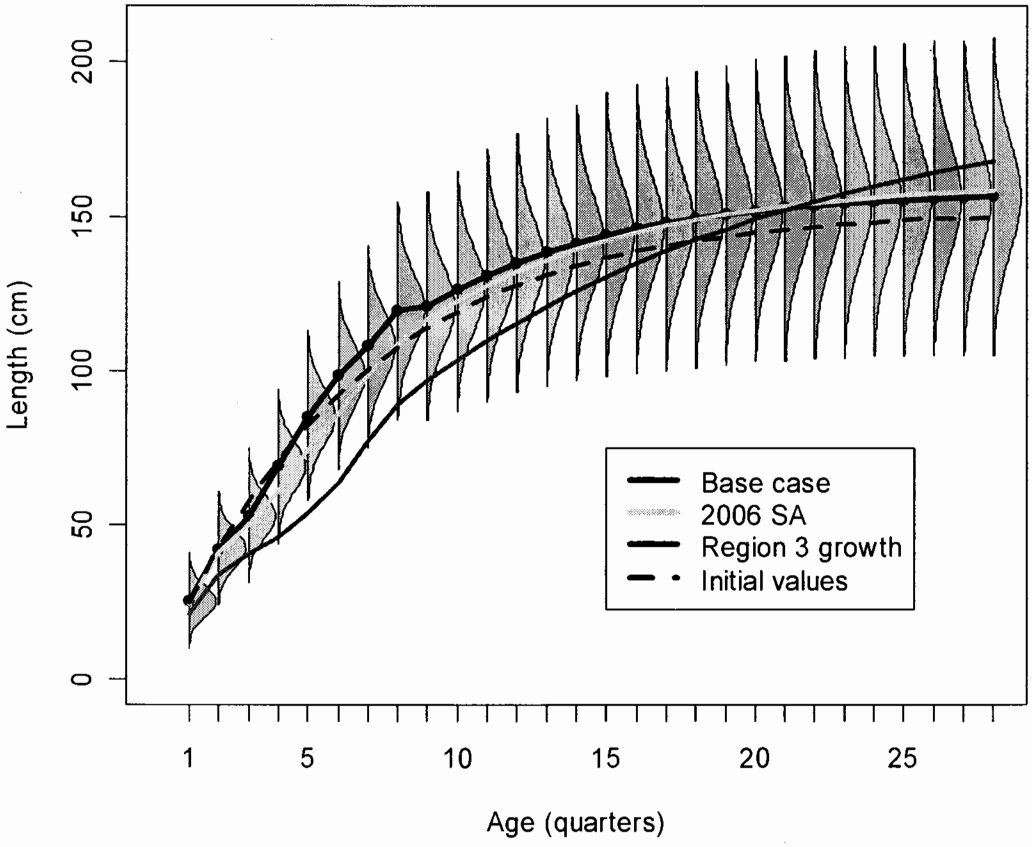

Figure 23. Estimated growth of yellowfin derived from the base-case assessment model. The black line represents the estimated mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age. The estimated mean length at age is also plotted for last year's base-case assessment and the region 3 growth included in the sensitivity analysis.

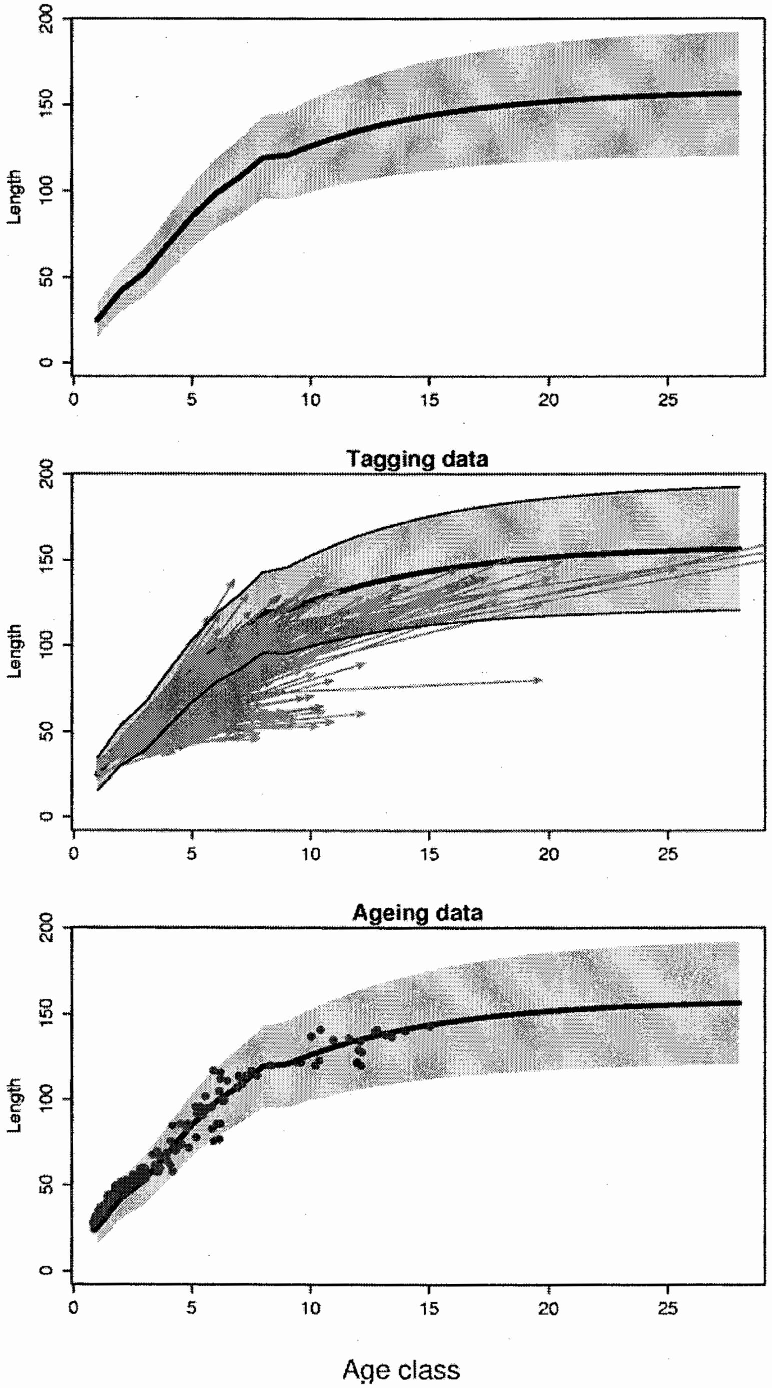

Figure 24. Estimated mean lengths-at-age (heavy line) and the variability of length-at-age (shaded area represents ± 2 SD). Age is in quarters and length is in cm (top figure). For comparison, length at age estimates are presented from tag release and recapture data (middle figure) and empirical age 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.

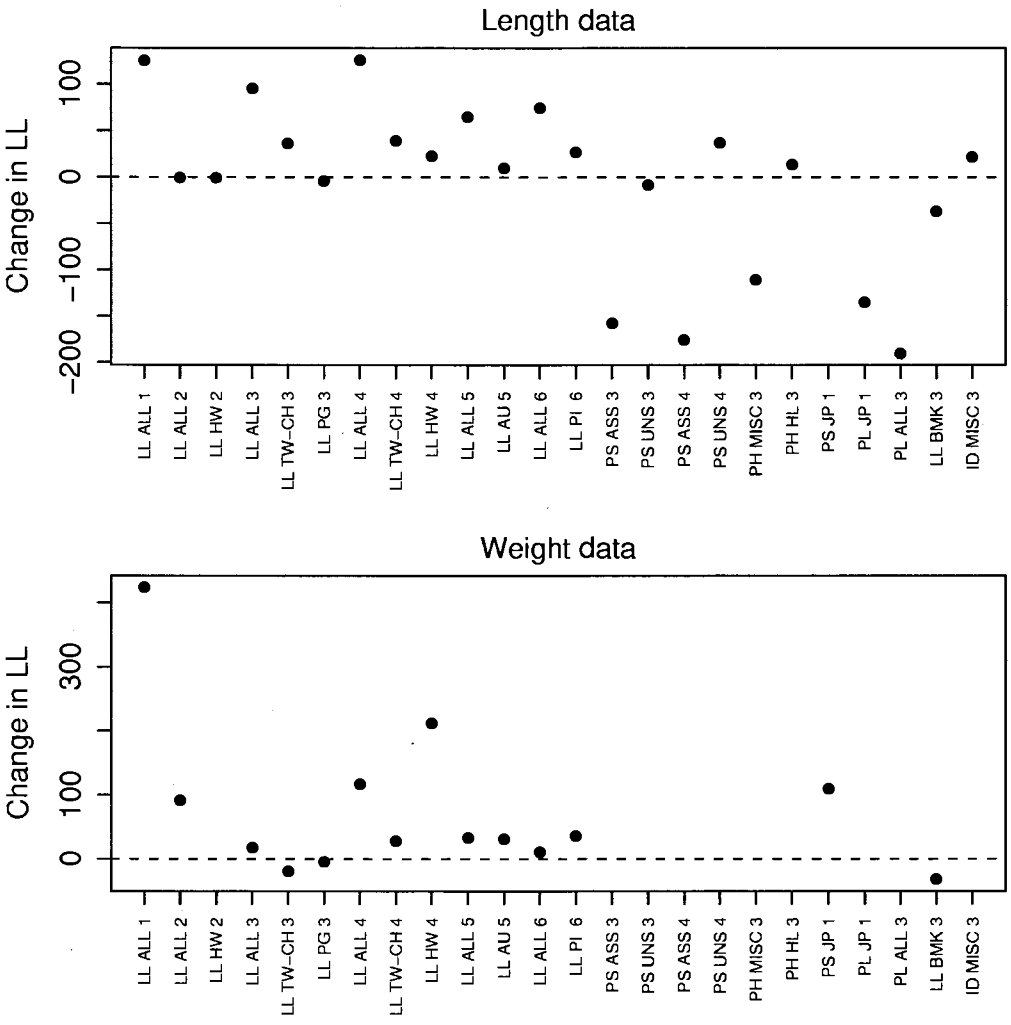

Figure 25. The change in the fishery-specific components of the length frequency (top) and weight frequency (bottom) in the model objective function (negative log-likelihood) between the base-case model and the WCPO model using the growth parameters from MFCL region 3 (region3-growth sensitivity). The difference in log-likelihood is expressed as the log-likelihood value from the region3-growth sensitivity minus the value from the base-case. Negative values reveal an increase in the fit to the size data.

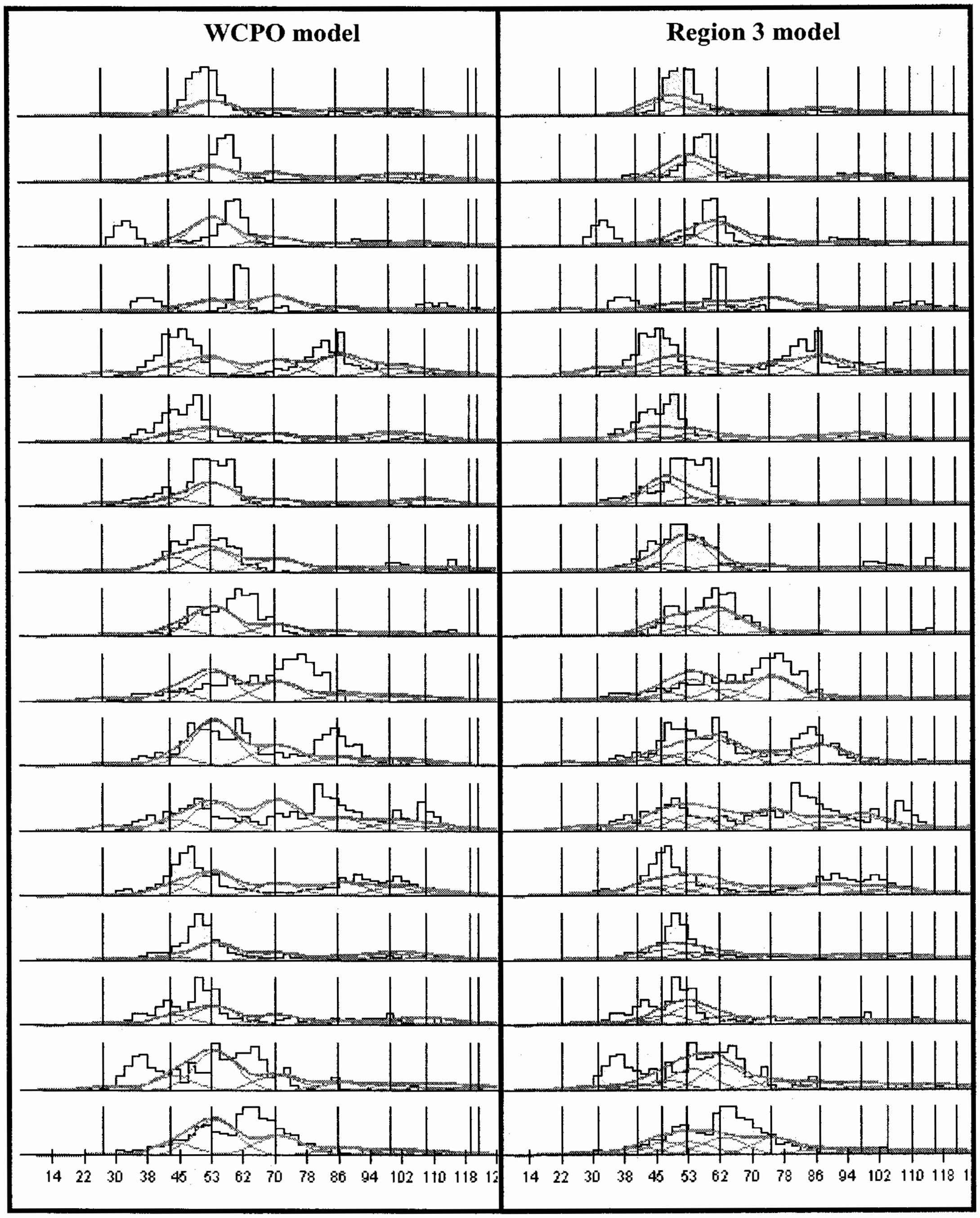

Figure 26. A comparison of the model fits to the length frequency data from the region 3 purse-seine associated set fishery (PS ASS 3) from the entire WCPO base-case model (left) and the western equatorial region model (region 3 model, right) for 1995 to 1999. The yellow histograms represent the observed length frequency distribution, the heavy red line represents the predicted length distribution, ad the vertical lines represent the mean length at age for each age class.

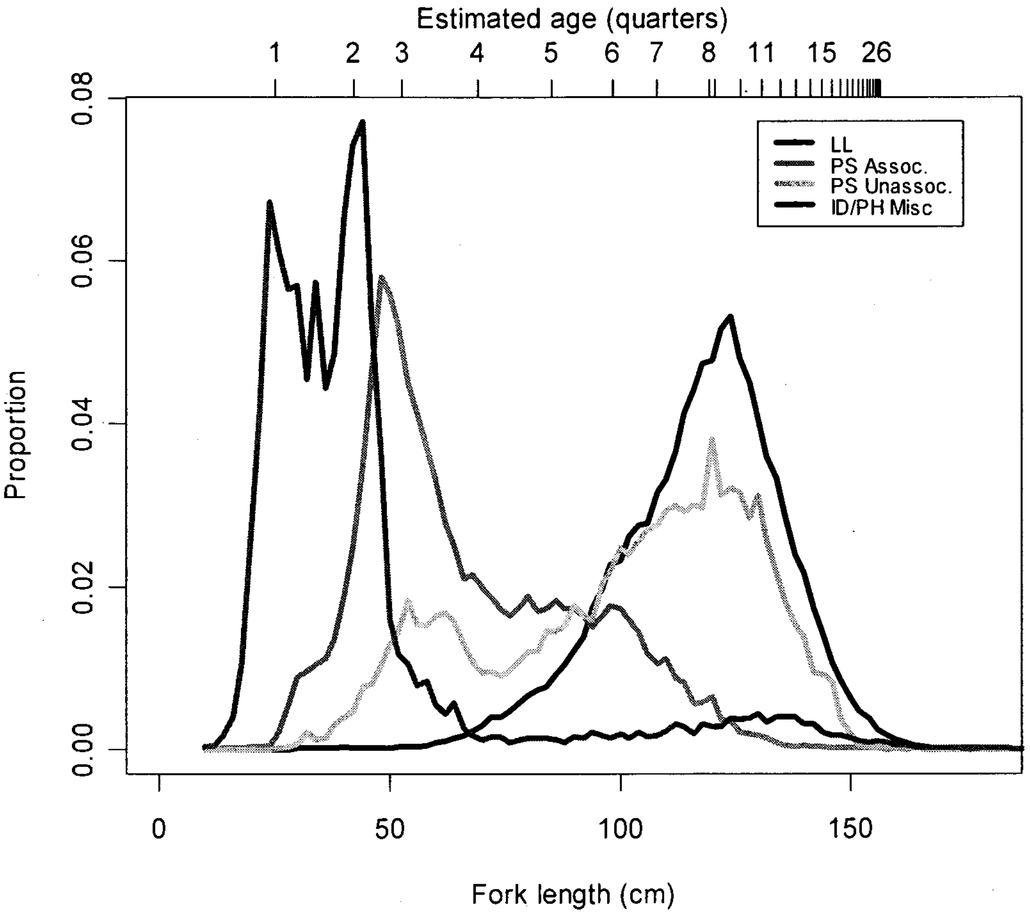

Figure 27. Aggregated length compositions for the main fishery method groups included in the WCPO yellowfin assessment (all time periods combined) compared to the estimated mean length at age from the base-case assessment (growth estimated) (top axis).

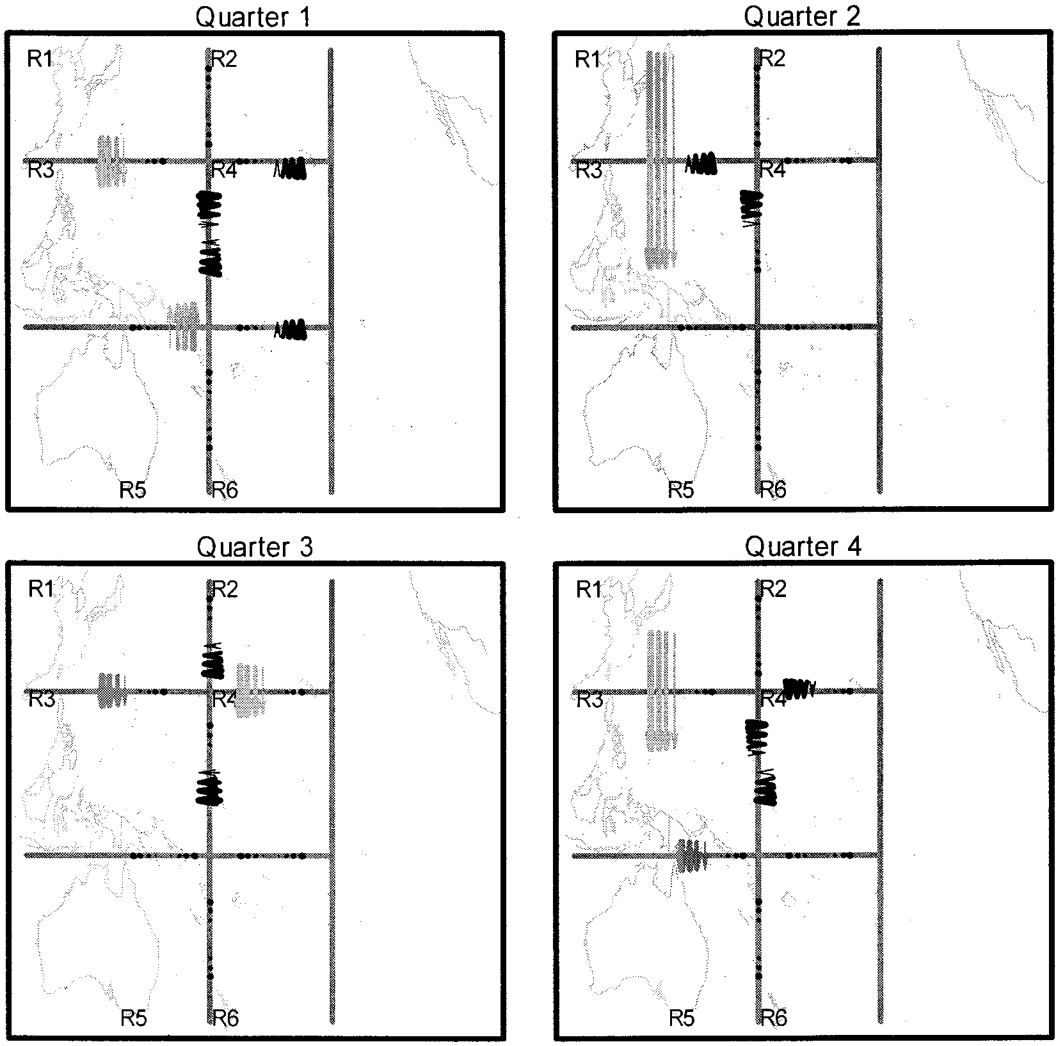

Figure 28. Estimated quarterly movement coefficients at age (1, 7, 15, 25 quarters) from the base-case model. The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age. The maximum movement (quarter 2, region 1 to region 3) represents movement of 51% of the fish at the start of the quarter. Movement rates are colour coded: black, 0.5–5%; red 5–10%; green >10%.

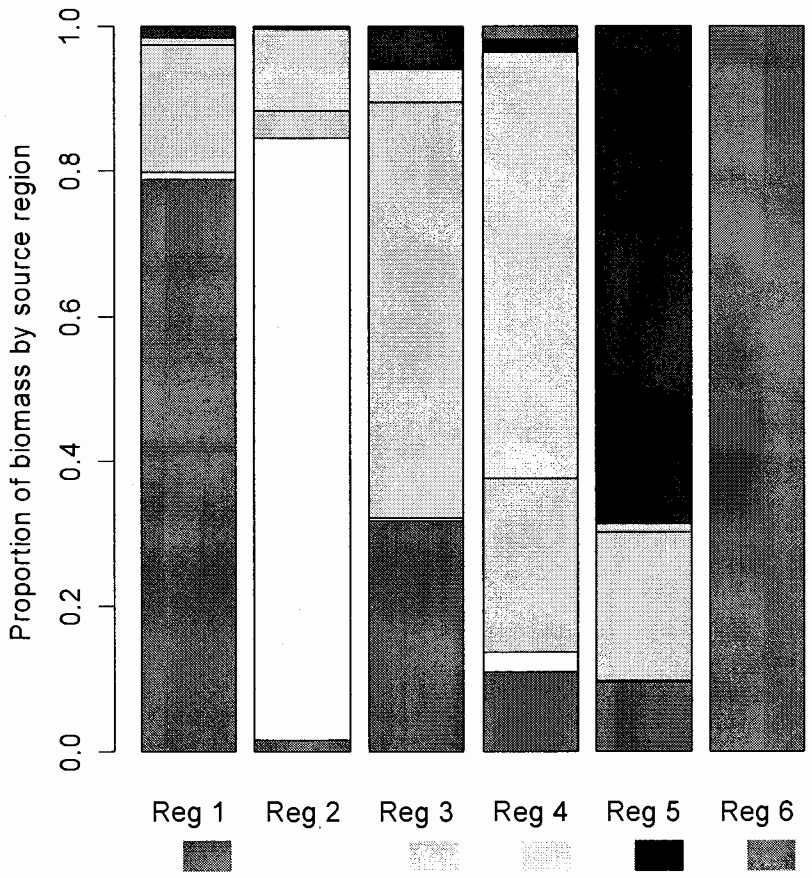

Figure 29. Proportional distribution of total biomass (by weight) in each region (Reg 1–6) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment among regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

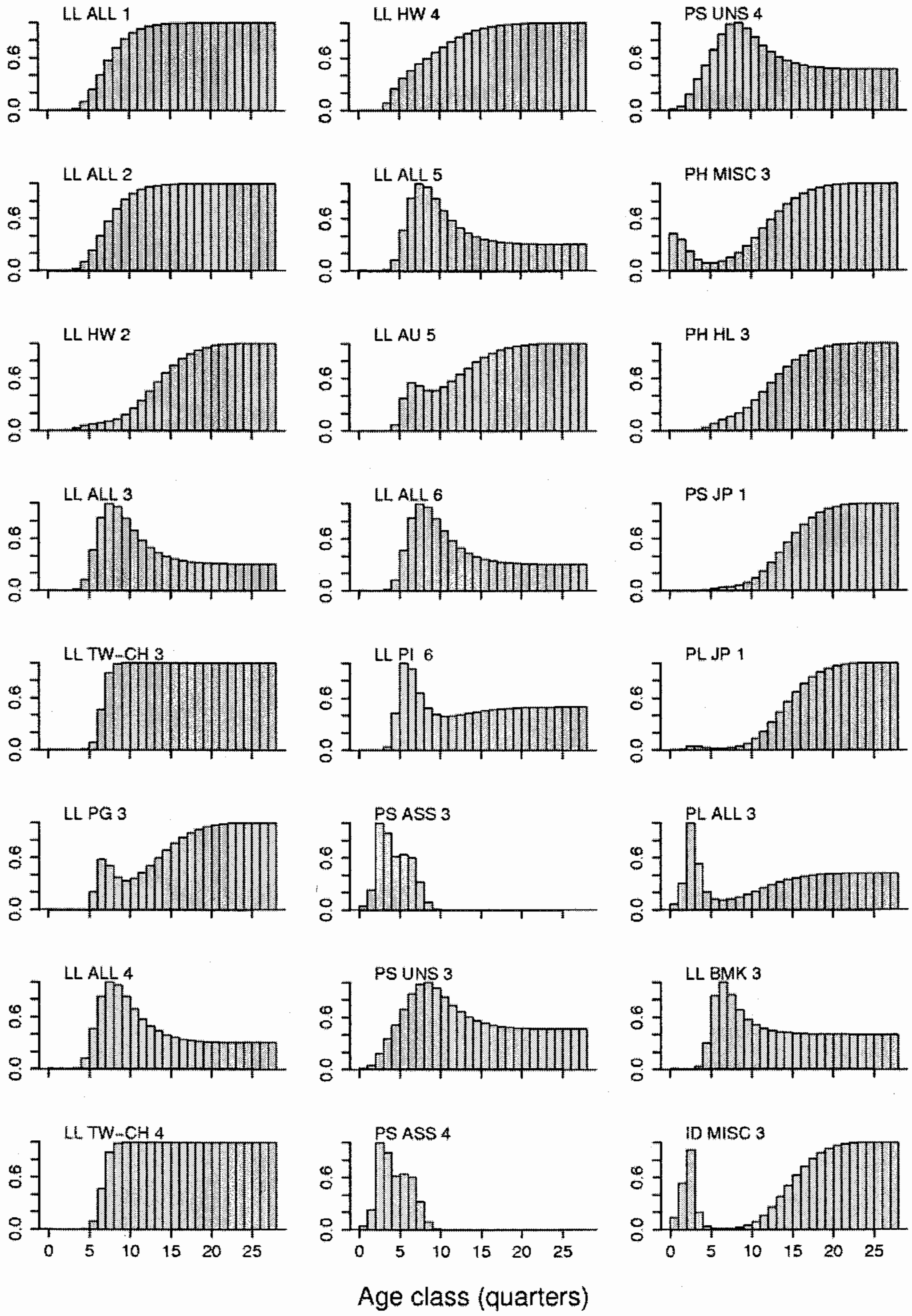

Figure 30. Selectivity coefficients, by fishery.

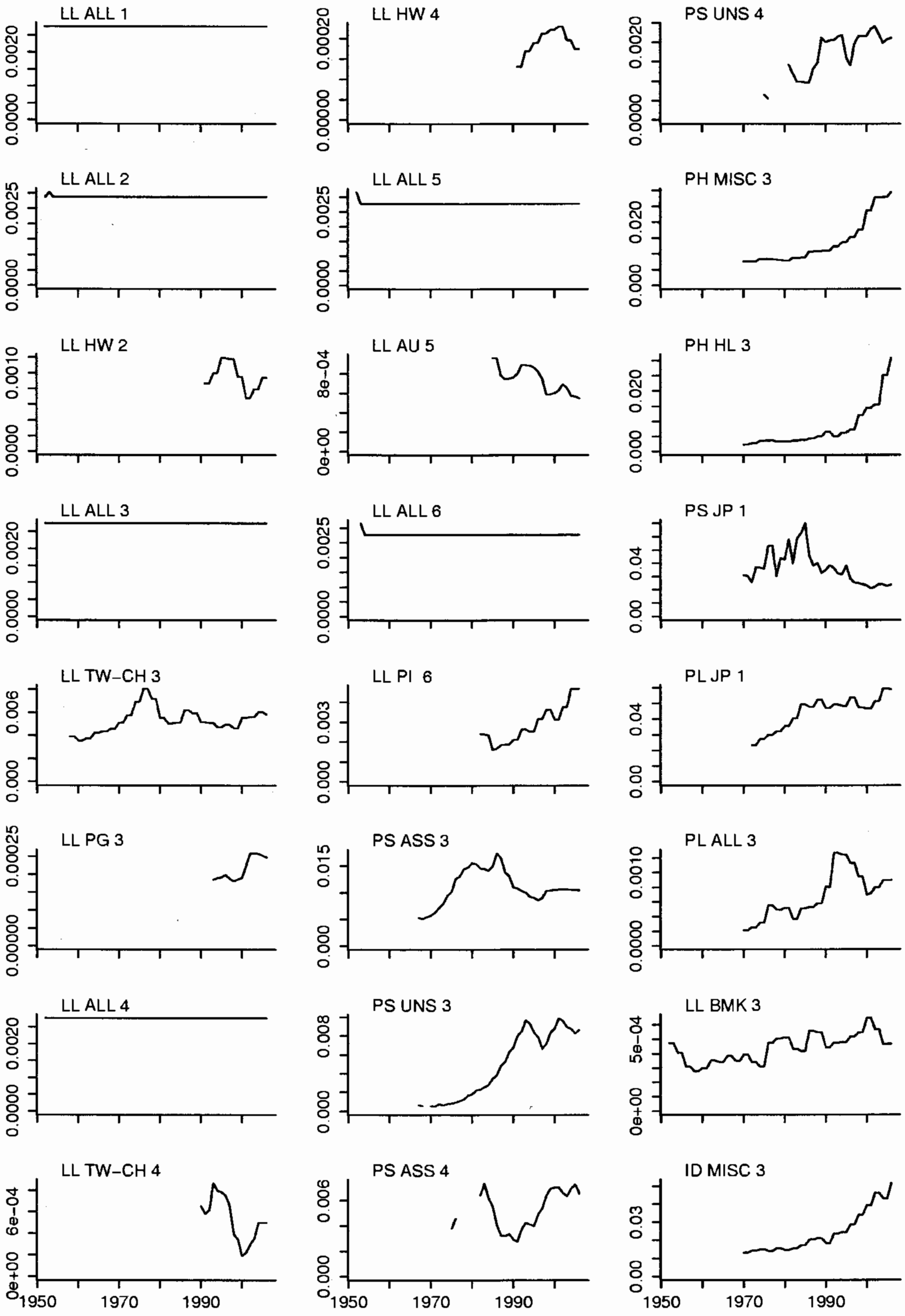

Figure 31. Average annual catchability time series, by fishery.

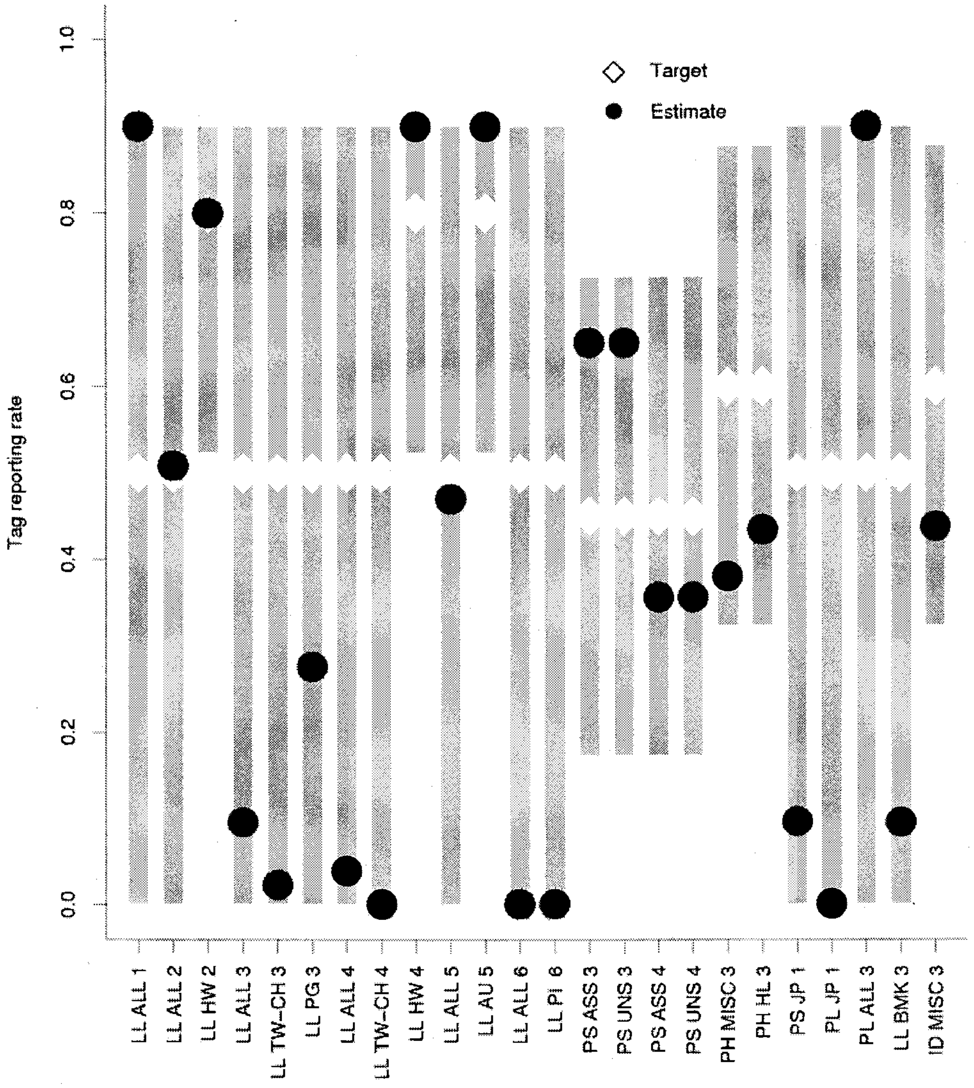

Figure 32. Estimated tag-reporting rates by fishery (black circles). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars indicate a range of ±1 SD.

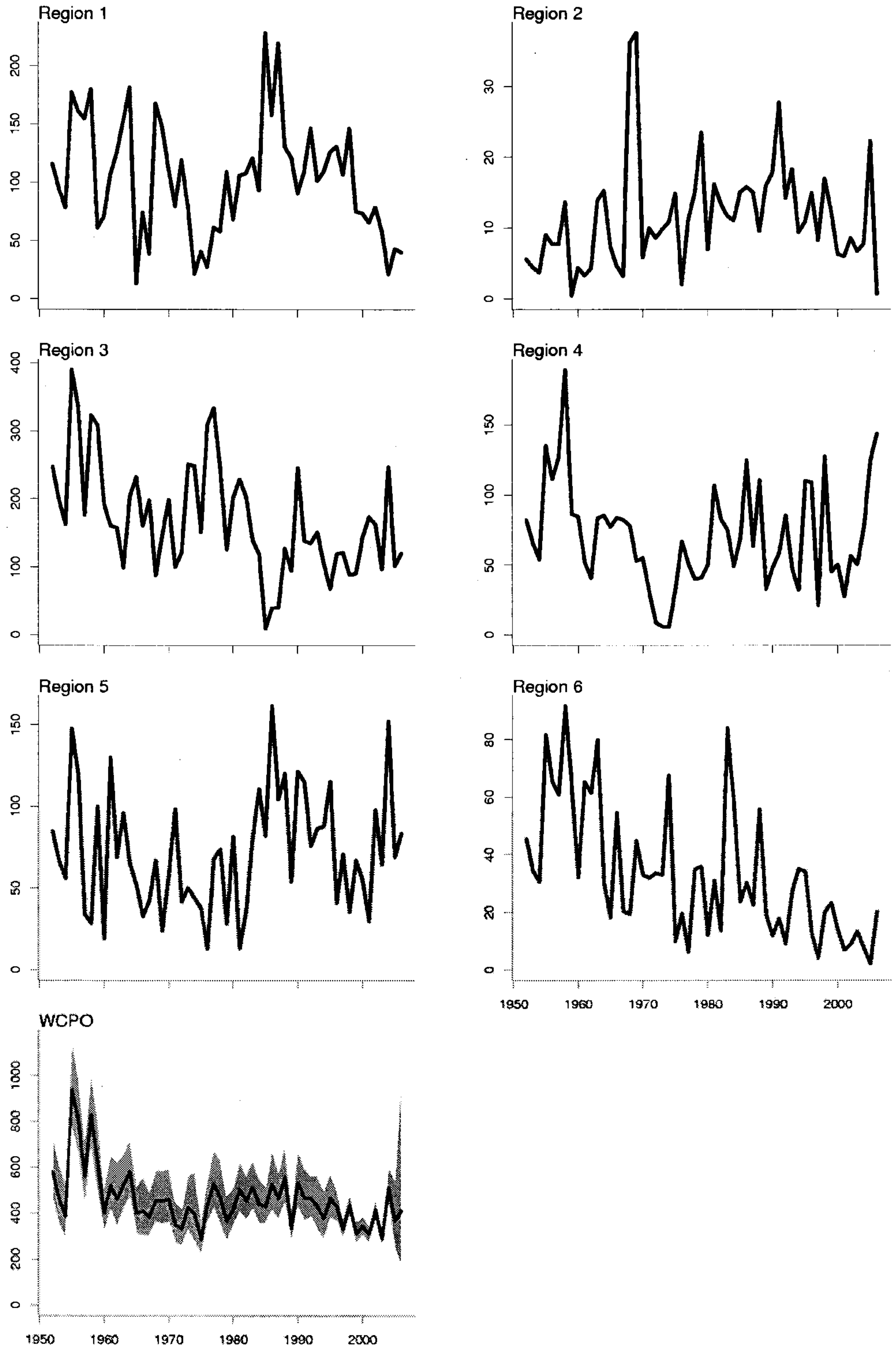

Figure 33. Estimated annual recruitment (millions of fish) by region and for the WCPO. The shaded area for the WCPO indicates the approximate 95% confidence intervals.

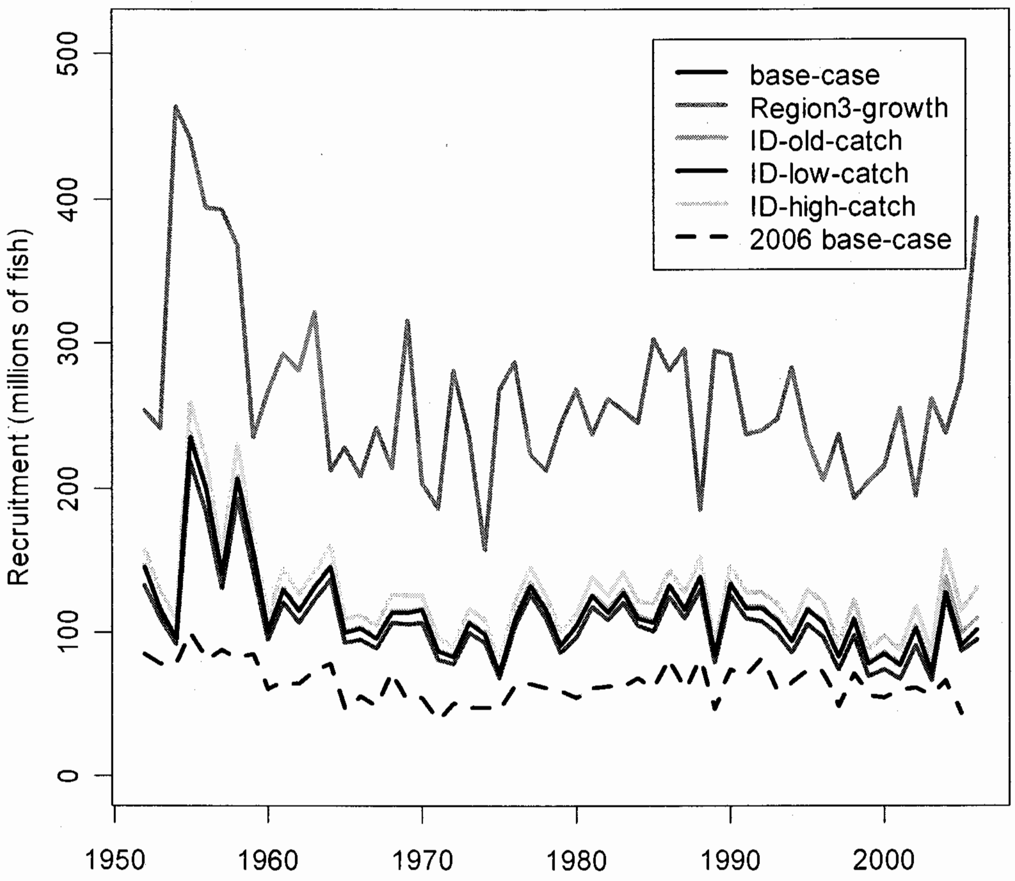

Figure 34. Estimated annual recruitment (millions of fish) for the WCPO obtained from the different model options and the 2006 base-case model.

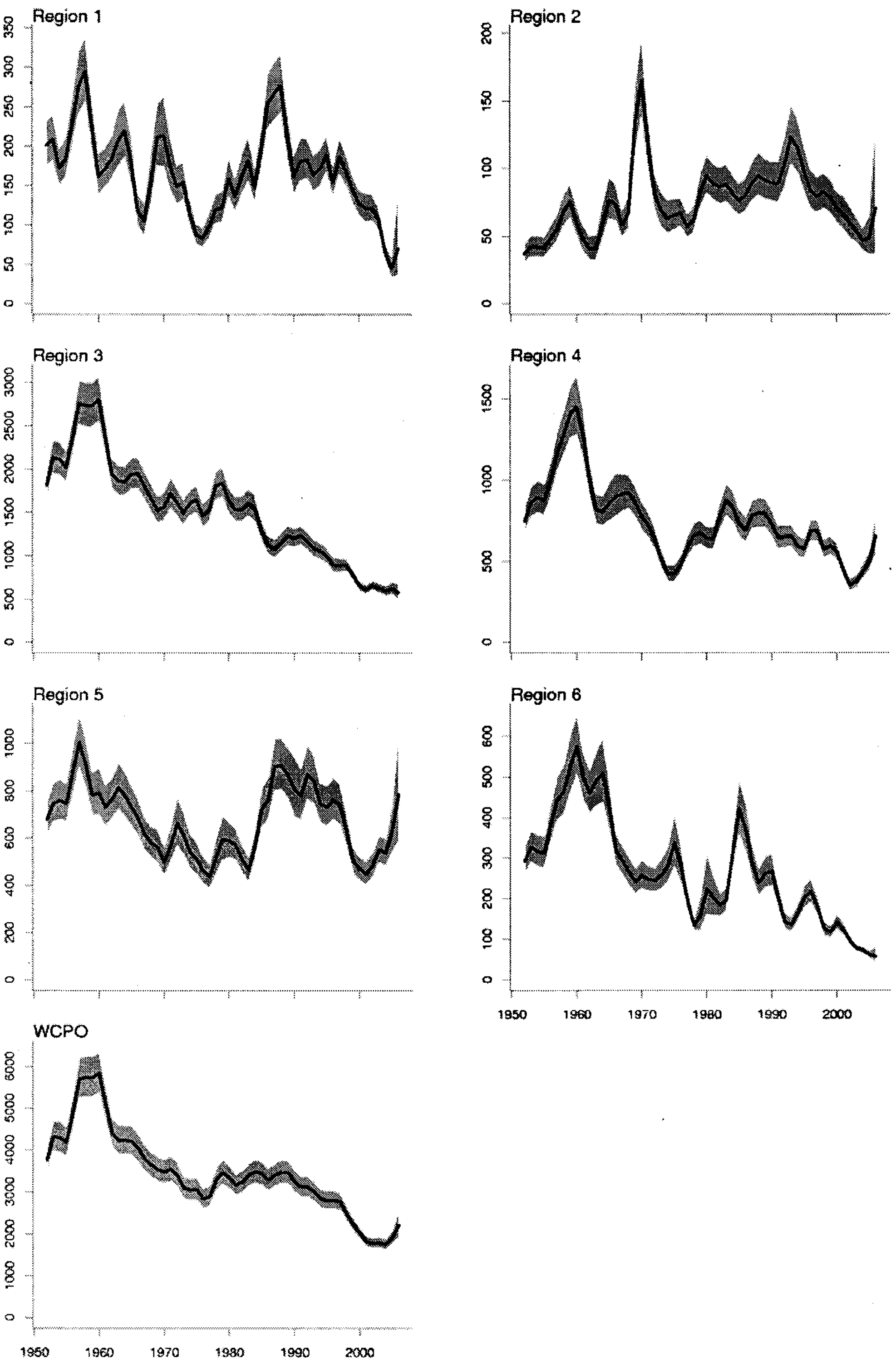

Figure 35. Estimated annual average total biomass (thousand mt) by region and for the WCPO for the base-case analysis. The shaded areas indicate the approximate 95% confidence intervals.

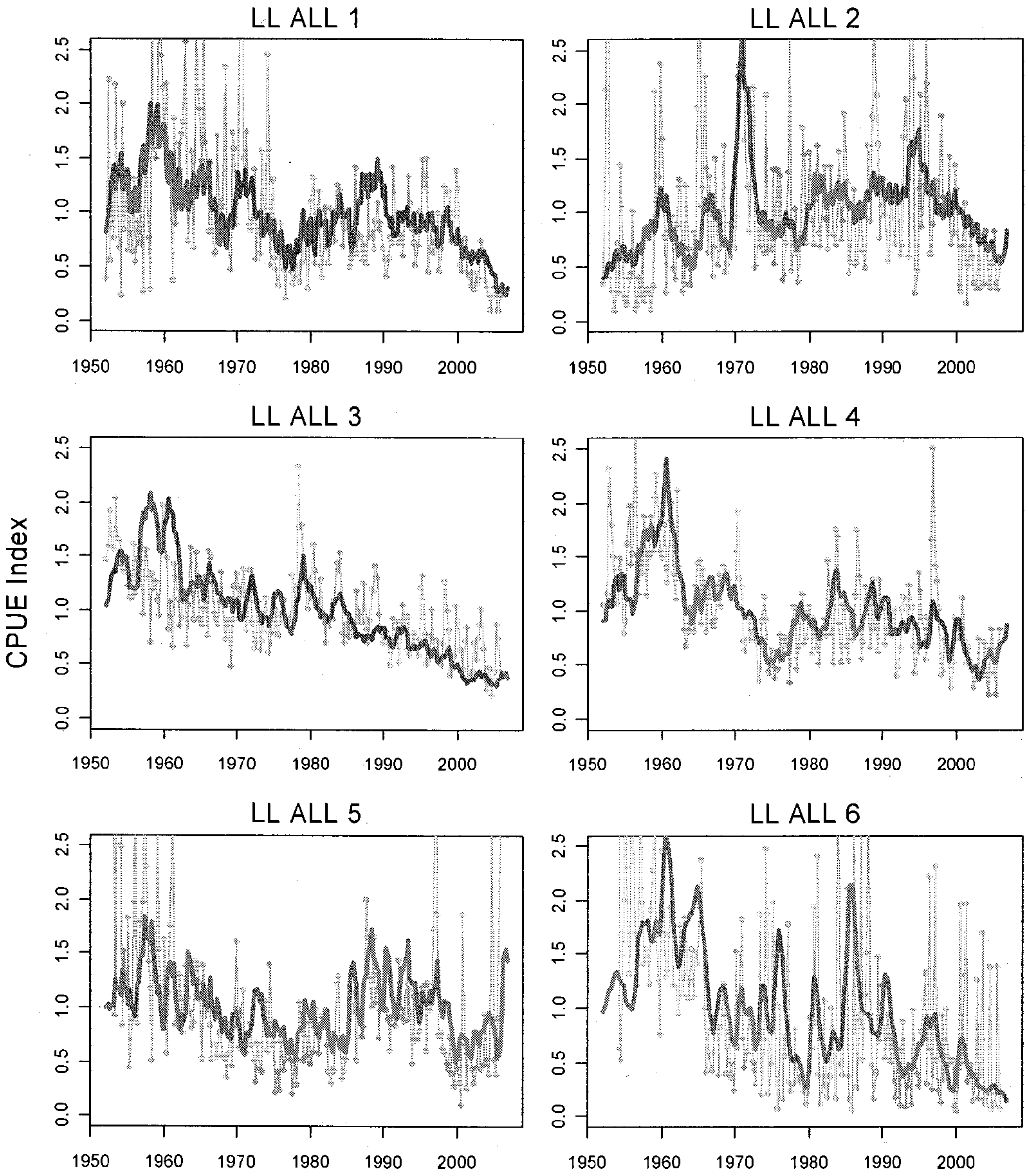

Figure 36. A comparison of longline exploitable biomass by quarter and region (red line) and the quarterly standardised CPUE indices for the fisheries. For comparison, both series are scaled to the average of the series.

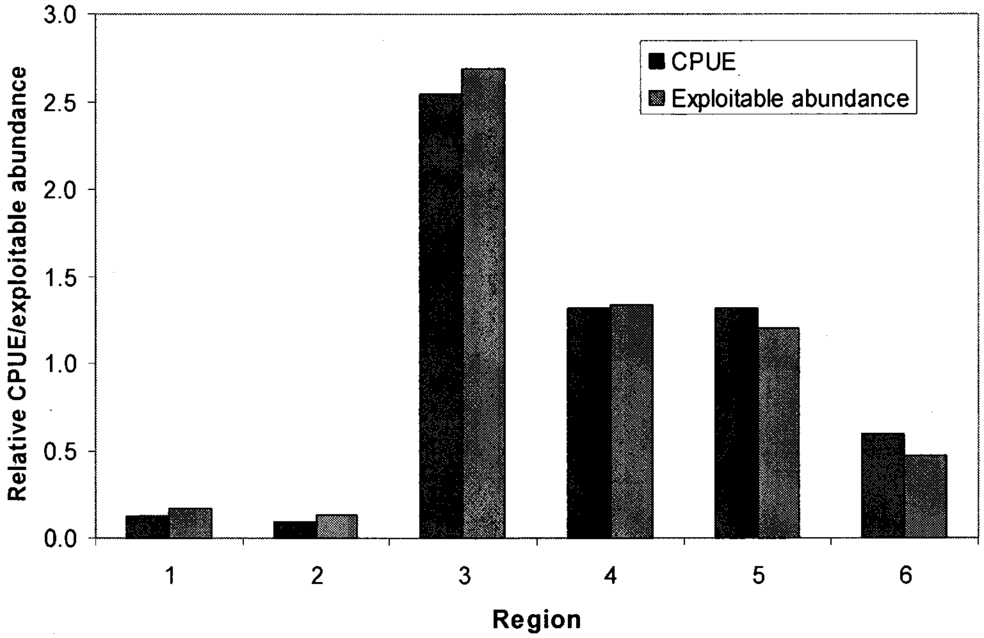

Figure 37. CPUE and exploitable abundance for LL ALL 1–6 averaged over all time periods. Values for each region are scaled relative to their averages across all regions.

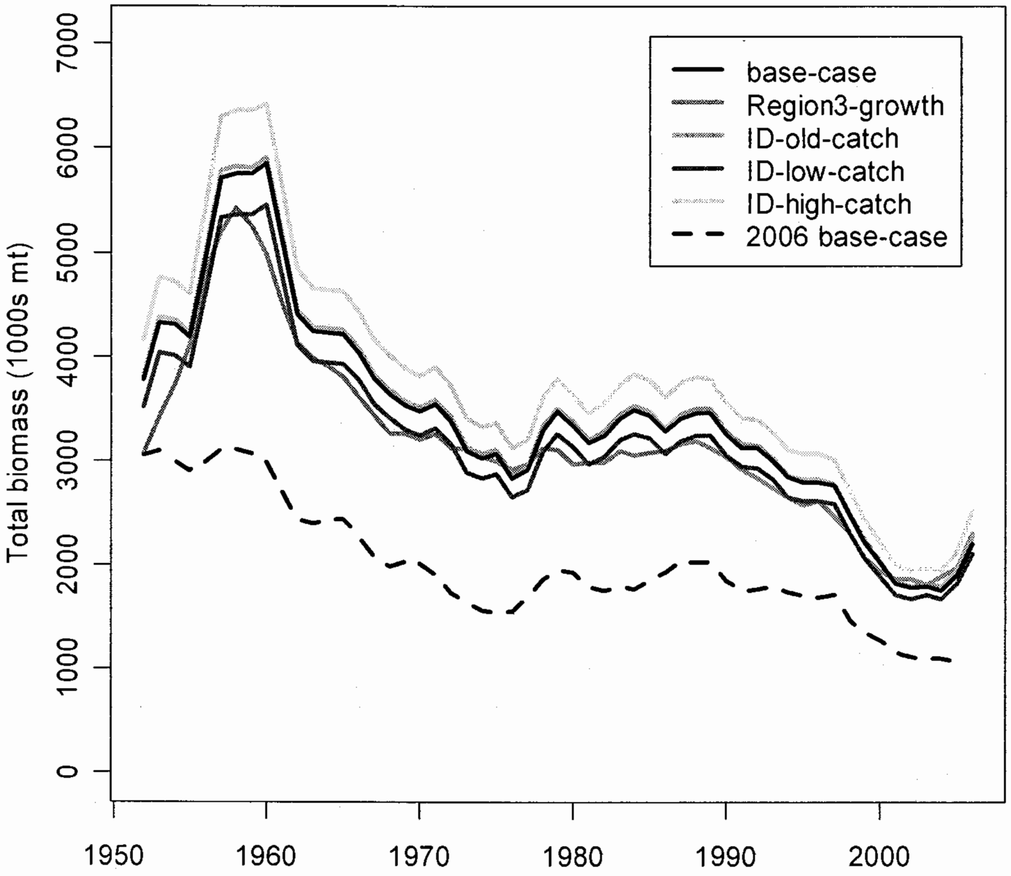

Figure 38. Estimated annual average total biomass (thousands mt) for the WCPO obtained from a range of different model options.

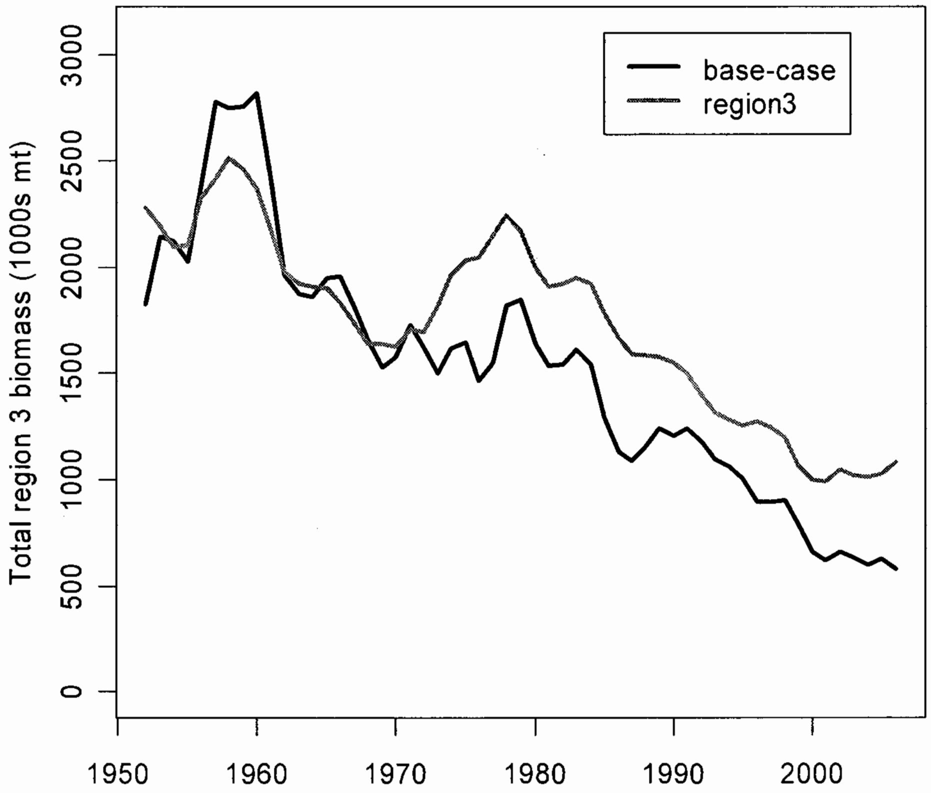

Figure 39. Annual total biomass for MFCL region 3 from the WCPO base-case model and for the single region model sensitivity (region3).

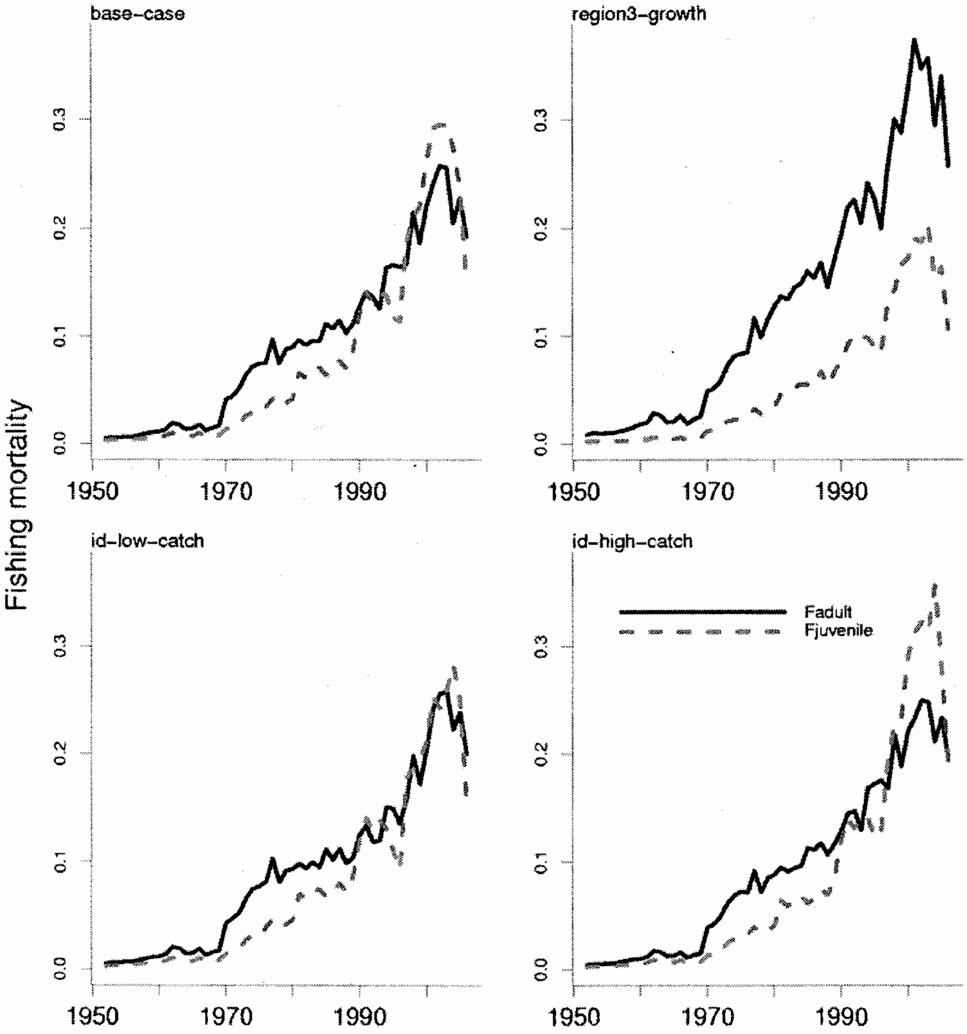

Figure 40. Estimated annual average juvenile and adult fishing mortality for the WCPO obtained from the three separate model options.

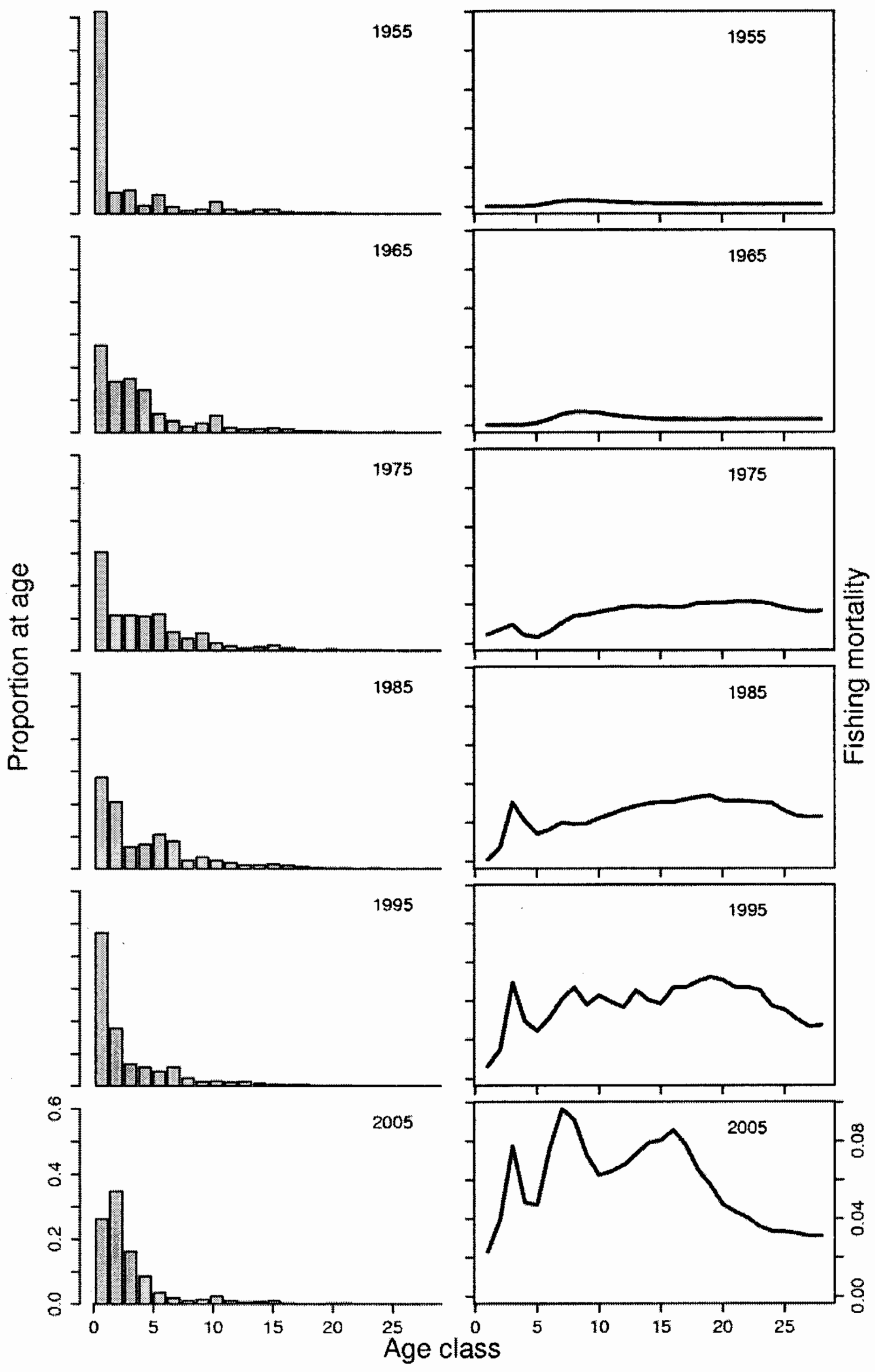

Figure 41. Estimated proportion at age (quarters) for the WCPO yellowfin population (left) and fishing mortality at age (right) by year at decade intervals.

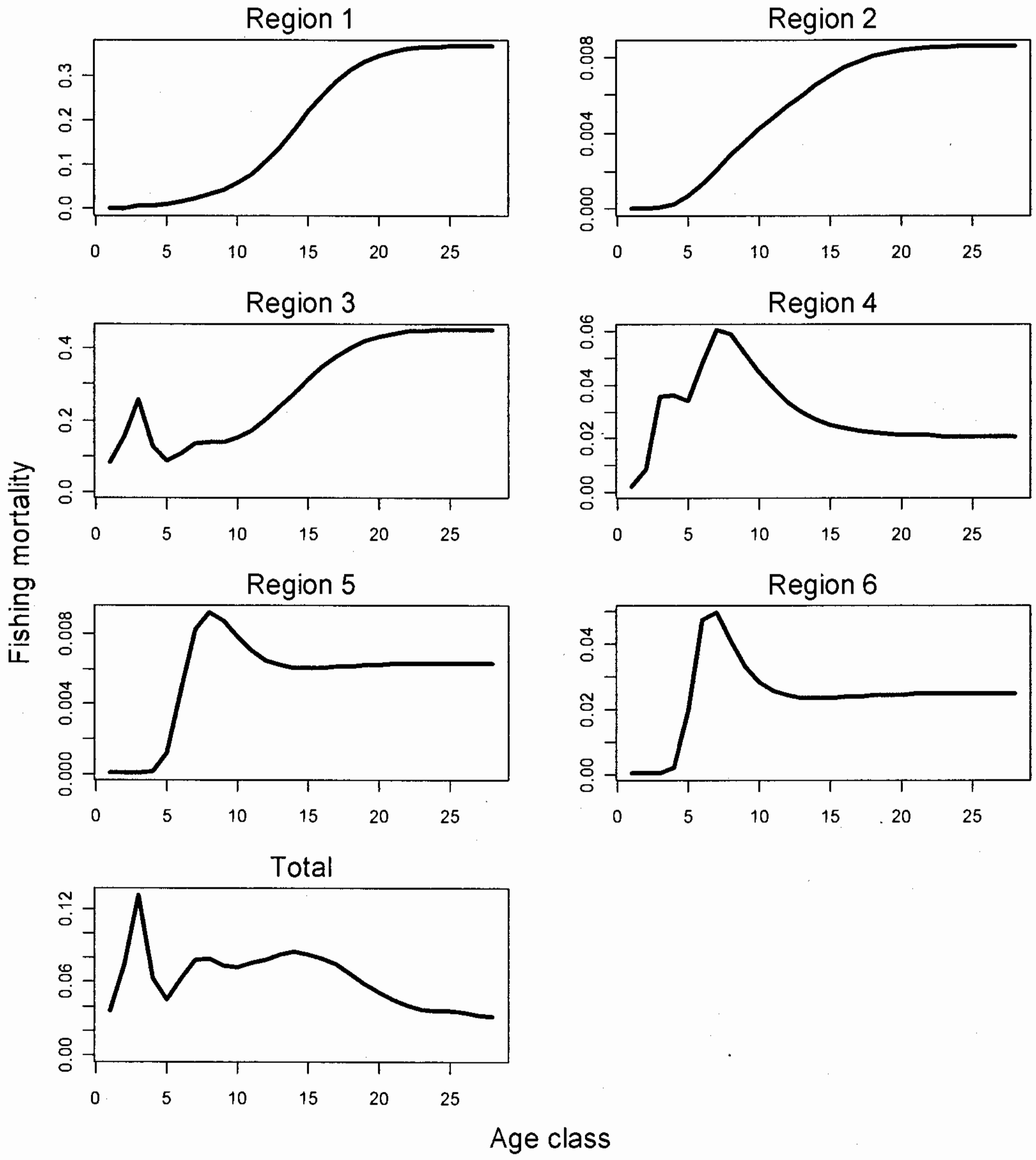

Figure 42. Fishing mortality by age class and region for the period used to determine the total F-at-age included in the calculation of MSY based reference points (2002–05). Note that the y-axis varies between plots.

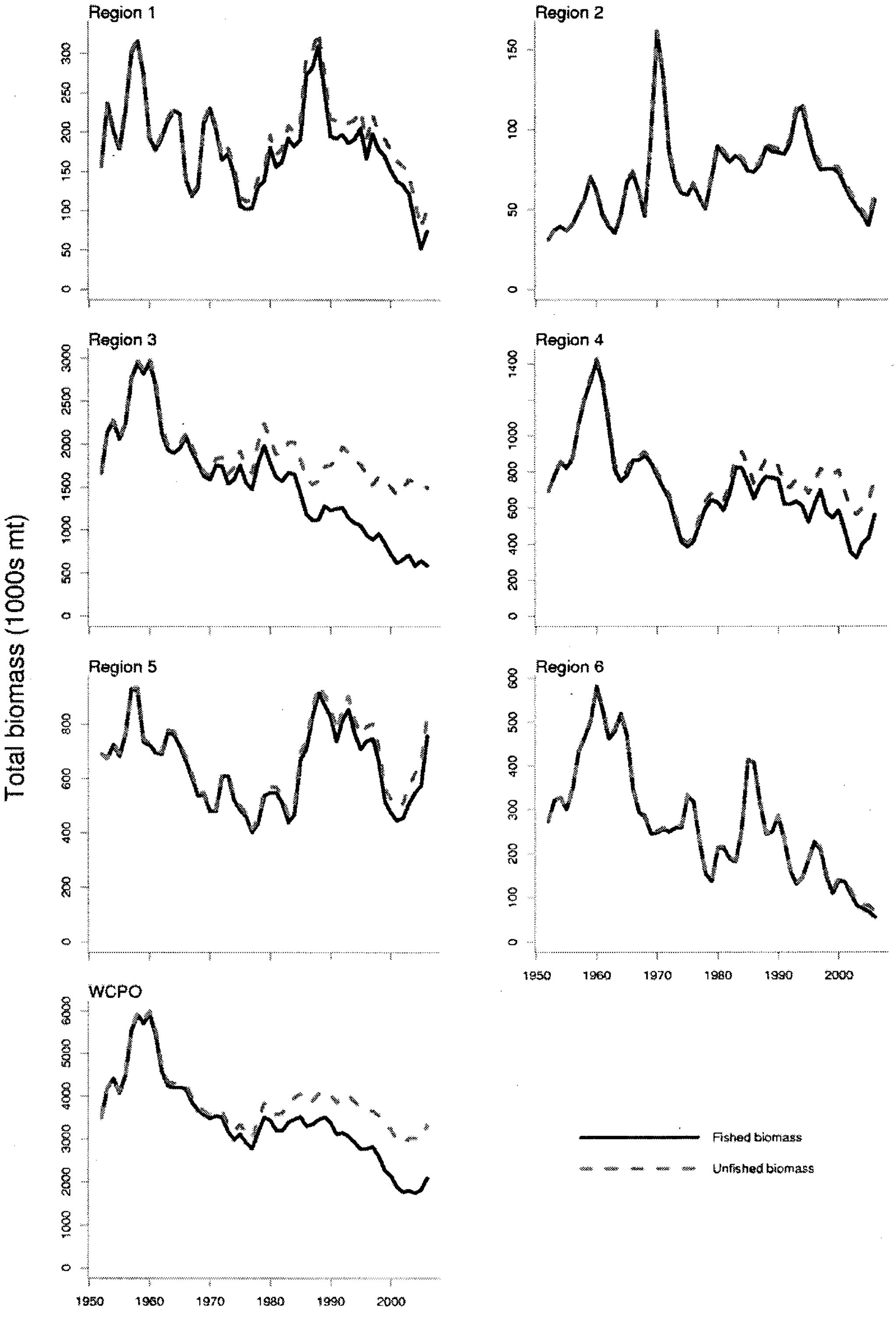

Figure 43. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper thin lines) for the base-case model for each region and for the WCPO.

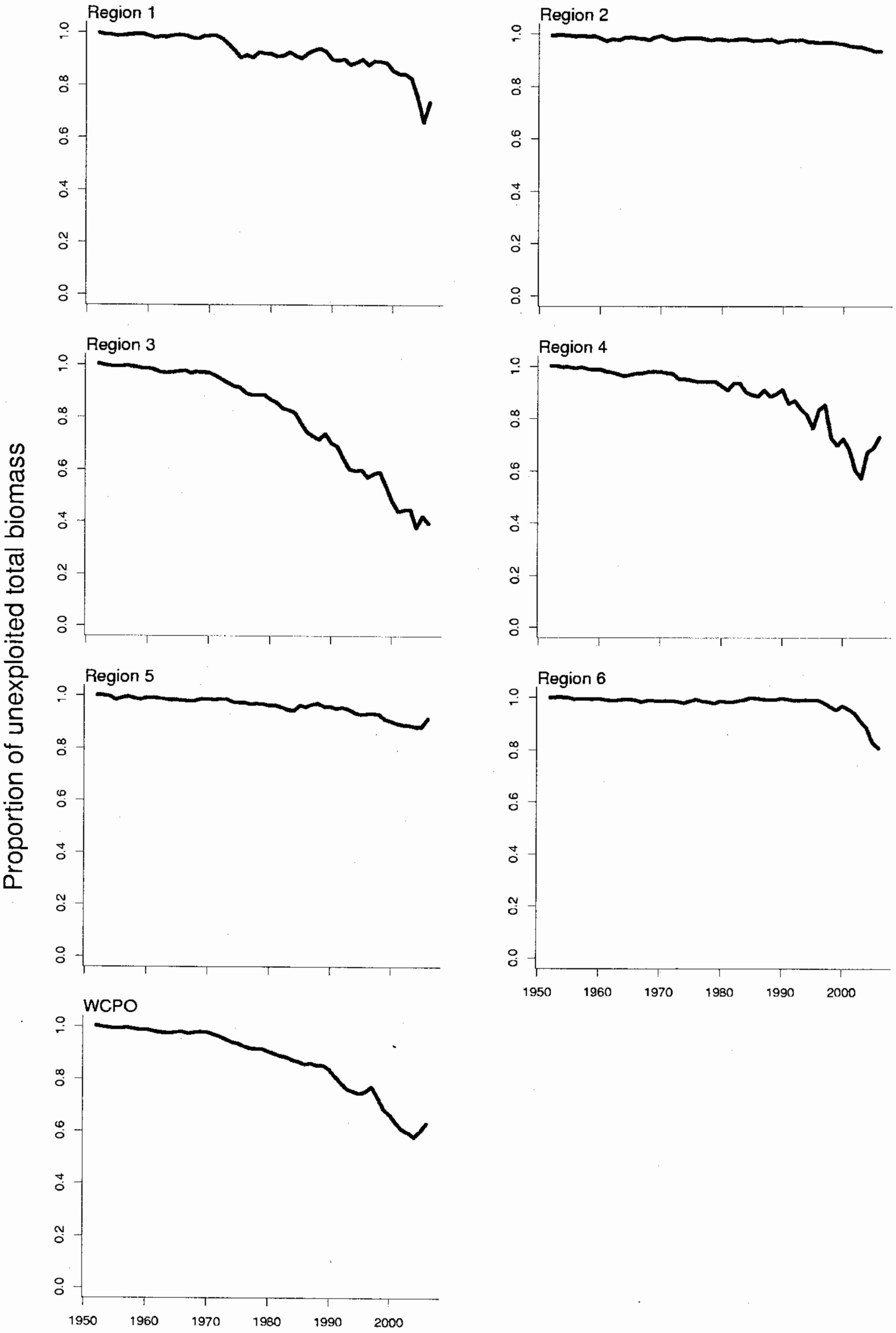

Figure 44. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the WCPO.

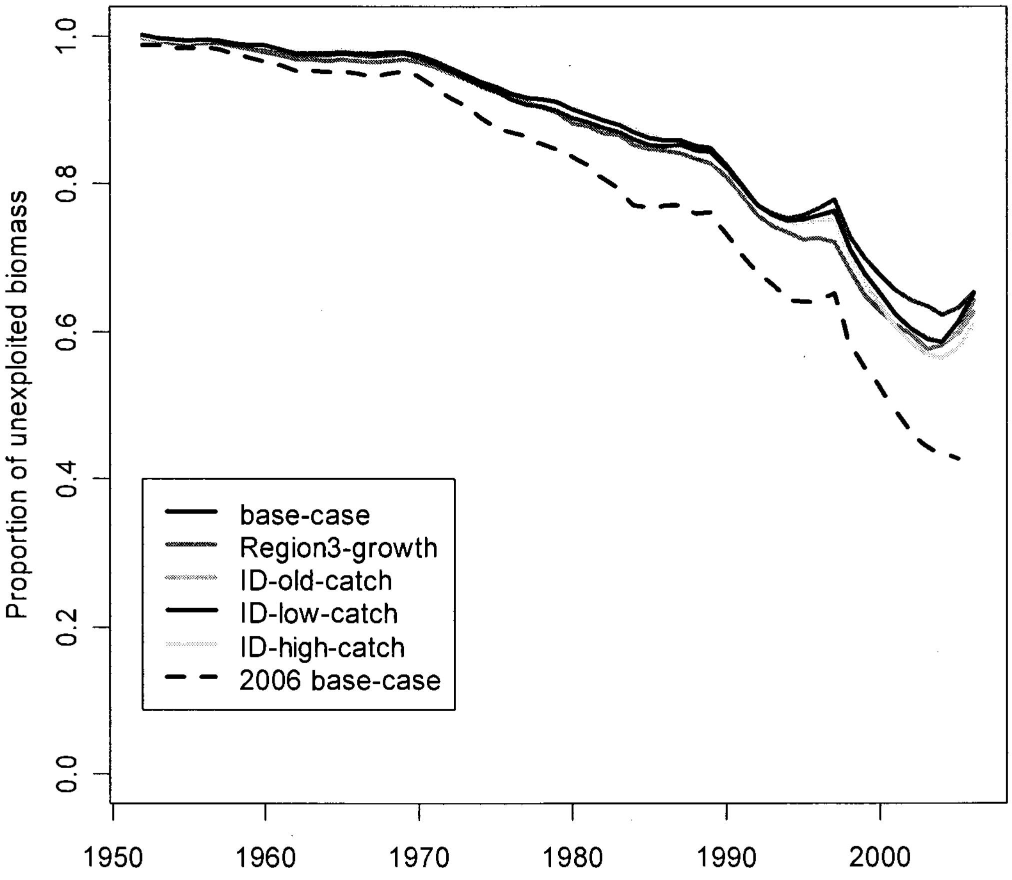

Figure 45. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for the WCPO obtained from the separate analyses.

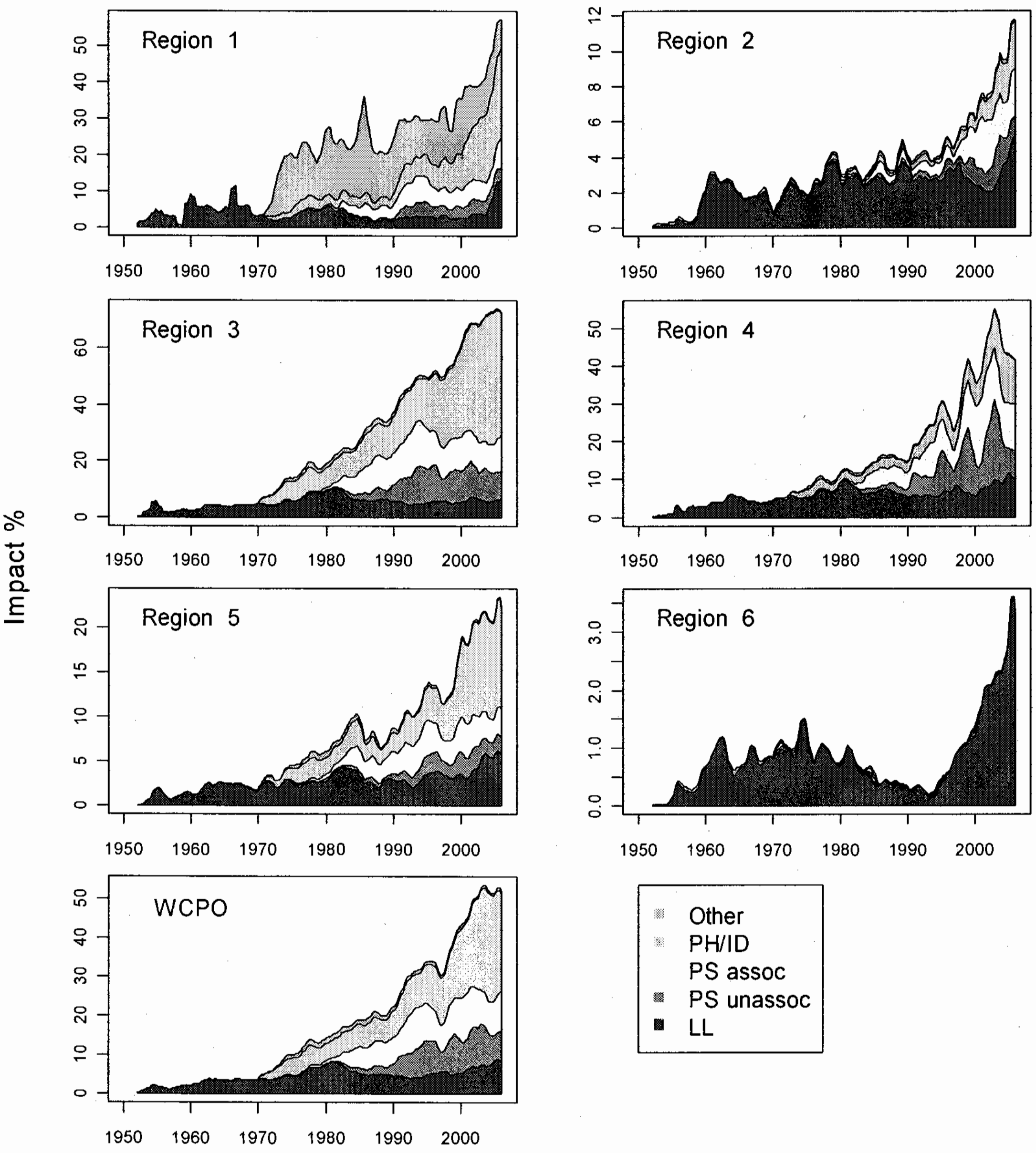

Figure 46. Estimates of reduction in spawning biomass due to fishing (fishery impact = 1-$SB_t/SB_{0,t}$) by region and for the WCPO attributed to various fishery groups. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine FAD and log sets; PS unassoc = purse seine school sets; Other = JP coastal PL & PL and equatorial PL.

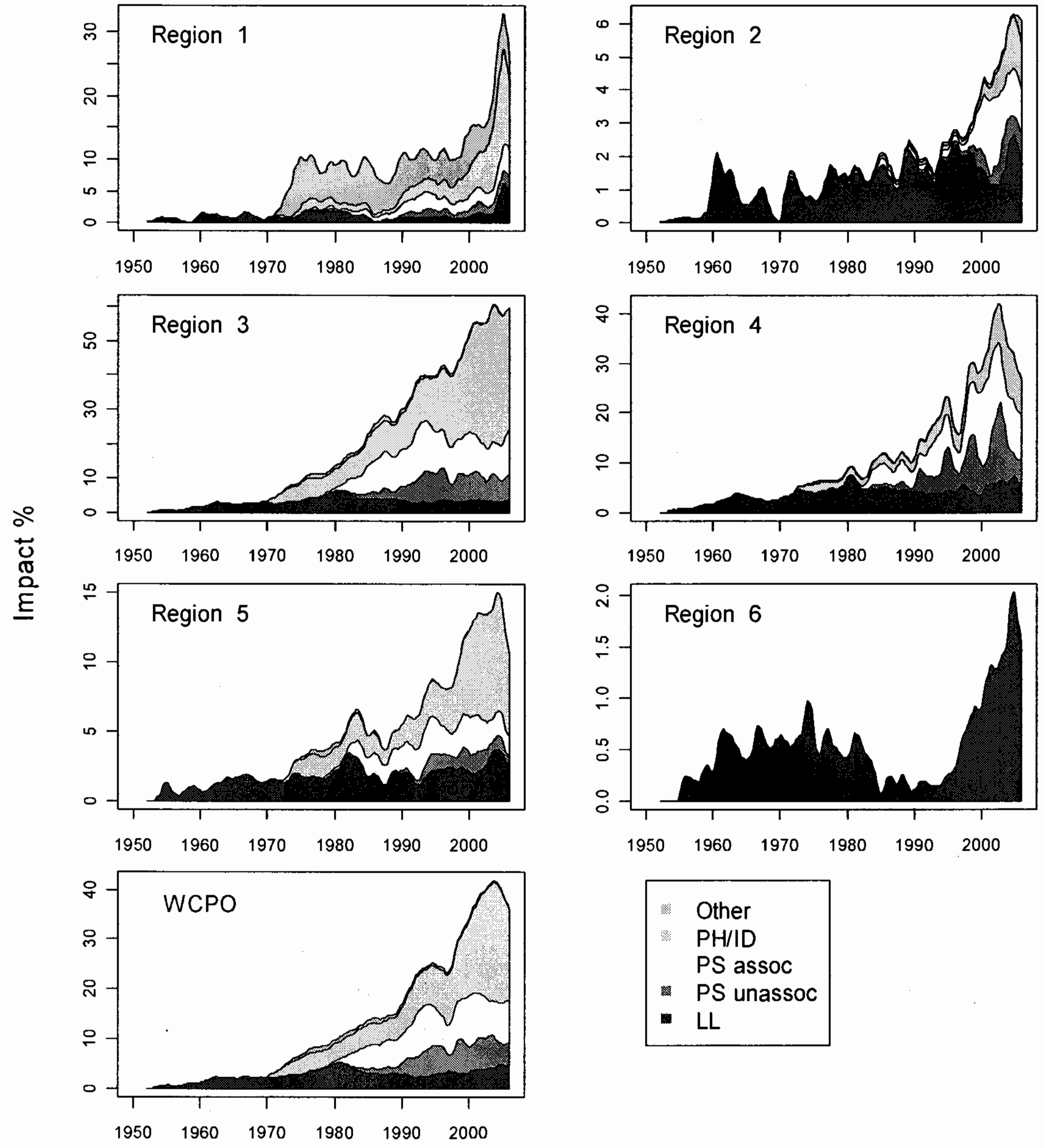

Figure 47. Estimates of reduction in total biomass due to fishing (fishery impact = 1-$B_t/B_{0,t}$) by region and for the WCPO attributed to various fishery groups. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine FAD and log sets; PS unassoc = purse seine school sets; Other = JP coastal PL & PL and equatorial PL.

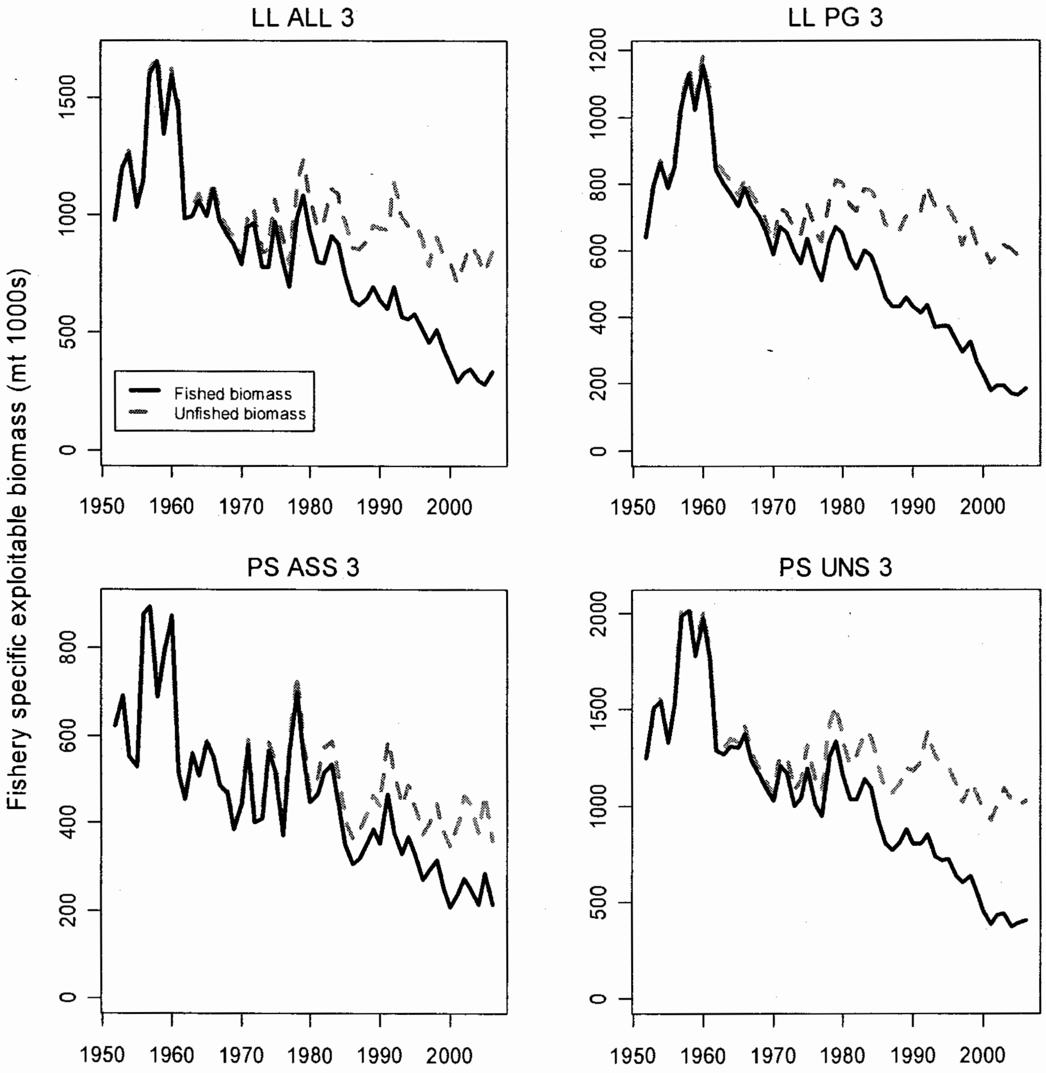

Figure 48. Trends in fishery specific vulnerable biomass under fishing and the trend in biomass that would have occurred in the absence of fishing for four fisheries within region 3; the principal distant-water longline fishery (LL ALL 3), PNG domestic longline fishery (LL PG 3) and the associated (PS ASS 3) and unassociated (PS UNS 3) purse-seine fisheries.

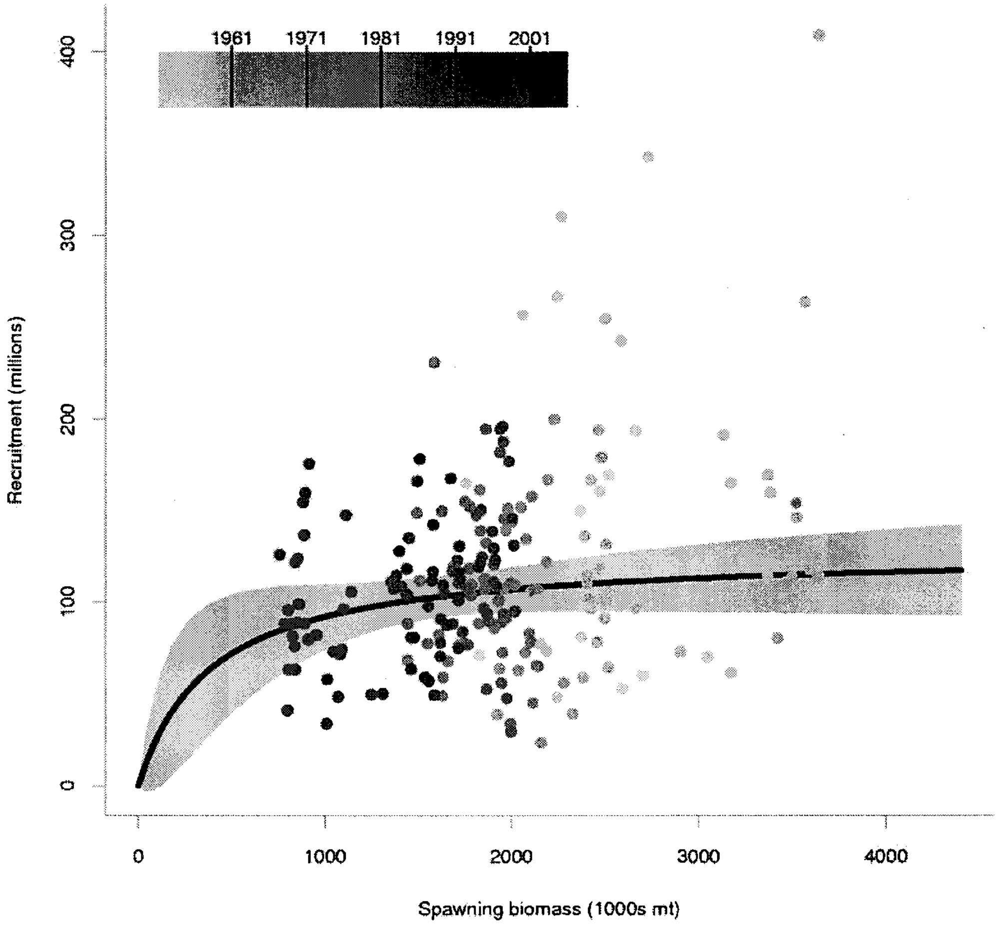

Figure 49. Estimated relationship between equilibrium recruitment and equilibrium spawning biomass. The grey area indicates the 95% confidence region. The points represent the estimated recruitment-spawning biomass and the colour of the points denotes the time period from which the estimate was obtained (see legend).

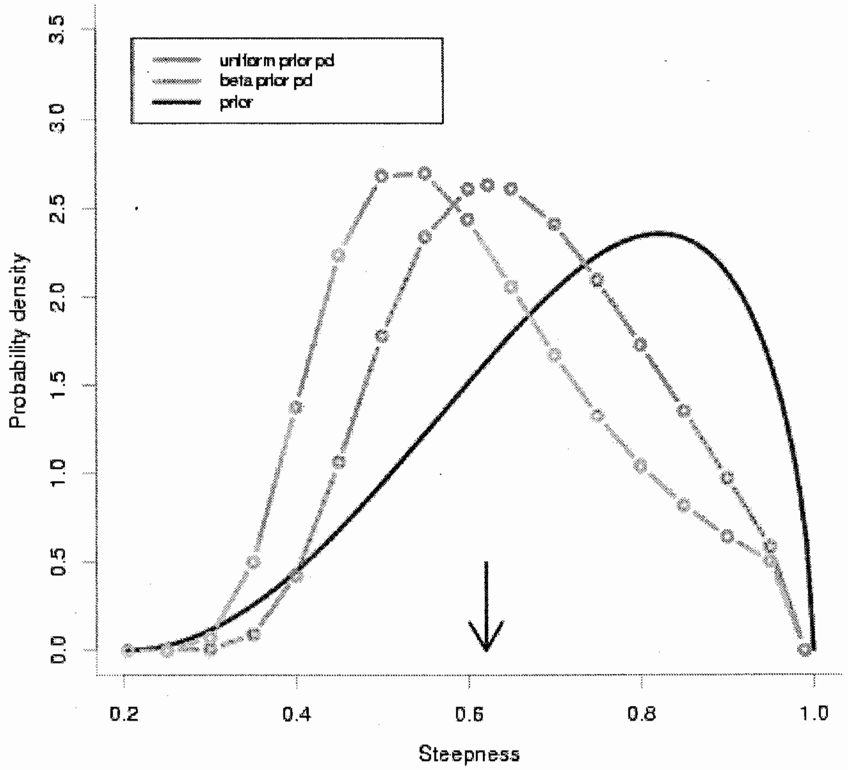

Figure 50. A comparison of the prior distribution of steepness (blue line) included in the base-case assessment model and the likelihood profile of the steepness parameter for the base-case model (with the beta prior distribution) (green line) and the model using an uninformative prior on steepness (steepness-no-prior sensitivity) (orange line). For the base-case analysis, steepness is estimated at 0.62 (arrow).

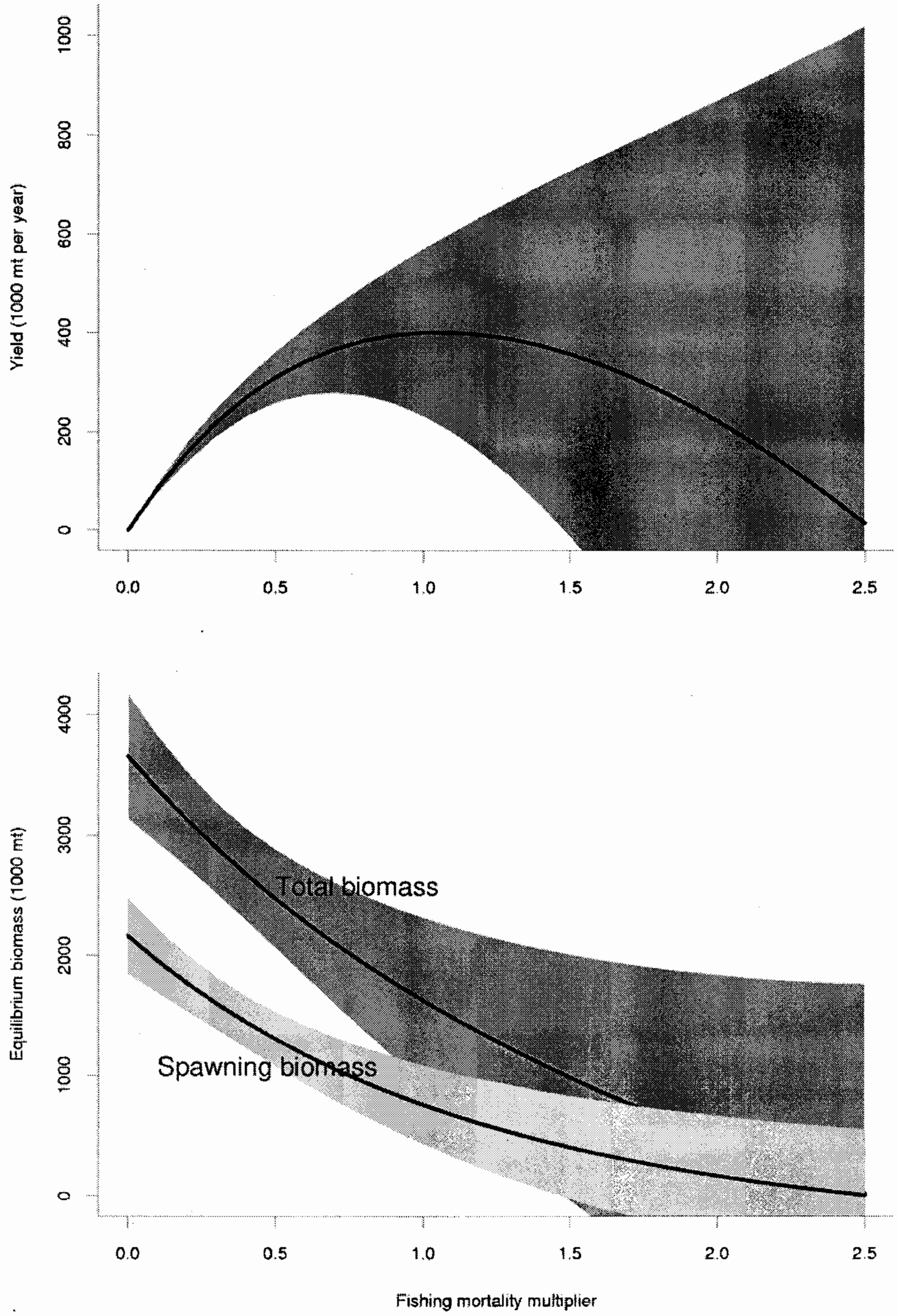

Figure 51. Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier. The shaded areas represent approximate 95% confidence intervals.

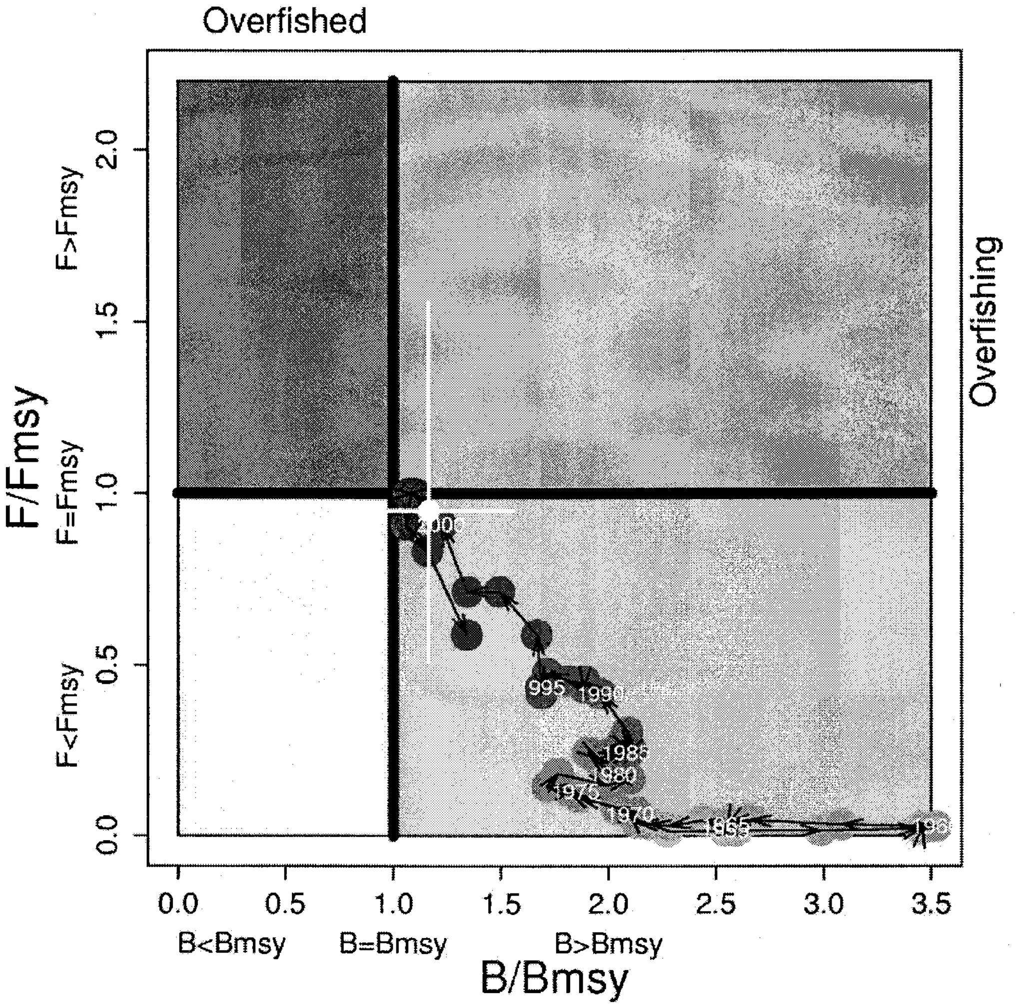

Figure 52. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1952–2006). The colour of the points is graduated from mauve (1952) to dark purple (2006) and the points are labelled at 5-year intervals. The white point represents the reference points computed for the "current" period (2002–2005) and the white lines represent the associated 95% confidence interval.

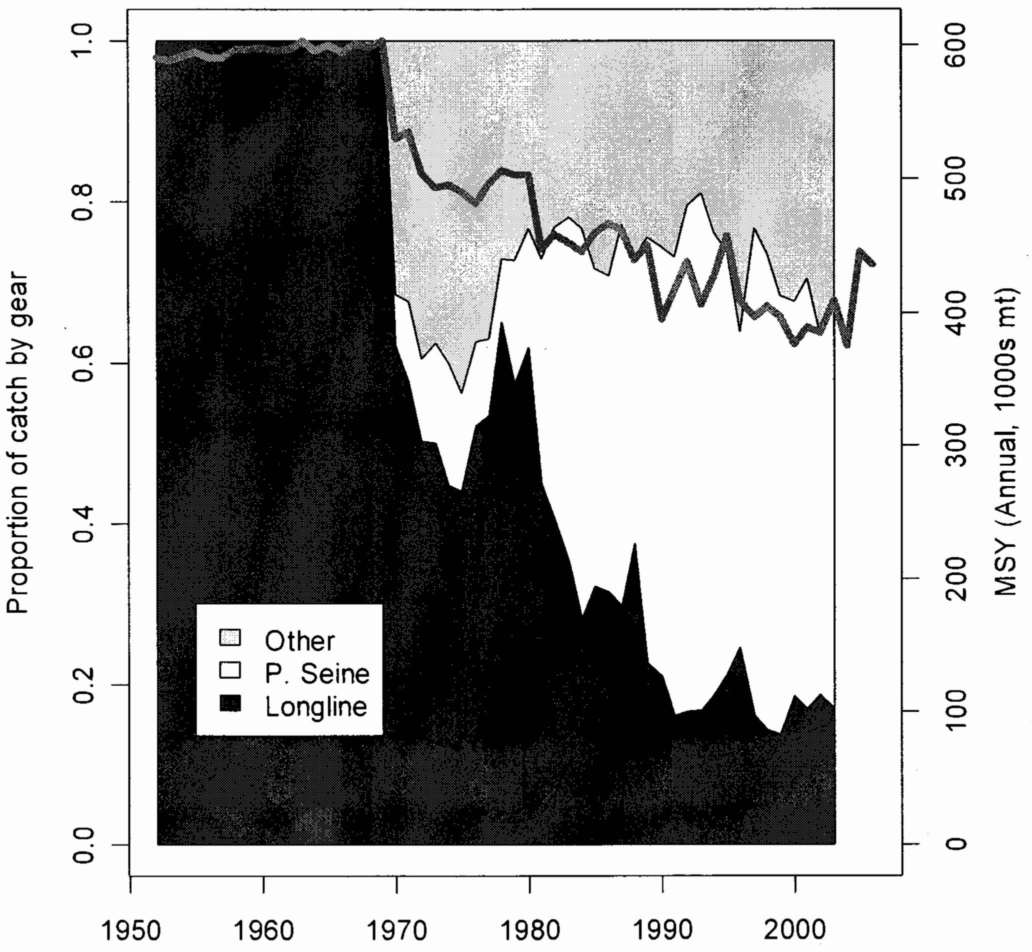

Figure 53. Temporal trend in annual Maximum Sustainable Yield (MSY) (red line) estimated for each year included in the yellowfin stock assessment model. This is compared to the proportional distribution in the annual yellowfin catch by main gear type for the entire WCPO. The "other" fishery is principally the Indonesia and Philippines domestic fisheries combined (PH MISC and ID MISC).

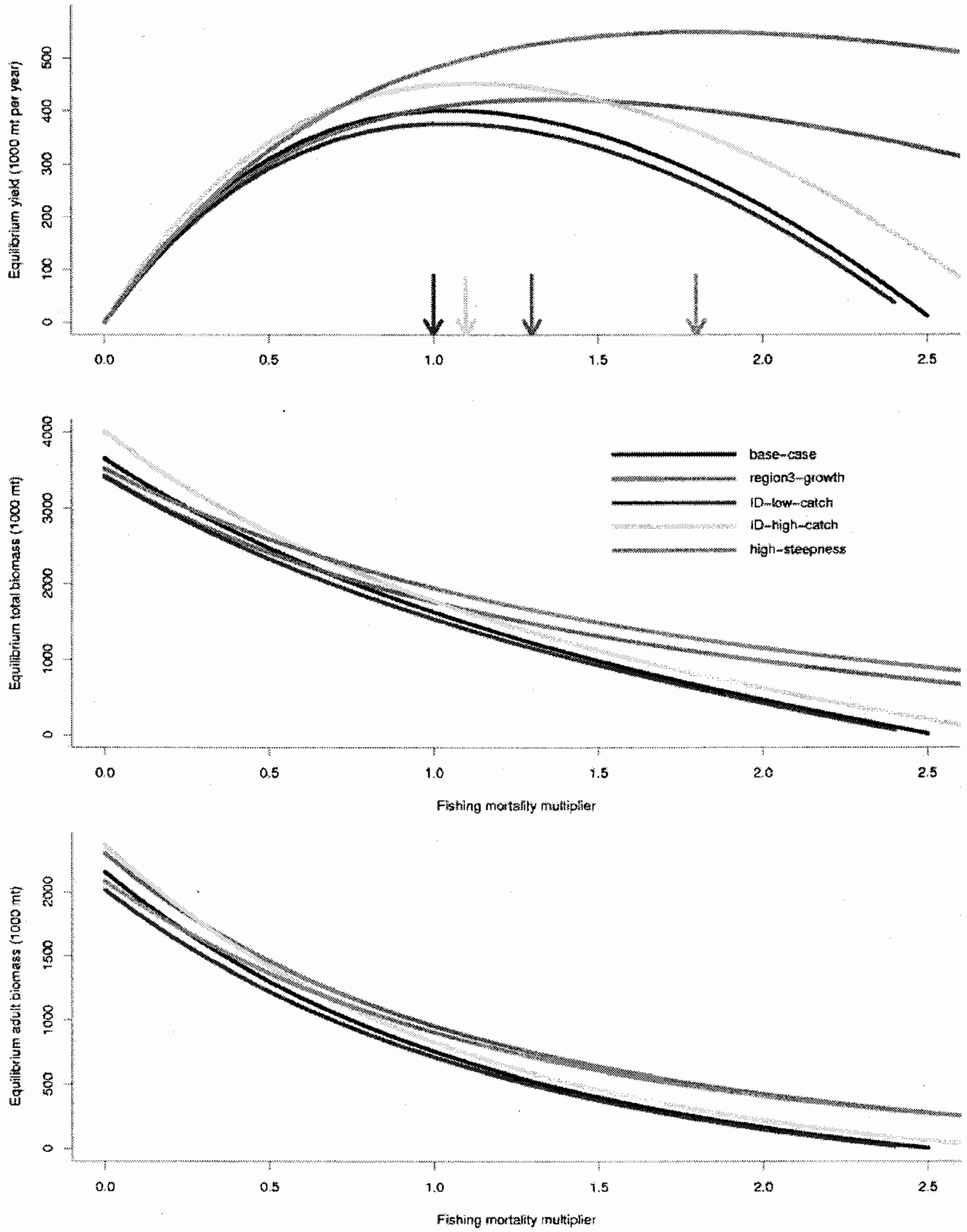

Figure 54. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier obtained from the separate model options. In the upper panel, the arrows indicate the value of the fishing mortality multiplier at maximum yield.

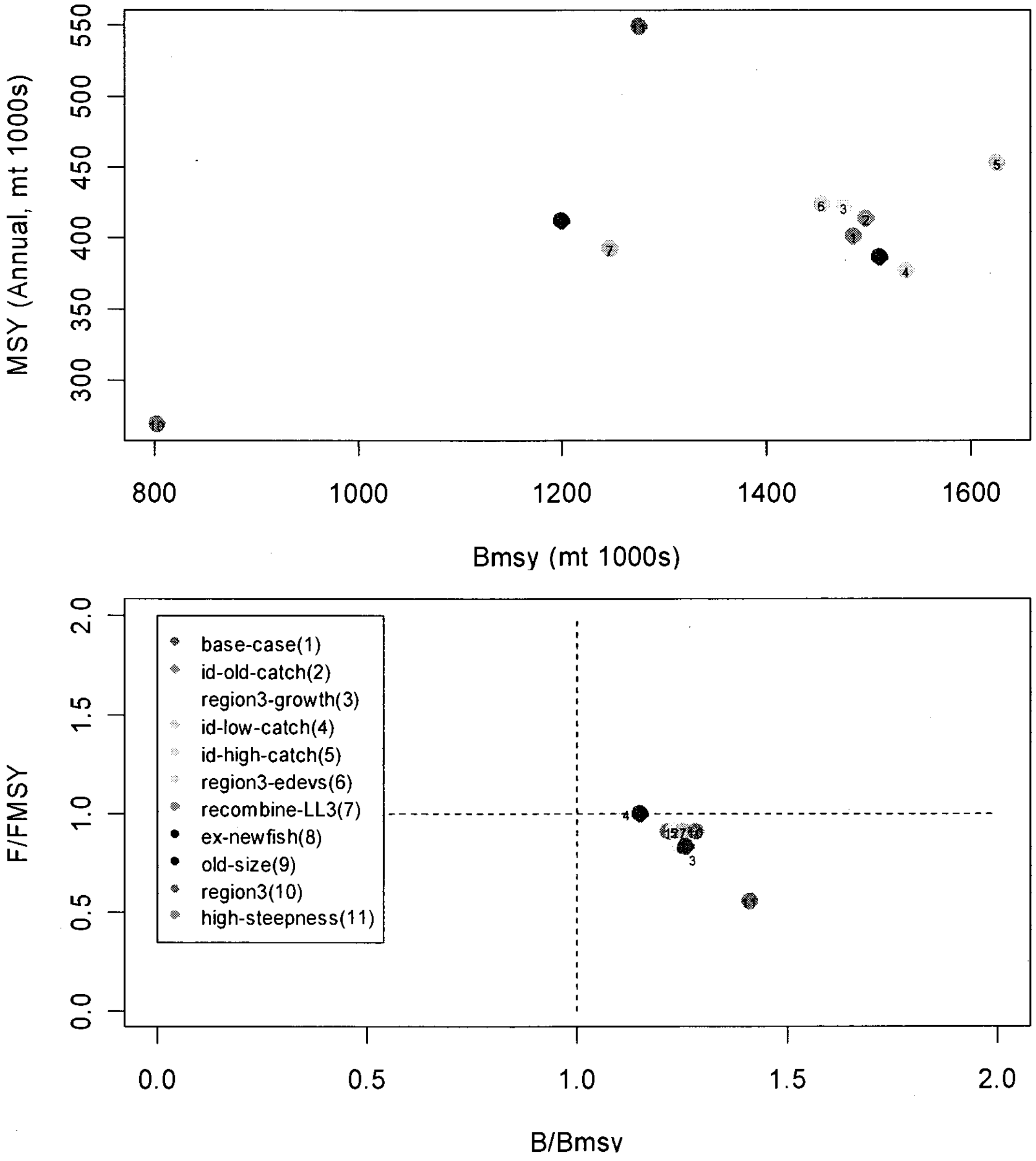

Figure 55. A comparison of MSY and B_{MSY} (top) and current exploitation rates and biomass levels relative to the MSY-based reference points (bottom) for the range of sensitivity analyses (see Table 5).

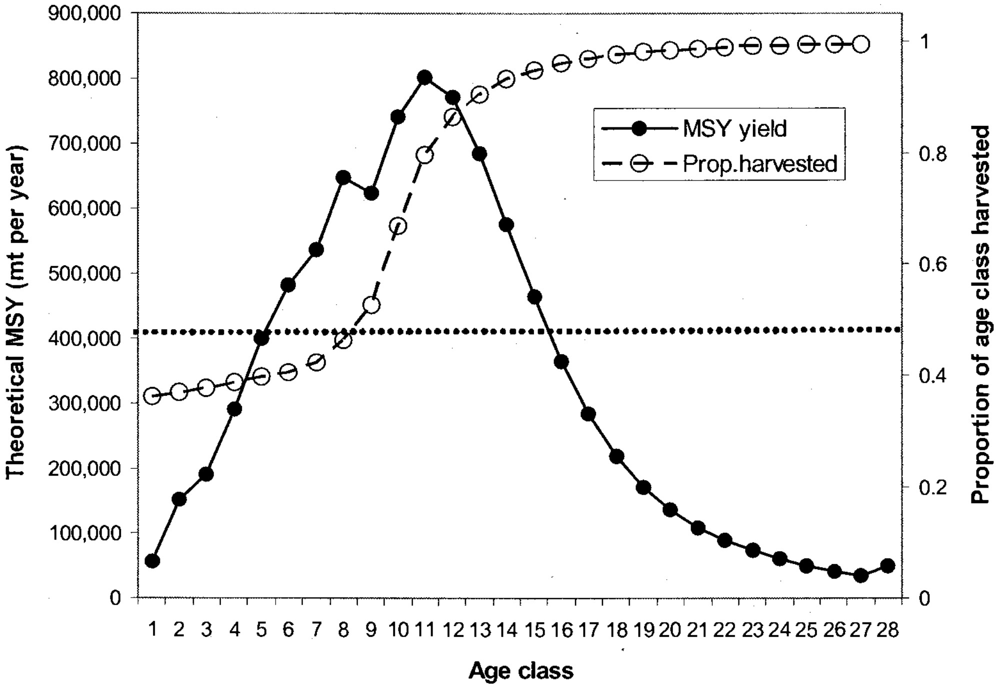

Figure 56. Theoretical maximum sustainable yields that could be generated by harvesting the stock at individual age classes and the proportion of the total biomass of that age class that would be harvested to achieve the theoretical MSY. The current MSY (400,000 mt per year) is represented by the dashed horizontal line.

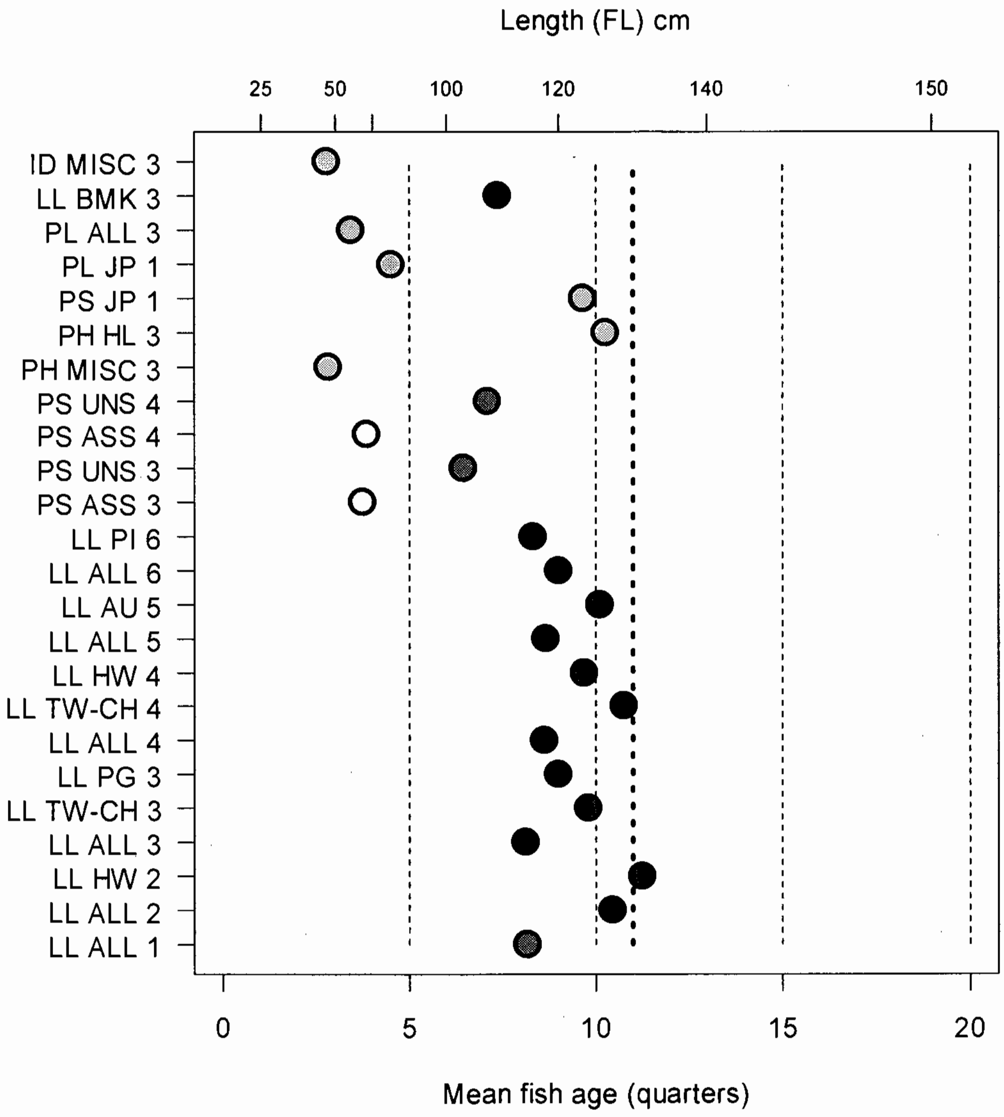

Figure 57. Average age class of fish harvested by each fishery. The dashed vertical line represents the "critical age" (11 quarters); the critical age is the age of capture that generates the maximum yield from the stock.

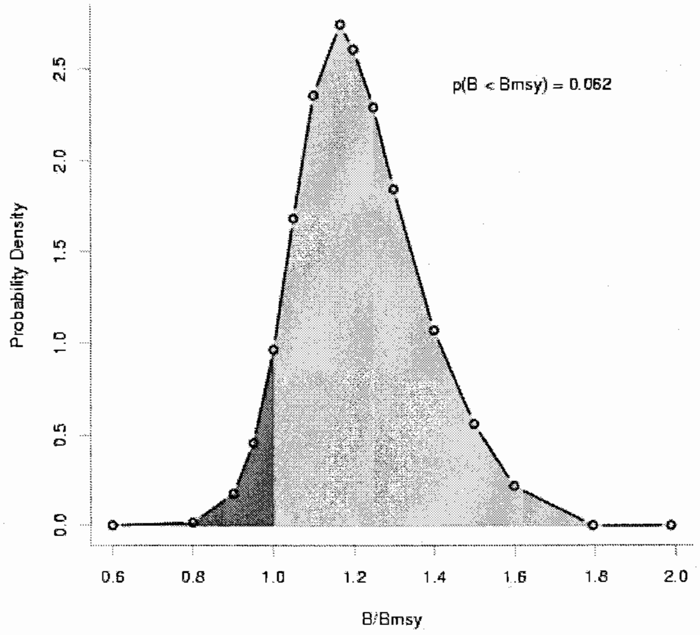

Figure 58. Likelihood profile for $B_{current}/\widetilde{B}_{MSY}$ from the base-case model. The probability of $B_{current}/\widetilde{B}_{MSY} < 1$ (red region) is approximately 6.2%.

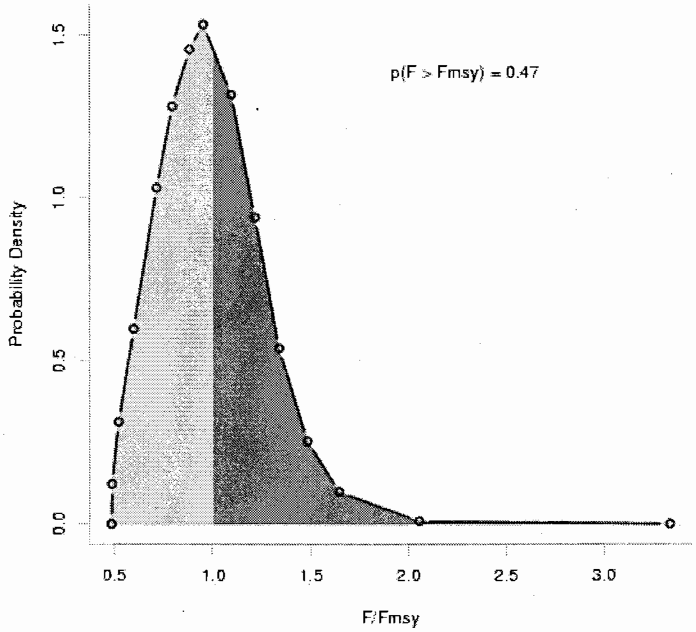

Figure 59. Likelihood profile for $F_{current}/\widetilde{F}_{MSY}$ from the base-case model. The probability of $F_{current}/\widetilde{F}_{MSY} > 1$ (red region) is approximately 47%.

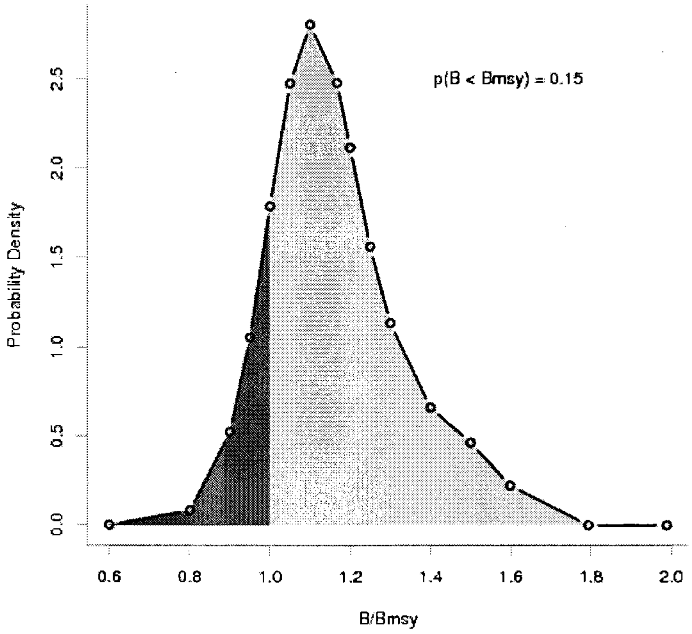

Figure 60. Likelihood profile for $B_{current} / \widetilde{B}_{MSY}$ from the model with the uninformative prior on steepness of the SRR. The probability of $B_{current} / \widetilde{B}_{MSY} < 1$ (red region) is approximately 15.0%.

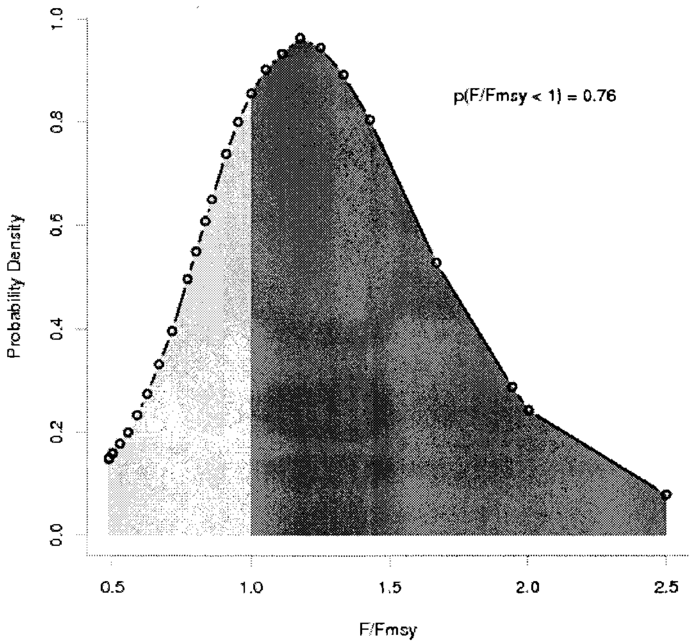

Figure 61. Likelihood profile for $F_{current} / \widetilde{F}_{MSY}$ from the model with the uninformative prior on steepness of the SRR. The probability of $F_{current} / \widetilde{F}_{MSY} > 1$ (red region) is approximately 76%.

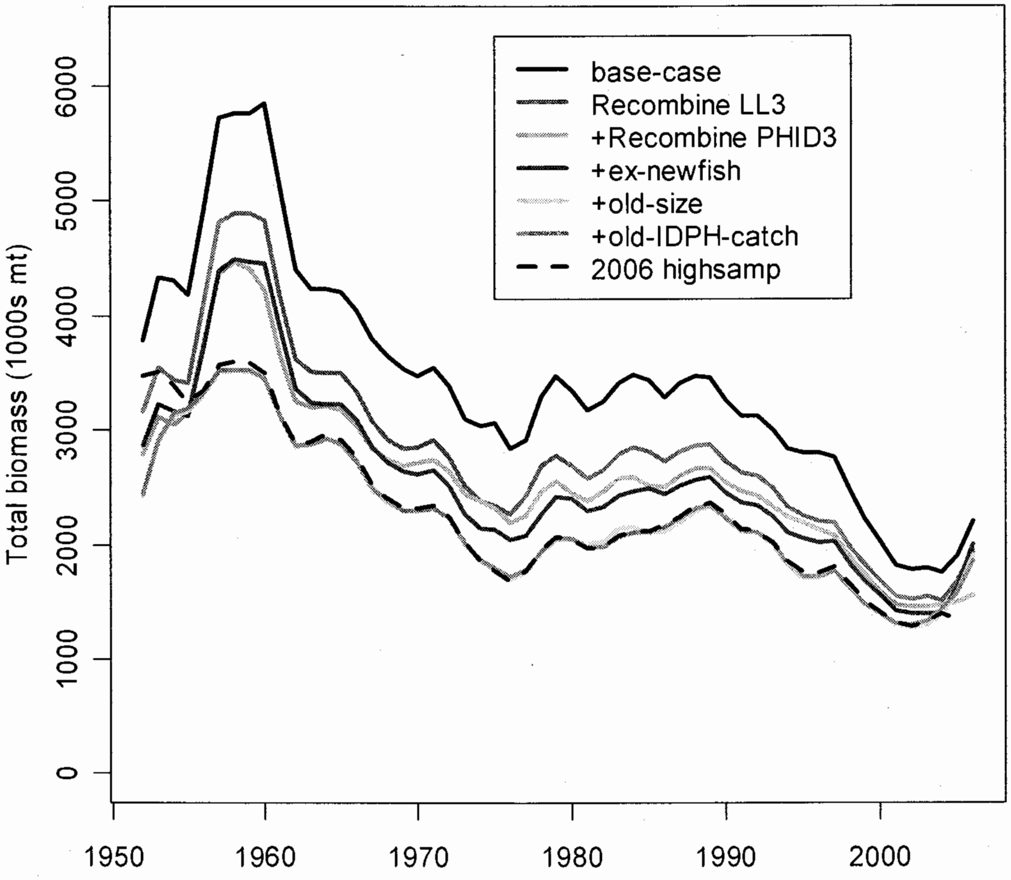

Figure 62. Comparison of the total biomass trajectory from the current base-case assessment and the 2006 assessment model (HIGHSAMP) and the biomass from a stepwise reconfiguration of the 2007 data set to the equivalent format in 2006. The first step in reconfigurating the data was to recombine the LL ALL 3 fishery (combining LL ALL 3 and LL BMK 3).

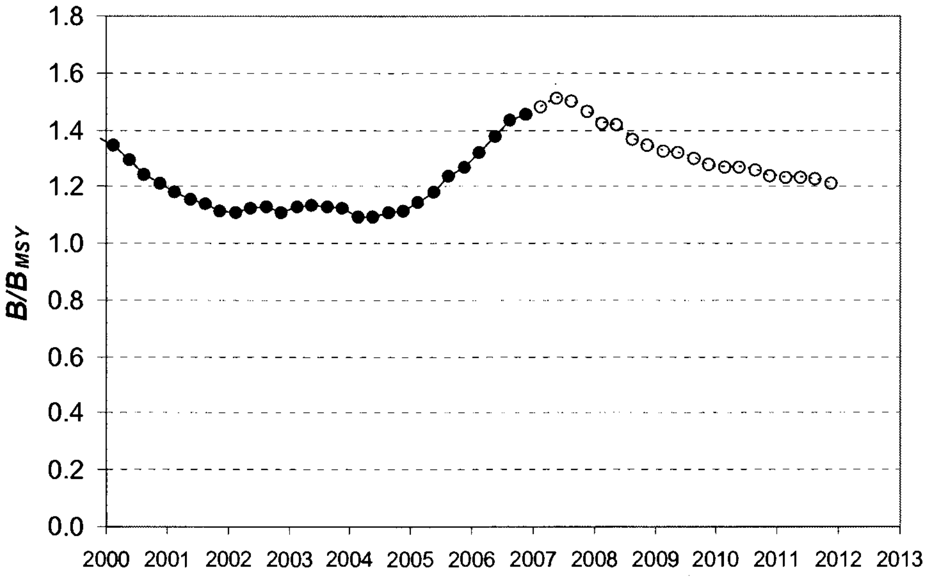

Figure 63. Projected ratio of $B_t/\widetilde{B}_{MSY}$ where $\widetilde{B}_{MSY}$ is computed based on the average *F*-at-age in the final year (5) of the projection (1,580,000 mt). The black circles and solid line are estimates from the stock assessment; the open circles and dashed line are the projection.

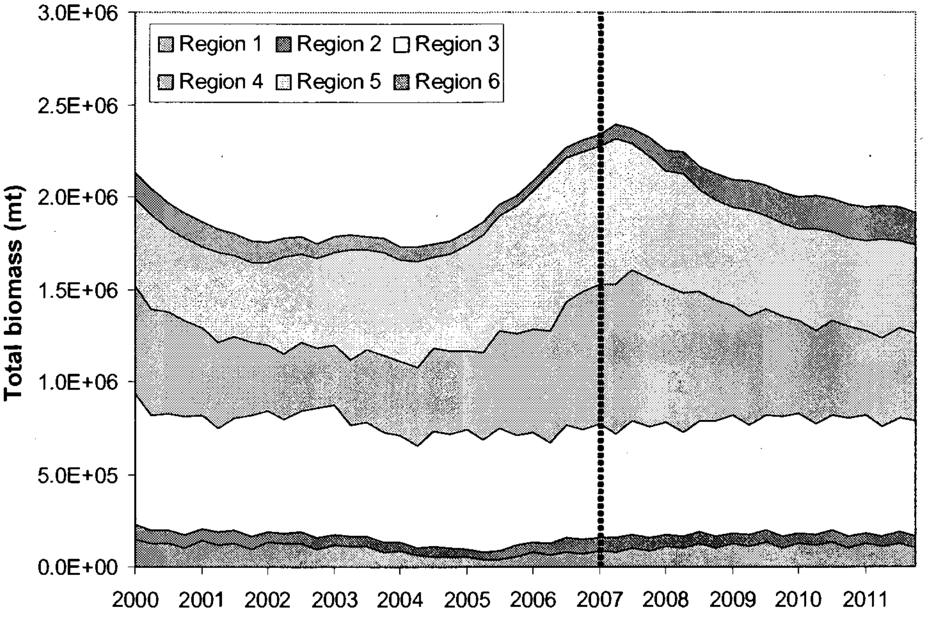

Figure 64. Recent and projected total biomass (mt) by region. The vertical dotted line represents the start of the five-year projection period.

Appendix 1 *doitall.yft*

```
# ------------------------
# PHASE 0 - create initial par file
# ------------------------
#
if [ ! -f 00.par ]; then
 mfclopt yft.frq yft.ini 00.par -makepar
fi
#
# ------------------------
# PHASE 1 - initial par
# ------------------------
#
if [ ! -f 01.par ]; then
 mfclopt yft.frq 00.par 01.par -file - <<PHASE1
  1 149 100      # recruitment penalties
  2 113 1        # estimate initpop/totpop scaling parameter
  2 177 1        # use old totpop scaling method
  2 32 1        # and estimate the totpop parameter
  -999 49 10     # divide LL LF sample sizes by 10 (default)
  -999 50 10     # divide LL WF sample sizes by 10 (default=10)
  -20 50 20      # except for PS in area 1 - lower confidence in these weight data
  1 32 2        # sets standard control
  1 111 4        # sets likelihood function for tags to negative binomial
  1 141 3        # sets likelihood function for LF data to normal
  2 57 4        # sets no. of recruitments per year to 4
  2 69 1        # sets generic movement option (now default)
  2 93 4        # sets no. of recruitments per year to 4 (is this used?)
  2 94 2 2 95 20  # initial age structure based on Z for 1st 20 periods
  -999 26 2      # sets length-dependent selectivity option
  -9999 1 2      # sets no. mixing periods for all tag release groups to 2
# sets non-decreasing selectivity for longline fisheries
 -999 57 3      # uses cubic spline selectivity
 -999 61 3      # with 3 nodes for cubic spline
   -5 57 1      # logistic selectivity for 3 TWCH fisheries
   -8 57 1
# 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
# sets penalties for effort deviations (negative penalties force effort devs
# to be zero when catch is unknown)
 -999 13 -10     # higher for longline fisheries where effort is standardized
   -1 13 -50
   -2 13 -50
   -4 13 -50
   -7 13 -50
  -10 13 -50
  -12 13 -50
  -18 13 10
  -23 13 -10
  -24 13 10
# 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
  mfclopt yft.frq 01.par 02.par -file - <<PHASE2
  -999 3 25      # all selectivities equal for age class 25 and older
  -999 4 4      # possibly not needed
  -999 21 4      # possibly not needed
  1 189 1       # write graph.frq (obs. and pred. LF data)
  1 190 1       # write plot.rep
```

```
 1 1 200       # set max. number of function evaluations per phase to 100
 1 50 -2       # set convergence criterion to 1E+01
 -999 14 10    # Penalties to stop F blowing out
 -999 62 2     # add more nodes to cubic spline
PHASE2
fi
# ---------
#  PHASE 3
# ---------
if [ ! -f 03.par ]; then
 mfclopt yft.frq 02.par 03.par -file - <<PHASE3
 2 70 1        # activate parameters and turn on
 2 71 1        # estimation of temporal changes in recruitment distribution
 1 183 20      # penalties on devs for first 20 time periods
 -100001 1 1000  # pen wt on region rec diffs in region 1
 -100001 2 1000  # pen wt on region rec diffs in region 2
 -100001 3 1000  # pen wt on region rec diffs in region 3
 -100001 4 1000  # pen wt on region rec diffs in region 4
 -100001 5 1000  # pen wt on region rec diffs in region 5
 -100001 6 1000  # pen wt on region rec diffs in region 6
PHASE3
fi
# ---------
#  PHASE 4
# ---------
if [ ! -f 04.par ]; then
 mfclopt yft.frq 03.par 04.par -file - <<PHASE4
 2 68 1        # estimate movement coefficients
PHASE4
fi
# ---------
#  PHASE 5
# ---------
if [ ! -f 05.par ]; then
 mfclopt yft.frq 04.par 05.par -file - <<PHASE5
 1 16 1        # estimate length dependent SD
PHASE5
fi
# ---------
#  PHASE 6
# ---------
if [ ! -f 06.par ]; then
 mfclopt yft.frq 05.par 06.par -file - <<PHASE6
 1 173 8       # estimate independent mean lengths for 1st 8 age classes
 1 182 10
PHASE6
fi
# ---------
#  PHASE 7
# ---------
if [ ! -f 07.par ]; then
 mfclopt yft.frq 06.par 07.par -file - <<PHASE7
 -999 27 1     # estimate seasonal catchability for all fisheries
 -18 27 0      # except those where
 -19 27 0      # only annual catches
 -24 27 0
PHASE7
fi
# ---------
#  PHASE 8
```

```
# ---------
if [ ! -f 08.par ]; then
  mfclopt yft.frq 07.par 08.par -file - <<PHASE8
  -3 10 1        # estimate
  -5 10 1        # catchability
  -6 10 1        # time-series
  -8 10 1        # for all
  -9 10 1        # non-longline
  -11 10 1        # fisheries
  -13 10 1
  -14 10 1
  -15 10 1
  -16 10 1
  -17 10 1
  -18 10 1
  -19 10 1
  -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
  mfclopt yft.frq 08.par 09.par -file - <<PHASE9
  1 14 1         # estimate von Bertalanffy K
  1 12 1         # and mean length of age 1
PHASE9
fi
# ---------
#   PHASE 10
# ---------
if [ ! -f 10.par ]; then
  mfclopt yft.frq 09.par 10.par -file - <<PHASE10
# grouping of fisheries for estimation of negative binomial parameter a
   -1 44 1
   -2 44 1
   -3 44 1
   -4 44 1
   -5 44 1
   -6 44 1
   -7 44 1
   -8 44 1
   -9 44 1
  -10 44 1
  -11 44 1
  -12 44 1
  -13 44 1
  -14 44 2
  -15 44 2
  -16 44 2
  -17 44 2
  -18 44 3
  -19 44 3
  -20 44 1
  -21 44 1
```

```
 -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
 mfclopt yft.frq 10.par 11.par -file - <<PHASE11
 -100000 1 1    # estimate
 -100000 2 1    # time-invariant
 -100000 3 1    # distribution
 -100000 4 1    # of
 -100000 5 1    # recruitment
 -100000 6 1
PHASE11
fi
# ---------
#  PHASE 12
# ---------
if [ ! -f 12.par ]; then
 mfclopt yft.frq 11.par 12.par -file - <<PHASE12
 2 145 1
 1 149 0
 2 146 1
 2 147 1
 2 148 20       # Current is defined as 2002-2005
 2 155 4
 2 153 31
 2 154 16
 1 1 2000
 1 50 -3
 -999 14 0
PHASE12
fi
```

Appendix 2 *yft.ini*

```
# number of age classes
 28
# MATURITY AT AGE
 0 0 0 0 0 0 0.25 0.50 0.75 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
# natural mortality
0.249404147000
# movemap
 1 2 3 4
# diffusion coffs
  0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
  0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
  0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
  0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
# age_pars
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0.695533437000  0.567700066000  0.421096592000  0.249246335000  0.041606970000  -0.220757290000  -
0.220757290000  -0.220757290000  -0.220757290000  -0.220757290000  -0.171967130000  -0.041774192000
0.061062580000   0.133805664000   0.174460761000   0.182064874000   0.157959023000   0.107378580000
0.040072948000 -0.031368892000 -0.095330229000 -0.144824574000 -0.178525605000 -0.199049425000 -
0.210388972000 -0.216136835000 -0.218830926000 -0.220004603000
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
# recruitment distribution among regions
  0.05 0.06 0.40 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
```