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

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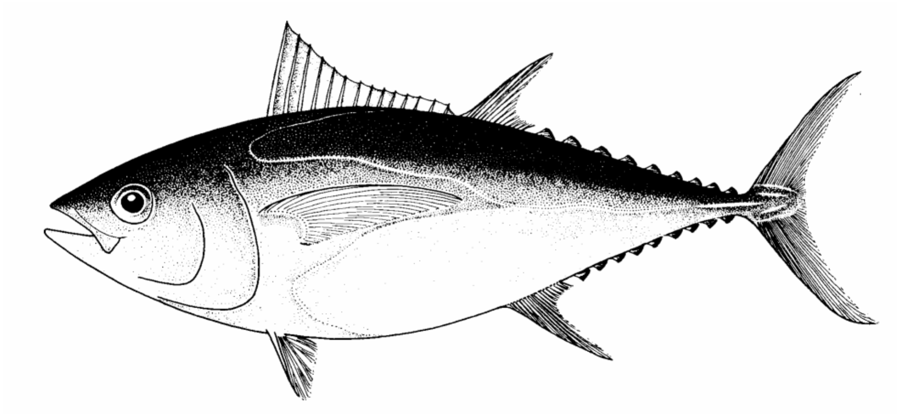

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Executive summary

This paper presents the 2006 assessment of bigeye tuna in the western and central Pacific Ocean. The assessment uses the stock assessment model and computer software known as MULTIFAN-CL. The bigeye tuna model is age (40 age-classes) and spatially structured (6 regions) and the catch, effort, size composition and tagging data used in the model are classified by 20 fisheries and quarterly time periods from 1952 through 2005.

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

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

In summary, the sensitivity analyses carried out were:

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

The main conclusions of the current assessment are as follows:

1. Recruitment in all analyses is estimated to have increased since about 1980. This result was very similar to that for the 2005 assessment. However, while the seven-region model exhibits a comparable temporal trend in recruitment, the recent increase in recruitment is less pronounced as the recruitment in region 3 represents a smaller proportion of the total recruitment. The overall magnitude of recruitment is considerably higher for the seven-region model than for the six-region model.
2. For the three analyses, total biomass for the WCPO is estimated to have declined to about half of its initial level by about 1970 and has been fairly stable or subject to slight decline since then. Adult biomass has declined by about 20% over the last decade.
3. The biomass trends in the model are strongly driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. For some of the main longline fisheries, there is an apparent inconsistency between the trends in the size-frequency data and the trends in longline catch and effort; i.e., the two types of data are providing inconsistent information about the relative level of fishing mortality in the region. The LOWSAMP model was adopted as the base case because it was considered that the catch and effort data are more informative than the size-frequency data in the estimation of trends in fishing mortality. However, further research is

required to explore the relationship between longline CPUE and bigeye abundance and the methodology applied to standardise the longline CPUE data, particularly to account for temporal trends in fishing efficiency. The latter issue was examined by way of a sensitivity analysis in the 2005 assessment and shown to be highly influential in the conclusions of the assessment.

4. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. For the two models with lower effective sample sizes (LOWSAMP and 7REGION), fishing mortality on adult bigeye is relatively comparable to that for juvenile bigeye, whereas, the HIGHSAMP model predicts a higher level of exploitation on the adult component of the stock.

5. The ratios $B_t / B_{t,F=0}$ provide a time-series index of population depletion by the fisheries. Overall, depletion is estimated to have been rapid, particularly since the mid-1980s. Even though the estimated total biomass has remained fairly stable since 1970, it appears to have been sustained only by above average recruitment. If recruitment were to return to the average level estimated in this assessment, biomass decline would be rapid, as suggested by the stock projections. The current level of biomass is 28% of the unexploited level ($B_{current} / B_{current,F=0}$ = 0.28) for the six-region models and 44% for the 7REGION model. Depletion is more extreme for some individual model regions, notably region 3 (recent $B_t / B_{t,F=0}$ ratios around 0.20 in the base-case model) and region 4 (0.25). Other regions are less depleted, with recent $B_t / B_{t,F=0}$ ratios of around 0.4 or greater.

6. The attribution of depletion to various fisheries or groups of fisheries indicates that the longline fishery has the greatest impact throughout the model domain. The purse seine and Philippines/Indonesian domestic fisheries also have substantial impact in region 3 and to a lesser extent in region 4.

7. The reference points that predict the status of the stock under equilibrium conditions are $\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$ and $S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$. For the six-region models, these ratios are 0.79 and 0.68, respectively, indicating that the long-term average biomass would fall below that capable of producing *MSY* at 2001–2004 average fishing mortality. For all analyses undertaken in this assessment, current biomass exceeds the biomass yielding *MSY* ($B_{current} / \tilde{B}_{MSY}$ > 1.0) with a high probability; i.e. **the bigeye stock in the WCPO is not in an overfished state** due to above average recruitment. However, biomass levels in recent years have been declining under increasing levels of fishing mortality, and the probability of the stock becoming overfished is increasing over time.

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

9. Stock projections for 2006–2015 — that attempt to simulate the conservation and management measures adopted at WCPFC2 — indicate that $B_t / \tilde{B}_{MSYfinal}$ falls below 1.0 under long-term average recruitment with high probability but remains above 1.0 if 1995–2004 average recruitment is assumed to continue throughout the projection period. The projections based on long-term average recruitment indicate a strong shift in the spatial distribution of biomass with continued depletion occurring in the equatorial regions due to constant high longline catches.

10. At the request of the Commission, various levels of purse seine effort reduction (which could be implemented by time closures) were investigated using stock projections. The projections indicated that, under assumed long-term average recruitment and maintenance of non-purse seine

fisheries at 2004 catch/effort levels, a purse seine effort reduction (closure) of 75% would be required to maintain biomass above $\tilde{B}_{MSYfinal}$ for the 10-year projection period.

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

1 Introduction

This paper presents the current stock assessment of bigeye tuna (*Thunnus obesus*) in the western and central Pacific Ocean (WCPO, west of 150°W). Since 1999, the assessment has been conducted annually and the most recent assessments are documented in Hampton et al. (2004 and 2005). A comparison of results with those from a similarly-structured Pacific-wide analysis is given in a separate paper (Hampton and Maunder 2006). 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 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 ($F_{current}/\tilde{F}_{MSY}$). Likelihood profiles of these ratios are used to describe their uncertainty. The effects of the continuation of the current management arrangements for bigeye tuna, and several possible future arrangements, are investigated through stock projections.

The underlying 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 likelihood (data) and prior information components.

2 Background

2.1 Biology

Bigeye tuna are distributed throughout the tropical and sub-tropical waters of the Pacific Ocean. There is little information on the extent of mixing across this wide area. Analysis of mtDNA and DNA microsatellites in nearly 800 bigeye tuna failed to reveal significant evidence of widespread population subdivision in the Pacific Ocean (Grewe and Hampton 1998). While these results are not conclusive regarding the rate of mixing of bigeye tuna throughout the Pacific, they are broadly consistent with the results of SPC's tagging experiments on bigeye tuna. Bigeye tuna tagged in locations throughout the western tropical Pacific have displayed movements of up to 4,000 nautical miles (Figure 1) over periods of one to several years, indicating the potential for gene flow over a wide area; however, the large majority of tag returns were recaptured much closer to their release points. Also, recent tagging experiments in the eastern Pacific Ocean (EPO) using archival tags have so far not demonstrated long-distance migratory behaviour (Schaefer and Fuller 2002) over relatively short time scales (up to 3 years). In view of these results, stock assessments of bigeye tuna are routinely undertaken for the WCPO and EPO separately[1].

[1] Efforts continue to develop a bigeye tuna model for the Pacific Ocean as a whole, incorporating spatial structure into the analysis to allow for the possibility of restricted movement between some areas. The results of

Bigeye tuna are relatively fast growing, and have a maximum fork length (FL) of about 200 cm. The growth of juveniles departs from von Bertalanffy type growth with the growth rate slowing between about 40 and 70 cm FL (Lehodey et al. 1999). The natural mortality rate is likely to be variable with size, with the lower rates of around 0.5 yr^{-1} for bigeye >40 cm FL (Hampton 2000). Tag recapture data indicate that significant numbers of bigeye reach at least eight years of age. The longest period at liberty for a recaptured bigeye tuna tagged in the western Pacific at about 1–2 years of age is currently 14 years (SPC unpubl. data).

2.2 Fisheries

Bigeye tuna are an important component of tuna fisheries throughout the Pacific Ocean and are taken by both surface gears, mostly as juveniles, and longline gear, as valuable adult fish. They are a principal target species of both the large, distant-water longliners from Japan and Korea and the smaller, fresh sashimi longliners based in several Pacific Island countries. Prices paid for both frozen and fresh product on the Japanese sashimi market are the highest of all the tropical tunas. Bigeye tuna are the cornerstone of the tropical longline fishery in the WCPO; the catch in the SPC area had a landed value in 2001 of approximately US$1 billion.

Since 1980, the longline catch of bigeye tuna in the WCPO has varied between about 40,000 and 60,000 mt (Figure 2), although catches in excess of 70,000 mt were taken in 2002 and 2004. Since about 1994, there has been a rapid increase in purse-seine catches of juvenile bigeye tuna, first in the eastern Pacific Ocean (EPO) and since 1996, to a lesser extent, in the WCPO. In the WCPO, purse-seine catches of bigeye tuna are estimated to have been less than 20,000 mt per year up to 1996, mostly from sets on natural floating objects (Hampton et al. 1998). In 1997, the catch increased to 35,000 mt, primarily as a result of increased use of fish aggregation devices (FADs). High purse seine catches were also recorded in 1999 (38,000 mt) and 2000 (33,000 mt).

The spatial distribution of WCPO bigeye tuna catch during 1990–2004 is shown in Figure 3. The majority of the catch is taken in equatorial areas, by both purse seine and longline, but with significant longline catch in some sub-tropical areas (east of Japan, north of Hawaii and the east coast of Australia). High catches are also presumed to be taken in the domestic artisanal fisheries of Philippines and Indonesia. These catches, along with small catches by pole-and-line vessels operating in various parts of the WCPO, have approached 20,000 mt in recent years. The statistical basis for the catch estimates in Philippines and Indonesia is weak; however, we have included the best available estimates in this analysis in the interests of providing the best possible coverage of bigeye tuna catches in the WCPO.

3 Data compilation

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

3.1 Spatial stratification

The geographic area considered in the assessment is the WCPO, defined by the coordinates 40°N–35°S, 120°E–150°W. Within this overall area, a six-region spatial stratification was adopted for the assessment (Figure 3). The rationale for this stratification was to separate the tropical area, where both surface and longline fisheries occur year-round, from the higher latitudes, where the longline fisheries occur more seasonally. The stratification is equivalent to the regional structure adopted in the 2005 assessment. The area north of 20°N has been split into two regions, while the boundary separating eastern and western regions has been shifted from 160°E to 170°E.

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the most recent Pacific-wide model are compared with the WCPO results and the results of the most recent IATTC assessment for the EPO in Hampton and Maunder (2006).

Time series of total catches by major gear categories are shown in Figure 4. Most of the catch occurs in the tropical regions (3 and 4), with most juvenile catches (by purse seine and Philippines/Indonesian fisheries) occurring in region 3 and large longline catches occurring in both regions 3 and 4.

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

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

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

3.2 Temporal stratification

The primary time period covered by the assessment is 1952–2005, thus including all significant post-war tuna fishing in the WCPO. 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). Twenty fisheries have been defined for this analysis on the basis of region, gear type and, in the case of purse seine, set type (Table 1).

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

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

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

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

The Hawaiian handline fishery (HL HW 4) accounts for a relatively small component of the bigeye catch. The fishery was included in the model because it provides a long time-series of weight frequency samples from the catch.

The purse-seine and pole-and-line fisheries within model region 1 were not included in the assessment model. Catches of bigeye by the Japanese coastal surface fleet averaged at about 3,000 mt per annum since the mid 1980s, principally taken by the pole-and-line fishery.

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

3.4 Catch and effort data

Catch and effort data were compiled according to the fisheries defined above. Catches by the longline fisheries were expressed in numbers of fish, and catches for all other fisheries expressed in weight. This is consistent with the form in which the catch data are recorded for these fisheries. Purse seine catches of bigeye are not reliably recorded on logsheets for most fleets, and must be estimated from sampling data. The method used to derive such estimates for the purse seine fishery is based on the two-variable (set type and year) analysis of variance described in Lawson (2005).

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

Effort data units for purse seine fisheries are defined as days fishing and/or searching, allocated to set types based on the proportion of total sets attributed to a specified set type (associated or unassociated sets) in logbook data. For the principal longline fisheries (LL ALL 1–6 or LL ALL 1–7), effective (or standardised) effort was derived using generalized linear models (GLM) (Langley et al. 2005). Time-series of catch and catch-per-unit-effort (CPUE) for all fisheries Figure 5 and Figure 6. The GLM standardise CPUE trends for the principal longline fisheries (LL ALL 1–6 or LL ALL 1–7), for both the six- and seven-region model, are presented in Figure 7.

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. In the standardisation of longline effort, the scaling of standardised CPUE among regions included a correction to allow for the effective area exploited by the fishery in each region. Therefore longline standardised CPUE can be interpreted as an index of exploitable abundance in each region (rather than density).

3.5 Length-frequency data

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

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

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

Purse seine: Length-frequency samples from purse seiners have been collected from a variety of port sampling and observer programmes since the mid-1980s. Most of the early data is sourced from the U.S. National Marine Fisheries Service (NMFS) port sampling programme for U.S. purse seiners in Pago Pago, American Samoa and an observer programme conducted for the same fleet. Since the early 1990s, port sampling and observer programmes on other purse seine fleets have provided additional data. Only data that could be classified by set type were included in the final data set. For each purse seine fishery, size samples were 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 bigeye in the various model regions. Japanese data for 1952–1964 have recently become available, and are included in the assessment. In recent years, data have also been collected by OFP and national port sampling and observer programmes in the WCPO.

3.6 Weight-frequency data

Individual weight data for the Japanese longline fisheries are 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.

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

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

3.7 Tagging data

A modest amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. The data used consisted of bigeye tuna tag releases and returns from the OFP's Regional Tuna Tagging Project conducted during 1989–1992, and more recent releases and returns from tagging conducted in the Coral Sea by CSIRO. 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 (Kaltongga 1998; Hampton and Williams 2004).

In recent years, a large number of tags were released in the Hawaii handline fishery. Inclusion of these data in the six-region model is problematic as all tags are released and recovered around the boundary of regions 2 and 4 (latitude 20° N). This results in large changes in the estimated movement coefficients between regions 2 and 4 and other model parameters influenced by tagging data. On this basis, these data were not included in the current six-region assessment. The revision of the latitudinal boundary between regions 2 and 4 in the seven-region model resolves this problem as all tags released by the handline fishery were recovered in the same region.

For incorporation into the MULTIFAN-CL analyses, tag releases were stratified by release region (all bigeye tuna releases occurred in regions 3, 4 and 5), time period of release (quarter) and the same length classes used to stratify the length-frequency data. For the six-region model, a total of 8,622 releases were classified into 23 tag release groups in this way. 959 tag returns were received that could be assigned to the fisheries included in the model. The inclusion of the recent tag releases in the seven-region model increases the data set to 17,950 releases, classified into 46 tag release groups of which 2,099 tags were recovered.

Tag returns that could not be assigned to recapture fisheries 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 classified by recapture fishery and recapture time period (quarter). Because tag returns by purse seiners were often not accompanied by information concerning the set type, tag-return data were aggregated across set types for the purse seine fisheries in each region. The population dynamics model was in turn configured to predict equivalent estimated tag recaptures by these grouped fisheries.

4 Model description – structural assumptions, parameterisation, and priors

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

4.1 Population dynamics

The six-region model partitions the population into 6 spatial regions and 40 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 et al. 1999). The last age-class comprises a “plus group” in which mortality and other characteristics are assumed to be constant. For the purpose of computing the spawning biomass, we assume a fixed maturity schedule (Table 2).

The population is “monitored” in the model at quarterly time steps, extending through a time window of 1952–2005. The main population dynamics processes are as follows:

4.1.1 Recruitment

Recruitment is the appearance of age-class 1 fish in the population. We have assumed that recruitment occurs instantaneously at the beginning of each quarter. This is a discrete approximation to continuous recruitment, but provides sufficient flexibility to allow a range of variability to be incorporated into the estimates as appropriate.

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

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

Typically, fisheries data are not very informative about SRR parameters and it is generally necessary to constrain the parameterisation in order to have stable model behaviour. We incorporated a beta-distributed prior on the "steepness" (*S*) of the SRR, with *S* defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Francis 1992; Maunder and Watters 2003). The prior was specified by mode = 0.85 and SD = 0.16 (a = 3.1, b = 1.6, lower bound = 0.2, upper bound = 1.0). This prior reasonably reflects our knowledge of tuna stock-recruitment relationships. The prior probability distribution for steepness is shown in Figure 9.

4.1.2 Initial population

The population age structure in the initial time period in each region was assumed to be in equilibrium and determined as a function of the average total mortality during the first 20 quarters. This assumption avoids having to treat the initial age structure, which is generally poorly determined, as independent parameters in the model. Note that the assumption used does not assume virgin conditions at the start of the assessment data. Rather, we assume that exploitation in the years leading up to 1952 was similar to exploitation over the period 1952–1956. This probably overestimates total mortality in the initial population, but the bias should be minimal. 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 distribution of weight-at-age is a deterministic function of the length-at-age and a specified weight-length relationship (see Table 2). As noted above, the population is partitioned into 40 quarterly age-classes.

Previous analyses assuming a standard von Bertalanffy growth pattern indicated that there was substantial departure from the model, particularly for sizes up to about 80 cm. Similar observations have been made on bigeye tuna growth patterns determined from daily otolith increments and tagging data (Lehodey et al. 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). For the six-region model, there are seven inter-regional boundaries in the model with movement possible across each in both directions. Four seasonal movements were allowed, each with their own movement coefficients. Thus there is a need for $2 \times 7 \times 4 = 56$ movement parameters. We did not incorporate age-dependent movement into this assessment, to avoid the addition of more parameters. Trials indicated that this additional structure did not impact the overall results in a substantive way. The seasonal pattern of movement persists from year to year with no allowance for longer-term variation in movement.

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

4.1.5 Natural mortality

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

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

4.2 Fishery dynamics

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

4.2.1 Selectivity

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

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

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

4.2.2 Catchability

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

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

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

4.2.3 Effort deviations

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

4.3 Dynamics of tagged fish

4.3.1 Tag mixing

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

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

4.3.2 Tag reporting

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

4.4 Observation models for the data

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

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

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

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

4.5 Parameter estimation and uncertainty

The parameters of the model were estimated by maximizing the log-likelihoods of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. The maximization was performed by an efficient optimization using exact derivatives with respect to the model parameters. Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters. A bash shell script, *doitall.bet*, 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 *bet.ini* file (Appendix B) [2].

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

[2] 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).

function for deviations from the target ratio) over the range of possible values. The likelihood function values resulting from these runs were then used to construct a probability distribution for each ratio.

4.6 Stock assessment interpretation methods

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

4.6.1 Fishery impact

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

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

4.6.2 Yield analysis

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

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

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

5 Sensitivity analyses

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

In summary, the analyses carried out are:

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

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

6 Results

The results from the three analyses are presented below. In the interests of brevity, some categories of results are presented for the LOWSAMP analysis only, which is designated the base-case analysis. Significant differences between the base case and the two sensitivity analyses are summarised in Section 6.4. The main stock assessment-related results are also summarised for all analyses.

6.1 Fit statistics and convergence

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

6.2 Fit diagnostics (LOWSAMP)

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

- The log total catch residuals by fishery are shown in Figure 11. The magnitude of the residuals is in keeping with the model assumption (CV=0.05) and they generally show even distributions about zero. One noteworthy exception is for LL ALL 3, which shows a group of negative residuals in the 1990s.
- There is some systematic lack of fit to the length data for the longline fisheries as revealed from a comparison of the observed and predicted length data aggregated over time (Figure 12).

For some of the longline fisheries (LL ALL 1 and LL TW-CH 4) the model over-estimates the proportion of fish in the larger length classes and, correspondingly, under-estimates the proportion of fish in the smaller length classes. However, the fit to these data is superior to the previous assessment (Hampton et al. 2005) largely due to the refinement of the treatment of the weight frequency data (see Langley 2006a for details). These changes resolved much of the apparent conflict between the length- and weight-frequency data included in the model.

- For a number of the longline fisheries, the size composition of the catch is multimodal (LL ALL 1–2, LL HW 2, and LL PG 3); however, the overall fit to the size data is poor as the model is unable to predict the strong modal structure. This appears partly attributable to an inconsistency between the mean length of individual modes and the estimated growth function for the fish in the smaller age classes (predicted to be age classes 5–8 in the model).
- The surface fisheries (the purse-seine fisheries and PHID MISC 3) reveal a similar discrepancy between the observed and predicted size composition. These fisheries principally catch small fish and there is a strong modal structure to the length frequency data. The predicted size composition does not adequately predict the magnitude of these modes and generally has a broader size distribution than observed. As for the longline data, this discrepancy appears due to an inconsistency between the estimated growth function and the observed modal structure of the length frequency samples.
- For most fisheries, the size composition of individual length samples is consistent with the temporal trend in the size composition of the fishery-specific exploitable component of the population (Figure 13). However, a number of the principal longline fisheries reveal substantial changes in the size composition of the sampled catch that are not predicted by the model. For example, the LL ALL 3 fishery length samples were comprised of significantly smaller fish during the 1970s and 1980s than during the 1990s, while the model does not predict a strong temporal trend in the size composition (Figure 13). Similarly, there is a marked shift in the observed length-composition in the LL ALL 2 fishery in the late 1970s–early 1980s with significantly smaller fish sampled in the latter period. Such changes are indicative of temporal changes in the selectivity of individual fisheries and may be, at least partly, explained by temporal trends in the spatial distribution of fishing and sampling effort within a sub-region that exhibits spatial heterogeneity in size structure (see Langley 2006c).
- For most of the longline fisheries, there is a good fit aggregated fit to the weight frequency data (Figure 14). However, for a number of fisheries with a strong modal structure in the weight distribution for which the model does not reliably predict the size composition. These fisheries include LL ALL 1, LL ALL 2, LL PG 3, and LL HW 4 for which the model tends to consistently under-estimate the magnitude of the stronger modes of the weight distribution. There is also a relatively poor fit to the weight data from those fisheries with limited size data, especially LL TW-CH 4. This fishery is constrained to have a selectivity equivalent to that of the Chinese/Taiwanese longline fishery in region 3 (LL TW-CH 3). This assumption requires further examination.
- The temporal trends in the fit to the weight data are similar to those described for the length data, most notably for LL ALL 1 and LL ALL 2 (Figure 15). The consistency in the trends between the length- and weight-frequency data further supports the presumption of a temporal trend in the selectivity of these fisheries. The temporal trend observed in the fit to the LL ALL 3 length data is not observed in the weight data. This may be partly explained by a difference in the spatial distribution of the collection of length- and weight-frequency data within this region (see Langley 2006c).
- 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, respectively. Overall, the model predicts tag attrition reasonably well. However, there is some lack of fit for individual fisheries, in particular the under-estimation of tag returns from the Australian longline fishery (see panel LL AU 5 of Figure 18). These returns were all from releases in the north-western Coral Sea and were recaptured over a long period of time in a relatively small area around the release site (some

tags were recaptured from further a field, but these were relatively few). Therefore, the observed tag returns suggest a pattern of small-scale residency (or homing) that the relatively coarse spatial scale of the model is unable to capture completely. The model fit to the other fisheries is generally good for fisheries that returned large numbers of tags.

- The overall consistency of the model with the observed effort data can be examined in plots of effort deviations against time for each fishery (Figure 19). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. On the other hand, if there was an obvious trend in the effort deviations with time, this may indicate that a trend in catchability had occurred and that this had not been sufficiently captured by the model. Of particular interest are the effort deviations for the LL ALL 1–6 longline fisheries, which were constrained to have the same average catchability and to have no year-to-year variation in the base-case model. There are no patterns in the distributions of effort deviations for these fisheries to suggest failure of these assumptions.
- Effort deviations for the purse seine fisheries, particularly those in region 4, are highly variable and reveal short-term fluctuations (Figure 19). This observation indicates availability of bigeye to the purse-seine fishery is highly variable and may be related to short-term fluctuations in oceanographic conditions.

6.3 Model parameter estimates (LOWSAMP unless otherwise stated)

6.3.1 Growth

The estimated growth curve is shown in Figure 20. The non-von Bertalanffy growth of juvenile bigeye tuna is evident, with near-linear growth in the 50–100 cm size range. For the base-case model, growth in length is estimated to continue throughout the lifespan of the species, without the attenuation of length approaching a maximum level. The estimated variance in length-at-age is very low — much lower than estimated from the 2005 assessment (Hampton et al. 2005). For example, at age 20 the current assessment estimates a standard deviation at length of 7.2 cm compared to 19.1 cm from the 2005 assessment.

Comparisons of the estimated growth curve with length increments from tagging data and daily otolith readings (Lehodey et al. 1999) show some inconsistencies (Figure 21). Most of the tagging length- and age-at-recapture observations occur below the estimated growth curve, particularly for long-term releases. On the other hand, the otolith length-age observations occur slightly above the estimated curve. These inconsistencies could be related to spatial or other growth variability not included in the model. Further analysis is required to resolve this issue.

There is also a considerable difference in the growth curve estimated from the seven-region model compared to the six-region models (Figure 20). For the seven-region model, growth is estimated to be higher for the younger ages (less than 12 quarters) and attenuates at a mean length of about 150 cm. The standard deviation at length is also considerably greater than for the six-region models.

For such a complex model, it is difficult to speculate on the cause of the differences in the growth parameterisation between the six- and seven-region models, except for the obvious difference in the spatial aggregation of the size-frequency data and differences in estimated fishing mortality rates among regions. Similarly, the only substantive differences between the 2005 and 2006 assessments are with the treatment of the weight frequency data and in the estimation of selectivity for some of the principal longline fisheries.

6.3.2 Natural mortality

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

6.3.3 Movement

Two representations of movement estimates are shown in Figure 22 and Figure 23. The estimated movement coefficients for adjacent model regions are shown in Figure 22. Coefficients for some region boundaries are close to zero, while overall, movement rates are low. The highest movement rates occur from region 3 to region 4 (7%) and vice versa (4%) in the second quarter and from region 2 to region 4 in the third quarter (6%).

The distribution of regional biomass by source region derived from a simulation using the movement coefficients is presented in Figure 23. The simulation indicates that most biomass within a region is sourced from recruitment within the region, particularly for regions 2, 3, 5 and 6. The mixing between the equatorial regions results in a significant (about 25%) mixing of biomass between the two regions. There is a similar proportion of biomass within region 1 that is sourced from fish recruited in region 2. Regional fidelity is highest in region 6 with virtually no transfer of biomass from this region and almost all biomass sourced from recruitment within the region (Figure 23).

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

6.3.4 Selectivity

Estimated selectivity coefficients are generally consistent with expectation with longline fisheries principally selecting larger, older fish and the associated purse-seine sets (FAD and log sets) catching smaller bigeye (Figure 24). The composite Philippines/Indonesia surface fisheries (PH/ID MISC 3) principally catch small fish; however, there are also some observations of larger fish in the catch (see Figure 12) that explain the high selectivity of older fish also.

For the all the principal longline fisheries (LL ALL 1–6), selectivity is estimated to decline for the older age classes and the catch is predicted to be principally comprised of age 5–9 fish and selectivity of older fish is relatively low. This is consistent with the slightly smaller size of fish caught by these fisheries compared to the corresponding TW-CH fisheries. The functional form of the (common) selectivity of the latter fisheries is constrained to have full selectivity for the oldest age classes. Other longline fisheries are also estimated to have a high selectivity for the older age classes (LL PG 3, LL AU 5, and LL PI 6).

Selectivity functions are temporally invariant. However, for a number of fisheries there is a clear temporal change in the size-frequency data and an associated lack of fit to the predicted size composition (see Section 6.2). This is particularly evident for the LL ALL 1 fishery with a substantial change in size composition in the late 1970s.

6.3.5 Catchability

Time-series changes in catchability are evident for several fisheries (Figure 25). There is evidence of a general increase in catchability for the purse seine fisheries and some of the domestic longline fisheries (LL PG 3, LL AU 5, and PH HL 3). Catchability in the LL ALL 1–6 longline fisheries was assumed to be constant over time, with the exception of seasonal variation (not shown in Figure 25).

Since the early 1990s, the model estimates a strong increase in the catchability from the Philippines and Indonesian surface fisheries (PH/ID MISC 3). There is no effort data for this PHID MISC 3 fishery and the model assumes catches are proportional to effort throughout the history of the fishery.

6.3.6 Tag-reporting rates

Estimated tag-reporting rates by fishery are shown in Figure 26. Reporting rates vary widely among fisheries. Note that some reporting rates could reflect the fine-scale distribution of fishing effort and tag releases, as well as the propensity of the fisheries to return recaptured tags. For example, the high estimated reporting rate for LL AU 5 in part reflects the close proximity of tag releases to the operational area of this fishery. By contrast, the very low reporting rate for LL ALL 5 in parts reflects the fact that this fishery is distributed mainly to the east of the tag release locations in region 5.

The estimates for the Philippine/Indonesia domestic fisheries are significantly below their prior mode, indicating that the model has used information contained in the data to estimate this reporting rate.

6.4 Sensitivity analyses

This section summarises the key differences in the main parameters between the base-case (LOWSAMP) model and the two sensitivity analyses. Overall, the two six-region models produce very similar results despite the difference in the relative weighting of the size frequency data. The HIGHSAMP model, with higher weighting to the size frequency data, differs from the base case assessment in respect to the following.

i. There are some minor differences in the seasonal movement patterns although the overall magnitude of movements between regions appears to be comparable between the two models.
ii. Fishery-specific selectivities are very similar for the all the main fisheries, the only exception is the higher selectivity of older fish by the purse-seine unassociated set fisheries from the HIGHSAMP model.
iii. Overall, there is an improvement in the fit to the size-frequency data. However, the HIGHSAMP model is still not able to adequately predict the modal structure of the size composition of the surface fisheries (purse-seine and Indonesia/Philippines) and specific longline fisheries.
iv. For the main longline fisheries, effort deviations from the HIGHSAMP model are more variable and reveal stronger temporal trends than for the LOWSAMP model. Most notable is a general trend in region 3 from predominantly positive effort deviations in the first half of the model period to strongly negative effort deviations in the last decade of the model period (Figure 27). Strongly negative effort deviations are also evident in the LL ALL 6 fishery during the last decade. By contrast, for the LL ALL 1 and 2 fisheries, there is a strong positive temporal trend in the effort deviations from the HIGHSAMP model.

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

i. There are considerable differences in the estimated growth parameters. For the 7REGION model, initial growth is slightly higher although maximum average length is lower and attained at a younger age. There is also a much broader distribution of length at age compared to the two six-region models.
ii. The movement parameterisation is comparable between the two models, although there is a higher level of movement from region 3 to region 4 in the 7REGION model. There is only limited exchange between region 7 and the adjacent regions (1 and 3).
iii. The common selectivity of the main longline fisheries in regions 3–6 (LL ALL 3–6) is similar to the LOWSAMP model. For the 7REGION model, selectivity of the principal longline fisheries in the northern regions exhibits a greater decline for the older age classes compared to the LOWSAMP model.
iv. The selectivity of the purse-seine fisheries is similar between the two models, albeit that the selectivity for the 7REGION model is shift slightly to younger age classes to account for the difference in growth. The principal difference in selectivity between the two models is for the PHID MISC fishery. In the seven-region model, the highest selectivity occurs for the two youngest age classes and selectivity decreases sharply with increasing age, although there is still

some selectivity for old age classes. In contrast, the six-region model estimates a selectivity function with relatively low selectivity for the young age classes and high selectivity for old age classes.

v. The 7REGION model estimates similar higher tag reporting rates for all fisheries, particularly those that account for most of the tag recoveries.

vi. For regions 2–6, the magnitude and trends in regional recruitment are very similar between the 7REGION and LOWSAMP model. However, total recruitment is considerably higher for the 7REGION model with higher recruitment in region 1 and a significant additional source of recruitment from region 7. The latter area accounts for about 8% of recruitment for the entire time period and a higher level of recruitment from the last decade (12%).

vii. A qualitative examination of the 7REGION model fit to the size data reveals a significant improvement to the fit to the length data from the equatorial surface fisheries compared to the LOWSAMP model. However, there remains an inconsistency in the fit to length frequency data from those longline fisheries exhibiting a strong modal structure in the length distribution (LL ALL 1–2, LL HW 2).

viii. For the 7REGION model, the variation in effort deviations for the principal longline fisheries in regions 1–4 (LL ALL 1–4) is considerably lower than for the base case (LOWSAMP) model. There is also no temporal trend in the effort deviations evident for any of the principal longline fisheries. This may indicate an improvement in the standardisation of the longline CPUE data achieved through the adoption of a spatial structure that represents a more consistent trend in abundance within each region (see Langley 2006a).

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

6.5 Stock assessment results

6.5.1 Recruitment

The LOWSAMP recruitment estimates (aggregated by year for ease of display) for each region and the entire WCPO are shown in Figure 28. The regional estimates display large interannual variability and variation on longer time scales, as well as differences among regions. For the aggregated estimates, there is a decreasing trend to about 1970 and an increasing trend thereafter. This pattern is similar to that estimated in last year’s assessment. There are sharp initial declines in recruitment in several regions (1, 2, 4), which are the model’s response to the rapid declines in CPUE in these regions. The post-1970 increase in WCPO recruitment is due primarily to an increasing trend in the estimates for region 3 and, to a lesser extent, region 4. This trend, and its correspondence with increasing juvenile catch in the same region, has been noted in previous WCPO bigeye assessments.

Approximate 95% confidence intervals are provided for the aggregate WCPO recruitment estimates. Confidence intervals are wider in the early part of the time series because of the absence of fisheries targeting small fish and lower size frequency sample sizes (Figure 8). There is also the usual expansion in confidence intervals towards the end of the time-series where cohorts have experienced only a short period of exploitation. Confidence intervals for recruitment estimated from the HIGHSAMP analysis are somewhat smaller than those from the LOWSAMP analysis (Figure 29).

A comparison of WCPO recruitment estimates for the different analyses is provided in Figure 30. There is no substantive difference in the recruitment series from the different weighting applied to the size frequency data included in the six-region models. However, while the seven-region model exhibits a comparable temporal trend in recruitment, the recent increase in recruitment is less pronounced as the recruitment in regions 3 represents a smaller proportion of the total recruitment. As previously noted, the overall magnitude of recruitment is considerably higher for the seven-region model than for the six-region model.

6.5.2 Biomass

The estimated biomass trajectory for each region and for the entire WCPO is shown in Figure 31 for the base-case analysis. Biomass is estimated to decline during the 1950s and 1960s in all regions. In region 3, biomass stabilises during the 1970s and 1980s before declining from the mid-1990s. Biomass levels are highest in region 4 and the biomass trend from this region dominates the overall trend in the WCPO; biomass declines rapidly during the 1950s and 1960s, is relatively stable through the 1970s and 1980s, and then declines gradually through the 1990s.

There are very narrow confidence intervals around the time-series of estimated biomass for each region (Figure 31). These confidence intervals do not accurately reflect the true level of uncertainty as they are predicated on the high precision of estimated recruitment time-series and the assumption that natural mortality at age is known without error.

The comparison of total biomass trends for the different analyses is shown in Figure 32. Similar patterns are shown in all analyses, although the seven-region model estimates a substantially higher level of overall biomass compared to the two six-region models.

A useful diagnostic is to compare model estimates of exploitable abundance for those longline fisheries with assumed constant catchability with the CPUE data from those fisheries. The time series comparison of these quantities (Figure 33) shows generally good correspondence between the model estimates and the data, particularly for the equatorial regions where seasonal variation in CPUE is low. Also, the model estimates of exploitable abundance show very similar scaling among regions as the CPUE data (Figure 34). This indicates that model estimates are consistent with the CPUE data in terms of both time-series and spatial variability.

6.5.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase strongly throughout the time series, particularly for the two six-region models (Figure 35). For the two models with lower effective sample sizes (LOWSAMP and 7REGION), fishing mortality on adult bigeye is relatively comparable to that for juvenile bigeye, whereas, the HIGHSAMP model predicts a higher level of exploitation on the adult component of the stock.

Changes in fishing mortality-at-age and population age structure are shown for decadal time intervals in Figure 36. Significant juvenile fishing mortality begins in the 1980s with the development of purse seining in the WCPO. There is also a significant increase in fishing mortality for the middle age-classes in the last decade. Changes in age-structure are also apparent, in particular the decline in abundance of age-classes 20 and older.

6.5.4 Fishery impact

We measure fishery impact at each time step as the ratio of the estimated biomass to the biomass that would have occurred in the historical absence of fishing. This is a useful variable to monitor, as it can be computed both at the region level and for the WCPO as a whole. The two trajectories are plotted in Figure 37. Impacts are significant in all regions, but are particularly strong in the tropical regions 3 and 4, where most of the catch is taken. The patterns for these two regions therefore dominate the overall picture for the WCPO.

The biomass ratios are plotted in Figure 38. These figures indicate strong fishery depletion of bigeye tuna in regions 3 and 4, and moderate levels of depletion in regions 1, 5 and 6. Depletion in region 2 is slight by comparison. For the WCPO as a whole, recent biomass ratios are lower (0.28) for the six-region models than for the seven-region model (0.43) (Figure 39).

It is possible to ascribe 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. Figures are presented for both adult (Figure 40) and total (Figure 41) biomass. In contrast with yellowfin tuna, the longline fishery has a significant impact on the bigeye tuna population in all model regions; it is the most significant component of overall fishery impact in all regions with the exception of region 3 and is responsible for about half of the WCPO impact on total biomass and two-thirds of the impact on adult biomass in recent years. In region 3, the purse seine fisheries and the Indonesian and Philippines domestic fisheries also have high impact on both total and adult biomass. In region 4, purse seine impacts are significant.

6.5.5 Yield analysis

Symbols used in the following discussion are defined in Table 4. The yield analyses conducted in this assessment incorporate the SRR (Figure 42) into the equilibrium biomass and yield computations. The estimated steepness coefficient is 0.95, indicating that there is little evidence of recruitment decline as a function of adult biomass. The high steepness is principally due, at least in part, to the very high estimates of recruitment obtained from the recent lower levels of adult biomass (Figure 42).

Equilibrium yield and biomass (spawning and total) are computed as a function of multiples of the 2001–2004 average fishing mortality-at-age (Figure 43). For the LOWSAMP model, a maximum yield (*MSY*) of 73,000 mt per annum (18,200 mt per quarter) is achieved at *fmult* = 0.8; i.e. at 80% of the current level of fishing effort. This represents a ratio of $F_{current}/\tilde{F}_{MSY}$ equal to 1.25 (approximately 1/0.8); current exploitation rates are higher than the exploitation rates to produce the *MSY*. The equilibrium biomass at *MSY* is estimated at 251,100 mt, approximately 30% of the equilibrium unexploited biomass (Table 5).

The approximate 95% confidence interval associated with the equilibrium yield curve is also presented in Figure 43. The narrow confidence interval across the range of fishing mortality rates suggests a high level of precision associated with the equilibrium yield estimates. This is attributable to the high precision associated with the SRR and the steepness coefficient in particular (Figure 42); i.e. there is apparent high certainty regarding recruitment across a wide range of levels of spawning biomass and, therefore, fishing mortality levels.

For the LOWSAMP model, the reference points $F_t/\tilde{F}_{MSY}$ and $B_t/\tilde{B}_{MSY}$ were computed for each year (*t*) included in the model (1952–2005). These computations incorporated the overall fishery selectivity in year *t*. This enables trends in the status of the stock relative to these two reference points to be followed over the model period (Figure 44). From 1952 to 1970, exploitation rates were low while total biomass declined rapidly relative to $\tilde{B}_{MSY}$. Over the subsequent 25 years, the biomass level ($B_t/\tilde{B}_{MSY}$) remained relatively constant while $F_t/\tilde{F}_{MSY}$ steadily increased. The increase in $F_t/\tilde{F}_{MSY}$ accelerated from the mid-1990s to recent years, exceeding 1.0 in 1997 and remaining above 1.0 in the subsequent years. During the same period, $B_t/\tilde{B}_{MSY}$ has remained relatively constant, due to increased recruitment, and total biomass has remained above the overfished threshold ($\tilde{B}_{MSY}$)(Figure 44). For the LOWSAMP model, current (2001–2004) total biomass is estimated to be 35% higher than $\tilde{B}_{MSY}$ ($B_{current}/\tilde{B}_{MSY}$ = 1.35) (Table 5).

For the LOWSAMP model, the maximum equilibrium yield (MSY_t) was also computed for each year (*t*) in the model. This analysis enables an assessment of the *MSY* level that would be theoretically achievable under the different patterns of age-specific fishing mortality observed through the history of the fishery (Figure 45). Prior to 1970, the WCPO bigeye fishery was almost exclusively conducted by the longline method, with a low exploitation of small bigeye. The associated age-specific selectivity resulted in a substantially higher level of *MSY* (100,000 mt per annum) compared to that estimated for the fishery based on the recent age-specific fishing mortality pattern (about 70,000 mt). The decline in the *MSY* over time follows the increased development of those fisheries that catch smaller bigeye, principally the surface fisheries (Figure 45).

Equilibrium yield and total biomass as functions of multiples of the 2001–2004 average fishing mortality-at-age are shown in Figure 46 for the various analyses. The value of *fmult* associated with *MSY* varies from 0.68 to 1.15 (i.e. $F_{current}/\tilde{F}_{MSY}$ of 0.87–1.48) with the seven-region model being considerably more optimistic than the six-region models. The equilibrium total and adult biomass at *MSY* are estimated to be 30–33% and 18–22% of the equilibrium unexploited total and adult biomass, respectively.

The *MSY* estimates for these analyses range from about 60,000 mt to 90,000 mt per year. These estimates of equilibrium yield are substantially less than recent catches, which have been of the order of 100,000–125,000 mt 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 recruitment from the past 10 years (1995–2004) rather than the equilibrium recruitment, we obtain a clearer picture of *MSY* under current recruitment conditions (Figure 47). Under recent recruitment conditions, maximum yields are estimated to be 110,000–120,000 mt annually.

A number of quantities of potential management interest associated with the yield analyses are provided in Table 5. In the top half of the table, absolute quantities are provided, while the bottom half of the table contains ratios of various biomass and fishing mortality measures that might be useful for stock monitoring purposes. It is useful to distinguish three different types of ratio: (i) ratios comparing a measure for a particular time period with the corresponding equilibrium measure (unshaded rows); (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. The range of values observed in this and other assessments suggests that the category (ii) ratios are considerably more robust than those in category (i).

For the six-region LOWSAMP model, profile likelihood-based estimates of the posterior probability distribution of $B_{current}/\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ were calculated. The profile likelihood distribution reveals that there is a low probability that $B_{current}/\tilde{B}_{MSY}$ is below 1.0 (0.8%) and that the highest probability is at about the level of the point estimate from the model (1.27) — there is a 66% probability that $B_{current}/\tilde{B}_{MSY}$ is within 1.1–1.3 (Figure 48 and Table 7). The posterior probability distribution of $F_{current}/\tilde{F}_{MSY}$ is skewed with the mode of the distribution at about the point estimate of 1.35 and a 100% probability of $F_{current}/\tilde{F}_{MSY}$ exceeding 1.0 (Figure 49). The broad upper tail of the distribution includes a 38% probability that $F_{current}/\tilde{F}_{MSY}$ exceeds 1.5 (Table 7).

Comparable profile likelihoods for the 7REGION model for $B_{current}/\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ are shown in Figure 50 and Figure 51, respectively, showing the more optimistic outcome for $F_{current}/\tilde{F}_{MSY}$ in particular (P>1.0 = 49%) under this model.

6.6 Analyses of management options

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

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

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

6.6.1 Fishing Effort and B_{MSY}

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

Table 8 provides estimates of fishing effort scalars (relative to the 2001–2004 average) that result in equilibrium total biomass at various levels above B_{MSY}. The fishing effort scalar consistent with B_{MSY} is 0.75. In other words, fishing effort would need to be reduced across the board by 25% to obtain an equilibrium biomass equal to B_{MSY}. Progressively lower fishing effort is required to achieve higher equilibrium biomass relative to B_{MSY}.

6.6.2 Stock Projections

a. Effects of WCPFC-2 Conservation and Management Arrangements

Projections were constructed to simulate the application of the WCPFC-2 conservation and management arrangements as they apply to bigeye tuna. The CMAs with respect to bigeye tuna are contained in Attachment D of the WCPFC-2 report[3], and the pertinent paragraphs are:

> *1. Through the adoption of necessary measures, the total level of fishing effort for bigeye and yellowfin tuna in the Convention Area shall not be increased beyond current levels.*
>
> *8. CCMs shall take necessary measures to ensure that purse seine effort levels do not exceed either 2004 levels, or the average of 2001 to 2004 levels, in waters under their national jurisdiction, beginning in 2006.*
>
> *17. The* [longline] *catch of bigeye for each CCM for the next 3 years shall not exceed the average annual bigeye catch for the years 2001-2004 or the year 2004* [the year 2004 applying only to China and the United States].
>
> *18. Paragraph 17 does not apply to CCMs that caught less than 2,000 tonnes in 2004. Each CCM that caught less than 2,000 tonnes of bigeye in 2004 shall ensure that their catch does not exceed 2,000 tonnes in each of the next 3 years.*

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

- Purse seine effort levels for 2004 were assumed for the ten-year projection period (2006–2015). The distribution of effort among regions, quarters and set types was specified according to the average distributions for the period 2001–2004. The use of a multi-year average distribution reduces the risk of anomalous results arising from unusually high or low effort occurring in one of these strata in an individual year.
- Longline effort levels averaged over 2001–2004 were assumed for the projection period, with the exception of the United States and Chinese fleets, which were assigned 2004 levels of effort. Because the extent to which CCMs catching less than 2,000 mt in 2004 might increase their catch is unknown, we did not incorporate catch increases through this provision into the projection; 2001–2004 average catches were used in these cases.

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

- o Relative effort levels for the Philippines and Indonesian domestic fisheries were assumed to continue through the projection period at 2004 levels (due to increases in estimated effective effort for those fisheries during 2001–2004).
- o For fisheries with estimated time-series variation in catchability, the estimated catchability for the last data year (2005) was assumed to continue through the projection period.
- o Recruitment during the projection period was predicted using (i) the estimated SRR; and (ii) an average recruitment for the period 1995–2004. In the case of (i) above, recruitment in the projection period is distributed among regions in accordance with the long-term proportional recruitment distribution.

The results of the projection were expressed as the ratio of total biomass to $\tilde{B}_{MSYfinal}$ where the latter was computed using the *F*-at-age for the final year of the projection. $\tilde{B}_{MSYfinal}$ was virtually identical to $\tilde{B}_{MSY}$ at $F_{current}$. $B_t / \tilde{B}_{MSYfinal}$ for the final years of the assessment (2001–2005) and the ten-year projection period is shown in Figure 52. Projected biomass and $B_t / \tilde{B}_{MSYfinal}$ increases initially due to above-average recruitments estimated towards the end of the assessment time period, but declines sharply under both SRR and average-recruitment scenarios from about 2008. Under average recruitment, the biomass stabilises near $B_t / \tilde{B}_{MSYfinal}$ = 1.2, but under SRR recruitment, $B_t / \tilde{B}_{MSYfinal}$ falls below 0.8.

During the projection period, there is a considerable shift in the regional distribution of total biomass with an increase in the proportion of biomass in regions 1 and 2 and a decline in biomass in the equatorial regions (regions 3 and 4) (Figure 53). The change in biomass distribution is due to the assumption that future recruitment is distributed according to the long-term distribution, resulting in an increased the level of recruitment in regions 1 and 2 in the projection period compared to recent years. Exploitation rates are lower in these two regions and, therefore, provide some buffer to the increasing *F*'s in the tropical region associated with maintaining constant longline catches.

A profile likelihood for the biomass ratio in the final year of the projection ($B_{final} / \tilde{B}_{MSYfinal}$) was computed in order to characterize the uncertainty (Figure 54). The mode of the probability distribution is around 0.75, consistent with the SRR-based projection and substantially less than the mode of the $B_{current} / \tilde{B}_{MSY}$ profile (see Figure 48). The variance of the $B_{final} / \tilde{B}_{MSYfinal}$ profile also is much greater, as expected, due to propagation of uncertainty in recruitment and other parameters through the projection period. Due to this increased uncertainty, the probability of $B_{final} < \tilde{B}_{MSYfinal}$ is approximately 86%, compared to 0.8% for $B_{current} < \tilde{B}_{MSY}$.

The stock projections are highly sensitive to the underlying assumptions described above, particularly regarding the magnitude and distribution of future recruitments. For this reason, the profile likelihood underestimates the magnitude of the uncertainty associated with the stock projections.

b. The effects of closures of the purse seine fishery

The efficacy of purse seine closures as a potential conservation and management measure for bigeye was investigated for the SRR-based projections. Due to the pessimistic projections derived from this recruitment scenario, it was considered that only a large temporal closure would achieve a biomass level above $\tilde{B}_{MSYfinal}$ at the end of the projection period. Simulated closures were applied to the industrial purse seine fisheries throughout the equatorial region. While the closures were applied to the total tropical purse seine fishery, essentially the same results would have been obtained had the closure been applied to FAD/log sets only, as this operational mode is responsible for almost all of the purse seine bigeye catch. No corresponding measures were applied to the domestic surface fisheries of Indonesia/Philippines or the longline fisheries. Three levels of closure were investigated: 6-month (50%), 9-month (75%), and 12-month (100%) closures in each year of the projection period. The reduction in effort to simulate each closure was distributed throughout the year.

The projections revealed that approximately a 75% reduction in purse seine effort would be necessary to maintain the total biomass above the $\tilde{B}_{MSYfinal}$ level throughout the 10-year projection period (Figure 55). For the 75% closure scenario, the total biomass is predicted to be still declining at the end of the period, although it is predicted to stabilise at about the $\tilde{B}_{MSYfinal}$ level.

For the projection based on recent (1995–2004) average recruitment, $B_t \big/ \tilde{B}_{MSYfinal}$ remains above 1.0 for the duration of the projection period and, consequently, there was no need to investigate purse seine closures under this recruitment scenario.

Should the SC wish to investigate the effects of other specific closure scenarios, these can be run during the meeting and the results presented.

7 Discussion and conclusions

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

- The weight frequency sample data were reprocessed to account for temporal and fishery-specific changes in the conversion factors used to convert processed weights (usually gilled-and-gutted) to whole fish weights. The principal effect of this change was to increase the weight (in whole weight) of bigeye sampled by the Japanese longline fisheries subsequent to 1973 (see Langley et al. 2006) and, thereby, reduce the magnitude of the decline in fish size from the longline fishery over the model period.
- A change in the bigeye length-weight relationship was included in the model, applying a relationship more consistent with established values for the species. The relationship predicts a marginally higher weight-at-length compared to the relationship applied in the 2005 assessment.
- Selectivity was parameterised to allow declining selectivity of older fish for the principal (LL ALL 1–6) fisheries. In the previous assessment, all longline fisheries were constrained to be non-decreasing with increasing age and, thereby, have full selectivity for the oldest age classes.
- The base-case assessment (LOWSAMP) applied a lower effective sample size to the length- and weight-frequency data compared to the 2005 assessment. This gives greater influence to the effort data included in the model, resulting in trends in exploitable biomass for the principal longline fisheries being more consistent with the catch and effort series. The HIGHSAMP model applies effective sample sizes that are equivalent to those used in all of the 2005 bigeye tuna assessment runs.
- Only the general linear modelling (GLM) approach was applied to the standardization of the longline effort series. The alternative statistical habitat based standardisation (SHBS) approach used in the 2005 assessment was not used in the current assessment.
- There was a change in the application of the regional scaling effects in the calculation of the standardised effort series for the principal longline fisheries. This resulted in an increased weighting to the LL ALL 2 longline CPUE index and, consequently, a higher total biomass estimated for this region compared to the 2005 assessment.
- A sensitivity analysis was undertaken to investigate the effect of a substantial change in the regional structure of the model with the inclusion of an additional region in the western equatorial region encompassing the fisheries in Indonesian and Philippines waters.

- The addition of recent catch, effort, and size frequency data from most fisheries as well as the inclusion of a significant time-series of length frequency data (and some effort data) from the Philippines domestic fisheries.

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

- Lack of fit to the size data for some fisheries is indicative of temporal changes in selectivity. Some of these changes may be accommodated in future assessments by temporal stratification of certain fisheries. For example, as for yellowfin, it is likely that a substantial improvement in fit to the size data for LL ALL 1 would result by separating the fishery into pre- and post-1978 fisheries. Lack of fit may also result from changes in the distribution of sampling programmes in relation to the distribution of catch and effort. Improved methods for aggregating samples in some fisheries may result in size data that are more representative of the total catch.
- The lack of fit to the juvenile modes in the size frequency data from some fisheries may indicate a bias in the model estimates of growth for the youngest age classes. There is also some divergence between the model estimates of initial growth and length-at-age derived from otolith readings. Further, more detailed, analysis of the modal structure of the size frequency data is required to understand this apparent discrepancy in the growth estimates from the model.
- Residuals in the tag return data for the Australian longline fishery suggested that bigeye tuna may have patterns of long-term residency or homing that cannot be captured by the spatial resolution or movement parameterisation of this model.

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 1 and 2 during the early 1950s. The model attempted to explain these CPUE trends by estimating very high initial recruitments in those regions. While high recruitment in the early 1950s is a possibility (and is in fact suggested by SEAPODYM simulations – see Lehodey 2005), there may be other explanations for the high initial longline CPUE, including short-term targeting of "hot-spots", changes in the spatial distribution of effort within region, higher initial catchability by longline due to higher competition for food, and others. This is the subject of ongoing research.

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

The HIGHSAMP (six-region, high effective sampling size) model most closely approximates the base case assessment from 2005. However, these assessments are not directly comparable due to a number of changes in the assessment from last year (Hampton et al. 2005). These changes are outlined above and represent refinements to the model rather than substantive changes to model structure. The results and conclusions of the six-region models presented here are similar to those presented in the 2005 base-case assessment – depletions levels estimated in the 2005 assessment (0.33) are similar to the current base-case (0.29), $F_{current}/\tilde{F}_{MSY}$ is slightly more pessimistic (1.32 cf 1.23) and $B_{current}/\tilde{B}_{MSY}$ is similar (1.25 cf 1.27).

The LOWSAMP model is slightly more optimistic than the HIGHSAMP model; biomass based reference points are slightly higher ($B_{current}/\tilde{B}_{MSY}$ of 1.27 compared to 1.33), levels of depletion are similar, and fishing mortality based reference points are higher ($F_{current} / \tilde{F}_{MSY}$ of 1.32 compared to 1.48). Recent declines in biomass were similar for the two models.

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

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

Nevertheless, the seven-region model does not address the main deficiency of the current six-region assessment; rather, the uncertainty is partitioned into another region. The western equatorial region (region 7) is estimated to account for a substantial proportion of the total WCPO bigeye biomass (about 12% in recent years). Trends in longline CPUE for this region differ from other areas within the western equatorial waters, hence, the rationale for partitioning this area. However, changes in the spatial distribution and targeting practices of the longline fishery in region 7 mean that there is no reliable index of stock abundance from the late 1980s onward.

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

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

1. Recruitment in all analyses is estimated to have increased since about 1980. This result was very similar to that for the 2005 assessment. However, while the seven-region model exhibits a comparable temporal trend in recruitment, the recent increase in recruitment is less pronounced as the recruitment in region 3 represents a smaller proportion of the total recruitment. The overall magnitude of recruitment is considerably higher for the seven-region model than for the six-region model.

2. For the three analyses, total biomass for the WCPO is estimated to have declined to about half of its initial level by about 1970 and has been fairly stable or subject to slight decline since then. Adult biomass has declined by about 20% over the last decade.

3. The biomass trends in the model are strongly driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. For some of the main longline fisheries, there is an apparent inconsistency between the trends in the size-frequency data and the trends in longline catch and effort; i.e., the two types of data are providing inconsistent information about the relative level of fishing mortality in the region. The LOWSAMP model was adopted as the base case because it was considered that the catch and effort data are more informative than the

size-frequency data in the estimation of trends in fishing mortality. However, further research is required to explore the relationship between longline CPUE and bigeye abundance and the methodology applied to standardise the longline CPUE data, particularly to account for temporal trends in fishing efficiency. The latter issue was examined by way of a sensitivity analysis in the 2005 assessment and shown to be highly influential in the conclusions of the assessment.

4. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. For the two models with lower effective sample sizes (LOWSAMP and 7REGION), fishing mortality on adult bigeye is relatively comparable to that for juvenile bigeye, whereas, the HIGHSAMP model predicts a higher level of exploitation on the adult component of the stock.

5. The ratios $B_t / B_{t,F=0}$ provide a time-series index of population depletion by the fisheries. Overall, depletion is estimated to have been rapid, particularly since the mid-1980s. Even though the estimated total biomass has remained fairly stable since 1970, it appears to have been sustained only by above average recruitment. If recruitment were to return to the average level estimated in this assessment, biomass decline would be rapid, as suggested by the stock projections. The current level of biomass is 28% of the unexploited level ($B_{current} / B_{current,F=0}$ = 0.28) for the six-region models and 44% for the 7REGION model. Depletion is more extreme for some individual model regions, notably region 3 (recent $B_t / B_{t,F=0}$ ratios around 0.20 in the base-case model) and region 4 (0.25). Other regions are less depleted, with recent $B_t / B_{t,F=0}$ ratios of around 0.4 or greater.

6. The attribution of depletion to various fisheries or groups of fisheries indicates that the longline fishery has the greatest impact throughout the model domain. The purse seine and Philippines/Indonesian domestic fisheries also have substantial impact in region 3 and to a lesser extent in region 4.

7. The reference points that predict the status of the stock under equilibrium conditions are $\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$ and $S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$. For the six-region models, these ratios are 0.79 and 0.68, respectively, indicating that the long-term average biomass would fall below that capable of producing *MSY* at 2001–2004 average fishing mortality. For all analyses undertaken in this assessment, current biomass exceeds the biomass yielding *MSY* ($B_{current} / \tilde{B}_{MSY}$ > 1.0) with a high probability; i.e. **the bigeye stock in the WCPO is not in an overfished state** due to above average recruitment. However, biomass levels in recent years have been declining under increasing levels of fishing mortality, and the probability of the stock becoming overfished is increasing over time.

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

9. Stock projections for 2006–2015 — that attempt to simulate the conservation and management measures adopted at WCPFC2 — indicate that $B_t / \tilde{B}_{MSYfinal}$ falls below 1.0 under long-term average recruitment with high probability but remains above 1.0 if 1995–2004 average recruitment is assumed to continue throughout the projection period. The projections based on long-term average recruitment indicate a strong shift in the spatial distribution of biomass with continued depletion occurring in the equatorial regions due to constant high longline catches.

10. At the request of the Commission, various levels of purse seine effort reduction (which could be implemented by time closures) were investigated using stock projections. The projections indicated that, under assumed long-term average recruitment and maintenance of non-purse seine

fisheries at 2004 catch/effort levels, a purse seine effort reduction (closure) of 75% would be required to maintain biomass above $\tilde{B}_{MSYfinal}$ for the 10-year projection period.

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

8 Acknowledgements

We are grateful to all fisheries agencies that have contributed data to the SPC for this assessment. We also acknowledge the assistance of Peter Williams (SPC) and Naozumi Miyabe (NRIFSF) in the compilation of the various data sets.

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

Fishery Number	Reference Code	Nationality	Gear	Region
1	LL ALL 1	Japan, Korea, Chinese Taipei	Longline	1
2	LL ALL 2	Japan, Korea, Chinese Taipei	Longline	2
3	LL HW 2	United States (Hawaii)	Longline	2
4	LL ALL 3	All excl. Chinese Taipei & China	Longline	3
5	LL TW-CH 3	Chinese Taipei and China	Longline	3
6	LL PG 3	Papua New Guinea	Longline	4
7	LL ALL 4	Japan, Korea	Longline	4
8	LL TW-CH 4	Chinese Taipei and China	Longline	4
9	LL HW 4	United States (Hawaii)	Longline	4
10	LL ALL 5	All excl. Australia	Longline	5
11	LL AU 5	Australia	Longline	5
12	LL ALL6	Japan, Korea, Chinese Taipei	Longline	6
13	LL PI 6	Pacific Island Countries/Territories	Longline	6
14	PS ASS 3	All	Purse seine, log/FAD sets	3
15	PS UNS 3	All	Purse seine, school sets	3
16	PS ASS 4	All	Purse seine, log/FAD sets	4
17	PS UNS 4	All	Purse seine, school sets	4
18	PHID MISC 3	Philippines, Indonesia	Miscellaneous (small fish)	3
19	PH HL 3	Philippines, Indonesia	Handline (large fish)	3
20	HL HW 4	United States (Hawaii)	Handline	4

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

Category	Assumptions	Estimated parameters (ln = log transformed parameter)	No.	Prior		Bounds	
				μ	σ	Low	High
Observation model for total catch data	Observation errors small, equivalent to a residual SD on the log scale of 0.07.	None	na	na	na	na	na
Observation model for length-frequency data	Normal probability distribution of frequencies with variance determined by effective sample size and observed frequency. Effective sample size assumed to be 0.02 times actual sample size for all fisheries with a maximum effective sample size of 20.	None	na	na	na	na	na
Observation model for weight-frequency data	Normal probability distribution of frequencies with variance determined by effective sample size and observed frequency. Effective sample size assumed to be 0.02 times actual sample size for all fisheries with a maximum effective sample size of 20.	None	na	na	na	na	na
Observation model for tagging data	Tag numbers in a stratum have negative binomial probability distribution, with estimated variance parameters for fishery groups.	Variance parameters	3	-	-	0	100
Tag reporting	Purse seine reporting rates constrained to be equal within regions. PH /ID fishery reporting rates constrained to be equal. All reporting rates constant over time.	LL 1–LL6, CH/TW LL, PNG LL, PI LL	10	0.5	0.7	0.001	0.9
		AU LL, HW LL, HW HL	4	0.8	0.7	0.001	0.9
		PS	2	0.42	0.1	0.001	0.9
		PH, ID fisheries	1	0.6	0.1	0.001	0.9
Tag mixing	Tags assumed to be randomly mixed at the model region level two quarters following the quarter of release.	None	na	na	na	na	na
Recruitment	Occurs as discrete events at the start of each quarter. Spatially-aggregated recruitment is weakly related to spawning biomass in the prior quarter via a Beverton-Holt SRR (beta prior for steepness with mode at 0.85 and SD of 0.16, lower bound 0.2) .The spatial distribution of recruitment in each quarter is allowed to vary with a small penalty on deviations from the average spatial distribution.	Average spatially aggregated recruitment (ln)	1	-	-	-20	20
		Spatially aggregated recruitment deviations (ln)	216	SRR	0.7	-20	20
		Average spatial distribution of recruitment	5	-	-	0	1
		Time series deviations from average spatial distribution (ln)	1,074	0	1	-3	3

Initial population	A function of the initial recruitment and equilibrium age structure in each region, which is in turn assumed to arise from the total mortality estimated for 1952–56 and movement rates.	Initial recruitment scaling (ln)	1	-	-	-8	8
Age and growth	40 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*=0.000019729, *b*=3.0247 independently estimated from available length-weight data, source N. Miyabe, NRIFSF).	Mean length age class 1	1	-	-	20	40
		Mean length age class 40	1	-	-	140	200
		von Bertalanffy *K*	1	-	-	0	0.3
		Independent mean lengths	7	0	0.7		
		Length-at-age SD	1	-	-	3	10
		Dependency on mean length (ln)	1	-	-	-1.00	1.00
Selectivity	Constant over time. Coefficients for the last 4 age-classes are constrained to be equal. Longline fisheries LL ALL 1–2 and LL ALL 3–6 share selectivity parameters. Purse-seine fisheries share selectivity among regions. For all fisheries, selectivity parameterised with 5-node cubic spline, except Taiwanese/Chinese longline selectivities with logistic function (non decreasing with age).	Selectivity coefficients (5 cubic spline nodes or 2 logistic parameters per fishery)	62	-	-	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)	15	-	-	-15	1
		Seasonality amplitude (ln)	18	0	2.2	-	-
		Seasonality phase	18	-	-	-	-
		Catchability deviations PH/ID (ln)	34	0	0.7	-0.8	0.8
		Catchability deviations other (ln)	105	0	0.1	-0.8	0.8
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.1 for LL ALL 1–6 and SD 0.22 for other fisheries at the average level of effort for each fishery. SD inversely proportional to the square root of effort.	Effort deviations LL 1, 2, 4, 7, 10, 12 (ln)	1,266	0	0.16	-6	6
		Effort deviations PH, ID (ln)	280	0	0.22	-6	6
		Effort deviations other (ln)	1,010	0	0.22	-6	6
Natural mortality	Age-dependent but constant over time and among regions.	Average natural mortality (ln)	0	-	-	-	-
		Age-specific deviations (ln)	0	0	0.22	-5	5
Movement	Age-independent and variant by quarter but constant among years. No age-dependent variation.	Movement coefficients	56	0	0.32	0	3
		Age-dependent component (ln)	0	0	0.32	-4	4
Maturity	Age-dependent and specified – age-class 0-10: 0; 11: 0.05; 12: 0.1; 13: 0.2; 14: 0.4; 15: 0.6; 16: 0.7; 17: 0.8; 18: 0.85; 19: 0.9; 20: 0.95; 21-40: 1	None	na	na	na	0	1

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

Objective function component	LOWSAMP	HIGHSAMP	7REGION
Total catch log-likelihood	427.87	452.25	469.73
Length frequency log-likelihood	-256,231.57	-359,374.42	-286,241.80
Weight frequency log-likelihood	-662,624.14	-852,745.28	-755,395.64
Tag log-likelihood	1,397.62	1,492.59	2,518.62
Penalties	4,215.79	4,871.88	4,553.49
Total function value	-912,814.43	-1,205,302.98	-1,034,095.60

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

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2001–2004
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (*MSY*)
$\tilde{Y}_{F_{current}}$	Equilibrium yield at $F_{current}$
$\tilde{Y}_{F_{MSY}}$ (or *MSY*)	Equilibrium yield at F_{MSY}, or maximum sustainable yield
$\tilde{B}_0$	Equilibrium unexploited total biomass
$\tilde{B}_{F_{current}}$	Equilibrium total biomass at $F_{current}$
$\tilde{B}_{MSY}$	Equilibrium total biomass at MSY
$S\tilde{B}_0$	Equilibrium unexploited adult biomass
$S\tilde{B}_{F_{current}}$	Equilibrium adult biomass at $F_{current}$
$S\tilde{B}_{MSY}$	Equilibrium adult biomass at MSY
$B_{current}$	Average current (2001–2004) total biomass
$SB_{current}$	Average current (2001–2004) adult biomass
B_{1995}	Total biomass in 1995
SB_{1995}	Adult biomass in 1995
$B_{current,F=0}$	Average current (2001–2004) total biomass in the absence of fishing.

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

Management quantity	Units	LOWSAMP	HIGHSAMP	7REGION
$\tilde{Y}_{F_{current}}$	mt per year	70,280	60,720	90,460
$\tilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	72,880	64,600	91,400
$\tilde{B}_0$	mt	826,400	687,700	1,180,000
$\tilde{B}_{F_{current}}$	mt	197,700	156,700	469,400
$\tilde{B}_{MSY}$	mt	251,100	224,100	393,900
$S\tilde{B}_0$	mt	563,300	470,200	744,000
$S\tilde{B}_{F_{current}}$	mt	69,430	49,400	214,000
$S\tilde{B}_{MSY}$	mt	102,400	90,580	166,700
$B_{current}$	mt	339,003	302,569	651,100
$SB_{current}$	mt	122,433	99,512	289,489
$B_{current,F=0}$	mt	1,181,458	1,092,747	1,479,460
$B_{current} / \tilde{B}_0$		0.41	0.44	0.55
$B_{current} / \tilde{B}_{F_{current}}$		1.71	1.93	1.39
$B_{current} / \tilde{B}_{MSY}$		1.27	1.33	1.59
$B_{current} / B_{current,F=0}$		0.29	0.28	0.44
$SB_{current} / S\tilde{B}_0$		0.22	0.21	0.39
$SB_{current} / S\tilde{B}_{F_{current}}$		1.76	2.01	1.35
$SB_{current} / S\tilde{B}_{MSY}$		1.20	1.10	1.74
$\tilde{B}_{F_{current}} / \tilde{B}_0$		0.24	0.23	0.40
$S\tilde{B}_{F_{current}} / S\tilde{B}_0$		0.12	0.11	0.29
$\tilde{B}_{MSY} / \tilde{B}_0$		0.30	0.33	0.33
$S\tilde{B}_{MSY} / S\tilde{B}_0$		0.18	0.19	0.22
$F_{current} / \tilde{F}_{MSY}$		1.32	1.48	0.87
$\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$		0.79	0.70	1.19
$S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$		0.68	0.55	1.28
$\tilde{Y}_{F_{current}} / MSY$		0.96	0.94	0.99
$B_{current} / B_{1995}$		0.94	0.98	0.93
$SB_{current} / SB_{1995}$		0.70	0.75	0.78

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

Gear type / fishery group	MSY (mt per year)	Relative fishing effort to achieve MSY	B_{MSY} (mt)
Longline only	101,456	1.63	270,800
Purse seine only	27,900	4.25	156,700
Philippines/Indonesia only	77,564	5.00	318,900

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

Reference level	Probability (%) of exceeding reference level	
	$B_{current}/\tilde{B}_{MSY}$	$F_{current}/\tilde{F}_{MSY}$
0.5	100.0	100.0
0.6	100.0	100.0
0.7	100.0	100.0
0.8	100.0	100.0
0.9	100.0	100.0
1.0	99.2	100.0
1.1	92.9	100.0
1.2	69.2	100.0
1.3	25.3	100.0
1.4	2.3	66.7
1.5	0.0	37.6
1.6	0.0	19.4
1.7	0.0	8.7
1.8	0.0	3.4
1.9	0.0	1.3
2.0	0.0	0.0

Table 8. Fishing effort scalars relative to the 2001-2004 average required to produce equilibrium total biomass at various levels above B_{MSY}.

Equilibrium biomass relative to B_{MSY}	Equilibrium biomass relative to $\tilde{B}_0$	Fishing Effort Scalar relative to 2001-2004 average
1.00	0.32	0.75
1.05	0.33	0.71
1.10	0.35	0.68
1.15	0.37	0.64
1.20	0.38	0.61
1.25	0.40	0.58
1.30	0.41	0.56
1.35	0.43	0.53
1.40	0.45	0.51

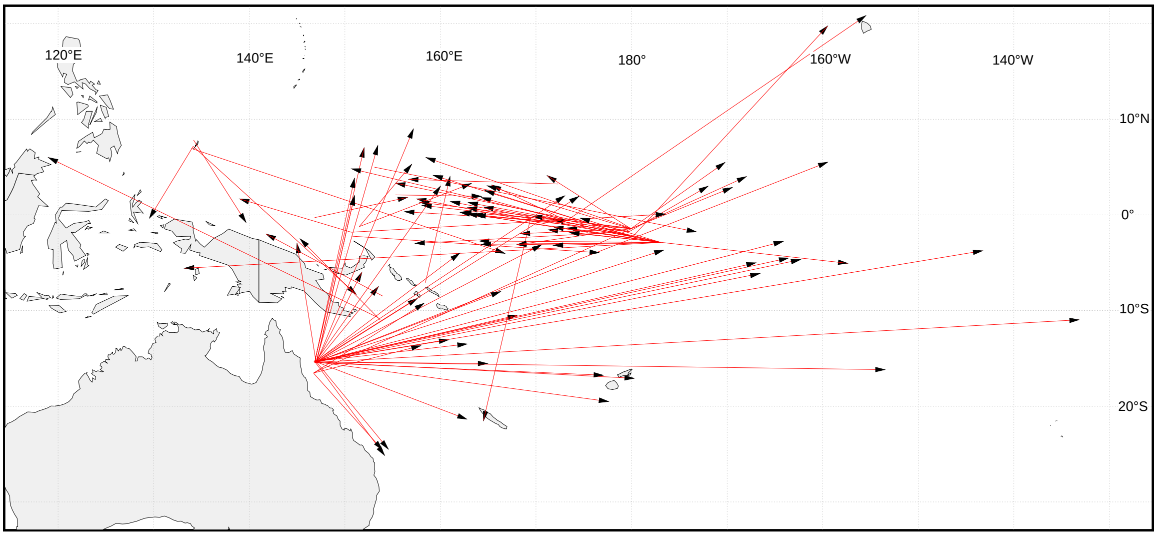


Figure 1. Long-distance (greater than 500 nmi) movements of tagged bigeye tuna.

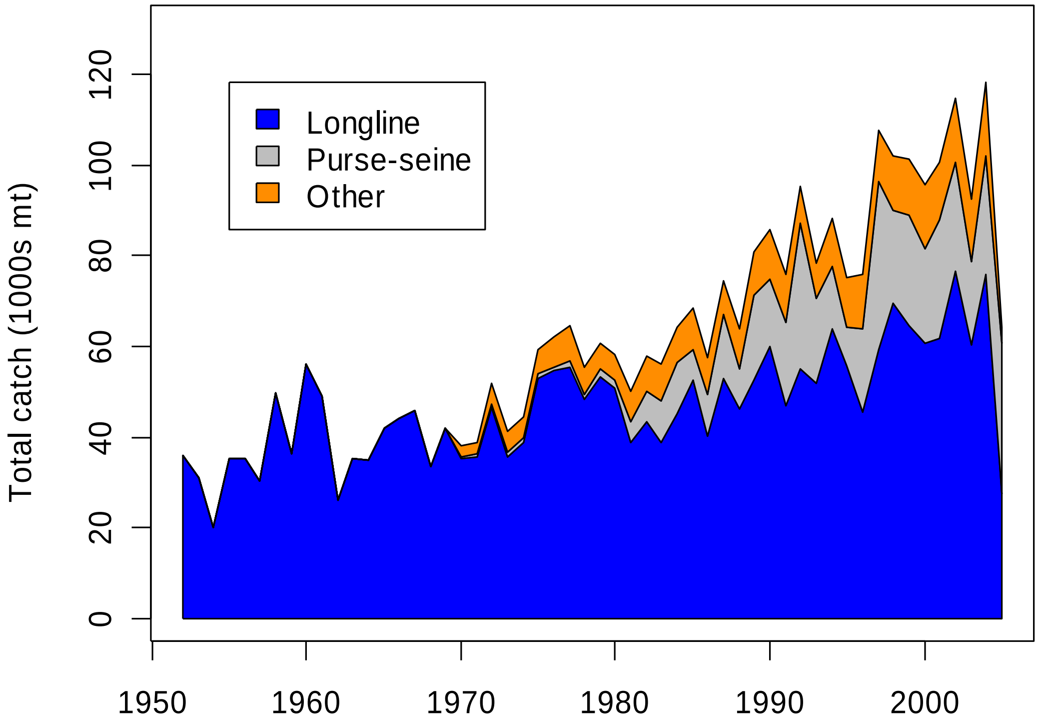
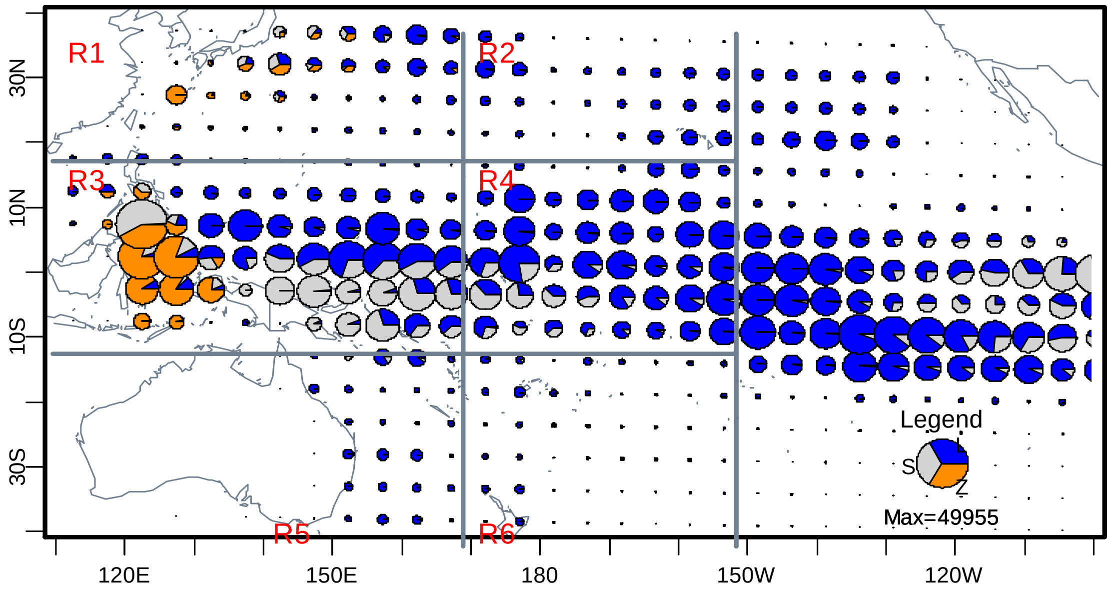


Figure 2. Total annual catch (1000s mt) of bigeye tuna from the WCPO by fishing method from 1952 to 2005. Data from 2005 are incomplete.

(a) Six-region spatial stratification



(b) Seven-region spatial stratification

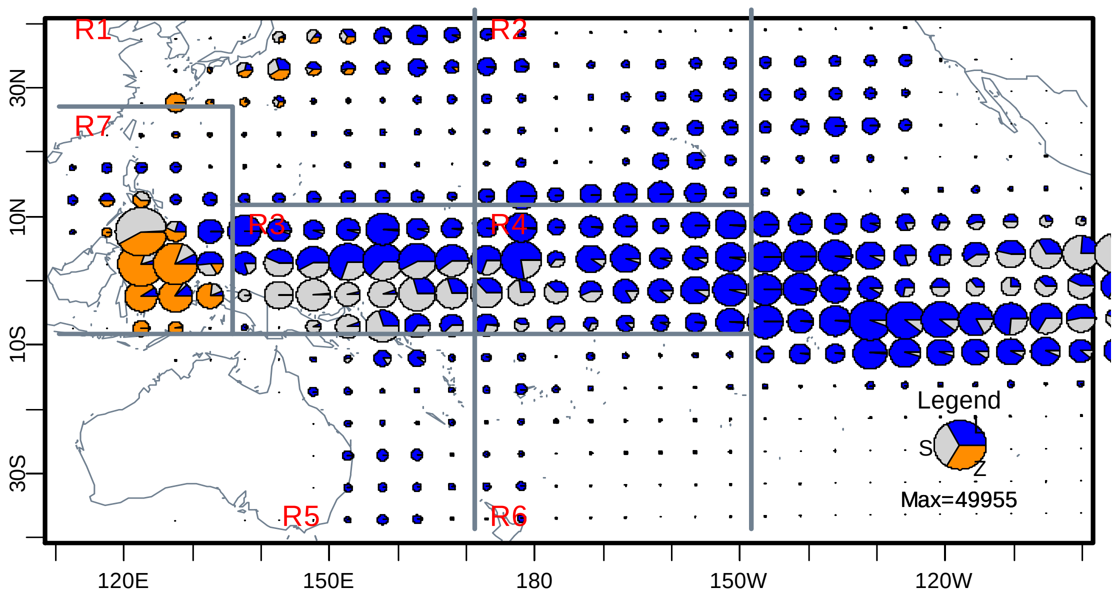


Figure 3. Distribution of cumulative bigeye tuna catch from 1990–2004 by 5 degree squares of latitude and longitude and fishing gear; longline (blue), purse-seine (grey), and other (dark orange). The maximum circle size represents a catch of 50,000 mt. The grey lines indicate the spatial stratification in the six-region model (upper panel) and the seven-region model (lower panel).

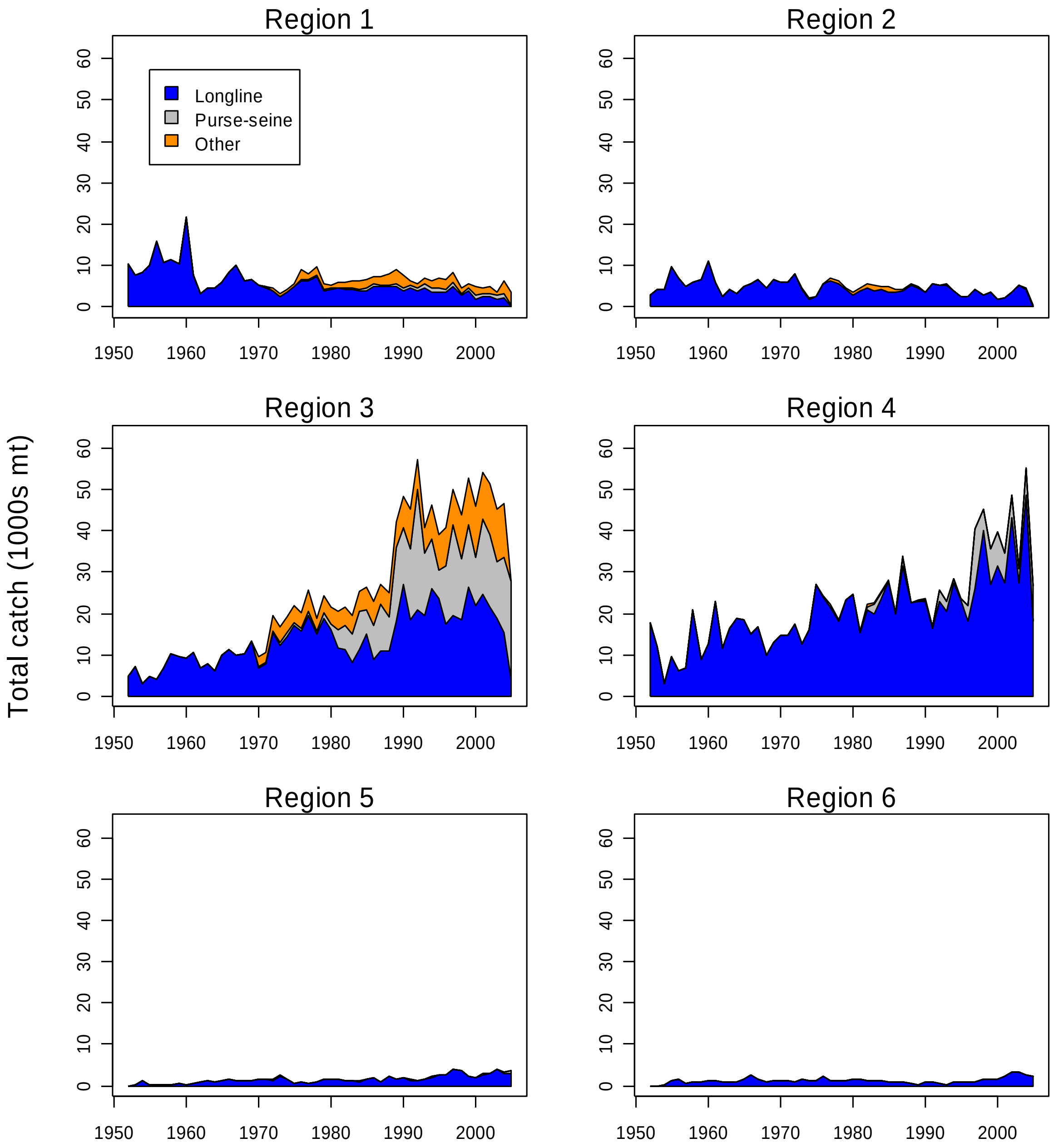


Figure 4. Total annual catch (1000s mt) of bigeye tuna by fishing method and MFCL region from 1952 to 2005. Data from 2005 are incomplete.

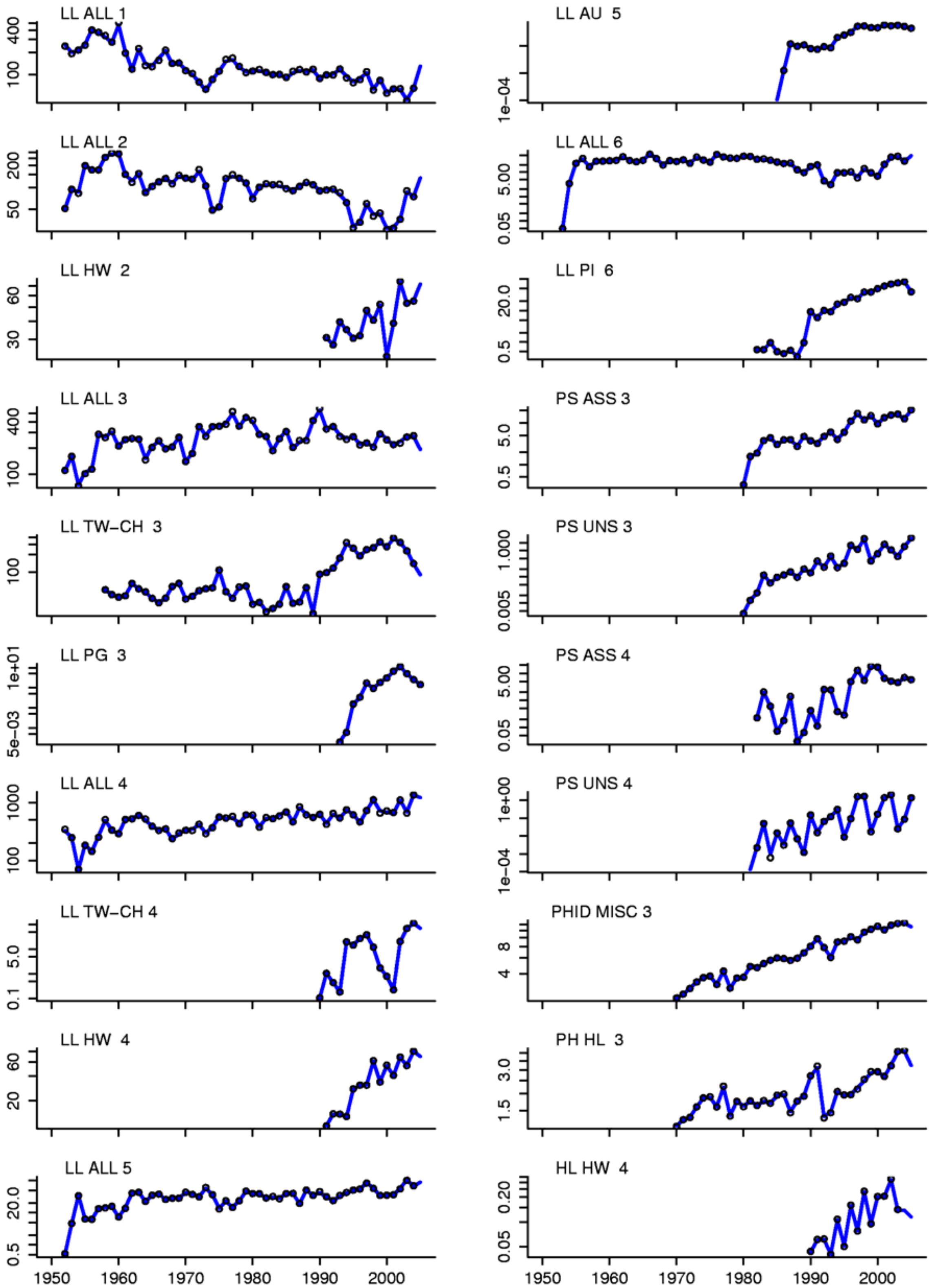


Figure 5. Annual catches by fishery. Circles are observed and the lines are model predictions. Units are catch number of fish (in thousands) for the longline fisheries and thousand metric tonnes for all other fisheries.

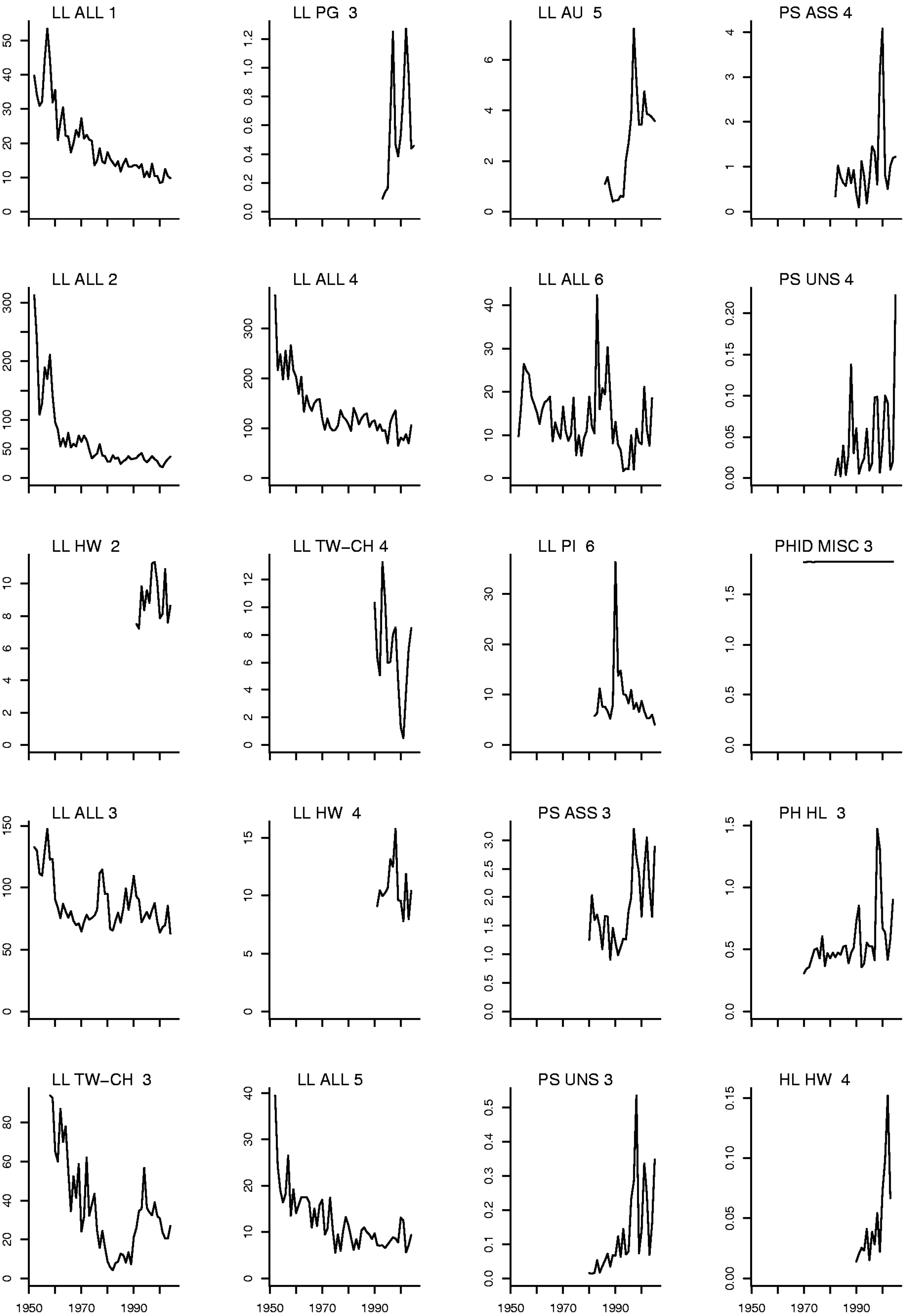


Figure 6. Catch-per-unit-effort (CPUE) by fishery. Units are catch number per GLM-standardised effort (fisheries LL ALL 1–LL ALL 6), catch number per 100 nominal hooks (LL HW, CH/TW LL, LL PI, LL PG) and catch (mt) per day fished/searched (all PS fisheries). Note that CPUE for PH RN, PH HL and ID are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

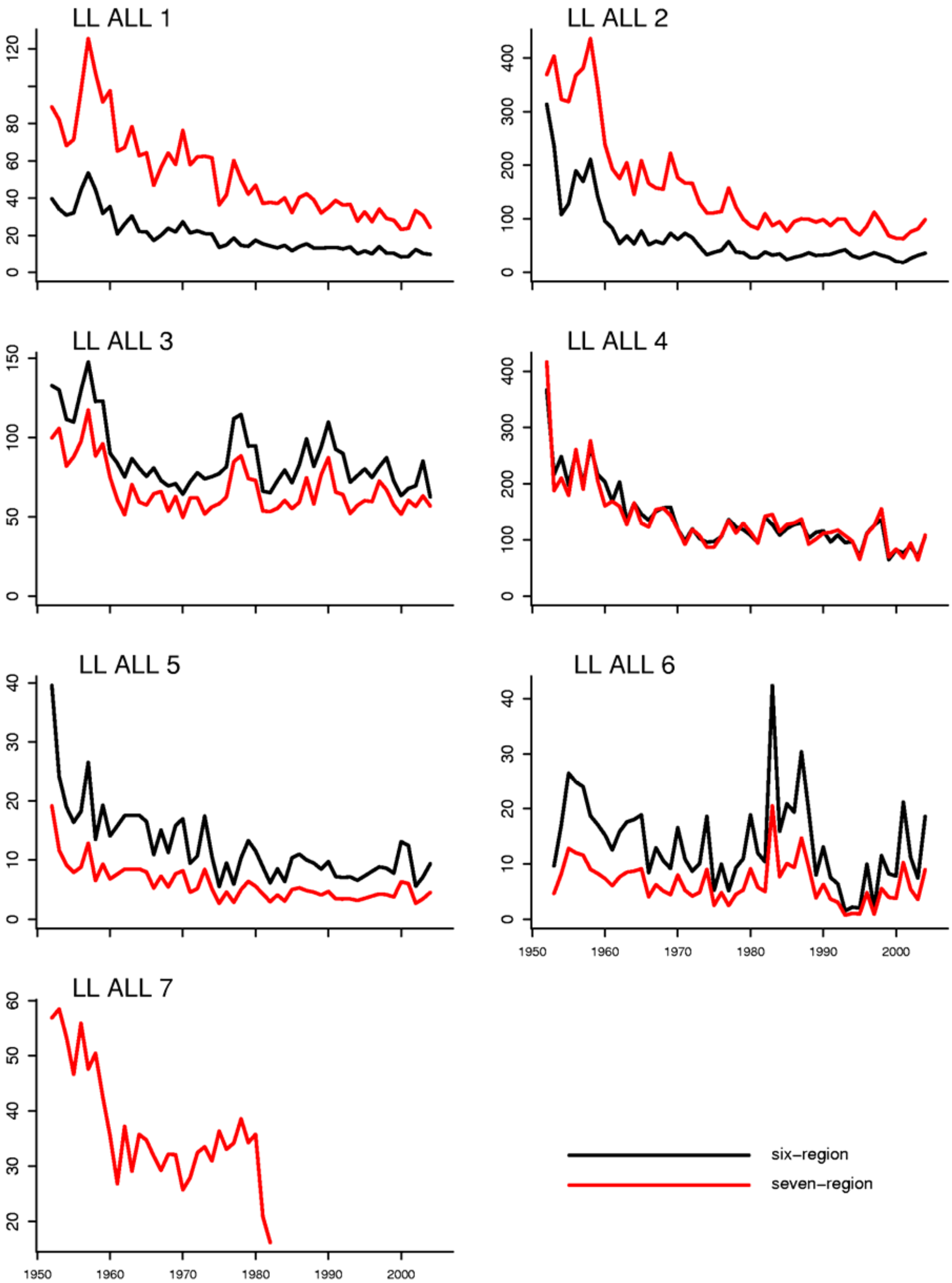


Figure 7. GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL ALL 1–6 and LL ALL 1–7) for the six-region and seven-region models and scaled by the respective region scalars. The LL ALL 7 index extends to 1983 only.

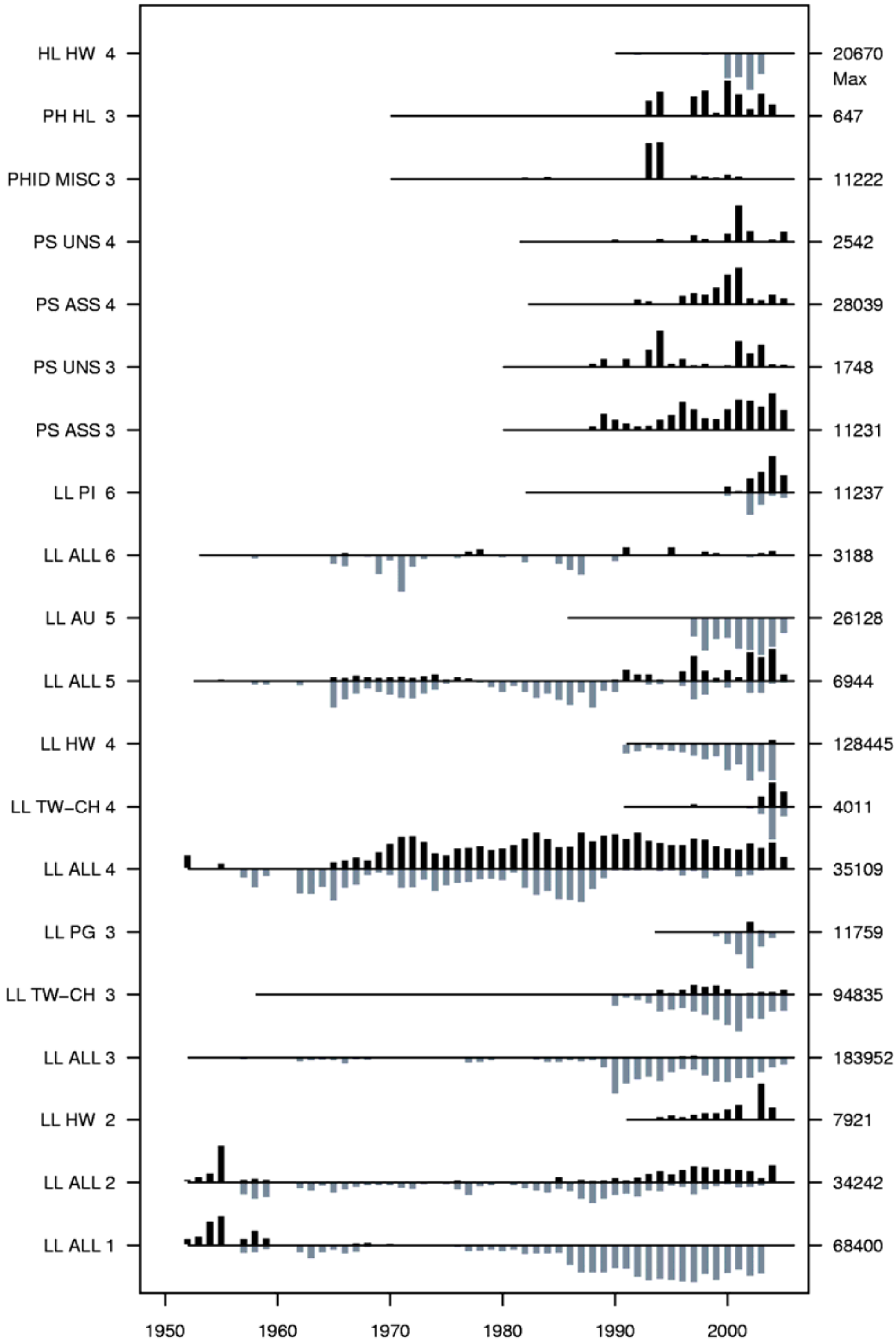


Figure 8. Number of fish size measurements by year for each fishery. The upper black bars represent length measurements and the lower grey bars represent weight measurements. The sample size corresponding to the maximum bar length for each fishery is given on the right-hand side. The extent of the horizontal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

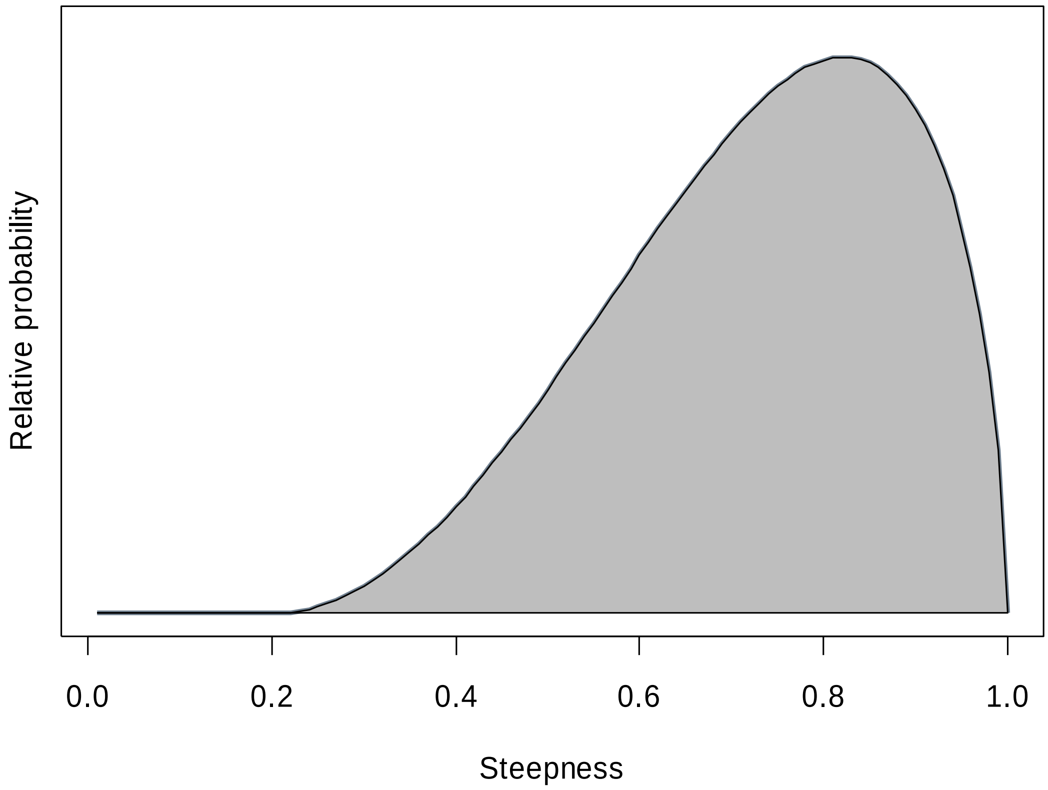


Figure 9. Prior for the steepness parameter of the relationship between spawning biomass and recruitment.

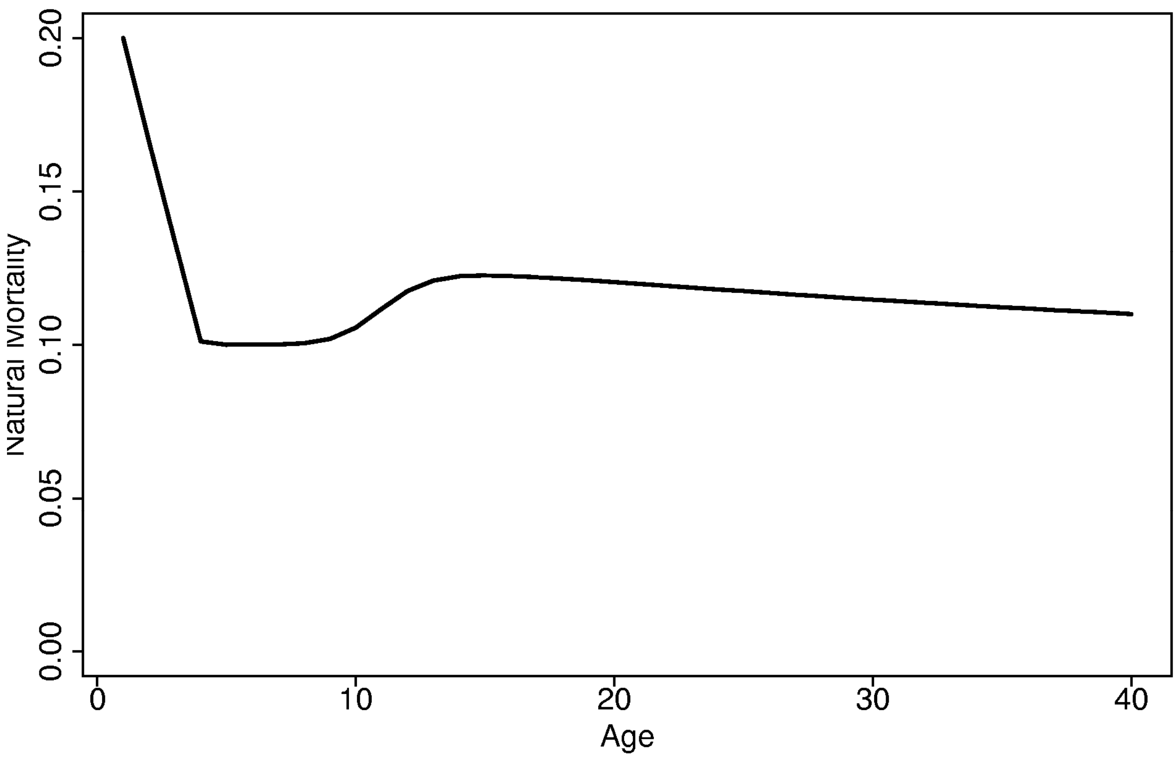


Figure 10. Natural mortality-at-age used in the assessment.

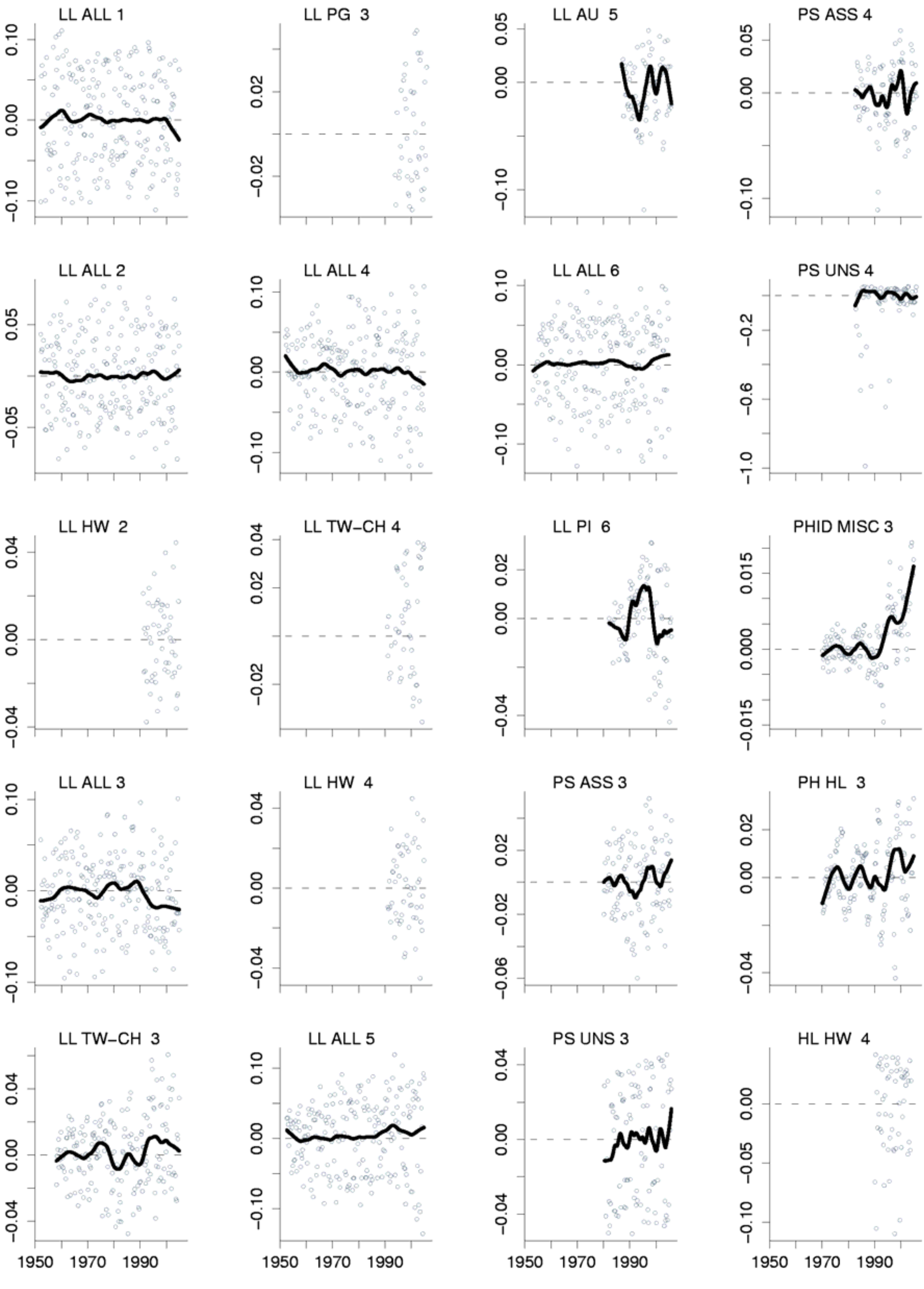


Figure 11. Residuals of ln (total catch) for each fishery (six-region LOWSAMP model). The dark line represents a lowess smoothed fit to the residuals.

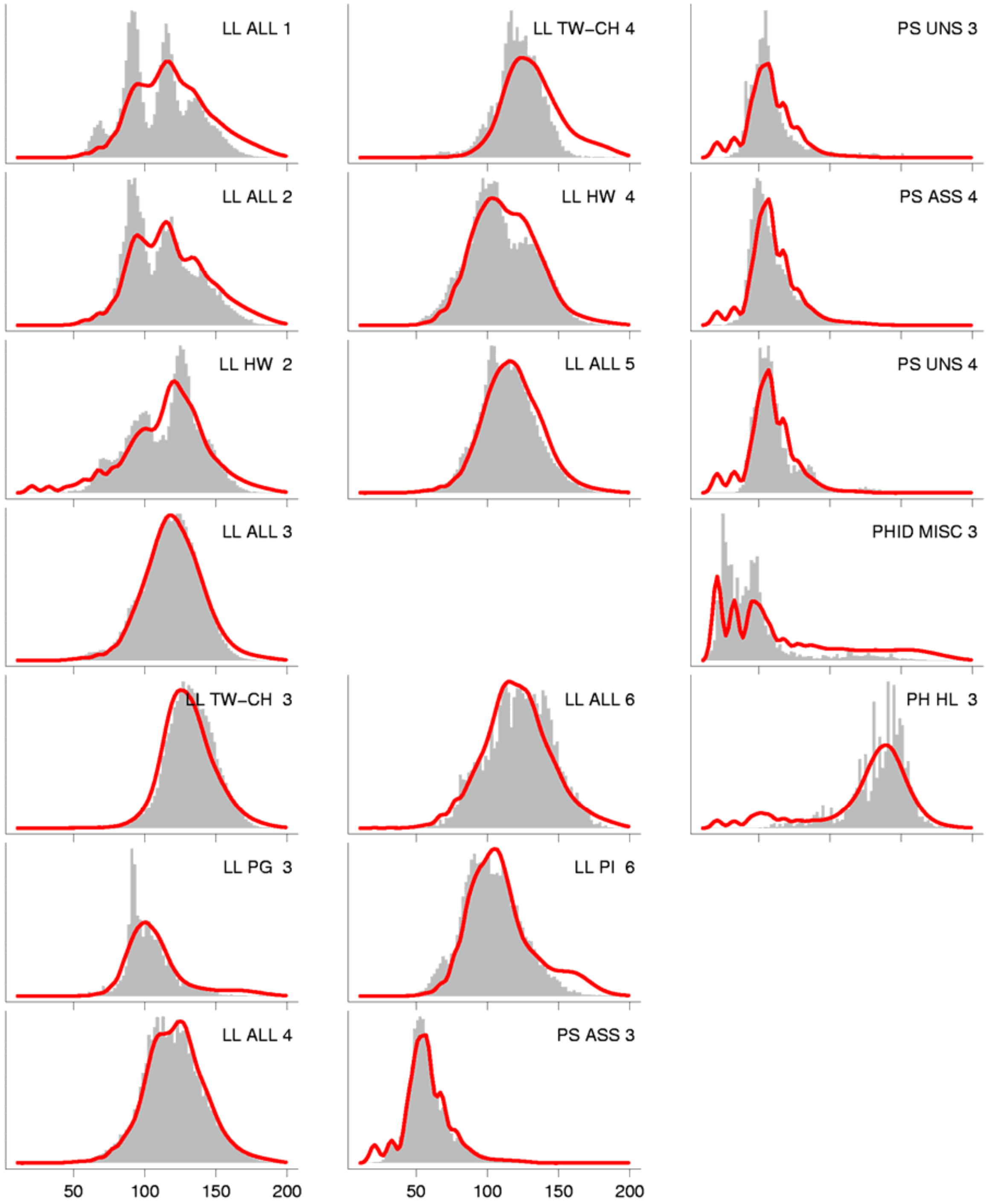


Figure 12. Observed (histograms) and predicted (line) length frequencies (in cm) for each fishery aggregated over time (six-region LOWSAMP model).

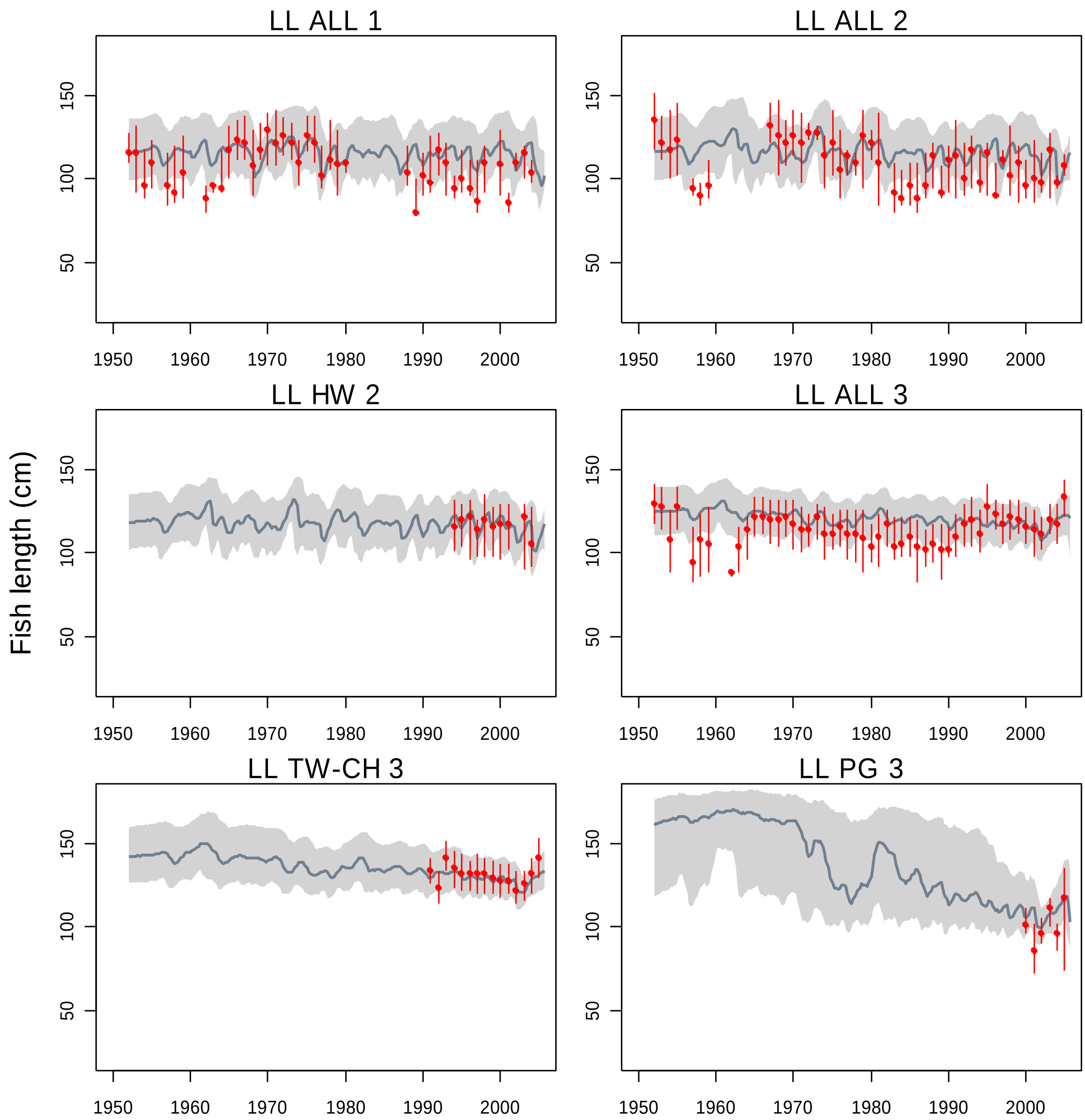


Figure 13. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of bigeye tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and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

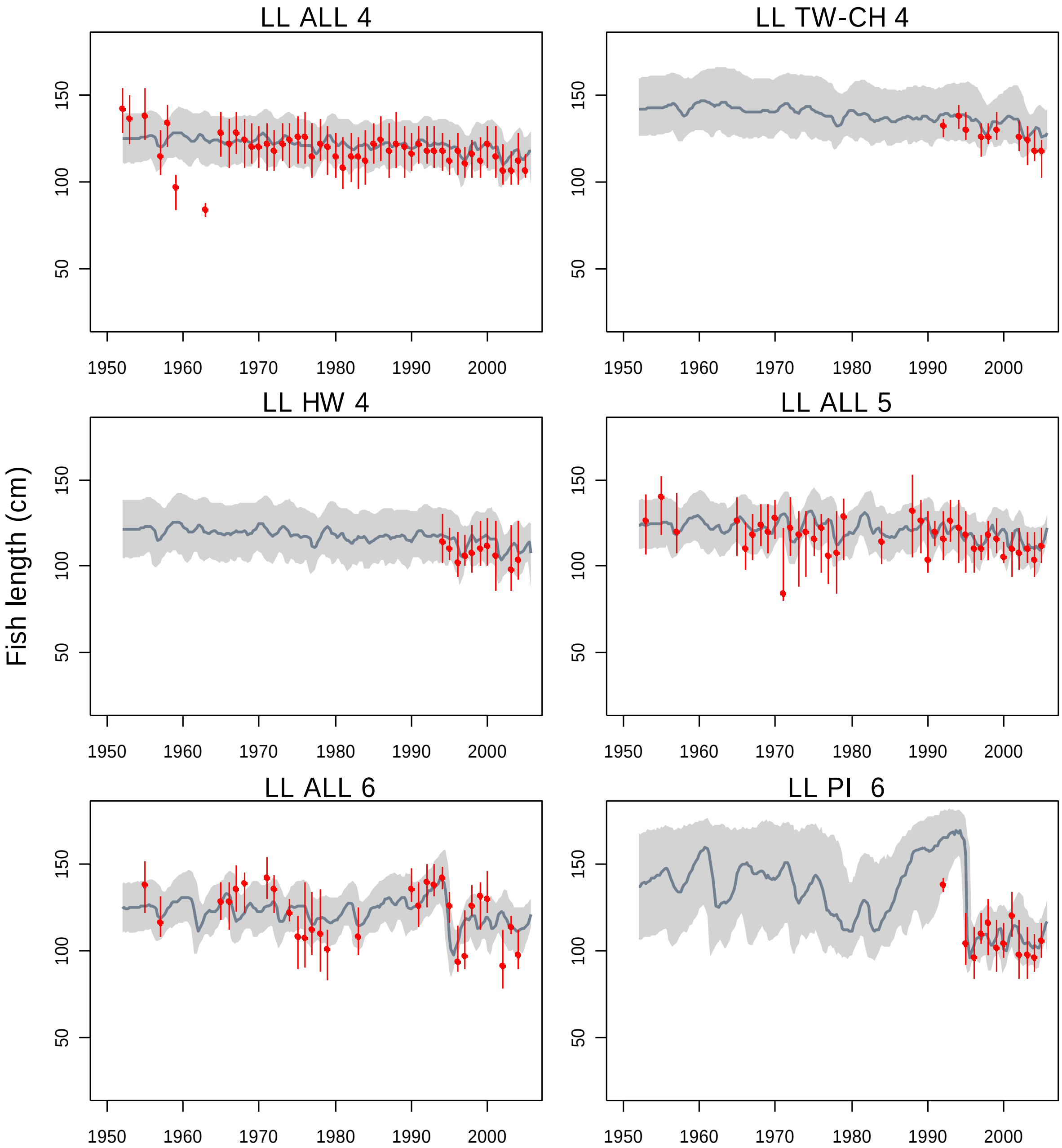


Figure 13 (continued)

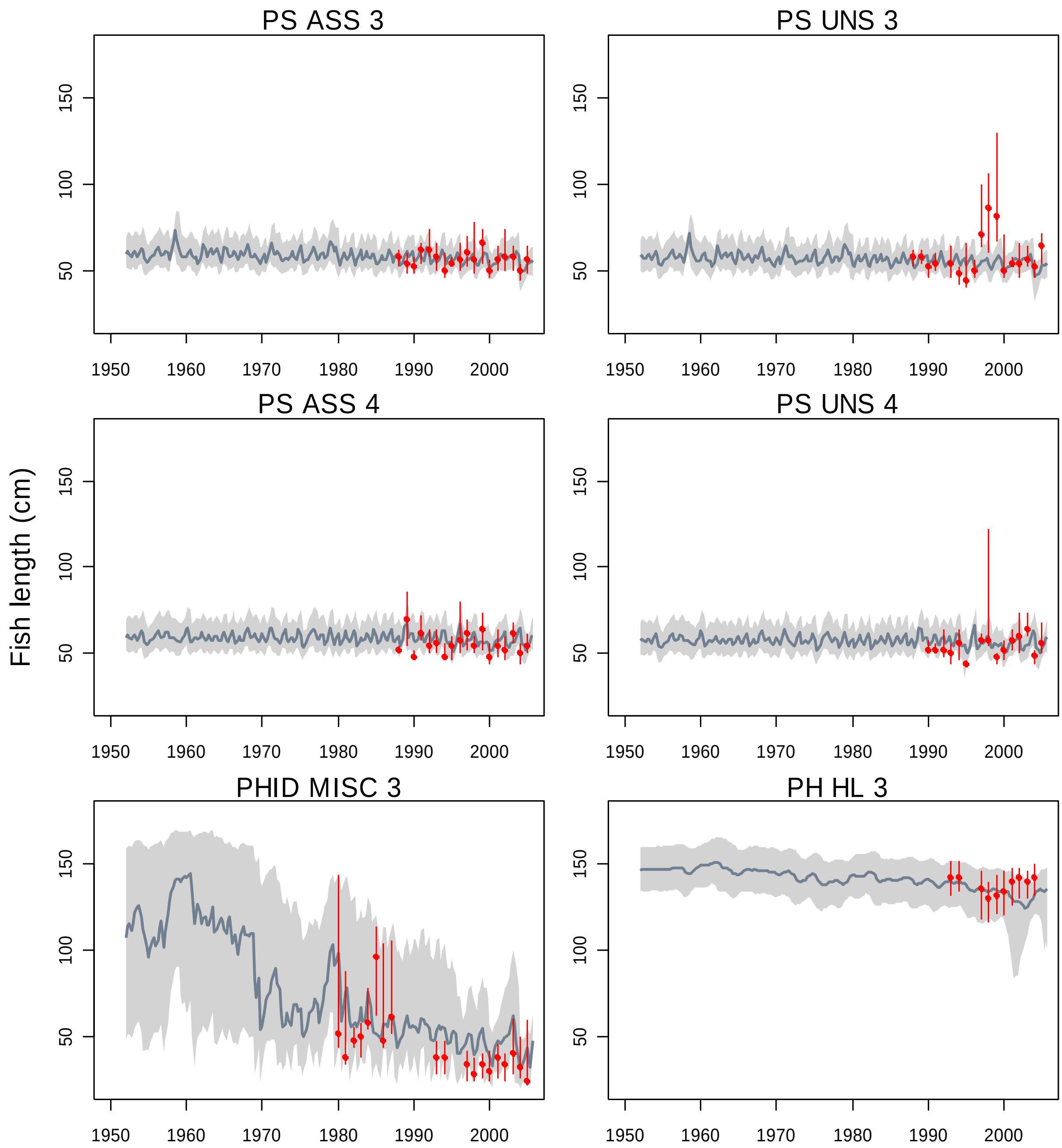


Figure 13 (continued)

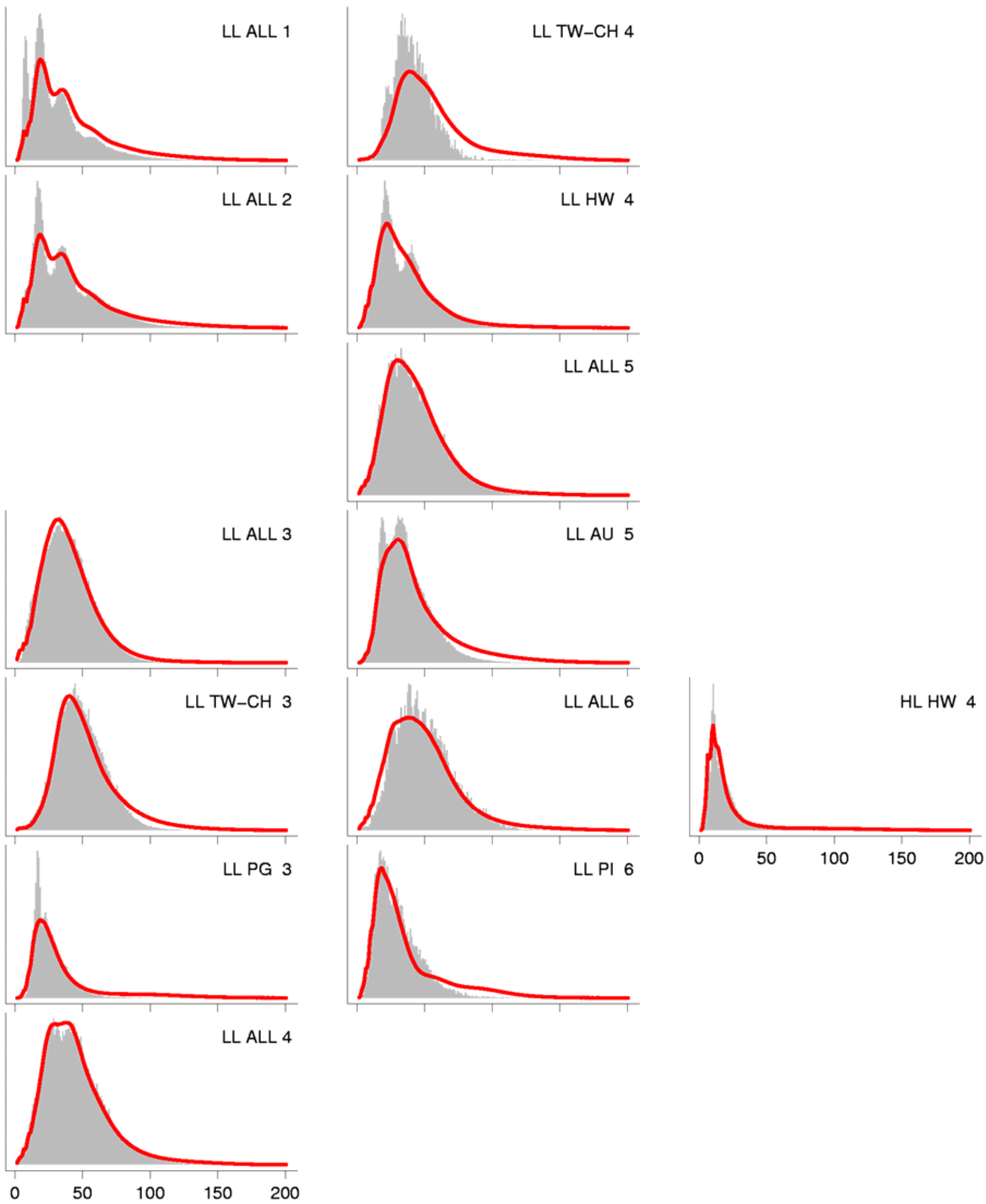


Figure 14. Observed (histograms) and predicted (line) weight frequencies (in kg) for each fishery aggregated over time (six-region LOWSAMP model).

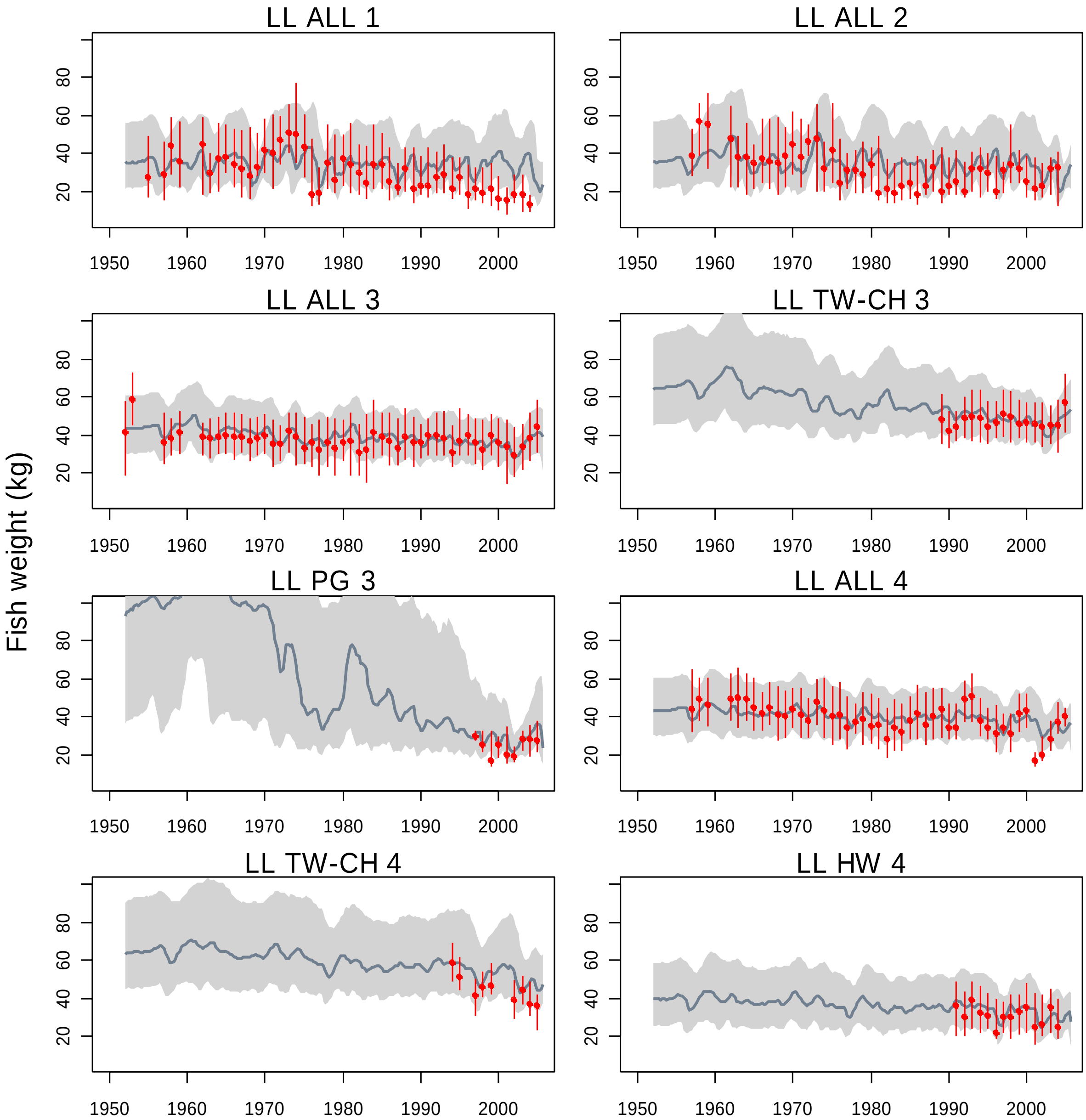


Figure 15. A comparison of the observed (red points) and predicted (grey line) median fish weight (whole weight, kg) of bigeye tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated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

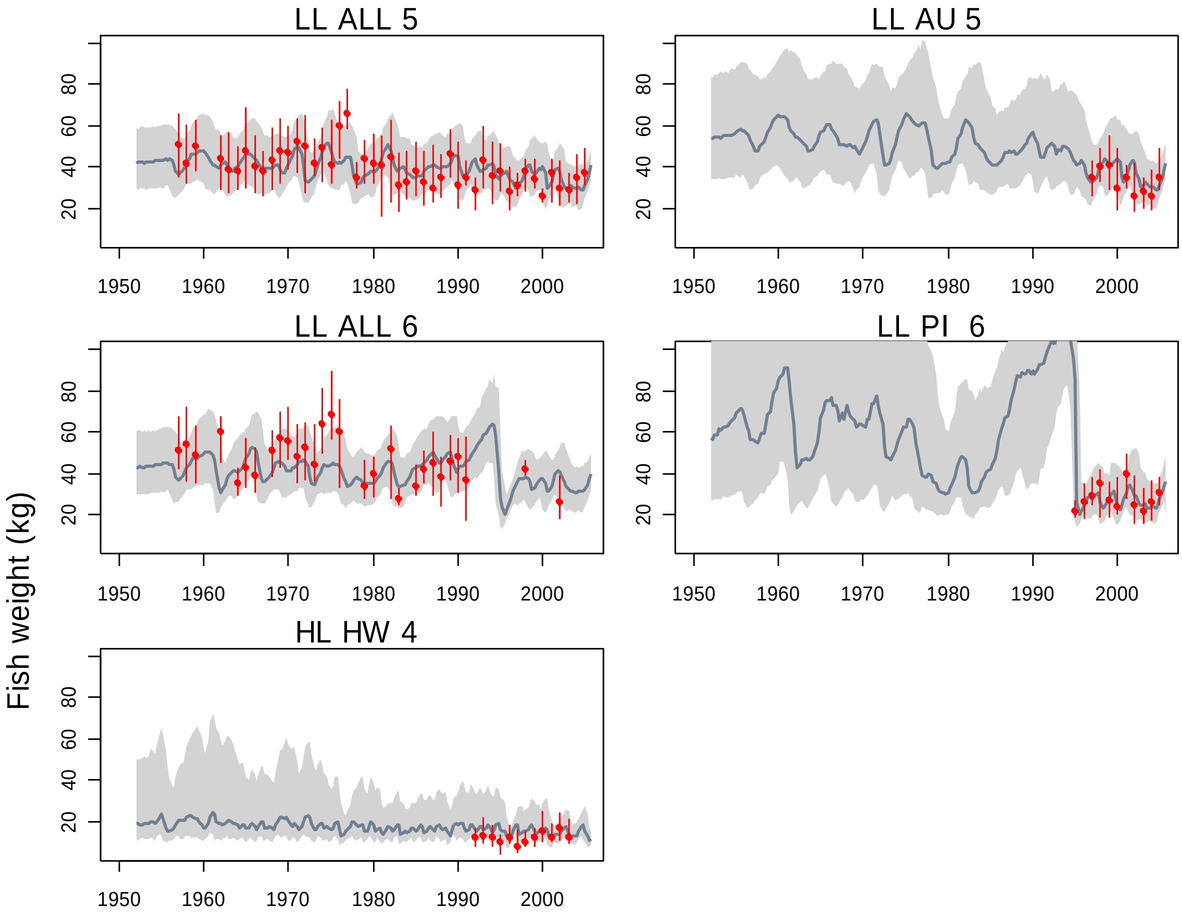


Figure 15. (continued).

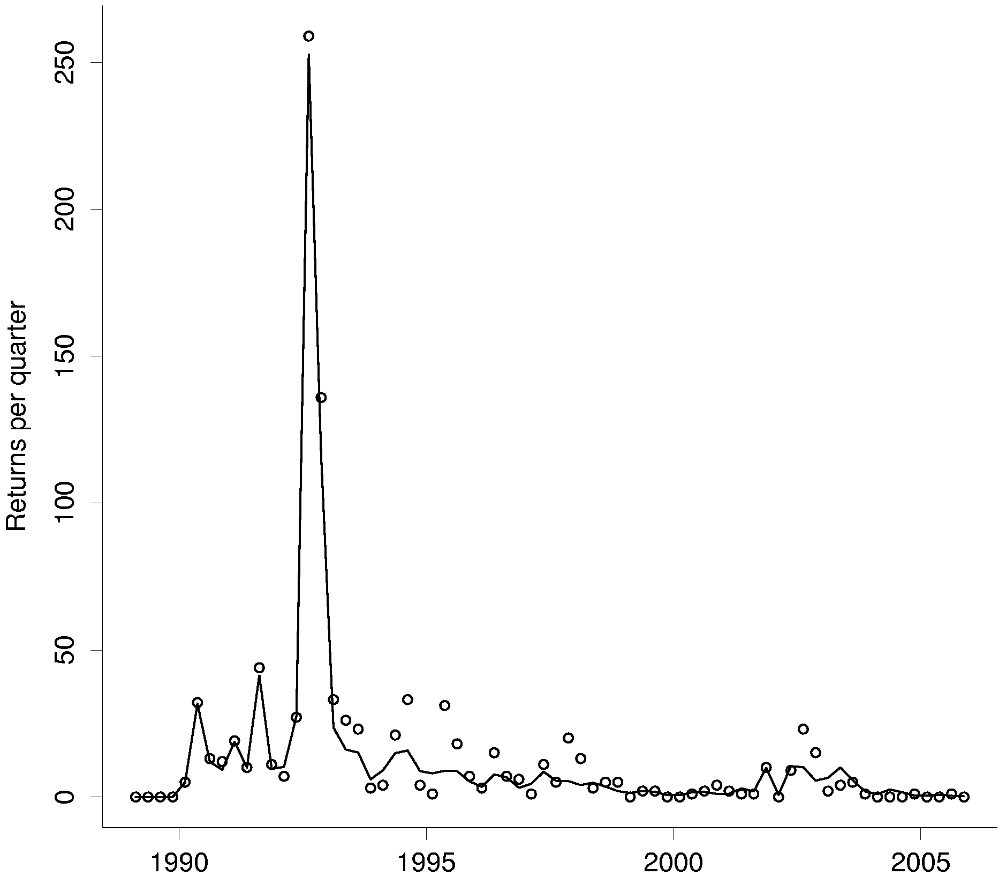


Figure 16. Number of observed (points) and predicted (line) tag returns by recapture period (quarter).

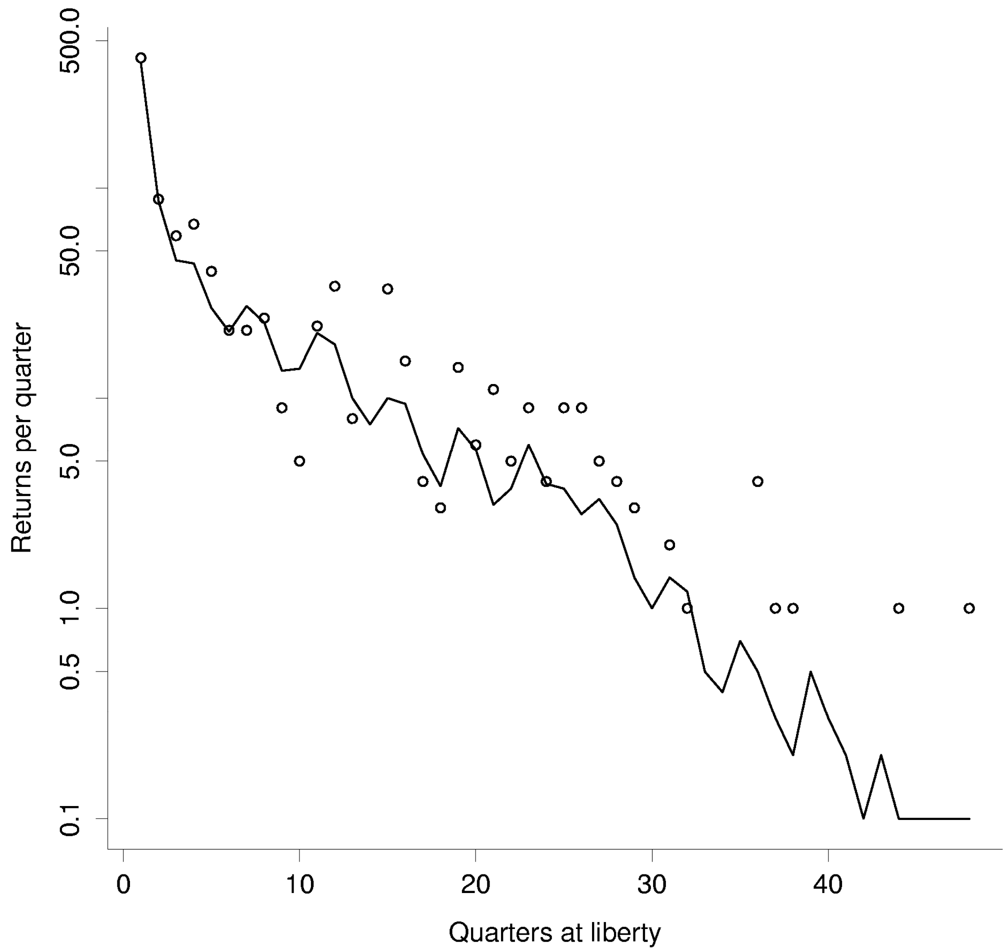


Figure 17. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters).

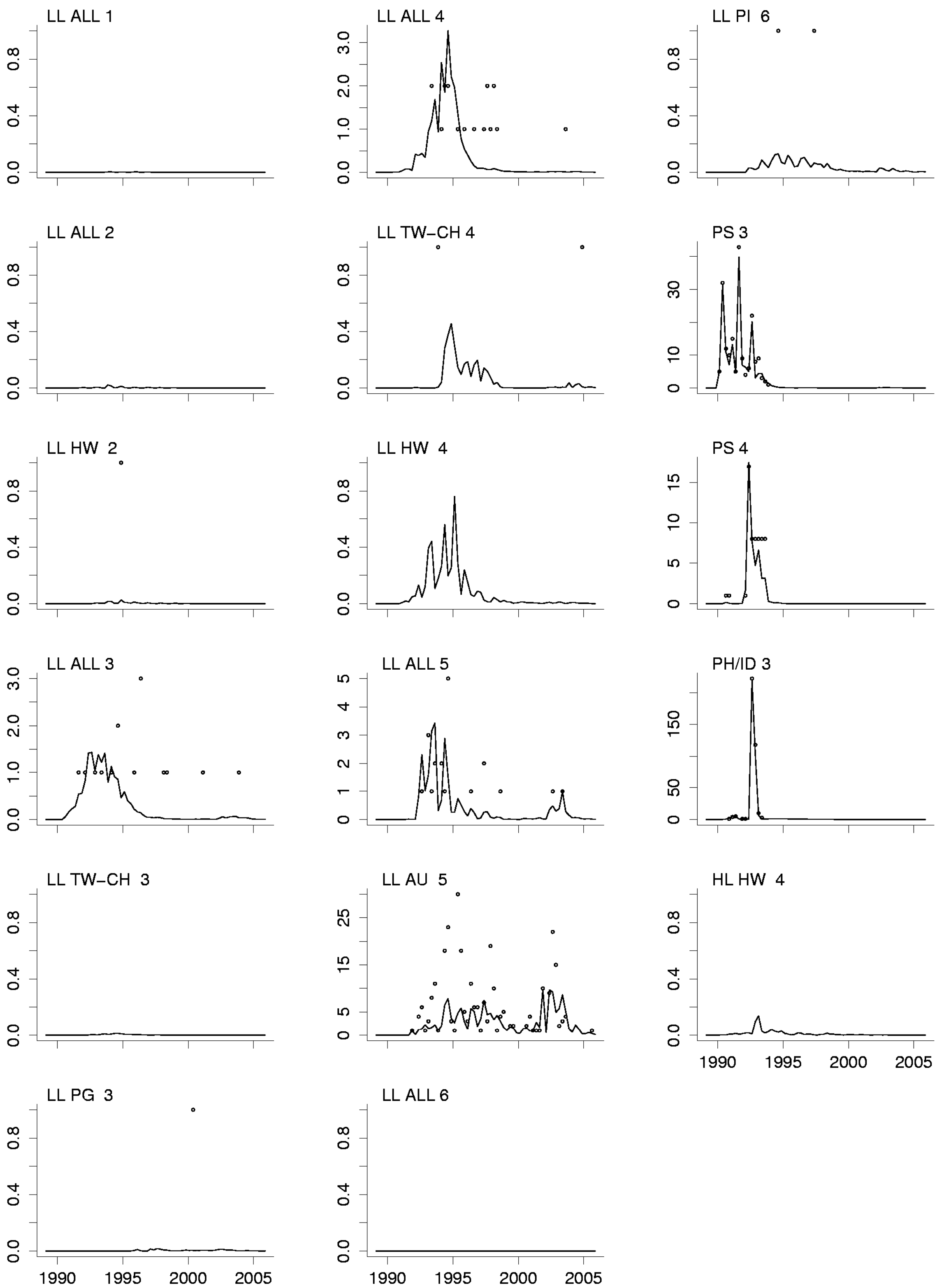


Figure 18. Number of observed (points) and predicted (line) tag returns by recapture period (quarter) for the various fisheries (or groups of fisheries) defined in the model.

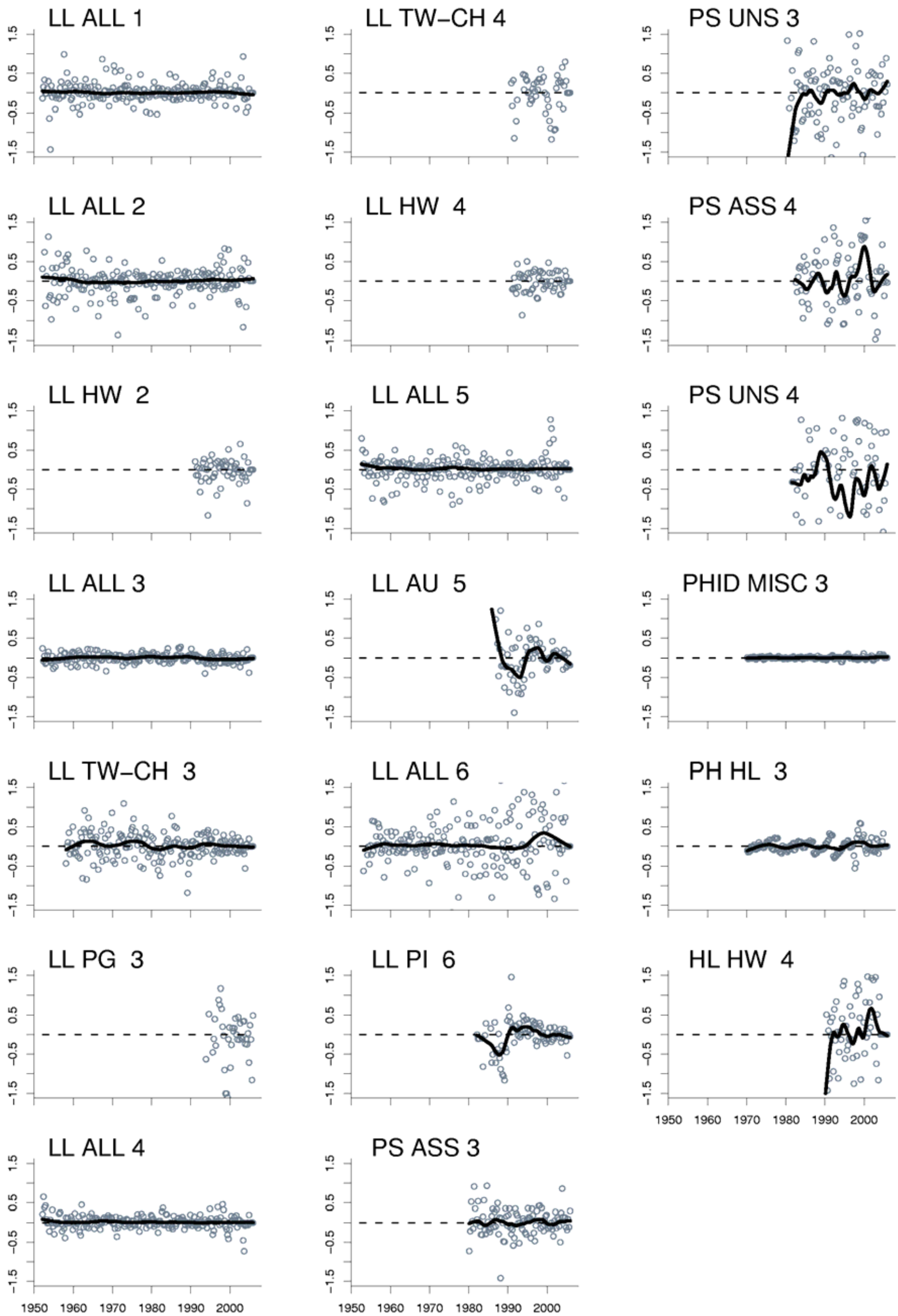


Figure 19. Effort deviations by time period for each fishery (six-region LOWSAMP model). For fisheries with longer time series, the dark line represents a lowess smoothed fit to the effort deviations.

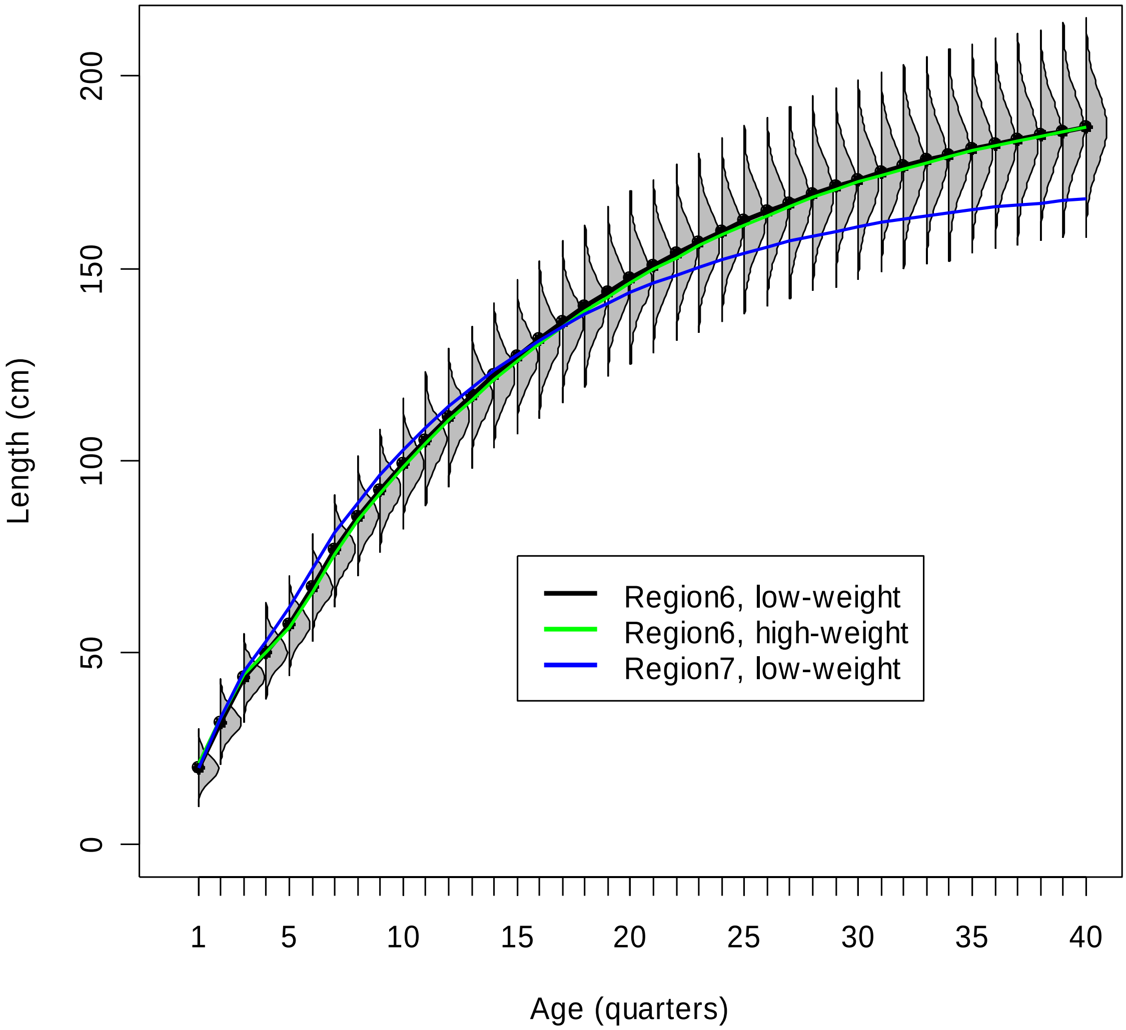


Figure 20. Estimated growth of bigeye derived from the assessment model. The black line represents the estimated length (FL, cm) at age and the grey area represents the estimated distribution of length at age. The growth functions for the two sensitivity analyses are also presented.

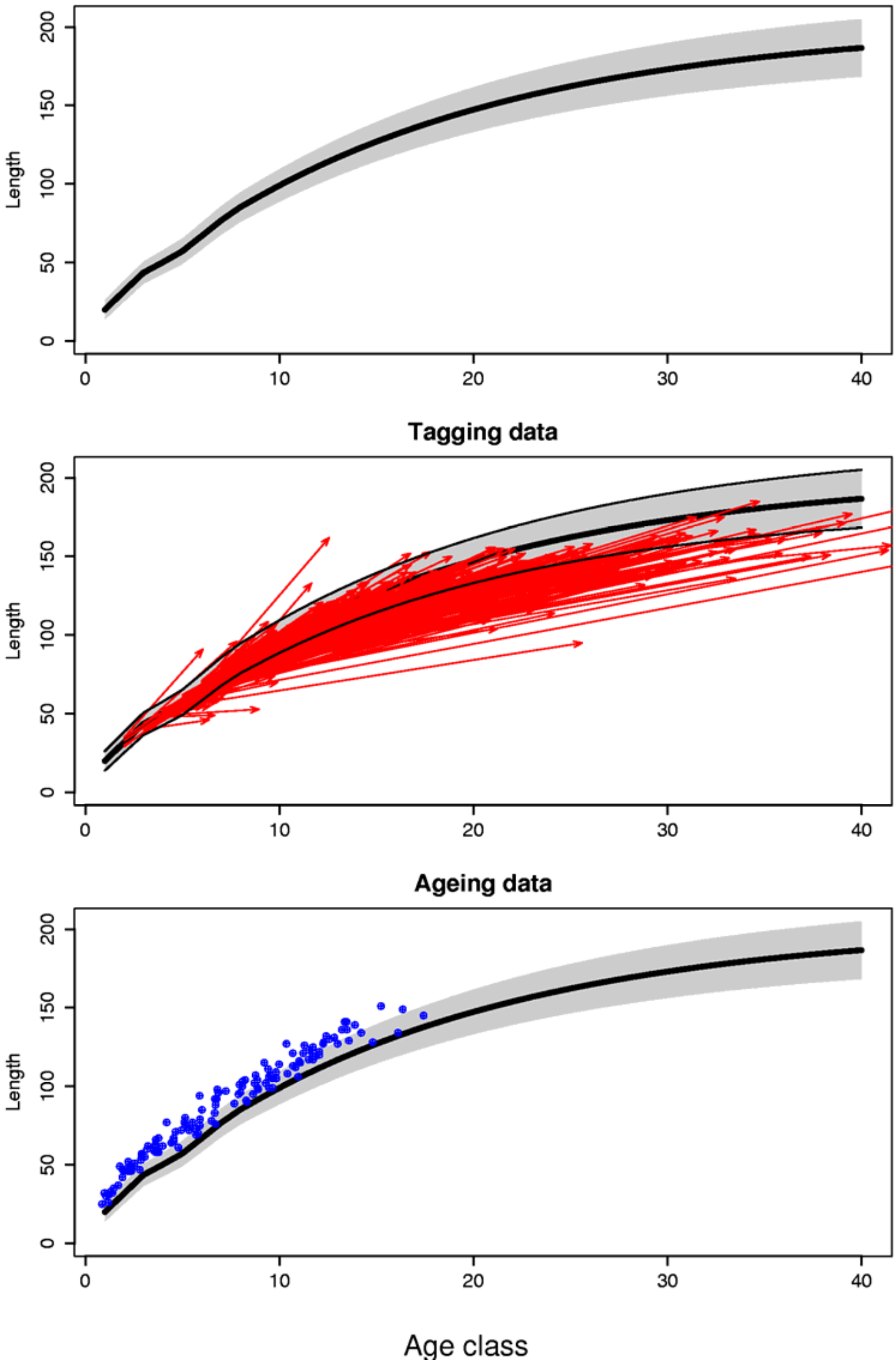


Figure 21. Estimated mean lengths-at-age (heavy line) and the variability of length-at-age (shaded area represents ± 2 SD) (six-region LOWSAMP model). Age is in quarters and length is in cm (top figure). For comparison, length at age estimates are presented from tag release and recapture data (middle 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. Age at release is assumed from the estimated growth function.

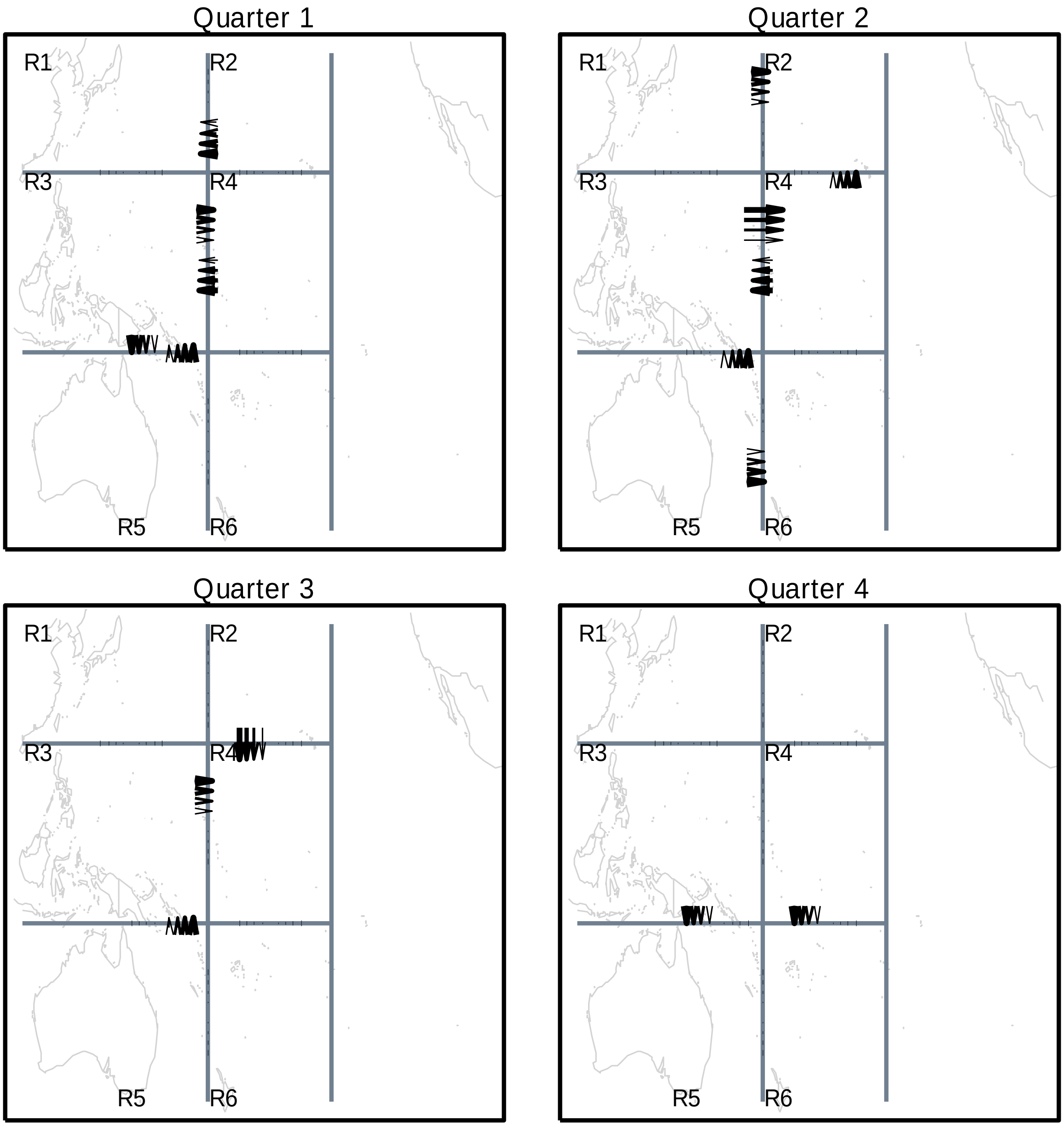


Figure 22. Estimated quarterly movement coefficients at age (1, 10, 20, 30 quarters) from the six-region LOWSAMP model. The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age. The maximum movement (quarter 2, region 3 to region 4) represents movement of 7% of the fish at the start of the quarter.

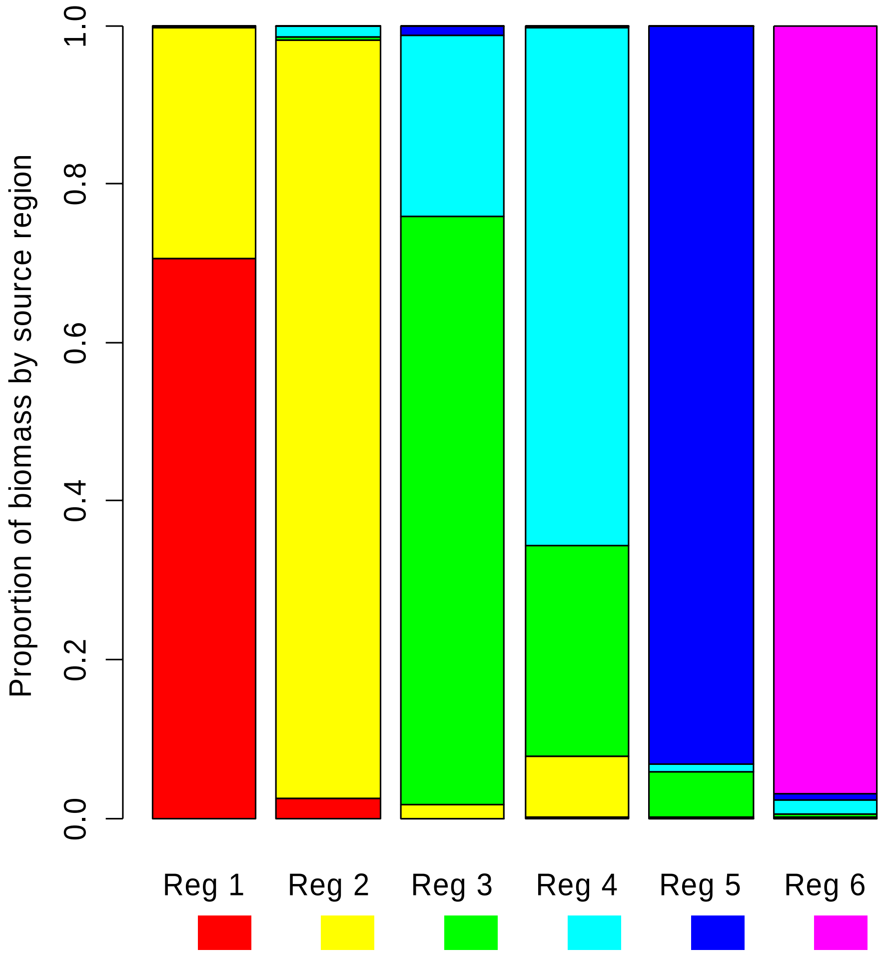


Figure 23. Proportional distribution of total biomass (by weight) in each region (Reg 1–6) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment between regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

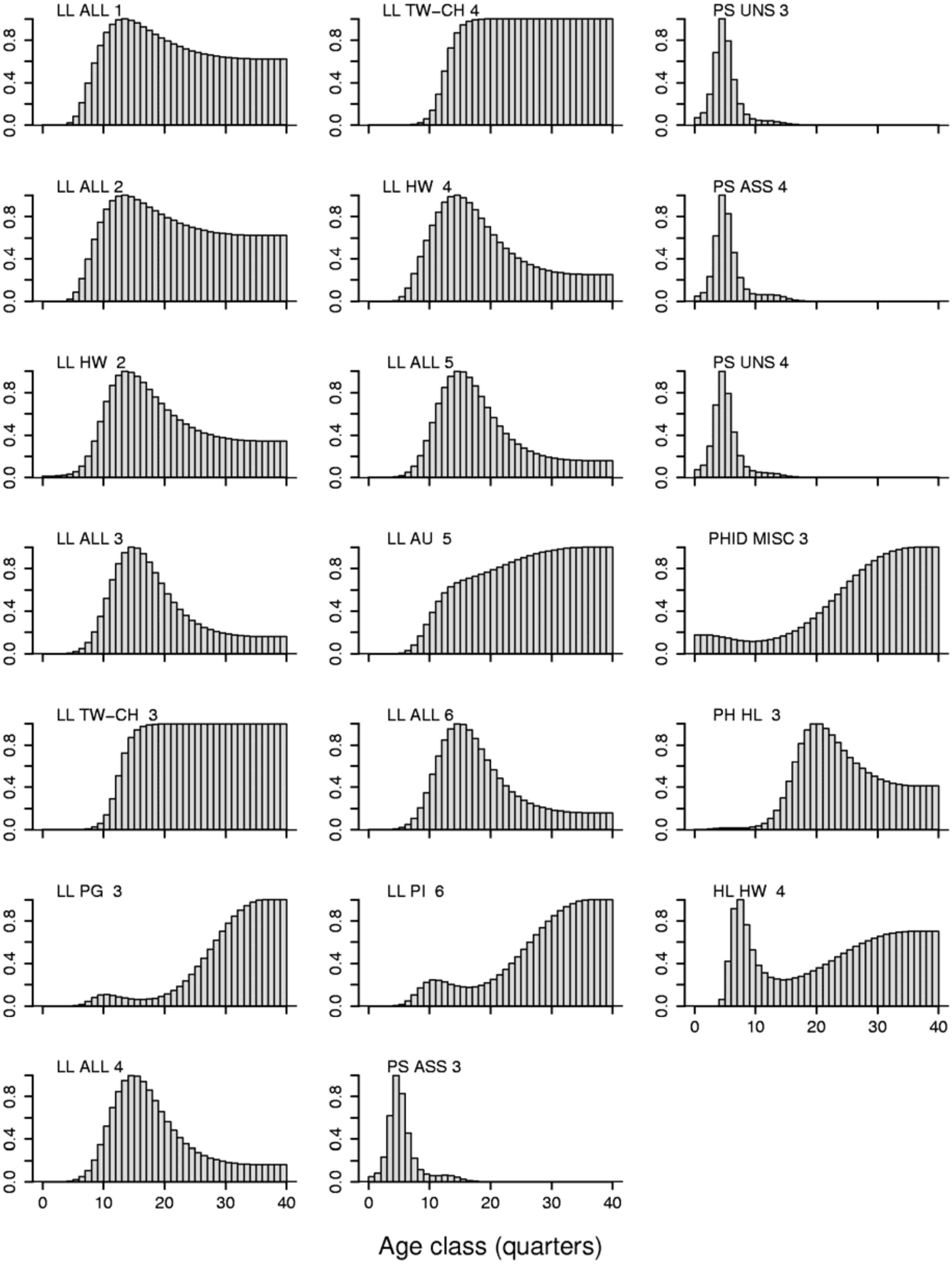


Figure 24. Selectivity coefficients, by fishery.

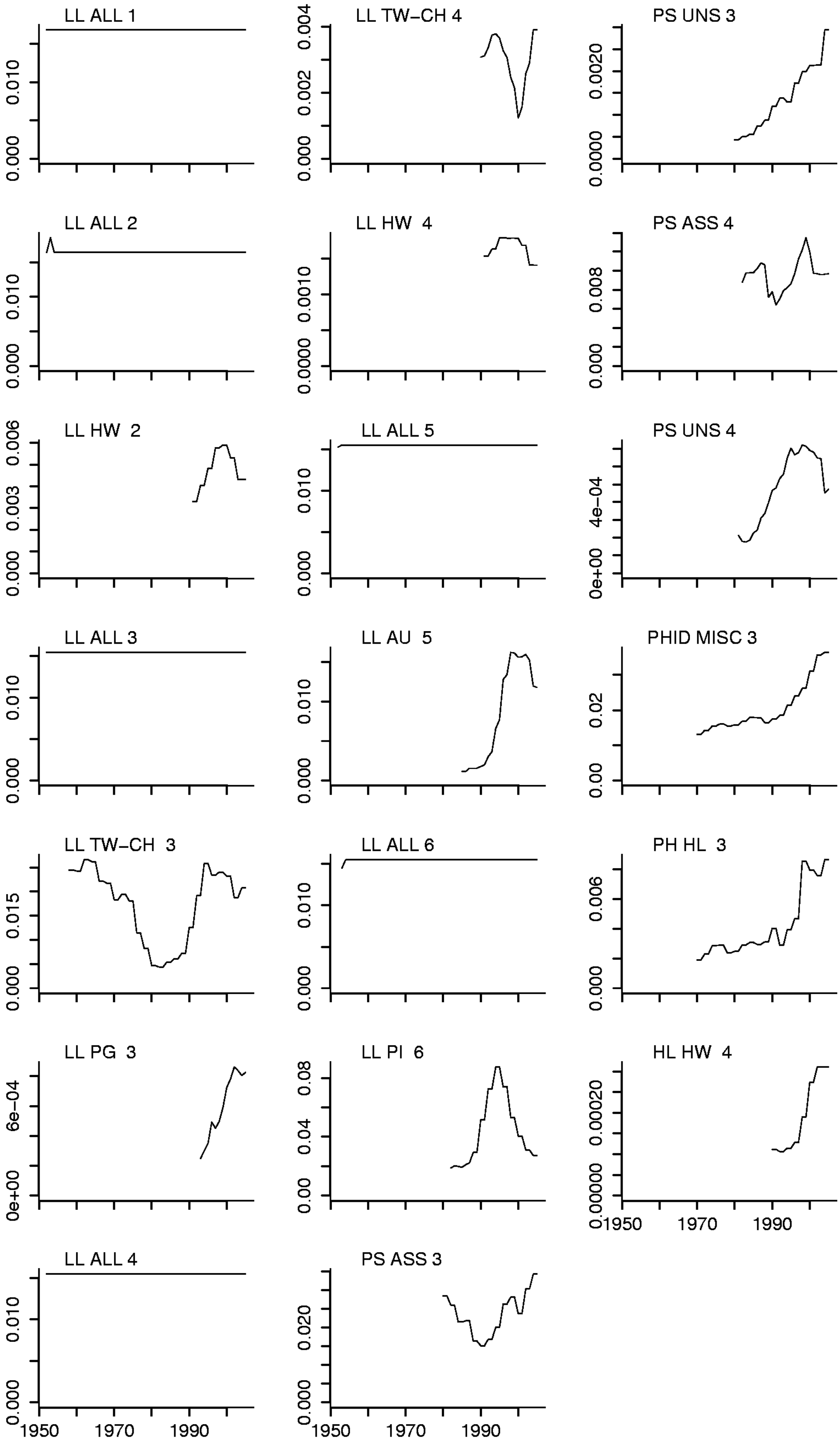


Figure 25. Average annual catchability time series, by fishery (six-region LOWSAMP model).

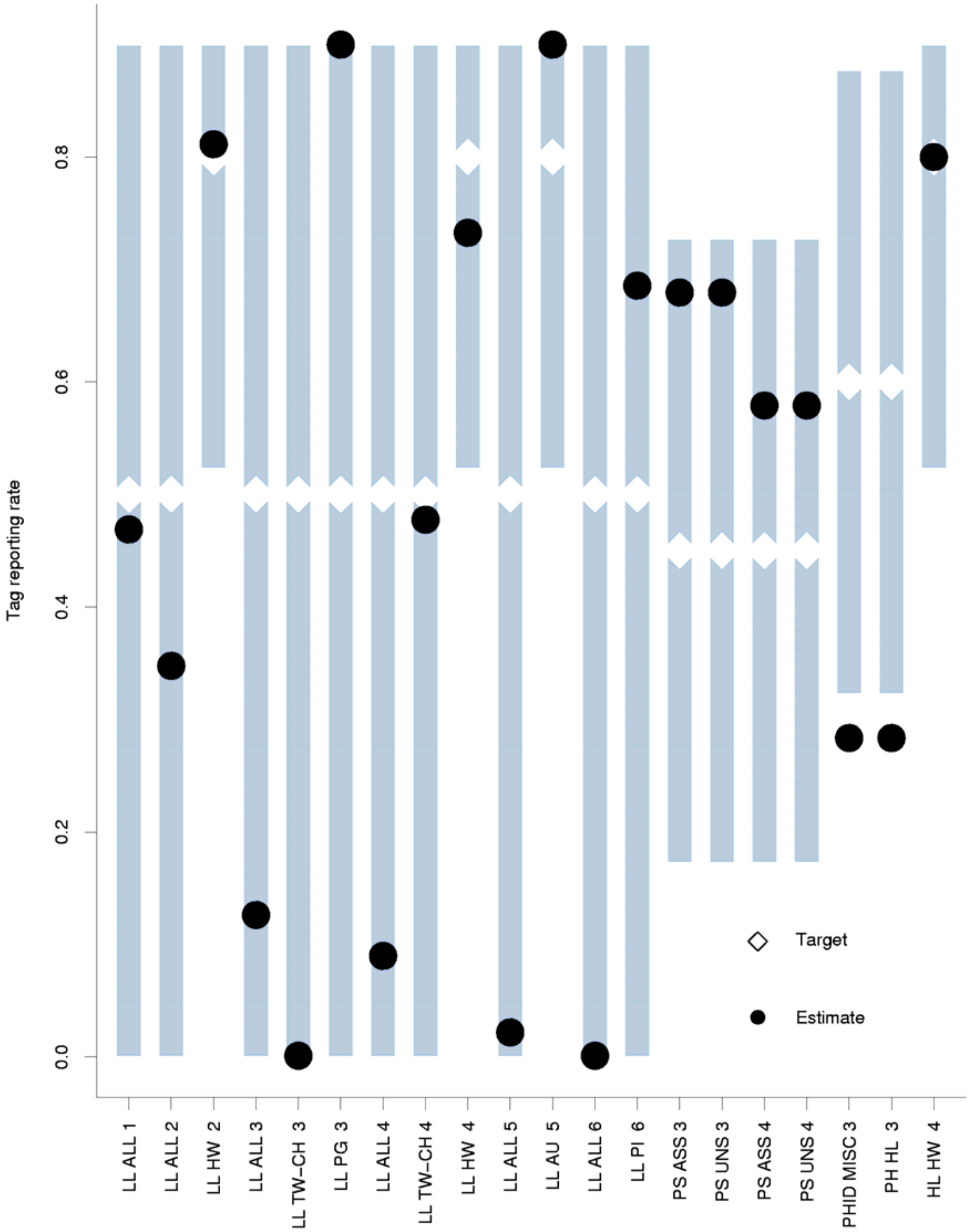


Figure 26. Estimated tag-reporting rates by fishery (black circles) (six-region LOWSAMP model). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars (truncated at zero and 0.9, which were the bounds of the parameter estimates) indicate a range of ±1 prior SD.

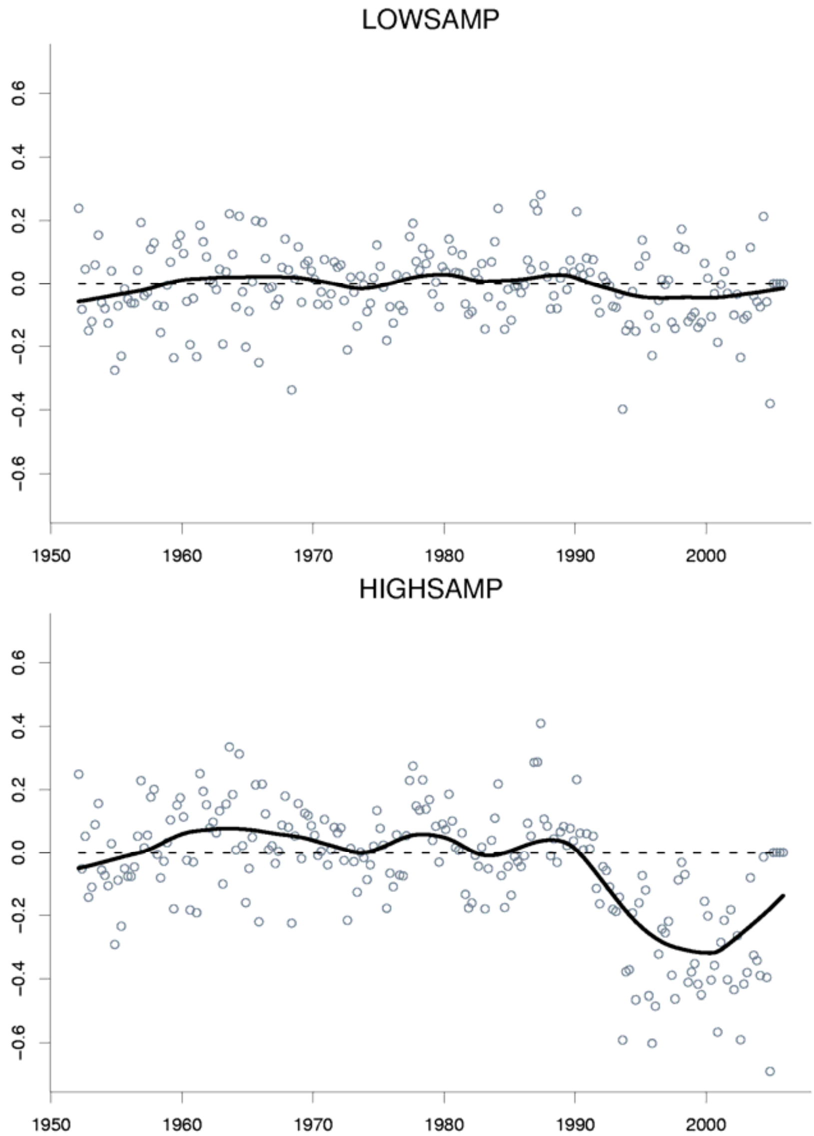


Figure 27. Temporal trend in the effort deviations from the principal longline fishery in region 3 (LL ALL 3) for the six-region LOWSAMP (top) and HIGHSAMP (bottom) models. The line represents the lowess smoothed fit to the estimates.

Figure 28. Estimated annual recruitment (millions) by region and for the WCPO (six-region LOWSAMP model). The shaded area for the WCPO indicates the approximate 95% confidence intervals.

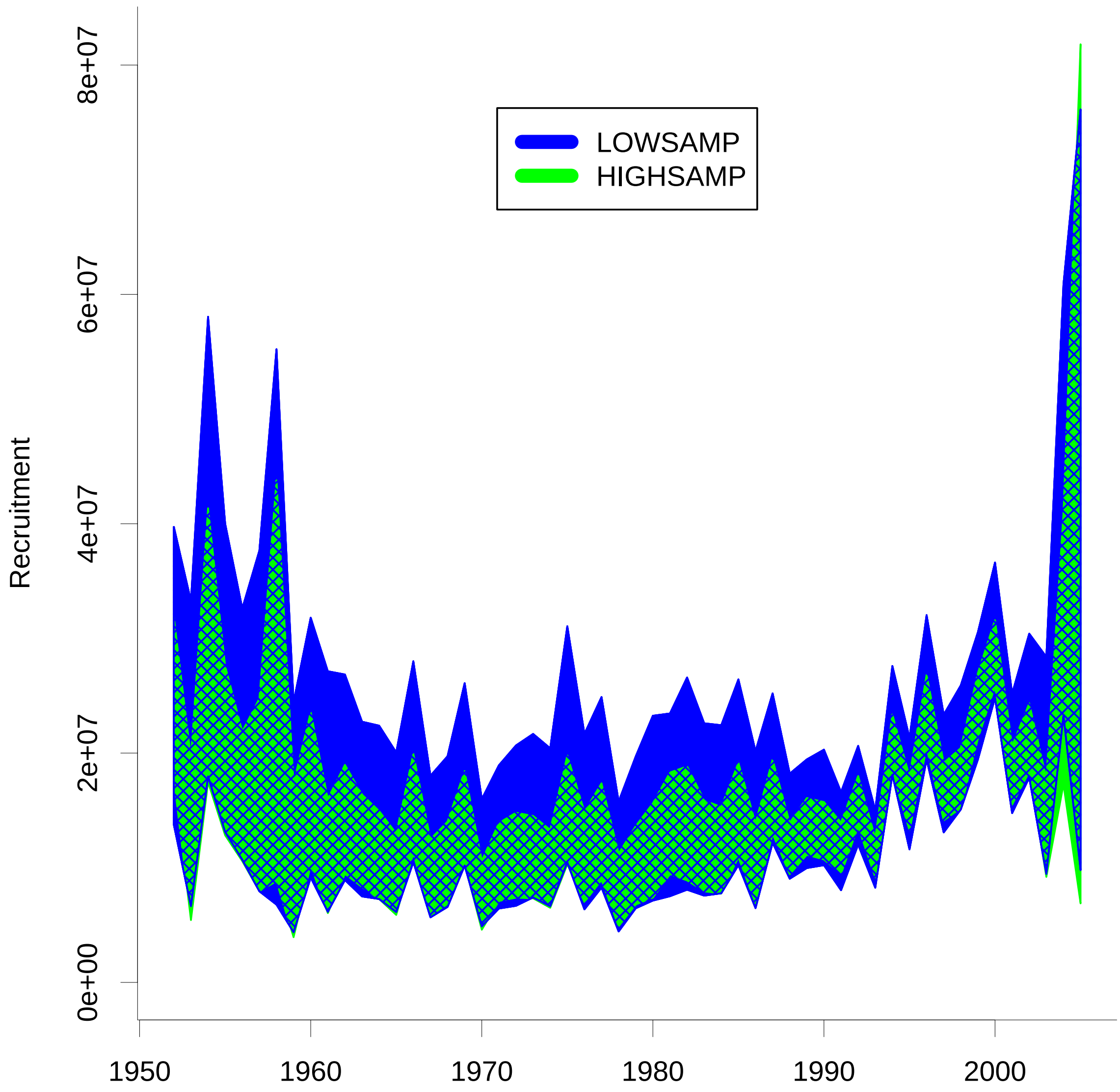


Figure 29. A comparison of 95% confidence intervals for total recruitment estimated for the LOWSAMP and HIGHSAMP models. The hatched area indicates the region of overlap of 95% confidence intervals.

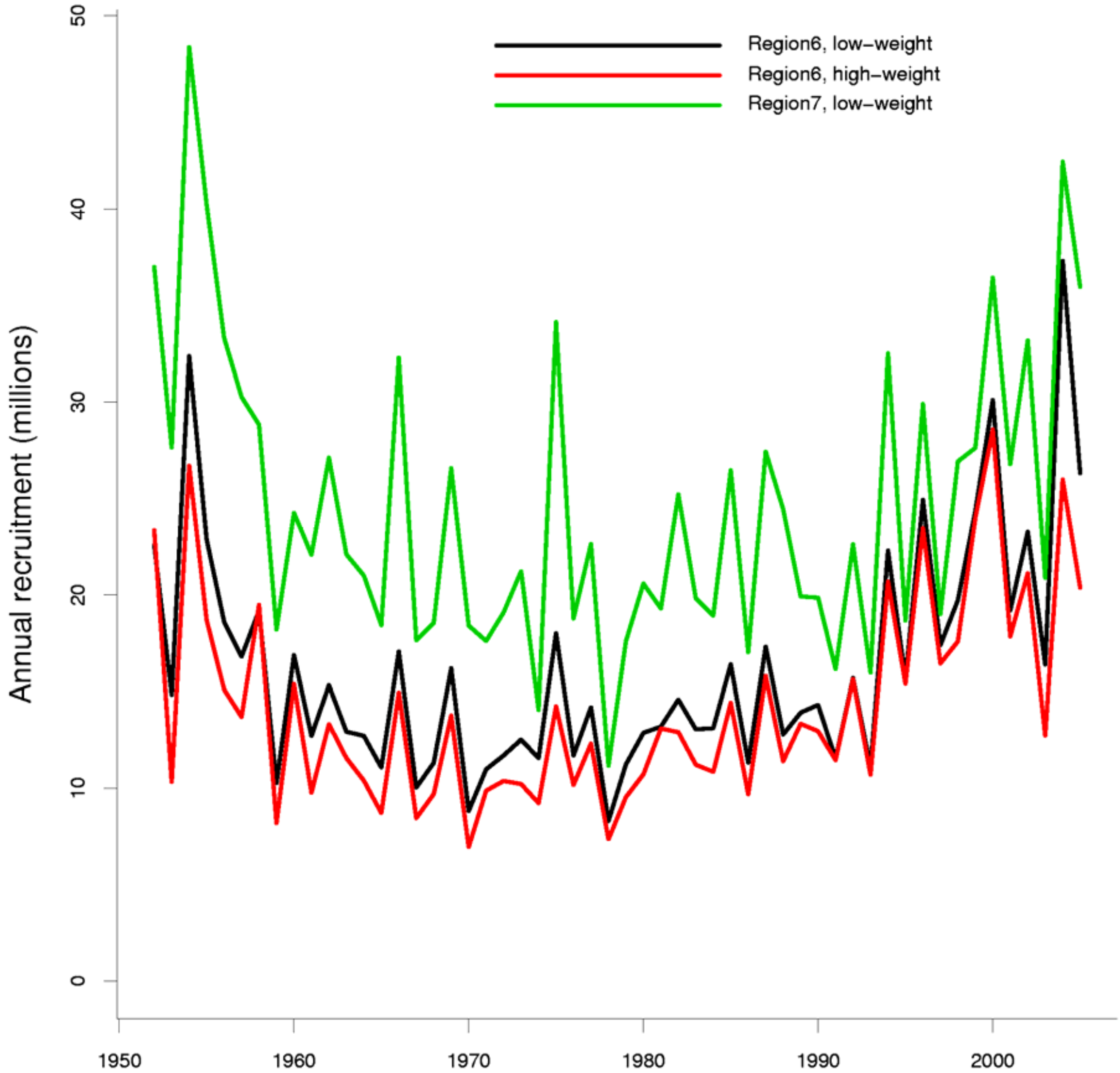


Figure 30. Estimated annual recruitment (millions of fish) for the WCPO obtained from the three different model options.

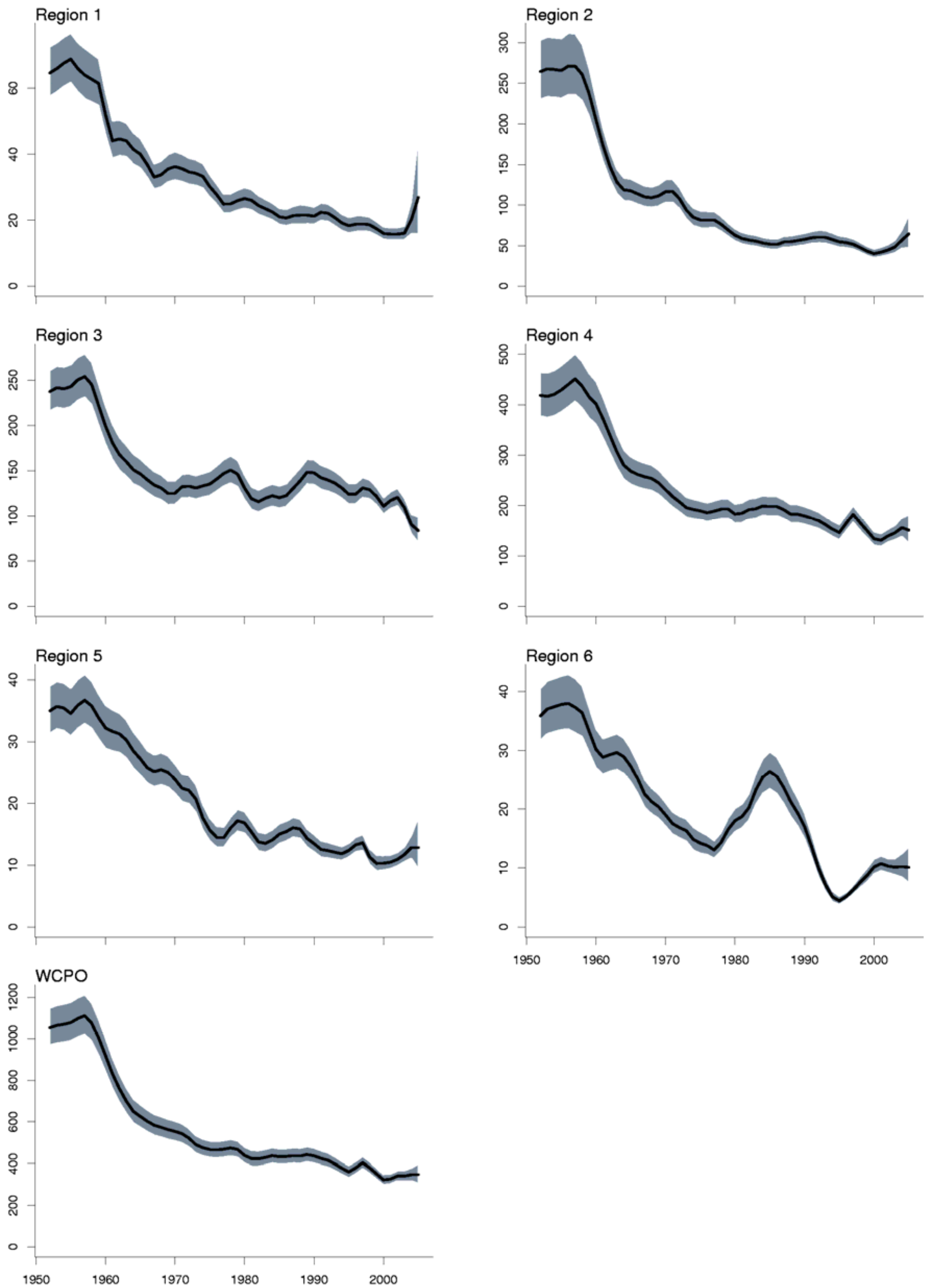


Figure 31. Estimated annual average total biomass (thousand mt) by region and for the WCPO (six-region LOWSAMP model). The shaded areas indicate the approximate 95% confidence intervals.

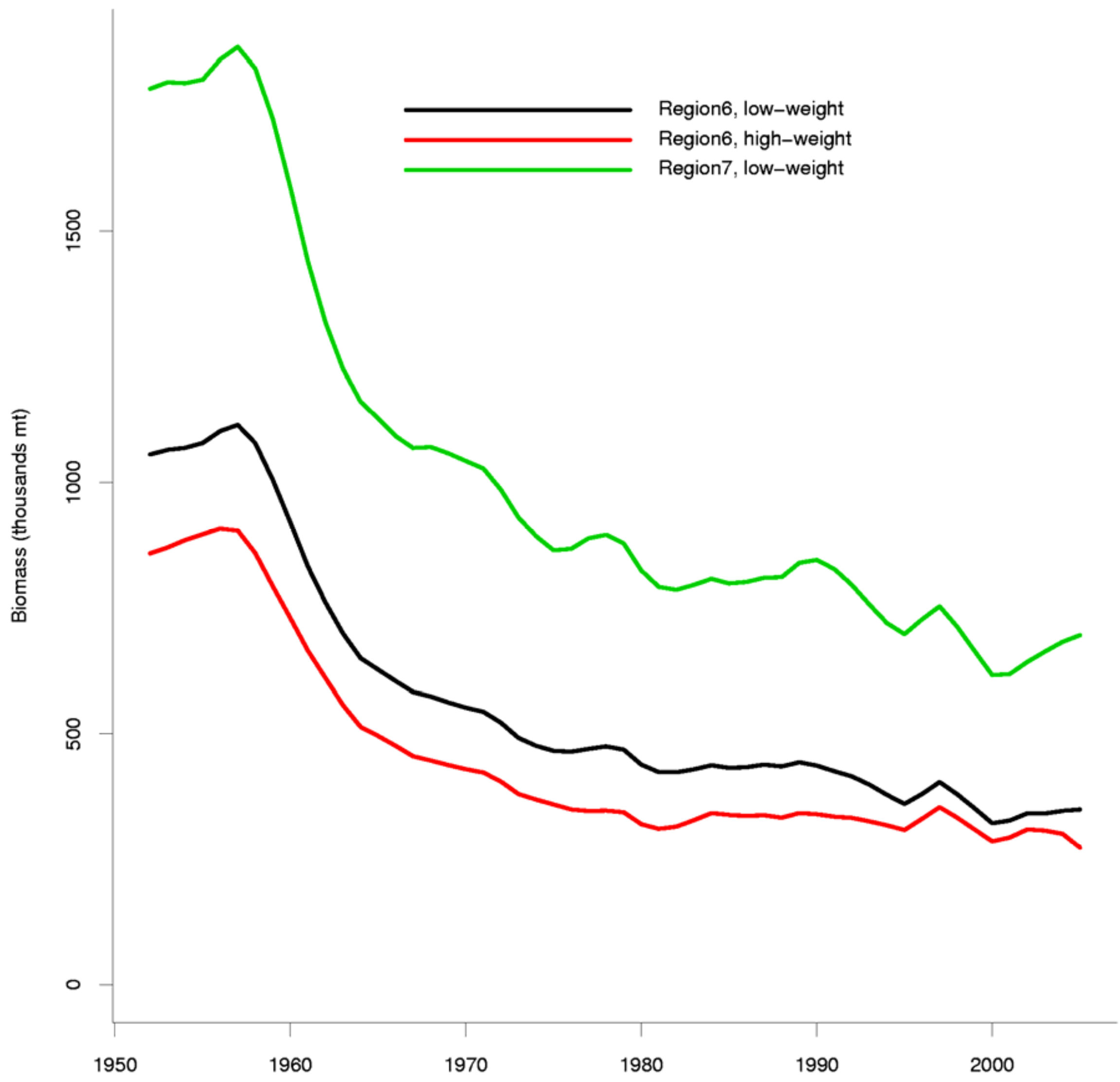


Figure 32. Estimated annual average total biomass (thousands mt) for the WCPO obtained from the separate analyses.

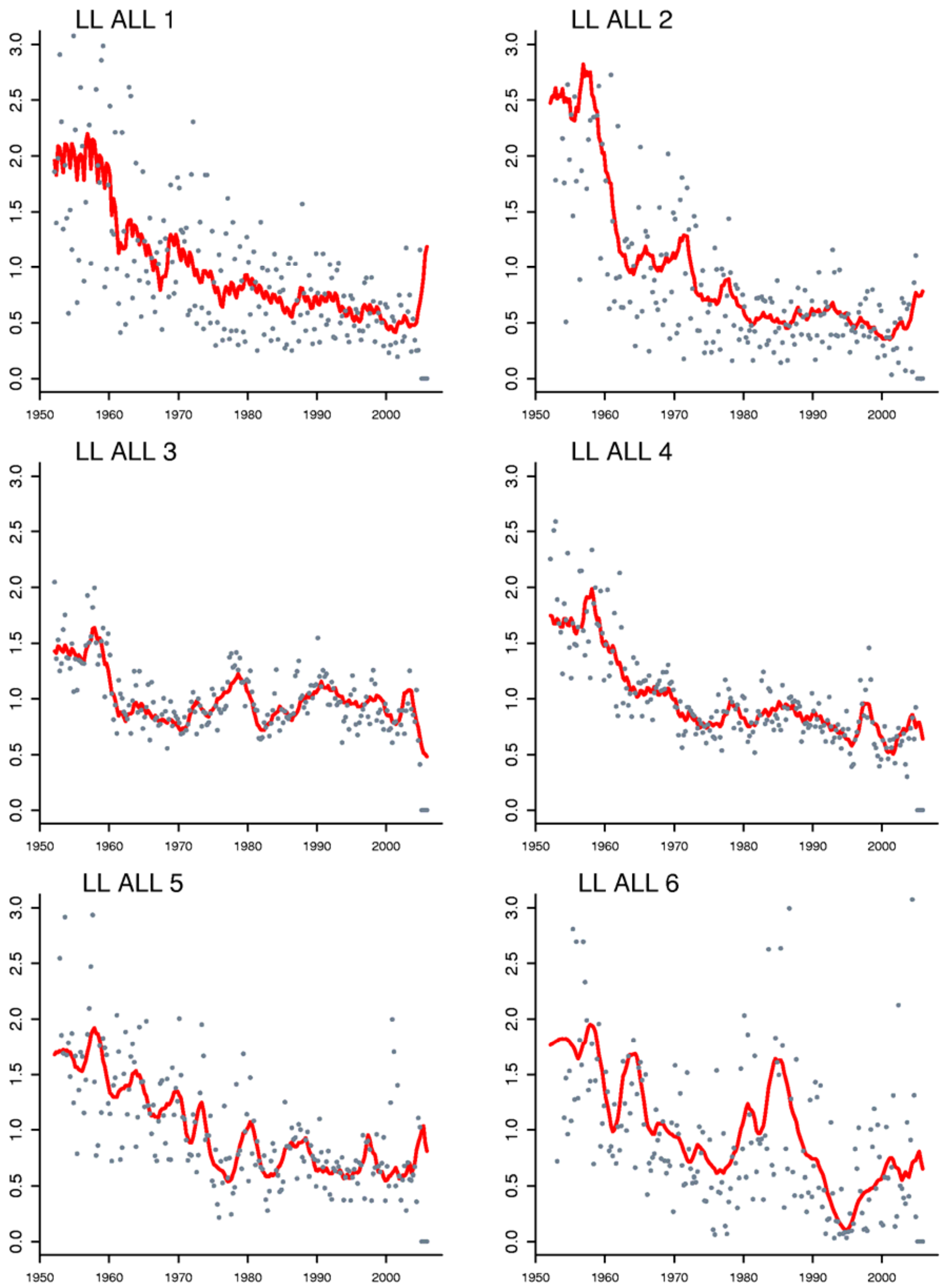


Figure 33. A comparison of longline exploitable biomass by quarter and region (red line) and the quarterly standardised CPUE indices for the fisheries. For comparison, both series are scaled to the average of the series.

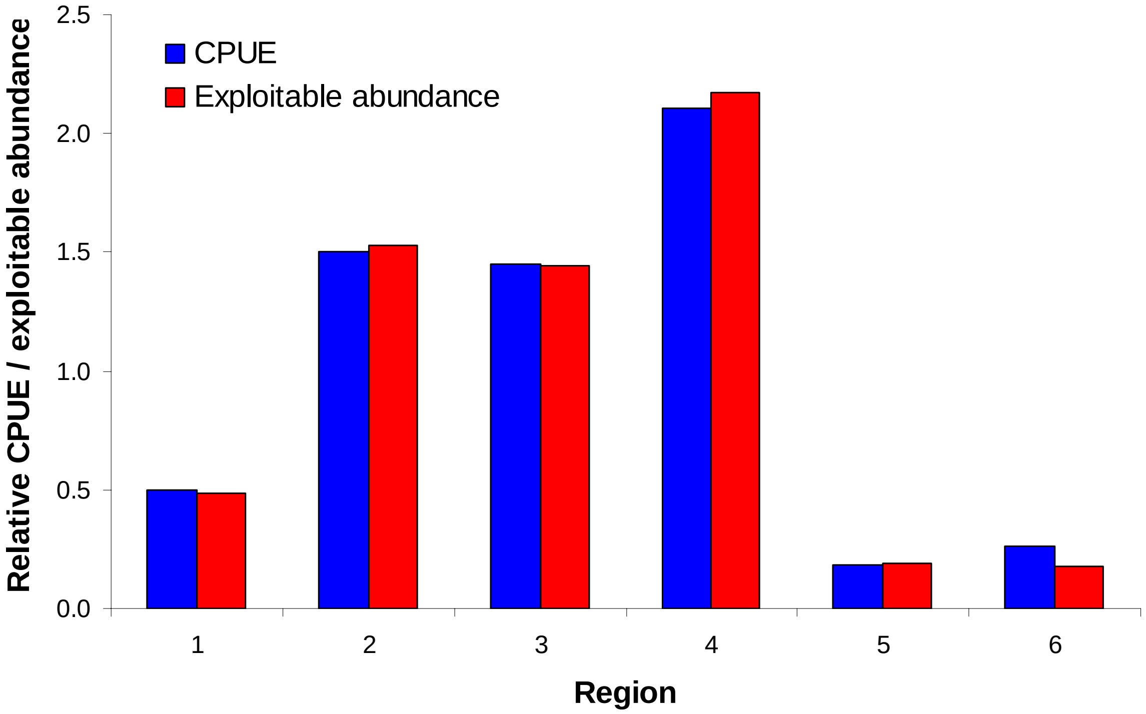


Figure 34. CPUE and exploitable abundance for LL ALL 1–6 averaged over all time periods. Values for each region are scaled relative to their averages across all regions.

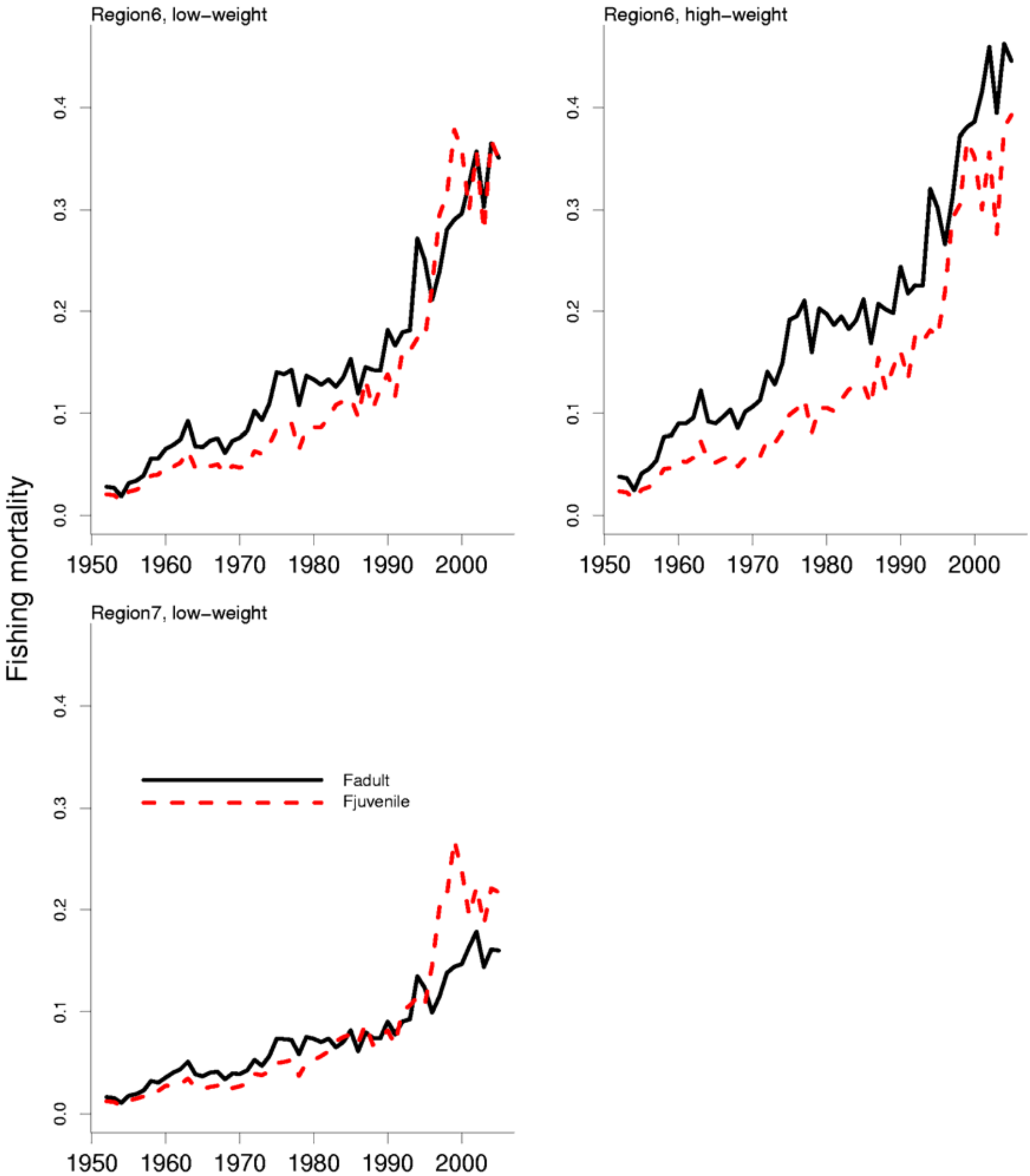


Figure 35. Estimated annual average juvenile and adult fishing mortality for the WCPO obtained from the separate analyses.

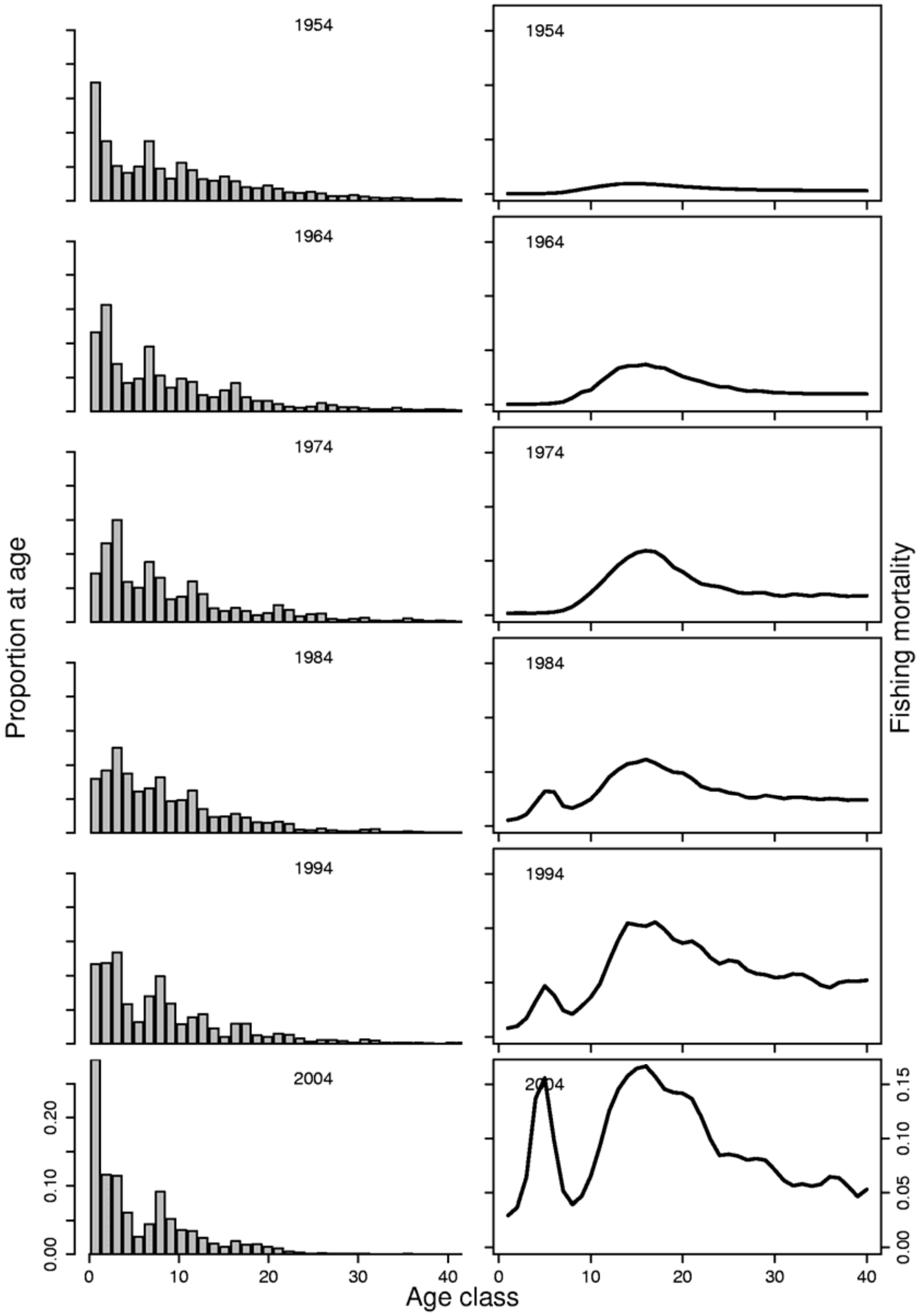


Figure 36. Estimated proportion at age (quarters) for the WCPO bigeye population (left) and fishing mortality at age (right) by year at decade intervals.

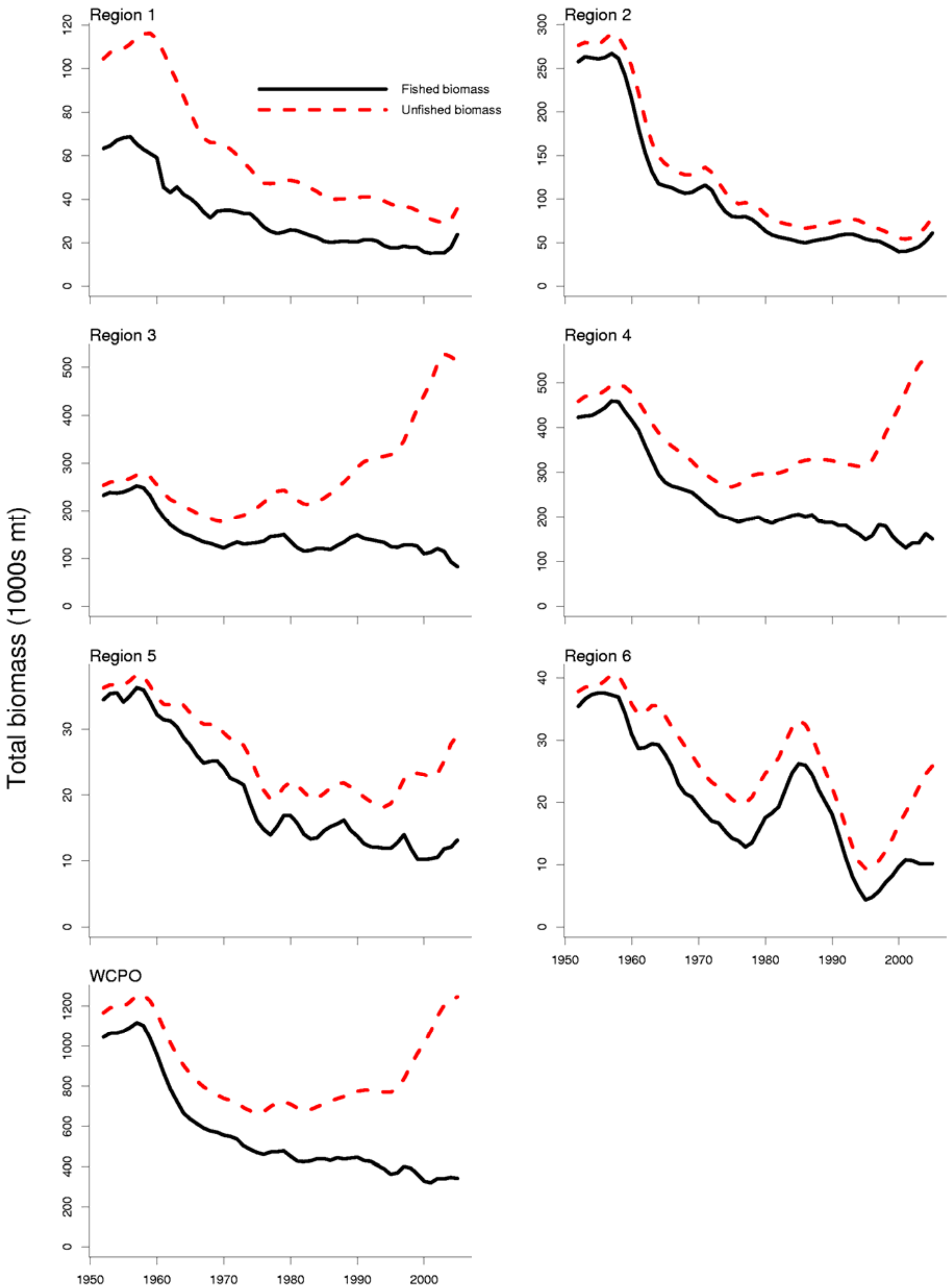


Figure 37. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper dashed lines) for each region and for the WCPO (six-region LOWSAMP model).

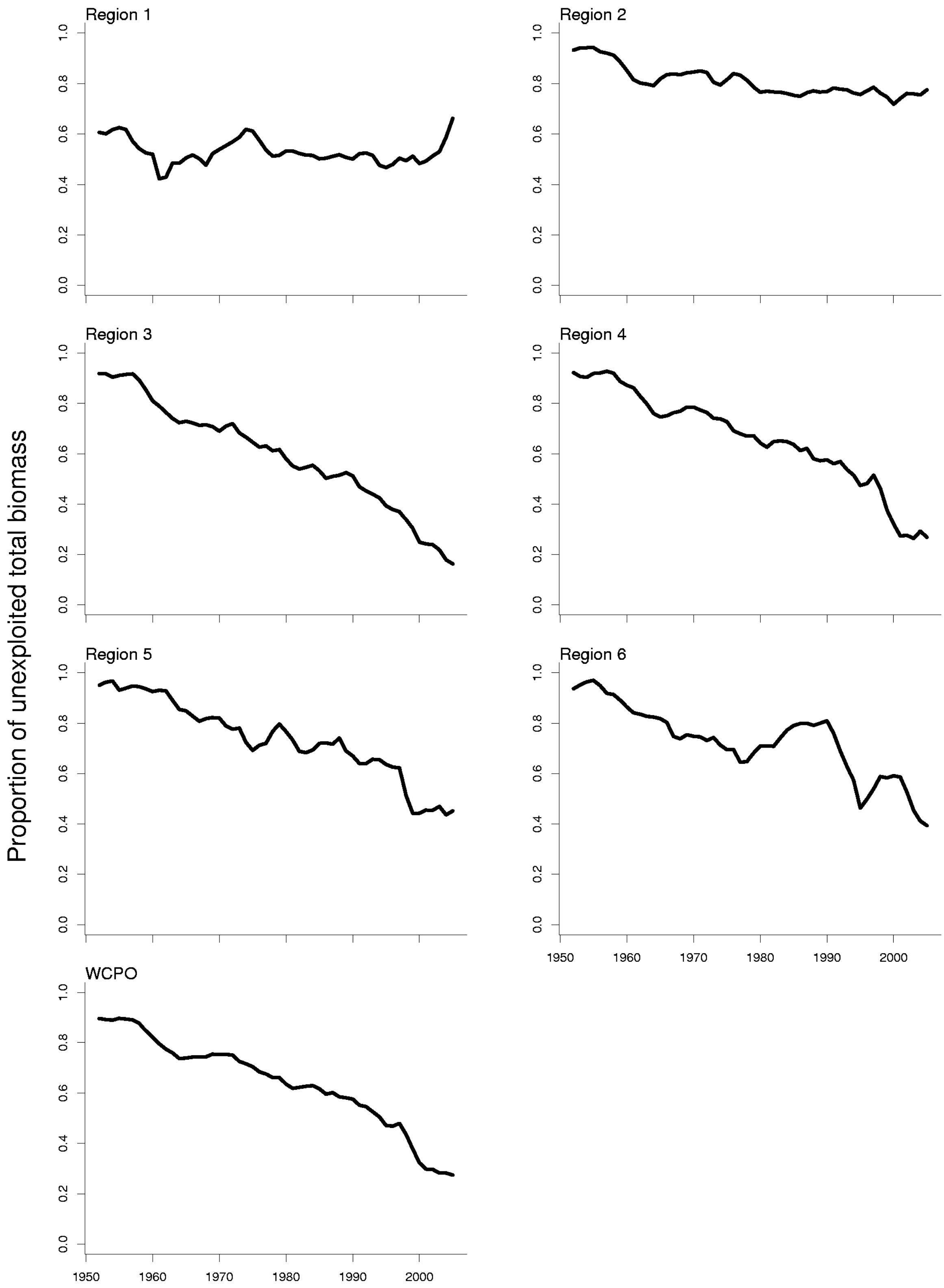


Figure 38. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the WCPO (six-region LOWSAMP model).

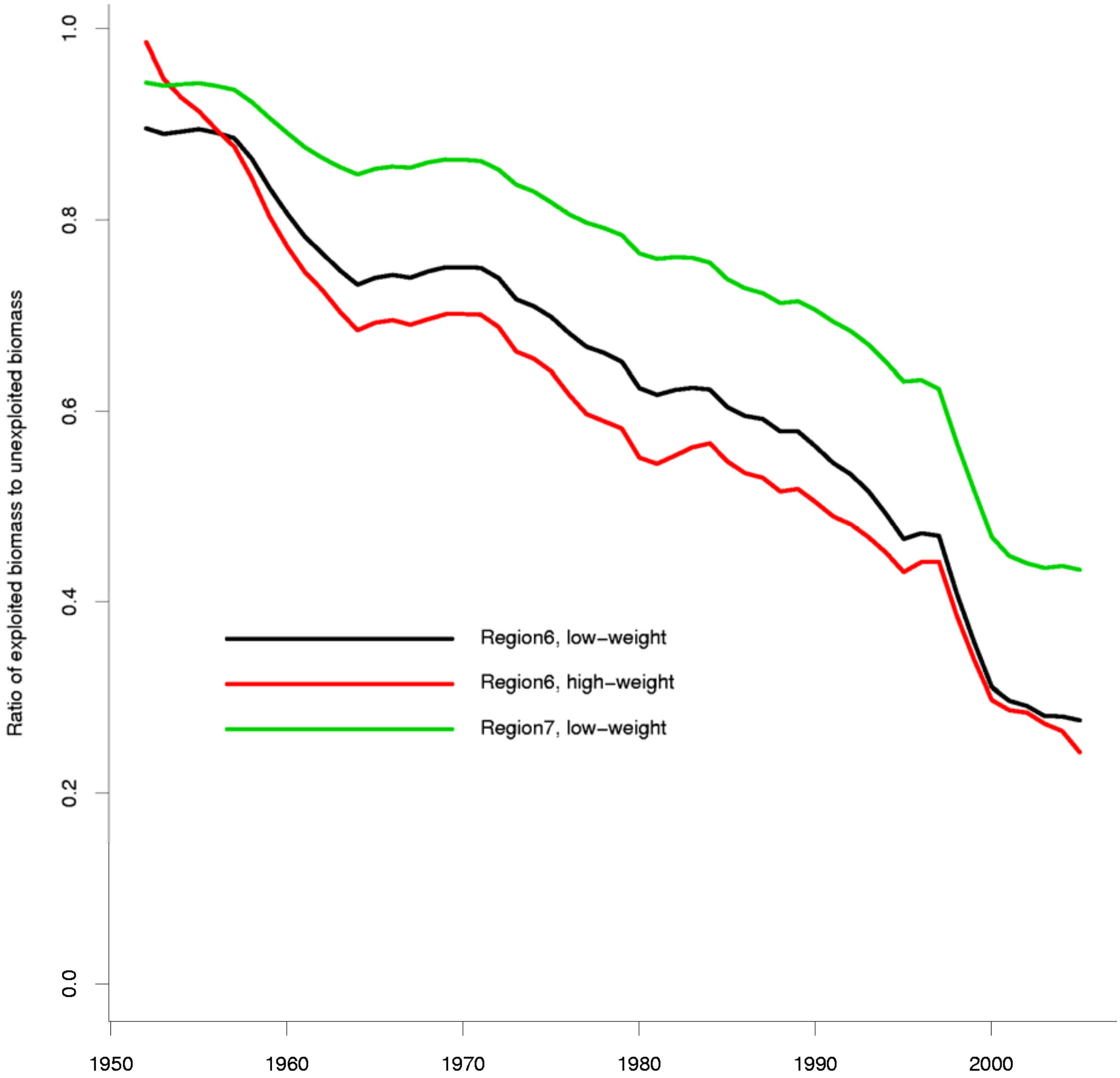


Figure 39. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for the WCPO obtained from the separate analyses.

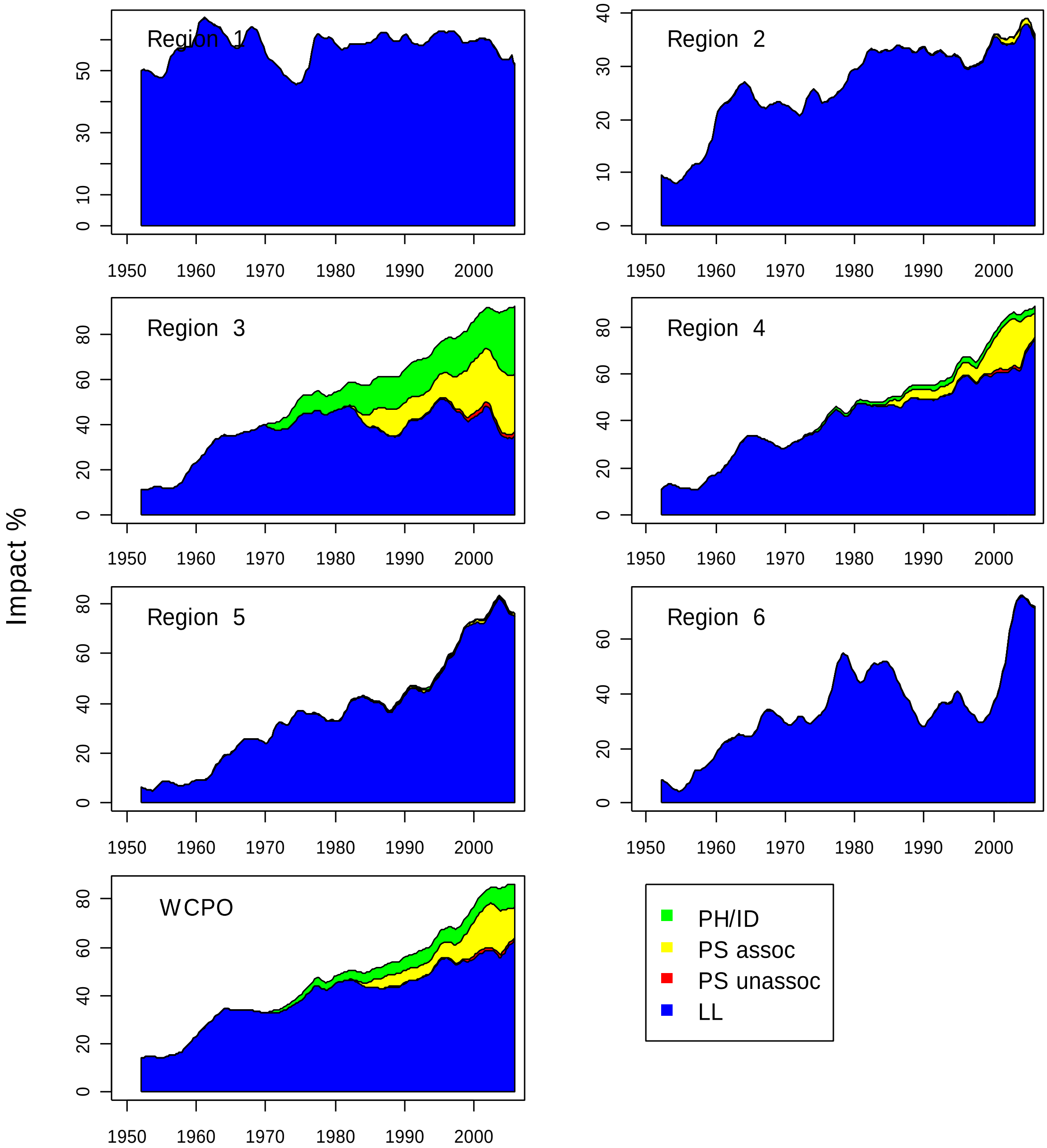


Figure 40. Estimates of reduction in spawning biomass due to fishing (fishery impact = 1-$SB_t/SB_{0,t}$) by region and for the WCPO attributed to various fishery groups (six-region LOWSAMP model). LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine log and FAD sets; PS unassoc = purse seine school sets.

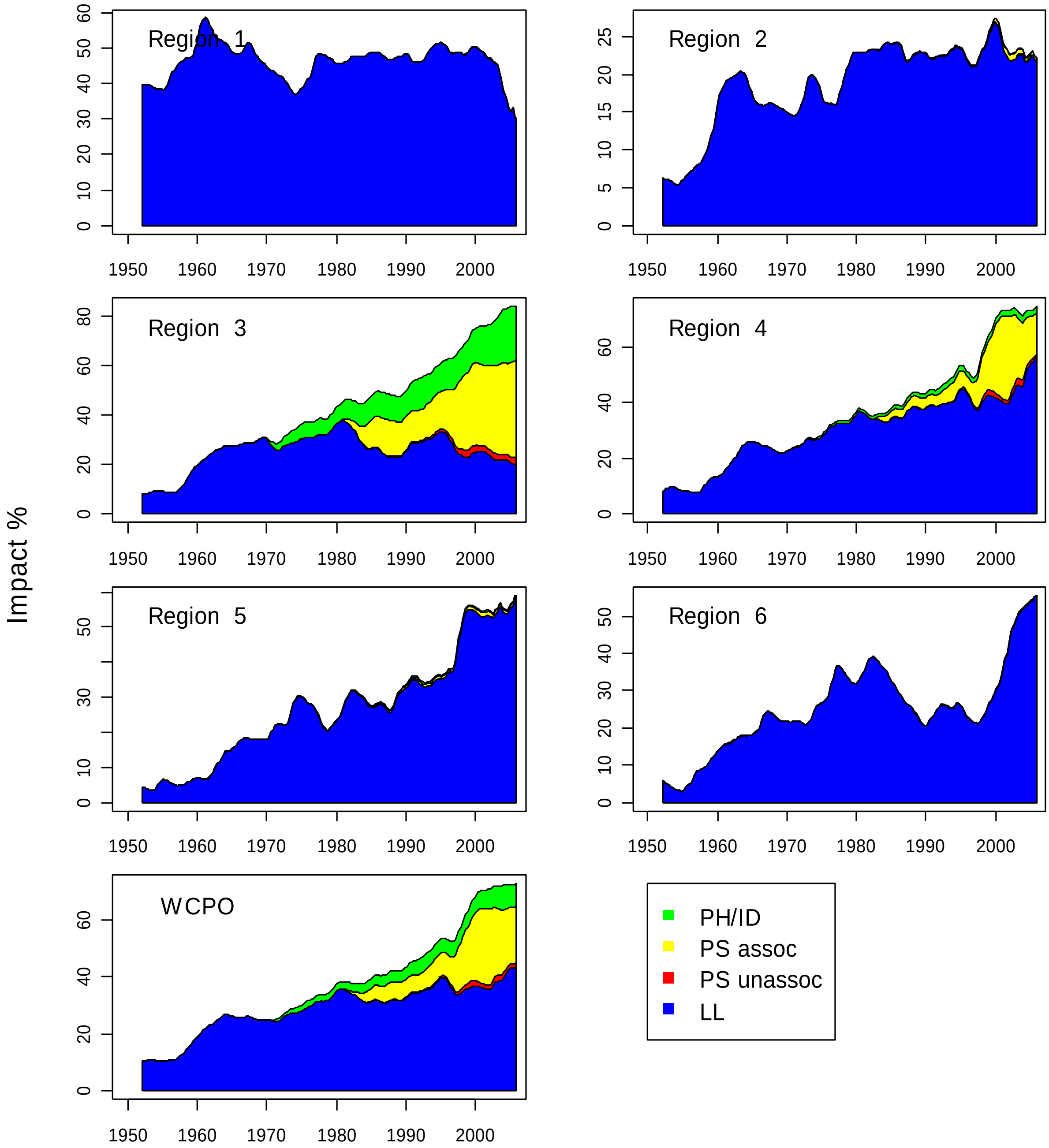


Figure 41. Estimates of reduction in total biomass due to fishing (fishery impact = 1-$B_t/B_{0,t}$) by region and for the WCPO attributed to various fishery groups (six-region LOWSAMP model). LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine log and FAD sets; PS unassoc = purse seine school sets.

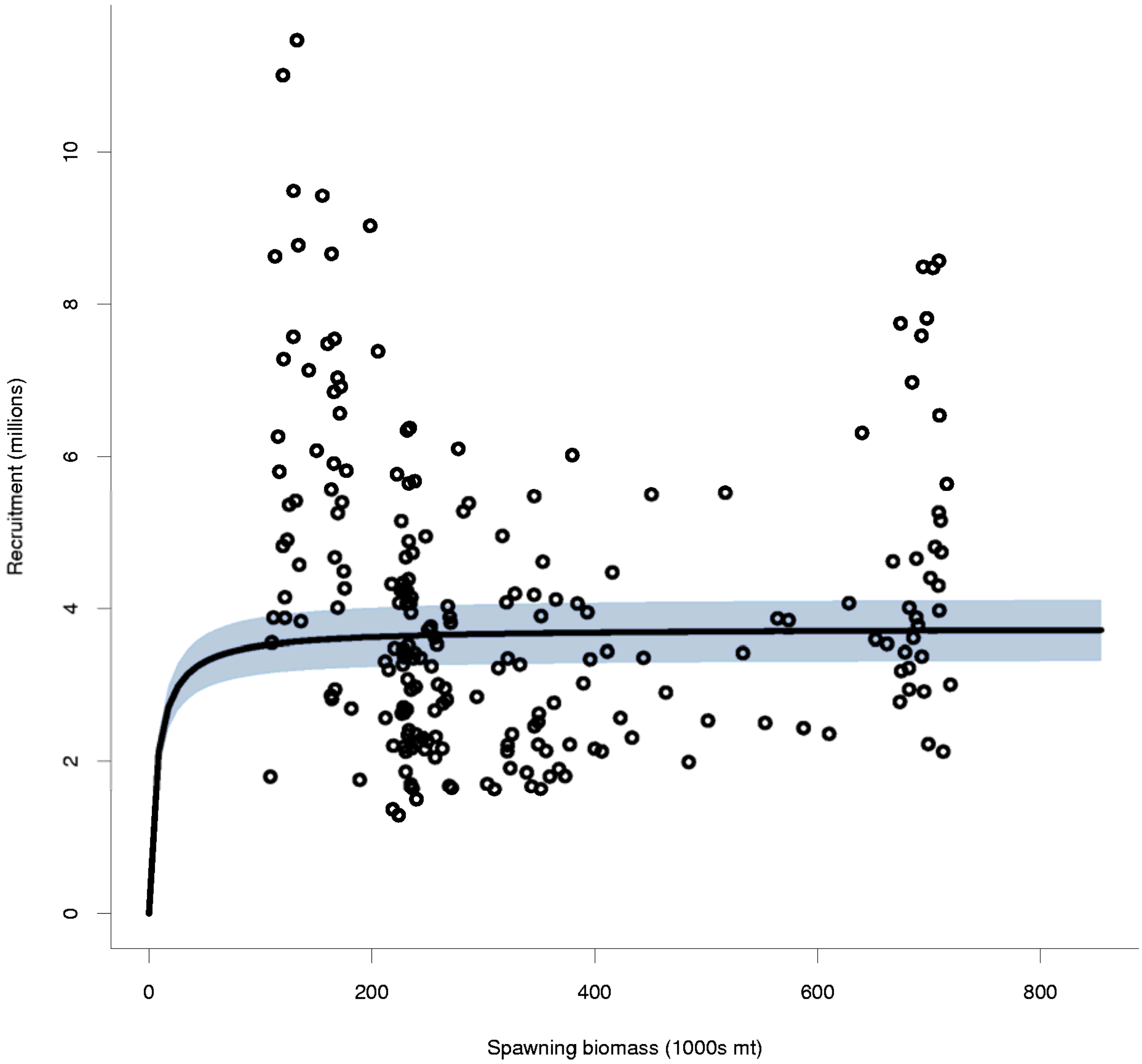


Figure 42. Estimated relationship between equilibrium recruitment and equilibrium spawning biomass (six-region LOWSAMP model). The grey area indicates the 95% confidence region. Estimated recruitment-spawning biomass points are plotted as open circles.

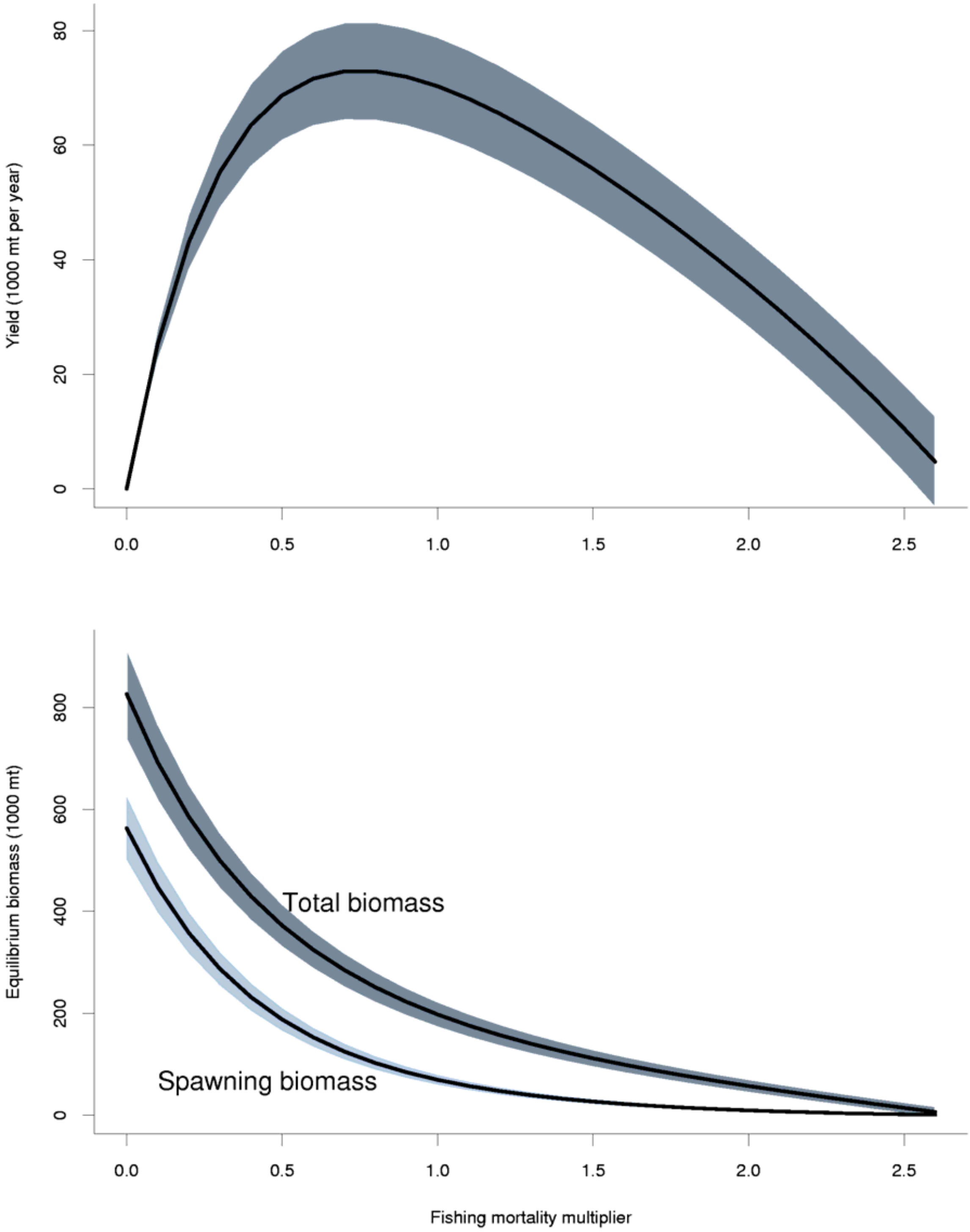


Figure 43. Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier. The shaded areas represent approximate 95% confidence intervals.

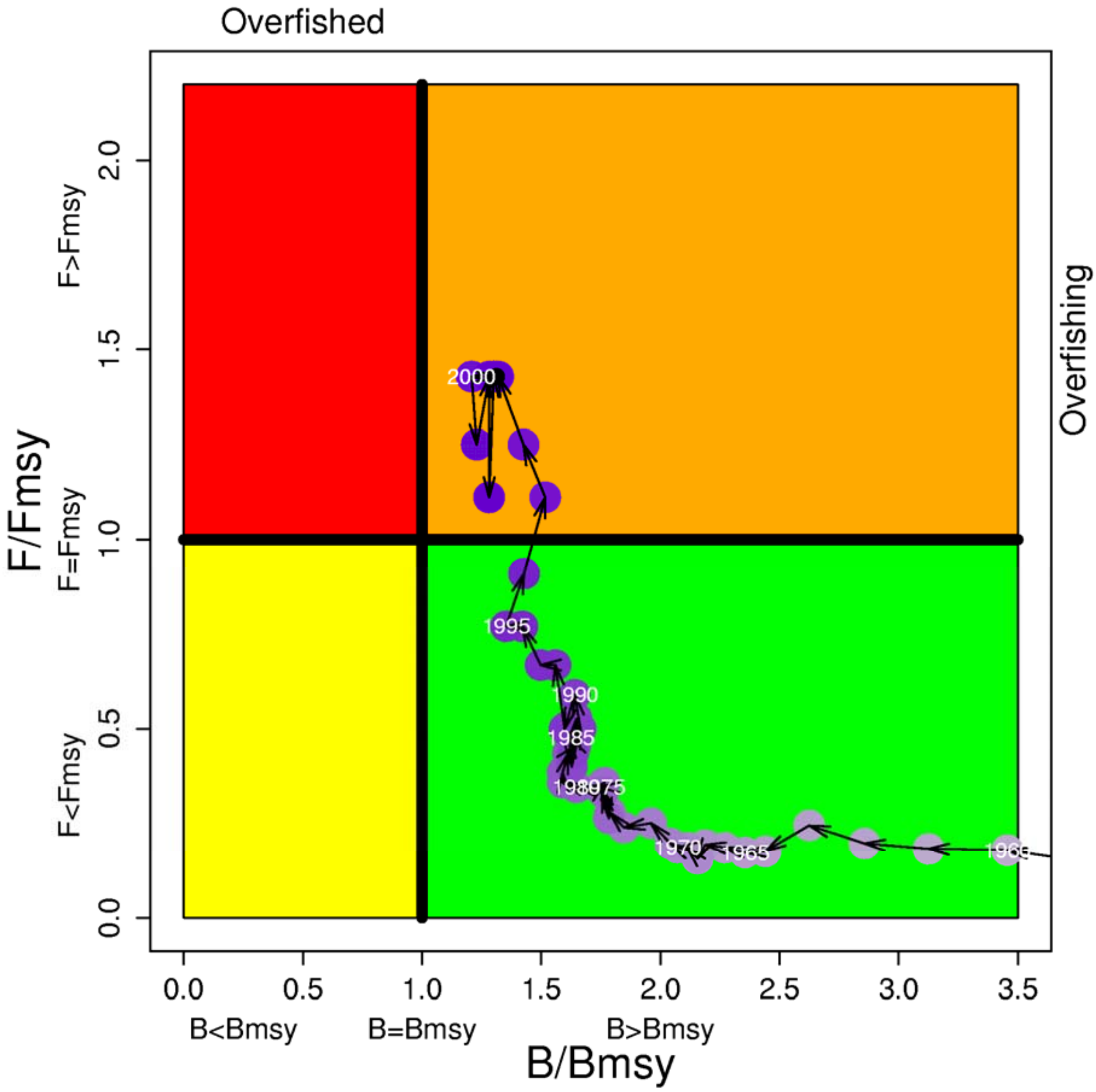


Figure 44. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1952–2005). The colour of the points is graduated from mauve (1952) to dark purple (2005) and the points are labelled at 5-year intervals.

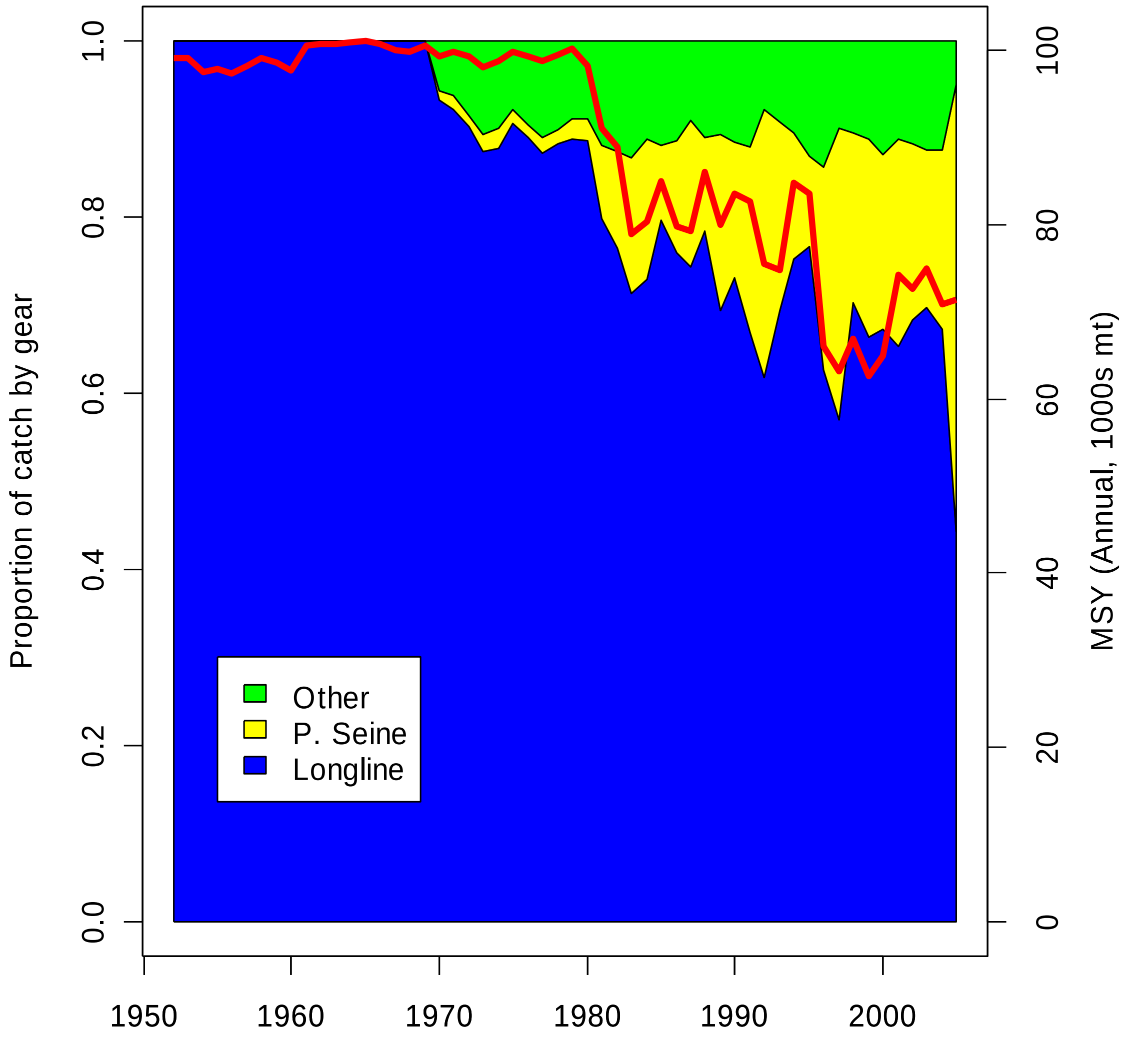


Figure 45. Temporal trend in annual Maximum Sustainable Yield (MSY) (red line) estimated for each year included in the bigeye stock assessment model. This is compared to the proportional distribution in the annual bigeye catch by main gear type for the entire WCPO.

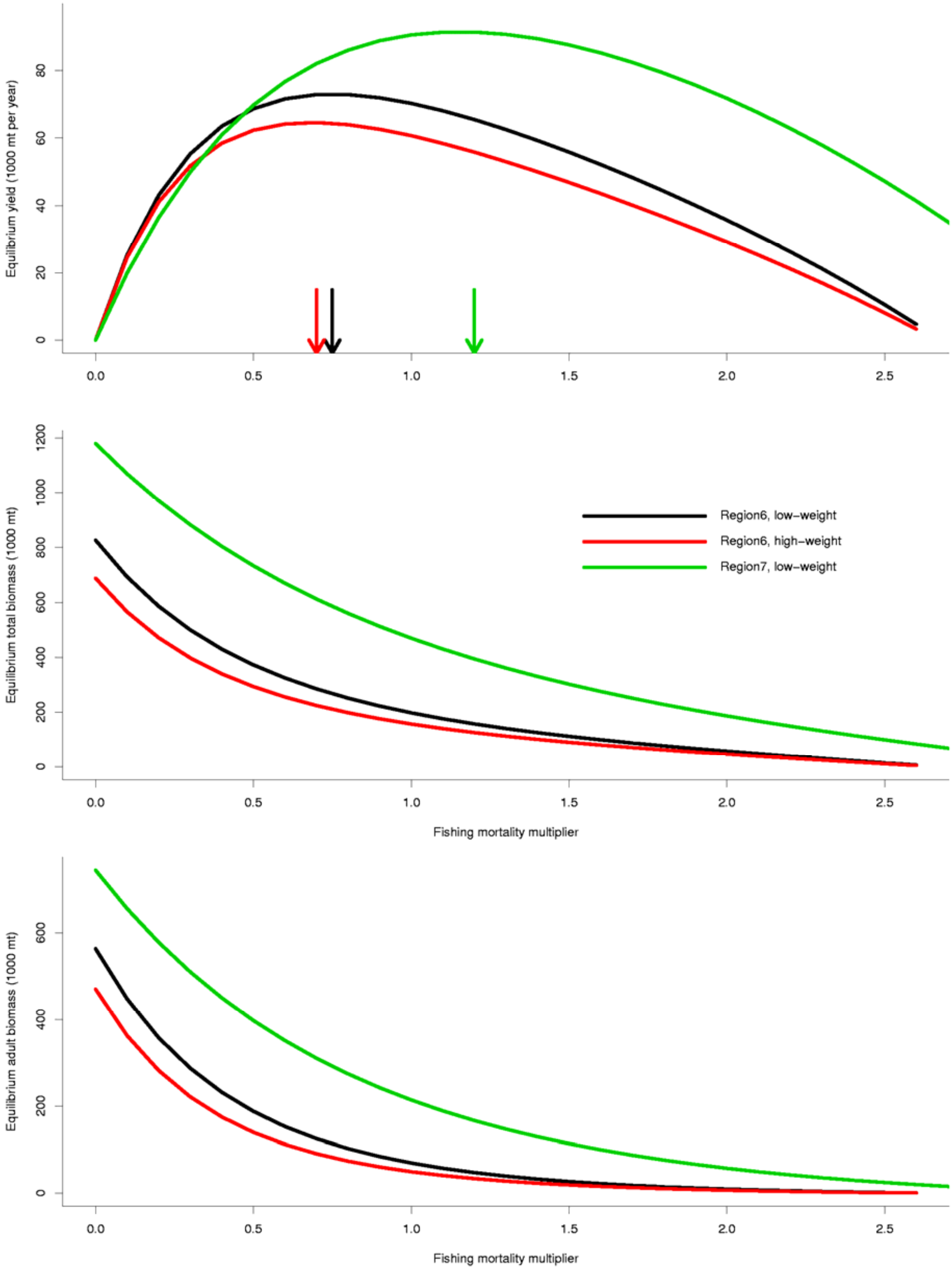


Figure 46. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier (*F*-mult) obtained from the separate analyses.

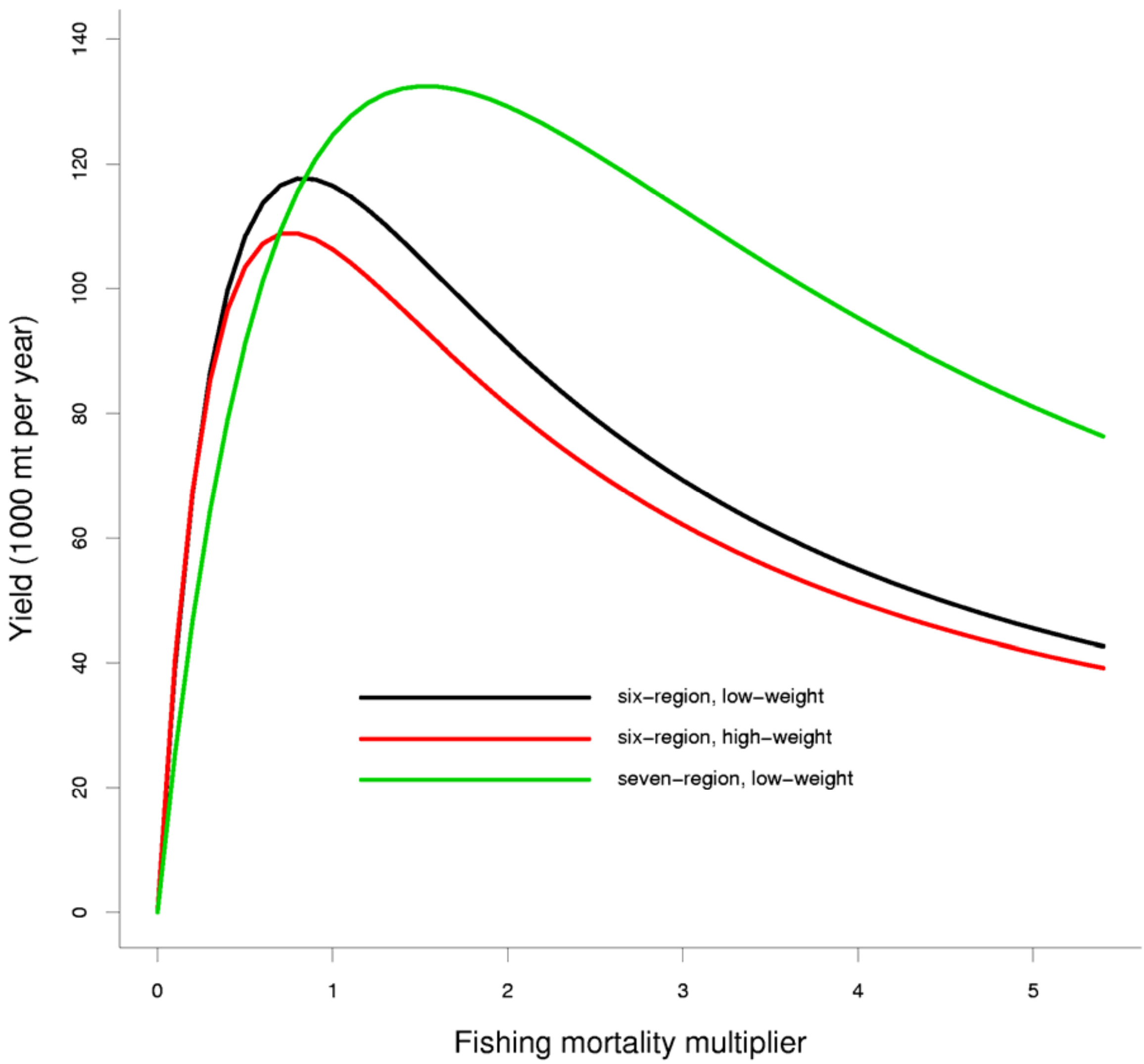


Figure 47. Yield curves based on 1995–2004 average recruitment.

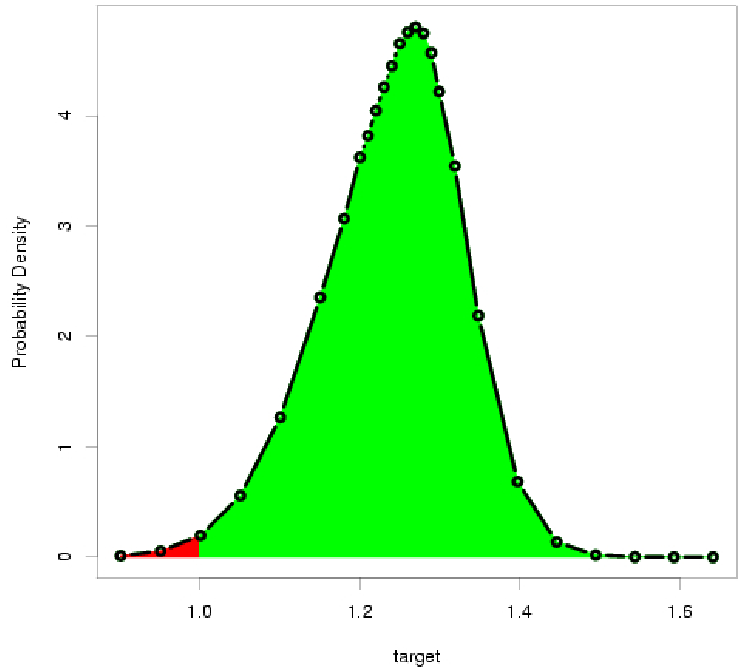


Figure 48. Probability distribution of $B_{current}/\tilde{B}_{MSY}$ based on the likelihood profile method for the six-region LOWSAMP model. The probability of $B_{current}/\tilde{B}_{MSY} < 1$ (red region) is approximately 0.8%.

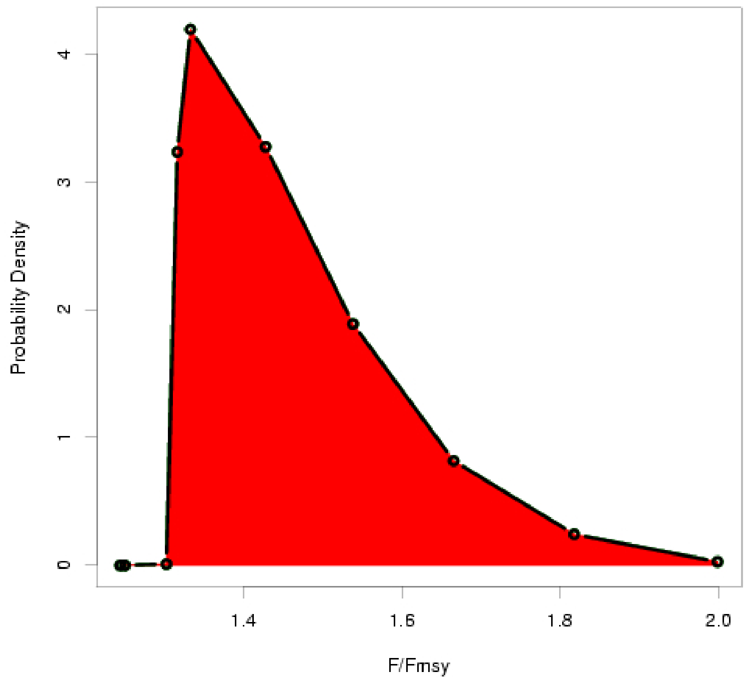


Figure 49. Probability distribution of $F_{current}/\tilde{F}_{MSY}$ based on the likelihood profile method for the six-region LOWSAMP model. The probability of $F_{current}/\tilde{F}_{MSY} > 1$ (red region) is 100%.

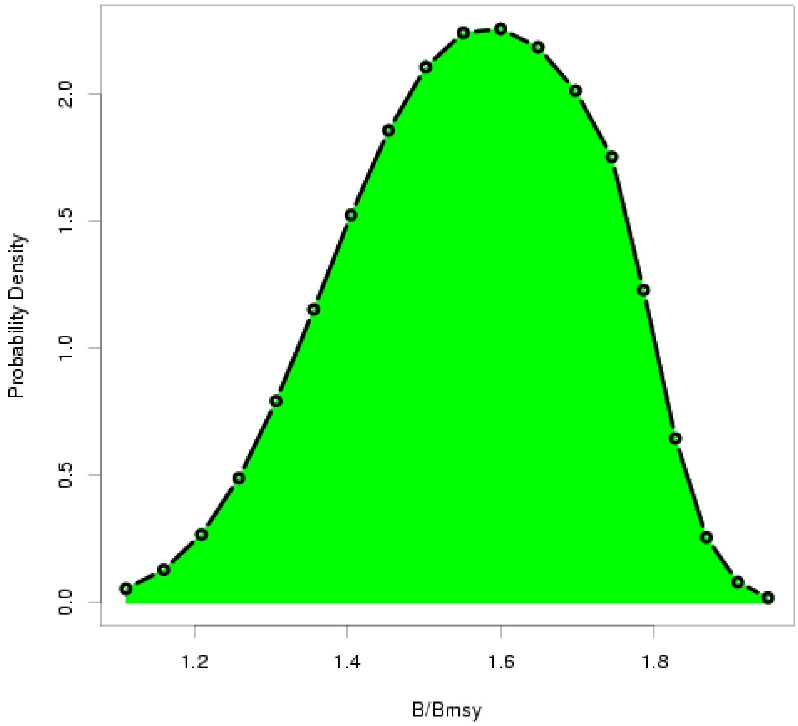


Figure 50. Probability distribution of $B_{current}/\tilde{B}_{MSY}$ based on the likelihood profile method for the 7REGION model.

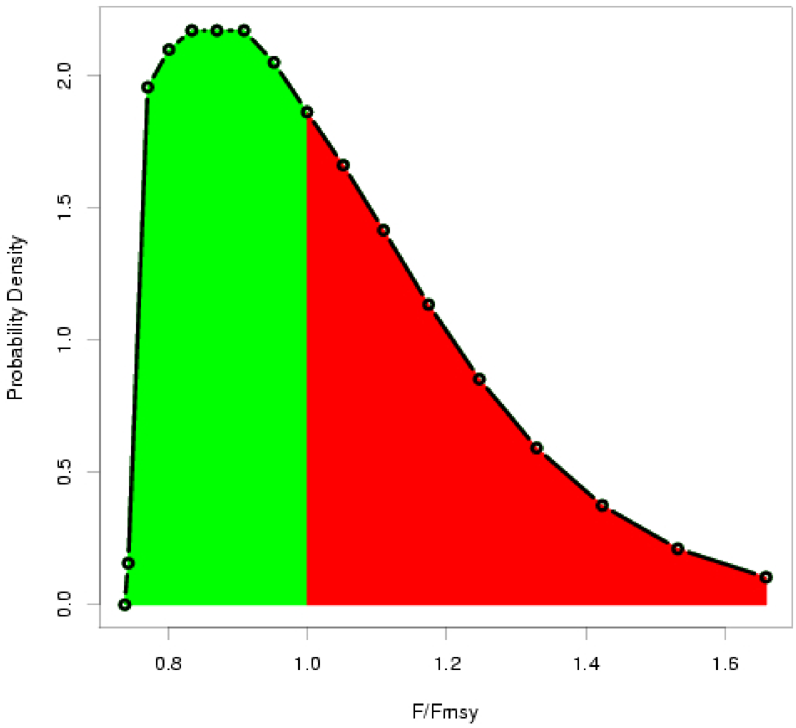


Figure 51. Probability distribution of $F_{current}/\tilde{F}_{MSY}$ based on the likelihood profile method for the 7REGION model. The probability of $F_{current}/\tilde{F}_{MSY}$ > 1 (red region) is approximately 49%.

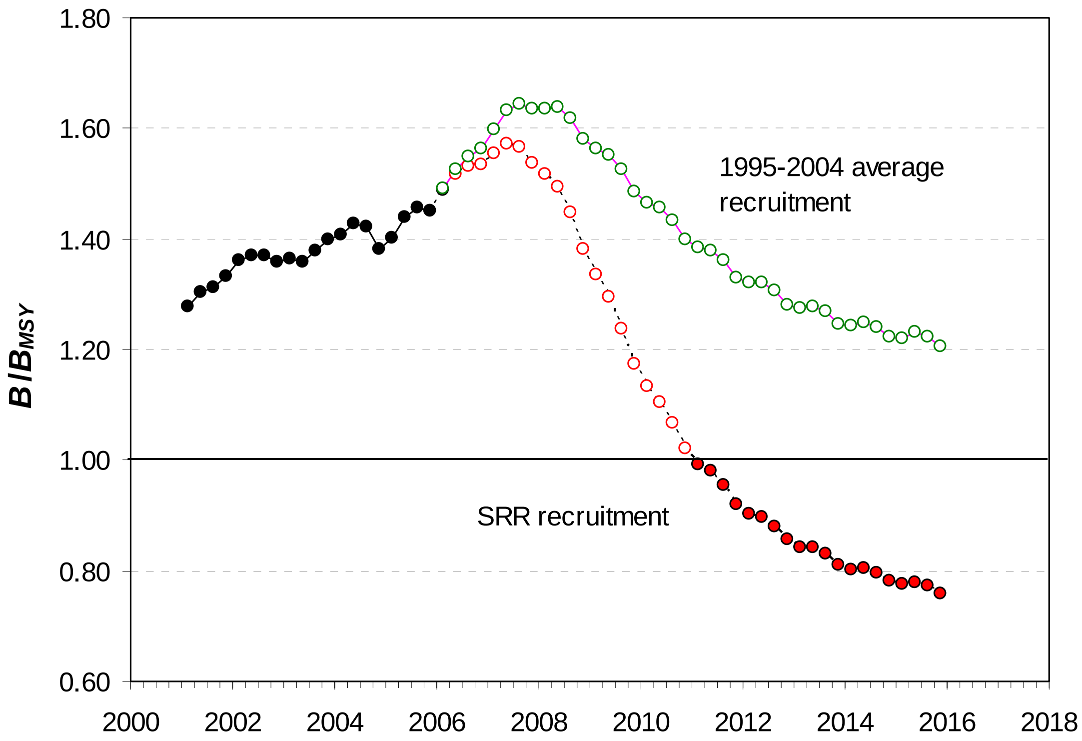


Figure 52. Projected ratio of $B_t / \tilde{B}_{MSYfinal}$ where $\tilde{B}_{MSYfinal}$ is computed based on the average *F*-at-age in the final year (10) of the projection. Projections using the estimated SRR and the average recruitment in 1995–2004 to predict recruitment in the projection period are shown for comparison.

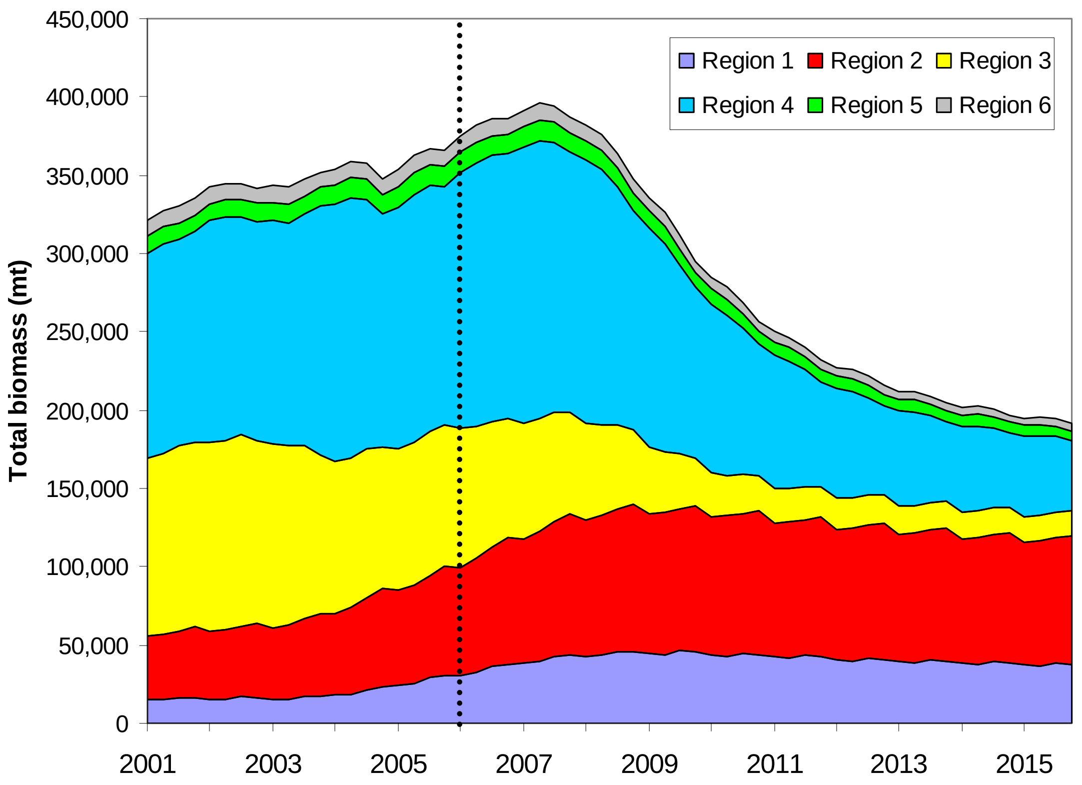


Figure 53. Recent and projected (SRR recruitment) total biomass (mt) by region. The vertical dotted line represents the start of the ten-year projection period.

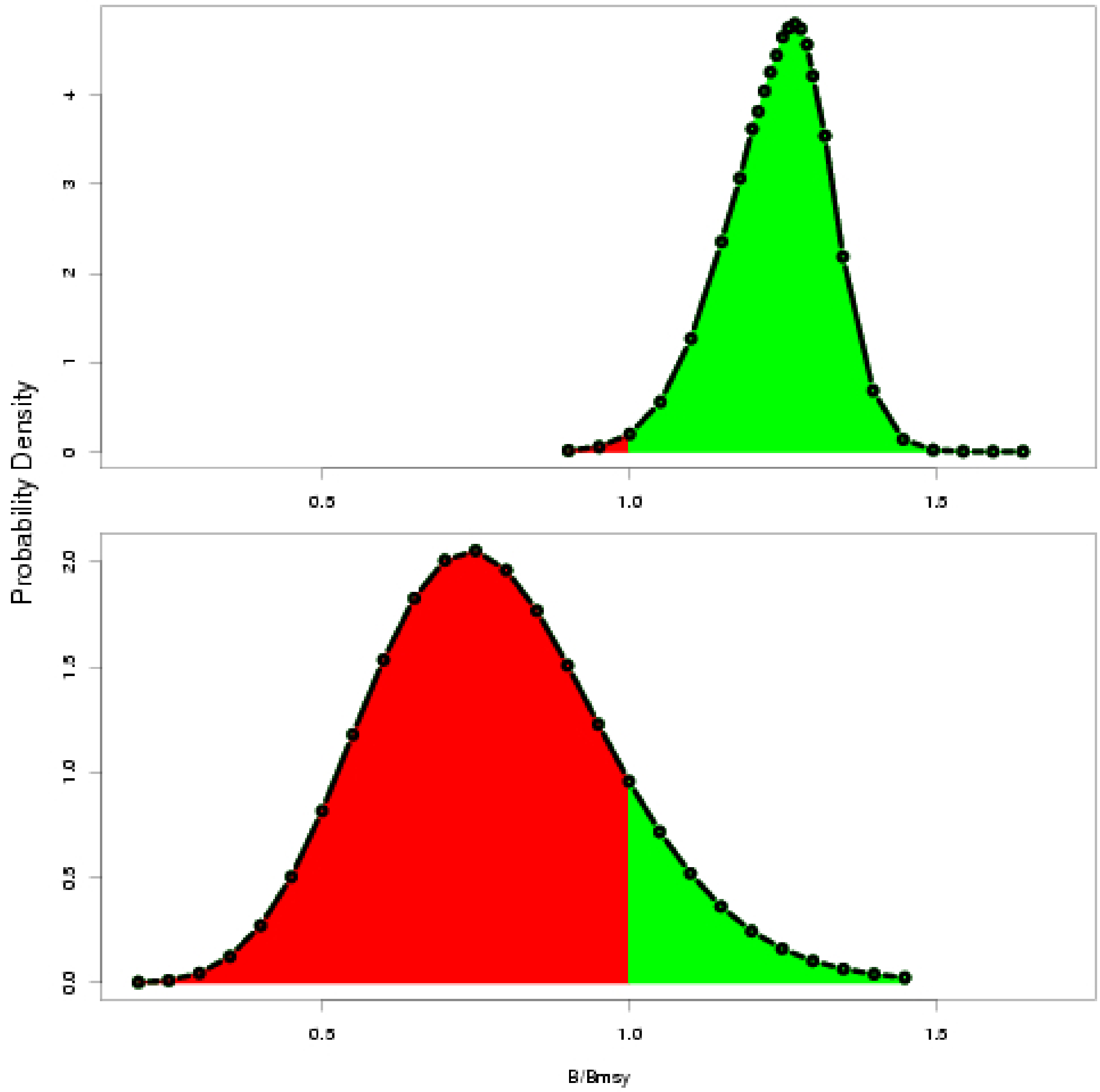


Figure 54. Profile likelihood for $B_{final}/\tilde{B}_{MSYfinal}$, i.e., the biomass ratio for the final year (5) of the projection (lower panel). The $B_{current}/\tilde{B}_{MSY}$ profile likelihood based on 2001–2004 average F-at-age is shown on the same scale in the upper panel for comparison. The probability that $B_{current}/\tilde{B}_{MSY} < 1$ is approximately 0.8%; the probability that $B_{final}/\tilde{B}_{MSYfinal} < 1$ is approximately 86.5%.

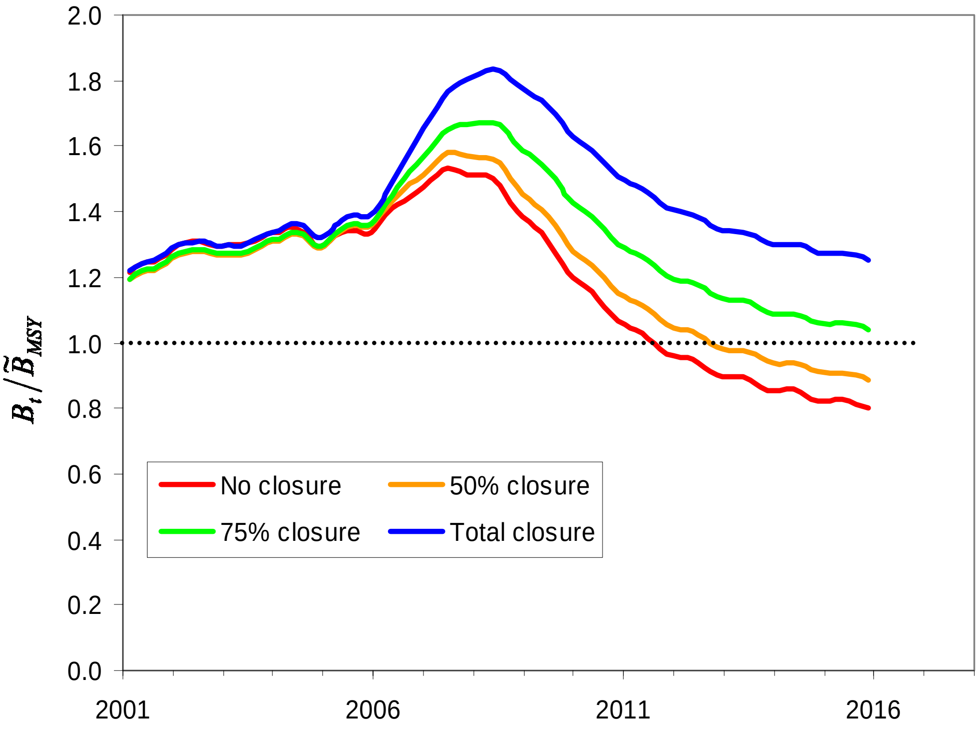


Figure 55. Recent total biomass and projected total biomass (2006–2015) relative to the $\tilde{B}_{MSYfinal}$ level for different levels of reduction in total purse-seine fishing effort simulating an equivalent period of closure for the fishery. $\tilde{B}_{MSYfinal}$ is computed based on the average *F*-at-age in the final year (10) of the projection period. Projections assume recruitments predicted from the estimated SRR.

Appendix A: *doitall.bet*

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

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

```
  -20 32 17
# grouping of fisheries with common tag-reporting rates - as for tag grouping
   -1 34 1
   -2 34 2
   -3 34 3
   -4 34 4
   -5 34 5
   -6 34 6
   -7 34 7
   -8 34 8
   -9 34 9
  -10 34 10
  -11 34 11
  -12 34 12
  -13 34 13
  -14 34 14        # PS assoc. and unassoc. returns are grouped
  -15 34 14
  -16 34 15
  -17 34 15
  -18 34 16        # PH/ID returns returns are grouped
  -19 34 16
  -20 34 17
# sets penalties on tag-reporting rate priors
   -1 35 1        # The penalties are set to be small for LL fisheries
   -2 35 1
   -3 35 50        # HI LL fishery thought to be high rep. rate
   -4 35 1
   -5 35 1
   -6 35 1
   -7 35 1
   -8 35 1
   -9 35 50
  -10 35 1
  -11 35 50        # AU LL region 4 thought to be high rep. rate
  -12 35 1
  -13 35 1
  -14 35 50        # WTP PS based on tag seeding
  -15 35 50
  -16 35 50
  -17 35 50
  -18 35 50        # PH/ID based on high recovery rate
  -19 35 50
  -20 35 50        # HI HL thought to be high rep. rate
# sets prior means for tag-reporting rates
   -1 36 50        # Mean of 0.5 and penalty of 1 -> uninformative prior
   -2 36 50
   -3 36 80        # HI LL
   -4 36 50
   -5 36 50
   -6 36 50
   -7 36 50
   -8 36 50
   -9 36 80
  -10 36 50
  -11 36 80        # AU LL region 4
  -12 36 50
  -13 36 50
  -14 36 45        # WTP PS based on tag seeding and discounted for unable returns
  -15 36 45
  -16 36 45
```

```
   -17 36 45
   -18 36 60        # PH/ID
   -19 36 60        # PH HL
   -20 36 80        # HI HL
# sets penalties for effort deviations (negative penalties force effort devs
# to be zero when catch is unknown)
 -999 13 -10      # higher for longline fisheries where effort is standardized
   -1 13 -50
   -2 13 -50
   -4 13 -50
   -7 13 -50
  -10 13 -50
  -12 13 -50
  -18 13 10
# sets penalties for catchability deviations
   -18 15 1       # low penalty for PH.ID MISC.
  -999 33 1       # estimate tag-reporting rates
  1 33 90         # maximum tag reporting rate for all fisheries is 0.9
PHASE1
fi
#  ---------
#   PHASE 2
#  ---------
if [ ! -f 02.par ]; then
  mfclopt bet.frq 01.par 02.par -file - <<PHASE2
  1 149 100       # set penalty on recruitment devs to 400/10
  -999 3 37       # all selectivities equal for age class 37 and older
  -999 4 4        # possibly not needed
  -999 21 4       # possibly not needed
  1 189 1         # write graph.frq (obs. and pred. LF data)
  1 190 1         # write plot.rep
  1 1 200         # set max. number of function evaluations per phase to 100
  1 50 -2         # set convergence criterion to 1E+01
  -999 14 10      # Penalties to stop F blowing out
  -999 62 2       # Add 2 more nodes to cubic spline
PHASE2
fi
#  ---------
#   PHASE 3
#  ---------
if [ ! -f 03.par ]; then
  mfclopt bet.frq 02.par 03.par -file - <<PHASE3
  2 70 1          # activate parameters and turn on
  2 71 1          # estimation of temporal changes in recruitment distribution
  1 183 20        # penalties on devs for first 20 time periods
  -100001 1 1000  # pen wt on region rec diffs in region 1
  -100001 2 1000  # pen wt on region rec diffs in region 2
  -100001 3 1000  # pen wt on region rec diffs in region 3
  -100001 4 1000  # pen wt on region rec diffs in region 4
  -100001 5 1000  # pen wt on region rec diffs in region 5
  -100001 6 1000  # pen wt on region rec diffs in region 6
PHASE3
fi
#  ---------
#   PHASE 4
#  ---------
if [ ! -f 04.par ]; then
  mfclopt bet.frq 03.par 04.par -file - <<PHASE4
  2 68 1          # estimate movement coefficients
PHASE4
```

```
fi
#  ---------
#   PHASE 5
#  ---------
if [ ! -f 05.par ]; then
  mfclopt bet.frq 04.par 05.par -file - <<PHASE5
  1 16 1          # estimate length dependent SD
PHASE5
fi
#  ---------
#   PHASE 6
#  ---------
if [ ! -f 06.par ]; then
  mfclopt bet.frq 05.par 06.par -file - <<PHASE6
  1 173 8         # estimate independent mean lengths for 1st 8 age classes
  1 182 10
PHASE6
fi
#  ---------
#   PHASE 7
#  ---------
if [ ! -f 07.par ]; then
  mfclopt bet.frq 06.par 07.par -file - <<PHASE7
  -999 27 1       # estimate seasonal catchability for all fisheries
  -18 27 0        # except those where
  -19 27 0        # only annual catches
PHASE7
fi
#  ---------
#   PHASE 8
#  ---------
if [ ! -f 08.par ]; then
  mfclopt bet.frq 07.par 08.par -file - <<PHASE8
  -3 10 1         # estimate
  -5 10 1         # catchability
  -6 10 1         # time-series
  -8 10 1         # for all
  -9 10 1         # non-longline
  -11 10 1        # fisheries
  -13 10 1
  -14 10 1
  -15 10 1
  -16 10 1
  -17 10 1
  -18 10 1
  -19 10 1
  -20 10 1
  -999 23 23      # and do a random-walk step every 23+1 months
PHASE8
fi
#  ---------
#   PHASE 9
#  ---------
if [ ! -f 09.par ]; then
  mfclopt bet.frq 08.par 09.par -file - <<PHASE9
  1 14 1          # estimate von Bertalanffy K
  1 12 1          # and mean length of age 1
PHASE9
fi
#  ---------
```

```
#   PHASE 10
#  ---------
if [ ! -f 10.par ]; then
  mfclopt bet.frq 09.par 10.par -file - <<PHASE10
# grouping of fisheries for estimation of negative binomial parameter a
   -1 44 1
   -2 44 1
   -3 44 1
   -4 44 1
   -5 44 1
   -6 44 1
   -7 44 1
   -8 44 1
   -9 44 1
  -10 44 1
  -11 44 1
  -12 44 1
  -13 44 1
  -14 44 2
  -15 44 2
  -16 44 2
  -17 44 2
  -18 44 3
  -19 44 3
  -20 44 4
 -999 43 1        # estimate a for all fisheries
PHASE10
fi
#  ---------
#   PHASE 11
#  ---------
if [ ! -f 11.par ]; then
  mfclopt bet.frq 10.par 11.par -file - <<PHASE11
  -100000 1 1     # estimate
  -100000 2 1     # time-invariant
  -100000 3 1     # distribution
  -100000 4 1     # of
  -100000 5 1     # recruitment
  -100000 6 1
PHASE11
fi
#  ---------
#   PHASE 12
#  ---------
if [ ! -f 12.par ]; then
  mfclopt bet.frq 11.par 12.par -file - <<PHASE12
  2 145 1
  1 149 0
  2 146 1
  2 147 1
  2 148 20
  2 155 4
  2 153 31
  2 154 16
  1 1 1000
  1 50 -3
PHASE12
fi
cp plot.rep plot-12.rep
cp length.fit length-12.fit
```

```
cp weight.fit weight-12.fit
#  ----------
#   PHASE 13
#  ----------
if [ ! -f 13.par ]; then
  mfclopt bet.frq 12.par 13.par -file - <<PHASE13
  -999 49 50
  -999 50 50
PHASE13
fi
```

Appendix B: *bet.ini*

```
# number of age classes
  40
# maturity at age
  0.0 0.0 0.0 0.0
  0.0 0.0 0.0 0.0
  0.0 0.0 0.05 0.1
  0.2 0.4 0.6 0.7
  0.8 0.85 0.9 0.95
  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
# natural mortality
0.112828307
# movement map
    1 2 3 4
# diffusion coffs
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
# 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
  0.57270008 0.388151602 0.169824717 -0.109880777 -0.120429055 -0.120184071 -0.119736681 -
0.118950236 -0.117624734 -0.115488279 -0.112200121 -0.107371589 -0.100609865 -0.091587038 -
0.080133729 -0.06684202 -0.051242744 -0.034614946 -0.018129082 -0.00301803 0.009741098 0.019643201
0.026664669 0.031113414 0.033443002 0.034116377 0.033536898 0.032027915 0.029837148 0.027150142
0.024104578 0.020802649 0.017320587 0.013715783 0.010031876 0.006302492 0.00255379 -0.001193612 -
0.004923295 -0.008622116
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 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
   0.05 0.06 0.40 0.35 0.05 0.09
# The von Bertalanffy parameters
28.000000000000  20.000000000000   40.000000000000
180.000000000000  140.000000000000   200.000000000000
0.075000000000   0   0.300000000000
# Length-weight coefficients
1.9729e-5 3.0247
# Variance parameters
6.000000000000  3.000000000000  12.000000000000
0.100000000000  -1.500000000000   1.500000000000
# The number of mean constraints
0
#7 99  1  20.000000000000   28.000000000000   0.100000000000   0.900000000000
#7 99  2  34.000000000000   40.000000000000   0.100000000000   0.900000000000
```