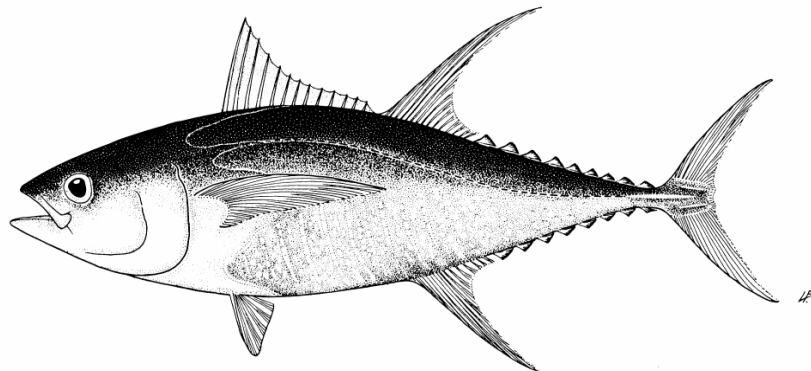




Stock assessment of yellowfin tuna in the western and central Pacific Ocean



John Hampton¹, Pierre Kleiber², Adam Langley¹, Yukio Takeuchi³ and Momoko Ichinokawa³

¹Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia.

²Pacific Islands Fishery Science Center, National Marine Fisheries Service, Honolulu, Hawaii, USA.

³Japan National Research Institute of Far Seas Fisheries, Shimizu, Japan.

July 2005

Table of Contents

Executive summary	1
1 Introduction.....	2
2 Background	2
2.1 Biology.....	2
2.2 Fisheries	3
3 Data compilation	3
3.1 Spatial stratification	3
3.2 Temporal stratification.....	4
3.3 Definition of fisheries	4
3.4 Catch and effort data.....	4
3.5 Length-frequency data	5
3.6 Weight-frequency data.....	6
3.7 Tagging data	6
4 Model description – structural assumptions, parameterisation, and priors	6
4.1 Population dynamics	6
4.1.1 Recruitment	7
4.1.2 Initial population.....	7
4.1.3 Growth.....	7
4.1.4 Movement.....	8
4.1.5 Natural mortality.....	8
4.2 Fishery dynamics	8
4.2.1 Selectivity	8
4.2.2 Catchability.....	8
4.2.3 Effort deviations	9
4.3 Dynamics of tagged fish	9
4.3.1 Tag mixing.....	9
4.3.2 Tag reporting	9
4.4 Observation models for the data	10
4.5 Parameter estimation.....	10
4.6 Stock assessment interpretation methods.....	11
4.6.1 Fishery impact	11
4.6.2 Yield analysis	11
5 Sensitivity analyses	12
6 Results.....	12
6.1 Fit statistics and convergence	12
6.2 Fit diagnostics (GLM-MFIX)	13
6.3 Model parameter estimates (GLM-MFIX)	15
6.3.1 Growth.....	15

6.3.2	Natural mortality.....	15
6.3.3	Movement.....	15
6.3.4	Selectivity.....	15
6.3.5	Catchability.....	15
6.3.6	Tag-reporting rates.....	15
6.4	Stock assessment results.....	16
6.4.1	Recruitment.....	16
6.4.2	Biomass.....	16
6.4.3	Fishing mortality.....	17
6.4.4	Fishery impact.....	17
6.4.5	Yield analysis.....	18
7	Discussion and conclusions.....	19
8	Acknowledgements.....	22
9	References.....	23

Executive summary

This paper presents the 2005 assessment of yellowfin tuna in the western and central Pacific Ocean. The assessment uses the stock assessment model and computer software known as MULTIFAN-CL. The yellowfin tuna model is age (28 age-classes) and spatially structured (6 regions) and the catch, effort, size composition and tagging data used in the model are classified by 19 fisheries and quarterly time periods from 1952 through 2004.

Six independent analyses are conducted to test the impact of using different methods of standardising fishing effort in the main longline fisheries, using estimated or assumed values of natural mortality-at-age, and examining the effect of applying an incremental increase in effective fishing effort to mimic increased fishing efficiency. The analyses conducted are:

SHBS-MEST	Statistical habitat-based standardised effort for “main” longline fisheries, M (assumed constant across age-class) estimated.
SHBS-MFIX	Statistical habitat-based standardised effort for “main” longline fisheries, M -at-age assumed at fixed levels.
GLM-MEST	General linear model standardised effort for “main” longline fisheries, M (assumed constant across age-class) estimated.
GLM-MFIX	General linear model standardised effort for “main” longline fisheries, M -at-age assumed at fixed levels.
FPOW-MEST	General linear model standardised effort for “main” longline fisheries, M (assumed constant across age-class) estimated. Fishing power expansions incorporated into longline (1% per year) and purse seine (4 % per year) effort. No temporal trend in purse-seine catchability.
FPOW-MFIX	General linear model standardised effort for “main” longline fisheries, M -at-age assumed at fixed levels. Fishing power expansions incorporated into longline (1% per year) and purse seine (4 % per year) effort. No temporal trend in purse-seine catchability.

The order (from best to worst) of the models in terms of their fit to the composite data and prior assumptions was: FPOW-MEST, GLM-MEST, FPOW-MFIX, GLM-MFIX, SHBS-MEST and SHBS-MFIX.

The catch, size and tagging data used in the assessment were the same as those used last year, with the exception that additional recent fishery data (2003 and 2004 for longline, 2003 for Philippines and Indonesia, 2004 for purse seine) were included. It should be noted that 2004 data are not complete for some fisheries. The estimation of standardised effort for the main longline fisheries using the GLM and SHBS approaches involved a new method of scaling indices of abundance among regions (see Langley et al. 2005 for details). Overall, the new procedure resulted in higher relative abundance in the tropical regions (3 and 4) and lower relative abundance in the northern (1 and 2) and southern (5 and 6) regions compared to the method used in previous years.

The SBHS analyses were slightly more optimistic than the GLM-based analyses with higher recruitment, lower current fishing mortality, and higher current and equilibrium biomass. The models incorporating an incremental increase in fishing power (FPOW) were more pessimistic than the corresponding GLM models, with higher levels of stock depletion and lower yield estimates, although the levels of current biomass and exploitation rates were comparable. Most of the increased decline in longline CPUE in the early years (imposed by the increase in longline fishing power) was explained by higher earlier recruitment compared to the other models. This trend in recruitment also explains the lower values of stock-recruitment steepness for the FPOW model options, which in turn resulted in lower estimates of equilibrium yield (MSY).

The current assessment is more pessimistic than previous yellowfin assessments for the WCPO. The most influential change in the current assessment is likely to be the differences in the

relative weightings applied to the different model regions, essentially down-weighting the proportion of the total longline exploitable biomass in the non-equatorial regions. For region 3, recent exploitation rates and levels of fishery impact are similar between the current and previous assessments. However, because the current assessment assumes that this region accounts for a much larger proportion of the total stock biomass, current exploitation rates and overall impacts on the WCPO stock are predicted to be substantially higher than previous assessments (depletion to 40–46% of unexploited biomass in the current GLM-based assessments compared to 51–60% in the equivalent 2004 assessments). Other key performance indicators for the stock are also considerably more pessimistic than last year – current stock size is lower ($B_{current}/\tilde{B}_{MSY}$ of 1.75–1.80 for the 2004 assessment compared to 1.16–1.32 for the current assessment) and fishing mortality is higher ($F_{current}/\tilde{F}_{MSY}$ 0.83–1.11 for the 2004 assessment compared to 1.22–1.35 for the current assessment).

The reference points that predict the status of the stock under equilibrium conditions indicate that the long-term average biomass would approximate or fall substantially below that capable of producing *MSY* at 2001–2003 average fishing mortality ($\tilde{B}_{F_{current}}/\tilde{B}_{MSY} = 0.69–1.00$ and $s\tilde{B}_{F_{current}}/s\tilde{B}_{MSY} = 0.62–1.00$). Overall, current biomass exceeds the biomass yielding *MSY* ($B_{current}/\tilde{B}_{MSY} > 1$) due to sustained high recent recruitment, except for the FPOW analyses.

The estimate of $F_{current}/\tilde{F}_{MSY}$ reveals that overfishing of yellowfin is now likely to be occurring in the WCPO. While all analyses except those incorporating assumed incremental increases in fishing power indicate that the stock is not yet in an overfished state ($B_{current}/\tilde{B}_{MSY} > 1$), further biomass decline is likely to occur at 2001–2003 levels of fishing mortality.

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). The current assessment incorporates the most recent data from the yellowfin fishery and revises some of the structural assumptions of the model, most importantly the regional stratification of the model and the approach for inclusion of the standardisation longline effort series — the principal index of relative abundance included in the model.

The overall objectives of the assessment are to estimate population parameters, such as time series of recruitment, biomass and fishing mortality, that indicate the status of the stock and impacts of fishing. We also summarise stock status in terms of well-known reference points, such as the ratios of recent stock biomass to the biomass at maximum sustainable yield ($B_{current}/\tilde{B}_{MSY}$) and recent fishing mortality to the fishing mortality at *MSY* ($F_{current}/\tilde{F}_{MSY}$). 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 of both likelihood (data) and prior information components.

2 Background

2.1 Biology

Yellowfin tuna are distributed throughout the tropical and sub-tropical waters of the Pacific Ocean. However, there is some indication of restricted mixing between the western and eastern Pacific based on analysis of genetic samples (Ward et al. 1994) and tagging data (Figure 1). Adults

(larger than about 100 cm) spawn, probably opportunistically, in waters warmer than 26°C (Itano 2000), while juvenile yellowfin are first encountered in commercial fisheries (mainly surface fisheries in Philippines and eastern Indonesia) at several months of age.

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

2.2 Fisheries

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

Since 1990, the yellowfin tuna catch in the WCPO has varied between 320,000 and nearly 500,000 t (Figure 2). Purse seiners harvest the majority of the yellowfin tuna catch (47% by weight in 1998–2002), with the longline and pole-and-line fisheries comprising 15% and 3% of the total catch, respectively. Yellowfin tuna usually represent approximately 20–25% of the overall purse-seine catch and may contribute higher percentages of the catch in individual sets. Yellowfin tuna is often directly targeted by purse seiners, especially as unassociated schools.

Longline catches in recent years (57,000–77,000 t) are well below catches in the late 1970s to early 1980s (which peaked at 117,000 t), presumably related to changes in targeting practices by some of the larger fleets. Catches in the ‘Other’ category in Figure 2 are largely composed of yellowfin tuna from the Philippines and eastern Indonesia. These catches come from a variety of gear types (e.g. ringnet, gillnet, handline and seine net) and have increased steadily over the past decade. Based on catch data provided by those countries, recent catches represent approximately 35% of total WCPO yellowfin tuna catches.

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

3 Data compilation

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

3.1 Spatial stratification

The geographic area considered in the assessment is the WCPO, defined by the coordinates 40°N–35°S, 120°E–150°W. Within this overall area, a six-region spatial stratification was adopted for the assessment (Figure 3). The rationale for this stratification was to separate the tropical area, where both surface and longline fisheries occur year-round, from the higher latitudes, where the longline fisheries occur more seasonally. The stratification is different to that used in the 2004 assessment, in

response to discussions held at SCTB 17 and subsequently. The area north of 20°N has been split into two regions, while the boundary separating eastern and western regions has been shifted from 160°E to 170°E.

3.2 Temporal stratification

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

3.3 Definition of fisheries

MULTIFAN-CL requires the definition of “fisheries” that consist of relatively homogeneous fishing units. Ideally, the fisheries so defined will have selectivity and catchability characteristics that do not vary greatly over time (although in the case of catchability, some allowance can be made for time-series variation). Nineteen fisheries have been defined for this analysis on the basis of region, gear type and, in the case of purse seine, set type (Table 1). There is a single general longline fishery in each region (LL1-6) and two additional Chinese/Taiwanese longline fisheries 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), and an aggregate of the Pacific Island domestic longline fisheries (LL PI 6) were included as separate fisheries in the model (Table 1).

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

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

The purse-seine and pole-and-line fisheries within model region 1 were not included in the assessment model.

3.4 Catch and effort data

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

Effort data for the composite Philippines/Indonesian fishery (PHID MISC 3) were unavailable and the relative catch was used as a proxy for effort. Alternatively, we could have defined effort for these fisheries to be missing, in which case the relative effort over time would have been determined only by the effort deviations, which have a lognormal probability distribution with constant mean and variance. We felt that it was better to have a “null hypothesis” of effort proportional to catch, rather than constant over time. In practice, this assumption has not been found to influence the results overly, as the variance of the catchability deviations for these fisheries is set at a high level to give the model flexibility to fit the total catch.

Effort data units for purse seine fisheries are defined as days fishing and/or searching, allocated to set types based on the proportion of total sets attributed to a specified set type (associated or unassociated sets) in logbook data. For the longline fisheries, two estimates of effective (or standardised) effort were derived using generalized linear models (GLM) and an unconstrained statistical habitat-based standardisation (Langley et al. 2005). Time-series of catch and catch-per-unit-effort (CPUE) for all fisheries, and CPUE constructed using the two sets of longline effort data are shown in Figure 6 and Figure 7, respectively.

The two techniques for standardising longline effort were also applied to determine the relative weightings of longline effort between regions. These weighting 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). These weighting factors were applied to scale the longline effort series and, thereby, trends in longline CPUE between regions were comparable indicators of exploitable biomass among regions. This was a substantial difference from last year's assessment which scaled the regional biomass by a series of region area sizes that were determined from a qualitative assessment of the distribution of longline fishing in each region.

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

3.5 Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 95 2-cm size classes (10–12 cm to 188–200 cm). Each length-frequency observation consisted of the actual number of yellowfin tuna measured. A graphical representation of the availability of length (and weight) samples is provided in Figure 8. The data were collected from a variety of sampling programmes, which can be summarized as follows:

Philippines: Size composition data for the Philippines domestic fisheries derived from a sampling programme conducted in the Philippines in 1993–94 were augmented with data from the 1980s and for 1995. In addition, data collected during 1997–2002 from the Philippines hand-line (PH HL 3) and surface fisheries (PHID MISC 3) under the National Stock Assessment Project (NSAP) were included in the current assessment.

Indonesia: Limited size data were obtained for the Indonesian domestic fisheries from the former IPTP database. Note that the miscellaneous Indonesian fishery has been combined with the Philippines small-fish fishery in this assessment, and therefore the size composition of the catch is assumed to be represented by the combined data.

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

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

3.6 Weight-frequency data

Individual weight data for the Japanese longline fisheries previously converted to lengths and aggregated with length measurement data were available and included in this assessment in their original form. For many other longline fleets, “packing list” data are available from export documentation, and these data are progressively being processed and incorporated into the assessment database. For this assessment, the available weight data (apart from those provided by Japan) originated from vessels unloading in various ports around the region from where tuna are exported, including Guam, Palau, FSM, Marshall Islands, Fiji, Papua New Guinea, Hawai’i, and eastern Australian ports. Data were compiled by 1 kg weight intervals over a range of 1–150 kg. As the weights were generally gilled-and-gutted weights, the frequency intervals were adjusted by a gilled-and-gutted to whole weight conversion factor for yellowfin (1.1561). The time-series distribution of available weight samples is shown in Figure 8.

3.7 Tagging data

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

For incorporation into the MULTIFAN-CL analyses, tag releases were stratified by release region (all yellowfin tuna releases occurred in regions 3, 4, 5 and 6), time period of release (quarter) and the same length classes used to stratify the length-frequency data. A total of 39,424 releases were classified into 27 tag release groups in this way. Of the 4,952 tag returns in total, 4,116 could be assigned to the fisheries included in the model. Tag returns that could not be so assigned were included in the non-reported category and appropriate adjustments made to the tag-reporting rate priors and bounds. The returns from each size class of each tag release group were then classified by recapture fishery and recapture time period (quarter). Because tag returns by purse seiners were often not accompanied by information concerning the set type, tag-return data were aggregated across set types for the purse seine fisheries in each region. The population dynamics model was in turn configured to predict equivalent estimated tag recaptures by these grouped fisheries.

4 Model description – structural assumptions, parameterisation, and priors

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

4.1 Population dynamics

The model partitions the population into 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 that yellowfin in age-classes 1–6 are

immature, 25%, 50% and 75% of yellowfin in age-classes 7–9, respectively, are mature, and 100% of fish in age-classes 10–28 are mature. This maturity schedule is consistent with the observations of Itano (2000). The population is “monitored” in the model at quarterly time steps, extending through a time window of 1952–2004. 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. The time-series variation in spatially-aggregated recruitment was somewhat constrained by a lognormal prior. The variance of the prior was set such that recruitments of about three times and one third of the average recruitment would occur about once every 25 years on average.

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

Typically, fisheries data are not very informative about SRR parameters and it is generally necessary to constrain the parameterisation in order to have stable model behaviour. We incorporated a beta-distributed prior on the “steepness” (S) of the SRR, with S defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Francis 1992; Maunder and Watters 2001). The beta-distribution of the prior has a lower bound at 0.2, a mode = 0.85, and standard deviation = 0.16 (Figure 9).

4.1.2 Initial population

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

4.1.3 Growth

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

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

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

4.1.4 Movement

Movement was assumed to occur instantaneously at the beginning of each quarter through movement coefficients connecting regions sharing a common boundary. Note however that fish can move between non-contiguous regions in a single time step due to the “implicit transition” computational algorithm employed (see Hampton and Fournier 2001 for details). Movement is parameterised as the proportion of fish in a given region that move to the adjacent region. There are seven inter-regional boundaries in the model with movement possible across each in both directions. Four seasonal movements were allowed, each with their own movement coefficients. Thus there is a need for $2 \times 7 \times 4 = 56$ movement parameters. The seasonal pattern of movement persists from year to year with no allowance for longer-term variation in movement. The previous 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 either held fixed at pre-determined age-specific levels (MFIX) or was estimated as a single parameter with no age-related variability (MEST). We did not estimate M -at-age in these assessments because trial fits estimating M -at-age produced biologically unreasonable results. For the fixed M runs, M -at-age was determined outside of the MULTIFAN-CL model using yellowfin sex-ratio data and the assumed maturity-at-age schedule. An identical procedure is used to determine fixed M -at-age for assessments in the EPO (Maunder 2005). Essentially, this method reflects the hypothesis that the higher proportion of males in sex-ratio samples with increasing length is due to the higher natural mortality of females after they reach maturity. The externally-estimated M -at-age used for the MFIX runs is shown in Figure 10.

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 new 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. For the longline fisheries (which catch mainly adult yellowfin) selectivity was assumed to increase with age and to remain at the maximum once attained. 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). The coefficients for the last four age-classes, for which the mean lengths are very similar, were constrained to be equal for all fisheries.

4.2.2 Catchability

Catchability was allowed to vary slowly over time (akin to a random walk) for all purse seine fisheries, the Philippines and Indonesian fisheries, the Australian, Taiwanese/Chinese, Hawaii, PNG and other Pacific-Island longline fisheries, using a structural time-series approach. Random walk steps

were taken every two years, and the deviations were constrained by prior distributions of mean zero and variance specified for the different fisheries according to our prior belief regarding the extent to which catchability may have changed. For the Philippines and Indonesian fisheries, 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, for which reliable effort data were unavailable, we set the prior variance at a high level (equivalent to a CV of about 0.7), to allow the effort deviations to account for short-term fluctuations in the catch caused by variation in real effort. For the purse seine fisheries and the Australian longline fishery, the variance was set at a moderate level (CV of about 0.2). For the LL ALL 1–6 longline fisheries, the variance was set at a lower level (CV of about 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. Effective sample size is assumed to be 0.1 times the actual sample size, with a maximum effective sample size of 100. Reduction of the effective sample size recognises that (i) length-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. A similar likelihood function was used for the weight-frequency data.

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

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 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 *ini* file (Appendix B)¹.

The Hessian matrix computed at the mode of the posterior distribution was used to obtain estimates of the covariance matrix, which was used in combination with the Delta method to compute approximate confidence intervals for parameters of interest. In addition, the likelihood profile method was used to generate probability distributions for the critical reference points $F_{current}/\tilde{F}_{MSY}$ and $B_{current}/\tilde{B}_{MSY}$. Likelihood profiles were generated by undertaking model runs with either

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).

$F_{current}/\tilde{F}_{MSY}$ or $B_{current}/\tilde{B}_{MSY}$ set at various levels (by applying a penalty to the likelihood function for deviations from the target ratio) over the range of possible values. The likelihood function values resulting from these runs were then used to construct a probability distribution for each ratio.

4.6 Stock assessment interpretation methods

Several ancillary analyses are conducted in order to interpret the results of the model for stock assessment purposes. These 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 and adult biomass at MSY can also be determined. The ratios of the current (or recent average) levels of fishing mortality and biomass to their respective levels at MSY are of interest as limit reference points. These ratios are also determined and their confidence intervals estimated using a likelihood profile technique.

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In this assessment, we use the average over the period 2001–2003. The last year in which catch and effort data are available for all fisheries is 2004. We do not include 2004 and subsequent years in the average as fishing mortality tends to have high uncertainty for the terminal data years of the analysis and the catch and effort data for this terminal year are usually incomplete.

The assessments indicate recruitment over the last two decades was higher than for the preceding period. Consequently, yield estimates determined based on the long-term equilibrium recruitment estimated from the Beverton and Holt SRR may substantially under-estimate the actual equilibrium yields currently available from the stock under current recruitment conditions. For this reason, a separate yield analysis was conducted based on the average level of recruitment from 1994–2003.

5 Sensitivity analyses

Standardised effort for the “main” longline fisheries (LL ALL 1–6) was estimated using two alternative standardisation methods: one based on a GLM and the other on a statistical habitat-based standardisation (Langley et al. 2005). We also conducted a series of runs in which the effort data for longline (GLM standardised) and purse seine fisheries were expanded by 1% and 4%, respectively, per year from the base year to mimic expansion of fishing power.

Sensitivity to natural mortality estimates was investigated by conducting separate runs in which M -at-age was fixed and runs in which a generic M assumed constant across age-class was estimated. The fixed M -at-age used in these runs is shown in Figure 10.

In summary, the analyses carried out are:

SHBS-MEST	Statistical habitat-based standardised effort for “main” longline fisheries, M (assumed constant across age-class) estimated.
SHBS-MFIX	Statistical habitat-based standardised effort for “main” longline fisheries, M -at-age assumed at fixed levels.
GLM-MEST	General linear model standardised effort for “main” longline fisheries, M (assumed constant across age-class) estimated.
GLM-MFIX	General linear model standardised effort for “main” longline fisheries, M -at-age assumed at fixed levels.
FPOW-MEST	General linear model standardised effort for “main” longline fisheries, M (assumed constant across age-class) estimated. Fishing power expansions incorporated into longline (1% per year) and purse seine (4 % per year) effort. No temporal trend in purse-seine catchability.
FPOW-MFIX	General linear model standardised effort for “main” longline fisheries, M -at-age assumed at fixed levels. Fishing power expansions incorporated into longline (1% per year) and purse seine (4 % per year) effort. No temporal trend in purse-seine catchability.

6 Results

Results for the five analyses are presented below. In the interests of brevity, some categories of results are presented for the GLM-MFIX analysis only, which is designated the base-case analysis. However, the main stock assessment-related results are summarised for all analyses.

6.1 Fit statistics and convergence

A summary of the fit statistics for the five analyses is given in Table 3. Overall, the models incorporating GLM standardised longline effort (GLM- and FPOW-) provided better fits to the composite data and prior information (penalties) than the SHBS standardised longline effort models. The latter models attract a considerably higher overall penalty mostly attributable to the effort deviations. The models with the incremental increase in fishing power (FPOW-) perform slightly better than the comparable models without increasing efficiency (GLM-).

For the three different effort series, the model options estimating natural mortality (constant with respect to age-class, -MEST) provide a slightly better fit to the composite data than the models that include the fixed mortality-at-age schedule (-MFIX).

While the GLM-MFIX model does not represent the best fit to the composite data set, the performance of the model approaches that of the models with superior fitting criteria (GLM-MEST and FPOW- models). The model was selected as the designated base-case on the basis that the fixed natural mortality schedule is consistent with our understanding of the biology of the species. The GLM- based effort series is also not subject to the assumed level of increase in fishing efficiency of

both the longline and purse-seine fleets used in the FPOW- model. Nevertheless, the superior fit of the FPOW- models indicates that these effort scenarios are not implausible and the resulting model conclusions should not be discounted.

6.2 Fit diagnostics (GLM-MFIX)

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

- The log total catch residuals by fishery are shown in Figure 11. The residuals are all relatively small and, for most fisheries, generally show even distributions about zero. However, some patterns are worthy of comment. First, there appears to be some autocorrelation in residuals for fisheries LL ALL 1 and LL ALL 3, which could be evidence of 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.
- Some systematic lack of fit for the longline fisheries is suggested by comparisons of observed and predicted length data aggregated over time (Figure 12). For some of the longline fisheries (LL ALL 1, LL ALL 3, LL ALL 4, LL PG 3, LL TW-CH 3 & 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. Most of these fisheries also have considerable weight frequency data (Figure 13). The lack of fit to the length data was examined in further detail by comparing the proportion of larger fish (125–170 cm) in observed and predicted length compositions over the study period (Figure 14). This analysis reveals strong temporal trends in the residuals from the LL ALL 1–3 and LL ALL 5 fisheries over the time period.
- The aggregated fit to the weight frequency data (Figure 13) from LL ALL 1, LL ALL 3, LL TW-CH 3 and LL HW 4 is considerably better than for the length frequency data. However, the converse is the case for the fit to the weight frequency data from the LL ALL 6 fishery. Strong temporal trends in the residuals of the proportion of large fish are also evident in the weight data for most of the main longline fisheries (Figure 15).
- For the Australian longline fishery, the weight-frequency prediction is good. In this case, there is no competing length-frequency data in the model. There is also no evidence of a temporal shift in the residuals of the proportion of larger fish in the catch (Figure 15).
- The most likely explanation for the observed discontinuity between the fits to the length and weight data from the main longline fisheries is the appropriateness of the generic correction factor applied to convert processed (gilled-and-gutted) weights to whole weights (1.1561). The consistent over-estimation of predicted length distribution, as evident in most of the main longline fisheries, is consistent with too high a conversion factor being applied to the corresponding weight data. For many of these fisheries, the composite size frequency data set is dominated by the weight frequency data (see Figure 8) and, therefore, dominates the estimation of selectivity-at-age for the fishery. Further, the observed temporal trends in the fits to the two data sets (Figure 14 and Figure 15) may also be explained by temporal changes in the relative proportion of length and weight data in the cumulative size frequency data set. For example, prior to 1975 the LL ALL 3 size frequency data was dominated by length data and the proportion of larger fish was consistently over-estimated by the model. However, during the subsequent period, the size frequency data was dominated by the weight data and the model estimates of the size composition were closer to the observations. Similar trends are also evident for some of the other main longline fisheries.

- The presumption that the generic conversion factor may be inappropriate, at least for some fisheries, was examined by rerunning the model with a lower generic conversion factor (1.05). This resulted in a considerable improvement in fit to the composite model data, in particular the size frequency data (both length and weight). However, these results are preliminary and further work is required to ascertain the most appropriate conversion factors for the individual weight frequency data sets, particularly for the Japanese fleets.
- There are other plausible explanations for the observed discrepancy between the two sources of size frequency data. The results may indicate that the current generic length-weight relationship is inappropriate for the WCPO stock, particularly for the equatorial region where the discrepancy between the length and weight data is greatest. It is also possible that these trends may be influenced by temporal trends in some of the size-based model parameters, for example fishery specific selectivity at age.
- In contrast, the overall fit to the length data from the purse-seine fisheries and Philippine/Indonesian fisheries is good, although there are no corresponding weight frequency data from these fisheries. For some of the other fisheries with limited size frequency data, in particular LL PI 6 and LL TW-CH 4, the fit to the size frequency data is poor (Figure 12), reflecting the low sample sizes and high variability in size composition between samples.
- The fits of the model to the tagging data compiled by calendar time and by time at liberty are shown in Figure 16 and Figure 17. The model generally approximates the observed number of tag returns by time interval, although there is a systematic over-estimation of tag-return numbers towards the end of the tag recovery period. This is also evident in the over-estimation of tag returns for about 6–13 quarters at liberty (Figure 17). The model under-estimates the recovery of fish at liberty for long periods (greater than 20 quarters), although the number of observations is small). The fits for individual fishery groups are shown in Figure 18. There is a very good fit to the observed number of returns for those fisheries that returned large numbers of tags: the equatorial purse-seine and Philippines/Indonesian fisheries.
- Observed and predicted tag recovery rates for the longline fisheries are very low due to the relatively low total catch and the emphasis on the tagging of smaller yellowfin (Figure 18). For most of these fisheries, the tagging data is uninformative. Of the longline fisheries, most recoveries have been made from the Australian fishery. However, there is some considerable discrepancy in the number of observed and predicted returns from the fishery (Figure 18). This is possibly related to the coarse resolution of spatial structure in the model and a lack of adequate mixing of tagged fish with the wider population.
- The overall consistency of the model with the observed effort data can be examined in plots of effort deviations against time for each fishery (Figure 19). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. On the other hand, if there was an obvious trend in the effort deviations with time, this may indicate that a trend in catchability had occurred and that this had not been sufficiently captured by the model. Of particular interest are the effort deviations for the LL ALL 1–6 longline fisheries, which were constrained to have the same average catchability and to have no year-to-year variation (i.e., catchability deviations were assumed to be zero). Some autocorrelation of effort deviations for the LL ALL 1 and LL ALL 3 fisheries are evident, indicating that the effort standardisation for this fishery has not completely removed time-series catchability effects. For the LL ALL 3 fishery, the recent high effort deviations may indicate that catches are being sustained by increased fishing efficiency. Also noteworthy is the positive effort deviations for LL ALL 5 at the beginning of the time series. These deviations correspond to very high CPUE observations during the development of the fisheries (Figure 7). The converse is evident in the early period of the LL ALL 2 and LL ALL 4 fisheries, which have negative effort deviations.

6.3 Model parameter estimates (GLM-MFIX)

6.3.1 Growth

The estimated growth curve is shown in Figure 20. The non-von Bertalanffy growth of juvenile yellowfin is clearly evident, with near-linear growth in the 50–100 cm size range. This growth pattern is similar to that observed in the otolith length-increment data (Figure 20) (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 20).

6.3.2 Natural mortality

Natural mortality was not estimated in the base-case assessment and an age-specific mortality function was applied (Figure 21). For the models where natural mortality was estimated (MEST), only an age-invariant natural mortality rate was estimated. These estimates were comparable for the three model options at 0.275–0.290 qtr^{-1} (Figure 21), considerably higher than the fixed value of natural mortality for most of the exploitable component of the stock (age classes greater than 5).

6.3.3 Movement

The model estimates very large movements of fish — up to 55% of all fish per quarter — southward from region 1 to region 3 in the first and third quarters of the year (Figure 22). Movements between all other adjacent regions are relatively low, with movements from region 3 to regions 1, 4, and 5 of about 3.5%, 3%, and 0.5% per quarter, respectively. Note that the lack of substantial movement for some regions could be due to limited data on movement. In the model, a small penalty is placed on movement coefficients different to zero. This is done for reasons of stability, but it would tend to promote low movement rates in the absence of data that are informative about movement. An alternative model formulation would be to have high movement rates, rather than zero movement, as the “null hypothesis”. This is a topic for further research.

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 23). Unassociated purse-seine sets generally catch substantially larger fish than from associated sets. The composite Philippines/Indonesia surface fisheries principally catch small fish; however, there are also some observations of larger fish in the catch that explain the high selectivity of older fish also.

6.3.5 Catchability

Time-series changes in catchability are evident for several fisheries (Figure 24). Catchability in the principal longline fisheries (LL ALL 1–6) has been assumed to be constant over time. There is evidence of a general increasing catchability in the unassociated purse seine fisheries and some of the domestic longline fisheries (LL PG 3, LL HW 4, and LL PI 6). Since the early 1990s, the model estimates a strong increase in the catchability from the Philippines and Indonesian domestic fisheries (PHID MISC 3 and PH HL 3). There is limited effort data for the PHID MISC 3 fishery and the model assumes catches are proportional to effort throughout the history of the fishery. During a period of declining stock biomass, the model has attempted to account for the catches from the fisheries by increasing the catchability inversely proportion to the trend in exploitable biomass.

6.3.6 Tag-reporting rates

Estimated tag-reporting rates by fishery are shown in Figure 25. The estimates for the purse seine fisheries deviated from the mode of their prior distributions and reporting rates from the purse-seine fisheries in region 3 were estimated to be about 50% of the reporting rates from region 4. The estimates for the Philippine/Indonesia domestic fisheries are significantly below their prior mode, indicating that the model has used information contained in the data to estimate this reporting rate. The estimates for the longline fisheries are highly variable, ranging from near zero to the upper limit allowed (0.9). However, the estimated reporting rates from the longline fisheries are based on a very small number of tag recoveries and, consequently, the tagging data are not very informative.

6.4 Stock assessment results

6.4.1 Recruitment

The GLM-MFIX recruitment estimates (aggregated by year for ease of display) for each region and the WCPO are shown in Figure 26. Recruitment is highest in regions 1 and 3, although the estimated movement coefficients result in an immediate transfer of recruits from region 1 to region 3 (see Section 6.3.3). The regional estimates display large interannual variability and variation on longer time scales, particularly in region 3 where average recruitment during the 1980s and 1990s was substantially higher than in the preceding period. The recruitments from regions 1 and 3 strongly influence the trend in the aggregate WCPO recruitment estimates and overall recruitment from the mid 1970s to 2000 was considerably higher than during the 1960s and early 1970s.

The increase in recruitment estimates during the mid 1970s is consistent with the increase in CPUE from the equatorial longline fisheries (LL ALL 3 & 4) during that time (Figure 7), as well as the sustained increase in catches from the mid 1970s to 1990. The model also explains the high initial CPUE observed in a number of the main longline fisheries (LL ALL 4–6) by high estimates of recruitment during the early period (Figure 26).

A comparison of WCPO recruitment estimates for the various model options is provided in Figure 27. All analyses reveal the same trend in overall recruitment with recruitment declining from 1950 to 1970 and then increasing during the late 1970s to plateau at a higher level. The overall magnitude of recruitment varied between analyses; the analyses with natural mortality estimated (MEST) all have consistently higher recruitment than the fixed natural mortality models (MFI) and the models with incrementally increasing fishing power (FPOW) have substantially higher recruitment in the earlier period compared to the GLM standardised effort series. Conversely, the recruitment estimates from the models incorporating SHBS standardised longline effort have higher recruitment from the mid-1970s compared to the corresponding GLM models (Figure 27).

6.4.2 Biomass

Estimated biomass time-series for each region and for the WCPO are shown in Figure 28 for the GLM-MFIX analysis. The trends are variable between regions, reflecting the CPUE trends from the main longline fisheries (LL ALL 1–6) (Figure 29). Also, the model estimates of exploitable abundance show very similar scaling among regions as the CPUE data (Figure 30). This indicates that model estimates are consistent with the CPUE data in terms of both time-series and spatial variability. Overall, a higher proportion of the biomass is within region 3, although there has been a steady decline in this region throughout the model period. For regions 4–6, the biomass is estimated to have declined sharply in the early model period to a low level during the 1970s and then subsequently increased to a higher level during the 1980s and 1990s. These historical trends are an effect of long-term trends in recruitment rather than attributable to the impacts of fishing. Similarly, the biomass trends from regions 1 and 2 are consistent with the trends in longline CPUE (Figure 29) and are essentially driven by the estimated trends in recruitment.

The trend in biomass for the WCPO is largely driven by the biomass trend from region 3 (Figure 28). Biomass declines steadily during the early model period, remains relatively stable from the mid 1970s to mid 1990s, and then declines sharply (by about 50%) during the last decade.

The comparison of biomass trends for the five model options is shown in Figure 31. As with the recruitment estimates, the general trends in overall biomass were comparable between the five model options, although there was considerable difference in the magnitude of the biomass level. For each longline effort series, the total biomass is estimated to be higher from the models where natural mortality is estimated (MEST) compared to the fixed natural mortality schedule (MFI). The overall decline in total biomass is more pronounced for the effort series with incrementally increasing fishing power (FPOW) than for the GLM standardised effort series. The SHBS longline effort models reveal a higher biomass level during the 1990s, although the magnitude of the decline in biomass during the last decade is higher.

6.4.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase strongly throughout the time series, particularly during the last decade (Figure 32). There are differences among the analyses, with the highest recent exploitation rates evident in the GLM and FPOW model options. The fishing mortality rates on juvenile yellowfin are higher for the MFIX models compared to the models that estimate natural mortality (MEST).

Recent exploitation rates are highest on the youngest age class due to the impact of the PHID MISC 3 fishery (Figure 33). There is also a high exploitation rate on the older age classes (8–18 age classes), largely attributable to the equatorial purse-seine fisheries. Overall, there has been a substantial decline in the proportion of old (> age class 10) fish in the population since the mid 1970s (Figure 33).

6.4.4 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 34. It is immediately evident that the impact has been substantial in region 3 and significant impact has also occurred in region 4. Impacts are slight in the four sub-equatorial regions.

Overall, the impact of fishing has reduced the WCPO biomass to about 30% of unexploited levels (Figure 35), largely driven by the impact in regions 3 and 4. There was also a sharp increase in the level of impact from region 1 in recent years, largely due to the sharp decline in recruitment in the region while catches have not declined proportionally. In regions 5 and 6, the biomass has been reduced to about 75% and 85% of unexploited levels, respectively.

A comparison of relative impact of fishing on the entire WCPO biomass from the various model options is presented in Figure 36. Recent levels of fishery impact are slightly greater for the models with increasing fishing power (FPOW-), while impacts from the SHBS models are generally lower than for the GLM base-case. In all cases, the models with fixed natural mortality (MFIX) are slightly more pessimistic than the corresponding model with natural mortality estimated (MEST).

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 37 and Figure 38). 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 by far the greatest impact. The purse seine fishery (PS ASS 3 and PS UNS 3) had the greatest impact in the early to mid-1990s, but has since declined.

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

It is noteworthy that in both regions, the longline fishery has a relatively insignificant impact. 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 4%.

The overall fishery-specific impacts in the WCPO are broadly consistent with the proportional impacts within region 3; low impact from the longline fishery (4%), moderate impact from the purse-seine fisheries (18%), and highest (44%) and increasing impacts from the Philippines/Indonesian domestic fisheries.

6.4.5 Yield analysis

Symbols used in the following discussion are defined in Table 4. The yield analyses conducted in this assessment incorporate the SRR (Figure 39) into the equilibrium biomass and yield computations. The estimated steepness coefficient for the base-case is 0.93, close to the prior mode of 0.85.

Equilibrium yield and total biomass as functions of multiples of the 2001–2003 average fishing mortality-at-age are shown in Figure 40 for the six separate analyses. For the GLM-MFIX analysis, yield is maximized at $fmult = 0.8$ for a MSY of 65,600 t per quarter. This implies that the ratio $F_{current}/\tilde{F}_{MSY}$ is 1.22 (approximately $1/0.8$); i.e. current exploitation rates are considerably higher than the exploitation rates to produce the MSY . The equilibrium biomass at MSY is estimated at 759,700 t, approximately 37% of the equilibrium unexploited biomass (Table 5).

The yield and equilibrium biomass curves for the six analyses are shown in Figure 40. The analyses produced variable results, with the $fmult$ which maximised equilibrium yield varying between 0.4 and 1.0 (equivalent to $F_{current}/\tilde{F}_{MSY}$ ratios of 1.00–2.33).

The MSY estimates for these analyses range from about 52,300 t to 78,400 t per quarter (209,200 t to 313,400 t per year). These estimates of equilibrium yield are substantially less than recent catches, which have been of the order of 400,000–450,000 t annually. This apparent anomaly results because the equilibrium computations use equilibrium recruitment determined from the SRR fitted to all of the recruitment time series. This equilibrium recruitment is close to the average recruitment over the time series and is much lower than the estimated recruitment post-1993. When yield is computed using the average post-1993 recruitment rather than the equilibrium recruitment, we obtain a clearer picture of MSY under current recruitment conditions (Figure 41). For the base-case, yield estimates at current effort levels ($fmult = 1.0$) are considerably higher, approximately 300,000 t per year (compared to about 262,000 t per year). However, the yield estimates are still substantially lower than recent catches indicating catches have been sustained by the removal of the accumulated biomass, as is evident from the recent accelerated fishery impacts on the stock.

The SHBS- models are slightly more optimistic than the equivalent GLM models; yielding higher estimates of MSY and $F_{current}/\tilde{F}_{MSY} \approx 1.0$ (Figure 40). On the other hand, the models including incremental increases in fishing power (FPOW-) are much more pessimistic with considerably lower estimates of MSY and very high current exploitation rates ($F_{current}/\tilde{F}_{MSY}$ about 2.0). In fact, in the case of the FPOW-MEST model, current exploitation rates ($F_{current}$) are predicted to almost drive the stock to extinction under equilibrium conditions due to the implausibly low value of steepness estimated for the SRR (0.44) (see Figure 40). For this model, recent catches have only been sustained by recent recruitment being substantially higher than predicted from the SRR (Figure 41). For the FPOW-MEST model, the management quantities based on equilibrium measures should be discounted due to the very low value of estimated value of steepness for the SRR.

A number of quantities of potential management interest associated with the yield analyses are provided in Table 5. In the top half of the table, absolute quantities are provided, while the bottom half of the table contains ratios of various biomass and fishing mortality measures that might be useful for stock monitoring purposes. It is useful to distinguish three different types of ratio: (i) ratios comparing a measure for a particular time period with the corresponding equilibrium measure; (ii) ratios comparing two equilibrium measures (rows shaded grey); and (iii) ratios comparing two measures pertaining to the same time period (row shaded black). Several commonly used reference points, such as $B_{current}/\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ fall into the first category. These ratios are usually subject to greater variability than the second category of ratios because recruitment variability is present in the numerator but not in the denominator. Indeed, the range of values observed over the four analyses conducted in this assessment 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. In recent assessments, we compared likelihood profile-based estimates of the posterior probability distribution of $F_{current}/\tilde{F}_{MSY}$ with the normal approximation based on the Hessian-Delta method, and found that the normal approximation could under-estimate the probability of higher values of the ratio. We have continued the likelihood profile approach in this assessment, applying it to both $F_{current}/\tilde{F}_{MSY}$ and $B_{current}/\tilde{B}_{MSY}$ for the GLM-MFIX analysis (Figure 42). The likelihood profile distributions reveal that there is a high certainty that $F_{current}/\tilde{F}_{MSY}$ is well above 1.0 and close to the point estimate (1.22) from the model (Figure 42), while the probability that $B_{current}/\tilde{B}_{MSY}$ is less than 1.0 is close to zero (Figure 43).

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 substantial changes, notably:

- The regional structure of the model was changed to form two separate regions in the northern assessment area, thereby creating a sixth model region. There were also other alterations to the regional boundaries to better reflect the distribution of fishing effort and relative catch rates.
- In keeping with the new regional structure, there were considerable changes to the definitions of the various fisheries. These included the creation of separate fisheries for a number of the domestic longline fisheries, the rationalisation of the Philippines and Indonesian domestic fisheries, and the amalgamation of the purse-seine associated set-types in the two equatorial regions.
- Two principal longline effort series were considered this year; the general linear model standardized (GLM) and the statistical habitat based standardized (SHBS) effort time-series. The methodology for deriving the SHBS effort series was modified and the resulting region-specific indices were more similar to the GLM indices compared to previous year.
- The two techniques for standardising longline effort were also applied to determine the relative weightings of longline effort among regions. These weighting factors incorporated both the size of the region and the relative catch rate to estimate the relative level of exploitable longline biomass between regions. The weighting factors were used to scale the longline effort series and, thereby, trends in longline CPUE among regions were comparable indicators of absolute biomass. This was a substantial difference from last year's assessment which scaled the regional biomass by a series of region area sizes that were determined from a qualitative assessment of the distribution of longline fishing in each region. The impact of this change resulted in an increase in the proportion of the biomass in the equatorial regions and a decline in biomass in the northern and southern regions. This is likely to represent the most substantial change in the assessment from 2004.
- The GLM index resulted in a substantially better overall fit to the various sources of data and prior information than the SHBS index and was designated the base-case assessment. In addition, as a sensitivity analysis, an incremental annual increase in fishing effective fishing effort was applied to the GLM longline effort series (1% per annum) and the purse-seine effort (4% per annum) to mimic incremental increases in fishing efficiency over the history of the fishery;
- The impact of fixing the age-specific natural mortality was investigated and compared to estimating a single age-invariant value for natural mortality (MEST vs MFIX);

- The inclusion of recent catch, effort, and size frequency data from most fisheries as well as the inclusion of a significant time-series of length frequency data (and some effort data) from the Philippines domestic fisheries; and
- Further technical improvements were made to the MULTIFAN-CL software, including a more parsimonious parameterisation of selectivity and inclusion of the SRR in the computation of unexploited biomass and fishery impacts.

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

- There is a poor fit to the length frequency data for those fisheries where weight frequency data, which are well fitted, are also available. This apparent conflict between the two sources of data was evident in the previous assessment, but not to the extent observed in the current analysis – the difference between the two assessments is related to the different weighting factors applied to the two sets of size frequency data. The systematic lack of fit may indicate that the generic factor applied to convert processed weights to whole weights may be inappropriate for some fisheries, particularly the Japanese longline fleet that provides most of the weight frequency data. Alternatively, the deterministic length-weight relationship used in the model may be inappropriate for yellowfin in some or all model regions, particularly in the equatorial regions where the discrepancy between the two data sets is greatest. This issue needs to be addressed prior to the next assessment.
- Residuals in the tag return data for the Australian longline fishery suggested that yellowfin tuna may have patterns of residency that cannot be captured by the spatial resolution of this model. However, the excess in observed tag returns over those predicted was relatively minor in this case.

While not a failure of the model *per se*, the model did have some difficulty in interpreting the very strong declines in longline CPUE in regions 5 and 6 during the early 1950s. The model attempted to explain these CPUE trends by estimating very high initial recruitments in those regions. The effect was not as marked as in the previous assessment due to the exclusion of data from the exploratory period of the fishery (1950–51) when CPUE was exceptionally high in all regions except the northern area of the fishery (see Hampton et al 2004). 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 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.

Several alternative analyses have been presented in order to assess the impact on stock assessment results of (i) using different methods of longline effort standardisation (SHBS, GLM, and incremental increases in fishing power) and (ii) using estimated (MEST) versus assumed (MFI) natural mortality-at-age. Overall, the SBHS analyses were slightly more optimistic than the GLM-based analyses, with higher recruitment, lower current fishing mortality, and higher current and equilibrium biomass. The models incorporating an incremental increase in fishing power (FPOW) were more pessimistic than the corresponding GLM models, with higher levels of stock depletion and lower yield estimates, although the levels of current biomass and exploitation rates were comparable. Most of the increased decline in longline CPUE in the early years (imposed by the increase in longline fishing power) was explained by higher earlier recruitment compared to the other models. This trend

in recruitment also explains the lower values of stock-recruitment steepness for the FPOW model options, which in turn resulted in lower estimates of equilibrium yield and MSY.

The impact of estimated versus fixed natural mortality on the assessments varied. For the GLM and FPOW models, the MFIX versions produced somewhat more optimistic results, while the reverse was true for the SHBS models.

It is difficult to directly compare the results of the individual models with previous assessments (Hampton and Kleiber 2003, Hampton et al. 2004) due to the substantial changes in the structural assumptions of the model for this year's assessment (see above). The most influential change in the current assessment is likely to be the differences in the relative weightings applied to the different model regions, essentially down-weighting the proportion of the total longline exploitable biomass in the non-equatorial regions. For region 3, recent exploitation rates and levels of fishery impact were similar between the current and previous assessments. However, because the current assessment assumes that this region accounts for a much larger proportion of the total stock biomass, current exploitation rates and overall impacts on the WCPO stock are predicted to be substantially higher than previous assessments (depletion to 40–46% of unexploited biomass in the current GLM-based assessments compared to 51–60% in the equivalent 2004 assessments). Other key performance indicators for the stock are also considerably more pessimistic than last year – current stock size is lower ($B_{current} / \tilde{B}_{MSY}$ of 1.75–1.80 for the 2004 GLM-based assessment compared to 1.16–1.32 for the current assessment) and fishing mortality is higher ($F_{current} / \tilde{F}_{MSY}$ 0.83–1.11 for the 2004 GLM-based assessment compared to 1.22–1.35 for the current assessment). While some of these differences are due to changes in the assessment method, in particular that relating to the scaling of relative abundance among regions, the differences are also due in part to advancing the time window used to define “current” from 1999–2001 in the 2004 assessment to 2001–2003 in the current assessment and the increase in fishing mortality estimated to have occurred between these two periods.

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 1960s and early-1970s. Recruitment subsequently increased during the late-1970s and remained relatively high during the 1980s and 1990s. This is similar to the pattern obtained in previous assessments and is largely attributable to the trends in the principal longline CPUE indices, particularly from regions 3 and 4.
2. For all analyses, the trends in biomass were 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 1960s and early-1970s, before increasing in the mid-1970s. Biomass levels remained relatively stable during the 1980s. For all model options, biomass is predicted to have declined sharply since 1990, largely due to the decline in the biomass within region 3 but also evident in most other regions.
3. The FPOW analyses are an attempt to account for systematic trends in increasing fishing efficiency over the history of the fishery — trends that are not already captured in the standardisation of longline CPUE data. Undoubtedly, such increases in fishing efficiency have occurred, although it is very difficult to quantify these effects and even a small annual incremental increase, such as applied to the longline fishery, has a very large effect on fishing power when applied over the complete history of the fishery; i.e. the 1% annual increase represents a 67% increase in effective fishing power over the history of the fishery. The model explained this increased efficiency largely through a substantial increase in recruitment during the earlier period of the fishery, and correspondingly higher initial biomass levels. Consequently, compared to the corresponding GLM models, current biomass is substantially lower than initial biomass. However, this resulted in temporal trends in both recruitment and spawning biomass that in turn resulted in low estimated SRR steepness. In fact, the FPOW-MEST model predicts that under equilibrium conditions, spawning biomass is driven to almost nil at current levels of exploitation. Consequently, while the FPOW models may provide a useful comparison of current vs. historical

stock size the resulting management quantities based on equilibrium measures may not be realistic.

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 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 for the first time. 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.
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 recent level of 30% of unexploited biomass (a fishery impact of 70%) in 2004. This represents a high level of stock-wide depletion that is close to or exceeds the equivalent equilibrium-based limit reference point ($\tilde{B}_{MSY}/\tilde{B}_0 = 0.37-0.41$). Further, depletion is somewhat greater for some individual model regions, notably in the equatorial regions 3 and 4 where recent depletion levels are approximately 0.2 and 0.3, respectively. Other regions are less depleted, with indices of 0.8 or greater for most other regions. If stock-wide over-fishing criteria were applied at the level of our model regions, we would conclude that regions 3 and 4 are over-exploited and the remaining regions are under-exploited.
6. The attribution of depletion to various fisheries or groups of fisheries indicates that the Indonesian fishery has the greatest impact, particularly in its home region (3) and is contributing significantly to the impact in adjacent regions 1, 4 and 5. The purse seine fishery also has high impact in regions 3 and 4 and accounts for a significant component of the impact in region 1. It is notable that the composite longline fishery is responsible for biomass depletion of about 5% in the WCPO during recent years, although higher longline impacts are evident in regions 4 and 5.
7. The reference points that predict the status of the stock under equilibrium conditions are $\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$ (0.69–1.00) and $S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$ (0.62–1.00), which indicate that the long-term average biomass would approximate or fall substantially below that capable of producing *MSY* at 2001–2003 average fishing mortality. Overall, current biomass exceeds the biomass yielding *MSY* ($B_{current}/\tilde{B}_{MSY} > 1.0$) due to sustained high recent recruitment. It is also important to note that the definition of $F_{current}$ is derived from a period when exploitation rates were rapidly increasing and choosing a more recent period (for example, 2003 only) would result in a more pessimistic interpretation of the stock status.
8. In conclusion, the estimate of $F_{current}/\tilde{F}_{MSY}$ reveals that overfishing of yellowfin is now likely to be occurring in the WCPO. While the stock is not yet in an overfished state ($B_{current}/\tilde{B}_{MSY} > 1$), further biomass decline is likely to occur at 2001–2003 levels of fishing mortality.

8 Acknowledgements

We are grateful to all fisheries agencies who have contributed data to the SPC for this assessment. We also acknowledge the assistance of Peter Williams for their assistance in data compilation.

9 References

- Bigelow, K. A., Langley, A.D. and Patterson, T. 2004. Relative abundance indices of the Japanese longline fishery for bigeye and yellowfin tuna in the western and central Pacific Ocean. WP SA-7, SCTB 17, Majuro, Marshall Islands, 9–18 August 2004.
- Bigelow, K. A., Maunder, M., and Hinton, M. 2003. Comparison of deterministic and statistical habitat-based models to estimate effective longline effort and standardized CPUE for bigeye and yellowfin tuna. WP RG-3, SCTB 16, Mooloolaba, Australia, 9–16 July 2003.
- Fournier, D.A., Hampton, J., and Sibert, J.R. 1998. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, *Thunnus alalunga*. *Can. J. Fish. Aquat. Sci.* **55**: 2105–2116.
- Francis, R.I.C.C. 1992. Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. *Can. J. Fish. Aquat. Sci.* **49**: 922–930.
- Hampton, J. 1997. Estimates of tag-reporting and tag-shedding rates in a large-scale tuna tagging experiment in the western tropical Pacific Ocean. *Fish. Bull. U.S.* **95**:68–79.
- Hampton, J. 2000. Natural mortality rates in tropical tunas: size really does matter. *Can. J. Fish. Aquat. Sci.* **57**: 1002–1010.
- Hampton, J., and Fournier, D.A. 2001. A spatially-disaggregated, length-based, age-structured population model of yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean. *Mar. Freshw. Res.* **52**:937–963.
- Hampton, J., Kleiber, P. 2003. Stock assessment of yellowfin tuna in the western and central Pacific Ocean. WP YFT-1, SCTB 16, Mooloolaba, Australia, 9–16 July 2003.
- Hampton, J., Kleiber, P., Langley, A., Hiramatsu, M. 2004. Stock assessment of yellowfin tuna in the western and central Pacific Ocean. WP SA-1, SCTB 17, Majuro, Republic of Marshall Islands, 9–18 August 2004.
- Hampton, J., Kleiber, P., Takeuchi, Y., Kurota, H., and Maunder, M. 2003. Stock assessment of bigeye tuna in the western and central Pacific Ocean, with comparisons to the entire Pacific Ocean. WP BET-1, SCTB 16, Mooloolaba, Australia, 9–16 July 2003.
- Itano, D.G. 2000. The reproductive biology of yellowfin tuna (*Thunnus albacares*) in Hawaiian waters and the western tropical Pacific Ocean: project summary. SOEST 00-01 JIMAR Contribution 00-328. Pelagic Fisheries Research Program, JIMAR, University of Hawaii.
- Kaltongga, B. 1998. Regional Tuna Tagging Project: data summary. Technical Report No. 35, (Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia.) 70 pp.
- Kleiber, P., Hampton, J., and Fournier, D.A. 2003. MULTIFAN-CL Users' Guide. <http://www.multifan-cl.org/userguide.pdf>.
- Labelle, M. 2004. Testing the accuracy of MULTIFAN-CL assessments of the western and central Pacific Ocean yellowfin tuna (*Thunnus albacares*) fisheries. *Fish. Res.* Submitted.
- Langley, A. 2003. Standardised analysis of yellowfin and bigeye CPUE data from the Japanese longline fleet, 1952–2001. WP RG-2, SCTB 16, Mooloolaba, Australia, 9–16 July 2003.
- Langley, A., Bigelow, K., Maunder, M. and Miyabe, N. 2005. Longline CPUE indices for bigeye and yellowfin in the Pacific Ocean using GLM and statistical habitat standardisation methods. WP SA-8, WCPFC-SC1, Noumea, New Caledonia, 8–19 August 2005.
- Lehodey, P. 2005. Application of SEAPODYM to the Pacific pelagic ecosystem: recent results and perspectives. WP EB-8, WCPFC-SC1, Noumea, New Caledonia, 8–19 August 2005.

- Lehodey, P. and B. Leroy. 1999. Age and growth of yellowfin tuna (*Thunnus albacares*) from the western and central Pacific Ocean as indicated by daily growth increments and tagging data. WP YFT-2, SCTB 12, Papeete, French Polynesia, 16–23 June 1999.
- Maunder, M. N. 2005. The influence of new biological parameters on the bigeye tuna assessment. Document SAR-6-07b SUP, Inter-American Tropical Tuna Commission, Working Group on Stock Assessment, 6th Meeting, 2–6 May 2005, La Jolla, California.
- Maunder, M.N., and Harley, S.J. 2003. Methodological improvements to the EPO tuna stock assessments. WP MWG-3, SCTB 16, Mooloolaba, Australia, 9–16 July 2003.
- Maunder, M.N., and Harley, S.J. 2004. Status of yellowfin tuna in the eastern Pacific Ocean in 2003 and outlook for 2004. Working Paper SAR-5-05-YFT. Inter-American Tropical Tuna Commission Working Group on Stock Assessments, 5th Meeting, La Jolla, California, 11–13 May 2004.
- Maunder, M.N., and Watters, G.M. 2001. A-SCALA: An age-structured statistical catch-at-length analysis for assessing tuna stocks in the eastern Pacific Ocean. Background Paper A24, 2nd meeting of the Scientific Working Group, Inter-American Tropical Tuna Commission, 30 April – 4 May 2001, La Jolla, California.
- McAllister, M.K., and Ianelli, J.N. 1997. Bayesian stock assessment using catch-at-age data and the sampling – importance resampling algorithm. *Can. J. Fish. Aquat. Sci.* **54**: 284–300.
- Myers, R.A., and Worm, B. 2003. Rapid worldwide depletion of predatory fish communities. *Nature* **423**: 280–283.
- Ward, R.D., Elliott, N.G., and Grewe, P.M. 1994. Allozyme and mitochondrial DNA variation in yellowfin tuna (*Thunnus albacares*) from the Pacific Ocean. *Mar. Biol.* **118**: 531–39.

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

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

Table 2. Main structural assumptions of the yellowfin tuna base-case analysis (GLM-MFIX), 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 0.1 times the actual sample size for all fisheries with a maximum effective sample size of 100.	None	na	na	na	na	na
Observation model for tagging data	Tag numbers in a stratum have negative binomial probability distribution, with estimated variance parameters for fishery groups.	Variance parameters	3	-	-	0	100
Tag reporting	Purse seine reporting rates constrained to be equal within regions. PH /ID fishery reporting rates constrained to be equal. All reporting rates constant over time.	LL 1–LL6, CH/TW LL, PNG LL, PI LL	10	0.5	0.7	0.001	0.9
		AU LL, HW LL	3	0.8	0.7	0.001	0.9
		PS	2	0.45	0.05	0.001	0.9
		PH, ID fisheries	1	0.6	0.05	0.001	0.9
Tag mixing	Tags assumed to be randomly mixed at the model region level two quarters following the quarter of release.	None	na	na	na	na	
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)	212	SRR	0.7	-20	20
		Average spatial distribution of recruitment	5	-	-	0	1

		Time series deviations from average spatial distribution (ln)	1,054	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 natural mortality 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=0.00002784, b=2.8992 independently estimated from available length-weight data).	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. Various smoothing penalties applied. Coefficients for the last 4 age-classes are constrained to be equal. Longline selectivities are non-decreasing with increasing age. Longline fisheries L2-L5 share selectivity parameters.	Selectivity coefficients (5 cubic spline nodes per fishery)	95	-	-	0	1
Catchability	Constant over years and among regions for longline fisheries (effort data are scaled to reflect different region sizes). Seasonal variation for all fisheries apart from Philippines and Indonesian fisheries. Non-longline fisheries and the Australian and Taiwanese/Chinese longline fisheries have structural time-series variation, with random steps (catchability deviations) taken every 2 years.	Average catchability coefficients (ln)	14	-	-	-15	1
		Seasonality amplitude (ln)	17	0	2.2	-	-
		Seasonality phase	17	-	-	-	-
		Catchability deviations PH/ID (ln)	34	0	0.1	-0.8	0.8
		Catchability deviations other (ln)	118	0	0.7	-0.8	0.8
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.22 (SD is 0.7 for Philippines and Indonesian fisheries with missing effort data) at the average level of effort for each fishery - SD inversely proportional to the square root of effort.	Effort deviations LL 1, 2, 4, 7, 10, 12 (ln)	1262	0	0.16	-6	6
		Effort deviations PH, ID (ln)	280	0	0.22	-6	6
		Effort deviations other (ln)	982	0	0.7	-6	6
Natural mortality	Age-dependent but constant over time and among regions.	Average natural mortality (ln)	0	-	-	-	-
		Age-specific deviations (ln)	0	0	0.22	-5	5
Movement	Age-dependent and varies 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

Table 3. Details of objective function components for the six analyses using alternative longline effort series (SHBS, GLM) and with either estimated (MEST) or fixed (MFI) natural mortality-at-age.

Objective function component	SHBS-MEST	SHBS-MFI	GLM-MEST	GLM-MFI	FPOW-MEST	FPOW-MFI
Total catch log-likelihood	482.15	492.65	479.87	482.06	473.43	478.74
Length frequency log-likelihood	-372,467.75	-372,409.94	-372,473.38	-372,407.30	-372,457.54	-372,378.13
Weight frequency log-likelihood	-478,730.10	-478,750.31	-478,739.59	-478,734.02	-478,754.24	-478,747.04
Tag log-likelihood	2,235.68	2,260.50	2,237.52	2,257.34	2,239.01	2,255.62
Penalties	7,597.29	7,689.49	6,041.84	6,119.09	5,998.10	6,081.66
Total function value	-840,882.73	-840,717.61	-842,453.74	-842,282.83	-842,501.24	-842,309.15

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

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2001–2003
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (<i>MSY</i>)
$\tilde{Y}_{F_{current}}$	Equilibrium yield at $F_{current}$
$\tilde{Y}_{F_{MSY}}$ (or <i>MSY</i>)	Equilibrium yield at F_{MSY} , or maximum sustainable yield
\tilde{B}_0	Equilibrium unexploited total biomass
$\tilde{B}_{F_{current}}$	Equilibrium total biomass at $F_{current}$
\tilde{B}_{MSY}	Equilibrium total biomass at <i>MSY</i>
\tilde{SB}_0	Equilibrium unexploited adult biomass
$\tilde{SB}_{F_{current}}$	Equilibrium adult biomass at $F_{current}$
\tilde{SB}_{MSY}	Equilibrium adult biomass at <i>MSY</i>
$B_{current}$	Average current (2001–2003) total biomass
$SB_{current}$	Average current (2001–2003) adult biomass
$B_{current, F=0}$	Average current (2001–2003) total biomass in the absence of fishing.

Table 5. Estimates of management quantities for the four analyses using alternative longline effort series. 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	SHBS-MEST	SHBS-MFIX	GLM-MEST	GLM-MFIX	FPOW-MEST	FPOW-MFIX
$\tilde{Y}_{F_{current}}$	t per quarter	78,360	71,130	61,110	64,350	479	38,900
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per quarter	78,360	71,130	65,420	65,600	52,330	59,080
\tilde{B}_0	t	2,537,000	2,348,000	2,193,000	2,042,000	2,667,000	2,384,000
$\tilde{B}_{F_{current}}$	t	1,050,000	810,000	699,200	610,000	5,491	360,100
\tilde{B}_{MSY}	t	1,050,000	810,000	1,013,000	759,700	1,340,000	1,036,000
$\tilde{S}\tilde{B}_0$	t	1,439,000	1,591,000	1,219,000	1,384,000	1,459,000	1,615,000
$\tilde{S}\tilde{B}_{F_{current}}$	t	441,200	406,100	268,500	284,400	4	166,300
$\tilde{S}\tilde{B}_{MSY}$	t	441,200	406,100	433,400	383,100	629,300	583,800
$B_{current}$	t	1,459,299	1,256,340	1,175,319	1,005,103	1,172,996	964,877
$SB_{current}$	t	624,213	651,878	477,325	507,286	472,742	484,065
$B_{current, F=0}$	t	2,828,036	2,873,374	2,569,589	2,526,359	3,364,924	2,963,254
$B_{current} / \tilde{B}_0$		0.58	0.54	0.54	0.49	0.44	0.40
$B_{current} / \tilde{B}_{F_{current}}$		1.39	1.55	1.68	1.65	213.62	2.68
$B_{current} / \tilde{B}_{MSY}$		1.39	1.55	1.16	1.32	0.88	0.93
$B_{current} / B_{current, F=0}$		0.52	0.44	0.46	0.40	0.35	0.33
$SB_{current} / \tilde{S}\tilde{B}_0$		0.43	0.41	0.39	0.37	0.32	0.30
$SB_{current} / \tilde{S}\tilde{B}_{F_{current}}$		1.41	1.61	1.78	1.78	121,060.67	2.91
$SB_{current} / \tilde{S}\tilde{B}_{MSY}$		1.41	1.61	1.10	1.32	0.75	0.83
$\tilde{B}_{F_{current}} / \tilde{B}_0$		0.41	0.34	0.32	0.30	0.00	0.15
$\tilde{S}\tilde{B}_{F_{current}} / \tilde{S}\tilde{B}_0$		0.31	0.26	0.22	0.21	0.00	0.10
$\tilde{B}_{MSY} / \tilde{B}_0$		0.41	0.34	0.46	0.37	0.50	0.43
$\tilde{S}\tilde{B}_{MSY} / \tilde{S}\tilde{B}_0$		0.31	0.26	0.36	0.28	0.43	0.36
$F_{current} / \tilde{F}_{MSY}$		1.00	1.02	1.35	1.22	2.33	1.89
$\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$		1.00	1.00	0.69	0.80	0.00	0.35
$\tilde{S}\tilde{B}_{F_{current}} / \tilde{S}\tilde{B}_{MSY}$		1.00	1.00	0.62	0.74	0.00	0.28
$\tilde{Y}_{F_{current}} / MSY$		1.00	1.00	0.93	0.98	0.01	0.66

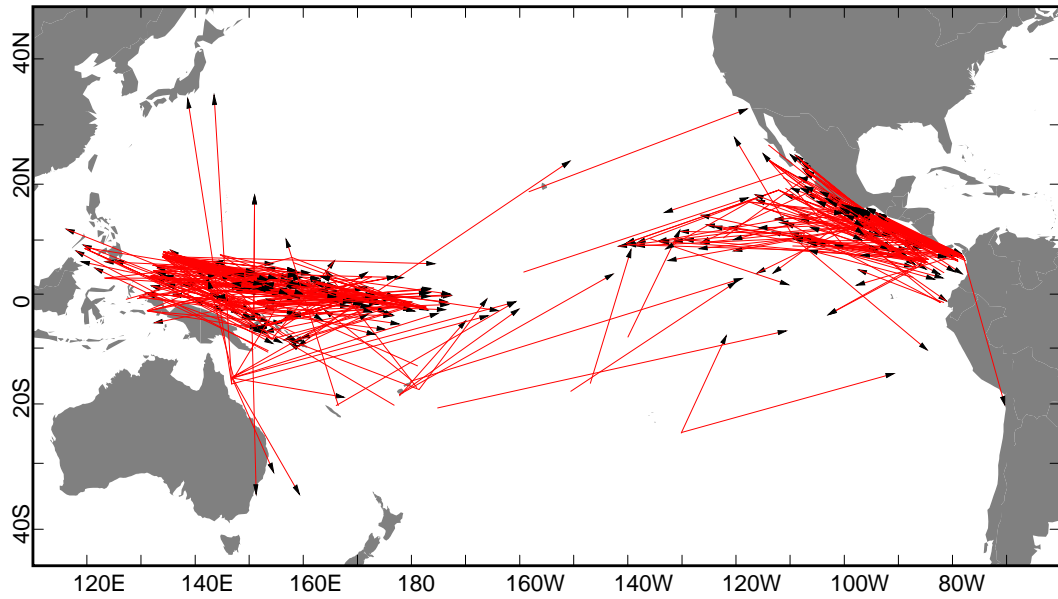


Figure 1. Long-distance (>1,000 nmi) movements of tagged yellowfin tuna.

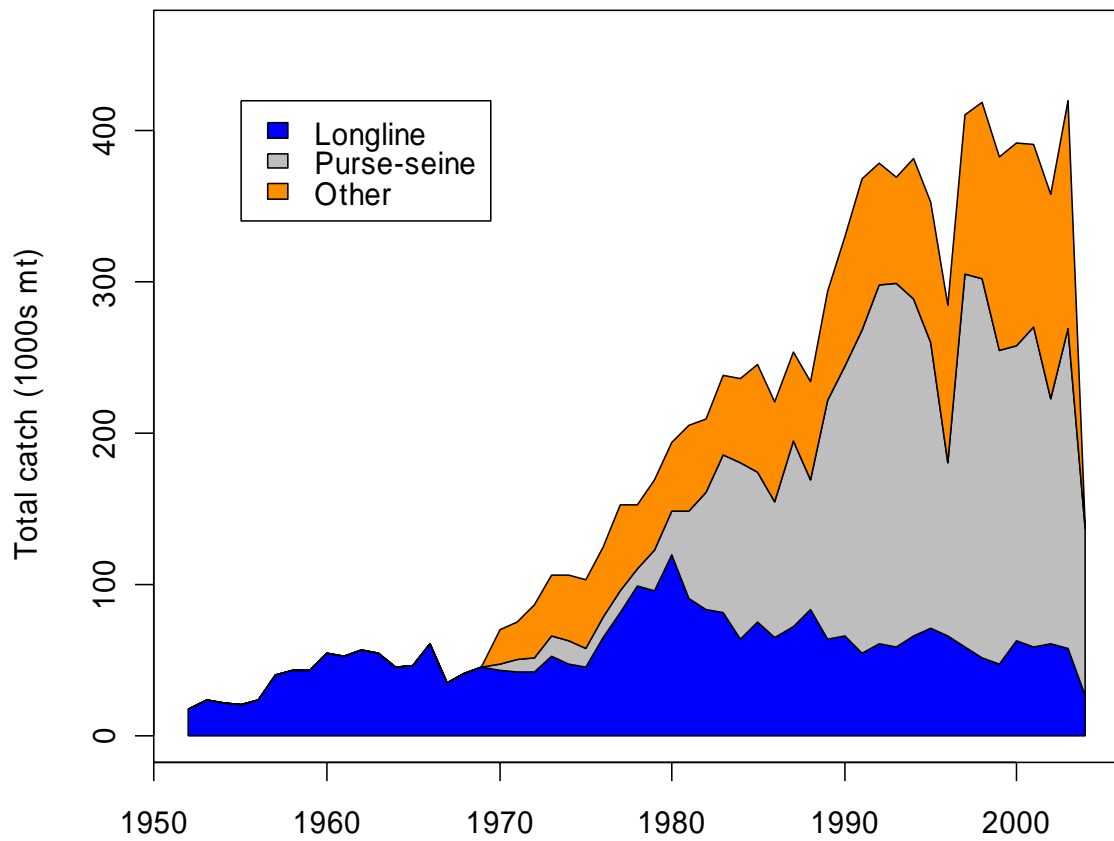


Figure 2. Total annual catch (1000s mt) of yellowfin from the WCPO by fishing method from 1952 to 2004. Data from 2004 are incomplete.

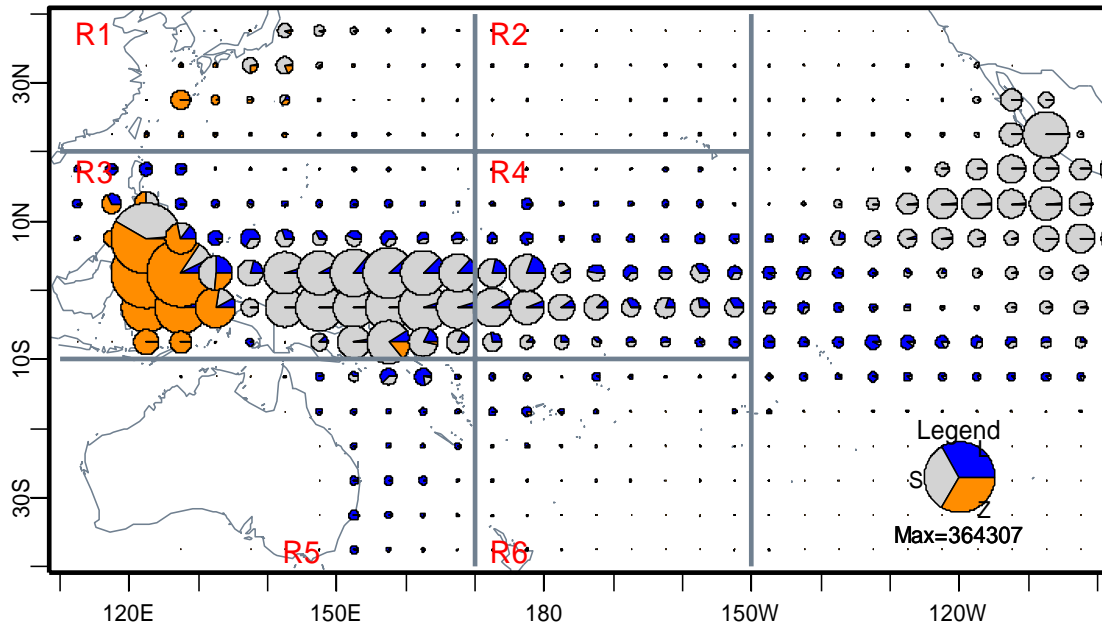


Figure 3. Distribution of cumulative yellowfin tuna catch from 1990–2004 by 5 degree squares of latitude and longitude and fishing gear; longline (L, blue), purse-seine (S, grey), and other (Z, dark orange). The grey lines indicate the spatial stratification used in the MULTIFAN-CL model.

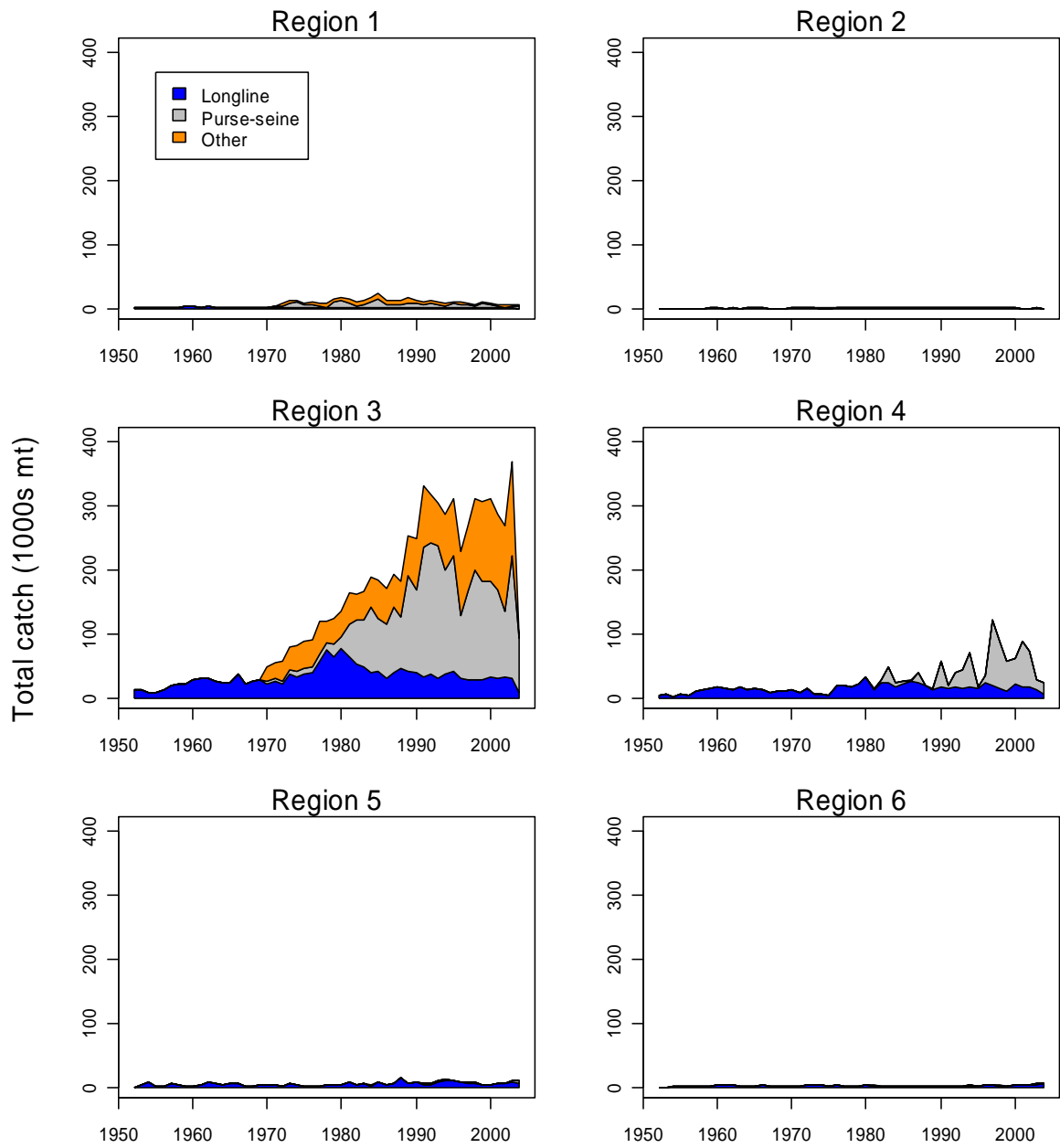


Figure 4. Total annual catch (1000s mt) of yellowfin by fishing method and MFCL region from 1952 to 2004. Data from 2004 are incomplete.

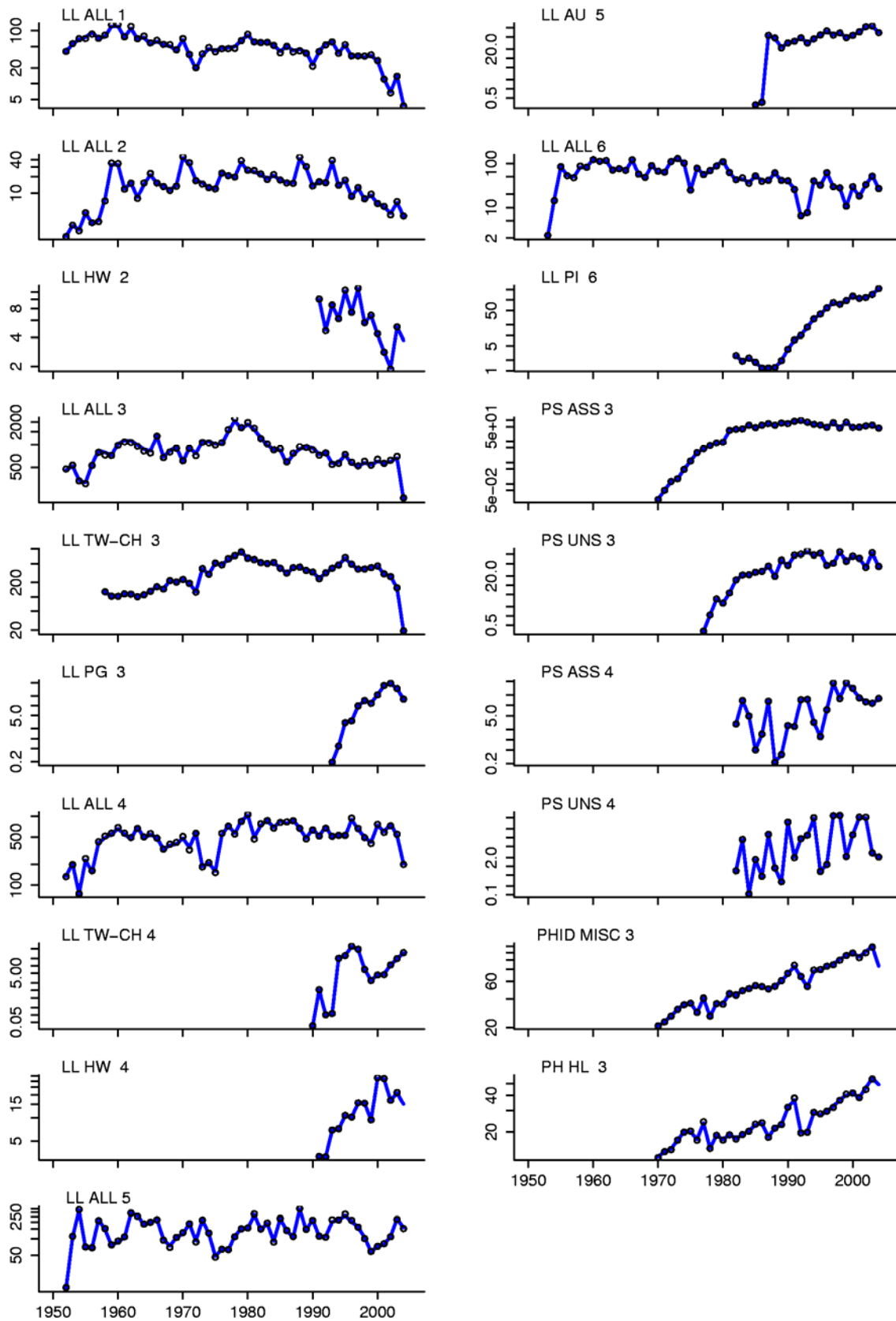


Figure 5. Annual catches, by fishery. Circles are observed and the lines are model predictions. Units are catch number in thousands for the longline fisheries and thousand metric tonnes for all other fisheries.

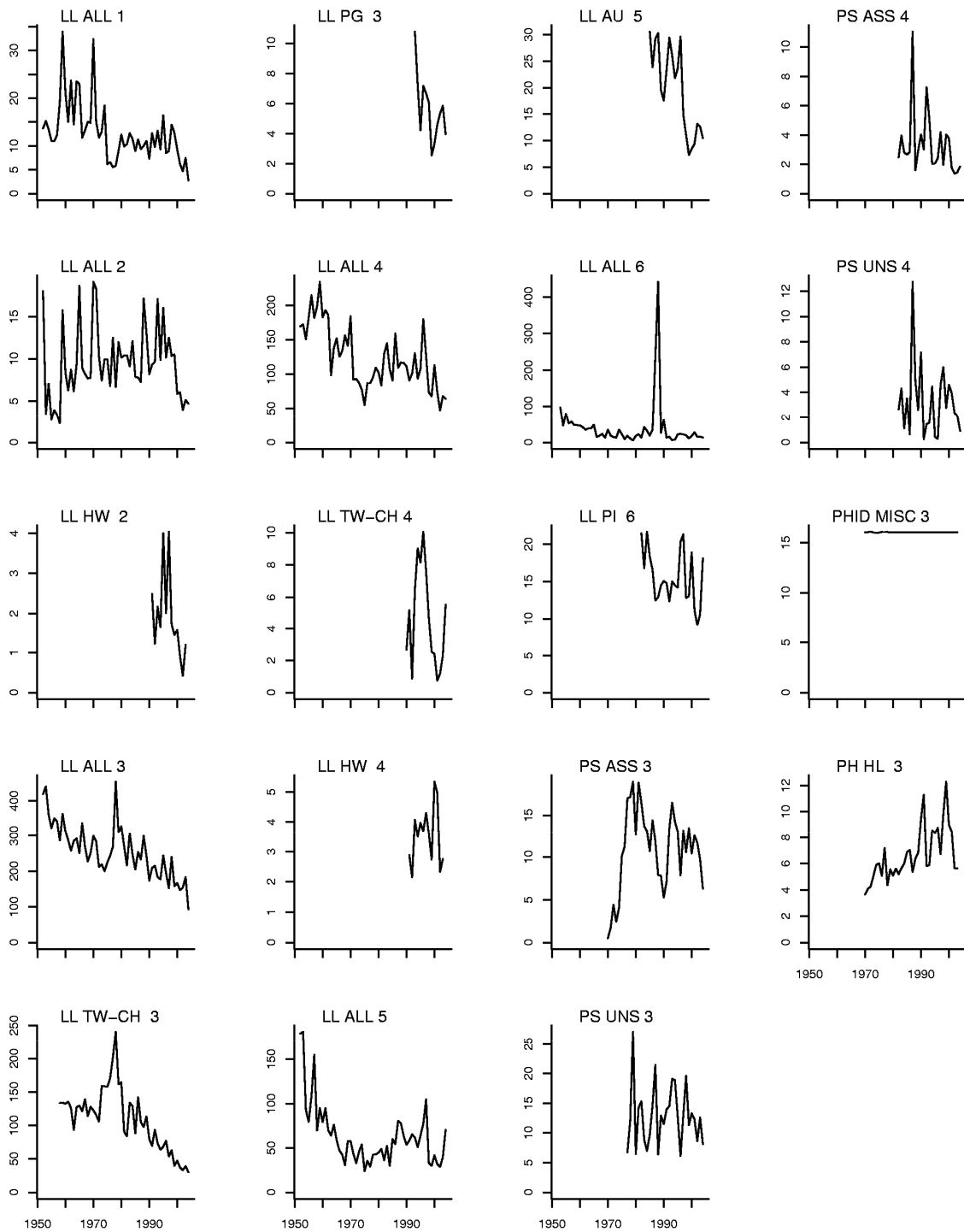


Figure 6. Catch-per-unit-effort (CPUE) by fishery. Units are catch number per GLM-standardised effort (fisheries LL ALL 1–LL ALL 6), catch number per 100 nominal hooks (LL HW, CH/TW LL, LL PI, LL PG) and catch (t) per day fished/searched (all PS fisheries). Note that CPUE for PHID MISC 3 is arbitrary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

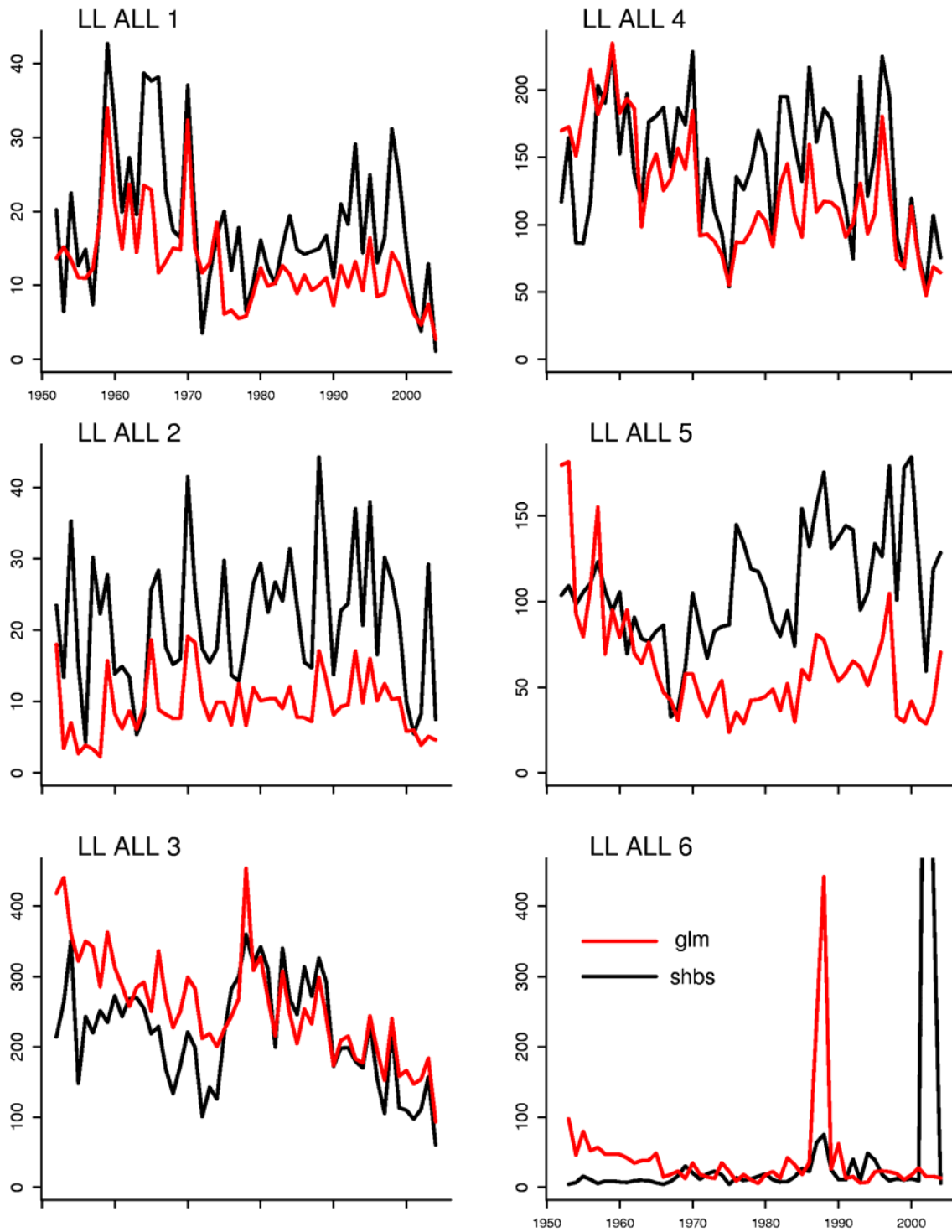


Figure 7. Catch-per-unit-effort (CPUE) for the longline fisheries LL ALL 1–6 standardised using two different methodologies (glm = general linear model; shbs = statistical habitat-based standardisation) and scaled by the respective region scalars.

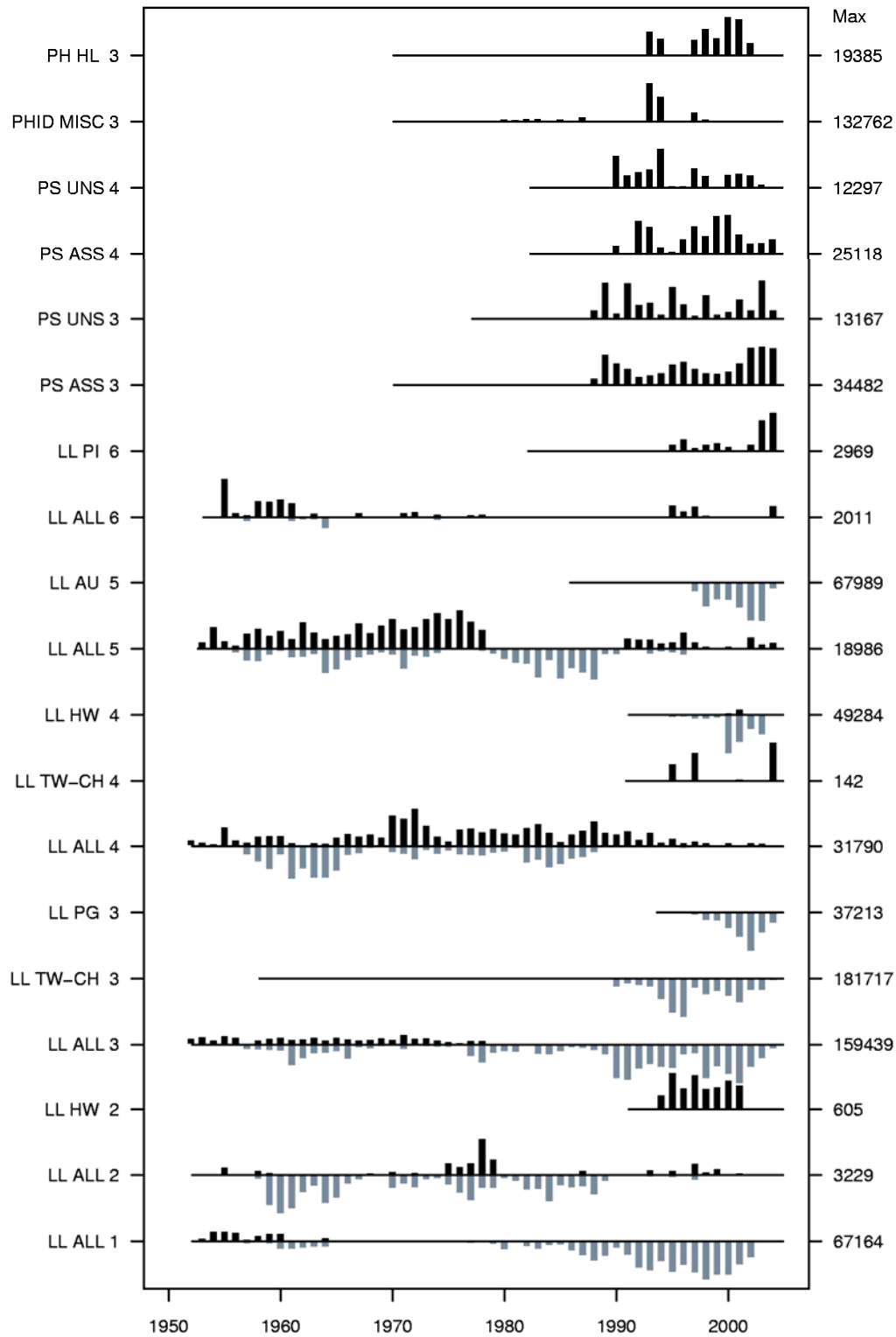


Figure 8. Number of fish size measurements by year for each fishery. The upper black bars represent length measurements and the lower grey bars represent weight measurements. The maximum bar length for each fishery is given on the right-hand side. The extent of the horizontal lines indicates the period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

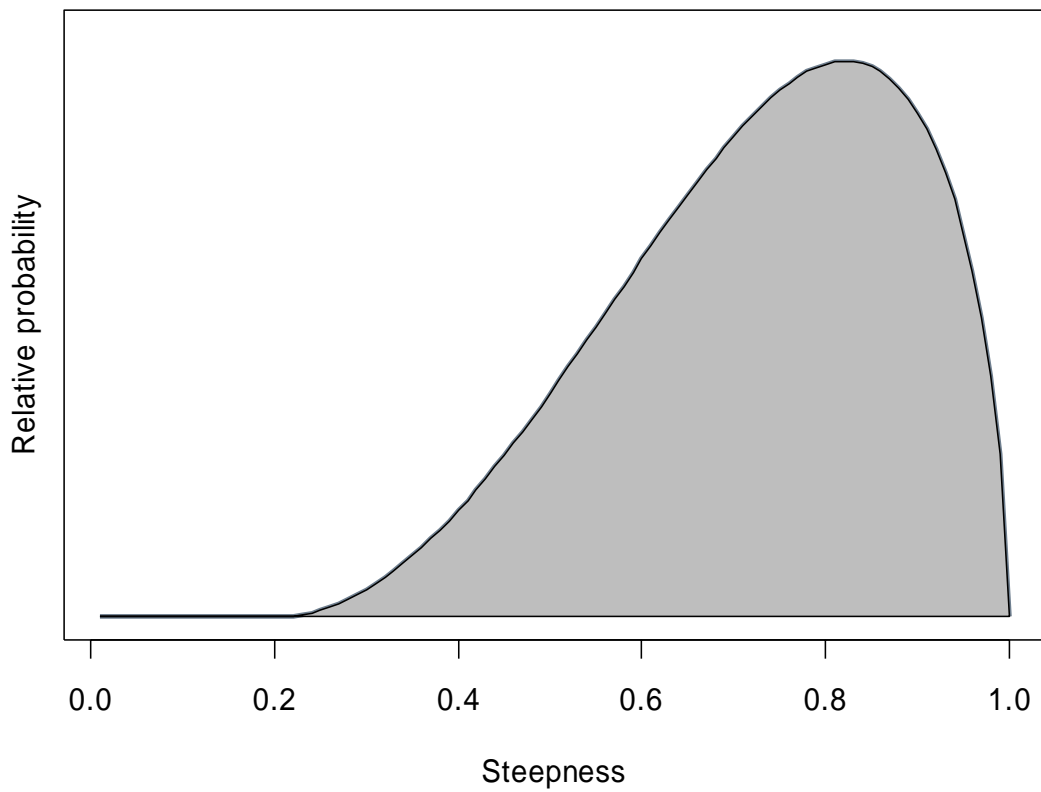


Figure 9. Prior for the steepness parameter of the relationship between spawning biomass and recruitment (SSR) (mode = 0.85, standard deviation = 0.16).

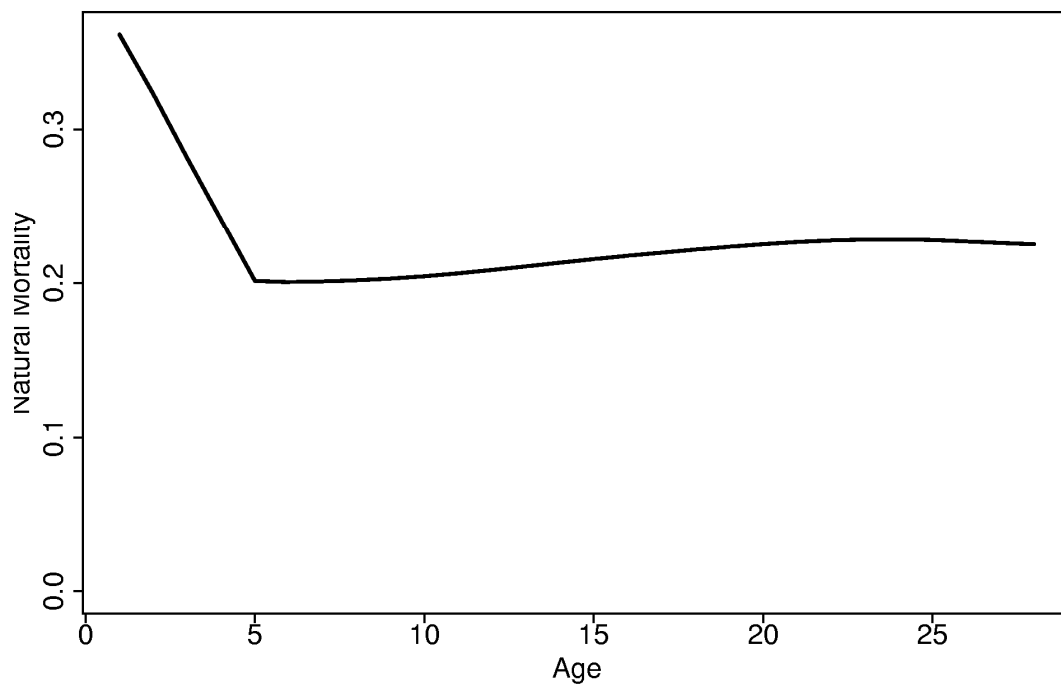


Figure 10. Age-specific natural mortality assumed for the sensitivity analyses using a fixed natural mortality (SHBS-Mest and GLM-Mest) from Maunder and Harley (2004).

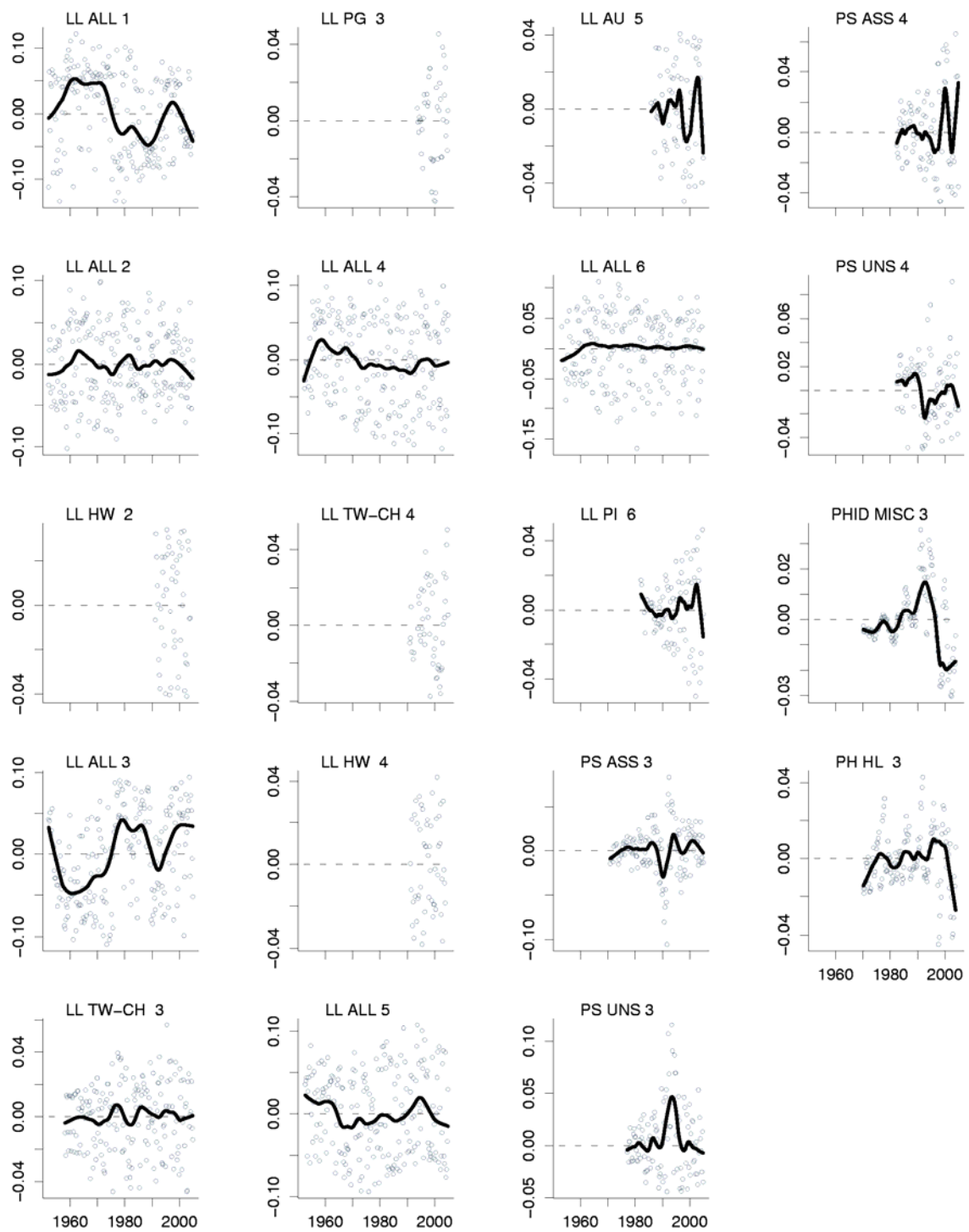


Figure 11. Residuals of \ln (total catch) for each fishery (GLM-MFIX model). The solid line represents a lowess fit to the data.

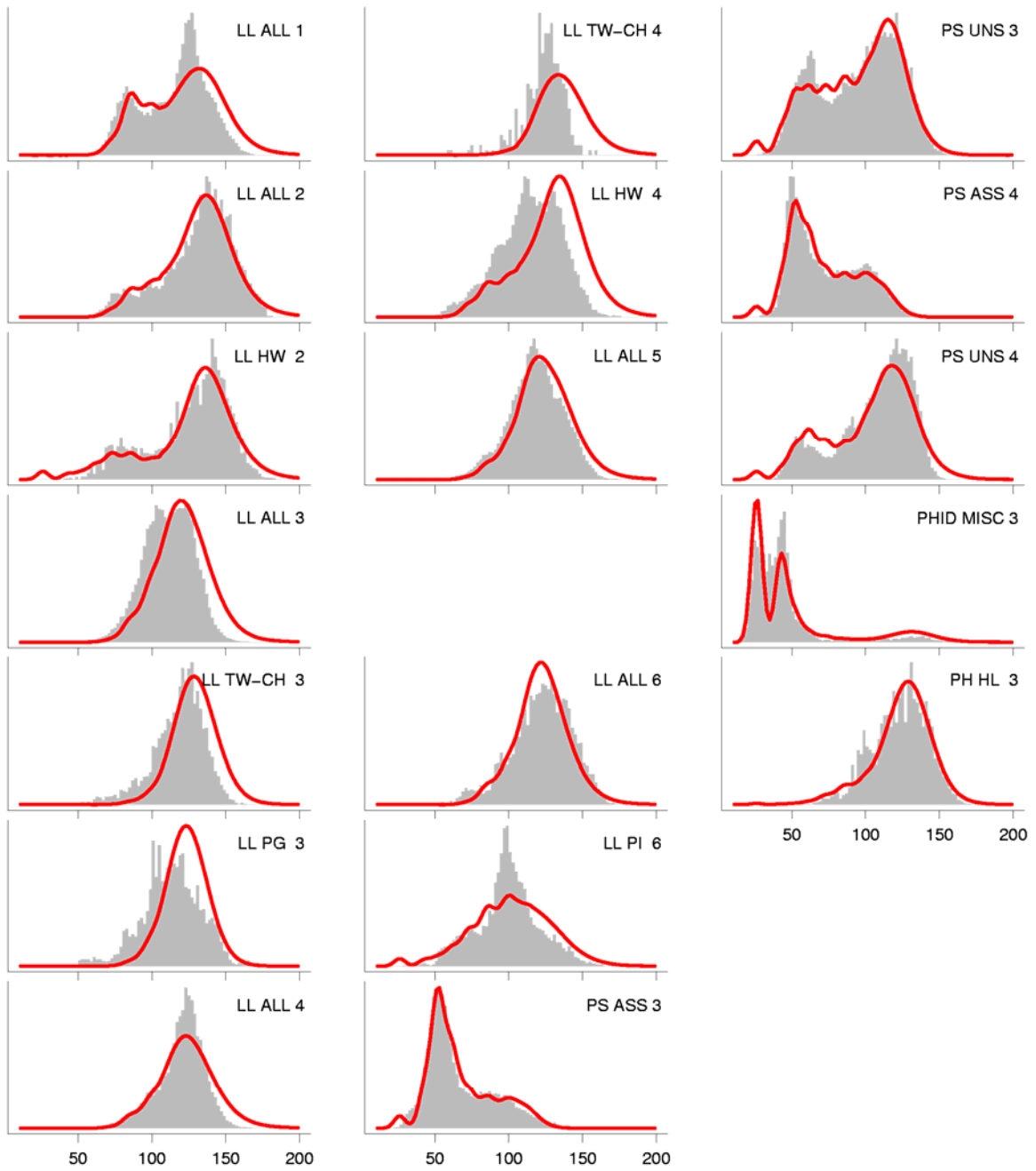


Figure 12. Observed (histograms) and predicted (line) length frequencies (in cm) for each fishery aggregated over time.

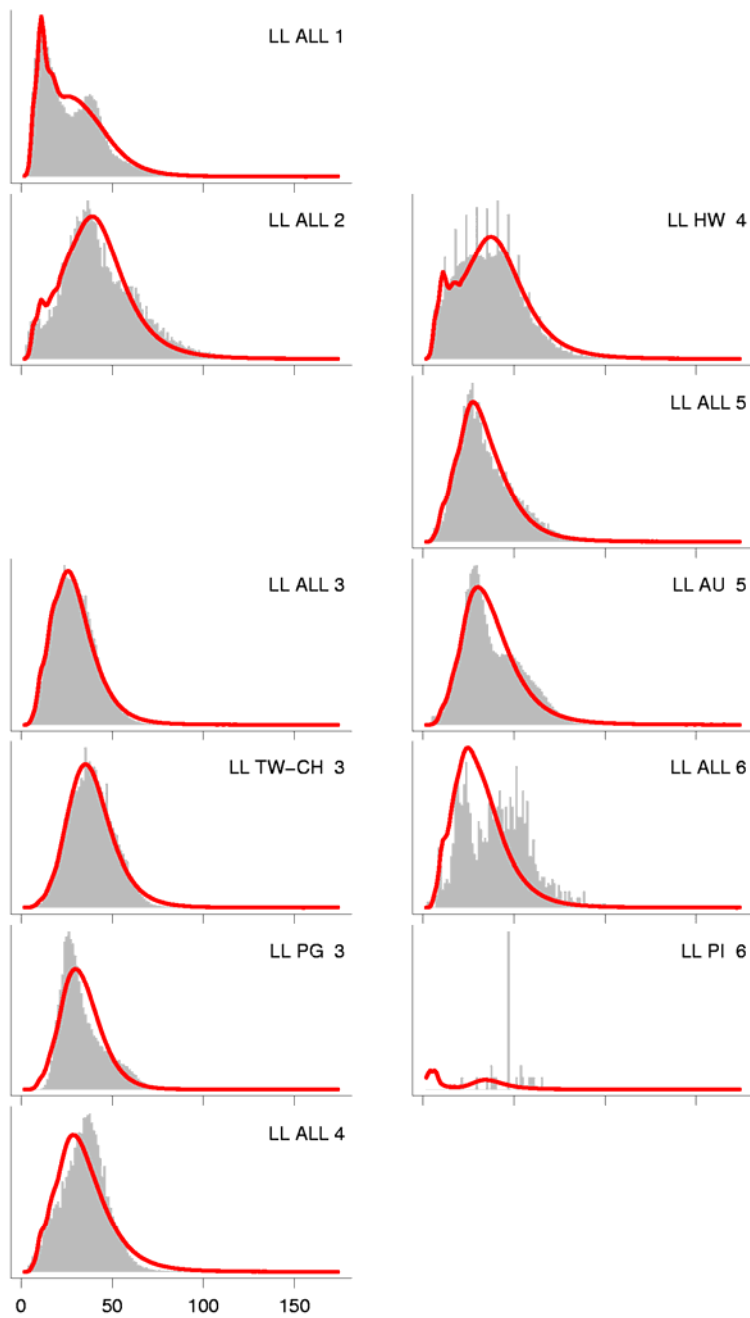


Figure 13. Observed (histograms) and predicted (line) weight frequencies (in kg) for each fishery aggregated over time (GLM-MFIX model).

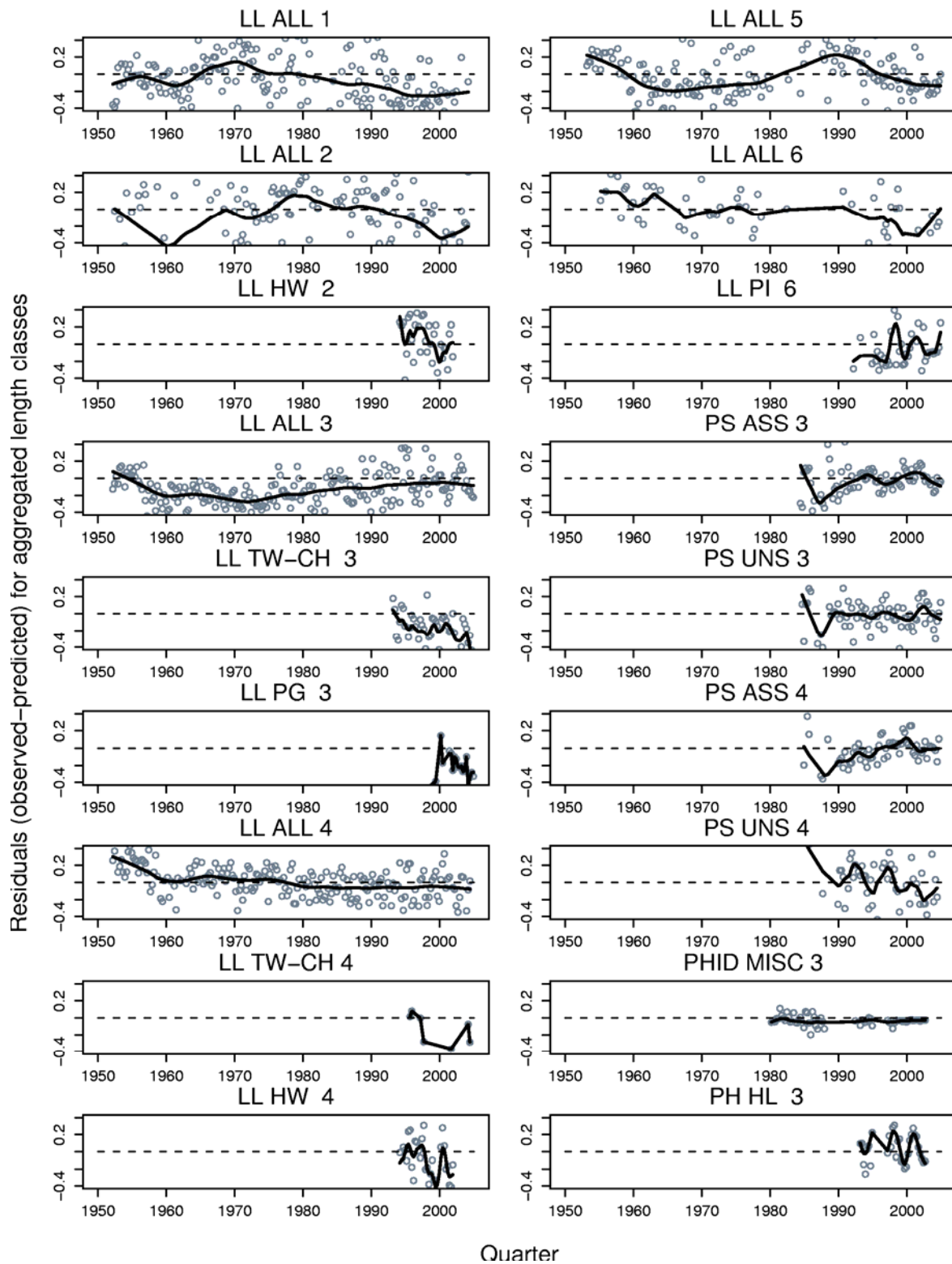


Figure 14. Residuals (observed – predicted) of the aggregated proportion of fish in the larger length classes from sampled and predicted catches by fishery and sample period. The aggregated length range is 125–170 cm for all the longline fisheries and 70–120 cm for all other fisheries. The line represents a lowess smoothed fit to the data.

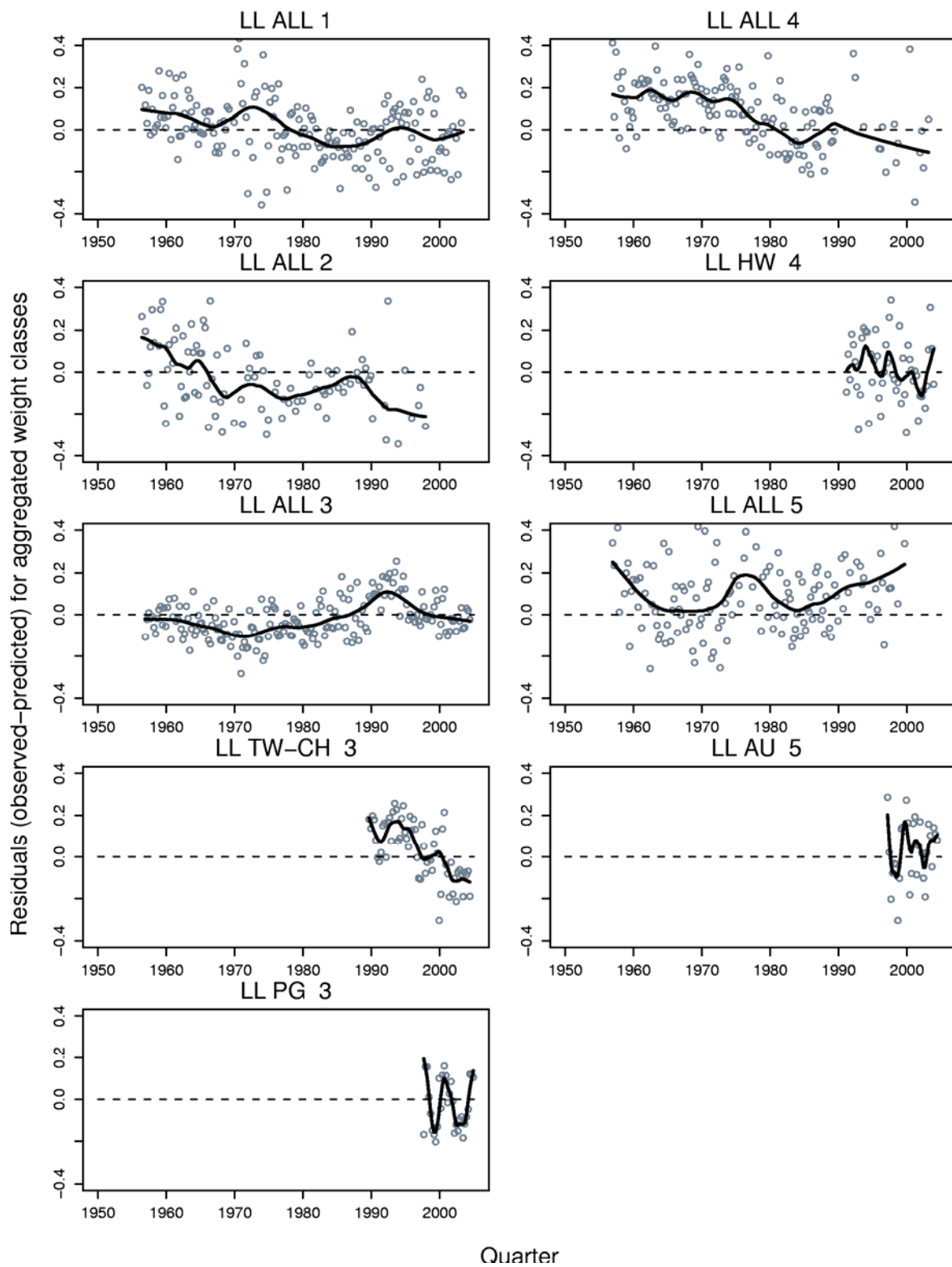


Figure 15. Residuals (observed - predicted) of the aggregated proportion of fish in the larger weight classes (35-70 kg) from sampled and predicted catches by fishery and sample period. The line represents a lowess smoothed fit to the data.

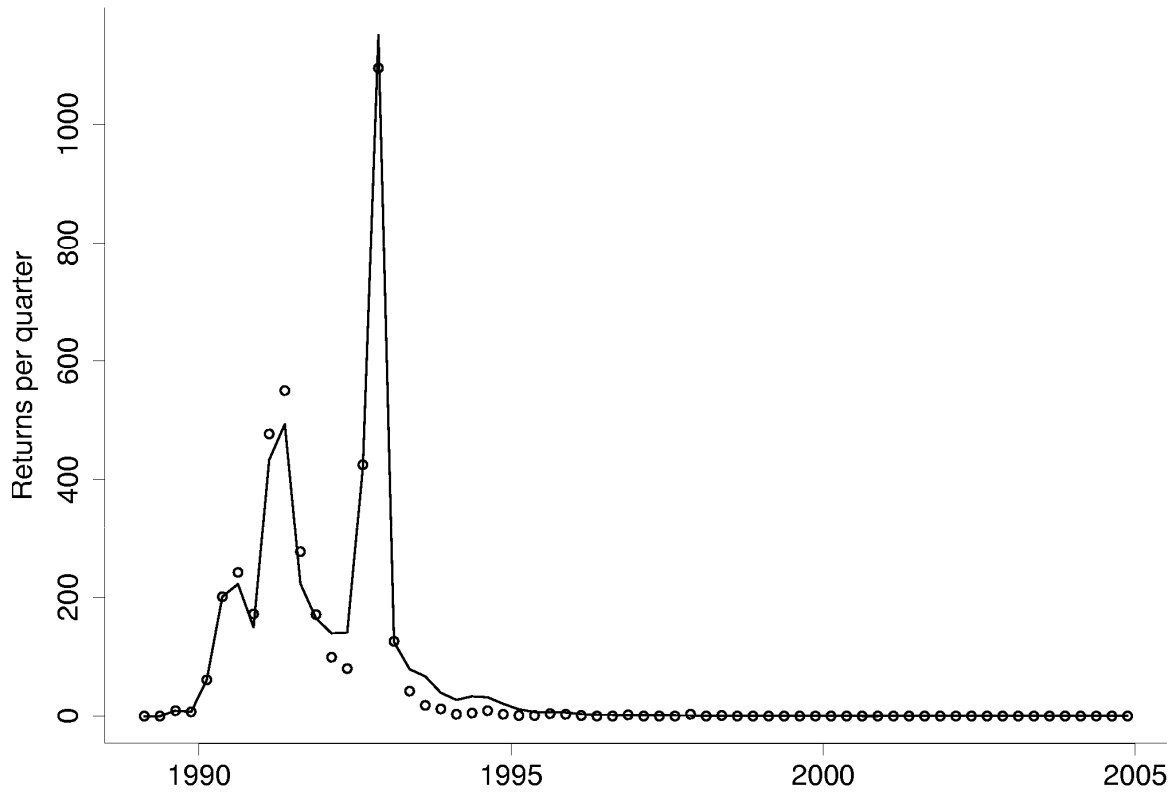


Figure 16. Number of observed (points) and predicted (line) tag returns by recapture period (quarter).

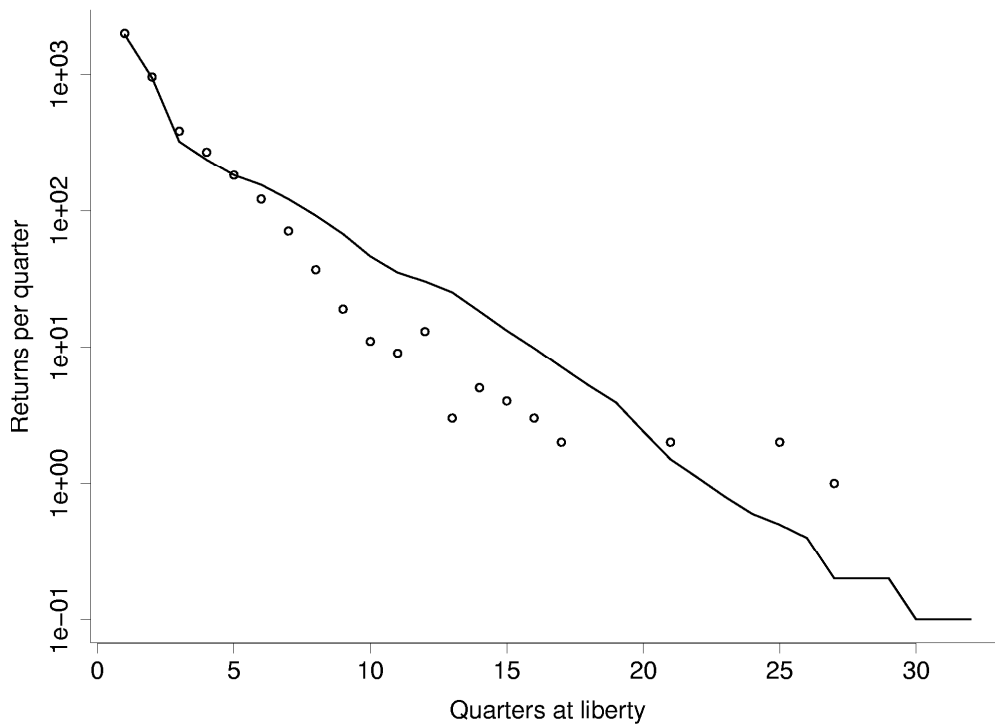


Figure 17. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters).

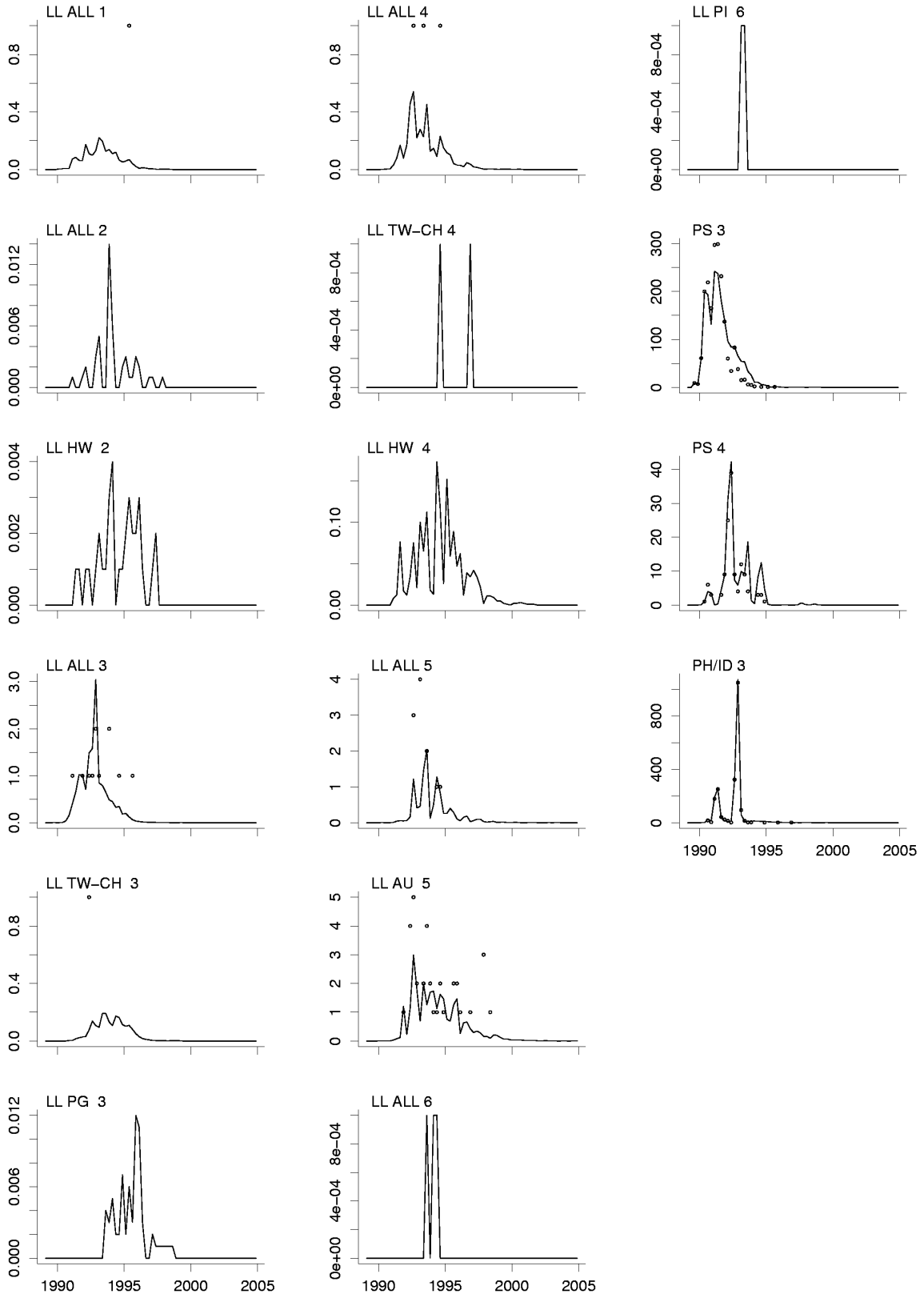


Figure 18. Number of observed (points) and predicted (line) tag returns by recapture period (quarter) for the various fisheries (or groups of fisheries) defined in the model. Only non-zero observations are plotted.

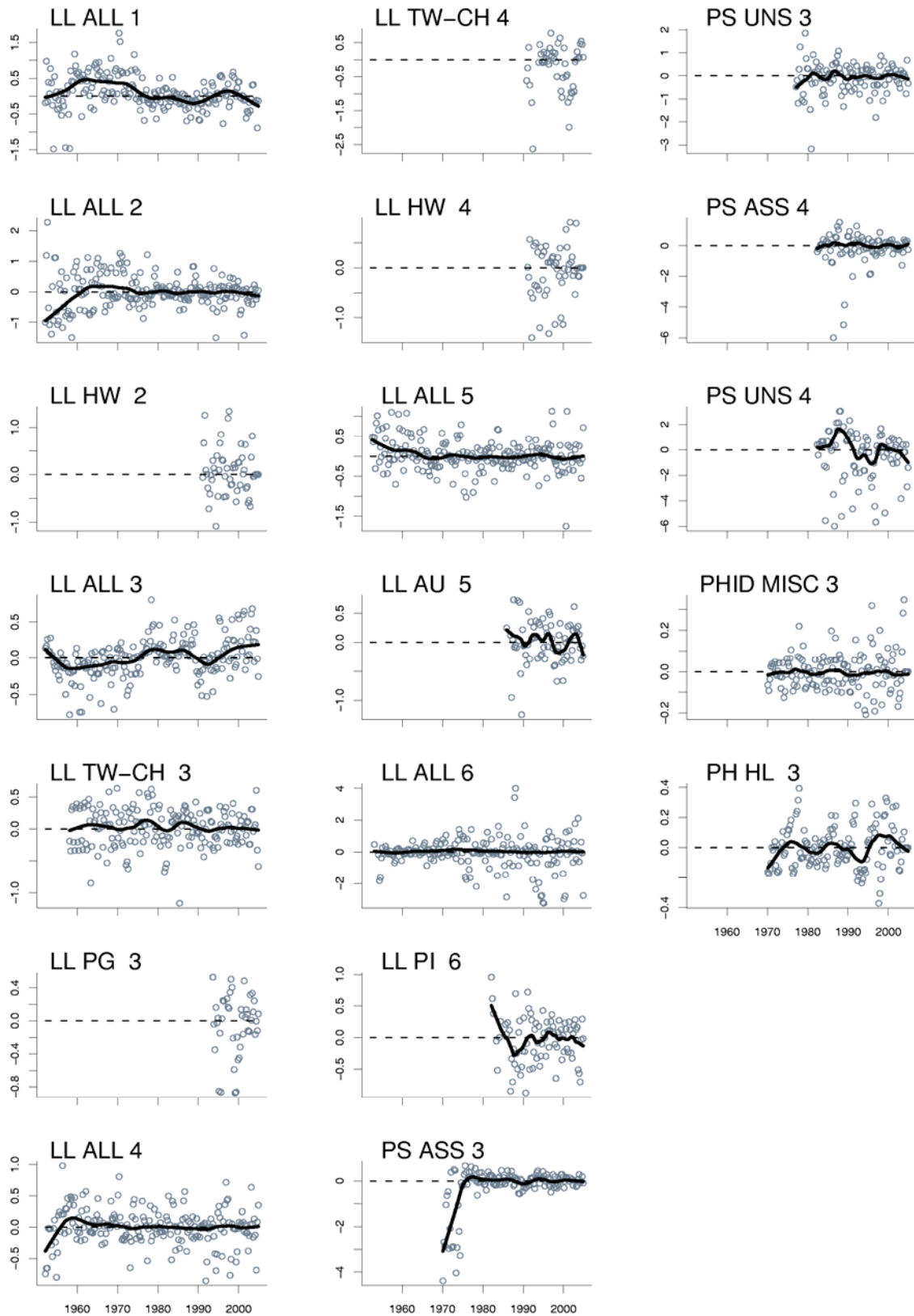


Figure 19. Effort deviations by time period for each fishery. The solid line represents a lowess fit to the data.

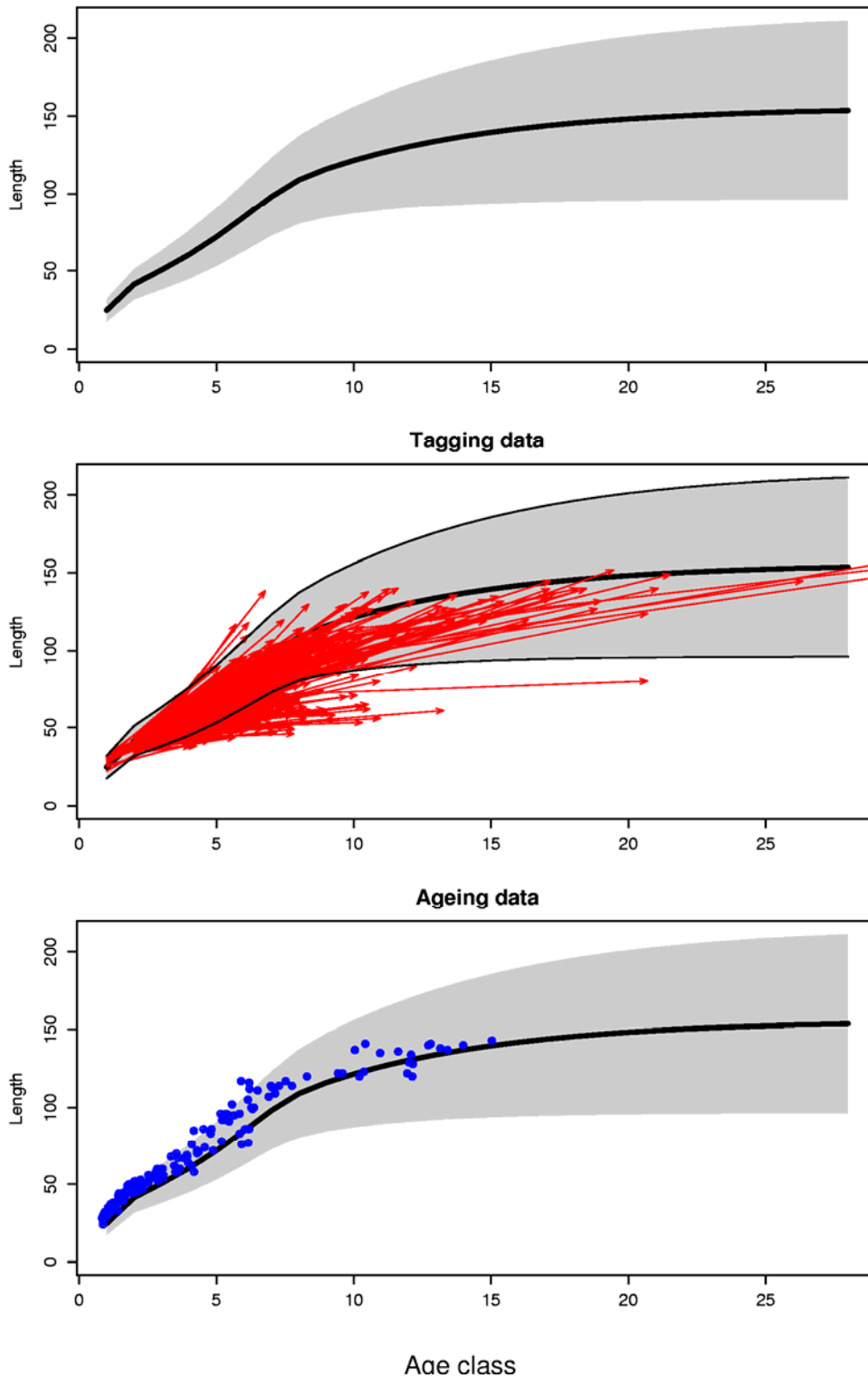


Figure 20. Estimated mean lengths-at-age (heavy line) and the variability of length-at-age (shaded area represents ± 2 SD). Age is in quarters and length is in cm (top figure). For comparison, length at age estimates are presented from tag release and recapture data (middle figure) and empirical age 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.

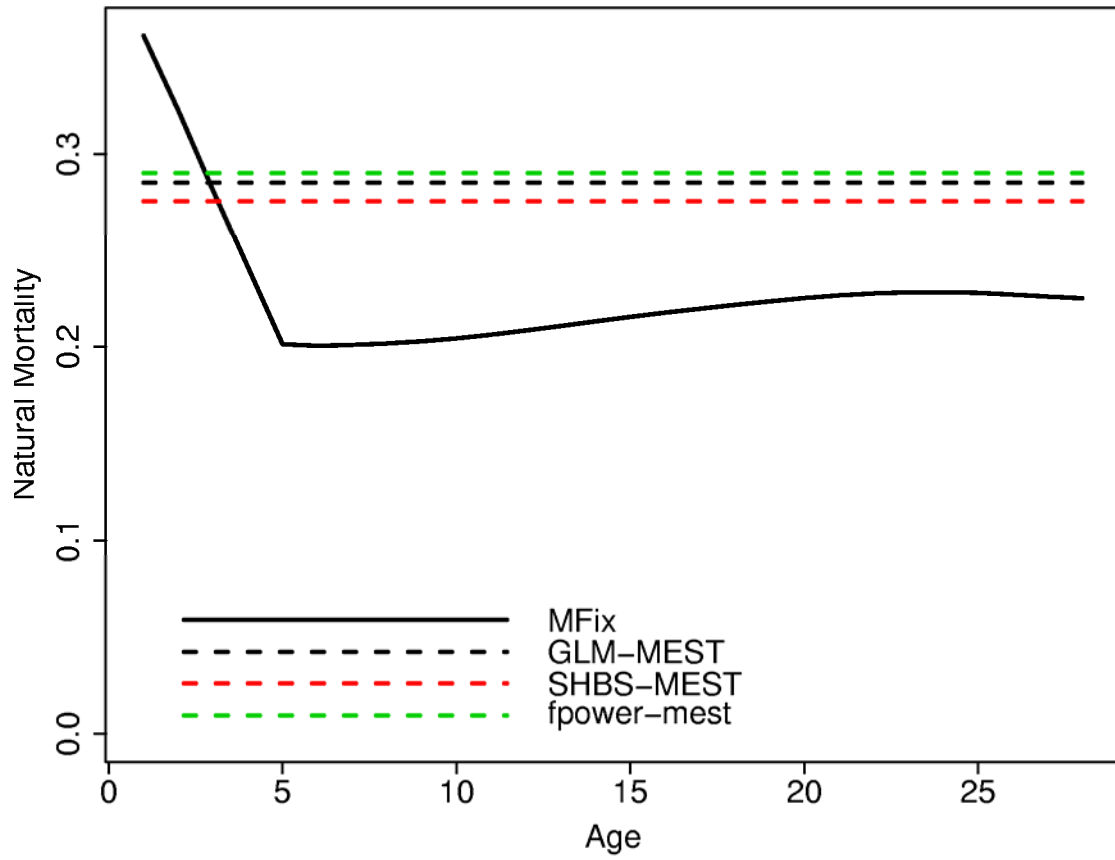


Figure 21. Natural mortality at age estimated externally to the MULTIFAN-CL model on the basis of biological data (Mfix) and the estimates of age-invariant natural mortality estimated within MULTIFAN-CL for the -MEST models.

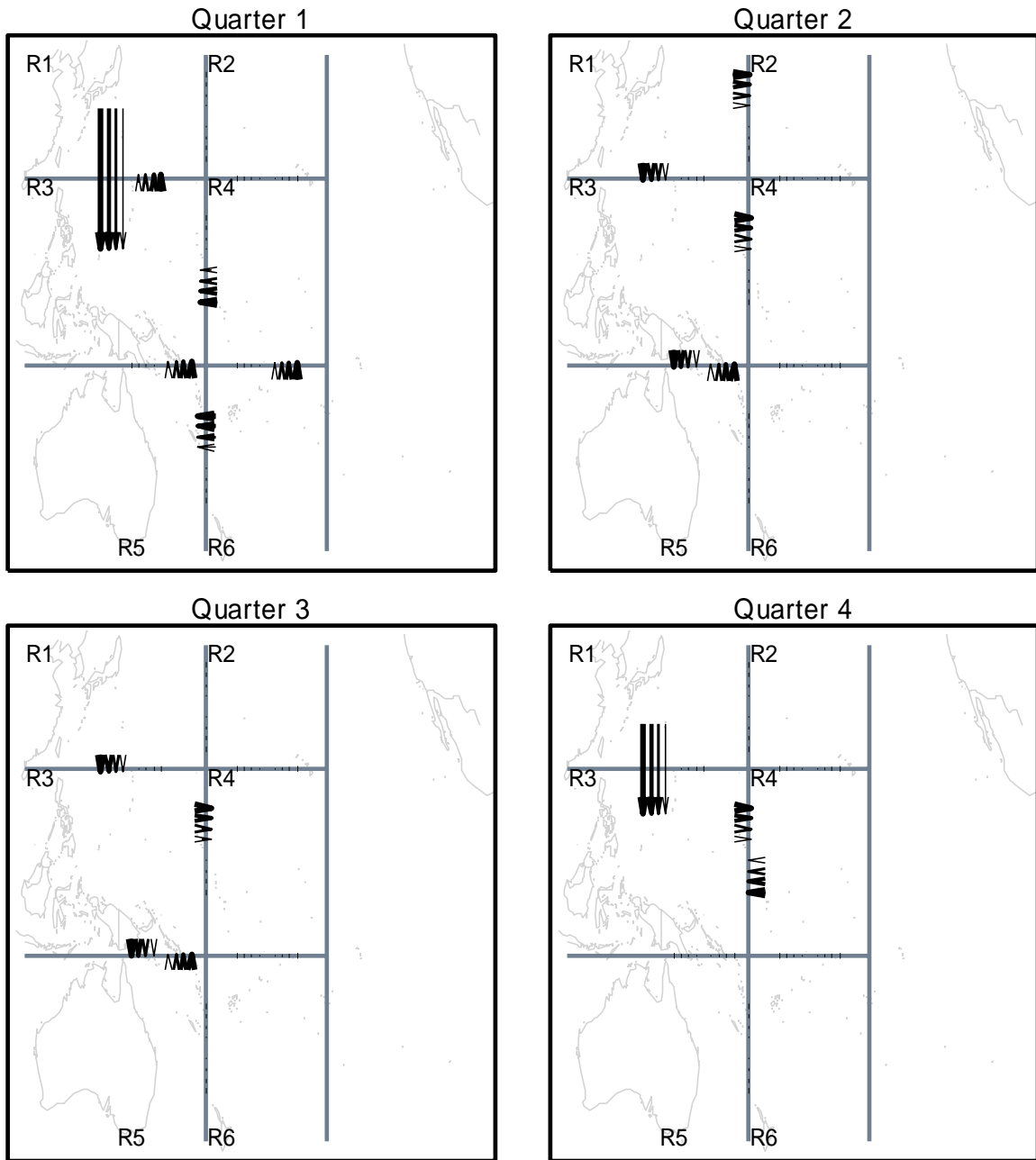


Figure 22. Estimated quarterly movement coefficients at age (1, 7, 15, 25 quarters) from the GLM-MFIX model. The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age. The maximum movement (quarter 1, region 1 to region 3) represents movement of 53% of the fish at the start of the quarter.

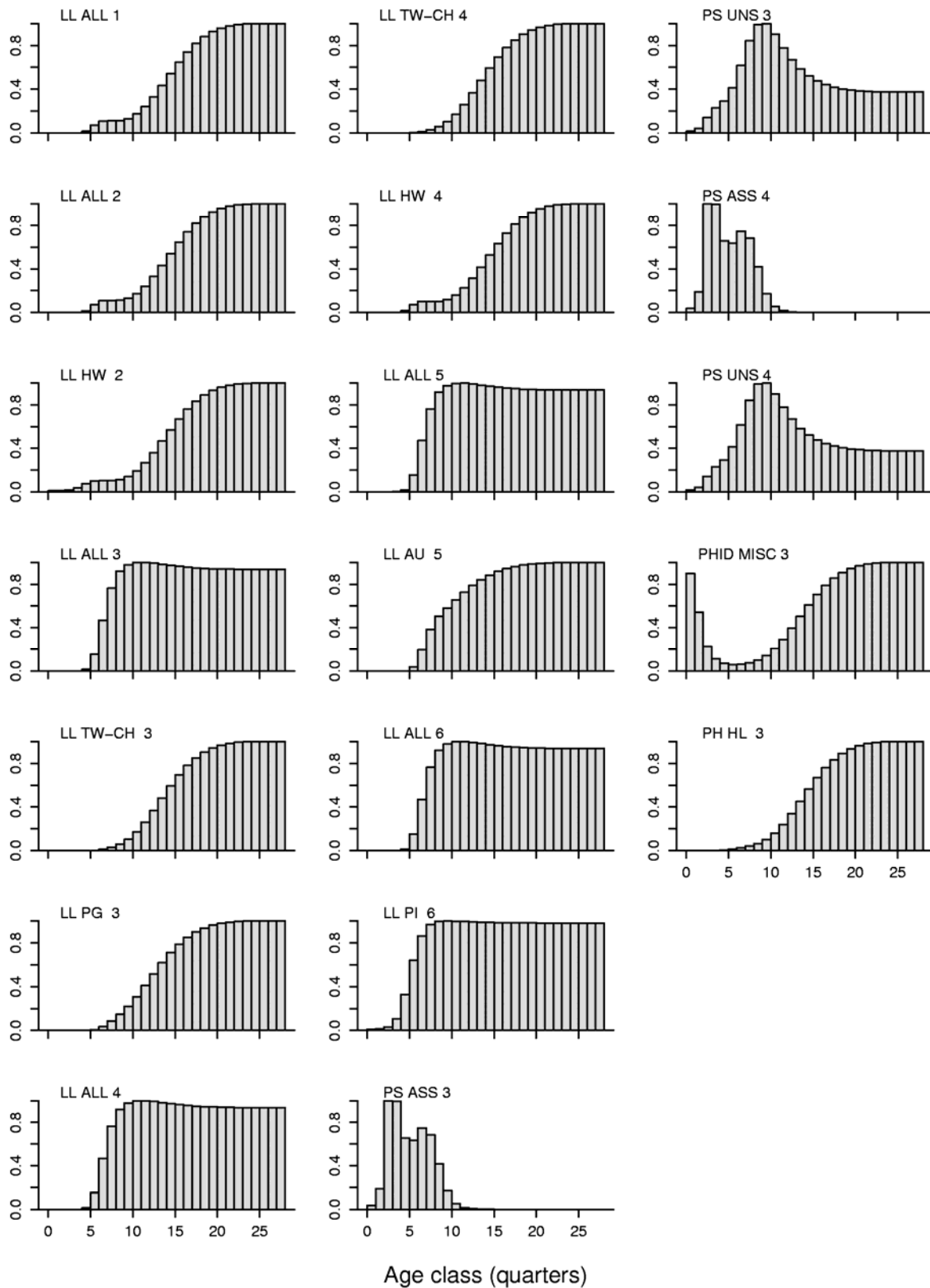


Figure 23. Selectivity coefficients, by fishery.

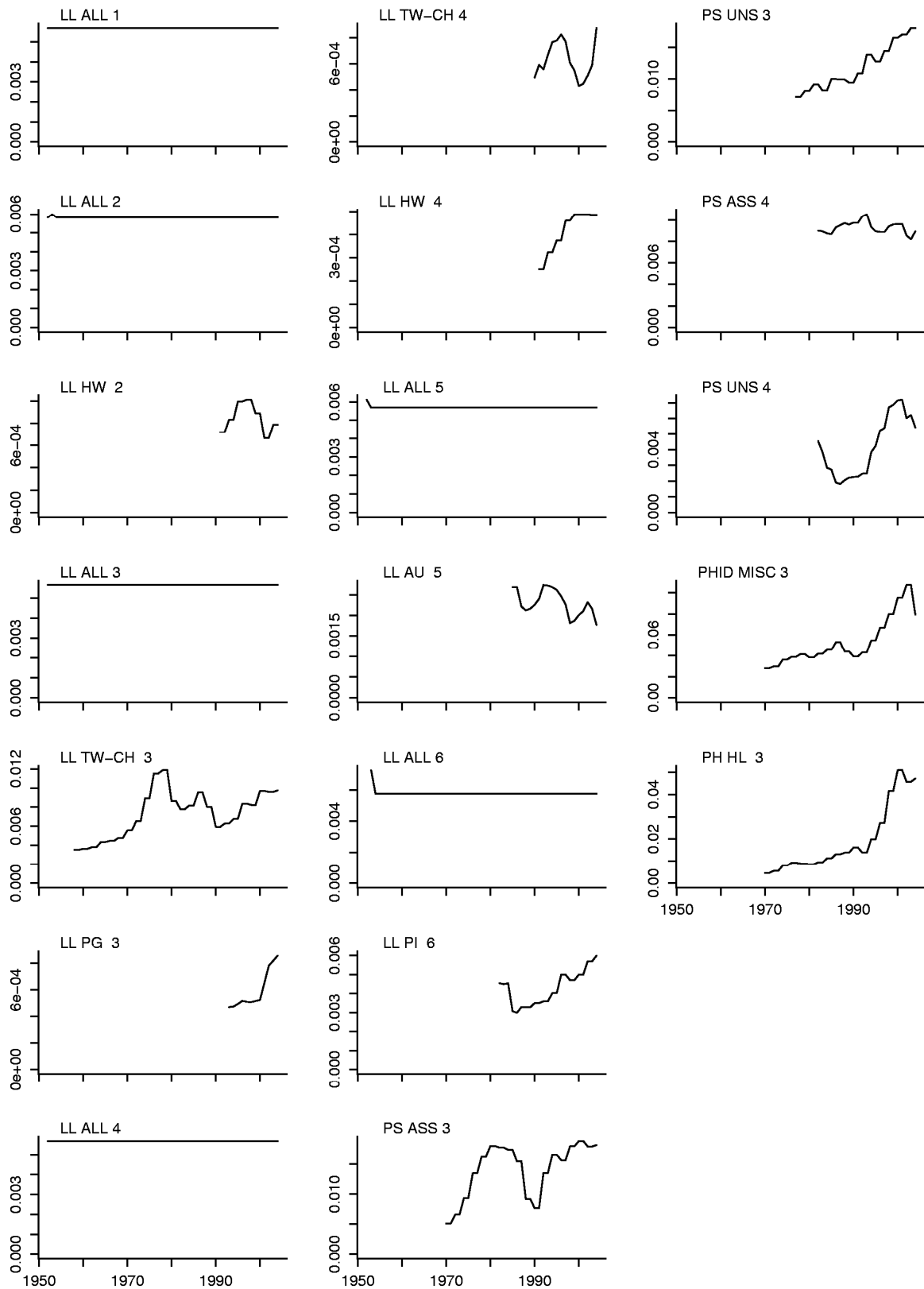


Figure 24. Average annual catchability time series, by fishery from the GLM-MFIX model.

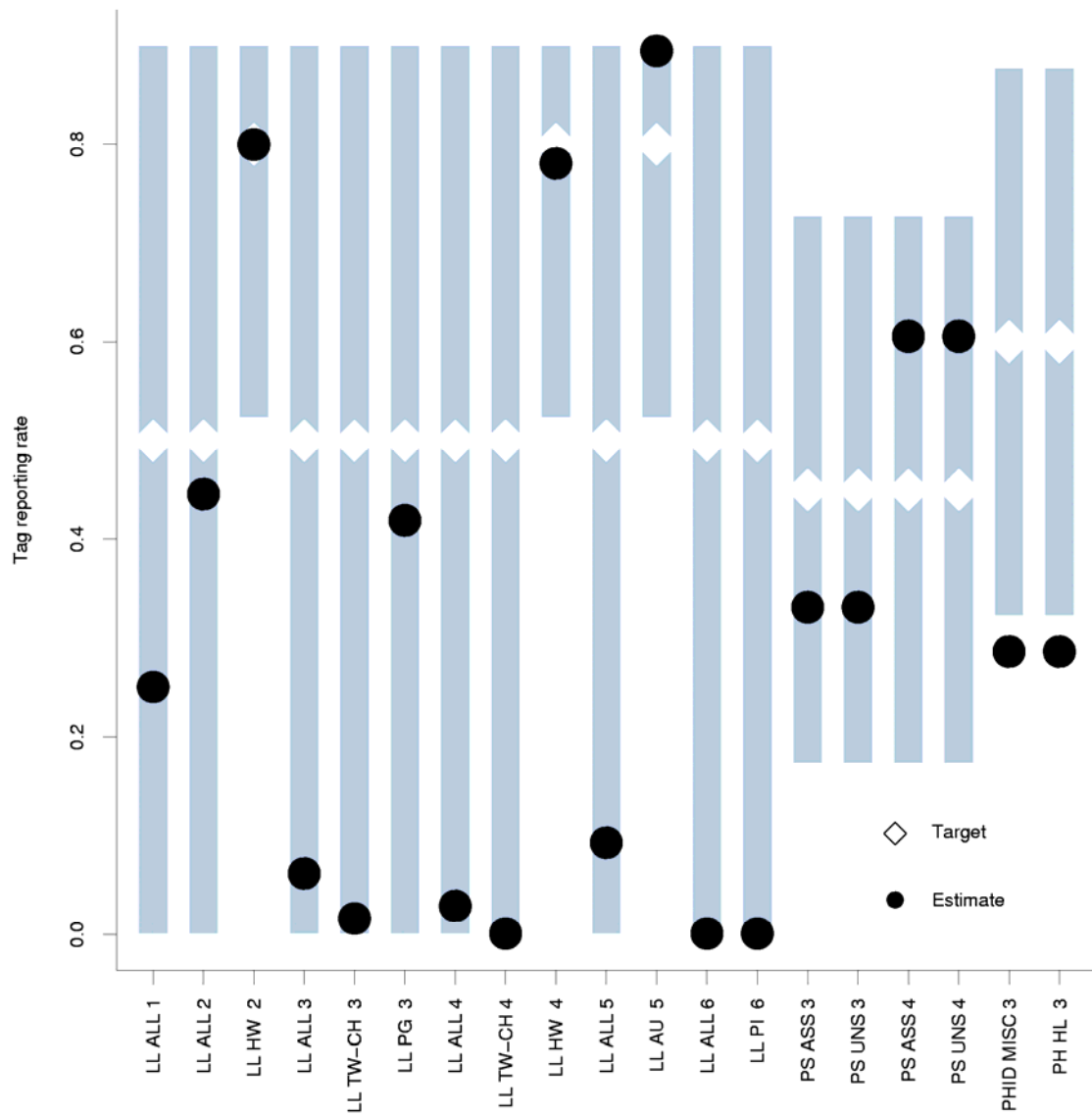


Figure 25. Estimated tag-reporting rates by fishery (black circles). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars indicate a range of ± 1 SD.

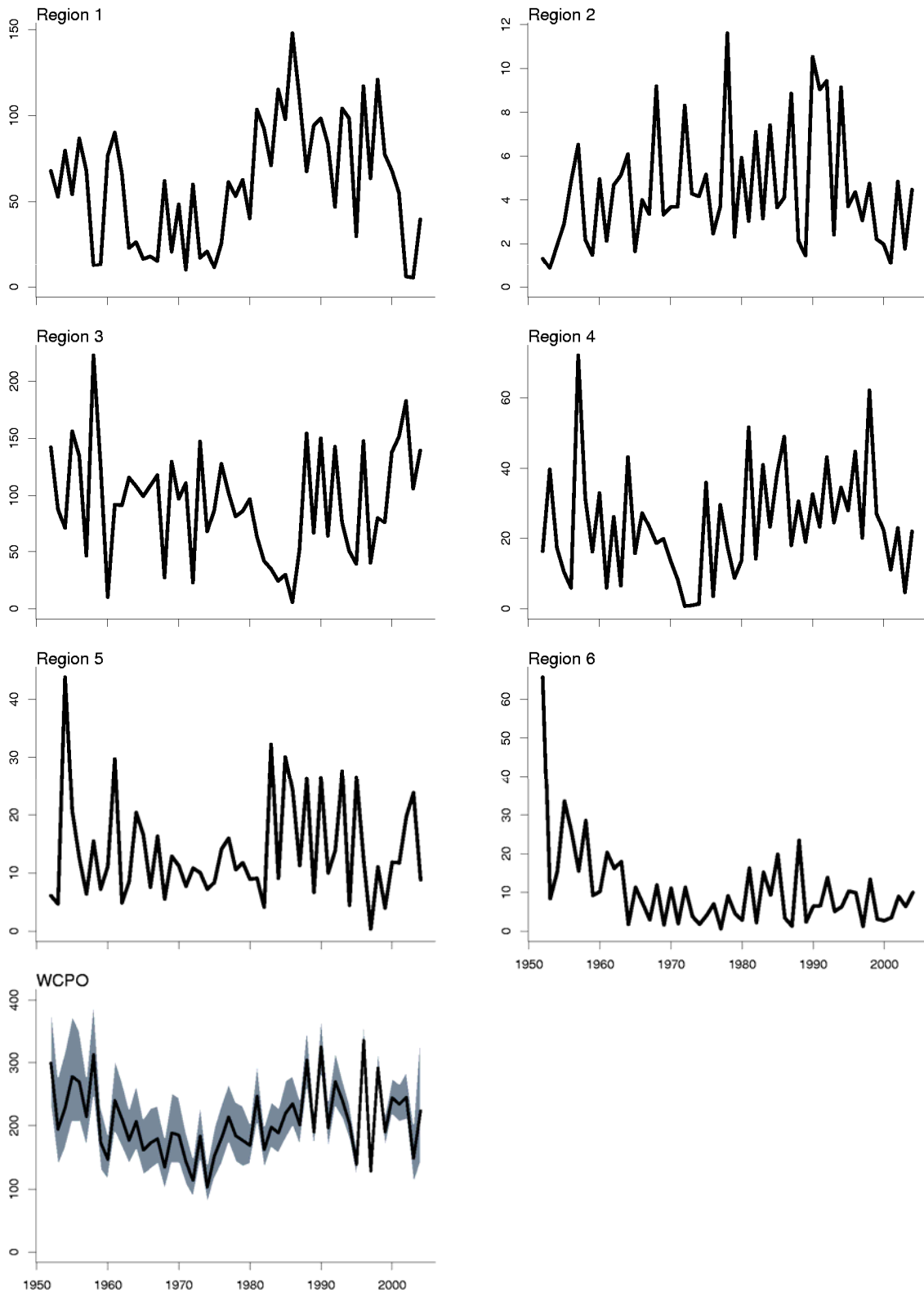


Figure 26. Estimated annual recruitment (millions of fish) by region and for the WCPO. The shaded area for the WCPO indicates the approximate 95% confidence intervals.

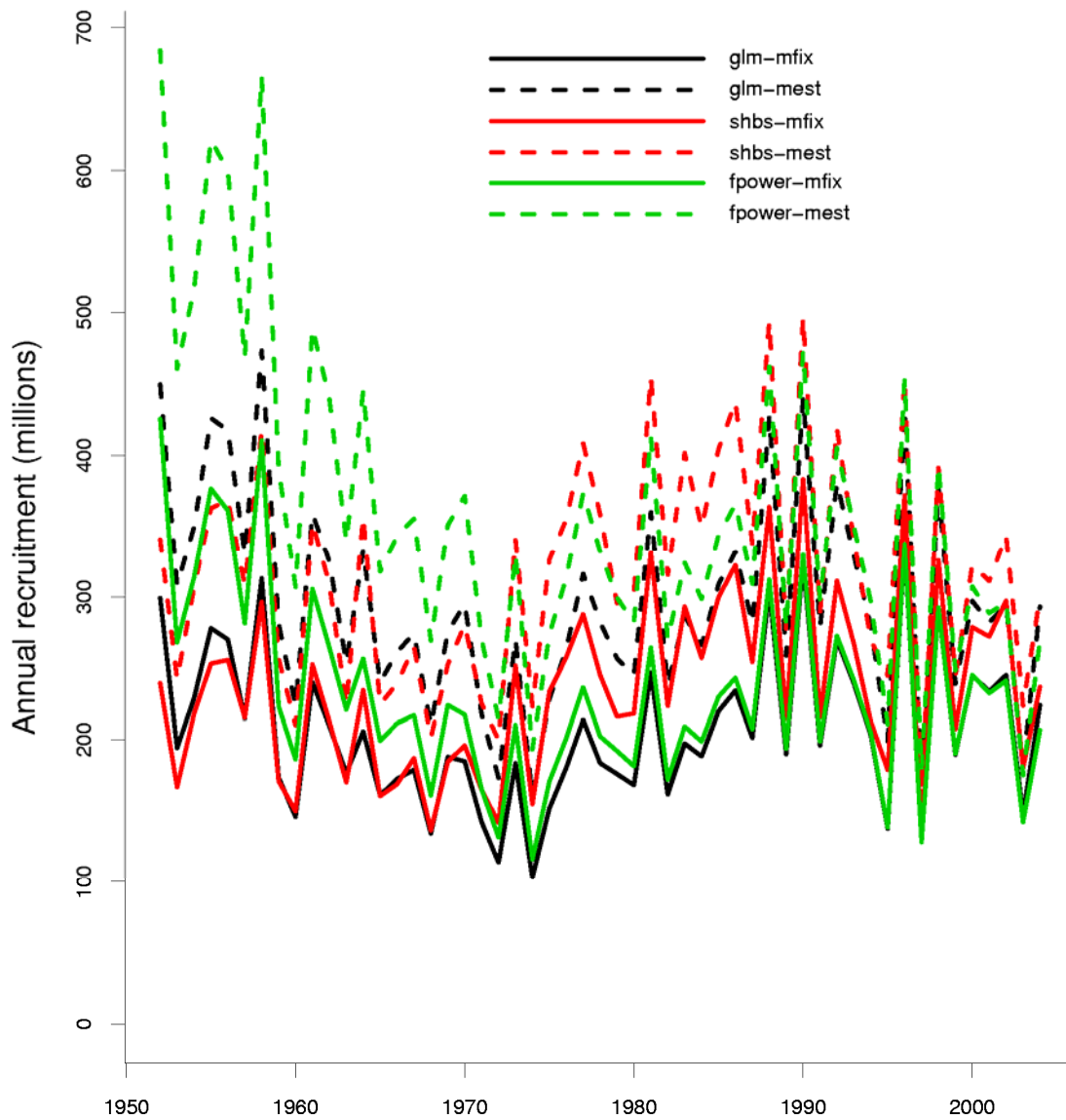


Figure 27. Estimated annual recruitment (millions of fish) for the WCPO obtained from the six different model options.

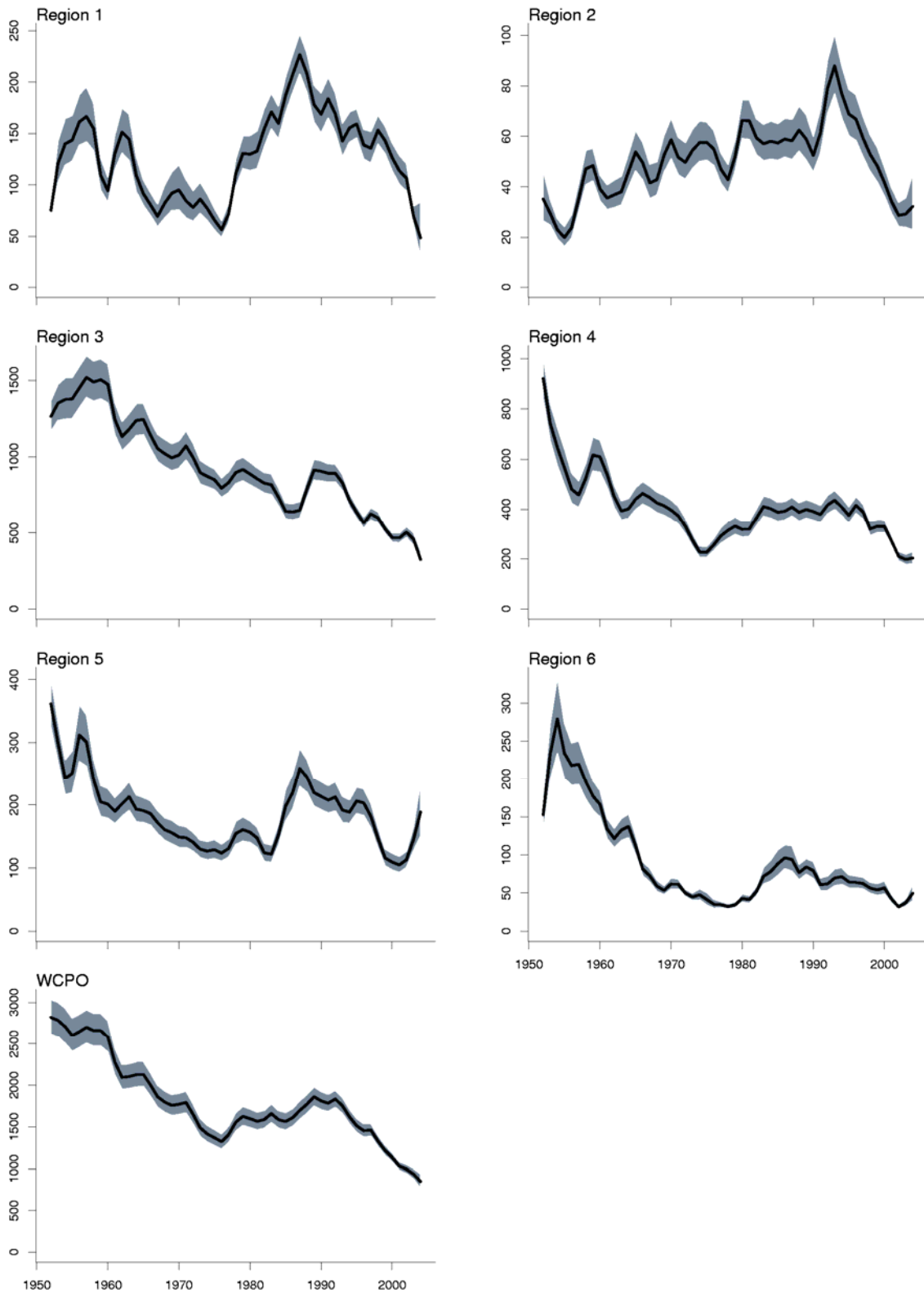


Figure 28. Estimated annual average total biomass (thousand t) by region and for the WCPO for the base-case analysis (GLM-MFIX). The shaded areas indicate the approximate 95% confidence intervals.

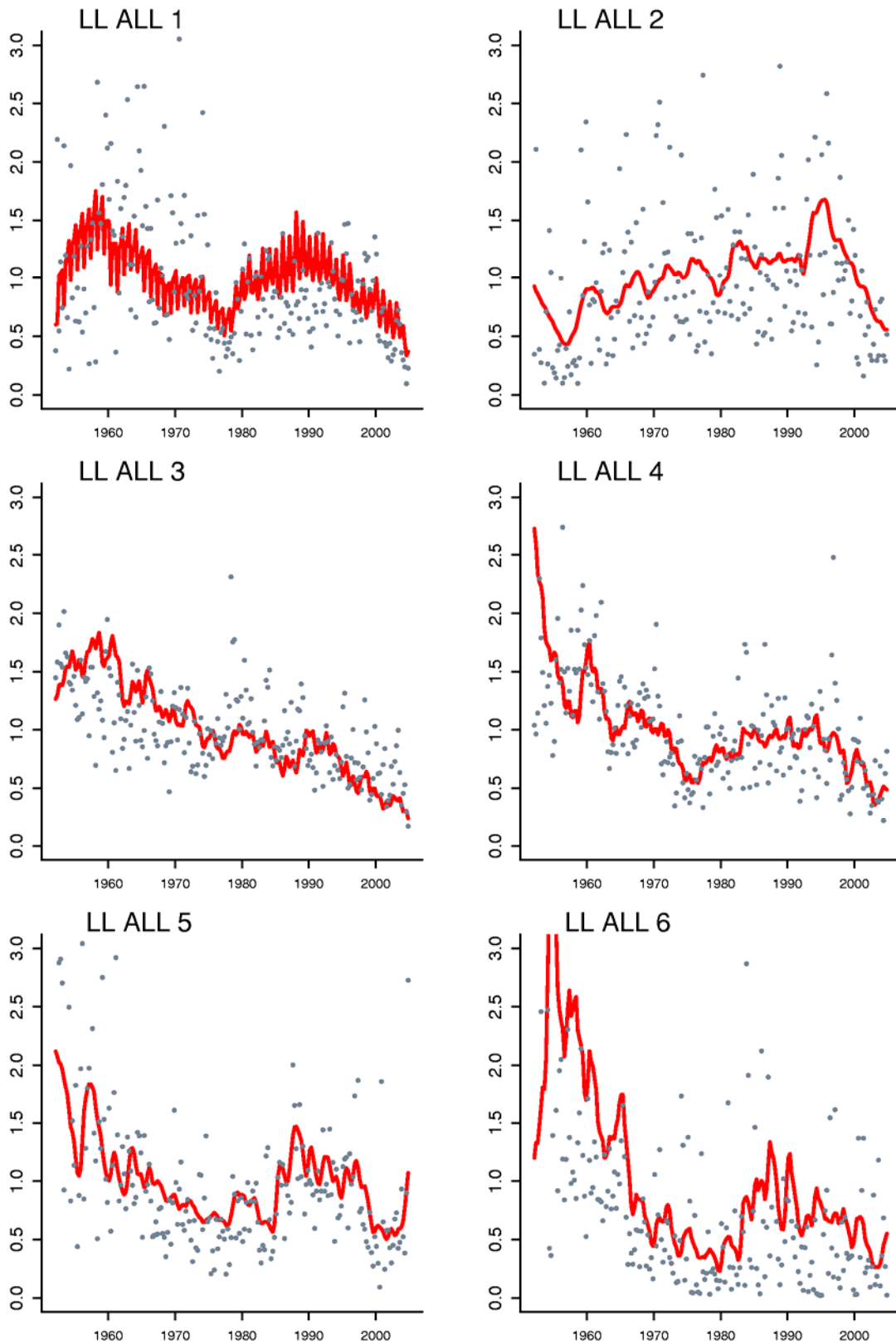


Figure 29. A comparison of longline exploitable biomass by quarter and region (red line) and the quarterly standardised CPUE indices for the fisheries. For comparison, both series are scaled to the average of the series.

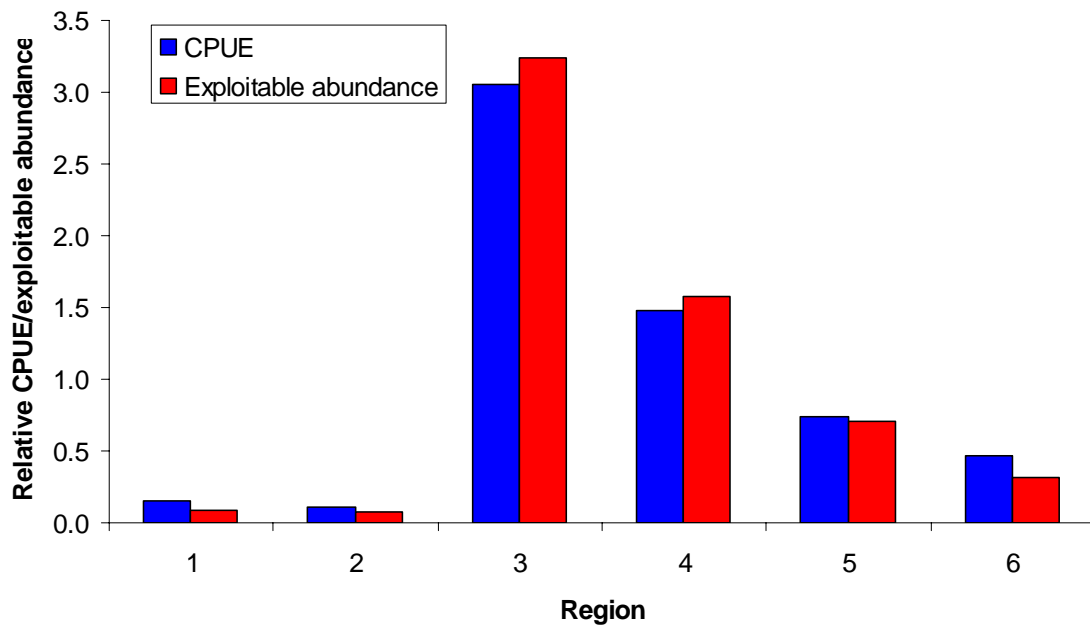


Figure 30. CPUE and exploitable abundance for LL ALL 1–6 averaged over all time periods. Values for each region are scaled relative to their averages across all regions.

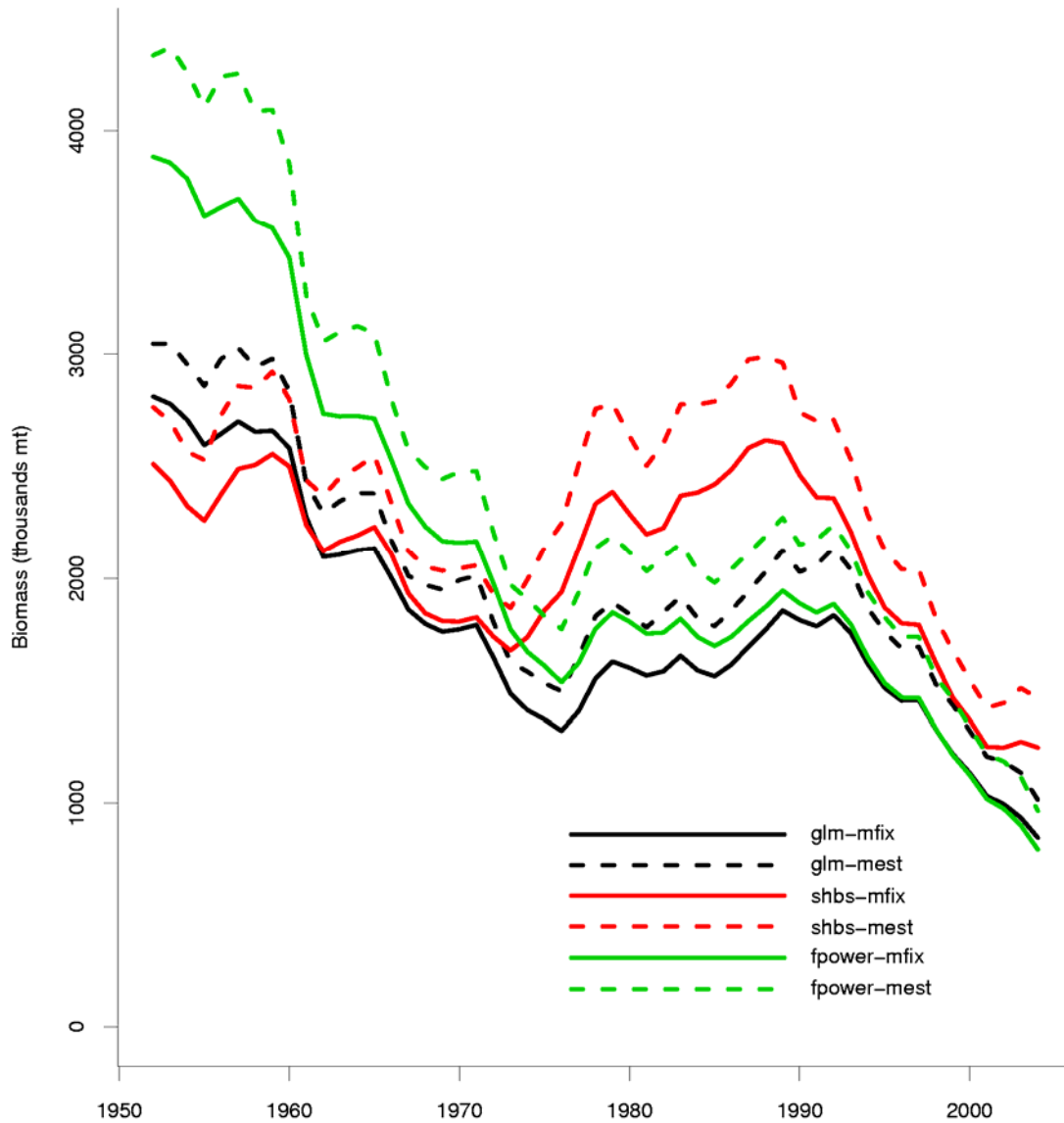


Figure 31. Estimated annual average total biomass (thousands mt) for the WCPO obtained from the six different model options.

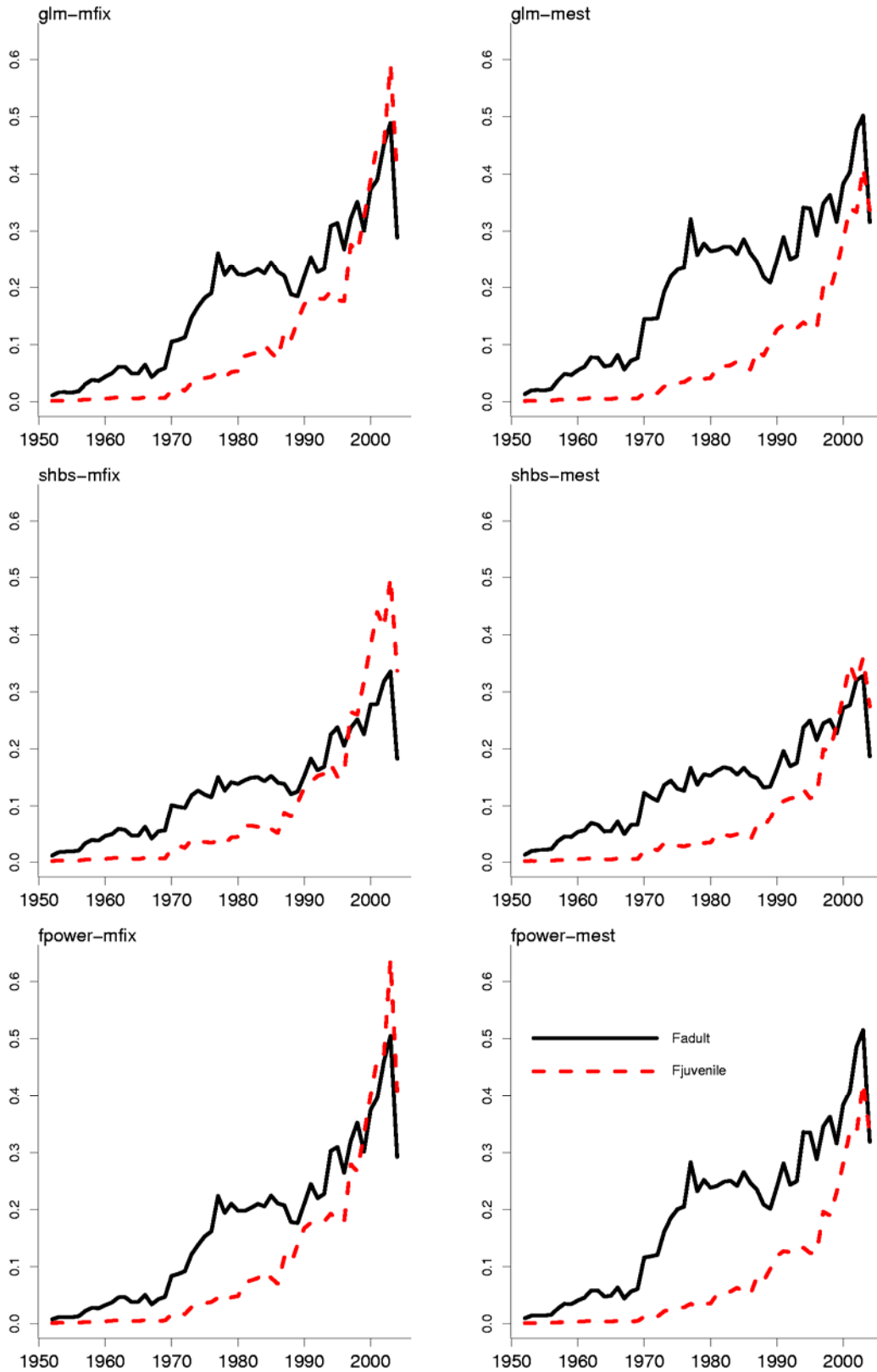


Figure 32. Estimated annual average juvenile and adult fishing mortality for the WCPO obtained from the six separate model options.

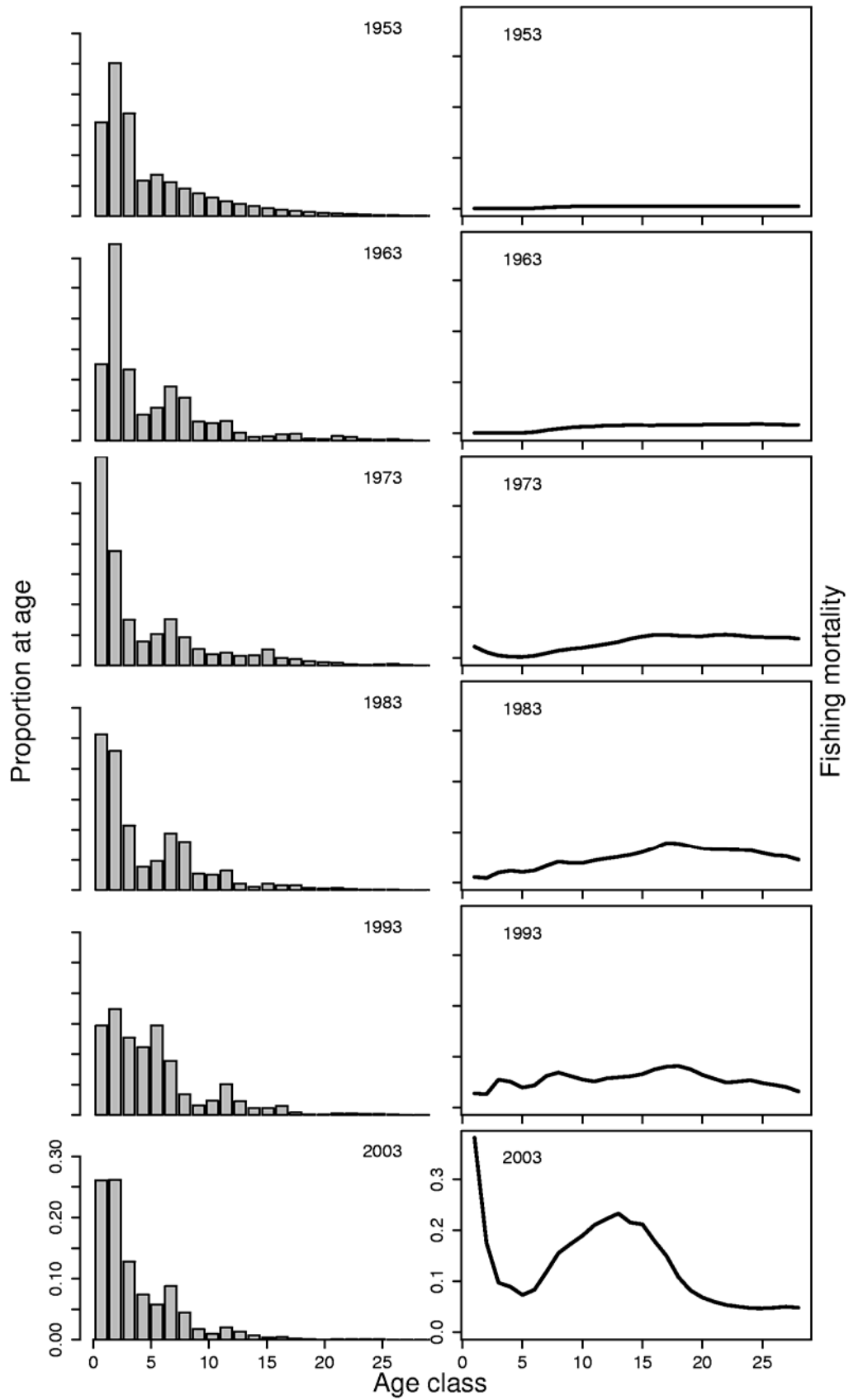


Figure 33. Estimated proportion at age (quarters) for the WCPO yellowfin population (left) and fishing mortality at age (right) by year at decade intervals.

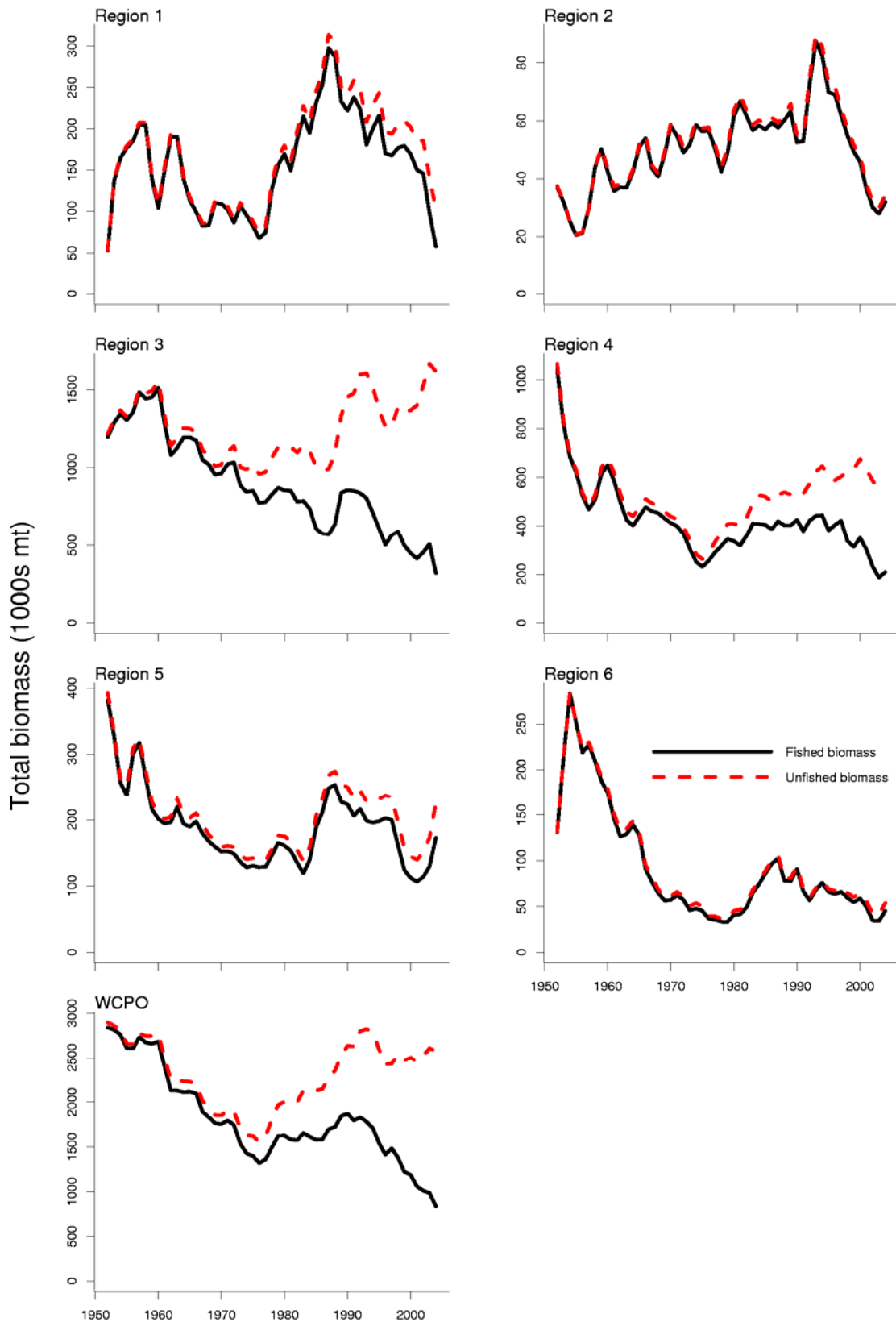


Figure 34. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper thin lines) for the GLM-MFIX model for each region and for the WCPO.

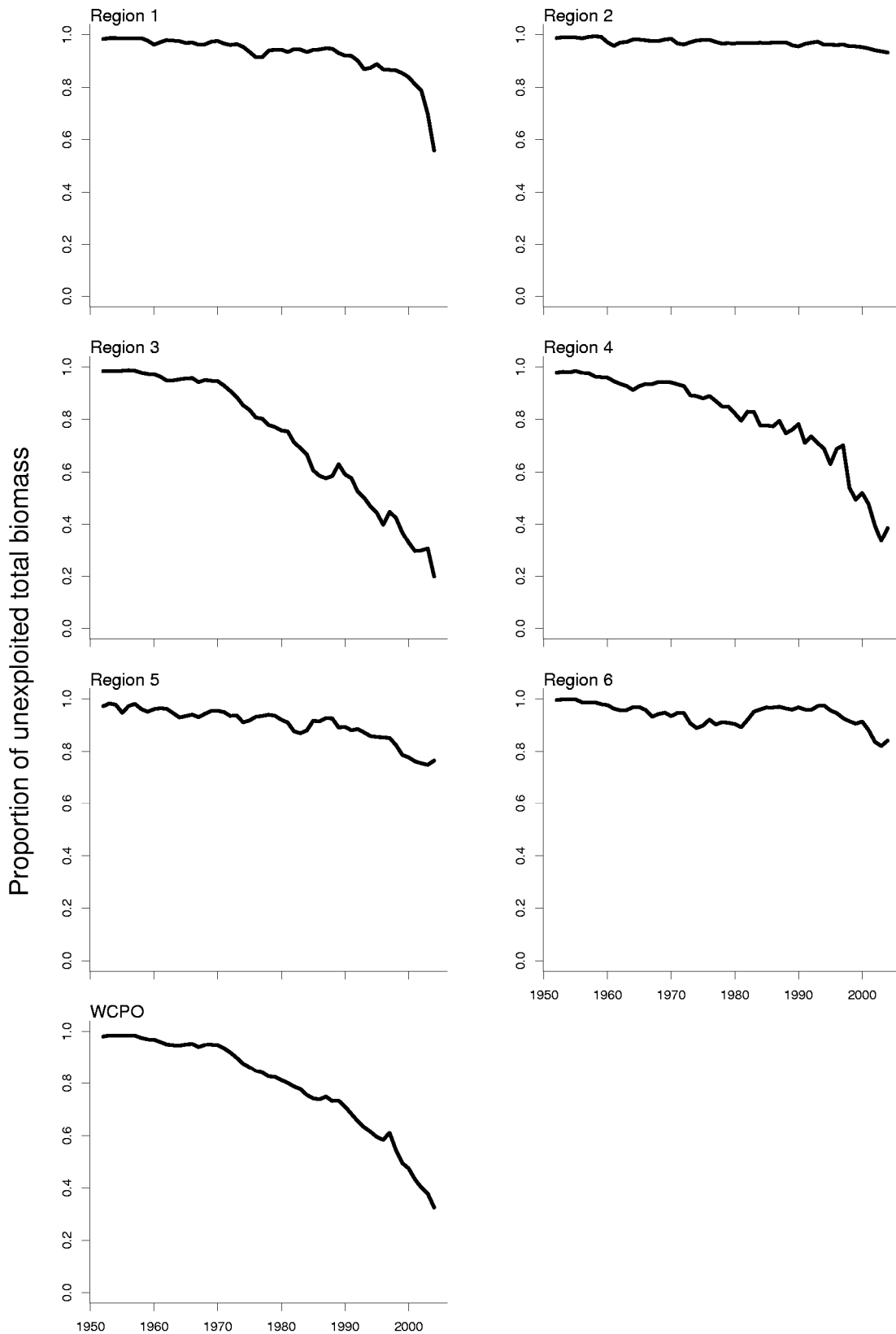


Figure 35. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the WCPO.

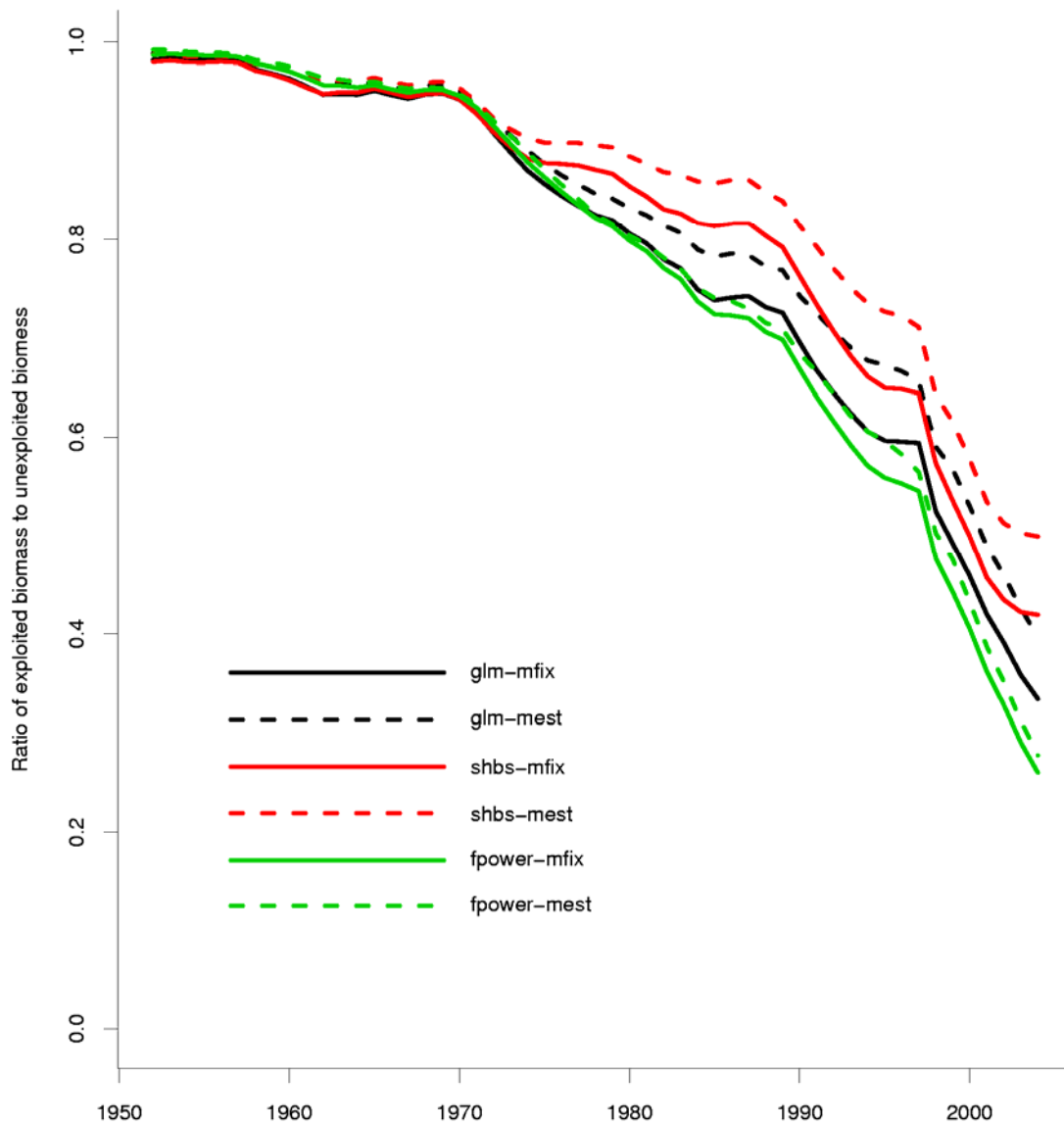


Figure 36. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for the WCPO obtained from the separate analyses.

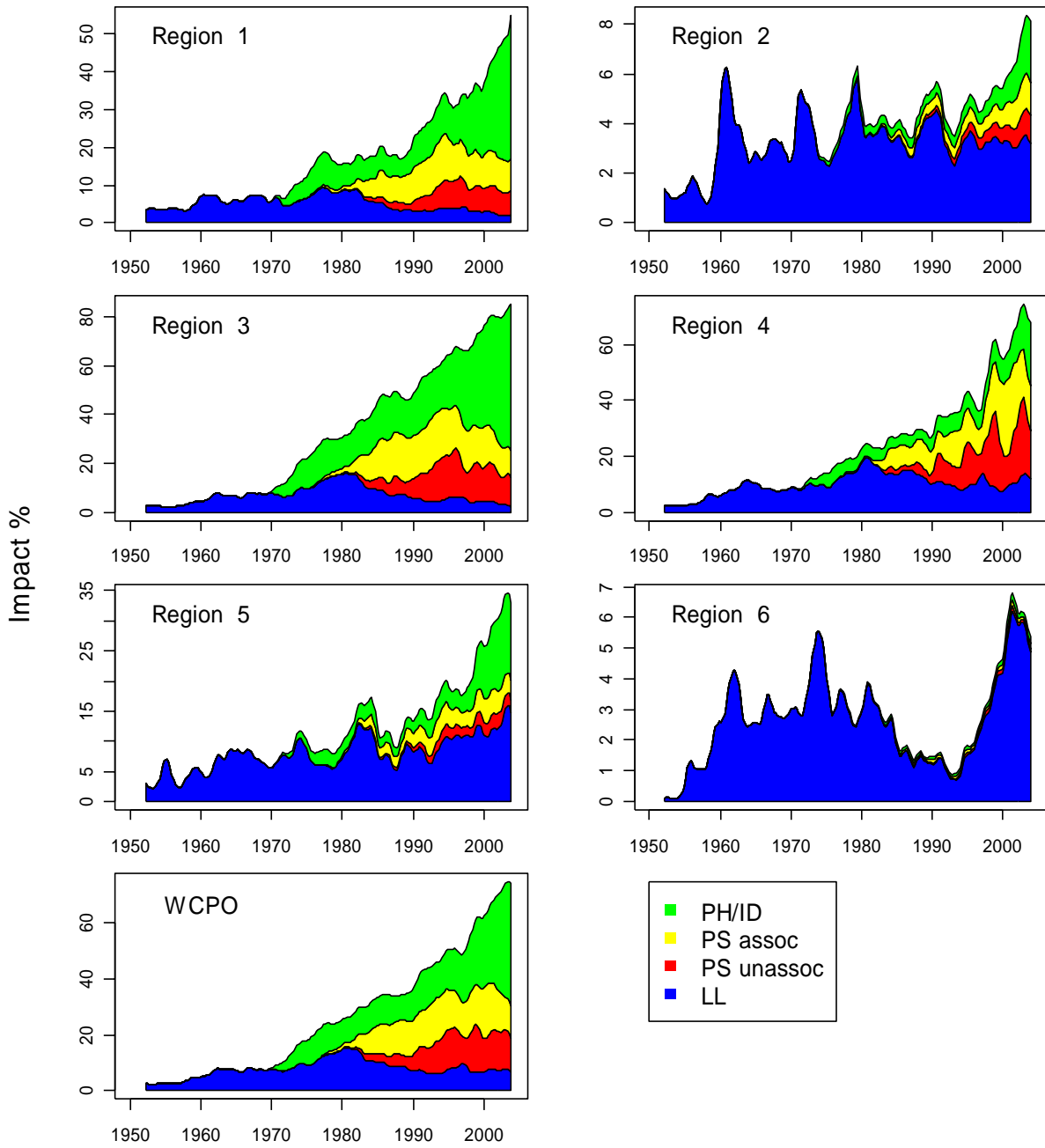


Figure 37. Estimates of reduction in spawning biomass due to fishing (fishery impact = $1 - SB_t/SB_{0,t}$) by region and for the WCPO attributed to various fishery groups. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine FAD and log sets; PS unassoc = purse seine school sets.

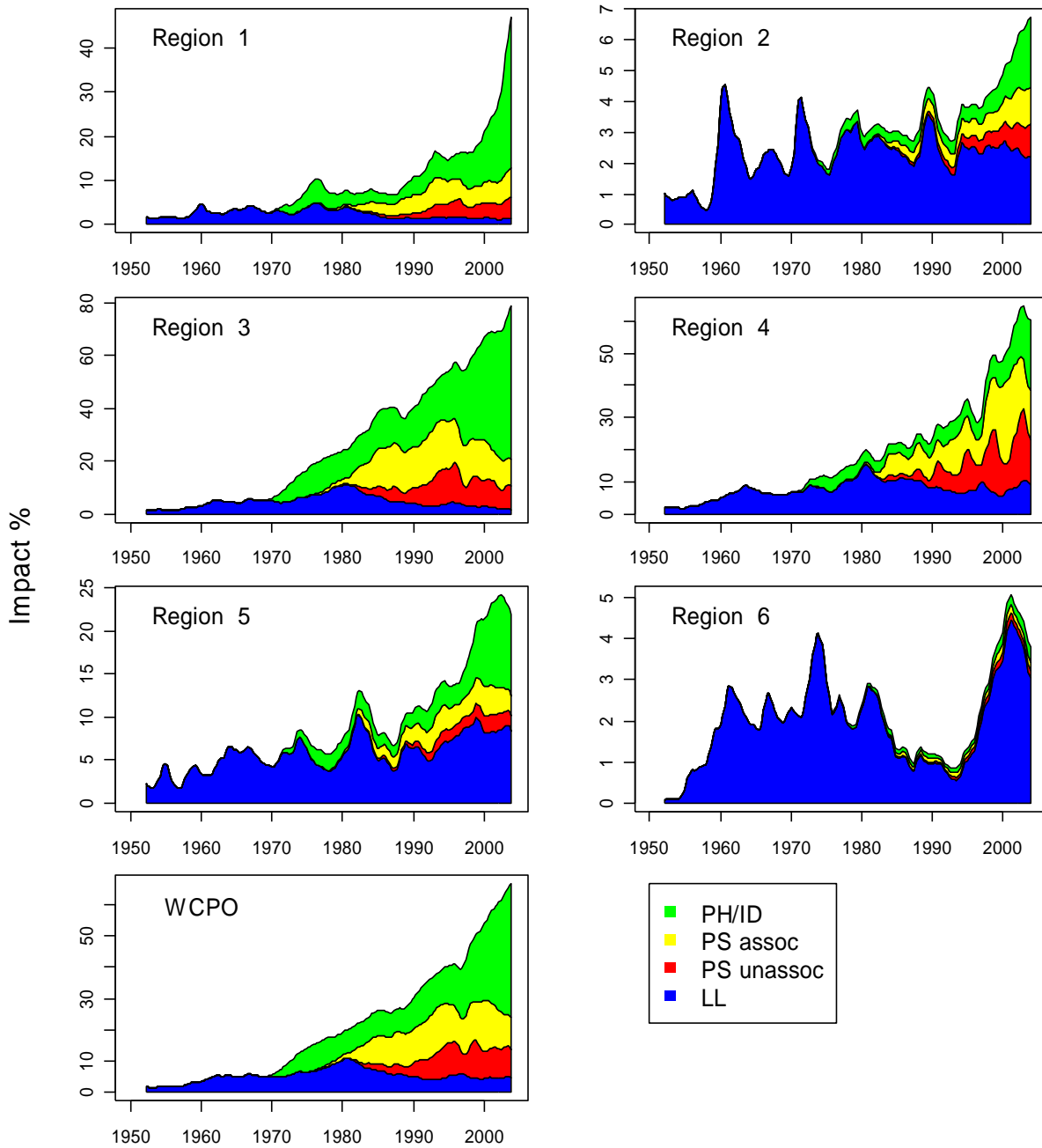


Figure 38. Estimates of reduction in total biomass due to fishing (fishery impact = $1 - B_t/B_{0,t}$) by region and for the WCPO attributed to various fishery groups. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine FAD and log sets; PS unassoc = purse seine school sets.

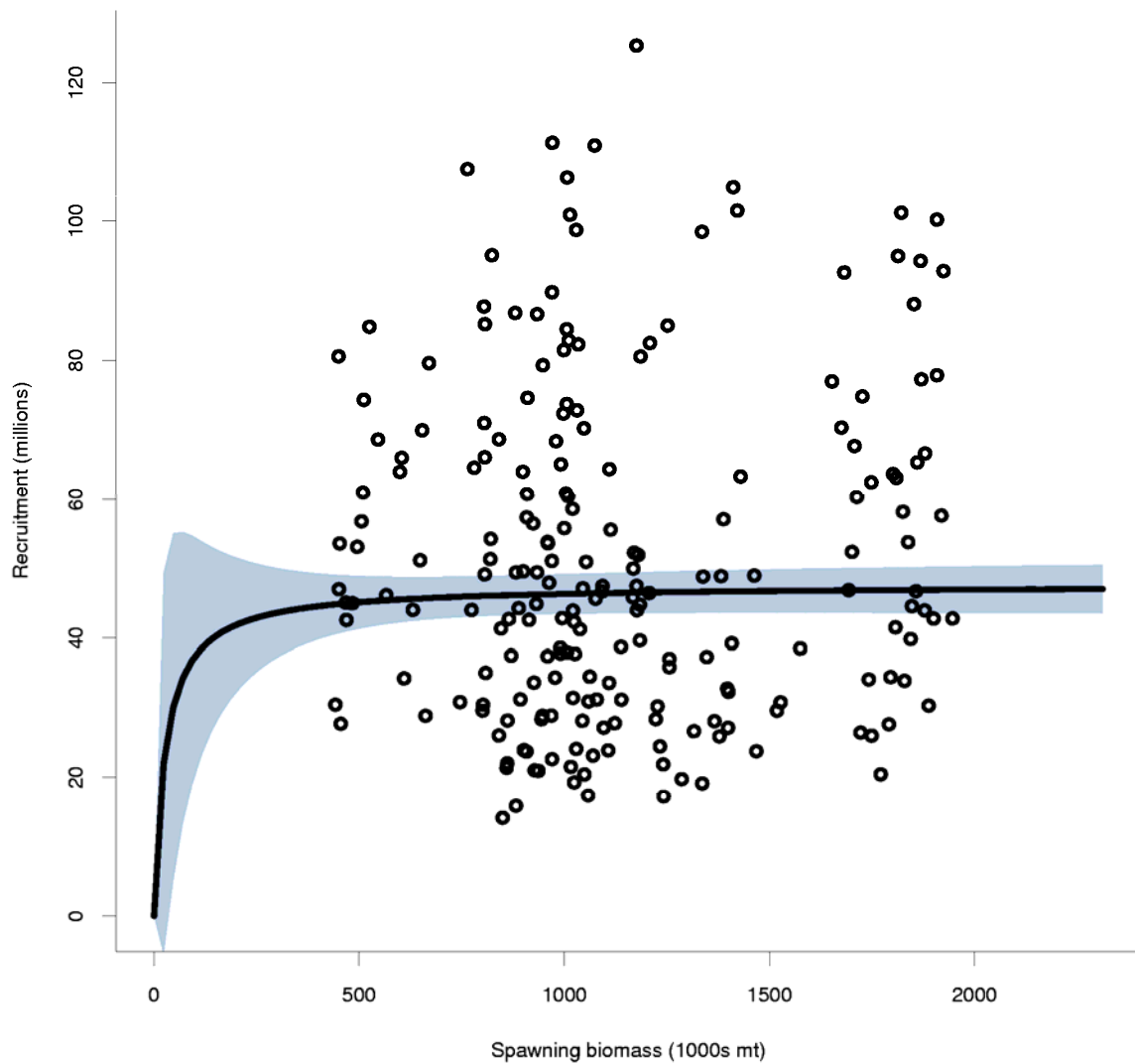


Figure 39. Estimated relationship between equilibrium recruitment and equilibrium spawning biomass. The grey area indicates the 95% confidence region. Estimated recruitment-spawning biomass points are plotted as open circles.

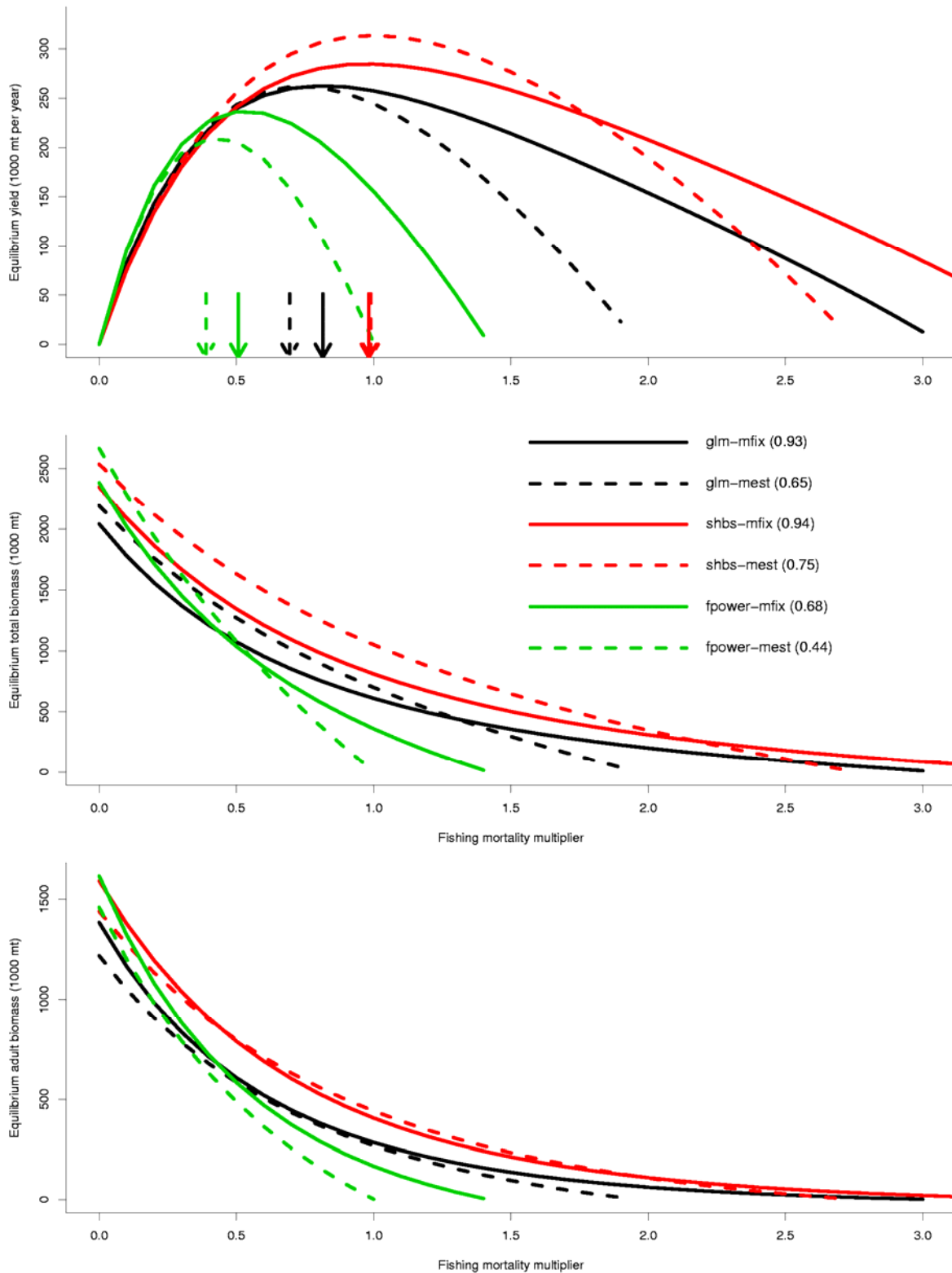


Figure 40. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier obtained from the five separate model options. In the upper panel, the arrows indicate the value of the fishing mortality multiplier at maximum yield. The values in the brackets of the legend are the estimated values of steepness σ of the SRR for each model.

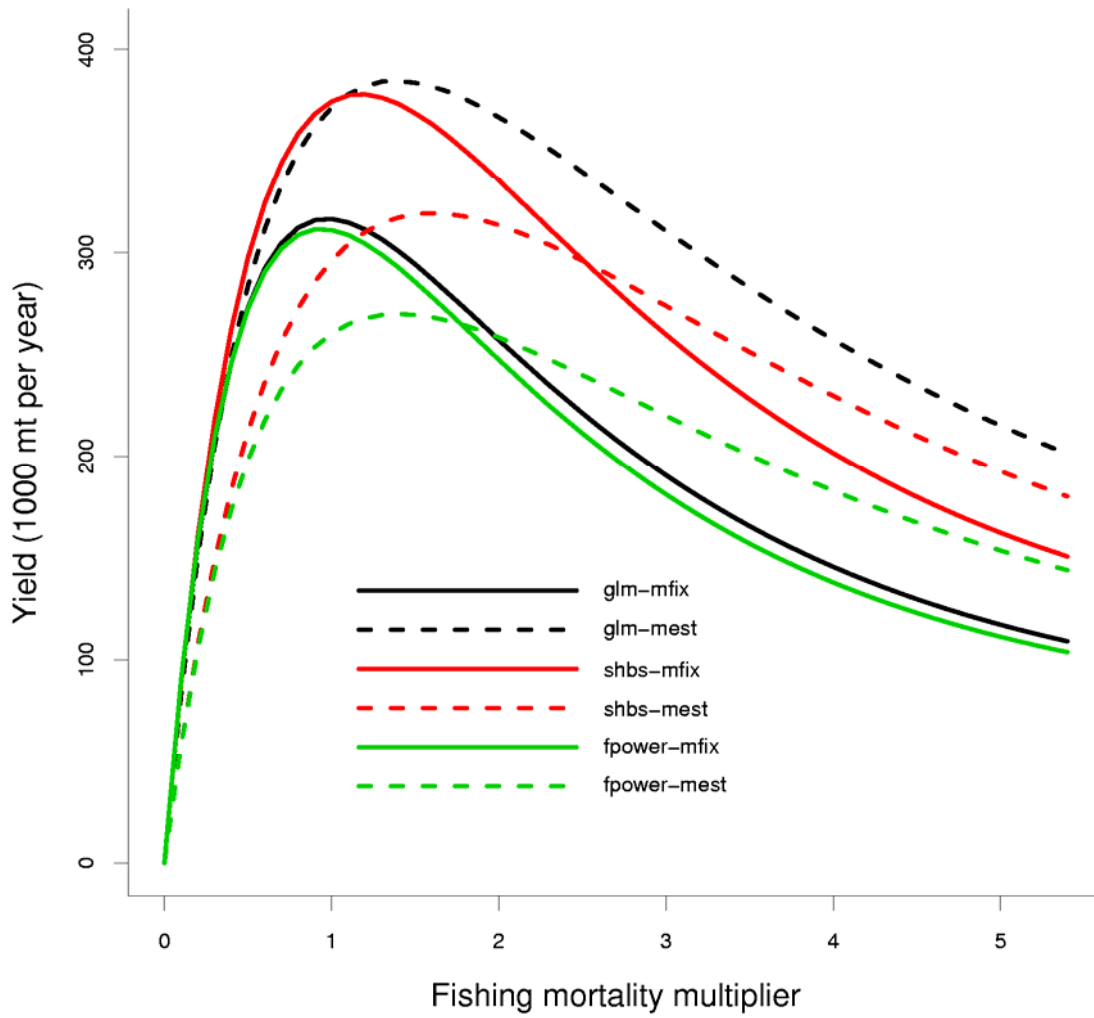


Figure 41. Yield curves based on 1994–2003 average recruitment.

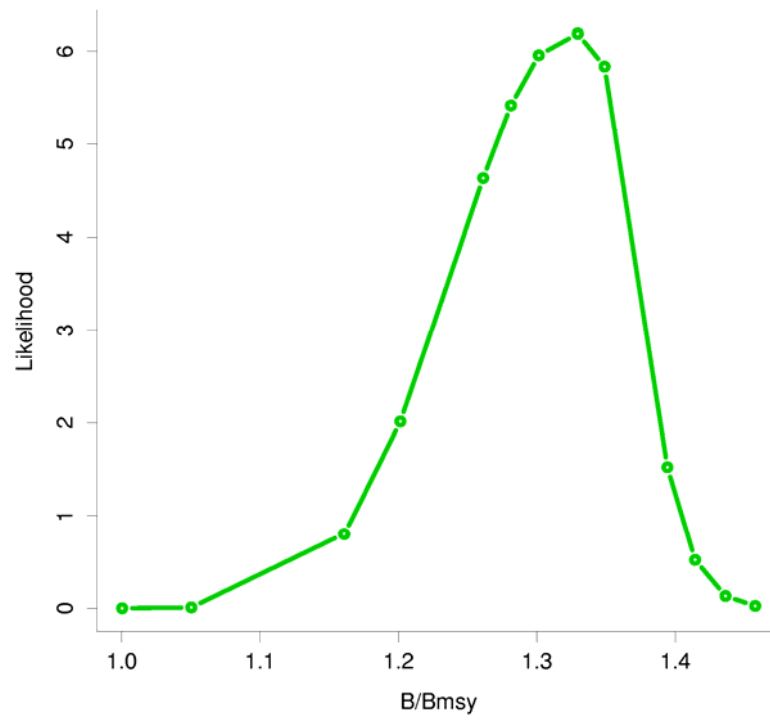


Figure 42. Likelihood profile for $B_{current} / \tilde{B}_{MSY}$ from the GLM-MFIX model.

TO BE INCLUDED

Figure 43. Likelihood profile for $F_{current} / \tilde{F}_{MSY}$ from the GLM-MFIX model.

Appendix 1 *doitall.yft*

```
#!/bin/sh
# -----
# 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
  2 113 1 # estimate initpop/totpop scaling parameter
  2 177 1 # use old totpop scaling method
  2 32 1 # and estimate the totpop parameter
  -999 49 10 # divide LL LF sample sizes by 10 (default)
  -999 50 10 # divide LL WF sample sizes by 5 (default=10)
  1 32 2 # sets standard control
  1 111 3 # 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
-1 16 1
-2 16 1
-3 16 1
-4 16 1
-5 16 1
-6 16 1
-7 16 1
-8 16 1
-9 16 1
-10 16 1
-11 16 1
-12 16 1
-13 16 1
-19 16 1 # and large-scale PH HL
-999 57 3 # uses cubic spline selectivity
-999 61 5 # with 5 nodes for cubic spline
# 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
 # 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
 -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
 # grouping of fisheries for tag return data
 -1 32 1
 -2 32 2
 -3 32 3
 -4 32 4
 -5 32 5
 -6 32 6
 -7 32 7
 -8 32 8
 -9 32 9
 -10 32 10
 -11 32 11
 -12 32 12
 -13 32 13
 -14 32 14 # PS assoc. and unassoc. returns are grouped
 -15 32 14
 -16 32 15
 -17 32 15
 -18 32 16 # PH/ID returns returns are grouped
 -19 32 16
 # grouping of fisheries with common tag-reporting rates - as for tag grouping
 -1 34 1
 -2 34 2
 -3 34 3
 -4 34 4
 -5 34 5
 -6 34 6

```

-7 34 7
-8 34 8
-9 34 9
-10 34 10
-11 34 11
-12 34 12
-13 34 13
-14 34 14 # PS assoc. and unassoc. returns are grouped
-15 34 14
-16 34 15
-17 34 15
-18 34 16 # PH/ID returns returns are grouped
-19 34 16
# 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
# 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
# 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 1
# sets penalties for catchability deviations
-18 15 1 # low penalty for PH.ID MISC.
-999 33 1 # estimate tag-reporting rates
1 33 90 # maximum tag reporting rate for all fisheries is 0.9

```

```

PHASE1
fi
# -----
# PHASE 2
# -----
if [ ! -f 02.par ]; then
  mfclopt yft.frq 01.par 02.par -file - <<PHASE2
  1 149 400 # set penalty on recruitment devs to 400/10
  -999 3 25 # all selectivities equal for age class 37 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
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
PHASE3
fi
# -----
# PHASE 4
# -----
if [ ! -f 04.par ]; then
  mfclopt yft.frq 03.par 04.par -file - <<PHASE4
  2 68 1 # estimate movement coefficients
PHASE4
fi
# -----
# PHASE 5
# -----
if [ ! -f 05.par ]; then
  mfclopt yft.frq 04.par 05.par -file - <<PHASE5
  1 16 1 # estimate length dependent SD
PHASE5
fi
# -----
# PHASE 6
# -----
if [ ! -f 06.par ]; then
  mfclopt yft.frq 05.par 06.par -file - <<PHASE6
  1 173 8 # estimate independent mean lengths for 1st 8 age classes
  1 182 10
PHASE6
fi
# -----
# PHASE 7
# -----
if [ ! -f 07.par ]; then
  mfclopt yft.frq 06.par 07.par -file - <<PHASE7
  -999 27 1 # estimate seasonal catchability for all fisheries
  -18 27 0 # except those where
  -19 27 0 # only annual catches
PHASE7
fi
# -----
# PHASE 8
# -----
if [ ! -f 08.par ]; then
  mfclopt yft.frq 07.par 08.par -file - <<PHASE8

```

```

-3 10 1 # estimate
-5 10 1 # catchability
-6 10 1 # time-series
-8 10 1 # for all
-9 10 1 # non-longline
-11 10 1 # fisheries
-13 10 1
-14 10 1
-15 10 1
-16 10 1
-17 10 1
-18 10 1
-19 10 1
-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
-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 5
1 149 0
2 146 1
2 147 1
2 148 16
2 155 4
2 153 31
2 154 16
1 1 3000
1 50 -3
PHASE12
fi
```

Appendix 2 *yft.ini*

```
# number of age classes
28
# MATURITY AT AGE
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 1 1 1 1
# natural mortality
0.249404147000
# movemap
1 2 3 4
# diffusion coeffs
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 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 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
28.0 20.0 40.0
145.0 140.0 200.0
0.1 0.0 0.3
# Weight-length parameters
2.784e-05 2.8992
# Variance parameters (Average SD by age class, SD dependency on mean length)
# Initial value Lower bound Upper bound
6.0 3.0 8.0
0.40 -0.69 0.69
# The number of mean constraints
0
```