SCIENTIFIC COMMITTEE

FIFTH REGULAR SESSION

10-21 August 2009

Port Vila, Vanuatu

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

WCPFC-SC5-2009/SA-WP-4

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Table of Contents

Executive summary

This paper presents the streamlined 2009 assessment of bigeye tuna in the western and central Pacific Ocean. The primary purpose of this assessment is to allow for an evaluation of the potential benefits of CMM2008-01 using the most recent information[4]. Consequently, this paper contains less background material and supporting material (e.g. diagnostics) than the 2008 assessment report and interested readers should consult that report if further information is required.

Further, we attempted to produce an assessment consistent with the 2008 assessment, with only minor modifications. We do not view this model run ("run 10"), which is most comparable to the 2008 assessment "run 4", as containing the most plausible set of data and model structure assumptions. Other model runs, which we believe contain more plausible assumptions are also presented.

Changes to the data from the 2008 assessment included: updated catch, effort, and size data for 2007 and some limited data for 2008[5]; revisions to recent historical data for some fisheries (e.g. since 2000); an extended purse seine catch history that partially corrects for logsheet reporting bias; 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. Other changes included: an updated version of the MULTIFAN-CL software which had some new features and minor bug fixes; and decreased penalties for effort deviates for all fisheries (i.e. increased c.v.'s) to make them both more realistic and consistent with approaches used in other Pacific tuna assessments.

Over 130 different model runs were undertaken in developing this assessment[6], examining the impacts of changes in data, weighting of different data sources, key parameter values, and other structural model assumptions. The key assumptions in the main model runs presented in this paper are described below and we again emphasise that the many of the 'alternative' assumptions considered in the assessment are as least as plausible, if not more plausible, than some of the assumptions in the model which is more comparable to the 2008 base case assessment:

Component	**Model comparable to 2008**	**Alternatives**
Longline data weighting	CPUE cv=0.2, size data = n/20	CPUE cv=0.2, size data = n/50
Steepness	Estimated	0.55, 0.65, 0.75, 0.85, 0.95
Purse seine catches	Grab sample (s_best)	Spill sample corrected
Effort creep	No effort creep	0.47% per year (non-compounding)
ID/PH small-fish fishery catches	As submitted	Reduced by 33%

The main conclusions of the current assessment are as follows.

1. Recruitment in all analyses is estimated to have been high during 1995–2005. This result was similar to that of previous assessments, and there are some indications that the high recruitment may be, at least partly, an artefact of the structural assumptions of the model. Recruitment in the

[4] 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. SPC, Noumea, New Caledonia. WCPFC-SC5-GN-WP-17

[5] 2008 catch, effort, and size data were not available for the distant water longline fleets of JPN, KOR, CHN, and TWN or the USA domestic longline fleet operating out of Hawaii

[6] Representing about 75 days of computing on a top of the line desktop computer

most recent years is estimated to have declined to a level approximating the long-term average, although these estimates have high uncertainty.

2. Total and spawning biomass for the WCPO are estimated to have declined to about half of its initial level by about 1970, with total biomass remaining relatively constant since then ($B_{current}$ / B_0= 47.4%) (where current is the average for 2004-07), while spawning biomass has continued to decline ($SB_{current}$ /SB_0=29.2%). Declines are larger for the model with increasing longline catchability and increased purse seine catches.

3. 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 biomass is at 15% of the level predicted to exist in the absence of fishing considering the average over the period 2004-07, and that value is reduced to 10% when we consider 2008 spawning biomass levels.

4. The attribution of depletion to various fisheries or groups of fisheries indicates that the longline fishery has the greatest impact throughout the model domain. The purse seine and Philippines/Indonesian domestic fisheries also have substantial impact in region 3 and to a lesser extent in region 4. 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 higher purse seine catch, the longline and purse seine fisheries are estimated to have approximately equal impact on spawning biomass.

5. Recent catches are well above the *MSY* level of 56,880 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 20% higher than the re-calculated *MSY*. **Based on these results, we conclude that current levels of catch are not sustainable even at the recent [high] levels of recruitment estimated for the last decade**.

6. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. For the models with higher purse-seine catch and increasing longline catchability, estimates of recent juvenile fishing mortality are considerably higher than for run 10, while the opposite is the case for the PH/ID low catch option.

7. For all of the model runs $F_{current}$ /F_{MSY} is considerably greater than 1. For run 10 the ratio is estimated at 1.785 indicating that a 44% reduction in fishing mortality is required from the 2004-07 level to reduce fishing mortality to sustainable levels. The results are far worse with lower values of steepness. **Based on these results, we conclude that overfishing is occurring in the bigeye tuna stock.**

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 total biomass and spawning biomass would be reduced to 48.1% and 33.6%, respectively, of the level that supports *MSY*. In terms of the reduction against virgin biomass the declines reach as low as 8% for spawning biomass. Current stock status compared to these reference points indicates that the current total and spawning biomass are higher than the associated MSY levels ($\frac{B_{current}}{B_{MSY}} = 1.44$ and $\frac{SB_{current}}{SB_{MSY}} = 1.22$). However, in the case of spawning biomass, the estimate for 2008 (still considered relatively reliable) is below SB_{MSY} (0.947). The likelihood profile analysis indicates a 3% probability that $SB_{current} < SB_{MSY}$ which increases to 70% for SB_{latest} (based on 2008 levels). Some of the more plausible alternative models are more pessimistic as are the conclusions of the structural uncertainty analysis. **Based on these results, we conclude that it is likely that bigeye tuna is in, at least, a slightly overfished state, or will be in the near future**.

9. Consideration of current levels of fishing mortality and historical patterns in the mix of fishing gears indicates that considerable levels of potential yields from the bigeye tuna stock are being lost through harvest of juveniles and overfishing. **Based on these results, we conclude that greater overall yields could be obtained by reducing the mortality of small fish**.

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) and Langley et al. (2008). At the request of WCPFC, this is a streamlined, rather than full assessment and subsequently, this paper contains less background material and supporting material than the 2008 assessment of Langley et al. (2008) and interested readers should consult that report if further information is required. The key purpose of this assessment was to provide a basis for the evaluation of the potential benefits of CMM2008-01 (Hampton and Harley 2009). This paper focuses on changes to the previous assessment (e.g. data and model structure) and reports the key model results.

2 Background

2.1 Biology

Bigeye tuna are distributed throughout the tropical and sub-tropical waters of the Pacific Ocean. There is little information on the extent of mixing across this wide area. Analysis of mtDNA and DNA microsatellites in nearly 800 bigeye tuna failed to reveal significant evidence of widespread population subdivision in the Pacific Ocean (Grewe and Hampton 1998). While these results are not conclusive regarding the rate of mixing of bigeye tuna throughout the Pacific, they are broadly consistent with the results of SPC's tagging experiments on bigeye tuna. Bigeye tuna tagged in locations throughout the western tropical Pacific have displayed movements of up to 4,000 nautical miles (Figure 1) over periods of one to several years, indicating the potential for gene flow over a wide area; however, the large majority of tag returns were recaptured much closer to their release points. Also, recent tagging experiments in the eastern Pacific Ocean (EPO) using archival tags have so far not demonstrated long-distance migratory behaviour (Schaefer and Fuller 2002) over relatively short time scales (up to 3 years). In view of these results, stock assessments of bigeye tuna are routinely undertaken for the WCPO and EPO separately[7], however, recent tagging efforts in the central and western Pacific Oceans will provide further opportunity to examine this hypothesis.

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 be variable with size, with the lower rates of around 0.5 yr^{-1} for bigeye >40 cm FL (Hampton 2000). Tag recapture data indicate that significant numbers of bigeye reach at least eight years of age. The longest period at liberty for a recaptured bigeye tuna tagged in the western Pacific at about 1–2 years of age is currently 14 years (SPC 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 longliners from Japan and Korea and the smaller, fresh sashimi longliners based in several Pacific Island countries. Prices paid for both frozen and fresh product on the Japanese sashimi market are the highest of all the tropical tunas. Bigeye tuna are the cornerstone of the tropical longline fishery in the WCPO; the catch in the SPC area had a landed value in 2006 of approximately US$504 million (Williams and Reid 2007).

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

From 1980 to 1995, the longline catch of bigeye tuna in the WCP-CA varied between about 40,000 and 65,000 mt (Figure 2). Catches increased in subsequent years, reaching a peak of about 84,000 mt in 2004 and 82,000 mt in 2006. Longline catches have declined to 71,000 mt in 2007, the most recent year for which complete catch data are available.

Since about 1994, there has been a rapid increase in purse-seine catches of juvenile bigeye tuna, first in the eastern Pacific Ocean (EPO) and since 1996, to a lesser extent, in the WCPO. In the WCPO, purse-seine catches of bigeye tuna are estimated to have been less than 20,000 mt per year up to 1996, mostly from sets on natural floating objects (Hampton et al. 1998). In 1997, the catch increased to 55,000 mt, primarily as a result of increased use of fish aggregation devices (FADs). High purse seine catches were also recorded in 2005 (37,000 mt) and 2006 (5000 mt). Since 2001, annual purse seine catches have average over 28,000 mt. However, there remains considerable uncertainty regarding the accuracy of the purse-seine catch and reported catches may significantly under-estimate actual catch levels (Lawson 2008).

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.

The spatial distribution of WCPO bigeye tuna catch during 1998–2007 is shown in Figure 3. The majority of the catch is taken in equatorial areas, by both purse seine and longline, but with significant longline catch in some sub-tropical areas (east of Japan, north of Hawaii and the east coast of Australia). High catches are also presumed to be taken in the domestic artisanal fisheries of Philippines and Indonesia using a variety of gear types (e.g. pole-and-line, ringnet, gillnet, handline and seine net). The total catch for both countries combined are estimated to have exceeded 30,000 mt in recent years. The statistical basis for the catch estimates in Philippines and, in particular, Indonesia is weak; however, we have included the best available estimates in this analysis in the interests of providing the best possible coverage of bigeye tuna catches in the WCPO. Model runs which consider alternative catch histories for these fisheries were conducted.

3 Data compilation

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

3.1 Spatial stratification

The geographic area considered in the assessment is the WCPO, defined by the coordinates 40°N–35°S, 120°E–150°W. Within this overall area, a six-region spatial stratification was adopted for the assessment (Figure 3). The rationale for this stratification was to separate the tropical area, where both surface and longline fisheries occur year-round, from the higher latitudes, where the longline fisheries occur more seasonally. The stratification is equivalent to the regional structure adopted in the 2006 base case assessment.

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

3.2 Temporal stratification

The primary time period covered by the assessment is 1952–2007, thus including all significant post-war tuna fishing in the WCPO. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec).

3.3 Definition of fisheries

MULTIFAN-CL requires the definition of "fisheries" that consist of relatively homogeneous fishing units. Ideally, the fisheries so defined will have selectivity and catchability characteristics that do not vary greatly over time (although in the case of catchability, some allowance can be made for time-series variation). Twenty-five fisheries were defined for the 2008 assessment on the basis of region, gear type and, in the case of purse seine, set type, and these definitions have been retained for the current assessment (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.

Time series of catch and CPUE for all fisheries are provided in Figure 5 and Figure 6.

3.4.1 Purse seine

Two sets of purse-seine input catch data were used in the analyses. The first set 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. In a change from the 2008 assessment, the species compositions for 1967-1987, for which sampling data are not available, were estimated using categorical linear models (Lawson 2009) of quarter, MFCL area and school association (but not year), and interactions, fitted to s_best data for 1988-2008 grouped by year, quarter, MFCL area and school association.

The second set of input data was derived by extracting the data from s_best, as for the first set of data, and then adjusting the proportions of skipjack, yellowfin and bigeye for 1996-2008 on the basis of observer data corrected for selectivity bias in grab samples (Lawson 2009). For strata in the period 1996-2008 for which observer data are missing or insufficient, the species compositions were estimated with categorical linear models of year, quarter, MFCL area and school association, and interactions, fitted to observer data corrected for selectivity bias. For 1967-1995, for which observer data are not available, the species compositions were estimated with categorical linear models of quarter, MFCL area and school association, and interactions.

Both sets of input data are biased. In the first set of data, 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 first set of input data are therefore over-estimated and the catches of yellowfin and bigeye are under-estimated. The second set of data was adjusted on the basis of observer data collected from grab samples, which are known to under-select very small and very large fish (Lawson 2009), with the result that the proportion of skipjack determined from observer data is under-estimated and the proportion of yellowfin is over-estimated. While the observer data were corrected for selectivity bias, the correction was based on paired grab and spill samples collected from only four trips, all of which took place in the waters of Papua New Guinea in 2008 onboard purse seiners fishing anchored FADs. The correction for selectivity bias is therefore only indicative and the proportions of skipjack and yellowfin in the second set of input data are probably still under-estimated and over-estimated respectively. The correction of the observer data for selectivity bias should improve as more data from paired grab and spill samples become available.

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

3.4.2 Indonesia / Philippines

Revised catch histories were obtained for the Indonesia and Philippines fisheries (Figure 11). Effort data for the Philippines and Indonesian fisheries small fish fisheries were unavailable and were set to missing using a new feature available within MULTIFAN-CL.

3.4.3 Longline fisheries

For the principal longline fisheries (LL ALL 1–6), effective (or standardised) effort was derived using generalized linear models (GLM) (Hoyle 2009). The method used by Hoyle (2009) differed in two main ways from previous approaches: (1) the logarithm of effort, rather than effort, was used as an explanatory variable which is appropriate as the logarithm of catch is the response variable; and (2) a proxy for regional yellowfin abundance was used as a time-dependent off-set to help account for changes in yellowfin abundance when considering targeting. The net effect of these changes was flatter 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 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[8]). This assumption has been applied to all LL-ALL fisheries and probably reflects a minimum value for longline ‘effort creep’ and is considered more plausible than the assumption of no increase in catchability.

The standardised CPUE indices based on the old and new methodologies, plus the indices based on the new method including the 0.47% effort creep are presented in Figure 7.

The technique for standardising 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.

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.

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[8] 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.

3.5 Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 95 2-cm size classes (10–12 cm to 188–200 cm). Each length-frequency observation consisted of the actual number of bigeye tuna measured. 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 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.

For the current assessment we closely examined the 1980s data and sampling programme (Figure 8). Whilst these data had been attributed to the 'small fish fishery' (fishery 18), careful examination of the data indicated that large fish were also present. Subsequent examination of the source of the data indicated that the samples were not solely from the small fish fishery and also represented large fish fishery catches (fishery 19). As it is not possible to objectively separate the data, these samples were excluded 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 is sourced from the U.S. National Marine Fisheries Service (NMFS) port sampling programme for U.S. purse seiners in Pago Pago, American Samoa and an observer programme conducted for the same fleet. Since the early 1990s, port sampling and observer programmes on other purse seine fleets have provided additional data. Only data that could be classified by set type were included in the final data set. For each purse seine fishery, size samples were aggregated without weighting within temporal strata.

Longline: The majority of the historical data were collected by port sampling programmes for Japanese longliners unloading in Japan and from sampling aboard Japanese research and training vessels. 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.

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

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

As in previous assessments, length (and weight) data from each fishery/quarter were simply aggregated assuming that the collection of samples was broadly representative of the operation of the fishery in each quarter. An alternative approach for computing the size compositions for the Japanese longline fisheries, comparable to that used in the 2007 yellowfin stock assessment (Langley et al. 2007), was trialled for bigeye tuna (Langley & Hoyle 2008). However, due to the lack of evidence of strong spatial heterogeneity in the size data within each region (Langley 2006c) and the substantial loss of size data (using the predetermined selection criteria) the approach was not adopted for the current assessment.

3.6 Weight-frequency data

Individual weight data for the Japanese longline fisheries are included in this assessment in their original form. For many other longline fleets, "packing list" data are available from export documentation, and these data are progressively being processed and incorporated into the assessment database. For this assessment, the available weight data (apart from those provided by Japan) originated from vessels unloading in various ports around the region from where tuna are exported, including Guam, Palau, FSM, Marshall Islands, Fiji, Papua New Guinea and eastern Australian ports.

All weight data were recorded as processed weights (usually recorded to the nearest kg). Processing methods varied between fleets requiring the application of fishery-specific conversion factors to standardise the weight data to whole fish weights. Details of the conversion to whole weight are described in Langley et al. (2006). For each fishery, quarterly weight frequency data were compiled by 1 kg weight intervals over a range of 1–200 kg.

In the 2008 bigeye assessment, some weight frequency data from Japanese vessels was incorrectly attributed to Taiwanese vessels which fish using different fishing strategies. This error was corrected in the current assessment.

3.7 Tagging data

A modest amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. The data used consisted of bigeye tuna tag releases and returns from the OFP's Regional Tuna Tagging Project conducted during 1989–1992, and more recent (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 include the tag release and recovery data from the 2006–09 tagging programme undertaken throughout the western part of the WCPO (but predominantly PNG and Solomon Islands waters) as these data were not yet in a format suitable for inclusion.

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

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 fishery dynamics; (iii) the dynamics of tagged fish; (iv) observation models for the data; (v) parameter estimation procedure; and (vi) stock assessment interpretations. Detailed technical descriptions of components (i) – (iv) are given in Hampton and Fournier (2001) and are not repeated here. Brief descriptions of the various processes are given, including information on structural assumptions, estimated parameters, priors and other types of penalties used to constrain the parameterisation were provided in Langley et al. (2008) 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 of about three times and one third of the average recruitment would occur about once every 25 years on average.

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

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

4.1.2 Initial population

The population age structure in the initial time period in each region was assumed to be in equilibrium and determined as a function of the average total mortality during the first 20 quarters. This assumption avoids having to treat the initial age structure, which is generally poorly determined, as independent parameters in the model. Note that the assumption used does not assume virgin conditions at the start of the assessment data. Rather, we assume that exploitation in the years leading up to 1952 was similar to exploitation over the period 1952–1956. This probably overestimates total mortality in the initial population, but the bias should be minimal. The initial age structure was applied to the initial recruitment estimates to obtain the initial populations in each region.

4.1.3 Growth

The standard assumptions made concerning age and growth are (i) the lengths-at-age are normally distributed for each age-class; (ii) the mean lengths-at-age follow a von Bertalanffy growth curve, except for the 2^{nd}-8^{th} 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 due to the "implicit transition" computational algorithm employed (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. Thus there is a need for $2 \times 7 \times 4 = 56$ movement parameters. We did not incorporate age-dependent movement into this assessment, to avoid the addition of more parameters. Previous trials have indicated that this additional structure did not impact the overall results in a substantive way. The seasonal pattern of movement persists from year to year with no allowance for longer-term variation in movement.

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. *M*-at-age was 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. The externally-estimated *M*-at-age for the 2008 assessment and the new value used in the current assessment shown in Figure 10.

No alternative values for *M*-at-age were investigated in this streamlined assessment.

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[9].

4.2 Fishery dynamics

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

4.2.1 Selectivity

In many stock assessment models, selectivity is modelled as a functional relationship with age, e.g. using a logistic curve to model monotonically increasing selectivity and various dome-shaped curves to model fisheries that select neither the youngest nor oldest fish. In previous assessments, we have modelled selectivity with separate age-specific coefficients (with a range of 0–1), but constraining the parameterisation with smoothing penalties. This has the disadvantage of

[9] Consequently we no longer calculate spawning biomass, rather an index of spawning potential. Unfortunately not all graphs have been updated to reflect this change in nomenclature.

requiring a large number of parameters to describe selectivity. In this assessment we have used a new method based on a cubic spline interpolation to estimate age-specific selectivity. This is a form of smoothing, but the number of parameters for each fishery is the number of cubic spline "nodes" that are deemed to be sufficient to characterise selectivity over the age range. We chose five nodes, which seems to be sufficient to allow for reasonably complex selectivity patterns.

Selectivity is assumed to be fishery-specific and time-invariant. Selectivity coefficients for "main" longline fisheries LL ALL 1 and LL ALL 2 (northern fisheries) were constrained to be equal, as were LL ALL 3–6 (equatorial and southern fisheries) and the Chinese/Taiwanese fisheries (LL TW-CH 3 and 4). For the two latter fisheries, selectivity was parameterised using a logistic functional form rather than the cubic spline method. Selectivity was also constrained to be equal for the corresponding purse seine fisheries in the two equatorial regions. The selectivity of the Indonesian domestic fishery was assumed to be equivalent to the Philippines domestic fishery.

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

Recently length-specific selectivity has been implemented within MULTIFAN-CL, and while a run assuming length-specific selectivity was undertaken in the early stages of model development, it was not included here.

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. Subsequently we set the variance of the priors on catchability deviates to be high (approximating a CV of about 0.7), thus allowing for catchability changes to compensate for the missing effort data. For the other fisheries with time-series variability in catchability, the catchability deviation priors were assigned a variance approximating a CV of 0.10.

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

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

4.2.3 Effort deviations

Effort deviations, constrained by prior distributions of zero mean, were used to model the random variation in the effort – fishing mortality relationship. For the Philippines and Indonesian fisheries, purse seine fisheries, pole-and-line fisheries, and the Australian, Hawaii and Taiwanese-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). For the main longline fisheries (LL ALL 1−6), the variance was set at a lower level (approximating a CV of 0.2 – but an increase from 0.1 assumed in the 2008 assessment) because the effort had been standardised in prior analyses and these longline fisheries provide wide spatial coverage of the respective areas in which they occur.

In the early development of the model it was found that several of the effort deviates were estimated at the bounds. This can have a dramatic impact of the model as the effort deviates are needed used to help the model 'take' the catch. The very tight CV assumed for catch means that the model has to modify the population dynamics to fit to the catch data if effort deviates are on the bounds. Fortunately in the case of this bigeye tuna assessment, the relaxation of the bounds from +/- 6 to +/- 10 had little impact on the stock dynamics so fortunately the boundary values were not having a significant impact. Nevertheless, we stayed with the increased bounds (+/- 10) and in future assessments this should be revisited (e.g. are the observations valid).

4.3 Dynamics of tagged fish

4.3.1 Tag mixing

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

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

4.3.2 Tag reporting

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

4.4 Observation models for the data

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

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

The size frequency data is assigned an effective sample size lower than the actual number of fish sampled. Reduction of the effective sample size recognises that (i) length- and weight-frequency samples are not truly random (because of clumping in the population with respect to size) and would have higher variance as a result; and (ii) the model does not include all possible process error, resulting in further under-estimation of variances. The influence of the size frequency data in the model can be examined by varying the effective sample size in the model. 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. An alternative weighting scheme was investigated where the length and weight frequency were further down-weighted to a maximum effective sample size of 20.

A log-likelihood component for the tag data was computed using a negative binomial distribution in which fishery-specific variance parameters were estimated from the data. The negative binomial is preferred over the more commonly used Poisson distribution because tagging data often exhibit more variability than can be attributed by the Poisson. We have employed a parameterisation of the variance parameters such that as they approach infinity, the negative binomial approaches the Poisson. Therefore, if the tag return data show high variability (for example, due to contagion or non-independence of tags), then the negative binomial is able to recognise this. This should then provide a more realistic weighting of the tag return data in the overall log-likelihood and allow the variability to 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) [10].

In this assessment we have not calculated the Hessian matrix to obtain estimates of the covariance matrix, which is typically used in combination with the Delta method to compute approximate confidence intervals for parameters of interest. Instead a 'grid' of 64 model runs was undertaken to attempt to characterize uncertainty in this way and a summary of these results are provided. Likelihood profiles for the critical reference points $F_{current}\ /F_{MSY}$ and $SB_{current}\ /SB_{MSY}$ were undertaken for the main model run (run 10).

4.6 Stock assessment interpretation methods

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

4.6.1 Fishery impact

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

We approach this problem by computing biomass time series (at the region level) using the estimated model parameters, but assuming that fishing mortality was zero. Because both the *real* biomass B_t and the *unexploited* biomass $B_{t_{F=0}}$ 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.

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

4.6.2 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 2004–2007. The last year in which catch and effort data are available for all fisheries is 2007. We do not include 2008 in the average as fishing mortality tends to have high uncertainty for the terminal data years of the analysis and the catch and effort data for this terminal year are usually incomplete (see Langley 2006a and Harley et al. 2009).

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 1999–2007.

5 Model runs

In undertaking this streamlined assessment over 120 model runs were undertaken. The purpose of these runs included: testing the impacts of new or revised data, development of a new run most consistent with the 2008 assessment, developing models with alternative assumptions for several important inputs or model structures, and finally to assess structural uncertainty in the assessment. Twenty of these model runs, developed in a stepwise manner), are provided in Table 2 and will be described in further detail below.

- Taking the 2008 data set and running it with the new version of MULTIFAN-CL (run 1 – New MFCL)
- Taking the assessment from 2008, the first change was to estimate seven offsets from the Von Bertalanffy growth curve for the youngest ages. This was an oversight from the 2008 assessment (run 1a – Growth offset).
- Next we changed the order of estimation of growth and used more realistic starting values for growth variability. Previously growth had been estimated early in the estimation procedure and in some of our investigations the resulting estimates of growth were not plausible. The model was found to have gotten stuck at a local minimum (when testing length-specific selectivity). By delaying the estimation of growth these problems appeared to be overcome (run 2 – Growth estimation).
- Next we included the revised biological parameters based on the work of Hoyle and Nicol (2008) (run 3 – Biol.) (Figure 10).
- At this point we updated the data used in the assessment to incorporate new and revised historical data (run 4 – 2009 data).
- As no attempt had previously been made to correct historical (pre-observer) purse seine catch estimates, these had been based on logbook estimates. A year-aggregated model was used to predict the BET component of BET/YFT in early years (run 5 – extra PS) (Figure 12).
- The CPUE indices for the LL-ALL fisheries are based on a standardisation of Japanese longline catch and effort data. Based on the revised methodology of Hoyle (2009), new indices were developed (run 6 – CPUE) (Figure 7).

- Investigation of early catch sampling data for the Philippines indicated that the catch of the so-called "small fish fishery" contained a noticeable number of big fish in some years during the 1980s. Revisiting the basis for these data indicated that it was almost certain that these data were contaminated with samples from the large-fish fishery. Subsequently these samples were removed (run 7 – Excl. Size 18).
- It was noted that the effort deviate SD's for the non-standardised fisheries was only 0.2 and given that catchability only changed every two years it was possible that data were being given too much weight. Consequently the SD's were increased to 0.4 (run 8 – Incr. effdev).
- As some of the effort deviates were still estimated to be on the bounds, they bounds were increased from +/-6 to +/- 10 (run 9 – Effdev. bound).
- The final change was the increase in the effort deviate SD for the LL-ALL fisheries from 0.1 to 0.2. This was done as it was recognised that, even though the indices were standardised, we were still weighting them too highly (run 10 – Incr. LL).

This final model, run 10, represented our best model which was comparable to the 2008 assessment. From this model, the following one change alternative models were developed:

- We reduced the weight of the LL-ALL size frequency data to illustrate the different signals being suggested by the size and CPUE data (run 11 – low size).
- We substituted the purse seine catch history for on based corrections estimated through the recent spill sampling trials. Even noting the limited nature of these experiments, this catch history is probably more plausible that that for run 10 (run 14 – spill) (Figure 12).
- The analysis of Hoyle (2009) indicated an effect of our inability to consider vessel effects in the CPUE standardisation. He estimated that each year the catchability increased by 0.47% for bigeye (non-compounding) in the longline fishery. This CPUE trend is probably more plausible than that for run 10 (run 15 – creep) (Figure 7).
- Like catches from purse seine fisheries, catches from the small fish fisheries from Indonesia and the Philippines are highly uncertain and quite influential. We investigated an alternative catch history where the reported catches were reduced by a third (run 16 – low IDPH) (Figure 11).
- Finally, the steepness of the spawner recruitment curve is notoriously difficult to estimate, and the current estimate is very close to 1 and most likely an over-estimate. Models were run with steepness fixed at values of 0.55, 0.65, 0.75, 0.85, and 0.95 (runs 17-21 – Steep (x)).

In addition to this a full grid of 64 model runs was produced with all combinations of the following options included:

- Steepness[4 levels]: 0.65, 0.75, 0.85, and 0.95
- Size data weighting [2 levels]: run 10 and run 11
- Purse seine catch [2 levels]: run 10 and run 14
- Longline CPUE [2 levels]: run 10 and run 15
- ID/PH catches [2 levels]: run 10 and run 16

This grid was run using all the assumptions in run 10, except that the effort deviate boundaries were still at +/- 6, which should make little difference. One feature of this grid is that it does not include steepness at the level estimated in any of the runs (0.96-0.98) so all of the runs in the grid are more pessimistic that the results in runs 10, 11, and 14-16.

6 Results

6.1 Impact of model changes

Given the stepwise design of changes from the 2008 bigeye assessment it is useful to examine the impact of individual changes involved from run 1 to run 10. Estimates of key reference points for each of the runs are provided in Table 4 (including the base case model run from the 2008 assessment) and the total WCPO biomass is provided in Figure 27 and Figure 28. Key observations from these model runs were:

- The minor changes to the MULTIFAN-CL software had very little impact on any of the key reference points;
- Estimation of growth offsets leads to a slightly more productive stock, but in a slightly worse state;
- Estimation of growth is difficult and the order of estimation can impact on model fit and reference point estimates. The new approach found a much better fit;
- The new biological estimates made the stock more productive and also led to a more optimistic stock status;
- The new data led to a continuation of a decline in stock status and increase in fishing mortality. The large (10% decrease) in *MSY* was due to increased catches from the ID DOM 3 and PH DOM 3 fisheries and the estimated selectivity of these fisheries switching to solely on small fish;
- The increase in historical purse seine catches had little impact aside from a small increase in *MSY*;
- The new longline CPUE series were far more optimistic in terms of stock status and increased absolute abundance, though productivity (*MSY*) was reduced slightly;
- Exclusion of the contaminated early PH DOM 3 size data led to a further shift in the selectivity of this fishery to small fish. This reduced the *MSY* and worsened stock status;
- Neither the decrease in effort deviate penalties for non- LL-ALL fisheries nor the increase in the effort deviate boundaries had a noticeable impact on any of the key reference points; and
- The increase in effort deviate penalties for the LL-ALL fisheries made stock status slightly more optimistic. Interestingly, this change in model structure caused a shift in the estimated selectivity for the unassociated purse seine fishery. This fishery has very little catch of bigeye, but size frequency data does include some larger fish which were previously not fitted by the model. The selectivity curves for the PS UNA 3 and PH DOM 3 fisheries estimated in the 2008 assessment and here are provided in Figure 13.

All of the models run using the 2009 data were rerun assuming the previous MSY time window (2003-06) to see how the view of the past has changed. Not only have conditions deteriorated since the previous assessment, our view of past conditions is now more pessimistic, for example the $F_{current}$ $/F_{MSY}$ for run 10 when calculated using the period 2003-06 is 1.57 compared to 1.44 from run 4 in the 2008 assessment. The main reason for this appears to be the shift in the selectivity for the increasingly influential domestic fisheries in Indonesia and the Philippines.

6.2 Fit diagnostics – Run 10

In this streamlined assessment we have focussed less on the various diagnostics. Where examined, the patterns found here were similar to those found in the 2008 assessment. We will briefly touch on patterns observed in two key diagnostics: 1) the fit to the size frequency data, and 2) the estimated effort deviates. The following observations are made:

- There remains some systematic lack of fit to the size data for the longline fisheries (Figure 15 and Figure 16). 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 smaller fish observed in the length data during the 1980s;
    - LL TW-CH 4: the declines in median length and weight not picked by the model;
    - LL Bismark 3: the smaller median weights in the historic data relative to the later median weights
- 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

assessment are the negative effort deviations for the LL ALL 3 fishery in the last two decades (Figure 17).

- Effort deviations for the purse seine fisheries, particularly those in region 4, are highly variable and reveal short-term fluctuations (Figure 17). 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.

In addition to these diagnostics, there are other model results which can have diagnostic value. In particular regional trends in recruitment may be evidence of data / model structure issues. This appears to be the case in region 3 and it is probably no coincidence that there is a strong trend in recruitment and effort deviates for the principal fishery indexing abundance.

6.3 Model parameter estimates (run 10 unless otherwise stated)

6.3.1 Growth

The estimated growth curve is shown in Figure 18. For the base-case model, growth in length is estimated to continue throughout the lifespan of the species, without the attenuation of length approaching a maximum level – the estimated mean length of the final age-class is 179.2 cm, over 6 cm larger than estimated for the 2008 assessment, and the estimated L_{∞} is 194.5 cm. The estimated variance in length-at-age is slightly less than that estimated for the 2008 assessment.

The potential for regional variation in the growth rate of bigeye, as evident in the 2007 yellowfin assessment, was investigated in Langley & Hoyle (2008) by comparing growth curves derived from separate region models. There was no strong evidence to suggest regional variation in growth although the approach was limited by the lack of small bigeye in the fishery size samples from the non equatorial regions.

6.3.2 Movement

Two representations of movement estimates are shown in Figure 19 and Figure 20. The estimated movement coefficients for adjacent model regions are shown in Figure 19. Movement patterns are generally similar, but greater movement was estimated in the current assessment compared to the 2008 assessment. Some notable differences are:

- Movements from regions 5 to 3 and regions 4 to 2 in quarter 2
- Movements from region 3 to 4 in quarters 1, 2, and 3 (compared to previous estimates of movement only for quarter 1)
- The current assessment has movement into region 6 from region 5 (3^{rd} quarter) and region 4 (4^{th} quarter) that were not previously estimated;

These differences lead to some noticeable changes in the distribution of regional biomass by source region derived from a simulation using the movement coefficients (Figure 20). Region 4 is now more reliant on recruitment from region 3 and the southern regions (5 and 6) source more biomass from region 3 as well. The simulation indicates that most biomass within a region is sourced from recruitment within the region, with the exception of region 1 which gets a large proportion of its recruitment from region 2.

Movement patterns should be the focus of future assessment work, particularly as new tagging data become available. Examination of movement could also be useful in the examination of the regional trends in estimated recruitment which could be aliasing for other processes.

6.3.3 Selectivity

There are two notable changes in the selectivity curves estimated in the current assessment compared to the 2008 assessment. The most important of these is (due to the large catches reported) the change in the selectivity ogive for the Philippines domestic small fish fishery. The addition of new data led to the model no longer selecting these larger fish that were sometimes in the catch. This shift was amplified when the contaminated data were excluded. This shift will lead to the model not being able to predict any large fish in the catch, but is due to a trade-off between penalties on the shape of the selectivity curve and the fit to any resulting data. As there are no size data available for the Indonesian domestic fishery, we assume that the non-longline fisheries in Indonesia have the same selectivity as the Philippines small-fish fishery.

The opposite shift occurred in the purse seine unassociated fisheries with the selectivity curves shifting to allow for selectivity of larger fish. This is less of a concern because of the small catches from this fishery. Examination of the length frequency data did show large fish in recent years. Given the level of depletion of the stock, the model needs to increase the selectivity on these ages to fit the length frequency observations.

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 fishery with a substantial change in size composition in the early 1980s.

6.3.4 Catchability

Time-series changes in catchability are evident for several fisheries and the patterns are consistent with the 2008 assessment (Figure 22). 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.

6.4 Stock assessment results

Symbols used in the following discussion are defined in Table 3 and the key results are provided in Table 5.

6.4.1 Recruitment

The run 10 recruitment estimates (aggregated by year for ease of display) for each region and the entire WCPO are shown in Figure 23 and are broadly similar to those estimated for the 2008 assessment. The regional estimates display large interannual variability and variation on longer time scales, as well as differences among regions. For the aggregated estimates, there is a decreasing trend to about 1970 and an increasing trend thereafter, 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. the increase in median size from the LL-ALL 3 fishery).

There are sharp initial declines in recruitment in regions 2 which are still evident, but the declines in regions 4 and 5 are less than estimated previously. The post-1970 increase in WCPO recruitment is due primarily to an increasing trend in the estimates for region 3 and, to a lesser extent, region 4. This trend, and its correspondence with increasing juvenile catch in the same region, has been noted in previous WCPO bigeye assessments and is investigated in detail in Langley & Hoyle (2008).

A comparison of WCPO recruitment estimates for the different analyses is provided in Figure 24. The six reveal comparable trends in recruitment although there is some temporal variation in the magnitude of the trend in recruitment among analyses. There is also a substantial increase in recruitment from the mid-1990s for the model option with increased purse-seine catch, while the converse is the case for the low catch alternative for the Indonesia and Philippines domestic fisheries (Figure 24).

6.4.2 Biomass

The estimated total biomass trajectory for each region and for the entire WCPO for run 10 is shown in Figure 25 and the plot of spawning potential is provided in Figure 26. 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 following the decline in regional recruitment and increase in regional catches. 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 biomass the continued decline over time is still evident.

The comparison of trends in total biomass for run 10 and the alternative models are shown in Figure 29. The patterns are quite comparable, with run 11 (low size) being the most different with high biomass in absolute terms and a lesser decline.

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 (Figure 30). For the models with higher purse-seine catch and increasing longline catchability, estimates of recent juvenile fishing mortality are considerably higher than for run 10, while the opposite is the situation for the PH/ID low catch option.

Changes in fishing mortality-at-age and population age structure are shown for decadal time intervals in Figure 31. Significant juvenile fishing mortality begins in the 1980s with the development of purse seining in the WCPO. There is also a significant increase in fishing mortality for the 15–25 age-classes from 1990 and a sharp increase in the juvenile fishing mortality in the last decade. Changes in age-structure are also apparent, in particular the decline in abundance of age-classes 20 and older (Figure 31).

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 32 and Figure 33. Of interest is: the indication that region 1 was already impacted by fishing at the start of the model (1952); the low estimated impact for region 2 (i.e. the trends in biomass are due to recruitment rather than fishing); and the particularly strong 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 34 and Figure 35 in terms of total biomass and spawning biomass. These figures indicate increasing fishery impacts over time in all regions, with the impacts being higher for spawning biomass than total biomass. A comparison of spawning biomass ratios for the WCPO for the main model results are provided in Figure 36 and Table 5. For run 10 it is estimated that current biomass (average 2004-07) is 24.3% of the level that is predicted in the absence of fishing. This drops to 15% for spawning biomass and to 10.2% if we consider the last year in the model. The levels of depletion are greater for runs 14 (spill), 15 (creep) and 19 (h=0.75).

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 biomass (Figure 37). In contrast with yellowfin tuna, the longline fishery has a significant impact on the bigeye tuna population in all model regions and it is the most significant component of overall fishery impact in regions 2 and 4–6 and is responsible for two-thirds of the impact in recent years. In region 3, the purse seine fisheries and the Indonesian and Philippines domestic fisheries combined now have a higher impact on the spawning stock than the longline fisheries. In region 4, purse seine impacts are significant. In region 1 the coastal pole-and-line and purse-seine fisheries have a significant impact.

A comparison of fishery impacts on spawning biomass at the WCPO level for the four runs with differing catch compositions is provided in Figure 38. For the, arguably more plausible, spill sampling model run (run 14), surface fishery impacts are essentially equal to those of the longline fishery. The inclusion of effort creep has little effect and reducing the catches for the Indonesia and Philippines domestic fisheries reduces the impact of those fisheries.

6.4.5 Yield analysis

The yield analyses conducted in this assessment incorporate the spawner recruitment relationship (Figure 39) 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 39).

As outlined in Table 5, we will go through the main results considering the catch (including consideration of these 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 56,880 mt, a reduction from the 2008 assessment which is mostly due to the change in the estimated selectivity for the domestic fisheries of Indonesia and the Philippines and their increased catches. Given the high estimated fishing mortalities, current equilibrium yield ($Y_{F_{current}}$) is 85.6% of the MSY at 48,680 mt. Current catches, sustained by estimates of high recruitment, are more than double the MSY. Considering the alternative model runs, MSY is higher in runs 11 (low size) and 14 (spill), lower in run 19 (h=0.75) and similar in the other two runs. For the low steepness, current equilibrium yield ($Y_{F_{current}}$) is only 12% of the MSY, due to the high level of fishing mortality relative to F_{MSY}.

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 and this is done in Table 6. We compare MSY based on the predicted SRR to that based on average recruitment over the period 1999-2007. The estimated MSY's that incorporate the above average recruitment are about double those based on the SRR, however, current catches are still in excess of these. **Based on these results, we conclude that current levels of catch are not sustainable even at the recent [high] levels of recruitment estimated for the last decade**.

Fishing mortality

For run 10, the MSY is achieved at F_{mult} = 0.56; i.e. at 56% of the current (2004-07) level of age-specific fishing mortality (see also Figure 40). This represents a ratio of $F_{current}/F_{MSY}$ equal to 1.785 (1/0.56); therefore, current exploitation rates are considerably higher than the exploitation rates to produce the MSY. A reduction in fishing mortality of 44% (1-F_{mult}) is necessary to reduce fishing mortality to the F_{MSY} level. For all of the model runs $F_{current}/F_{MSY}$ is considerably greater than 1. Further, all of the model runs undertaken in the structural uncertainty grid (Figure 47) had estimates of $\frac{F_{current}}{F_{MSY}} > 1$. **Based on these results, we conclude that overfishing is occurring in the bigeye tuna stock**.

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 32.9% and 23.9% 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 38.3% and 31.2% respectively.

Comparing current biomass to the estimated virgin biomass ($B_{current}/B_0$ and $SB_{current}/SB_0$) for run 10, it is predicted that current total and spawning biomass levels are 47.4% and 29.2% of the respective virgin levels.

Current stock status compared to these reference points indicate the current total and spawning biomass are higher than the associated MSY levels, more so for the total biomass reference points which are more influenced by the recent estimates of recruitment. However, in the case of spawning biomass, the estimate for 2008 (still considered relatively reliable) is below SB_{MSY} (0.893).

For models 14 (spill) and 15 (creep) current spawning biomass is closer to SB_{MSY}. Considering spawning biomass in 2008, only run 11 (low size) has the stock above SB_{MSY}.

The so-called 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 42 while the complementary spawning biomass plot is provided in Figure 43. 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 where they are estimated to have increased, exceeding F_{MSY} in the late 1980s and remaining above ever since. While total biomass is estimated to have remained above B_{MSY}, spawning biomass has been very close to, or below SB_{MSY} in recent years.

Comparison of the spawning biomass based Kobe plots for run 10 and the main alternative runs are provided in Figure 44. The patterns are consistent with the observations about fishing and biomass levels for the runs noted previously.

Considering the results from the likelihood profiling (Figure 46) and the structural uncertainty analysis (Figure 47), the probability that $SB_{current}$ and SB_{latest} exceed some common SB-related reference points is provided in Table 8. For the likelihood profile, considering only parameter uncertainty for run 10, there is a 3% probability that $SB_{current} < SB_{MSY}$, but this increases to 70% for $SB_{latest} < SB_{MSY}$. It is recognised that all the values of steepness considered in the grid are lower than that estimated for run 10 (0.98 versus the range from 0.65-0.95). The probability that current biomass levels were below the *MSY* levels was over 50% and this increased to over 90% when 2008 levels were considered. There is greater than a 10% probability that 2008 spawning biomass levels are less than half the *MSY* level, and over a 80% probability that spawning biomass is less than 20% of the level predicted to exist if fishing had not occurred.

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 10 the model predicts that biomass would be reduced to 49.4% and 35.3% of the level that supports *MSY*. In terms of the reduction against virgin biomass the declines are greater reaching as low as 8% for spawning biomass.

Based on these results, we conclude that it is likely that bigeye tuna is in, at least, a slightly overfished state, or will be in the near future.

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 10, 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 48). Prior to 1970, the WCPO bigeye fishery was almost exclusively conducted by the longline method, with a low exploitation of small bigeye. The associated age-specific selectivity resulted in a substantially higher level of *MSY* (100,000 mt per annum) compared to that estimated for the fishery based on the recent age-specific fishing mortality pattern (about 57,000 mt). The decline in the *MSY* over time follows the increased development of those fisheries that catch smaller bigeye, principally the surface fisheries (Figure 48).

Another way to consider utilisation is in terms of yield per recruit. Figure 50 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 10. In this example the biomass of the cohort is maximised at an age of 15 quarters and this declines quite rapidly either side; 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 is provided in Table 7 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 2/3 of the potential yield would be a suitable reference point, i.e. selectivity patterns be modified so that only 1/3 of potential yield was 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. We note that, based on the previously estimated selectivity curve for the domestic fisheries of Indonesian and the Philippines, this was ~50%. **Based on these results we conclude that greater overall yields could be obtained by reducing the mortality of small fish.**

7 Discussion and conclusions

For the first time in 2008 the WCPFC-SC asked for a 'streamlined' stock assessment rather than just an assessment. While the WCPFC-SC did not provide guidance on what the difference between a streamlined and standard assessment might be, our interpretation is that the intention was to basically update the previous assessment using the most recent data and corrections or refinements to previous uncertainties – in order to provide a basis for the evaluation of CMM2008-01 (Hampton and Harley 2009). Therefore this assessment report provided fewer details of some of the technical diagnostics, which are provided in the 2008 assessment of Langley et al. (2008). Also, as the evaluation of CMM2008-01 does not consider parameter uncertainty, and that the estimation of parameter uncertainty in these models is very time consuming, we have focussed on point estimation in this assessment. In the report, we have focussed on differences in results from the 2008 assessment, rather than a detailed description of the current assessment results. It is recommended that SC-5 consider what elements that it would expect to see in a streamlined versus 'full' assessment to assist in future stock assessment planning.

Nevertheless, over 130 different model runs were undertaken in developing this assessment representing about 75 days of computing using a top of the line desktop computer. These model runs were necessary to examine the impacts of changes in data, weighting of different data sources, key parameter values, and other structural model assumptions.

For comparability with the 2008 assessment, we have focussed most attention on the model 'run 10'. However, we have not designated it as a base case model. This run may not have the most plausible assumptions for some important data inputs and model structures. In particular, the purse seine catches used in run 14, and the effective effort for the LL-ALL fisheries in run 15 are arguably more plausible than those used in run 10 and in both cases lead to more pessimistic results in terms of stock status (but are associated with slightly increased productivity: *MSY*). These should be considered in the development of the next base case model.

Based on feedback from WCPFC-SC4, and the pre-assessment workshop, several improvements were made to the 2008 assessment to get to run 10, notably:

- The addition of recent catch, effort, and size frequency data from most fisheries;
- A revised purse seine catch history that 'corrects' for bias in logsheet recorded estimates prior to the collection of species composition data by observers;
- New biological parameters;
- Exclusion of some contaminated length frequency data from the Philippines; and
- More realistic assumptions about the effort deviate standard deviations for all fisheries.

Whilst we paid less attention to model diagnostics for this streamlined update, there are several noteworthy issues that were encountered in fitting these models, including some previously recognised, that are important to consider for the purpose of the next assessment:

- Compared to the yellowfin tuna assessment, it is often more difficult to obtain good gradients (i.e. model convergence) for the bigeye assessment. This could be due to conflicts between various data sources etc.
- Most model outputs, particularly those relating to biomass, are sensitive to the estimated growth curve. Changes to the order of estimation were made to stabilize growth estimation, but ultimately better information on growth is needed.
- Lack of fit to the size data for some fisheries is indicative of temporal changes in selectivity. Some of these changes may be accommodated in future assessments by temporal stratification

of certain fisheries. For example, it is likely that a substantial improvement in fit to the size data for LL ALL 2 would result from separating the fishery into pre- and post-1980 fisheries. Lack of fit may also result from changes in the distribution of sampling programmes in relation to the distribution of catch and effort. Improved methods for aggregating samples in some fisheries may result in size data that are more representative of the total catch.

- There are notable trends in some of the model outputs for region 3, e.g. the effort deviates for the LL-ALL 3 fishery, and recruitment. These have been examined in previous assessments and should continue to be the focus of attention.
- There are strong recruitment trends in other regions that should be examined to determine what data sources and / or model structures are driving them.
- There exists a conflict between the CPUE and LL-ALL size frequency data with the former indicating more optimistic conditions that the latter.

Overall the model results were generally similar to those from the 2008 assessment, but some notable differences were the shifts in the estimated selectivity curves for the domestic fisheries of Indonesia and the Philippines and purse seine unassociated set fisheries and the increased reliance of other regions on recruitment from region 3.

The main conclusions of the current assessment are as follows.

1. Recruitment in all analyses is estimated to have been high during 1995–2005. This result was similar to that of previous assessments, and there are some indications that the high recruitment may be, at least partly, an artefact of the structural assumptions of the model. 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.

2. Total and spawning biomass for the WCPO are estimated to have declined to about half of its initial level by about 1970, with total biomass remaining relatively constant since then ($B_{current}$ / B_0= 47.4%) , while spawning biomass has continued to decline ($SB_{current}$ /SB_0=29.2%). Declines are larger for the model with increasing longline catchability and increased purse seine catches.

3. 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 biomass is at 15% of the level predicted to exist in the absence of fishing considering the average over the period 2004-07, and that value is reduced to 10% when we consider 2008 spawning biomass levels.

4. The attribution of depletion to various fisheries or groups of fisheries indicates that the longline fishery has the greatest impact throughout the model domain. The purse seine and Philippines/Indonesian domestic fisheries also have substantial impact in region 3 and to a lesser extent in region 4. 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 higher purse seine catch, the longline and purse seine fisheries are estimated to have approximately equal impact on spawning biomass.

5. Recent catches are well above the *MSY* level of 56,880 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 20% higher than the re-calculated *MSY*. **Based on these results, we conclude that current levels of catch are not sustainable even at the recent [high] levels of recruitment estimated for the last decade**.

6. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. For the models with higher purse-seine catch and increasing longline catchability, estimates of recent juvenile fishing mortality are considerably higher than for run 10, while the opposite is the case for the PH/ID low catch option.

7. For all of the model runs $F_{current}$ /F_{MSY} is considerably greater than 1. For run 10 the ratio is estimated at 1.785 indicating that a 44% in fishing mortality is required from the 2004-07 level to

reduce fishing mortality to sustainable levels. The results are far worse with lower values of steepness. **Based on these results, we conclude that overfishing is occurring in the bigeye tuna stock.**

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 48.1% and 33.6% of the level that supports MSY. In terms of the reduction against virgin biomass the declines reach as low as 8% for spawning biomass. Current stock status compared to these reference points indicate the current total and spawning biomass are higher than the associated MSY levels ($\frac{B_{current}}{B_{MSY}} = 1.44$ and $\frac{SB_{current}}{SB_{MSY}} = 1.22$). However, in the case of spawning biomass, the estimate for 2008 (still considered relatively reliable) is below SB_{MSY} (0.947). The likelihood profile analysis indicates a 3% probability that $SB_{current} < SB_{MSY}$ which increases to 70% for SB_{latest}. Some of the more plausible alternative models are more pessimistic as are the conclusions of the structural uncertainty analysis. **Based on these results, we conclude that it is likely that bigeye tuna is in, at least, a slightly overfished state, or will be in the near future**.
9. Consideration of current levels of fishing mortality and historical patterns in the mix of fishing gears indicates that considerable levels of potential yields from the bigeye tuna stock are being lost through harvest of juveniles and overfishing. **Based on these results, we conclude that greater overall yields could be obtained by reducing the mortality of small fish**.

In undertaking the next assessment for bigeye tuna, and improving bigeye tuna assessments undertaken in the medium to long term, the following activities should be considered:

- For the next full bigeye tuna assessment
  - Further examination of all size frequency data should be undertaken, and the splitting of fisheries should be considered (e.g. LL-ALL 2 and potentially splitting the TWN distant-water longline fleet out from the LL-ALL fisheries);
  - A thorough examination of all time series included for region 3 and then conducting a structural sensitivity analyses to determine the key data sources or structural assumptions leading to the various trends in estimated quantities (e.g. recruitment and effort deviates); and
  - Incorporation of new tagging data, if available. Further, if data for the central Pacific tagging is available for inclusion, then the Pacific-wide assessment should be updated in collaboration with the IATTC.
- For bigeye assessments in the medium term
  - Noting the strong trends in recruitment estimated for many regions in both the bigeye and yellowfin stock assessments, an operating model should be used to create simulated data sets that can be used within to examine the potential trends in model estimates that can come about through incorrect model assumptions, such as movement and age-specific natural mortality; and
  - Consideration be given as to the best approach to estimate uncertainty in key model outputs, e.g. biomass trajectories and stock status.
- Non-stock assessment related activities
  - Improved estimates of growth, including variability in length at age;
  - Increased confidence in the levels and species composition of catches from the domestic fisheries of Indonesia and the Philippines; and
  - Improved estimates of the catches from purse seine fisheries – based on sampling programmes that address known biases (e.g. Lawson 2009).

8 Acknowledgements

We are grateful to all fisheries agencies that have contributed data to the SPC and/or the WCPFC for this assessment. We also acknowledge the assistance of Peter Williams (SPC). We thank participants at the preparatory stock assessment workshop (Noumea, April 2009) for their contribution

to the assessment, and Andrew Wright, Keith Bigelow, and Naozumi Miyabe for casting their eye over the final draft of this report.

9 References

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. 2009. Characteristics of potential reference points for use in WCPFC tuna stock assessments. WCPFC-SC5 ME-WP-02. Port Vila, Vanuatu, 10-21 August 2009.

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., 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. 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.

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, 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.

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

Fishery Number	Reference Code	Nationality	Gear	Region
1	LL ALL 1	Japan, Korea, Chinese Taipei	Longline	1
2	LL ALL 2	Japan, Korea, Chinese Taipei	Longline	2
3	LL HW 2	United States (Hawaii)	Longline	2
4	LL ALL 3	All excl. Chinese Taipei & China	Longline	3
5	LL TW-CH 3	Chinese Taipei and China	Longline	3
6	LL PG 3	Papua New Guinea	Longline	4
7	LL ALL 4	Japan, Korea	Longline	4
8	LL TW-CH 4	Chinese Taipei and China	Longline	4
9	LL HW 4	United States (Hawaii)	Longline	4
10	LL ALL 5	All excl. Australia	Longline	5
11	LL AU 5	Australia	Longline	5
12	LL ALL6	Japan, Korea, Chinese Taipei	Longline	6
13	LL PI 6	Pacific Island Countries/Territories	Longline	6
14	PS ASS 3	All	Purse seine, log/FAD sets	3
15	PS UNS 3	All	Purse seine, school sets	3
16	PS ASS 4	All	Purse seine, log/FAD sets	4
17	PS UNS 4	All	Purse seine, school sets	4
18	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, Solomons, PNG	Pole-and-line	3
23	LL BMK 3	All, excluding PNG	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 2009 bigeye tuna assessment. D=development; P=principal; A=alternative.

Run	Type	Description
1	D	2008 data and doitall file with new version of MULTIFAN-CL (New MFCL)
1a	D	As per 1 and with seven initial offsets from the Von Bertalanffy growth curve estimated. (Growth offset)
2	D	As per 1a and revised order of estimation and starting values to stabilize growth (Growth est.)
3	D	As per 2 and new biological parameters (Biol.)
4	D	As per 3 and with new data (2009 data)
5	D	As per 4 and with s_best purse seine catches extrapolated back to the start of the purse seine fishery (Extra PS)
6	D	As per 5 and with standardised CPUE based on the method of Hoyle (2009) (CPUE)
7	D	As per 6 and with 1980s size frequency data for fishery 18 excluded (Excl. Size 18)
8	D	As per 7 and with effort deviate SD's increased from 0.2 to 0.4 for the non LL-ALL fisheries (Incr. Effdev)
9	D	As per 8 and with the effort deviate boundaries increased from ± 6 to ± 10 (Effdev bound)
10	P	As per 9 and with LL-ALL effort deviate SD's increased from 0.1 to 0.2
11	A	As per 10 and with LL-ALL fishery size data sample sizes reduced from n/20 to n/50 (low size)
12		Not included in the report
13		Not included in the report
14	A	As per 10 and with purse seine catches estimated using the spill sampling correction (spill)
15	A	As per 10 and with LL-ALL effort increased by 0.47% per year to account for increased efficiency due to fleet changes (creep)
16	A	As per 10 and with the catches from the PH and ID small fish fisheries (fisheries 18 and 24 respectively) reduced by 1/3 (low IDPH)
17	A	As per 10, but steepness fixed at 0.55 (h=0.55)
18	A	As per 10, but steepness fixed at 0.65 (h=0.65)
19	A	As per 10, but steepness fixed at 0.75 (h=0.75)
20	A	As per 10, but steepness fixed at 0.85 (h=0.85)
21	A	As per 10, but steepness fixed at 0.95 (h=0.95)

Table 3. Description of symbols used in the yield analysis. For the purpose of this assessment, 'current' is the average over the period 2004-2007 and 'latest' is 2008.

Symbol	Description
$C_{current}$	Average annual catch over a recent period[11]
C_{latest}	Catch in the most recent year
$F_{current}$	Average fishing mortality-at-age[12] for a recent period
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (MSY[13])
$Y_{F_{current}}$	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[14].
$B_{current}/B_0$	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

[11] 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. 2004-2007.

[12] 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

[13] 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

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

Table 4. *MSY* based performance measures from the principal model runs and sensitivity analyses.

Run	$SB_{current}$	SB_{MSY}	MSY	F_{mult}	$F_{current}$ $/F_{MSY}$	$SB_{current}$ $/SB_{MSY}$	Obj. Fnt value	npars	gradient
2008 (run 4)	120,134	100,600	64,600	0.69	1.44	1.19			
run1	117,922	99,780	65,080	0.70	1.42	1.18	1,246,483	5,643	0.07
run1a	116,016	106,000	65,560	0.67	1.48	1.09	1,246,812	5,650	0.08
run2	119,338	106,000	65,760	0.69	1.46	1.13	1,246,850	5,650	0.01
run3	106,059	89,280	67,000	0.72	1.39	1.19	1,246,855	5,650	0.08
run4	90,574	88,710	61,040	0.54	1.85	1.02	1,293,545	5,802	0.04
run5	91,249	90,360	62,600	0.55	1.83	1.01	1,294,135	5,802	0.06
run6	102,730	84,920	60,080	0.59	1.71	1.21	1,294,533	5,802	0.01
run7	103,796	94,660	57,480	0.54	1.87	1.10	1,289,391	5,802	0.07
run8	105,656	94,150	56,680	0.53	1.89	1.12	1,291,569	5,802	0.02
run9	105,242	94,200	56,800	0.53	1.89	1.12	1,291,618	5,802	0.03
run10	110,520	90,510	56,880	0.56	1.79	1.22	1,293,123	5,802	0.00
run11	134,038	94,270	62,240	0.66	1.51	1.42	1,167,570	5,802	0.00
run14	113,667	109,200	67,800	0.50	2.01	1.04	1,293,337	5,802	0.07
run15	101,394	92,290	58,480	0.54	1.86	1.10	1,293,088	5,802	0.02
run16	100,125	81,080	56,160	0.59	1.69	1.24	1,293,141	5,802	0.09
run17	116,639	195,800	50,120	0.28	3.57	0.60	1,293,101	5,801	0.07
run18	110,110	156,000	50,600	0.33	3.00	0.71	1,293,083	5,801	0.07
run19	112,935	133,300	52,120	0.39	2.55	0.85	1,293,116	5,801	0.04
run20	111,653	113,500	54,000	0.46	2.19	0.98	1,293,120	5,801	0.01
run21	103,260	93,660	55,880	0.52	1.92	1.10	1,293,098	5,801	0.04

Table 5. Estimates of management quantities for the selected stock assessment models. The highlighted rows are key reference points.

Quantity	Run10	Run11 (low size)	Run14 (spill)	Run15 (creep)	Run16 (low IDPH)	Run19 (h=0.75)
$C_{current}$	141,206	141,304	174,154	140,631	130,689	141,377
C_{latest}	126,051	129,479	129,874	124,853	115,759	126,252
$Y_{F_{current}}$	48,680	57,520	54,280	48,840	49,720	6,224
$Y_{F_{MSY}}$ or MSY	56,880	62,240	67,800	58,480	56,160	52,120
$Y_{F_{current}}\ /MSY$	0.856	0.924	0.801	0.835	0.885	0.119
$C_{current}\ /MSY$	2.483	2.27	2.569	2.405	2.327	2.713
$C_{latest}\ /MSY$	2.216	2.08	1.916	2.135	2.061	2.422
F_{MSY}	0.06	0.06	0.059	0.059	0.063	0.042
F_{mult}	0.560	0.664	0.498	0.538	0.593	0.392
$F_{current}\ /F_{MSY}$	1.785	1.506	2.009	1.859	1.685	2.549
B_0	726,400	788,900	927,800	757,000	675,200	819,200
B_{MSY}	238,800	260,900	286,200	246,200	223,300	313,600
B_{MSY}/B_0	0.329	0.331	0.308	0.325	0.331	0.383
$B_{current}$	344,234	403,642	370,609	328,583	321,304	348,719
B_{latest}	263,790	354,604	255,255	251,709	248,733	271,097
$B_{F_{current}}$	117,900	162,100	109,900	113,000	122,400	15,230
$B_{current\ F=0}$	1,413,917	1,393,349	2,047,232	1,432,520	1,263,412	1,796,876
$B_{latest\ F=0}$	1,506,655	1,472,473	2,043,165	1,517,196	1,282,781	1,880,117
SB_0	378,500	398,600	479,600	391,700	349,700	426,700
SB_{MSY}	90,510	94,270	109,200	92,290	81,080	133,300
SB_{MSY}/SB_0	0.239	0.237	0.228	0.236	0.232	0.312
$SB_{current}$	110,520	134,038	113,667	101,394	100,125	112,935
SB_{latest}	80,799	115,043	88,066	79,150	80,063	90,329
$SB_{F_{current}}$	31,930	47,040	26,810	29,050	32,310	4,165
$SB_{current\ F=0}$	737,560	705,793	1,060,121	738,206	664,557	936,685
$SB_{latest\ F=0}$	789,322	740,714	1,107,838	790,920	680,641	998,205
$B_{current}\ /B_0$	0.474	0.512	0.399	0.434	0.476	0.426
$B_{latest}\ /B_0$	0.363	0.449	0.275	0.333	0.368	0.331
$B_{F_{current}}\ /B_0$	0.162	0.205	0.118	0.149	0.181	0.019
$B_{current}\ /B_{MSY}$	1.442	1.547	1.295	1.335	1.439	1.112
$B_{latest}\ /B_{MSY}$	1.105	1.359	0.892	1.022	1.114	0.864
$B_{F_{current}}\ /B_{MSY}$	0.494	0.621	0.384	0.459	0.548	0.049
$B_{current}\ /B_{current\ F=0}$	0.243	0.29	0.181	0.229	0.254	0.194
$B_{latest}\ /B_{latest\ F=0}$	0.175	0.241	0.125	0.166	0.194	0.144
$SB_{current}\ /SB_0$	0.292	0.336	0.237	0.259	0.286	0.265
$SB_{latest}\ /SB_0$	0.213	0.289	0.184	0.202	0.229	0.212
$SB_{F_{current}}\ /SB_0$	0.084	0.118	0.056	0.074	0.092	0.01
$SB_{current}\ /SB_{MSY}$	1.221	1.422	1.041	1.099	1.235	0.847
$SB_{latest}\ /SB_{MSY}$	0.893	1.22	0.806	0.858	0.987	0.678
$SB_{F_{current}}\ /SB_{MSY}$	0.353	0.499	0.246	0.315	0.398	0.031
$SB_{current}\ /SB_{current\ F=0}$	0.15	0.19	0.107	0.137	0.151	0.121
$SB_{latest}\ /SB_{latest\ F=0}$	0.102	0.155	0.079	0.1	0.118	0.09
Steepness (h)	0.977	0.967	0.987	0.981	0.976	0.75

Table 6. Comparison of estimates of yields based on long-term recruitment predicted from the SRR and that estimated assuming recruitment equal to the recent period (199-2007).

	$C_{current}$	MSY^{LT}	$Y^{LT}_{F_{current}}$	MSY^{rec}	$Y^{rec}_{F_{current}}$	$C_{current}/MSY^{rec}$	$C_{current}/Y^{rec}_{F_{current}}$
run10	141,206	56,880	48,680	117,979	103,135	1.20	1.37
run11	141,304	62,240	57,520	120,608	114,661	1.17	1.23
run14	174,154	67,800	54,280	146,114	118,890	1.19	1.46
run15	140,631	58,480	48,840	117,867	99,998	1.19	1.41
run16	130,689	56,160	49,720	109,703	99,251	1.19	1.32
run19	141,377	52,120	6,224	117,154	102,931	1.21	1.37

Table 7. Estimates of utilisation related management quantities for the selected stock assessment models.

Run	MSY	$Y_{F_{current}}$	$Crit_{age}$	$Crit_{length}$	$Mean_{age}$	$Mean_{length}$	Y_{lost}
run1	65,080	61,720	15	126.2	6.7	69.1	0.44
run1a	65,560	61,400	16	130.2	6.9	69.2	0.50
run2	65,760	61,960	15	125.7	6.9	69.6	0.49
run3	67,000	63,960	15	125.7	6.8	69.3	0.50
run4	61,040	51,280	15	125.6	5.1	56.8	0.74
run5	62,600	53,080	15	125.6	5.1	56.9	0.74
run6	60,080	52,880	15	125.6	5.4	59.0	0.74
run7	57,480	47,880	15	125.6	4.3	50.9	0.80
run8	56,680	46,760	15	125.5	4.3	51.1	0.80
run9	56,800	46,800	15	125.5	4.3	51.1	0.80
run10	56,880	48,680	15	125.6	4.8	54.5	0.74
run11	62,240	57,520	15	125.3	5.1	57.1	0.73
run14	67,800	54,280	15	125.6	4.7	54.8	0.73
run15	58,480	48,840	15	125.6	4.6	53.4	0.74
run16	56,160	49,720	15	125.6	5.4	59.3	0.74
run17	50,120	0	15	124.2	5.2	57.1	0.74
run18	50,600	0	15	125.5	5.0	56.3	0.74
run19	52,120	6,224	15	124.2	5.0	54.9	0.74
run20	54,000	29,628	15	124.2	4.9	54.7	0.74
run21	55,880	44,040	15	125.6	4.8	54.4	0.74

Table 8. Estimates of the probability that $SB_{current}$ and SB_{latest} are less than some commonly used spawning biomass reference points based on the 64 model runs undertaken for the structural uncertainty analysis and the likelihood profile for run 10.

	Structural uncertainty		**Likelihood profile**	
	$SB_{current}$	SB_{latest}	$SB_{current}$	SB_{latest}
$p(x < SB_{MSY})$	56%	92%	3%	70%
$p(x < 0.5SB_{MSY})$	0%	13%		
$p(x < 0.2SB_0)$	2%	39%		
$p(x < 0.2SB_{F=0})$	83%	100%		

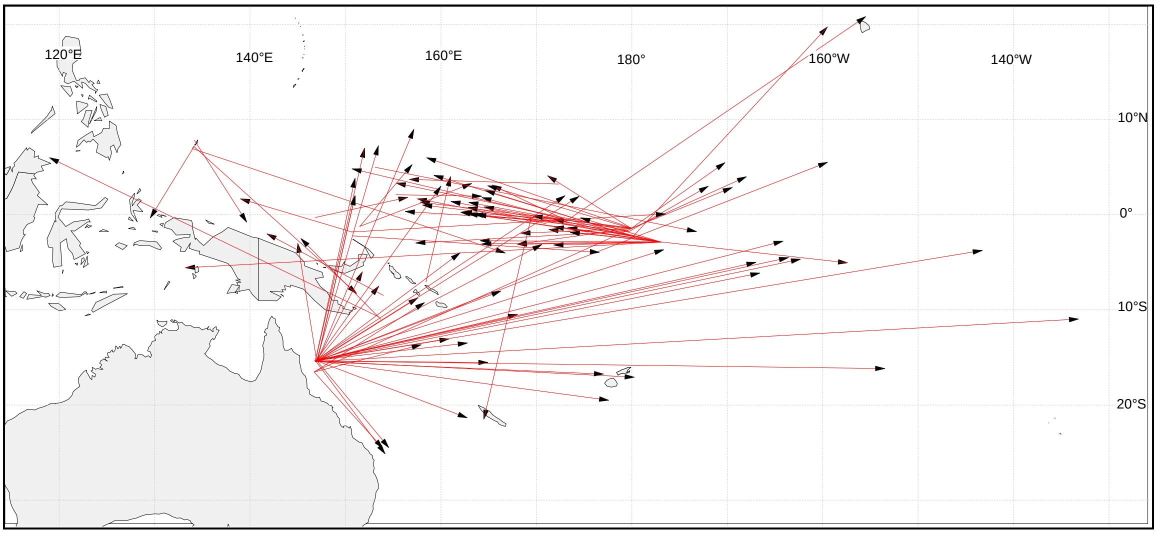


Figure 1. Long-distance (greater than 500 nmi) movements of tagged bigeye tuna.

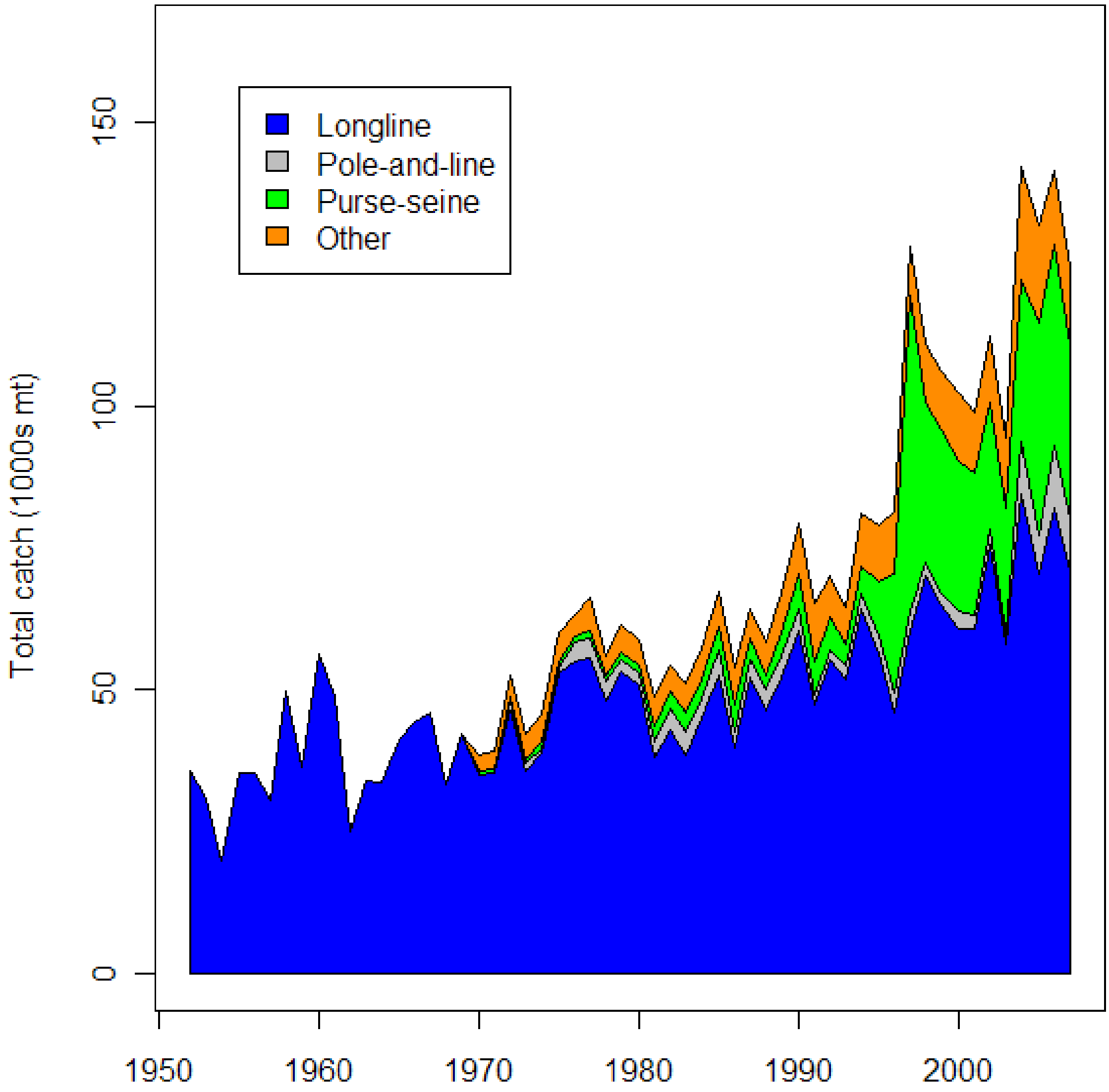


Figure 2. Total annual catch (1000s mt) of bigeye tuna from the WCPO by fishing method from 1952 to 2007. Data from 2008 are too incomplete to plot. Purse seine catch estimates are not corrected for grab-sample bias.

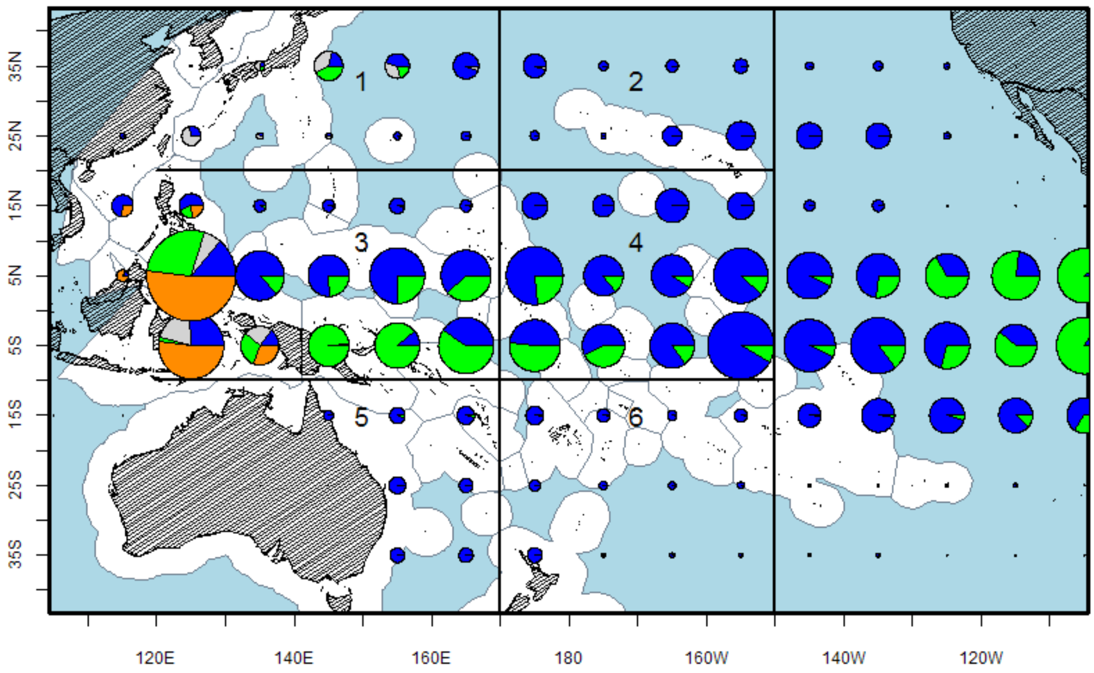


Figure 3. Distribution of cumulative bigeye tuna catch from 1998–2007 by 10 degree squares of latitude and longitude and fishing gear; longline (blue), purse-seine (green), pole-and-line (grey) and other (dark orange). The maximum circle size represents a catch of 75,000 mt. The grey lines indicate the spatial stratification of the six-region assessment model.

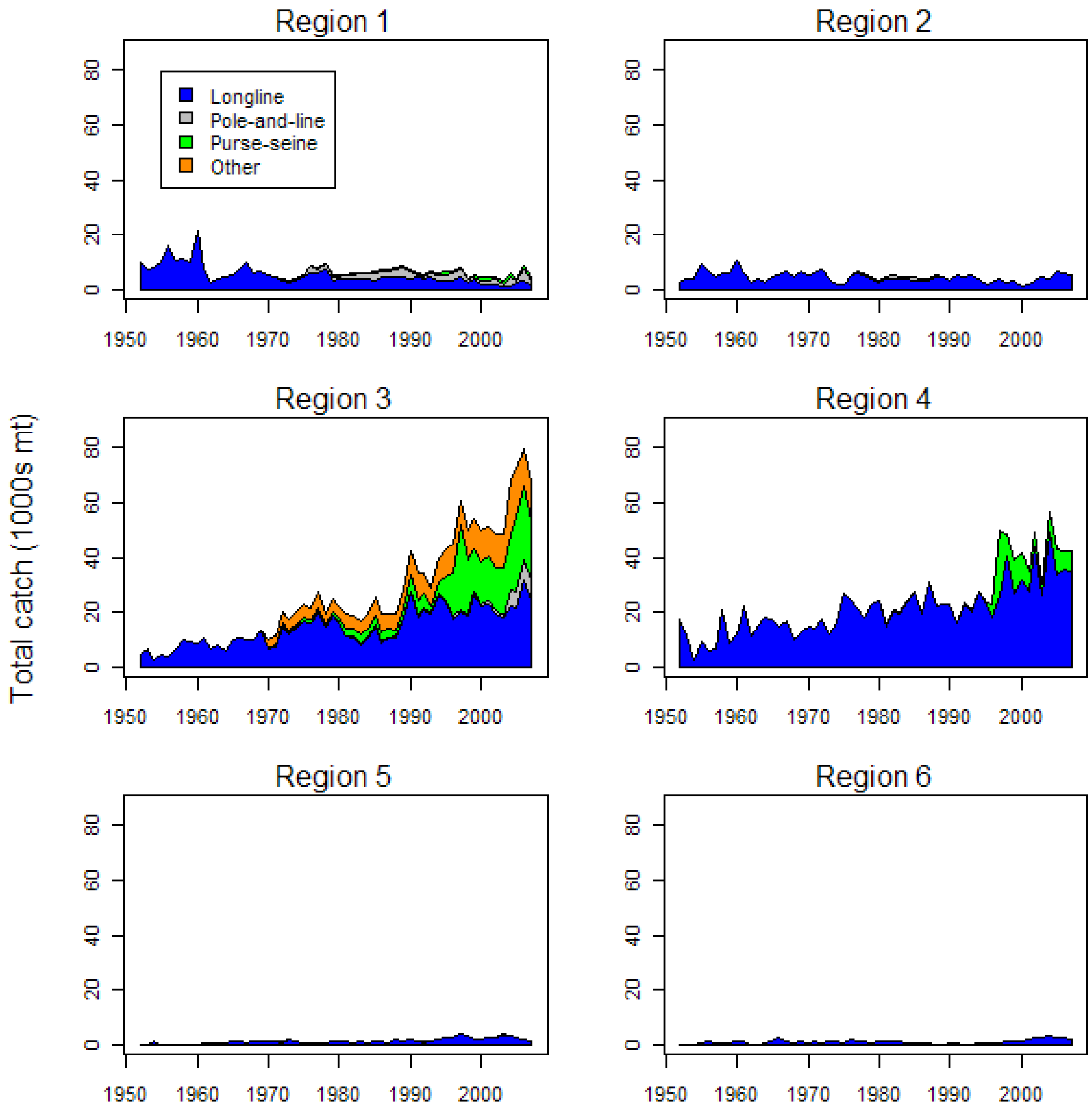


Figure 4. Total annual catch (1000s mt) of bigeye tuna by fishing method and MFCL region from 1952 to 2007.

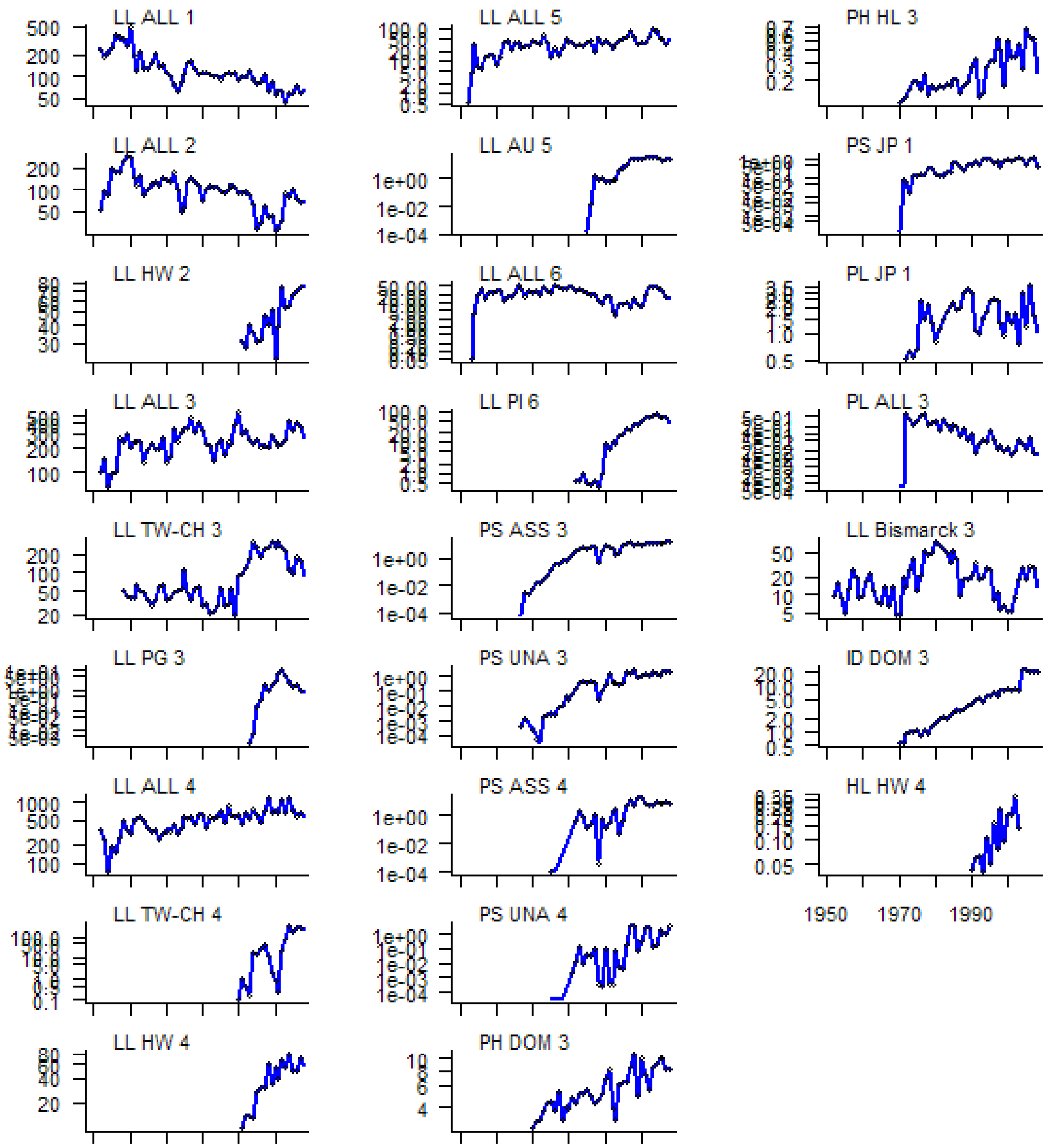


Figure 5. Annual catches by fishery. Circles are observed and the lines are model predictions. Units are catch number of fish (in thousands) for the longline fisheries and thousand metric tonnes for all other fisheries.

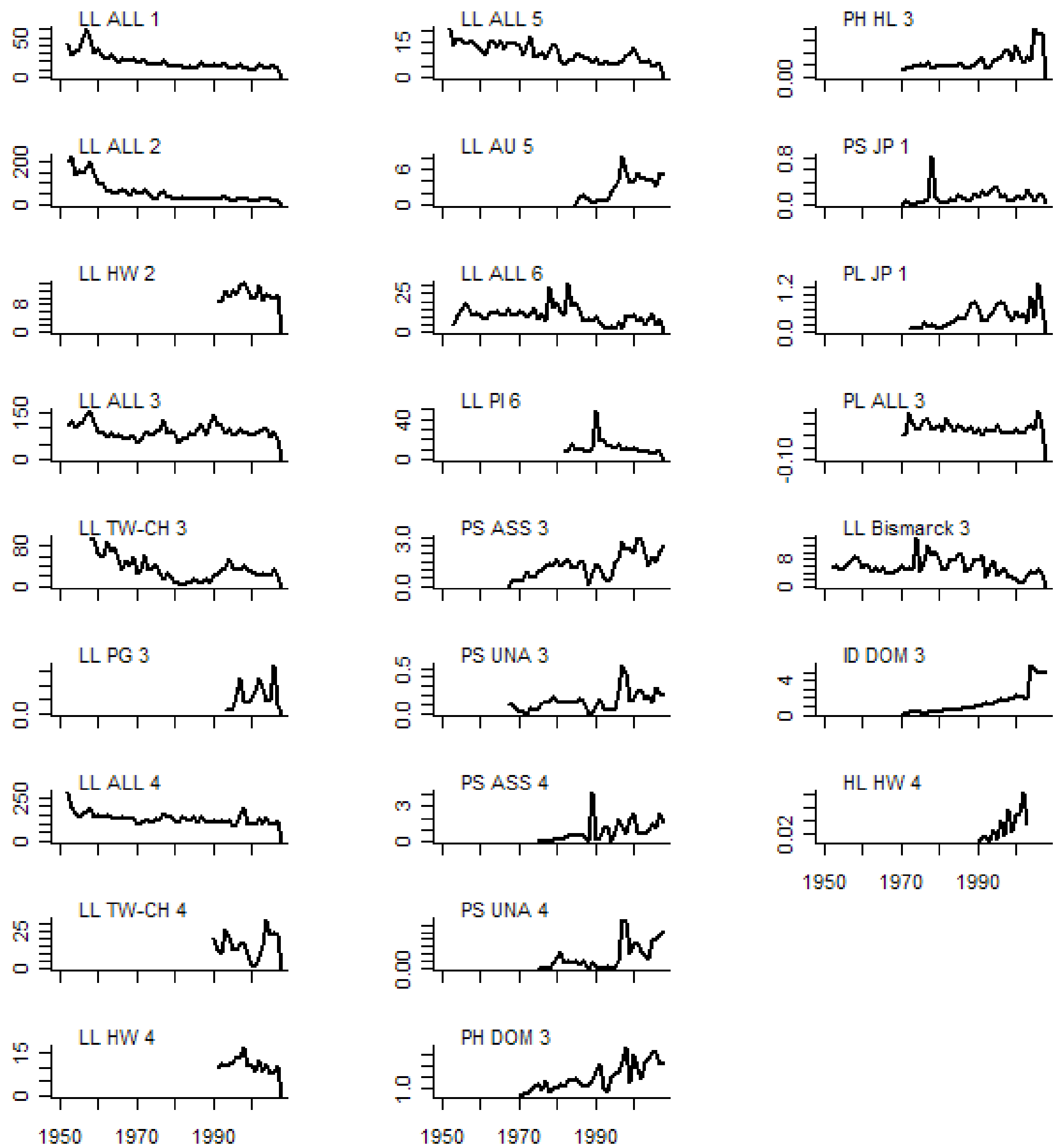


Figure 6. Catch-per-unit-effort (CPUE) by fishery. Units are catch number per GLM-standardised effort (fisheries LL ALL 1–LL ALL 6), catch number per 100 nominal hooks (LL HW, CH/TW LL, LL PI, LL PG, LL BMK) and catch (mt) per day fished/searched (all PS and PL fisheries). Note that CPUE for PH MISC,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

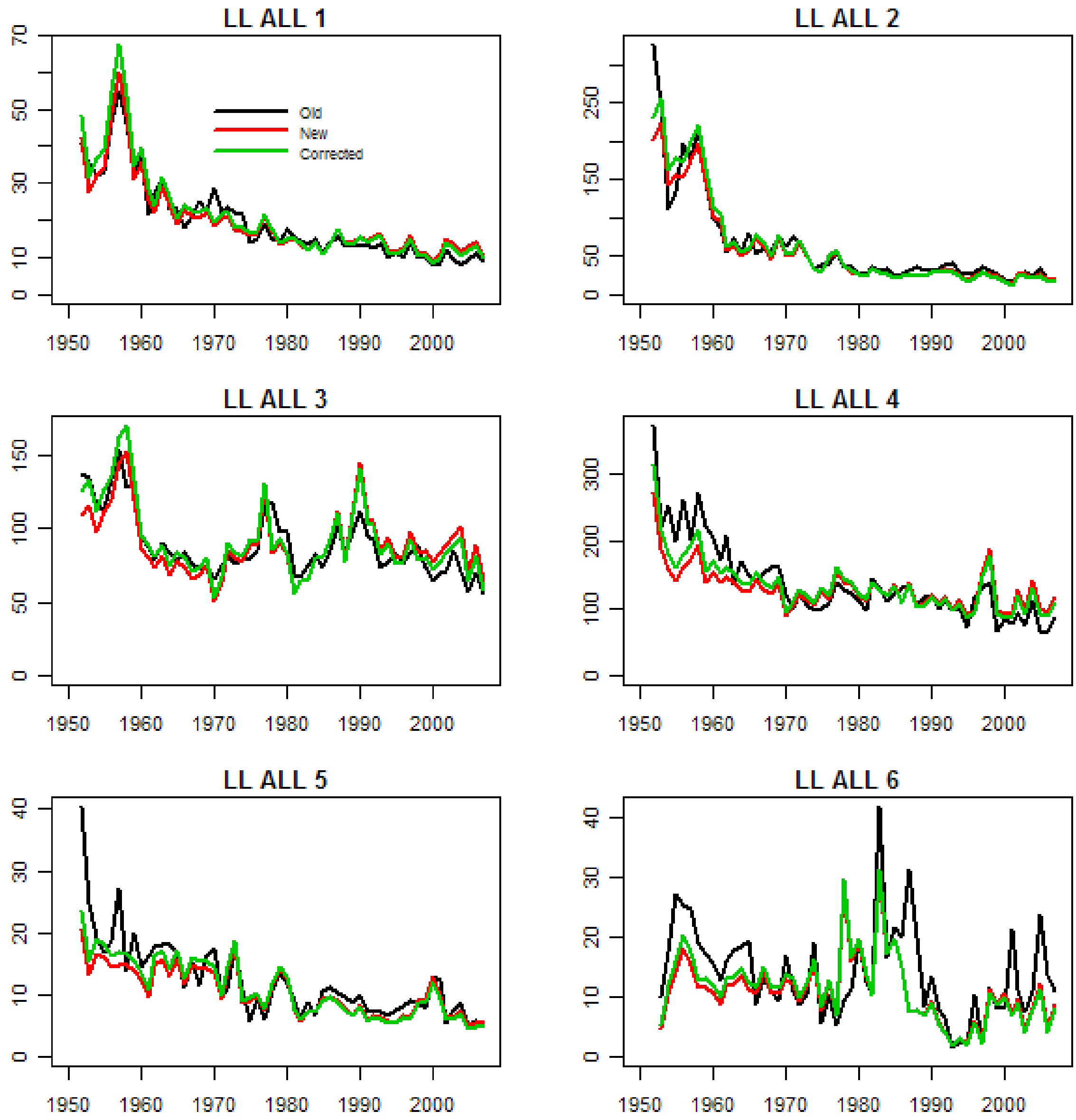


Figure 7. GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL ALL 1–6) scaled by the respective region scalars based on the methodology used in the 2008 assessment (old – black line); the revised methodology of Hoyle (2009) (new – red line); and the revised methodology including the correction for increases in efficiency due to fleet turnover (corrected – green line).

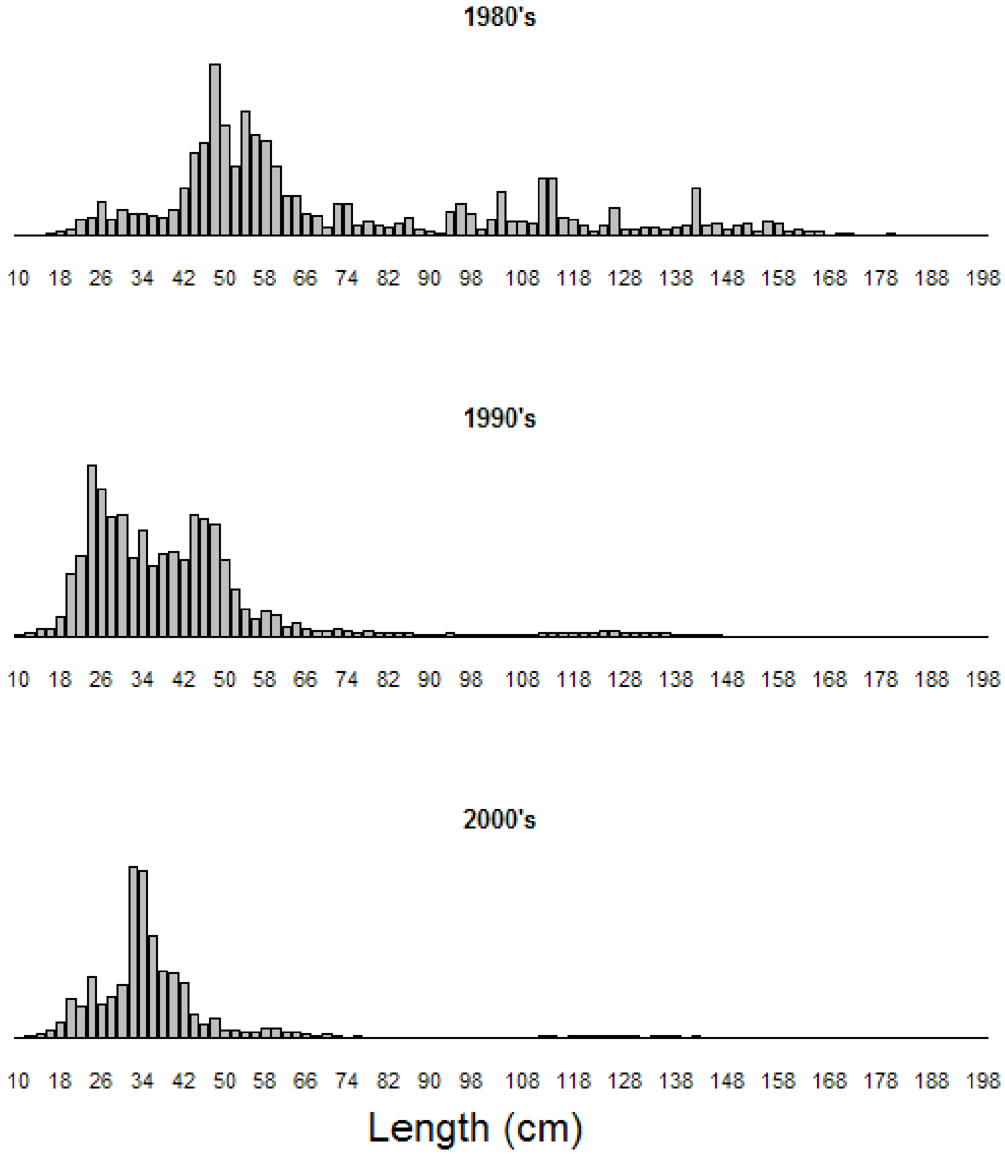


Figure 8. A comparison of the length frequency samples by decade attributed to the Philippines domestic fishery (Fishery 18: PH DOM 3) as used in the 2008 bigeye assessment. Samples from the 1980s were excluded from the current assessment.

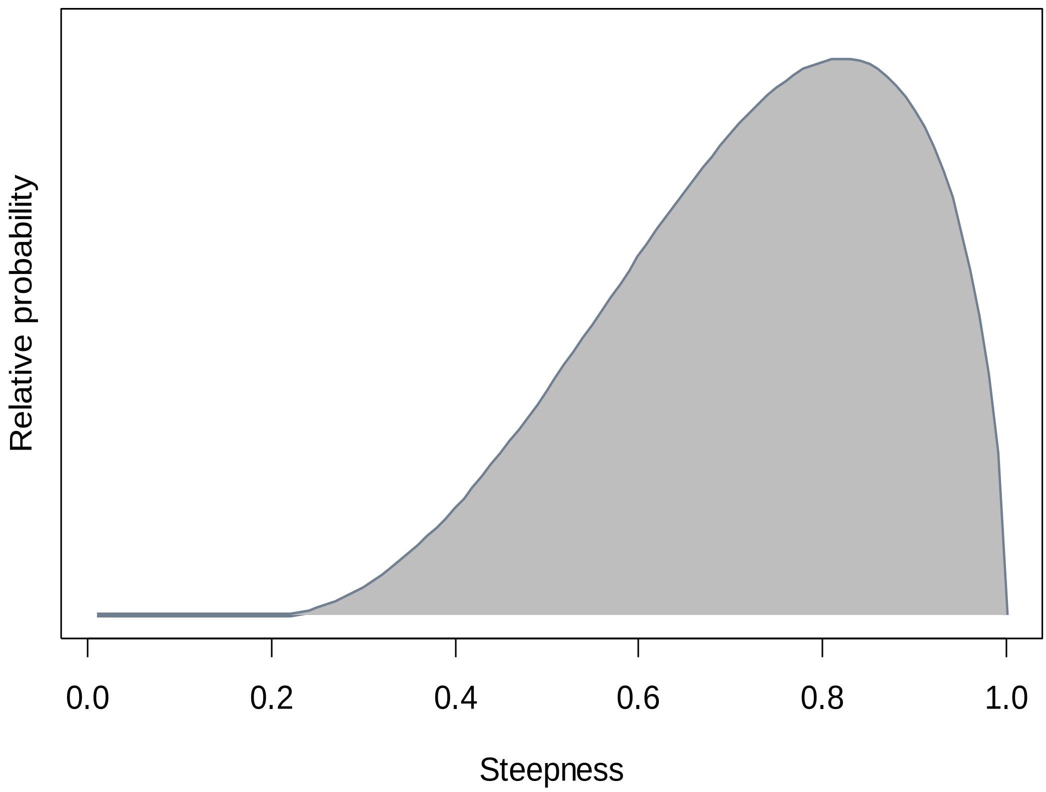
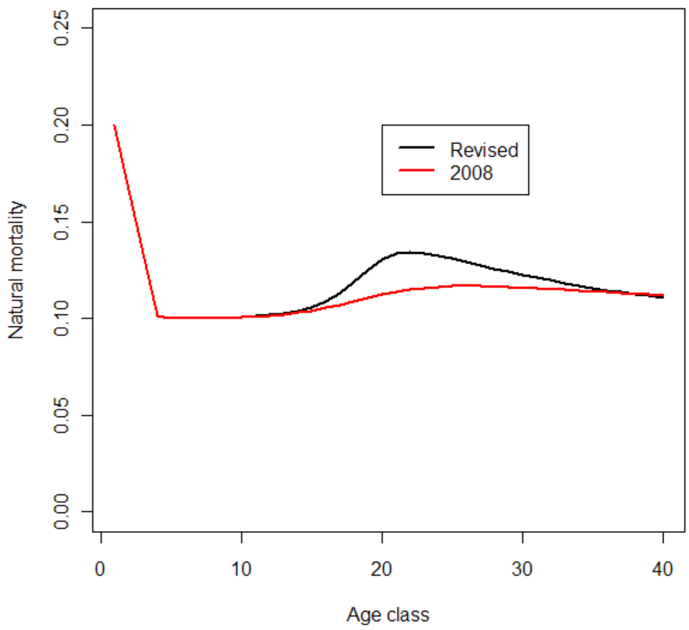


Figure 9. Prior for the steepness parameter of the relationship between spawning biomass and recruitment.



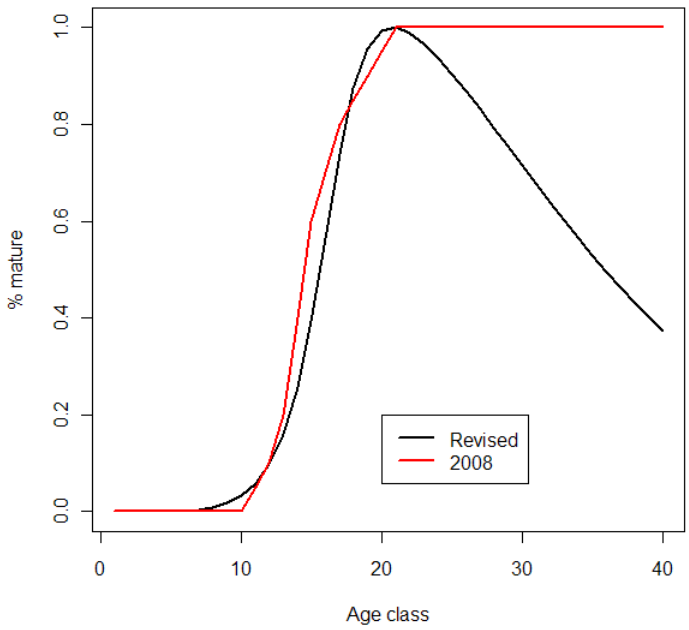


Figure 10. Natural mortality-at-age (top) and % mature (bottom) as assumed in the 2008 assessment (2008 – red line) and the current assessment (Revised – black line). Note that new estimate of maturity is actually used to define an index of spawning potential incorporating information on sex ratios, maturity at age, fecundity, and spawning fraction.

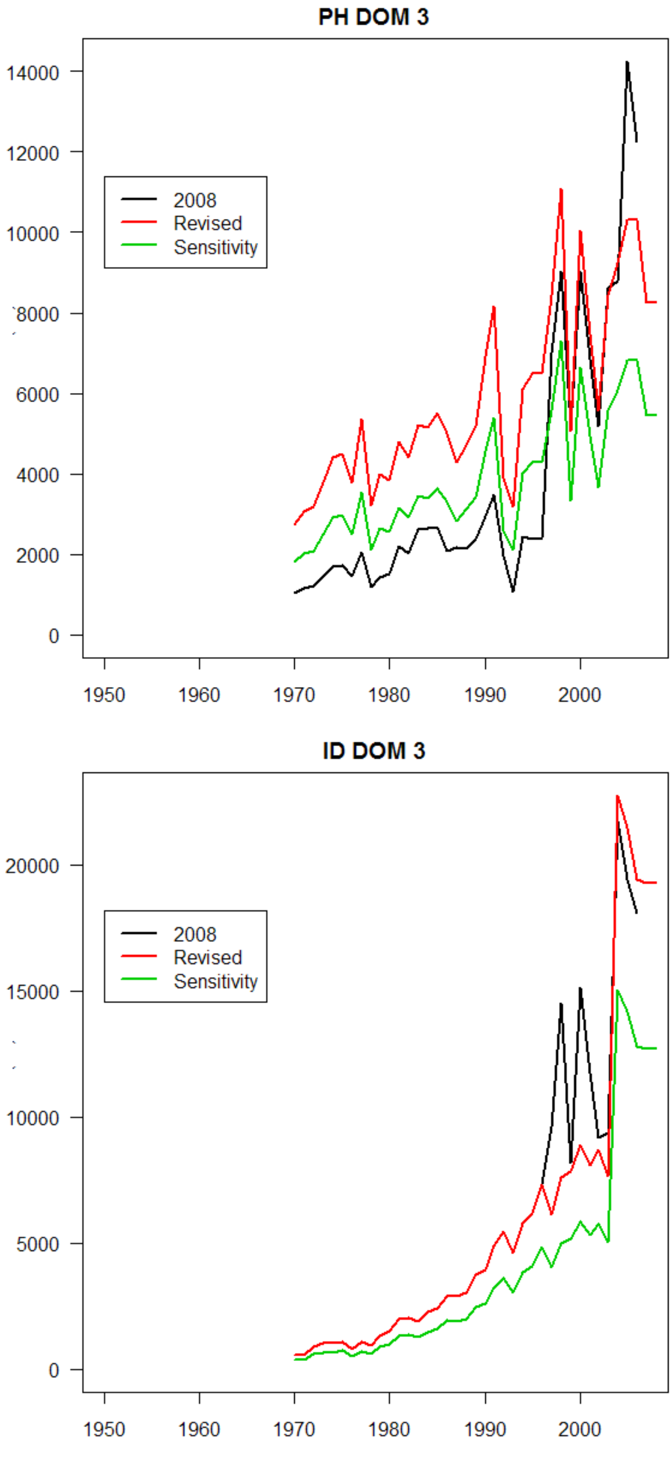


Figure 11. A comparison of the alternative catch histories for the Philippines (top) and Indonesian (bottom) domestic fisheries included in the sensitivity analyses. Included is the catch history assumed in the 2008 assessment (2008 – black line); the revised series used in run 10 (revised – red line); and the alternative series used in run 16 (sensitivity – green line).

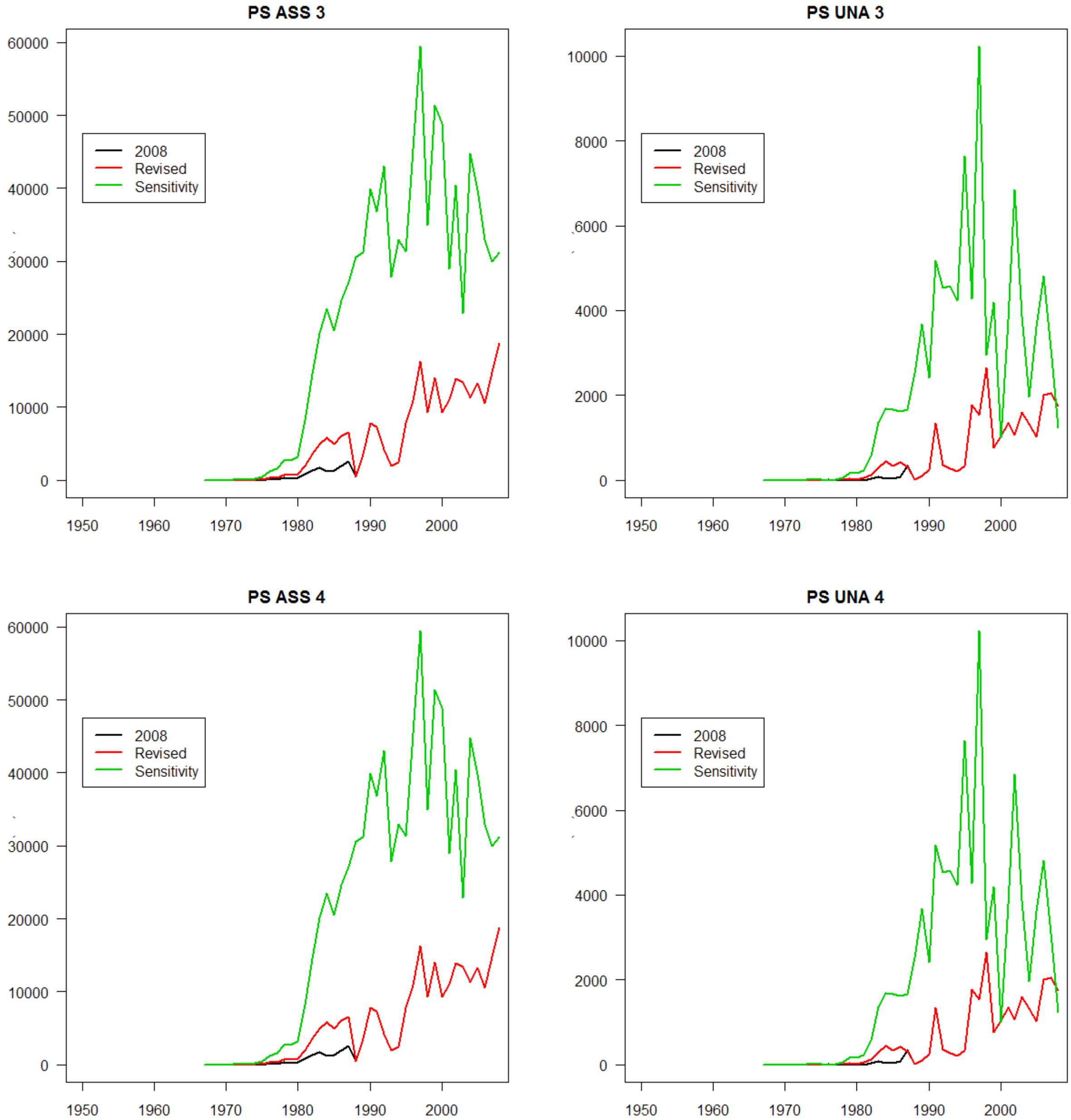


Figure 12. A comparison of the alternative catch histories (annual catches in mt) used for the purse seine fisheries. Included is the catch history assumed in the 2008 assessment (2008 – black line); the revised series used in run 10 to include scaled catches back to the start of the fishery (revised – red line); and the alternative series used in run 15 based on spill samples corrections (sensitivity – green line).

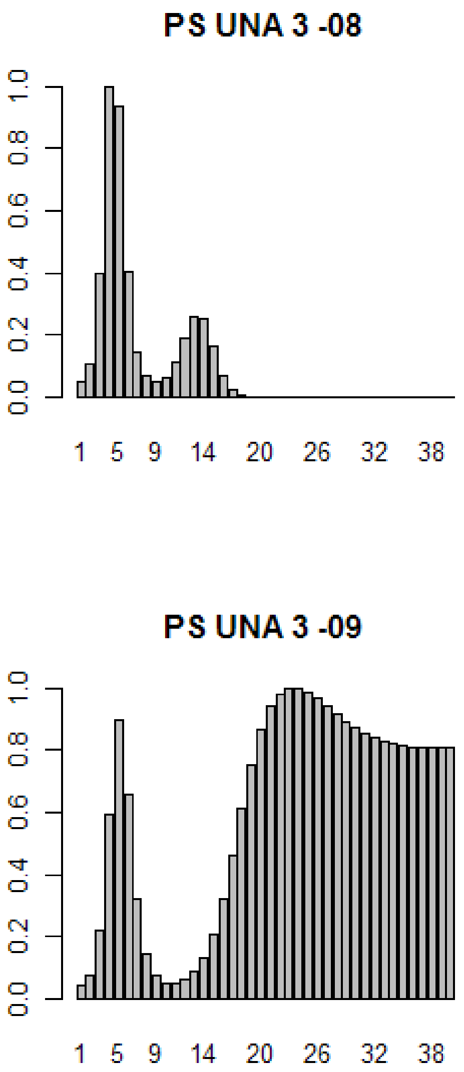


Figure 13. A comparison of selectivity curves for the purse seine unassociated set fishery (Fishery 15: PS UNA 3) and the Philippines domestic fishery (Fishery 18: PH DOM 3), from the 2008 assessment of Langley et al. (2008) and that estimated for run 10

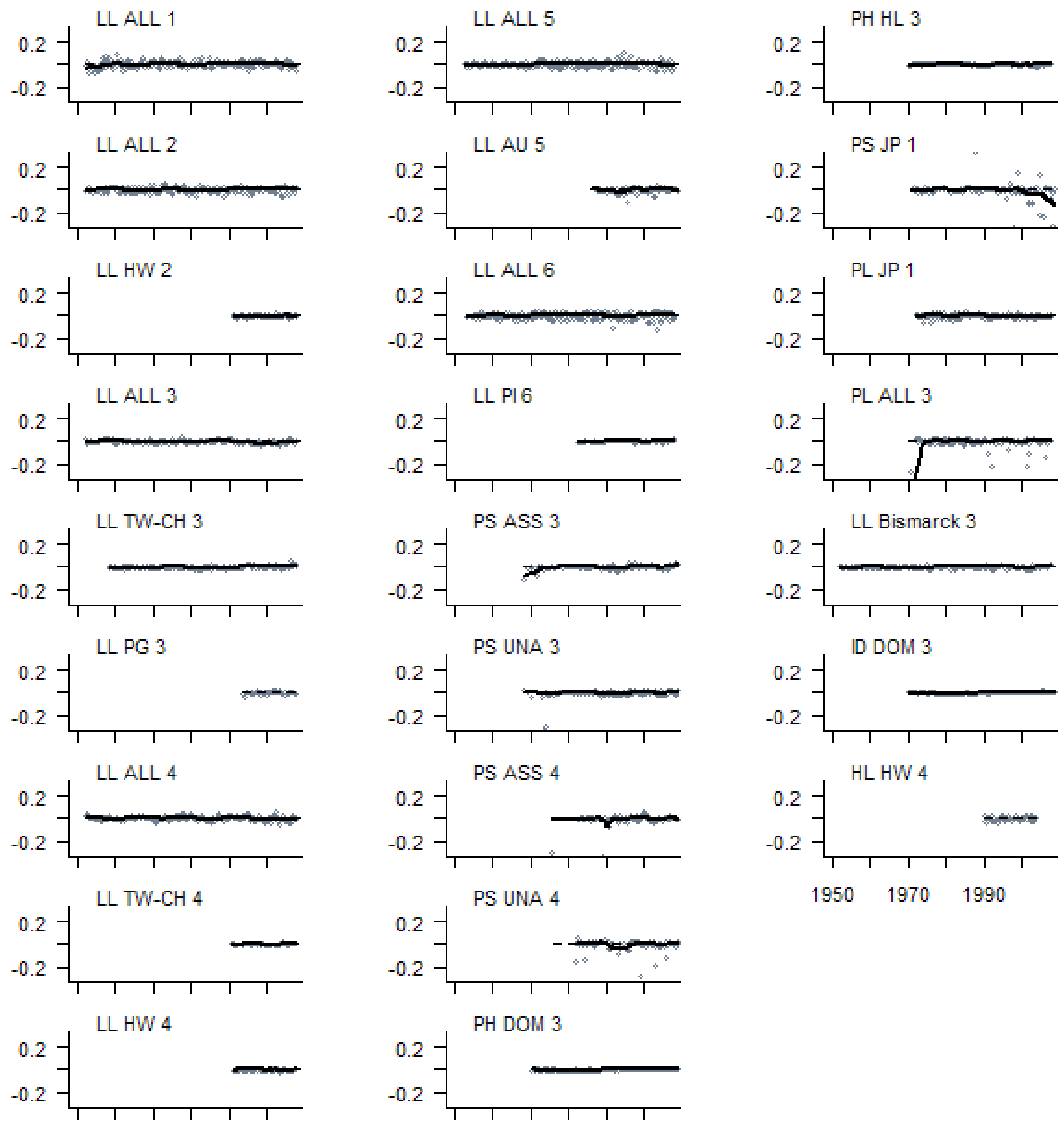


Figure 14. Residuals of ln (total catch) for each fishery (base-case model). The dark line represents a lowess smoothed fit to the residuals.

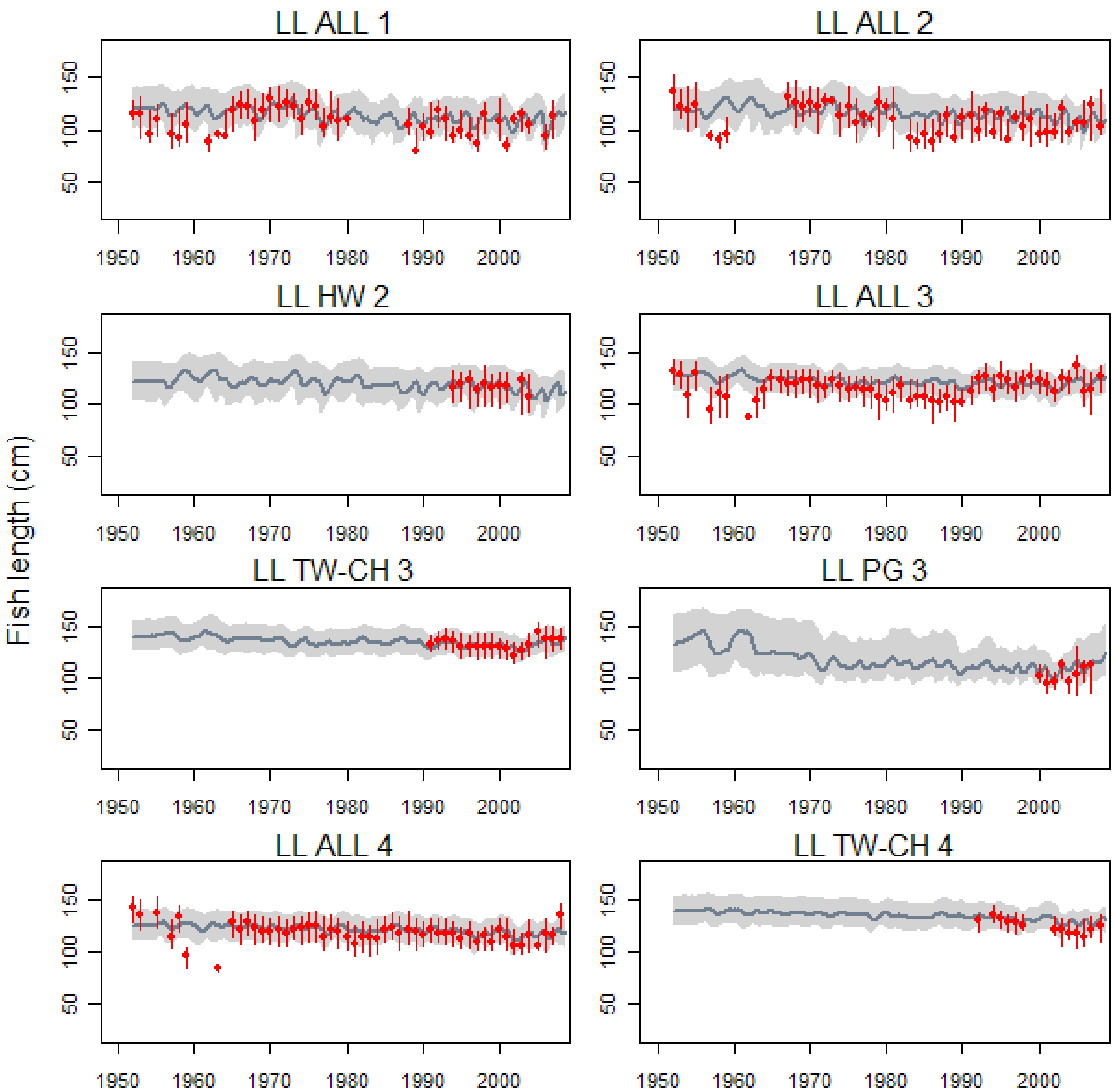


Figure 15. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of bigeye tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and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

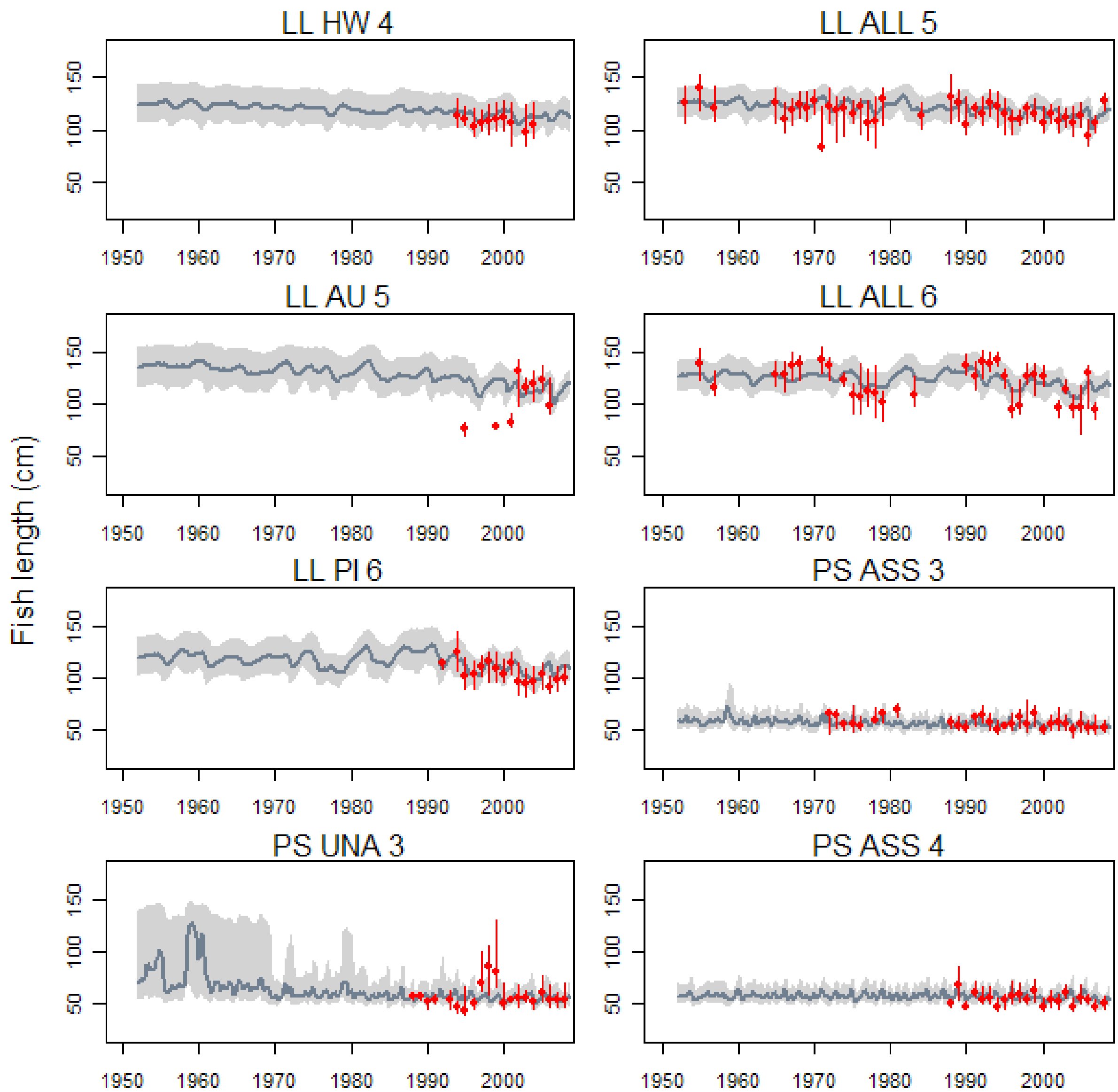


Figure 15 (continued)

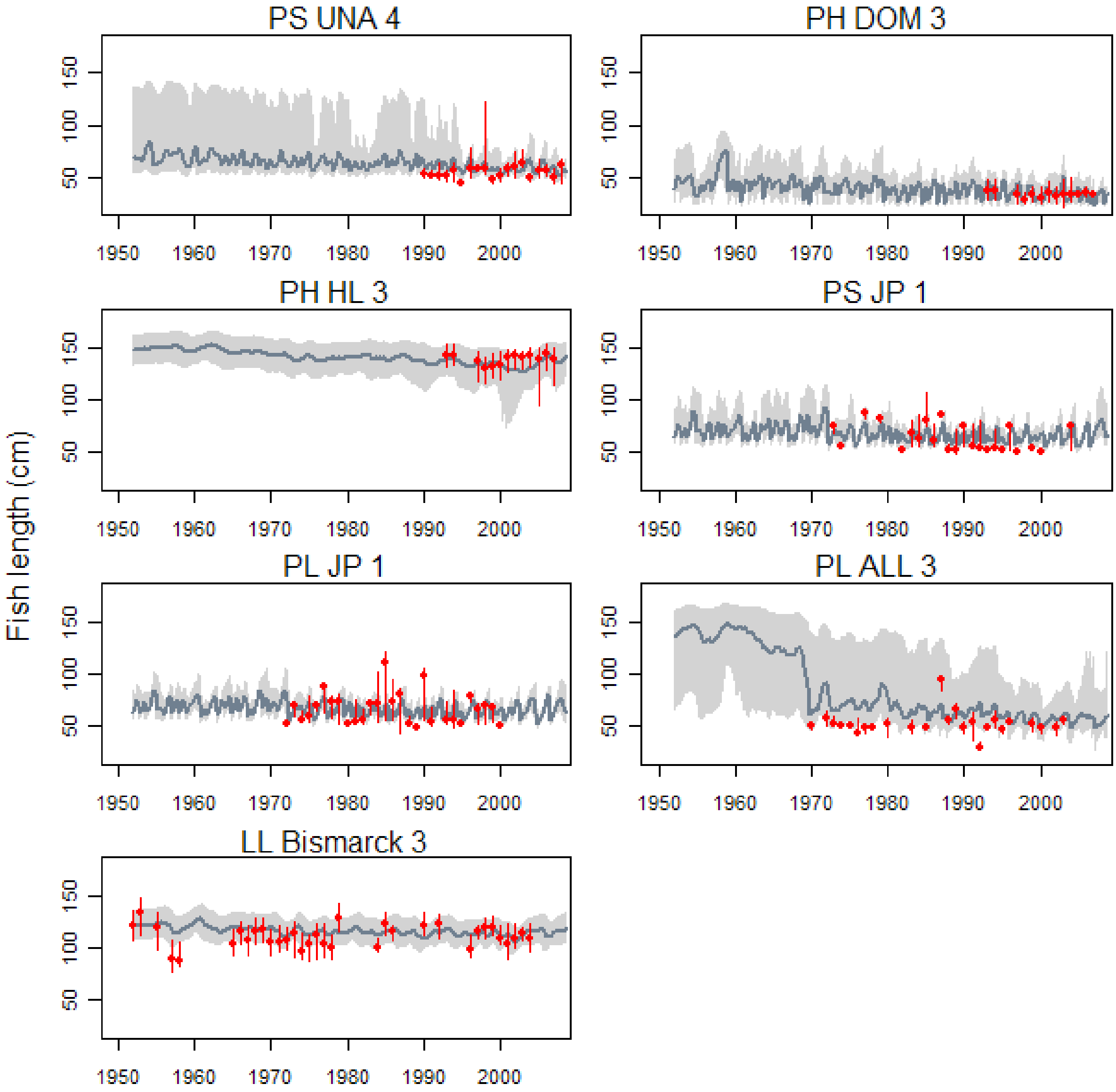


Figure 15. Continued.

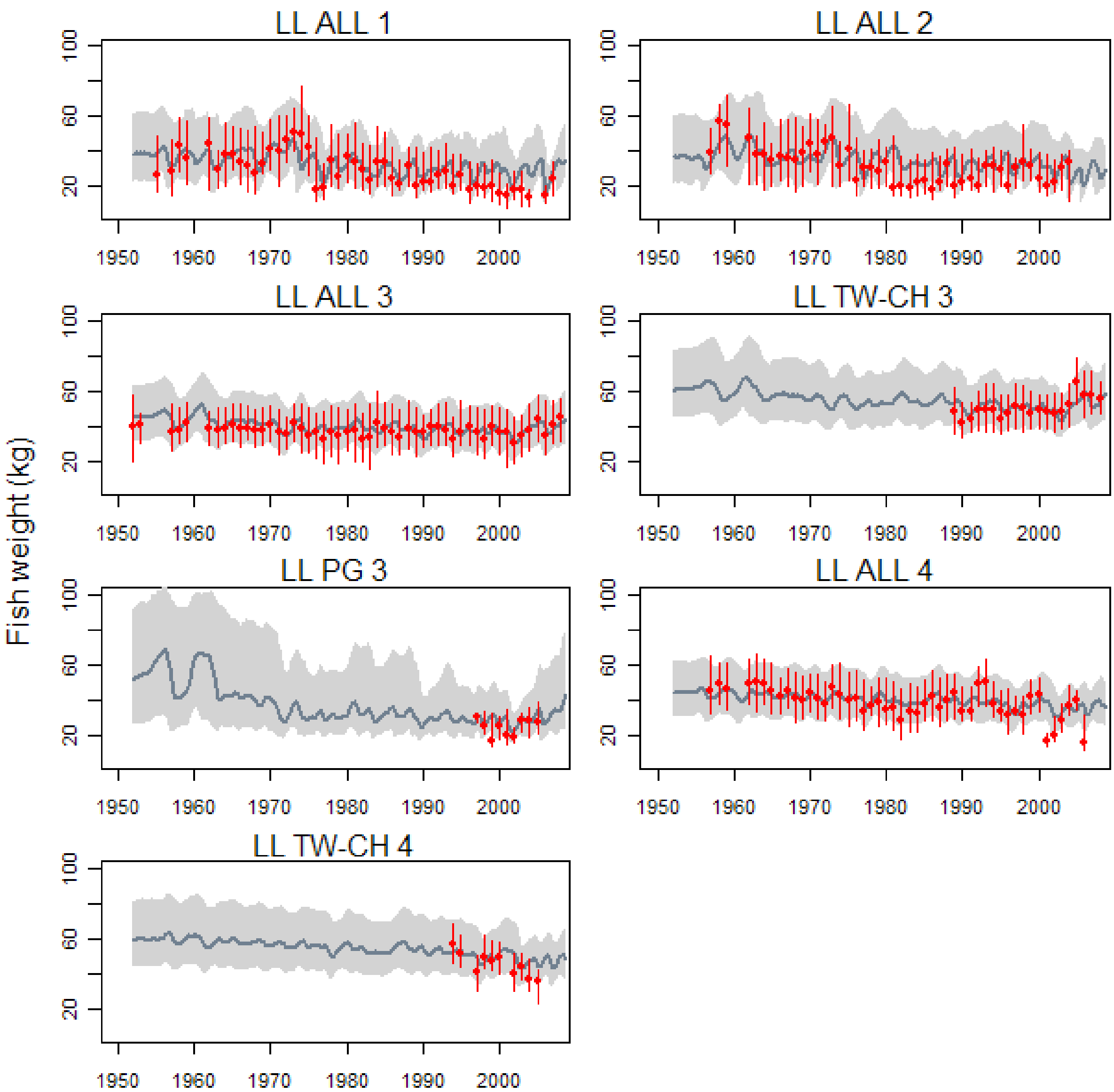


Figure 16. A comparison of the observed (red points) and predicted (grey line) median fish weight (whole weight, kg) of bigeye tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated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

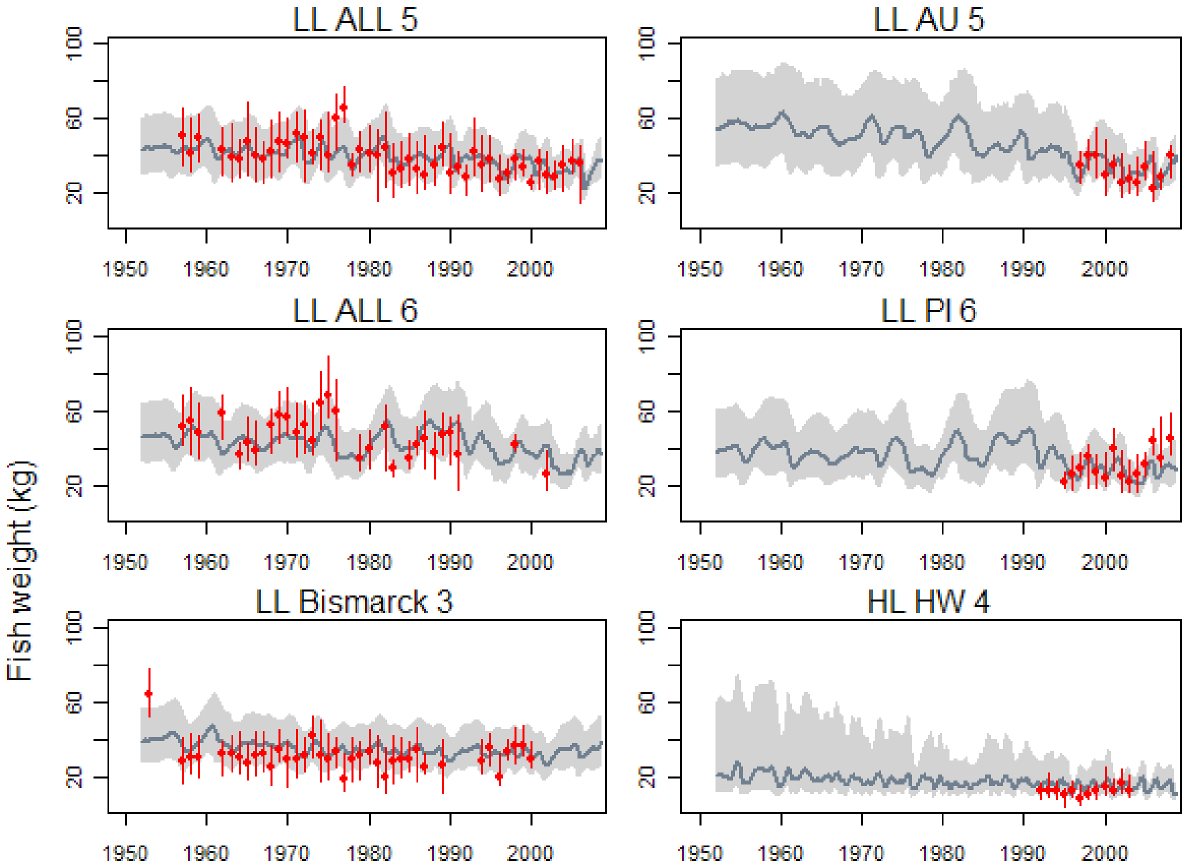


Figure 16. Continued.

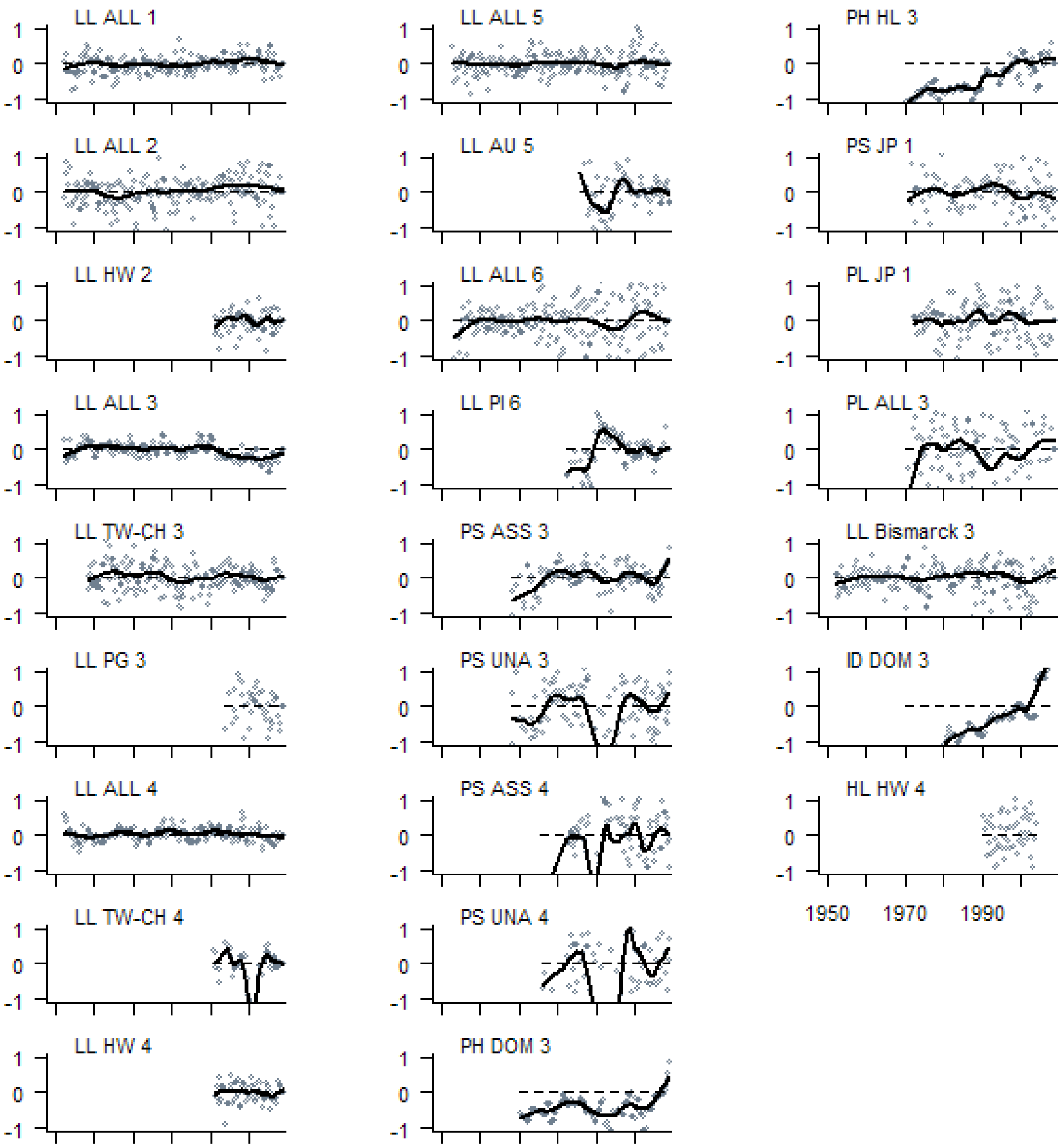


Figure 17. Effort deviations by time period for each fishery (base-case model). For fisheries with longer time series, the dark line represents a lowess smoothed fit to the effort deviations. Some values lie outside the bounds of the plot.

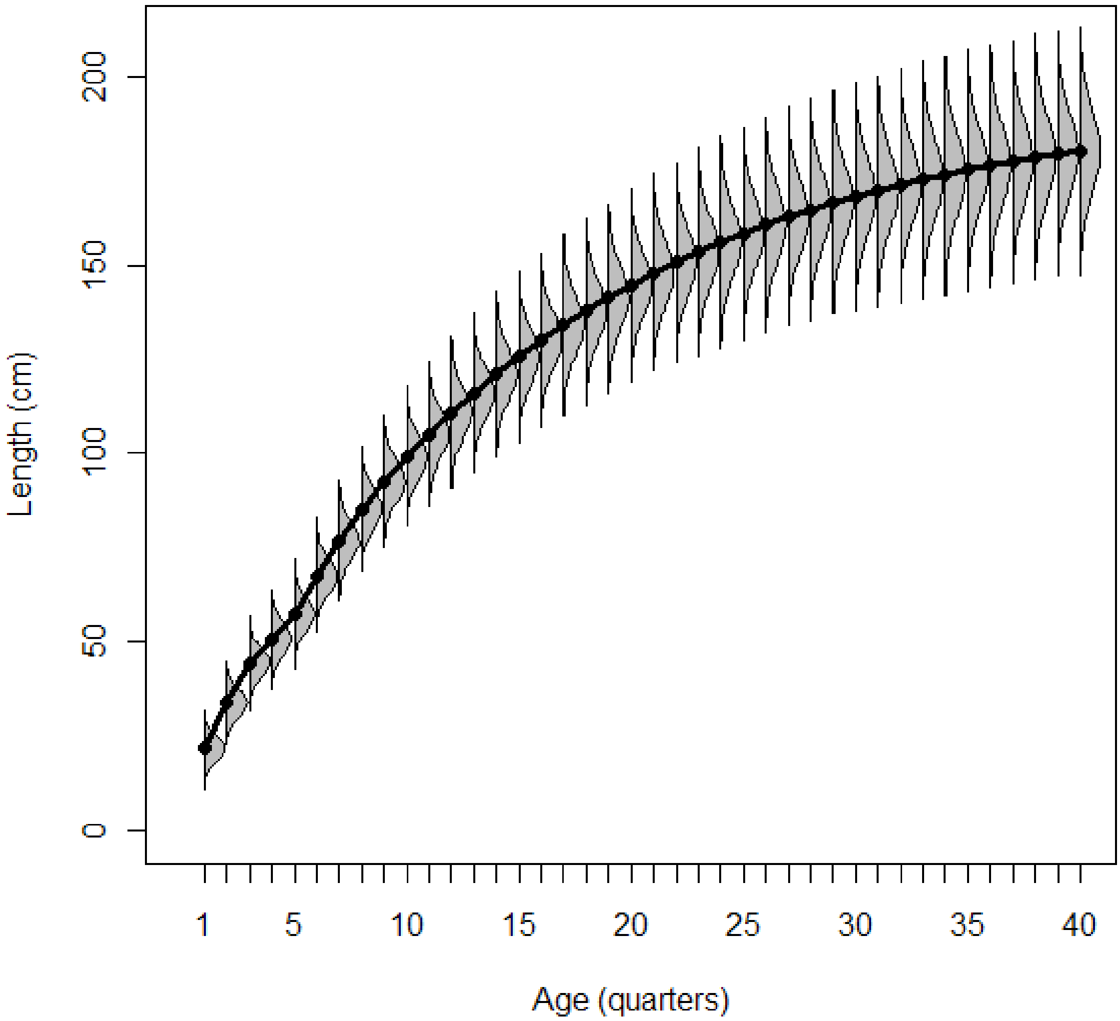


Figure 18. Estimated growth of bigeye derived from the assessment model. The black line represents the estimated mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age.

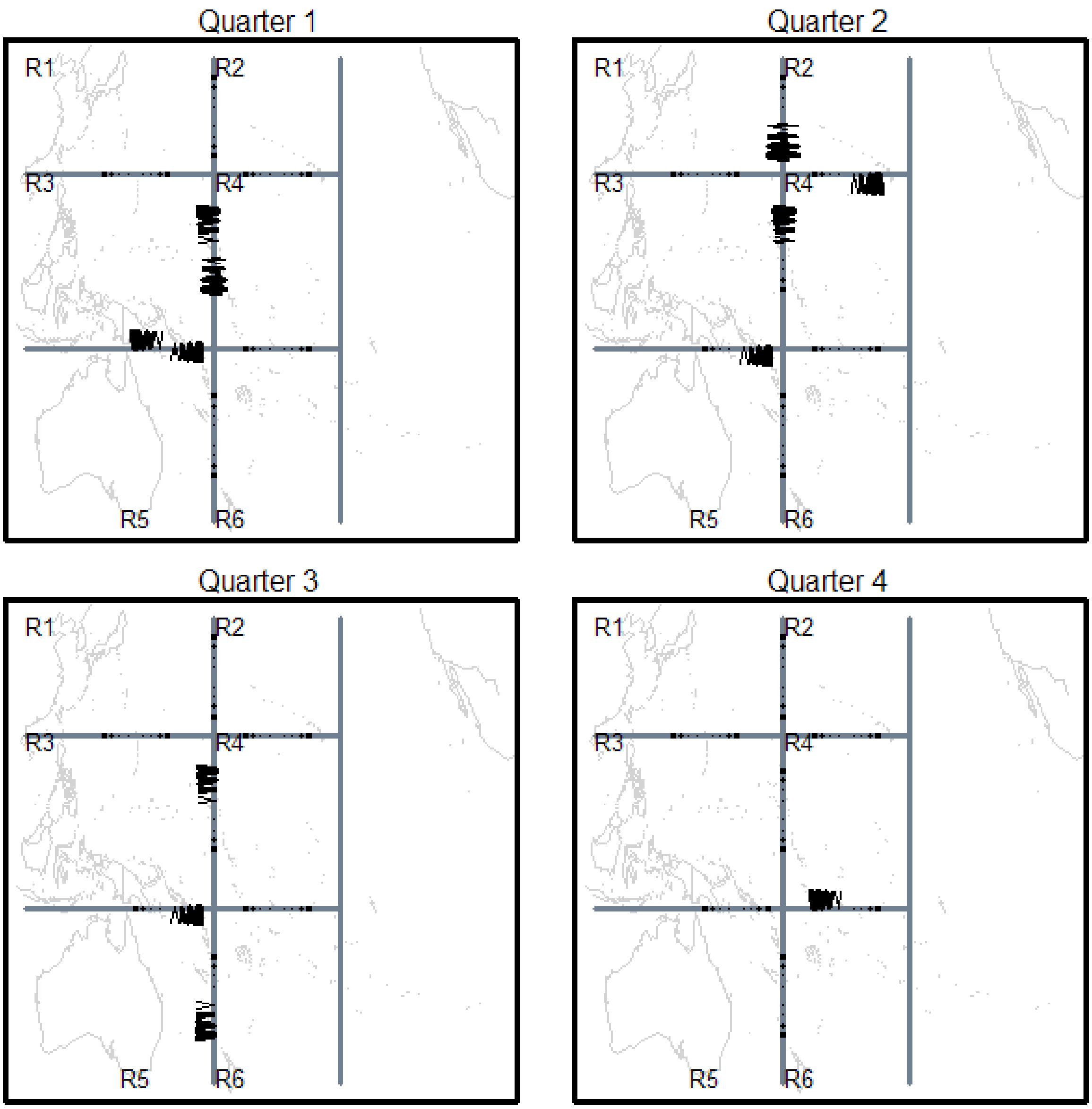


Figure 19. Estimated quarterly movement coefficients at age (1, 10, 20, 30 quarters). The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age. The largest percentage movement was 5%, from Region 2 to Region 1 during quarter 2.

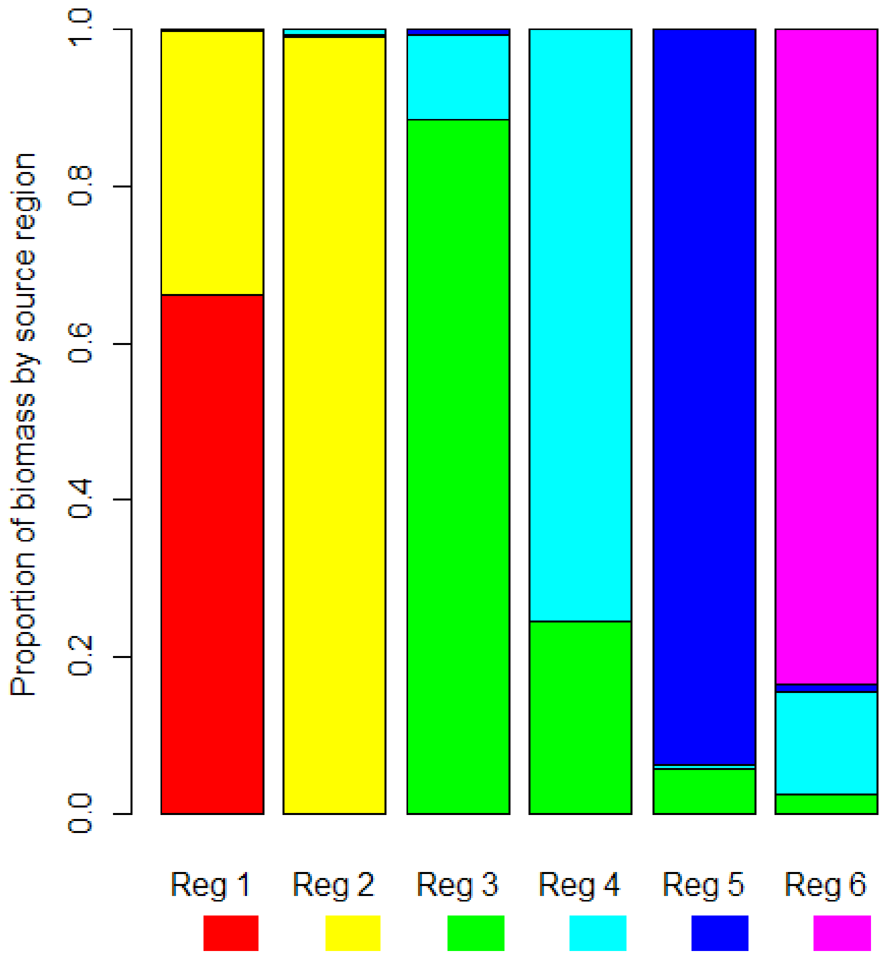


Figure 20. Proportional distribution of total biomass (by weight) in each region (Reg 1–6) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment between regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

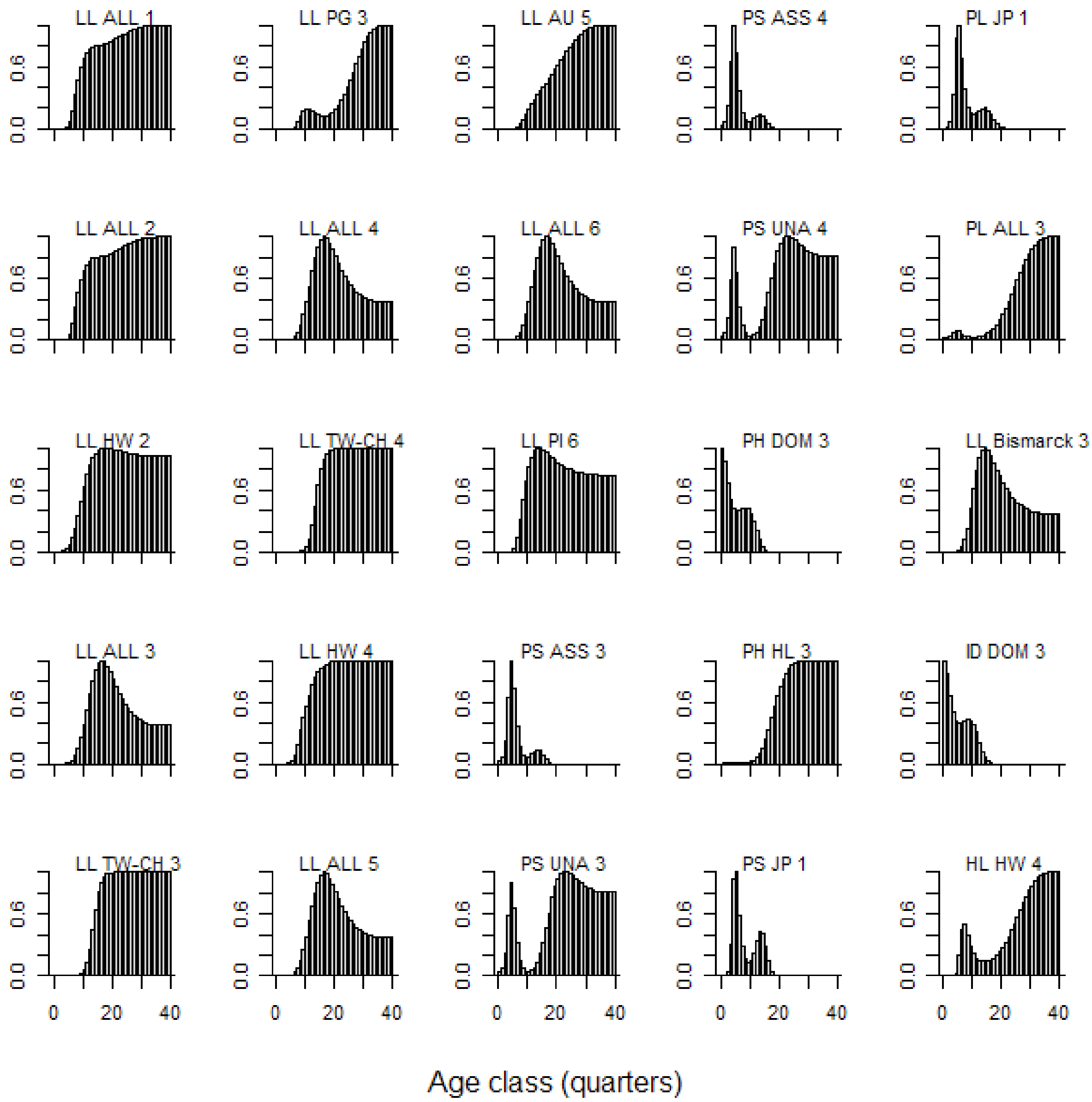


Figure 21. Selectivity coefficients, by fishery.

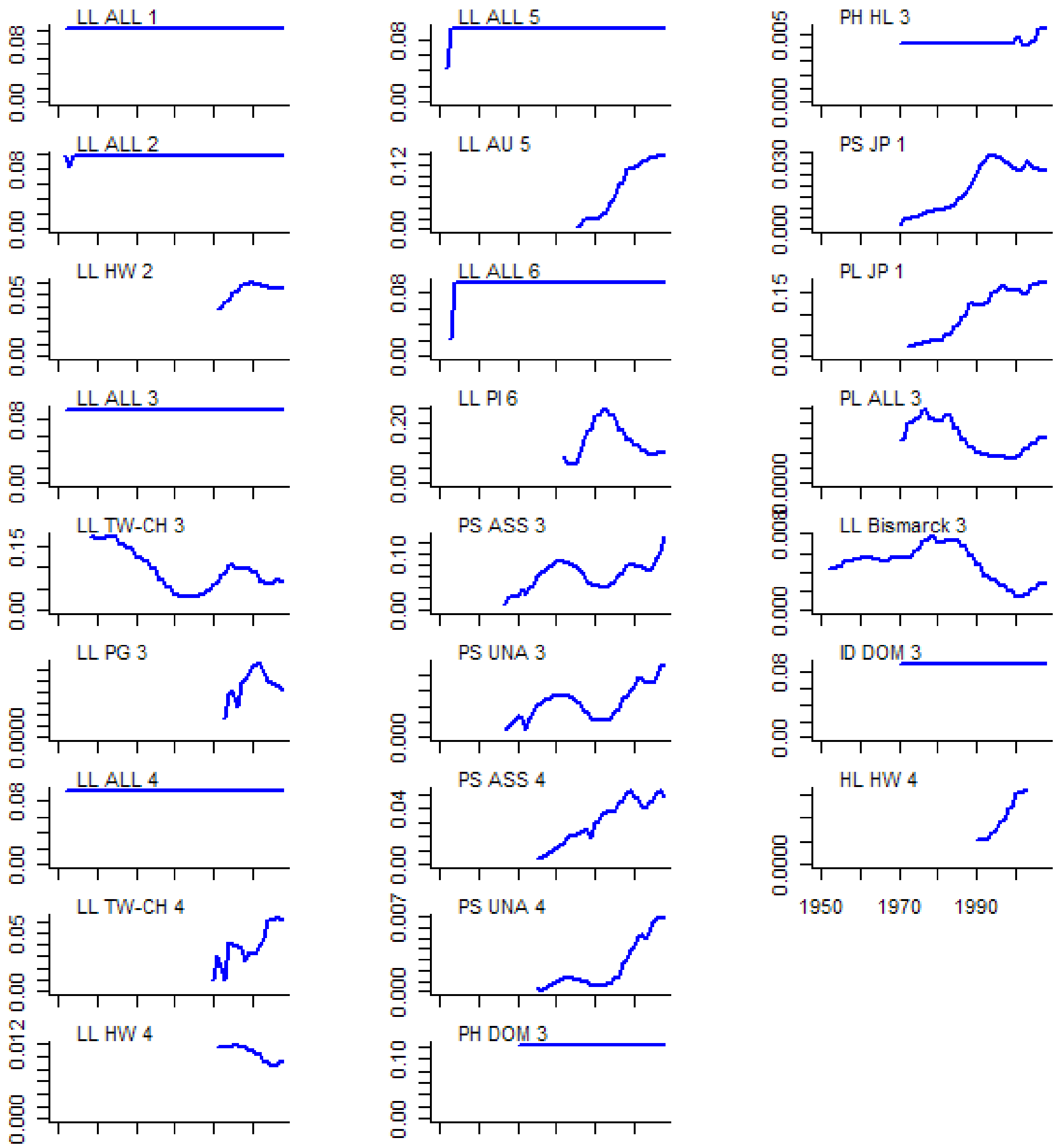


Figure 22. Average annual catchability time series, by fishery.

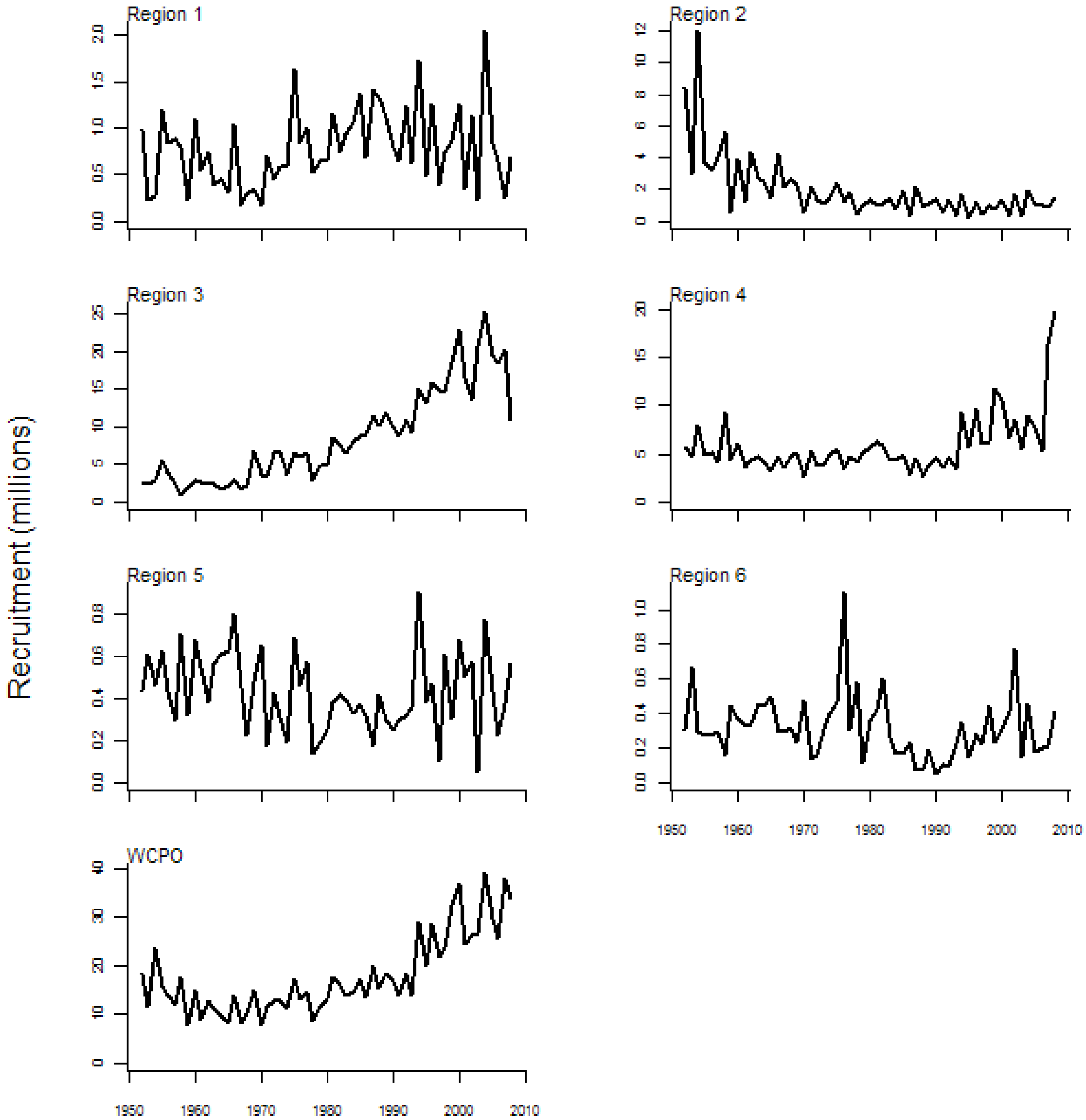


Figure 23. Estimated annual recruitment (millions) by region and for the WCPO.

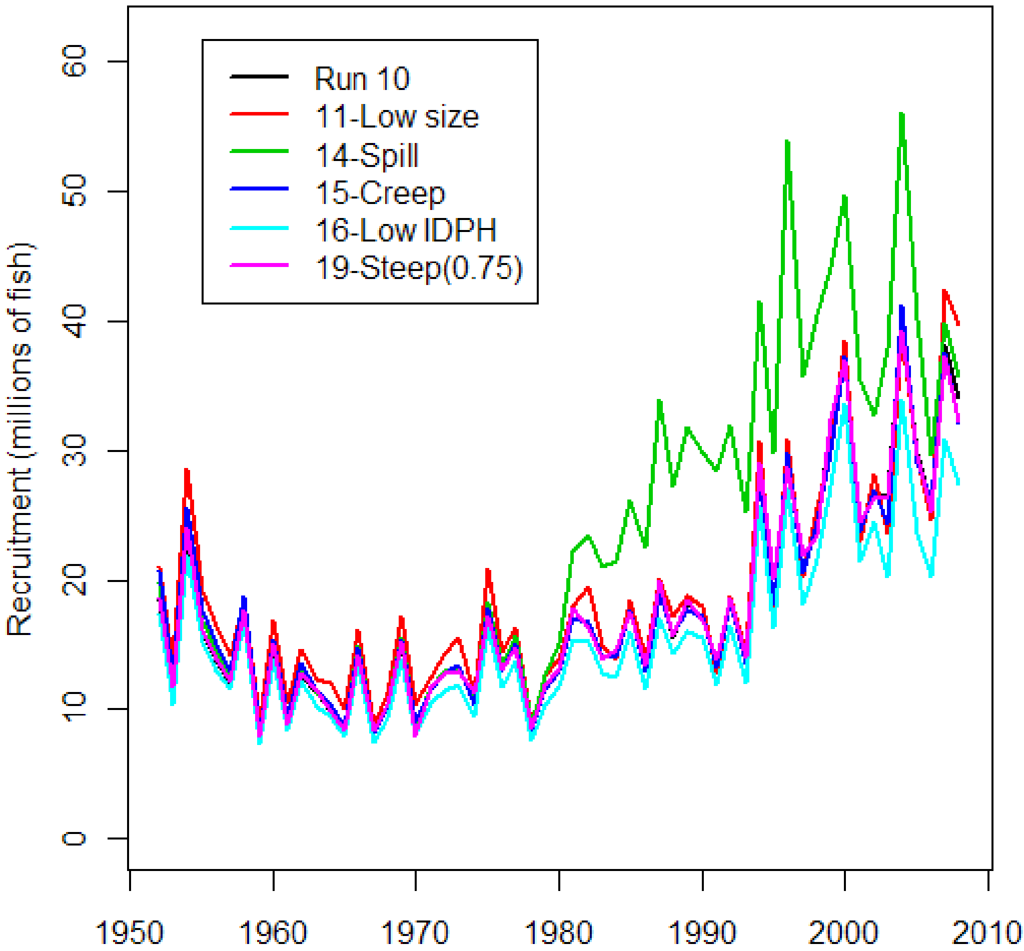


Figure 24. Estimated annual recruitment (millions of fish) for the WCPO obtained from five different model options.

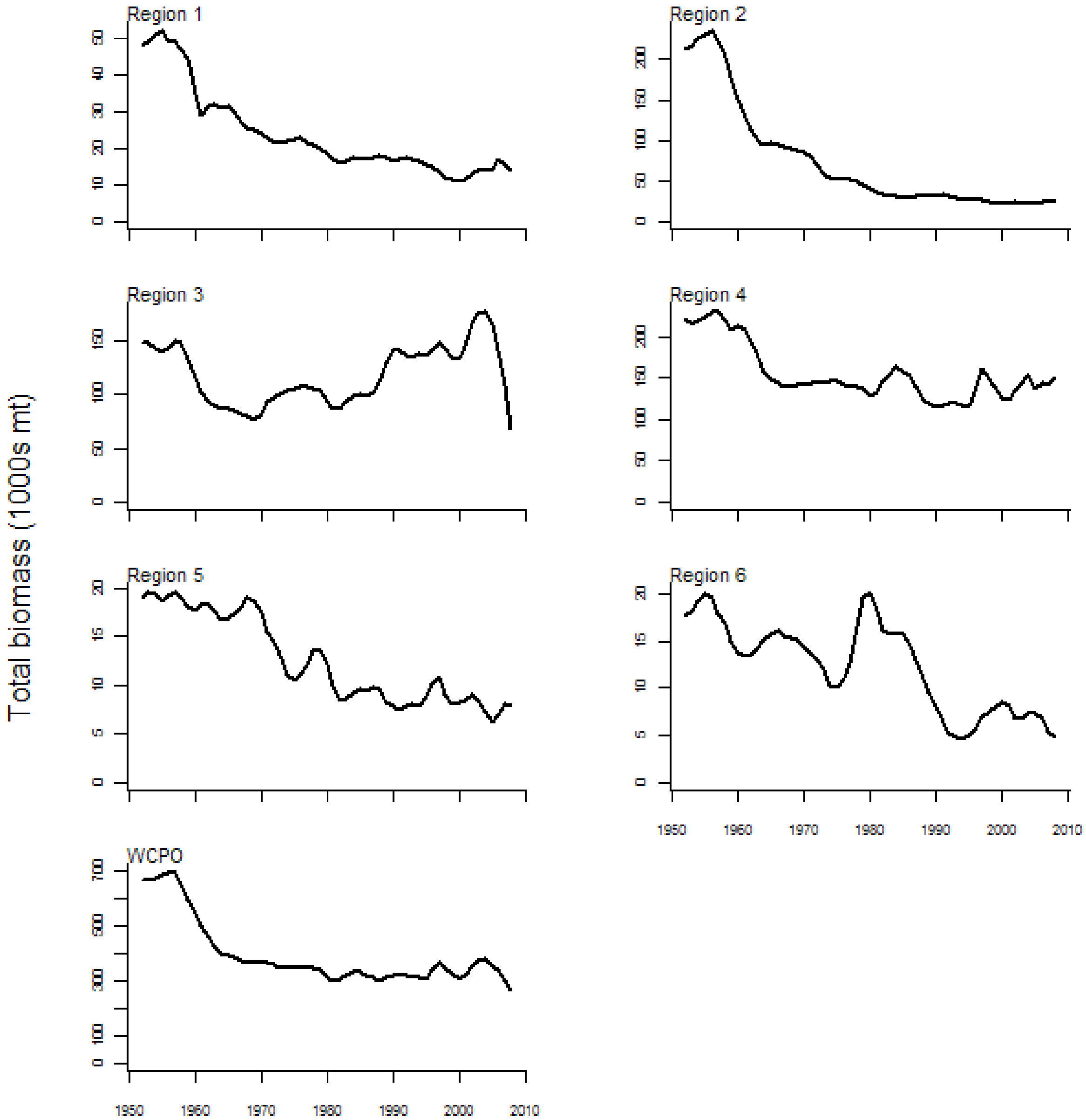


Figure 25. Estimated annual average total biomass by region and for the WCPO.

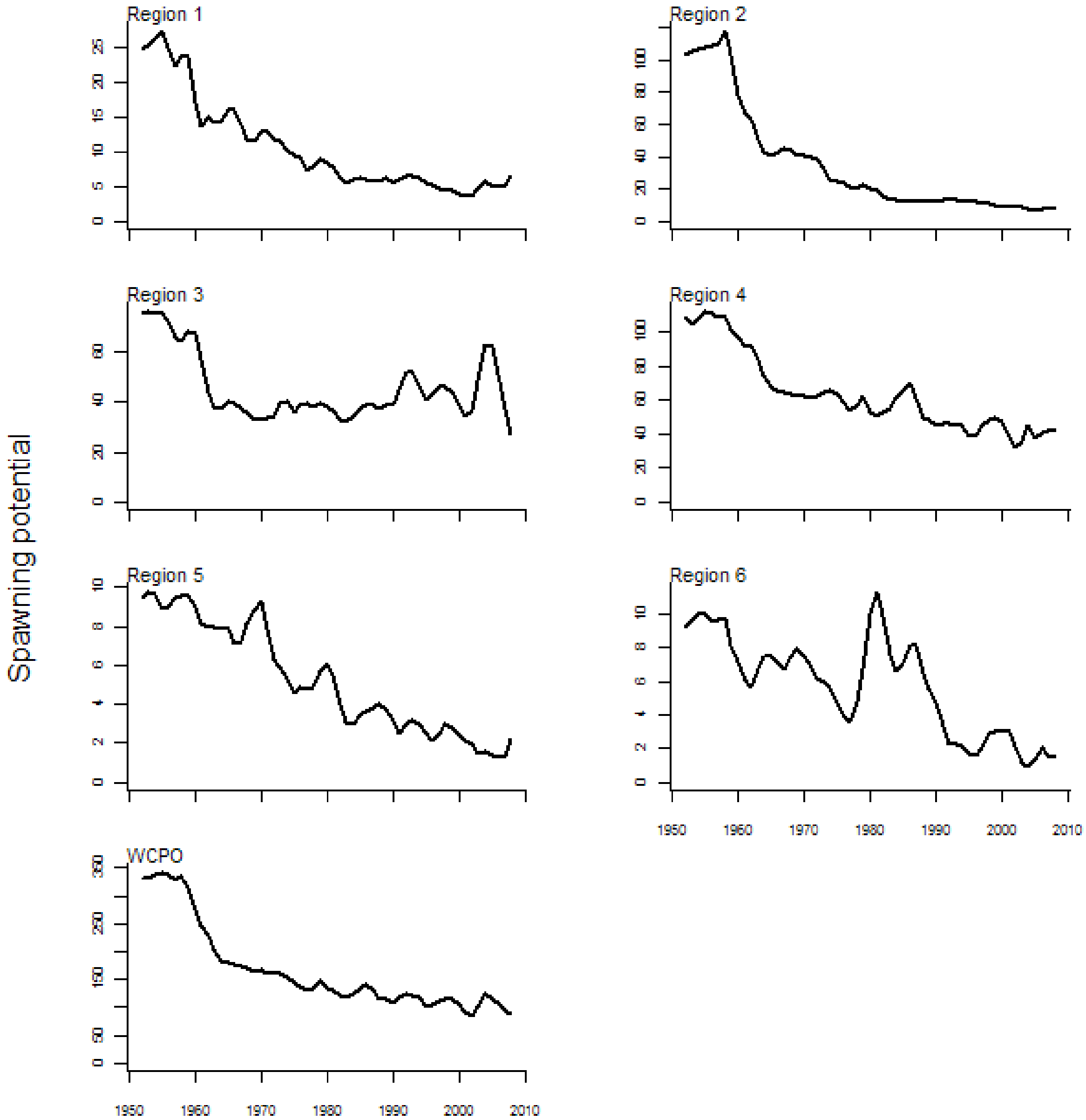


Figure 26. Estimated annual average spawning potential by region and for the WCPO.

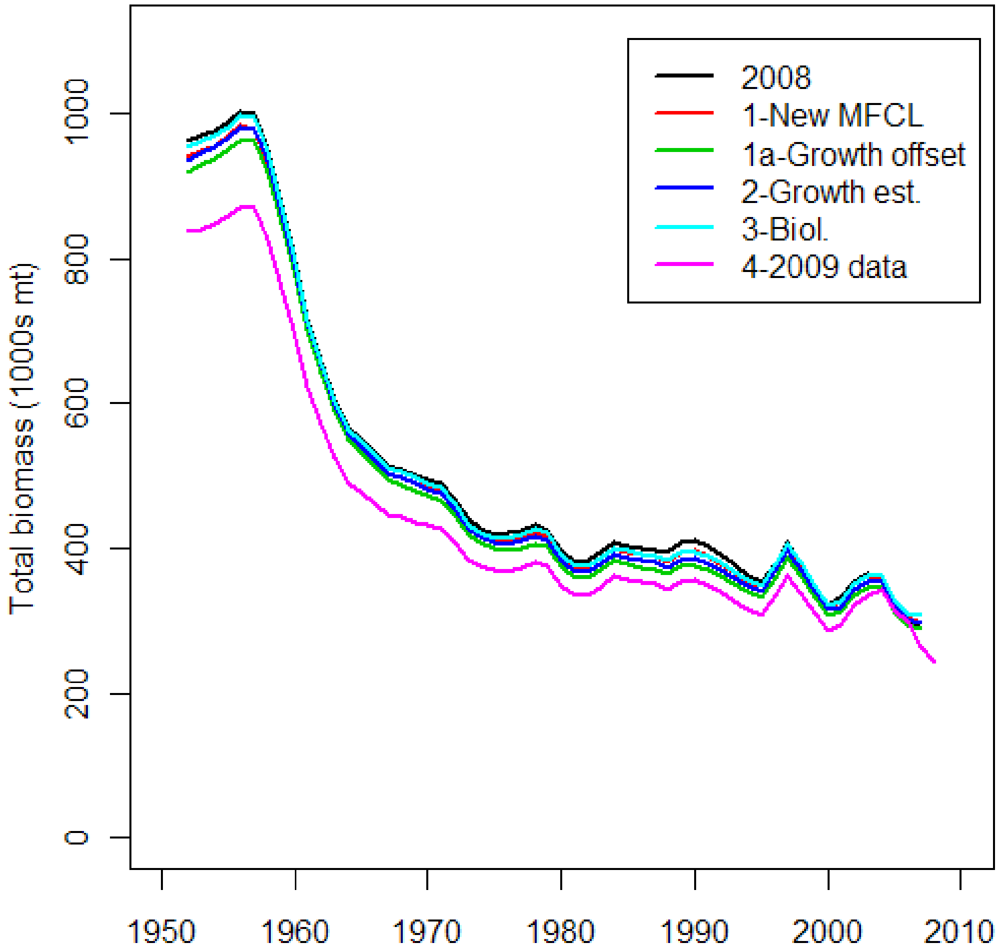


Figure 27. Estimated annual average total biomass (thousand mt) for the WCPO obtained from separate runs undertaken in the stepwise development of run 10 (runs 1 to 4 are shown).

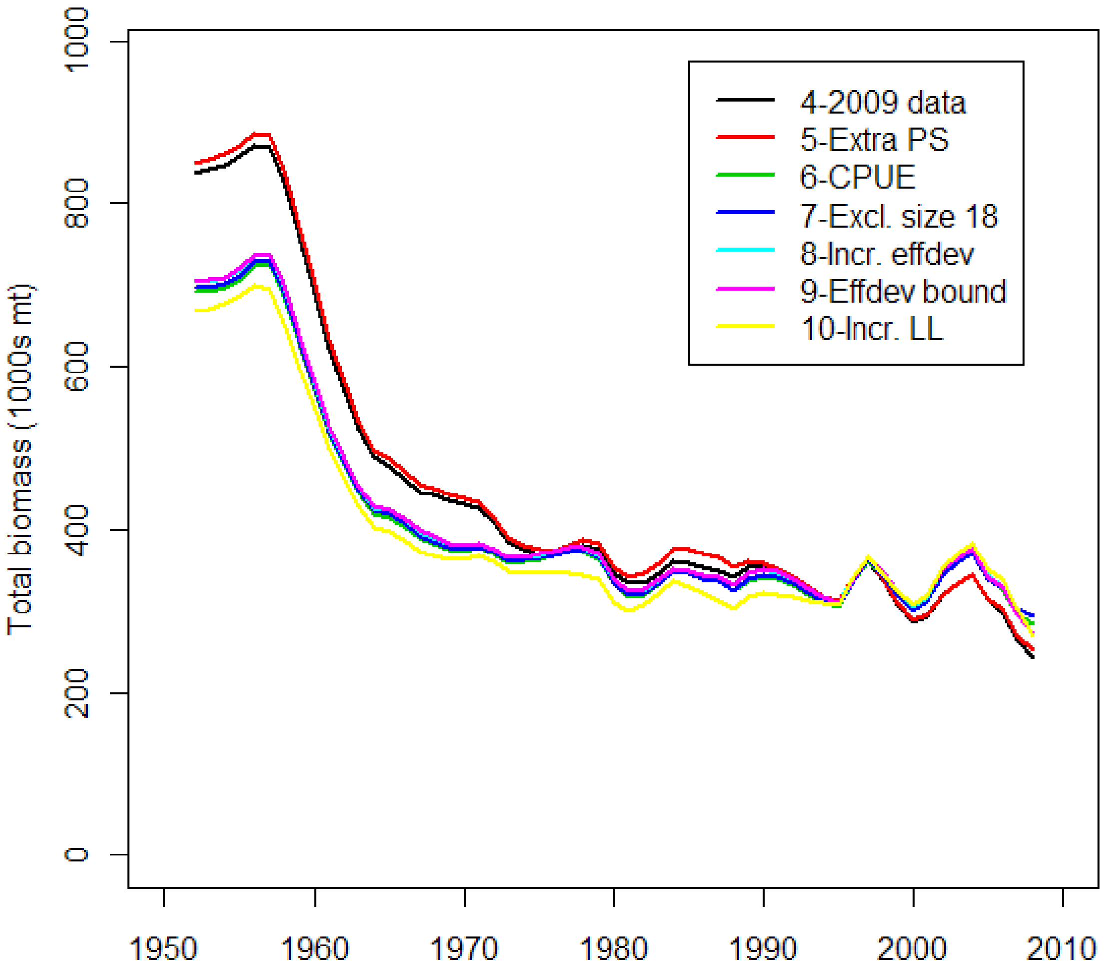


Figure 28. Estimated annual average total biomass (thousand mt) for the WCPO obtained from separate runs undertaken in the stepwise development of run 10 (runs 4 to 10 are shown).

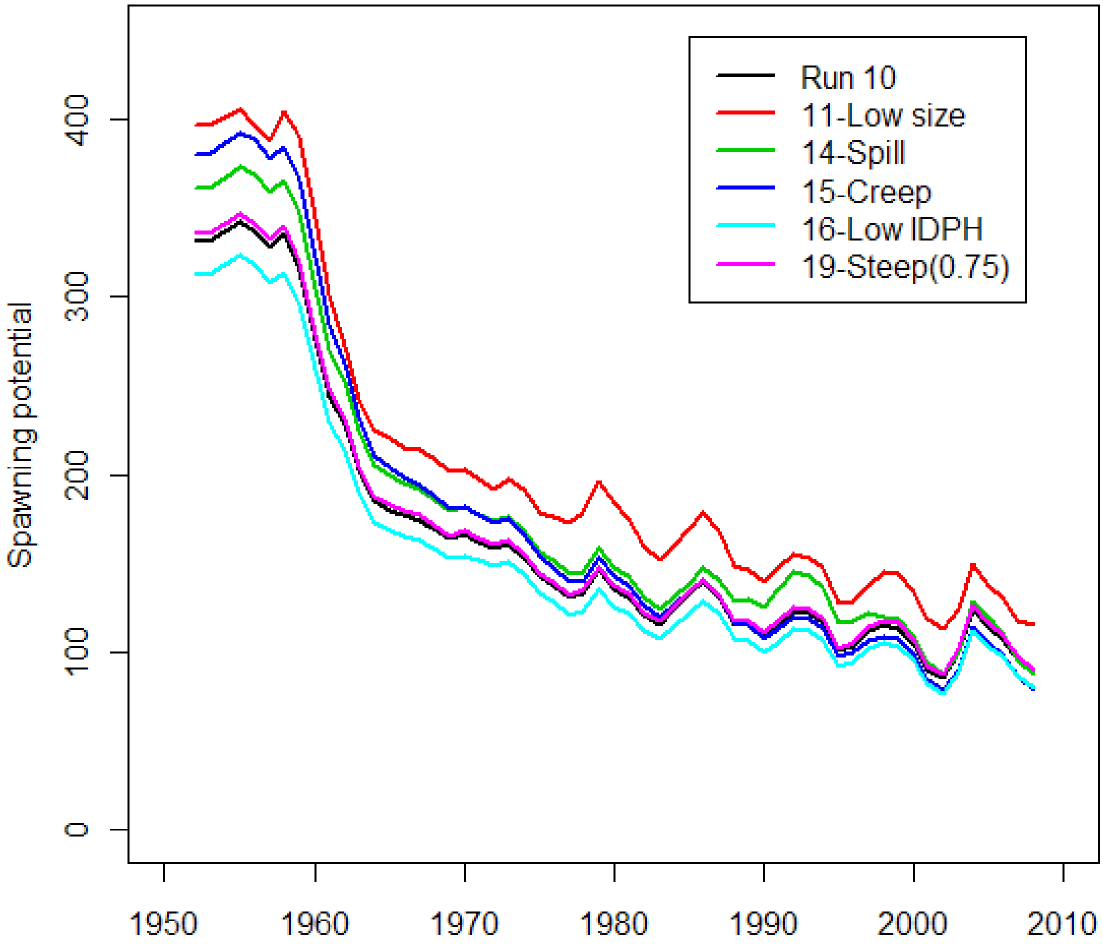


Figure 29. Estimated annual average spawning biomass for the WCPO obtained from run 10 and the alternative runs.

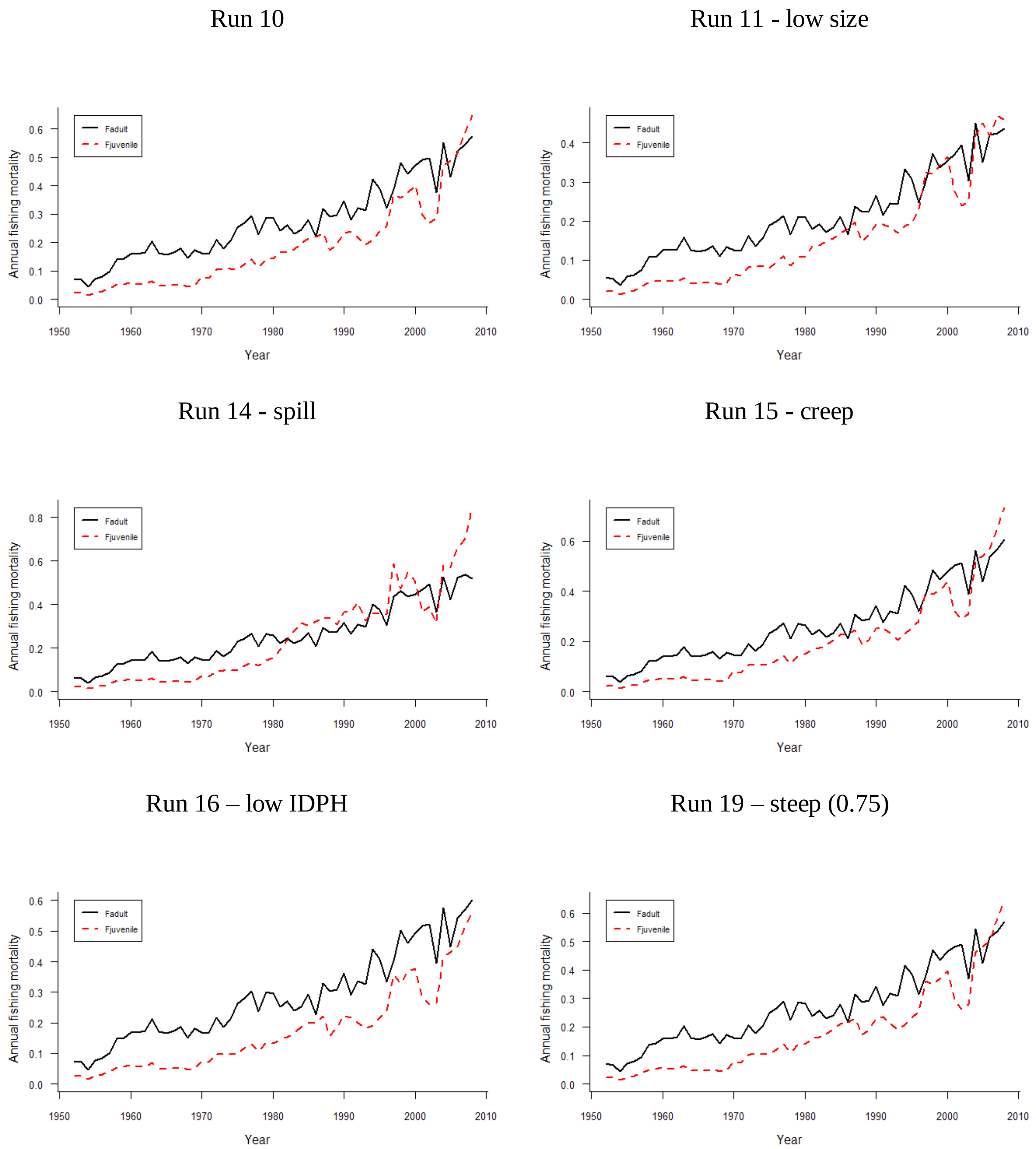


Figure 30. Estimated annual average juvenile and adult fishing mortality for the WCPO obtained from selected analyses.

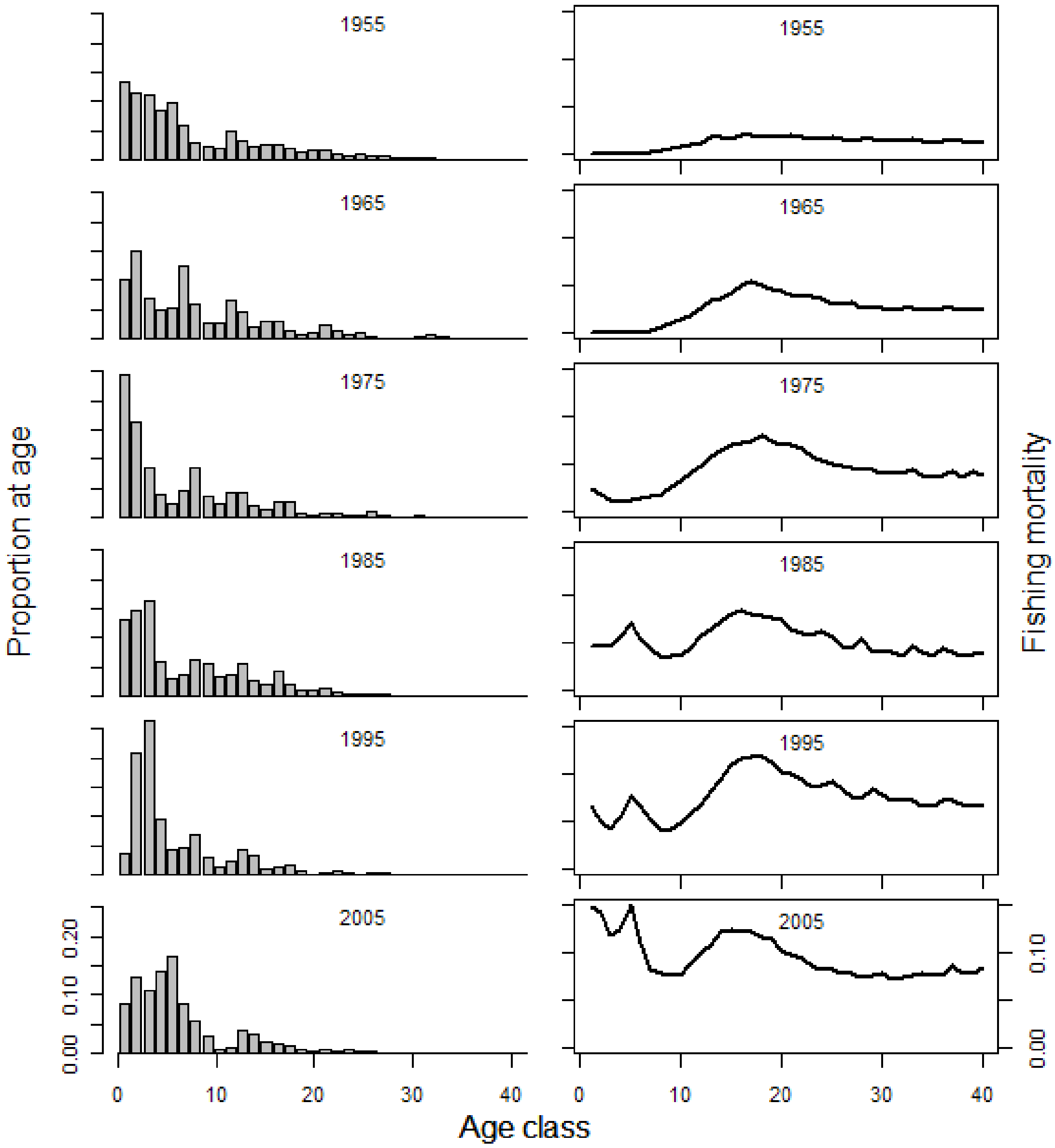


Figure 31. Estimated proportion at age (quarters) for the WCPO bigeye population (left) and fishing mortality at age (right) by year at decade intervals.

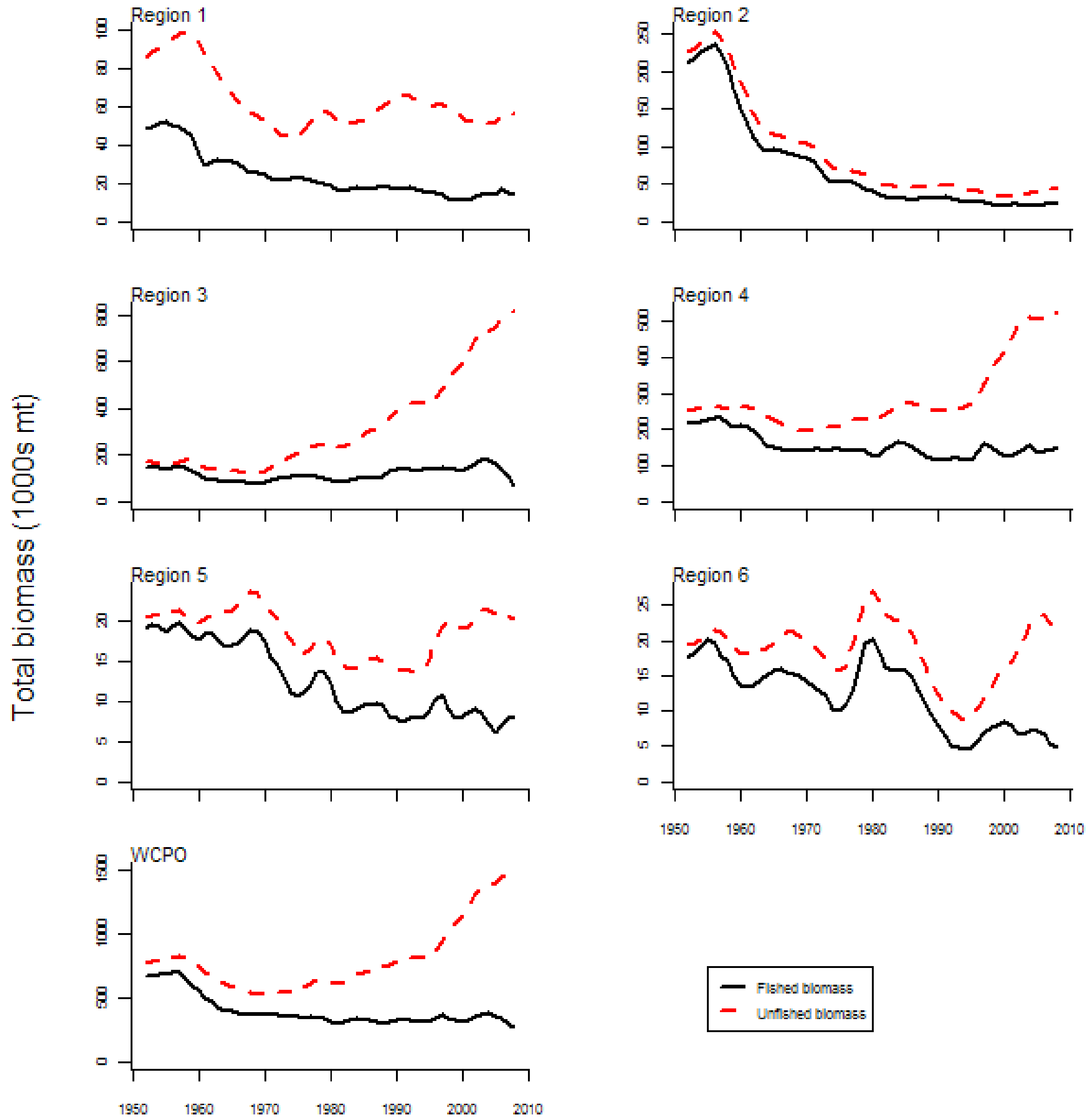


Figure 32. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper dashed lines) for each region and for the WCPO (base case model).

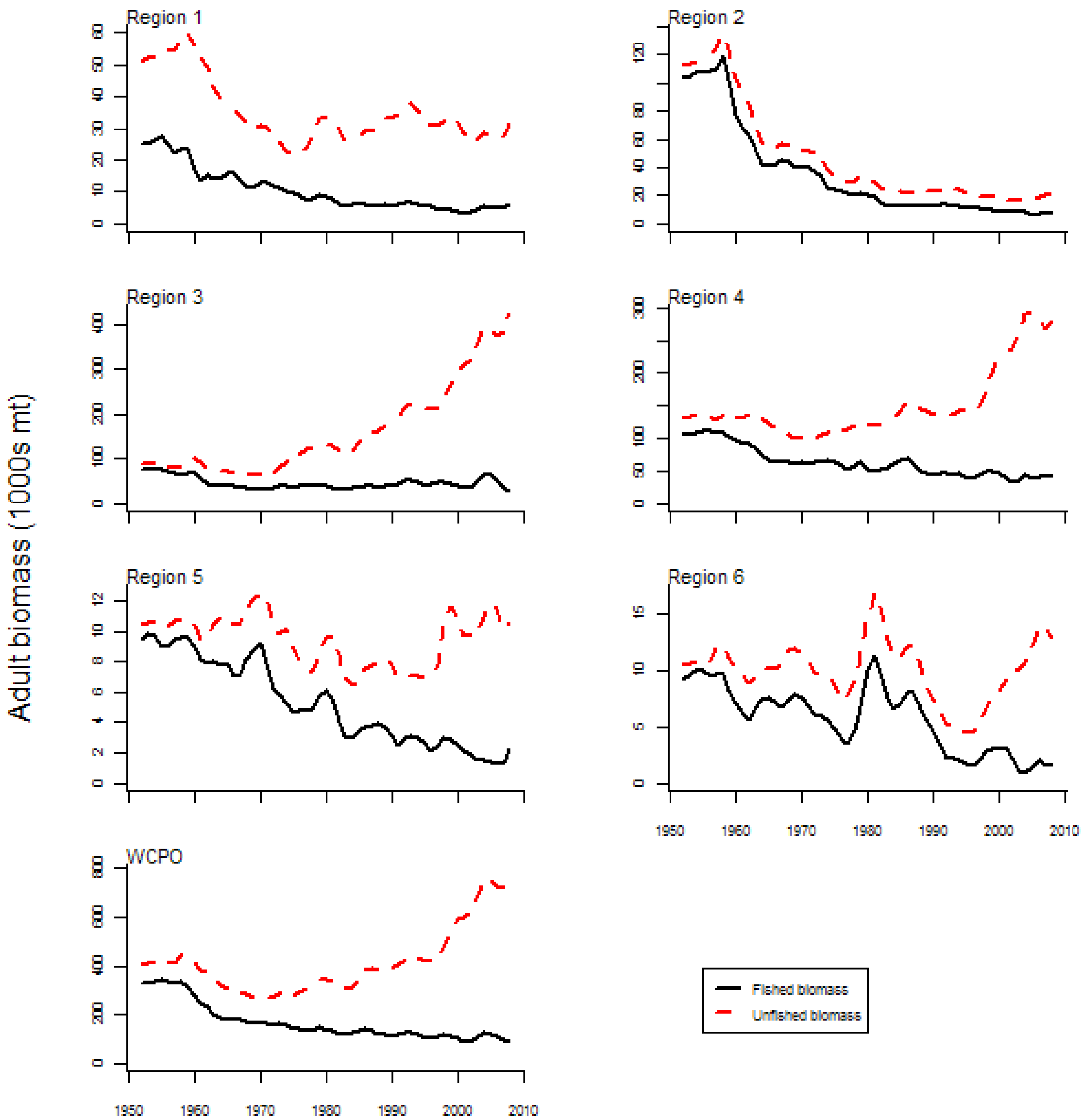


Figure 33. Comparison of the estimated adult biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper dashed lines) for each region and for the WCPO (base case model).

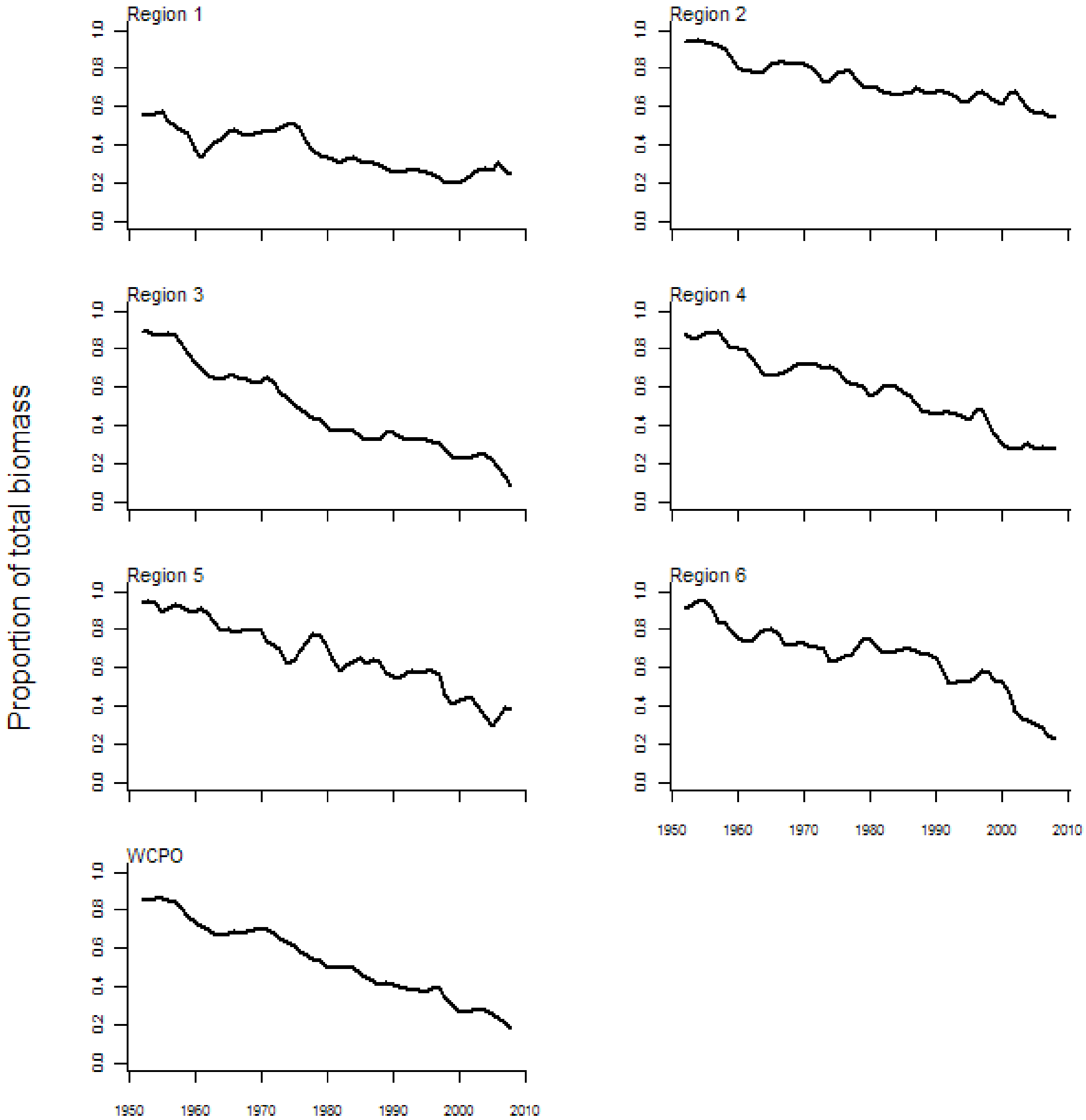


Figure 34. Ratios of exploited to unexploited total biomass $\boldsymbol{B_t/B_{t_{F=0}}}$ for each region and the WCPO.

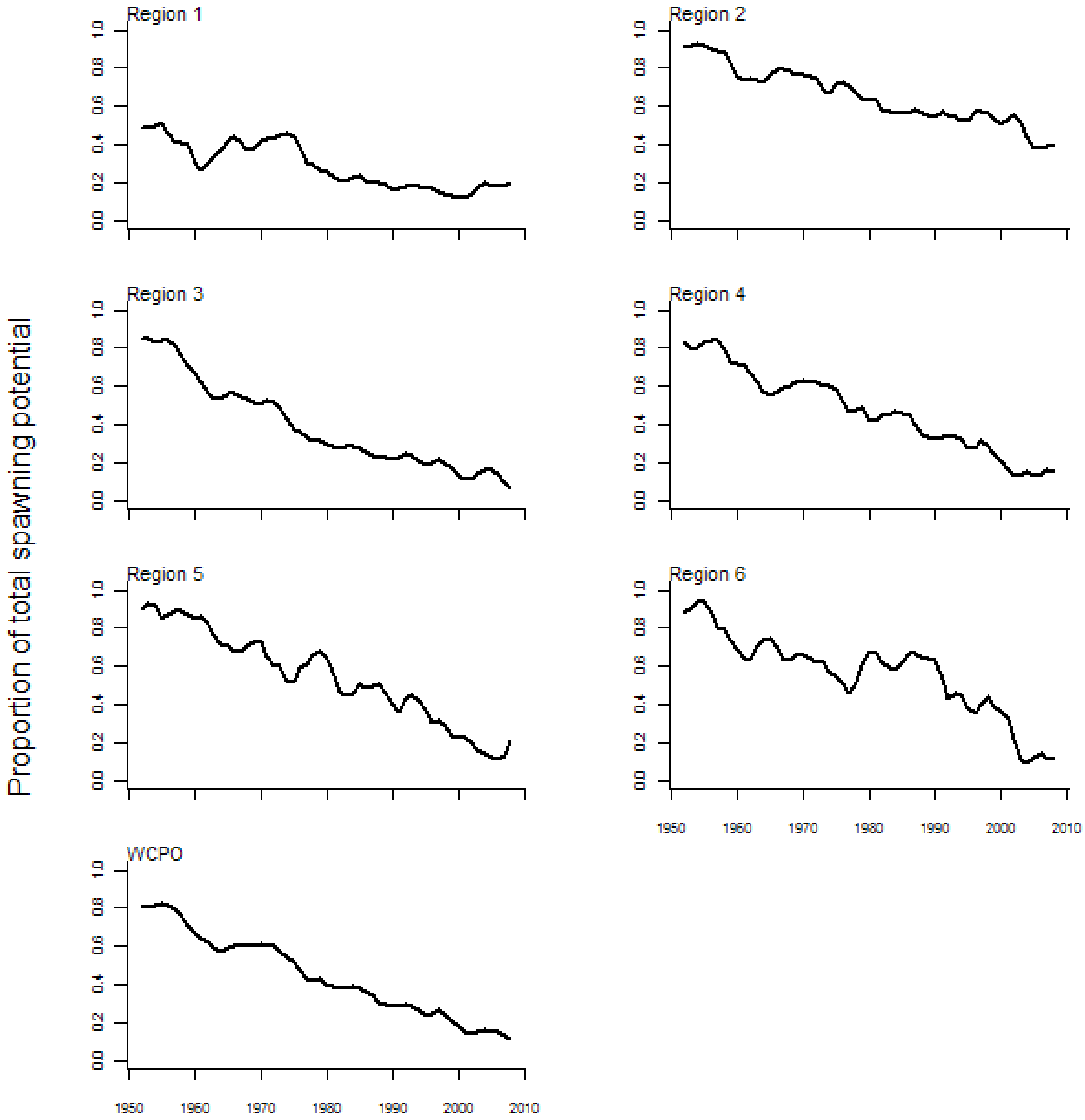


Figure 35. Ratios of exploited to unexploited total biomass $SB_t/SB_{t_{F=0}}$ for each region and the WCPO.

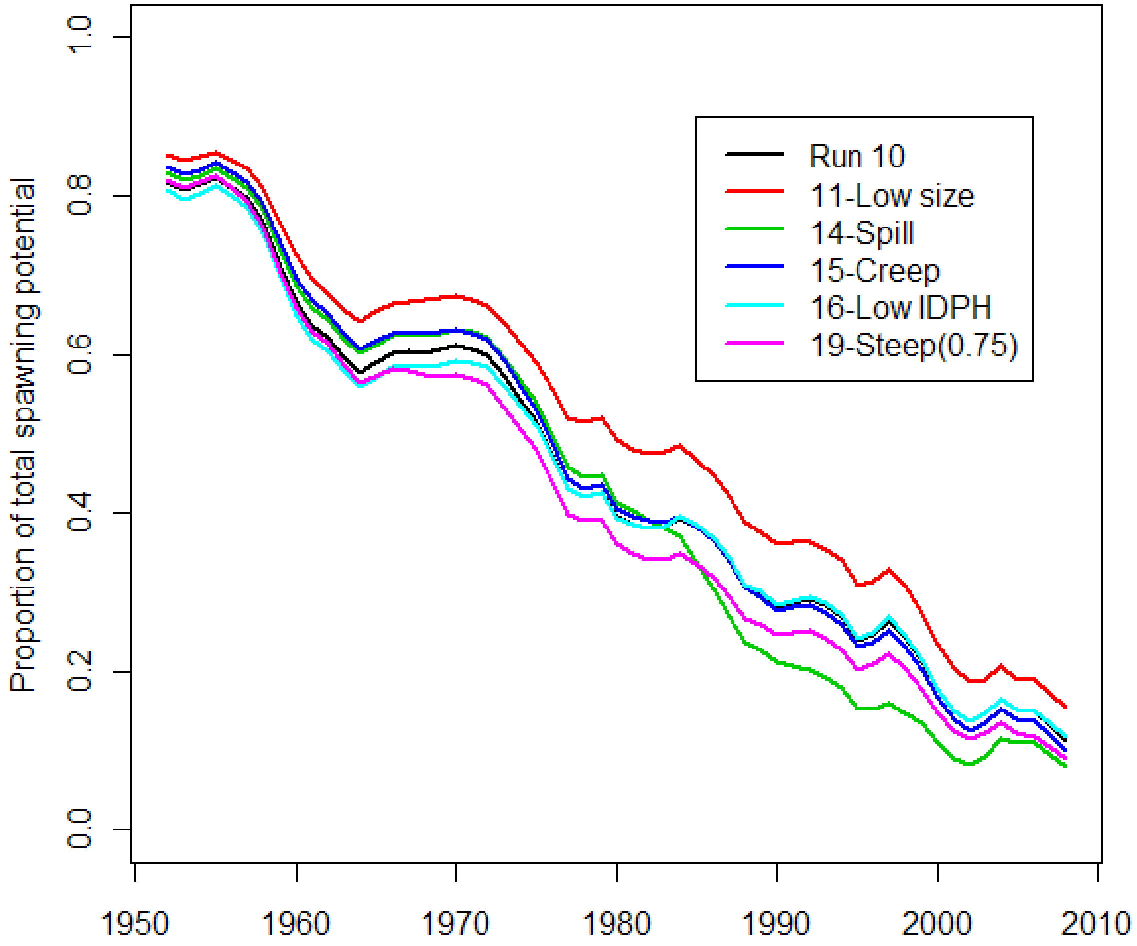


Figure 36. Ratios of exploited to unexploited spawning biomass, $\boldsymbol{SB_t/SB_{t_{F=0}}}$, for the WCPO obtained from the separate analyses.

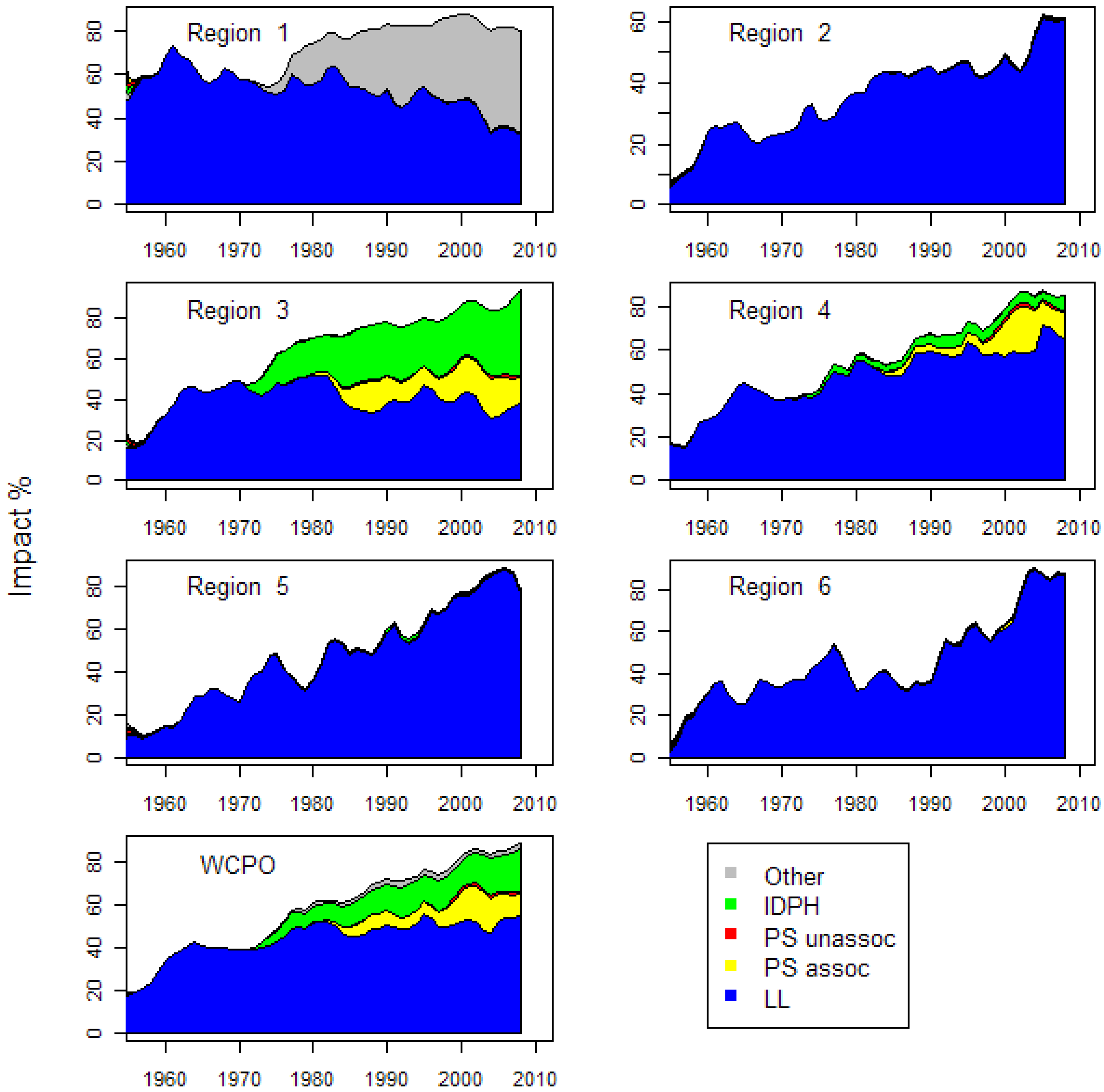


Figure 37. Estimates of reduction in spawning biomass due to fishing (fishery impact = $\mathbf{1 - SB_t/SB_{t_{F=0}}}$) by region and for the WCPO attributed to various fishery groups (base case model). LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine log and FAD sets; PS unassoc = purse seine school sets; Other = pole and line fisheries and coastal Japan purse-seine.

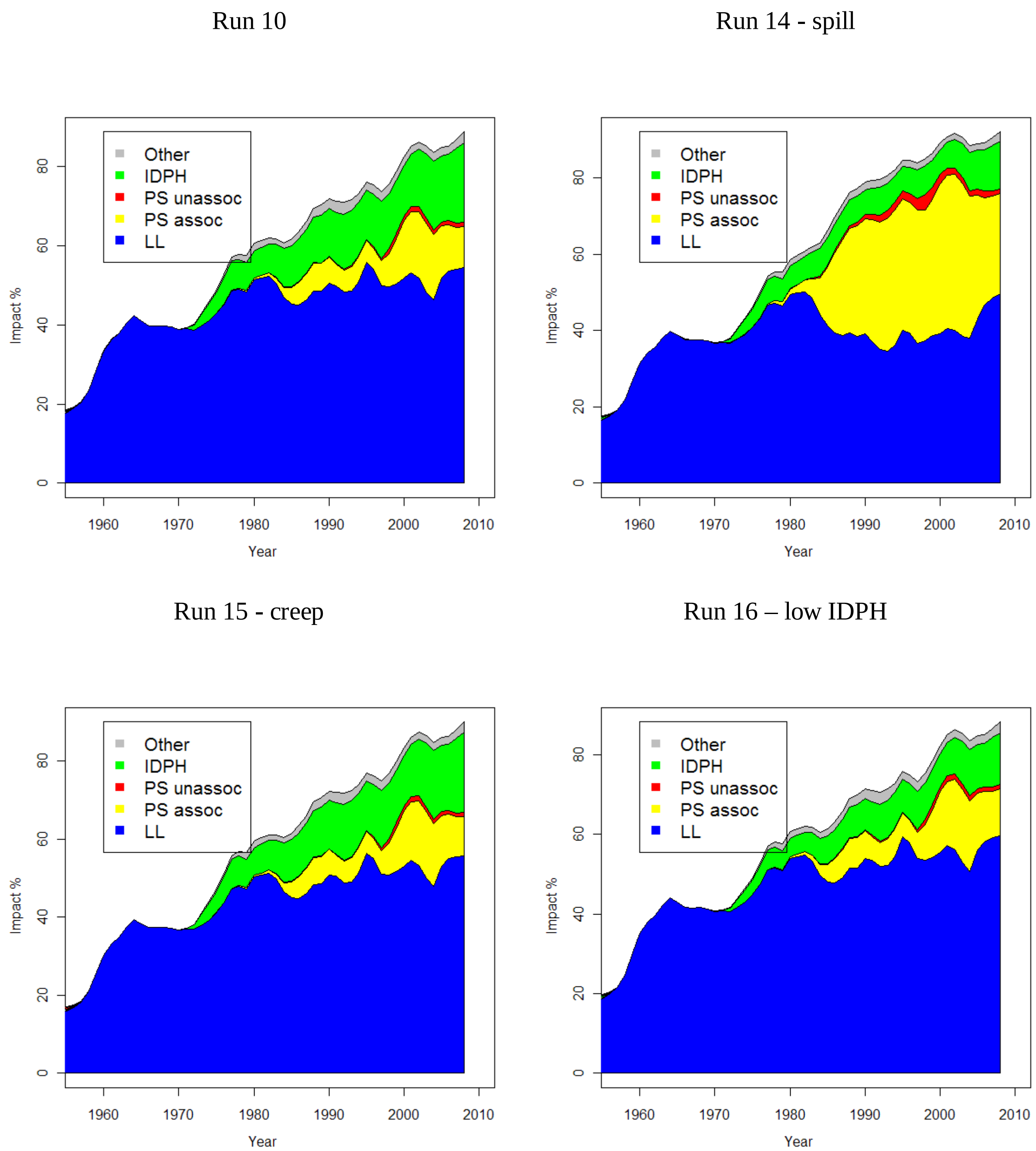


Figure 38. Estimates of reduction in WCPO spawning biomass due to fishing (fishery impact = $\mathbf{1 - SB_t / SB_{t_{F=0}}}$) attributed to various fishery groups for the four main alternative models. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine log and FAD sets; PS unassoc = purse seine school sets; Other = pole and line fisheries and coastal Japan purse-seine.

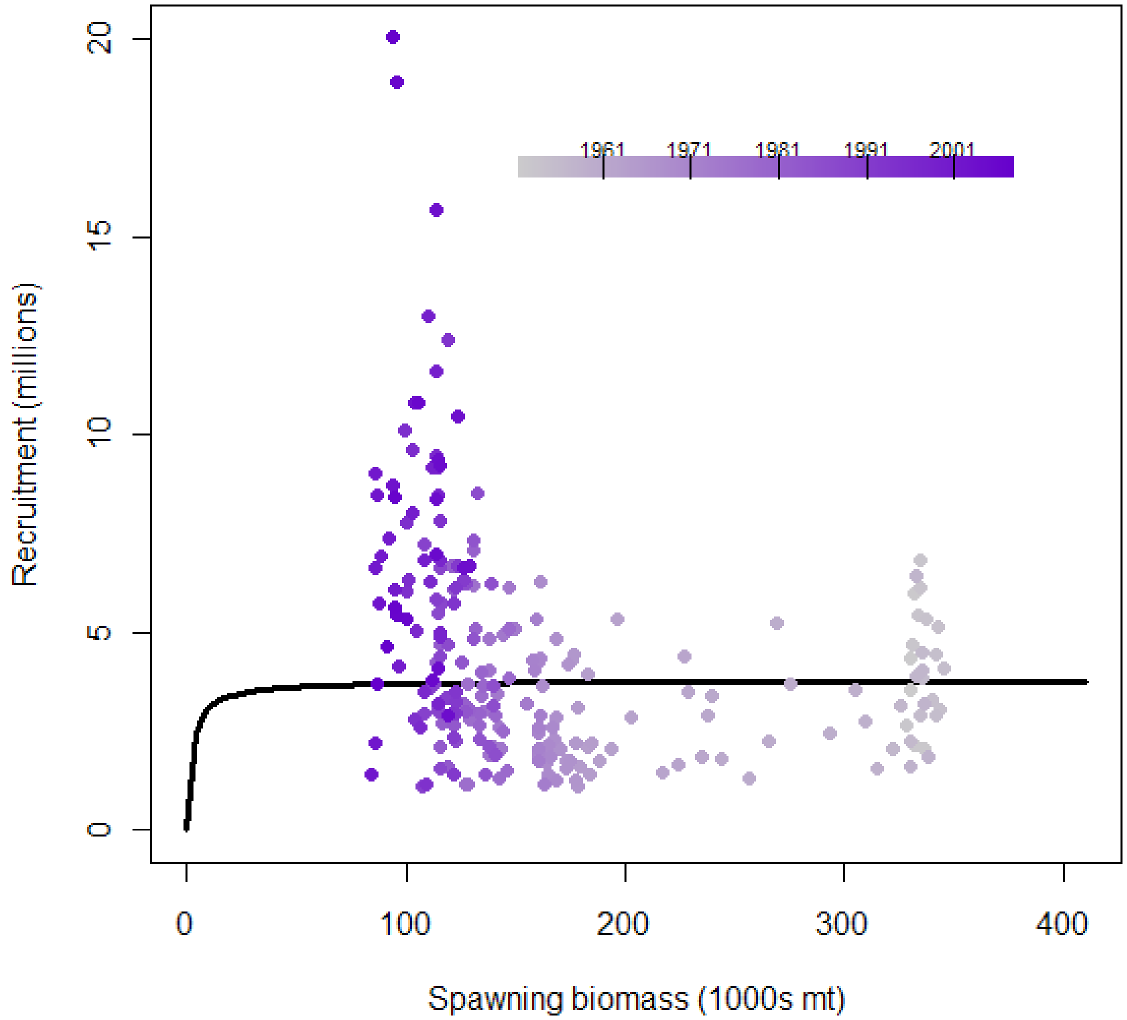


Figure 39. Estimated relationship between equilibrium recruitment and equilibrium spawning biomass. Estimated recruitment-spawning biomass points are plotted as points. The legend denotes the quarter of recruitment.

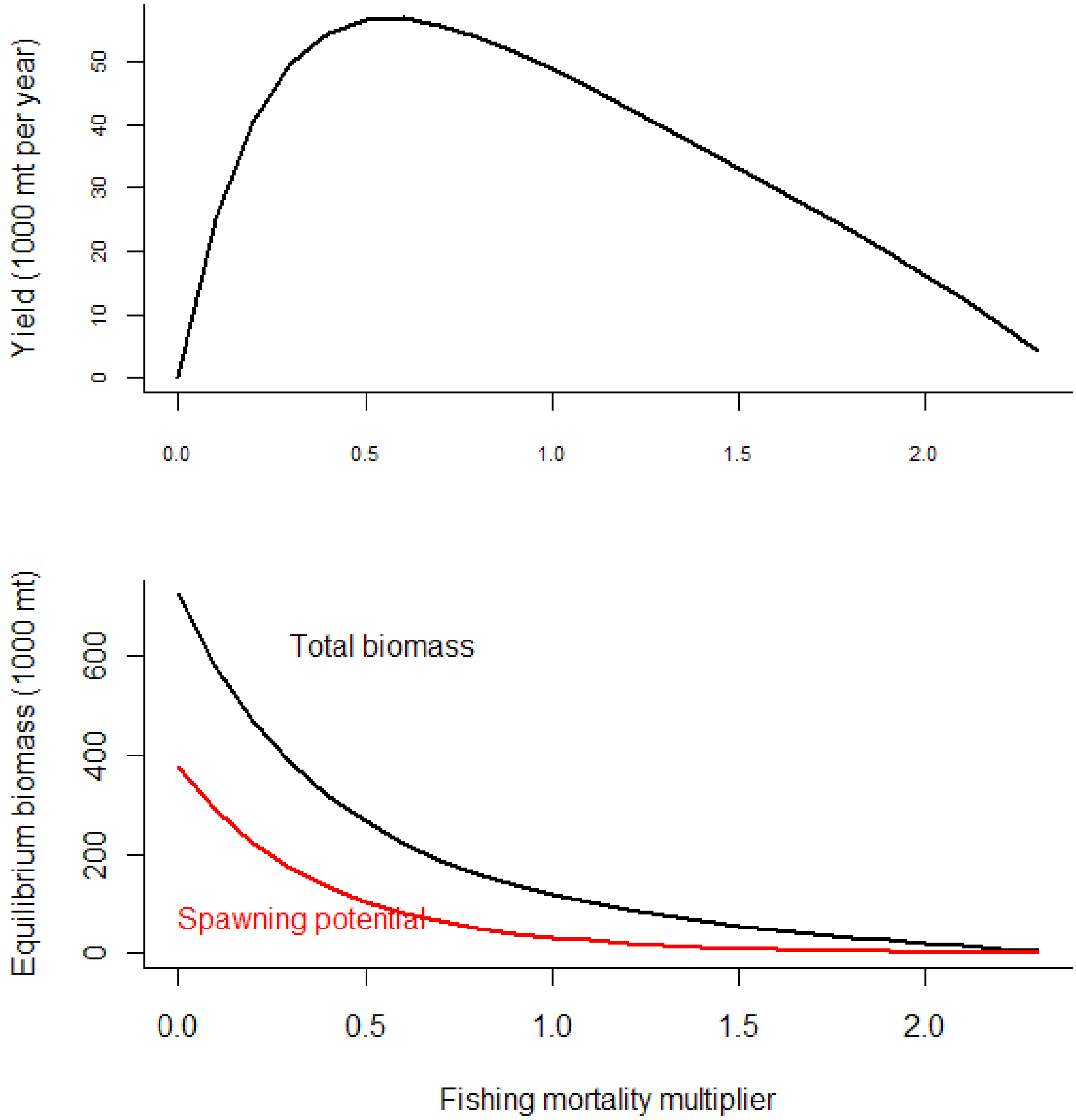


Figure 40. Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier. The shaded areas represent approximate 95% confidence intervals.

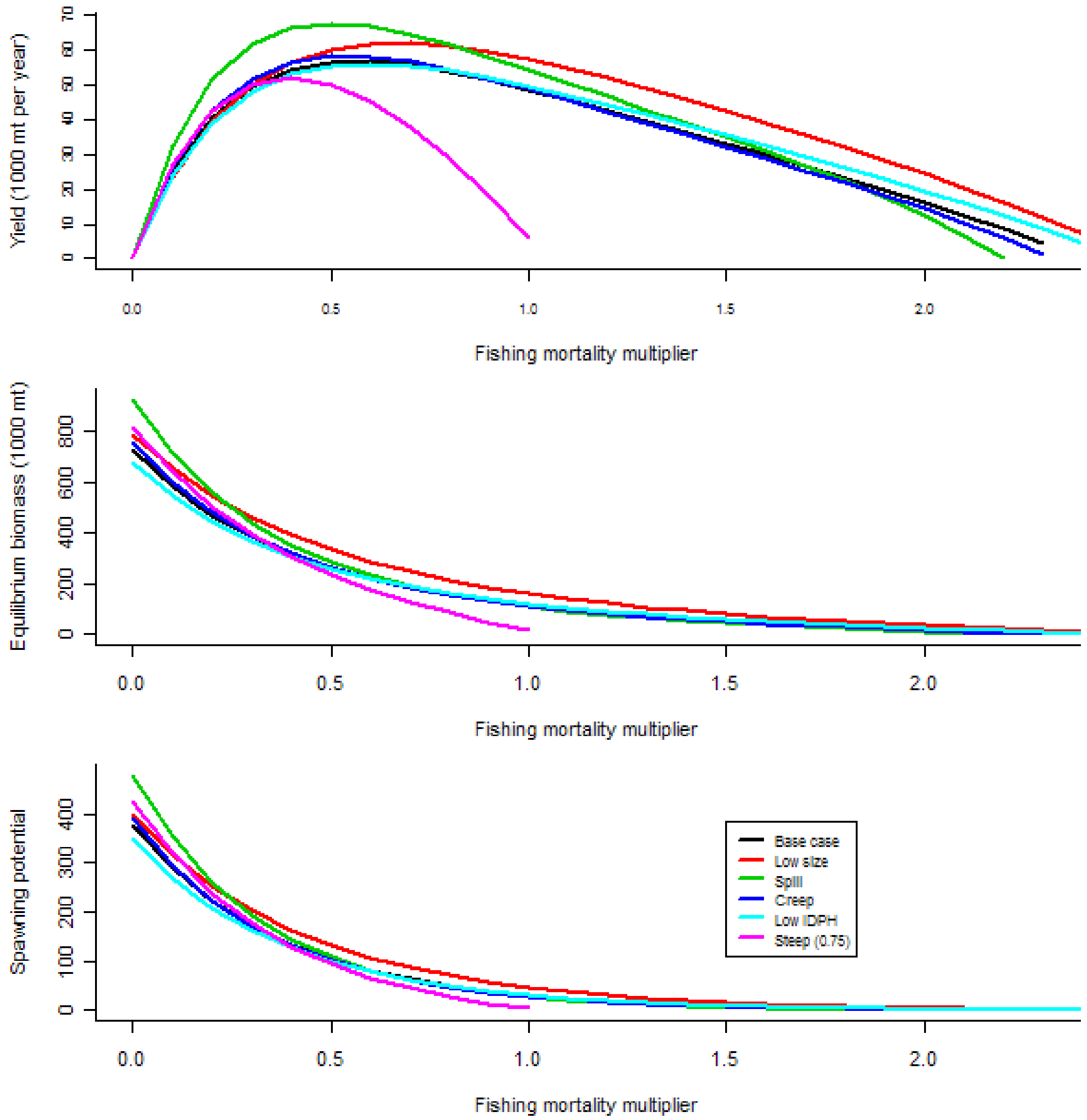


Figure 41. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier ($\boldsymbol{F_{mult}}$) obtained from the separate analyses.

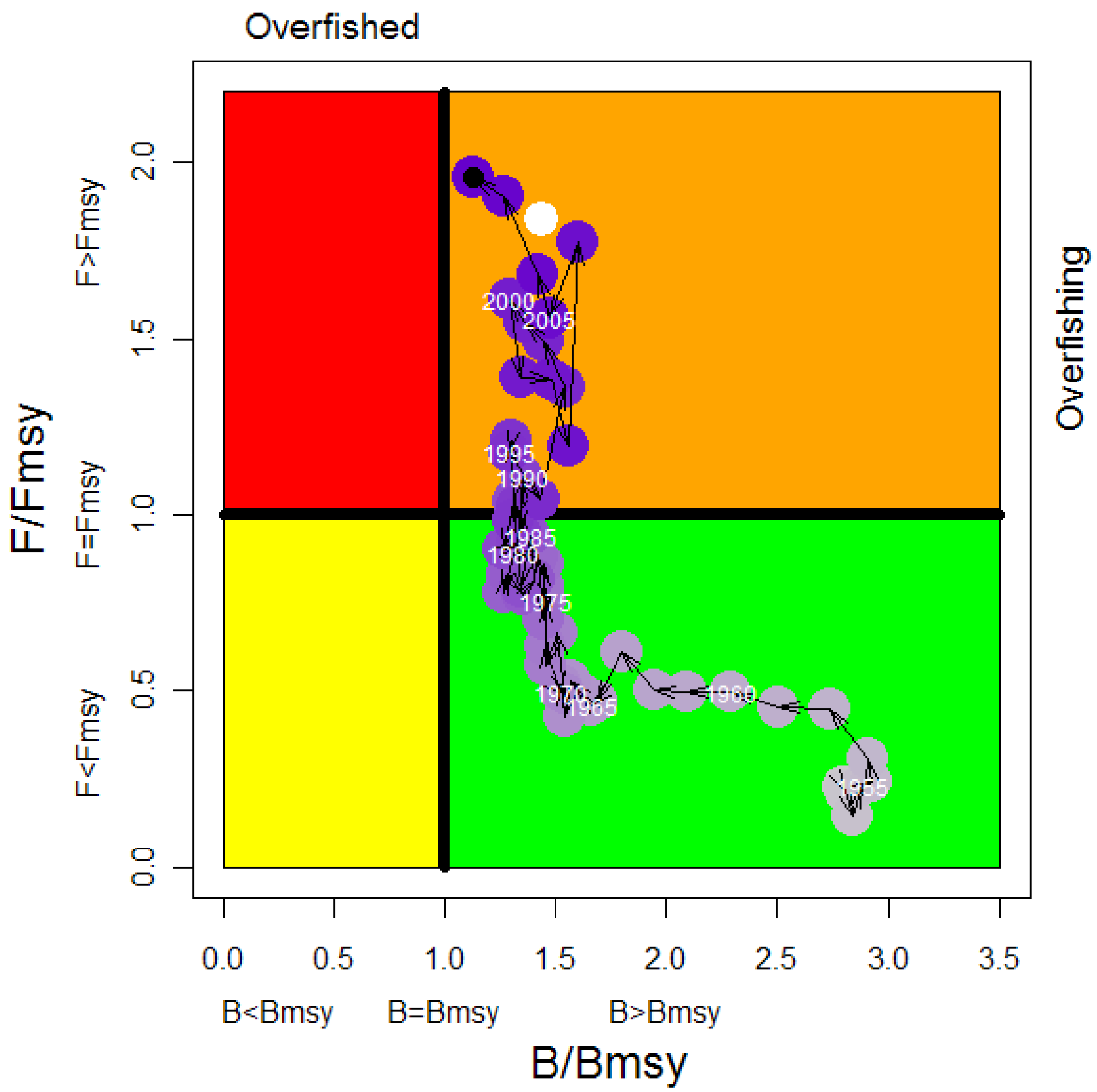


Figure 42. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1952–2008) from run 10. The colour of the points is graduated from mauve (1952) to dark purple (2008) and the points are labelled at 5-year intervals. The white circle represents the average for the period 2004-07 and the black dot represents the last year of the model (2008) which is uncertain for total biomass.

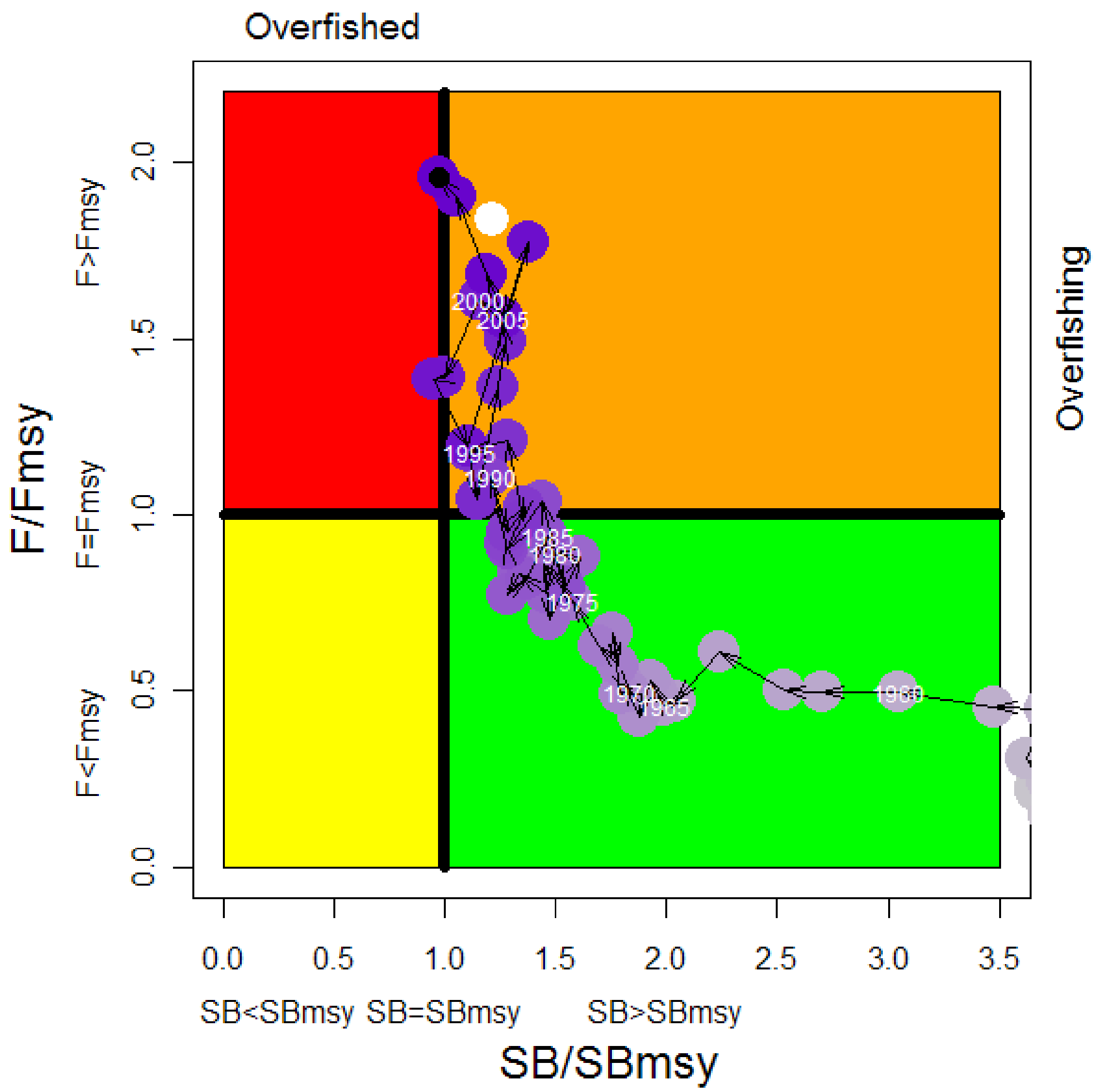


Figure 43. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1952–2006) from run 10. The colour of the points is graduated from mauve (1952) to dark purple (2008) and the points are labelled at 5-year intervals. The white circle represents the average for the period 2004-07 and the black dot represents the last year of the model (2008) which is considered more reliable for spawning biomass than for total biomass.

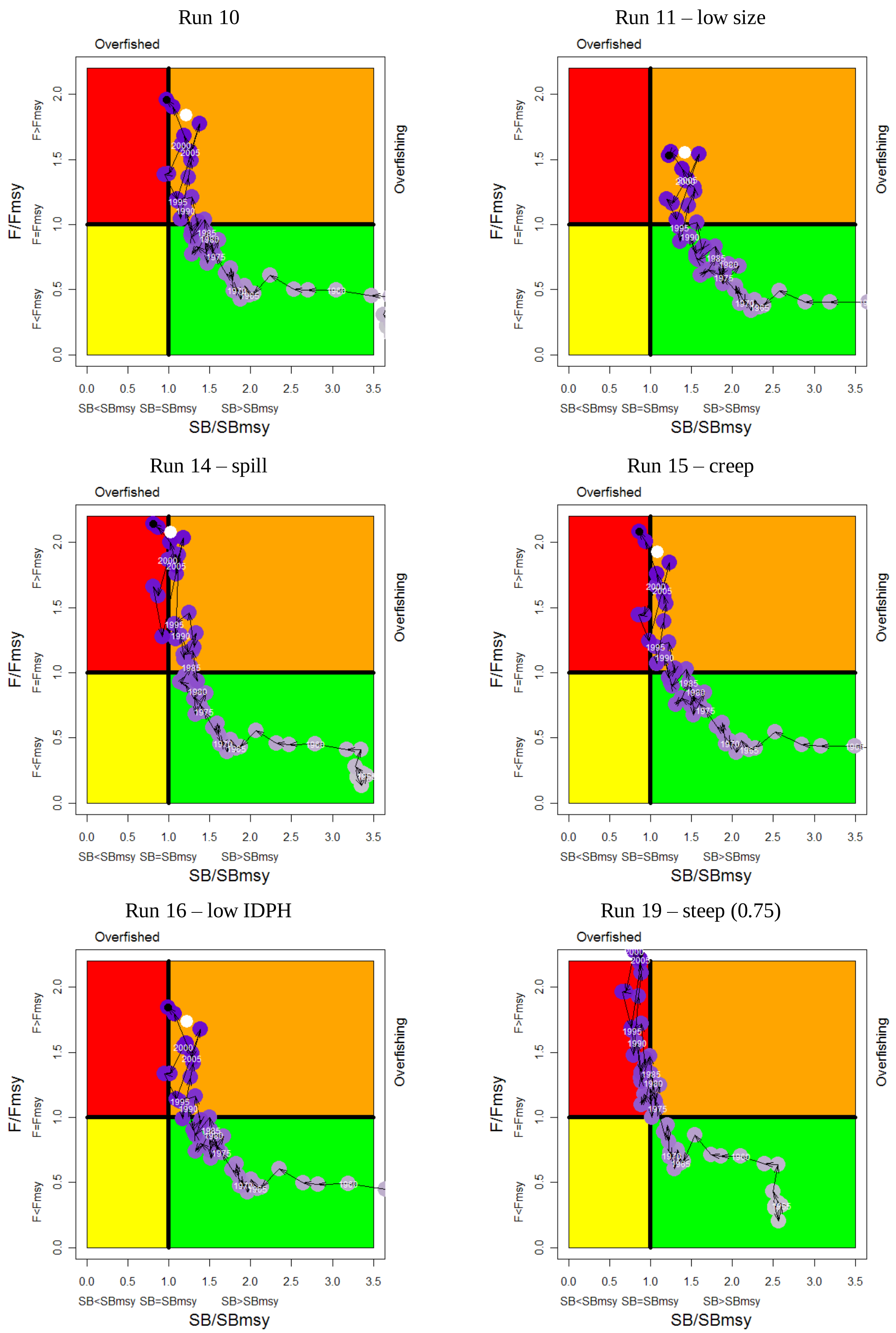


Figure 44. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points for selected model runs.

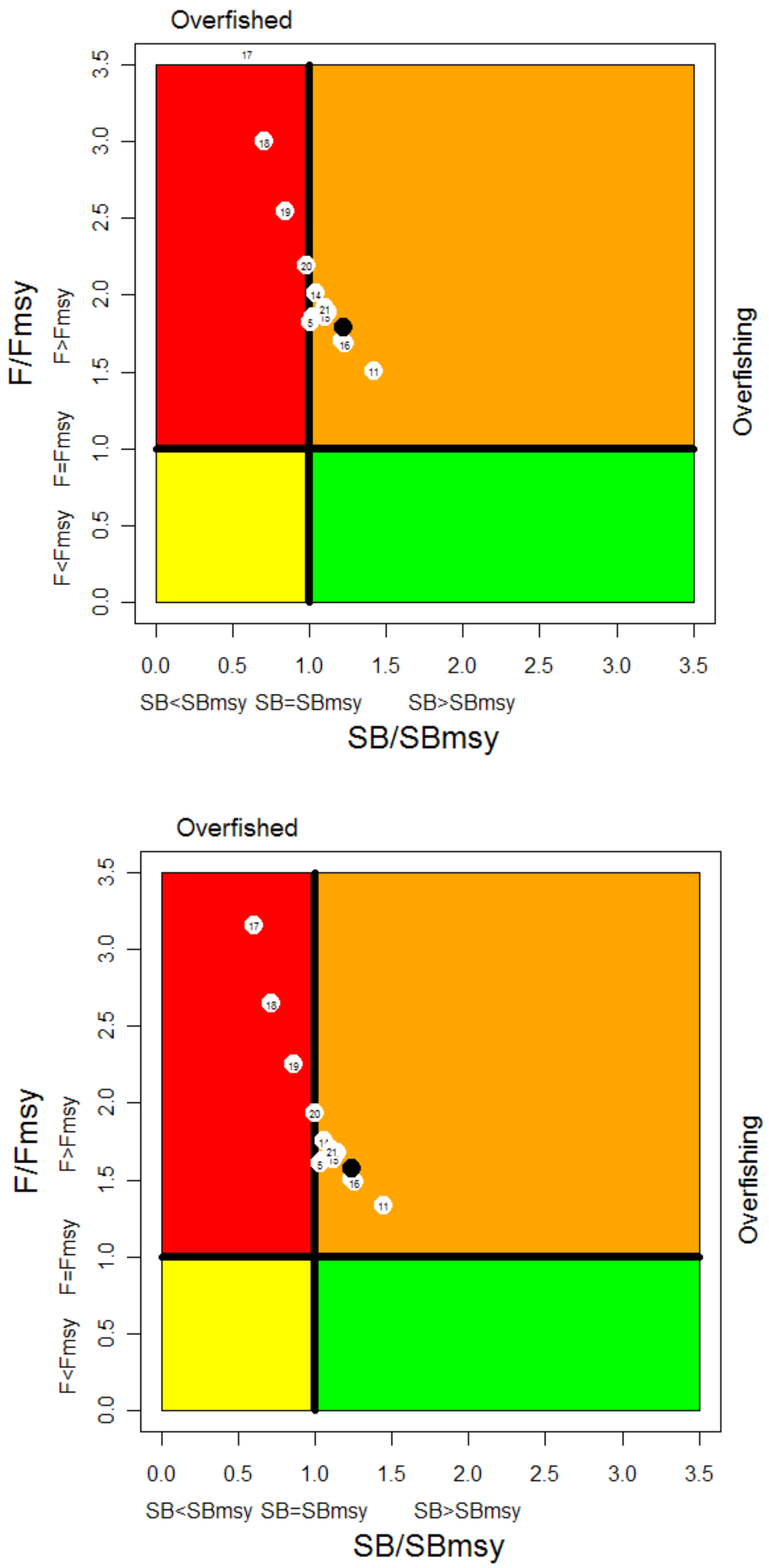


Figure 45. A comparison of $\boldsymbol{SB_{current}/SB_{MSY}}$ versus $\boldsymbol{F_{current}/F_{MSY}}$ for selected model runs (denoted in the plot) based on MSY being calculated for the period 2004-07 (top) versus 2003-06 (bottom).

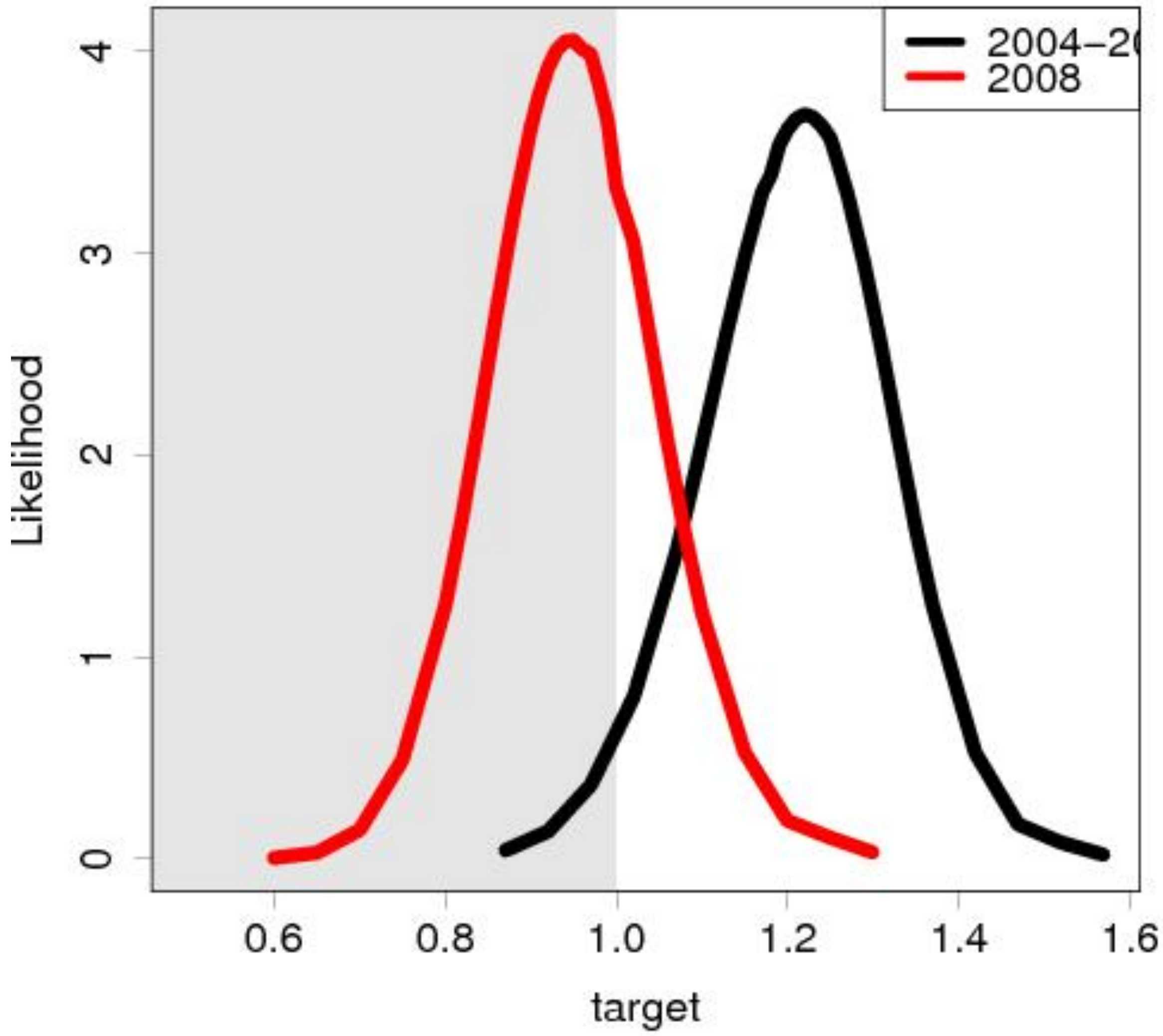
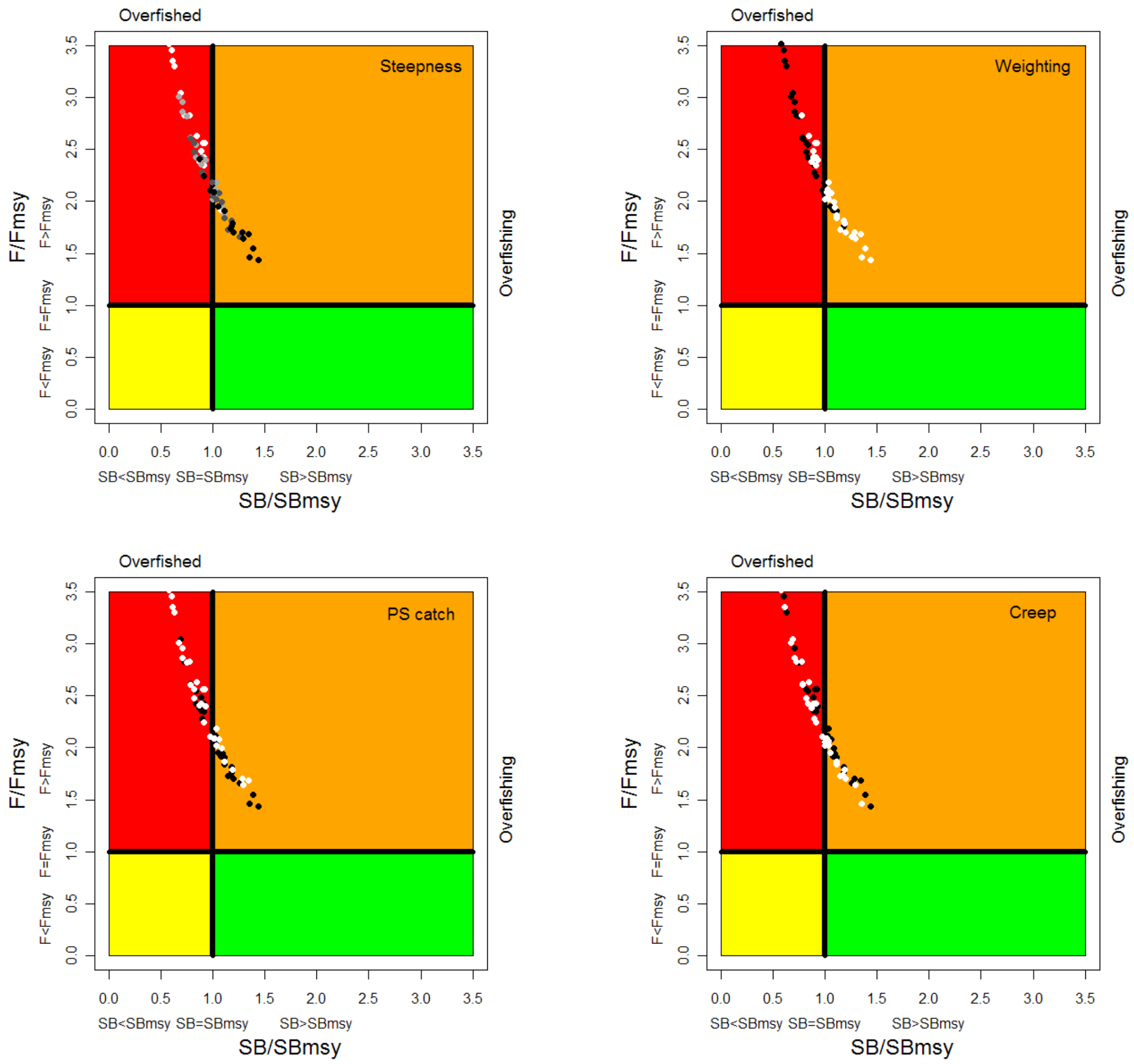
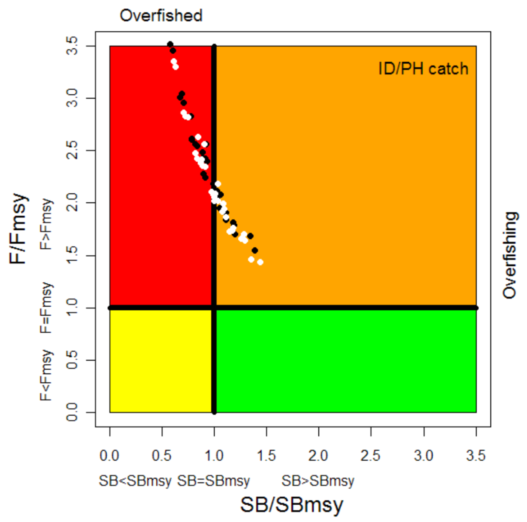


Figure 46: Likelihood profiles for $\boldsymbol{SB_{current}/SB_{MSY}}$ (2004-07) and $\boldsymbol{SB_{latest}/SB_{MSY}}$ (2008) for run 10. The shaded area represents the values below $\boldsymbol{SB_{MSY}}$ and are estimated to be 3% and 70% respectively.





Legend:

- Steepness (0.55 to 0.95 by 0.1; white to black)
- Weighting (run 10: black, low size: white)
- Purse seine catch (run 10: black; spill sampling: white)
- Effort creep (run 10: black; 0.47% per year: white)
- IDPH catch (run 10: black; 1/3 reduction: white)

Figure 47: Plot of $SB_{current}/SB_{MSY}$ versus $F_{current}/F_{MSY}$ for the 64 model runs undertaken for the structural uncertainty analysis. See lower right panel for description of the colour coding (white/black) of the model options.

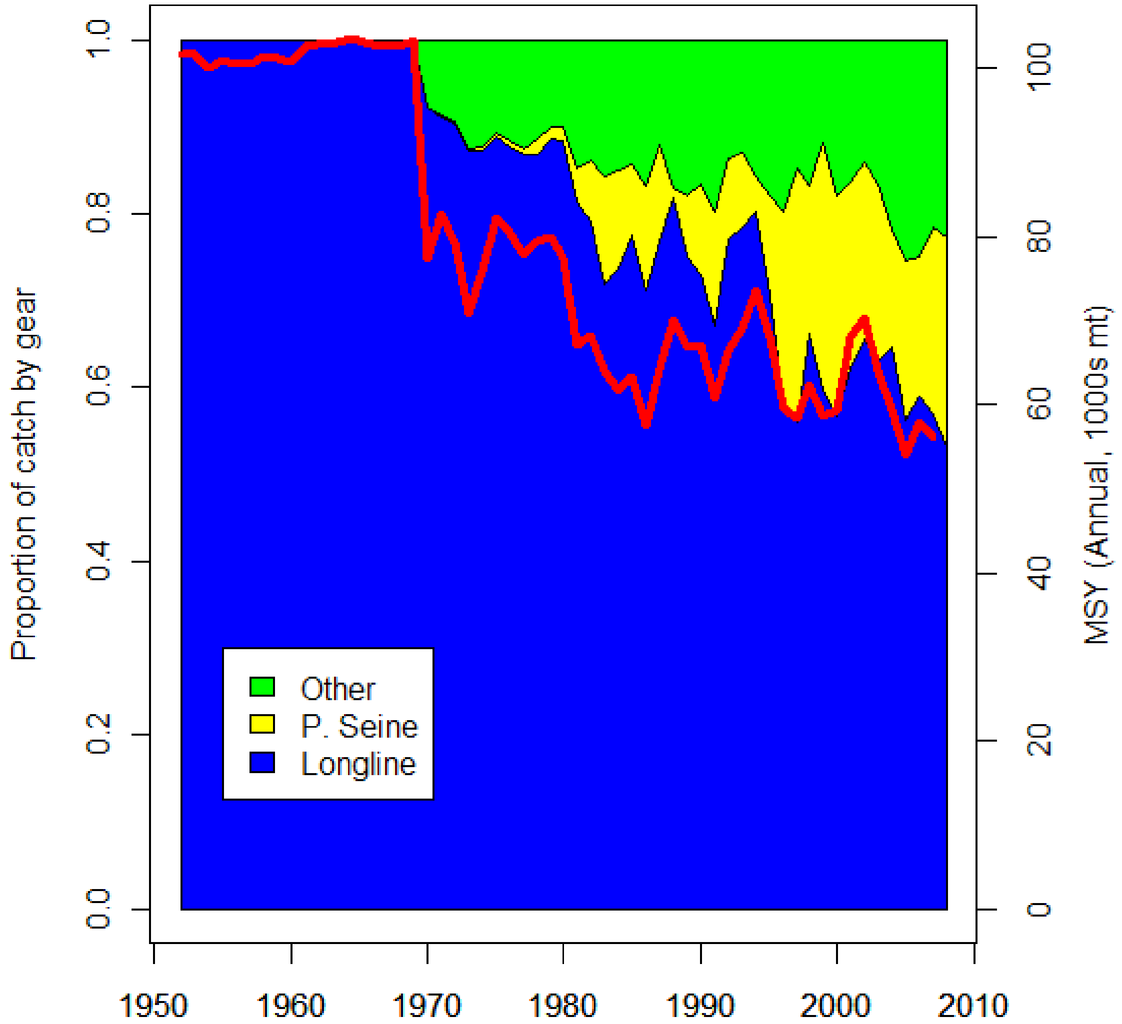


Figure 48. Temporal trend in annual Maximum Sustainable Yield (MSY) (red line) estimated for each year included in the bigeye stock assessment model. This is compared to the proportional distribution in the annual bigeye catch by main gear type for the entire WCPO.

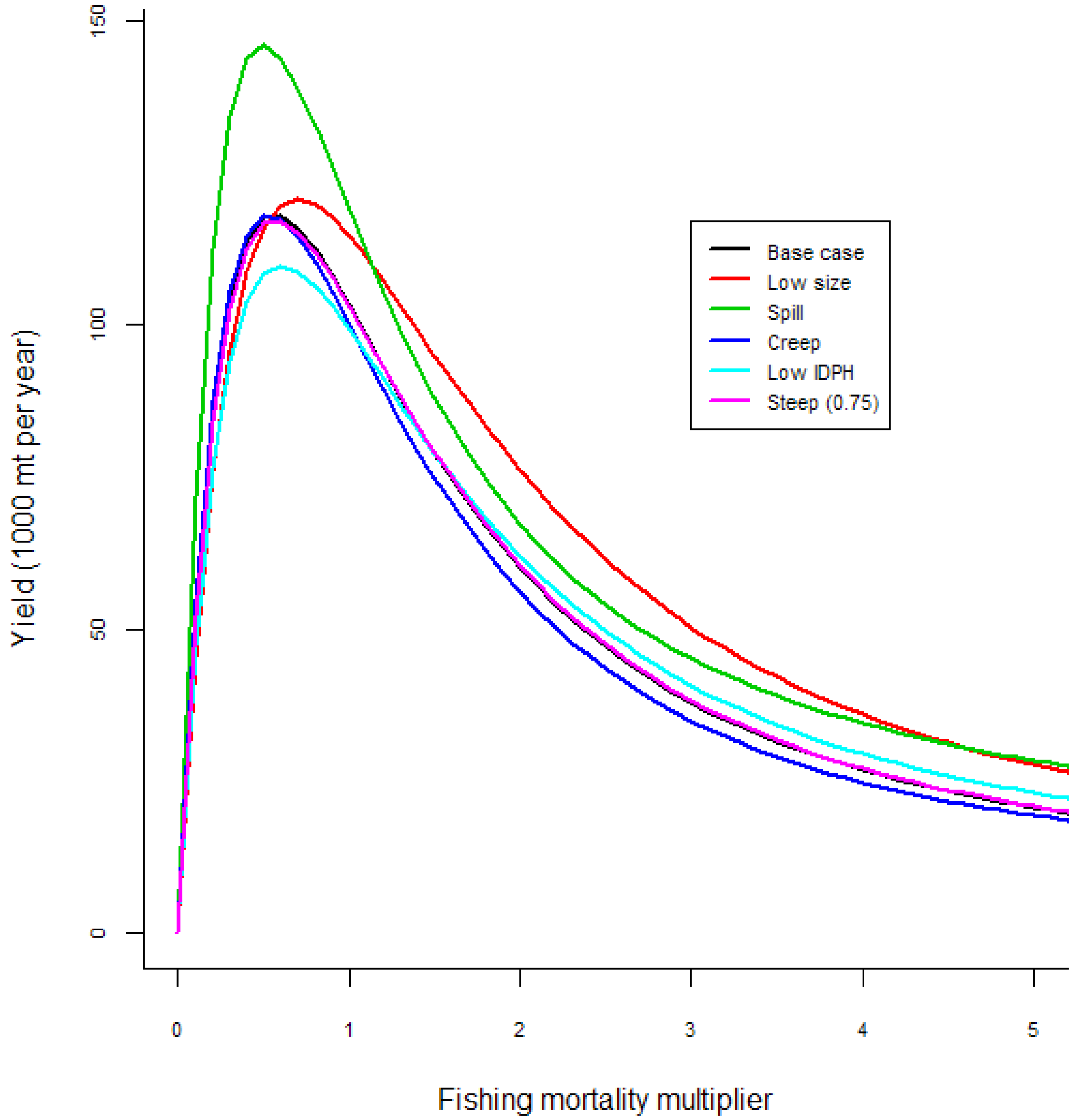


Figure 49. Yield curves based on 1997–2006 average recruitment.

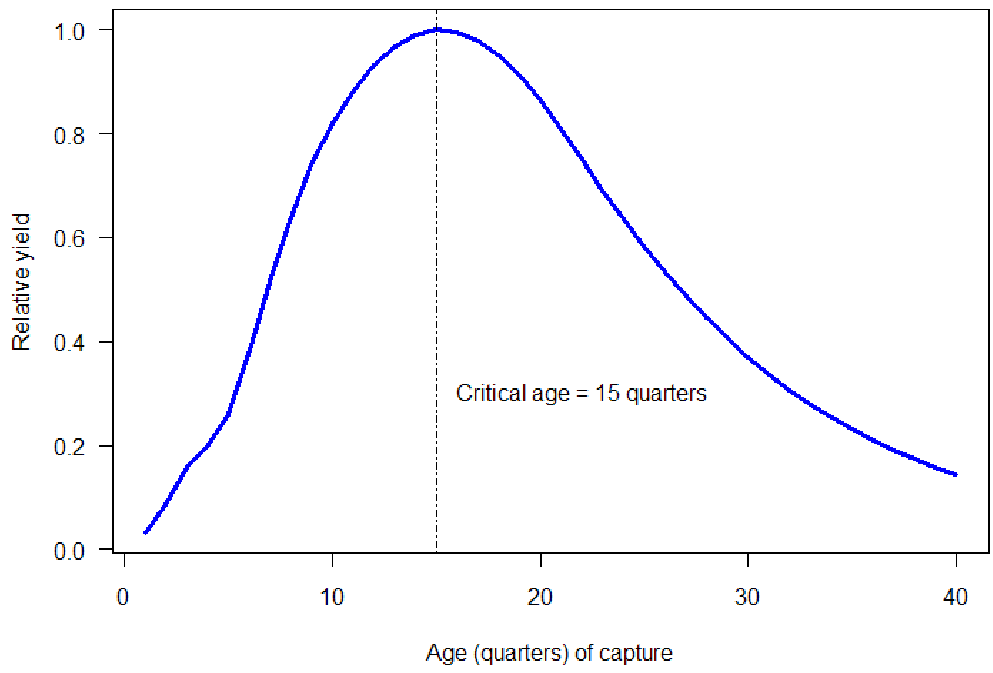


Figure 50. Estimates of the relative yield that could theoretically be taken from a cohort depending on the age of first harvest**.**

Appendix A: ***doitall.bet***

```
#!/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
  2 35 10
# sets penalties for catchability deviations
   -18 15 1       # low penalty for PH.ID MISC.
   -24 15 1
  -999 33 1       # estimate tag-reporting rates
  1 33 90         # maximum tag reporting rate for all fisheries is 0.9
PHASE1
fi
#  ---------
#   PHASE 2
#  ---------
if [ ! -f 02.par ]; then
  ./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
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 4500     #maximum of 3000 function evaluations for the final phase
  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
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0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 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
```