SCIENTIFIC COMMITTEE
SIXTH REGULAR SESSION
10-19 August 2010
Nuku'alofa, Tonga

STOCK ASSESSMENT OF BIGEYE TUNA IN THE WESTERN AND CENTRAL PACIFIC OCEAN

WCPFC-SC6-2010/SA-WP-04

Shelton Harley[1], Simon Hoyle[1], Peter Williams[1], John Hampton[1], and Pierre Kleiber[2]

[1]Oceanic Fisheries Programme, Secretariat of the Pacific Community
[2]Pacific Islands Fisheries Science Center, National Marine Fisheries Service

Table of Contents

Executive summary

This paper presents the 2010 assessment of bigeye tuna in the western and central Pacific Ocean. This assessment is supported by several other analyses which are documented separately, but should be considered when reviewing this assessment. These include detailed examinations of input data and sensitivity analyses (Harley et al. 2010), evaluation of paired spill / grab sample trials leading to alternative purse seine catch histories (Lawson 2010), reviews of the catch statistics of the Philippines and Indonesia (Williams 2010), and standardised CPUE analyses for both aggregate (Hoyle 2010) and operational level (Hoyle et al. 2010) longline catch and effort data.

The assessment includes several model runs describing stepwise changes from the 2009 assessment (run 14) to develop a new "base[1]" model (run3d) and then several other key model runs which represent a set of plausible model runs for consideration in developing management advice. These key model runs represent a single change from the base model run.

One of the major features of the 2010 assessment is that for the first time the assessment includes catch estimates for all fleets for the last year of the assessment (2009). This is a significant improvement, but data for several key fleets were submitted late and therefore the complete model inputs only became available in the first week of July. This delayed the assessment. Other data changes from the 2009 assessment include: revised longline fishery definitions to group together more similar fleets; revised catch estimates for all fleets from the Indonesia and Philippines; exclusion of further length samples from the Philippines "small fish" fishery which include large bigeye tuna; new standardised CPUE series for the main longline fisheries based on an improved methodology; exclusion of some historical size data from the Philippines which was 'contaminated' with samples from two different fisheries; exclusion of some early Japanese length data which was inconsistent with other data; and revised spill sample purse seine estimate incorporating the results of recent experimental work.

Other changes to the assessment included: increased flexibility for temporal changes in purse seine catchability, and decreased weight given to certain length and weight frequency data sets.

The key assumptions from the "base" model from the 2009 assessment (run 10), the base model for the 2010 assessment (run3d), and the alternative assumptions in the other main model runs are provided below:

Component	**2009 assessment (run 10)**	**2010 assessment (run 3d)**	**2010 alternatives**
Longline CPUE	Aggregate indices	Aggregate indices	Excluding all CPUE prior to 1975
Steepness	Estimated	Estimated	0.55, 0.75, 0.95
Purse seine catches	Grab sample (s_best)	Spill sample corrected	Grab sample (s_best)
Fleet catchability adjustment	None	None	0.47% per year (non-compounding)
Longline size data	Up-weighted	Down-weighted	Up-weighted
Natural mortality	Base	Base	Increased for juveniles

The main conclusions of the current assessment are as follows.

[1] While run3d is designated the "base" model for the purpose of structuring the modelling analyses, the most appropriate model run(s) upon which to base management advice will be determined by the Scientific Committee.

1. The estimated recruitment trends from recent bigeye assessments appear to be primarily the result of conflict (disagreement) among the various data sources, in particular between the longline CPUE indices and the reported catch histories, and between and within some of the size composition data sets. The current assessment has indentified some of these conflicts and includes some model runs that begin to address them.

2. Recruitment in all analyses is estimated to have been high during 1995–2005. This result was similar to that of previous assessments, and appears to be partly driven by conflicts between some of the CPUE, catch, and size data inputs. Recruitment in the most recent years is estimated to have declined to a level approximating the long-term average, although these estimates have high uncertainty. If we consider the recruitment estimates in the second half of the time series to be more plausible and representative of the overall productivity of the bigeye stock, then consideration might be given to basing stock status estimation only on this period. This could in effect be implemented simply by estimating the stock-recruitment relationship for this latter period and applying that in the yield analyses.

3. Total and spawning biomass for the WCPO are estimated to have declined to about half of their initial levels by about 1970, with total biomass remaining relatively constant since then ($B_{current}/B_0$= 42%), while spawning biomass has continued to decline ($SB_{current}/SB_0$=32%). Declines are larger for the model with increasing longline catchability and increased purse seine catches.

4. When the non-equilibrium nature of recent recruitment is taken into account, we can estimate the level of depletion that has occurred. It is estimated that spawning potential is at 17% of the level predicted to exist in the absence of fishing considering the average over the period 2005-08, and that value is reduced to 15% when we compare using the 2009 spawning potential levels.

5. The attribution of depletion to various fisheries or groups of fisheries indicates that the purse seine and other surface fisheries have an equal or greater impact than longline fisheries on the current BET biomass. The purse seine and Philippines/Indonesian domestic fisheries also have substantial impact in region 3 and to a lesser extent in region 4. The Japanese coastal pole-and-line and purse-seine fisheries are also having a significant impact in their home region (region 1). For the sensitivity analysis with lower purse seine catches, the longline fisheries are estimated to have a higher impact.

6. Recent catches are well above the *MSY* level of 73,840 mt, but this is mostly due to a combination of above average recruitment and high fishing mortality. When *MSY* is re-calculated assuming recent recruitment levels persist, catches are still around 10% higher than the re-calculated *MSY*. **Based on these results, we conclude that current levels of catch are unlikely to be sustainable in the long term even at the recent [high] levels of recruitment estimated for the last decade**.

7. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. For all of the model runs $F_{current}/F_{MSY}$ is considerably greater than 1. For run 3d (base) the ratio is estimated at 1.41 indicating that a 29% reduction in fishing mortality is required from the 2005-08 level to reduce fishing mortality to sustainable levels. If we consider historical levels of fishing mortality, a 31% reduction in fishing mortality from 2004 levels is required (consistent with the aim of CMM2008-01), and only a 20% reduction from average 2001-04 levels. The results are far worse with lower values of steepness or when a higher weight is given to the size data. **Based on these results, we conclude that overfishing is occurring in the bigeye tuna stock, but possibly at a lower level than previously estimated**.

8. The reference points that predict the status of the stock under equilibrium conditions are $B_{F_{current}}/B_{MSY}$ and $SB_{F_{current}}/SB_{MSY}$. The model predicts that biomass would be reduced to 64% and 56% of the level that supports *MSY*. In terms of the reduction against virgin biomass the declines reach as low as 13% of spawning potential. Current stock status compared to these reference points indicate the current total and spawning biomass are higher than the associated MSY levels ($\frac{B_{current}}{B_{MSY}} = 1.39$ and $\frac{SB_{current}}{SB_{MSY}} = 1.43$). The likelihood profile analysis indicates a

0.5% probability that $SB_{current} < SB_{MSY}$ which increases to 60% if a lower value of steepness ins assumed. Some of the more plausible alternative models are more pessimistic as are the conclusions of the structural uncertainty analysis based on the grid. **Based on these results above, and the recent trend in spawning biomass, we conclude that bigeye tuna is approaching an overfished state, if it is not already slightly overfished.**

9. Analysis of current levels of fishing mortality and historical patterns in the mix of fishing gears indicates that MSY has been reduced to less than half its levels prior to 1970 through harvest of juveniles. Because of that and overfishing, considerable potential yield from the bigeye tuna stock is being lost. **Based on these results, we conclude that MSY levels would rise if mortality of small fish were reduced which would allow greater overall yields to be sustainably obtained.**

This paper also includes recommendations for future stock assessments of bigeye tuna, including research activities to improve model inputs.

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 regularly and the most recent assessments are documented in Hampton et al. (2004, 2005 and 2006), Langley et al. (2008), and Harley et al. (2009b). This assessment is supported by several other analyses which are documented separately, but should be considered in reviewing this assessment. These include detailed examinations of input data and sensitivity analyses (Harley et al. 2010), evaluation of paired spill / grab sample trials leading to alternative purse seine catch histories (Lawson 2010), reviews of the catch statistics of the Philippines and Indonesia (Williams 2010), and standardised CPUE analyses for both aggregate (Hoyle 2010) and operational level (Hoyle et al. 2010) longline catch and effort data.

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 and IATTC's tagging experiments on bigeye tuna. Bigeye tuna tagged in locations throughout the 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. Recent tagging of bigeye tuna in the central Pacific has shown a similar pattern. The majority of tag returns with verified recapture positions show displacements of less than 1,000 nm (SPC, unpubl. data). In addition, 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 time scales of up to 3 years; however one recent four-year archival tag return displayed long-distance movements from the EPO to the central Pacific and back in years 3 and 4 of the archival tag record (Schaefer, pers. comm). In view of these results, stock assessments of bigeye tuna are routinely undertaken for the WCPO and EPO separately[2], however, current bigeye tuna tagging efforts in all areas of the tropical Pacific will provide further opportunity to examine this hypothesis.

[2] 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 the most recent (2006) Pacific-wide model are compared with WCPO and EPO assessments conducted in the same year in Hampton and Maunder (2006).

Bigeye tuna are relatively fast growing, and have a maximum fork length (FL) of about 200 cm. The growth of juveniles appears to depart somewhat from von Bertalanffy type growth with the growth rate slowing between about 40 and 70 cm FL (Lehodey et al. 1999) although this effect is not as marked as for yellowfin tuna. The natural mortality rate is likely to vary 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 unpublished 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 longline fleets of Japan and Korea and the smaller, fresh sashimi longline fleets 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 longline catch in the SPC area had a landed value in 2008 of approximately US$724 million (Williams and Terawasi 2009).

From 1980 to 1993, the longline catch of bigeye tuna in the WCP-CA varied between about 44,000 and 62,000 mt (Figure 2). Catches increased in subsequent years, reaching peaks in 1998 (84,000 mt), 2002 (81,000 mt), and 2004 (99,000 mt). Since 2004 catches have ranged from 67,000 mt to 77,000 mt.

The history of purse seine catches depends on the data sources used to derive the estimates. Bigeye in purse catches are taken almost exclusively from sets on natural and artificial floating objects (FADs). There remains considerable uncertainty regarding the accuracy of the purse-seine catch and reported catches may significantly under-estimate actual catch levels (Lawson 2008, 2009, 2010). Based on spill-sample corrected purse seine estimates, purse seine catches first exceeded 20,000 mt in 1982, and increased up to 40-50,000 mt by the mid 1990s (Figure 2). Catches were over 60,000 mt were reported from 1996-2001 with a peak of 105,000 mt in 1997. Since 2001 catches have ranged between 36,000 mt (2003) and 65,000 (2004). Conversely the previous estimates of purse seine catches (“s_best”; see Lawson (2005; 2007) for further details of how this dataset is constructed) are different (Figure 3). This alternative catch history indicates that catches did not exceed 20,000 mt until 1997 and have ranged between 21,000 mt (1998) and 38,000 mt (2008) since then.

A small purse seine fishery also operates in the coastal waters off Japan with an annual bigeye catch of approximately 1,000 mt. A similar level of bigeye catch is taken by the coastal Japanese pole-and-line fishery. These are included in the ‘other’ category.

The spatial distribution of WCPO bigeye tuna catch during 1990–2009 is shown in Figure 4. 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 the Philippines and Indonesia using a variety of gear types (e.g. pole-and-line, ringnet, gillnet, handline and seine net). The total catch for both countries combined is estimated to have approached 20,000 mt in recent years. The statistical basis for the catch estimates in the Philippines and, more so in Indonesia is weak, but improving. 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 provided 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 4). 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 on a seasonal basis. This stratification has remained unchanged since the 2006 base case assessment.

Total annual catches by major gear categories are shown in Figure 5. 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.

3.2 Temporal stratification

The primary time period covered by the assessment is 1952–2009, thus including all significant post-war tuna fishing in the WCPO. Within this period, data were compiled into quarters (January−March, April−June, July−September, October−December).

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). The 25 fisheries defined for the 2008 and 2009 assessments on the basis of region, gear type and, in the case of purse seine, set type, were modified slightly for the 2010 assessment based on the analyses described in Harley et al. (2010). The changes included removing locally based longline fleets flying the flags of Indonesia, the Philippines, FSM, and the Marshall Islands from fisheries 4, 7, and 23 and instead including them in fisheries 5 and 8 (Table 1).

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.

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.

For the first time in 2010, we were able to include almost complete catch estimates for the most recent year, 2009. Past assessments have been constrained by considerable missing data for the most recent year. However, this came at a cost as the data sets for the assessment could not be finalised until the first week of July (one month prior to the SC), due to the late data submission by several CCM's. This resulted in delays in the assessment.

Annual catch and CPUE for all fisheries are provided in Figure 6 and Figure 7.

3.4.1 Purse seine

Two sets of purse-seine input catch data were used in the analyses, but in contrast to the 2009 assessment, it is the spill sample based estimates which are used as the "base" catches for the 2010 assessment (as the spill sample-based estimates are considered more plausible). These are presented in Figure 8.

The "base" set of input data was derived by extracting the data from the s_best[3] database and then adjusting the proportions of skipjack, yellowfin and bigeye for 1996-2008 on the basis of observer data corrected for selection bias in grab samples (Lawson 2009, 2010). For strata of grouped catch data with less than 20 observed sets, predictions of the species composition (for all three species) were applied to the catch data. Species composition was predicted using categorical linear models that were fit with species compositions determined from the grouped observer data. Separate models were fit for the two periods 1967-1995 and 1996-2009. For 1967-1995, for which there are no observer data, the independent variables were quarter (but not year), area, school association and all first order interactions. For 1996-2009, for which there are observer data, the independent variables were year, quarter, area, school association and all first order interactions except year:area.

The second set of input data consisted of data extracted from the OFP "s_best" database of catches aggregated by 1° latitude, 1° longitude, month and flag. Except for data covering the Japanese fleet, these data represent grouped operational data held by the OFP that have been raised to represent the total catch and effort. Aggregated data covering the Japanese fleet were provided by Japan. The proportions of yellowfin and bigeye in these data have been adjusted on the basis of species composition samples; data for 1988-1995 were adjusted with port sampling data covering the United States fleet and data for 1996-2008 were adjusted with observer data covering most fleets. The species compositions for 1967-1987, for which sampling data are not available, were estimated using categorical linear models (Lawson 2009) of quarter (but not year), MFCL area and school association. Interactions, fitted to s_best data for 1988-2008 were grouped by year, quarter, MFCL area and school association.

Both sets of input data are likely to be biased. Grab samples, which are known to under-select very small and very large fish (Lawson 2009, 2010), with the result that the proportion of skipjack determined from observer data is under-estimated and the proportion of yellowfin is over-estimated, were adjusted for this selectivity bias on the basis of observer data collected from spill samples, which are thought to be unbiased, The correction was based on paired grab and spill samples collected from only a limited (but increasing) number of trips (Lawson 2010). The correction of the observer data for selectivity bias should improve as more data from paired grab and spill samples become available. In the second set of estimates, the proportion of skipjack was not adjusted, whereas it is known that the catches of skipjack reported on logsheets are biased upwards. The catches of skipjack in the second set of input data are therefore over-estimated and the catches of yellowfin and bigeye are under-estimated.

As in previous assessments, effort data units for purse seine fisheries are defined as days fishing and/or searching, and are allocated to set types based on the proportion of total sets attributed to a specified set type (associated or unassociated sets) in logbook data. We did not explicitly assume temporal changes in catchability in purse seine fisheries in any of the model runs, i.e. catchability was estimated rather than fixed.

3.4.2 Indonesia / Philippines

Revised catch histories were obtained for the Indonesia and Philippines fisheries. The current assessment includes considerably lower catch histories for the fisheries of Indonesia and slightly reduced catches from the Philippines based on refinements to the species composition of these catches (Figure 9). Effort data for the Philippines and Indonesian fisheries small fish fisheries were not available for all components of the fishery so were set to missing[4].

[3] The s_best data set incorporates logsheet estimates of skipjack and yellowfin+bigeye combined and then the split of yellowfin and bigeye is estimated from general linear models that incorporate observer grab samples (Lawson 2005;2007)

[4] In the final year effort was set to a nominal value of one to allow for effort-based projections to be undertaken for this fleet (noting that effort is proportional to fishing mortality).

3.4.3 Longline fisheries

For the principal longline fisheries (LL ALL 1–6), effective (standardised) effort was derived using generalized linear models (GLM) (Hoyle 2010). One change was made to the methods for estimating indices of abundance for the bigeye and yellowfin stock assessments from that used by Hoyle (2009) involving removal of the targeting indicator based on the CPUE of other species. This change had little effect on the CPUE trends.

As only aggregate 5x5 degree data are available for the entire WCPO region and these data do not include vessel information. There is thus a potential for bias in the CPUE indices as it is not possible to account for some of the potential increases in efficiency over time due to the phasing out of old vessels and introduction of new ones. To consider this potential bias, Hoyle (2009) standardised operational level CPUE data for the Japanese longline fleet, which is available from the coastal states in which the vessels fish, both including and excluding vessel as an explanatory variable. This was only possible for model region 3. Over the time period for which data are available, this subset of operational level data comprises between 25-75% of the annual Japanese effort in this region (Langley 2007). Hoyle (2009) found that including vessel as a factor in the GLM led to a greater decline in the CPUE series, and in the case of bigeye tuna this represented an increase in effective effort of 0.47% per year (not compounding[5]). This assumption has been applied to the LL-ALL 3 fishery in one of the key model runs described later. Annualised CPUE indices used in the assessment, and the new index for LL-ALL 3 that incorporates the vessel adjustment are presented in Figure 10.

In 2010, SPC and the Japanese National Research Institute of Far Seas Fisheries undertook collaborative analyses of Japanese operational level data (Hoyle et al. 2010). Given the preliminary nature of these investigations, and that the analyses did not consider data covering the entire time period of the model (unlike the analysis of the aggregated data in Hoyle (2010)), we have not included these new indices in any model runs described here, but would anticipate including these in future assessments as recommended by the authors.

The technique for standardising aggregate longline effort was also applied to determine the relative scaling of longline effort among regions. These scaling factors incorporated both the effective size of the region and the relative catch rate to estimate the relative level of exploitable longline biomass among regions (see Langley et al. 2005 and Hoyle & Langley 2007). The scaling factors were derived from the Japanese longline CPUE data from 1960–86. This period was chosen as it represented the period when Japanese longline effort was most widely distributed over the WCPO.

The scaling factors allowed trends in longline CPUE among regions to be comparable indicators of exploitable biomass among regions. For each of the principal longline fisheries, the GLM standardised CPUE index was normalised to the mean of the GLM index from 1960–86 — the equivalent period for which the region scaling factors were derived. The normalised GLM index was then scaled by the respective regional scaling factor to account for the regional differences in the relative level of exploitable longline biomass between regions. Standardised effort was calculated by dividing the quarterly catch by the quarterly (scaled) CPUE index.

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

3.5 Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 95 2-cm size classes (10−12 cm to 198−200 cm). Each length-frequency observation consisted of the actual number of bigeye tuna measured. The data were collected from a variety of sampling programmes, which can be summarized as follows:

Philippines: For the 2008 bigeye assessment, size composition data for the Philippines domestic fisheries derived from a sampling programme conducted in the Philippines in 1993−94 were

[5] For example, after five years effort is estimated to be 2.35% more efficient, 4.7% after ten years and 23.5% after 50 years.

augmented with data from the 1980s and for 1995. In addition, data collected during 1997−2006 from the Philippines hand-line (PH HL 3) and surface fisheries (PH MISC 3) under the National Stock Assessment Project (NSAP) were included in the current assessment.

In 2009 it was determined that the samples from the 1980s were a mixture of the small fish hook and line and large fish handline fisheries and therefore had to be excluded. For the current assessment we again looked closely at the remaining data and found that there were small numbers of bigeye tuna of sizes much greater than 100cm (Figure 11) which, by definition, could not have come from the small fish hook and line fishery. It is suspected that this may be due to mis-reporting of the fishing gear in some of the regional sampling programmes. A further complication was that these data are influential in the estimation of selectivity for this fishery and led to increased selection of large fish. To address this issue we excluded all reported fish lengths greater than 90 cm for PH MISC 3 from the current assessment.

Indonesia: No fishery size data were available for the Indonesian domestic fisheries. For the purposes of the assessment, the ID MISC 3 fishery was assumed to have a selectivity equivalent to the PH MISC 3 fishery.

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 are 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.

The investigations described in Lawson (2010) indicate the possibility that these length samples may be biased such that medium sized fish are over-represented and small fish are under-represented. If true, this could be influential on the assessment (Harley et al. 2010) and should be the focus of further investigation.

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. This comprehensive set of data is available for the entire model period. In recent years, length data from longline catches have also been collected by OFP and national port sampling and observer programmes in the WCPO. A detailed analysis of longline length-frequency data was provided in Harley et al. (2010). These analyses indicated some concerns about the representativeness of some of the length frequency samples, particularly in the early years, and also some evidence of spatial stratification in fish sizes. The Japanese length samples collected between 1954-65 gave very strong negative residuals in all regions (Harley et al. 2010).

In this assessment we have also excluded the size frequency data from Chinese off-shore longline vessels in region 4. This is because most of the Chinese catch in that region comes from the distant water fleet, but the size data are only available for the off-shore fleet which we suspect uses different fishing techniques.

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

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

As in previous assessments, length (and weight) data from each fishery/quarter were aggregated as it is assumed that all samples are representative of the operation of the fishery in each quarter. This assumption is likely to be more robust in the current assessment on the basis of the new fishery definitions for the longline fisheries. It is possible that further investigation of the length frequency data would lead to further changes in the fisheries definitions or data used in the assessments, in particular, the spatial extent of the current fishery definitions.

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 which export tuna including those located in 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 convert the available weight data to whole fish equivalents. 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.

3.7 Tagging data

A modest amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. These data consisted of bigeye tuna tag releases and returns from the OFP's Regional Tuna Tagging Project conducted during 1989–1992, and more recent (1995, 1999–2001) releases and returns from tagging conducted in the Coral Sea by CSIRO (Evans et al. 2008). 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).

The model does not yet include the tag release and recovery data from the 2006–09 Pacific Tuna Tagging Programme (PTTP) undertaken throughout the western part of the WCPO and in the central Pacific (Nicol et al. 2010). These data are currently being subject to ongoing quality checking at it was considered premature to include them in the current assessment. It is expected that PTTP data will be included as appropriate in assessments conducted from 2011.

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 in other model parameters influenced by tagging data. On this basis, these data were not included in the current six-region assessment.

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.

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 dynamics of the fisheries; (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. Brief descriptions of the various processes, including information on structural assumptions, estimated parameters, priors and other types of penalties used to constrain the parameterisation were provided in Langley et al. (2008 – Table 2) and only changes to these assumptions are reported here (Table 2).

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 20 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.

The population is "monitored" in the model at quarterly time steps, extending through a time window of 1952−2008. The main population dynamics processes are as follows:

4.1.1 Recruitment

Recruitment is the appearance of age-class 1 fish in the population. 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 exceeding the average recruitment by a factor of 3.3would occur about once every 25 years.

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. Because the SRR was expected to be weak, we therefore opted to apply a relatively weak penalty for deviation from it so that such deviation would have only a slight effect on 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 a beta distribution with 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 12.

4.1.2 Initial population

The population age structure in the initial time period in each region was assumed to be in equilibrium and determined as a function of the average total mortality during the first 20 quarters. This assumption avoids having to treat the initial age structure, which is generally poorly determined, as independent parameters in the model. Note that this assumption 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 concerning age and growth were (i) the lengths-at-age are normally distributed for each age-class; (ii) the mean lengths-at-age follow a von Bertalanffy growth curve, except for the 2nd-8th mean lengths at age which are estimated as free parameters (but constrained to be similar to the VBGF); (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. As noted above, the population is partitioned into 40 quarterly age-classes.

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 under the "implicit transition" computational algorithm (see Hampton and Fournier 2001 for details). 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, therefore there were $2\times7\times4 = 56$ movement parameters. In order to avoid the addition of more parameters to the model, we did not incorporate age-dependent movement into this assessment. Previous trials have indicated that such additional structure did not impact the overall results in a substantive way. The seasonal pattern of movement is assumed to persist from year to year with no allowance for longer-term variation in movement.

4.1.5 Natural mortality

As in previous assessments, natural mortality (*M*) was held fixed at pre-determined age-specific levels. No attempt was made to estimate *M*-at-age in these assessments because previous trial fits estimating *M*-at-age produced biologically unreasonable results. The values used in the current assessment were the same as those used in the 2009 assessment (Figure 13). These estimates of *M*-at-age were determined outside of the MULTIFAN-CL model using bigeye sex-ratio data and the assumed maturity-at-age schedule as described by Hoyle and Nicol (2008). A similar 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.

Two alternative *M*-at-age ogives were examined by Harley et al (2010) and one of these, relating to increased natural mortality of juvenile bigeye, was included here (Figure 13). The assumed values of natural mortality for the first 4 quarters are quite different for bigeye and yellowfin and some have questioned why this might be so. One of the key model runs, run 3g, included the assumed levels of YFT M for the first 4 quarters.

4.1.6 Sexual maturity

Reproductive output at age, which is used to derive spawning biomass, was recalculated for the 2008 assessment (Hoyle and Nicol 2008), using data collected in the WCPO and EPO. The calculations were based on relative reproductive potential rather than (as previously) the relative biomass of both sexes above the age of female maturity. Similar approaches have been applied to albacore (Hoyle 2008) and yellowfin (Hoyle et al. 2009) tunas in the WCPO. The reproductive potential of each age class was assumed to be the product of the proportion of females at age, the proportion of females mature at age, the spawning frequency at age of mature females, and the fecundity at age per spawning of mature females[6].

[6] As this method thus calculates spawning potential rather than spawning biomass, references in figures to spawning biomass should be interpreted as spawning potential.

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. For example, a logistic curve can be used to model monotonically increasing selectivity, and various dome-shaped curves can be used 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 constrained 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 the minimum number sufficient to allow for reasonably complex selectivity patterns.

Selectivity is assumed to be fishery-specific and time-invariant. Selectivity coefficients for the "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/ Chinese Taipei fishery in region 4 (see section 3.5 for further details). For the Chinese/ Chinese Taipei fishery in region 3, selectivity was parameterised using a logistic functional form rather than the cubic spline method. Selectivity was also constrained to be equal for the corresponding purse seine fisheries in the two equatorial regions (e.g. the associated set fisheries had the same selectivity in regions 3 and 4).

The selectivity of the Indonesian domestic fishery was assumed to be equivalent to the Philippines domestic fishery, but some problems were encountered in estimating selectivity for these important fisheries. Even in the absence of observed lengths greater than 90 cm (see section 3.5), the model estimates of selectivity gave significant non-zero selectivity above this size. This selectivity curve, not surprisingly, resulted in strong negative residuals. The model was clearly trading off the fit to these data with other data in the model. To overcome this problem, selectivity for these two fisheries were constrained to be zero above 12 quarters of age (approximately equivalent to 100 cm). Further work is required to determine the best selectivity curve (including functional form), for these important small-fish fisheries

For all other fisheries, the selectivity for the last four age-classes, for which the mean lengths are very similar, was constrained to be equal..

4.2.2 Catchability

Catchability was allowed to vary slowly over time (akin to a random walk) for all fisheries, except for the principal 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. Therefore, we set the variance of the priors on catchability deviates to be high (approximating a CV of about 0.7), thereby allowing for catchability changes to compensate for the missing effort data. As a result of the investigations described in Harley et al. (2010) it was also decided to set the variance of the priors on catchability deviates to be high (approximating a CV of about 0.7) for the purse seine fisheries. This was considered preferable to increasing the frequency of temporal catchability changes which would greatly increase the number of estimated parameters.

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 (for 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, pole-and-line fisheries, and the Australian, Hawaii and Chinese Taipei/Chinese longline fisheries, the variance was set at a moderate level (approximating a CV of 0.4 – an increase from 0.2 assumed in the 2008 assessment).

Three approaches were used to model the assumed effort deviates for the main longline fisheries (LL-ALL 1-6) with the standardised CPUE indices. In the base model we assumed an overall CV=0.2 for each region, but with individual observations weighted again relative to the square root of the effort. Two other approaches were compared using the MULTIFAN-CL feature where user-defined CV's can be included. In the first approach we took the CVs estimated by Hoyle (2010), but scaled them so that the mean CV for each series was still 0.2 (run 3e), while in the second we used the actual CVs estimated and did not rescale them (run 3e2). The resulting CVs are provided in Figure 14. Only LL-ALL 3 has CVs which are close to the value of 0.2 and these are slightly lower. For LL-ALL 5 and 6 the CVs are above 0.5.

In the 2009 assessment problems with large effort deviates were noted and the effort deviate bounds were increased from +/- 6 to +/- 10. We continued that practice in the current assessment, but also set to missing the zero catches which were previously set to 0.1. These observations had been associated with almost all the large negative effort deviates.

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 distribution 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 is required for reasonably precise estimates to be obtained. We provided reporting rate priors for all fisheries that reflect our expect judgement regarding the reporting rate and the confidence we have in that judgement. Relatively informative priors were specified for reporting rates for the Philippines and Indonesian domestic fisheries and the purse seine fisheries, based on independent estimates of reporting rates for these fisheries 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 are 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 can be examined by varying the effective sample size in the model. In the 2009 assessment the principal model runs were conducted using an effective sample size of 0.02 times the actual sample size, with a maximum effective sample size of 50. As a result of the investigations of the size frequency data provided in Harley et al. (2010) our confidence in some of the size frequency samples has been reduced pending further investigation. For the base model the length frequency data for fisheries 1, 2, 4, 7, 10, 12, and 23 were downweighted to a maximum size of only 1. This effectively removes the influence of these length data on the model, which then relies almost exclusively on the weight frequency data for these fisheries. The same was done for the fishery 5 length and weight frequency data. The 2009 size data weighting assumptions were, however, retained in one of the key model runs (run 3a2).

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 influence 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) [7].

In this assessment three approaches were used to describe the uncertainty in key model outputs. The first two focus on the statistical variation **within** a given assessment run, while the third focuses on the structural uncertainty in the assessment by considering the variation **across** model runs. First we calculated the Hessian matrix for the base model run to obtain estimates of the covariance matrix, which is used in combination with the Delta method to compute approximate confidence intervals for parameters of interest. This approach provided approximate confidence intervals for the biomass and recruitment trajectories. Second, we used the likelihood profiling capability within MULTIFAN-CL to calculate likelihood profiles for the critical reference points $F_{current}/F_{MSY}$ and $SB_{current}/SB_{MSY}$ for run 3d (base) and run 4b (h=0.7). Thirdly, we undertook a crosswise grid of 96 model runs which incorporated many of the options included in the key model runs. This last procedure attempts to capture the main sources of structural and data uncertainty in the assessment.

Several ancillary analyses were 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. (2008). 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).

4.5.1 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 $B_{t_{F=0}}$ incorporate recruitment variability, their ratio at each time step of the analysis $B_t/B_{t_{F=0}}$ 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.

4.5.2 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, F_{mult}, 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 F_{mult}, 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 F_{mult} 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 2005–2008. The last year in which catch and effort data are available for all fisheries is 2009. We do not include 2009 in the average as fishing mortality tends to have high uncertainty for the terminal data years of the analysis (see Langley 2006 and Harley et al. 2009a). To allow for retrospective evaluation we recalculated the key MSY-based reference points using annual time periods from 2000 to 2008.

[7] 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. (2008).

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 1999−2008.

5 Model runs

In undertaking this assessment over 150 model runs were undertaken and these have been presented to the pre-assessment workshop (Harley and Hoyle 2010), included with the background analyses (Harley et al. 2010), and presented here. The purpose of these runs included: investigation of the cause(s) of the estimated recruitment trend, testing the impacts of new or revised data, stepwise development of a base model, developing models with alternative assumptions for several important inputs or model structures, and finally assessing structural uncertainty in the assessment. Of these model runs 18 are described in detail in Table 2 and Table 3, including a description of the key differences from the 2009 assessment. The rationale for the models and changes are provided both in the proceeding sections and in Harley et al. (2010) and Harley and Hoyle (2010).

A base model (run 3d) and seven 'one-change' sensitivity analyses comprised the 'key model runs' for the assessment. In addition a grid of 96 model runs was produced with all combinations of the following options included:

- Natural mortality [2 levels]: from run 3d and run 3g
- Steepness[3 levels]: 0.55, 0.75, and 0.95
- Size data weighting [2 levels]: from run 3d and run 3a2
- Purse seine catch [2 levels]: from run 3d and run 4a
- Vessel adjusted longline CPUE [2 levels]: from run 3d and run 3f
- Temporal CPUE CVs [2 levels]: from run 3d and run 3e2

Two notable features of the grid are that it does not include the option contained in run 4c, i.e. the exclusion of all LL-ALL CPUE prior to 1975 and that it has fixed values of steepness. Because run 4c was run late in the assessment process and inclusion in the grid would have required a further 96 model runs and time did not allow for this . The values of steepness estimated in the key model runs are at the upper end of the range considered in the grid, but as noted in previous analyses (Harley et al. 2009), there is considerable scepticism regarding the ability to accurately estimate steepness and the incorporation of uncertainty in steepness is important given its influence on stock status reference points.

6 Results

6.1 Impact of model changes on key reference points

In order to examine the impacts of the stepwise changes from the 2009 bigeye assessment (run 14) to run3d (base) ,estimates of key reference points for each of the runs are provided in Table 5 and the total WCPO spawning potential is provided in Figure 30. For the purpose of comparing the impact of the additional year of data, and therefore advanced MSY-calculation window, see Table 7and Table 8. Key observations from these model runs were:

- The addition of one year's data, including the significant changes to the catches from Indonesia and the Philippines lead to a 10% reduction in fishing mortality, but estimated levels of spawning potential remain largely unchanged (run 1);
- Runs 1a through 1c had little impact on any of the key reference points, nor on the recruitment trend, but the exclusion of the 1954-65 length data did result in an increase in biomass estimates for those early years;
- The new fisheries definitions had little impact (run 3);
- The exclusion of the non-Japanese size data from fisheries 1, 2, 4, 7, and 23 resulted in increased fishing mortality and much lower spawning stock biomass (run 3a);

- Exclusion of the fishery 8 size data and linking the selectivity to that of the other equatorial LL-ALL fisheries greatly improved stock status indicators and reduced the recruitment ratio. It lifted the absolute levels of biomass (run 3a2);
- Stepwise downweighting of various size data sources led to a continual improvement in stock status for both fishing mortality and spawning potential reference points, an increase in MSY, and a reduction in the recruitment ratio (run 3b-3d).

When comparing current results (run 3d) to run 14-09, F/F_{MSY} for the period 2004-07 is now 32% lower, SB/SB_{MSY} is 33% higher, MSY is 9% higher, and the ratio of late to early recruitment[8] is 20% lower. The key change responsible for these differences is the downweighting / exclusion of various size frequency data sets.

6.2 Model diagnostics – Run 3d

As noted in the 2009 assessment and in Harley and Hoyle (2010) there are three key areas of model diagnostics: 1) the fit to the size frequency observations; 2) the estimated effort deviates for the LL-ALL fisheries; and 3) the estimated increase in recruitment through time. Diagnostics of the fits to all the size frequency data are provided in a summarised form in Figure 16 and Figure 17 and residual plots for the length frequency fits for the length data for several longline fisheries are provided in Figure 18. Patterns in effort deviates and recruitment are covered in later sections.

Harley et al. (2010) focussed much attention of patterns in the size frequency data and it was found that changes in the sources of the size frequency samples through time, in conjunction with some inappropriate fisheries definitions were responsible for some of the lack of fit observed in the 2009 assessment. Excluding some of these data and restructuring the fisheries has addressed some of these issues, but others remain. In the current assessment the main longline fisheries LL-ALL 1-4 only include Japanese size data, but as was noted in Harley et al. (2010), there remains some strong patterns in these data which the stock assessment models have difficulty reconciling with the other data inputs. The following observations are made:

- There remains some systematic lack of fit to the size data for the longline fisheries. In many instances these patterns are due to conflicts between the length frequency data and the weight frequency data for the same fishery. Noteworthy patterns include:
    - LL ALL 1: the decline in median weights not matched in the length data
    - LL ALL 2: the drastic shift in median length and weight (in the early 1980s) which the model struggles to follow;
    - LL ALL 3: the patterns of larger fish in the length data from the 1970s and 1990s, but smaller fish during the 1980s and 2000s. Many of these patterns are not found in the weight data;
    - LL TW-CH 4: increases in the median length and weight not picked by the model;
- For the LL-ALL fisheries, where catchability is assumed constant, trends in effort deviates can indicate inconsistencies in the model fit. Of particular concern, as noted in the 2008 and 2009 assessment are the negative effort deviations for the LL ALL 3 fishery in the last two decades (Figure 19). With the downweighted size frequency data in the base case model this pattern is strongly reduced.
- 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.

Given the downweighting of many of the length frequency data sets in the base model, the lack of fit is not unexpected and recommendations for further examination of these data sets is provided later in the paper. Interestingly the negative trend in the LL-ALL 3 effort deviates and the

[8] The ratio represents the average recruitment during the second half of the temporal model domain divided by the average of the first half.

positive trends in recruitment were minimized in the model run that excluded the first half of the standardised longline CPUE series (run 4c).

6.3 Model parameter estimates (run 3d (base) unless otherwise stated)

6.3.1 Growth

The estimated growth curve is shown in Figure 20. For the base model, growth in length is estimated to continue throughout the lifespan of the species, without any attenuation of length approaching a maximum level. The estimated mean length of the final age-class is 180.7 cm and the associated L_∞ is 195.6 cm.

Figure 21 compares the estimated growth curve to two external sources of information on growth, tagging and direct ageing data. The tagging estimates are generally less than what would be predicted by the growth curve, while the direct ageing estimates are greater. There are concerns that tagging can impact on fish growth. This could explain the first pattern, but the direct ageing suggests that there is information in the data that implies a different and slower growth rate. Regional variation in growth is one potential reason for this difference. The lack of small fish in some regions, and confounding with selectivity, makes it difficult to determine if there are regional differences in growth rates, but such differences are likely.

6.3.2 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. These movement patterns are generally similar to previous assessments. Notable model results are the estimated dependence of the northern and southern region on local recruitment rather than migrants from the tropical regions (but recognising that the model can also ‘move’ fish to these regions through regional recruitment processes), and that region 3 is more of a source of fish to region 4 than the other way around.

Movement patterns should be the focus of future assessment work, particularly given the current tagging work will produce data which can better inform the model. Examination of movement could also be useful in assessing regional trends in estimated recruitment which could be aliasing for other processes.

6.3.3 Selectivity

Aside from the Indonesia and Philippines small fish fishery selectivity curves (fisheries 18 and 24) and the LL TW-CH 4 fishery (fishery 8), the estimated curves for the 2010 assessment are broadly similar to those from the 2009 assessment (Figure 24). The two northern LL-ALL fisheries now have a slightly descending right-hand limb which is associated with the increased estimate of maximum length resulting from the downweighting of the various size data sets.

The change in the LL TW-CH 4 fishery selectivity was due to a change in the assumption that its selectivity was linked to LL TW-CN 3. However these fisheries are actually quite different with the region 3 fishery dominated by off-shore fishing operations and region 4 is dominated by distant-water operations. So for the current assessment the selectivity was linked to that of the other equatorial distant water longline fisheries (LL-ALL 3 and 4).

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. This is particularly evident for the LL ALL 2 and 4 fisheries. Further examination of these data is necessary to determine if they reflect a change in the selectivity in the fishery (through either operation changes or changes in the locations fished) or simply unrepresentative sampling data.

6.3.4 Catchability

Time-series changes in catchability are evident for several fisheries and the patterns are consistent with the 2009 assessment (Figure 25). Trends for the Indonesia and Philippines domestic small fish fisheries are picked up in the effort deviates rather than catchability due to effort being treated as missing data.

6.4 Stock assessment results

Symbols used in the following discussion are defined in Table 4 and the key results are provided in Table 6.

6.4.1 Recruitment

The run 3d recruitment estimates (aggregated by year for ease of display) for each region and the entire WCPO are shown in Figure 26 and are broadly similar to those estimated in the 2009 assessment, though the absolute levels of recruitment are generally higher due to the assumption of higher purse seine catches. 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 1965 and an increasing trend thereafter, with exceptionally high recruitment during 1995–2005, particularly in 2000 and again in 2005. Since 2005, recruitment is estimated to have declined to approximately the long-term average, but it is not known if this is an artefact of the recruitment estimation constraints (convergence to the mean), or data driven (e.g. by the slightly declining purse seine catches). As indicated by the approximate confidence intervals, these recent recruitment estimates are less certain.

Recruitment in regions 1, 5, and 6 is relatively low and the trends are stable/slightly decreasing through time. While the trends in these regions seem plausible the regional recruitment trends for regions 2-4 are questionable. Estimated recruitment in region 2 is much higher for the first five years and then drops sharply to a lower level by 1960 and continues to decline slowly thereafter. The model estimates a two-step recruitment pattern for region 3: lower and stable recruitment from 1952-1978 followed by a sharp and substantial increase to a level around five times higher by 1980, at which it has remained ever since. Recruitment in region 4 is relatively high throughout the time series and shows an increase in both level and variability in the mid 1990s. Explanatory hypotheses for these trends are discussed later in this report.

A comparison of WCPO recruitment estimates for the key model runs is provided in Figure 27 and the ratio of late to early recruitment in Table 5. The absolute level of recruitment is much higher when a higher level of juvenile natural mortality is assumed (run 3g). In terms of the ratio of recruitment, for run 3d (base) later recruitment is double early recruitment and a higher ratio is obtained for run 3a2 (high weight). All the other model runs give lower ratios, especially runs 4a (lower PS catch) (1.64) and run 4c (early CPUE) (1.14). In run 4a this comes about by a lowering of late recruitment due to lower purse seine catches, while for run 4c it comes about through increased early recruitment.

The spawner recruitment observations on a quarterly and annual scale are provided in Figure 42. As in previous assessments, most of the high estimates of recruitment occur at low estimated spawning stock sizes which leads to very high estimates of steepness (0.98 for run 3d). Those model runs with the lower estimated recruitment ratios had lower estimates of steepness (runs 4a and 4c), but these steepness values were all still 'in the high end of the range' (above 0.90).

6.4.2 Biomass

The estimated total biomass trajectory for each region and for the entire WCPO for run 3d is shown in Figure 28 and a plot of spawning potential is provided in Figure 29. Biomass is estimated to decline during the 1950s and 1960s in all regions. In region 3, total biomass remains relatively stable from the mid 1970s to 2000 and declines sharply from 2003 onwards. 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, in contrast to the previous assessment where biomass declined further, has remained at the 1970s level ever since. However, for spawning potential the continued decline over time is still evident.

A comparison of trends in spawning potential for run 3d (base) with the other key model runs are shown in Figure 31. With the exception of run 4c (early CPUE) the relative trends are very similar and there are moderate differences in the absolute biomass levels with the lower biomass trajectories associated with runs 3a2 (high weight) and 4a (lower PC catch). The trajectory for run 4c (early CPUE) is very different from the others with a considerably higher initial biomass but a smaller difference from the other model runs for more recent estimates. To investigate this further we examined the regional contributions to overall spawning biomass for runs 3d (base) and 4c (early CPUE) (Figure 32). One of the troubling features in run 3d (base) and other key model runs is the high levels of biomass in region 2 during the early years of the model. Biomass levels exceeded those estimated for region 3 which is thought to be more in the core area of the population. This pattern is driven by the very high initial and subsequently declining CPUE in the LL ALL 2 fishery. In run 4c (early CPUE), which is not influenced by the initial longline CPUE, there is a very different, and potentially more plausible regional distribution with region 4 still the dominant source of biomass, but with region 3 clearly the second highest biomass region. In this run 4c (early CPUE) the higher latitudes have much lower estimated biomass levels.

6.4.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase strongly throughout the time series for all model runs and in all cases the levels of juvenile mortality are greater than those for adults (Figure 33).

Changes in fishing mortality-at-age and population age structure are shown for decadal time intervals in Figure 34. The major difference from the similar plot for the 2009 assessment is the much higher, and earlier, juvenile fishing mortality due to the spill-sample based catch estimates which have substantial purse seine catches beginning earlier than the s_best data set.

6.4.4 Fishery impact

We measure fishery impact at each time step as the ratio of the estimated biomass to the biomass that would have occurred in the historical absence of fishing. This is a useful variable to monitor, as it can be computed both at the region level and for the WCPO as a whole. The two trajectories are plotted in Figure 35 and Figure 36 for total biomass and spawning potential respectively, and illustrate three interesting points. First that region 1 was already impacted by fishing at the start of the model (1952). Second, the estimated impact for region 2 is low and the trends in biomass are estimated to be due to recruitment rather than fishing. Finally, there are particularly strongly estimated impacts 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, which represent the level of depletion, are plotted in Figure 37 and Figure 38 in terms of total biomass and spawning biomass. These figures indicate increasing fishery impacts over time in all regions, with higher impacts on spawning potential than on total biomass. A comparison of spawning potential ratios for the WCPO for the main model results is provided in Figure 39 and Table 6. For run 3d it is estimated that current biomass (average 2005-08) is 23% of the level that is predicted in the absence of fishing. This drops to 17% for spawning potential and to 15% if we consider 2009, the final year in the assessment. The levels of depletion were lower for all runs except run3a2 (high weight) which estimated levels of 19 and 13% respectively for current total biomass and spawning potential.

It is possible to ascribe the fishery impact to specific fishery components in order to see which types of fishing activity have the largest impact on the spawning potential (Figure 40). In regions 2, 5, and 6, longline fishing is almost entirely responsible for the fisheries impacts. In region 1 the current impact is shared between the longline and Japanese coastal surface fisheries, and in region 3 the purse seine fishery has the greatest impact followed by longline and the domestic fisheries of Indonesia and the Philippines. The increased impact of the purse seine fishery compared to the 2009 assessment is due to the higher assumed purse seine catches. In region 4 the purse seine and longline fisheries have similar impacts.

A comparison of fishery impacts on spawning potential at the WCPO level for the four key model runs which were identified as having the most divergent results are provided in Figure 41. For run 4a (lower PS catch) the longline impact is much higher, as is the impact of the domestic fisheries of Indonesia and the Philippines. The increase in the relative impact for both of these fisheries, despite catches being the same, is attributed to the models response to the lower purse seine catches, which resulted in a lesser recruitment increase in recent years. The higher longline impacts estimated by run 3a2 (high weight) were comparable to the purse seine impacts, while longline impacts were lowest for run 4c (early CPUE).

6.4.5 Yield analysis

The yield analyses conducted in this assessment incorporate the spawner recruitment relationship (Figure 42) into the equilibrium biomass and yield computations. The estimated steepness coefficient is 0.98, indicating that there is little evidence for a decline in recruitment as a spawning biomass is reduced. 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).

As outlined in Table 6, the following section describes the main results considering the catch (including consideration of catch-related reference points in the context of recent high recruitment), fishing mortality, and biomass related reference points. Finally, we will discuss some reference points related to utilisation and yield per recruit considerations.

Catch and MSY

MSY was estimated at 73,840 mt, an increase from the 2009 assessment which is entirely due to the higher assumed purse seine catches. Given the high estimated fishing mortalities, current equilibrium yield ($Y_{F_{current}}$) is 94% of the *MSY* at 69,720 mt. Current catches, sustained by estimates of high recruitment, are double the *MSY*. With regard to the alternative model runs, *MSY* is slightly higher in runs 3e2 (temporal CVs), 3f (vessel adj.), and 3f (high juv. M) and much higher in run 4c (early CPUE) where the estimated value is 95,680 mt. Lower values of *MSY*'s are estimated for runs 3a2 (high weight), 4a (lower PS catch), and 4b (h=0.75).

Noting that recent recruitment is estimated to have been well above the long term average predicted by the SRR, it is useful to consider recent catches in that context (Table 9 and Figure 45). We compare *MSY* based on the predicted SRR to that based on average recruitment over the period 1999-2008, but not taking into account the estimated steepness. For run 3d the recent recruitment suggested sustainable catches 1.8 times the current *MSY* estimate, while the range for the key model runs is quite large from 1.38 times for run 4c (early CPUE) to 1.99 times for run 4b (h=0.75). However, current catches are still around 10% higher than these alternative estimates. **Based on these results, we conclude that current levels of catch are unlikely to be sustainable in the long term even at the recent [high] levels of recruitment estimated for the last decade**.

Fishing mortality

For run 3d, the *MSY* is achieved at F_{mult} = 0.71; i.e. at 71% of the current (2005-08) level of age-specific fishing mortality (see also Figure 43). This represents a ratio of $F_{current}/F_{MSY}$ equal to 1.41 (1/0.71); therefore, current fishing mortality rates are considerably higher than the fishing mortality rates to which would produce the *MSY*. A reduction in fishing mortality of 29% (1-F_{mult}) from the average 2005-08 levels is necessary to reduce fishing mortality to the F_{MSY} level. When we compare this to historical time periods (Table 7 and Figure 46) a 31% reduction in fishing mortality levels from 2004 is required, but only a 20% reduction from average 2001-04 levels[9].

For all of the model runs $F_{current}/F_{MSY}$ is considerably greater than 1, but lower than the estimates from the 2009 assessment for those runs that include the downweighted size data. All of the

[9] While these were the reference periods used for most limits under CMM2008-01, in most cases CCMs had a choice as to the higher value of the two when determining their catch and effort limit. As has been shown in the evaluation of CMM2008-01, the actual levels of catch and effort allowed for will result in much higher fishing mortality levels than those estimated for 2004.

model runs undertaken in the structural uncertainty grid (Figure 52) had estimates of $\frac{F_{current}}{F_{MSY}} > 1$. **Based on these results, we conclude that overfishing is occurring in the bigeye tuna stock, but possibly at a lower level than previously estimated**.

Biomass

Reference points are provided for both total and spawning biomass. In terms of potential concerns over sustainability and risks to the stock, the spawning biomass reference points are most relevant. The total and spawning biomass that support the *MSY* are 30% and 24% of the virgin total and spawning biomasses. These 'low' values are due to the high estimate of steepness. For the model where steepness is 0.75, these quantities increase to 36% and 31% respectively.

Comparing current biomass to the estimated virgin biomass ($B_{current}/B_0$ and $SB_{current}/SB_0$) for run 3d, it is predicted that current total and spawning biomass levels are 42% and 32% of the respective virgin biomass levels.

In addition, total biomass and spawning potential are higher than the associated *MSY* levels. This is more apparent for the total biomass reference points which are more influenced by the recent estimates of recruitment. The only exception is current spawning biomass for run 4b (h=0.75) which is slightly less than 1. Considering the 2009 estimates of spawning biomass, all runs except for 3a2 (high weight) and 4b (h=0.75) estimate that spawning biomass is above SB_{MSY}.

The Kobe-plot enables trends in the status of the stock relative to F_{MSY}, B_{MSY}, and SB_{MSY} reference points to be followed over the model period. Trends for total biomass are provided in Figure 47 while the complementary spawning potential plot is provided in Figure 48. The trends of the two are similar, with the spawning biomass values being lower on the biomass axis. Fishing mortality rates were moderate through to the 1970s at which they are estimated to have increased, exceeding F_{MSY} in the late 1980s and remaining above F_{MSY}ever since. While total biomass is estimated to have remained well above B_{MSY}, spawning biomass has been closer to SB_{MSY} in recent years.

The spawning biomass based Kobe plots for run 3d (base) and some of the key model runs are compared in Figure 49. The overall temporal patterns in the two reference points are similar to those of runs noted previously.

Considering the results from the likelihood profiling (Figure 51) and the grid-based structural uncertainty analysis (Figure 52), the probability that $SB_{current}$ and SB_{latest} exceed some of the more commonly applied SB-related reference points is provided in Table 11. For the likelihood profile, considering only parameter uncertainty for run 3d, there is only a 0.5% probability that $SB_{current} < SB_{MSY}$, but this increases to 60% for run 4b (h=0.75). Steepness represents the key uncertainty which has the largest influence on our interpretation of stock status in the current assessment. Likelihood profiles for individual years could not be calculated for this assessment due to time constraints.

It is recognised that all the values of steepness considered in the grid (0.55-0.95) are lower than that estimated for run 3d (0.98). The probability that current spawning biomass levels are below the *MSY* level is 57% and this increased to over 82% when 2009 spawning biomass levels were considered. There is a 12% probability that the 2009 spawning biomass level is less than half the *MSY* level, and >95% probability that spawning biomass is less than 20% of the level predicted to exist if fishing had not occurred. Probabilities considering only grid runs with steepness values of 0.75 are also provided in Table 11.

The yield analysis can also predict the level of biomass that would result at equilibrium if current levels of fishing mortality continued ($B_{F_{current}}/B_{MSY}$ and $SB_{F_{current}}/SB_{MSY}$). For run 3d (base) the model predicts that biomass would be reduced to 64% and 56% of the level that supports *MSY*. In terms of the reduction against virgin biomass the declines are greater reaching as low as 13% for spawning biomass. **Based on the results above, and the recent trend in spawning biomass, we conclude that bigeye tuna is at best approaching an overfished state, if not already slightly overfished.**

Utilisation

As the age-specific pattern in fishing mortality has an impact on the estimates of *MSY* and related quantities, our views on *MSY* are based on the current pattern of fishing. It is also possible to examine how the potential *MSY* changed with changes to the mix of fishing gears over time. For run 3d (base), the MSY_t was also computed for each year (t) in the model. This analysis enables an assessment of the *MSY* level that would be theoretically achievable under the different patterns of age-specific fishing mortality observed through the history of the fishery (Figure 53). Prior to 1970, the WCPO bigeye fishery was almost exclusively conducted using longlines, with a low exploitation of small bigeye. The associated age-specific selectivity resulted in a substantially higher level of *MSY* (170,000 mt per annum) compared to that estimated for the fishery based on the recent age-specific fishing mortality pattern (about 73,840 mt). The decline in the *MSY* over time follows the increased development of those fisheries that catch smaller bigeye, principally the surface fisheries and was also associated with a reduction in the F_{MSY} (Figure 53).

Another way to consider utilisation is in terms of yield per recruit. Figure 53 (lower left panel) shows the relative biomass of a cohort through its life in the absence of fishing based on the estimates of growth and natural mortality from run 3d. In this example the biomass of the cohort is maximised at an age of 15 quarters and this declines quite rapidly both above and below this age. This indicates that if it was possible to harvest this entire cohort at this age, yield would be maximised (ignoring spawner recruitment considerations). Estimates of the mean age and length at harvest for each of the model runs are provided in Table 10 along with an estimate of the proportion of potential yield lost. This concept is the same as the MSY_{ref} of Maunder (2002). When considering YFT in the EPO, Maunder (2002) suggested that achieving two-thirds of the potential yield would be a suitable reference point, i.e. selectivity patterns should be modified so that only one-third of potential yield is lost. For the current assessment, it is estimated that almost 75% of the potential *MSY* from the stock is lost due to the selectivity patterns. **Based on these results, we conclude that MSY levels would rise if mortality of small fish were reduced which would allow greater overall yields to be sustainably obtained.**

7 Discussion and conclusions

This report documents the stock assessment results for BET in the WCPO in 2010, but the broader stock assessment itself was supported by numerous auxiliary analyses and investigations (e.g. Harley and Hoyle 2010; Harley et al. 2010; Hoyle 2010; Hoyle et al. 2010; and Lawson 2010). Over 150 model runs were undertaken in developing this assessment, and nearly 120 of these are presented in this final assessment report. The main focus of these investigations and this revised assessment was to address one of the major concerns with previous assessments, namely the strong increasing trend in recruitment, particularly in region 3. This trend leads to estimates of *MSY* that are much lower than recent catches, estimates of 'unfished' biomass much higher than estimated for the start of the fishery, and estimates of steepness that approach the maximum possible value of 1. The adoption of the spill sample-based purse seine catches in the base model has exacerbated this problem.

While this assessment describes some major steps towards addressing this issue, it remains unresolved. The results described here and in Harley et al. (2010) have pinpointed several areas of data conflict in the current assessment that require further investigation. The most critical of these is the longline CPUE indices which are assumed to reflect an index of abundance. In Harley et al. (2010) the inclusion of a continually declining YFT CPUE index in region 3 lead to major change in the recruitment trend for that region and overall. The nature of this conflict has been verified by the results of key model run 4c (early CPUE) where all CPUE prior to 1975 was excluded. Figure 54 shows the estimates of LL exploitable biomass estimated for model runs 3d (base) and 4c (early CPUE). The biomass trends for run 3d essentially follow the assumed CPUE indices. The most striking and relevant differences are for regions 2-4. In region 2, run 4c (early CPUE) estimates that the decline in abundance in the early years is far less than the CPUE suggest, while for regions 3 and 4 the model is estimating much greater declines in the early time period. Run 4c estimates a much reduced recruitment trend, a higher MSY, and a lower steepness. Despite these differences, the overall stock status is still similar to the other models (e.g. overfishing occurring, but not overfished).

Although, there is some justification to place a lower reliability on the early CPUE series due to the lack of data pertaining to some of the key operational characteristics (e.g. hooks per basket); there is seldom much difference between the nominal and standardised indices for regions 3 and 4 (Hoyle 2010). This suggests that all of the variables for which we have data and believe to describe the changes in targeting over almost 60 years have actually had little impact on longline catchability in the core fishery. We are either missing some fundamental variables that describe targeting or we are using the wrong type of modelling approach. There have been large expansions and contractions in Japanese longline fishing effort since 1952 and it is clear that what effort exists is generally targeted at bigeye tuna when the vessels are fishing in tropical waters (Harley 2009). We suggest that alternative CPUE methodologies be considered that explicitly take into account the spatial extent of fishing activities (e.g. Ahrens 2010). It may be possible to use the information from other fishing fleets to fill in some of the gaps that have resulted from the contracted fishing effort.

Other conflicts exist within some of the size frequency time series for the longline fisheries and these are very obvious in the residual plots (Figure 18). Currently we are assuming time-invariant selectivity for fisheries which are defined at the level of the region. Within the Chinese, Chinese Taipei, and Japanese size data for region 3 there are some clear changes in the size composition of the samples through time. It is not known if these reflect changes in the composition of the overall catch. If they do, then we still need to determine whether these are driven by operational changes in fishing practices (e.g. changes in the time of day, use of live bait, or changing the hooks per basket) or spatial differences in the sizes of fish within these regions. In this assessment we have chosen to downweight some of the data sets for which there were the greatest levels of concern, but this is an analytical tactic rather than a solution. Solving these data issues requires descriptions of the data collection protocols and detailed operational level data (or observer data) from the fleets. Some of these data are currently held by SPC on behalf of its members, but they may not be representative of the fleets as a whole. These patterns are not restricted to the tropical areas, but analyses of data from the equatorial regions are probably the most urgent.

Uncertain catch statistics from the fisheries of Indonesia and the Philippines have been the cause of considerable uncertainty in recent assessments and the most recent (and lower) catch estimates have reduced some of the data conflicts that were observed in the assessments (e.g. recruitment trends). However, the small-fish catches from the domestic fisheries in this region remain very high, and will require ongoing consideration to provide the best basis for the assessment.

The current assessment has used the higher spill sample-based corrected purse seine catches in the base model on the basis that these estimates are more plausible than the previously used “s_best” catch estimates. However, these higher catches lead to much increased recruitment in recent years and an increased recruitment trend. To date, there has not been sufficient experimental data collected to allow reliable correction of the length frequency samples from the purse seine fishery to reflect the potential bias that would be introduced if small bigeye are being under-represented in the length samples. If this bias is on the order of 4cm, as assumed by Harley et al. (2010) incorporating these revised length samples should reduce the recruitment trend. One interesting feature of the current set of assessment runs is that the model run with spill sample-based catches gives a more optimistic result than the model with the lower purse seine catches (run 4a) thereby reversing the pattern seen in the 2009 assessment. To investigate why this might occur, we used the model runs from the grid to compare the results with the two catch estimates across all the other model changes in the grid (Table 12). This comparison showed that in 21% of the model comparisons, the runs with spill sampling-corrected catches estimated a higher level of fishing mortality, while 46% of the runs estimated a lower spawning potential (i.e. more pessimistic outcomes). This suggests that the spill sample-corrected catches alone do not lead directly to a predictable change in status. This contrasts with the change in the data weighting or juvenile natural mortality changes (Table 12). It should be noted that prediction of the impact of a change in catches on estimated stock status would not be expected to be straightforward as the model does have some ability to compensate for changes in catches through its estimates of recruitment.

Notwithstanding the issues raised in the preceding paragraphs, the 2010 assessment represents an improvement over the previous assessments on several fronts: the improved estimates of catches from the fleets of Indonesia and the Philippines; the improved modelling of fishery events where catches were missing or uncertain; exclusion of non-representative length samples from the Philippines small fish fishery; improved modelling of the selectivity of that fishery to reduce the model tendency to overestimate the sizes of fish taken; downweighting of conflicting size frequency data sets; and investigation of the sensitivity of the model to aspects of the longline CPUE series.

Overall these model results are slightly more optimistic than those from the 2009 assessment, but the general conclusions remain unchanged. The main conclusions of the current assessment are as follows.

10. The estimated recruitment trends from recent bigeye assessments appear to be primarily the result of conflict (disagreement) among the various data sources, in particular between the longline CPUE indices and the reported catch histories, and between and within some of the size composition data sets. The current assessment has indentified some of these conflicts and includes some model runs that begin to address them.

11. Recruitment in all analyses is estimated to have been high during 1995–2005. This result was similar to that of previous assessments, and appears to be partly driven by conflicts between some of the CPUE, catch, and size data inputs. Recruitment in the most recent years is estimated to have declined to a level approximating the long-term average, although these estimates have high uncertainty. If we consider the recruitment estimates in the second half of the time series to be more plausible and representative of the overall productivity of the bigeye stock, then consideration might be given to basing stock status estimation only on this period. This could in effect be implemented simply by estimating the stock-recruitment relationship for this latter period and applying that in the yield analyses.

12. Total and spawning biomass for the WCPO are estimated to have declined to about half of their initial levels by about 1970, with total biomass remaining relatively constant since then ($B_{current}/B_0$= 42%), while spawning biomass has continued to decline ($SB_{current}/SB_0$=32%). Declines are larger for the model with increasing longline catchability and increased purse seine catches.

13. When the non-equilibrium nature of recent recruitment is taken into account, we can estimate the level of depletion that has occurred. It is estimated that spawning potential is at 17% of the level predicted to exist in the absence of fishing considering the average over the period 2005-08, and that value is reduced to 15% when we compare using the 2009 spawning potential levels.

14. The attribution of depletion to various fisheries or groups of fisheries indicates that the purse seine and other surface fisheries have an equal or greater impact than longline fisheries on the current BET biomass. The purse seine and Philippines/Indonesian domestic fisheries also have substantial impact in region 3 and to a lesser extent in region 4. The Japanese coastal pole-and-line and purse-seine fisheries are also having a significant impact in their home region (region 1). For the sensitivity analysis with lower purse seine catches, the longline fisheries are estimated to have a higher impact.

15. Recent catches are well above the *MSY* level of 73,840 mt, but this is mostly due to a combination of above average recruitment and high fishing mortality. When *MSY* is re-calculated assuming recent recruitment levels persist, catches are still around 10% higher than the re-calculated *MSY*. **Based on these results, we conclude that current levels of catch are unlikely to be sustainable in the long term even at the recent [high] levels of recruitment estimated for the last decade**.

16. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. For all of the model runs $F_{current}/F_{MSY}$ is considerably greater than 1. For run 3d (base) the ratio is estimated at 1.41 indicating that a 29% reduction in fishing mortality is required from the 2005-08 level to reduce fishing mortality to sustainable levels. If we consider historical levels of fishing mortality, a 31% reduction in fishing mortality from 2004 levels is required (consistent with the aim of CMM2008-01), and only a 20% reduction from average 2001-04 levels. The results are far worse with lower values of steepness or when a higher weight is given to the size data. **Based on these results, we conclude that**

overfishing is occurring in the bigeye tuna stock, but possibly at a lower level than previously estimated.

17. The reference points that predict the status of the stock under equilibrium conditions are $B_{F_{current}}/B_{MSY}$ and $SB_{F_{current}}/SB_{MSY}$. The model predicts that biomass would be reduced to 64% and 56% of the level that supports MSY. In terms of the reduction against virgin biomass the declines reach as low as 13% of spawning potential. Current stock status compared to these reference points indicate the current total and spawning biomass are higher than the associated MSY levels ($\frac{B_{current}}{B_{MSY}} = 1.39$ and $\frac{SB_{current}}{SB_{MSY}} = 1.43$). The likelihood profile analysis indicates a 0.5% probability that $SB_{current} < SB_{MSY}$ which increases to 60% if a lower value of steepness ins assumed. Some of the more plausible alternative models are more pessimistic as are the conclusions of the structural uncertainty analysis based on the grid. **Based on these results above, and the recent trend in spawning biomass, we conclude that bigeye tuna is approaching an overfished state, if it is not already slightly overfished.**
18. Analysis of current levels of fishing mortality and historical patterns in the mix of fishing gears indicates that MSY has been reduced to less than half its levels prior to 1970 through harvest of juveniles. Because of that and overfishing, considerable potential yield from the bigeye tuna stock is being lost. **Based on these results, we conclude that MSY levels would rise if mortality of small fish were reduced which would allow greater overall yields to be sustainably obtained.**

In order to further improve the bigeye tuna stock assessment recommendations are provided below under the categories of General, MULTIFAN-CL/Modelling, Data analysis, and Research.

<u>General Recommendations</u>

- The SC consider the timing of its annual SC on the basis that several CCMs continue to have difficulty submitting their data by the data submission deadline. In 2010 these delays meant that the model inputs were not finalised until the first week of July. This makes it very difficult to prepare a stock assessment by the SC paper deadline.
- The SC considers the frequency of assessments for the key tuna species, and if annual, what types of auxiliary analyses and model outputs they require. The management-related analyses (e.g. Kobe-plots, impact analyses, likelihood profiles, and structural uncertainty grids) are time consuming. So if, in a given year, there is unlikely to be any modification to current CMM’s, the time spent on management analyses could be better spent on other areas, e.g. investigations of CPUE and size data.

<u>MULTIFAN-CL/Modelling</u>

- MULTIFAN-CL be modified to allow the incorporation of direct ageing observations to improve the estimation of growth.
- MULTIFAN-CL be modified to allow the estimation of the spawner recruitment relationship over a given time period rather than the entire model domain.
- Alternative functional forms, including length-based selectivity be considered for the Indonesia and Philippines small-fish domestic fisheries (fisheries 18 and 24).
- Any available tagging data, in particular from the Pacific Tuna Tagging Programme, be incorporated into the next assessment.

<u>Data analysis</u>

- Alternative approaches to the modelling of CPUE data that incorporate the spatial extent of fishing operations should be considered. This is the highest priority activity to support the assessment.
- Detailed investigations be undertaken of the Japanese longline length data throughout the WCPO and other length and weight frequency data from longline fisheries in regions 3 and 4. Such investigations will require details of sampling protocols and operational level CPUE data. Collaborations with national scientists will be important.

- Analyses of operational data for the fishery 5 fleets (“off-shore” operations) to determine the most appropriate grouping of the fleets and time periods into MULTIFAN-CL fisheries.
- Analysis of available tagging data to further examine the differences in juvenile mortality of bigeye and yellowfin tuna.

Research

- Continued experiments and activities to improve purse seine catch estimates, in particular spill sampling trials with consideration of corrections to length frequency samples. Further development of cannery data sources may also be useful.
- Continuation of the work to refine both the species composition and total catches from the domestic fisheries that occur in Indonesia and the Philippines.
- Direct ageing of bigeye tuna, in particular large bigeye tuna in different regions throughout the WCPO.

8 Acknowledgements

We are grateful to all fisheries agencies that have contributed data to the SPC and/or the WCPFC for this assessment. We thank Tim Lawson for providing the spill sample-based purse seine catch estimates. We thank participants at the preparatory stock assessment workshop (Noumea, April 2010) for their contribution to the assessment, and Don Bromhead and Shelley Clarke their comments on the final draft of this report.

9 References

Ahrens, R. N. M. 2010. A global analysis of apparent trends in abundance and recruitment of large tunas and billfishes inferred from Japanese longline catch and effort data. PhD Thesis, University of British Columbia, Vancouver, Canada. 388 pages.

Evans, K., Langley, A., Clear, N.P., Williams, P., Paterson, T., Sibert, J.R., Hampton, J., Gunn, J.S. 2008. Behaviour and habitat preferences of bigeye tuna (*Thunnus obesus*) and their influence on longline fishery catches in the western Coral Sea. *Can. J. Fish. Aquat. Sci.*65: 2427-2443

Francis, R.I.C.C. 1992. Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. *Can. J. Fish. Aquat. Sci.* 49: 922–930.

Grewe, P.M., and Hampton, J. 1998. An assessment of bigeye (*Thunnus obesus*) population structure in the Pacific Ocean based on mitochondrial DNA and DNA microsatellite analysis. SOEST 98-05, JIMAR Contribution 98-330.

Hampton, J. 1997. Estimates of tag-reporting and tag-shedding rates in a large-scale tuna tagging experiment in the western tropical Pacific Ocean. *Fish. Bull. U.S.* **95**:68–79.

Hampton, J. 2000. Natural mortality rates in tropical tunas: size really does matter. *Can. J. Fish. Aquat. Sci.* **57**: 1002–1010.

Hampton, J., K. Bigelow, and M. Labelle. 1998. A summary of current information on the biology, fisheries and stock assessment of bigeye tuna (*Thunnus obesus*) in the Pacific Ocean, with recommendations for data requirements and future research. Technical Report No. 36, (Oceanic Fisheries Programme Secretariat of the Pacific Community, Noumea, New Caledonia) 46 pp.

Hampton, J., and Fournier, D.A. 2001. A spatially-disaggregated, length-based, age-structured population model of yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean. *Mar. Freshw. Res.* **52**:937–963.

Hampton, J., and Harley, S. J. 2009. Predicted impact of CMM-2008-01 on stock status of bigeye and yellowfin tuna in the western and central Pacific Ocean. WCPFC-SC5-GN-WP-17. Port Vila, Vanuatu, 10-21 August 2009.

Hampton, J., Kleiber, P, Langley, A., and Hiramatsu, K. 2004. Stock assessment of bigeye tuna in the western and central Pacific Ocean. Working Paper SA-2, SCTB 17, Majuro, Marshall Islands, 9–18 August, 2004.

Hampton, J., Kleiber, P, Langley, A., Takeuchi, Y., and Ichinokawa, M. 2005. Stock assessment of bigeye tuna in the western and central Pacific Ocean. WCPFC-SC1 SA WP-2, Noumea, New Caledonia, 8–19 August 2005.

Hampton, J., Langley, A., Kleiber, P, 2006. Stock assessment of bigeye tuna in the western and central Pacific Ocean, including an analysis of management options. WCPFC-SC2 SA WP-2, Manila, Philippines, 7–18 August 2006.

Hampton, J., Maunder, M. 2006. An update of Pacific-wide assessment of bigeye tuna with comparisons with eastern Pacific assessment results. Document SAR-7-07c.ii. IATTC Working Group to Review Stock Assessments, 7th meeting, La Jolla, California (USA), 15-19 May 2006.

Hampton, J., and Williams, P. 2004. A description of tag-recapture data for bigeye tuna in the western and central Pacific Ocean. SCRS 2004/058. *Col. Vol. Sci. Pap. ICCAT*, 57(2).

Harley, S. J., Hoyle, S., Hampton, J., and Kleiber, P. 2009a. Characteristics of potential reference points for use in WCPFC tuna stock assessments. WCPFC-SC5 ME-WP-02. Port Vila, Vanuatu, 10-21 August 2009.

Harley, S. J., Hoyle, S., Hampton, J., and Kleiber, P. 2009b. Stock assessment of bigeye tuna in the western and central Pacific Ocean. WCPFC-SC5-2009/SA-WP-04. Port Vila, Vanuatu, 10-21 August 2009.

Harley, S. J., and Hoyle, S. D. 2010. Report from the SPC pre-assessment workshop, Noumea, April 2010. WCPFC-SC6-2010/SA-IP-01. Nuku'alofa, Tonga, 10-19 August 2010..

Harley, S. J., Hoyle, S., Williams, P., and Hampton, J. 2010. Background analyses in the development of the 2010 WCPO bigeye tuna assessment. WCPFC-SC6-2010/SA-WP-01, Nuku'alofa, Tonga, 10-19 August 2010.

Hoyle, S. 2008. Adjusted biological parameters and spawning biomass calculations for albacore tuna in the south Pacific, and their implications for stock assessments. WCPFC-SC4 ME-WP-02. Port Moresby, Papua New Guinea, 11-22 August 2008.

Hoyle, S. 2009. Standardized CPUE for bigeye and yellowfin tuna. WCPFC-SC5 SA-WP-01. Port Vila, Vanuatu, 10-21 August 2009.

Hoyle, S. 2010. Standardized CPUE for bigeye and yellowfin tuna. WCPFC-SC6-2010/SA-WP-03, Nuku'alofa, Tonga, 10-19 August 2010.

Hoyle, S.D., Shono, H., Okamoto, H, and Langley, A.D. 2010. Analyses of Japanese longline operational catch and effort for bigeye tuna in the WCPO. WCPFC-SC6-2010/SA-WP-02, Nuku'alofa, Tonga, 10-19 August 2010.

Hoyle, S., Langley, A. 2007. Regional weighting factors for yellowfin tuna in WCP-CA stock assessments. WCPFC SC3 ME WP-1, Honolulu, Hawai'i, USA, 13–24 August 2007.

Hoyle, S., Langley, A., Hampton, J. 2008. General structural sensitivity analysis for the bigeye tuna stock assessment. WCPFC SC4 SA WP-3, Port Moresby, Papua New Guinea, 11–22 August 2008.

Hoyle, S., Nicol, S. 2008. Sensitivity of bigeye stock assessment to alternative biological and reproductive assumptions. WCPFC SC4 ME WP-1, Port Moresby, Papua New Guinea, 11–22 August 2008.

Hoyle, S. Nicol, S., and Itano, D. G. 2009. Adjusted biological parameters and spawning biomass calculations for yellowfin tuna in the WCPO. WCPFC-SC5-BI-WP-03. Port Vila, Vanuatu, 10-21 August 2009.

Kaltongga, B. 1998. Regional Tuna Tagging Project: data summary. Technical Report No. 35, (Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia.) 70 pp.

Kleiber, P., Hampton, J., and Fournier, D.A. 2008. MULTIFAN-CL Users' Guide.

Langley, A. 2006a. Summary report from yellowfin and bigeye stock assessment workshop. ME WP-1, WCPFC-SC2, Manila, Philippines, 7–18 August 2006.

Langley, A. 2006b. Spatial and temporal trends in yellowfin and bigeye longline CPUE for the Japanese fleet in the WCPO. ME IP-1, WCPFC-SC2, Manila, Philippines, 7–18 August 2006.

Langley, A. 2006c. Spatial and temporal variation in the size composition of the yellowfin and bigeye longline catch in the WCPO. ME IP-2, WCPFC-SC2, Manila, Philippines, 7–18 August 2006.

Langley, A., Bigelow, K., Miyabe, N., and Maunder, M. 2005. Longline CPUE indices for yellowfin and bigeye in the Pacific Ocean using GLM and statistical habitat standardisation methods. WCPFC-SC1 SA WP-8, Noumea, New Caledonia, 8–19 August 2005.

Langley, A., Hampton, J., Kleiber, P., Hoyle, S. 2007. Stock assessment of yellowfin tuna in the western and central Pacific Ocean, including an analysis of management options. WCPFC SC4 SA WP-1, Honolulu, Hawaii, 13–24 August 2007.

Langley, A., Hampton, J., Kleiber, P., Hoyle, S. 2008. Stock assessment of bigeye tuna in the western and central Pacific Ocean, including an analysis of management options. WCPFC SC3 SA WP-1. Port Moresby, Papua New Guinea, 11–22 August 2008.

Langley, A., Hoyle, S. 2008. Report from the stock assessment preparatory workshop, Noumea, February 2008. WCPFC SC4 SA IP-5. Port Moresby, Papua New Guinea, 11–22 August 2008.

Langley, A., Methot, R. 2008. A preliminary stock assessment of bigeye tuna in the western and central Pacific Ocean using Stock Synthesis 3 (SS3); a comparison with MULTIFAN-CL. WCPFC SC4 SA WP-2, Port Moresby, Papua New Guinea, 11–22 August 2008.

Langley, A., H. Okamoto, P. Williams, N. Miyabe, K. Bigelow 2006. A summary of the data available for the estimation of conversion factors (processed to whole fish weights) for yellowfin and bigeye tuna. ME IP-3, WCPFC-SC2, Manila, Philippines, 7–18 August 2006.

Lawson, T. 2005. Update on the proportion of bigeye in "yellowfin plus bigeye" caught by purse seiners in the western and central Pacific Ocean. WCPFC-SC1 ST WP-3, Noumea, New Caledonia, 8–19 August 2005.

Lawson, T. 2007. Further analysis of the proportion of bigeye in "yellowfin plus bigeye" caught by purse seiners in the western and central Pacific Ocean. WCPFC-SC1 ST WP-3, Honolulu, Hawaii, 13-24 August 2007.

Lawson, T. 2008. Factors affecting the use of species composition data collected by observers and port samplers from purse seiners in the western and central Pacific. WCPFC SC4 ST WP-3, Port Moresby, Papua New Guinea, 11–22 August 2008.

Lawson, T. 2009. Selectivity bias in grab samples and other factors affecting the analysis of species composition data collected by observers on purse seiners in the Western and Central Pacific Ocean. WCPFC SC5 ST WP-3, Port Vila, Vanuatu, 10-21 August 2009.

Lawson, T. 2010. Update on the estimation of selectivity bias based on paired spill and grab samples collected by observers on purse seiners in the western and central Pacific Ocean. WCPFC-SC5-2009/ST- WP-3, Nuku'alofa, Tonga, 10-19 August 2010.

Lehodey, P., Hampton, J., and B. Leroy. 1999. Preliminary results on age and growth of bigeye tuna (*Thunnus obesus*) from the western and central Pacific Ocean as indicated by daily growth increments and tagging data. Working Paper BET-2, SCTB 12, Papeete, French Polynesia, 16 –23 June 1999.

Maunder, M. N. 2002. The relationships between fishing methods, fisheries management and the estimation of MSY. *Fish and Fisheries* 3: 251-260

Maunder, M. N. 2005. The influence of new biological parameters on the bigeye tuna assessment. Document SAR-6-07b SUP, Inter-American Tropical Tuna Commission, Working Group on Stock Assessment, 6th Meeting, 2–6 May 2005, La Jolla, California.

Maunder, M. N., and Watters, G. M. 2003. A-SCALA: An age-structured statistical catch-at-length analysis for assessing tuna stocks in the eastern Pacific Ocean. *IATTC Bul.* **22**: 433–582.

Schaefer, K.M., and Fuller, D.W. 2002. Movements, behavior, and habitat selection of bigeye tuna (*Thunnus obesus*) in the eastern equatorial Pacific, ascertained through archival tags. *Fish. Bull.* **100**: 765–788.

Williams P., and Reid C. 2007. Overview of the tuna fisheries in the western and central Pacific Ocean, including economic conditions – 2006. WCPFC SC3 GN WP-1, Honolulu, United States of America, 13–24 August 2007.

Williams P., and Terawasi, P. 2009. Overview of the tuna fisheries in the western and central Pacific Ocean, including economic conditions – 2008. WCPFC-SC5-2009/GN-WP-1, , Port Vila, Vanuatu, 10-21 August 2009.

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	All	Longline	1
2	LL ALL 2	All, except United States	Longline	2
3	LL HW 2	United States (Hawaii)	Longline	2
4	LL ALL 3	All, except CT-Offshore, CN, FSM, MH, PH, ID, and PNG	Longline	3
5	LL TW-CH 3	CT-Offshore, CN, FSM, MH, PH, and ID	Longline	3
6	LL PG 3	Papua New Guinea	Longline	4
7	LL ALL 4	All except CT-Offshore, CN, FSM, MH, PH, ID, and US	Longline	4
8	LL TW-CH 4	CT-Offshore, CN, FSM, MH, PH, and ID	Longline	4
9	LL HW 4	United States (Hawaii)	Longline	4
10	LL ALL 5	All except Australia	Longline	5
11	LL AU 5	Australia	Longline	5
12	LL ALL6	All DWFN	Longline	6
13	LL PI 6	Pacific Island Countries/Territories	Longline	6
14	PS ASS 3	All	Purse seine, log/FAD sets	3
15	PS UNS 3	All	Purse seine, school sets	3
16	PS ASS 4	All	Purse seine, log/FAD sets	4
17	PS UNS 4	All	Purse seine, school sets	4
18	PH MISC 3	Philippines	Miscellaneous (small fish)	3
19	PH HL 3	Philippines, Indonesia	Handline (large fish)	3
20	PS JP 1	Japan	Purse seine	1
21	PL JP 1	Japan	Pole-and-line	1
22	PL ALL 3	Japan, Solomon’s, PNG	Pole-and-line	3
23	LL BMK 3	All, except CT-Offshore, CN, FSM, MH, PH, ID, and PG	Longline, Bismarck Sea	3
24	ID MISC 3	Indonesia	Miscellaneous (small fish)	3
25	HL HW 4	United States (Hawaii)	Handline	4

Table 2. Summary of the key model runs undertaken for the 2010 bigeye tuna assessment. Those bolded model runs are the key model runs for the assessment.

Run	Name	Description
14-09		Run 14 (spill sample catches) from the 2009 assessment
1	New data	Updated data for 2010 including revised ID/PH and spill sample catch estimates. PH small fish fishery (fishery 18) length frequency observations greater than 90cm were excluded and selectivity was constrained to be zero above the age associated with this size.
1a	Zero catch	As per 1, but with 58 instances of observed zero catches set to missing for fisheries 6, 8, 11, and 14-17
1b	PS q-dev	As per 1a, but with the catchability deviation CV for fisheries 14-17 increased from 0.4 to 0.7
1c	Early lengths	As per 1b, but with Japanese length frequency data from 1954-1965 excluded
3	New fisheries	As per 1c, but with revised fisheries definitions for fisheries 4, 5, 7, 8, and 23 (as provided in Table 1)
3a	Excl. Non-JP	As per 3, but excluding non-Japanese size data for fisheries 1, 2, 4, 7, and 23
3a2	**Fix fish8**	As per 3a, but excluding all fishery 8 size data and setting its selectivity the same as fisheries 4, and 7 (**key model run – high weight**)
3b	DW fish5	As per 3a2, but downweight fishery 5 size data by 1000 (compared to 20)
3c	DW fish4 length	As per 3b, but downweight fishery 4 length data by 1000 (compared to 20)
3d	**Base**	As per 3c, but downweight length data for fisheries 1, 2, 4, 7, 10, 12, and 23 by 1000 (compared to 20) (**key model run – base**)
3e	Temporal -same	As per 3d, but with temporal CV's for the LL-ALL CPUE series. Average CV constrained to be 0.2 for each series.
3e2	**Temporal -different**	As per 3d, but with temporal CV's for the LL-ALL CPUE series as estimated by Hoyle (2010) (**key model run – temporal CV's**)
3f	**Vessel adj.**	As per 3d, but including the catchability increase of 0.47% per year from Hoyle (2009) in the LL-ALL 3 CPUE series (**key model run – vessel adj.**)
3g	**High juv. M**	As per 3d, but including the assumed natural mortality values for yellowfin for the first 4 quarters (**key model run – high juv. M**)
4a	**Lower PS**	As per 3d, but with lower purse seine catch estimates from s-Best data base (as used in rum 10 in 2009) (**key model run – lower PS**)
4b	**h=0.75**	As per 3d, but with steepness fixed at 0.75 (**key model run – h=0.75**)
4c	**Early CPUE**	As per 3d, but with LL-ALL effort (and therefore CPUE) set to missing prior to 1975 (**key model run – early CPUE**)

Table 3: Comparison of the base model from the 2009 assessment (run 10), the base model for the 2010 assessment (run 3d) and the other key model runs from 2010.

Component	2009 assessment (run 10)	2010 assessment (run 3d)	2010 alternatives
Fishery 18 (PHI DOM) size data	Excluded 1980s samples	Excluded fish over 90 cm	
Fishery 18 PHI DOM) selectivity	Unconstrained cubic spline	Cubic spline, but constrained for zero selectivity above 10 quarters of age	
Japanese length frequency data	All used	Excluded observations from 1954-65	
Fishery 8 (CN/TW LL in region 4)	Included length and weight observations and logistic selectivity linked to fishery 5	Excluded length and weight observations and dome-shaped selectivity linked to fisheries 4, 7, 10, and 12	
Longline CPUE	Aggregate indices	Aggregate indices	Excluding all CPUE prior to 1975
Steepness	Estimated	Estimated	0.55, 0.75, 0.95
Purse seine catches	Grab sample (s_best)	Spill sample corrected	Grab sample (s_best)
Fleet catchability adjustment	None	None	0.47% per year (non-compounding)
Longline size data	Up-weighted	Down-weighted	Up-weighted
Natural mortality	Base	Base	Increased for juveniles

Table 4. Description of symbols used in the yield analysis. For the purpose of this assessment, 'current' is the average over the period 2005-2008 and 'latest' is 2009.

Symbol	Description
$C_{current}$	Average annual catch over a recent period[10]
C_{latest}	Catch in the most recent year
$F_{current}$	Average fishing mortality-at-age[11] for a recent period
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (MSY[12])
$Y_{F_{current}}$	Equilibrium yield at $F_{current}$
$Y_{F_{MSY}}$	Equilibrium yield at F_{MSY}. Better known as MSY
$C_{current}/MSY$	Average annual catch over a recent period relative to MSY
C_{latest}/MSY	Catch in the most recent year relative to MSY
F_{mult}	The amount that $F_{current}$ needs to be scaled to obtain F_{MSY}
$F_{current}/F_{MSY}$	Average fishing mortality-at-age for a recent period relative to F_{MSY}
B_0	Equilibrium unexploited total biomass
B_{MSY}	Equilibrium total biomass that results from fishing at F_{MSY}
B_{MSY}/B_0	Equilibrium total biomass that results from fishing at F_{MSY} relative to B_0
$B_{current}$	Average annual total biomass over a recent period
B_{latest}	Total annual biomass in the most recent year
$B_{F_{current}}$	Equilibrium total biomass that results from fishing at $F_{current}$
$B_{current_{F=0}}$	Average annual total biomass over a recent period in the absence of fishing
$B_{latest_{F=0}}$	Total biomass predicted to exist in the absence of fishing
SB_0	Equilibrium unexploited total biomass[13].
$B_{current}/B_0$	Average annual total biomass over a recent period relative to B_0
B_{latest}/B_0	Total annual biomass in the most recent year relative to B_0
$B_{F_{current}}/B_0$	Equilibrium total biomass that results from fishing at $F_{current}$relative to B_0
$B_{current}/B_{MSY}$	Average annual total biomass over a recent period relative to B_{MSY}
B_{latest}/B_{MSY}	Total annual biomass in the most recent year relative to B_{MSY}
$B_{F_{current}}/B_{MSY}$	Equilibrium total biomass that results from fishing at $F_{current}$relative to B_{MSY}
$B_{current}/B_{current_{F=0}}$	Average annual total biomass over a recent period / the biomass in the absence of fishing
$B_{latest}/B_{latest_{F=0}}$	Total annual biomass in the most recent year / the biomass in the absence of fishing
$Crit_{age}$	The age at which harvest would maximize the yield per recruit
$Crit_{length}$	The length at which harvest would maximize the yield per recruit
$Mean_{age}$	The mean age of the catch over a recent period
$Mean_{length}$	The mean length of the catch over a recent period
Y_{lost}	The proportion of the maximum yield per recruit lost by the mean age at harvest

[10] Some recent period used for the purpose of averaging fishing mortality or other quantities. Typically excludes the most recent year due to uncertainty, but covers the preceding four years, e.g. 2005-2008.

[11] This age-specific pattern is dependent on both the amount of fishing and the mix of fishing gears, e.g. relative catches of small and large fish

[12] MSY and other MSY-related quantities are linked to a particular fishing pattern and the MSY will change, for example, based on changes in the relative catches of small and large fish

[13] Similar quantities as above for total biomass can also be calculated for spawning biomass and are not repeated here

Table 5. Some performance statistics for the model runs described in Table 2. $\boldsymbol{Rec_{ratio}}$ is the average recruitment for the second half the of the model period divided by the average for the first half. Note that the MSY-related quantities are not comparable between run14-09 and the other model runs due to the different time windows used in each (but see Table 6).

Run	MSY	$F_{current}$ $/F_{MSY}$	$SB_{current}$ $/SB_{MSY}$	Rec_{ratio}	*steepness*	Obj. Fnt value	npars	gradient
run14-09	67,800	2.01	1.04	2.51	0.99	1,293,337	5803	0.07
run1	67,120	1.83	1.00	2.50	0.99	1,365,801	5994	0.01
run1a	67,560	1.81	1.01	2.51	0.99	1,366,603	5936	0.00
run1b	67,440	1.81	1.02	2.51	0.99	1,366,676	5936	0.01
run1c	67,600	1.80	1.02	2.49	0.99	1,341,852	5936	0.01
run3	68,400	1.79	1.01	2.47	0.99	1,333,420	5941	0.14
run3a	69,760	1.85	0.89	2.52	0.99	1,325,815	5941	0.01
run3a2	69,120	1.67	1.10	2.36	0.99	1,283,768	5941	0.02
run3b	70,880	1.55	1.17	2.20	0.98	1,238,116	5941	0.25
run3c	71,160	1.55	1.19	2.18	0.98	1,207,336	5941	0.01
run3d	73,840	1.41	1.34	2.00	0.98	1,061,612	5941	0.06
run3e	73,680	1.41	1.36	2.00	0.98	1,061,493	5941	0.66
run3e2	76,680	1.30	1.50	1.82	0.97	1,062,179	5941	0.19
run3f	75,120	1.40	1.34	1.93	0.98	1,061,599	5941	0.03
run3g	75,400	1.33	1.43	1.93	0.97	1,061,580	5941	0.01
run4a	57,280	1.51	1.28	1.64	0.97	1,061,534	5945	0.03
run4b	65,840	1.97	0.97	1.97	0.75	1,061,606	5940	0.02
run4c	95,680	1.28	1.24	1.14	0.94	1,062,106	5941	0.01

Table 6. Estimates of management quantities for the selected stock assessment models. For the purpose of this assessment, 'current' is the average over the period 2005-2008 and 'latest' is 2009.

	run3d (base)	run3a2 (high weight)	run3e2 (temporal CV's)	run3f (vessel adj.)	run3g (high juv. M)	run4a (lower PS)	run4b (h=0.75)	run4c (early CPUE)
$C_{current}$	147,506	145,649	148,677	147,553	147,256	121,738	147,774	147,272
C_{latest}	126,769	124,645	128,181	126,731	126,599	117,332	127,040	126,743
$Y_{F_{current}}$	69,720	61,240	74,080	71,120	72,560	52,520	37,016	92,560
$Y_{F_{MSY}}$ or MSY	73,840	69,120	76,680	75,120	75,400	57,280	65,840	95,680
$Y_{F_{current}}/MSY$	0.94	0.89	0.97	0.95	0.96	0.92	0.56	0.97
$C_{current}/MSY$	2.00	2.11	1.94	1.96	1.95	2.13	2.24	1.54
C_{latest}/MSY	1.72	1.80	1.67	1.69	1.68	2.05	1.93	1.33
F_{MSY}	0.05	0.05	0.05	0.05	0.05	0.05	0.03	0.05
F_{mult}	0.71	0.60	0.77	0.71	0.75	0.66	0.51	0.78
$F_{current}/F_{MSY}$	1.41	1.67	1.30	1.40	1.33	1.51	1.97	1.28
B_0	1,252,000	1,053,000	1,375,000	1,291,000	1,209,000	937,900	1,389,000	1,719,000
B_{MSY}	377,200	323,800	413,000	387,700	361,400	297,300	501,800	531,200
B_{MSY}/B_0	0.30	0.31	0.30	0.30	0.30	0.32	0.36	0.31
$B_{current}$	525,660	404,039	616,915	537,445	526,466	413,215	544,491	651,467
B_{latest}	426,286	311,303	498,068	439,868	424,282	334,503	440,715	532,305
$B_{F_{current}}$	239,500	163,200	292,800	248,800	250,900	173,700	131,300	384,800
$B_{current_{F=0}}$	2,267,121	2,110,238	2,355,156	2,285,639	2,133,485	1,654,574	2,280,393	2,335,137
$B_{latest_{F=0}}$	2,149,947	2,005,516	2,219,023	2,172,932	2,007,905	1,653,556	2,158,524	2,203,155
SB_0	651,500	547,300	715,400	671,700	624,300	488,800	722,400	883,800
SB_{MSY}	155,500	130,400	173,000	160,400	143,700	122,200	224,700	220,700
SB_{MSY}/SB_0	0.24	0.24	0.24	0.24	0.23	0.25	0.31	0.25
$SB_{current}$	207,974	143,512	260,114	214,489	204,746	156,274	218,469	274,047
SB_{latest}	181,528	119,841	224,547	187,844	177,785	135,758	190,640	241,744
$SB_{F_{current}}$	86,740	51,700	112,400	90,970	88,720	60,690	48,200	147,800
$SB_{current_{F=0}}$	1,196,581	1,105,285	1,246,179	1,205,988	1,120,013	872,334	1,204,157	1,220,163
$SB_{latest_{F=0}}$	1,199,166	1,125,553	1,240,003	1,209,783	1,117,234	885,169	1,205,023	1,222,266
$B_{current}/B_0$	0.42	0.38	0.45	0.42	0.44	0.44	0.39	0.38
B_{latest}/B_0	0.34	0.30	0.36	0.34	0.35	0.36	0.32	0.31
$B_{F_{current}}/B_0$	0.19	0.16	0.21	0.19	0.21	0.19	0.10	0.22
$B_{current}/B_{MSY}$	1.39	1.25	1.49	1.39	1.46	1.39	1.09	1.23
B_{latest}/B_{MSY}	1.13	0.96	1.21	1.14	1.17	1.13	0.88	1.00
$B_{F_{current}}/B_{MSY}$	0.64	0.50	0.71	0.64	0.69	0.58	0.26	0.72
$B_{current}/B_{current_{F=0}}$	0.23	0.19	0.26	0.24	0.25	0.25	0.24	0.28
$B_{latest}/B_{latest_{F=0}}$	0.20	0.16	0.22	0.20	0.21	0.20	0.20	0.24
$SB_{current}/SB_0$	0.32	0.26	0.36	0.32	0.33	0.32	0.30	0.31
SB_{latest}/SB_0	0.28	0.22	0.31	0.28	0.29	0.28	0.26	0.27
$SB_{F_{current}}/SB_0$	0.13	0.09	0.16	0.14	0.14	0.12	0.07	0.17
$SB_{current}/SB_{MSY}$	1.34	1.10	1.50	1.34	1.43	1.28	0.97	1.24
SB_{latest}/SB_{MSY}	1.17	0.92	1.30	1.17	1.24	1.11	0.85	1.10
$SB_{F_{current}}/SB_{MSY}$	0.56	0.40	0.65	0.57	0.62	0.50	0.22	0.67
$SB_{curr}/SB_{curr_{F=0}}$	0.17	0.13	0.21	0.18	0.18	0.18	0.18	0.23
$SB_{latest}/SB_{latest_{F=0}}$	0.15	0.11	0.18	0.16	0.16	0.15	0.16	0.20
Steepness (h)	0.98	0.99	0.97	0.98	0.97	0.97	0.75	0.94

Table 7: Comparison of historical estimates of $F_{current}/F_{MSY}$ for each year from 2000-2008 and the average for the period 2001-04 for the model runs described in Table 2.

	$F_{current}/F_{MSY}$									
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2001-04
old14-09	1.75	1.39	1.61	1.14	1.99	1.75	2.10	2.19	2.39	1.53
run1	1.79	1.39	1.66	1.31	1.74	1.55	1.97	1.68	2.10	1.52
run1a	1.79	1.40	1.65	1.30	1.83	1.54	1.95	1.67	2.07	1.54
run1b	1.79	1.41	1.65	1.29	1.81	1.54	1.94	1.66	2.09	1.54
run1c	1.79	1.41	1.64	1.29	1.81	1.53	1.94	1.66	2.08	1.54
run3	1.83	1.43	1.66	1.29	1.83	1.54	1.92	1.64	2.05	1.55
run3a	1.86	1.47	1.73	1.37	1.97	1.64	2.00	1.67	2.07	1.64
run3a2	1.74	1.36	1.59	1.24	1.71	1.47	1.80	1.52	1.90	1.48
run3b	1.69	1.30	1.52	1.16	1.64	1.40	1.66	1.39	1.77	1.40
run3c	1.67	1.29	1.51	1.14	1.60	1.37	1.68	1.39	1.76	1.39
run3d	1.52	1.17	1.36	1.03	1.45	1.25	1.53	1.27	1.60	1.25
run3e	1.51	1.16	1.35	1.02	1.43	1.24	1.52	1.26	1.60	1.24
run3e2	1.38	1.05	1.22	0.93	1.32	1.15	1.41	1.17	1.49	1.13
run3f	1.50	1.15	1.34	1.02	1.44	1.24	1.52	1.26	1.58	1.24
run3g	1.45	1.10	1.32	0.96	1.39	1.18	1.44	1.20	1.51	1.19
run4a	1.49	1.29	1.31	1.23	1.40	1.33	1.57	1.37	1.79	1.31
run4b	2.13	1.62	1.92	1.42	2.05	1.75	2.12	1.77	2.22	1.76
run4c	1.36	1.00	1.15	0.95	1.36	1.19	1.39	1.16	1.40	1.11

Table 8: Comparison of the historical estimates of $SB_{current}/SB_{MSY}$ for each year from 2000-2008 for the model runs described in Table 2.

	$SB_{current}/SB_{MSY}$								
	2000	2001	2002	2003	2004	2005	2006	2007	2008
old14-09	1.04	0.90	0.84	0.95	1.20	1.10	1.01	0.86	0.78
run1	1.07	0.93	0.86	0.89	1.16	1.06	0.99	0.97	1.00
run1a	1.07	0.92	0.86	0.89	1.16	1.06	1.00	0.98	1.01
run1b	1.05	0.91	0.85	0.89	1.17	1.07	1.01	0.99	1.02
run1c	1.05	0.91	0.85	0.89	1.17	1.07	1.00	0.98	1.02
run3	1.04	0.89	0.83	0.86	1.13	1.05	1.00	0.97	1.01
run3a	1.00	0.86	0.79	0.82	1.07	0.95	0.87	0.83	0.90
run3a2	1.09	0.94	0.89	0.94	1.29	1.19	1.12	1.05	1.05
run3b	1.25	1.07	0.98	0.97	1.30	1.22	1.20	1.13	1.13
run3c	1.25	1.07	0.99	0.98	1.31	1.24	1.21	1.16	1.15
run3d	1.43	1.22	1.13	1.11	1.47	1.41	1.37	1.30	1.28
run3e	1.45	1.23	1.15	1.12	1.48	1.43	1.39	1.32	1.30
run3e2	1.59	1.37	1.28	1.25	1.64	1.59	1.55	1.46	1.43
run3f	1.44	1.23	1.14	1.12	1.46	1.41	1.37	1.30	1.28
run3g	1.52	1.29	1.19	1.19	1.55	1.50	1.46	1.38	1.36
run4a	1.39	1.19	1.11	1.07	1.40	1.32	1.30	1.26	1.24
run4b	1.02	0.89	0.81	0.82	1.03	1.02	1.00	0.94	0.94
run4c	1.33	1.14	1.08	1.03	1.36	1.28	1.29	1.20	1.21

Table 9. Comparison of estimates of yields based on long-term recruitment predicted from the SRR and that estimated assuming recruitment equal to the recent period (1999-2008) for the key model runs.

	$\boldsymbol{C_{current}}$	$\boldsymbol{MSY^{LT}}$	$\boldsymbol{MSY^{rec}}$	$\boldsymbol{C_{current} / MSY^{rec}}$
run3d	147,506	73,840	132,403	1.11
run3a2	145,649	69,120	136,281	1.07
run3e2	148,677	76,680	130,677	1.14
run3f	147,553	75,120	132,080	1.12
run3g	147,256	75,400	131,342	1.12
run4a	121,738	57,280	105,155	1.16
run4b	147,774	65,840	131,495	1.12
run4c	147,272	95,680	132,560	1.11

Table 10. Estimates of utilisation related management quantities for the key model runs.

Run	MSY	$Y_{F_{current}}$	$Crit_{age}$	$Crit_{length}$	$Mean_{age}$	$Mean_{length}$	Y_{lost}
run3d	73,840	69,720	15	124.30	4.86	54.77	0.74
run3a2	69,120	61,240	15	125.65	4.78	54.62	0.74
run3e2	76,680	74,080	15	125.65	4.81	54.69	0.74
run3f	75,120	71,120	15	125.66	4.76	54.45	0.74
run3g	75,400	72,560	15	125.60	4.74	54.22	0.74
run4a	57,280	52,520	15	125.66	4.57	52.55	0.75
run4b	65,840	37,016	15	125.65	4.80	54.72	0.74
run4c	95,680	92,560	15	125.48	4.71	54.13	0.73

Table 11. Estimates of the probability that $\boldsymbol{SB_{current}}$ and $\boldsymbol{SB_{latest}}$ are less than some commonly used spawning biomass reference points based on the 96 model runs undertaken for the structural uncertainty analysis and the likelihood profiles for runs 3d and 4b (h=0.75).

	Structural uncertainty		**Likelihood profile**
	$\boldsymbol{SB_{current}}$	$\boldsymbol{SB_{latest}}$	$\boldsymbol{SB_{current}}$
	All grid		
$p(x < SB_{MSY})$	57%	82%	Run 3d: 0.5%
$p(x < 0.5SB_{MSY})$	1%	12%	Run 4b: 60%
$p(x < 0.2SB_0)$	2%	22%	
$p(x < 0.2SB_{F=0})$	68%	96%	
	Only *h*=0.75		
$p(x < SB_{MSY})$	62%	97%	
$p(x < 0.5SB_{MSY})$	0%	0%	
$p(x < 0.2SB_0)$	0%	16%	
$p(x < 0.2SB_{F=0})$	72%	97%	

Table 12: Percentage of one-off changes from the 96 model run grid where the model run with the run 3d assumption had a higher $F_{current}/F_{MSY}$ or lower $SB_{current}/SB_{MSY}$ than the alternative.

Assumption	**Higher** $F_{current}/F_{MSY}$	**Lower** $SB_{current}$ $/SB_{MSY}$
Juvenile M	98%	98%
Size data weights	0%	0%
Temporal effort deviates	71%	79%
Purse seine catch	21%	46%
CPUE vessel adjustment	81%	75%

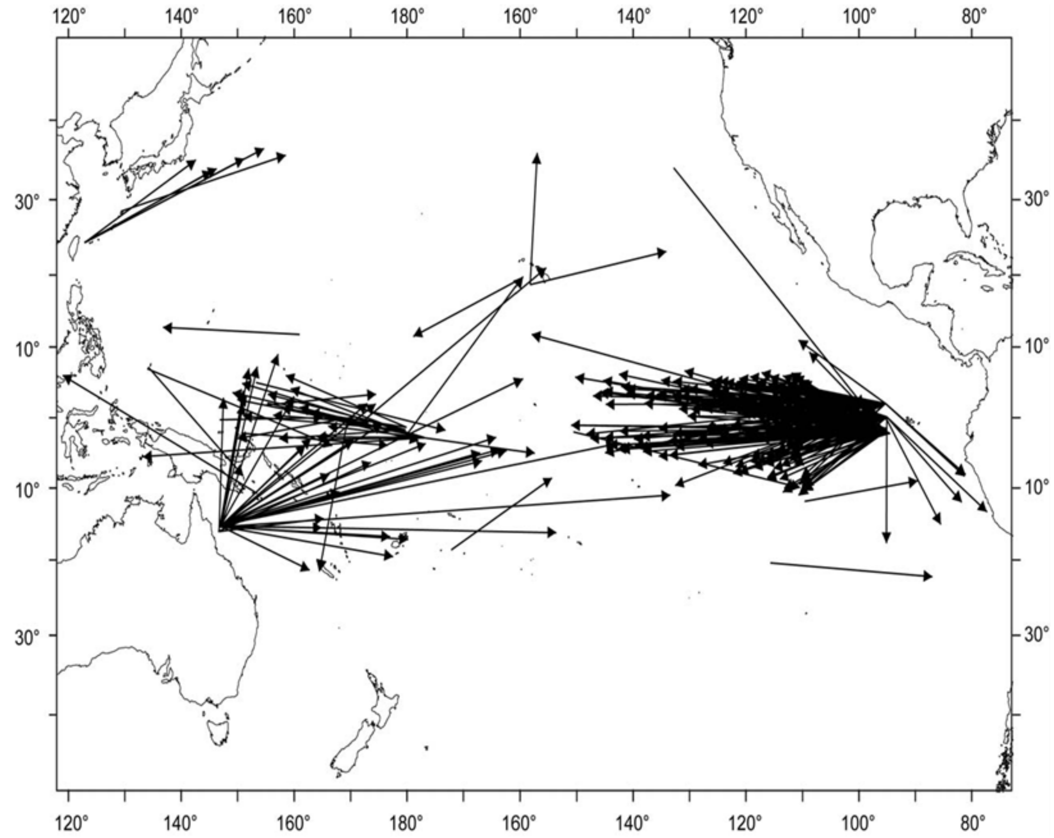


Figure 1. Long-distance (greater than 1,000 nmi) movements of tagged bigeye tuna in the Pacific Ocean (from Schaefer and Fuller 2009).

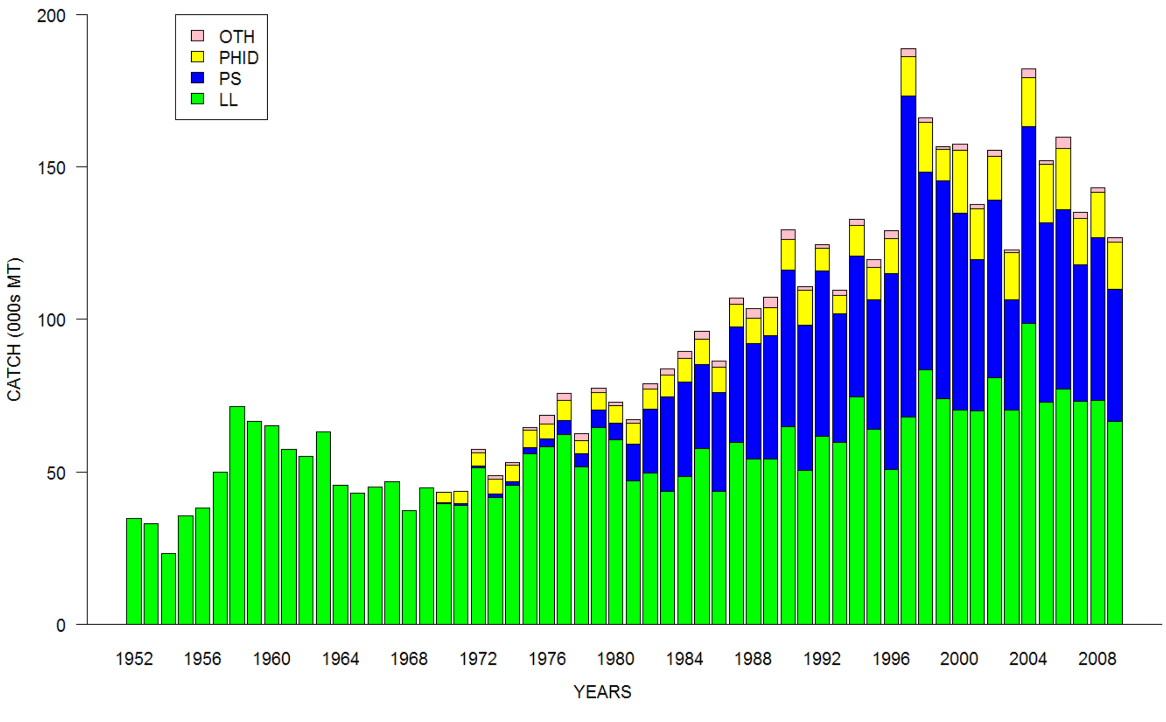


Figure 2. Total annual catch (1000s mt) of bigeye tuna from the WCPO by fishing method from 1952 to 2009 assumed in run 3d. These include purse seine catch estimates which **have been** corrected for grab-sample bias.

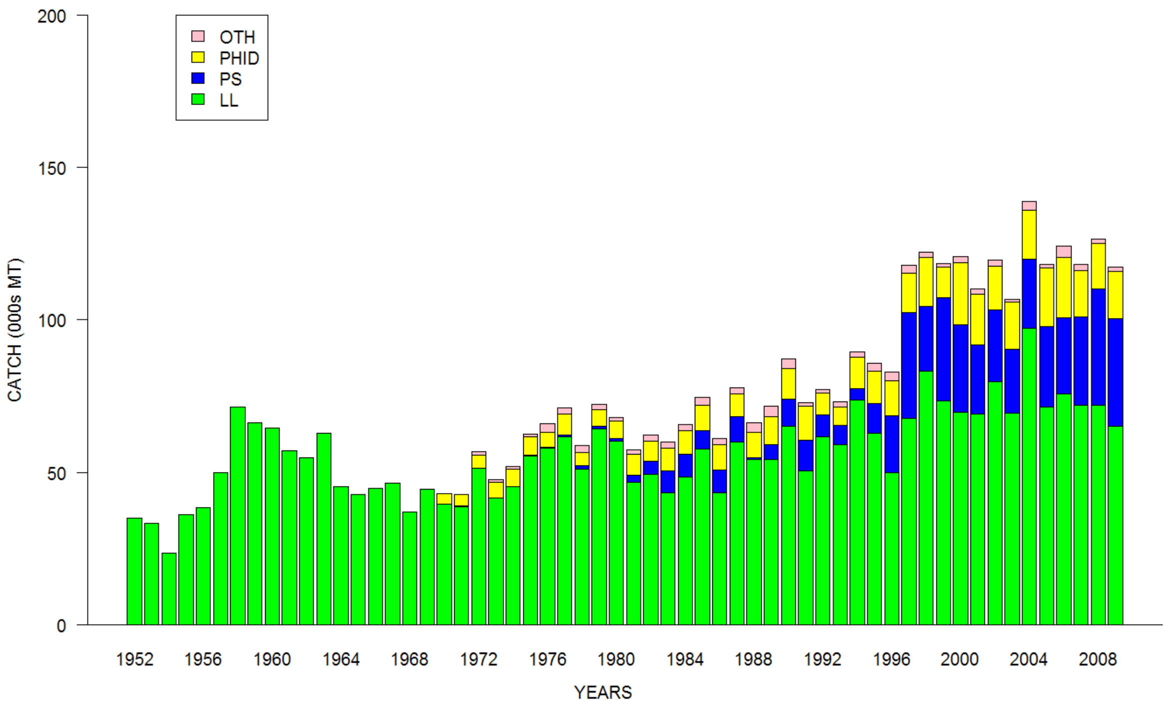


Figure 3. Total annual catch (1000s mt) of bigeye tuna from the WCPO by fishing method from 1952 to 2009 as assumed in run 4a. These purse seine catch estimates **have not been** corrected for grab-sample bias.

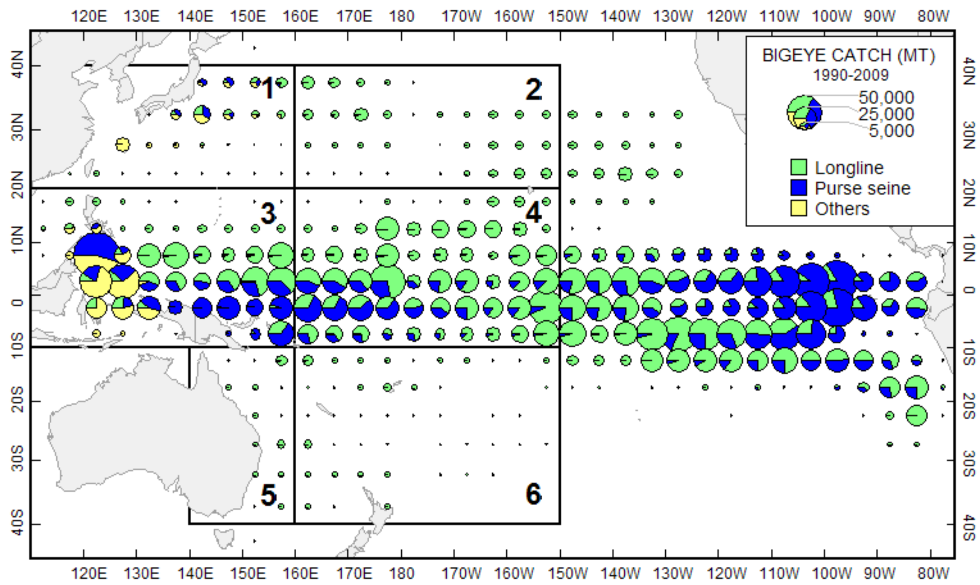


Figure 4. Distribution of cumulative bigeye tuna catch from 1990–2009 by 5 degree squares of latitude and longitude and fishing gear; longline (green), purse-seine (blue), and other (yellow). The grey lines indicate the spatial stratification of the six-region assessment model.

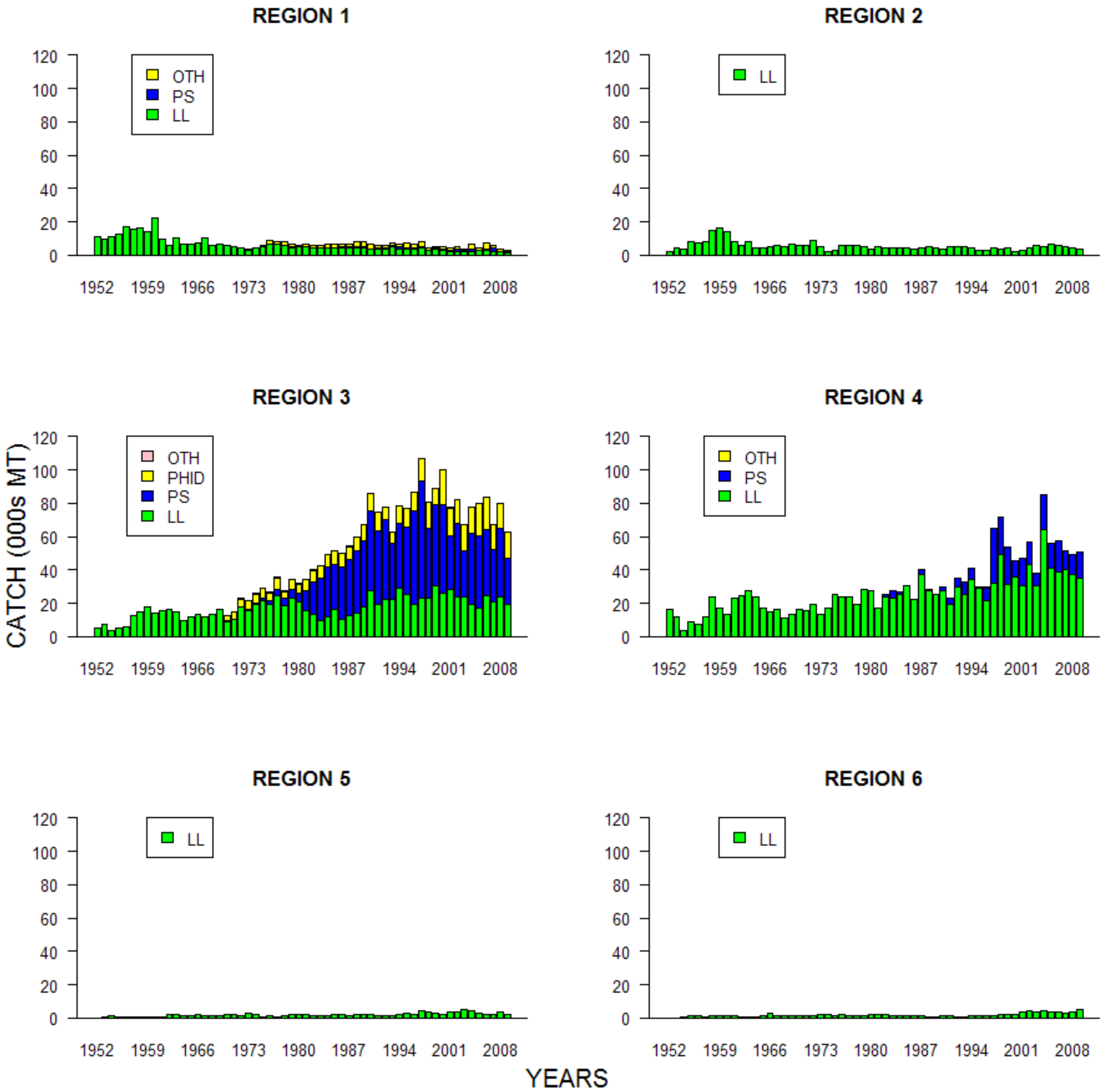


Figure 5. Total annual catch (1000s mt) of bigeye tuna by fishing method and MFCL region from 1952 to 2009 assumed in run 3d.

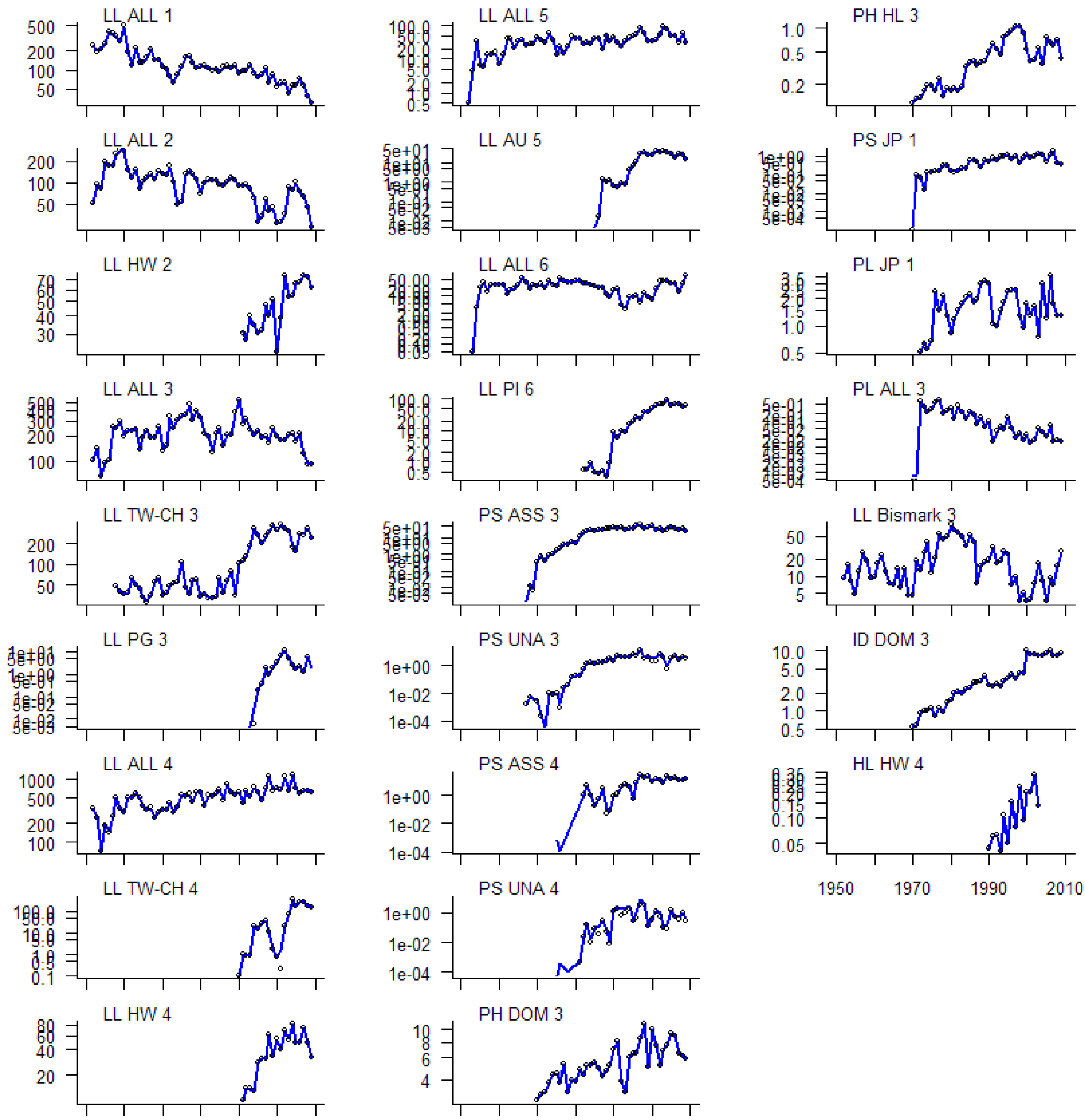


Figure 6. Annual catches by fishery. Circles are observed and the lines are model predictions. Units are catch number of fish (in thousands) for the longline fisheries and thousand metric tonnes for all other fisheries. The y-axis is on the log scale.

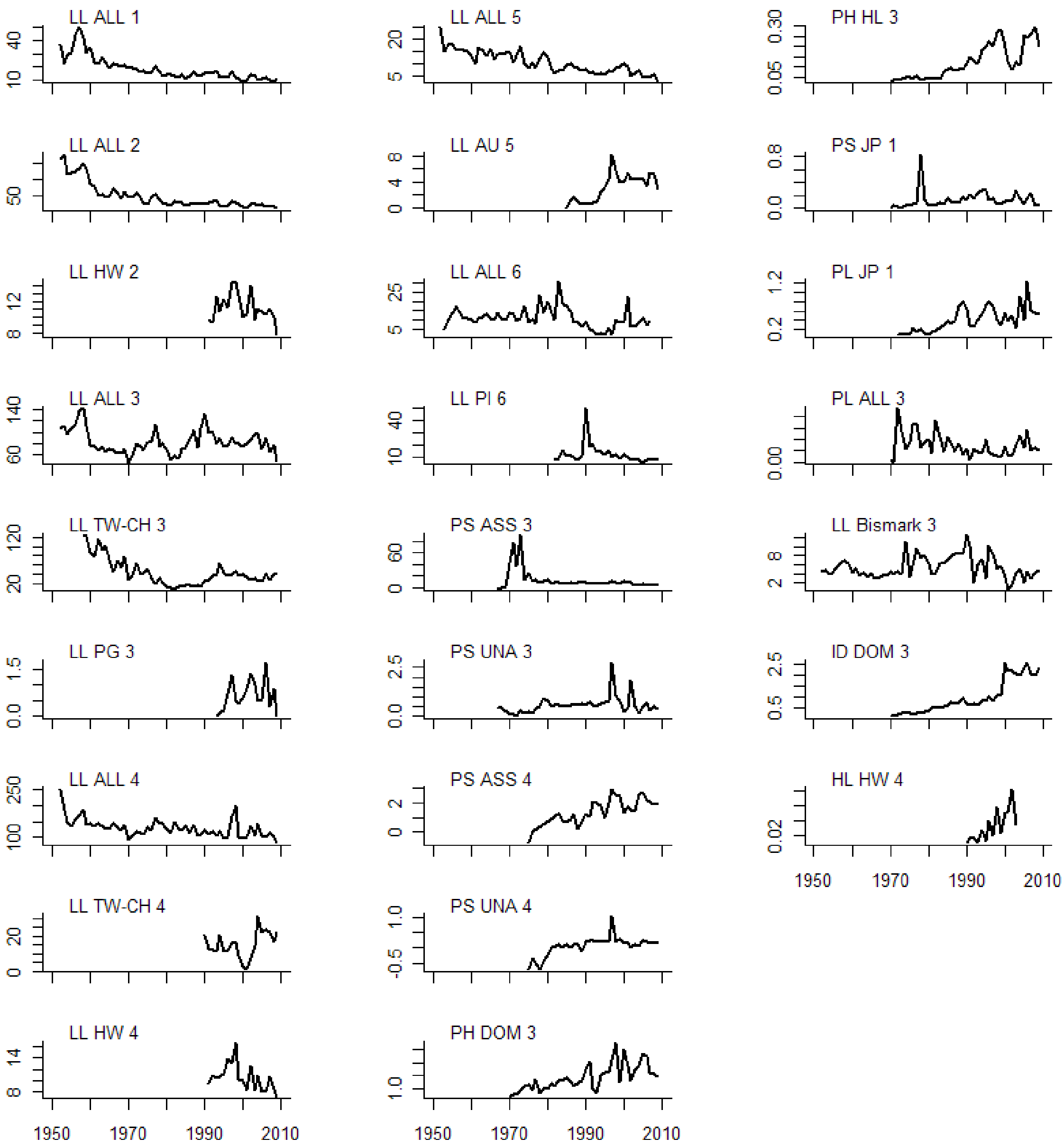


Figure 7. Catch-per-unit-effort (CPUE) by fishery. Units are catch number per GLM-standardised effort (fisheries LL ALL 1–LL ALL 6), catch number per 100 nominal hooks (LL HW, CH/TW LL, LL PI, LL PG, LL BMK) and catch (mt) per day fished/searched (all PS and PL fisheries). Note that CPUE for PH MISC, PH HL and ID are arbitrary and not based on data (see discussion on catchability and effort deviation constraints for these fisheries).

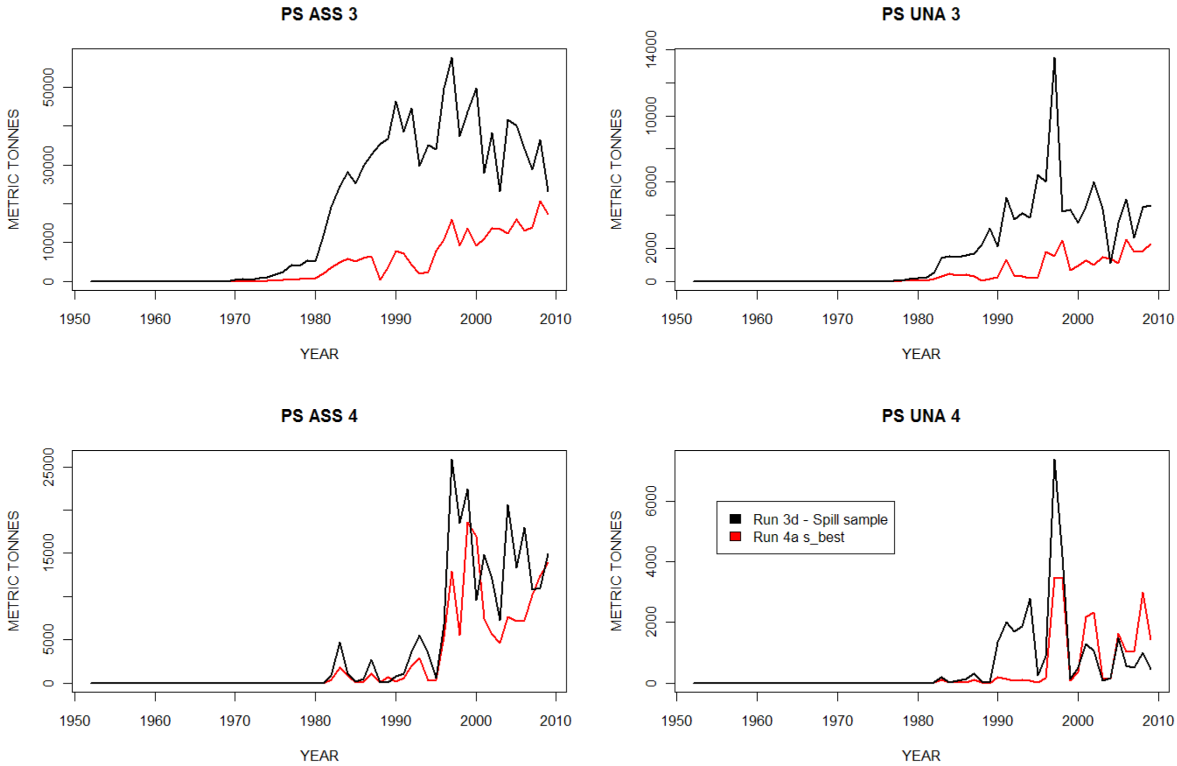


Figure 8. A comparison of the alternative catch histories (annual catches in mt) assumed for the purse seine fisheries.

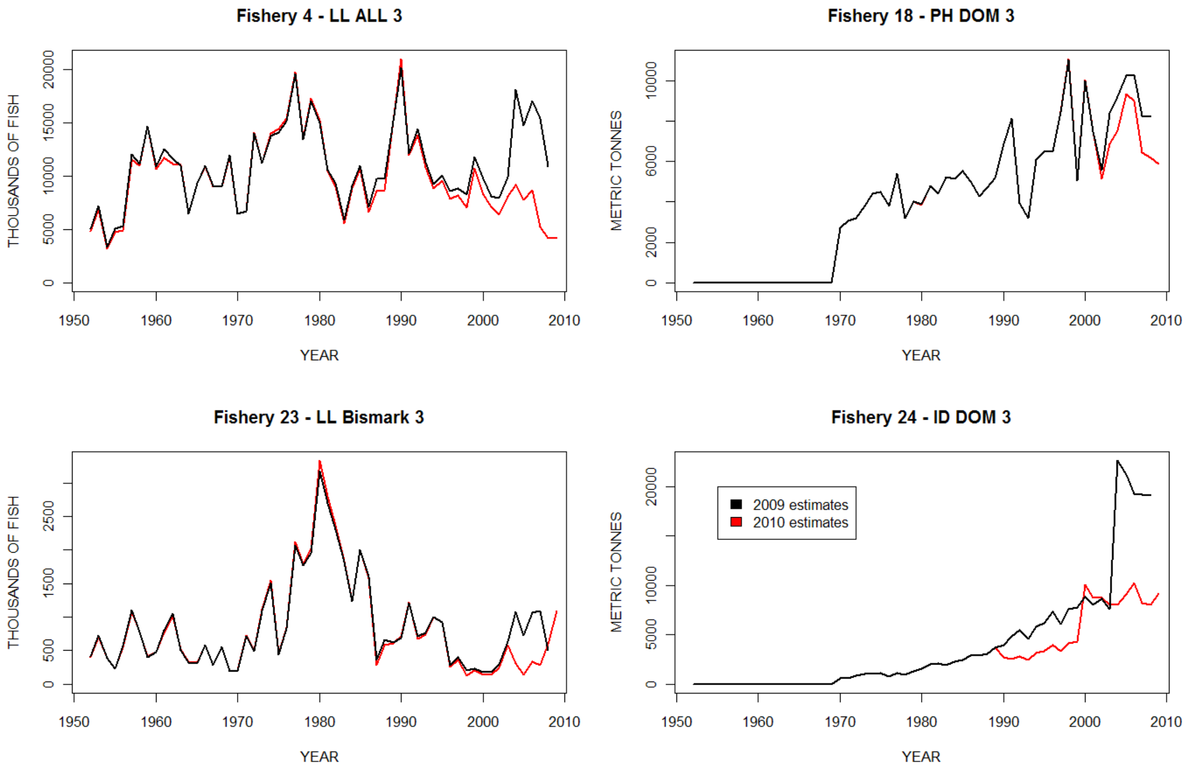


Figure 9. A comparison of the catch histories for the fisheries that incorporate catches from Indonesia and the Philippines from those assumed in the 2009 assessment (black) and those assumed in the 2010 assessment (red).

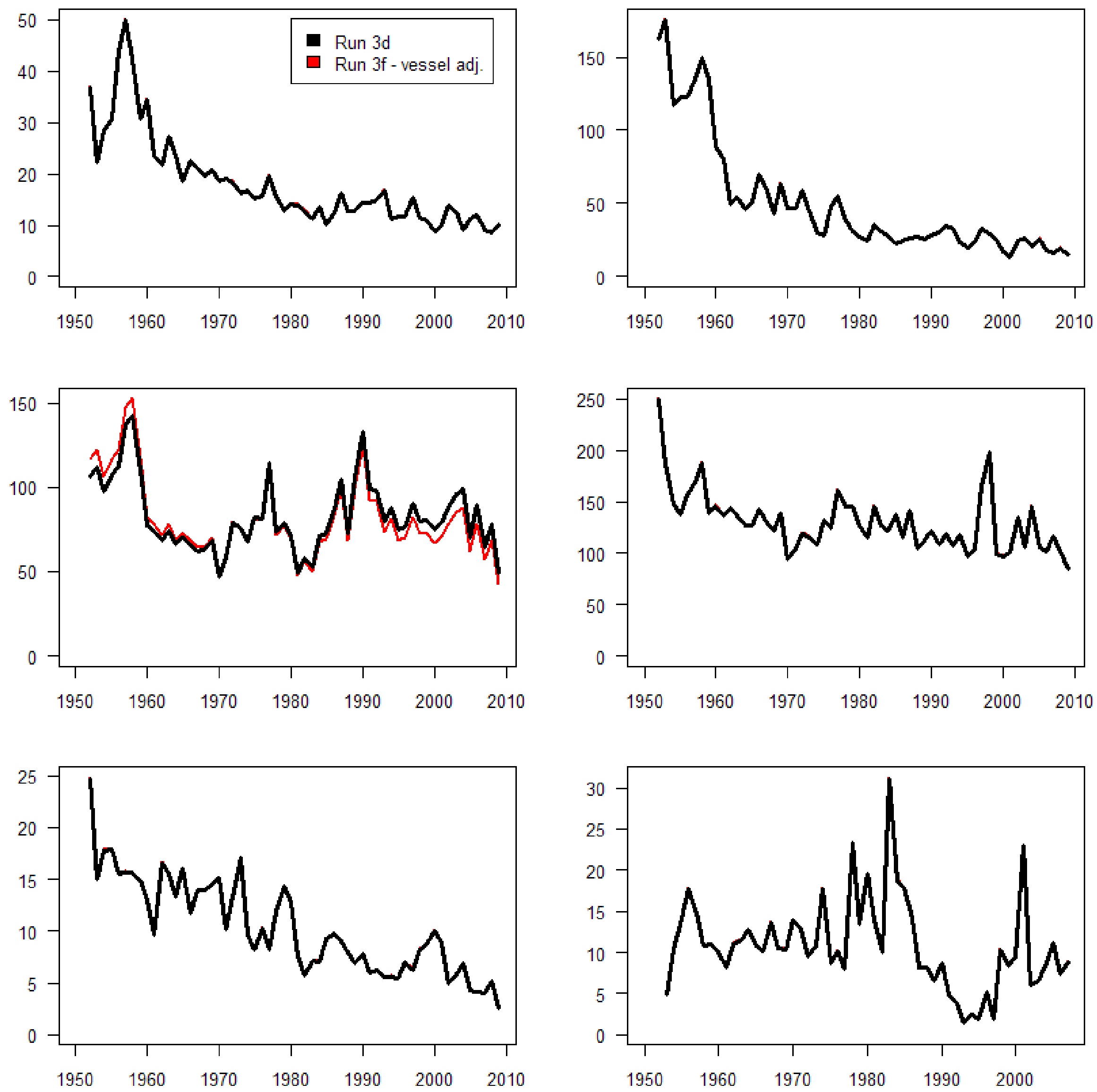


Figure 10. GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL ALL 1–6) scaled by the respective region scalars based on the methodology used in the Hoyle (2010) (black lines); and the CPUE series for LL-ALL 3 that incorporates the vessel adjustment factor of 0.47% per year from Hoyle (2009) (red line).

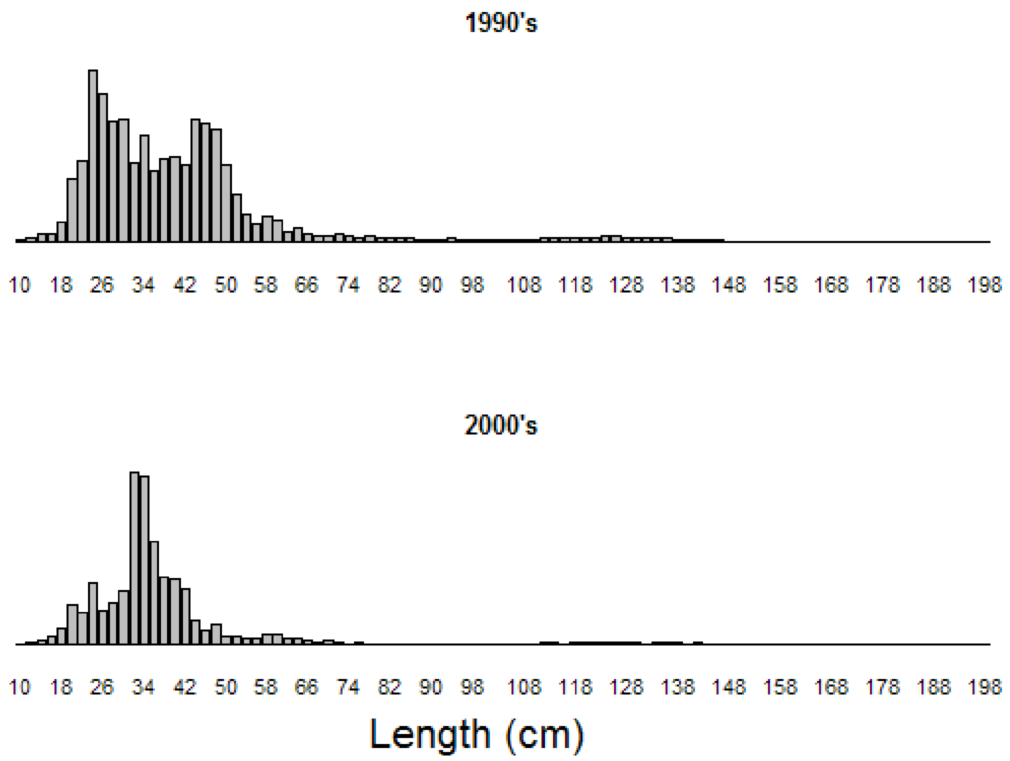


Figure 11. A comparison of the length frequency samples by decade attributed to the Philippines domestic fishery (Fishery 18: PH DOM 3) as used in the 2008 bigeye assessment. Samples of lengths greater than 90cm are excluded from the current assessment.

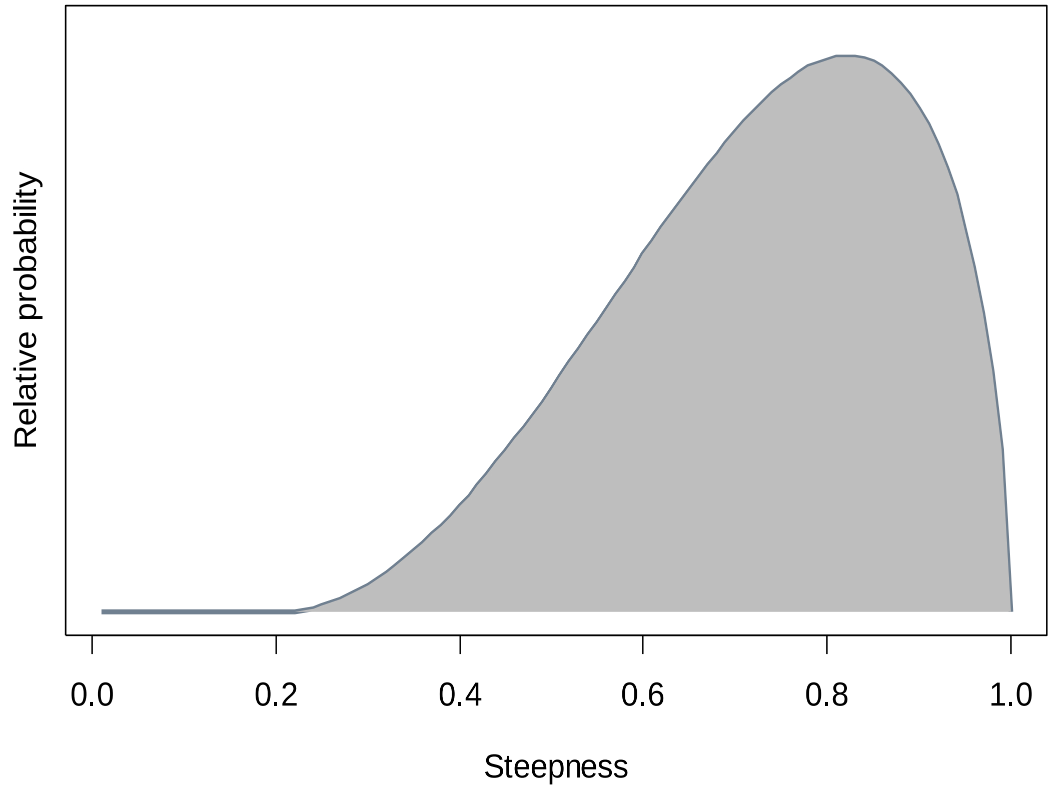


Figure 12. Prior for the steepness parameter of the relationship between spawning biomass and recruitment.

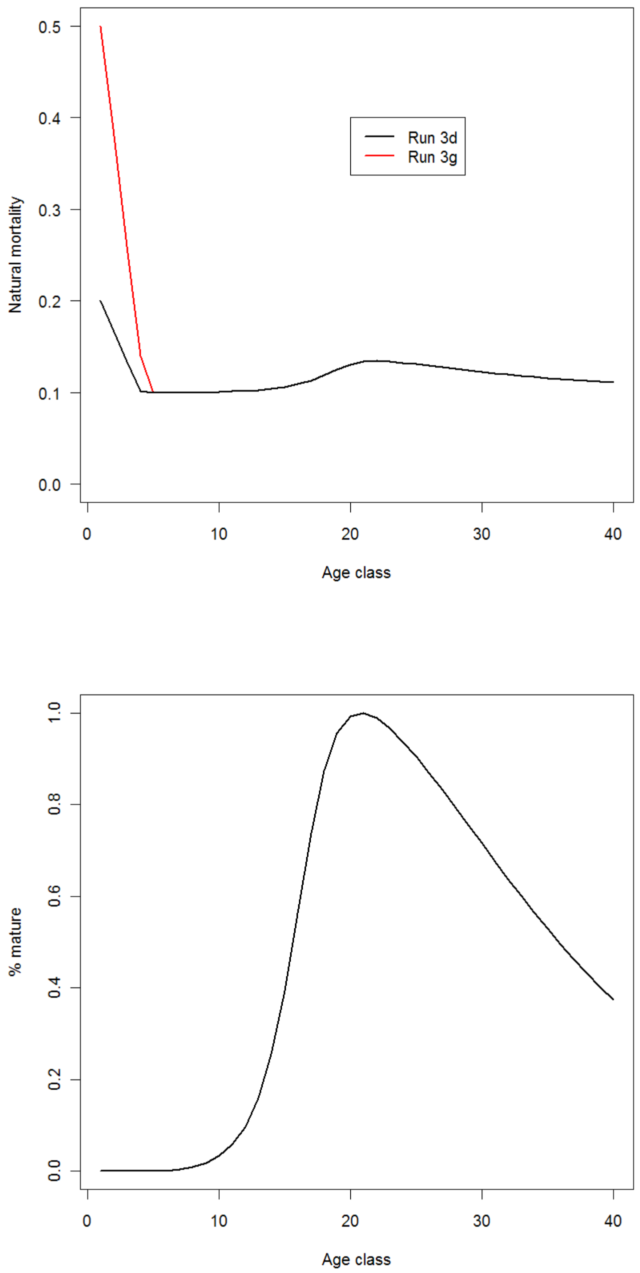


Figure 13. Natural mortality-at-age (top) and % mature (bottom) as assumed in the 2010 assessment. For natural mortality the alternative assumption (run 3g) based on YFT assumed levels of M for ages 1-4 quarters is also provided (red line). Note that estimate of maturity is actually used to define an index of spawning potential incorporating information on sex ratios, maturity at age, fecundity, and spawning fraction (see Hoyle and Nicol 2008 for further details).

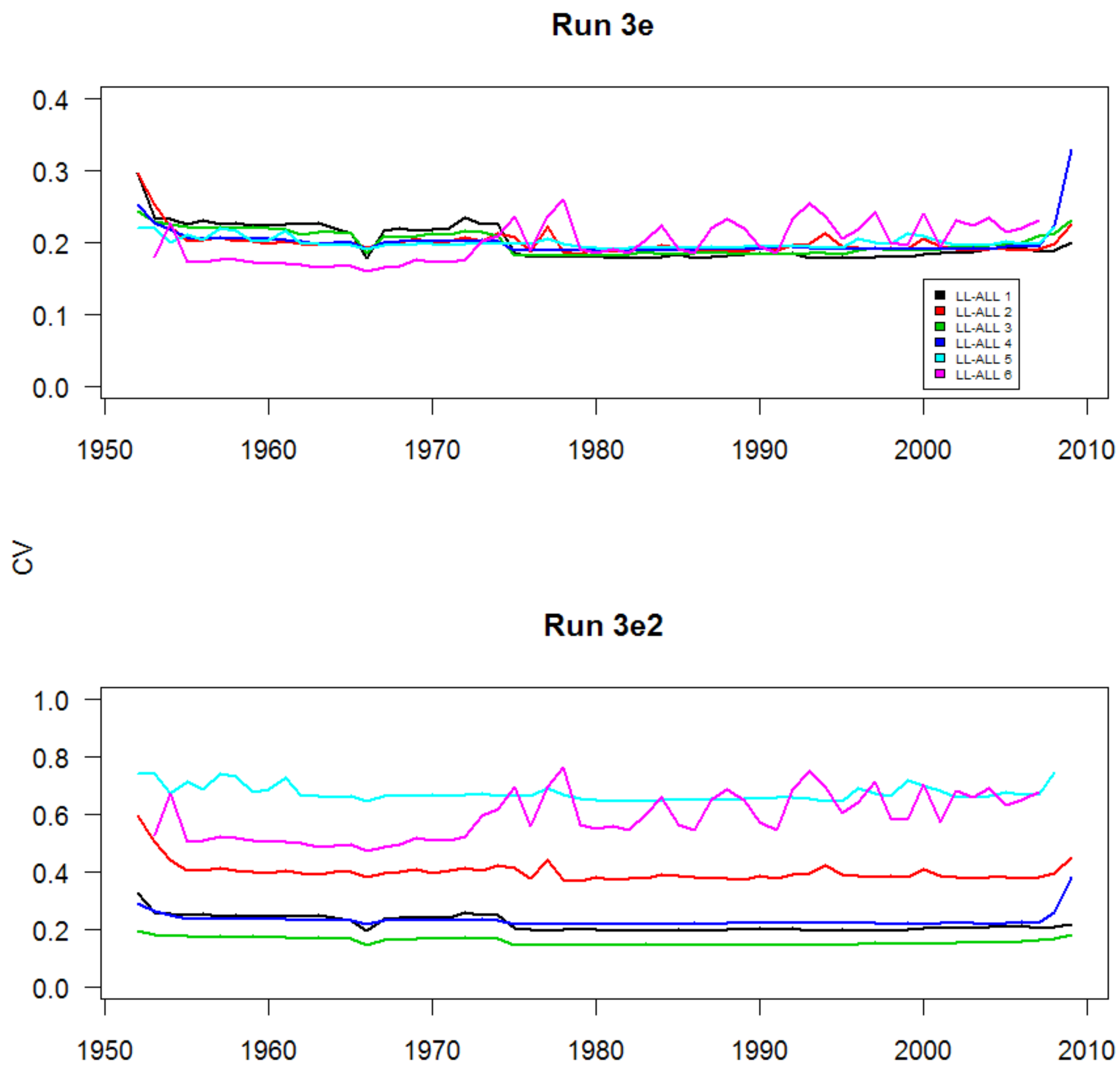


Figure 14: Assumed effort deviation CVs for the main LL-ALL fisheries assumed in model runs 3e (top) and run 3e2 (bottom). Note that the y-axes are not the same.

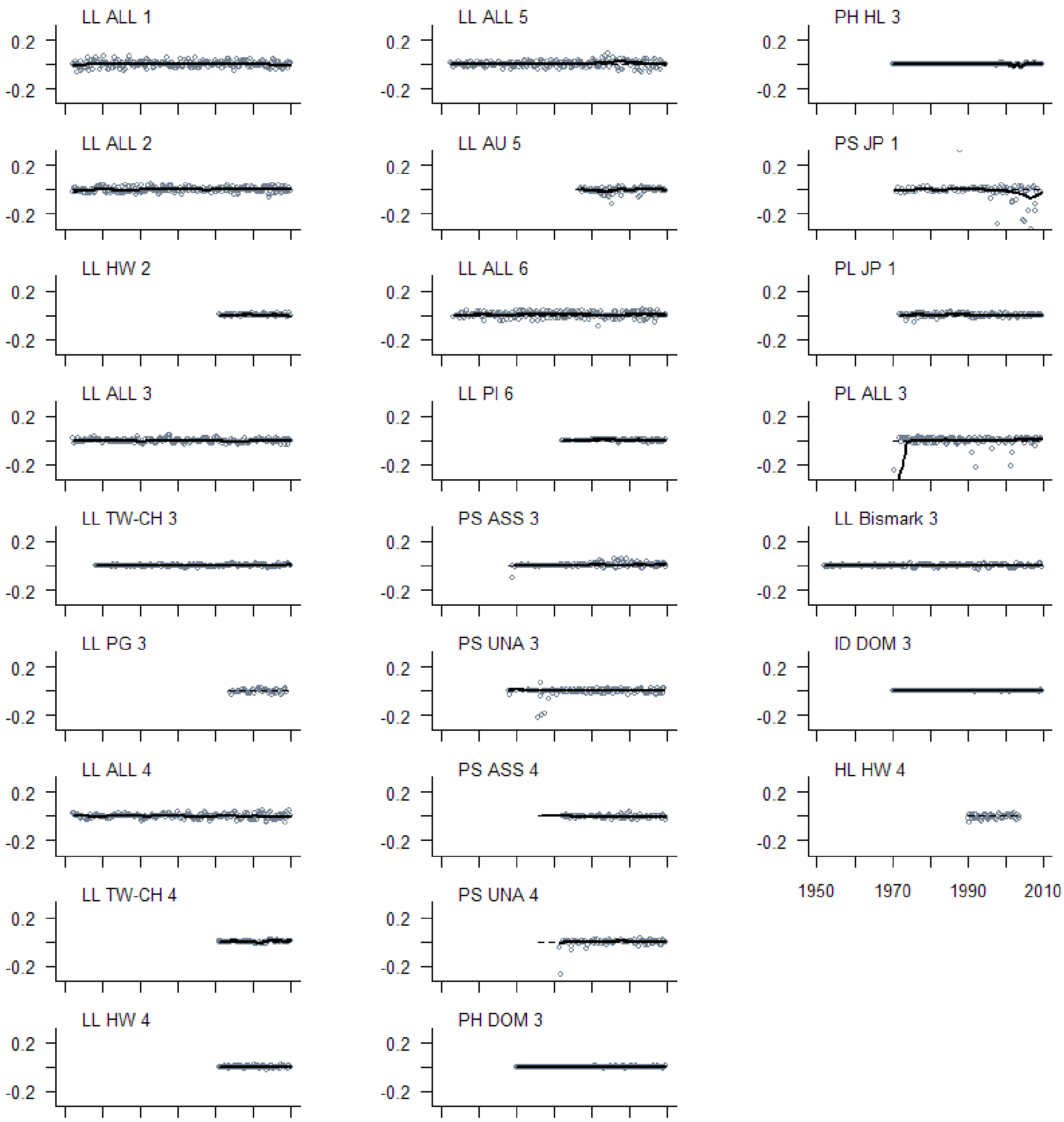


Figure 15. Residuals of ln (total catch) for each fishery (base-case model). The dark line represents a lowess smoothed fit to the residuals.

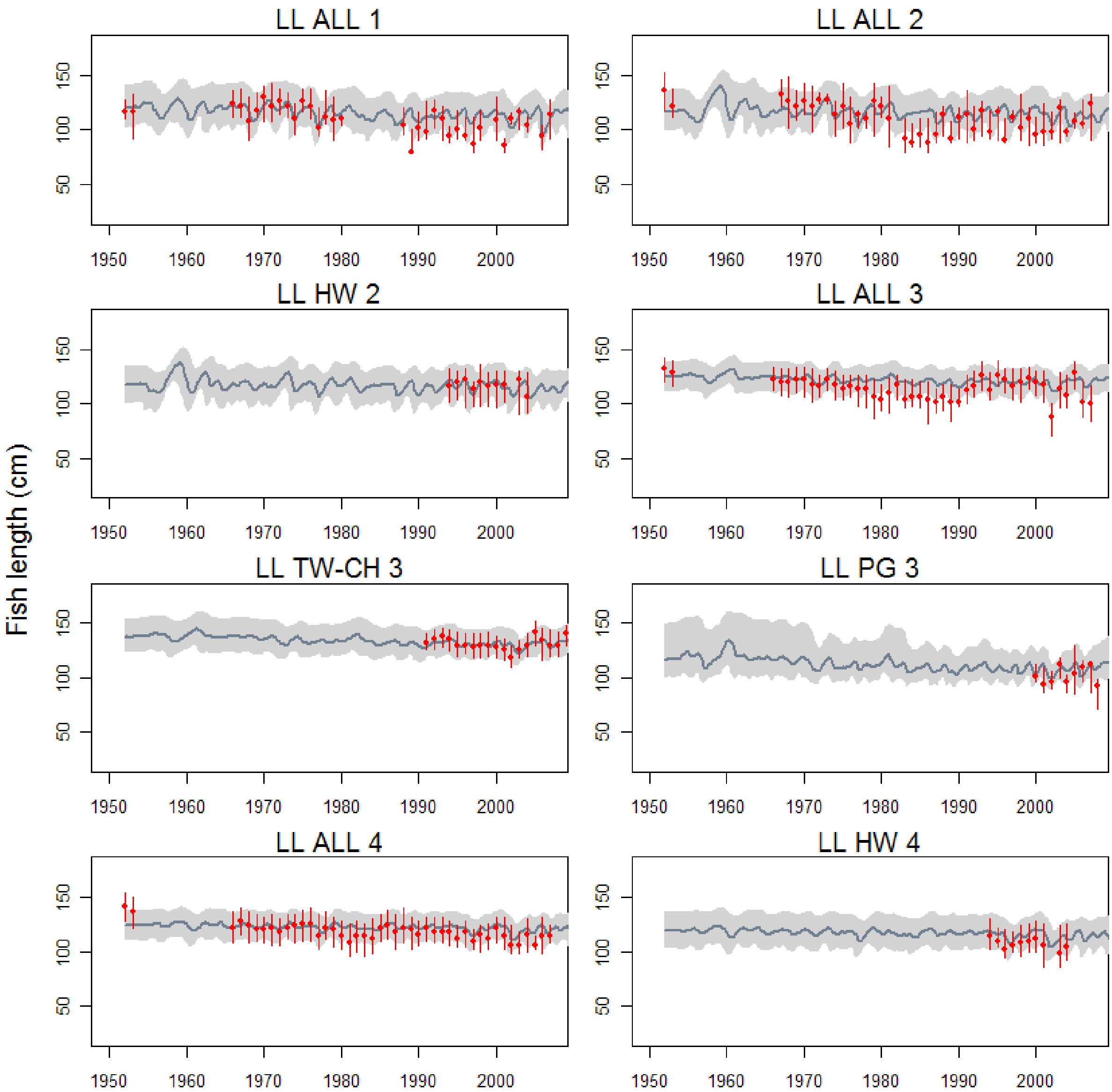


Figure 16. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of bigeye tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and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

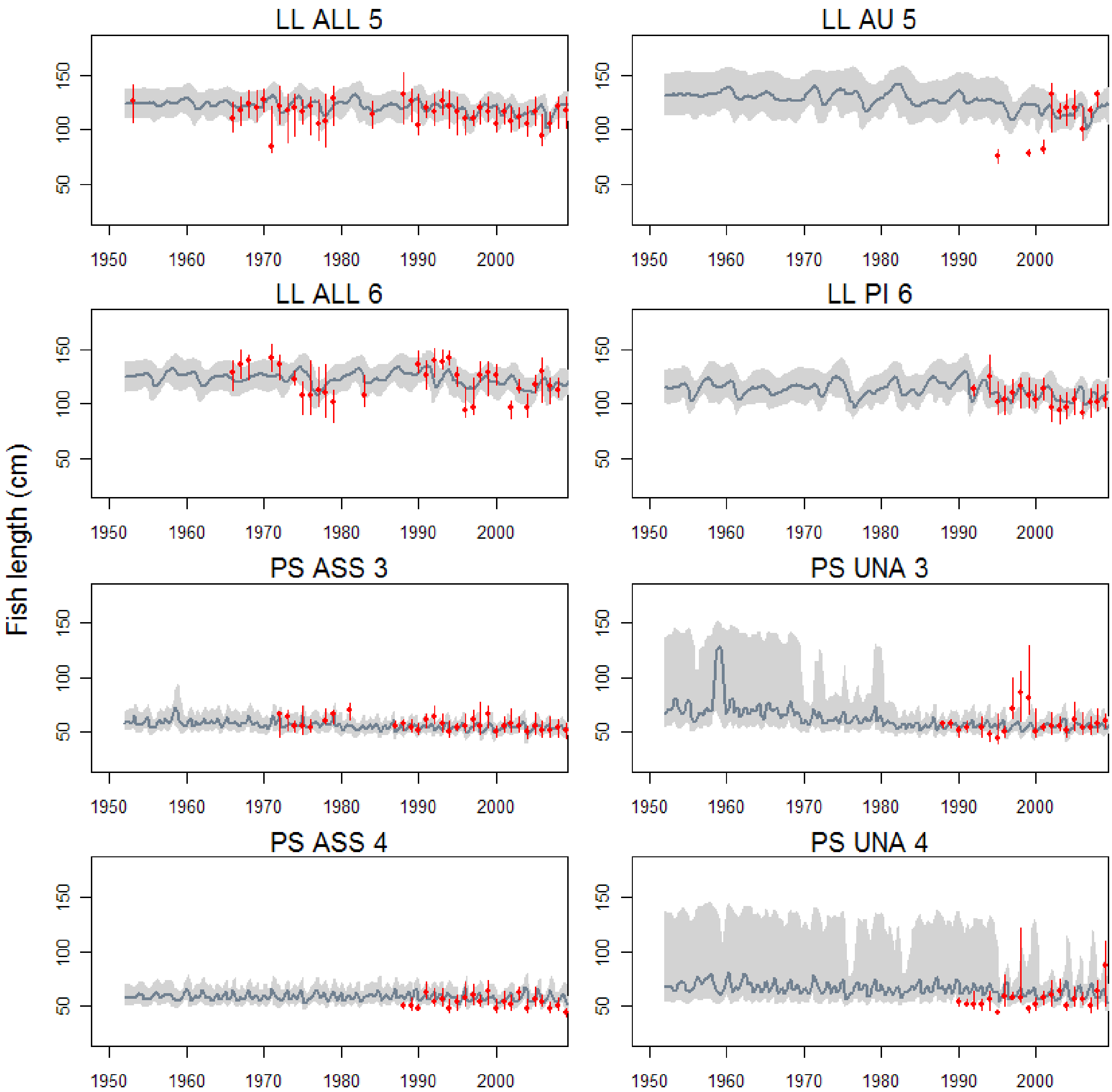


Figure 16 Continued.

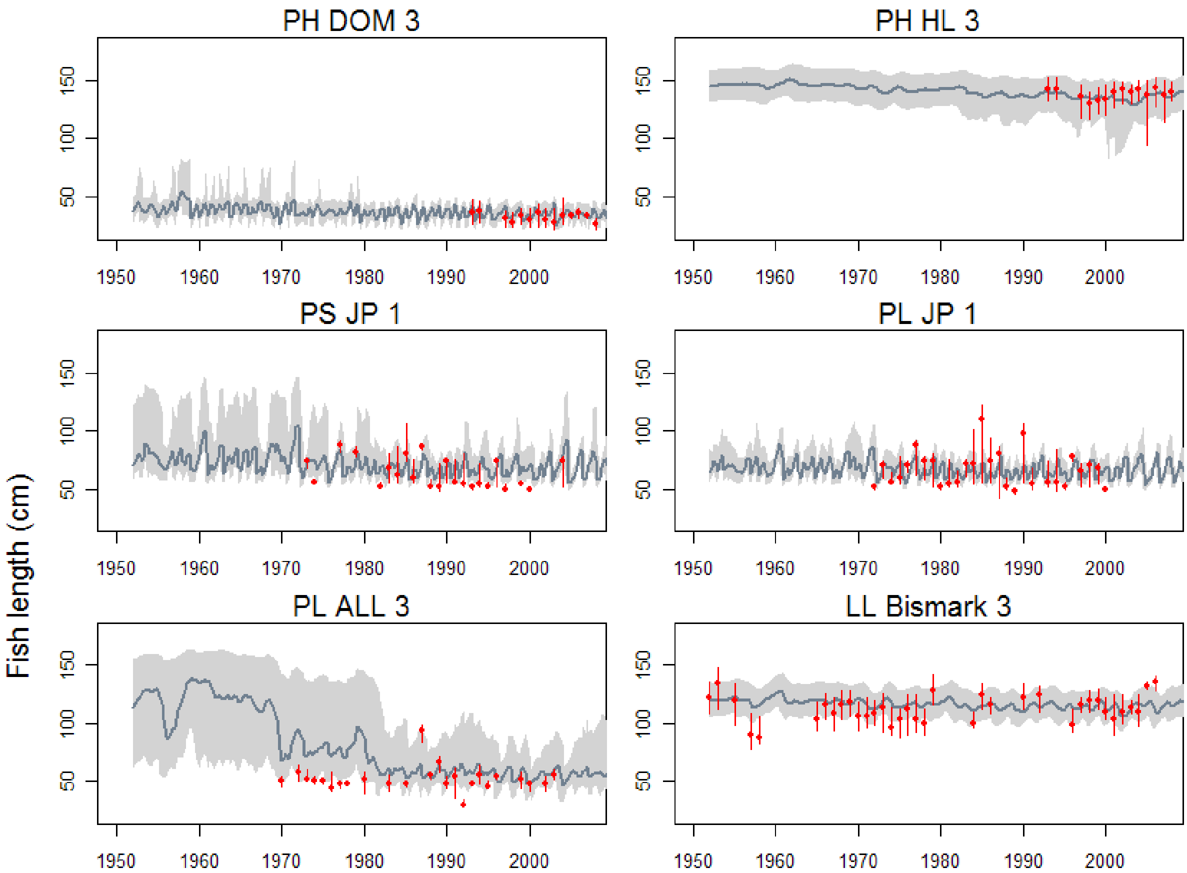


Figure 16. Continued.

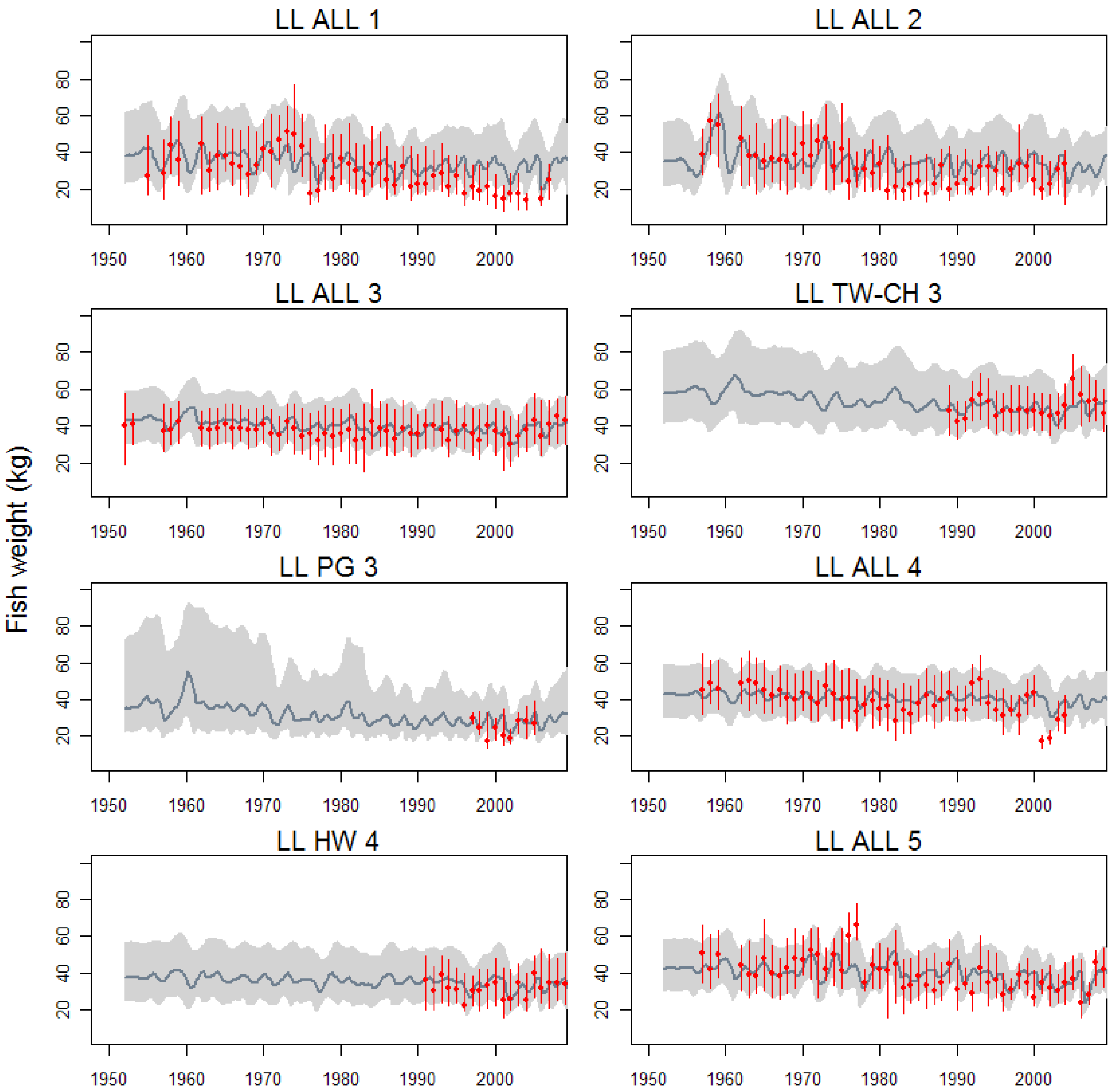


Figure 17. A comparison of the observed (red points) and predicted (grey line) median fish weight (whole weight, kg) of bigeye tuna by fishery for the main fisheries with weight data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only weight samples with a minimum of 30 fish per year are plotted.

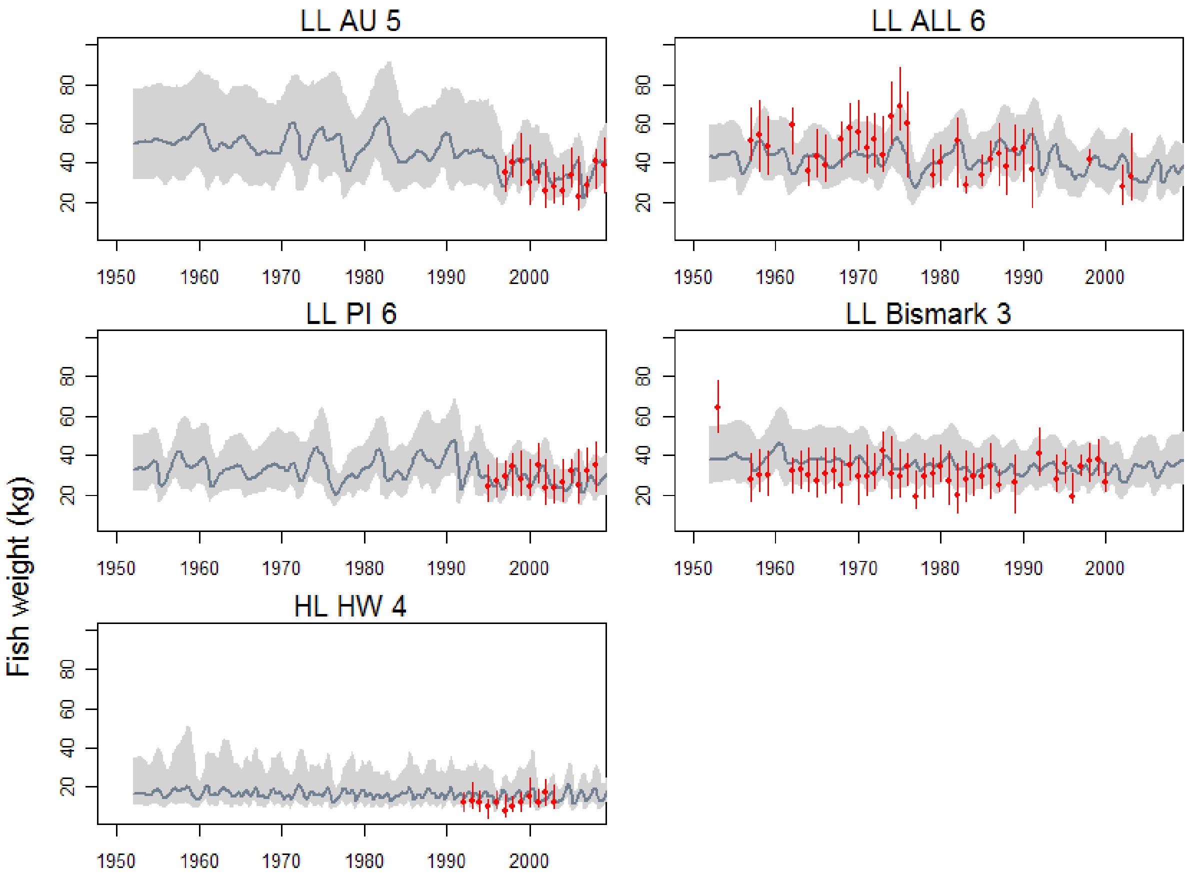


Figure 17. Continued.

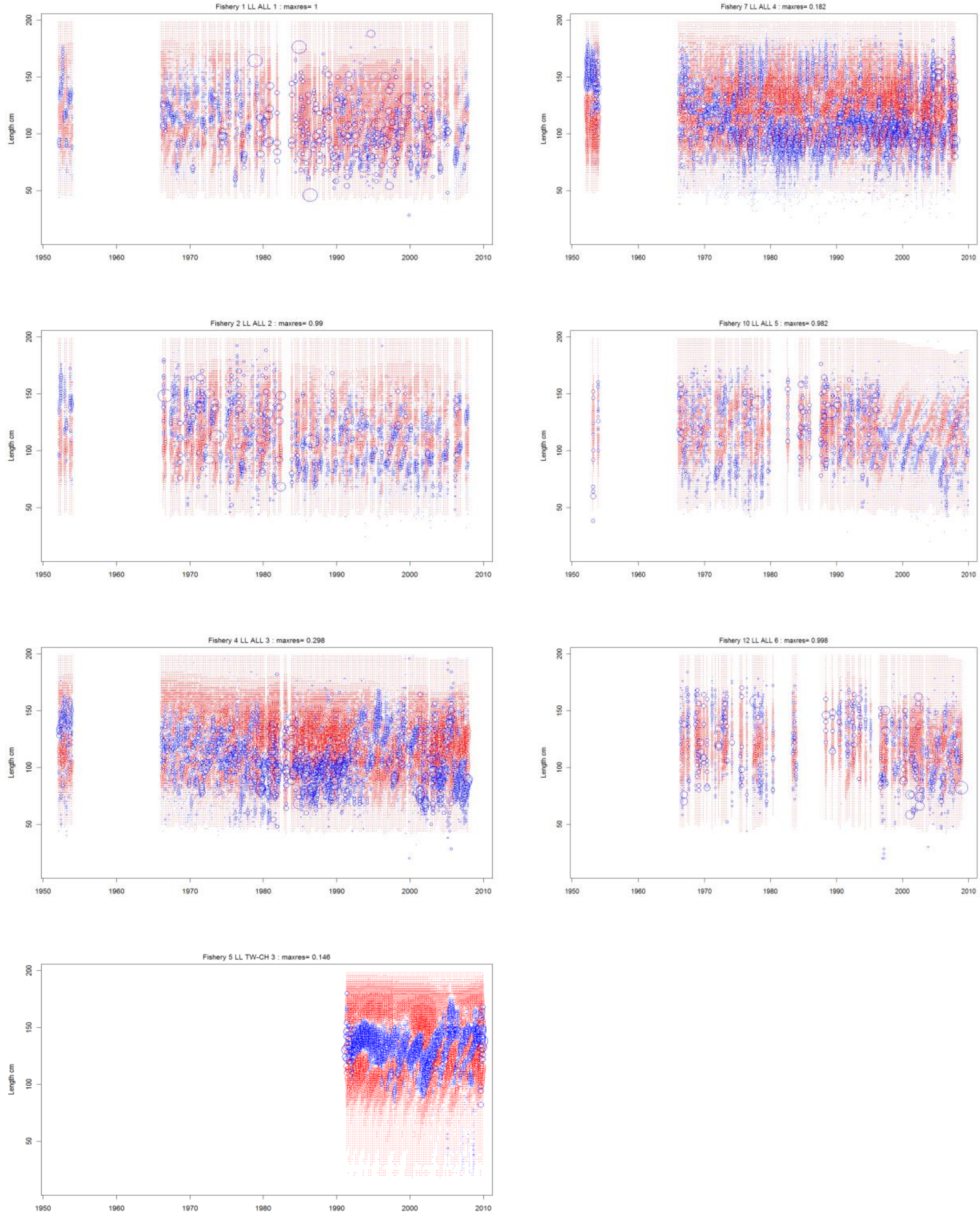


Figure 18: Residual plots of the fit to the length frequency data for the major longline fisheries for run 3d. Positive residuals (more fish presented than predicted) are shown in blue and negative residuals in red. The diameter of circle is proportional to the square root of the residual.

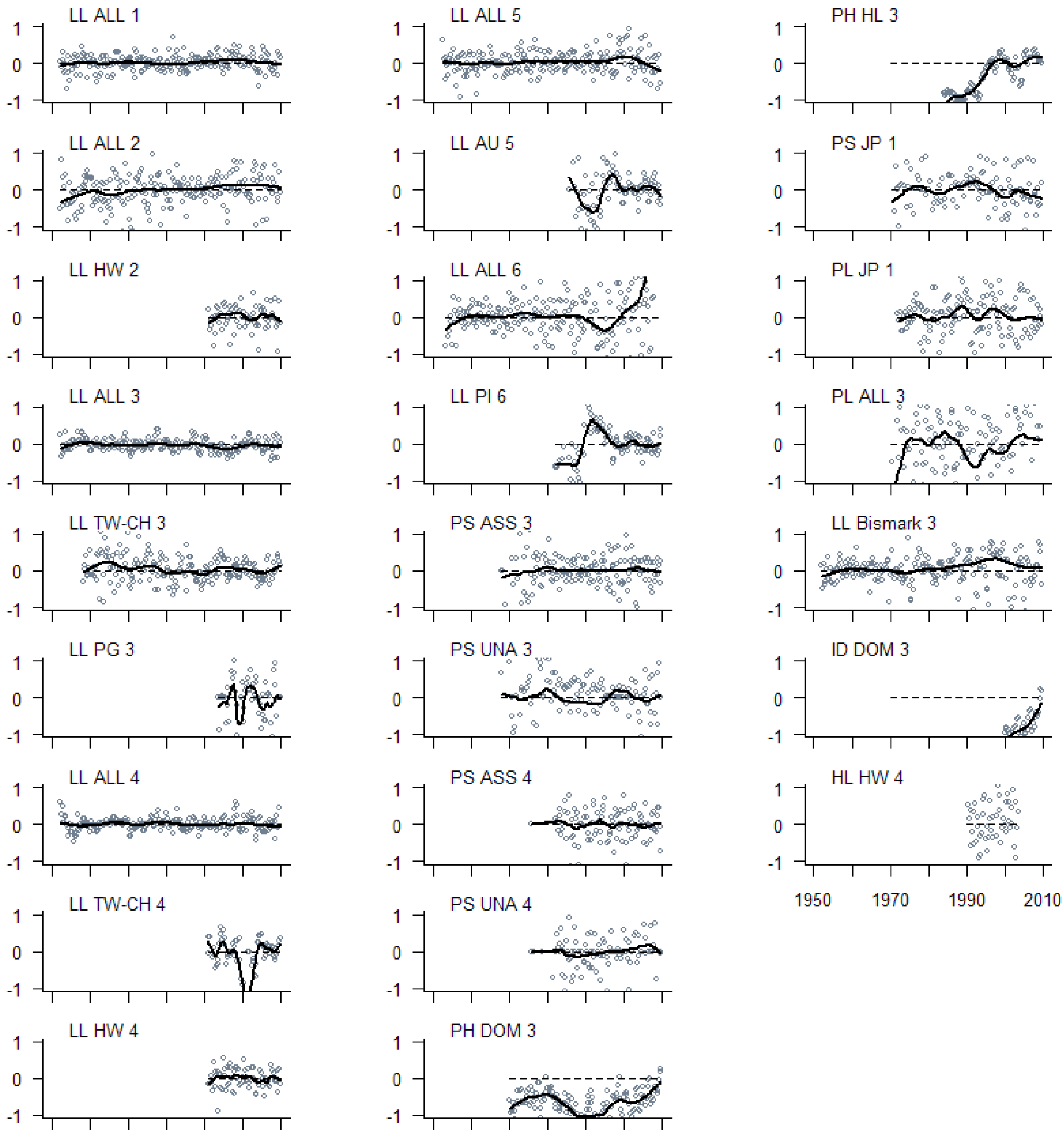


Figure 19. Effort deviations by time period for each fishery (base-case model). For fisheries with longer time series, the dark line represents a lowess smoothed fit to the effort deviations. Some values lie outside the bounds of the plot.

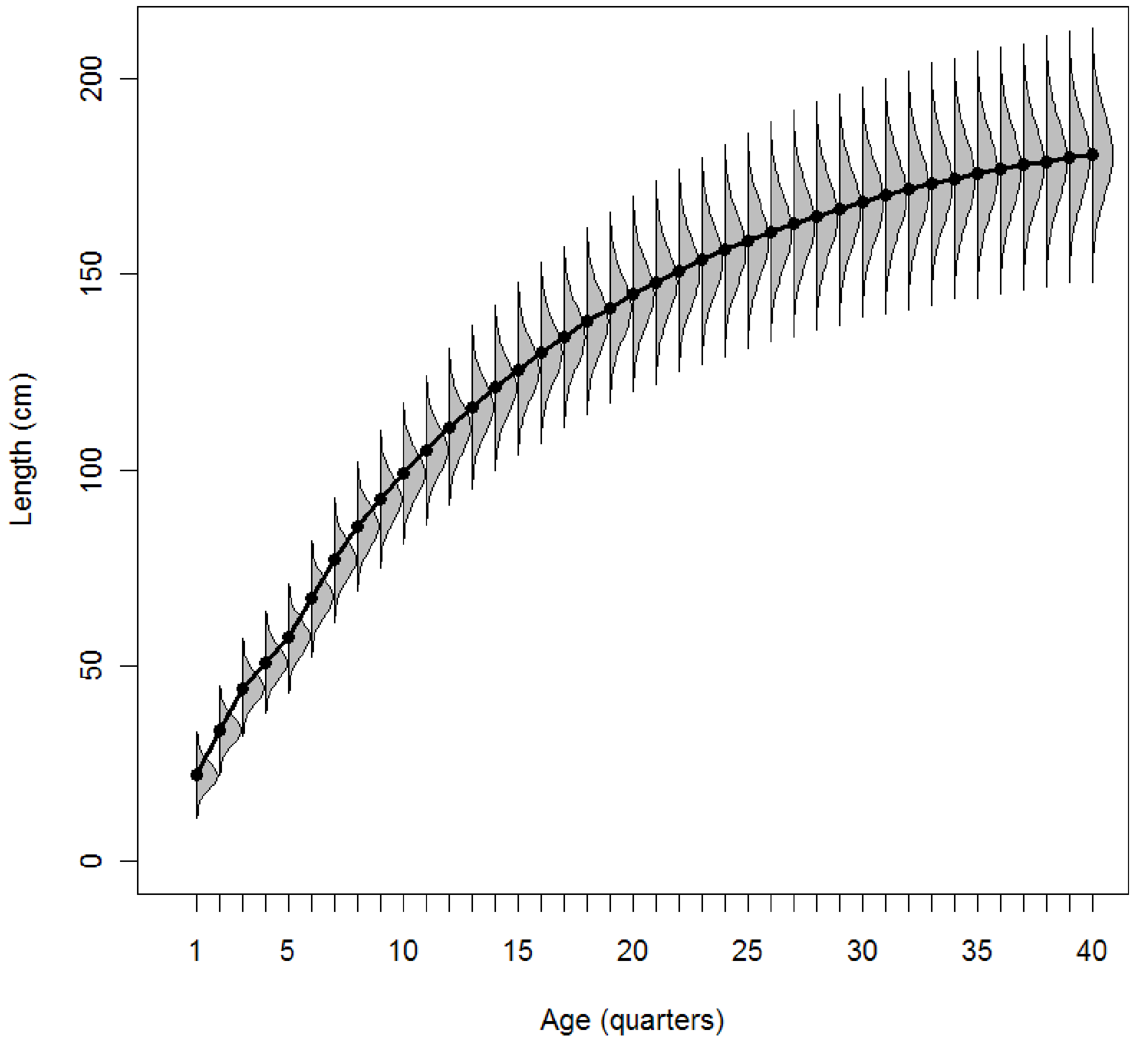


Figure 20. Estimated growth of bigeye derived from the assessment model. The black line represents the estimated mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age.

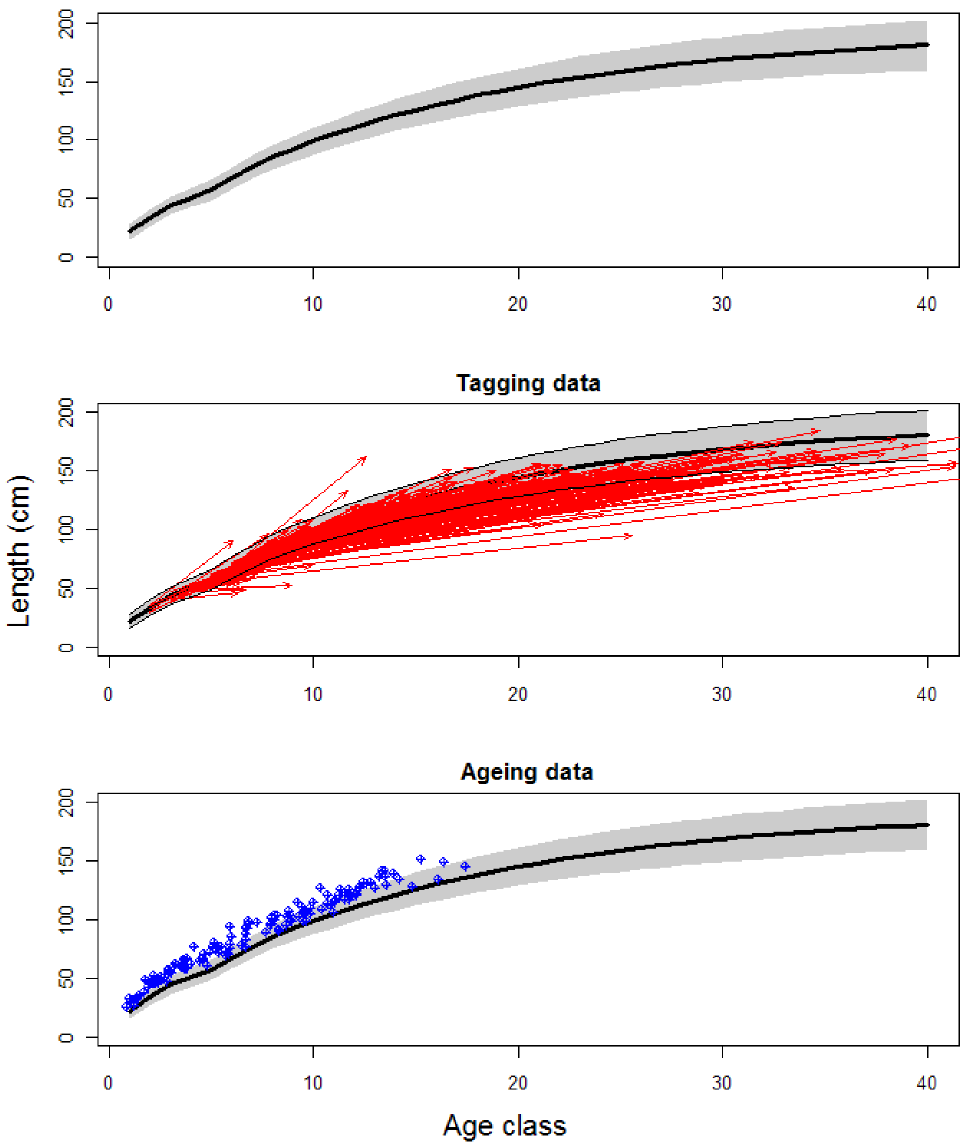


Figure 21. Estimated mean lengths-at-age (heavy line) and the variability of length-at-age (shaded area represents ± 2 SD). Age is in quarters and length is in cm. For comparison, length at age estimates are presented from tag release and recapture data (middle figure) and empirical age determination 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.

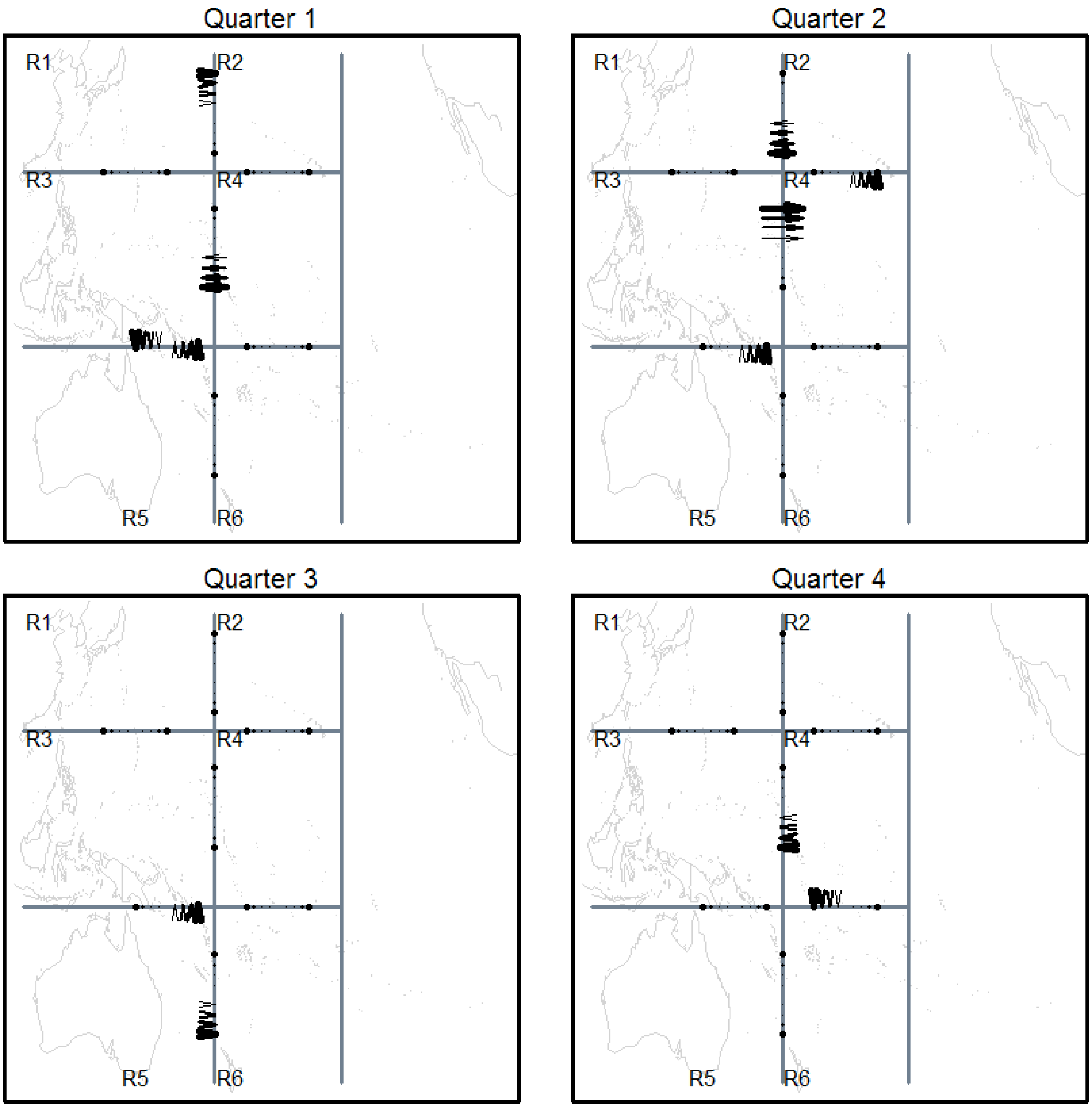


Figure 22. Estimated quarterly movement coefficients at age (1, 10, 20, 30 quarters). The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age. The largest percentage movement was 7%, from Region 3 to Region 4 during quarter 2.

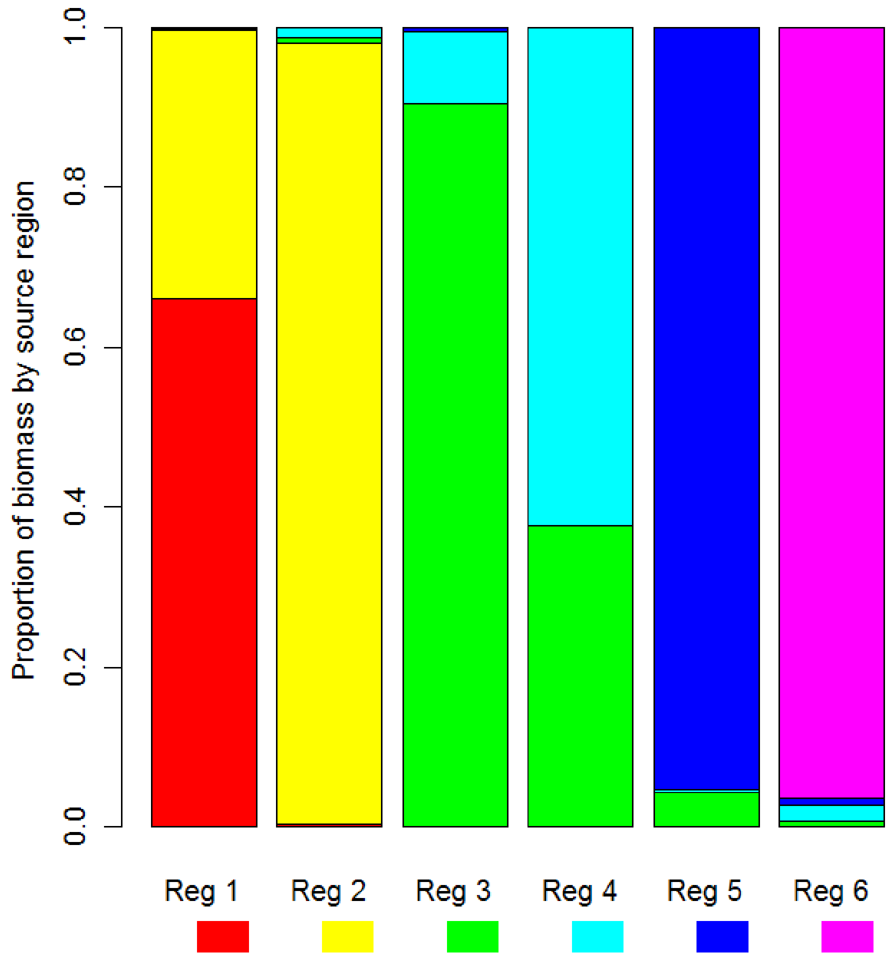


Figure 23. Proportional distribution of total biomass (by weight) in each region (Region 1–6) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution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

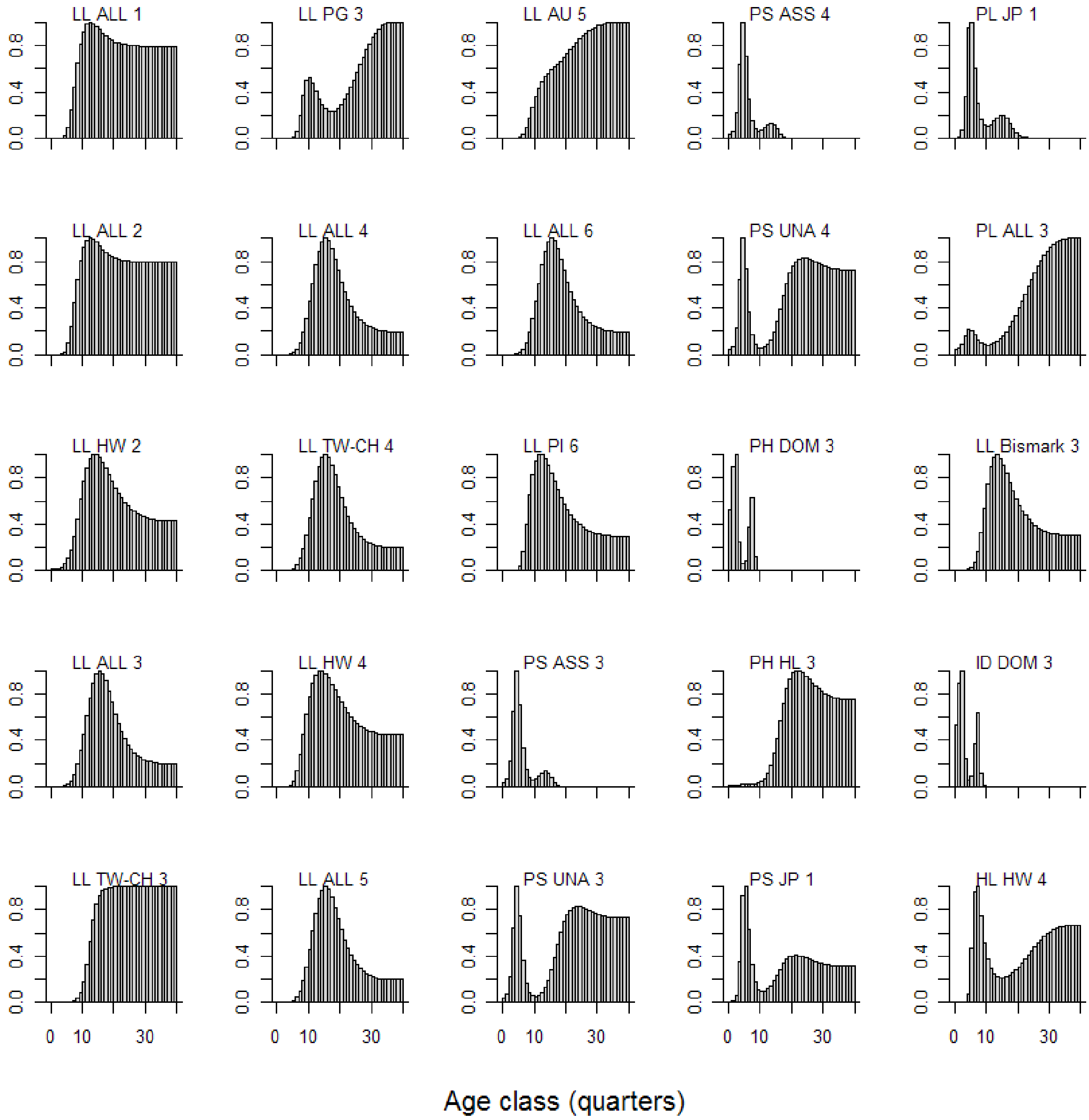


Figure 24. Selectivity coefficients, by fishery.

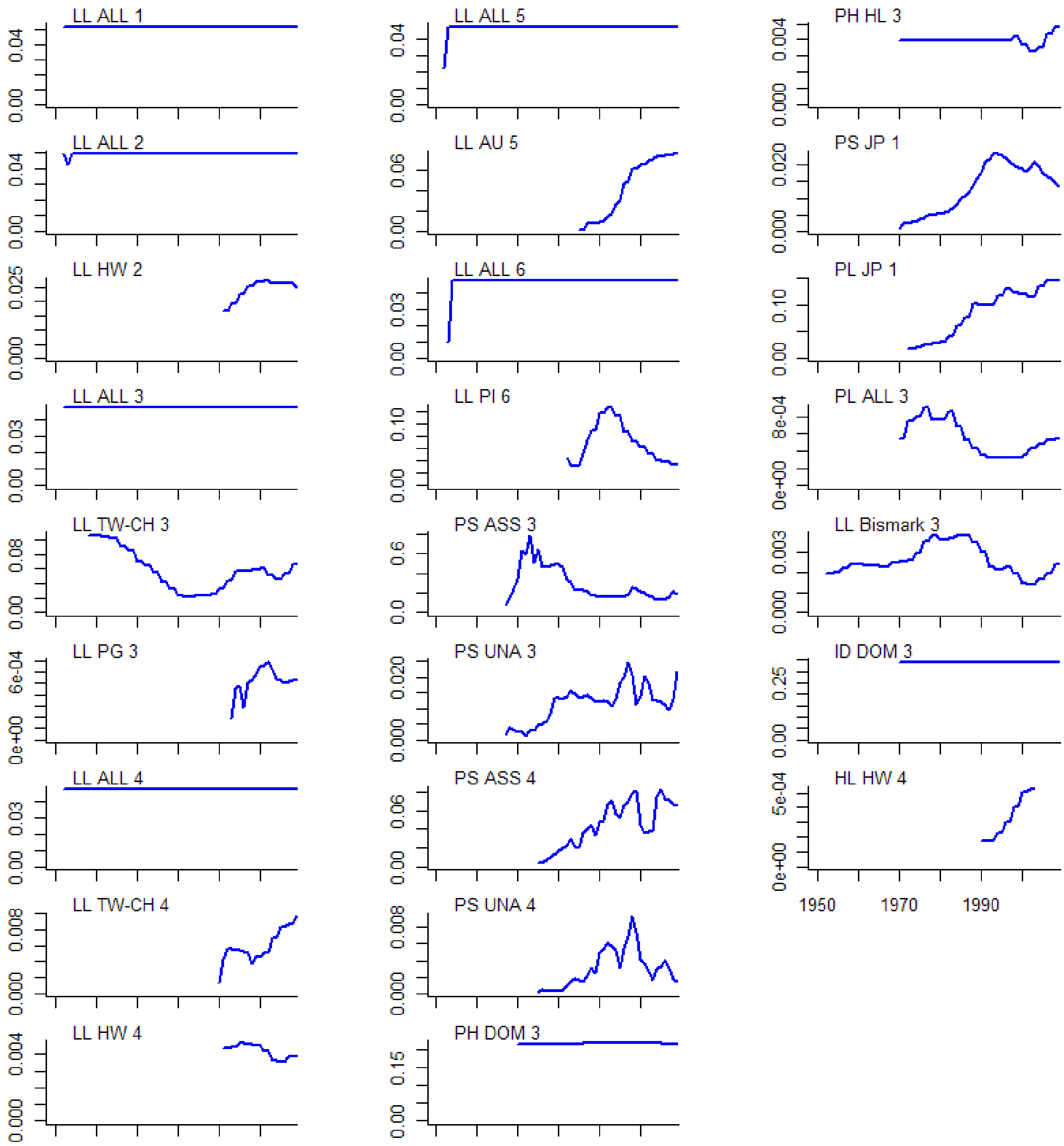


Figure 25. Average annual catchability time series, by fishery.

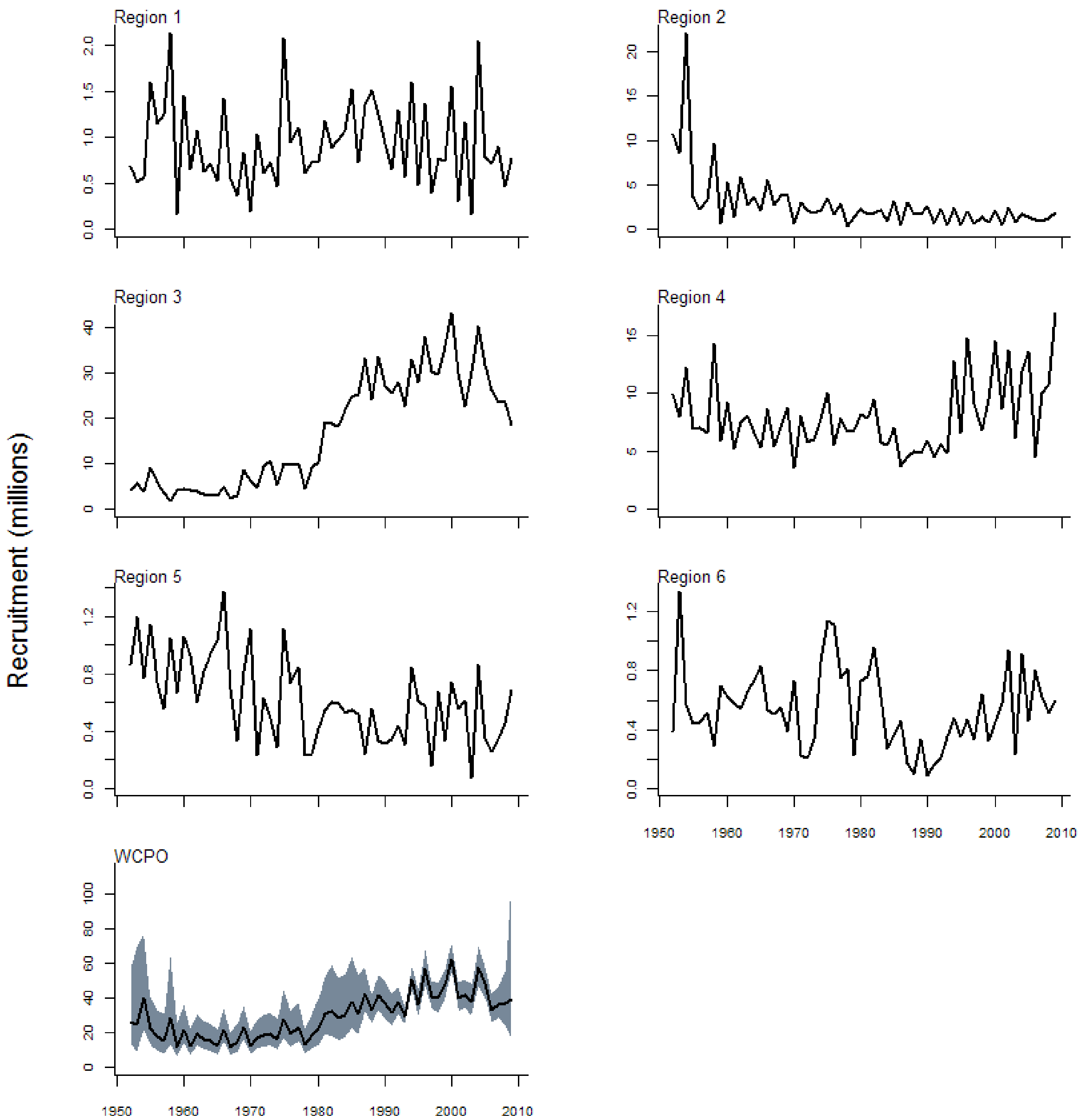


Figure 26. Estimated annual recruitment (millions) by region and for the WCPO. The shaded areas indicate the approximate 95% confidence intervals.

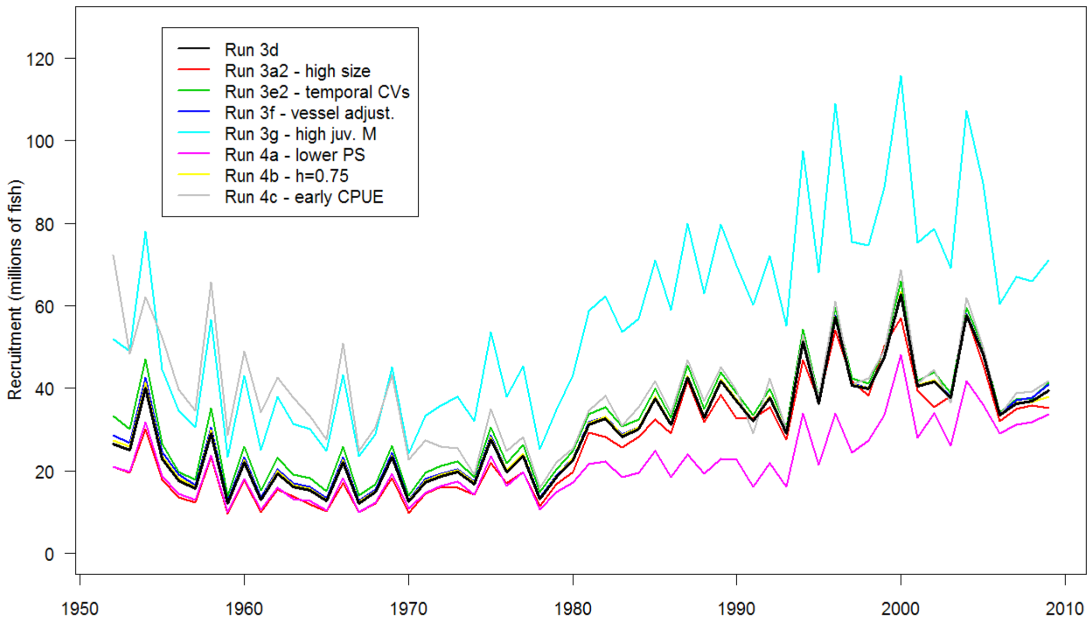


Figure 27. Estimated annual recruitment (millions of fish) for the WCPO obtained from the key model runs.

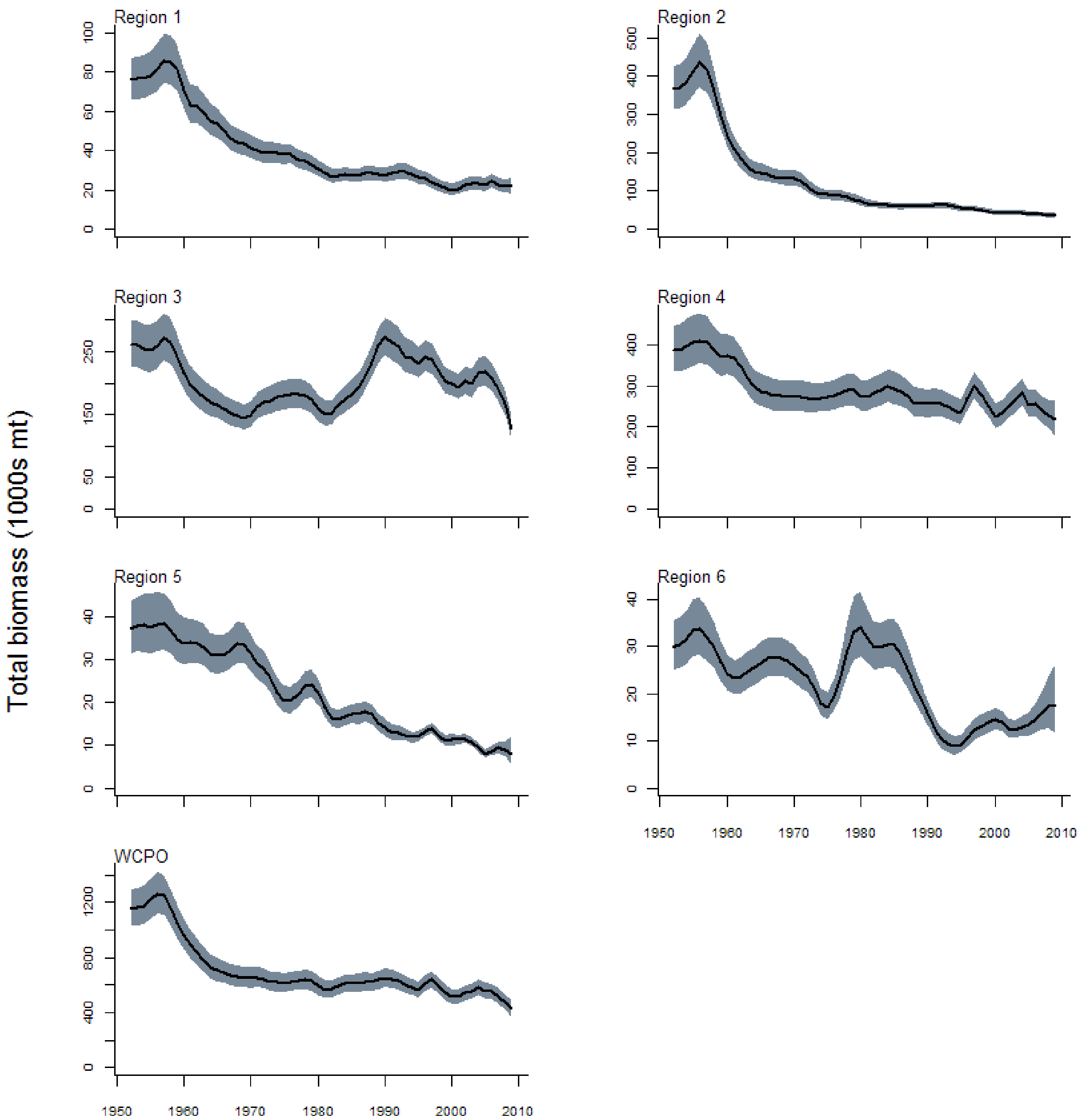


Figure 28. Estimated annual average total biomass by region and for the WCPO. The shaded areas indicate the approximate 95% confidence intervals.

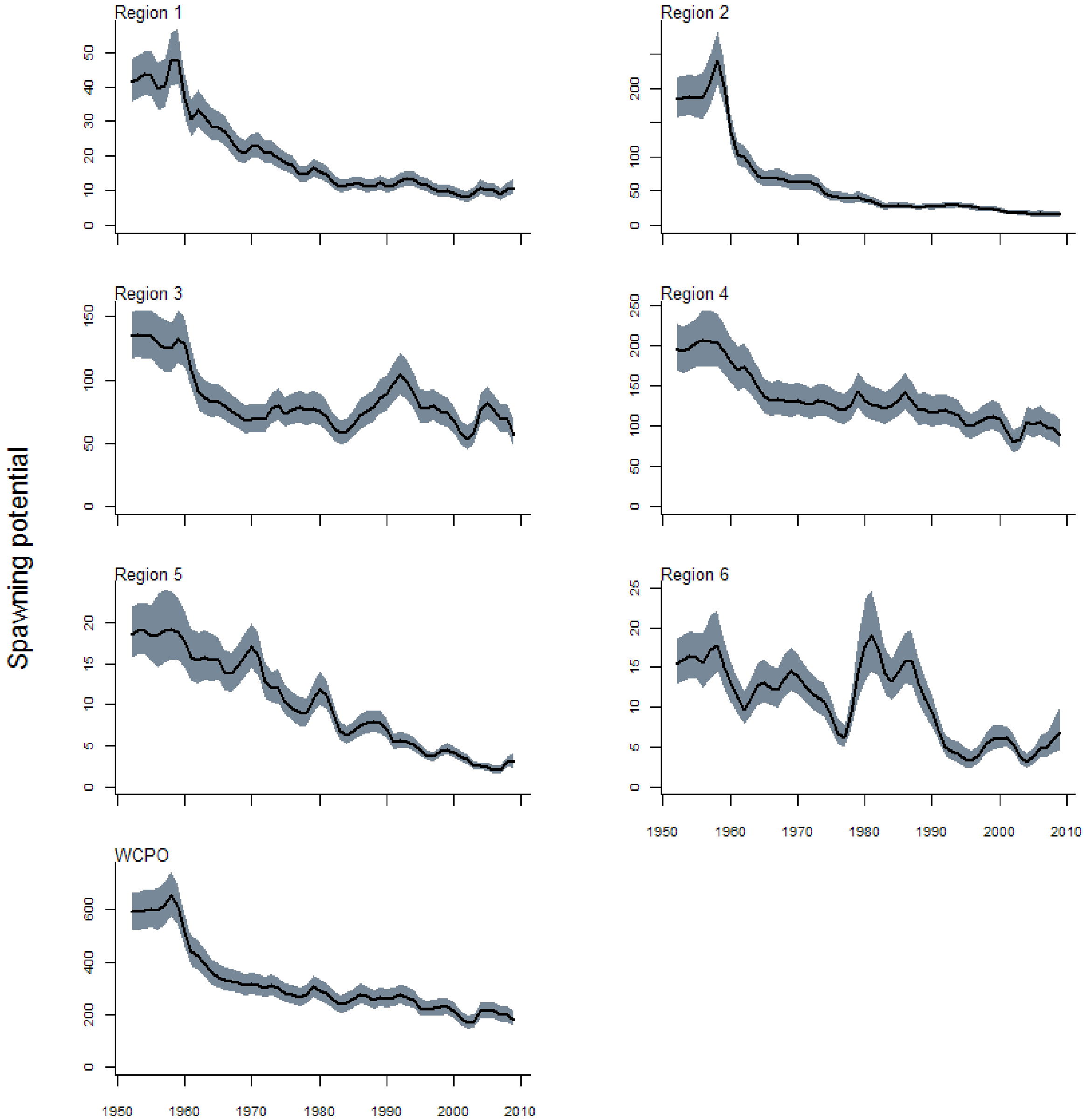
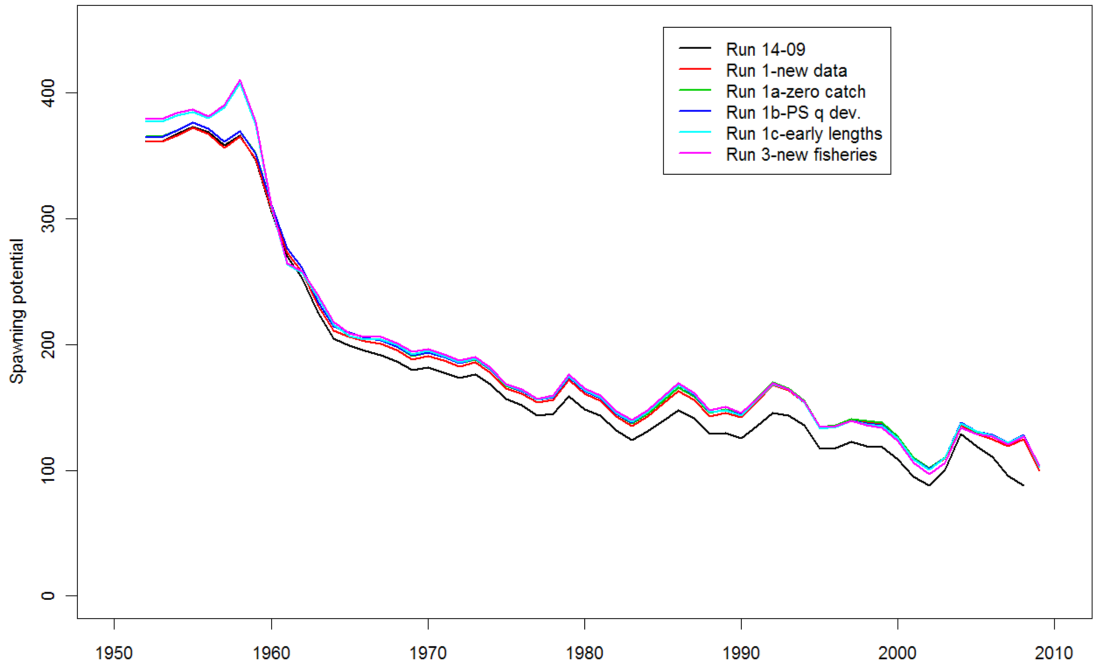


Figure 29. Estimated annual average spawning potential by region and for the WCPO. The shaded areas indicate the approximate 95% confidence intervals.



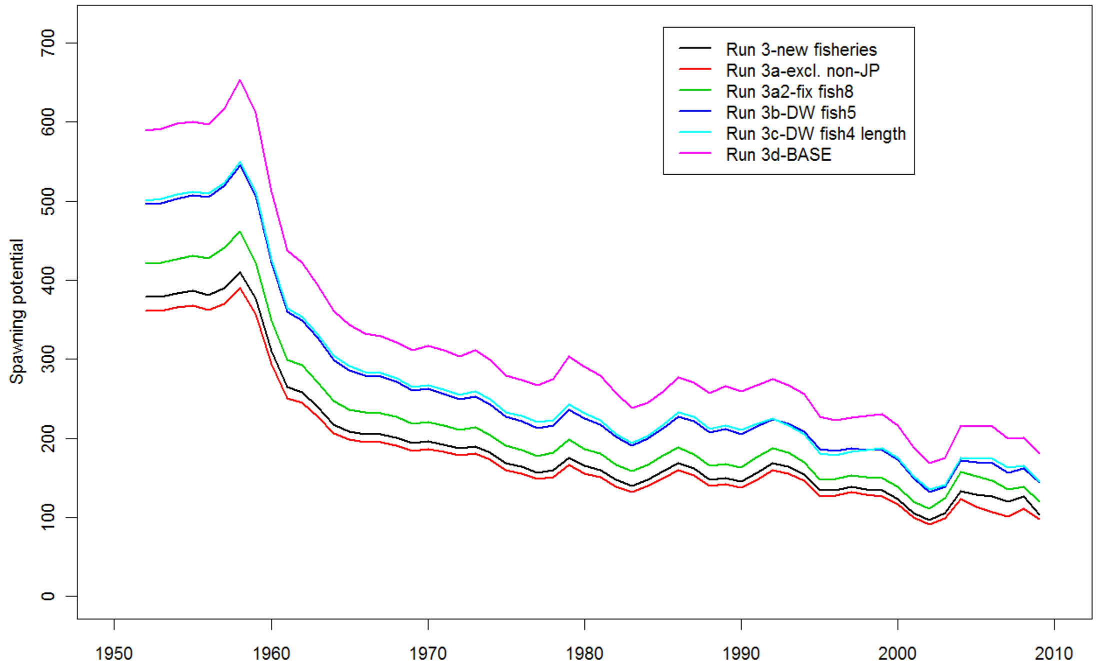


Figure 30. Estimated annual average spawning potential for the WCPO obtained from runs undertaken in the stepwise development of run 3d.

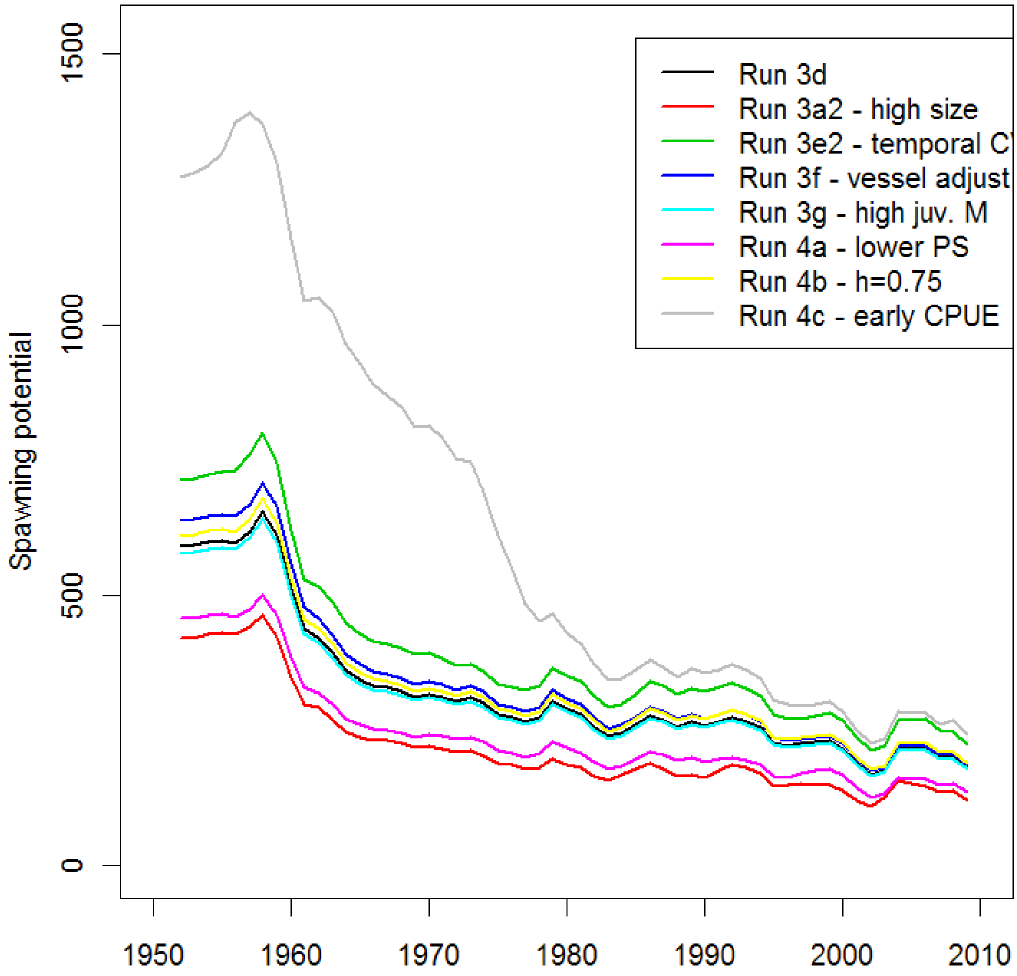
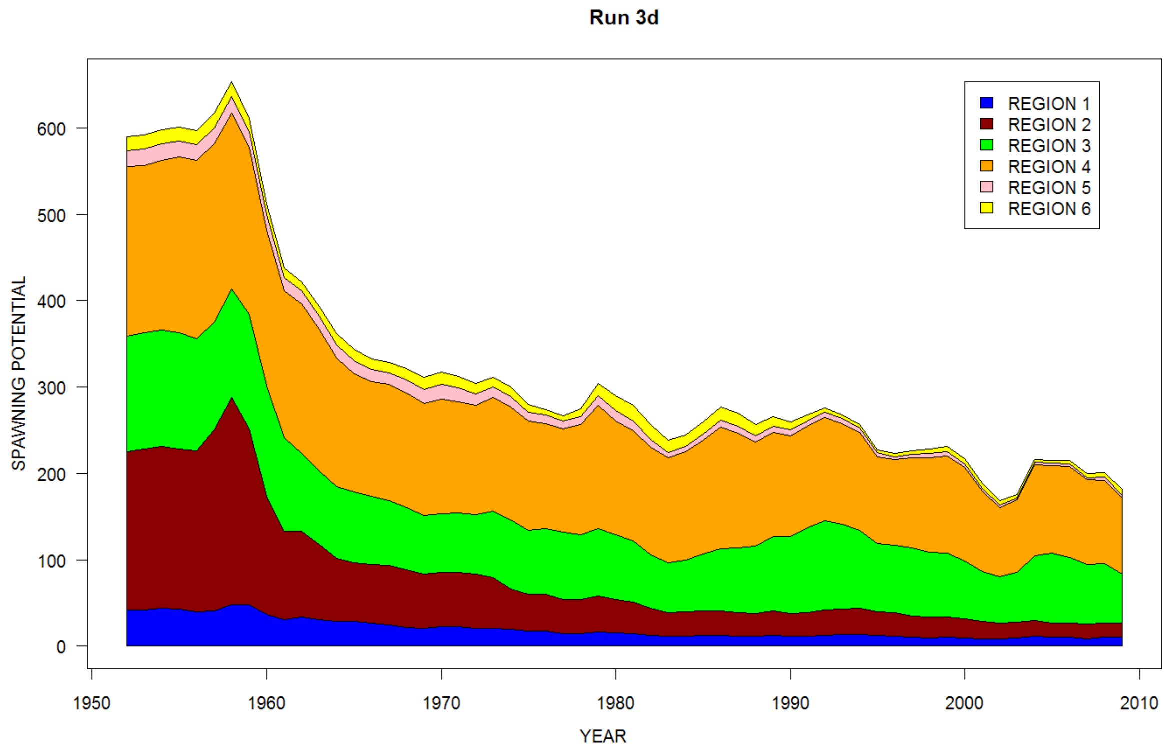


Figure 31. Estimated average annual spawning potential for the WCPO obtained from the key model runs.



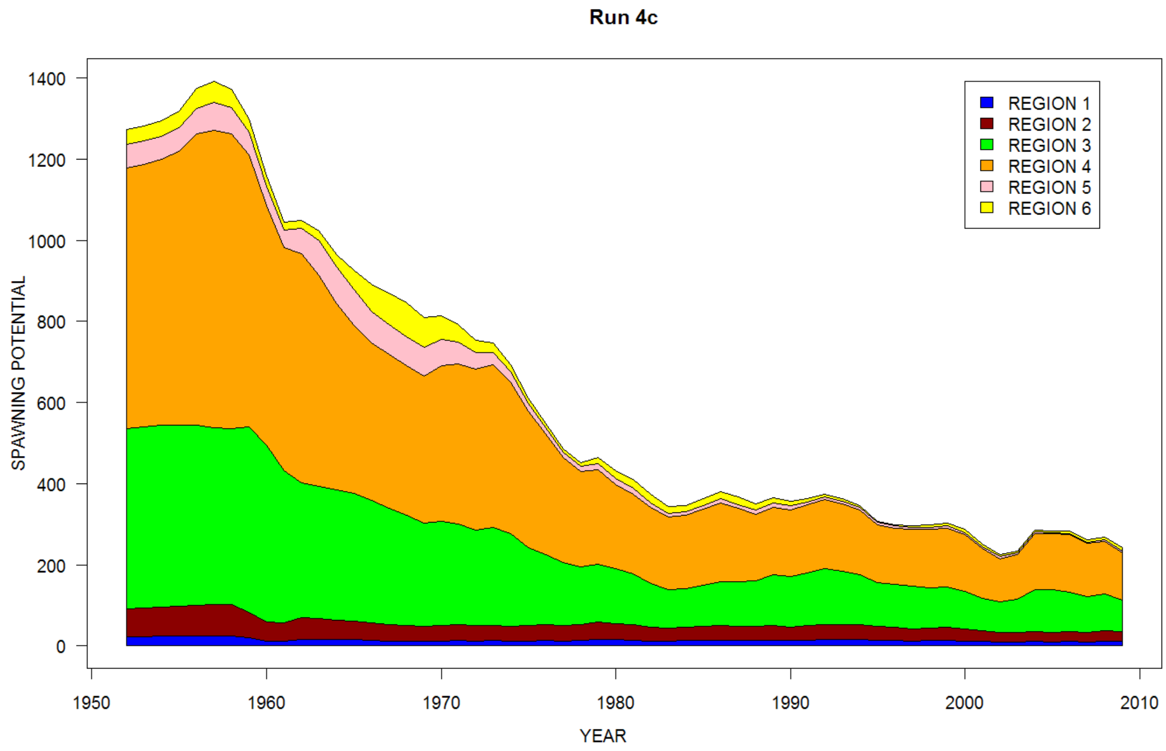


Figure 32. Estimated average annual spawning biomass by model region for run 3d (top) and run 4c (early CPUE – bottom).

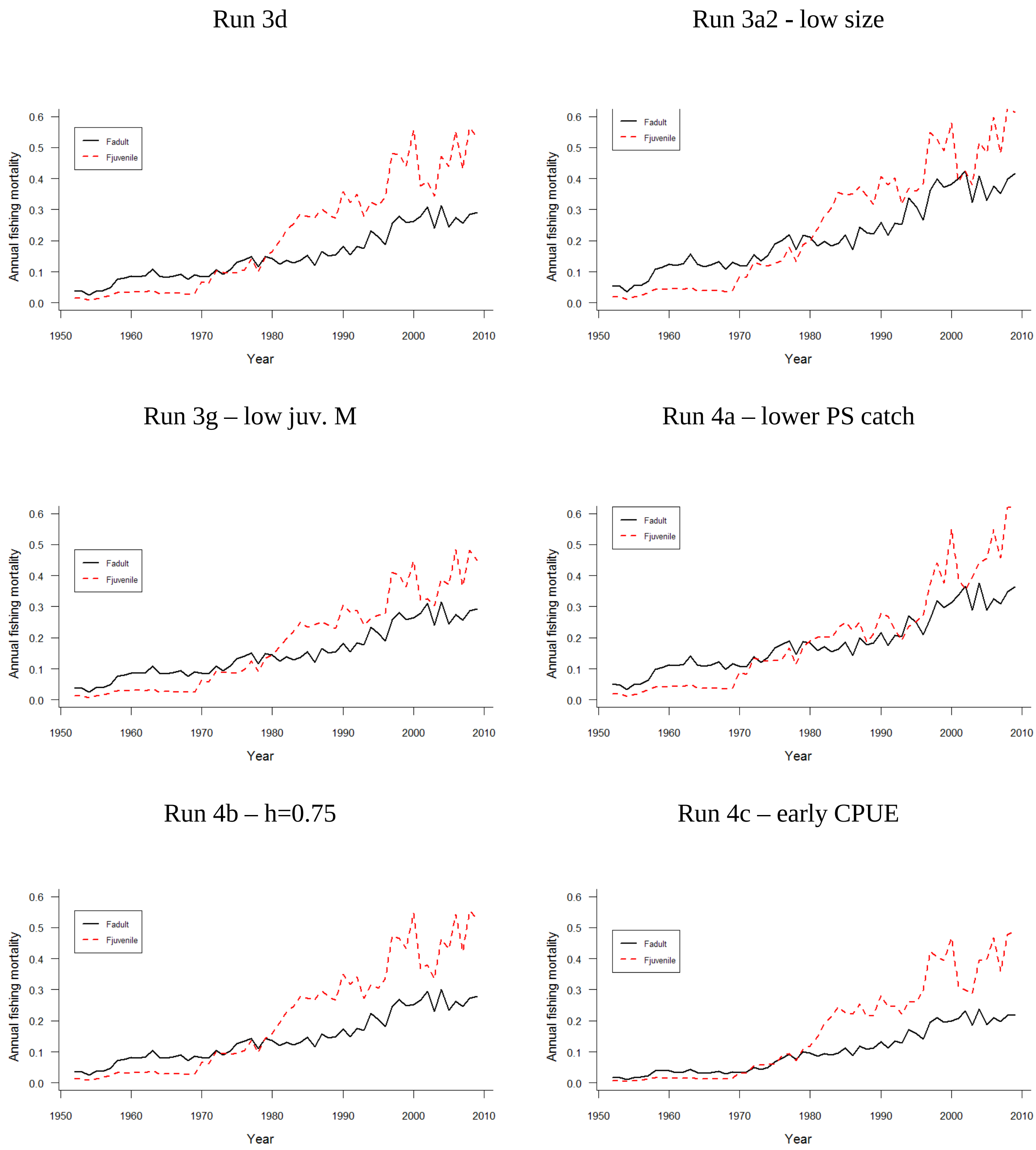


Figure 33. Estimated annual average juvenile and adult fishing mortality for the WCPO obtained from the key model runs.

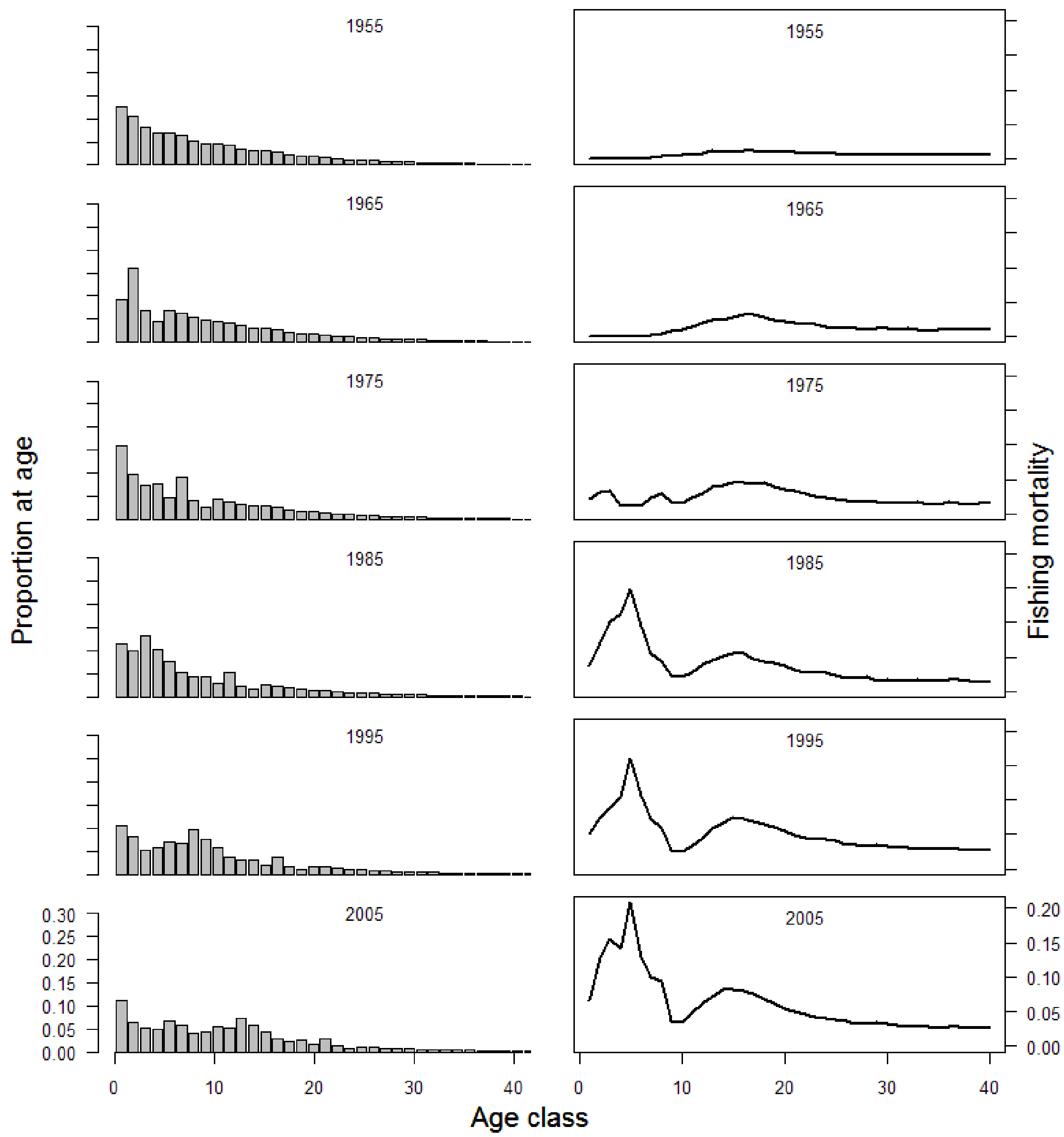


Figure 34. Estimated proportion at age (quarters) for the WCPO bigeye population (left) and fishing mortality at age (right) by year at decade intervals.

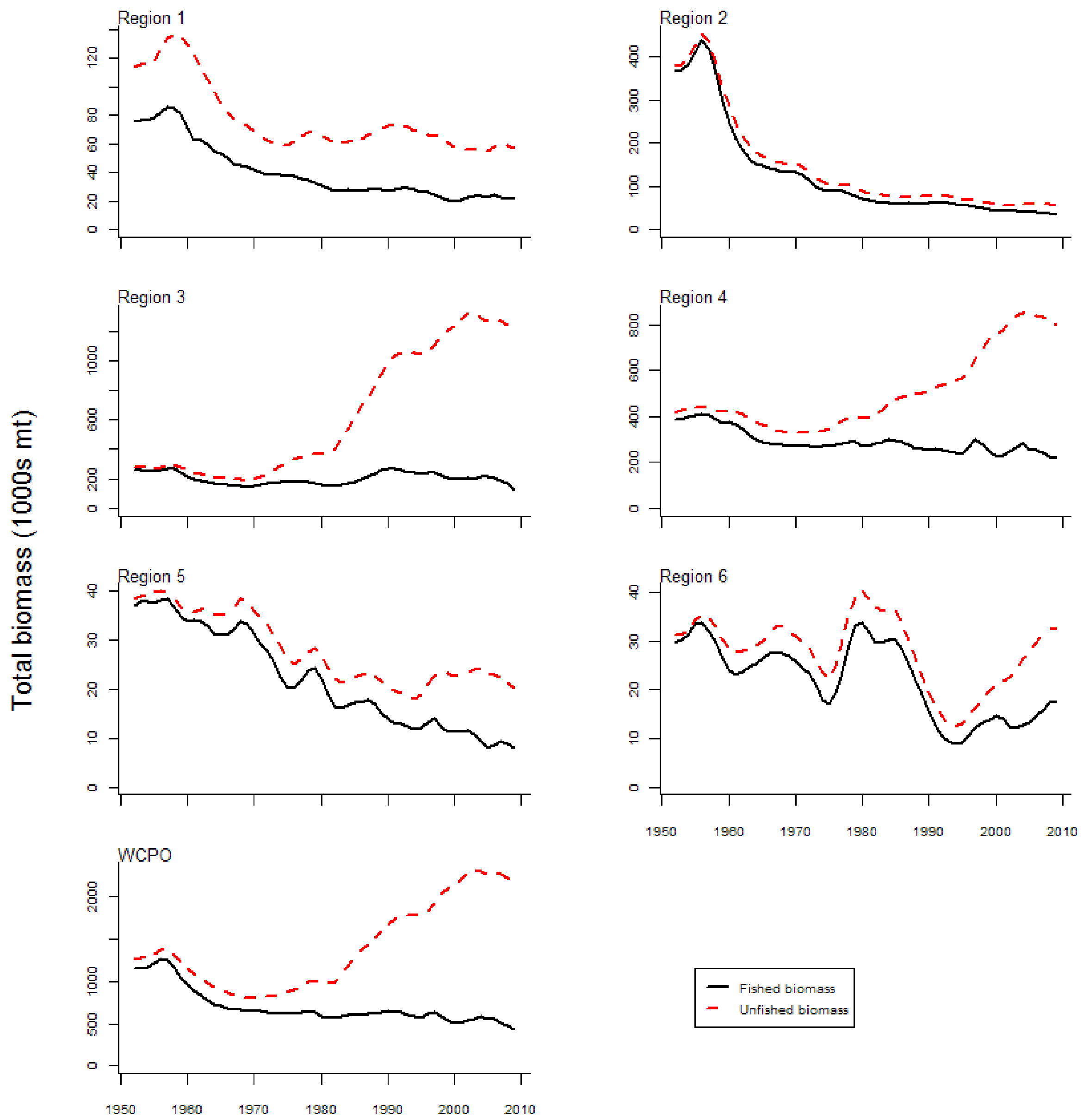


Figure 35. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper dashed lines) for each region and for the WCPO (base case model).

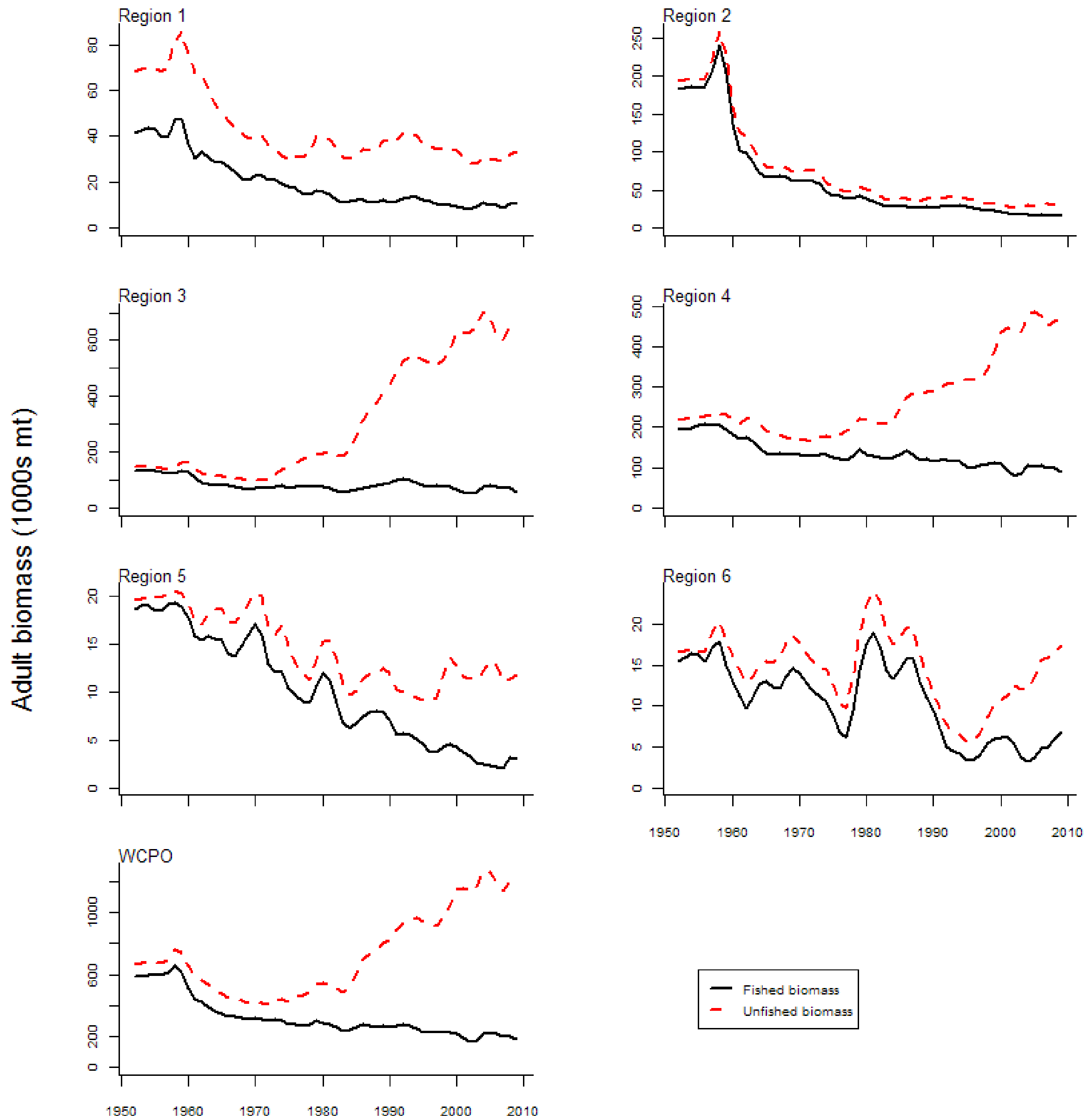


Figure 36. Comparison of the estimated adult biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper dashed lines) for each region and for the WCPO (base case model).

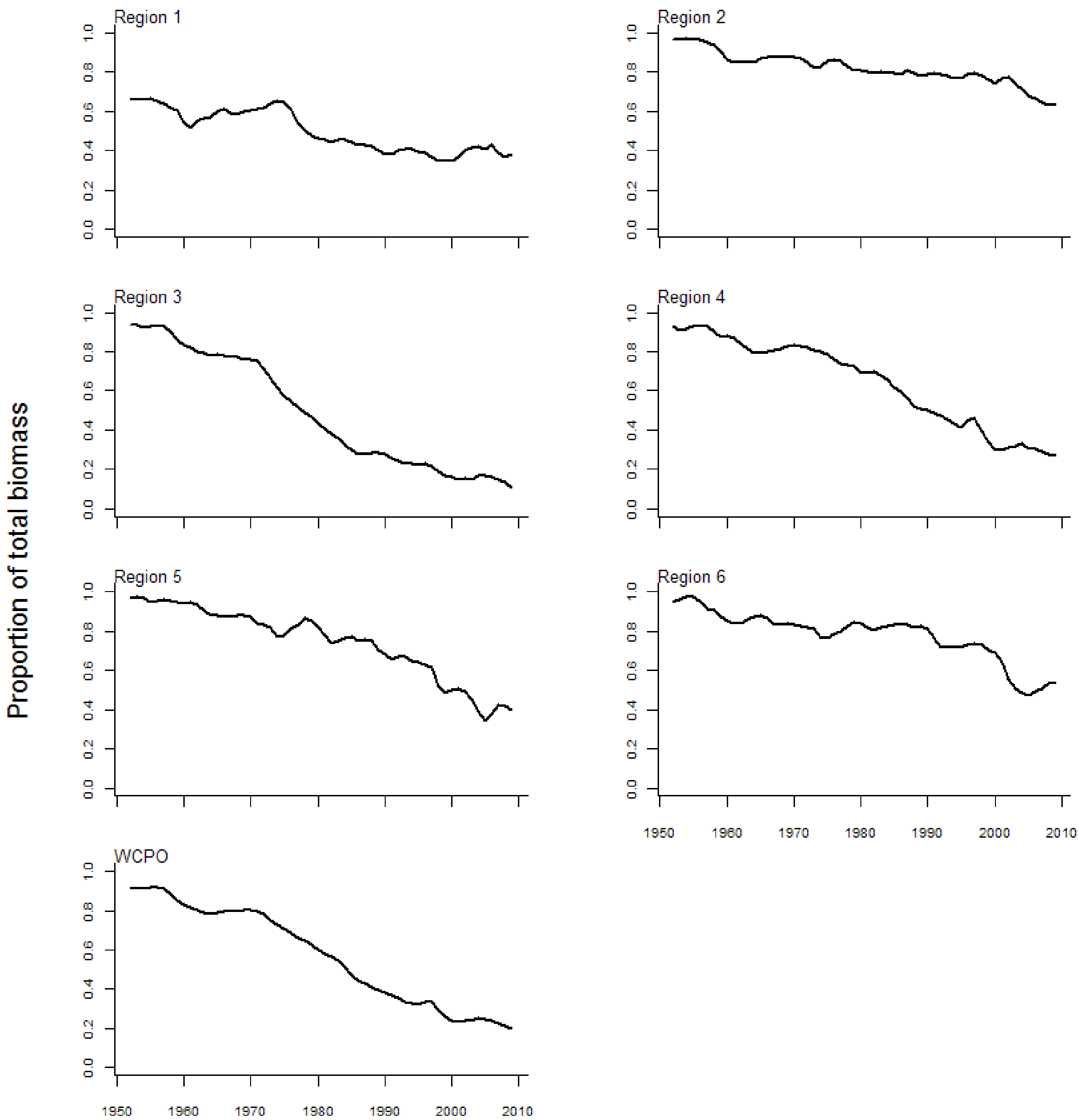


Figure 37. Ratios of exploited to unexploited total biomass $\boldsymbol{B_t/B_{t_{F=0}}}$ for each region and the WCPO.

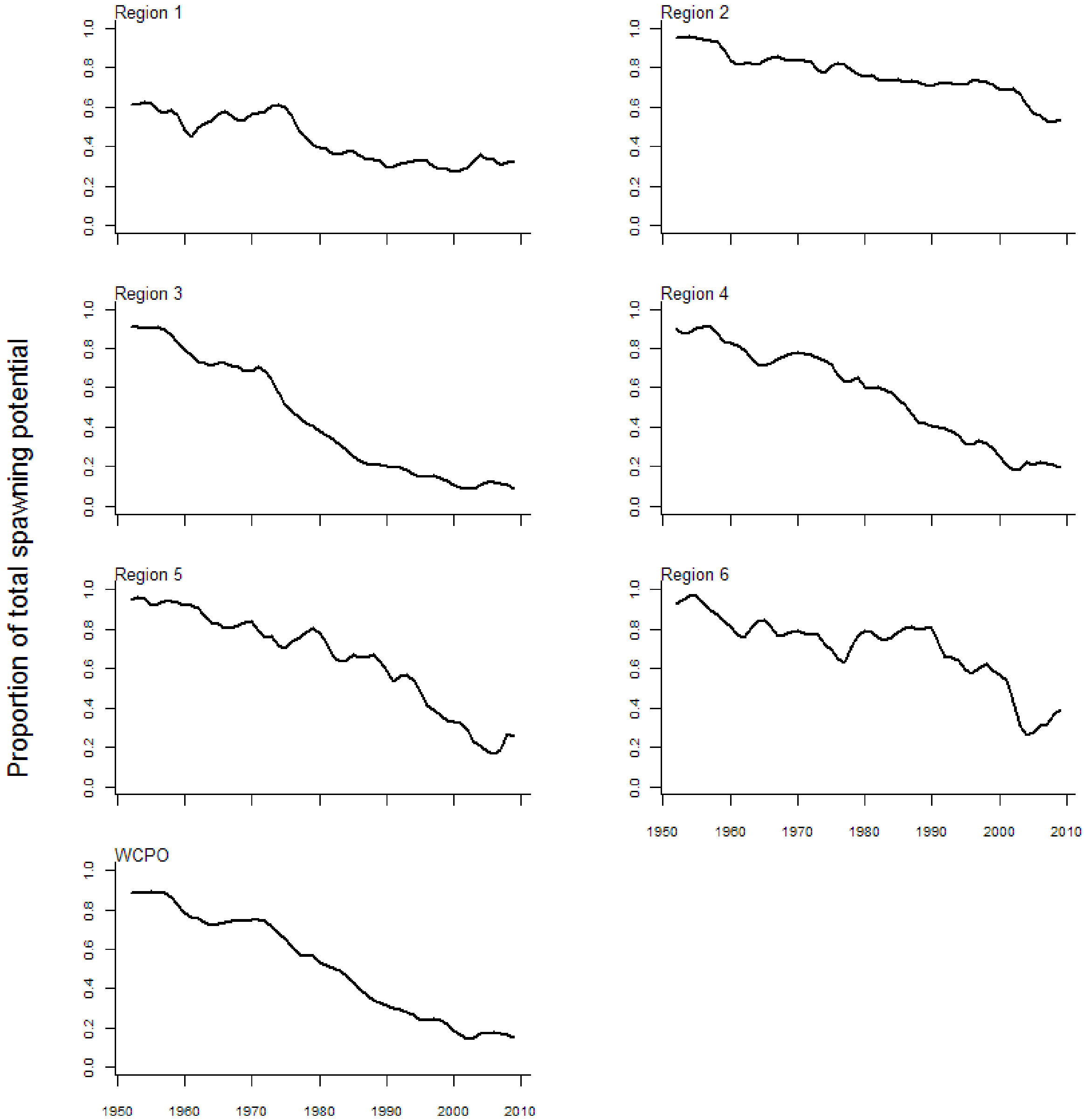


Figure 38. Ratios of exploited to unexploited spawning potential $SB_t/SB_{t_{F=0}}$ for each region and the WCPO.

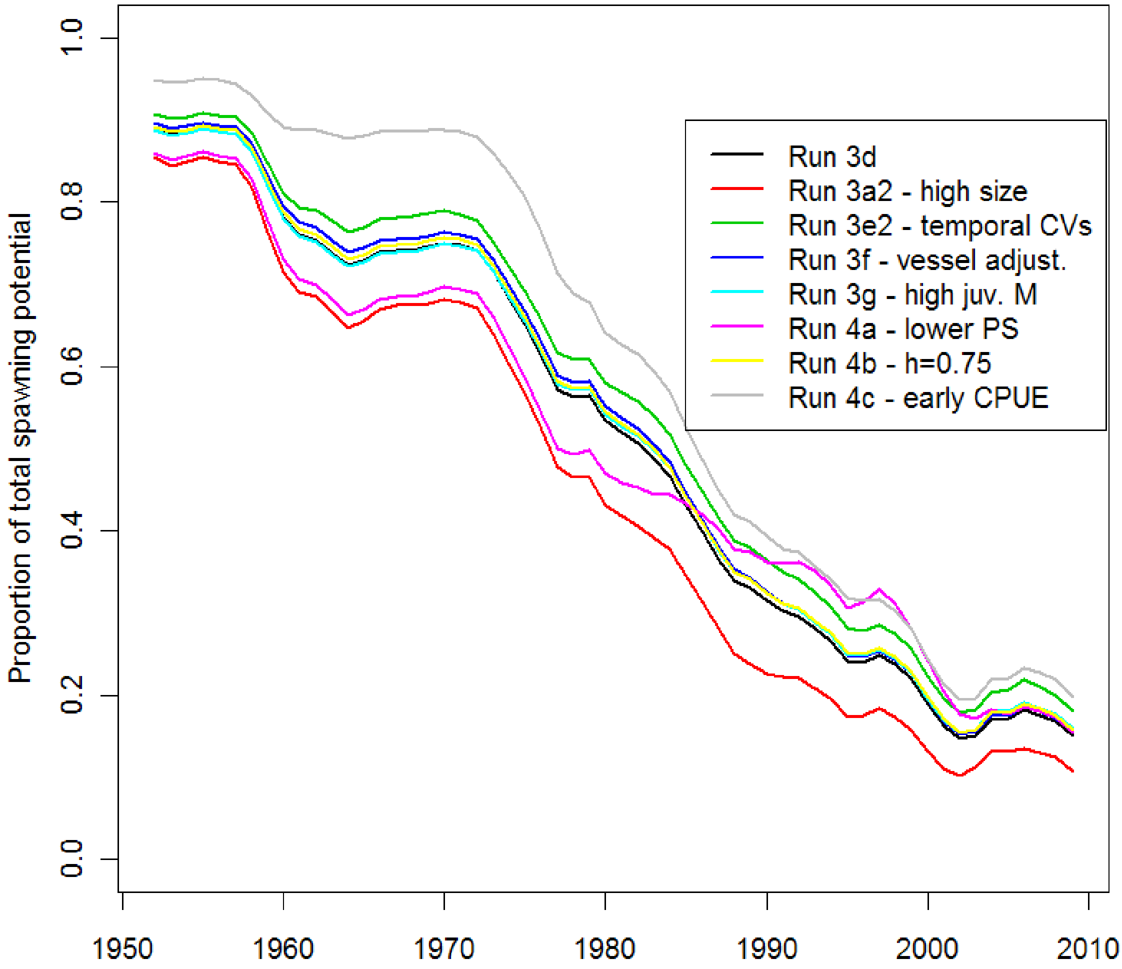


Figure 39. Ratios of exploited to unexploited spawning potential, $\boldsymbol{SB_t/SB_{t_{F=0}}}$, for the WCPO obtained from the separate analyses.

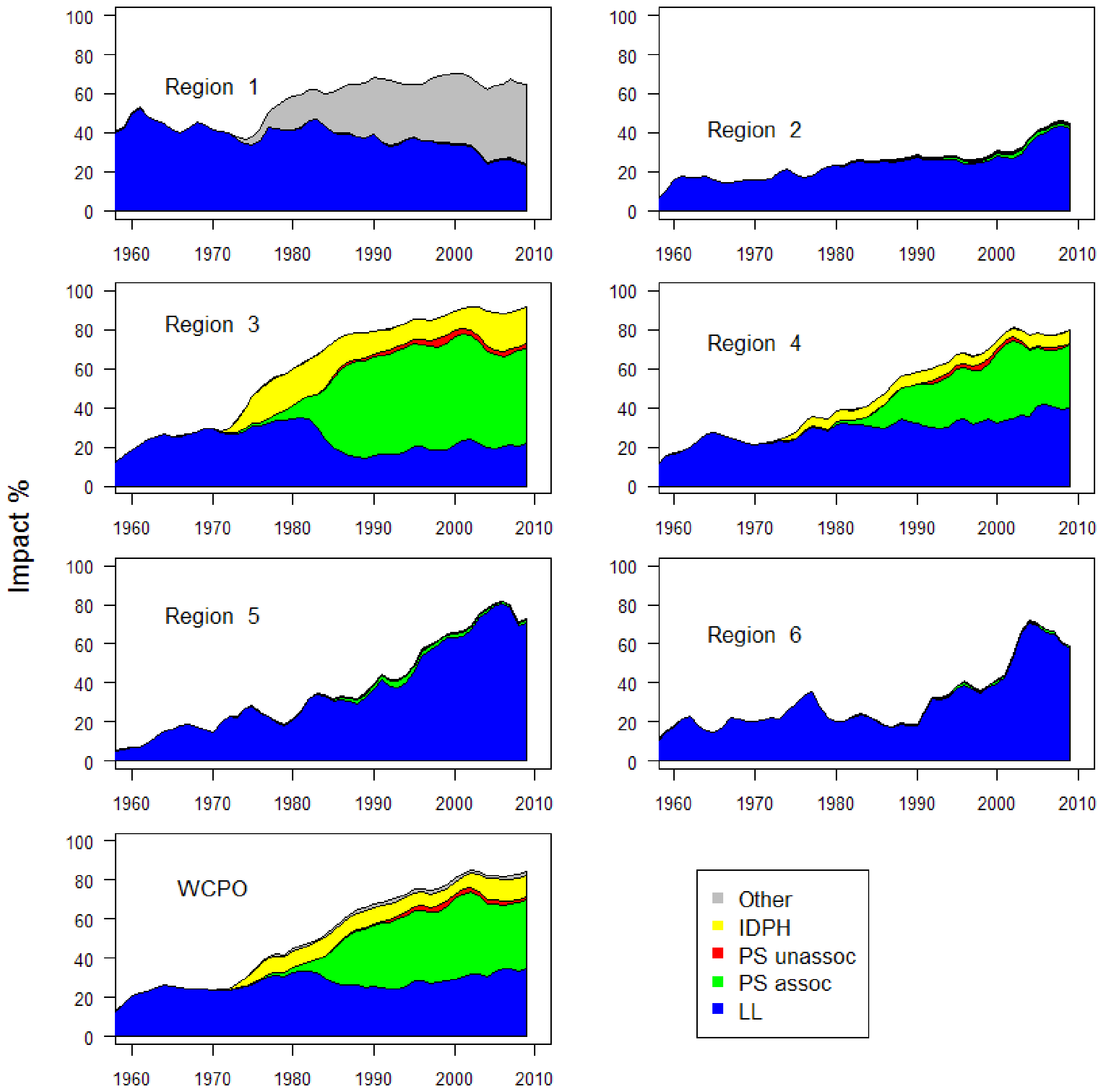


Figure 40. Estimates of reduction in spawning potential due to fishing (fishery impact = $\mathbf{1} - \boldsymbol{SB_t/SB_{t_{F=0}}}$) by region and for the WCPO attributed to various fishery groups (base case model). LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine log and FAD sets; PS unassoc = purse seine school sets; Other = pole and line fisheries and coastal Japan purse-seine.

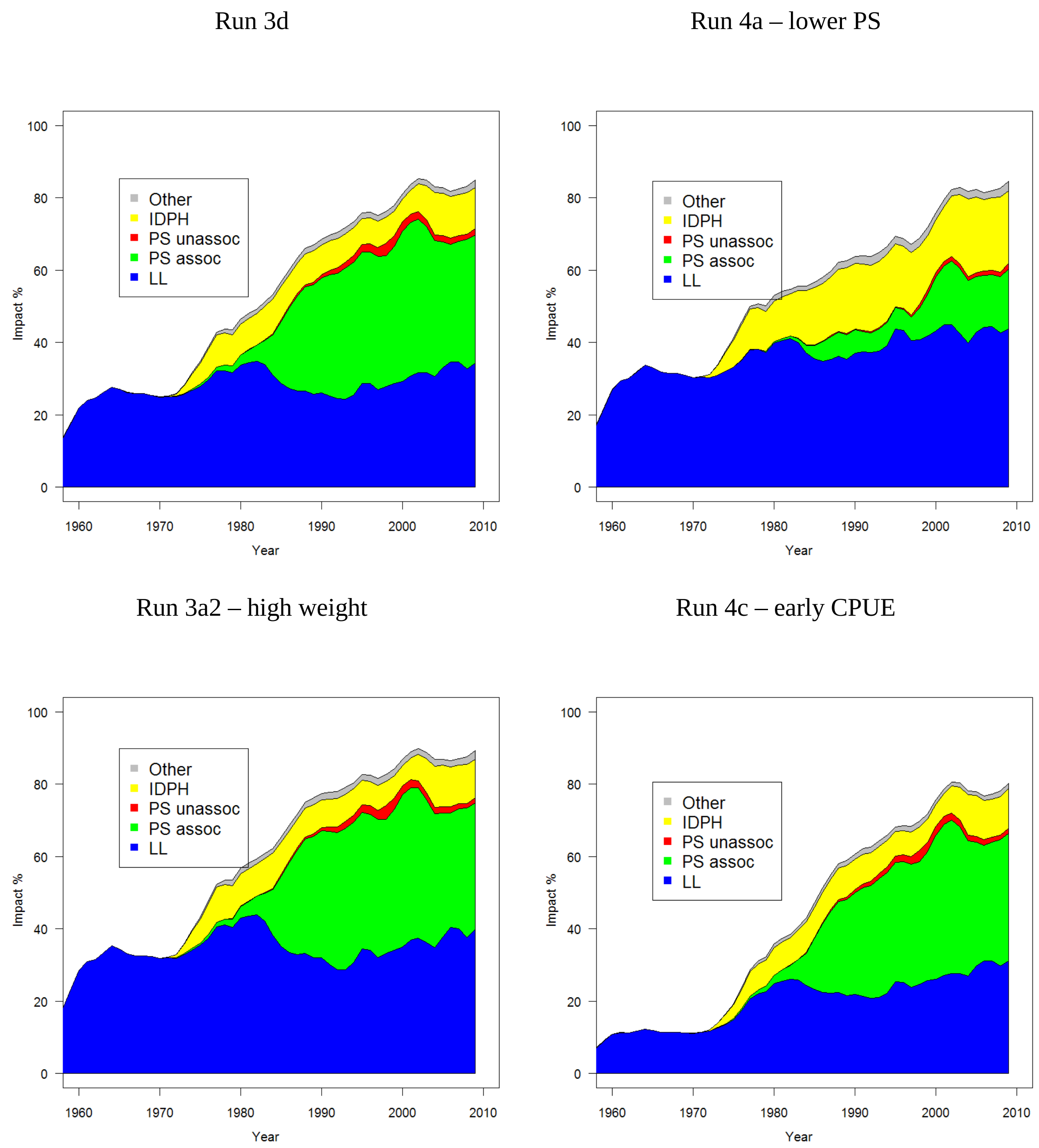


Figure 41. Estimates of reduction in WCPO spawning potential due to fishing (fishery impact = $\mathbf{1 - SB_t / SB_{t_{F=0}}}$) attributed to various fishery groups for the four main alternative models. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine log and FAD sets; PS unassoc = purse seine school sets; Other = pole and line fisheries and coastal Japan purse-seine.

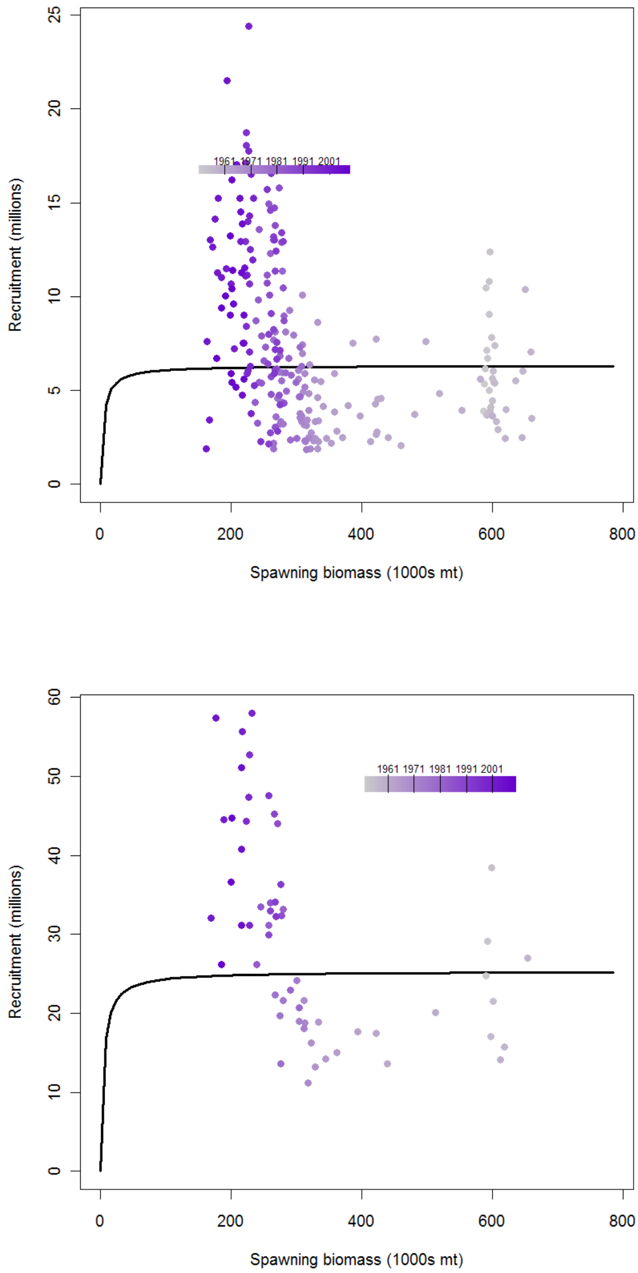


Figure 42. Estimated relationship between equilibrium recruitment and equilibrium spawning biomass based on quarterly (top) and annual (bottom) values.

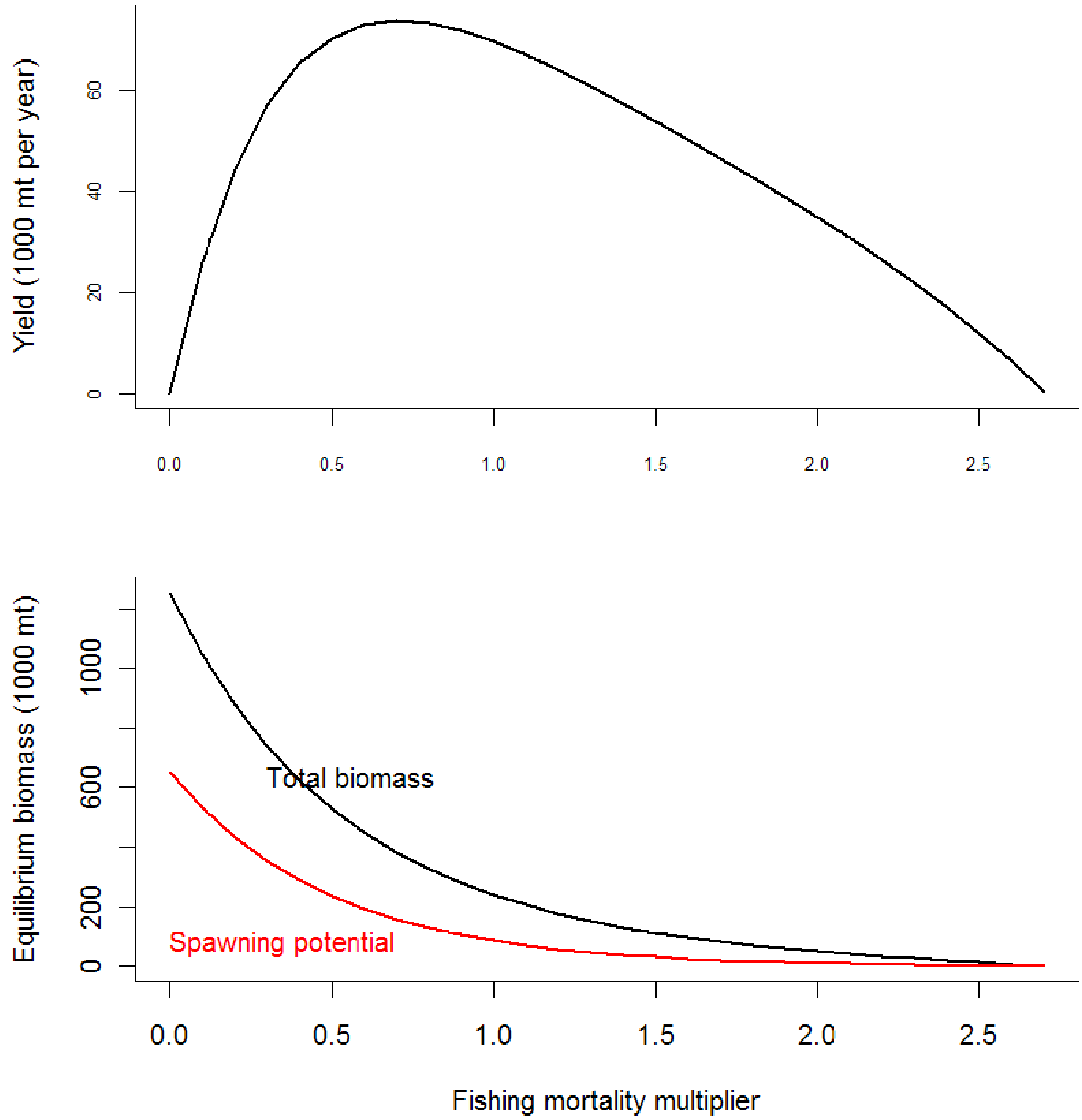


Figure 43. Yield (top), equilibrium total biomass and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier.

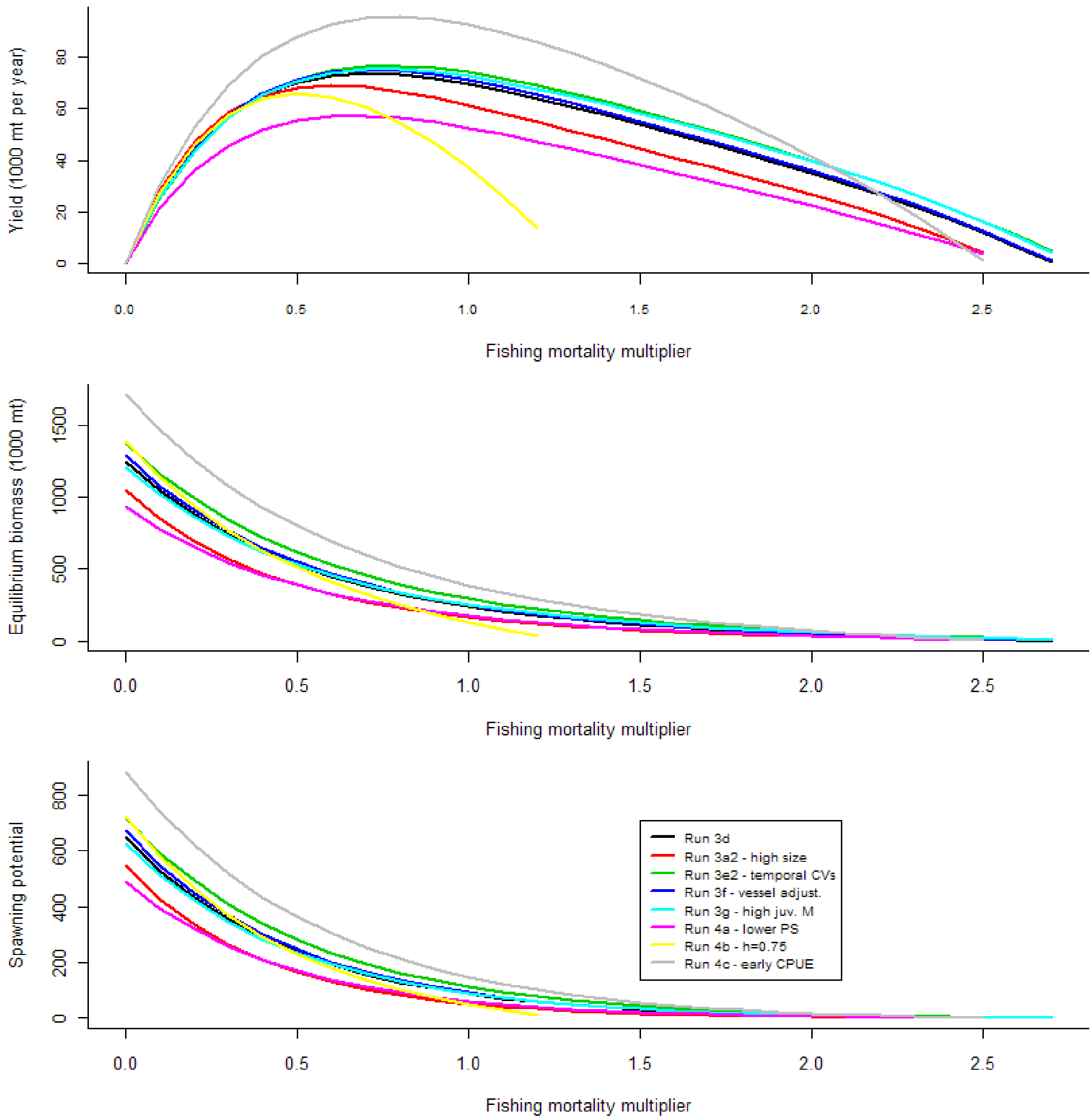


Figure 44. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier ($\boldsymbol{F_{mult}}$) obtained from the key model runs.

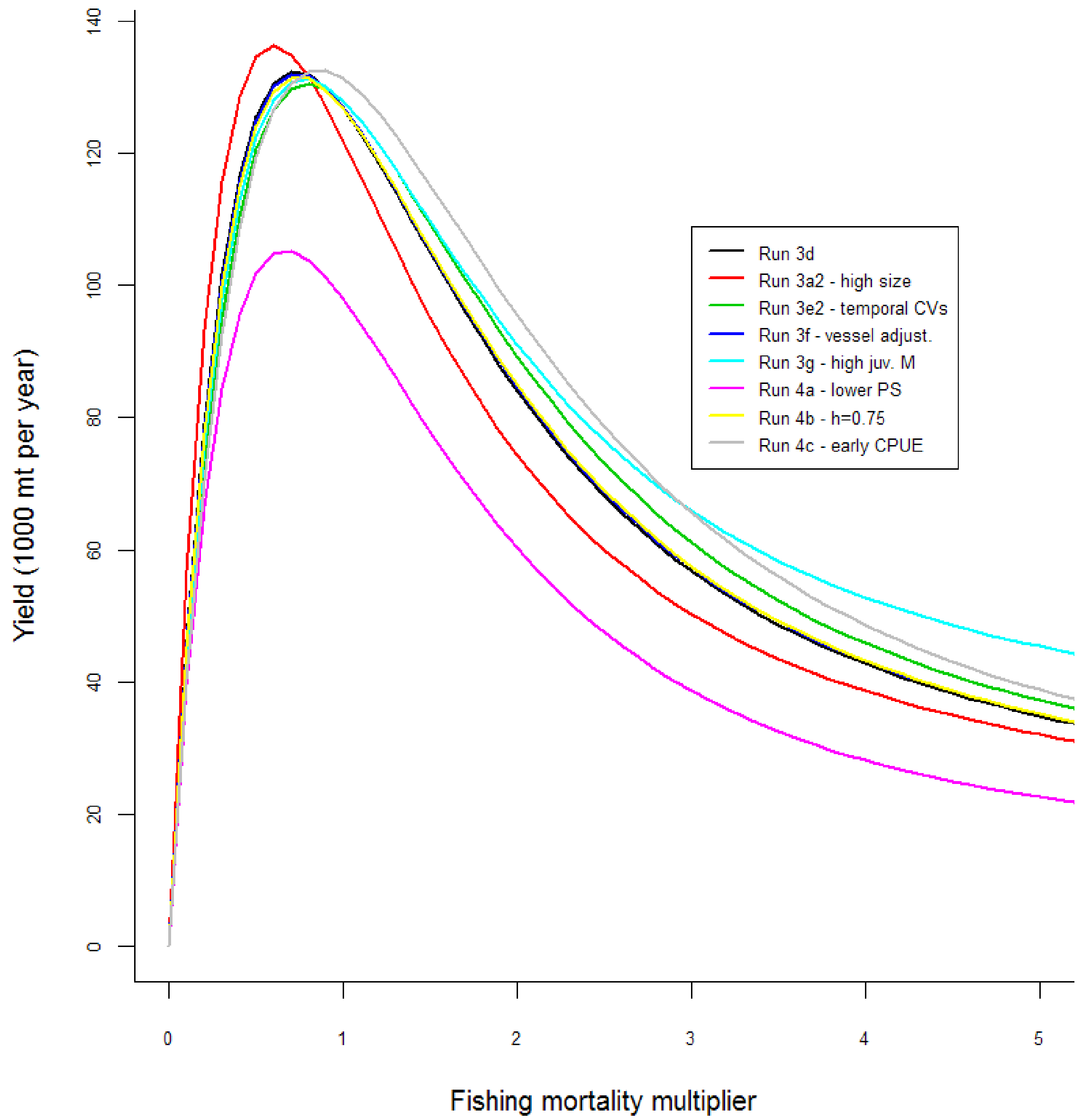


Figure 45. Yield curves based on 1999–2008 average recruitment for the key model runs.

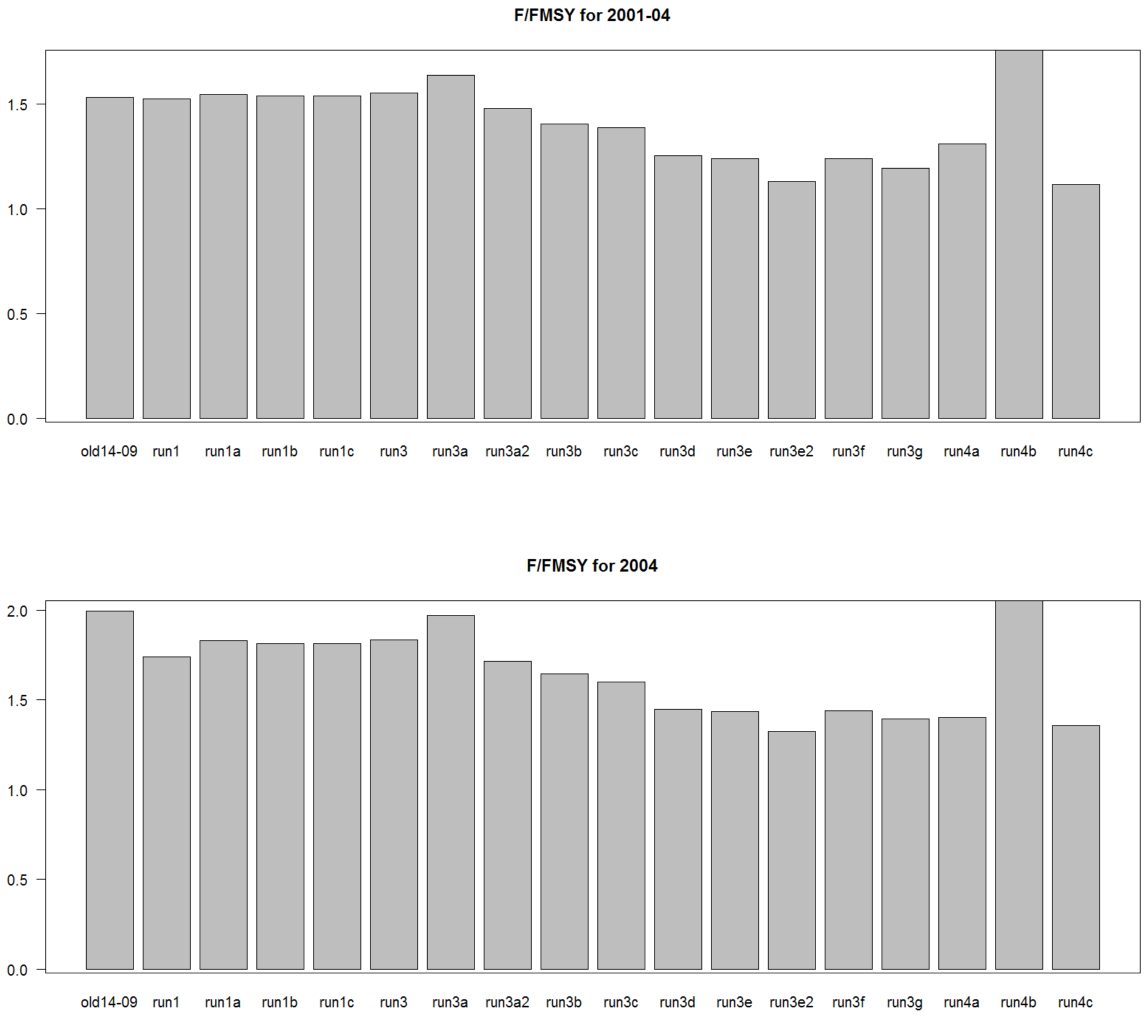


Figure 46. A comparison of $\boldsymbol{F_{current}/F_{MSY}}$ for the model runs from Table 2 based on *MSY* estimation windows of 2001-04 (top) and 2004 (bottom). Note that the y-axes are different.

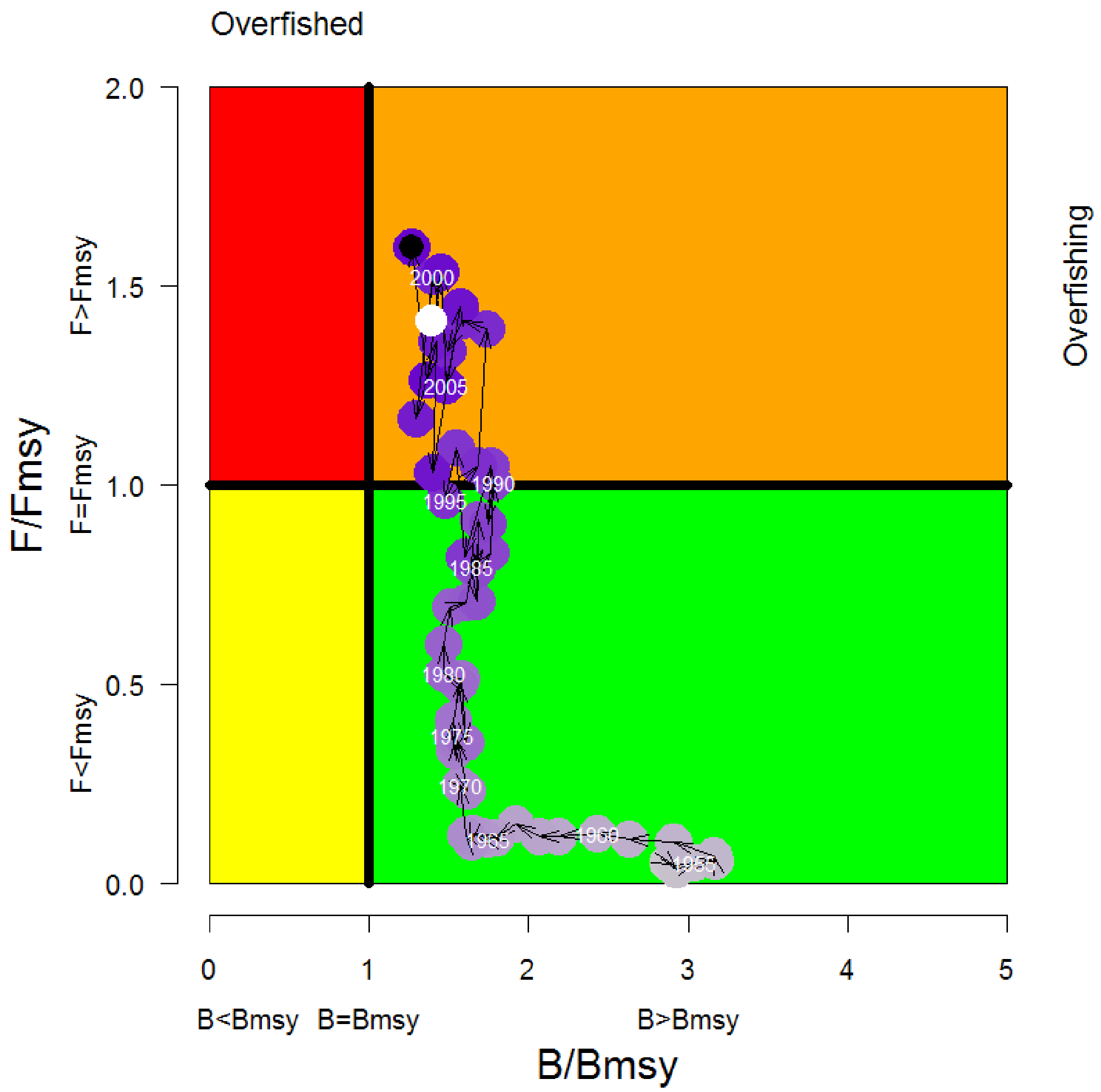


Figure 47. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the period 1952–2008 from run 3d. The colour of the points is graduated from mauve (1952) to dark purple (2009) and the points are labelled at 5-year intervals. The white circle represents the average for the period 2005-08 and the black circle the 2008 values.

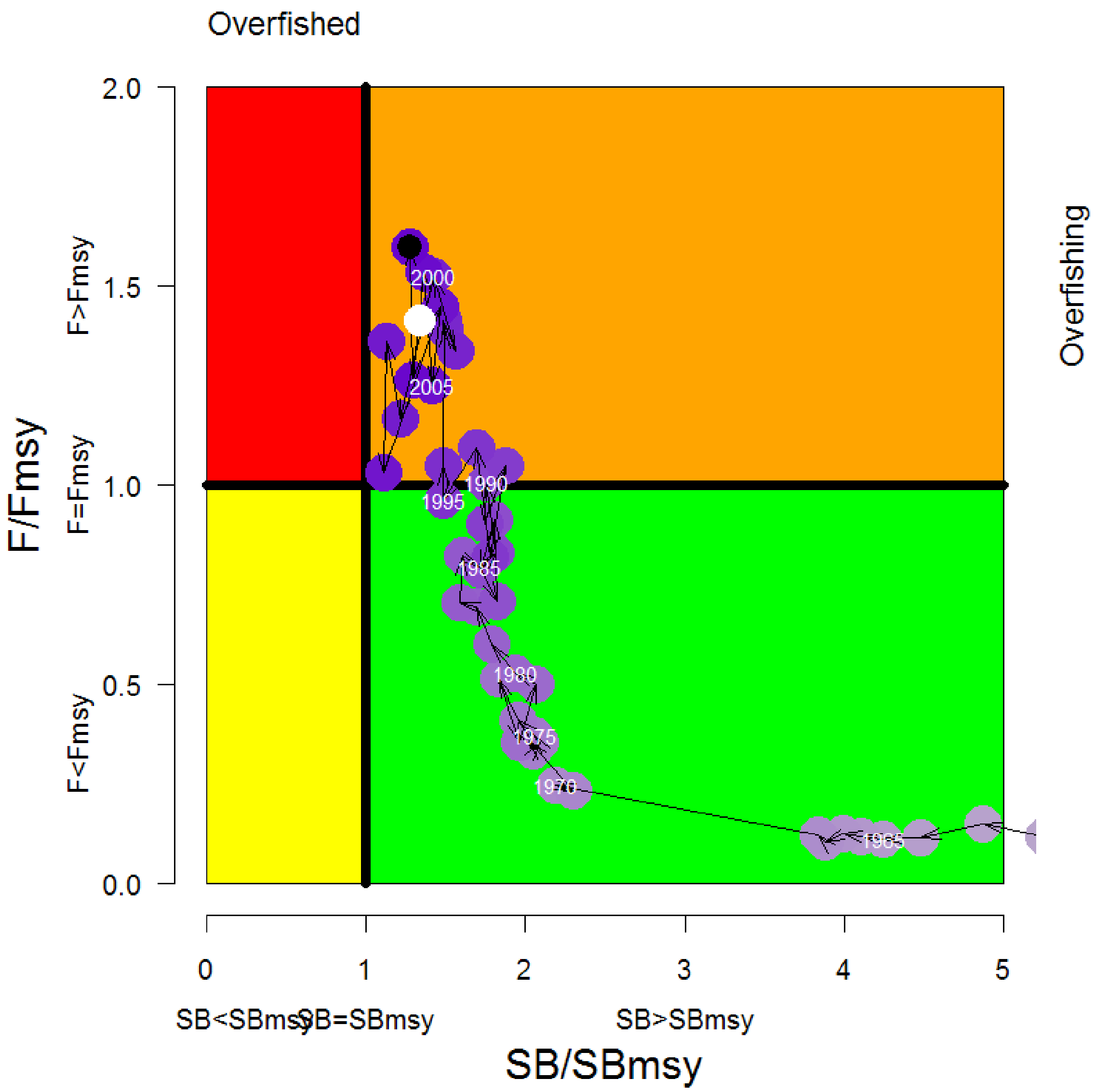


Figure 48. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the period 1952–2008 from run 3d. The colour of the points is graduated from mauve (1952) to dark purple (2008) and the points are labelled at 5-year intervals. The white circle represents the average for the period 2005-08 and the black circle the 2008 values.

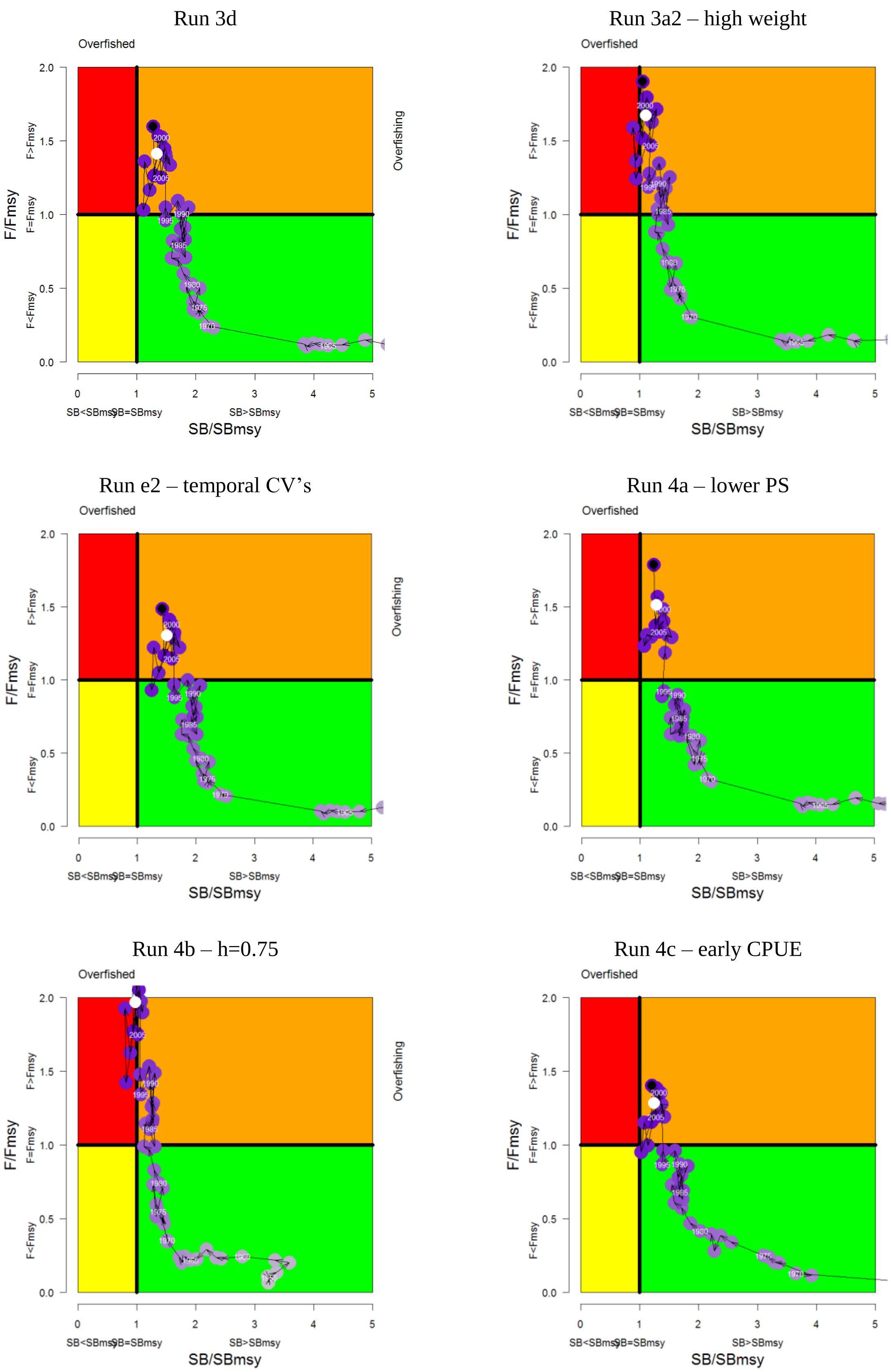


Figure 49. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points for selected model runs.

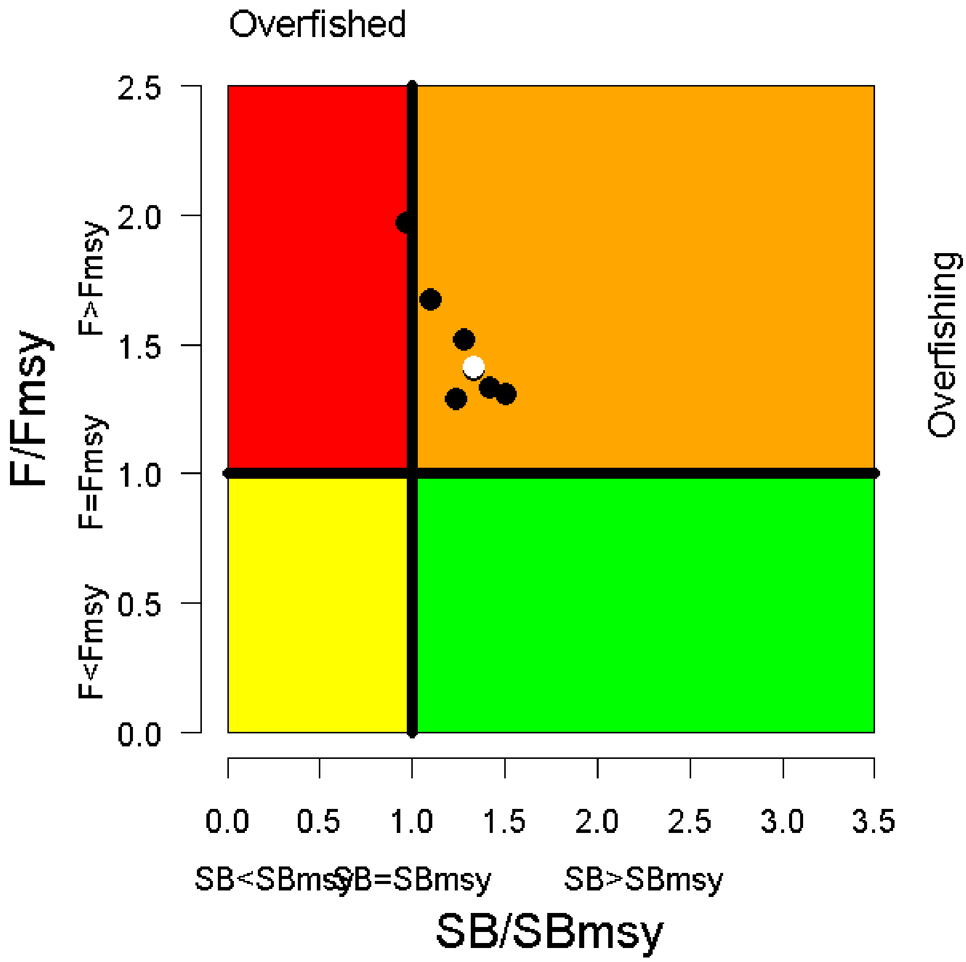
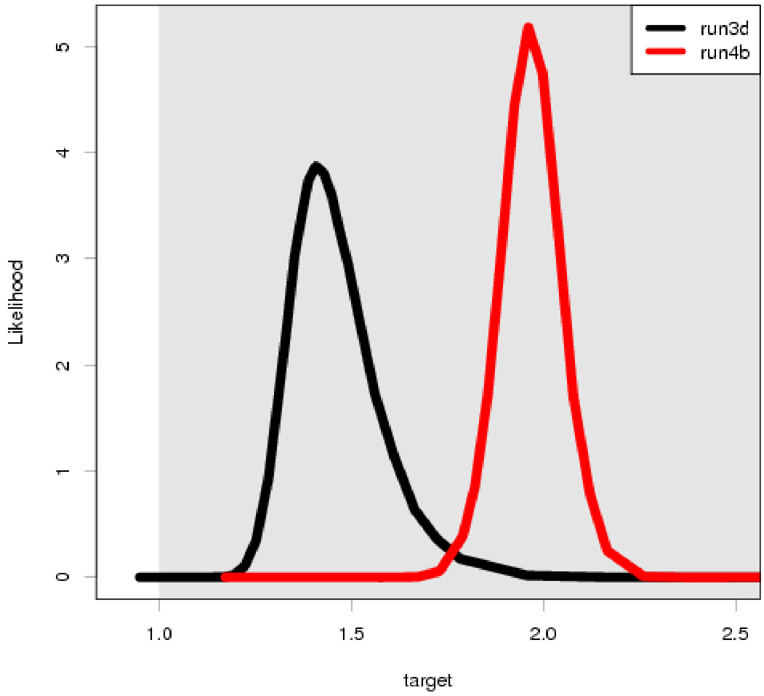


Figure 50. Summary of current stock status (based on 2005-08) for the key model runs. The white circle represents run 3d (base).



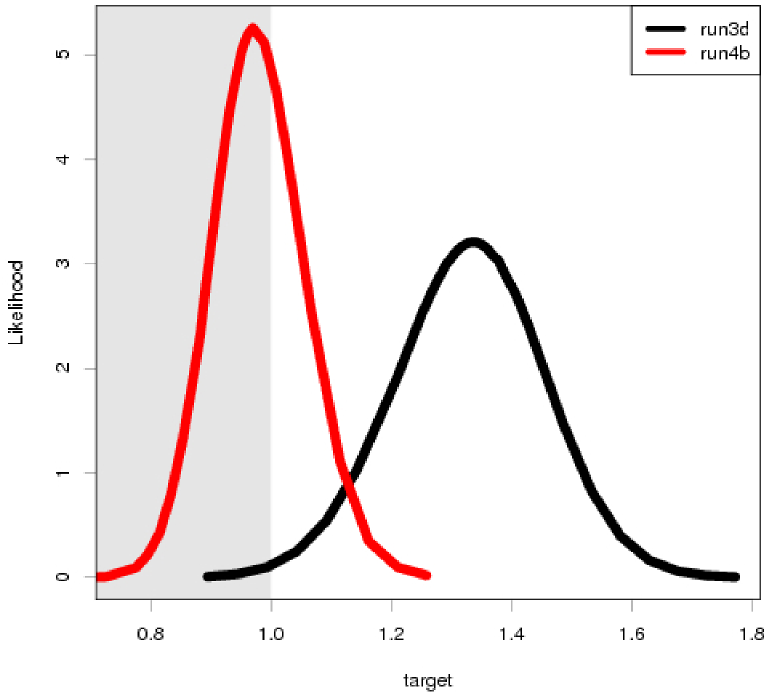


Figure 51: Likelihood profiles for $F_{current}/F_{MSY}$ (top) and $SB_{current}/SB_{MSY}$ (bottom) for runs 3d and 4b (h=0.75). The period for current is 2005-08. The shaded area represents the target values below SB_{MSY} and are estimated to be 0.5% and 60%, for models 3d and 4b respectively.

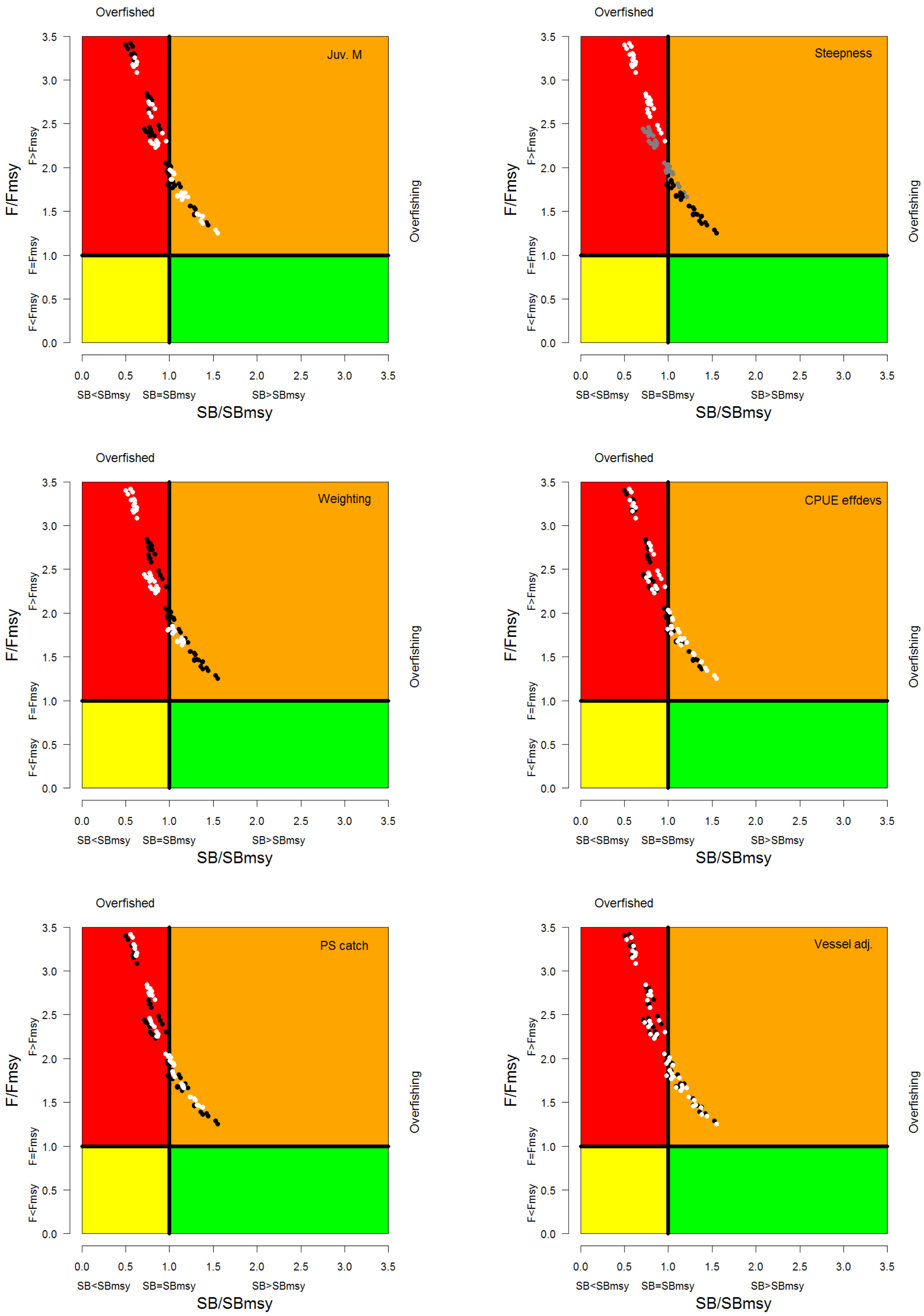


Figure 52: Plot of $SB_{current}/SB_{MSY}$ versus $F_{current}/F_{MSY}$ for the 96 model runs undertaken for the structural uncertainty analysis. Except for the steepness panel, the runs reflecting the run 3d assumption are denoted with black circles while the runs with the alternative assumption are denoted with white circles. For the steepness panel the labels are as follows: 0.55 (white), 0.75 (grey), and 0.95 (black).

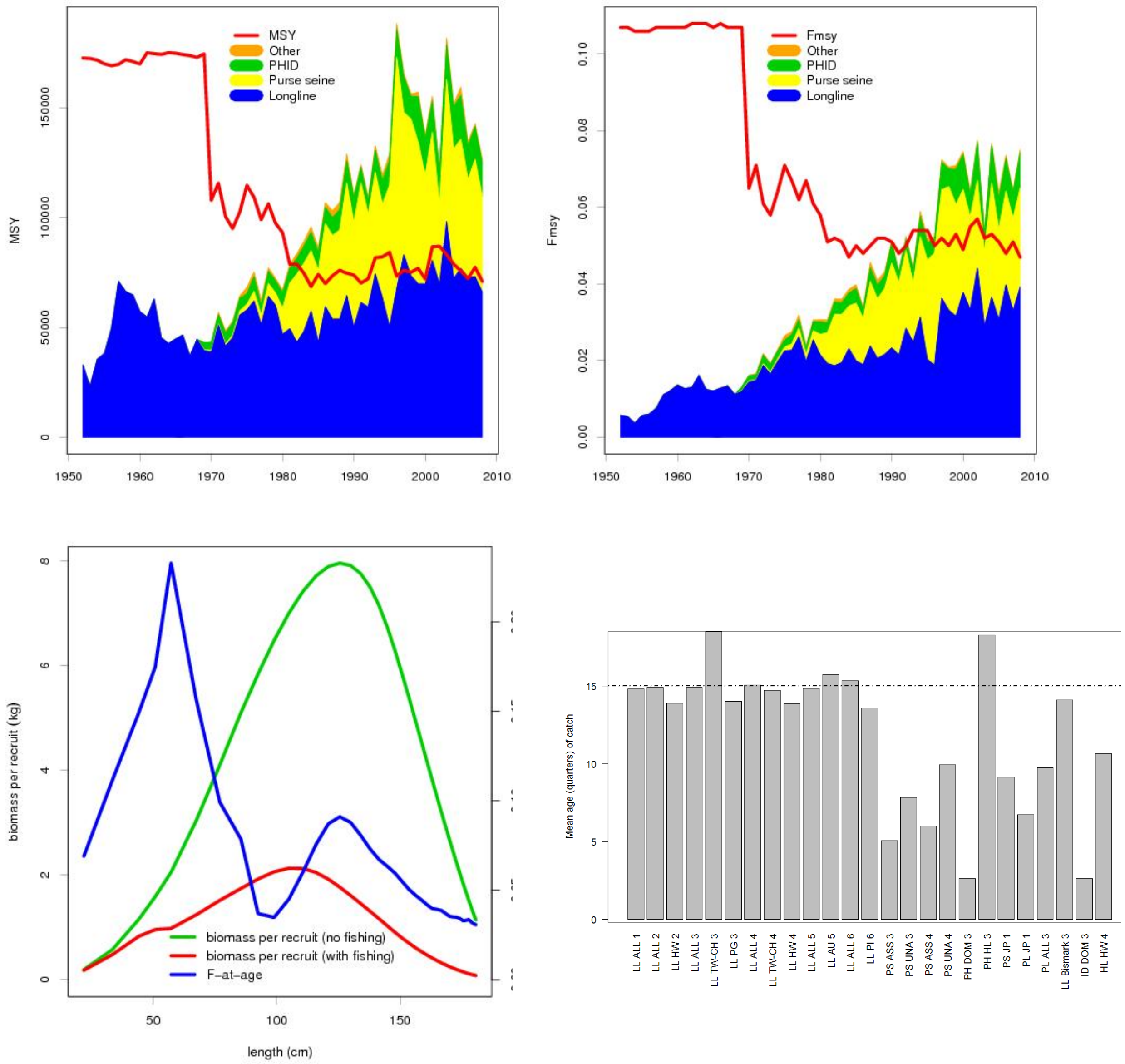


Figure 53. Four plots displaying various aspects of utilization. (top) History of the annual estimates of *MSY* (left) and F_{MSY} (right) compared with annual catch split into four sectors. (bottom left) Average selectivity pattern by length (blue line) over the last 15 years of the assessment (1995 – 2009) juxtaposed with the biomass per recruit of a cohort of bigeye as a function of average length of members of the cohort where the latter is a trade-off between growth in size and mortality -- either just natural mortality (green line) or natural plus average (1995 – 2009) fishing mortality (red line). (bottom right) Estimates of the mean age of harvest for the fisheries defined in the assessment**.**

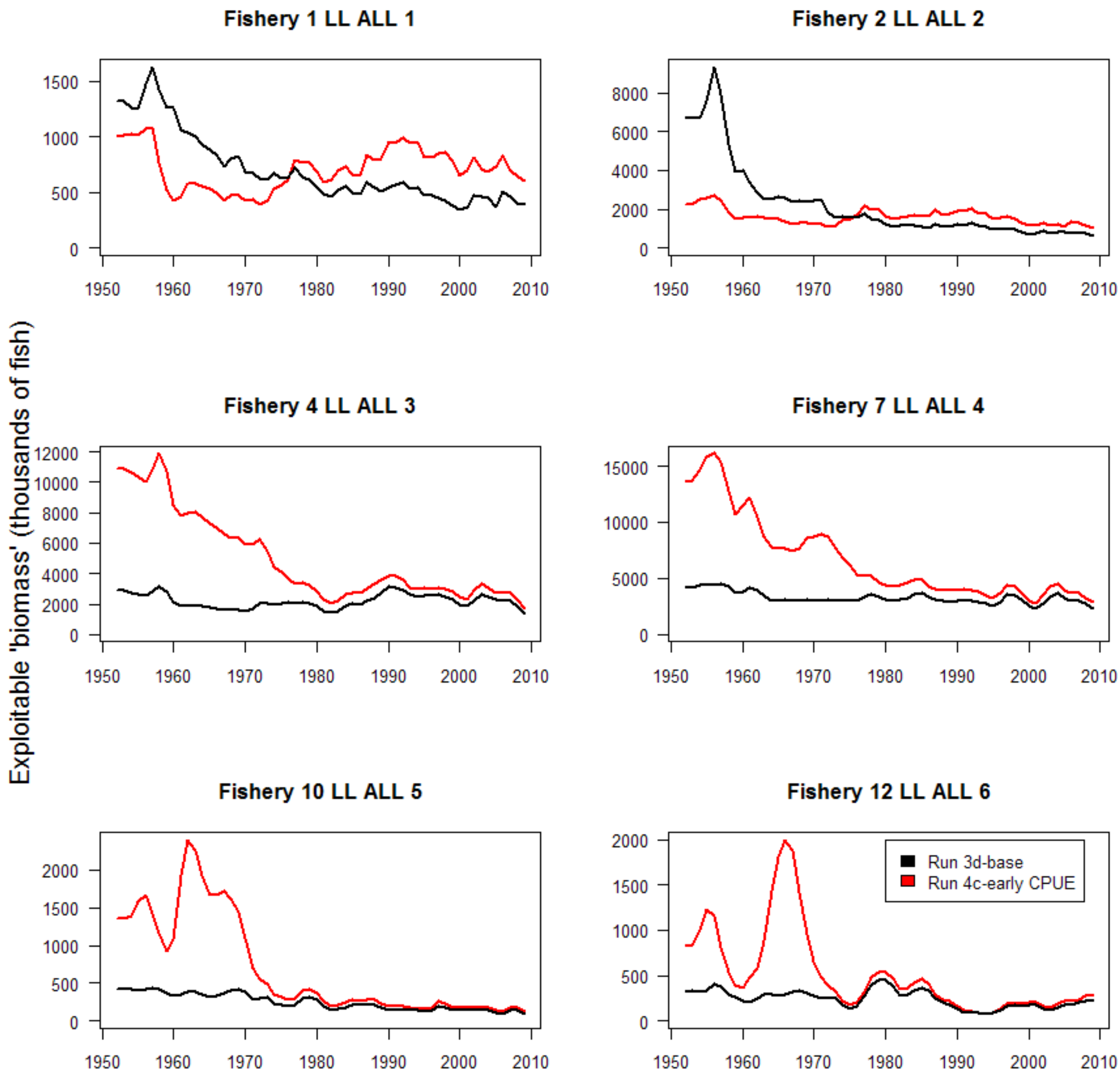


Figure 54: Comparison of annual estimates of exploitable abundance for each of the regional LL-ALL fisheries for runs 3d (base) and 4c (early CPUE).

Appendix A: *doitall.bet (for run3d)*

```
#!/bin/sh
export PATH=$PATH:$ADTMP1:/usr/local/lib/
export LD_LIBRARY_PATH=$LD_LIBRARY_PATH:/usr/local/lib
cd $ADTMP1
set

#  ------------------------
#  PHASE 0 - create initial par file
#  ------------------------
#

if [ ! -f 00.par ]; then
  ./mfclo32 bet.frq bet.ini 00.par -makepar
fi
#
#  ------------------------
#  PHASE 1 - initial par
#  ------------------------
#
if [ ! -f 01.par ]; then
  ./mfclo32 bet.frq 00.par 01.par -file - <<PHASE1
  1 149 100       # recruitment deviations penalty
  2 113 0         # scaling init pop - turned off
  2 177 1         # use old totpop scaling method
  2 32 1          # and estimate the totpop parameter
  -999 49 20      # divide LL LF sample sizes by 20 (default=10)
  -999 50 20      # divide LL WF sample sizes by 20 (default=10)
#  1 32 2          # sets standard control
  1 32 6          # keep growth parameters fixed
  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 5        # with 5 nodes for cubic spline
  -5 57 1         # logistic for TW-CN fisheries
  -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     #no size data for ID share with PH
  -19 24 12
  -20 24 13
  -21 24 14
  -22 24 15
  -23 24 16  # separate LL selectivity for smaller fish in PNG waters
  -24 24 11      # ID common with PH domestic
  -25 24 17
# grouping of fisheries with common catchability
   -1 29 1        # Longline fisheries grouped
   -2 29 1
   -3 29 2        # HI LL fishery different
   -4 29 1
   -5 29 3        # TW/CH LL fishery different
   -6 29 4
   -7 29 1        # AU LL fishery different
   -8 29 5        # JP LL in Aust. region 5 are targeting SBT in the south
   -9 29 6        # AU LL fishery different
  -10 29 1
  -11 29 7
  -12 29 1
  -13 29 8
  -14 29 9
  -15 29 10
  -16 29 11
  -17 29 12
  -18 29 13
  -19 29 14
  -20 29 15
  -21 29 16
  -22 29 17
  -23 29 18
  -24 29 19
  -25 29 20
   -1 60 1        # Longline fisheries grouped
   -2 60 1
   -3 60 2        # HI LL fishery different
   -4 60 1
   -5 60 3        # TW/CH LL fishery different
   -6 60 4
   -7 60 1        # AU LL fishery different
   -8 60 5        # JP LL in Aust. region 5 are targeting SBT in the south
   -9 60 6        # AU LL fishery different
  -10 60 1
  -11 60 7
  -12 60 1
  -13 60 8
  -14 60 9
  -15 60 10
  -16 60 11
  -17 60 12
  -18 60 13
  -19 60 14
  -20 60 15
  -21 60 16
  -22 60 17
  -23 60 18
```

```
  -24 60 19
  -25 60 20
# 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
   -19 32 17
   -20 32 18
   -21 32 19
   -22 32 20
   -23 32 4          # common with the LL fishery in region 3
   -24 32 21
   -25 32 22
# grouping of fisheries with common tag-reporting rates - as for tag
grouping
    -1 34 1
    -2 34 2
    -3 34 3
    -4 34 4
    -5 34 5
    -6 34 6
    -7 34 7
    -8 34 8
    -9 34 9
   -10 34 10
   -11 34 11
   -12 34 12
   -13 34 13
   -14 34 14         # PS assoc. and unassoc. returns are grouped
   -15 34 14
   -16 34 15
   -17 34 15
   -18 34 16         # PH/ID returns returns are grouped
   -19 34 17
   -20 34 18
   -21 34 19
   -22 34 20
   -23 34 4          # common with the LL fishery in region 3
   -24 34 21
   -25 34 22
# sets penalties on tag-reporting rate priors
    -1 35 1          # The penalties are set to be small for LL fisheries
    -2 35 1
    -3 35 50         # HI LL fishery thought to be high rep. rate
    -4 35 1
    -5 35 1
```

```
    -6 35 1
    -7 35 1
    -8 35 1
    -9 35 50
   -10 35 1
   -11 35 50        # AU LL region 4 thought to be high rep. rate
   -12 35 1
   -13 35 1
   -14 35 50        # WTP PS based on tag seeding
   -15 35 50
   -16 35 50
   -17 35 50
   -18 35 50        # PH/ID based on high recovery rate
   -19 35 50
   -20 35 1
   -21 35 1
   -22 35 1
   -23 35 1
   -24 35 50
   -25 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 50
   -21 36 50
   -22 36 50
   -23 36 50
   -24 36 60
   -25 36 80        # HI HL
# sets penalties for effort deviations (negative penalties force effort
devs
# to be zero when catch is unknown)
 -999 13 -3      # higher for longline fisheries where effort is
standardized
   -1 13 -12
   -2 13 -12
   -4 13 -12
   -7 13 -12
  -10 13 -12
  -12 13 -12
  -18 13 3
  -23 13 -3
  -24 13 3
```

```
# sets penalties for catchability deviations
   -18 15 1       # low penalty for PH.ID MISC.
   -24 15 1
  -999 33 1       # estimate tag-reporting rates
  1 33 90         # maximum tag reporting rate for all fisheries is 0.9
PHASE1
fi
#  ---------
#   PHASE 2
#  ---------
if [ ! -f 02.par ]; then
  ./mfclo32 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 length.fit and weight.fit
  1 190 1         # write plot-xxx.par.rep
  1 1 200         # set max. number of function evaluations per phase to
200
  1 50 -2         # set convergence criterion to 1E-02
  -999 14 10      # Penalties to stop F blowing out
  2 35 10          # Set effdev bounds to +- 10 (need to do AFTER phase 1)
  -18 16 2
  -18 3 12
  -24 16 2
  -24 3 12
  -14 15 1
  -15 15 1
  -16 15 1
  -17 15 1
PHASE2
fi
#  ---------
#   PHASE 3
#  ---------
if [ ! -f 03.par ]; then
  ./mfclo32 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
PHASE3
fi
#  ---------
#   PHASE 4
#  ---------
if [ ! -f 04.par ]; then
  ./mfclo32 bet.frq 03.par 04.par -file - <<PHASE4
  2 68 1          # estimate movement coefficients
PHASE4
fi
#  ---------
#   PHASE 5
#  ---------
if [ ! -f 05.par ]; then
  ./mfclo32 bet.frq 04.par 05.par -file - <<PHASE5
  -999 27 1       # estimate seasonal catchability for all fisheries
  -18 27 0        # except those where
  -19 27 0        # only annual catches
  -24 27 0
PHASE5
```

```
fi
#  ---------
#   PHASE 6
#  ---------
if [ ! -f 06.par ]; then
  ./mfclo32 bet.frq 05.par 06.par -file - <<PHASE6
  -3 10 1         # estimate
  -5 10 1         # catchability
  -6 10 1         # time-series
  -8 10 1         # for all
  -9 10 1         # non-longline
  -11 10 1        # fisheries
  -13 10 1
  -14 10 1
  -15 10 1
  -16 10 1
  -17 10 1
  -18 10 1
  -19 10 1
  -20 10 1
  -21 10 1
  -22 10 1
  -23 10 1
  -24 10 1
  -25 10 1
  -999 23 23      # and do a random-walk step every 23+1 months
PHASE6
fi
#  ---------
#   PHASE 7
#  ---------
if [ ! -f 07.par ]; then
  ./mfclo32 bet.frq 06.par 07.par -file - <<PHASE7
# grouping of fisheries for estimation of negative binomial parameter a
   -1 44 1
   -2 44 1
   -3 44 1
   -4 44 1
   -5 44 1
   -6 44 1
   -7 44 1
   -8 44 1
   -9 44 1
  -10 44 1
  -11 44 1
  -12 44 1
  -13 44 1
  -14 44 2
  -15 44 2
  -16 44 2
  -17 44 2
  -18 44 3
  -19 44 3
  -20 44 1
  -21 44 1
  -22 44 2
  -23 44 1
  -24 44 3
  -25 44 4
 -999 43 1        # estimate a for all fisheries
PHASE7
```

```
fi
#  ---------
#   PHASE 8
#  ---------
if [ ! -f 08.par ]; then
  ./mfclo32 bet.frq 07.par 08.par -file - <<PHASE8
  -100000 1 1     # estimate
  -100000 2 1     # time-invariant
  -100000 3 1     # distribution
  -100000 4 1     # of
  -100000 5 1     # recruitment
  -100000 6 1
PHASE8
fi

#  ---------
#   PHASE 9
#  ---------
if [ ! -f 09.par ]; then
  ./mfclo32 bet.frq 08.par 09.par -file - <<PHASE9
  1 14 1          # estimate von Bertalanffy K
  1 12 1          # and mean length of age 1
  1 13 1          # and mean length of age n
  1 1 300         #bit more of a chance

PHASE9
fi
#  ---------
#   PHASE 10
#  ---------
if [ ! -f 10.par ]; then
  ./mfclo32 bet.frq 09.par 10.par -file - <<PHASE10
  1 16 1          # estimate length dependent SD
  1 173 8         # activate independent mean lengths for 1st 8 age classes
  1 182 10        # penalty weight
  1 184 1         # estimate parameters
PHASE10
fi
#  ---------
#   PHASE 11
#  ---------
if [ ! -f 11.par ]; then
  ./mfclo32 bet.frq 10.par 11.par -file - <<PHASE11
  2 145 1        # use SRR parameters - low penalty for deviation
  2 146 1        # estimate SRR parameters
  2 162 1    # estimate steepness parameter
  2 163 0        # use steepness parameterization of B&H SRR
  1 149 0    # negligible penalty on recruitment devs
  2 147 1    # time period between spawning and recruitment
  2 148 20       # period for MSY calc - last 20 quarters
  2 155 4    # but not including last year
  2 153 31   # beta prior for steepness
  2 154 16       # beta prior for steepness
  1 1 500     #maximum of 1000 function evaluations for the final phase -
TO BEGIN WITH
  1 50 -3       #convergence criteria of 10^-3
  -999 55 1
  2 193 1
PHASE11
fi
```

Appendix B: *bet.ini*

```
# number of age classes
40
# maturity at age
0  0  0  0  0  0  0.00400395317140697  0.0090620208084776  0.0180060612167527
0.0330387520958537 0.0573902985342996 0.0970236867822348 0.159884640300079
0.255818526902294  0.392823118863806  0.563563999511659  0.737564543664718
0.873349855376351  0.955121228431595  0.992835343697603 1  0.988646552503548
0.965853785531792  0.937021774261042  0.904720819463276  0.869108374445115
0.831895989848481  0.793643708326688  0.754806283338424  0.715835214976602
0.677079000946573  0.638837166188084  0.601362904388722  0.564866117183414
0.529516747617393  0.495448303636788  0.462761472717955  0.431527738429156
0.401792922120901 0.373580586698095
# natural mortality (per year)
0.117807903982688
# movement map
1 2 3 4
# diffusion coffs (per year)
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
0.529511970569348 0.344963492569347 0.126636607569348 -0.153068886430652 -
0.163617164430652 -0.163885179605751 -0.163885179605751 -0.163885179605751
-0.163885179605751 -0.156486849146481 -0.152600947794065 -0.1465977706647 -
0.137688051002927 -0.124742019083764 -0.105564246936977 -0.0779704787956052
-0.0401084957979585         0.00771857746052794         0.0589327039802937
0.101721152591393  0.125959977021629  0.132366430407387  0.127815281660447
0.117724684936128  0.105376111973827  0.092101082809219  0.078781111843572
0.0657134265134084 0.0527459978289533 0.0401450777775319 0.0279429933437338
0.0161670693500227      0.00483956407764969      -0.00602228380189533      -
0.0164061088045999      -0.0263041869763792      -0.0357131347138716      -
0.0446335543122571 -0.0530696422103984 -0.0610287749575805
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 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 by region
0.05 0.06 0.4 0.35 0.05 0.09
# The von Bertalanffy parameters
# Initial  lower bound  upper bound
# ML1
21 20 40
# ML12
173 140 200
```

```
# K (per year)
0.075 0 0.3
# Length-weight parameters
1.9729e-05 3.0247
# Generic SD of length at age
6.71 3 12
# Length-dependent SD
0.7289 -1.5 1.5
# The number of mean constraints
0
```