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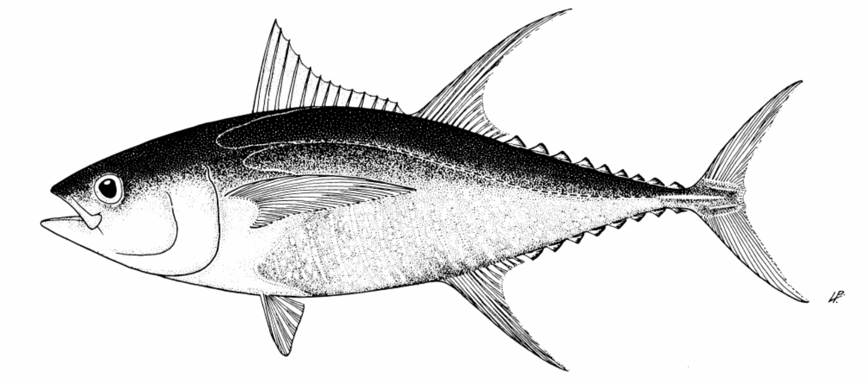
Stock assessment of yellowfin tuna in the western and central Pacific Ocean



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Executive summary

This paper presents the 2004 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 (5 regions) and the catch, effort, size composition and tagging data used in the model are classified by 17 fisheries and quarterly time periods from 1950 through 2007. The last 4–5 years (depending on the fishery) constitute a projection period in which the last year's fishing effort for each fishery is assumed to continue into the future.

Five 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 assuming fixed or variable catchability for the main longline fisheries. The analyses conducted are:

SHBS-MEST	Statistical habitat-based standardised effort for LL1–LL5, *M*-at-age estimated, constant catchability for LL1–LL5.
SHBS-MEST-LLq	Statistical habitat-based standardised effort for LL1–LL5, *M*-at-age estimated, catchability for LL1–LL5 allowed to vary independently over time, but with the initial catchability constrained to be equal.
SHBS-MFIX	Statistical habitat-based standardised effort for LL1–LL5, *M*-at-age assumed at fixed levels, constant catchability for LL1–LL5.
GLM-MEST	General linear model standardised effort for LL1–LL5, *M*-at-age estimated, constant catchability for LL1–LL5.
GLM-MFIX	General linear model standardised effort for LL1–LL5, *M*-at-age assumed at fixed levels, constant catchability for LL1–LL5.

The data used in the assessment were the same as those used last year, with the exception of an additional year of fishery data (2002 for longline, 2002 for Philippines and Indonesia, 2003 for purse seine) was included.

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, although natural mortality was lower in the SHBS analyses. Similarly, the MEST analyses were more optimistic than the corresponding MFIX analyses. Natural mortality was estimated to be considerably lower for the juvenile age classes and higher for the older age classes compared to the fixed age-specific natural mortality schedule. This was balanced with higher levels of recruitment for the MFIX analyses but lower levels of biomass and lower overall yields compared to the MEST analyses.

For the SHBS-MEST-LLq analysis, recruitment, MSY, and current and reference biomass is higher than for the base-case. However, because catchability is predicted to have increased in the main fishing regions (2 and 3), the $B_{current} / \tilde{B}_0$ is lower than for the base-case. While the fitting criteria indicated a statistically significant improvement in fit over the constant catchability models, further analysis of the LLq model is required to judge whether or not the estimated trends in longline catchability are reasonable and therefore whether or not this model should be accorded equal (or greater) weight in the overall evaluation of stock status.

Overall, the GLM-MEST and SHBS-MEST are most comparable to the GLM and SHBS analyses in last year's assessment. For both sets of analyses, the current results are more pessimistic than last year's results with lower overall recruitment, lower equilibrium yields, higher current exploitation rates, and higher impacts due to fishing.

At this stage, we regard the variable longline catchability model as experimental – more work is required to evaluate its characteristics so that some judgments can be made regarding its use in evaluating stock status. We include it in this assessment as a sensitivity analysis to indicate the impact that structural assumptions can have on stock assessment results.

It is also important to note that the key reference points are sensitive to our initial assumptions regarding the nature of the stock-recruitment relationship. The assumed prior distribution for the steepness parameter is highly influential and a relaxation of this assumption results in a more pessimistic assessment despite the lack of any evidence of a strong relationship between spawning stock biomass and recruitment. For future assessments, a comprehensive review of appropriate values of SRR steepness for yellowfin is required to determine appropriate values for inclusion in a range of sensitivity analyses.

The main reference points from the stock assessment indicate that the long-term average biomass should remain above that capable of producing *MSY*, except in the case of the most pessimistic assessment (GLM-MFIX) ($\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$ (0.89–1.45) and $S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$ (0.87–1.55)) and that there is limited potential to expand long-term yields from the fishery at the current pattern of age-specific selectivity ($\tilde{Y}_{F_{current}} / MSY$ (0.90–1.00)). We would note, however, that this apparently healthy situation arises mainly from low levels of exploitation in sub-equatorial regions of the WCPO. Reduction of juvenile fishing mortality in the western equatorial region (region 2), principally the Indonesian fishery, would have significant benefits for both the yellowfin tuna stock and the longline fishery.

1 Introduction

This paper presents the current stock assessment of yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean (WCPO, west of 150°W). The assessment provides an update of the results of Hampton and Kleiber (2003) with the inclusion of recent and historical data from the yellowfin fishery.

The overall objectives of the assessment are to estimate population parameters, such as time series of recruitment, biomass and fishing mortality, that indicate the status of the stock and impacts of fishing. We also summarise stock status in terms of well-known reference points, such as the ratios of recent stock biomass to the biomass at maximum sustainable yield ($B_{current} / \tilde{B}_{MSY}$) 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 >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 ten years. The majority of the catch is taken in equatorial areas, with declines in both purse-seine and longline catch towards the east. 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.

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 five-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.

3.2 Temporal stratification

The time period covered by the assessment has been extended back to 1950, to cover all significant post-war tuna fishing in the WCPO. The primary time period covered by the assessment is 1950–2003. An additional four years (i.e. to the end of 2007) are added as a projection period. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec).

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). Seventeen 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 (LL1-5) and two additional Chinese/Taiwanese longline fisheries fishing in regions 2 and 3. 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 eastern Australian longline fishery was included as a separate longline fishery within region 4 (AU LL).

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

Effort data for the Philippines and Indonesian fisheries were unavailable 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 (log, FAD or school sets) in logbook data. For the longline fisheries, we used two estimates of effective (or standardised) effort were derived using an unconstrained statistical habitat-based standardisation (SHBS – Bigelow et al. 2004) and from a generalized linear model (GLM – updated to include recent data following the approach of Langley 2003). 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 5 and Figure 6, respectively.

Within the model, effort for each fishery was normalised to an average of 1.0 to assist numerical stability. Some 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. Also, effort for these fisheries was divided by the relative size of the respective region. The application of these procedures allowed longline CPUE to index exploitable abundance in each region (rather than density), which in turn allowed simplifying assumptions to be made regarding the spatial and temporal constancy of catchability for the longline fisheries.

3.5 Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 100 2-cm size classes (10–12 cm to 208–210 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 7. 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 for the 2002 assessment. Additional size data have been collected in recent years, but these data have not yet been evaluated and so have not been included in the current assessment.

Indonesia: Limited size data were obtained for the Indonesian domestic fisheries from the former IPTP database. Under the assumption that most of the catch is by pole-and-line gear, catches by the SPC tagging vessels operating in Indonesia in 1980 and 1991–93 have also been used to represent the size composition of domestic fishery catches. Therefore, the size data available for this assessment are the same as those used in previous years.

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. Note that in previous years, Japanese length-frequency data had consisted of a combination of actual length measurements and weight measurements converted to length. These data have now been separated and the Japanese length data now consist of length-measured fish only.

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 and eastern Australian ports. Data were compiled by 1 kg weight intervals over a range of 1–100 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 7.

3.7 Tagging data

A large 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 2, 3, 4 and 5), 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. A summary of the five main model options included in the assessment is presented in Table 3. 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 5 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 1950–2004, with the final two years constituting a projection period. 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 five 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 prior was specified by mode = 0.9 and SD = 0.1 (a = 10, b = 2) (Figure 8). In other words, our prior belief is that the reduction in equilibrium recruitment when the equilibrium spawning biomass is reduced to 20% of its unexploited level would be fairly small (a decline of 10%). The sensitivity of the assessment to the assumptions regarding the prior distribution was investigated using an alternative formulation of the prior distribution (mode = 0.75 and SD = 0.18) (see Figure 8).

4.1.2 Initial population

In earlier yellowfin tuna assessments, 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. In this assessment, we assumed the initial equilibrium age structure to be a function of natural mortality only. This seemed reasonable given the insignificant levels of yellowfin tuna catch prior to 1950. 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). There are six 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 $2 \times 6 \times 4 = 48$ movement parameters. Furthermore, age dependency is accommodated with an exponential variation of movement coefficients with age, specified by an additional 48 parameters. The seasonal pattern of movement persists from year to year with no allowance for longer-term variation in movement.

4.1.5 Natural mortality

Natural mortality was assumed to be age-specific, invariant over time and region and continuous through the time steps. Penalties on the first difference, second difference and deviations from the mean were applied to restrict the age-specific variability to a certain extent.

Separate analyses were undertaken to investigate the sensitivity of the assessment to the assumptions of age-specific natural mortality. For each of the two longline standardised effort series, age-specific natural mortality was fixed based on Maunder and Harley (2004). The assumed age-specific natural mortality was high for the youngest age classes, low for age classes 6–10, high for the older age classes (13–19), and low for the oldest age classes (Figure 9).

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. We have preferred to model selectivity as separate age-specific coefficients (with a range of 0–1), but constraining the parameterisation with two types of smoothing penalties. First, the coefficients were smoothed according to the degree of length overlap between adjacent age-classes. This is appropriate where selectivity is thought to be a fundamentally length-based process (Fournier et al. 1998). The second type of smoothing influences the shape of the selectivity curve. Penalties based on the second and third differences were applied in order to avoid over-fitting and encourage some degree of regularity in the curves.

In this assessment, 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 longline fisheries L2–L5 were constrained to be equal. Fishery L1 was not included in this group because the size data show a very different pattern, suggestive of different selectivity, to those of the L2–L5 group. When fishery L1 was included in the group, significant departure in model fit resulted. 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 Taiwanese/Chinese longline fisheries and the Australian longline fishery, 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 catchability deviation priors to be high (equivalent to a CV of about 0.7 on the log scale), thus allowing catchability changes to compensate for failure of this assumption. For the other fisheries with time-series variability in catchability, the catchability deviation priors were assigned a variance equivalent to a CV of 0.10.

Longline fisheries LL1–LL5 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. Relaxation of this assumption is explored in sensitivity analyses (SHBS-Mest-LLq), whereby, catchability was allowed to vary temporally for each fishery while maintaining the relative difference in the initial catchability constant between regions.

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 L1–L5 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 first quarter after release. Alternative assumptions of two, three or four quarters after release had little effect on the results.

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 0.04 times the actual sample size for non-longline fisheries and 0.1 times the actual sample size for longline fisheries, with a maximum effective sample size for all fisheries 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. The differential treatment of longline and purse seine fisheries occurs because sampling coverage of purse seine catches is generally lower than longline, and the purse seine samples tend to be clumped by wells.

A similar likelihood function was used for the weight-frequency data. The only exception was that the effective sample size for the Australian longline fishery was assumed to be equal to 0.2 times the actual sample size recognising the high sampling coverage of this fishery

We recognise that the specifications for effective sample sizes used in this assessment are somewhat arbitrary. This issue has been dealt with in some assessments with respect to catch-at-age data by using iterative re-weighting to estimate the effective sample sizes for each fishery (McAllister and Ianelli 1997). Maunder and Harley (2003) have applied this method to length-frequency data in their tuna stock assessments and re-weighted the samples at the individual sample level rather than using fishery averages. We conducted a trial fit in last year's bigeye tuna assessment (Hampton et al. 2003) in which the mean effective sample size for each fishery was determined at each iteration using the method of McAllister and Ianelli (1997). The results indicated that effective sample sizes should be higher than assumed for length and weight frequency data for most longline fisheries and lower than assumed for the remaining fisheries. However, in the case of the bigeye tuna example, the use of the revised effective sample sizes did not materially change the results of the assessment. Nevertheless, we will consider adopting this procedure as routine in future assessments.

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].

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

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 $F_{current} / \tilde{F}_{MSY}$ 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 $B0_t$ 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.

4.6.2 Yield analysis and projections

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 1999–2001. We do not include 2002 and subsequent years in the average fishing mortality tends to have high uncertainty for the terminal data years of the analysis.

Projections to quarter 4, 2007 are incorporated into the assessment. These are constructed according to the method of Maunder et al. (2004). Essentially, the method entails the following:

- Data for all fisheries defined in the assessment are specified to quarter 4, 2007;

- Quarterly effort for the last year where data were available are repeated for each year of the projection period (i.e. from the period following that having the most recent real data to quarter 4, 2007);
- Catches during the projection period are defined as missing and are estimated by the model;
- All model parameters are estimated simultaneously for the period supported by data and for the projection period, with the exception of catchability deviations, which are set to zero for the projection period.

This procedure allows the computation of population parameters for the projection period to be integrated into the overall analysis. The advantage of this is that uncertainty in projected biomass, for example, is automatically computed by the Hessian-delta method and is inclusive of uncertainty in future recruitment (recruitment deviations are estimated) and effort effectiveness (effort deviations are estimated).

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 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 1999–2001.

5 Sensitivity analyses

Standardised effort for the longline fisheries LL1–LL5 was estimated using two alternative standardisation methods: one based on a GLM and the other on a statistical habitat-based standardisation (Bigelow et al. 2004). We did not test deterministic habitat-based standardisations (with specified habitat-preference parameters) as was the case last year, because the SHBS provided a greatly superior fit to the longline catch data than the deterministic models. The additional runs conducted for last year's assessment (one incorporating time-series expansion of fishing effort to mimic fishing power increase and the other incorporating higher purse seine catches) were not repeated this year as they were found not to have a material effect on the conclusions of the assessment.

Recent simulation analysis has indicated the possibility of spurious variation in *M*-at-age estimates (Labelle 2004). The causes of this are currently being investigated, but in the meantime, it is appropriate to conduct sensitivity analysis to see if bias in *M*-at-age, if it exists, has any bearing on the results of the assessment. We therefore conducted parallel runs in which *M*-at-age was assumed at levels similar to those used in EPO yellowfin stock assessments (Maunder and Harley 2004). The fixed *M*-at-age used in these runs is shown in Figure 9.

WCPO yellowfin tuna assessments to date have incorporated an assumption of constant catchability for the main longline fisheries (LL1–LL5) in the hope that any major time-series variation in catchability for these fisheries would have been removed by the effort standardisation procedures employed. However, it is possible, if not likely, that residual catchability variability not removed by the standardisation procedures could remain. Such variability could arise from numerous sources, including targeting effects not captured by gear configuration parameters, spatial heterogeneity in yellowfin tuna abundance within model regions, changes in the distribution of fishing effort within model regions, and others. In order to assess the potential impact of the assumption of constant catchability, a sensitivity analysis was conducted in which catchability was allowed to vary over time independently for each of fisheries LL1–LL5. However, we retained the constraint that the initial catchability for these fisheries be the same, thus inferring that the longline data are somewhat informative regarding the relative abundance of yellowfin tuna among model regions.

In summary, the analyses carried out are:

SHBS-MEST	Statistical habitat-based standardised effort for LL1–LL5, *M*-at-age estimated, constant catchability for LL1–LL5.

	For the yield analysis, a different steepness prior specification (mode = 0.75, sd = 0.18) was tested in comparison to the standard specification (mode = 0.9, sd = 0.1) (Figure 8).
SHBS-MEST-LLq	Statistical habitat-based standardised effort for LL1–LL5, *M*-at-age estimated, catchability for LL1–LL5 allowed to vary independently over time, but with the initial catchability constrained to be equal.
SHBS-MFIX	Statistical habitat-based standardised effort for LL1–LL5, *M*-at-age assumed at fixed levels, constant catchability for LL1–LL5.
GLM-MEST	General linear model standardised effort for LL1–LL5, *M*-at-age estimated, constant catchability for LL1–LL5.
GLM-MFIX	General linear model standardised effort for LL1–LL5, *M*-at-age assumed at fixed levels, constant catchability for LL1–LL5.

6 Results

Results for the five analyses are presented below. In the interests of brevity, some categories of results are presented for the SHBS-MEST 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 4. Of the constant longline catchability models, the SHBS-MEST analysis provided the best fit to the composite data and prior information (penalties). Next best was the SHBS-MFIX analysis, followed by GLM-MEST and GLM-MFIX. The GLM fits overall were substantially poorer than their SHBS counterparts, particularly in the total catch likelihood component and the higher penalties (assumed to be associated with the effort deviations).

The SHBS-MEST-LLq model provided a superior fit over the constant catchability version (SHBS-MEST) in all log-likelihood components and a significantly better fit overall according to the AIC criterion. However, despite the superior fit, the model was not considered to be an appropriate base-case (see comments below).

In order to verify (to the extent possible) that our final fit to the data was not a local solution, we conducted two fits based on the SHBS analysis in which the ratio of recent fishing mortality-at-age to the fishing mortality-at-age at MSY was constrained at values of 0.5 and 3. These constrained fits were subsequently unconstrained and allowed to converge to new solutions. In both cases, the fits converged close to the original best fit and provided essentially identical results.

6.2 Fit diagnostics (SHBS-Mest)

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 10. 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 LL1 and LL2, which could be evidence of time-series changes in catchability (catchability was constrained to be constant among years for LL1–LL5 fisheries). Secondly, the purse-seine log and school set fisheries (PS/LOG 2, PS/SCH 2, PS/LOG 3, and PS/SCH 3) show a very tight distribution of residuals up to about 1990 and are considerably more variable in the subsequent years.

- Some minor systematic lack of fit for the longline fisheries is suggested by comparisons of observed and predicted length data aggregated over time (Figure 11). Overall, 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. This lack of fit 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 12). This analysis reveals strong temporal trends in the residuals from the LL1, 2, 4, 5 fisheries over the time period, with comparable temporal trends in the residuals for both LL4 and 5. These trends may be attributable to a temporal change in the selectivity of the fisheries over the time period. For example, we speculate that the positive residuals from the fit to the length samples from LL 4 and 5 during the 1980s could relate to the shift in fishing effort to deeper longline sets yielding catches of larger fish (Figure 12). Further, the predominately negative residuals during the 1990s may be attributable to an increase in the sampling of domestic longline fisheries that may catch a higher proportion of smaller yellowfin.

- The aggregated fit to the weight frequency data (Figure 13) from LL2 and 3 is considerably better than for the length frequency data, although the proportion of larger fish in LL4 and 5 is over-estimated and there is a poor fit to the bimodal distribution of the weight data from LL1. No strong temporal trends in the residuals of the proportion of large fish are evident in the weight data, with the exception of a steady trend towards over-estimating the proportion of older fish caught by the LL1 fishery (Figure 14).

- For the CH/TW LL fisheries there is over-estimation of large fish for length data and under-estimation for weight data (Figure 11 and Figure 15). This suggests that the deterministic length-weight conversion used in the model is insufficient to accurately predict both length and weight frequencies for the same fisheries. Further, there has been a strong temporal trend in the residuals of the fits to the proportion of larger fish in both the length and weight data indicating a shift in the selectivity towards smaller fish (Figure 12 and Figure 14).

- For the Australian longline fishery, the weight-frequency prediction is very good (Figure 13 and Figure 15). 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 14).

- For some of the other fisheries with limited length frequency data, in particularly the Philippines hand-line and Indonesian fisheries, the fit to the length data, particularly for the smaller length classes, is poor (Figure 11). For these two fisheries, the model is predicting a bimodal distribution in the length composition of the catch that is not observed from the length sampling. This is likely attributable to the selectivity function that is strongly influenced by the relatively high number of tags recovered from these fisheries.

- 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. There is systematic over-estimation of tag-return numbers during the earlier 1990s. There is also an over-estimation of tag returns for about 6–13 quarters at liberty, while the model under-estimates the recovery of fish at liberty for long periods (greater than 20 quarters), although the number of observations is small (Figure 17). This requires further investigation. The fits for individual fishery groups are shown in Figure 18. The model fit to fisheries that returned large numbers of tags is generally good. The small spike in predicted returns for the Indonesia fishery, which is not matched by observations, results from the tag releases in the Philippines in 1992–93. The model expected some of these releases to be recaptured in the Indonesian fishery (which occurs in the same model region as the Philippines fisheries). It is possible that recaptures did occur, but were not returned because of a political dispute regarding fishing areas.

- 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 considerable discrepancy in the number of observed and predicted returns from the fishery (Figure 18). The higher numbers of observed tag returns indicates some degree of model failure, 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 LL1–LL5 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 LL1 fishery is evident, indicating that the effort standardisation for this fishery has not completely removed time-series catchability effects. We attempted to investigate the impact of relaxing the assumptions regarding constant catchability for the longline fisheries while maintaining some linkage between the relative catchabilities between regions (see Section 6.3.5). Also noteworthy are the positive effort deviations for LL2–5 at the beginning of the time series. These deviations correspond to very high CPUE records for these fisheries (Figure 6). This is discussed further in section 7.

6.3 Model parameter estimates (SHBS-Mest)

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 (Figure 20).

6.3.2 Natural mortality

Natural mortality shows considerable variation with size and age-class (Figure 21). There is an initial decline in natural mortality with age-class, reaching a minimum of 0.21 qtr^{-1}, after which the rate increases to about 0.45 qtr^{-1} before declining again to around 0.24 qtr^{-1} for the oldest age classes. The increase in natural mortality rate for the middle age-classes begins at about the size at first maturity. It is therefore possible that the increase is due to higher female mortality associated with spawning, and the subsequent decrease to lower natural mortality in an increasingly male-dominated population. However, we also recognise the possibility that the estimated age-specific pattern may be an artefact, and have undertaken sensitivity analyses using fixed natural mortality-at-age (Figure 9) to evaluate the significance of this for the assessment results.

6.3.3 Movement

A representation of the estimated movement probabilities is shown in Figure 22. This figure shows the regional distributions of cohorts over time, decremented for natural mortality. Movement is fairly restricted, with cohorts showing strong persistence in their regions of origin over long periods. The strongest movement occurs out of region 1 and into regions 1, 3, and 4. 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 (Figure 23). Some might be surprised at the high selectivities of older age-classes for the purse seine (particularly FAD and log sets) and Philippines fisheries. Note however that the coefficients act upon the population-at-age in the region in which the fisheries occur. If the population numbers beyond age-class 10 in a region are relatively small, high selectivity coefficients may be required to explain the size data, even if relatively few large fish are represented in the samples. For the longline fisheries, selectivity was constrained to be monotonically increasing with age-class, with the coefficients increasing to full recruitment at 3–4 years of age.

6.3.5 Catchability

Time-series changes in catchability are evident for several fisheries (Figure 24). There is evidence of a general increasing catchability in most of the purse seine fisheries. Catchability in the longline fisheries has been assumed to be constant over time in the base-case analysis, with the exception of seasonal variation (not shown in Figure 24).

For the sensitivity analysis with temporal variation in the catchability of the LL1–5 fisheries (SHBS-MEST-LLq), there were strong trends in the catchability of yellowfin although these trends differed among regions (Figure 24). For LL1, the catchability of yellowfin peaked about 1970 and then again in 2000, while catchability in LL2 and 3 steadily increased from 1970 to current. For LL4 and 5, catchabilities were highest at the commencement of the time-series, declined over the following two decades and remained relatively low through the remainder of the period (Figure 24). The higher initial catchability in these fisheries is attributable to the model attempting to improve the fit to the initial high CPUE in these two regions (Figure 6).

6.3.6 Tag-reporting rates

Estimated tag-reporting rates by fishery are shown in Figure 25. The estimates for the purse seine fisheries are all slightly higher than the modes of their prior distributions. The estimates for the Philippines 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 SHBS-MEST recruitment estimates (aggregated by year for ease of display) for each region and the WCPO are shown in Figure 26. The regional estimates display large interannual variability and variation on longer time scales, particularly in region 1 and 3 where average recruitment since the mid 1970s was substantially higher than in the preceding period. The recruitment in these regions strongly influences the trend in the aggregate WCPO recruitment estimates and overall recruitment from the mid 1970s to 2000 was considerably higher than from the 1960s and early 1970s.

For all regions 1 and 3, the increase in recruitment estimates during the mid 1970s is attributable to a steady increase in longline CPUE from these fisheries during this period (Figure 6). In previous analyses, the very high observed longline CPUE in some regions in the 1950s resulted in the estimation of very high recruitment in the early period. These trends in recruitment were considered to be unrealistic and, consequently, penalties were applied to the initial 10 deviations in the regional distribution of recruitment for regions 4 and 5 to avoid unrealistically high early recruitments. With these penalties in place, the model used positive effort deviations for LL4 and LL5 to explain the rapid decline in CPUE. The use of these penalties did not have any effect on the other model parameters or the results of yield analysis and other stock assessment interpretations.

For region 5, overall recruitment is relatively low throughout the model period, with the exception of very high recruitment in 2002. This estimate of recruitment is driven by a higher proportion of smaller fish in recent length samples from the longline catch. Given the limited observations of this cohort in the fishery, the recruitment estimate is highly uncertain. This is evident from the very broad confidence interval associated with the aggregate WCPO recruitment estimate (Figure 26). It is important to note the rapid expansion of the confidence region of the recruitment series towards the end of the time series, and in particular as the model enters the projection phase. This is expected, as the model receives no data-based information on recruitment in this phase – the point estimates and confidence region largely reflect the priors on the recruitment deviations.

A comparison of WCPO recruitment estimates for the five model options is provided in Figure 27. All analyses reveal the same trend in overall recruitment with recruitment declining from 1950 to 1960, remaining low through the 1960s and early 1970s, and then increasing during the late 1970s to plateau at a higher level. The overall magnitude of recruitment varied between analyses, with the SHBS-MEST and GLM-MEST options having lower levels of recruitment compared to the equivalent options with fixed natural mortality (SHBS-MFIX and GLM-MFIX). Recent overall recruitment was considerably higher and more variable for the SHBS-NEST-LLq option.

6.4.2 Biomass

Estimated biomass time-series for each region and for the WCPO are shown in Figure 28 for the SHBS-MEST analysis. The trends are variable between regions, reflecting the CPUE trends for LL1–LL5. There is a substantial decline in biomass in region 2, while biomass in the other regions tended to decline in the earlier period to a low level during the 1960s and then subsequently increased to a higher level during the 1980s and 1990s. These historical trends are essentially an effect of long-term trends in recruitment rather than an effect of fishing. For region 3, the biomass is estimated to have declined sharply since the late 1990s, while the biomass in region 2 continues to decline. Overall, biomass is projected to increase in the early projection period, largely due to increased biomass in region 4 and 5, the latter region driven by the estimate of very high recent recruitment. There is considerable uncertainty associated with this recruitment and this is partly evident in the confidence intervals associated with the projected biomass.

Over the longer-term of the projection, overall biomass is predicted to decline, largely due a substantial decline in the projected biomass in regions 1 and 2, although there is also a decline in projected biomass in regions 4 and 5 as the influence of the recent high recruitment is diminished (Figure 28). The projections do not indicate a decline in region 3. This is due to incomplete fishery data for 2003 resulting in lower exploitation rates being applied for the projection period.

The comparison of biomass trends for the five model options is shown in Figure 29. 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. The overall level of biomass for the two GLM models (GLM-MEST and GLM-MFIX) and the SHBS-MFIX models was lower than the base-case (SHBS-MEST) and the two GLM models revealed a considerable reduction (about 40%) in total biomass over the entire model period. Conversely, the SHBS-MEST-LLq model yielded a higher overall level of biomass than the base-case and higher variability in the biomass level largely due to greater variation in the recruitment series.

6.4.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase strongly throughout the time series (Figure 30). There are differences among the five analyses, with the highest recent exploitation rates evident in the two GLM model options. The two options with fixed natural mortality (SHBS-MFIX and GLM-MFIX) reveal a large increase in the exploitation rate of juvenile fish since 1990. A similar trend is also evident in the SHBS-MEST-LLq model.

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 31. It is immediately evident that impact has been substantial in region 2 and significant impacts have also occurred in regions 1 and 3. There is little difference in the two trajectories in regions 4 and 5. Overall, the impact of fishing has reduced the WCPO biomass by about 35% in recent years.

The exploited to unexploited biomass ratios with their approximate 95% confidence intervals are plotted in Figure 32. In recent years, the ratio is approximately 0.4 and 0.6 in regions 2 and 3, respectively. Ratios are more moderate in the sub-equatorial regions. For the WCPO as a whole, the ratio approaches 0.65 in recent years and is projected to increase slightly during the coming years at existing levels of effort.

A comparison of relative impact of fishing on the entire WCPO biomass from the five model options is presented in Figure 33. Recent levels of fishery impact are comparable for the base-case and the SHBS-MEST-LLq models, while the impacts are higher for the two GLM models. The fishery impacts are higher for the models with fixed natural mortality (SHBS-MFIX and GLM-MFIX) compared to the corresponding models with natural mortality estimated (SHBS-MEST and GLM-MEST).

It is possible to classify the fishery impact, $1-B_t/B_{0t}$, to specific fishery components in order to see which types of fishing activity have the largest impact on population biomass (Figure 34). In region 2, the Indonesian fishery has by far the greatest impact. The purse seine fishery (PS SCH 2 and PS LOG 2) had the greatest impact in the early to mid-1990s, but has since declined. In region 3, the purse seine fishery is responsible for about a third of the impact, while about 50% of the impact is attributable to the Indonesian fishery in region 2. This is due to the impact of this fishery on the overall juvenile abundance in region 2 that is conveyed to other regions by a reduction in the subsequent movement of these fish to other 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%.

6.4.5 Yield analysis

Symbols used in the following discussion are defined in Table 5. The yield analyses conducted in this assessment incorporate the SRR (Figure 35) into the equilibrium biomass and yield computations. The estimated steepness coefficient for the base-case is 0.86, close to the prior mode of 0.9. However, the steepness estimate and, consequently, the overall model results were sensitive to the assumed prior distribution (see below).

Equilibrium yield and total biomass as functions of multiples of the 1999–2001 average fishing mortality-at-age are shown in Figure 36 for the SHBS-MEST analysis. Yield is maximized at *fmult* = 1.6 for a *MSY* of 73,430 t per quarter. This implies that the ratio $F_{current}/\tilde{F}_{MSY}$ is approximately 0.63 (1/1.6). The equilibrium biomass at *MSY* is estimated at 1,173,000 t, approximately 37% of the equilibrium unexploited biomass.

The yield and equilibrium biomass curves for the five analyses are shown in Figure 37. The analyses produced variable results, with the *fmult* which maximised equilibrium yield varying between 0.9 and 1.6 (equivalent to $F_{current}/\tilde{F}_{MSY}$ ratios of 0.63–1.11).

The *MSY* estimates for these analyses range from about 62,000 t to 77,570 t per quarter (248,000 t to 310,280 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-1990. When yield is computed using the average post-1990 recruitment rather than the equilibrium recruitment, we obtain a clearer picture of *MSY* under current recruitment conditions (Figure 38). For the base-case, yield estimates at current effort levels (*fmult* = 1.0) are comparable to current catch levels and marginally higher yields could be achieved at substantially higher levels of exploitation (maximized at *fmult* = 2.5 for a *MSY* of 464,000 t per year) assuming a SRR steepness of 1.0.

A number of quantities of potential management interest associated with the yield analyses are provided in Table 6. 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 last year's assessment, 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 SHBS-MEST analysis (Figure 39). Using an approximate integration of the likelihood profile distributions, it is estimated that the probability of $F_{current}/\tilde{F}_{MSY}$ >1 is 0.15, while the probability that $B_{current}/\tilde{B}_{MSY}$ <1 is close to zero.

We found that the main way in which the model responds to the different *F* and *B* ratios is by varying the SRR steepness coefficient. It is therefore useful to compute the likelihood profile in the absence of a steepness prior. This resulted in considerable change in the stock status with respect to $F_{current}/\tilde{F}_{MSY}$ due to a shift in the steepness parameter from the prior-influenced estimate of 0.86 to and estimates of about 0.4 in the absence of a prior. Under the no steepness prior condition, the probability of $F_{current}/\tilde{F}_{MSY}$ >1 increased greatly to 0.90 (from 0.15) and the distribution is much broader indicating that higher values of $F_{current}/\tilde{F}_{MSY}$, associated with very low values of steepness, are plausible. The probability that $B_{current}/\tilde{B}_{MSY}$ <1 still remains close to zero, although the mode of the distribution is shifted considerably from 2.6 to 1.9 and the probability distribution has considerably broader tails.

The tendency towards lower values of steepness is due to the model attempting to improve the fit to the SSR. However, the data are uninformative given the broad scatter of observations (see Figure 35) and a wide range of functional relationships could be fitted to these data, hence the wide uncertainty in the $F_{current}/\tilde{F}_{MSY}$ estimates once the prior on steepness is relaxed. On this basis, it is appropriate to make assumptions regarding the plausible range of steepness and examine these through sensitivity analyses.

An alternative prior distribution for steepness was investigated in a further sensitivity analysis (prior distribution mode = 0.75 and SD = 0.18, see Section 4.1.1). This resulted in a more pessimistic assessment with an *fmult* = 0.9 ($F_{current}/\tilde{F}_{MSY}$ approximately 1.11) and $B_{current}/\tilde{B}_{MSY}$ = 2.00.

6.4.6 Projections

Biomass projections through 2007 have been incorporated into the current assessment. Uncertainty in projected biomass incorporates uncertainty in all model parameters as well as uncertainty in future recruitment and variability in the relationship between future fishing effort and fishing mortality. Catchability, however, is assumed to remain constant at the pre-projection level for all fisheries. For the projections shown in Figure 28, point estimates of biomass initially increase, largely due to the influence of the high recent recruitment in region 5, and subsequently decline steeply although uncertainty is high. The decline results because the recruitment point estimates during the projection period take values close to their long-term average, which is considerably less than the estimated recent recruitment (Figure 26).

A separate projection was undertaken removing the length samples generating the high recent recruitment in region 5. The projections based on this analysis were considerably more pessimistic, with the WCPO biomass declining sharply from the 2003 level.

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 further refinements, notably:

- Two principal effort series were considered this year; the general linear model standardized (GLM) and the statistical habitat based standardized (SHBS) effort time-series. The latter represented an overall improvement in the fit to the various sources of data and was designated as the base-case assessment. This effort series more closely approximates the effort series included in the 2002 stock assessment;
- The impact of fixing the age-specific natural mortality was investigated (MEST vs MFIX);
- The impact of relaxing the assumptions regarding the constant catchability of the LL1–5 fisheries was investigated (SHBS-MEST-LLq);
- The procedure for undertaking model projections was refined and model projections were extended to 2007 under current (2003) levels of fishing effort; and
- The computation of a wide range of reference points potentially useful for management purposes and an assessment of precision of the key reference points.

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 possibility of time-series variability in catchability in some of the longline fisheries for which catchability was assumed to be constant over years. This issue was partly addressed by allowing grouping of *initial* catchability across the LL1–LL5 fisheries (SHBS-MEST-LLq), thereby preserving some of the information on inter-regional variation in abundance inherent in the longline data, but allowing for independent time-series catchability deviations among fisheries. However, the results were inconclusive as the trends in catchability were not entirely consistent with our underlying assumptions regarding the impact of changes in the operation of the fishery over time.
- Some minor systematic lack of fit in longline length and weight samples was detected in fisheries for which both data types were available. This suggests that regional and/or time-series variation in the conversion of length-at-age to weight-at-age may be required to adequately model both types of data. There is also an indication of temporal changes in the size/age selectivity of the longline fisheries and some of the other fisheries. It may therefore be appropriate to consider time variant selectivity in some of the key fisheries. However, the benefits of adding such model structure would have to be assessed against the increased model complexity and whether such a change would make a practical difference to the model results.
- 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. The excess in observed tag returns over those predicted was relatively minor in this case, and is more of a concern for bigeye tuna.

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 2–5 during the 1950s. The model was penalised to prevent the estimation of extremely high initial recruitments in those regions. With these penalties in place, the high CPUE was ascribed to high initial catchability, as expressed by strongly positive effort deviations.

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 vs GLM); (ii) assuming constant versus time-series trends in longline catchability (LLq); and (iii) using estimated (MEST) versus assumed (MFIX) 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, although natural mortality was lower in the SHBS analyses. Similarly, the MEST analyses were more optimistic than the corresponding MFIX analyses. Natural mortality was estimated to be considerably lower for the juvenile age classes and higher for the older age classes compared to the fixed age-specific natural mortality schedule. This was balanced with higher levels of recruitment for the MFIX analyses but lower levels of biomass and lower overall yields compared to the MEST analyses.

For the SHBS-MEST-LLq analysis, recruitment, MSY, and current and reference biomass is higher than for the base-case. However, because catchability is predicted to have increased in the main fishing regions (2 and 3), the $B_{current} / \tilde{B}_0$ is lower than for the base-case. While the fitting criteria indicated a statistically significant improvement in fit over the constant catchability models, further analysis of the LLq model is required to judge whether or not the estimated trends in longline catchability are reasonable and therefore whether or not this model should be accorded equal (or greater) weight in the overall evaluation of stock status.

Overall, the GLM-MEST and SHBS-MEST are most comparable to the GLM and SHBS analyses in last year's assessment. For both sets of analyses, the current results are more pessimistic than last year's results with lower overall recruitment, lower equilibrium yields, higher current exploitation rates, and higher impacts due to fishing.

The main conclusions of the current assessment are as follow.

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 the 2002 assessment but differed from the stable pattern of recruitment in the 2003 base-case assessment (GLM standardised effort).
2. For all analyses, the trends in biomass were 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. The trends in the biomass trajectories from the various analyses deviated slightly during the early 1990s, with the GLM analyses yielding a declining trend in biomass during the 1990s, while the SHBS-MEST and SHBS-MFIX biomass levels remained relatively stable. The LLq analysis yielded a very high biomass level during the 1980s and a very steep decline in biomass during the 1990s. The three SHBS analysis predicted a very strong recent increase in biomass due to exceptionally high recent recruitment in region 5.

3. 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. This is of continuing concern. There has been recent progress made in the acquisition of a large amount of historical length frequency data from the Philippines. Once these data have been validated, they will be included in future assessments as appropriate.
4. 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 65–75% of unexploited biomass. This represents a moderate level of stock-wide depletion that would be well within the equivalent equilibrium-based limit reference point ($\tilde{B}_{MSY} / \tilde{B}_0$ = 0.34–0.37). However, depletion is somewhat greater for some individual model regions, notably in the equatorial regions 2 and 3 where recent depletion levels are approximately 0.40 and 0.50, respectively. Other regions are much less depleted, with indices of 0.90 or greater for regions 1, 4, and 5. If stock-wide over-fishing criteria were applied at the level of our model regions, we would conclude that region 2 was fully exploited, region 3 was approaching full exploitation, and the remaining regions were under-exploited.
5. 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 (2) and contributing significantly to the impact in adjacent regions 1 and 3. The purse seine fishery also has high impact in regions 2 and 3 and accounts for a significant component of the recent impact in region 5. It is notable that the composite longline fishery is responsible for biomass depletion of <5% in each region.
6. The other reference points that are useful in indicating the current status of the stock are $\tilde{Y}_{F_{current}} / MSY$ (0.90–1.00), $\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$ (0.89–1.45) and $S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$ (0.87–1.55). The yield-based reference point $\tilde{Y}_{F_{current}} / MSY$ indicates that there is limited potential to expand long-term yields from the fishery at the current pattern of age-specific selectivity. Both biomass-based reference points indicate that the long-term average biomass should remain above that capable of producing *MSY*, except in the case of the most pessimistic assessment (GLM-MFIX). We would note, however, that this apparently healthy situation arises mainly from low levels of exploitation in sub-equatorial regions of the WCPO.
7. It is also important to note that the key reference points are sensitive to our initial assumptions regarding the nature of the stock-recruitment relationship. The assumed prior distribution for the steepness parameter is highly influential and a relaxation of this assumption results in a more pessimistic assessment despite the lack of any evidence of a strong relationship between spawning stock biomass and recruitment. For future assessments, a comprehensive review of appropriate values of SRR steepness for yellowfin is required to determine appropriate values for inclusion in a range of sensitivity analyses.

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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., 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.

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., 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 1	All	Longline	1
LL 2	All excl. Taiwan & China	Longline	2
CH/TW LL 2	Taiwan and China	Longline	2
LL 3	All excl. Taiwan & China	Longline	3
CH/TW LL 3	Taiwan and China	Longline	3
LL 4	All excl. Australia	Longline	4
AU LL	Australia	Longline	4
LL 5	All	Longline	5
PS/LOG 2	All	Purse seine, log sets	2
PS/FAD 2	All	Purse seine, FAD sets	2
PS/SCH 2	All	Purse seine, school sets	2
PS/LOG 3	All	Purse seine, log sets	3
PS/FAD 3	All	Purse seine, FAD sets	3
PS/SCH 3	All	Purse seine, school sets	3
PH RN	Philippines	Ringnet	2
PH HL	Philippines	Handline	2
ID	Indonesia	Various	2

Table 2. Main structural assumptions of the yellowfin tuna base-case analysis (SHBS-MEST), 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 0.04 times actual sample size for non-longline fisheries and 0.1 times for longline 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 the actual sample size for the Australian longline fishery, and 0.1 times the actual sample size for other longline 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	5	-	-	0	100
Tag reporting	Purse seine reporting rates constrained to be equal. PH RN and PHHL rates constrained to be equal. All reporting rates constant over time.	LL 1–LL5, CH/TW LL fisheries	7	0.5	0.7	0.001	0.9
		AU LL fishery	1	0.8	0.7	0.001	0.9
		PS fisheries	1	0.42	0.05	0.001	0.9
		PH, ID fisheries	2	0.8	0.05	0.001	0.9
Tag mixing	Tags assumed to be randomly mixed at the model region level from the quarter following the quarter of release.	None	na	na	na	na	na
Recruitment	Occurs as discrete events at the start of each quarter. Spatially-aggregated recruitment is weakly related to spawning biomass in the prior quarter via a Beverton-Holt SRR (beta prior for steepness with mode at 0.9 and SD of 0.04) .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)	232	SRR	0.7	-20	20
		Average spatial distribution of recruitment	4	-	-	0	1

		Time series deviations from average spatial distribution (ln)	923	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	-	-	-0.69	0.69
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	350	-	-	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)	13	-	-	-15	1
		Seasonality amplitude (ln)	14	0	2.2	-	-
		Seasonality phase	14	-	-	-	-
		Catchability deviations PH/ID (ln)	48	0	0.1	-0.8	0.8
		Catchability deviations other (ln)	105	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–LL5 (ln)	1125	0	0.16	-6	6
		Effort deviations PH, ID (ln)	454	0	0.22	-6	6
		Effort deviations other (ln)	939	0	0.7	-6	6
Natural mortality	Age-dependent but constant over time and among regions. Smoothing penalties constrain the age-dependency.	Average natural mortality (ln)	1	-	-	-	-
		Age-specific deviations (ln)	27	0	0.22	-5	5
Movement	Age-dependent and varies by quarter but constant among years. Age-dependency for each coefficient (2 per region boundary) is log-linear.	Movement coefficients	48	0	0.32	0	3
		Age-dependent component (ln)	48	0	0.32	-4	4

Table 3. Summary of model options.

Option	Longline effort	Longline catchabilty	Natural mortality
SHBS-Mest	SHBS	Constant	Estimated
SHBS-Mest-LLq	SHBS	Estimated	Estimated
SHBS-Mfix	SHBS	Constant	Fixed
GLM-Mest	GLM	Constant	Estimated
GLM-Mfix	GLM	Constant	Fixed

Table 4. Details of objective function components for the two analyses using alternative longline effort series.

Objective function component	SHBS-Mest	SHBS-Mest-LLq	SHBS-Mfix	GLM-Mest	GLM-Mfix
Total catch log-likelihood	326.79	319.79	335.05	405.69	412.45
Length frequency log-likelihood	-395,825.12	-396,034.97	-395,889.65	-395,741.37	-395,813.67
Weight frequency log-likelihood	-273,636.60	-273,718.04	-273,548.95	-273,613.93	-273,604.32
Tag log-likelihood	2,254.67	2,290.61	2,217.05	2,317.08	2,247.15
Penalties	4,126.43	3,942.56	4,259.62	4,259.83	4,448.27
Total function value	-662,753.83	-663,200.05	-662,626.88	-662,372.70	-662,310.12
Maximum gradient at termination	0.0232	0.3015	0.6297	0.0649	0.0035

Table 5. Description of symbols used in the yield analysis.

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 1999–2001
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (*MSY*)
$\tilde{Y}_{F_{current}}$	Equilibrium yield at $F_{current}$
$\tilde{Y}_{F_{MSY}}$ (or *MSY*)	Equilibrium yield at F_{MSY} , or maximum sustainable yield
$\tilde{B}_0$	Equilibrium unexploited total biomass
$\tilde{B}_{F_{current}}$	Equilibrium total biomass at $F_{current}$
$\tilde{B}_{MSY}$	Equilibrium total biomass at MSY
$S\tilde{B}_0$	Equilibrium unexploited adult biomass
$S\tilde{B}_{F_{current}}$	Equilibrium adult biomass at $F_{current}$
$S\tilde{B}_{MSY}$	Equilibrium adult biomass at MSY
$B_{current}$	Average current (1999–2001) total biomass
$SB_{current}$	Average current (1999–2001) adult biomass
$B_{current,F=0}$	Average current (1999–2001) total biomass in the absence of fishing.

Table 6. 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 (gray shading).

Management quantity	Units	SHBS-Mest	SHBS-LLq-Mest	SHBS-Mfix	GLM-Mest	GLM-Mfix
$\tilde{Y}_{F_{current}}$	t per quarter	66,350	75,230	59,810	76,010	62,210
$\tilde{Y}_{F_{MSY}}$ (or MSY)	t per quarter	73,430	77,570	62,090	77,120	62,350
$\tilde{B}_0$	t	3,159,000	4,025,000	2,713,000	2,870,000	2,566,000
$\tilde{B}_{F_{current}}$	t	1,703,000	1,758,000	1,235,000	1,238,000	803,300
$\tilde{B}_{MSY}$	t	1,173,000	1,366,000	976,800	1,050,000	899,100
$\tilde{SB}_0$	t	1,781,000	2,300,000	1,694,000	1,596,000	1,602,000
$\tilde{SB}_{F_{current}}$	t	860,100	893,700	660,600	579,500	389,900
$\tilde{SB}_{MSY}$	t	553,700	668,500	496,800	474,800	448,500
$B_{current}$	t	2,885,688	3,135,970	2,406,873	1,889,955	1,569,918
$SB_{current}$	t	1,490,388	1,671,181	1,325,752	930,028	824,864
$B_{current, F=0}$	t	4,339,143	4,752,748	3,914,993	3,176,210	3,068,484
$B_{current} / \tilde{B}_0$		0.91	0.78	0.89	0.66	0.61
$B_{current} / \tilde{B}_{F_{current}}$		1.69	1.78	1.95	1.53	1.95
$B_{current} / \tilde{B}_{MSY}$		2.46	2.30	2.46	1.80	1.75
$B_{current} / B_{current, F=0}$		0.67	0.66	0.61	0.60	0.51
$SB_{current} / \tilde{SB}_0$		0.84	0.73	0.78	0.58	0.51
$SB_{current} / \tilde{SB}_{F_{current}}$		1.73	1.87	2.01	1.60	2.12
$SB_{current} / \tilde{SB}_{MSY}$		2.69	2.50	2.67	1.96	1.84
$\tilde{B}_{F_{current}} / \tilde{B}_0$		0.54	0.44	0.46	0.43	0.31
$\tilde{SB}_{F_{current}} / \tilde{SB}_0$		0.48	0.39	0.39	0.36	0.24
$\tilde{B}_{MSY} / \tilde{B}_0$		0.37	0.34	0.36	0.37	0.35
$\tilde{SB}_{MSY} / \tilde{SB}_0$		0.31	0.29	0.29	0.30	0.28
$F_{current} / \tilde{F}_{MSY}$		0.63	0.77	0.77	0.83	1.11
$\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$		1.45	1.29	1.26	1.18	0.89
$\tilde{SB}_{F_{current}} / \tilde{SB}_{MSY}$		1.55	1.34	1.33	1.22	0.87
$\tilde{Y}_{F_{current}} / MSY$		0.90	0.97	0.96	0.99	1.00

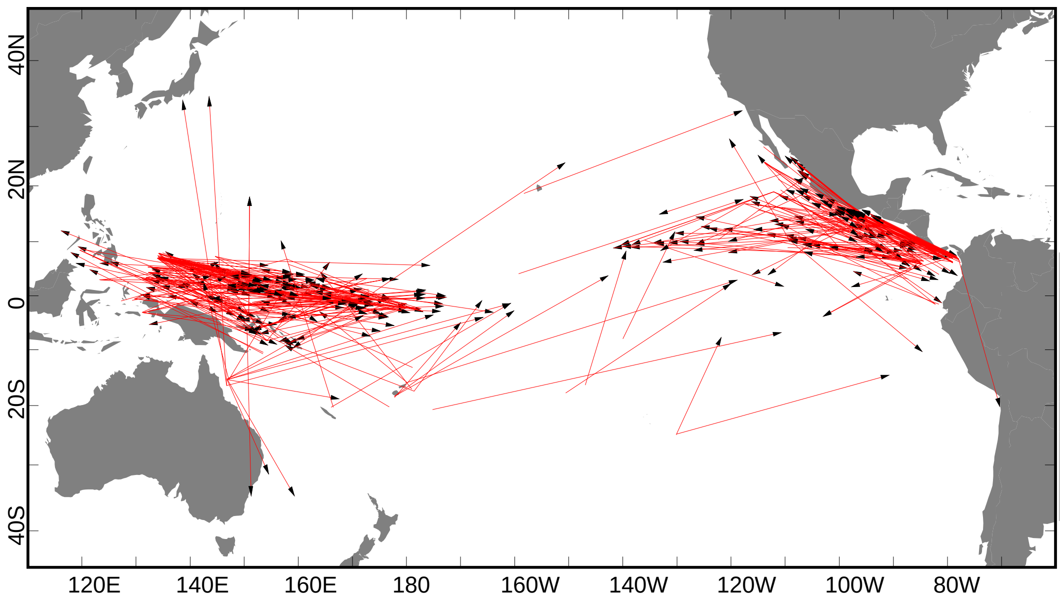


Figure 1. Long-distance (>1,000 nmi) movements of tagged yellowfin tuna.

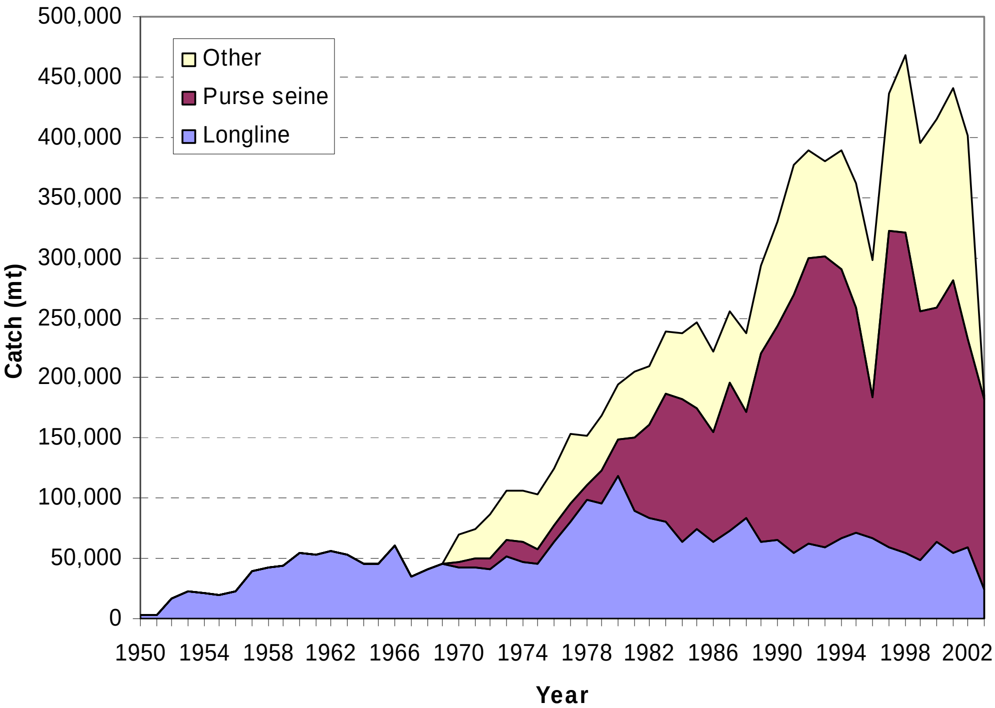


Figure 2. Annual WCPO yellowfin tuna catch, by gear.

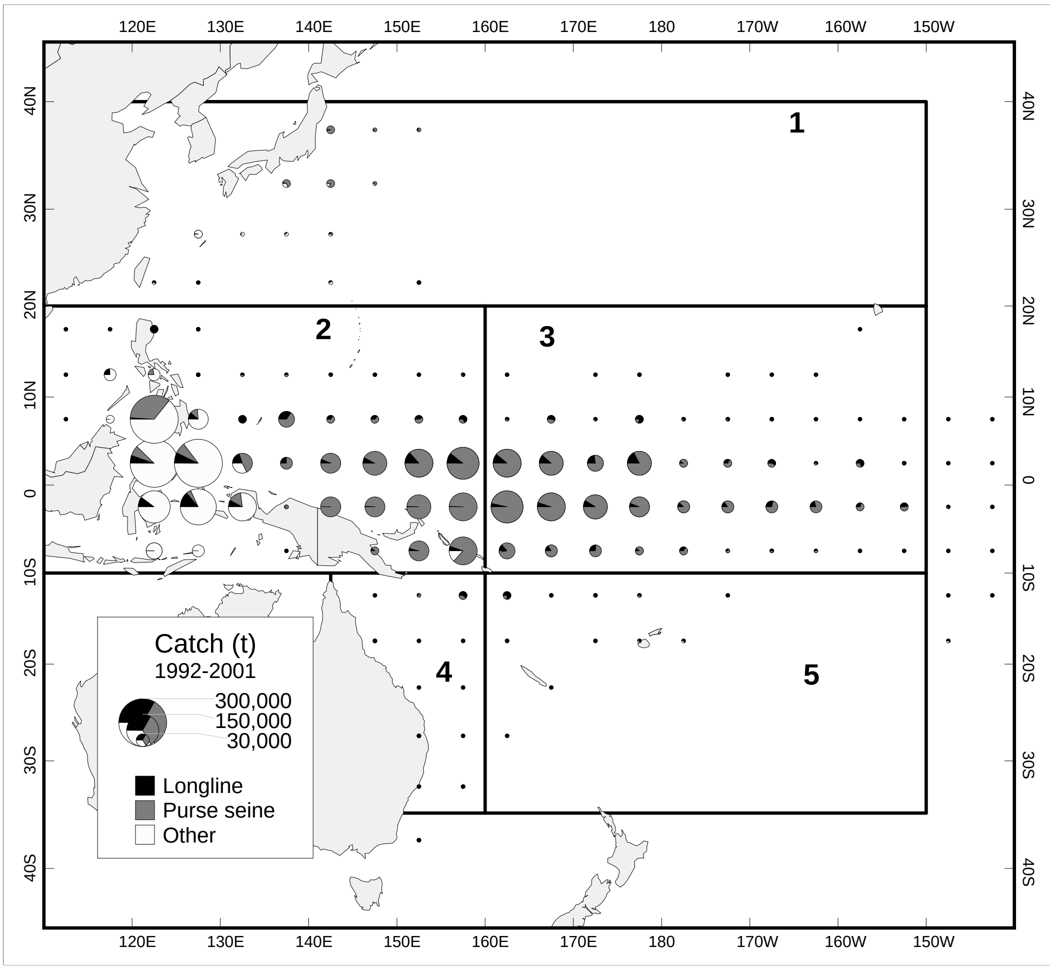


Figure 3. Distribution of yellowfin tuna catch, 1992–2001. The heavy lines indicate the spatial stratification used in the MULTIFAN-CL model.

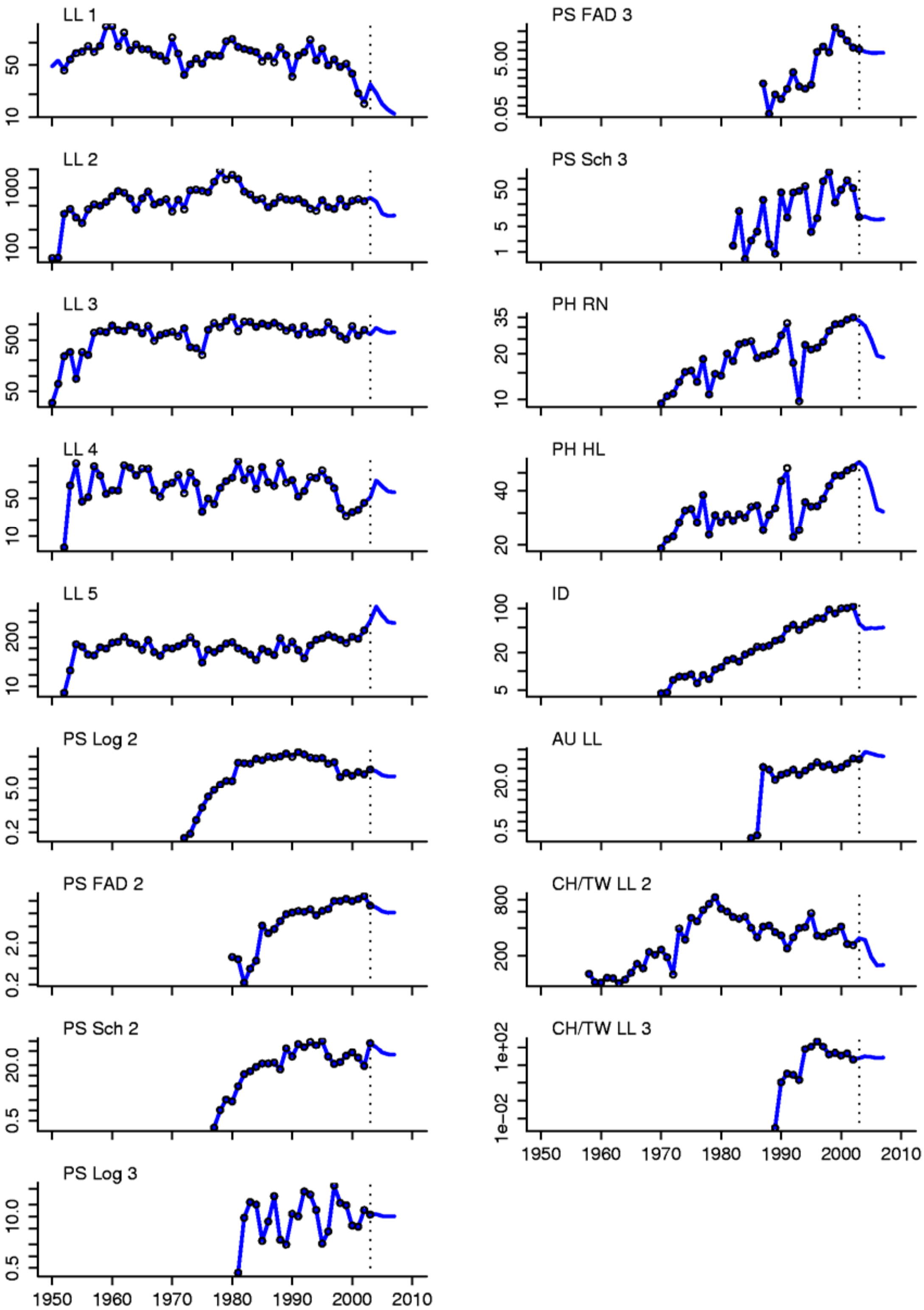


Figure 4. Annual catches, by fishery. Circles are observed and the lines are model predictions. Units are catch number in thousands for the longline fisheries and thousand metric tonnes for all other fisheries. The vertical dotted lines indicate the point at which population projections are made with assumed levels of effort.

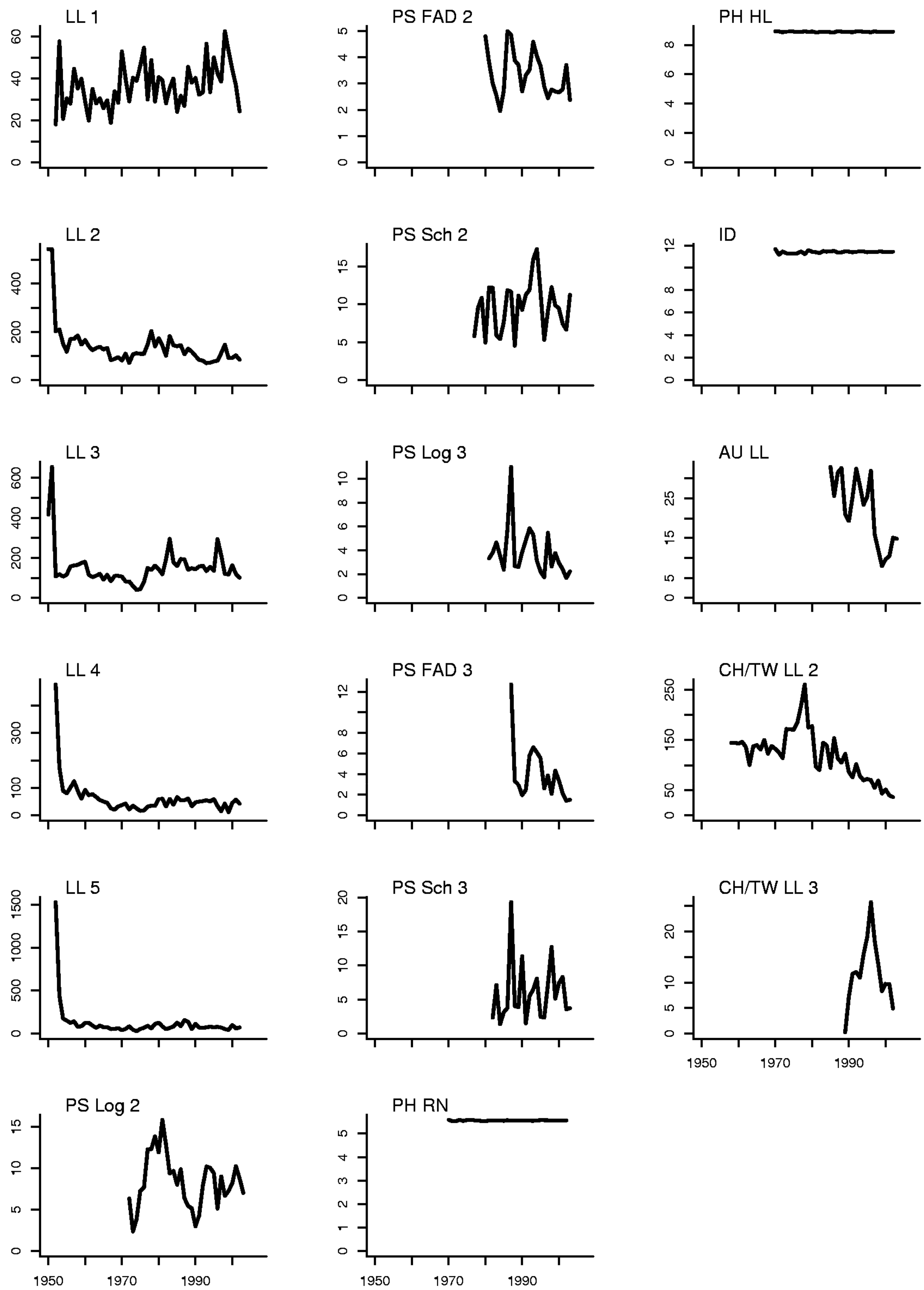


Figure 5. Catch-per-unit-effort (CPUE) by fishery. Units are catch number per statHBS-standardised effort (fisheries LL1–LL5), catch number per 100 nominal hooks (AU LL, CH/TW LL) and catch (t) per day fished/searched (all PS fisheries). Note that CPUE for PH RN, PH HL and ID are arbitrary and not based on data (see discussion on catchability and effort deviation constraints for these fisheries).

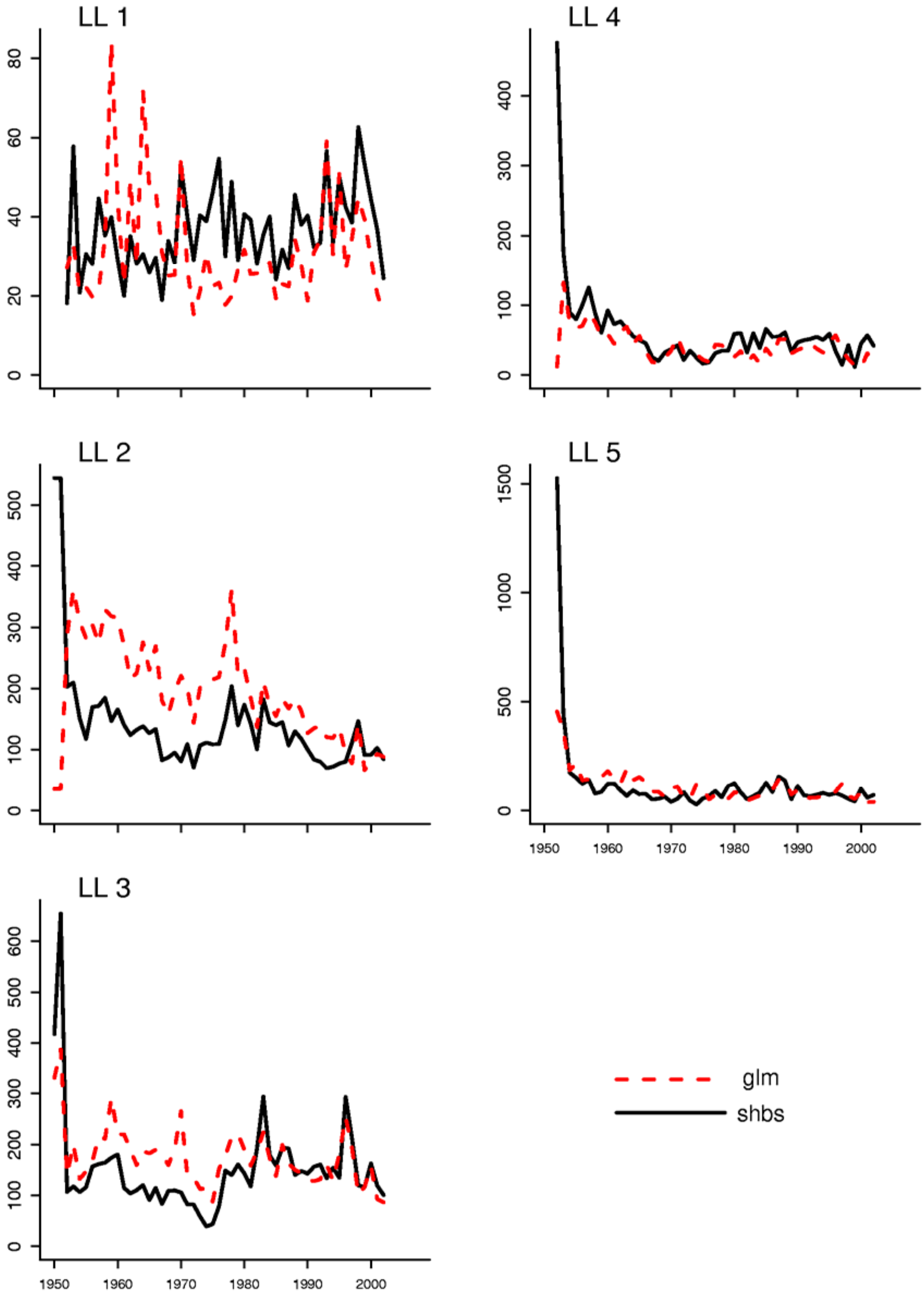


Figure 6. Catch-per-unit-effort (CPUE) for the longline fisheries LL1–LL5 standardised using two different methodologies (glm = general linear model; shbs = statistical habitat-based standardisation).

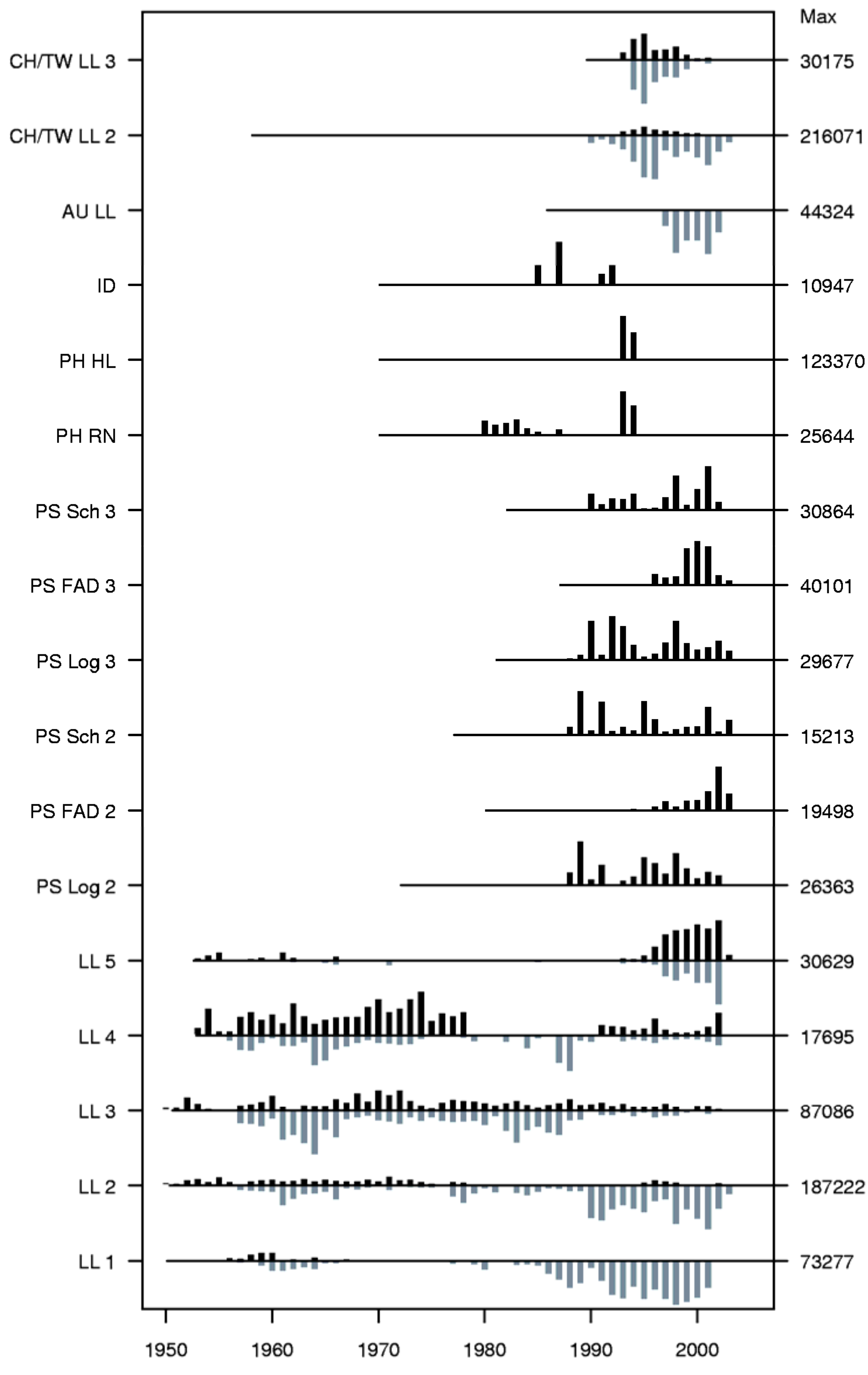


Figure 7. Number of fish size measurements by year for each fishery. The upper black bars represent length measurements and the lower grey bars represent weight measurements. The maximum bar length for each fishery is given on the right-hand side. The extent of the horizontal lines indicates the period over which each fishery occurred.

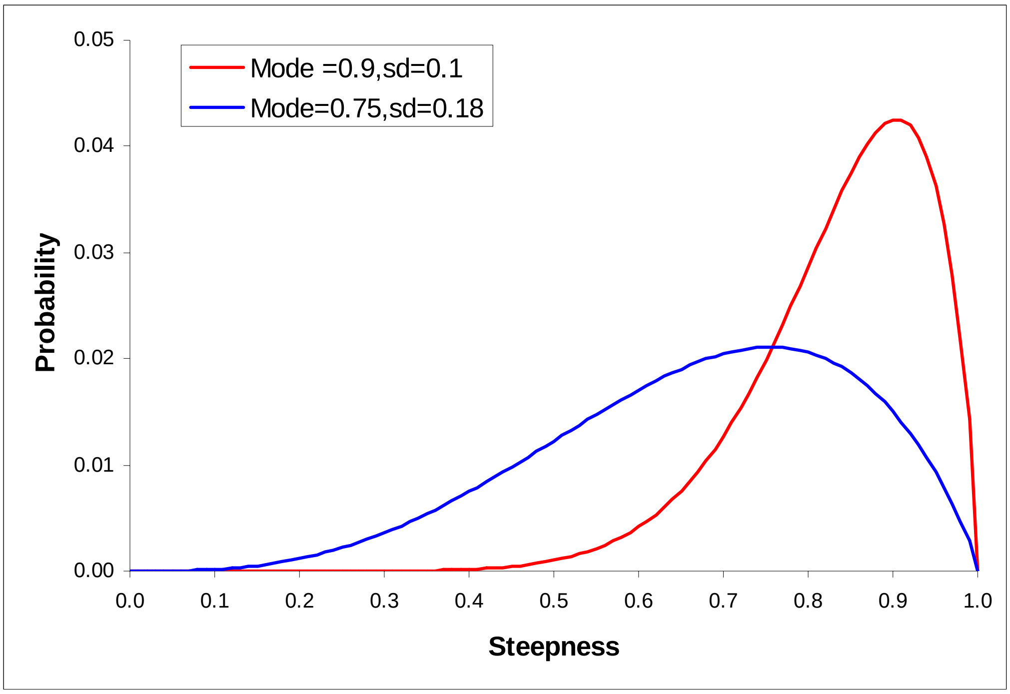


Figure 8. Priors for steepness parameter of the relationship between spawning biomass and recruitment (SSR).

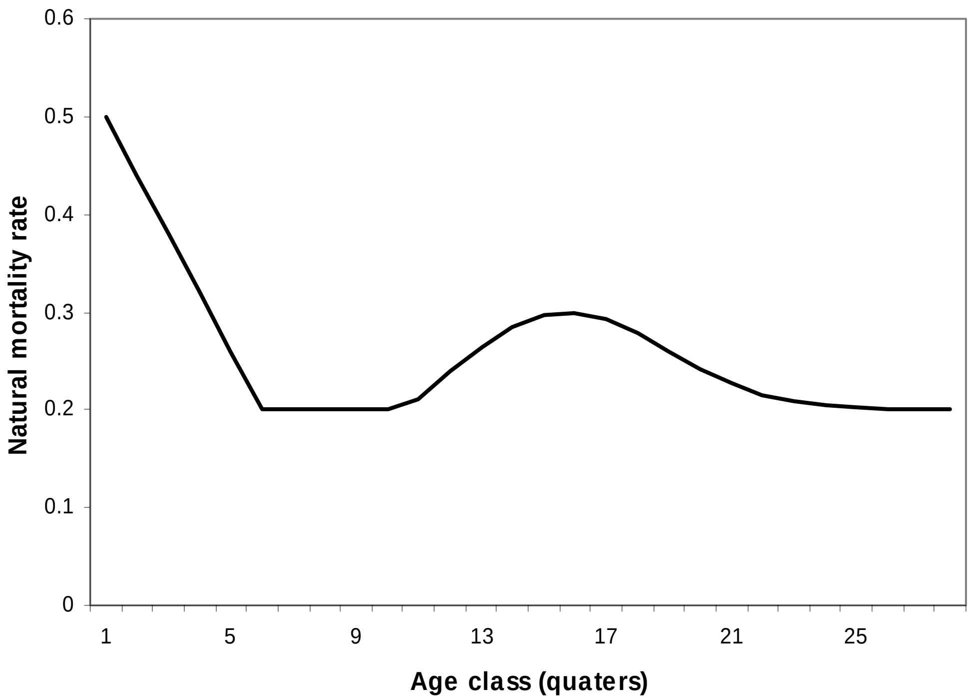


Figure 9. Age-specific natural mortality assumed for the sensitivity analyses using a fixed natural mortality (SHBS-Mest and GLM-Mest) from Maunder and Harley (2004).

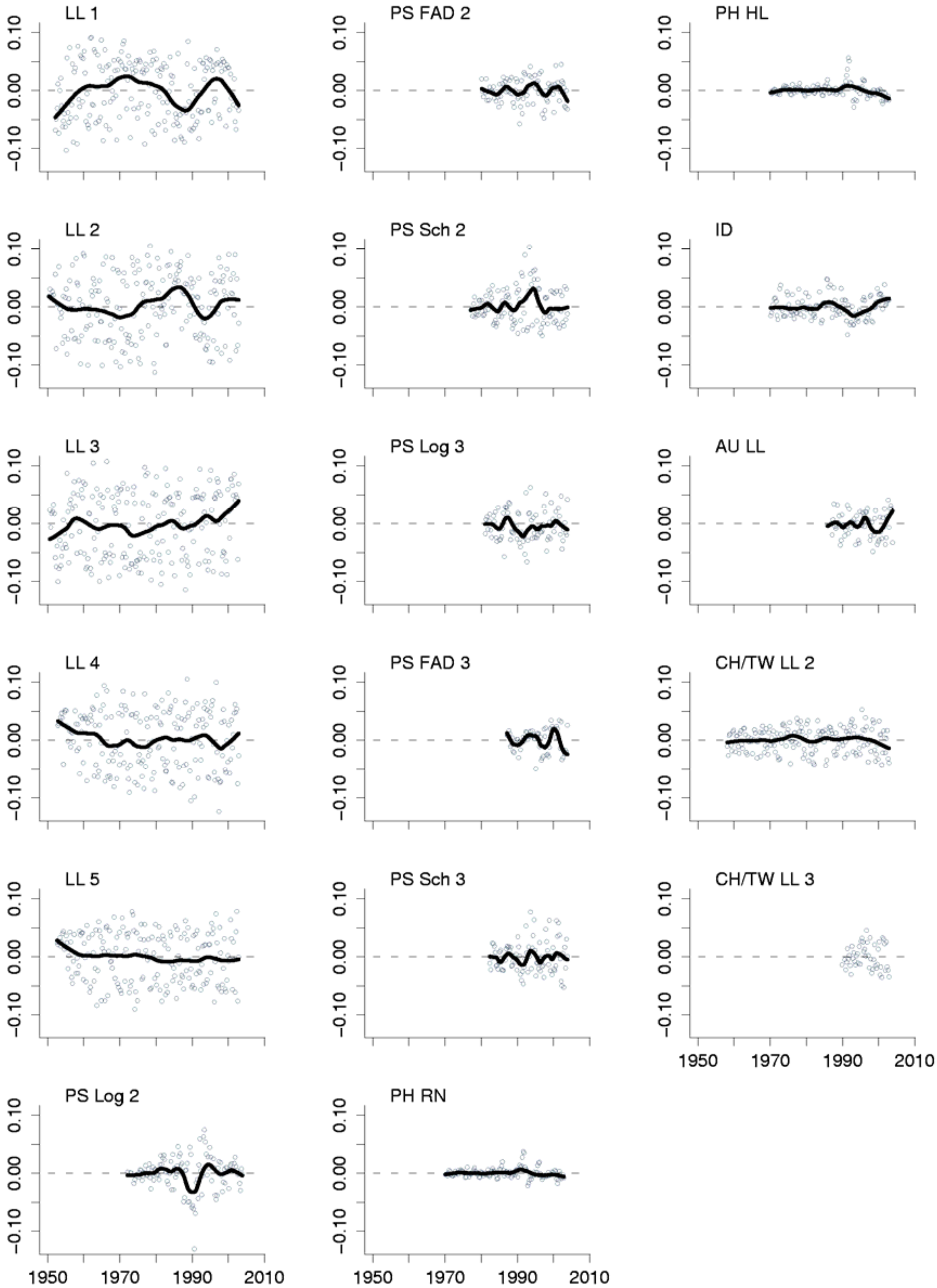


Figure 10. Residuals of ln (total catch) for each fishery. The solid line represents a lowess fit to the data.

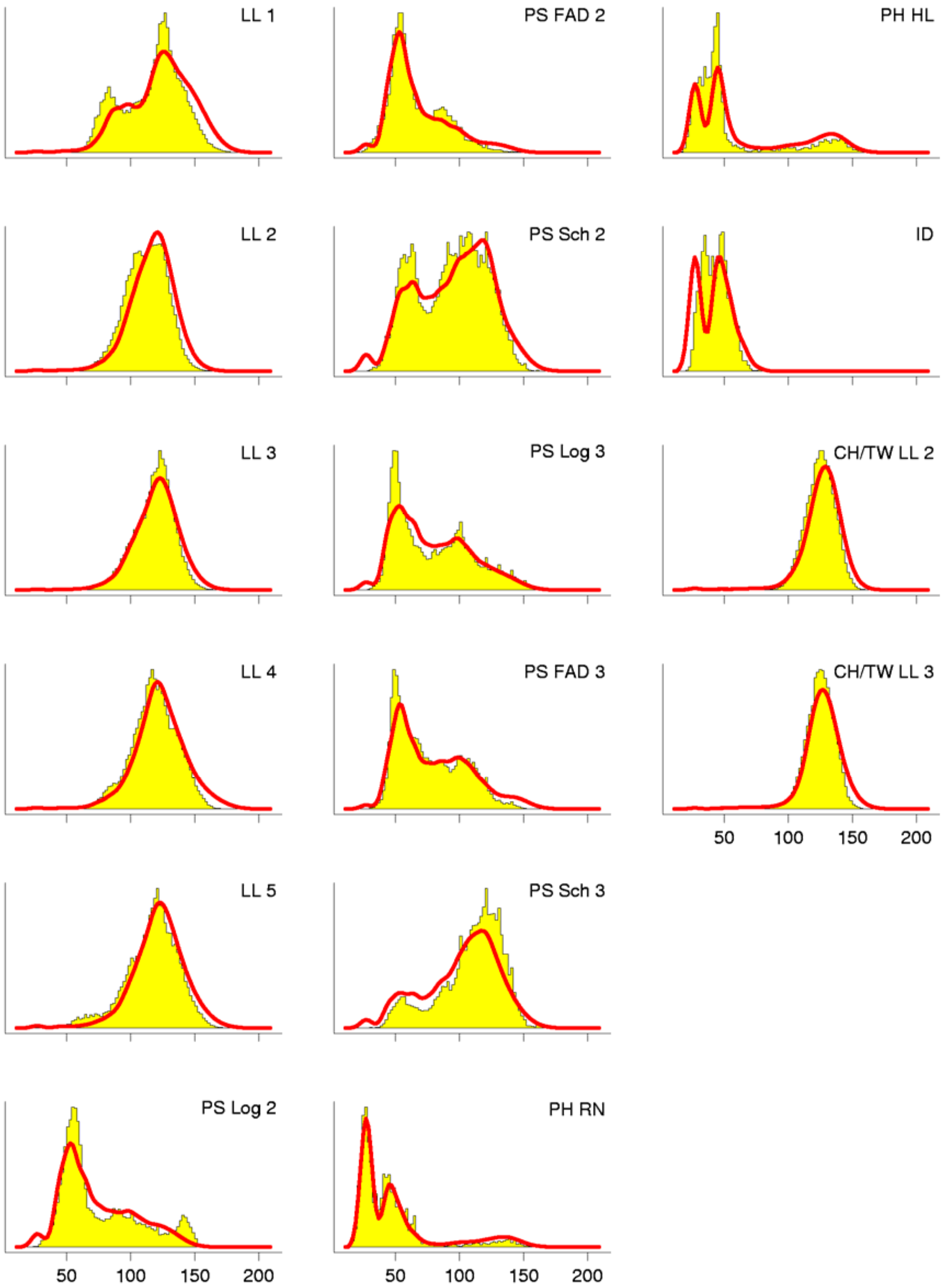


Figure 11. Observed (histograms) and predicted (line) length frequencies (in cm) for each fishery aggregated over time.

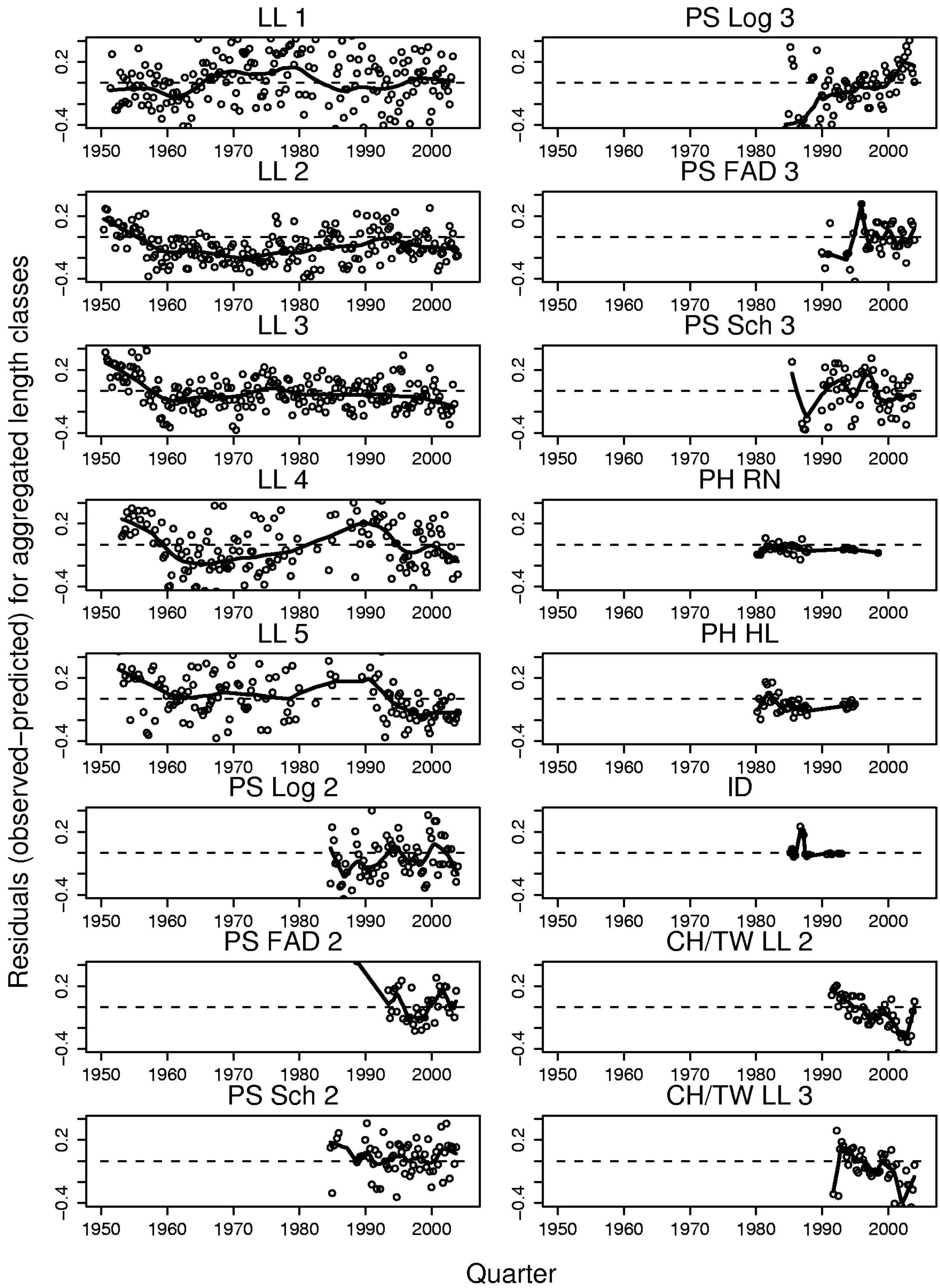


Figure 12. **Residuals (observed – predicted) of the aggregated proportion of fish in the larger length classes from sampled and predicted catches by fishery and sample period. The aggregated length range is 125-170 cm for all the longline fisheries and 70-120 cm for all other fisheries. The line represents a lowess smoothed fit to the data.**

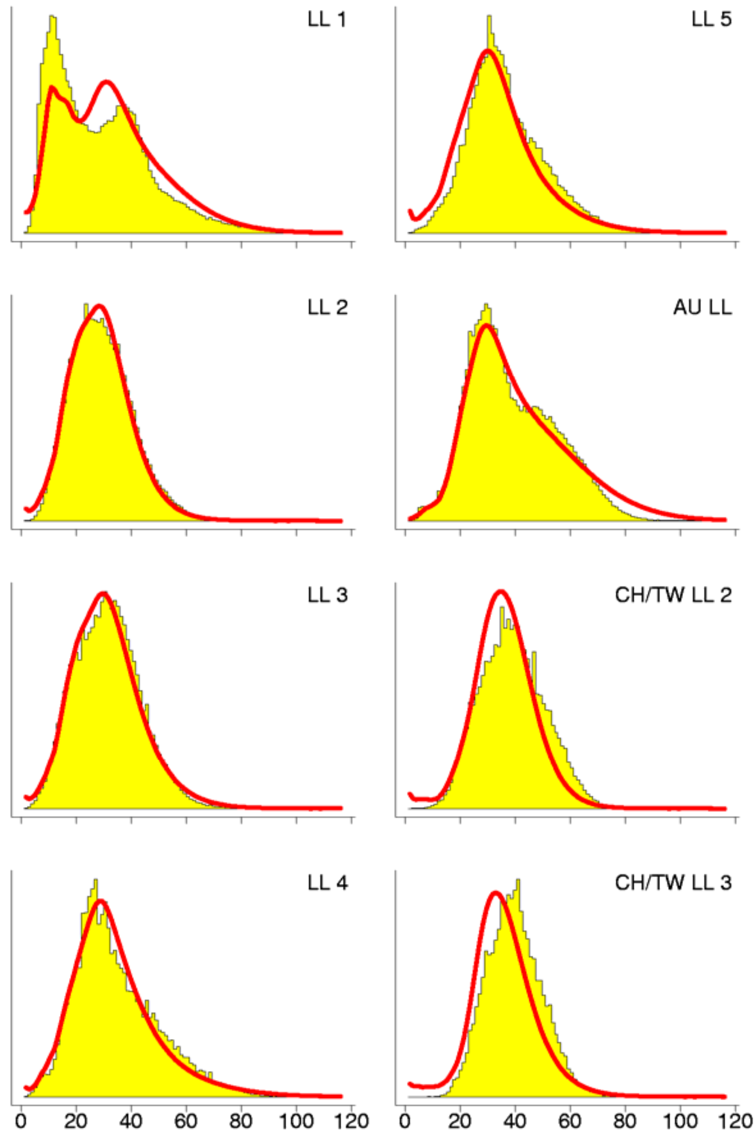


Figure 13. Observed (histograms) and predicted (line) weight frequencies (in kg) for each fishery aggregated over time.

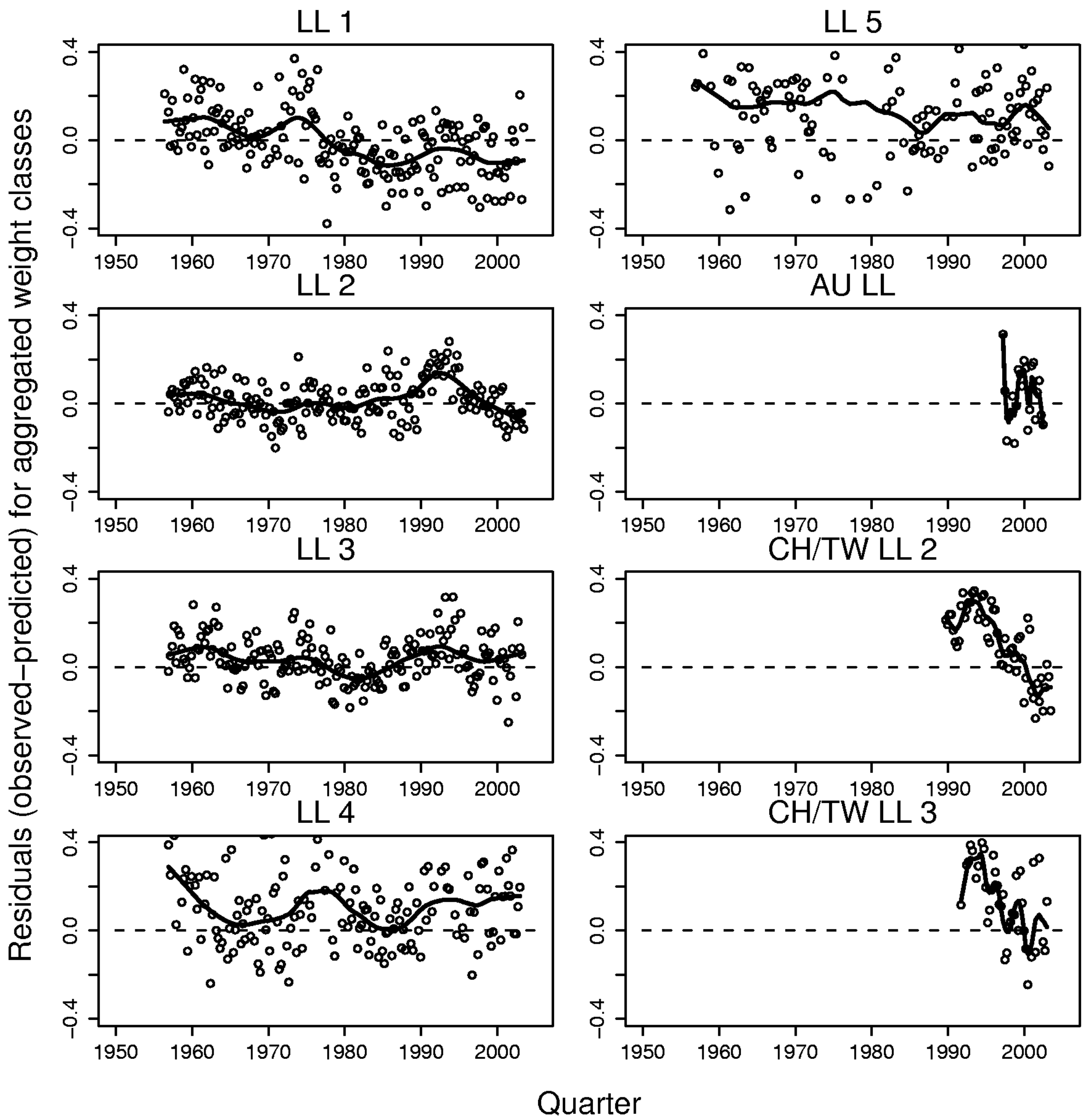
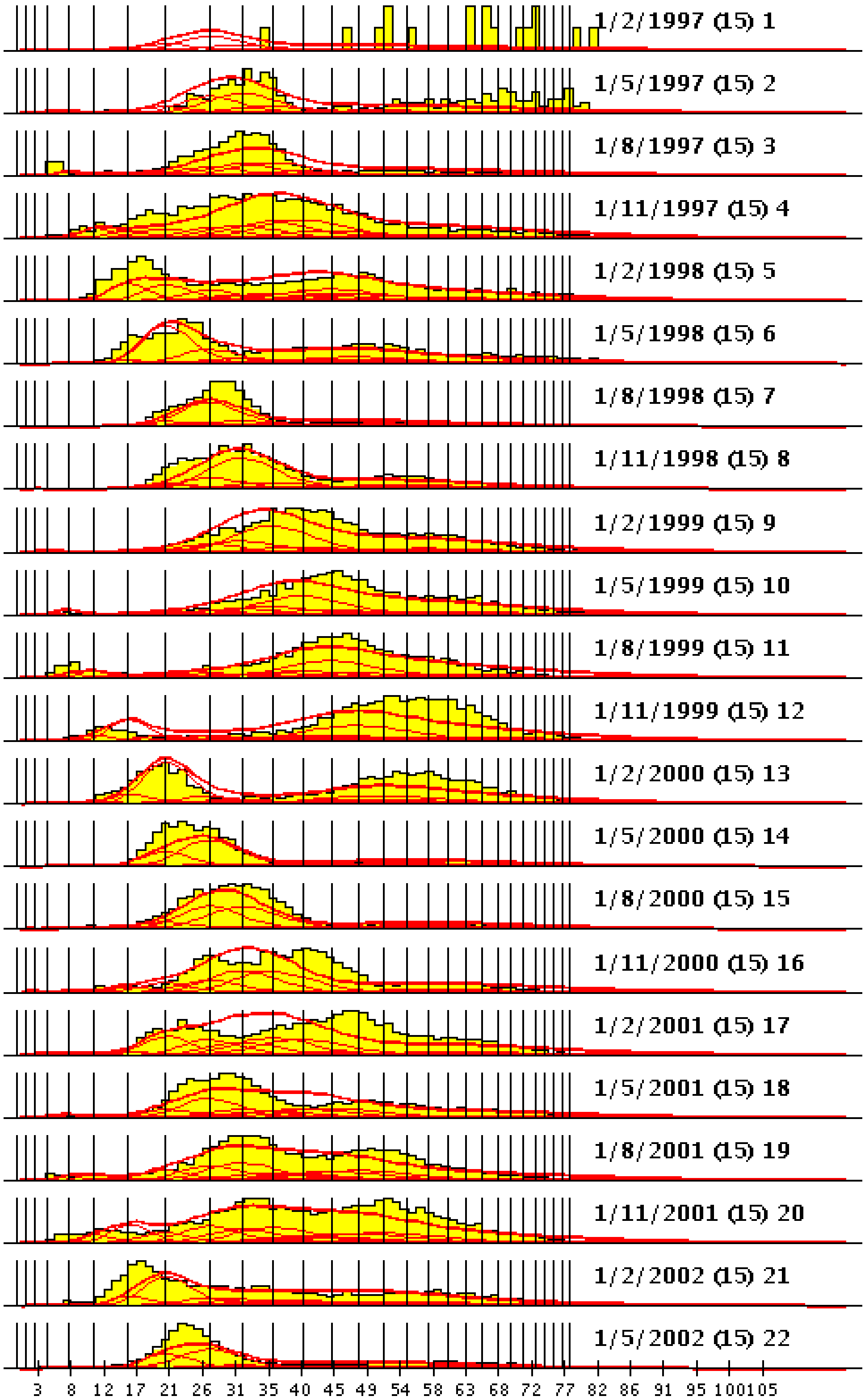


Figure 14. Residuals (observed – predicted) of the aggregated proportion of fish in the larger weight classes (35-70 kg) from sampled and predicted catches by fishery and sample period. The line represents a lowess smoothed fit to the data.



Weight (kg)

Figure 15. Time-series fit (lines) to weight-frequency data (histograms) for the Australian longline fishery. Vertical bars indicate the estimated mean weights at age (quarters). Labels are in the form week/month/year (fishery) sample number.

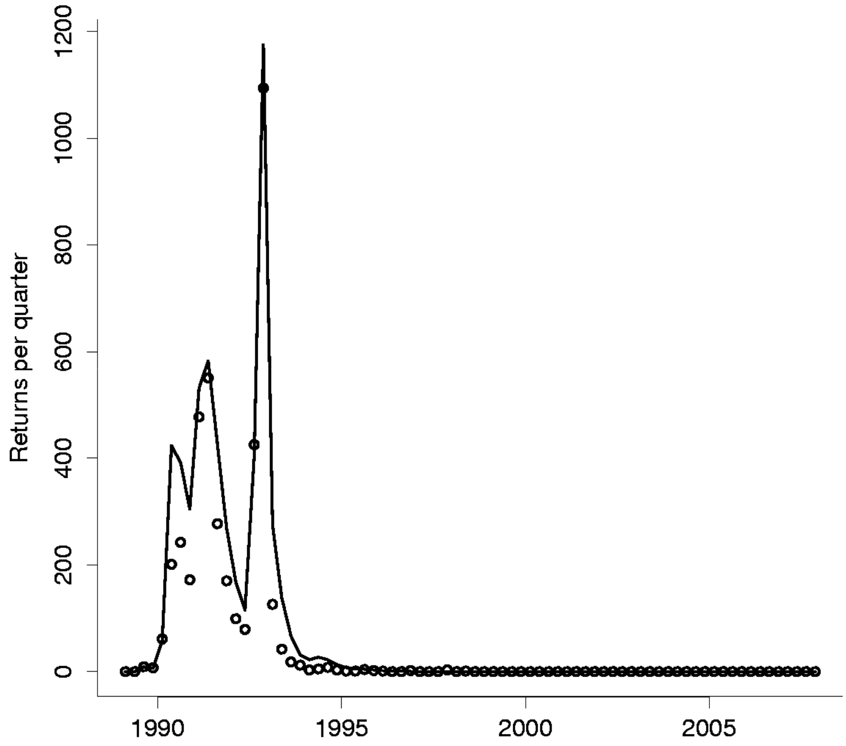


Figure 16. Number of tag returns by recapture period (quarter).

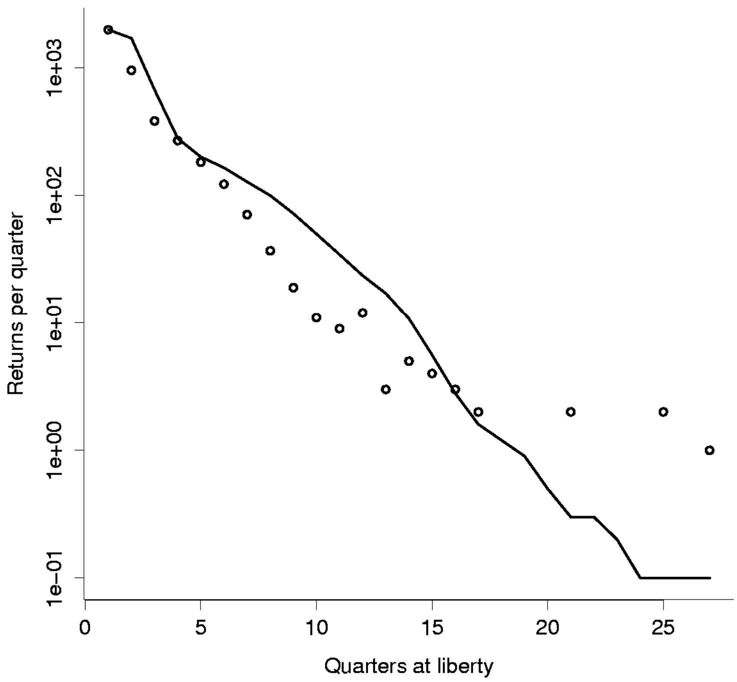


Figure 17. Number of tag returns by periods at liberty (quarters).

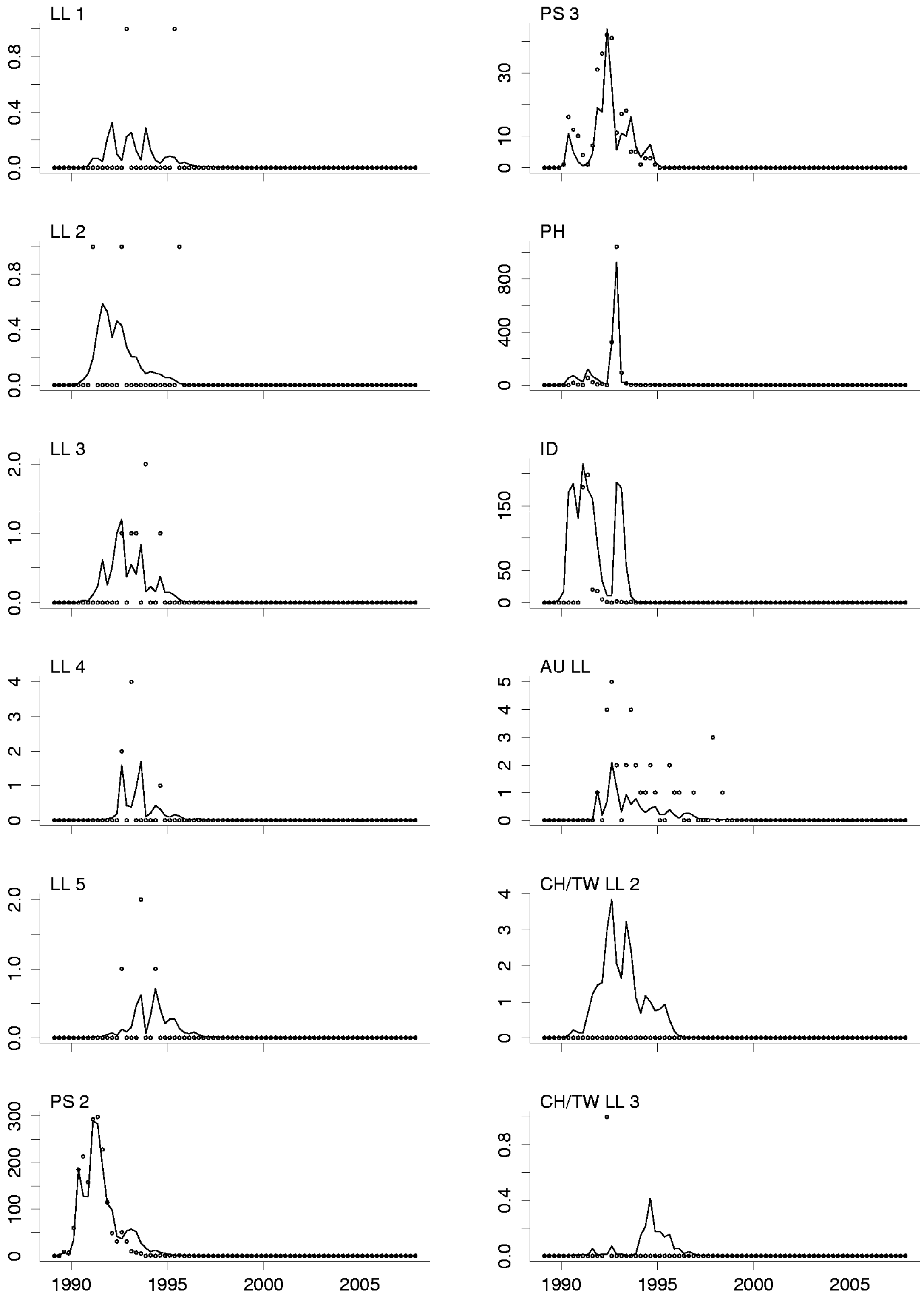


Figure 18. Number of tag returns by recapture period (quarter) for the various fisheries (or groups of fisheries) defined in the model.

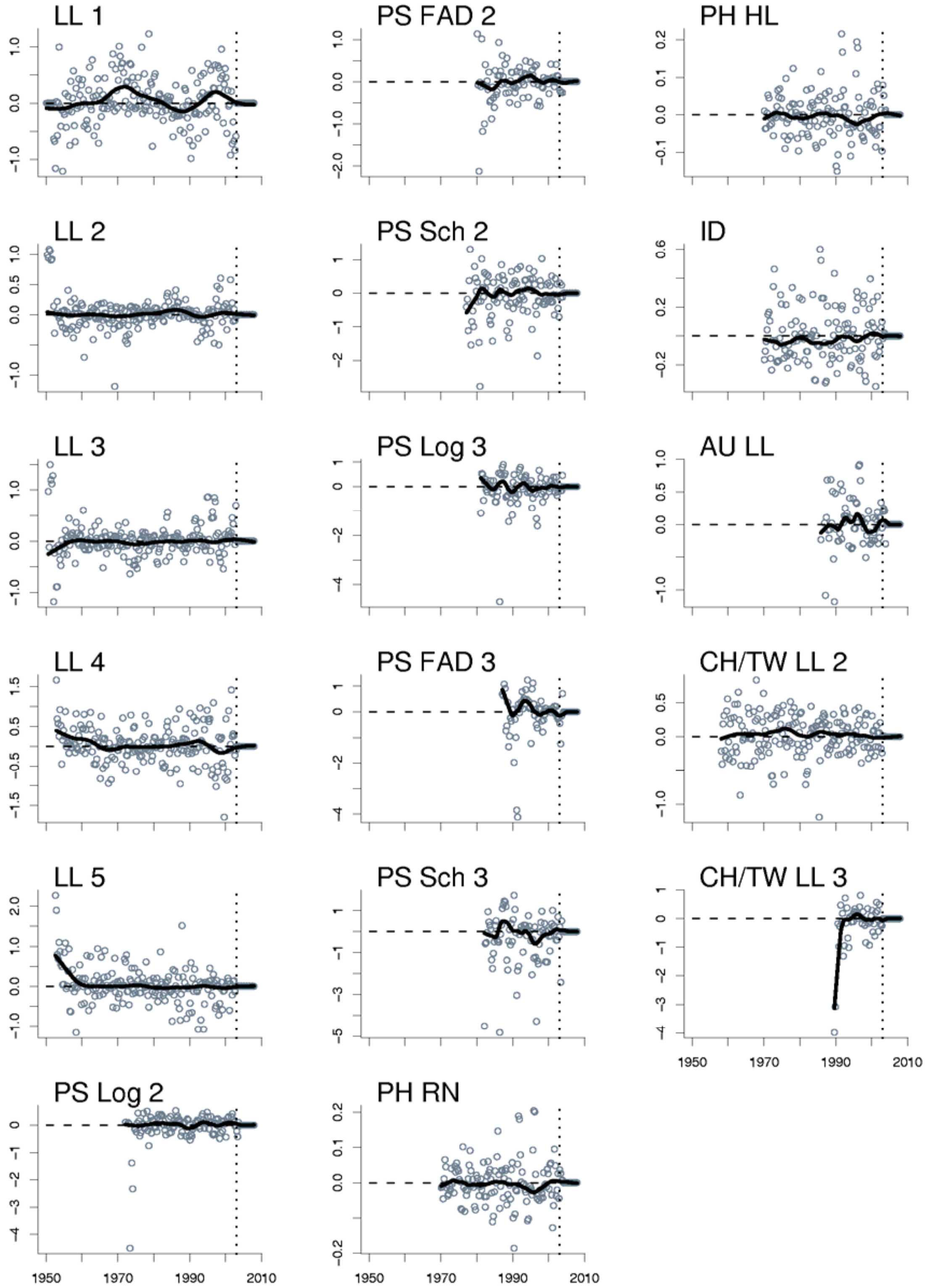


Figure 19. Effort deviations by time period for each fishery. The vertical dotted lines indicate the point at which population projections are made with assumed levels of effort. The solid line represents a lowess fit to the data.

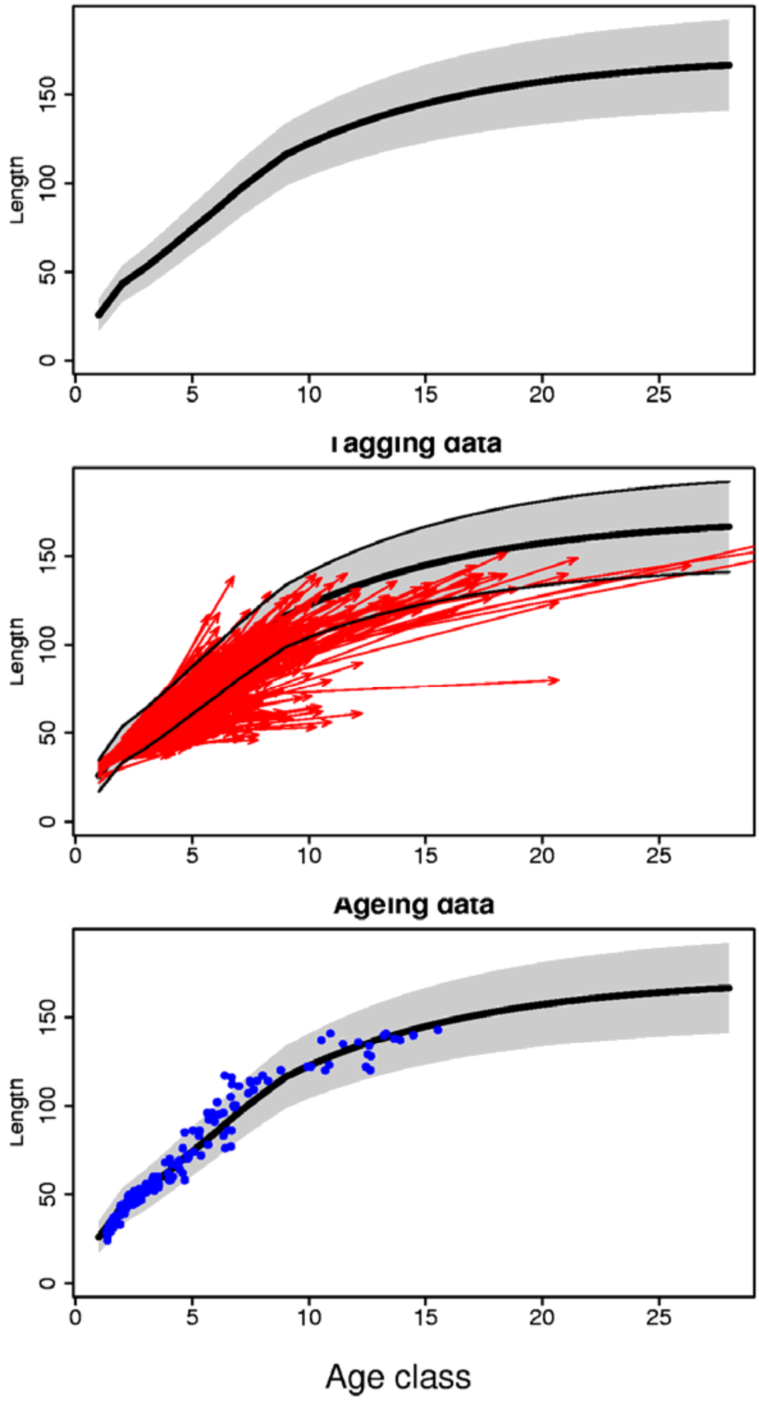


Figure 20. Estimated mean lengths-at-age (heavy line) and the variability of length-at-age (shaded area represents ± 2 SD). Age is in quarters and length is in cm (top figure). For comparison, length at age estimates are presented from tag release and recapture data (middle figure) and empirical age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

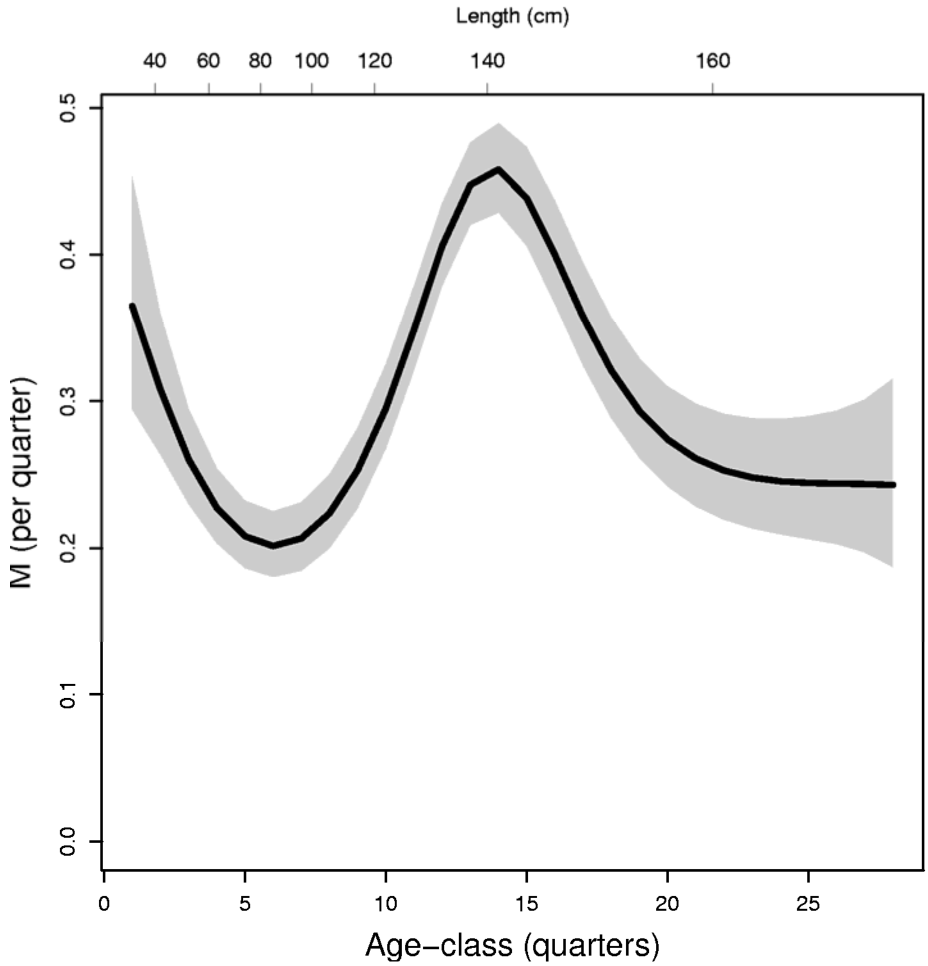


Figure 21. Estimated natural mortality rate by age class. The shaded area represents ± 2 SD.

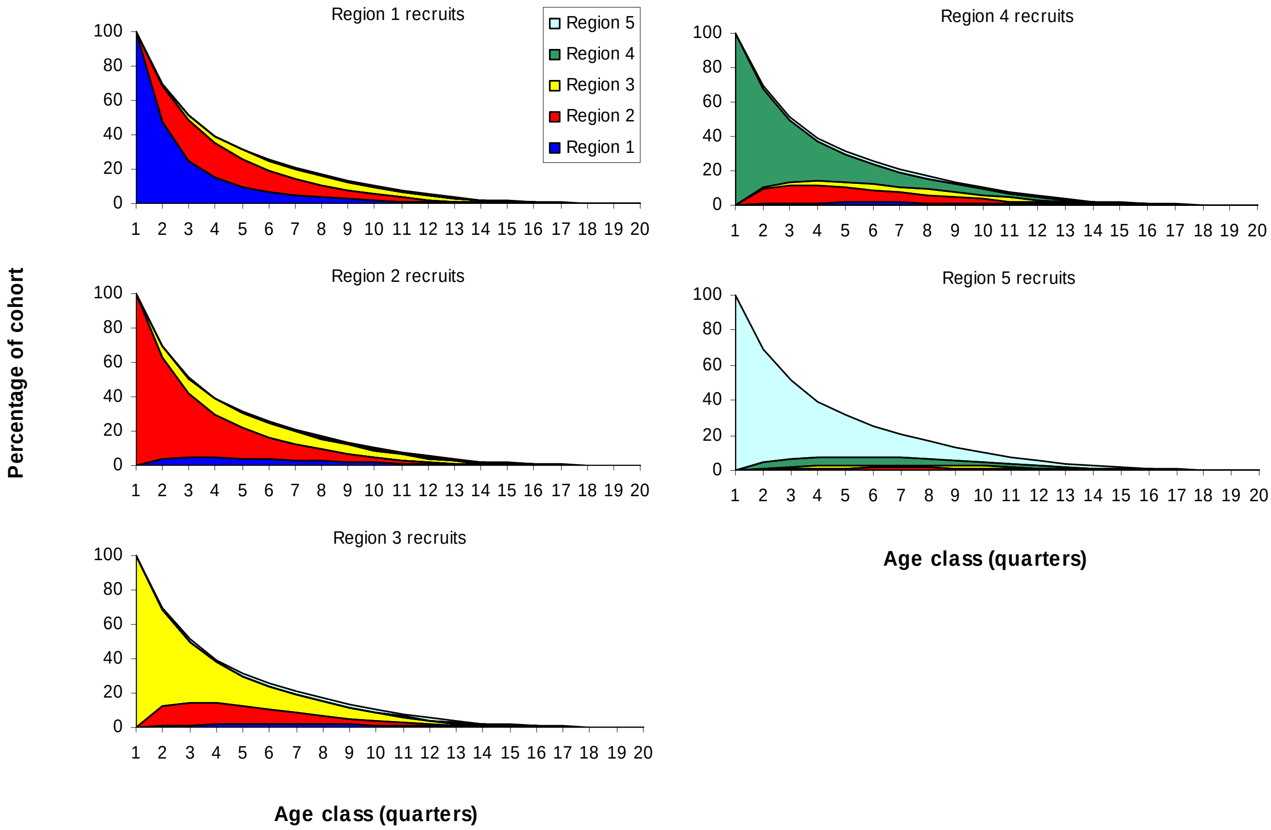


Figure 22. Regional distribution over time of simulated cohorts of 100 fish originating in each region (SHBS-MEST model). The cohorts have been decremented by age-specific natural mortality at each time step.

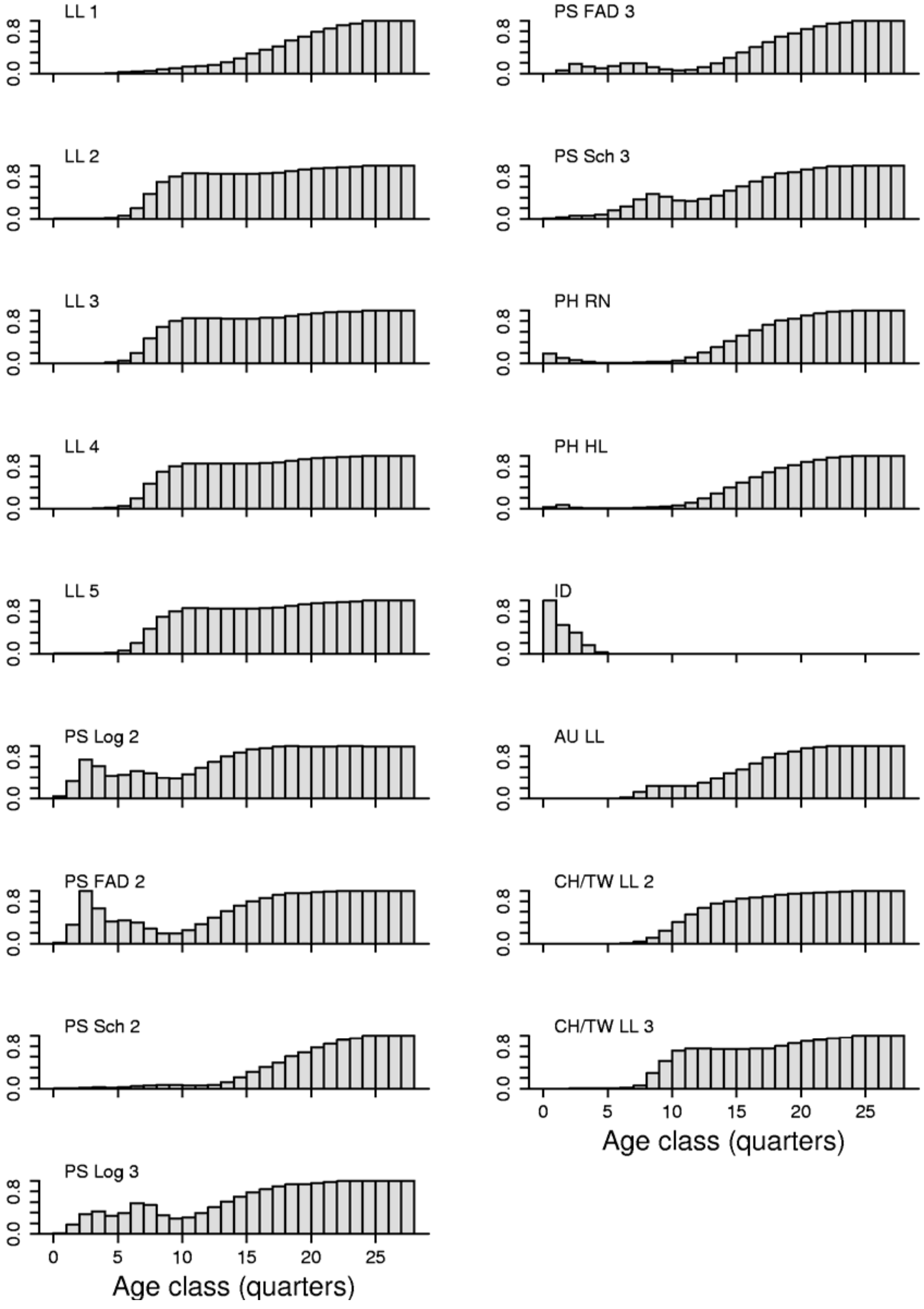


Figure 23. Selectivity coefficients, by fishery.

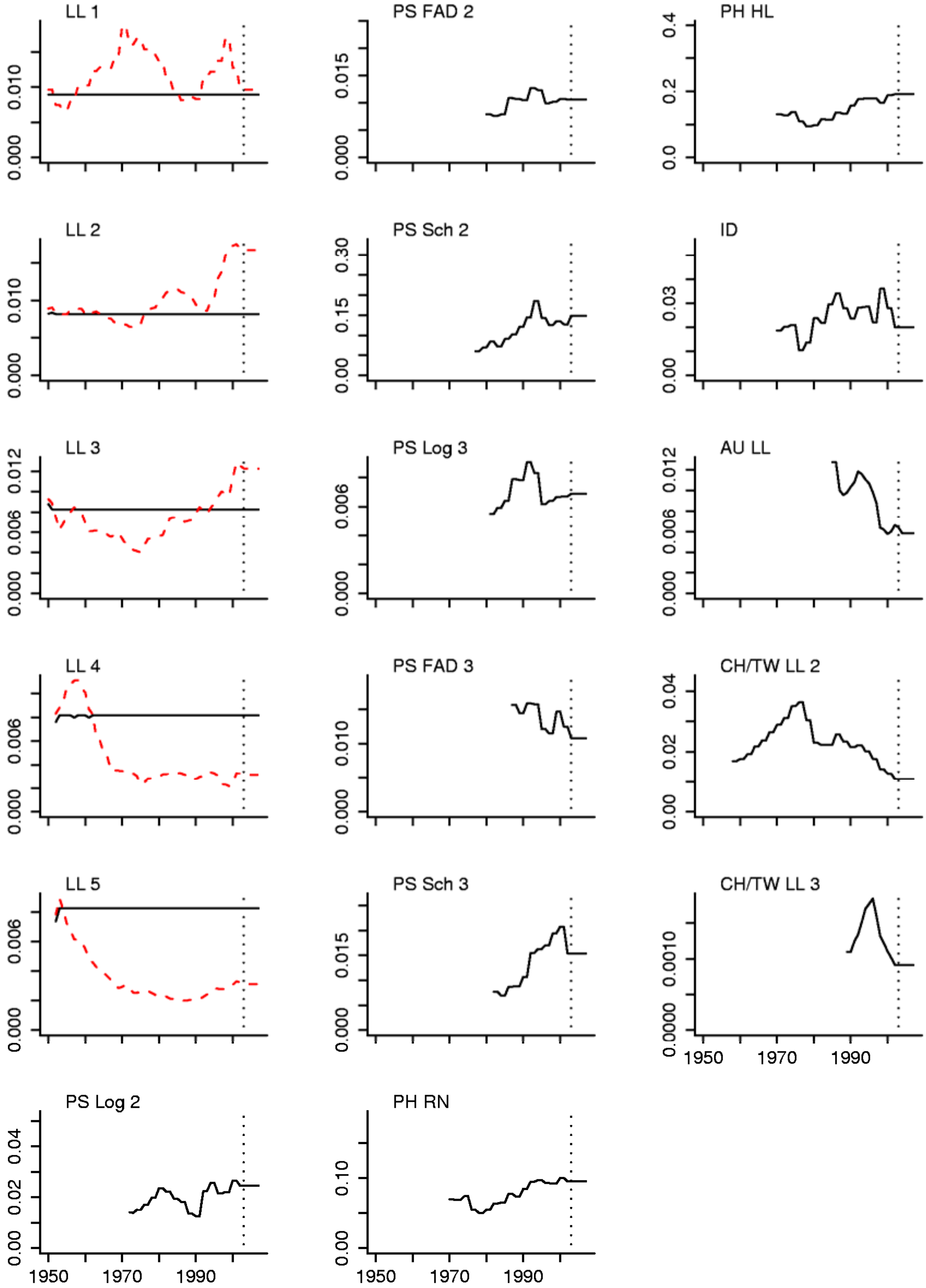


Figure 24. Average annual catchability time series, by fishery from the shbs-mest model (black lines). The annual catchability for the LL1-5 fisheries from the shbs-mest-LLq model is also presented (red dashed lines).

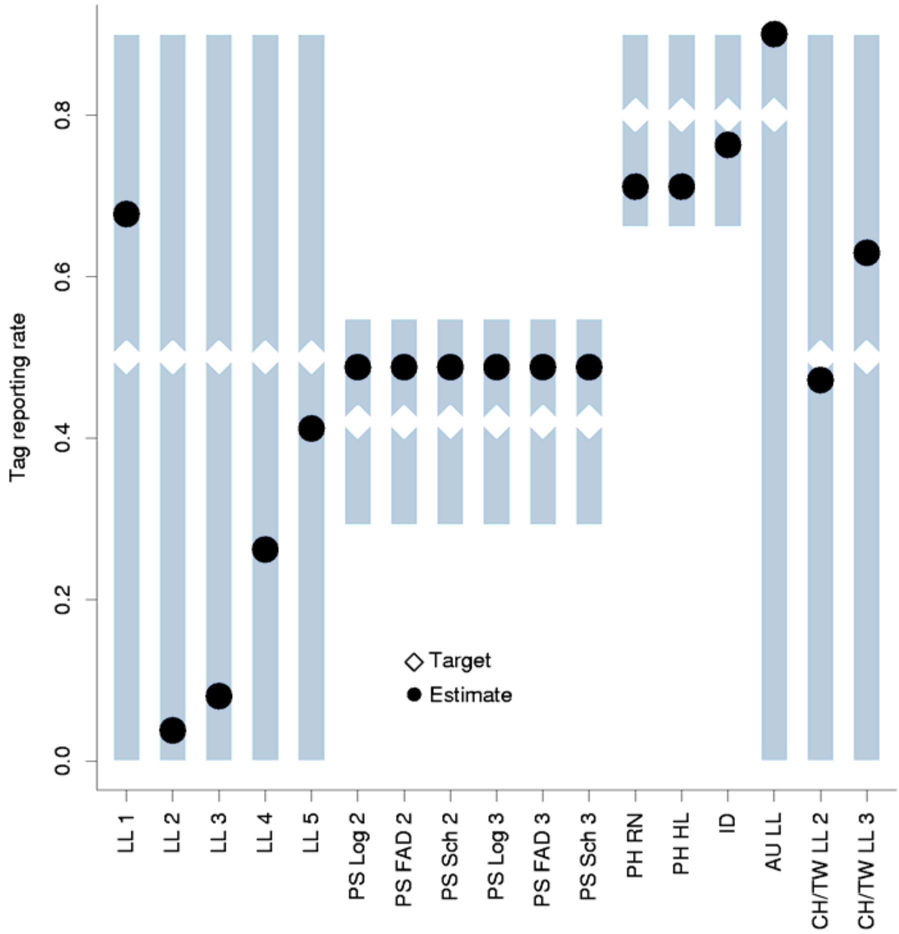


Figure 25. Estimated tag-reporting rates by fishery (black circles). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars indicate a range of ±1 SD.

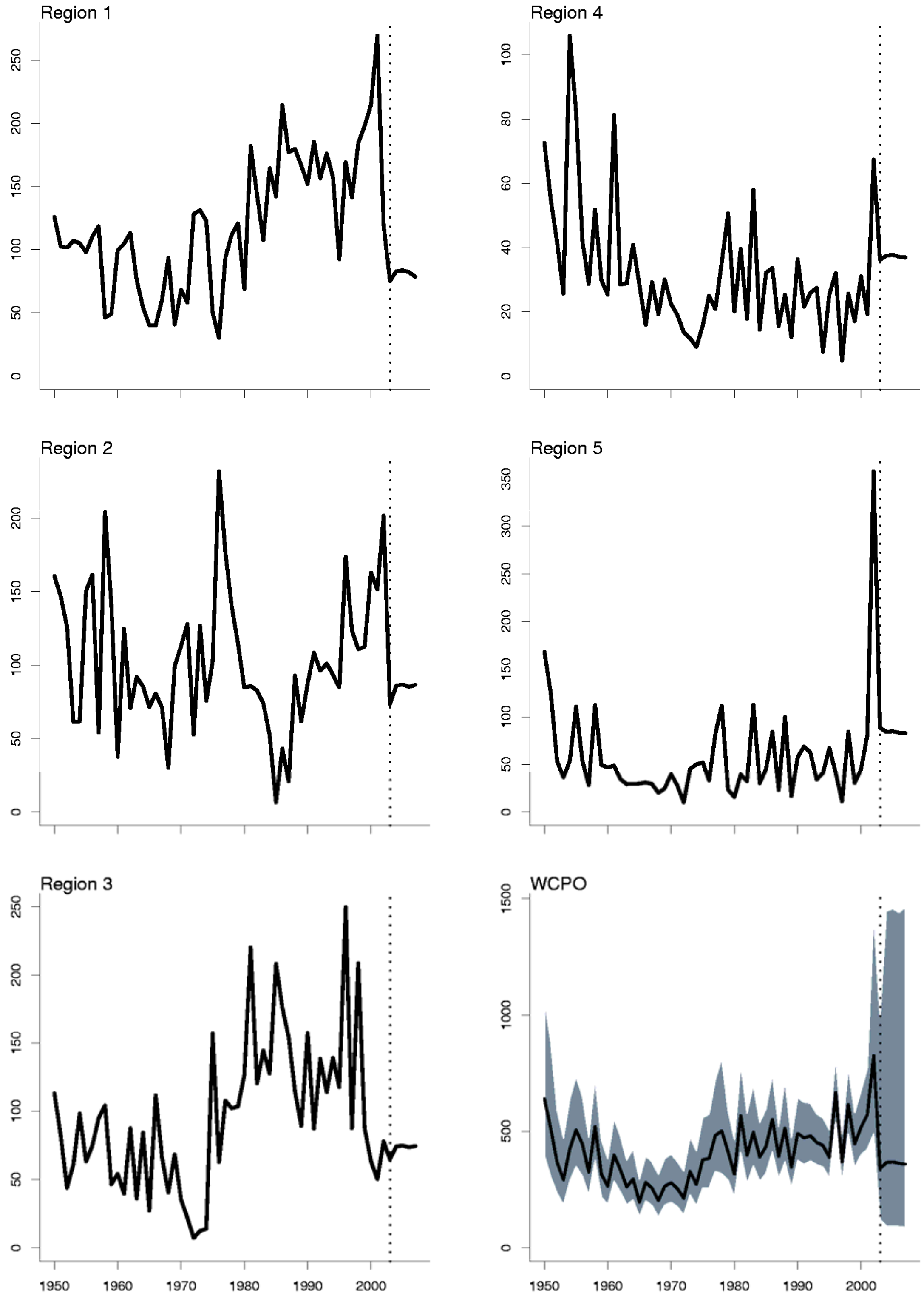


Figure 26. Estimated annual recruitment (millions) by region and for the WCPO. The shaded area for the WCPO indicates the approximate 95% confidence intervals. The dotted vertical line delineates data-supported model estimates from projections. The vertical dotted lines indicate the point at which population projections are made with assumed levels of effort.

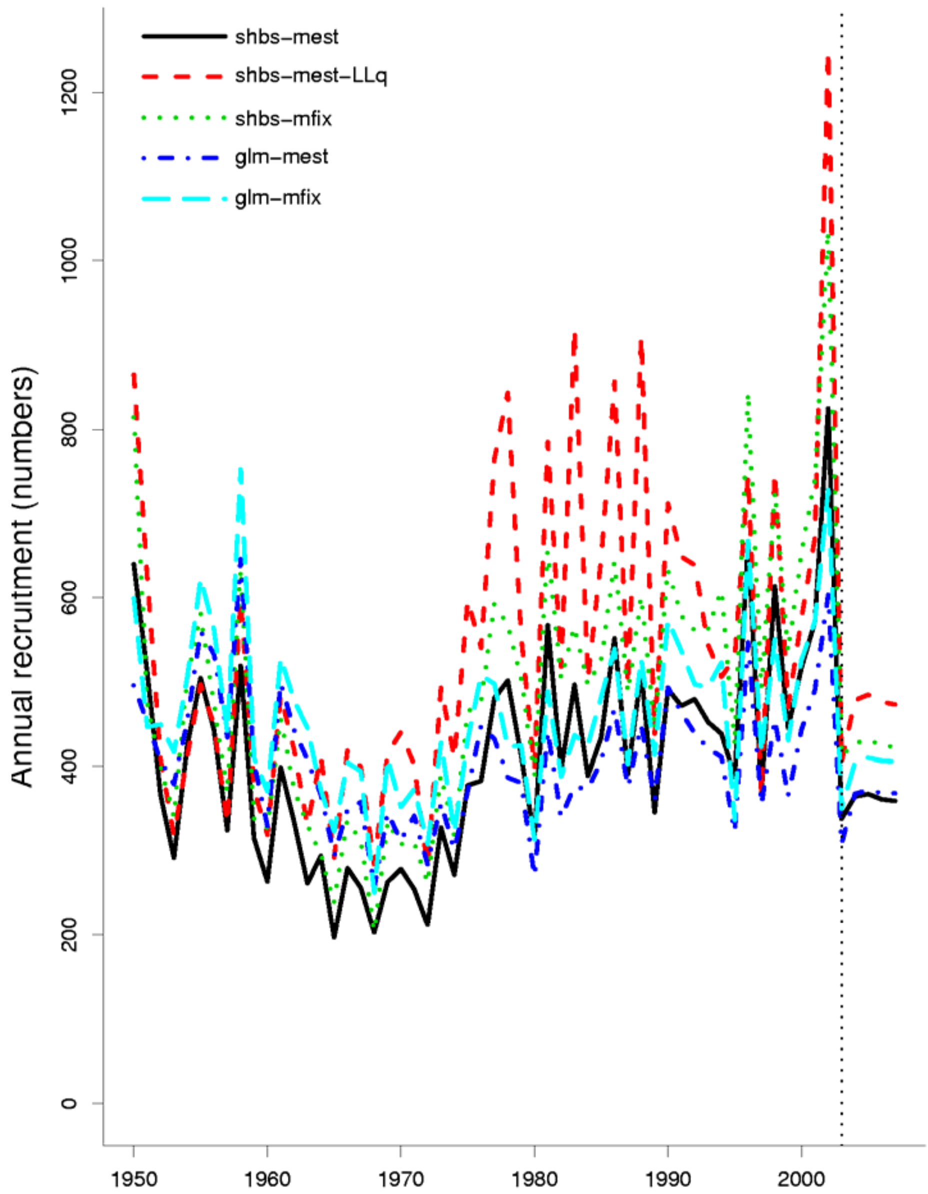


Figure 27. Estimated annual recruitment for the WCPO obtained from the five different model options. The vertical dotted line indicates the point at which population projections are made with assumed levels of effort.

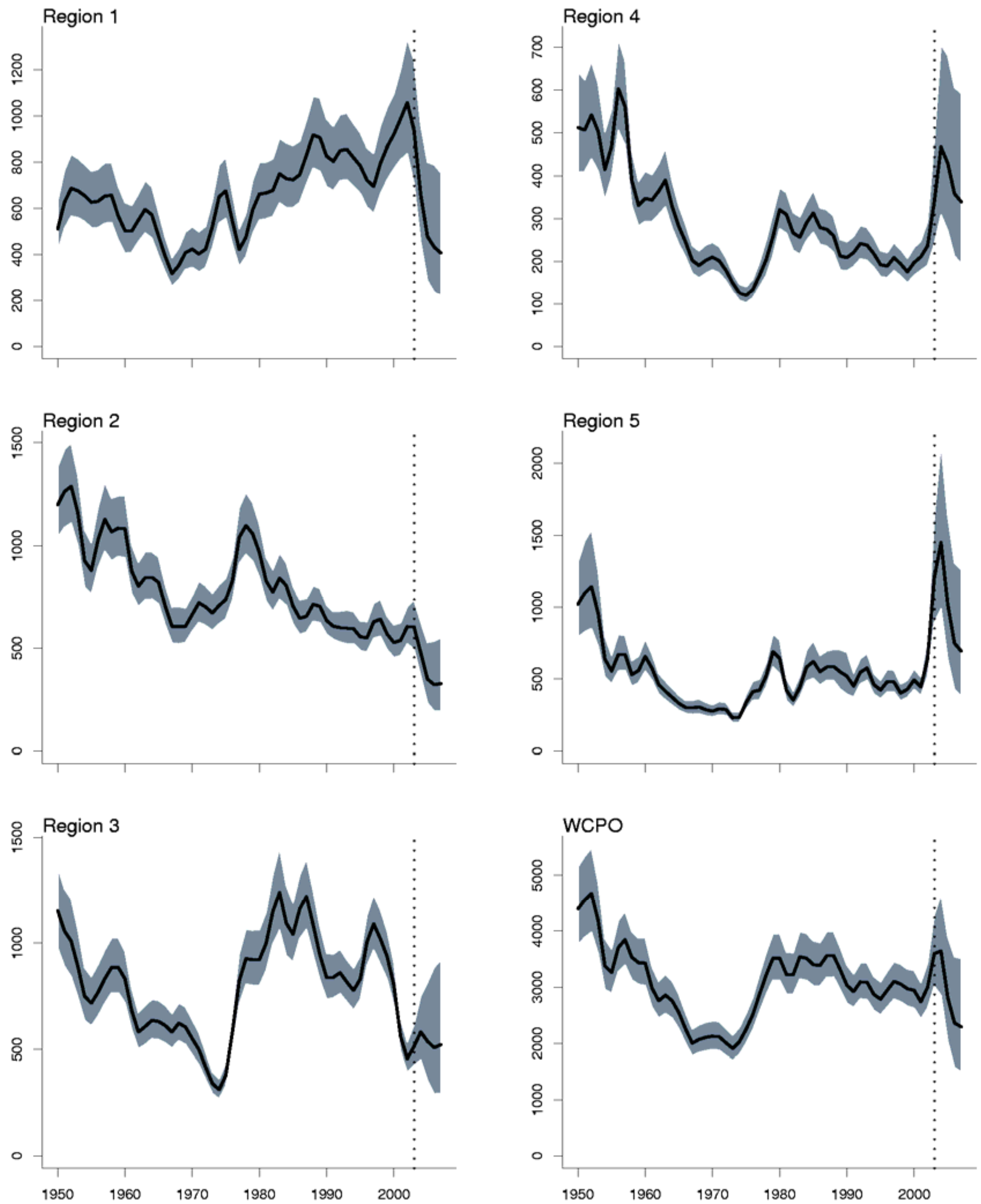


Figure 28. Estimated annual average total biomass (thousand t) by region and for the WCPO for the base-case analysis (statHBS longline effort). The shaded areas indicate the approximate 95% confidence intervals. The vertical dotted lines indicate the point at which population projections are made with assumed levels of effort.

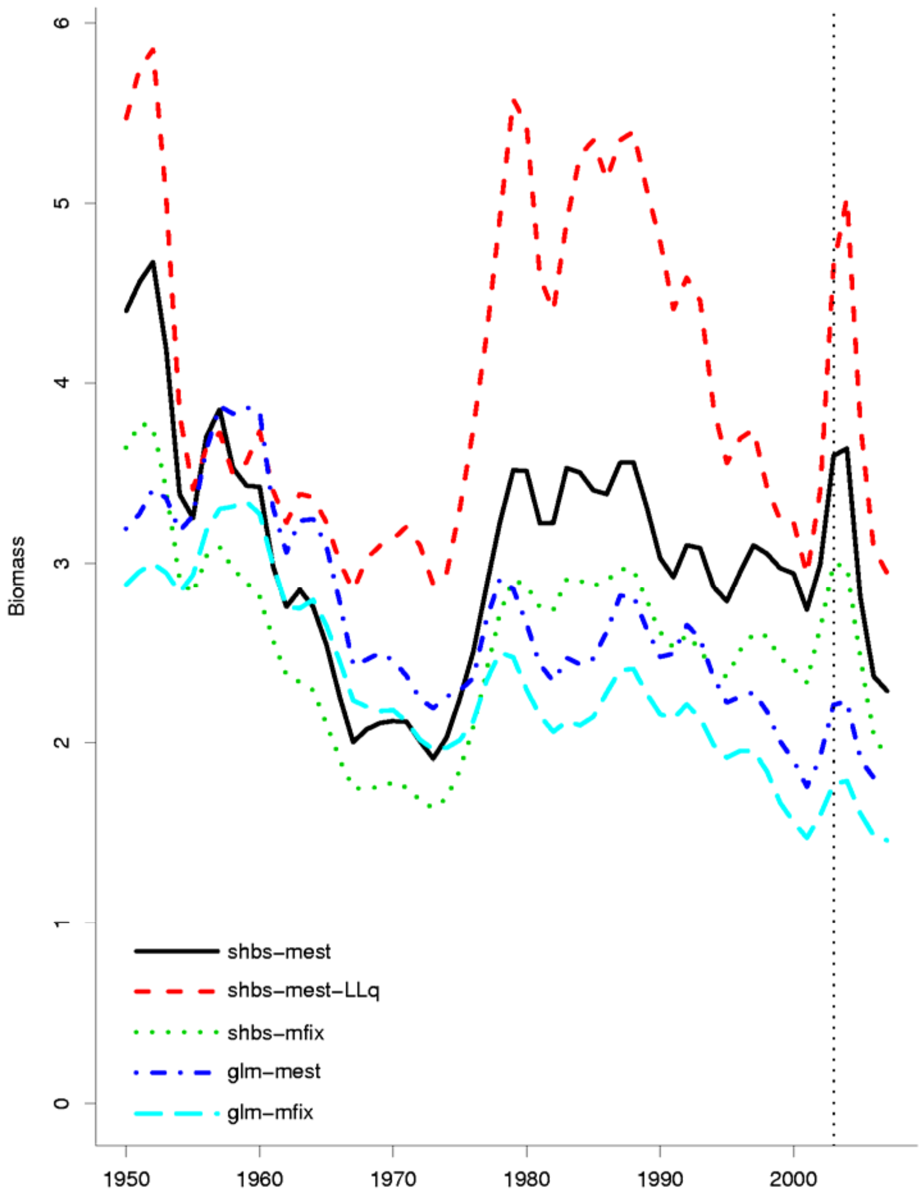


Figure 29. Estimated annual average total biomass (million t) for the WCPO obtained from the five different model options. The vertical dotted line indicates the point at which population projections are made with assumed levels of effort.

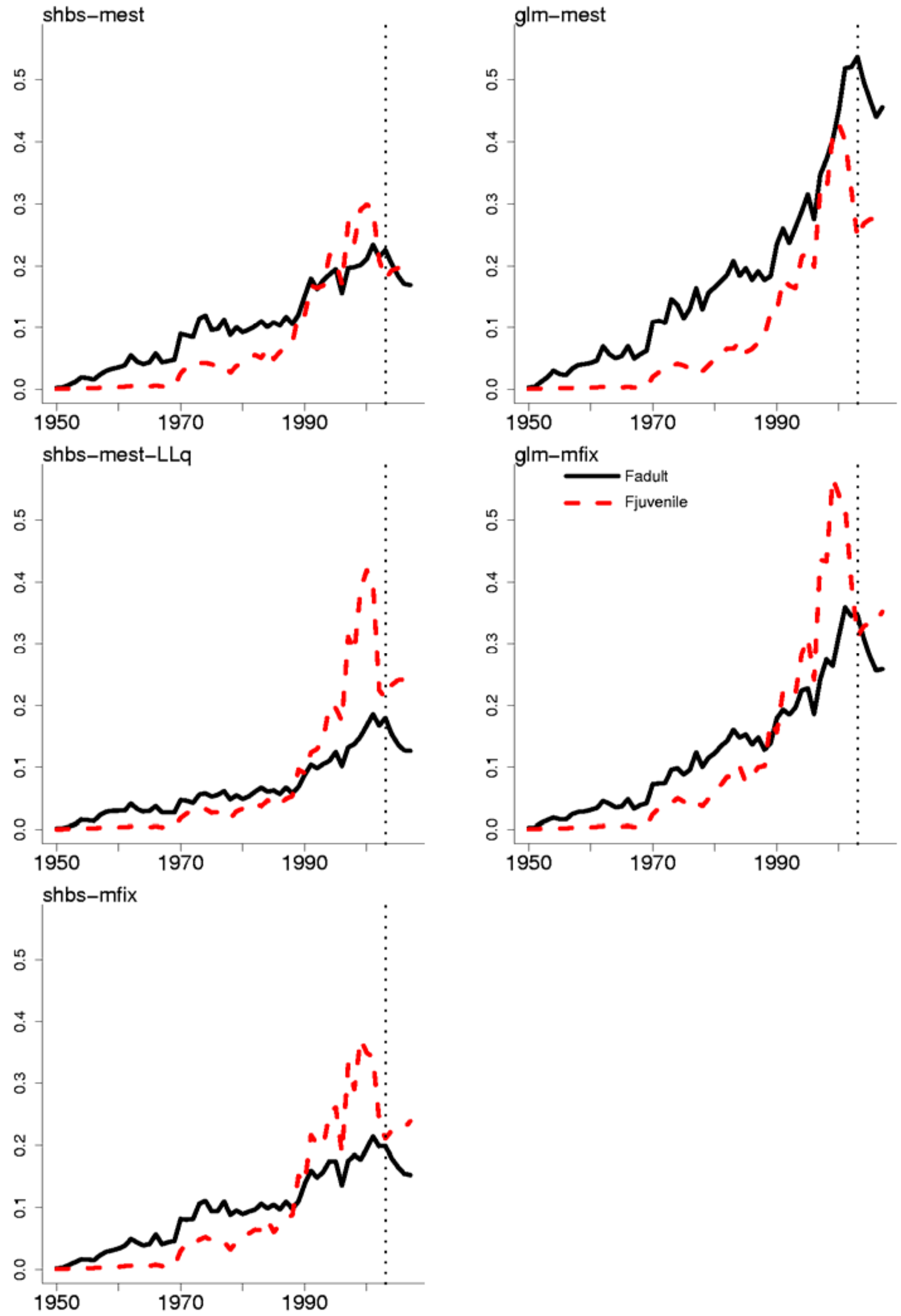


Figure 30. Estimated annual average juvenile and adult fishing mortality for the WCPO obtained from the five separate model options.

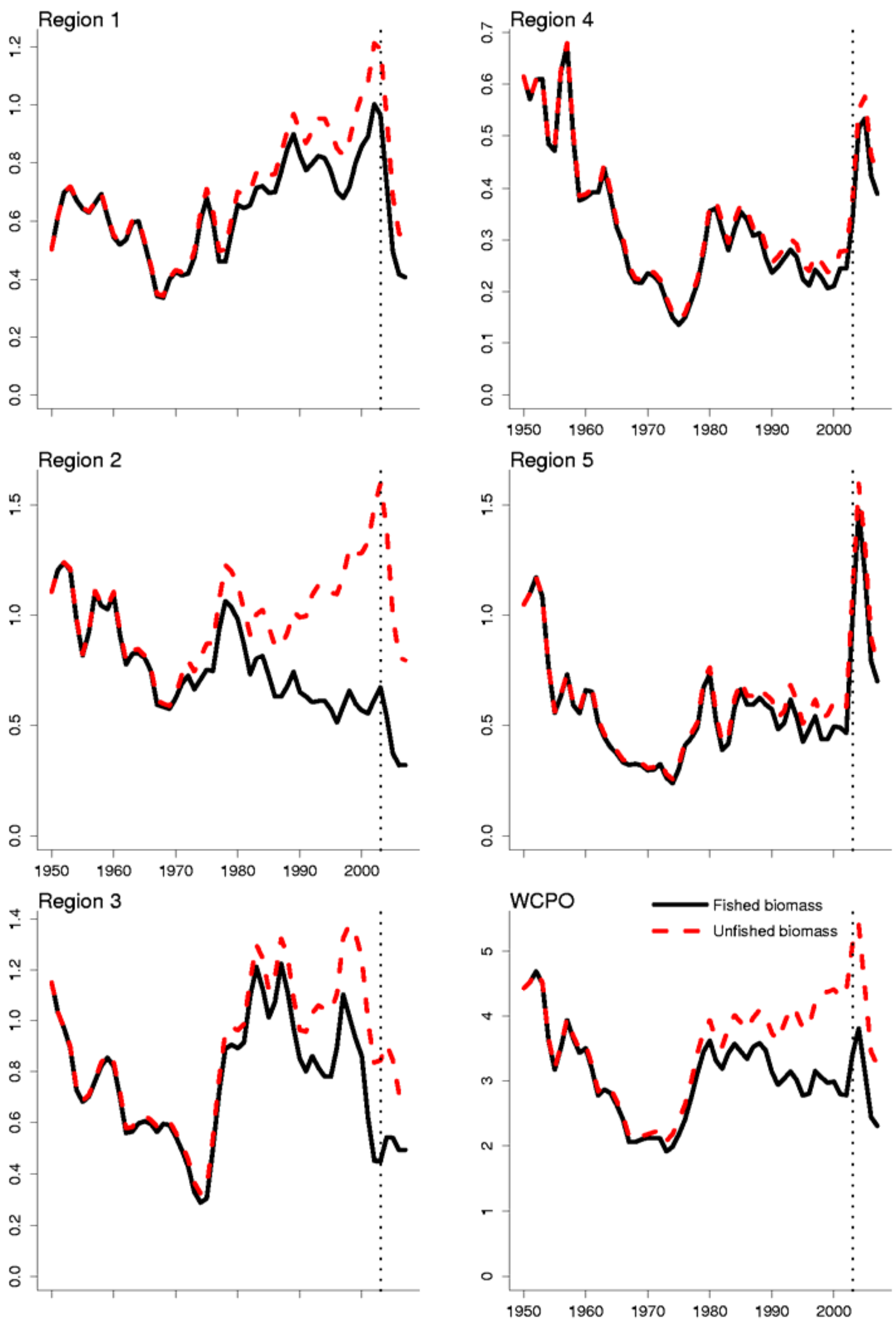


Figure 31. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper thin lines) for the shbs-Mest model for each region and for the WCPO.

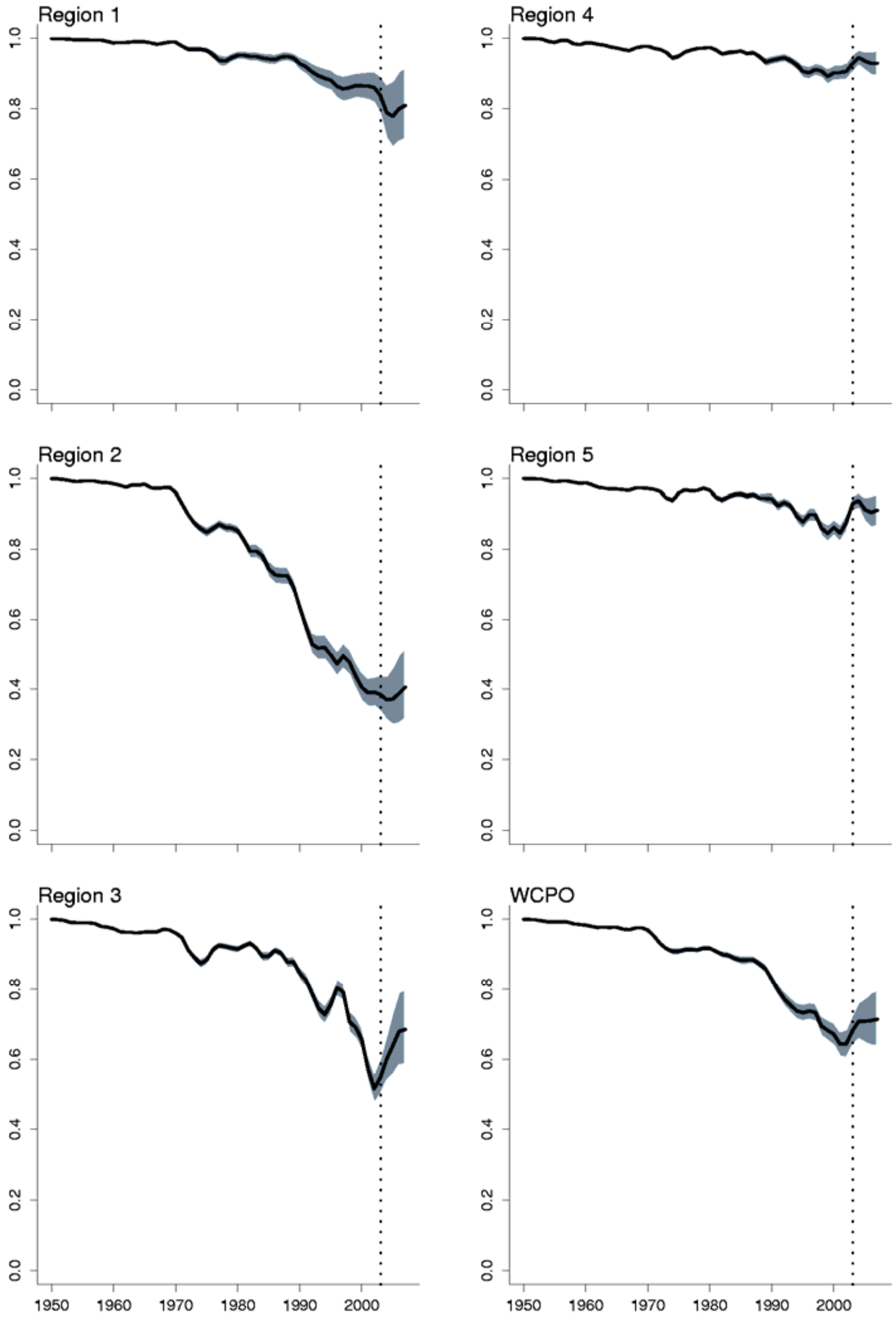


Figure 32. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the WCPO. The shaded areas indicate the approximate 95% confidence intervals. The vertical dotted line indicates the point at which population projections are made with assumed levels of effort.

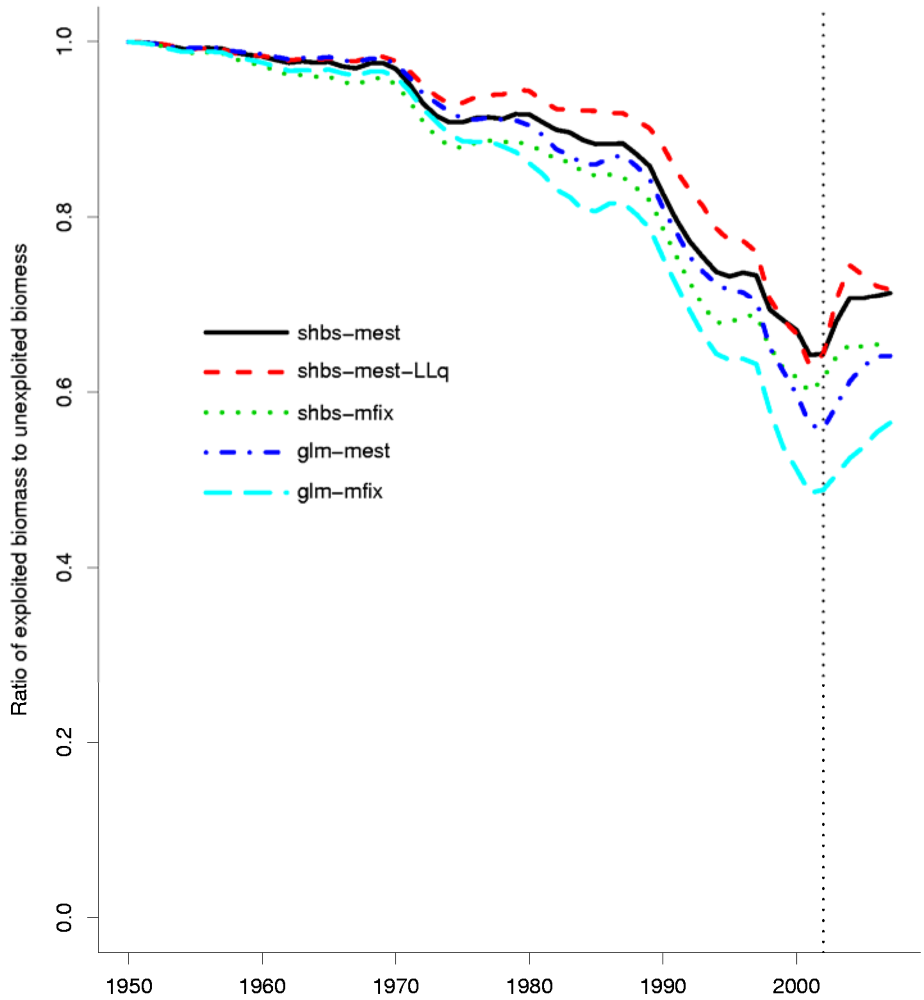


Figure 33. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for the WCPO obtained from the separate analyses. The vertical dotted line indicates the point at which population projections are made with assumed levels of effort.

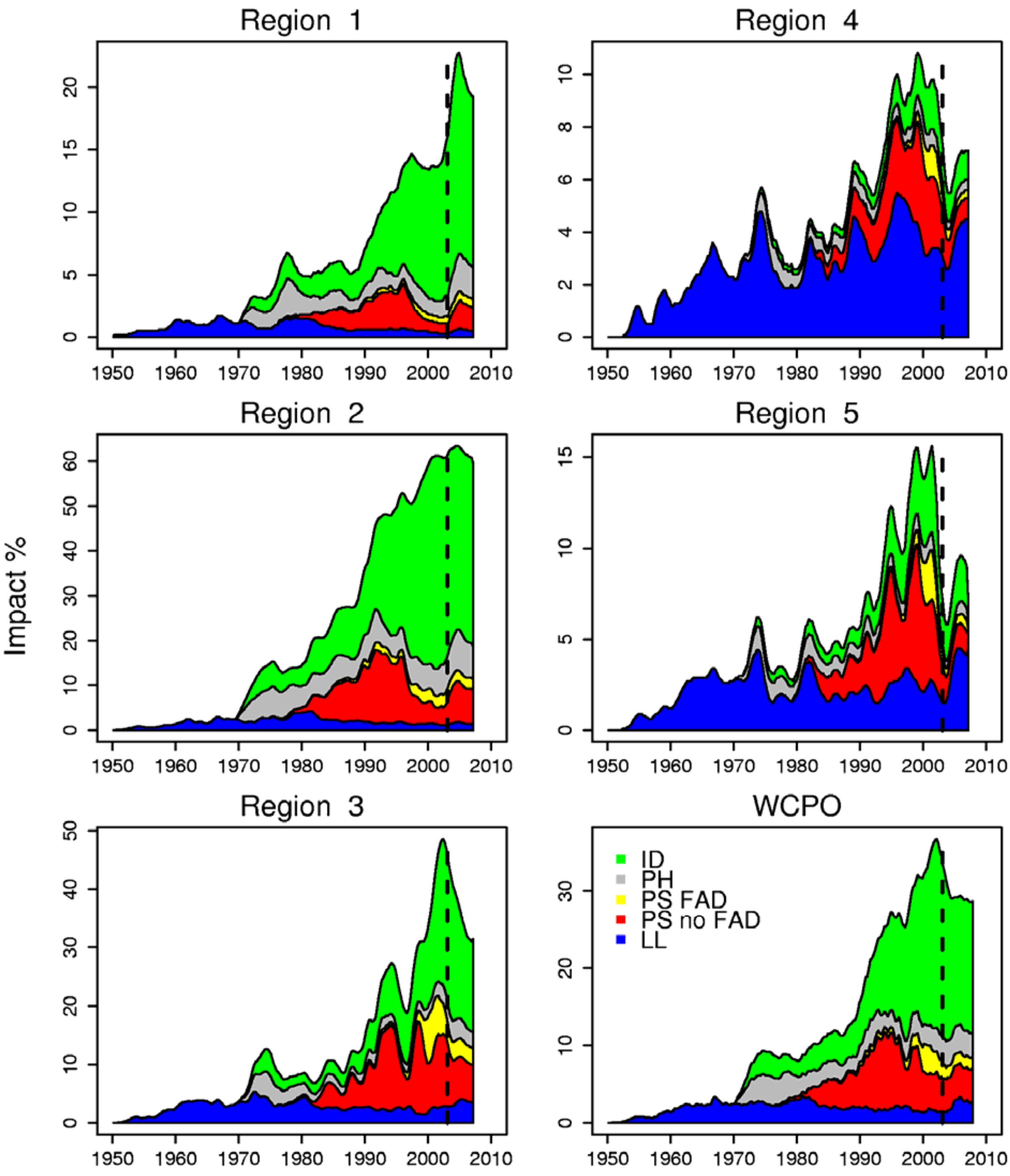


Figure 34. Estimates of reduction in total biomass due to fishing (fishery impact = 1-$B_t/B_{0,t}$) by region and for the WCPO attributed to various fishery groups. LL = all longline fisheries; ID = Indonesian domestic fishery; PH = Philippines domestic fisheries; PS FAD = purse seine FAD sets; PS non-FAD = purse seine log and school sets.

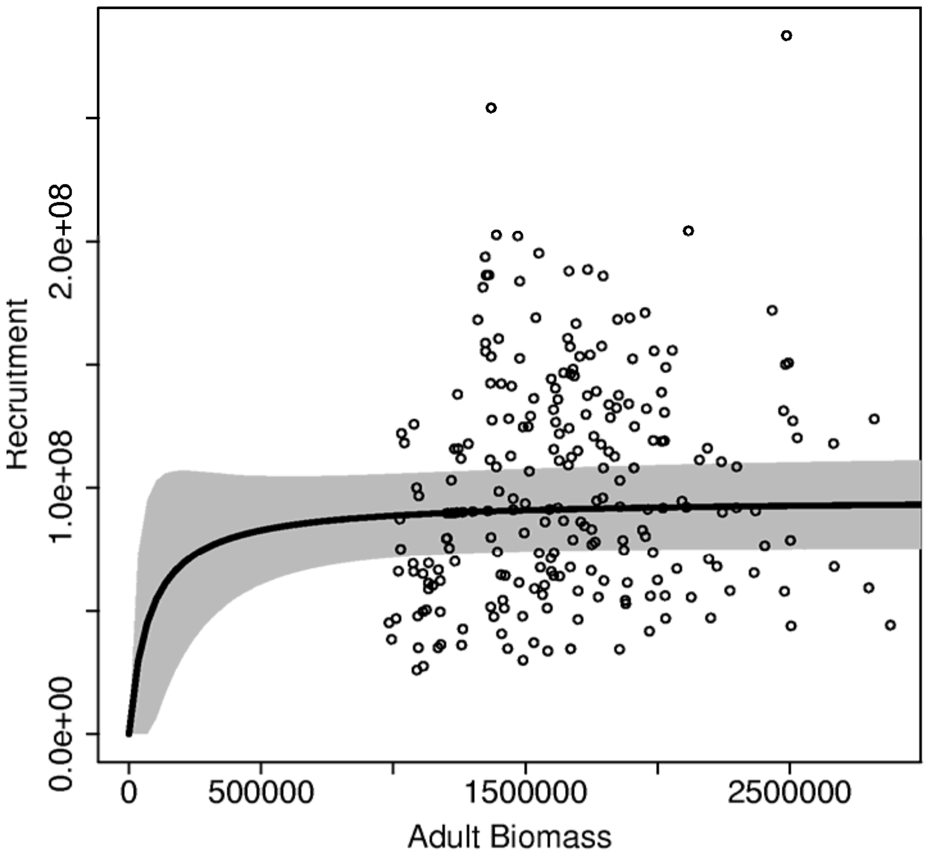


Figure 35. Estimated relationship between equilibrium recruitment and equilibrium spawning biomass. The grey area indicates the 95% confidence region. Estimated recruitment-spawning biomass points are plotted as open circles.

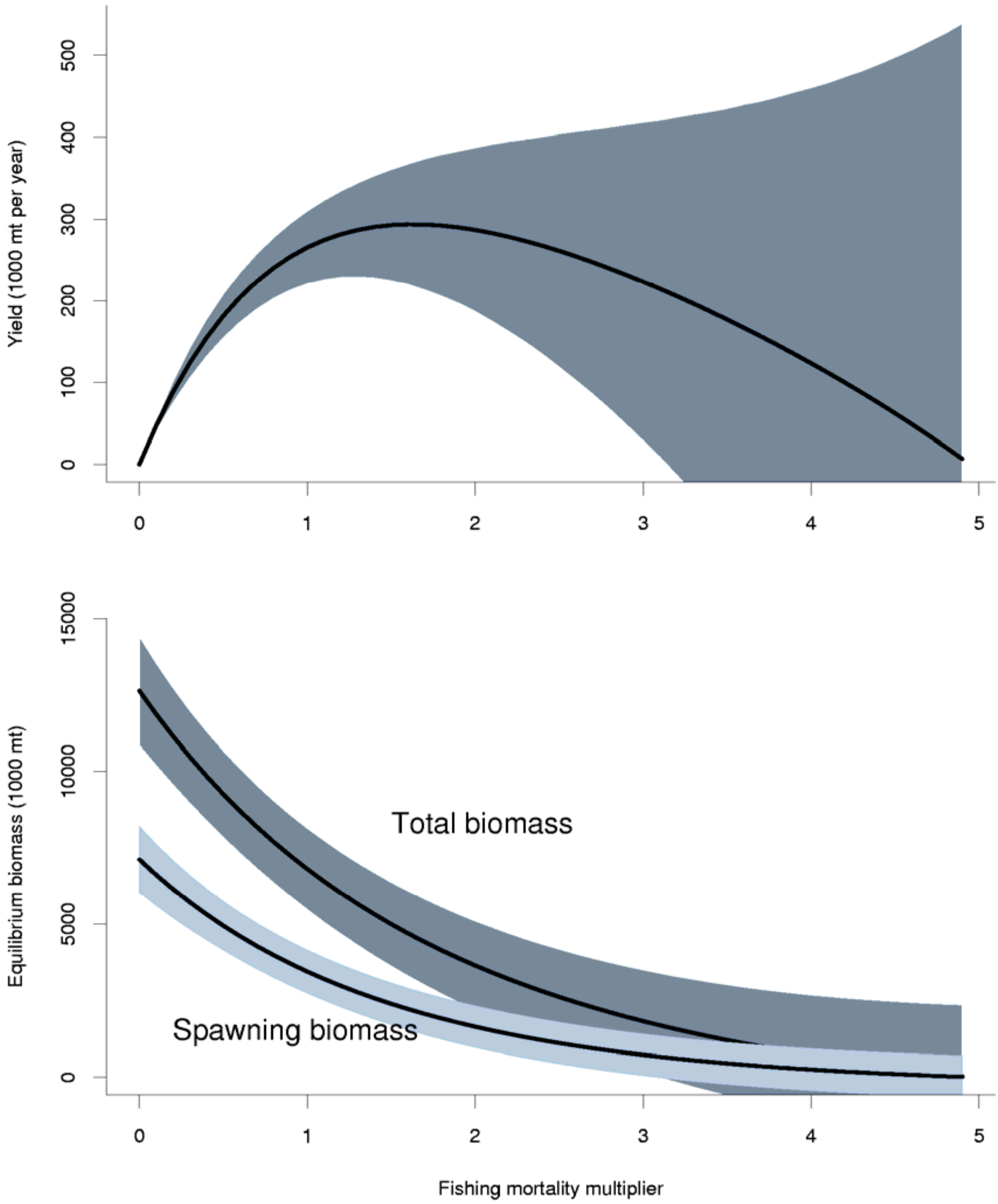


Figure 36. Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier. The shaded areas represent approximate 95% confidence intervals.

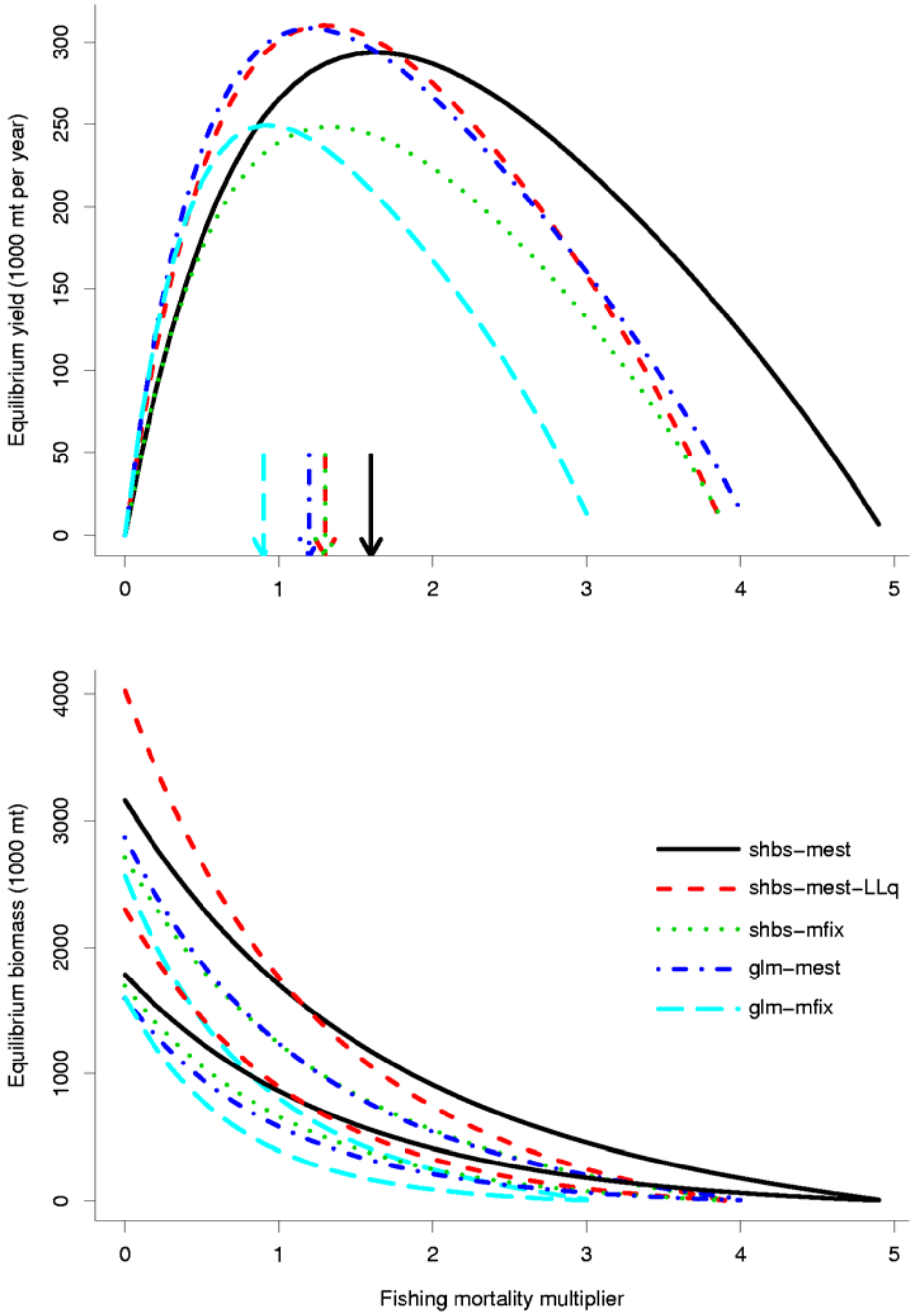


Figure 37. Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier obtained from the five separate model options. In the upper panel, the arrows indicate the value of the fishing mortality multiplier at maximum yield.

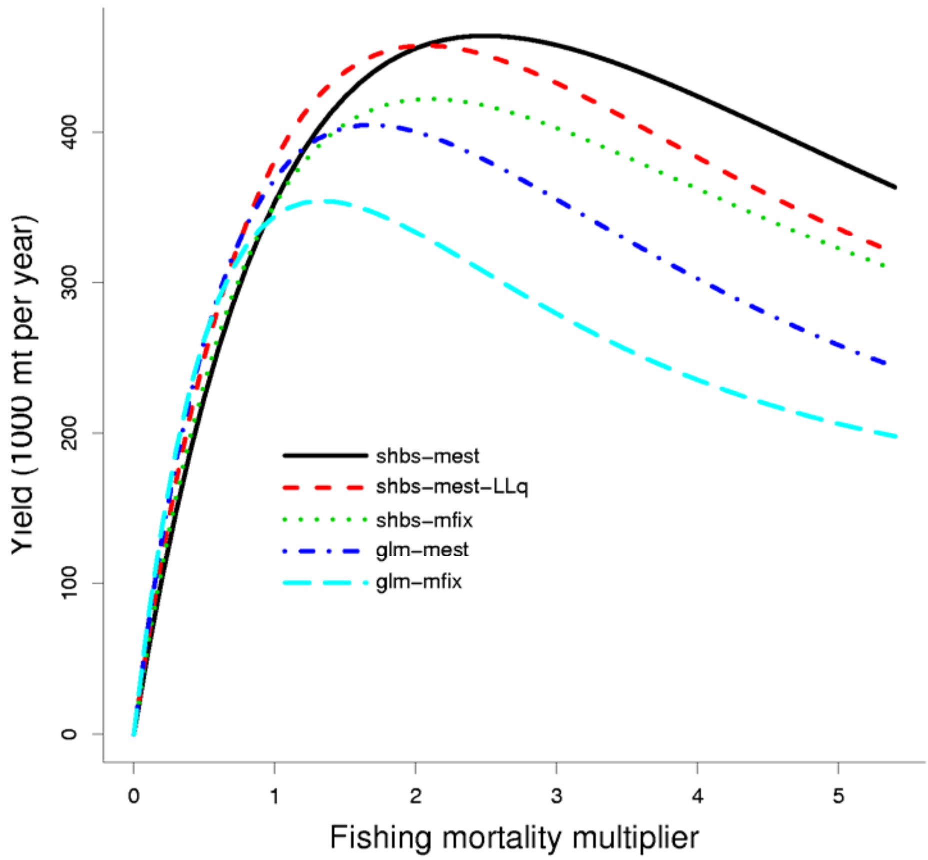


Figure 38. Yield curves based on post-1990 average recruitment.

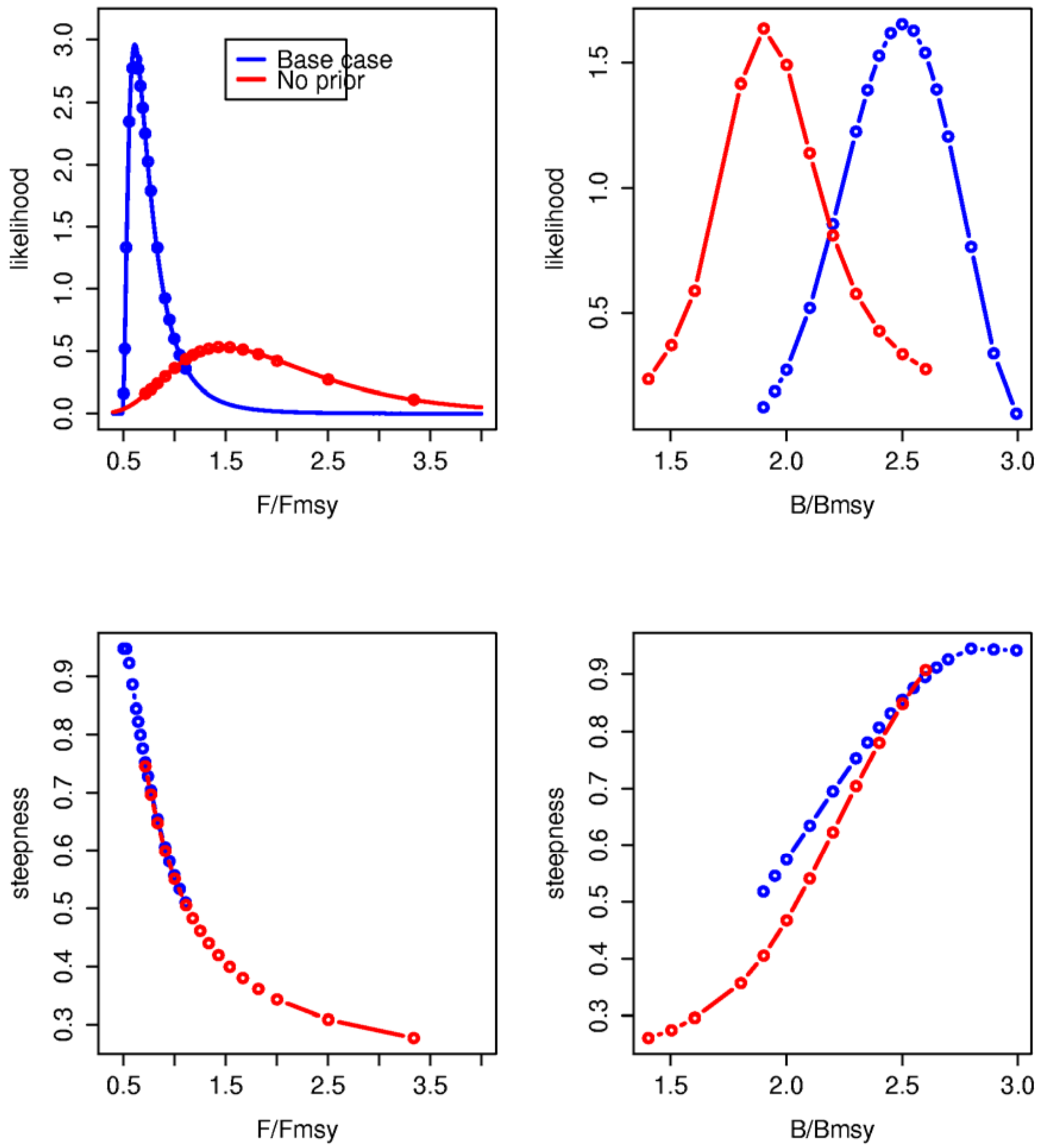


Figure 39. Probability distributions of $F_{current} / \tilde{F}_{MSY}$ (upper left panel) and $B_{current} / \tilde{B}_{MSY}$ (upper right panel) based on the likelihood profile method for models incorporating a prior on SRR steepness (base-case, mode=0.9, sd=0.1) and no prior on SRR steepness (SHBS-MEST model). Likelihood profile points used to construct the probability distributions are shown as open circles. The fitted lines are used to integrate the distributions. The steepness coefficients estimated for each likelihood profile point are plotted in the lower panels.

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
  -1 49 20        # divide LL LF sample sizes by 10 (default)
  -2 49 20        # "
  -3 49 20        # "
  -4 49 20        # "
  -5 49 20        # "
  -6 49 25        # divide PS LF sample sizes by 25
  -7 49 25        # "
  -8 49 25        # "
  -9 49 25        # "
  -10 49 25       # "
  -11 49 25       # "
  -16 49 20
  -17 49 20
  -1 50 20
  -2 50 20        # divide LL WF sample sizes by 10 (default)
  -3 50 20        # "
  -4 50 20        # "
  -5 50 20        # "
  -15 50 5        # divide LL WF sample sizes by 1 (sampling coverage is 100%)
  -16 50 20       # divide LL WF sample sizes by 1 (sampling coverage is 100%)
  -17 50 20       # divide LL WF sample sizes by 1 (sampling coverage is 100%)
  1 32 2          # sets standard initial estimation scheme
  1 111 4         # sets likelihood function for tags to negative binomial
  1 141 3         # sets likelihood function for LF data to normal
  2 57 4          # sets no. of recruitments per year to 4
  2 69 1          # sets generic movement option (now default)
  2 94 1 2 95 10  # initial age structure based on estimated M (assume virgin)
  -999 26 2       # sets length-dependent selectivity option
  -9999 1 1       # sets no. mixing periods for all tag release groups to 1
# sets non-decreasing selectivity for longline fisheries
  -1 16 1 -2 16 1 -3 16 1 -4 16 1 -5 16 1 -15 16 1 -16 16 1 -17 16 1
# sets dome shaped selectivity for fishery 14
  -14 16 2 -14 3 10
# grouping of fisheries with common selectivity
   -1 24 1        # Longline fisheries have common selectivity except LL1
   -2 24 2
   -3 24 2
   -4 24 2
   -5 24 2
   -6 24 3
   -7 24 4
   -8 24 5
   -9 24 6
  -10 24 7
  -11 24 8
  -12 24 9
  -13 24 10
  -14 24 11
  -15 24 12
```

```
  -16 24 13
  -17 24 14
# grouping of fisheries with common catchability
   -1 29 1        # Longline fisheries grouped
   -2 29 1
   -3 29 1
   -4 29 1
   -5 29 1
   -6 29 2
   -7 29 3
   -8 29 4
   -9 29 5
  -10 29 6
  -11 29 7
  -12 29 8
  -13 29 9
  -14 29 10
  -15 29 11
  -16 29 12
  -17 29 13
# grouping of average catchability
   -1 60 1        # Longline fisheries grouped
   -2 60 1
   -3 60 1
   -4 60 1
   -5 60 1
   -6 60 2
   -7 60 3
   -8 60 4
   -9 60 5
  -10 60 6
  -11 60 7
  -12 60 8
  -13 60 9
  -14 60 10
  -15 60 11
  -16 60 12
  -17 60 13
# 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        # All region 2
    -7 32 6        # PS fisheries grouped
    -8 32 6        # for tag returns
    -9 32 7        # Likewise region 3
   -10 32 7        #
   -11 32 7        #
   -12 32 8        # Philippines fisheries
   -13 32 8        # also grouped for tag returns
   -14 32 9
   -15 32 10
   -16 32 11
   -17 32 12
# grouping of fisheries with common tag-reporting rates
    -1 34 1
    -2 34 2
    -3 34 3
    -4 34 4
    -5 34 5
    -6 34 6
    -7 34 6
    -8 34 6
    -9 34 6
   -10 34 6
   -11 34 6
```

```
   -12 34 7
   -13 34 7
   -14 34 8
   -15 34 9
   -16 34 10
   -17 34 11
# sets penalties on tag-reporting rate priors
    -1 35 1         # The penalties are set to be small for LL fisheries.
    -2 35 1         # PS penalties moderate to reflect
    -3 35 1         # tag seeding data
    -4 35 1
    -5 35 1
    -6 35 234
    -7 35 234
    -8 35 234
    -9 35 234
   -10 35 234
   -11 35 234
   -12 35 200
   -13 35 200
   -14 35 200
   -15 35 1
   -16 35 1
   -17 35 1
# sets prior means for tag-reporting rates
    -1 36 50
    -2 36 50
    -3 36 50
    -4 36 50
    -5 36 50
    -6 36 42         # PS reporting rate priors adjusted for the
    -7 36 42         # proportion of usable tag returns - 77% of total returns
    -8 36 42         # Therefore prior = 0.77*0.55 = 0.45
    -9 36 42
   -10 36 42
   -11 36 42
   -12 36 80
   -13 36 80
   -14 36 80
   -15 36 80
   -16 36 50
   -17 36 50
# sets penalties for effort deviations (negative penalties force effort devs
# to be zero when catch is unknown)
   -1 13 -50      # higher for longline fisheries to reflect standardization
   -2 13 -50      #
   -3 13 -50      #
   -4 13 -50      #
   -5 13 -50      #
   -6 13 -10
   -7 13 -10
   -8 13 -10
   -9 13 -10
  -10 13 -10
  -11 13 -10
  -12 13 0        # Philippines and Indonesian fisheries have no effort
  -13 13 0        # data therefore penalty is set to a minimum value
  -14 13 0
  -15 13 -10
  -16 13 -10
  -17 13 -10
# sets penalties for catchability deviations
  -12 15 1        # No effort for Philippines and Indonesian fisheries so
  -13 15 1        # small penalty gives additional ability for catch prediction
  -14 15 1        # with minimal impact on population parameters
  -999 33 1       # estimate tag-reporting rates
  1 33 90         # maximum tag reporting rate for all fisheries is 0.9
  -999 41 1       # Selectivity smoothing penalties
```

```
  -999 42 10
PHASE1
fi
#  ---------
#   PHASE 2
#  ---------
if [ ! -f 03.par ]; then
  mfclopt yft.frq 01.par 03.par -file - <<PHASE2
  1 149 400       # set penalty on recruitment devs to 200/10
  -999 3 25       # all selectivities equal for age class 17 and older
  -999 4 4        # possibly not needed
  -999 21 4       # possibly not needed
  1 189 1         # write length.fit and weight.fit (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 -1         # set convergence criterion to 1E+01
PHASE2
fi
#  ---------
#   PHASE 4
#  ---------
if [ ! -f 04.par ]; then
  mfclopt yft.frq 03.par 04.par -file - <<PHASE4
  2 70 1          # activate parameters and turn on
  2 71 1          # estimation of temporal changes in recruitment distribution
  2 110 5         # penalty weight for deviations
PHASE4
fi
#  ---------
#   PHASE 5
#  ---------
if [ ! -f 05.par ]; then
  mfclopt yft.frq 04.par 05.par -file - <<PHASE5
  2 68 1          # estimate movement coefficients
PHASE5
fi
#  ---------
#   PHASE 6
#  ---------
if [ ! -f 06.par ]; then
  mfclopt yft.frq 05.par 06.par -file - <<PHASE6
  1 16 1          # estimate length dependent SD
PHASE6
fi
#  ---------
#   PHASE 6a
#  ---------
if [ ! -f 06a.par ]; then
  mfclopt yft.frq 06.par 06a.par -file - <<PHASE6a
  1 14 1          # estimate K
PHASE6a
fi
#  ---------
#   PHASE 7
#  ---------
if [ ! -f 07.par ]; then
  mfclopt yft.frq 06a.par 07.par -file - <<PHASE7
  1 173 8         # estimate independent mean lengths for 1st 8 age classes
  1 182 10        # penalty weight for deviations
PHASE7
fi
#  ---------
#   PHASE 8
#  ---------
if [ ! -f 08.par ]; then
  mfclopt yft.frq 07.par 08.par -file - <<PHASE8
  -999 27 1       # estimate seasonal catchability for all fisheries
  -12 27 0        # except those where
```

```
  -13 27 0        # only annual catches
  -14 27 0        # are available
    1 14 0        # de-activate K for the time being
PHASE8
fi
#  ---------
#   PHASE 9
#  ---------
if [ ! -f 09.par ]; then
  mfclopt yft.frq 08.par 09.par -file - <<PHASE9
  -6 10 1         # estimate
  -7 10 1         # catchability
  -8 10 1         # time-series
  -9 10 1         # for all
  -10 10 1        # non-longline
  -11 10 1        # fisheries
  -12 10 1
  -13 10 1
  -14 10 1
  -15 10 1
  -16 10 1
  -17 10 1
  -999 23 23      # and do a random-walk step every 23+1 months
PHASE9
fi
#  ---------
#   PHASE 10
#  ---------
if [ ! -f 10.par ]; then
  mfclopt yft.frq 09.par 10.par -file - <<PHASE10
  2 33 1          # estimate constant natural mortality rate
PHASE10
fi
#  ---------
#   PHASE 11
#  ---------
if [ ! -f 11.par ]; then
  mfclopt yft.frq 10.par 11.par -file - <<PHASE11
  2 88 1          # activate parameters
  2 89 1          # and estimate age-dependent movement
PHASE11
fi
#  ---------
#   PHASE 12
#  ---------
if [ ! -f 12.par ]; then
  mfclopt yft.frq 11.par 12.par -file - <<PHASE12
  2 73 1          # estimate age-sependent M
  2 77 250
  2 78 50
PHASE12
fi
#  ---------
#   PHASE 13
#  ---------
if [ ! -f 13.par ]; then
  mfclopt yft.frq 12.par 13.par -file - <<PHASE13
  1 14 1          # estimate von Bertalanffy K
PHASE13
fi
#  ---------
#   PHASE 14
#  ---------
if [ ! -f 14.par ]; then
  mfclopt yft.frq 13.par 14.par -file - <<PHASE14
# grouping of fisheries for estimation of negative binomial parameter a
  -1 44 1
  -2 44 2
```

```
  -3 44 3
  -4 44 4
  -5 44 5
  -6 44 6
  -7 44 6
  -8 44 6
  -9 44 7
 -10 44 7
 -11 44 7
 -12 44 8
 -13 44 8
 -14 44 9
 -15 44 10
 -16 44 11
 -17 44 12
 -999 43 1        # estimate a for all fisheries
PHASE14
fi
#  ---------
#   PHASE 15
#  ---------
if [ ! -f 15.par ]; then
  mfclopt yft.frq 14.par 15.par -file - <<PHASE15
  -100000 1 1     # estimate
  -100000 2 1     # time-invariant
  -100000 3 1     # distribution
  -100000 4 1     # of
  -100000 5 1     # recruitment
PHASE15
fi
#  ---------
#   PHASE 16
#  ---------
if [ ! -f 16.par ]; then
  mfclopt yft.frq 15.par 16.par -file - <<PHASE16
  2 145 1         # estimate Beverton Holt SRR with small penalty
  2 146 1         # SRR parameter active
  2 147 1         # recruitment lag is 1 quarter
  2 148 36        # base F is average over last 24 quarters
  2 155 24        # base F average does not include last 4 quarters
  2 153 100       # parameters of beta distribution defining prior for
  2 154 20        # steepness - mode = 0.9, sd = 0.10
  1 149 0         # reduce pens on devs from av. recr (to avoid 2 penalties)
  1 1 3000        # set no. function evaluations for final phase to 3000
  1 50 0          # set convergence criterion to 1E-04
PHASE16
fi
#  ---------
#   PHASE 17
#  ---------
if [ ! -f 17.par ]; then
  mfclopt yft.frq 16.par 17.par -file - <<PHASE17
  1 183 10        # penalise the first 10 regional recruitment deviation
  -200000 4 1000  # in region 4
  -200000 5 1000  # and region 5 with a penalty weight of 1000
PHASE17
fi
```

Appendix 2 *yft.ini*

```
# number of age classes
  28
# MATURITY AT AGE
  0 0 0 0 0 0 0.25 0.50 0.75 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
# natural mortality
    0.25
# movemap
  1 2 3 4
# diffusion coffs
   0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
   0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
   0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
   0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1
# 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 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 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
   0.15 0.40 0.30 0.05 0.10
# 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
```