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

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Table of Contents

Executive summary 4

1 Introduction 6

2 Background 6

2.1 Biology 6

2.2 Fisheries 7

3 Data compilation 8

3.1 Spatial stratification 8

3.2 Temporal stratification 8

3.3 Definition of fisheries 8

3.4 Catch and effort data 9

3.4.1 Purse seine 9

3.4.2 Indonesia / Philippines 10

3.4.3 Longline fisheries 10

3.5 Length-frequency data 11

3.6 Weight-frequency data 12

3.7 Tagging data 13

4 Model description – structural assumptions, parameterisation, and priors 13

4.1 Population dynamics 13

4.1.1 Recruitment 14

4.1.2 Initial population 14

4.1.3 Growth 14

4.1.4 Movement 14

4.1.5 Natural mortality 15

4.1.6 Sexual maturity 15

4.2 Fishery dynamics 15

4.2.1 Selectivity 15

4.2.2 Catchability 16

4.2.3 Effort deviations 17

4.3 Dynamics of tagged fish 17

4.3.1 Tag mixing 17

4.3.2 Tag reporting 18

4.4 Observation models for the data 18

4.5 Parameter estimation and uncertainty 19

4.6 Stock assessment interpretation methods 19

4.6.1 Fishery impact 19

4.6.2 Yield analysis 20

5 Model runs 20

5.1 Developments from the 2010 assessment 20

5.2 Sensitivity analyses 21
5.2.1 Catch and size data 21
5.2.2 Standardised CPUE indices 21
5.2.3 Tagging data 22
5.2.4 Steepness 22
5.2.5 Natural mortality 22
5.3 Structural uncertainty 22
6 Results 22
6.1 Impact of model developments on key reference points 22
6.2 Model diagnostics – Run3j – Ref.case 24
6.3 Model parameter estimates (Run3j - Ref.case, unless otherwise stated) 26
6.3.1 Growth 26
6.3.2 Movement 26
6.3.3 Selectivity 26
6.3.4 Catchability 27
6.3.5 Tag Reporting Rates 27
6.4 Stock assessment results 27
6.4.1 Recruitment 27
6.4.2 Biomass 28
6.4.3 Fishing mortality 29
6.4.4 Fishery impact 30
6.4.5 Yield analysis 30
7 Discussion and conclusions 33
8 Acknowledgements 37
9 References 37
Appendix A: *doitall.bet (for run3j)* 120
Appendix B: *bet.ini* 128

Executive summary

This paper presents the 2011 assessment of bigeye tuna in the western and central Pacific Ocean. This assessment is supported by several other analyses which are documented separately, but should be considered when reviewing this assessment as they underpin many of the fundamental inputs to the models. These include evaluation of paired spill / grab sample trials leading to observer-based species composition estimates with spill sampling correction for purse seine catch histories and size compositions (Lawson 2011; Lawson & Sharples 2011), reviews of the catch statistics of the component fisheries (Williams 2011; Williams & Terawasi 2011), standardised CPUE analyses of operational level Japanese longline catch and effort data (Hoyle & Okamoto 2011), standardised CPUE analyses of Taiwanese longline CPUE (Chang et al. 2011), an analysis of tag reporting rates for the RTTP and PTTP programs (Hoyle 2011), and the guidance of the Pre-Assessment Workshop held in April, 2011 (SPC 2011).

The assessment includes a series of model runs describing stepwise changes from the 2010 assessment (run 3d) to develop a new "reference case[3]" model (Run3j – Ref.case) and then a series of "one-off" sensitivity models that represent a single change from the Ref.case model run. A sub-set of key model runs was taken from the sensitivities that represent a set of plausible model runs and were included in a structural uncertainty analysis (grid) for consideration in developing management advice.

Besides updating the input data, the main developments to the inputs compared to the 2010 assessment were: including tagging data from the 2007-2010 PTTP program; standardised CPUE time series derived from operational-level catch-effort data for Japanese longline fisheries; weighting the Japanese longline size frequency data according to the estimated population relative abundance within regions; adjusting purse seine size frequency data using spill-samples to correct for grab-sample bias; and, including more reliable size composition data for Philippines and Indonesian domestic purse seine catches in offshore waters. The main developments to model structural assumptions were to define a separate Indonesian Philippines-based domestic purse seine fishery that operates beyond the national archipelagic waters and to the east of 125° E longitude.

During the Pre-Assessment Workshop held in April 2011 (PAW, SPC 2011), the key assumptions from the "base case" model from the 2010 assessment were reviewed in light of the developments proposed for the Ref.case model for the 2011 assessment. These and the alternative assumptions in the other key model runs are provided below:

Component	**2010 assessment (run 3d)**	**2011 assessment (Run3j – Ref.case)**	**2011 alternatives**
Longline CPUE	Aggregate indices, no temporal weighting of standardised effort	Operational indices, temporal weighting of standardised effort	- Exclude all CPUE prior to 1975 - Aggregate indices
Steepness	Estimated	Fixed = 0.8	0.65, 0.95, estimated
Purse seine catches	Spill sample corrected	Spill sample corrected (including size data)	Grab sample (SBEST)
Tagging data	Excluded PTTP	Included PTTP	Exclude PTTP
Longline size data	Down-weighted	Full weight	Down-weighted
Natural mortality	Base	Base	Increased for juveniles

[3] While Run3j is designated the "reference case" model for the purpose of structuring the modelling analyses, the most appropriate model run(s) upon which to base management advice will be determined by the Scientific Committee.

In comparing the 2011 Ref.case model results with the 2010 assessment, the decision to fix steepness at a more plausible value (0.8) to that estimated in recent assessments must be considered. Whereas, the Ref.case estimates of stock status are not dissimilar from the 2010 base case estimates, the 2011 model most comparable to an update of the 2010 base case was Run15 in which steepness was estimated, and which provided a more optimistic stock status. This difference indicates the effects of the new inputs (in particular the operational CPUE indices). If one compares $F_{current}/F_{MSY}$ and $SB_{current}/SB_{MSY}$ between a straight-forward update of the 2010 model (Run2b) and Run15, the values are 1.49 and 1.33 versus 1.13 and 1.54, respectively.

The main conclusions of the current assessment (based upon the median of the uncertainty grid estimates, and the sensitivity model runs) are as follows.

1. The estimated increasing trend in recruitment from recent bigeye assessments appears to have been addressed to a small extent in the current assessment, but remains an issue in region 3 and is primarily the result of conflict (disagreement) among the various data sources, in particular between the longline CPUE indices and the reported catch histories, and between and within some of the size composition data sets. The current assessment has indentified some of these conflicts and includes some model runs that begin to address them.

2. As in previous assessments, recruitment in almost all models is estimated to have been high during 1995–2005. As suggested in the 2010 assessment, an analysis is presented that estimates the stock-recruitment relationship (with steepness fixed) for this latter period and applied it in the yield analyses. If one considers the recruitment estimates in the second half of the time series to be more plausible and representative of the overall productivity of the bigeye stock, the results of this analysis (Run21) could be used for formulating management advice. In this case $F_{current}/F_{MSY}$ was 1.58 and $SB_{current}/SB_{MSY}$ was 0.61indicating that we would conclude that the stock is overfished and overfishing is occurring under this productivity assumption. The main reason for the much lower estimate of $SB_{current}/SB_{MSY}$ is that $SB_{MSY}$is approximately doubled because of the higher levels of recruitment being used to estimate it.

3. Total and spawning biomass for the WCPO are estimated to have declined to about half of their initial levels by the mid-1970s, with total biomass remaining relatively constant since then ($B_{current}/B_0$= 44%), while spawning biomass has continued to decline ($SB_{current}/SB_0$=35%). Declines are larger for models that exclude the early periods of the CPUE time series.

4. When the non-equilibrium nature of recent recruitment is taken into account, we can estimate the level of depletion that has occurred. It is estimated that spawning potential is at 26% of the level predicted to exist in the absence of fishing considering the average over the period 2006-09, and that value is reduced to 23% for the 2010 spawning potential levels.

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

6. Recent catches are well above the *MSY* level of 74,993 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 and recent mix of fisheries persist, catches are still around 7% higher than the re-calculated *MSY* (131,400 mt). **Based on these results, we conclude that current levels of catch are unlikely to be sustainable in the long term even at the recent [high] levels of recruitment estimated for the last two decades**.

7. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. For all of the model runs $F_{current}/F_{MSY}$ is

considerably greater than 1. For the grid median, the ratio is estimated at 1.42 indicating that a 30% reduction in fishing mortality is required from the 2006-09 level to reduce fishing mortality to sustainable levels. Using the Ref.case, if we consider historical levels of fishing mortality, a 39% reduction in fishing mortality from 2004 levels is required, and a 28% reduction from average 2001-04 levels. Larger reductions in fishing mortality are indicated when lower values of steepness are assumed. **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 65% and 60% of the level that supports MSY. In terms of the reduction against virgin biomass the declines reach as low as 15% of spawning potential. Current stock status compared to these reference points indicate the current total and spawning biomass are higher than the associated MSY levels ($\frac{B_{current}}{B_{MSY}} = 1.34$ and $\frac{SB_{current}}{SB_{MSY}} = 1.37$). The structural uncertainty analysis indicates a 13% probability that $SB_{current} < SB_{MSY}$. **Based on these results above, and the recent trend in spawning biomass, we conclude that bigeye tuna is approaching an overfished state. We note however, that if recent recruitment is assumed to represent the true productivity of the bigeye stock (Run21), then the higher levels of Bmsy and SBmsy implied would mean that bigeye tuna is already in an overfished state ($B_{current}/B_{MSY}$ = 0.67 and $SB_{current}/SB_{MSY}$ 0.61).**

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

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

1 Introduction

This paper presents the current stock assessment of bigeye tuna (*Thunnus obesus*) in the western and central Pacific Ocean (WCPO, west of 150°W). Since 1999, the assessment has been conducted regularly and the most recent assessments are documented in Hampton et al. (2004, 2005 and 2006), Langley et al. (2008), Harley et al. (2009b), and Harley et al.(2010). This assessment is supported by several other analyses which are documented separately, but should be considered in reviewing this assessment. These include evaluation of paired spill / grab sample trials leading to observer-based species composition estimates with spill sampling correction for purse seine catch histories and size compositions (Lawson 2011; Lawson & Sharples 2011), reviews of the catch statistics of the component fisheries (Williams 2011; Williams & Terawasi 2011), standardised CPUE analyses of operational level Japanese longline catch and effort data (Hoyle & Okamoto 2011), standardised CPUE analyses of Taiwanese longline CPUE (Chang et al. 2011), an analysis of tag reporting rates for the RTTP and PTTP programs (Hoyle 2011), and the guidance of the Pre-Assessment Workshop held in April, 2011 (SPC 2011).

2 Background

2.1 Biology

Bigeye tuna are distributed throughout the tropical and sub-tropical waters of the Pacific Ocean. There is little information on the extent of mixing across this wide area. Analysis of mtDNA and DNA microsatellites in nearly 800 bigeye tuna failed to reveal significant evidence of widespread population subdivision in the Pacific Ocean (Grewe and Hampton 1998). While these results are not conclusive regarding the rate of mixing of bigeye tuna throughout the Pacific, they are broadly consistent with the results of SPC's and IATTC's tagging experiments on bigeye tuna. Bigeye tuna tagged in locations throughout the tropical Pacific have displayed movements of up to 4,000 nautical miles (Figure 1) over periods of one to several years, indicating the potential for gene flow over a wide area; however, the large majority of tag returns were recaptured much closer to their release points. Recent tagging of bigeye tuna in the central Pacific has shown a similar pattern. The majority of tag returns with verified recapture positions show displacements of less than 1,000 nm (SPC, unpubl. data). In addition, recent tagging experiments in the eastern Pacific Ocean (EPO) using archival tags have so far not demonstrated long-distance migratory behaviour (Schaefer and Fuller 2002) over time scales of up to 3 years; however one recent four-year archival tag return displayed long-distance movements from the EPO to the central Pacific and back in years 3 and 4 of the archival tag record (Schaefer, pers. comm). In view of these results, stock assessments of bigeye tuna are routinely undertaken for the WCPO and EPO separately[4], however, current bigeye tuna tagging efforts in all areas of the tropical Pacific 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 vary with size, with the lower rates of around 0.5 yr^{-1} for bigeye >40 cm FL (Hampton 2000). Tag recapture data indicate that significant numbers of bigeye reach at least eight years of age (Hampton and Williams 2005). The longest period at liberty for a recaptured bigeye tuna tagged in the western Pacific at about 1–2 years of age is currently 14 years (SPC unpublished data).

2.2 Fisheries

Bigeye tuna are an important component of tuna fisheries throughout the Pacific Ocean and are taken by both surface gears, mostly as juveniles, and longline gear, as valuable adult fish. They are a principal target species of both the large, distant-water longline fleets of Japan, Korea, China and Chinese Taipei and the smaller, fresh sashimi longline fleets based in several Pacific Island countries and Hawaii. Prices paid for both frozen and fresh product on the Japanese sashimi market are the highest of all the tropical tunas. Bigeye tuna are the cornerstone of the tropical longline fishery in the WCPO; the longline catch in the SPC area had a landed value in 2008 of approximately US$724 million (Williams and Terawasi 2009).

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

The history of purse seine catches depends on the data sources used to derive the estimates. Bigeye in purse catches are taken almost exclusively from sets on natural and artificial floating objects (FADs). There remains considerable uncertainty regarding the accuracy of the purse-seine catch, and catches reported on logsheets significantly under-estimate actual catch levels (Lawson 2008, 2009, 2010). Based on species composition derived from observer sampling with a correction for grab sample selectivity bias , purse seine catches of bigeye first exceeded 20,000 mt in 1982, and increased up to 40-50,000 mt by the mid 1990s (Figure 2). Catches over 60,000 mt were reported from 1996-2001 with a peak of 105,000 mt in 1997. Since 2001 catches have ranged between 36,000 mt (2003) and 65,000 (2004). Conversely the previous estimates of purse seine catches of bigeye ("s_best"; see Lawson (2005; 2007) for further details of how this dataset is constructed) are considerably lower (Figure 3). This alternative catch history indicates that catches did not exceed 20,000 mt until 1997 and have ranged between 21,000 mt (1998) and 38,000 mt (2008) since then. We believe that the sample-based estimates with spill-sample correction are the more realistic estimates of purse seine bigeye catches – see section 3.4.1 for a full description of this issue.

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

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

The spatial distribution of WCPO bigeye tuna catch during 1990–2010 is shown in Figure 4. The majority of the catch is taken in equatorial areas, by both purse seine and longline, but with significant longline catch in some sub-tropical areas (east of Japan, north of Hawaii and the east coast of Australia). High catches are also presumed to be taken in the domestic artisanal fisheries of the Philippines and Indonesia using a variety of gear types (e.g. pole-and-line, ringnet, gillnet, handline and seine net). The total catch for both countries combined is estimated to have approached 20,000 mt in recent years. The statistical basis for the catch estimates in the Philippines and, more so in Indonesia is weak, but improving. We have included the best available estimates in this analysis in the interests of providing the best possible coverage of bigeye tuna catches in the WCPO. The catch time series input to this assessment is presented later in section 3.4.2.

3 Data compilation

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

3.1 Spatial stratification

The geographic area considered in the assessment is the WCPO, defined by the coordinates 40°N–35°S, 120°E–150°W. Within this overall area, a six-region spatial stratification was adopted for the assessment (Figure 4). The rationale for this stratification was to separate the tropical area, where both surface and longline fisheries occur year-round, from the higher latitudes, where the longline fisheries occur on a seasonal basis. This stratification has remained unchanged since the 2006 base case assessment.

Total annual catches by major gear categories by region are shown in Figure 5 and Figure 6 Most of the catch occurs in the tropical regions (3 and 4), with most catches by purse seine and Philippines/Indonesian fisheries occurring in region 3 and large longline catches occurring in both regions 3 and 4.

3.2 Temporal stratification

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

3.3 Definition of fisheries

MULTIFAN-CL requires the definition of "fisheries" that consist of relatively homogeneous fishing units. Ideally, the fisheries so defined will have selectivity and catchability characteristics that do not vary greatly over time (although in the case of catchability, some allowance can be made for time-series variation). The 25 fisheries defined for the 2010 assessment on the basis of: region, gear type and, in the case of purse seine, set type; were maintained for the 2011 assessment but with modification to the Philippines and Indonesian domestic fisheries. This change was based upon improved information available for the purse seine component of these fisheries. In previous assessments, these fisheries were included as a component of the Philippines and Indonesian domestic fisheries (PH MISC 3 and ID MISC 3). However, differences in the spatial distribution of the purse seine catch and the length composition of the associated catch relative to the other gear types warranted the additional resolution of these fisheries. The foreign-based Philippines industrial purse-seine fishery is included within the generic purse seine fisheries within region 3 (PS ASS 3 and PS UNS 3), while the purse seine fisheries operating within the national archipelagic waters were retained within the respective domestic fisheries (PH MISC 3 or ID MISC 3). A new fishery was defined for the domestically-based Indonesia and Philippines purse-seine fisheries that operate beyond the national archipelagic waters and to the east of about 125° E longitude (PH-ID PS 3), (

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.

Annual catch and CPUE for all fisheries are provided in Figure 7 and **Error! Reference source not found.**.

As was true for the 2010 assessment, almost complete catch estimates were included for the most recent year, in this assessment, 2010. However, data for the main longline fisheries appeared to be incomplete as indicated by atypical catch proportions among quarters in the final year (Figure 9). The effect of this on the assessment was examined, and is described later.

3.4.1 Purse seine

Two sets of purse-seine input catch data were used in the analyses, and as was assumed for the 2010 assessment, the spill sample-based estimates were used for the reference-case 2011 assessment (as the spill sample-based estimates are considered more plausible). These data sets are presented in Figure 10 for the purse seine fisheries only, and also shown in Figure 5 and Figure 6 with all other fisheries by region.

The first data set consisted of catches extracted from the OFP database of reported catches aggregated by 1° latitude, 1° longitude, month and flag. These catches are based on (i) accepting the logsheet declared proportions of skipjack and yellowfin+bigeye as being accurate; and (ii) using observer sampling data derived from grab-sampling to disaggregate the yellowfin and bigeye catches. Recent studies have shown that these catch estimates are likely to substantially under-estimate the actual catch of bigeye due to inaccurate reporting of the skipjack and yellowfin+bigeye catch composition on logsheets (Hampton and Williams 2011) and biases in the observer sampling procedures (grab sampling) (Lawson 2009). To address these biases, the catch data were corrected using a three-species disaggregation of the total purse seine catch using observer sampling data corrected for selection bias of grab sampling using the results of paired grab and spill samples. It is the three-species composition estimates in this correction procedure that has a substantive effect on the catch estimates. This correction produced the second data set having considerably higher estimates of bigeye catch particularly from associated sets (Figure 10). There remains a high level of uncertainty associated with these new estimates; however, on balance, the corrected catches are considered to be more reliable than the uncorrected catches. The corrected catches were used as the principal catch series in the assessment, while the uncorrected catches were incorporated in a sensitivity analysis (see below). In this report, the corrected catches are defined as the observer-based species composition estimates with spill sampling correction, “SPILL”, while the uncorrected catches are denoted as “SBEST”.

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

Effort data for the PH-ID PS 3 fishery were unavailable. In this situation, effort is declared as missing and the model directly computes fishing mortality consistent with the observed catch using a Newton-Raphson procedure.

3.4.2 Indonesia / Philippines

Revised catch histories were obtained for the Indonesia and Philippines fisheries, and allocated to the new fishery definitions for this assessment. The catch histories in fisheries 18 and 24 decline due to the removal of the domestic PS catches with their placement into fishery 26 (PH-ID PS 3) (Figure 11). Effort data for the Philippines and Indonesian fisheries small fish fisheries were not available for all components of the fishery so were set to missing[5].

3.4.3 Longline fisheries

For the principal longline fisheries (LL ALL 1–6), effective (or standardised) effort was derived from Japanese operational-level longline data using generalized linear models (GLM) and a delta-lognormal approach (Hoyle and Okamoto 2011). Use of operational level data permitted the analyses to a) compensate for some aspects of changing effort concentration in different areas through time, b) remove swordfish-targeted effort from the time series before 1976, and c) to compensate for changes in fishing power associated with individual vessels during the period after 1976. The standardised effort from this analysis was used for the reference case model (Ref.case) reported here.

As an alternative, standardised effort was also available from aggregate data available for the entire WCPO region and derived from Japanese longline data aggregated at the 5 degree square and year-quarter level (Langley et al. 2005, Hoyle 2010). As these data do not include vessel information, there is the potential for bias in the CPUE indices as it is not possible to account for some of the potential increases in efficiency over time such as the phasing out of old vessels and introduction of new ones. Where possible, such factors were included in the GLM applied to the operational data. Since standardised effort derived from aggregate data was applied in the 2010 assessment, it used in exploring the sensitivity of the 2011 Ref.case.

Standardised effort derived from operational level data were generated for region 3 using two approaches, one based upon the core area and another for the entire region (Hoyle and Okamoto 2011). Indices using the core area approach were applied in the Ref.case, while those for the whole of region 3 were used in a sensitivity run described later.

The three sets of annualised CPUE indices used in this assessment based on the operational level and aggregate data are presented in Figure 12. Coefficients of variation (CVs) for region-specific standardised effort are presented in Figure 13, illustrating the differences in precision of the indices derived from each data type. The calculation of CVs is described later in section 4.2.3.

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

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

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

The three sets of annualised CPUE indices used in this assessment based on the operational level and aggregate data are presented in Figure 12.

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

3.5 Length-frequency data

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

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

As for the 2010 assessment the length frequency samples from the small fish hook and line and large fish handline fisheries were adjusted to exclude all reported fish lengths greater than 90 cm for PH MISC 3 from the current assessment. This was done on the basis that it is suspected that the presence of these large fish may be due to mis-reporting of the fishing gear in some of the regional sampling programmes.

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

Purse seine: Length-frequency samples from purse seiners have been collected from a variety of port sampling and observer programmes since the mid-1980s. Most of the early data are sourced from the U.S. National Marine Fisheries Service (NMFS) port sampling programme for U.S. purse seiners in Pago Pago, American Samoa and an observer programme conducted for the same fleet. Since the early 1990s, port sampling and observer programmes on other purse seine fleets have provided additional data. Only data that could be classified by set type were included in the final data set.

The length frequency data collected by observers are susceptible to bias due to the grab sampling procedure (Lawson 2011). For the current assessment, a length-based correction factor was applied to the length frequency samples to correct for this source of bias. The bias correction resulted in an overall decline in the median length of the fish in the length samples from the associated purse-seine fisheries (PS ASS 3 and 4) particularly in the past five years (Figure 14). Insufficient data were available to correct the length samples from the period before 1996 and hence these data were excluded from the current assessment.

Longline: The majority of the historical data were collected by port sampling programmes for Japanese longliners unloading in Japan and from sampling aboard Japanese research and training vessels. This comprehensive set of data is available for the entire model period. In recent years, length data from longline catches have also been collected by OFP and national port sampling and observer programmes in the WCPO. A detailed analysis of longline length-frequency data was provided in Harley et al. (2010) that indicated some concerns about the representativeness of some of the length frequency samples, particularly in the early years, and also some evidence of spatial stratification in fish sizes. To take address this, for each temporal stratum, the composite length distribution for the fishery was derived following the approach described below. The Japanese length samples collected between 1954-65 gave very strong negative residuals in all regions (Harley et al. 2010).

As for the 2010 assessment, the size frequency data from Chinese off-shore longline vessels in region 4 have been excluded. This is because most of the Chinese catch in that region comes from the distant water fleet, but the size data are only available for the off-shore fleet which we suspect uses different fishing techniques.

For the current assessment, a new approach was applied to aggregate the Japanese longline size frequency data (lengths and weights) to reduce the influence of spatial changes in the distribution of catch and sample collection. The objective of this approach was to generate size frequency distributions that were more consistent with the underlying size distribution of the longline-exploitable population within a region (mediated by the long-term average selectivity of the fishery).

The following procedure was applied to generate an aggregated year/quarter length composition for a specific region longline fishery from the Japanese length frequency data (Hoyle and Langley 2011).

i. The average CPUE (number of fish per 100 hooks) for the Japanese longline fishery during 1960-1986 was determined for each of the 10*20 lat/long stratum that comprise a region (typically 6-9 cells per region). The CPUEs were applied to determine the relative weighting of the size data in each stratum. A maximum sample size was set at 1000 fish and the strata were assigned an individual sample size relative to the CPUE of the strata. The individual sample sizes for all strata in a region/quarter sum to 1000.

ii. The year/quarter samples (length measurements) from each 10*20 lat/long stratum were scaled to represent the individual sample size associated with the stratum.

iii. The rescaled numbers of fish (in each length interval) sampled from each stratum were combined, thereby, weighting the samples by the relative abundance of fish in each stratum.

These protocols result in samples from strata with a higher abundance of bigeye having more influence in the composite length composition. Conversely, in a year/quarter where samples are only available from strata with lower bigeye abundance, a composite length composition will be generated, although the overall sample size will be lower and hence the individual length composition will have a lower influence on the model. The same approach was applied to derive the weight frequency compositions from the Japanese weight frequency data (Section 3.6).

The new approach enabled a larger proportion of the length samples to be retained within the model data set compared to the previous approach where samples were excluded if insufficient data were available from the strata where most of the catch was taken. In the current formulation, these data are retained but are assigned a lower effective sample size as most of the more recent samples were collected from areas within the regions that have a lower abundance of bigeye. The length and weight compositions input to the model derived using this new approach are termed the "weighted" distributions, and were compared with the "unweighted" distributions in respect of the median lengths and weights to illustrate the relative effects of the method (Figure 15). The relative differences are discussed later when reviewing the effects on model estimates in section 6.1.

For the other fisheries, length 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.

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

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

3.6 Weight-frequency data

Individual weight data for the Japanese longline fisheries are included in this assessment by applying the new approach for aggregating the weight frequencies within regions (see above description for longline length-frequency data). For many other longline fleets, "packing list" data are available from export documentation, and these data are progressively being processed and incorporated into the assessment database. For this assessment, the available weight data (apart from those provided by Japan) originated from vessels unloading in various ports around the region which export tuna including those located in Guam, Palau, FSM, Marshall Islands, Fiji, Papua New Guinea and eastern Australian ports.

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

3.7 Tagging data

In previous assessments a modest amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. These data consisted of bigeye tuna tag releases and returns from the OFP's Regional Tuna Tagging Project (RTTP) conducted during 1989–1992, and more recent (1995, 1999–2001) releases and returns from tagging conducted in the Coral Sea (CS) 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 2005).

An additional tag data set was available for inclusion in the current assessment from the recent Pacific Tuna Tagging Programme (PTTP) undertaken mainly in the western tropical Pacific from Indonesia to the Gilbert Islands of Kiribati (Nicol et al. 2010). The complete data set includes a total of 18,956 releases, which were classified into region/quarter 36 tag release groups. A total of 3,125 tag returns could be assigned to the fisheries included in the model (Table 2). A considerable number of tag returns from the PTTP have been recovered but have yet to be assigned to a fishery (18% and 3% in regions 3 and 4, respectively), particularly for the more recent release groups. The individual release groups were corrected to account for these additional tags recoveries.

For incorporation into the MULTIFAN-CL analyses, tag releases were stratified by release region, time period of release (quarter) and the same length classes used to stratify the length-frequency data. Alternative model options were considered that either include all tag data, or excludes the PTTP tags.

In recent years, a large number of tags were released in the Hawaii handline fishery. Inclusion of these data in the six-region model is problematic as all tags are released and recovered around the boundary of regions 2 and 4 (latitude 20° N). This results in large changes in the estimated movement coefficients between regions 2 and 4 and in other model parameters influenced by tagging data. On this basis, these data were not included in the current six-region assessment. Due to a paucity of recaptures and no information for reporting rates, data from the Japanese tagging program has been excluded.

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

4 Model description – structural assumptions, parameterisation, and priors

The model can be considered to consist of several components, (i) the dynamics of the fish population; (ii) the dynamics of the fisheries; (iii) the dynamics of tagged fish; (iv) observation models for the data; (v) parameter estimation procedure; and (vi) stock assessment interpretations. Detailed technical descriptions of components (i) – (iv) are given in Hampton and Fournier (2001) and Kleiber et al (2003), and are not repeated here. Brief descriptions of the various processes, including information on structural assumptions, estimated parameters, priors and other types of penalties used to constrain the parameterisation were provided in Langley et al. (2008 – Table 2) and only changes to these assumptions are reported here (Table 3).

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 1952–2010. 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 spatially aggregated recruitments exceeding the average recruitment by a factor of 3.3 would occur about once every 25 years.

Spatially-aggregated recruitment was assumed to have a weak relationship with the spawning biomass via a Beverton and Holt stock-recruitment relationship (SRR) with a fixed value of steepness (*h*). Steepness is defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Francis 1992; Maunder and Watters 2001). The SRR was incorporated mainly so that a yield analysis could be undertaken for stock assessment purposes.

Typically, fisheries data are not very informative about SRR parameters, hence, the steepness parameter was fixed at a moderate value (0.80) informed by the analysis of gloabal spawner recruitment data (Harley 2011) and the sensitivity of the model results to the value of steepness was explored via model sensitivities with lower (0.65) and higher (0.95) values of steepness. The recommendations of the PAW also included a model option that estimated the value of steepness internally in the model. For all model options a relatively weak penalty for deviations from the SRR was applied to allow relatively unconstrained variability in recruitment by time.

4.1.2 Initial population

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

4.1.3 Growth

The standard assumptions concerning age and growth were (i) the lengths-at-age are normally distributed for each age-class; (ii) the mean lengths-at-age follow a von Bertalanffy growth curve, except for the 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 under the “implicit transition” computational algorithm (see Hampton and Fournier 2001 for details). There are seven inter-regional boundaries in the model with movement possible across each in both directions. Four seasonal movements were allowed, each with their own movement coefficients, therefore there were $2 \times 7 \times 4 = 56$ movement parameters. In order to avoid the addition of more parameters to the model, we did not incorporate age-dependent movement into this assessment. Previous trials have indicated that such additional structure did not impact the overall results in a substantive way. The seasonal pattern of movement is assumed to persist from year to year with no allowance for longer-term variation in movement.

A prior of 0.1 is assumed for all movement coefficients, inferring a relatively high mixing rate between regions. A small penalty is applied to deviations from the prior.

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 this assessment because previous trial fits estimating *M*-at-age produced biologically unreasonable results. The values used in the current assessment were the same as those used in the 2010 assessment (Figure 17). These estimates of *M*-at-age were determined outside of the MULTIFAN-CL model using bigeye sex-ratio data and the assumed maturity-at-age schedule as described by Hoyle and Nicol (2008). A similar procedure is used to determine fixed *M*-at-age for assessments in the EPO (Maunder 2005). Essentially, this method reflects the hypothesis that the higher proportion of males in sex-ratio samples with increasing length is due to the higher natural mortality of females after they reach maturity.

Two alternative *M*-at-age ogives were examined by Harley et al. (2010) and one of these, relating to increased natural mortality of juvenile bigeye, was included here (Figure 17). The assumed values of natural mortality for the first 4 quarters are quite different for bigeye and yellowfin and some have questioned why this might be so. Two of the key model runs in this assessment included the assumed levels of yellowfin tuna M for either the first 4, or 8 quarters.

4.1.6 Sexual maturity

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

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.

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

4.2.1 Selectivity

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

Selectivity is assumed to be fishery-specific and time-invariant. Selectivity coefficients for the "main" longline fisheries LL ALL 1 and LL ALL 2 (northern fisheries) were constrained to be equal, as were LL ALL 3–6 (equatorial and southern fisheries) and the LL TW-CH 4 fishery (see section 3.5 for further details). For the LL TW-CH 3 fishery, selectivity was parameterised using a logistic functional form rather than the cubic spline method. Selectivity was also constrained to be equal for the corresponding purse seine fisheries in the two equatorial regions (e.g. the associated set fisheries had the same selectivity in regions 3 and 4). The sensitivity of the Ref.case to the effects of these constraints was tested in a model run in which the selectivities of the longline and purse seine fisheries in regions 3 and 4 were decoupled (described later).

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

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

With length frequency data available for the newly defined fishery 26 (ID-PH PS 3) for most years since 1997, a unique selectivity function was estimated employing the same parameterisation as described above for the other purse seine fisheries.

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. In the absence of effort data, MFCL estimates partial fishing mortalities consistent with the observed catches using a Newton-Raphson procedure. Therefore, catchability deviations (and effort deviations) are not estimated for these fisheries. As a result of the investigations described in Harley et al. (2010) it was also decided to set the variance of the priors on catchability deviates to be high (approximating a CV of about 0.7) for the purse seine fisheries. This was considered preferable to increasing the frequency of temporal catchability changes which would greatly increase the number of estimated parameters.

For the other fisheries with time-series variability in catchability, the catchability deviation priors were assigned a variance approximating a CV of 0.10. The "main" longline fisheries were grouped for the purpose of initial catchability, and time-series variation was assumed not to occur in this group. This assumption is equivalent to assuming that the CPUE for these fisheries indexes the exploitable abundance both among areas and over time. Catchability for all fisheries apart from the Philippines and Indonesian fisheries (for which the data were based on annual estimates) was allowed to vary seasonally.

4.2.3 Effort deviations

Effort deviations, constrained by prior distributions of zero mean, were used to model the random variation in the effort – fishing mortality relationship. For the purse seine fisheries, pole-and-line fisheries, and the Australian, Hawaii and Chinese Taipei/Chinese longline fisheries, the variance was set at a moderate level (approximating a CV of 0.4 – as assumed in the 2010 assessment).

The region-specific longline CPUE indices represent the principal indices of stock abundance in the assessment model. Hence, the extent that the model can deviate from the CPUE indices is moderated by the penalty weights assigned to the standardised effort series for the longline fisheries. However, the precision of the CPUE indices varies temporally and among regions and, therefore, it is appropriate to implement a relative weighting on the individual effort observations. The CPUE indices from the region 3 longline fishery are considered to be the more reliable than the indices from the other regions and, given the high proportion of the total biomass within this region are the most influential in the assessment model.

The CPUE indices from region 3 were assumed to have an average coefficient of variation (CV) of 0.2 for the period with the most comprehensive data set (1960-86). A CV was then calculated for each effort observation from LL 3 by scaling the actual CV of the individual CPUE indices (from the GLM) relative to the mean of the CVs for individual observations from 1960-86. Similarly, the individual CVs of the CPUE indices from the other regions were scaled relative to the region 3 base period. The resulting scaled CVs were transformed to an effort penalty for each longline CPUE observation. The smaller effort penalties associated with less precise CPUE indices means that these indices are less influential in the assessment model.

The relative precision of the region-specific longline CPUE indices varies depending on the CPUE data sets (aggregated vs. operational). The aggregated CPUE indices from regions 2, 5 and 6 were assigned a considerably lower precision than the corresponding operational CPUE indices (Figure 13). For the Japanese operational indices, the precision of the CPUE indices for regions 4 and 6 were considerably lower than for the other regions, principally from 1980 onwards. The low precision and lack of indices for the recent period in region 6 was one of the main reasons for applying the Taiwanese CPUE indices from region 6 in a model sensitivity run (described later).

This approach represented a refinement on the approach used in the 2010 assessment base case whereby the penalty on the effort deviates for each region was set at a level that corresponded to an average CV of 0.2 over the entire model period with no temporal variation in the CV.

4.3 Dynamics of tagged fish

4.3.1 Tag mixing

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

We assumed that tagged bigeye mix fairly quickly with the untagged population at the region level and that this mixing process is complete by the end of the second quarter after release. Model sensitivity to this assumption was tested in a run in which the mixing period was extended to three quarters.

4.3.2 Tag reporting

In principal, tag-reporting rates can be estimated internally within the model. In practice, experience has shown that independent information on tag reporting rates for at least some fisheries is required for reasonably precise estimates to be obtained. We provided reporting rate priors for all fisheries that reflect our expect judgement regarding the reporting rate and the confidence we have in that judgement. Relatively informative priors were specified for reporting rates for the Philippines and Indonesian domestic fisheries and the purse seine fisheries, based on independent estimates of reporting rates for these fisheries from tag seeding experiments and other information (Hampton 1997). For the longline fisheries, we have no auxiliary information with which to estimate reporting rates, so relatively uninformative priors were used for those fisheries. The priors and bounds for tag-reporting rates estimated for purse seine recaptures from the RTTP and PTTP release programs were taken from an analysis of tag-seeding experiments (Hoyle 2011).

Given the voluntary basis for obtaining tag recapture observations, this variable depends upon factors relating to the tag release group and within the fish processing sector. These factors may include the visibility characteristics of tags, processing methods that entail individual fish identification, and most importantly, the goodwill of industry staff. Consequently, the probability of a recapture being reported may be specific to each tag release group and the factors surrounding it, such as the physical characteristics of the tag employed (colour, printed information), the perceived value of the incentive (reward), and the extent of publicity associated with the tag release group. Therefore, in the analysis of tag-recapture data for this assessment, reporting rates were estimated specific to tag release groups. Consequently the reporting rates estimated were specific to both fishery and tag release groups.

All reporting rates were assumed to be stable over time.

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 0.007, which represents an increase relative to the precision assumed for the 2010 assessment.

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

The size frequency data are assigned an effective sample size lower than the actual number of fish sampled. Reduction of the effective sample size recognises that (i) length- and weight-frequency samples are not truly random (because of clumping in the population with respect to size) and would have higher variance as a result; and (ii) the model does not include all possible process error, resulting in further under-estimation of variances.

The influence of the size frequency data in the model can be examined by varying the effective sample size in the model. For the base model in the 2010 assessment, the length frequency data for fisheries 1, 2, 4, 7, 10, 12, and 23 were downweighted to a maximum size of only 1, effectively removing all influence these length data have on the model, transferring almost all influence to the weight frequency data for these fisheries. The same was done for the fishery 5 length and weight frequency data. For the current assessment, the size compositions from the longline fisheries (1, 2, 4, 7, 10, 12) derived using the protocols described in Section 3.5 are considered to represent more reliable indicators of the trends in the size composition of the population over time (compared to previous years). On this basis, these size data were considered to be moderately informative and were given an according weighting in the likelihood function; individual length and weight frequency distributions were assigned an effective sample size of 0.05 times the actual sample size, with a maximum effective sample size of 50. However, the larger number of length and weight samples included in these data means that these data are likely to be more influential than in previous assessments. Therefore, the influence of the Japanese longline size data was explored using lower (n/50) effective sample sizes a model sensitivity run. The lower weight assumed for fisheries 5 and 23 in the 2010 assessment were retained for the current assessment.

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

4.5 Parameter estimation and uncertainty

The parameters of the model were estimated by maximizing the log-likelihoods of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. The maximization was performed by an efficient optimization using exact derivatives with respect to the model parameters. Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters. A bash shell script, *doitall.bet*, documenting the phased procedure is provided in Appendix A. Some parameters were assigned specified starting values consistent with available biological information. The values of these parameters are provided in the *bet.ini* file (Appendix B) [7].

In this assessment two approaches were used to describe the uncertainty in key model outputs. The first two focus on the statistical variation **within** a given assessment run, while the third focuses on the structural uncertainty in the assessment by considering the variation **across** model runs. First we calculated the Hessian matrix for the base model run to obtain estimates of the covariance matrix, which is used in combination with the Delta method to compute approximate confidence intervals for parameters of interest. This approach provided approximate confidence intervals for the biomass and recruitment trajectories. Secondly, we undertook a crosswise grid of 144 model runs which incorporated many of the options included in the key model runs. This last procedure attempts to capture the main sources of structural and data uncertainty in the assessment.

4.6 Stock assessment interpretation methods

Several ancillary analyses were conducted in order to interpret the results of the model for stock assessment purposes. The methods involved are summarized below and the details can be found in Kleiber et al. (2008). Note that, in each case, these ancillary analyses are completely integrated into the model, and therefore confidence intervals for quantities of interest are available using the Hessian-Delta approach.

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[7] Details of elements of the *doitall* and *.ini* files as well as other input files that structure a MULTIFAN-CL run are given in Kleiber et al. (2008).

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.

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 (steepness and a parameter that scales the recruitment). 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 2006–2009. The last year in which catch and effort data are available for all fisheries is 2009. We do not include 2010 in the average as fishing mortality tends to have high uncertainty for the terminal data years of the analysis (see Langley 2006 and Harley et al. 2009a). To allow for retrospective evaluation we recalculated the key MSY-based reference points using annual time periods from 2001 to 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 SRR estimated for the levels of recruitment and spawning potential that occurred in the period 1989–2009.

5 Model runs

5.1 Developments from the 2010 assessment

Following the recommendations of the PAW, a number of developments were made starting from the 2010 base case model (Table 4). Aside from updating the input data (catch, effort, size frequencies, and standardised CPUE derived from aggregate data), there are eight main differences in the input data and structural assumptions of the current assessment compared to the 2010 assessment (run3d).

i. Fixing the steepness parameter (h) of the SRR at 0.8 in the reference case rather than estimating this parameter.

ii. Incorporation of CPUE indices derived from operational catch and effort data from the Japanese (regions 1-6). For the 2010 assessment CPUE indices were derived from Japanese aggregated catch and effort data and were corrected for long-term changes in catchability based on an external analysis. For the current assessment a sensitivity model was run using standardised CPUE indices for the Taiwanese longline fishery in region 6.

iii. Applying temporally varying relative weight on the individual standardised effort indices for the Japanese longline effort time series.

iv. A revised protocol for deriving the length- and weight size compositions for the principal longline fisheries.

v. The correction of the purse-seine length frequency data to account for sampling bias and the exclusion of length data from the fisheries prior to 1996 (bias correction not available) (Lawson 2011).

vi. A revision of the corrected (spill sample) purse-seine fishery catch estimates (Lawson and Sharples 2011). The main difference was in PS ASS 3 where the time series of corrected catches were approximately 10% lower than the corrected catches in the 2009 assessment.

vii. Refinement to the Philippines and Indonesian fishery definitions, including the definition of a new fishery encompassing the Philippines and Indonesian purse-seine fleets operating west of 130° E and outside of archipelagic waters.

viii. Inclusion of the PTTP tagging data.

For comparison to the 2010 stock assessment, a step-wise sequence of models was formulated that modified the 2010 base-case model to sequentially incorporate each of the changes identified above (Table 3). The sequence of models firstly updated the model period of the 2010 assessment from 1952-2009 to 1952-2010 and then implemented the developments in a step-wise manner towards a reference case model (Run3j - Ref.case) against which all models in the current assessment would be compared.

5.2 Sensitivity analyses

Based upon the recommendations of the PAW, the sensitivity of the Ref.case model (Run3j) to a range of key assumptions was tested in a series of "one-off" sensitivity analyses (Table 3). As the assessment developed and uncertainties in model aspects became apparent, further sensitivities were added to those recommended, making up a list of eighteen runs. These can be divided in to five parts in respect of the assumptions being tested:

5.2.1 Catch and size data

- Purse seine catches and size composition not corrected for grab-sampling bias (**Run4 – SBEST**). As noted above, corrected catches from the purse-seine fisheries (PS ASS, PS UNA 3 & 4) are substantially higher than previously reported, principally for the associated fisheries. However, the corrected catch and size composition estimates are based on limited sampling data and are considered preliminary. In this sensitivity the uncorrected estimates (SBEST) were input.
- Low relative weight for Japanese longline length-frequency data (**Run11 – lowtLF**). The relative influence of the length composition data for the LL-ALL fisheries (regions 1 – 6) was reduced by assigning an effective sample size 0.02 times the individual samples, with a maximum sample size of 20.
- Longline and purse seine selectivity decoupled for regions 3 and 4 (Run19). Unique selectivity functions were estimated for the LL ALL 4 and PS ALL 4 fisheries.
- Carry over the reported longline catches in 2009 to 2010 for fisheries 1, 2, 4, 7, 10, and 12 (Run20).

5.2.2 Standardised CPUE indices

- Exclude parts of the operational Japanese longline CPUE time series: exclude the years pre-1975 (**Run5 – excl.pre75CPUE**); exclude the years pre-1990 (Run6); and, exclude the years post-1990 (Run7). The 2010 assessment identified the effect of CPUE in the early part of the time series on model estimates of recruitment and, hence the estimates of stock status. Excluding the early part of the time series tempers the increasing trend in recruitments.

- Input the operational CPUE time series that includes data for the whole of region3 (Run8)
- Input the operational CPUE time series from the Taiwanese longline fishery for region 6 (Run9)
- Input the CPUE time series for regions 1 – 6 derived from aggregate data (**Run10 – aggCPUE**).

5.2.3 Tagging data

- Exclude the PTTP data (**Run12 – excl.PTTP**)
- Extend the tag mixing period to three quarters (Run 18)

5.2.4 Steepness

- Fixed values of 0.65 (**Run13 – h0.65**) and 0.95 (**Run14 – h0.95**)
- Estimated (Run 15)

5.2.5 Natural mortality

- Increased juvenile mortality-at-age at the levels assumed for yellowfin for the first 4 quarters (Run16) and 8 quarters (**Run17 – hijuvM**).

The eight sensitivity runs in **bold** above were taken as the key model runs for examining the effects of the primary sources of uncertainty on management reference points in the current assessment.

5.3 Structural uncertainty

An examination of uncertainty in the model structure was integrated into a single analysis that explored the interactions of the assumptions tested in the one-off sensitivity runs, i.e. for the key model runs and that test the alternative assumptions recommended by the PAW (Table 4). These interactions were tested in a grid of 144 combinations of the following options:

- Purse seine catch and size composition [2 levels]: from Run3j and Run4 (SBEST)
- CPUE [3 levels]: from Run3j, Run10 (aggCPUE), and Run5 (excl.pre75CPUE)
- Japanese length data weighting [2 levels]: from Run3j and Run11 (lowtLF)
- Steepness[3 levels]: 0.8 - Run3j, 0.65 - Run13 (h0.65), and 0.95 - Run14 (h0.95)
- Tagging data [2 levels]: from Run3j and Run12 (excl.PTTP)
- Natural mortality [2 levels]: from Run3j and Run17 (hijuvM)

A separate model was run for each of the combinations in the grid. The model results were screened to ensure model convergence and reasonable values of key parameters. A non-parametric bootstrap of the grid results (n = 5000) was undertaken that generated a distribution for each management quantity, from which the median and 90%iles were reported.

6 Results

6.1 Impact of model developments on key reference points

In order to examine the impacts of the stepwise developments from the 2010 bigeye assessment (run 3d) to Run3j (Ref.case), estimates of key reference points, (symbols for which are defined in Table 5), for each of the runs are provided in Table 6, and the total WCPO spawning potential is provided in Figure 18.

Update 2010 base case

The biomass trajectory of a straight-forward update of the 2010 base case (Run2b) had a largely similar trend although absolute initial biomass was around 10% lower (Figure 18). The continuation of the population trend found in 2010 increased the estimated over-fished state with $F_{current}/F_{MSY}$ = 1.49 compared to 1.41 (Table 6).

New fisheries definitions

Adding a discrete fishery for the Indonesian and Philippines domestic purse seine operations in Run3a resulted in a similar biomass trend to the previous runs (Figure 18) and reduced the overall absolute recruitment levels. Although absolute biomass was lower, stock status was the same given that biomass-related reference points decreased proportionally.

Temporal weighting on aggregate CPUE

Model sensitivity to assumptions relating to indices of relative abundance was illustrated in Run3b where temporal variation in the relative weight of indices was applied, resulting in absolute biomass increasing to close to the 2010 base case level (Figure 18) and with similar stock status. This effect was also seen in the 2010 assessment (run3e2, Harley et al. 2010).

Operational CPUE indices

Including standardised CPUE indices derived from operational level data had a large effect (Run3c), essentially doubling absolute biomass with a steeper decline from historical levels (Figure 18). Including temporal variation in the relative weights of the indices reduced this effect with $B_{current}$ around 50% higher than Run3a. This development had a substantial effect on estimates of stock status predicting a more optimistic scenario compared to Run3b, with $F_{current}/F_{MSY}$ = 1.10 compared to 1.34 and $SB_{current}/SB_{MSY}$= 1.61 compared to 1.42 (Table 6). This effect is due to the difference in trend in the indices derived from aggregate and operational level data, with declines from higher historical levels predicted by the operational indices in most regions and a flat or increasing trend in region 2 (Figure 12). This tends to increase recruitments in the early period, which raises the absolute level of biomass. In the subsequent model run (Run3d), temporal weighting of the indices appears to lessen this effect due to the lower precision for the early period and in regions other than region 3 (Figure 13). Also, the lack of operational indices before 1959 reduces the influence of the series on model recruitment estimates for the early period.

Spill sample corrected size data

Using size data for purse seine catches corrected for grab sample bias in model Run3e produced a substantial reduction (16%) in absolute current spawning biomass (Figure 18), and more pessimistic estimates of stock status (Table 6). This effect is due to the changes in modelling purse seine fishing mortality due to the smaller size composition of the corrected data (Figure 14 – median lengths) with almost all large fish being removed from the catch composition. Given the catch is reported in weight, this results in a higher juvenile mortality being estimated. Selectivity-at-age estimates shifted to a smaller average size and the asymptotic length is substantially reduced. Estimates of overfishing for $F_{current}/F_{MSY}$ increased to 1.26 (Table 6).

Japanese longline length and weight frequency data - reweighted

Changes in the size compositions of the JP LL catches in regions 1 to 6 occurred as a consequence of the reweighting of these data by the estimated population relative abundance within regions (Hoyle and Langley 2011). A comparison of temporal trends in median length of unweighted and weighted length and size data in each region shows the effects of weighting the data compared to the unweighted (Figure 15). In region 1 the median weight is more stable from 1970 – 95, with a decline to levels similar to the unweighted median in 2009. In region 2 median weights have been higher since the mid-1970's. In region 3, the median length declined more since 1990, and the median weight showed slightly more of an overall decline. In region 4 both median length and weight declined less, while for region 5 median weight was lower in the 1960s and 1970s which indicates slightly less decline. For both regions 5 and 6, weighted length and weight data were not avail for the past 12 years. To summarise, besides region 3, the effect of weighting the length and weight frequency data is to reduce the decline in median fish size in regions 1, 2, 4 and possibly 5.

The effect of including the weighted size data in the model (Run3f) had little effect on absolute biomass but reduced the declining trend from 1960 to 2005, with a recent decline to a level similar to Run3e in 2010 (Figure 18). Increasing the relative weight assigned to the length frequency data in the model fit (Run3f_2) had little effect on this trend but increased a decline in biomass around the 1980s most likely due to the influence of a visible decline in median length in region 3 at that time (Figure 15).

The reweighting of these data, as described by Hoyle and Langley (2011) addresses a number of the concerns upon which the assumption was made to assign extremely low weight to the length frequency data for the 2010 assessment. Consequently, full relative weight was assigned to these data for the subsequent models.

PTTP tagging data

Relative to Run3f_2, including the PTTP data in the model (Run3g) resulted in a small reduction (5%) in current spawning biomass, but this was restored with the estimation of reporting rates specific to both tag release groups and recapture fishery groups (Run3h, Figure 18). This demonstrates that the fit to PTTP data was generally consistent with other observations in the model. Biomass in the final year of the model was slightly higher due to the higher recruitments estimated in recent time periods. Estimates of stock status remained more optimistic relative to the updated 2010 base case (Run2b) with $F_{current}/F_{MSY}$ = 1.15 compared to 1.49 and $SB_{current}/SB_{MSY}$= 1.56 compared to 1.33 (Table 6).

Steepness

Fixing the value of steepness at 0.8 had little effect on absolute biomass or the trend (Figure 18) but substantially increased the reference point estimate of SB_{MSY} by 32%, resulting in more pessimistic estimates of stock status: $F_{current}/F_{MSY}$ = 1.48 and $SB_{current}/SB_{MSY}$= 1.21 (Table 6), levels more similar to the 2010 base case.

Penalty on the total catch likelihood

Increasing the penalty on the total catch likelihood had minimal impact on model estimates, and this model was taken as the reference case for the 2011 assessment (Run3j – Ref.case).

In summary the key differences in biomass relative to the 2010 base case is a higher absolute biomass overall, with a steeper decline from initial levels to 1980, after which the trend is similar. However, the trend in last 3-5 years declines less steeply than the 2010 base case.

In terms of the reference points, compared to the 2010 model, $F_{current}/F_{MSY}$ is now slightly higher at 1.46, $SB_{current}/SB_{MSY}$ is lower at 1.19, MSY is 4% higher. The ratio of late to early recruitment[8] is 15% lower indicating that the model and data changes have partially mitigated the data conflict. The main developments responsible for these differences are: including standardised CPUE indices derived from operational-level data, input of the purse seine size data corrected for grab sample bias (spill samples), and fixing steepness at 0.8. Although the Ref.case model is more

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

pessimistic than the 2010 base case, the preceding stepwise run in which steepness was estimated (Run3h) indicates that this change is due largely to this model assumption. For Run3h, which is more comparable to the 2010 base case, stock status was estimated to be more optimistic, with $F_{current}/F_{MSY}$ at 1.15 and $SB_{current}/SB_{MSY}$ at 1.56. This indicates that the effects of the two data–related developments result in more optimistic estimates of stock status compared to the 2010 base case.

6.2 Model diagnostics – Run3j – Ref.case

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

- The log total catch residuals by fishery are shown in Figure 19. The residuals are small and, for most fisheries, generally show even distributions about zero. This reflects the high penalty applied to the catch deviations in the model likelihood. The large residuals relative to others for the PS ASS 4 fishery evident in 2009-10 reflects inconsistencies with other data, most likely the PTTP tag observations collected at that time.
- For most fisheries, there is a reasonable fit to the length data for the longline fisheries as revealed from a comparison of the observed and predicted median lengths over time (Figure 20). However, for some of the longline fisheries (LL ALL 1, 2, and 3) there is a systematic lack of fit since the 1980s – with the model over-estimating the proportion of fish in the larger length classes and, correspondingly, under-estimates the proportion of fish in the smaller length classes. In contrast to the relatively poor fit of the 2010 model to the LL ALL 4 observations, the Ref.case achieves a consistently good fit throughout the time series. A poor fit was obtained to the PS ASS 4 and PS UNA 4 observations collected around 2005-10 which may indicate a data conflict, most likely in respect of the PTTP tag data.
- Model predicted median weights for the LL ALL 3 fishery are highly consistent with the observed time series (Figure 21), which contrasts with the poor fit obtained to the length data. The other principal longline fisheries exhibit periods with a systematic lack of fit to the length data, viz. LL ALL 1, 2, and 4. Most notable is the lack of fit to the increasing trend in mean length of fish sampled from the LL ALL 4 fishery from the 1980s onwards. The low quality of fit for these fisheries is evident in a bimodal pattern of positive residuals for the small and large length classes (Figure 22). The lack of consistency in predicted and observed median lengths is reflected in a clear pattern of positive residuals that exists for the small length classes (60-110 cm) in the LL ALL 3 fishery. Whereas a steady decline has been observed since 1978 (Figure 20), this was not predicted by the model, confirming the conflict with these and other data in the model reported in previous bigeye assessments. However, the total effective sample size of the length frequency data post-1980 was 4 times less than the weight frequency samples resulting in lower relative weight in the model fit.
- Clearly a poor fit was obtained to the length frequency of the LL TW-CH 3 fishery, but this may be expected given the low relative weight assigned to these observations (Figure 22).
- For the unassociated purse-seine fishery in region 4 (PS ASS 4) the model under-estimates the observed length composition for the smaller length classes (**Error! Reference source not found.**). This systematic lack of fit to these data suggests the Ref.case model assumption of a common selectivity between the PS ASS 3 and 4 fisheries may not be valid, or the existence of conflict with other data in the model, e.g. PTTP tagging.
- Although a small collection of observations, model predicted median lengths were reasonably consistent with the observations from the newly defined ID-PH PS 3 fishery (Figure 20).
- The fit of the model to the total numbers observed recaptures of tagged fish by calendar time is shown in Figure 23 (recaptures plotted in log-space). The observed recaptures appear highly variable through the recovery phase, particularly during the second half of the RTTP program.

Nevertheless, the model predictions are broadly consistent with the observed recaptures, including the high numbers obtained from the PTTP in 2010. The low observed number of PTTP recaptures in 2008 warrants closer examination and may reflect movement processes into and out of region 4 not adequately described in the model. This feature may be addressed in future assessments.

- The overall consistency of the model with the observed effort data can be examined in plots of effort deviations against time for each fishery (Figure 24). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. On the other hand, if there was an obvious trend in the effort deviations with time, this may indicate that a trend in catchability had occurred and that this had not been sufficiently captured by the model. Of particular interest are the effort deviations for the LL ALL 1–6 longline fisheries, which were constrained to have the same average catchability and to have no year-to-year variation (i.e., catchability deviations were assumed to be zero) (Figure 24).
- For LL ALL 3, 5 and 6, the large effort deviations during the early and later periods is an artefact of the lack of standardised effort data available. During this period, the model has freedom to estimate deviates from the notional level of effort and thereby fit the observed catch from these two fisheries (Figure 24).
- The effort deviations for the main longline fisheries in regions 1 to 5 are relatively low and do not exhibit any systematic trends over the model period (Figure 24) indicating that the model estimates of longline exploitable biomass trends are consistent with the longline CPUE indices. This is evident in the generally consistency between the predicted and observed CPUE trends for these fisheries (Figure 25). The exception to this result was for the LL ALL 6 fishery that shows an unstable pattern in the effort deviates indicating that the trends in CPUE indices are unable to be predicted by the model. This result must take account of the high variable and intermittent observations in the time series for this fishery (Figure 25). No such pattern in the effort deviates was found for the sensitivity model Run9 fitted to the Taiwanese standardised CPUE for region 6, suggesting that no fundamental process error exists in the model in relation to this fishery. Consideration might be given to including the CPUE time series for the Taiwanese longline fishery in region 6 for the Ref.case model in future assessments.

6.3 Model parameter estimates (Run3j - Ref.case, unless otherwise stated)

6.3.1 Growth

The estimated growth curve is shown in Figure 26. For the Ref.case model, growth in length is estimated to continue throughout the lifespan of the species, approaching a maximum level. The estimated mean length of the final age-class is 179.0 cm and L_∞ is 191.65 cm.

A comparison of the estimated growth curve to two external sources of information on growth, (tagging and direct ageing data), (Figure 27), shows the tagging estimates to be generally less than what would be predicted by the growth curve, while the direct ageing estimates are greater. There are concerns that tagging can impact on fish growth. This could explain the first pattern, but the direct ageing suggests that there is information in the data that implies a different and slower growth rate. Regional variation in growth is one potential reason for this difference. The lack of small fish in some regions, and confounding with selectivity, makes it difficult to determine if there are regional differences in growth rates, but such differences are likely.

6.3.2 Movement

Two representations of movement estimates are shown in Figure 28 and Figure 29. The estimated movement coefficients for adjacent model regions are shown in Figure 28. These movement patterns are somewhat different to the 2010 assessments, with an increased exchange of fish between regions 3 and 4. This feature might have resulted from the large amount of tagging data input to the current assessment and from which movement can be inferred (Figure 30). These data are limited to regions 3, 4 and 5 but support the model estimates for mixing between regions 3 and 4, as well as from region 5 to 3. Similar to the 2010 result, the movement coefficients for most quarters suggest a dependence of the northern and southern region on local recruitment rather than on migrants from the tropical regions (Figure 29).

6.3.3 Selectivity

Selectivity estimates were broadly similar to that of the 2010 assessment but have improved for certain fisheries for which either bimodal functions were estimated or exhibited high asymptotes for the older age classes, e.g. the purse seine fisheries (Figure 31). Selectivity for older age classes in the PS UNA 3 and 4 fisheries is substantially lower than estimated previously. This result may be attributable to the correction made to size data from these fisheries for grab sample bias.

The selectivity estimated for the newly defined ID-PH PS 3 fishery appears plausible in that the age at full selection is higher than that of the function for the PH DOM 3 and ID DOM 3 fisheries (Figure 31).

Selectivity functions are temporally invariant. However, for a number of fisheries there is a clear temporal change in the size-frequency data and an associated lack of fit to the predicted size composition. This is particularly evident for the LL ALL 2 and 4 fisheries. Further examination of these data is necessary to determine if they reflect a change in the selectivity in the fishery (through either operational changes or changes in the locations fished) or simply unrepresentative sampling data.

6.3.4 Catchability

Time-series changes in catchability are evident for several fisheries and the patterns are consistent with the 2010 assessment (Figure 32).

6.3.5 Tag Reporting Rates

The 34 individual reporting rates of recaptured tagged bigeye estimated specific to release group (program) and recapture fishery are presented in Figure 33 relative to the assumed priors and penalty bounds for each. The estimates may best be considered in relation to the fisheries most accountable for recaptures, viz. purse seine, Philippines-Indonesian, Australian longline fisheries (11, 14, 16, 18, 24, and 26) that make up 97% of all recaptures. Three of the estimates are notable in that the estimates are at the upper bound. Firstly, that for the PTTP release group and recapture fishery group PS_R4_all which accounts for 62% of the PTTP recaptures. Secondly, that for the CS release group and recapture fishery group LL_R5_AU which accounts for 98% of CS recaptures. Thirdly, that for the RTTP release group and recapture fishery group LL_R5_AU which accounts for 23% of RTTP recaptures. Most likely these estimates are implausibly high, and this might indicate conflict with other data input to the model. In the case of the PTTP_ PS_R4_all estimate, a likely source of conflict is the PS catch estimate, noting that there were relatively large catch deviates during the PTTP recapture phase, (Figure 19). The observer-based species composition estimates with spill sampling correction effectively decreases the PS UNA 4 catch estimate for this period (Figure 10), creating a potential upper limit on biomass estimation by reducing the number of fish examined for tags. Reporting rates for the PS_R3_all, Misc_R3_PH, Misc_R3_ID, and PS_R3_PHID recapture fishery groups were generally not estimated at the bounds in accounting for 44.5% of the RTTP and PTTP recaptures combined.

6.4 Stock assessment results

Symbols used in the following discussion are defined in Table 5 and the key results are provided in Table 7.

6.4.1 Recruitment

The Run3j recruitment estimates (aggregated by year for ease of display) for each region and the entire WCPO are shown in Figure 34 and are broadly similar to those estimated in the 2010 assessment. Given the similarity in the model estimates, the following interpretations do not differ substantially from those made for the previous assessment (Harley et al. 2010).

The regional estimates display large interannual variability and variation on long time scales, as well as differences among regions. For the aggregated estimates, there is a decreasing trend to about 1965 and an increasing trend thereafter, with exceptionally high recruitment during 1995-2005, particularly in 2000 and again in 2005. Since 2005, recruitment is estimated to have declined towards the value of the long-term average, but it is not known if this is an artefact of the recruitment estimation constraints (convergence to the mean), or data driven (e.g. by the slightly declining purse seine catches). As indicated by the approximate confidence intervals, these recent recruitment estimates are less certain.

Recruitment in regions 1, 5, and 6 is relatively low and the trends are either stable or decreasing through time. While the trends in these regions seem plausible the regional recruitment trends for regions 2-4 are questionable. Estimated recruitment in region 2 is highly variable for the first 5-10 years and then drops sharply to a lower level by 1960 and continues to decline slowly thereafter. The model estimates a two-step recruitment pattern for region 3: lower and stable recruitment from 1952-1978 followed by a sharp and substantial increase to a level around three times higher on average thereafter. Although this result repeats the findings of previous assessments, the contrast between the two periods is substantially lower than for the 2010 assessment, in which recruitments were five times higher post-1978. The effect of this reduction of the increasing trend in recruitment is indicated by the decrease in the overall recruitment ratio from 2.02 obtained in the 2010 assessment, to 1.72 in the current assessment. Also recruitments since 2005 in regions 2 and 3 were higher than that estimated in the 2010 assessment. Recruitment in region 4 is relatively high throughout the time series and shows an increase in both level and variability in the mid 1990s.

A comparison of WCPO recruitment estimates for the one-off sensitivity model runs is provided in Figure 35 and the ratio of late to early recruitment in Table 6. Estimates were sensitive to assumptions regarding purse seine catch and size composition (Run4) resulting in lower average recruitment since 1985, being a consequence of the reduced catch time series and higher median size. The effect on recruitments was substantial for the run assuming higher natural mortality up to an age of 8 quarters (Run17), such that total average annual recruitments more than double to compensate for the higher total mortality on a subset of the exploitable population to some fisheries (Figure 35). Excluding standardised CPUE indices pre-1975 results in steeply declining recruitment estimates to 1980 (Run5, Figure 35), with recovery in recent years to around the average of historical levels. This “two-phase” pattern in recruitments results in the ratio of historical and recent recruitments being reduced from 1.72 for the Ref.case to 1.14 (Table 6). Assuming the CPUE time series derived from the aggregate data (Run10) results in lower recruitment estimates up to 1978.

The spawner recruitment observations on a quarterly and annual scale are provided in Figure 49. As in previous assessments, most of the high estimates of recruitment occur at low estimated spawning stock sizes. Estimating steepness in model Run15 gave a value (0.97, Table 6) almost identical to that of the 2010 base case model.

6.4.2 Biomass

The estimated total biomass trajectory for each region and for the entire WCPO for Run3j is shown in Figure 36 and a plot of spawning potential is provided in Figure 37. WCPO bigeye biomass is estimated to decline during the 1950s and 1960s in all regions, but the trends differ among regions, with a more upward trend in regions 1 and 2, and almost no trend in regions 3 and 4 (Figure 36). In region 3, total biomass remains relatively stable from the mid 1970s to 2000 and declines sharply from 2003 onwards. This contrasts with the recent declining trends estimated for regions 3 and 4 in the 2010 model. Biomass levels are highest in region 4 and the biomass trend from this region dominates the overall trend in the WCPO; where the biomass declines rapidly during the 1950s and 1960s, is relatively stable through the 1970s and 1980s, and has remained at the 1970s level ever since. A feature of the Ref.case model, compared to the previous assessments, is a lower level of biomass in region 2 during the early years of the model with a flat, to increasing, trend in recent years. This can be attributed to the difference mentioned earlier between the CPUE indices derived from the operational level data compared to those from the aggregate data for these regions. The feature is also evident in regions 1, 3 and 4, with either flat or increasing trends. This reflects the difference in the recent recruitment estimates for the current assessment. This difference is less apparent for the spawning biomass estimates, not yet affected by the new recruitment estimates, and the continued decline over time is still evident.

A comparison of trends in spawning potential for Run3j (Ref.case) with the other key model runs are shown in Figure 38. Of the sensitivity runs to test assumptions for purse seine catch and size data (Run4), relative weight on Japanese longline size data (Run11), longline and purse seine selectivity decoupled for regions 3 and 4 (Run19), and longline catch in 2010 (Run20), only Run4 affected the trend and absolute levels of biomass (Figure 38). There was lower relative decline in biomass for this run since 1985 for which lower average recruitment was estimated (Figure 35), largely being a consequence of the reduced purse seine catch time series assumed. Other sensitivity runs in this group had negligible effect on estimates of stock status.

The Ref.case model was highly sensitive to assumptions regarding the CPUE time series input, affecting both the absolute levels and trends in spawning biomass (Figure 38). Most extreme effects were evident for runs that excluded part of the CPUE time series (Run5, Run6 and Run7) which generally this doubled the estimates of initial biomass, with steeper declining trends. In the case of Run7 (excl.post90CPUE) absolute biomass overall was higher than the Ref.case, however, this is unlikely to be a plausible model result given the lack of observations of relative abundance for the past 20 years. The biomass increase in the mid-1980s in Run6 is due to steady increases in median weight in regions 2 and 4 (Figure 15) that dominate the model fit in the absence of an abundance index through that period. The steep biomass declines to 1980 for these models are driven by declining recruitment (see Run5, Figure 35), which then recovers in recent years to around the average of historical levels. In contrast with the Ref.case, the higher historical biomass estimated in Run5 occurs largely in regions 3 and 4 with a substantially lower proportion in region 2 (Figure 39). This “two-phase” pattern in recruitments for Run5 produces a ratio of historical : recent recruitments of 1.14, compared to 1.72 for the Ref.case (Table 6). Assuming the CPUE time series derived from the aggregate data (Run10) results in lower recruitment estimates in the early part of the time series (Figure 35), creating a lower, and flatter, biomass trajectory. Assuming the Taiwanese longline time series for region 6 (Run9) results in substantially higher recruitments in that region, and consequently a higher WCPO initial biomass. The model fit to this time series is reasonable and this information appears consistent with the other observations input to the model. The flatter trend from 1960 to 1995 in the CPUE time series derived from data for the whole area of region 3 (Figure 12) affected estimated biomass for that region, with a flatter trend in total biomass relative to the Ref.case (see Run8, Figure 38).

Spawning stock absolute biomass and its temporal trend of the Ref.case model were only moderately sensitive to the value of steepness, either assumed (Run13, Run14) or estimated (Run15, Figure 38). Lower and higher steepness values slightly raised and lowered (respectively) the absolute biomass level.

Increasing constant juvenile natural mortality (Run16, Run17) resulted in lower levels of absolute biomass, with minimal change to the temporal trend (Figure 38). The effect was substantial for that run assuming higher levels up to an age of 8 quarters (Run17) where total average annual recruitments more than doubled to compensate for the higher total mortality on a subset of the exploitable population vulnerable to some fisheries (Figure 35).

The relatively small effect on absolute biomass estimates caused by including the PTTP data that was observed during the stepwise development of the Ref.case model, was again reflected in the results of sensitivity Run12, (Figure 38). This apparent insensitivity to adding a substantial set of new observations to the fit suggests these data are generally consistent with other information being input. However, some contrast was visible in the very recent biomass trend between Ref.case and Run12, with a steeper decline for the sensitivity run (Figure 38). This is most likely due to a slight conflict with the region 3 CPUE data (having some low observations in 2010, Figure 25), and also with the purse seine catches in region 4, for which relatively large catch deviations were estimated in 2009-10 despite the high penalty applied to the likelihood (Figure 19). Increasing the length of the mixing period from 2 to 3 quarters raised the absolute level of biomass, which suggests proportionally higher recapture rates in the third quarter of the period at liberty than was observed in subsequent quarters.

6.4.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase strongly throughout the time series for all model runs and in all cases the levels of juvenile mortality are greater than those for adults (Figure 40). The Ref.case estimates were most sensitive to assumptions regarding purse seine catch and size composition (Run4) and juvenile natural mortality (Run17). In both cases the change in the recruitment estimates result in lower juvenile fishing mortality rates.

Changes in fishing mortality-at-age and population age structure are shown for decadal time intervals in Figure 41. Since the 1980s, the increase of juvenile fishing mortality to the current high levels is due to the substantial purse seine catches beginning at that time, resulting in the lower relative abundance in the younger age classes in last decade.

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 42 and Figure 43 for total biomass and spawning biomass, respectively, and illustrate three interesting points. First that region 1 was already impacted by fishing at the start of the model (1952). Second, the estimated impact for region 2 is low and the trends in biomass are estimated to be more due to recruitment trends rather than fishing. Finally, there are particularly strongly estimated impacts in the tropical regions 3 and 4, where most of the catch is taken, and these impacts are substantial since the 1980s. The patterns for these two regions therefore dominate the overall picture for the WCPO.

The biomass ratios (between annual biomass and the biomass that would have occurred in the historical absence of fishing), which represent the level of depletion, are plotted in Figure 44 and Figure 45 in terms of total biomass and spawning biomass, respectively. These figures indicate increasing fishery impacts over time in all regions, with higher impacts on spawning potential than on total biomass. A comparison of spawning potential ratios for the WCPO for the main model results is provided in Figure 46. For the Ref.case it is estimated that current biomass (average 2006-09) is 29% of the level that is predicted in the absence of fishing. This drops to 23% for spawning potential and to 21% if considering 2010, the final year in the assessment (Table 7). The levels of depletion were similar for all runs except Run10 (aggCPUE) and Run4 (SBEST) which estimated higher and lower levels of depletion, respectively.

It is possible to ascribe the fishery impact to specific fishery components in order to see which types of fishing activity have the largest impact on the spawning potential (Figure 47). In regions 2, 5, and 6, longline fishing is almost entirely responsible for the fisheries impacts. In region 1 the current impact is shared between the longline and Japanese coastal surface fisheries, and in region 3 the purse seine fishery has the greatest impact followed by longline and the domestic fisheries of Indonesia and the Philippines. The high relative impact of the purse seine fishery is very similar to that estimated in the 2010 assessment, and is due to the assumed purse seine catches corrected for grab sampling bias. In region 4 the purse seine/domestic and longline fisheries have similar impacts.

A comparison of fishery impacts on spawning potential at the WCPO level for six of the one-off sensitivity model runs is provided in Figure 48. The Ref.case estimates appear sensitive only to assumptions relating to purse seine catch (Run4 – SBEST) and juvenile natural mortality (Run17 – hijuvM). In the former, the longline impact is much higher, as is the impact of the domestic fisheries of Indonesia and the Philippines. The increase in the relative impact for both of these fisheries, despite catches being the same, is attributed to the models response to the lower purse seine catches, which resulted in a lesser recruitment increase in recent years. In the latter, the lower purse seine impacts were due to the substantially higher recruitment estimates as a consequence of the higher assumed natural mortality.

6.4.5 Yield analysis

The yield analyses conducted in this assessment incorporate the spawner recruitment relationship (Figure 49) into the equilibrium biomass and yield computations.

As outlined above, the following section describes the main results for the Ref.case considering the catch (including consideration of catch-related reference points in the context of recent high recruitment), fishing mortality, and biomass related reference points.

Catch and MSY

MSY was estimated at 76,760 mt, an increase from the 2010 assessment which is attibuted largely to the effects of fitting the model to standardised CPUE indices based upon operational data. Given the high estimated fishing mortalities, current equilibrium yield ($Y_{F_{current}}$) is 89% of the *MSY* at 68,320 mt (Table 7). Current catches, sustained by estimates of high recruitment, are double the *MSY*. With regard to the alternative model runs, *MSY* is much higher in Run5 (excl.pre75CPUE), and higher in Run14 (h0.95) where the estimated values were 97,120 mt and 83,720, respectively. Lower value was estimated for Run4 (SBEST) and Run13(h0.65).

Noting that recent recruitment is estimated to have been well above the long term average predicted by the SRR, it is useful to consider recent catches in that context (Table 7). For the one-off sensitivity model Run21, the *MSY* estimate was based upon the predicted SRR derived using recruitment and spawning potential estimates over the period 1989-2009, with steepness fixed at the Ref.case level. In this case the recent recruitments support an *MSY* of 131,400 t. However, current catches are still around 7% higher than this alternative estimate. **Based on these results, we conclude that current levels of catch are unlikely to be sustainable in the long term, even at the recent [high] levels of recruitment estimated for the last two decades**.

Fishing mortality

For Run3j, the *MSY* is achieved at F_{mult} = 0.68; i.e. at 68% of the current (2006-09) level of age-specific fishing mortality (Table 7, see also Figure 50). This represents a ratio of $F_{current}/F_{MSY}$ equal to 1.46 (1/0.68); therefore, current fishing mortality rates are considerably higher than the fishing mortality rates to which would produce the *MSY*. A reduction in fishing mortality of 32% (1-F_{mult}) from the average 2006-09 levels is necessary to reduce fishing mortality to the F_{MSY} level. Comparing this to historical time periods (

Table 8. and Figure 51), a 39% reduction in fishing mortality levels from 2004 is required, but a 28% reduction from average 2001-04 levels[9].

For all of the model runs $F_{current}/F_{MSY}$ is considerably greater than 1, hence $F_{mult} < 1$ (Figure 52 and Figure 53, and Table 7). For the run for which steepness was estimated, Run15, $F_{current}/F_{MSY}$ = 1.13, which is lower than the estimates from the 2010 assessment; a more optimistic result. Yet a high proportion (90%) of the model runs undertaken in the structural uncertainty grid (Figure 57) had estimates of $\frac{F_{current}}{F_{MSY}} > 1$, with the grid median value being 1.42, (lower s.e. = 1.36). Only those runs exploring combinations for options at the extremes of the plausible range (steepness =0.95 and high juvenile mortality) produced estimates < 1 (Figure 58). **Based on these results, we conclude that overfishing is occurring in the bigeye 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 estimated total and spawning biomass that support the *MSY* are 35% and 29% of the

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

virgin total and spawning biomass (Table 7). These values are higher than estimated in 2010 due to the fixed steepness = 0.8. For the model where steepness was 0.95 (close to the estimated value), these quantities decrease to 31% and 24% respectively.

Comparing current biomass to the estimated virgin biomass ($B_{current}/B_0$ and $SB_{current}/SB_0$) for the Ref.case, it is predicted that current total and spawning biomass levels are 44% and 35% of the respective virgin biomass levels.

In addition, total biomass and spawning biomass are higher than the associated MSY levels, true for almost all model runs presented and for the period 2001-09 (Table 9). The estimates of stock status according to the total biomass reference points are influenced by the recent estimates of recruitment. For example, an exceptional case was for Run21 where MSY was calculated from the SRR derived from recruitments over the period 1989-2009, with an estimate of $SB_{current}/SB_{MSY}$ = 0.61 (Table 7).

The Kobe-plot enables trends in the status of the stock relative to F_{MSY}, B_{MSY}, and SB_{MSY} reference points to be followed over the model period. Trends for total biomass are provided in Figure 54 while the complementary spawning biomass plot is provided in Figure 55. The trends of the two are similar, with the spawning biomass values being lower on the biomass axis. Fishing mortality rates were moderate through to the 1970s at which they are estimated to have increased, exceeding F_{MSY} in the late 1980s and remaining above F_{MSY}ever since. While total biomass is estimated to have remained well above B_{MSY}, spawning biomass has been closer to SB_{MSY} in recent years, and below this level during the period 2001-09 for some of the sensitivity runs (Table 9).

The spawning biomass based Kobe plots for Run3j (Ref.case) and for a range of the one-off sensitivity runs are compared in Figure 56. The general temporal patterns of the two reference points are similar among the runs with differences in the estimates of current status. The reference point estimates of current status for the key runs subsequently included in the structural uncertainty analysis (grid), indicate $F_{current}$ to be exceeding F_{MSY} and spawning biomass close to, or coincident with, SB_{MSY} (Figure 57). An exception to this was the sensitivity model Run21, where equilibrium yields were calculated based upon a SRR derived from recruitment and spawning potential estimates for the past 20 years, i.e. recent high recruitment levels. In this model, the biomass that supports MSY is substantially higher than the Ref.case (Table 7), resulting in a considerably lower $SB_{current}/SB_{MSY}$ = 0.61, and higher $F_{current}/F_{MSY}$ = 1.58 (Figure 56).

In considering the results from the structural uncertainty analysis (grid, Figure 58), besides steepness, almost all options for the factors examined produced a proportion of runs with spawning biomass below SB_{MSY}. The range of grid estimates was reasonably broad, with a median value for $SB_{current}/SB_{MSY}$ = 1.37, (lower s.e. of 1.31). The probability that $SB_{current}$ and SB_{latest} exceed some of the more commonly applied SB-related reference points is provided in Table 10. There is a 13% probability that $SB_{current} < SB_{MSY}$, and this increases to 36% for SB_{latest}, reflecting the lower recruitment estimates for the most recent time periods. For the grid runs where steepness was fixed = 0.8 the probability that $SB_{current} < SB_{MSY}$, decreased to 0%, and the probability that $SB_{latest} < SB_{MSY}$, decreased to 26%.

A comparison of the grid results with that of the 2010 assessment is feasible since the range of steepness options considered was similar. The current assessment estimates were more optimistic, having a lower percentage of runs exceeding the reference point levels. Due to its direct effect on *MSY*-related reference points, steepness remains a key uncertainty and has the largest influence on our interpretation of stock status in the current assessment.

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 $SB_{F_{current}}/SB_{MSY}$). The Ref.case model predicts that the total and spawning biomasses would be reduced to 58% and 52% of the levels that support *MSY*, respectively. In terms of the reduction from the virgin spawning biomass level, the decline is greater, reaching as low as 15% for spawning biomass (Table 7). **Based on the results above, and the recent trend in spawning biomass, we conclude that bigeye tuna is approaching an overfished state. We note however, that if recent recruitment is assumed to represent the**

true productivity of the bigeye stock (Run21), then the higher levels of Bmsy and SBmsy implied would mean that bigeye tuna is already in an overfished state ($B_{F_{current}}/B_{MSY}$ = 0.67 and $SB_{F_{current}}/SB_{MSY}$ = 0.61).

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 the Ref.case, the MSY_t was 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 59). Prior to 1970, the WCPO bigeye fishery was almost exclusively conducted using longlines, with a low exploitation of small bigeye. The associated age-specific selectivity resulted in a substantially higher level of *MSY* (~150,000 mt per annum) compared to that estimated for the fishery based on the recent age-specific fishing mortality pattern (about 77,000 mt). The decline in the *MSY* over time follows the increased development of those fisheries that catch younger bigeye, principally the surface fisheries (Figure 59). Harley et al. (2010) demonstrated using a yield-per recruit analysis, that almost 75% of the potential *MSY* from the WCPO bigeye stock is not accessed by the current fishery composition due to the selectivity patterns for smaller and younger fish. **Based on these analyses, we conclude that MSY levels would increase if mortality of small fish were reduced which would allow greater overall yields to be sustainably obtained.**

7 Discussion and conclusions

Changes from the 2010 assessment

The relatively few new inputs and changes made in the 2011 bigeye stock assessment from 2010 have had a significant effect on the reference point estimates used for formulating management advice. Differences are due to new inputs: CPUE indices, purse seine catch and size composition data, and Japanese longline size composition data; but also to an important structural assumption, i.e. fixing steepness in the Ref.case model = 0.8. The effect of this structural assumption must be borne in mind when making comparisons with the previous bigeye assessment. Whereas the Ref.case estimates of stock status are not dissimilar from the 2010 base case estimates, the most comparable model undertaken in 2011, Run15, (estimate steepness) provides a more optimistic stock status. This difference indicates the effects of the new inputs. To clearly illustrate this, if one compares $F_{current}/F_{MSY}$ and $SB_{current}/SB_{MSY}$ between the straight-forward update of the 2010 model (Run2b) and Run15, the values are 1.49 and 1.33 versus 1.13 and 1.54, respectively. Now the effect of making the structural assumption to fix steepness = 0.8 increases the reference point values for the 2011 Ref.case model to 1.46 and 1.19.

In discussing the changes from the 2010 assessment, we make comparisons with the straight-forward update of the 2010 model (Run2b), since this run includes the effects of updating the time series, but without any methodological changes to the construction of the datasets or the model structure. This model estimated a continuation of the downward trend in biomass that was indicated from the 2010 base case. In the stepwise development, replacing the standardised Japanese longline CPUE time series with that derived from operational-level data increased SB_{MSY} by 30%, but also increased $SB_{current}$ by 56%. Together with the 26% decrease in $F_{current}/F_{MSY}$, the new time series resulted in substantially more optimistic estimates of stock status. The degree of this effect reflects the large differences in the time series' regional trends with relative abundance being higher in the early periods and stable or increasing in the past 10 – 20 years for regions 1 to 4, hence, higher stock productivity was estimated.

The effects of the new CPUE time series were lessened somewhat after including the corrected purse seine catch and size estimates, the reweighted Japanese size data, and the PTTP data. The cumulative effects of these new inputs are represented in Run3h, where the percentage difference in these reference points relative to Run2b were an increase of 18% and 37% for SB_{MSY} and $SB_{current}$, and a 23% decrease in $F_{current}/F_{MSY}$. The mechanisms for these changes have been described earlier (see section 6.1), but essentially they relate to: less decline in median size for all regions besides region 3 in the reweighted size data which reduces the declining trend in biomass; higher juvenile mortality indicated in the corrected purse seine catch data which reduces the associated selectivity at age and hence the MSY-related reference point estimates; and, a 10% increase in very recent biomass as a result fitting to the PTTP data.

To understand the effect of fixing steepness at 0.8, it is useful to compare the model Run3i which includes this change, with the preceding Run3h, which incorporated the new inputs but for which steepness was estimated. Lower steepness changes the stock-production function, increasing SB_{MSY} by 32%, but has almost no effect on $SB_{current}$. It increases $F_{current}/F_{MSY}$ by 29%, resulting in more pessimistic estimates of stock status. The final combined effect of the new inputs and the assumption for steepness produced a 2011 Ref.case model not dissimilar from the Run2b, with $F_{current}/F_{MSY}$ of the same value, but with $SB_{current}/SB_{MSY}$ 11% lower. This brings the 2011 Ref.case into a similar order of stock status as reported in the 2010 assessment, but must be considered in light of this change in the assumption for steepness.

Sources of uncertainty

There is a major source of uncertainty in this assessment which results in the increasing trend in historical recruitments in region 3, and which has prevailed in previous bigeye assessments (Harley et al. 2010). Several of the one-off sensitivity runs presented here serve only to illustrate the effects of alternative assumptions upon this trend. A significant feature of this assessment has been the amelioration of this trend somewhat due to the new inputs. Whereas the ratio of recent to historical average recruitments was 2.02 for the 2010 base case, this ratio decreased to 1.72 in the Ref.case. A key driver in this change was the new CPUE time series that initially reduced the ratio to 1.33, but following inclusion of the other new inputs, the ratio increased to the Ref.case level.

This change in the recruitment trend may well relate to less conflict among the data compared to the 2010 assessment. An improvement in the model fit diagnostics to the size frequency data is reported, even with high relative weight assigned to the length frequency component. It seems the new CPUE time series is reasonably consistent with the reweighted Japanese size data, and this view is reinforced by the lack of sensitivity to the Ref.case estimates when lower relative weight is assigned (Run11). While there remains a discrepancy among the trends in length and weight frequency data in region 3, generally the new inputs appear to have reduced the degree of conflict among the data for the other regions.

The effects of the uncertain recruitment trend on management quantities are profound, and the alternative assumptions result in a lower biomass relative to *MSY* reference point levels. This is illustrated by model runs that excluded the early part of the time series (Run5 – excl.pre75CPUE) and a run using a SRR derived on the most recent average recruitments in calculating equilibrium yields (Run21 – MSY_89_09). In both cases SB_{MSY} increases (22% and 68%, respectively), resulting in a poorer stock status in terms of current biomass, with $SB_{current}/SB_{MSY}$ as low as 0.61 in the case of Run21, but less than a 10% change in the fishing mortality reference point. While excluding the early part of the CPUE time series almost removes the overall trend in recruitment (ratio = 1.14), the distinct two-phase nature of the recruitments raises questions as to its plausibility. In addition, the recruitment trend should not be seen in isolation – it may be indicative of problems elsewhere. For example, it is shown that region-specific differences in growth substantially affect the model estimates, including recruitments (Nicol et al. 2011). Investigating the source of uncertainty that produces this trend bigeye recruitment will remain an important focus for development in future assessments.

Also in relation to the recruitment estimates, the other major source of uncertainty in this assessment is steepness. As mentioned in previous bigeye assessments there is little information available with which to estimate this biological parameter, and nothing further of substance has been added to the current assessment that changes this predicament. Consequently, the parsimonious approach has again been taken to explore model sensitivity to this parameter over a plausible range (in the structural uncertainty analysis) and from which to summarise the management quantities.

Several features of the model fit to observations indicated uncertainty, either in relation to the observations or to the assumed model processes, namely the CPUE time series for region 6 and the PTTP recaptures in region 4. The CPUE time series based upon operational level data lacked observations for much of the past 20 years in region 6, due to lack of sufficient data. In contrast the standardised Taiwanese longline series tested in Run9 was complete. Diagnostics of the model fit to these indices appeared satisfactory, and the region 6 recruitments seemed plausible. Including this alternative series addresses a source of model uncertainty and may warrant being part of the reference case models for future assessments. Lacking GLM estimates of temporal coefficients of variation meant this series was considered only as an alternative for the 2011 assessment.

Although including the PTTP data had only a small effect on management quantities, diagnostics of the model fit to these data raised important questions that should be addressed to avoid uncertainty in future assessments. Including the PTTP data increased biomass estimates by 10% in the most recent 3-5 years, but signs of data conflict were evident in the purse seine (associated) fishery in region 4 for which relatively large catch deviations were estimated in 2008-10, and the reporting rate was at the upper bound. This fishery accounted for a high proportion of PTTP recaptures and the possibility of mis-specification in model recapture probabilities will translate to biomass estimates, perhaps becoming more important in future assessments as data conflicts develop as a result. Likely causes for the data conflict with the PTTP data in region 4 identified here included negative bias in the corrected purse seine catch estimates, and the relative abundance indices in region 3. Observer coverage of purse seine catches in region 4 have been reasonably good through time – so it is unlikely the lower corrected catches relate to poor sampling coverage. This issue warrants closer examination than was possible for this assessment, as do the assumptions made regarding fish movement across the eastern boundary of region 4 with the Eastern Pacific Ocean and their effect on the tag-recapture estimator implicit in the model.

The level of uncertainty in management quantities associated with assumed natural mortality for bigeye was substantial, with a 30% decrease in SB_{MSY}, which prompts a detailed consideration of this parameter in future assessments. A suggested approach is to derive estimates for natural mortality at age from model estimates based upon a fit to tagging data primarily, (pers. comm. John Hampton, SPC), and then to assume these as constants when fitting the model to all observations.

Main conclusions

The main conclusions of the current assessment (based upon the median of the uncertainty grid estimates, and the sensitivity model runs) are as follows.

1. The estimated increasing trend in recruitment from recent bigeye assessments appears to have been addressed to a small extent in the current assessment, but remains an issue in region 3 and is primarily the result of conflict (disagreement) among the various data sources, in particular between the longline CPUE indices and the reported catch histories, and between and within some of the size composition data sets. The current assessment has indentified some of these conflicts and includes some model runs that begin to address them.
2. As in previous assessments, recruitment in almost all models is estimated to have been high during 1995–2005. As suggested in the 2010 assessment, an analysis is presented that estimates the stock-recruitment relationship (with steepness fixed) for this latter period and applied it in the yield analyses. If one considers the recruitment estimates in the second half of the time series to be more plausible and representative of the overall productivity of the bigeye stock, the results of this analysis (Run21) could be used for formulating management advice. In this case $F_{current}/F_{MSY}$ was 1.58 and $SB_{current}/SB_{MSY}$ was 0.61indicating that we would conclude that the stock is overfished and overfishing is occurring under this productivity assumption. The main reason for the much lower estimate of $SB_{current}/SB_{MSY}$ is that $SB_{MSY}$is approximately doubled because of the higher levels of recruitment being used to estimate it.

3. Total and spawning biomass for the WCPO are estimated to have declined to about half of their initial levels by the mid-1970s, with total biomass remaining relatively constant since then ($B_{current}/B_0$= 44%), while spawning biomass has continued to decline ($SB_{current}/SB_0$=35%). Declines are larger for models that exclude the early periods of the CPUE time series.

4. When the non-equilibrium nature of recent recruitment is taken into account, we can estimate the level of depletion that has occurred. It is estimated that spawning potential is at 26% of the level predicted to exist in the absence of fishing considering the average over the period 2006-09, and that value is reduced to 23% for the 2010 spawning potential levels.

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

6. Recent catches are well above the *MSY* level of 74,993 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 and recent mix of fisheries persist, catches are still around 7% higher than the re-calculated *MSY* (131,400 mt). **Based on these results, we conclude that current levels of catch are unlikely to be sustainable in the long term even at the recent [high] levels of recruitment estimated for the last two decades**.

7. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. For all of the model runs $F_{current}/F_{MSY}$ is considerably greater than 1. For the grid median, the ratio is estimated at 1.42 indicating that a 30% reduction in fishing mortality is required from the 2006-09 level to reduce fishing mortality to sustainable levels. Using the Ref.case, if we consider historical levels of fishing mortality, a 39% reduction in fishing mortality from 2004 levels is required, and a 28% reduction from average 2001-04 levels. Larger reductions in fishing mortality are indicated when lower values of steepness are assumed. **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 65% and 60% of the level that supports *MSY*. In terms of the reduction against virgin biomass the declines reach as low as 15% of spawning potential. Current stock status compared to these reference points indicate the current total and spawning biomass are higher than the associated MSY levels ($\frac{B_{current}}{B_{MSY}} = 1.34$ and $\frac{SB_{current}}{SB_{MSY}} = 1.37$). The structural uncertainty analysis indicates a 13% probability that $SB_{current} < SB_{MSY}$. **Based on these results above, and the recent trend in spawning biomass, we conclude that bigeye tuna is approaching an overfished state. We note however, that if recent recruitment is assumed to represent the true productivity of the bigeye stock (Run21), then the higher levels of Bmsy and SBmsy implied would mean that bigeye tuna is already in an overfished state ($B_{current}/B_{MSY}$ = 0.67 and $SB_{current}/SB_{MSY}$ 0.61).**

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

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

General Recommendations

- The SC considers the frequency of assessments for the key tuna species, and the relative priority of other investigations of inputs to the models and examination of model assumptions, as are required to address key areas of uncertainty in the assessments.

MULTIFAN-CL/Modelling

- The current development of functionality in MULTIFAN-CL for multiple species/stocks/sexes be supported.
- Examine the implications of regional growth variation for stock assessment results, via simulation and region-scale models.
- MULTIFAN-CL be modified to allow the incorporation of direct ageing and tag-based length increment observations to improve the estimation of growth.
- Alternative functional forms, including length-based selectivity be considered for the Indonesia and Philippines small-fish domestic fisheries (fisheries 18 and 24).
- Estimate natural mortality from dedicated model fits to tagging data.

Data analysis

- Work to improve approaches to the modelling of CPUE data should continue. This is the highest priority activity to support the assessment.
- Detailed investigations be undertaken of the Japanese longline length data throughout the WCPO and other length and weight frequency data from longline fisheries in regions 3 and 4. Such investigations will require details of sampling protocols and operational level CPUE data. Collaborations with national scientists will be important if these data continue to not be provided to the WCPFC due to domestic legal constraints.
- Analyses of operational data for the fishery 5 fleets (“off-shore” operations) to determine the most appropriate grouping of the fleets and time periods into MULTIFAN-CL fisheries.
- Analysis of PTTP data in region 4 and the adjacent EPO to examine mixing processes.
- Analysis of available tagging data to examine the juvenile mortality rates of bigeye.

Data improvement

- Direct ageing of bigeye tuna, in particular throughout the WCPO so as to characterise any regional differences in growth.
- Continued experiments and activities to improve purse seine catch and size composition estimates, in particular spill sampling estimates of catches in region 4. Further development of cannery data sources may also be useful.
- Continuation of the work to refine both the species composition and total catches from the domestic fisheries that occur in Indonesia and the Philippines.
- Continuation of tag seeding work, to provide better estimates of tag reporting rates, particularly in region 4.

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

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

Table 2. Number of tagged fish released and recaptured by program, release group, region, and time period input to the 2011 assessment with the totals including and excluding the PTTP samples.

Release grp	Program	Reg	Year	Month	nRel	nRec
1	RTTP	3	1989	11	29	8
2	RTTP	3	1990	2	411	24
3	RTTP	3	1990	5	281	39
4	RTTP	3	1990	8	142	9
5	RTTP	3	1991	2	81	10
6	RTTP	3	1991	5	15	3
7	RTTP	3	1991	8	153	48
8	RTTP	3	1992	2	12	0
9	RTTP	3	1992	8	1020	254
10	RTTP	3	1992	11	319	102
11	PTTP	3	2006	8	300	143
12	PTTP	3	2006	11	251	76
13	PTTP	3	2007	2	25	2
14	PTTP	3	2007	5	64	1
15	PTTP	3	2007	11	53	6
16	PTTP	3	2008	2	314	42
17	PTTP	3	2008	5	264	84
18	PTTP	3	2008	8	80	6
19	PTTP	3	2008	11	800	185
20	PTTP	3	2009	2	357	114
21	PTTP	3	2009	5	45	3
22	PTTP	3	2009	8	188	52
23	PTTP	3	2009	11	478	79
24	RTTP	4	1991	8	60	4
25	RTTP	4	1992	2	232	24
26	RTTP	4	1992	5	825	78
27	PTTP	4	2008	5	1383	435
28	PTTP	4	2009	5	4067	488
29	PTTP	4	2009	11	1653	441
30	RTTP	5	1991	2	181	18
31	RTTP	5	1991	11	3564	216
32	RTTP	5	1992	11	557	36
33	CS	5	1995	11	173	23
34	CS	5	1999	11	64	4
35	CS	5	2001	11	474	62
36	PTTP	5	2009	2	41	6
	Total				18956	3125
	Total excluding PTTP				8593	962

Table 3. Summary of the stepwise development model runs undertaken for the 2011 bigeye tuna assessment leading to the Reference case. Run4 to Run21 are one-off sensitivities to the Reference case, and those in **bold** are key model runs for the assessment.

Run	Name	Description
2010_run3d	2010 base case run3d	Run 3d (spill sample catches) from the 2010 assessment.
Run2b	run 3d pdated to 2011	Updated data according to the 2010 model structure to 2011, including spill sample catch estimates for purse seine fisheries.
Run3a	2011 fishery structure	New fishery definitions for Indonesian-Philippines fisheries adding fishery 26: PH-ID PS 3. 2011 data updated as per Run2b, including revised ID/PH and spill sample catch estimates.
Run3b	CPUE_temporal	Temporal weighting on Japanese longline aggregate standardised effort.
Run3c	Operational CPUE	As per 3b, but with Japanese longline standardised effort from operational level data (Hoyle and Okamoto 2011), uses core area in region 3.
Run3d	OpCPUE_temporal	As per 3c, temporal weighting on operational standardised effort.
Run3e	Spill_sz_corrected	As per 3d, but with purse seine size data corrected using spill samples.
Run3f	Size data reweighted	As per 3e, but length and weight frequency data from Japanese longline fisheries reweighted by within-region relative abundance.
Run3f_2	Hi_weight on LF	As per 3f_2, but high weight to length data for fisheries 1, 2, 4, 7, 10, 12, by 20 (compared to 1000).
Run3g	PTTP tag data - fishery-grp RRs	As per 3f_2, but include PTTP tagging data, and estimate tag reporting rates specific to recapture fishery groups.
Run3h	Release and fishery-grp RRs	As per 3g, but estimate tag reporting rates specific to tag release groups and recapture fishery groups.
Run3i	Steepness0.8	As per 3h, but with stock recruitment relationship steepness = 0.8.
Run3j	**Ref.case**	As per 3i, but with high penalty on catch weight likelihood.
Run4	**SBEST**	Replace PS catches and size frequencies with SBEST (uncorrected).
Run5	**excl.pre75CPUE**	Exclude Japanese LL standardised effort pre-1975, regions 1-6.
Run6	excl.pre90CPUE	Exclude Japanese LL standardised effort pre-1990, regions 1-6.
Run7	excl.post90CPUE	Exclude Japanese LL standardised effort post-1990, regions 1-6.
Run8	Reg3_whole_CPUE	Japanese LL standardised effort uses whole area for region 3.
Run9	TW_CPUE_Reg6	Taiwanese LL standardised effort used for region 6.
Run10	**aggCPUE**	Replace operational standardised effort with that from aggregate data.
Run11	**lowtLF**	Low weight to length data for fisheries 1, 2, 4, 7, 10, 12, (assume 50).
Run12	**excl.PTTP**	Exclude PTTP tagging data.
Run13	**h0.65**	Assume stock recruitment relationship steepness = 0.65.
Run14	**h0.95**	Assume stock recruitment relationship steepness = 0.95.
Run15	h_est	Estimate stock recruitment relationship steepness.
Run16	hijuvM4	Assume YFT juvenile mortality for time periods 1 to 4.
Run17	**hijuvM**	Assume YFT juvenile mortality for time periods 1 to 8.
Run18	Tagmix3	Assume 3 time periods for tagged fish mixing.
Run19	sep_sel3&4	Decouple longline and purse seine selectivities for regions 3 & 4.
Run20	LL_09to10	Carry over 2009 catches to 2010 for fisheries 1, 2, 4, 7, 10, and 12.
Run21	MSY_89_09	Stock recruitment relationship calculated over 1989-2009 used for determining equilibrium yield.

Table 4: Comparison of the main assumptions of the base model from the 2010 assessment (run 3d), with the Ref.case model for the 2011 assessment (Run3j) and the alternative assumptions to be tested in other key model runs undertaken for the 2011 assessment, as recommended by the PAW.

Component	**2010 assessment (run 3d)**	**2011 assessment (Run3j)**	**2011 alternatives**
Fishery 18 and 24 (PHI and ID DOM)	Included domestic Purse seine fisheries	New fishery 26 for domestic purse seine fisheries; updated size data and revised catch estimates.	
Purse seine catches	Spill sample corrected	Spill sample corrected	Grab sample (SBEST)
Japanese length frequency data	Excluded observations from 1954-65	Excluded observations from 1954-65	
Fishery 8 (CN/TW LL in region 4)	Excluded length and weight observations and dome-shaped selectivity linked to fisheries 4, 7, 10, and 12	Excluded length and weight observations and dome-shaped selectivity linked to fisheries 4, 7, 10, and 12	
Longline CPUE	Aggregate indices, no temporal weighting of standardised effort	Operational indices, temporal weighting of standardised effort	- Exclude all CPUE prior to 1975 - Aggregate indices
Steepness	Estimated	Fixed = 0.8	0.65, 0.95
Tagging data	Excluded PTTP	Included PTTP	Exclude PTTP
Longline size data	Down-weighted	Full weight	Down-weighted
Natural mortality	Base	Base	Increased for juveniles

Table 5. Description of symbols used in the yield analysis. For the purpose of this assessment, 'current' is the average over the period 2005-2008 and 'latest' is 2009.

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

[10] Some recent period used for the purpose of averaging fishing mortality or other quantities. Typically excludes the most recent year due to uncertainty, but covers the preceding four years, e.g. 2006-2009.

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

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

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

Table 6. Some performance statistics for the model runs described in Table 3. $\boldsymbol{Rec_{ratio}}$ is the average recruitment for the second half the of the model period divided by the average for the first half. Note that the MSY-related quantities are not comparable between 2010_run3d and the other model runs due to the different time windows used in each.

Run	MSY	$F_{current}/F_{MSY}$	$SB_{current}/SB_{MSY}$	Rec_{ratio}	***steepness***	**Obj. Fnt value**	**npars**	**gradient**
2010_run3d	73,840	1.41	1.34	2.02	0.98	1061612	5941	0.06
Run2b	73,640	1.49	1.33	2.07	0.98	1089963	6006	0.01
Run3a	73,280	1.46	1.26	2.05	0.98	1083527	6168	0.00
Run3b	76,720	1.34	1.42	1.86	0.97	1084255	6168	0.00
Run3c	92,320	1.06	1.61	1.33	0.93	1083929	6168	0.00
Run3d	88,280	1.10	1.61	1.44	0.95	1083542	6168	0.00
Run3e	78,680	1.26	1.52	1.80	0.97	1057665	6168	0.05
Run3f	83,800	1.18	1.56	1.64	0.96	960554	6168	0.00
Run3f_2	82,680	1.23	1.54	1.74	0.96	1070130	6168	0.01
Run3g	82,480	1.17	1.53	1.74	0.97	1068680	6168	0.00
Run3h	83,480	1.15	1.56	1.74	0.97	1068674	6179	0.02
Run3i	75,960	1.48	1.21	1.72	0.80	1068675	6178	0.02
Run3j	**76,760**	**1.46**	**1.19**	**1.72**	**0.80**	**1068599**	**6178**	**0.05**
Run4	65,000	1.33	1.38	1.42	0.80	1094303	6099	0.02
Run5	97,120	1.35	1.03	1.14	0.80	1069065	6178	0.04
Run6	94,280	1.31	1.15	1.19	0.80	1069433	6178	0.04
Run7	94,800	1.09	1.49	1.27	0.80	1069138	6178	0.04
Run8	75,560	1.55	1.15	1.73	0.80	1068939	6178	0.00
Run9	78,000	1.38	1.26	1.62	0.80	1068671	6178	0.03
Run10	74,120	1.67	1.05	1.87	0.80	1069342	6178	0.03
Run11	76,720	1.44	1.22	1.73	0.80	964827.8	6178	0.01
Run12	76,400	1.55	1.21	1.69	0.80	1070008	6167	0.00
Run13	70,080	1.84	0.98	1.69	0.65	1068594	6178	0.04
Run14	83,720	1.16	1.49	1.73	0.95	1068602	6178	0.05
Run15	84,560	1.13	1.54	1.73	0.97	1068602	6179	0.05
Run16	76,360	1.40	1.27	1.67	0.80	1068541	6178	0.04
Run17	77,360	1.39	1.34	1.51	0.80	1068567	6178	0.00
Run18	81,200	1.33	1.26	1.67	0.80	1068730	6178	0.05
Run19	77,640	1.48	1.15	1.70	0.80	1068654	6193	0.02
Run20	77,400	1.44	1.19	1.72	0.80	1068584	6178	0.02
Run21	131,400	1.58	0.61	1.85	0.8	1068658	6178	0.02

Table 7. Estimates of management quantities for the selected stock assessment models and the structural uncertainty analysis (grid). 'Current' is the average over the period 2006-2009 and 'latest' is 2010.

	Run3j (Ref.case)	Run4 (SBEST)	Run5 (excl.pre75 CPUE)	Run10 (aggCPUE)	Run11 (lowtLF)	Run12 (exclPTTP)	Run13 (h=0.65)	Run14 (h=0.95)
$C_{current}$	141,160	122,836	140,242	141,561	140,067	143,477	141,365	141,029
C_{latest}	116,868	98,289	116,078	117,558	115,833	120,215	117,118	116,712
$Y_{F_{current}}$	68,320	61,360	90,920	58,280	69,200	64,960	41,720	82,800
$Y_{F_{MSY}}$ or MSY	76,760	65,000	97,120	74,120	76,720	76,400	70,080	83,720
$Y_{F_{current}}/MSY$	0.89	0.94	0.94	0.79	0.90	0.85	0.60	0.99
$C_{current}/MSY$	1.84	1.89	1.44	1.91	1.83	1.88	2.02	1.69
C_{latest}/MSY	1.52	1.51	1.20	1.59	1.51	1.57	1.67	1.39
F_{MSY}	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.05
F_{mult}	0.68	0.75	0.74	0.60	0.70	0.65	0.54	0.86
$F_{current}/F_{MSY}$	1.46	1.33	1.35	1.67	1.44	1.55	1.84	1.16
B_0	1,432,000	1,145,000	1,760,000	1,333,000	1,446,000	1,451,000	1,567,000	1,351,000
B_{MSY}	498,500	409,800	615,400	467,700	503,400	504,300	599,500	413,200
B_{MSY}/B_0	0.348	0.358	0.35	0.351	0.348	0.348	0.383	0.306
$B_{current}$	623,121	585,664	664,055	526,543	632,847	626,401	642,351	610,446
B_{latest}	626,634	608,385	685,045	495,007	632,509	564,216	641,170	616,976
$B_{F_{current}}$	289,000	284,800	414,000	207,400	302,100	261,400	181,400	343,800
$B_{current_{F=0}}$	2,161,465	1,697,905	2,160,075	2,048,449	2,155,808	2,182,690	2,177,032	2,152,443
$B_{latest_{F=0}}$	2,140,654	1,762,922	2,143,356	1,991,025	2,133,316	2,078,068	2,151,220	2,134,736
SB_0	739,900	586,200	909,900	688,400	733,800	756,600	810,000	698,500
SB_{MSY}	214,800	173,500	263,100	199,900	213,700	220,100	270,700	166,900
SB_{MSY}/SB_0	0.29	0.296	0.289	0.29	0.291	0.291	0.334	0.239
$SB_{current}$	255,293	239,208	271,045	209,854	259,877	266,649	265,930	248,336
SB_{latest}	232,248	222,148	257,196	175,565	230,792	224,239	241,136	226,428
$SB_{F_{current}}$	111,500	111,400	162,700	74,740	116,000	100,200	70,670	131,900
$SB_{current_{F=0}}$	1,124,945	867,244	1,123,857	1,071,637	1,104,680	1,157,837	1,133,702	1,120,185
$SB_{latest_{F=0}}$	1,091,878	863,387	1,088,850	1,026,397	1,065,982	1,104,353	1,098,850	1,088,250
$B_{current}/B_0$	0.44	0.51	0.38	0.40	0.44	0.43	0.41	0.45
B_{latest}/B_0	0.44	0.53	0.39	0.37	0.44	0.39	0.41	0.46
$B_{F_{current}}/B_0$	0.20	0.25	0.24	0.16	0.21	0.18	0.12	0.25
$B_{current}/B_{MSY}$	1.25	1.43	1.08	1.13	1.26	1.24	1.07	1.48
B_{latest}/B_{MSY}	1.26	1.49	1.11	1.06	1.26	1.12	1.07	1.49
$B_{F_{current}}/B_{MSY}$	0.58	0.70	0.67	0.44	0.60	0.52	0.30	0.83
$B_{current}/B_{current_{F=0}}$	0.29	0.35	0.31	0.26	0.29	0.29	0.30	0.28
$B_{latest}/B_{latest_{F=0}}$	0.29	0.35	0.32	0.25	0.30	0.27	0.30	0.29
$SB_{current}/SB_0$	0.35	0.41	0.30	0.31	0.35	0.35	0.33	0.36
SB_{latest}/SB_0	0.31	0.38	0.28	0.26	0.32	0.30	0.30	0.32
$SB_{F_{current}}/SB_0$	0.15	0.19	0.18	0.11	0.16	0.13	0.09	0.19
$SB_{current}/SB_{MSY}$	1.19	1.38	1.03	1.05	1.22	1.21	0.98	1.49
SB_{latest}/SB_{MSY}	1.08	1.28	0.98	0.88	1.08	1.02	0.89	1.36
$SB_{F_{current}}/SB_{MSY}$	0.52	0.64	0.62	0.37	0.54	0.46	0.26	0.79
$SB_{curr}/SB_{curr_{F=0}}$	0.23	0.28	0.24	0.20	0.24	0.23	0.24	0.22
$SB_{latest}/SB_{latest_{F=0}}$	0.21	0.26	0.24	0.17	0.22	0.20	0.22	0.21
Steepness (h)	0.80	0.80	0.80	0.80	0.80	0.80	0.65	0.95

Table 7 cont.

	Run3j (Ref.case)	Run17 (hijuvM)	Run21 (MSY_89_09)	Grid median	Grid 5%ile	Grid 95%ile
$C_{current}$	141,160	141,550	140,808	131,462	120,755	142,826
C_{latest}	116,868	118,566	116,973	108,642	97,695	120,071
$Y_{F_{current}}$	68,320	70,800	109,920	64,083	29,230	92,858
$Y_{F_{MSY}}$ or MSY	76,760	77,360	131,400	74,993	57,250	97,536
$Y_{F_{current}}/MSY$	0.89	0.92	0.84	0.84	0.4769	0.99915
$C_{current}/MSY$	1.84	1.83	1.07	1.78	1.40	2.13
C_{latest}/MSY	1.52	1.53	0.89	1.47	1.15	1.80
F_{MSY}	0.04	0.05	0.04	0.05	0.03	0.07
F_{mult}	0.68	0.72	0.63	0.75	0.51	1.13
$F_{current}/F_{MSY}$	1.46	1.39	1.58	1.42	0.89	1.96
B_0	1,432,000	1,155,000	2,405,000	1,231,299	873,215	1,658,150
B_{MSY}	498,500	406,800	840,900	436,754	302,300	606,535
B_{MSY}/B_0	0.35	0.35	0.35	0.35	0.30	0.40
$B_{current}$	623,121	552,314	560,064	565,173	428,147	668,375
B_{latest}	626,634	474,400	576,887	510,196	351,219	659,953
$B_{F_{current}}$	289,000	260,600	422,000	265,968	110,541	425,520
$B_{current_{F=0}}$	2,161,465	1,631,199	2,123,076	1,667,458	1,185,516	2,171,401
$B_{latest_{F=0}}$	2,140,654	1,530,958	2,116,116	1,611,011	1,136,852	2,143,190
SB_0	739,900	568,400	1,243,000	617,718	423,765	858,690
SB_{MSY}	214,800	149,600	361,000	173,487	94,578	270,835
SB_{MSY}/SB_0	0.29	0.26	0.29	0.28	0.20	0.34
$SB_{current}$	255,293	200,825	220,869	222,324	147,295	276,837
SB_{latest}	232,248	164,875	202,610	187,293	112,958	250,077
$SB_{F_{current}}$	111,500	82,280	157,200	93,873	32,780	153,330
$SB_{current_{F=0}}$	1,124,945	824,674	1,102,547	853,166	594,690	1,125,393
$SB_{latest_{F=0}}$	1,091,878	774,895	1,074,591	815,796	576,060	1,088,727
$B_{current}/B_0$	0.44	0.48	0.23	0.47	0.38	0.58
B_{latest}/B_0	0.44	0.41	0.24	0.42	0.33	0.53
$B_{F_{current}}/B_0$	0.20	0.23	0.18	0.22	0.09	0.35
$B_{current}/B_{MSY}$	1.25	1.36	0.67	1.34	1.01	1.71
B_{latest}/B_{MSY}	1.26	1.17	0.69	1.20	0.84	1.59
$B_{F_{current}}/B_{MSY}$	0.58	0.64	0.50	0.65	0.22	1.13
$B_{current}/B_{current_{F=0}}$	0.29	0.34	0.26	0.35	0.28	0.45
$B_{latest}/B_{latest_{F=0}}$	0.29	0.31	0.27	0.32	0.25	0.41
$SB_{current}/SB_0$	0.35	0.35	0.18	0.36	0.29	0.46
SB_{latest}/SB_0	0.31	0.29	0.16	0.31	0.23	0.39
$SB_{F_{current}}/SB_0$	0.15	0.15	0.13	0.15	0.06	0.25
$SB_{current}/SB_{MSY}$	1.19	1.34	0.61	1.37	0.92	2.06
SB_{latest}/SB_{MSY}	1.08	1.10	0.56	1.14	0.75	1.70
$SB_{F_{current}}/SB_{MSY}$	0.52	0.55	0.44	0.60	0.19	1.20
$SB_{curr}/SB_{curr_{F=0}}$	0.23	0.24	0.20	0.26	0.20	0.35
$SB_{latest}/SB_{latest_{F=0}}$	0.21	0.21	0.19	0.23	0.17	0.32
Steepness (h)	0.80	0.80	0.80	-	-	-

Table 8. Comparison of historical estimates of $\boldsymbol{F_{current}/F_{MSY}}$ for each year from 2001-2009 and the average for the period 2001-04 for the Ref.case and one-off sensitivity model runs described in Table 2.

	$F_{current}/F_{MSY}$									
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2001-04
Run3j	1.28	1.51	1.11	1.65	1.43	1.64	1.33	1.42	1.46	1.39
Run4	1.21	1.26	1.23	1.36	1.27	1.43	1.28	1.38	1.24	1.27
Run5	1.20	1.38	1.13	1.58	1.35	1.52	1.21	1.30	1.35	1.32
Run6	1.17	1.33	1.04	1.55	1.32	1.50	1.17	1.28	1.30	1.28
Run7	1.04	1.18	0.92	1.32	1.14	1.27	0.95	1.05	1.11	1.11
Run8	1.31	1.55	1.14	1.69	1.47	1.71	1.40	1.52	1.57	1.42
Run9	1.21	1.42	1.03	1.57	1.34	1.54	1.25	1.35	1.39	1.31
Run10	1.37	1.63	1.21	1.79	1.56	1.81	1.51	1.66	1.71	1.50
Run11	1.25	1.46	1.08	1.60	1.41	1.58	1.33	1.41	1.43	1.35
Run12	1.25	1.51	1.08	1.65	1.41	1.65	1.34	1.53	1.69	1.37
Run13	1.60	1.88	1.38	2.06	1.79	2.06	1.67	1.78	1.85	1.73
Run14	1.03	1.20	0.89	1.31	1.14	1.31	1.06	1.13	1.16	1.11
Run15	1.00	1.16	0.87	1.27	1.11	1.27	1.03	1.10	1.12	1.08
Run16	1.21	1.45	1.04	1.58	1.36	1.55	1.29	1.35	1.41	1.32
Run17	1.11	1.35	0.96	1.48	1.24	1.46	1.25	1.35	1.51	1.22
Run18	1.22	1.43	1.04	1.55	1.34	1.51	1.24	1.28	1.30	1.31
Run19	1.30	1.55	1.15	1.69	1.46	1.67	1.35	1.43	1.46	1.42
Run20	1.28	1.50	1.11	1.64	1.42	1.63	1.32	1.39	1.42	1.38

Table 9. Comparison of the historical estimates of $\boldsymbol{SB_{current}/SB_{MSY}}$ for each year from 2001-2009 for the Ref.case and one-off sensitivity model runs described in Table 2.

	$SB_{current}/SB_{MSY}$								
	2001	2002	2003	2004	2005	2006	2007	2008	2009
Run3j	1.14	1.07	1.06	1.28	1.25	1.27	1.19	1.17	1.13
Run4	1.27	1.22	1.22	1.50	1.43	1.46	1.38	1.37	1.32
Run5	0.98	0.92	0.90	1.12	1.08	1.10	1.02	1.01	0.99
Run6	1.08	1.04	1.03	1.26	1.20	1.25	1.17	1.12	1.08
Run7	1.26	1.25	1.27	1.58	1.52	1.59	1.51	1.46	1.42
Run8	1.12	1.05	1.03	1.24	1.21	1.23	1.15	1.13	1.07
Run9	1.18	1.13	1.12	1.32	1.29	1.33	1.26	1.24	1.21
Run10	1.11	1.02	0.99	1.18	1.14	1.14	1.06	1.03	0.97
Run11	1.17	1.11	1.09	1.30	1.27	1.29	1.22	1.20	1.16
Run12	1.17	1.11	1.13	1.34	1.30	1.31	1.22	1.19	1.13
Run13	0.95	0.89	0.89	1.05	1.04	1.05	0.98	0.97	0.93
Run14	1.41	1.34	1.30	1.61	1.56	1.58	1.48	1.46	1.43
Run15	1.45	1.38	1.34	1.66	1.61	1.63	1.53	1.51	1.48
Run16	1.22	1.14	1.14	1.37	1.35	1.36	1.26	1.25	1.20
Run17	1.30	1.23	1.25	1.51	1.46	1.48	1.35	1.31	1.22
Run18	1.20	1.13	1.12	1.34	1.32	1.33	1.25	1.25	1.21
Run19	1.12	1.05	1.03	1.23	1.20	1.22	1.15	1.14	1.10

Run20	1.14	1.07	1.06	1.28	1.25	1.27	1.19	1.18	1.14

Table 10. Estimates of the probability that $\boldsymbol{SB_{current}}$ and $\boldsymbol{SB_{latest}}$ are less than some commonly used spawning biomass reference points based on all the 138 model runs undertaken for the structural uncertainty analysis (All grid), and for those grid runs with steepness fixed equal to 0.8.

	Structural uncertainty	
	$\boldsymbol{SB_{current}}$	$\boldsymbol{SB_{latest}}$
	All grid	
$p(x < SB_{MSY})$	13%	36%
$p(x < 0.5SB_{MSY})$	0%	0%
$p(x < 0.2SB_0)$	0%	0%
$p(x < 0.2SB_{F=0})$	5%	22%
	Only *h*=0.8	
$p(x < SB_{MSY})$	0%	26%
$p(x < 0.5SB_{MSY})$	0%	0%
$p(x < 0.2SB_0)$	0%	0%
$p(x < 0.2SB_{F=0})$	7%	24%

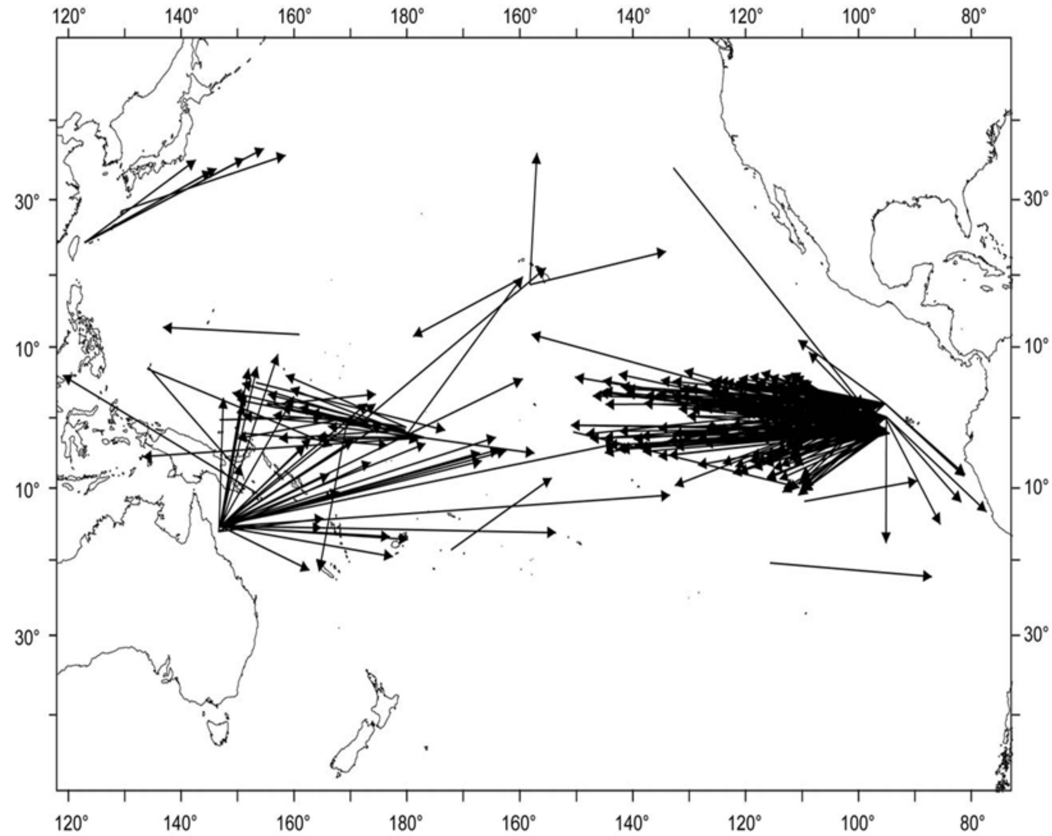


Figure 1. Long-distance (greater than 1,000 nmi) movements of tagged bigeye tuna in the Pacific Ocean (from Schaefer and Fuller 2009).

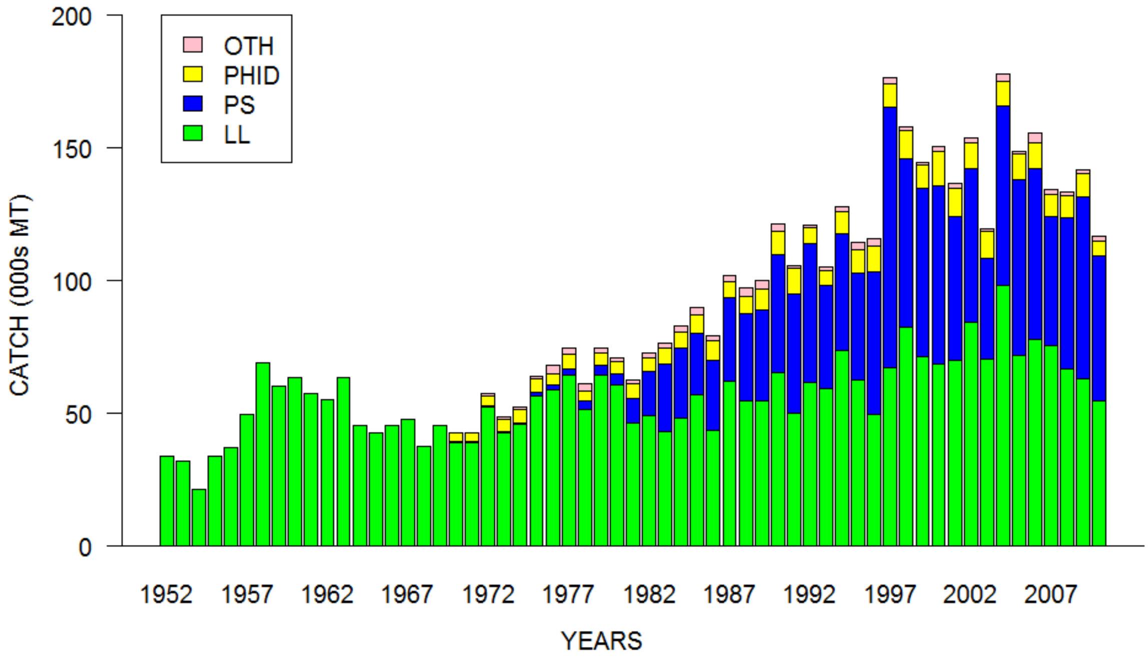


Figure 2. Total annual catch (1000s mt) of bigeye tuna from the WCPO by fishing method from 1952 to 2010 assumed in Run3j. These include purse seine catch estimates which **have been** corrected for grab-sample bias.

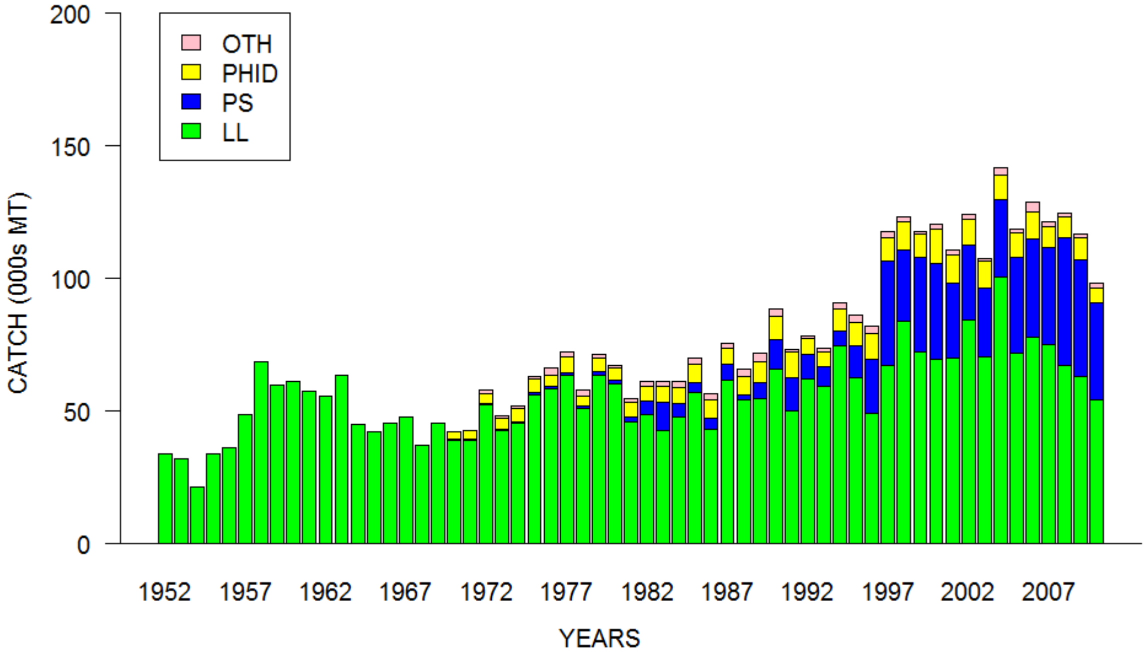


Figure 3. Total annual catch (1000s mt) of bigeye tuna from the WCPO by fishing method from 1952 to 2010 as assumed in Run4. These purse seine catch estimates **have not been** corrected for grab-sample bias.

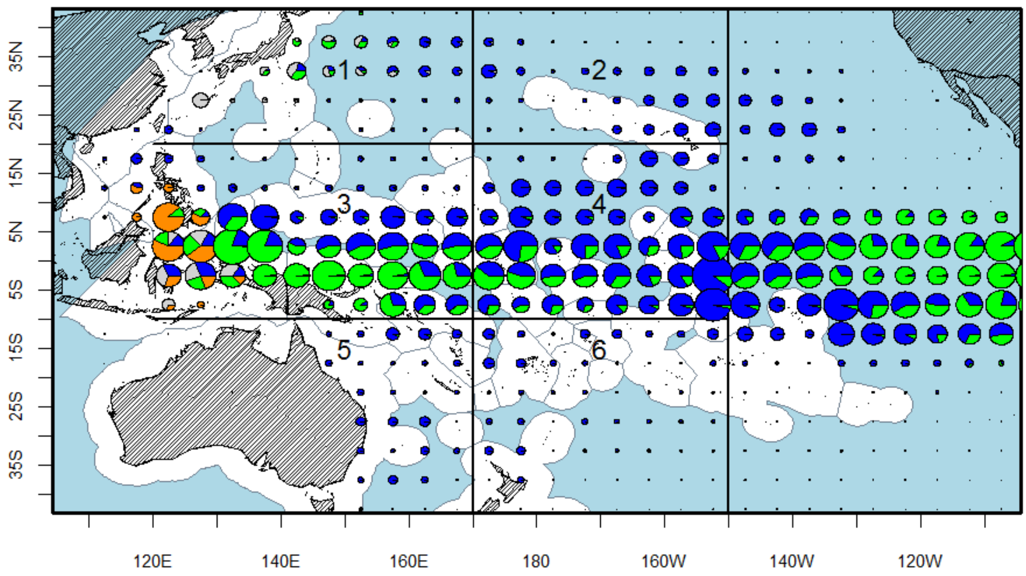


Figure 4. Distribution of cumulative bigeye tuna catch from 1990–2010 by 5 degree squares of latitude and longitude and fishing gear; longline (green), purse-seine (blue), and other (yellow). The grey lines indicate the spatial stratification of the six-region assessment model.

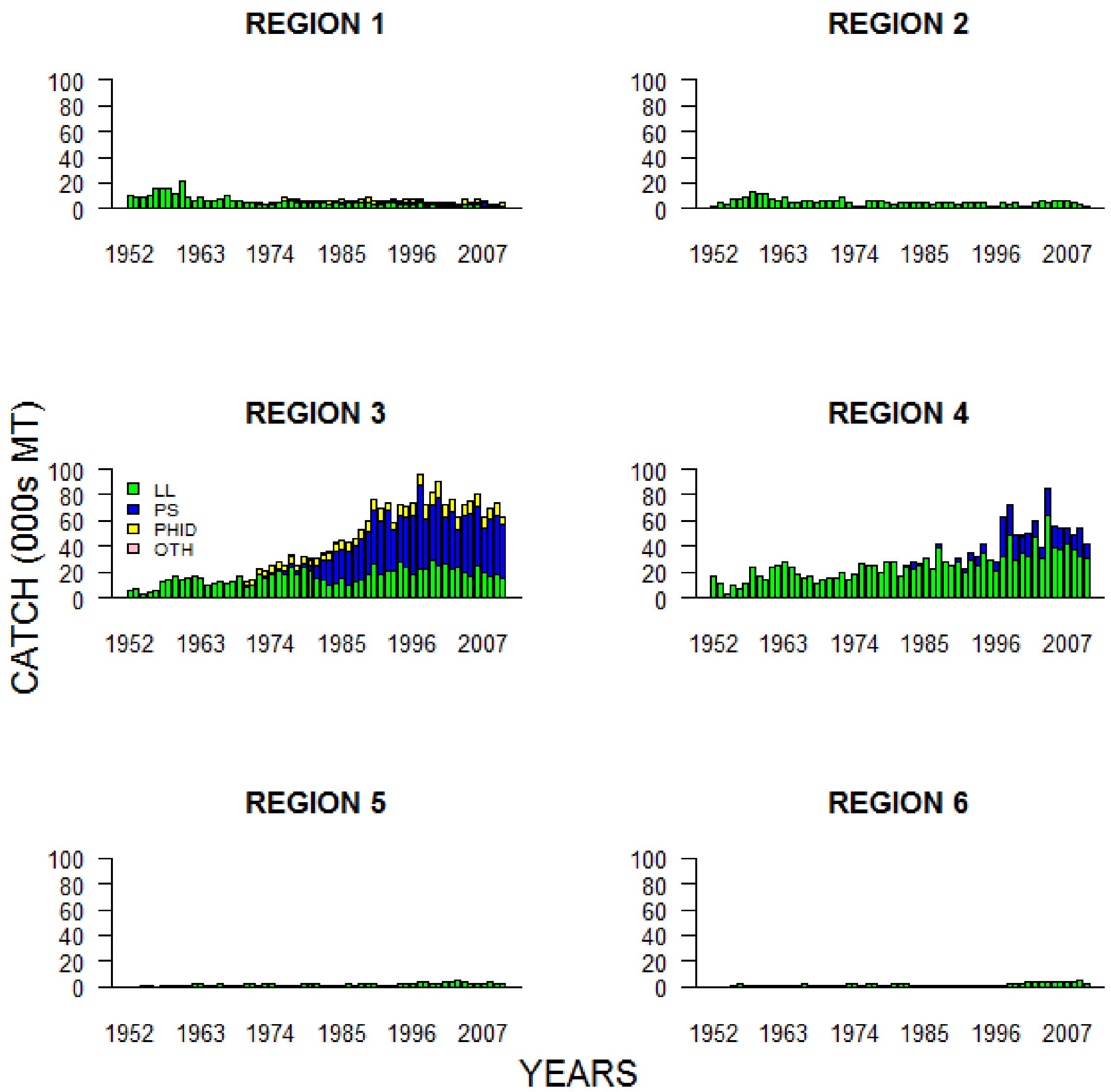


Figure 5. Total annual catch (1000s mt) of bigeye tuna by fishing method and MFCL region from 1952 to 2010 which **have been** corrected for grab-sample bias as assumed in Run3j.

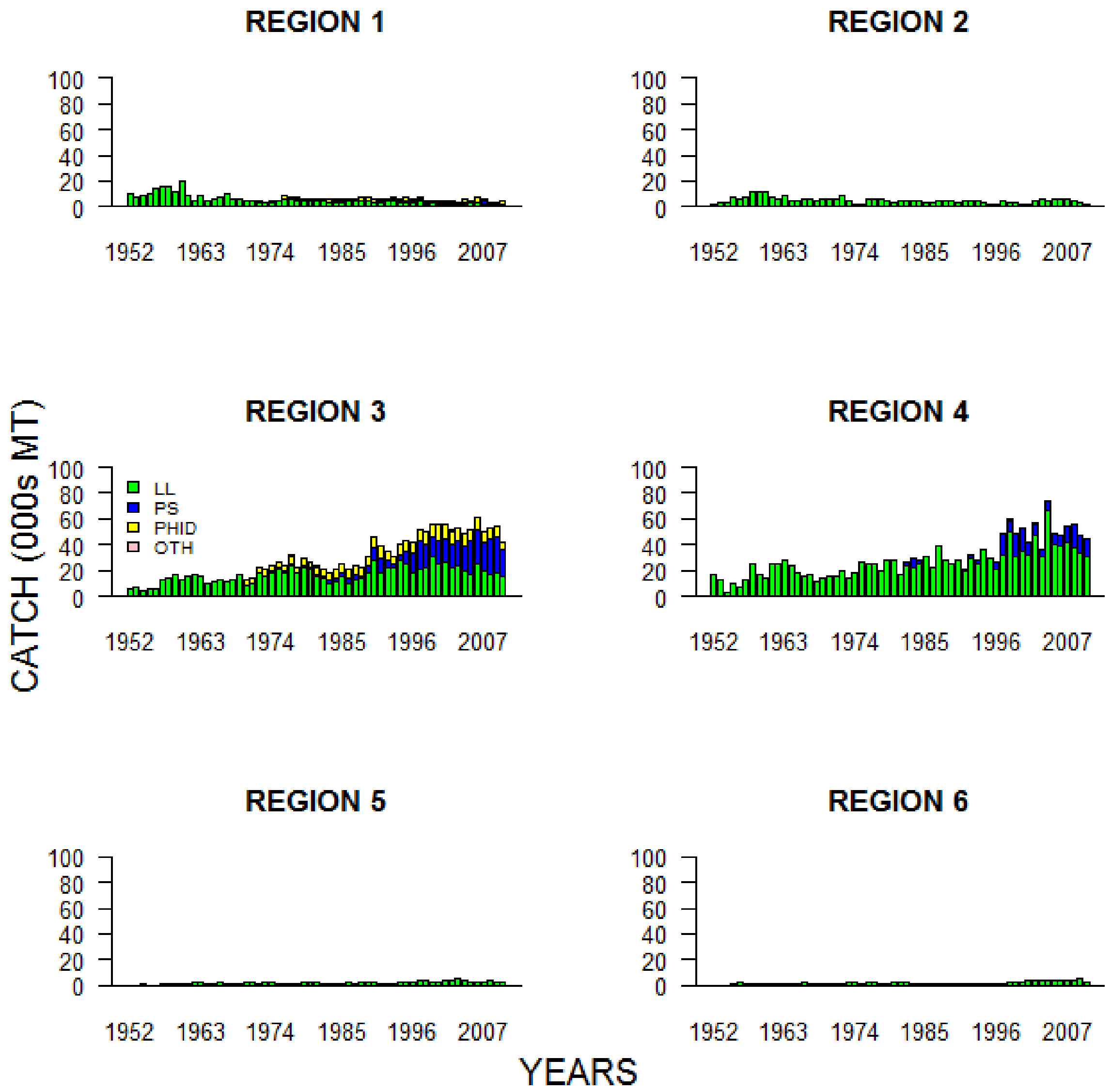


Figure 6. Total annual catch (1000s mt) of bigeye tuna by fishing method and MFCL region from 1952 to 2010 which **have not been** corrected for grab-sample bias as assumed in Run4.

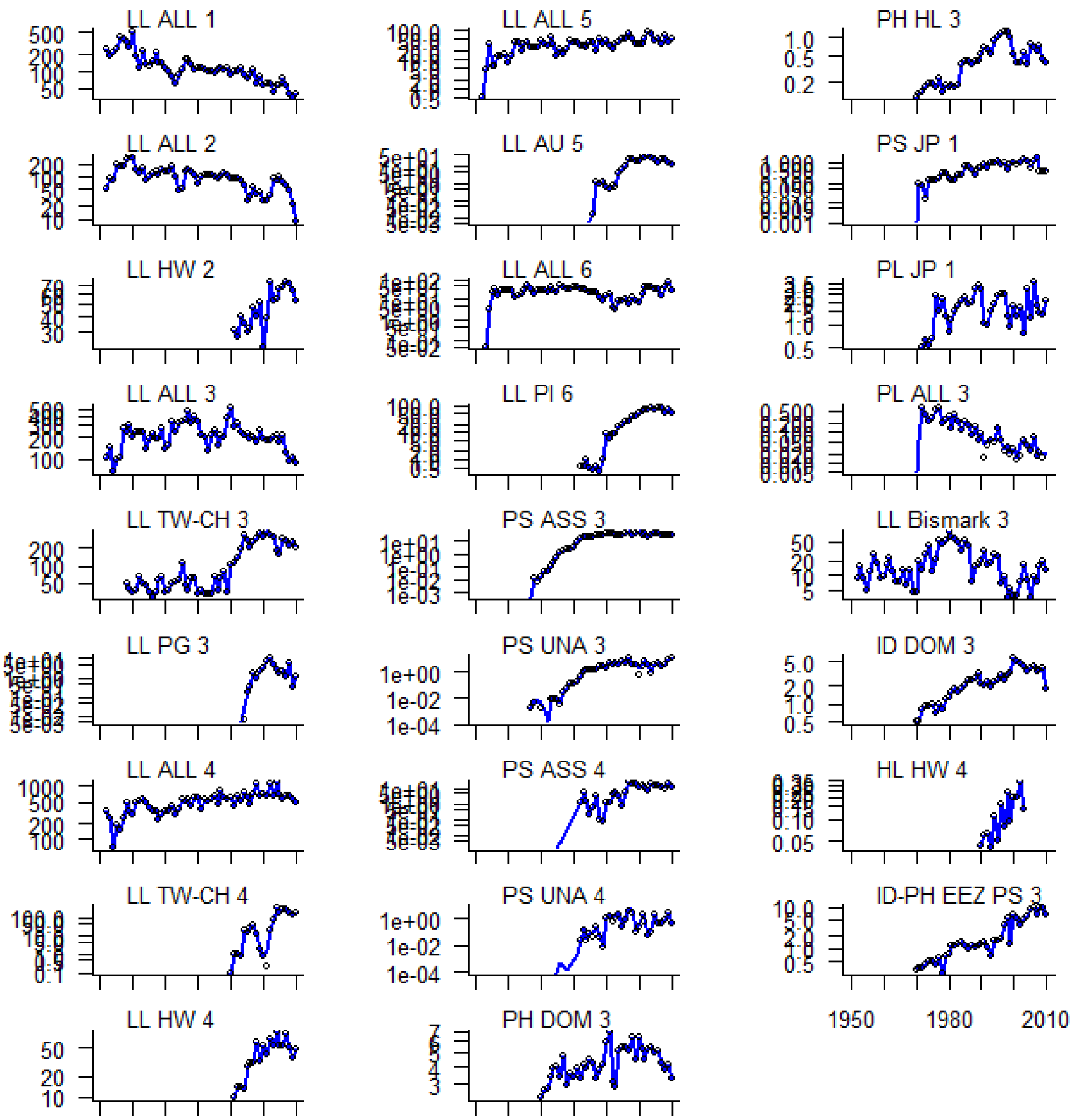


Figure 7. Annual catches by fishery. Circles are observed and the lines are model predictions. Units are catch number of fish (in thousands) for the longline fisheries and thousand metric tonnes for all other fisheries. The y-axis is on the log scale.

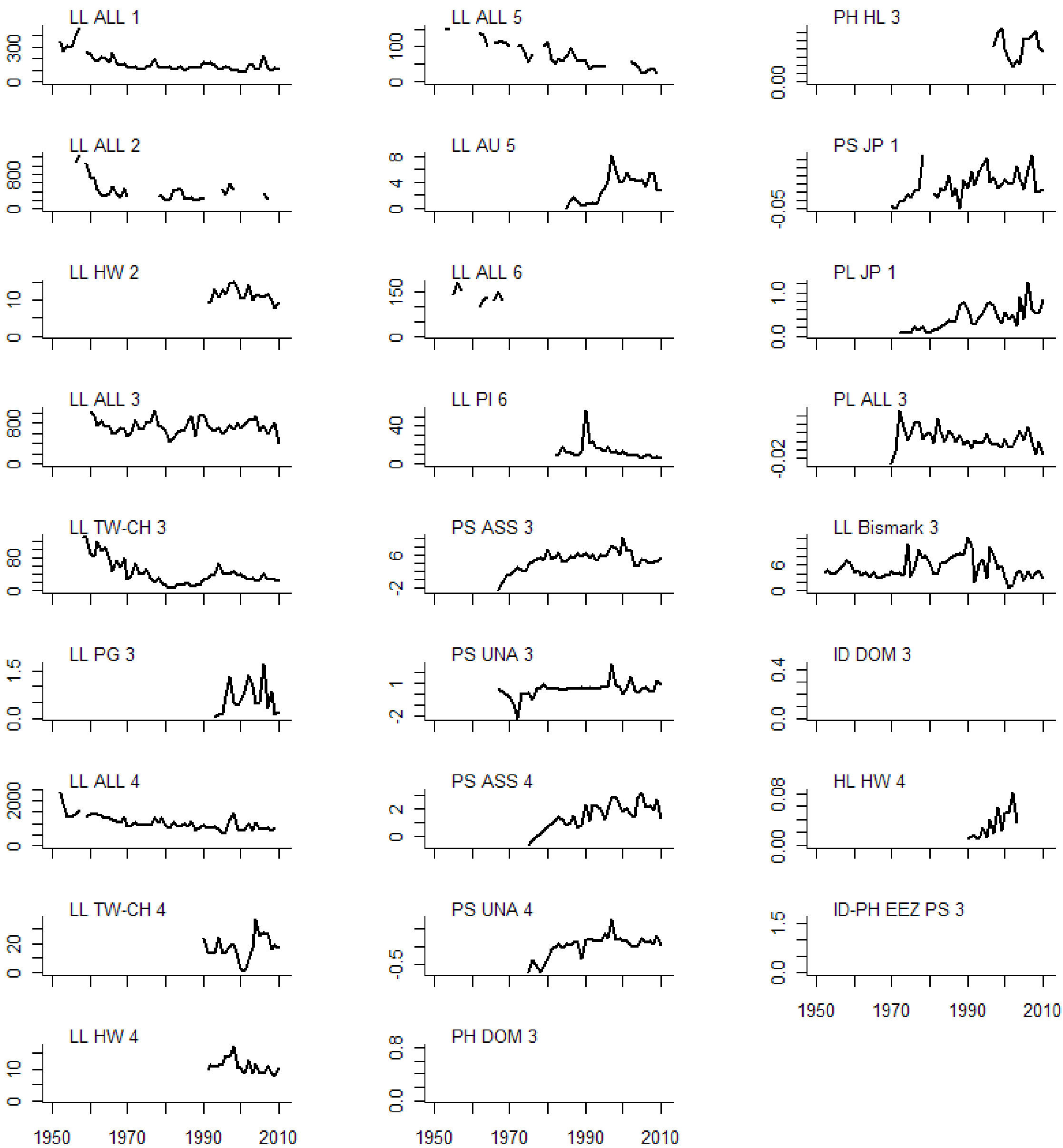


Figure 8. Catch-per-unit-effort (CPUE) by fishery. Units are catch number per GLM-standardised effort (fisheries LL ALL 1–LL ALL 6), catch number per 100 nominal hooks (LL HW, CH/TW LL, LL PI, LL PG, LL BMK) and catch (mt) per day fished/searched (all PS and PL fisheries). Note that CPUE for PH MISC, PH HL and ID are arbitrary and not based on data (see discussion on catchability and effort deviation constraints for these fisheries).

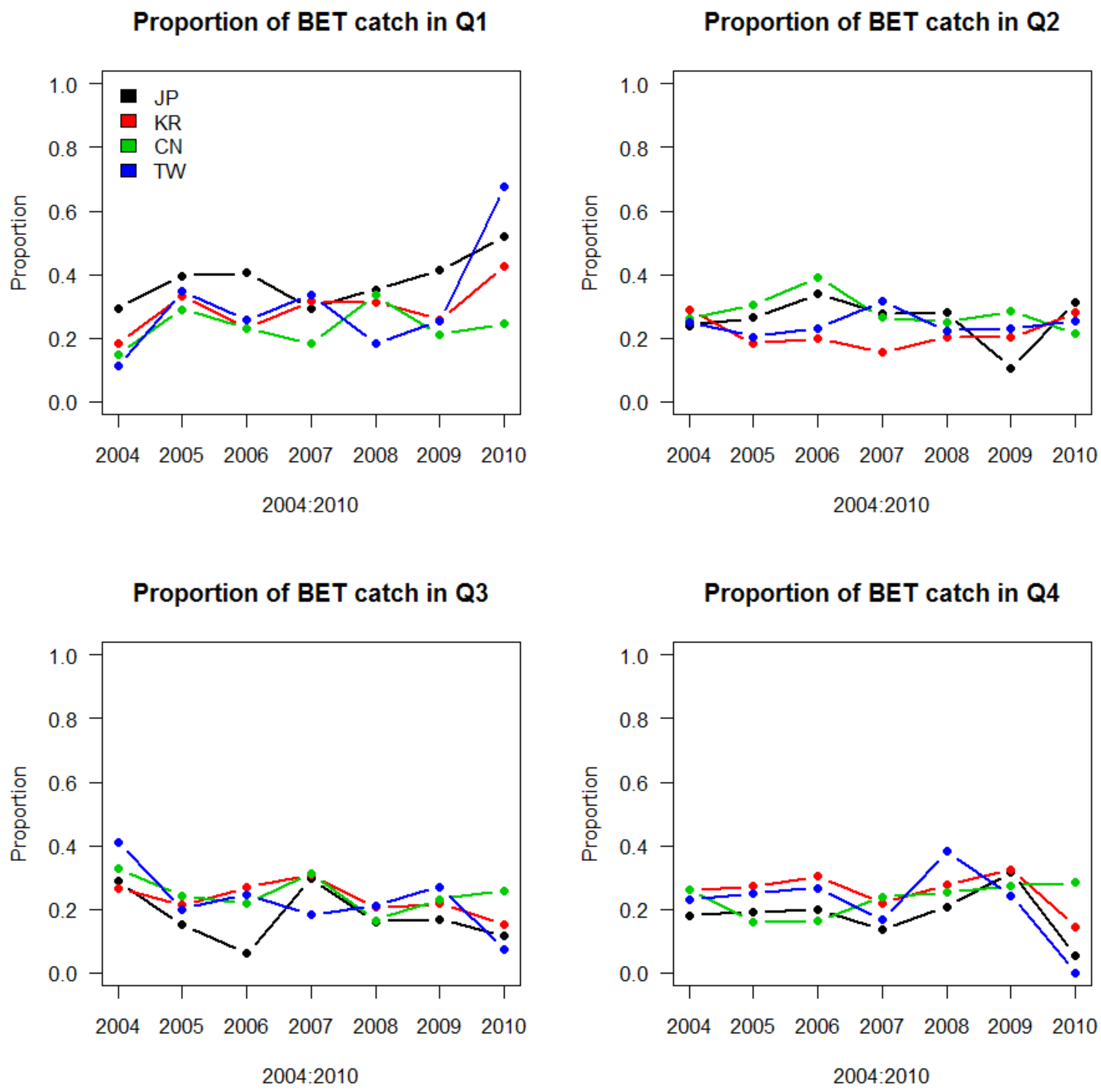


Figure 9. Quarterly proportions of longline catches from 2004 to 2010 for the main fishery participants indicating the shift in proportions in the final year.

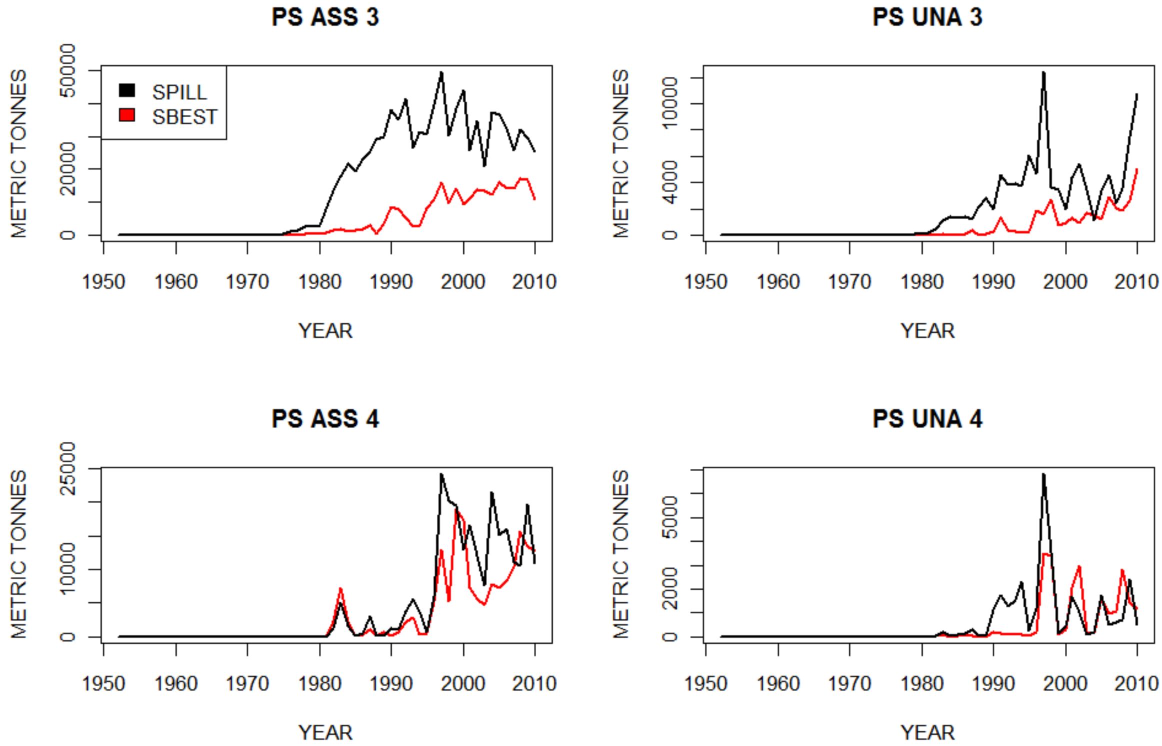


Figure 10. A comparison of the alternative catch histories (annual catches in mt) assumed for the purse seine fisheries, associated (FAD or other floating object) catch on the left, and unassociated (free school) catch on the right.

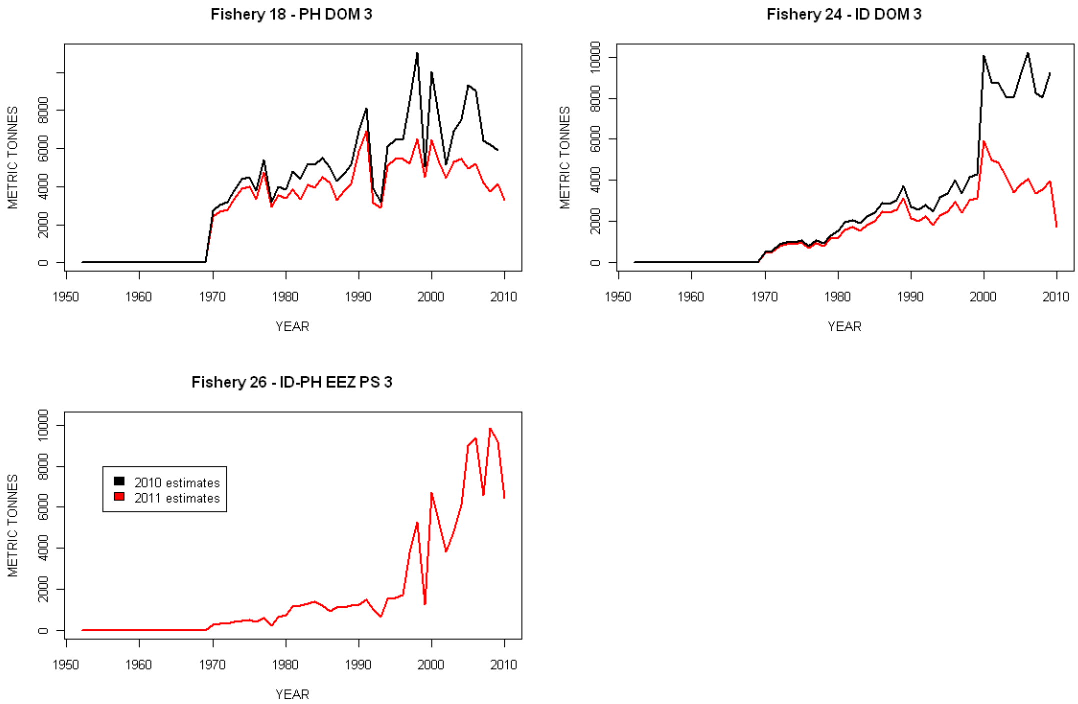


Figure 11. A comparison of the catch histories for the fisheries that incorporate catches from Indonesia and the Philippines from those assumed in the 2010 assessment (black) and those assumed in the 2011 assessment (red).

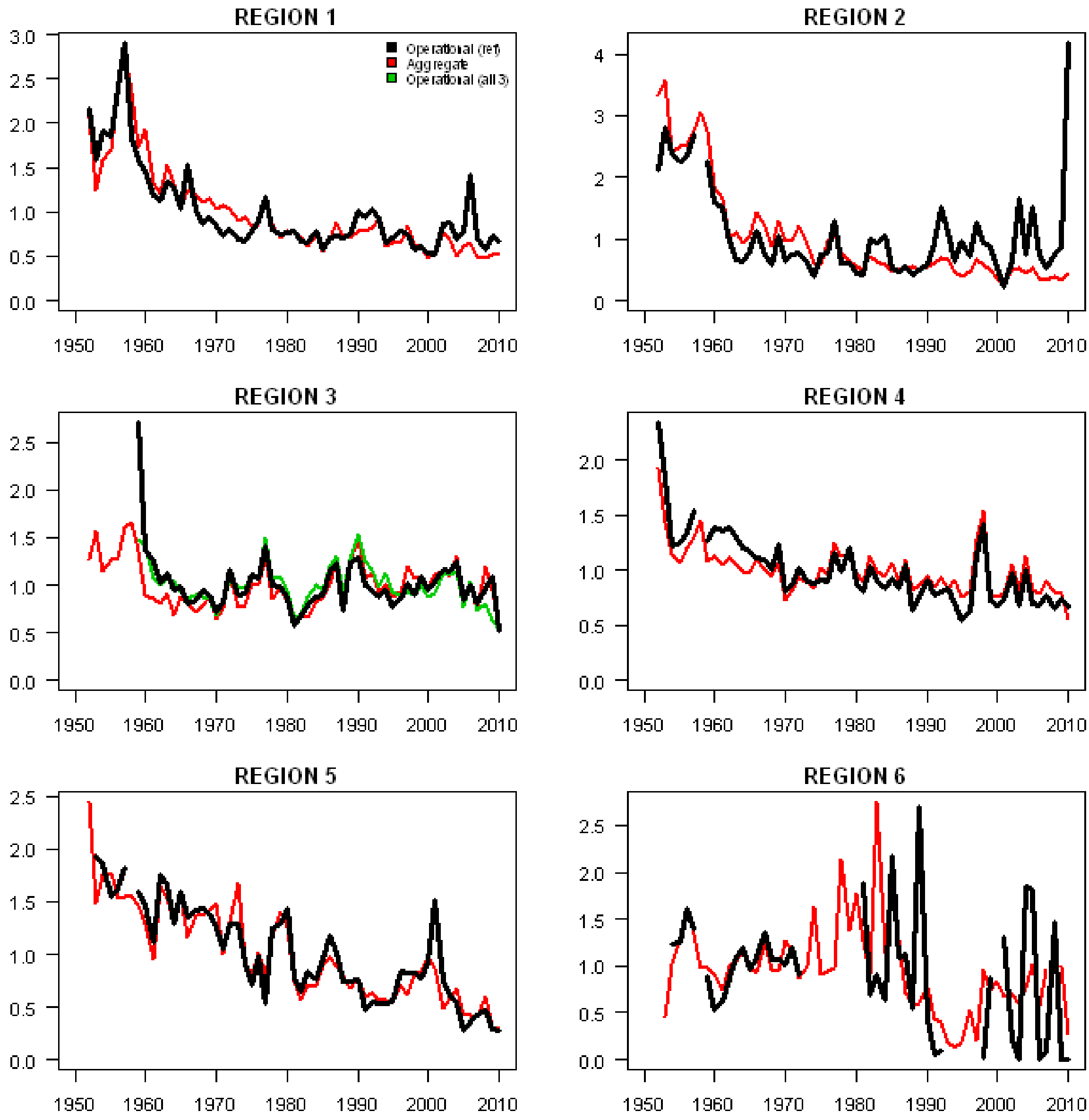


Figure 12. GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL ALL 1–6) scaled by the respective region scalars based on the methodology used in the Hoyle (2011) using: operational level data with that for region 3 taken from the core area (black lines – used in Run3j – Ref.case); operational level data with that for region 3 taken from the whole area (green lines – used in Run8), and aggregate data (red line – used in Run10 - aggCPUE).

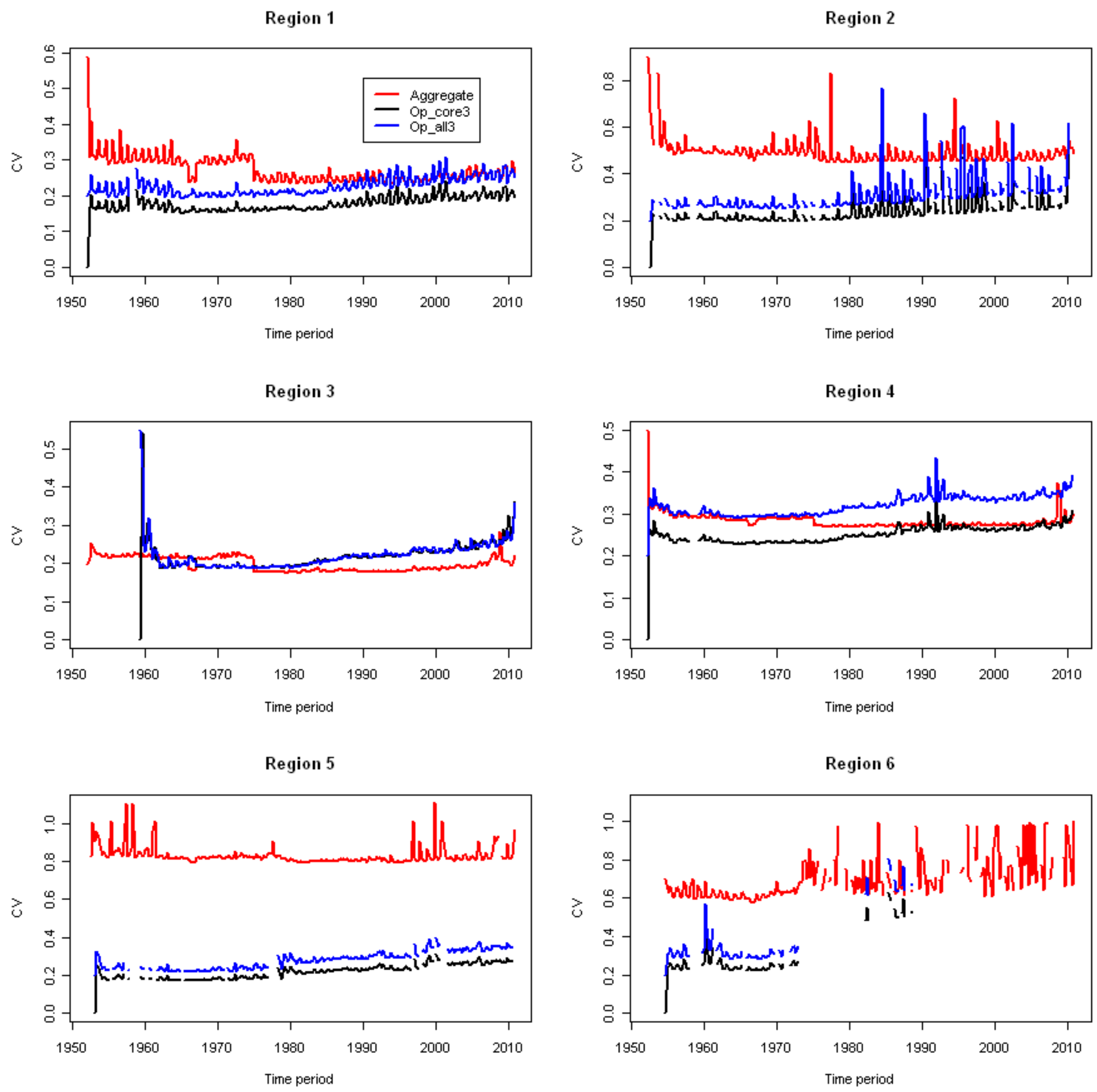
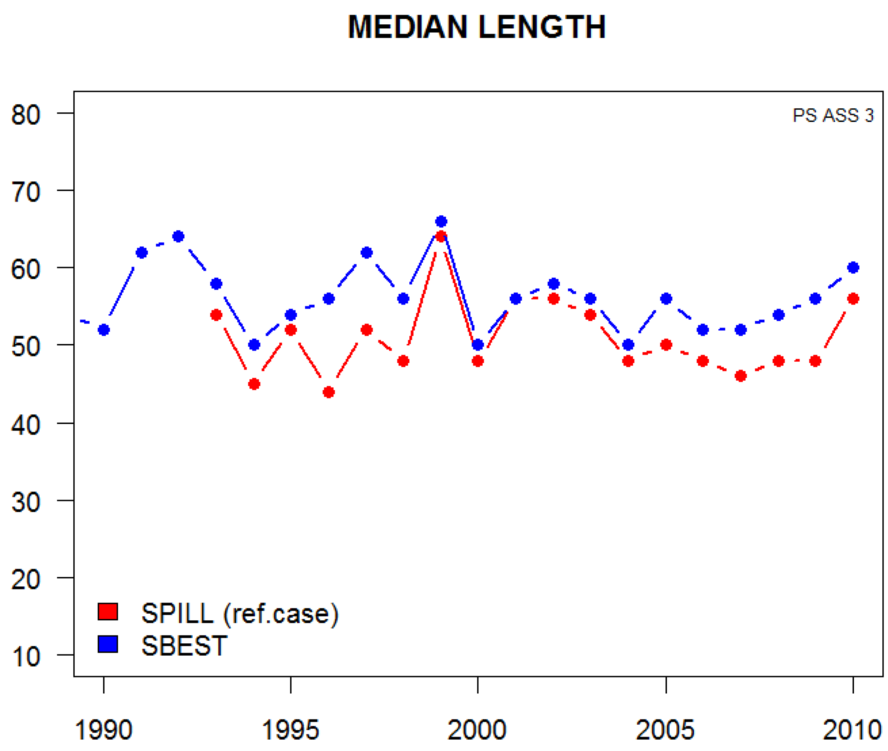


Figure 13. Assumed effort deviation CVs (scaled) for the main LL-ALL fisheries based on the methodology used in the Hoyle (2011) using: operational level data with that for region 3 taken from the core area (black lines – used in Run3j – Ref.case); operational level data with that for region 3 taken from the whole area (blue lines – used in Run8), and, aggregate data (red line – used in Run10 - aggCPUE). Note that the y-axes are not the same.



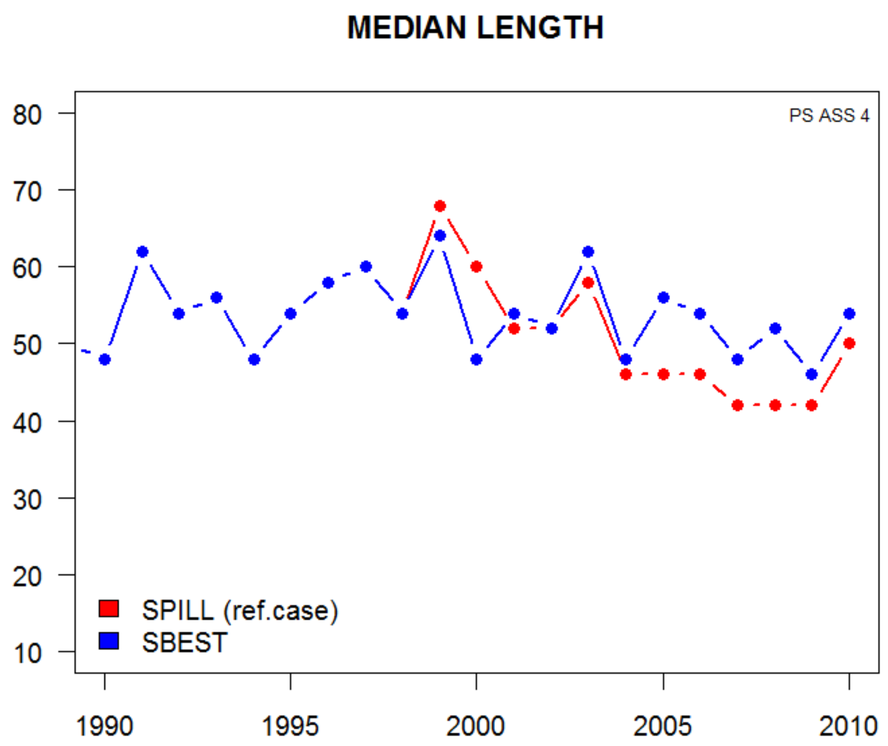


Figure 14. A comparison of the median annual length frequency samples obtained from grab or spill sampling of purse seine (associated) catches in regions 3 and 4 (Fisheries 14 and 16: PS ASS 3, 4).

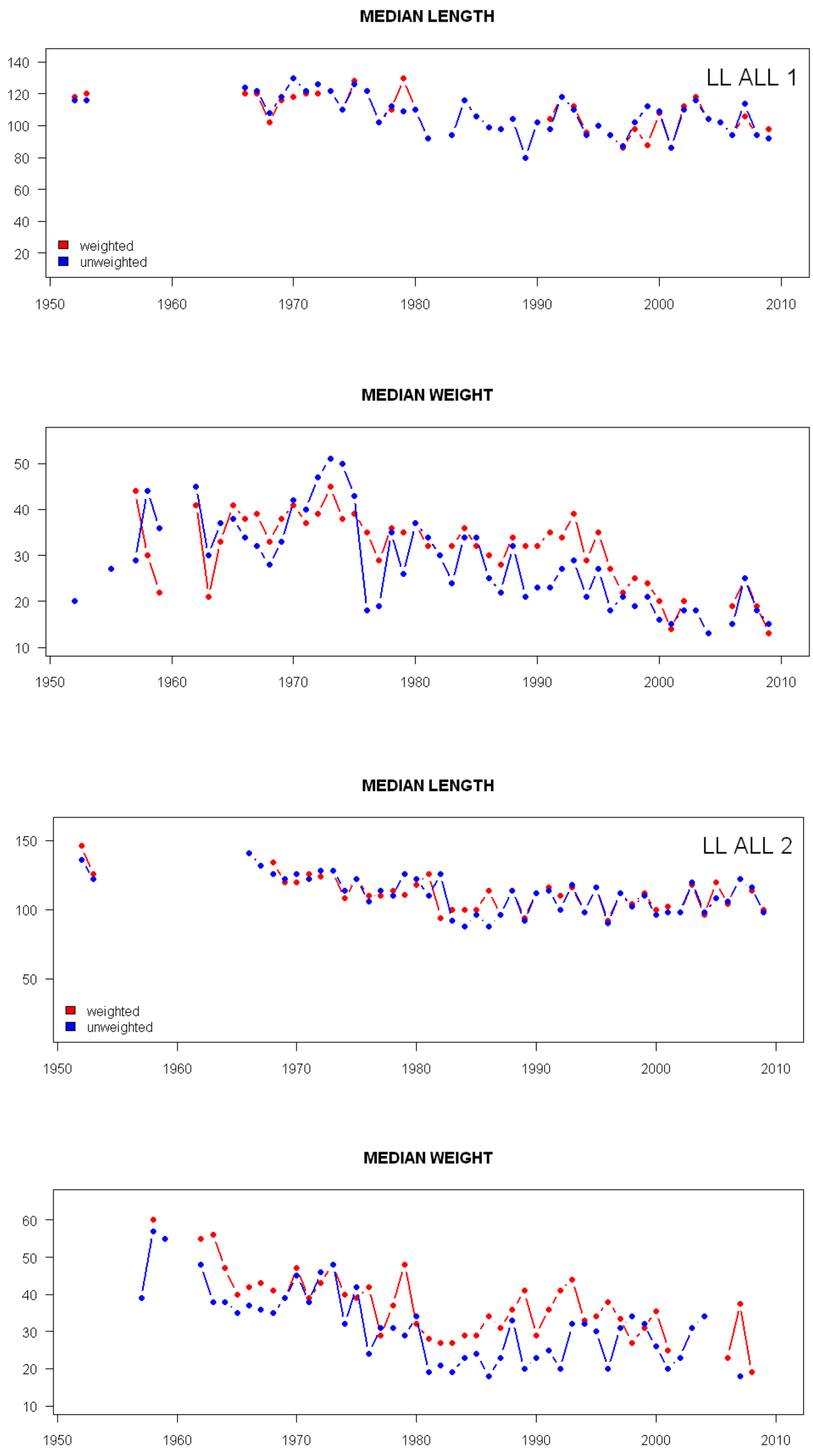


Figure 15. A comparison of the median annual length and weight frequency samples, unweighted and weighted, from Japanese longline catches in regions 1 to 6 (LL ALL 1, 2, 3, 4, 5, and 6).

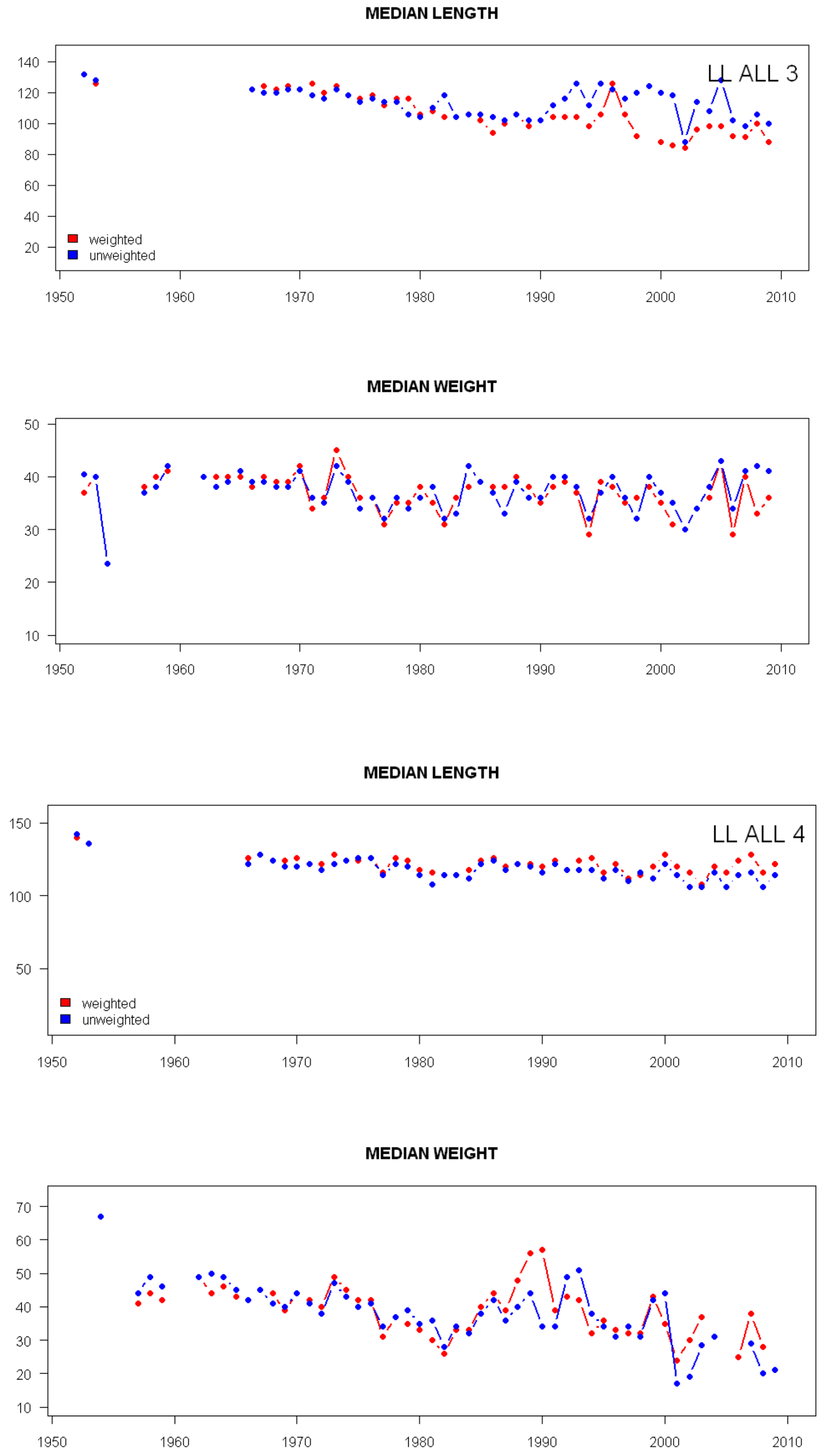


Figure 15 cont.

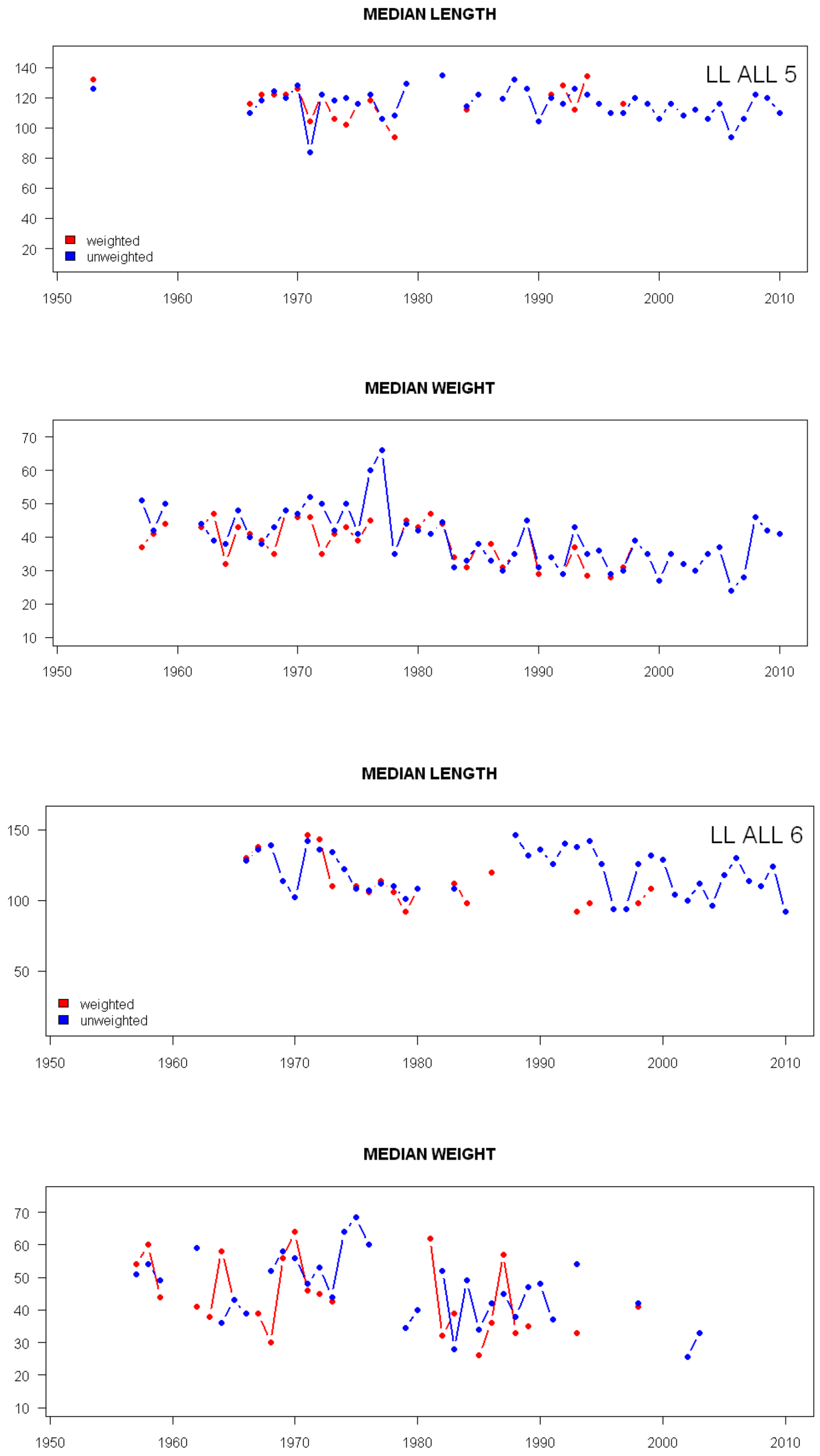


Figure 15 cont.

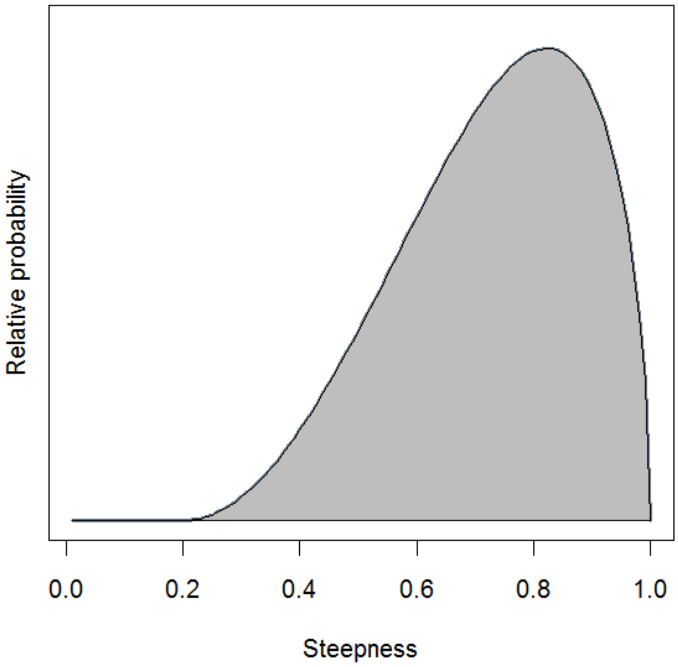
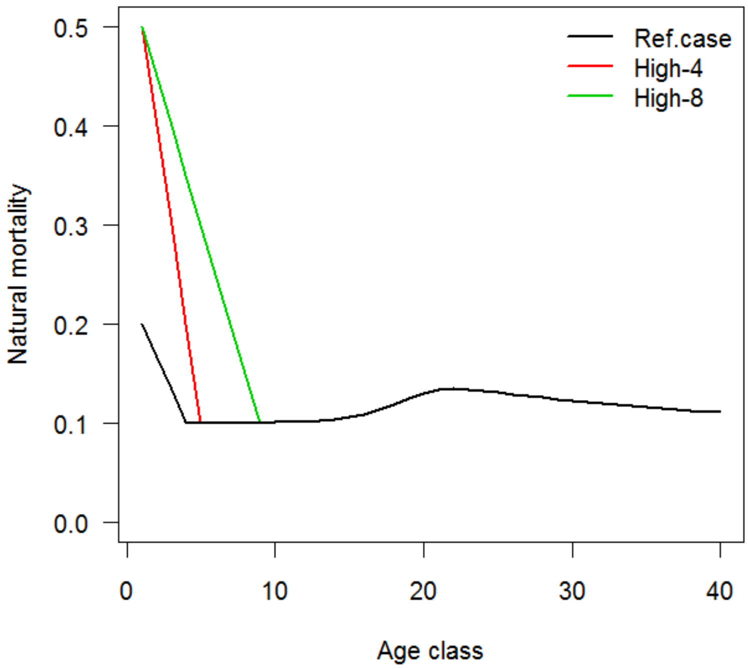


Figure 16. Prior for the steepness parameter of the relationship between spawning biomass and recruitment.



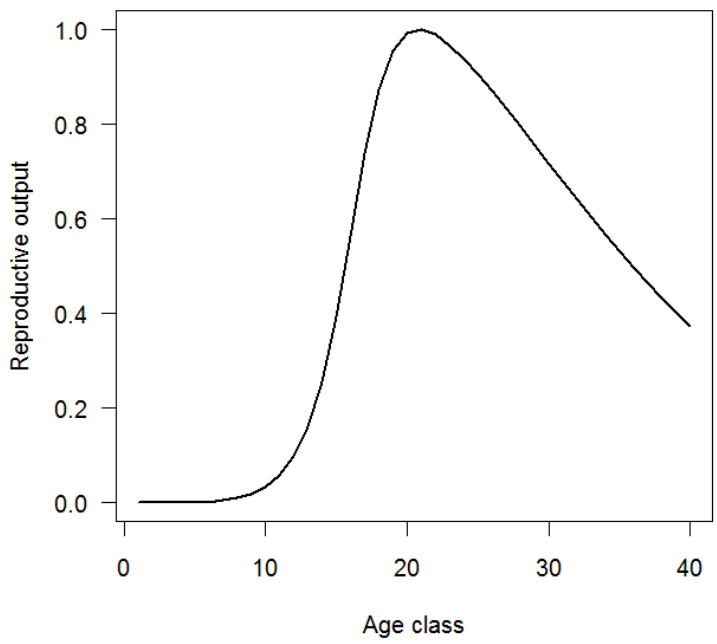


Figure 17. Natural mortality-at-age (top) and % mature (bottom) as assumed in the 2010 assessment (Ref.case). For natural mortality alternative assumptions (Run16 – High-4, Run17 – High-8) were based on YFT assumed levels of M for ages 1-4 and 1-8 quarters are also provided (red and green lines respectively). Note that estimate of maturity is actually used to define an index of spawning potential incorporating information on sex ratios, maturity at age, fecundity, and spawning fraction (see Hoyle and Nicol 2008 for further details).

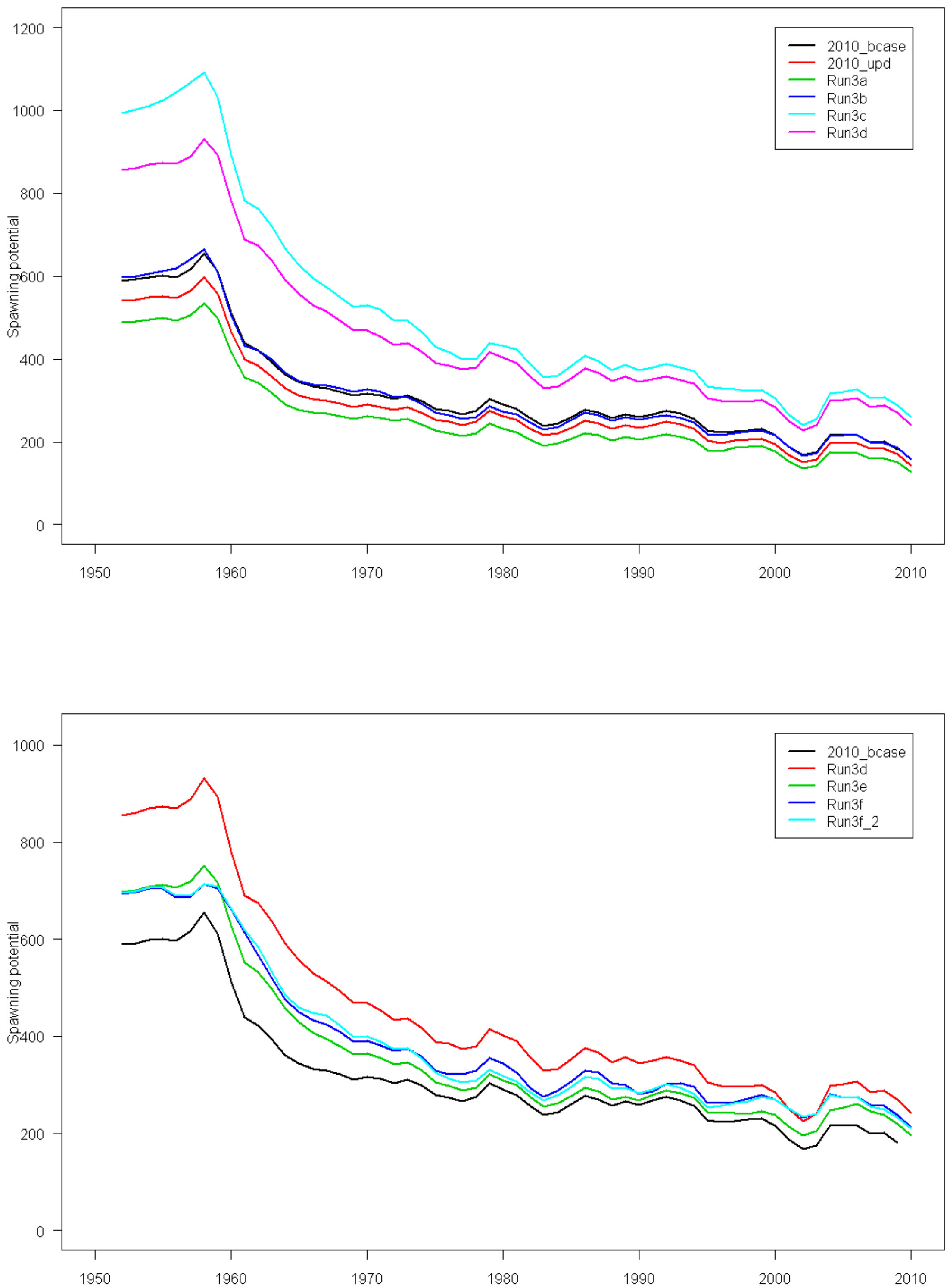


Figure 18. Estimated annual average spawning potential for the WCPO obtained from runs undertaken in the stepwise development of Run3j – Ref.case.

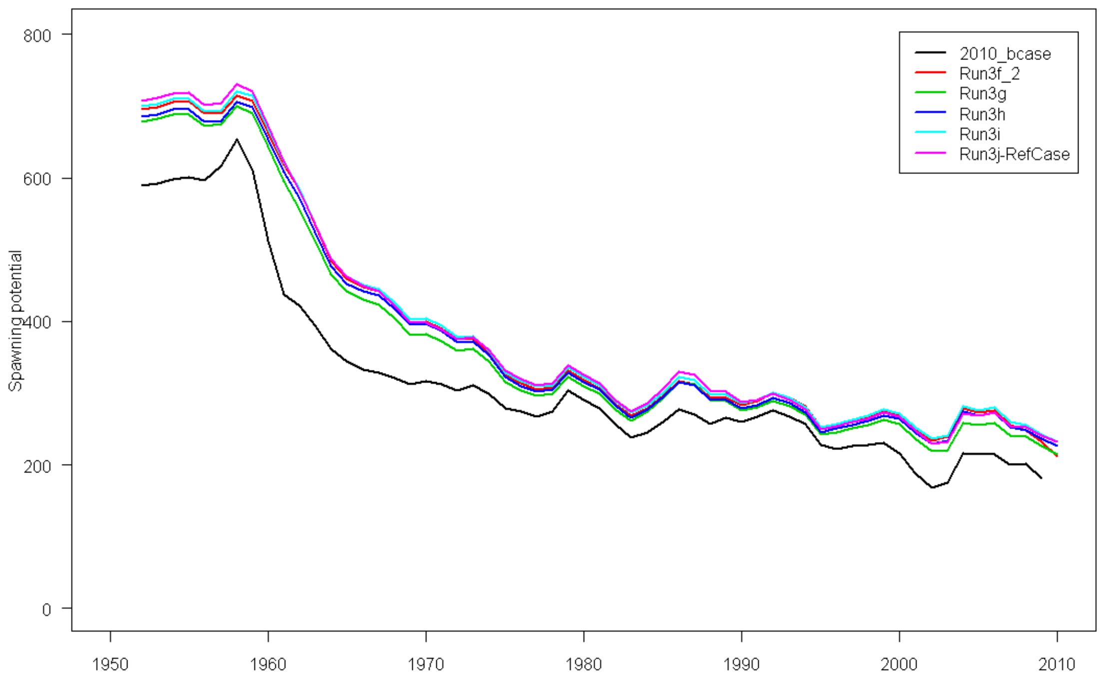


Figure 18 cont.

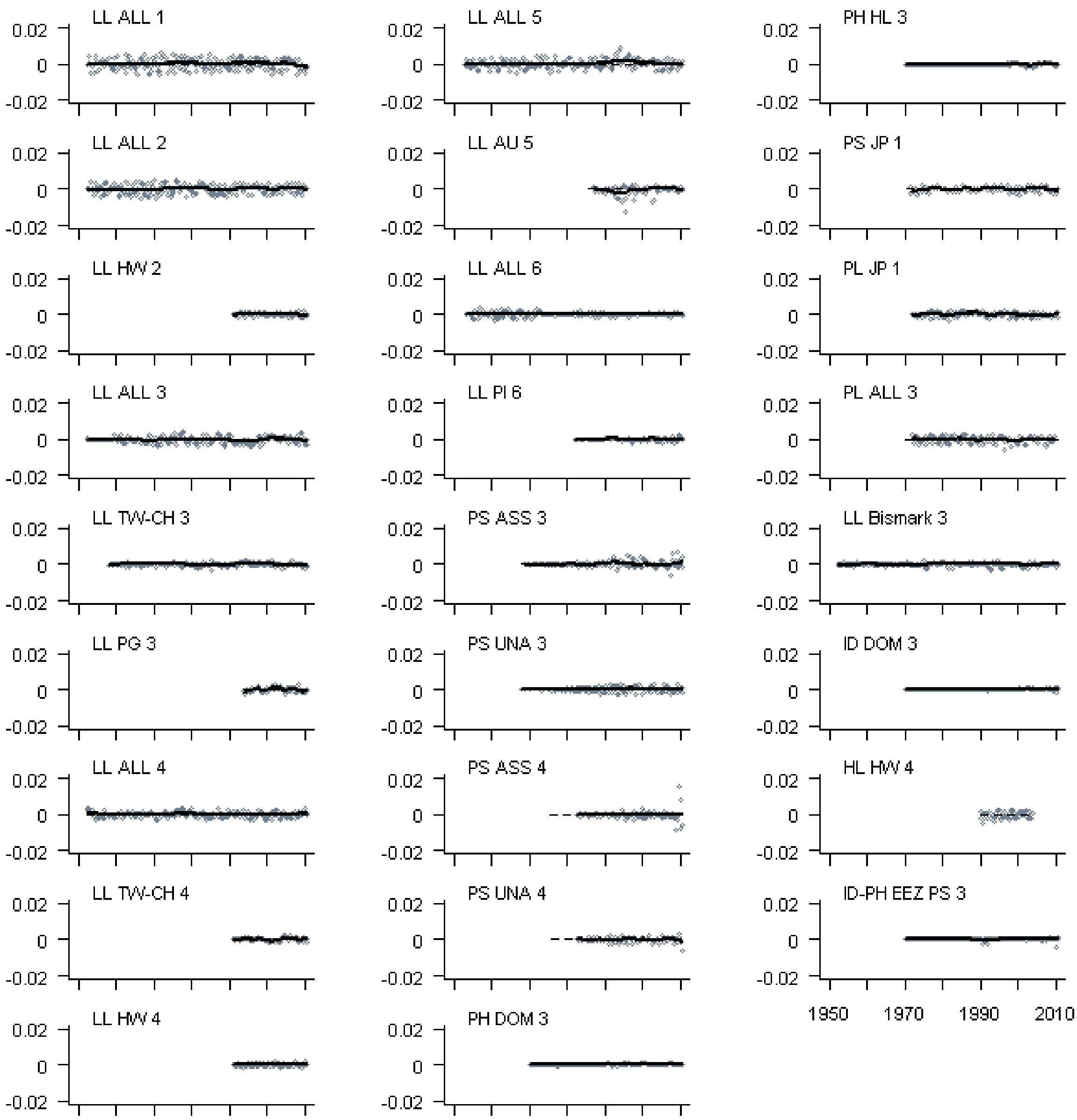


Figure 19. Residuals of ln (total catch) for each fishery (Run3j – Ref.case). The dark line represents a lowess smoothed fit to the residuals.

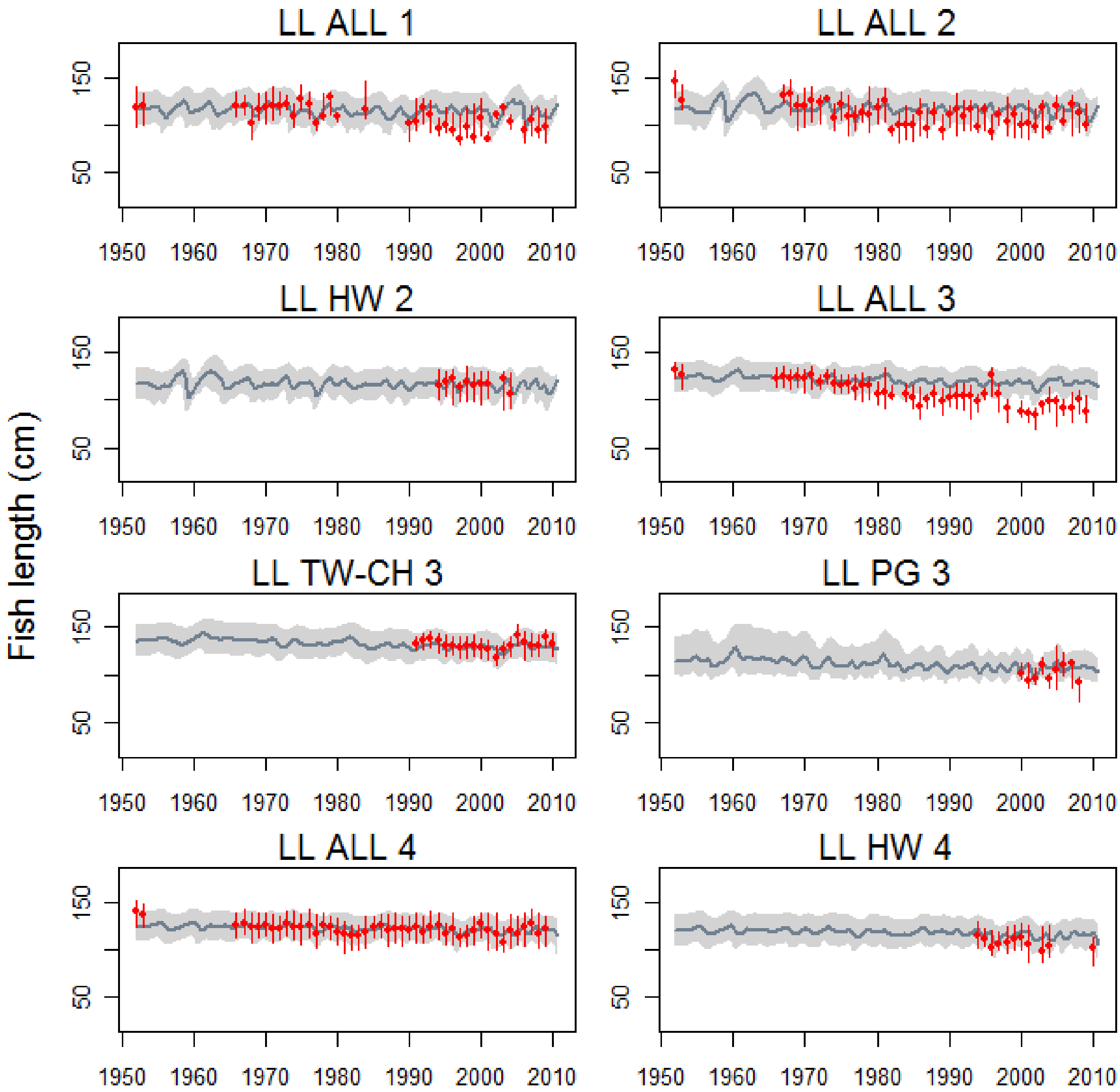


Figure 20. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of bigeye tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

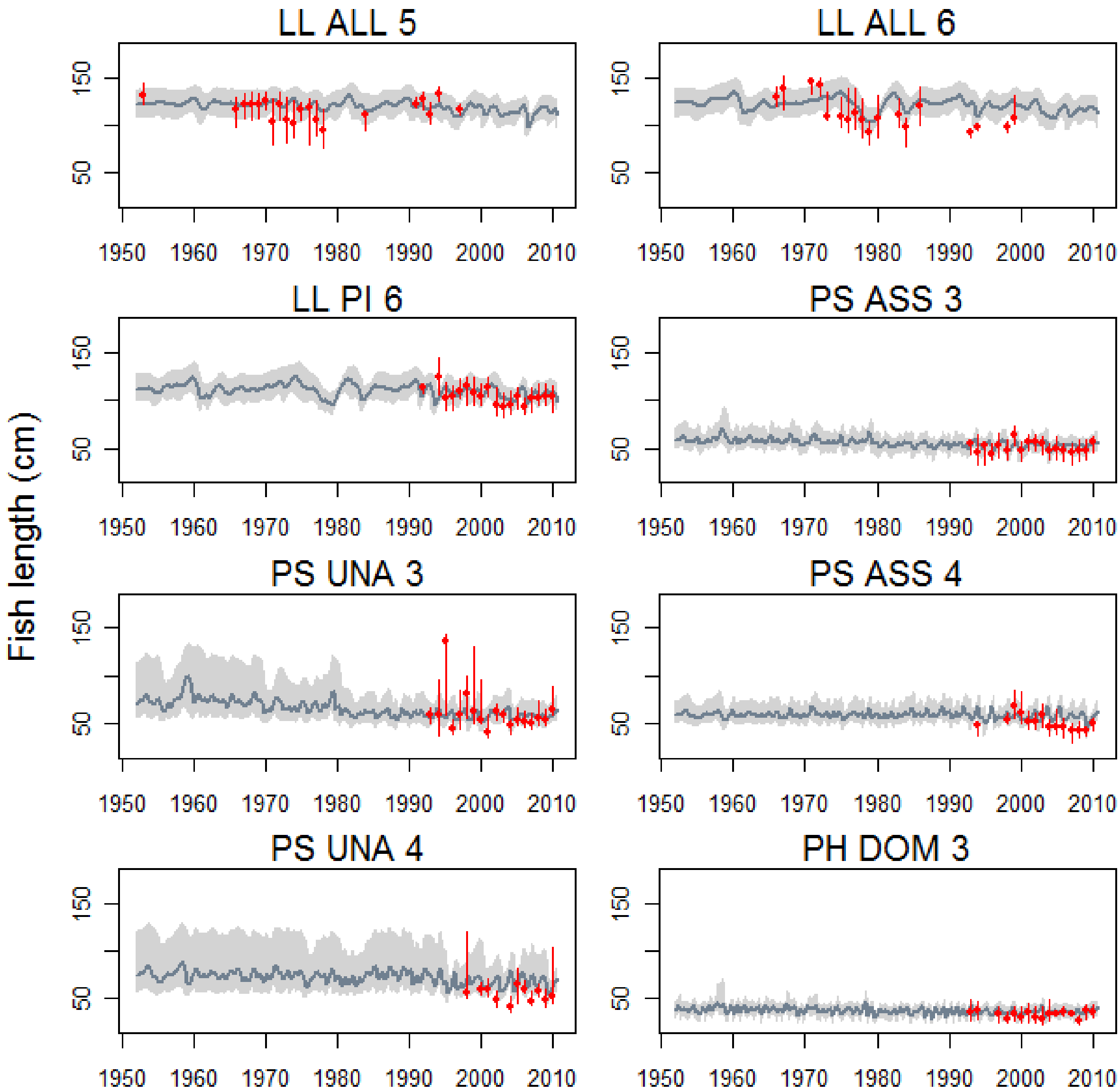


Figure 20 cont.

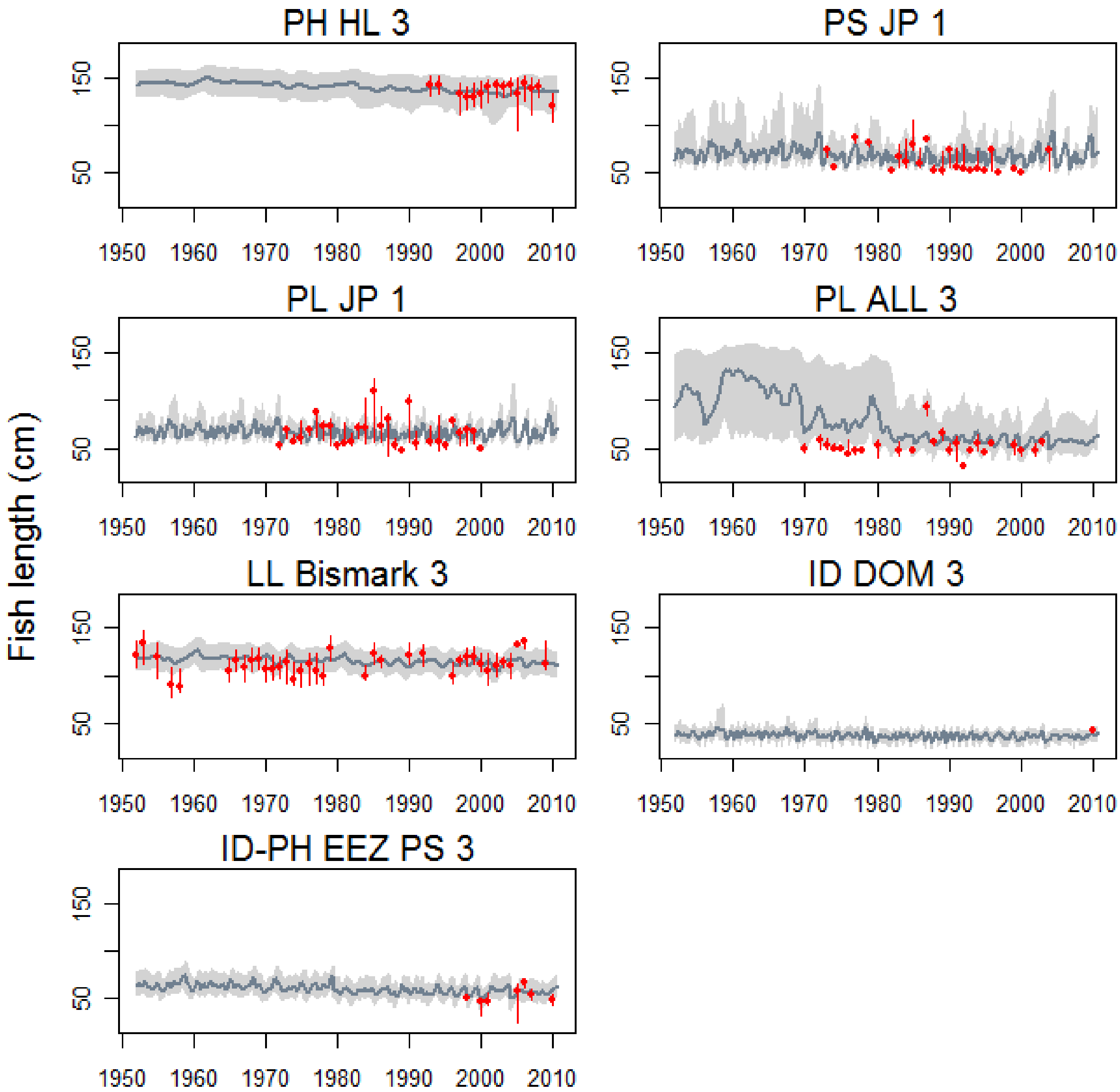


Figure 20 cont.

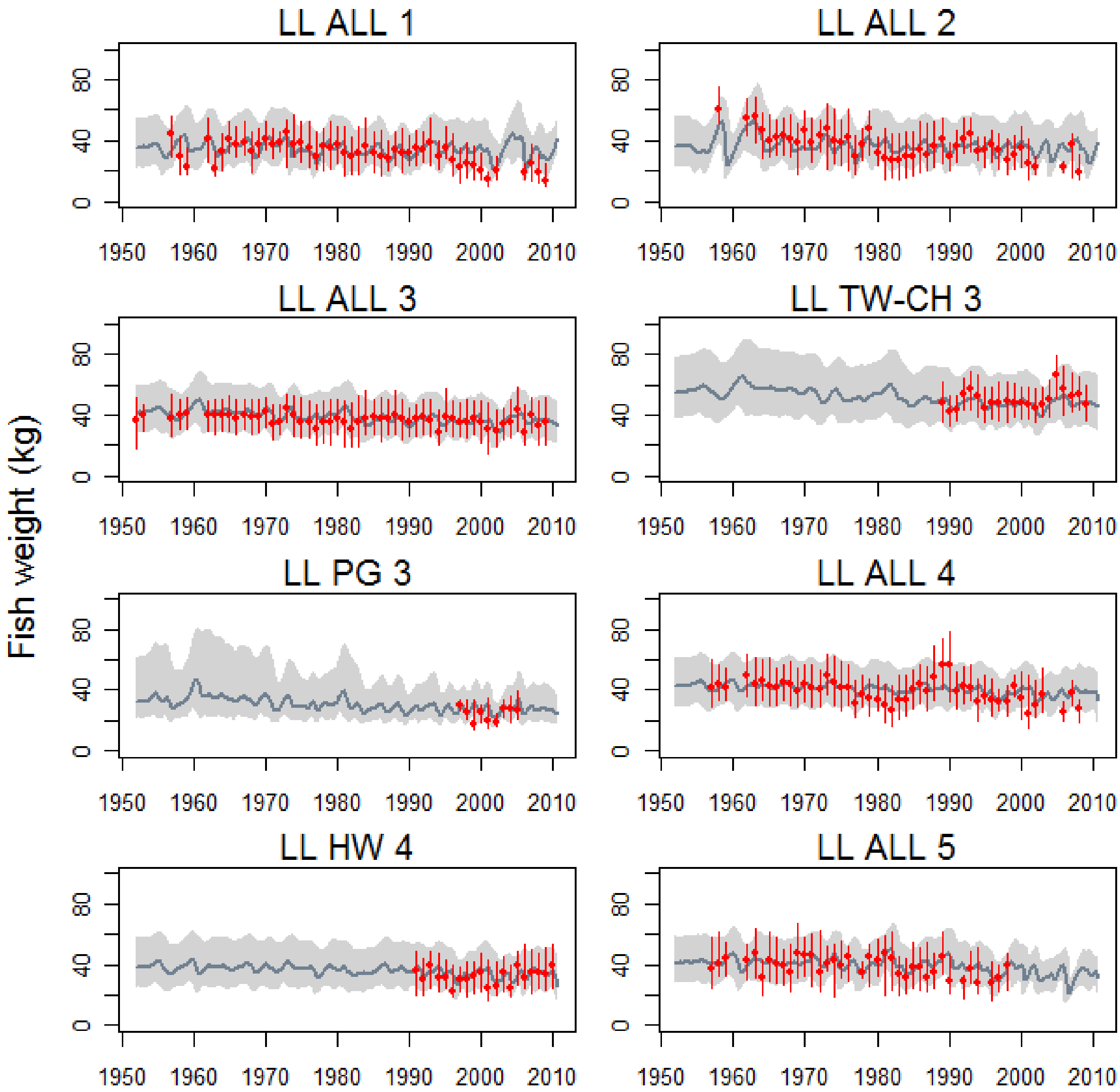


Figure 21. A comparison of the observed (red points) and predicted (grey line) median fish weight (whole weight, kg) of bigeye tuna by fishery for the main fisheries with weight data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only weight samples with a minimum of 30 fish per year are plotted.

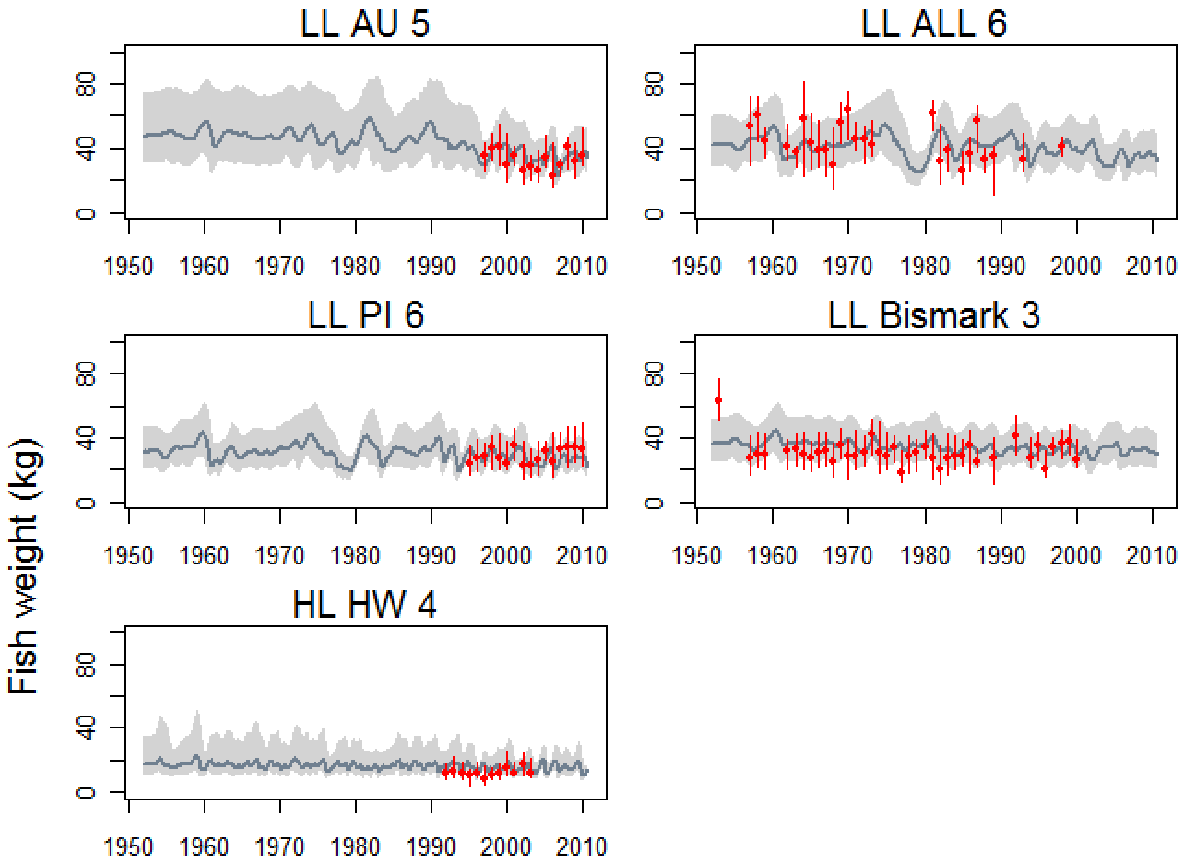


Figure 21 cont.

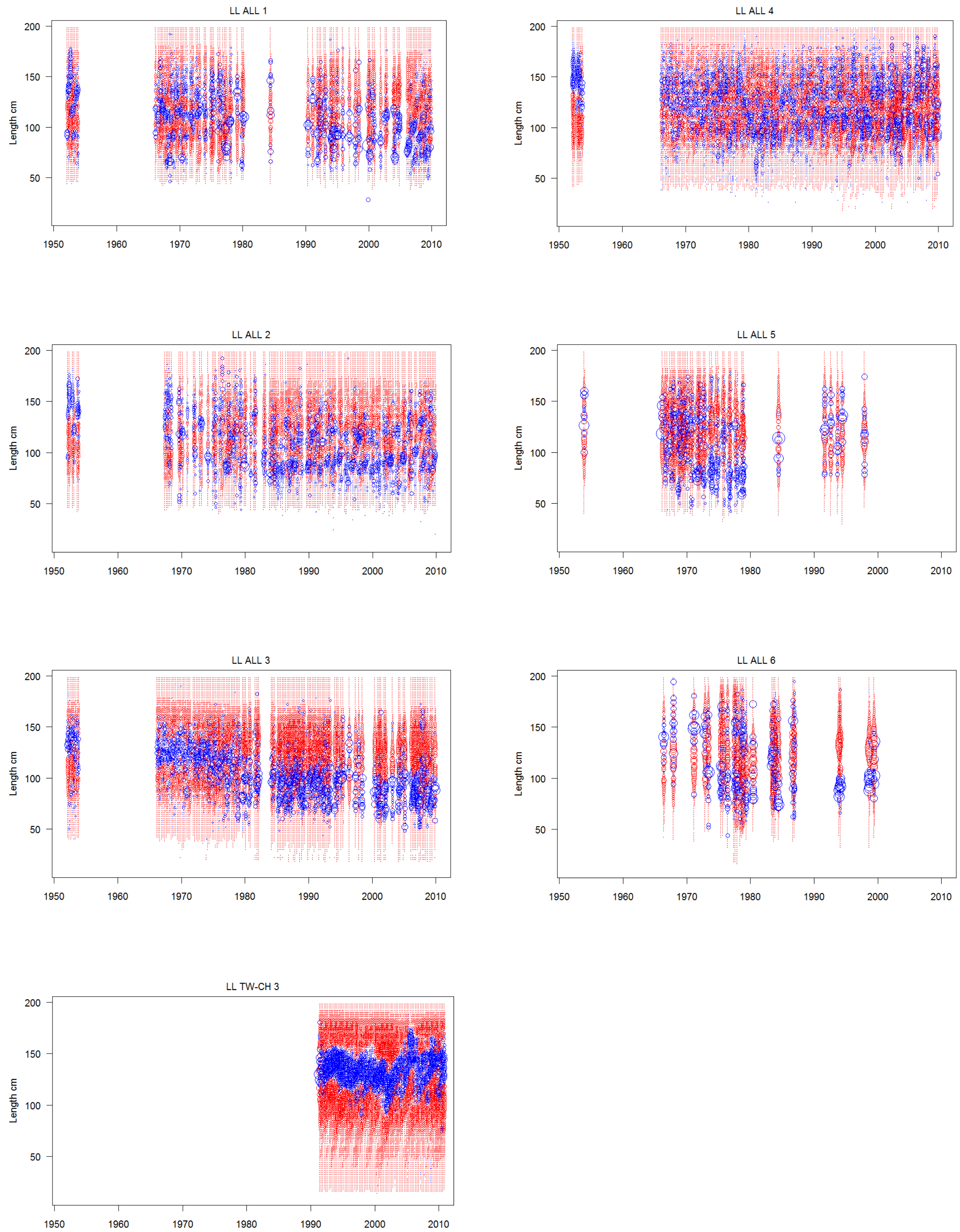
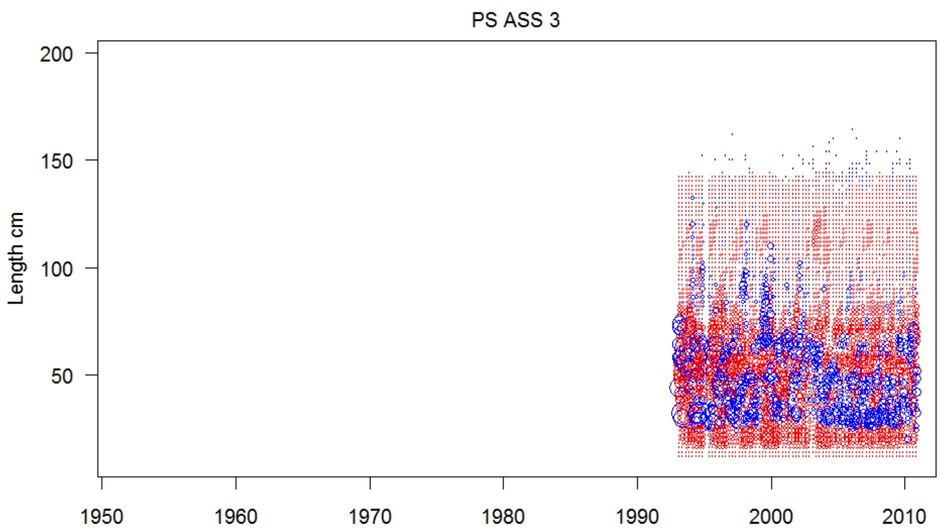


Figure 22. Residual plots of the fit to the length frequency data for the major longline fisheries for Run3j – Ref.case. Positive residuals (more fish presented than predicted) are shown in blue and negative residuals in red. The diameter of circle is proportional to the square root of the residual.



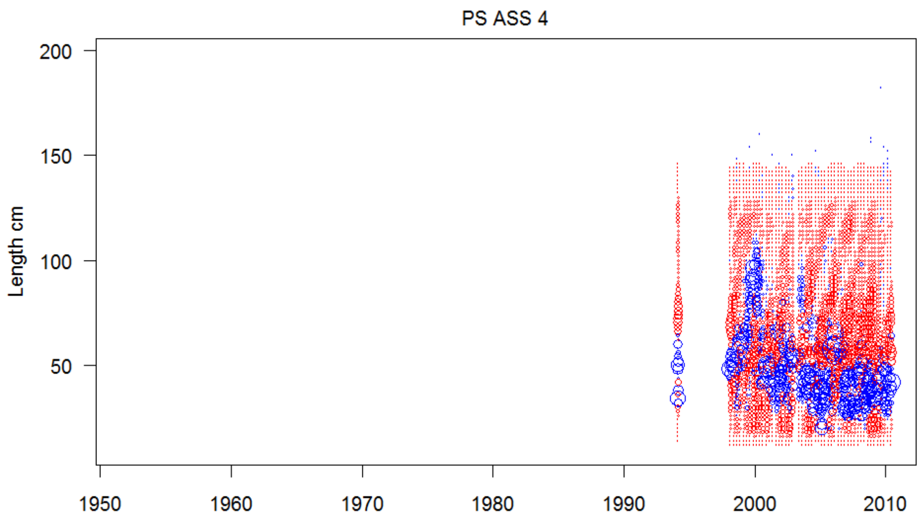


Figure 22 cont. Residual plots of the fit to the length frequency data for the major purse seine fisheries for run 3d. Positive residuals (more fish presented than predicted) are shown in blue and negative residuals in red. The diameter of circle is proportional to the square root of the residual.

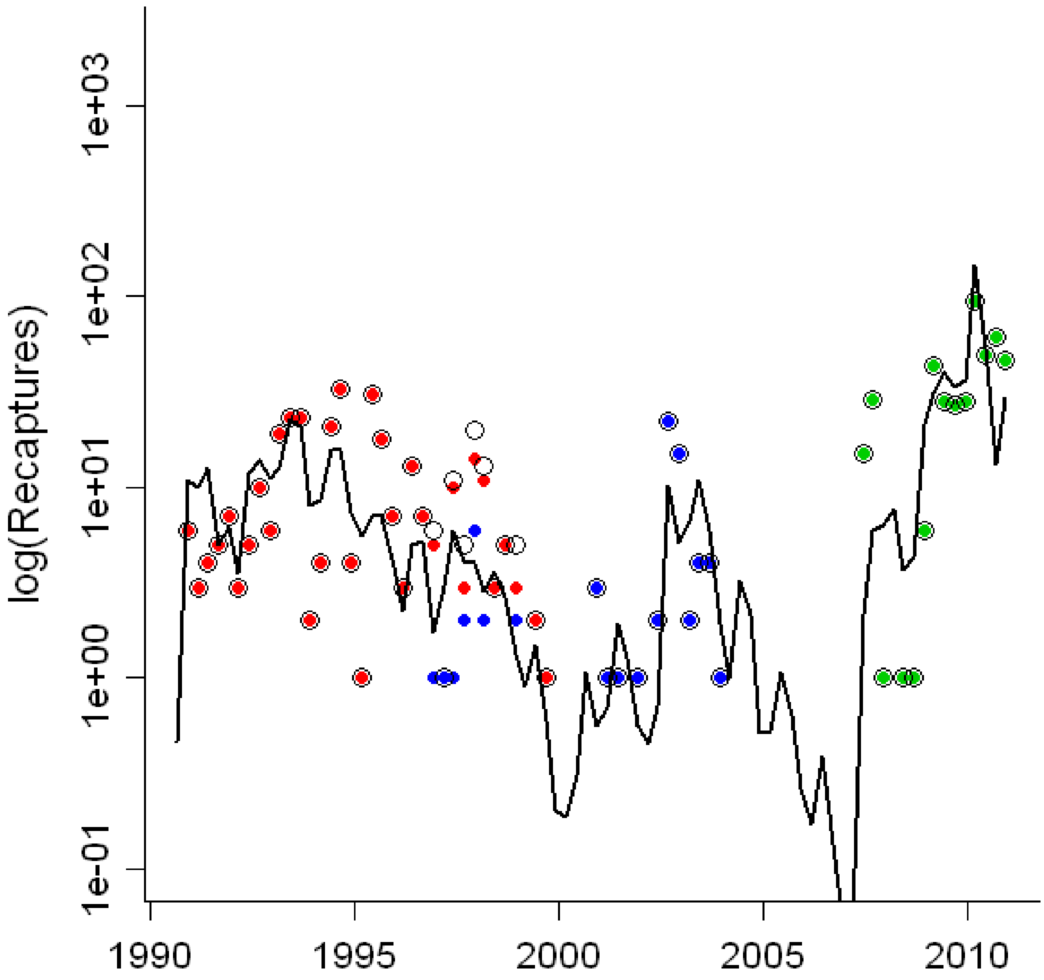


Figure 23. Fit of the Run3j – Ref.case model to log(observed recaptures) by time period specific to each release program shown by coloured dots: green = PTTP, blue = CS, red = RTTP. The model (black line) is fitted to the total observed recaptures in a time period (black circles), that are made up of the sum of the program-specific recaptures occuring in that time period, hence a dot and circle will coincide if recaptures are derived from only one program.

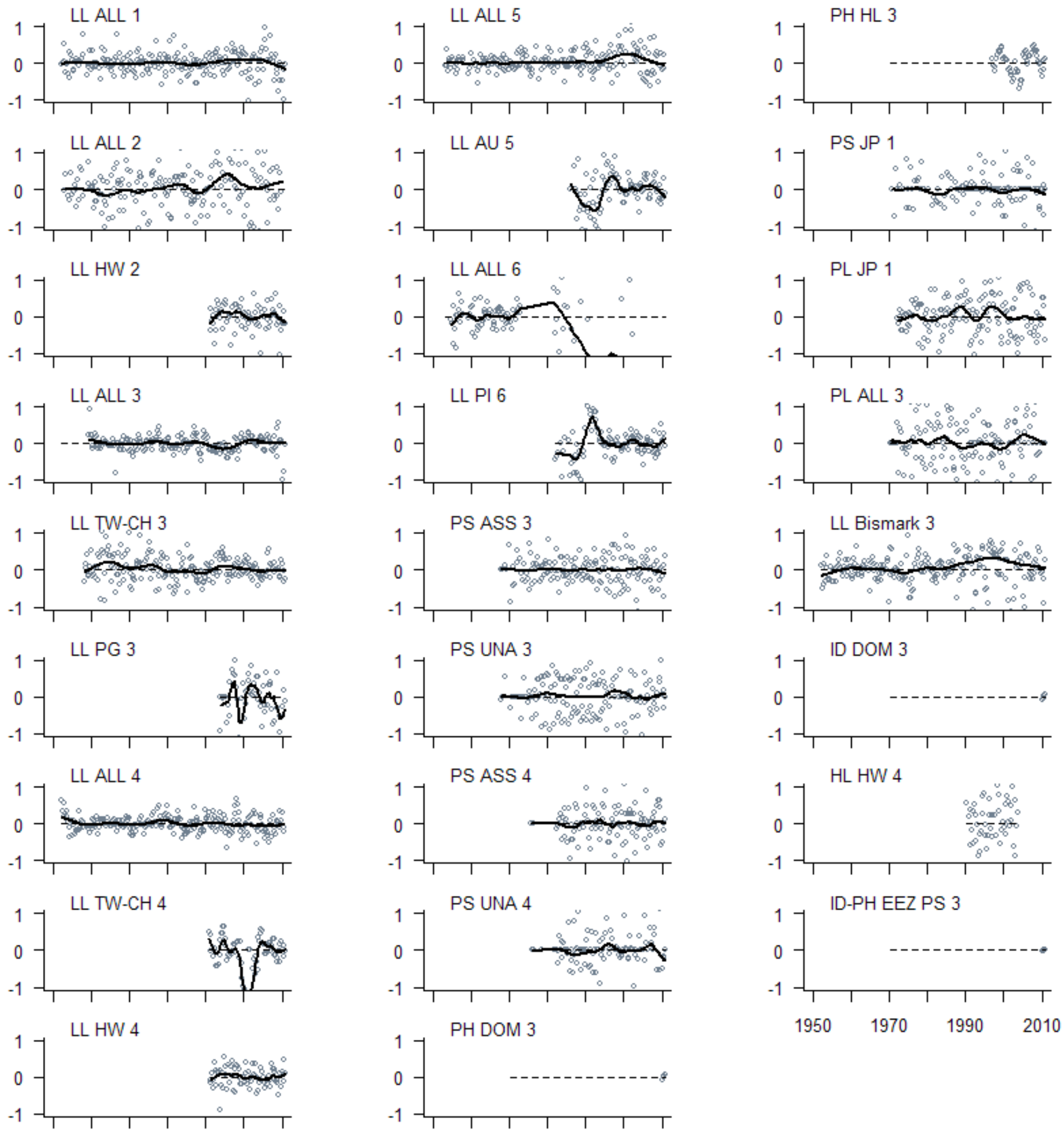


Figure 24. Effort deviations by time period for each fishery (Run3j – Ref.case). For fisheries with longer time series, the dark line represents a lowess smoothed fit to the effort deviations. Some values lie outside the bounds of the plot.

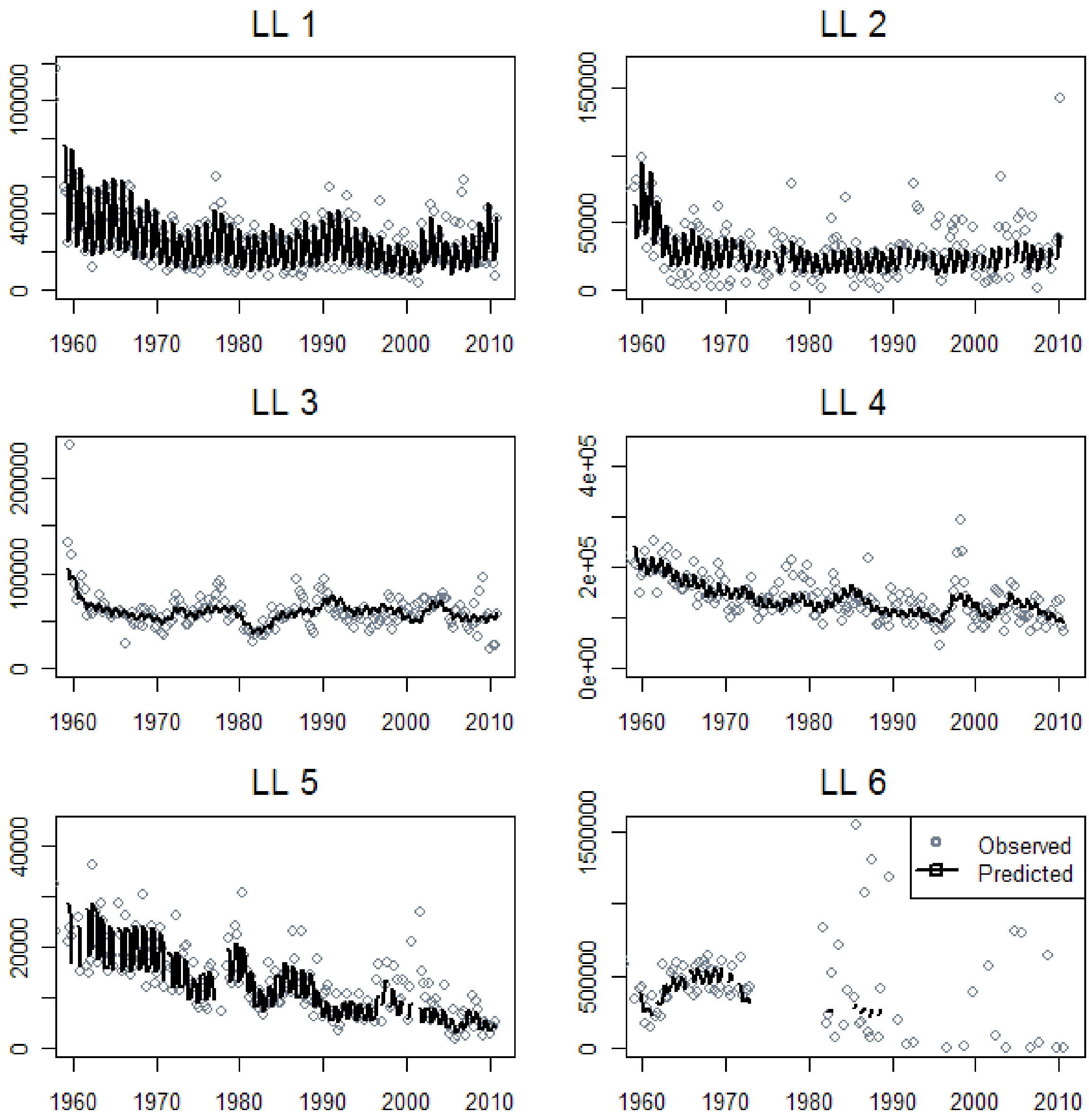


Figure 25. Observed and predicted CPUE for the major longline fisheries LL ALL in regions 1 to 6 for Run3j – Ref.case.

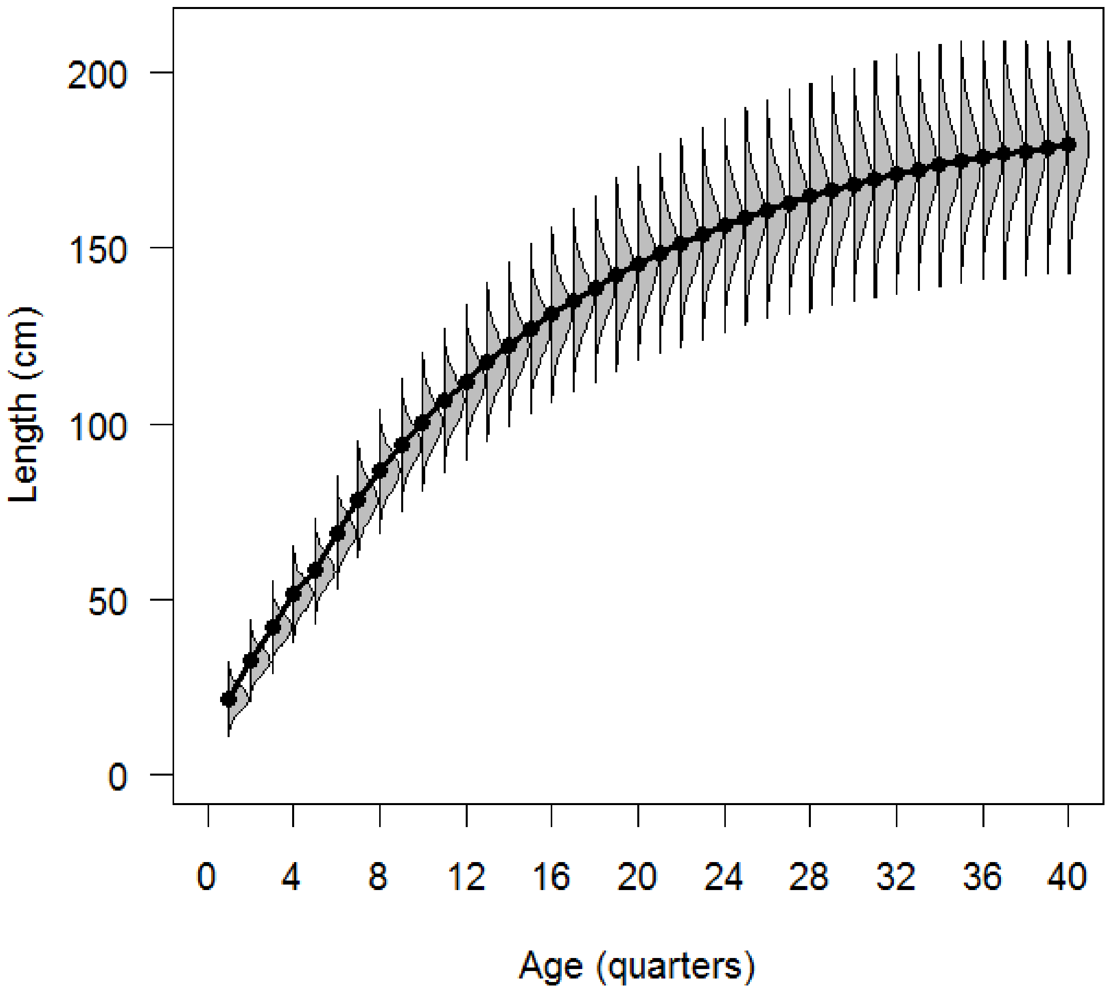


Figure 26. Estimated growth of bigeye derived from the assessment model. The black line represents the estimated mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age.

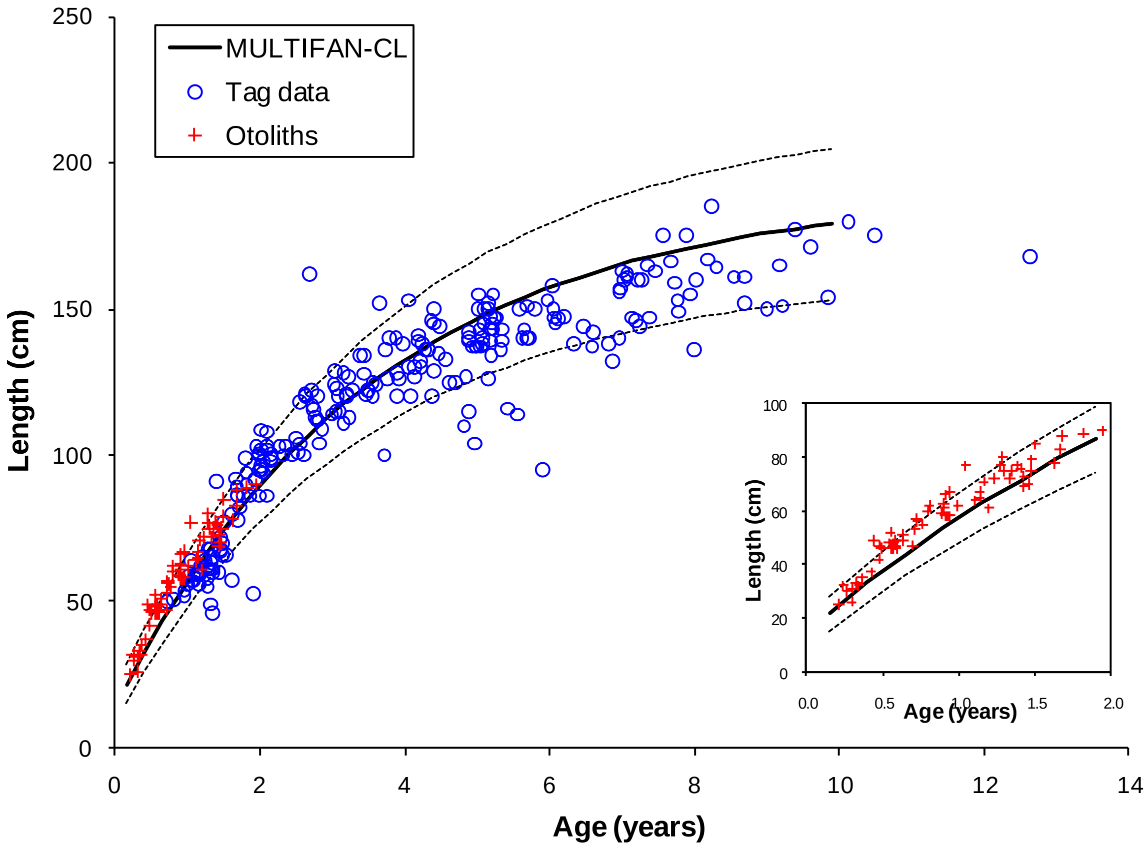


Figure 27. Estimated mean lengths-at-age (heavy line) from the Ref.case (± 2 sd). For comparison, length at age estimates are presented from tag release and recapture data (blue circles) and empirical age determination from otolith readings (red crosses), taken from Hampton and Williams (2005).

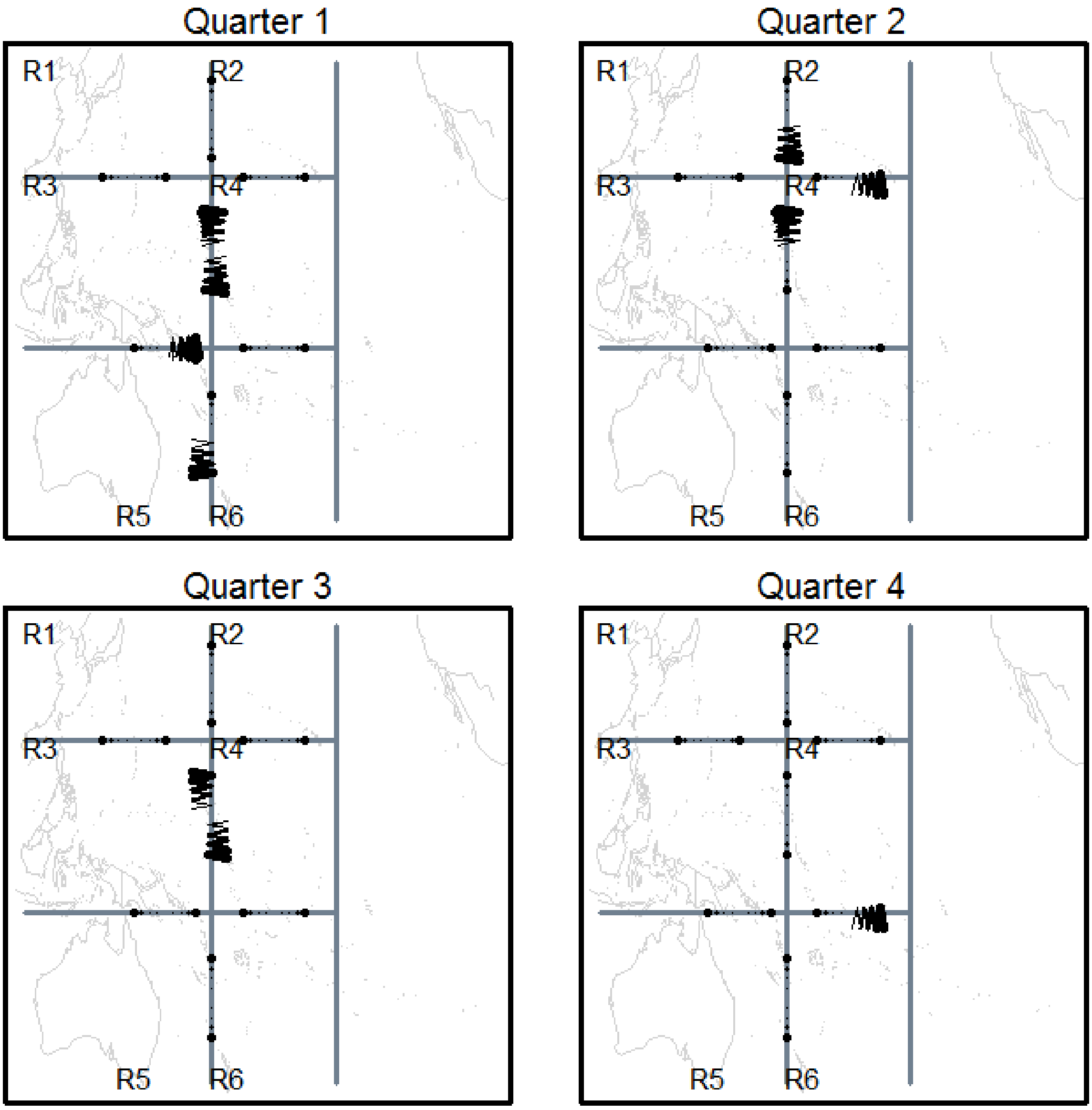


Figure 28. Estimated quarterly movement coefficients at age (1, 10, 20, 30 quarters). The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age.

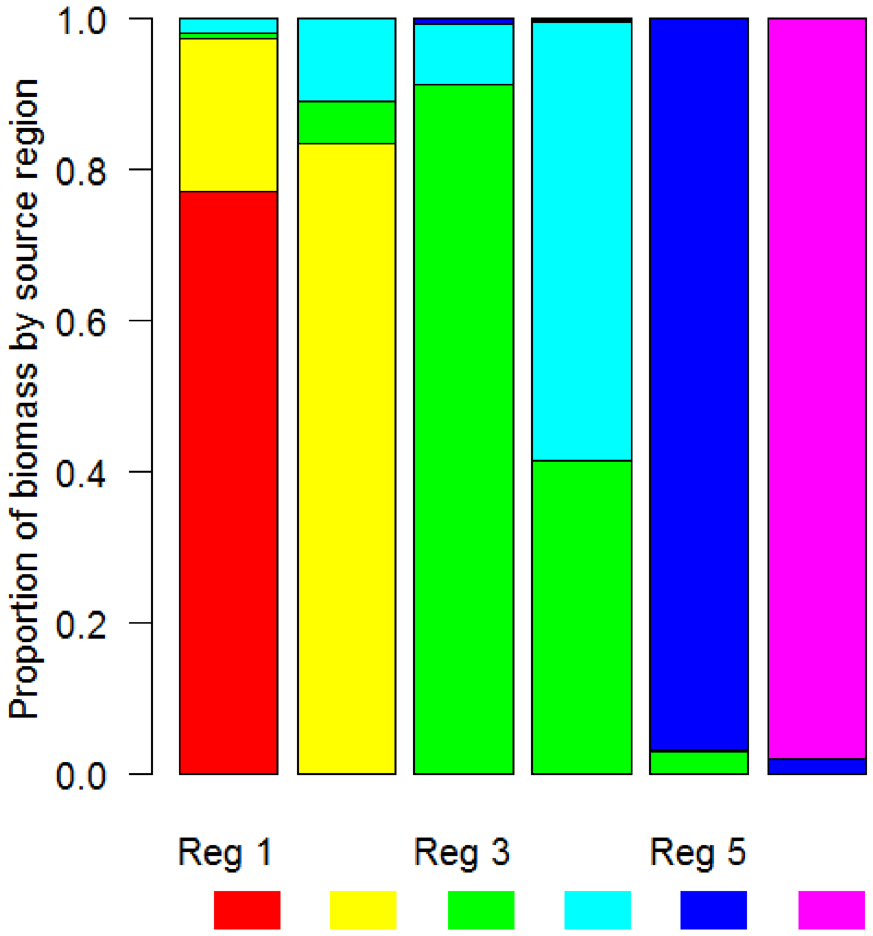


Figure 29. Proportional distribution of total biomass (by weight) in each region (Region 1–6) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment between regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

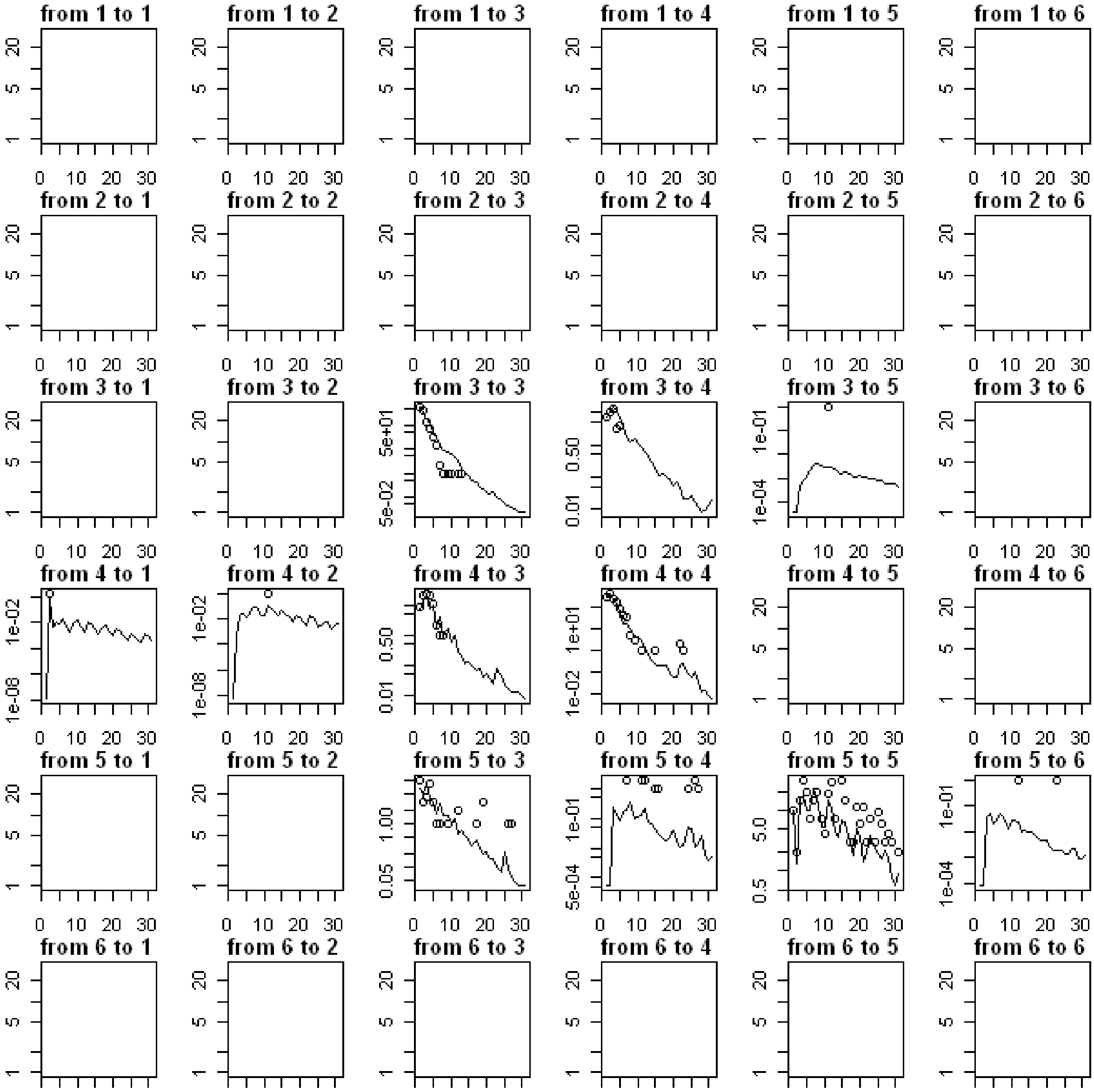


Figure 30. Predicted and observed recaptures of tagged fish by time period at liberty (quarter) from the region of release to the region of recapture.

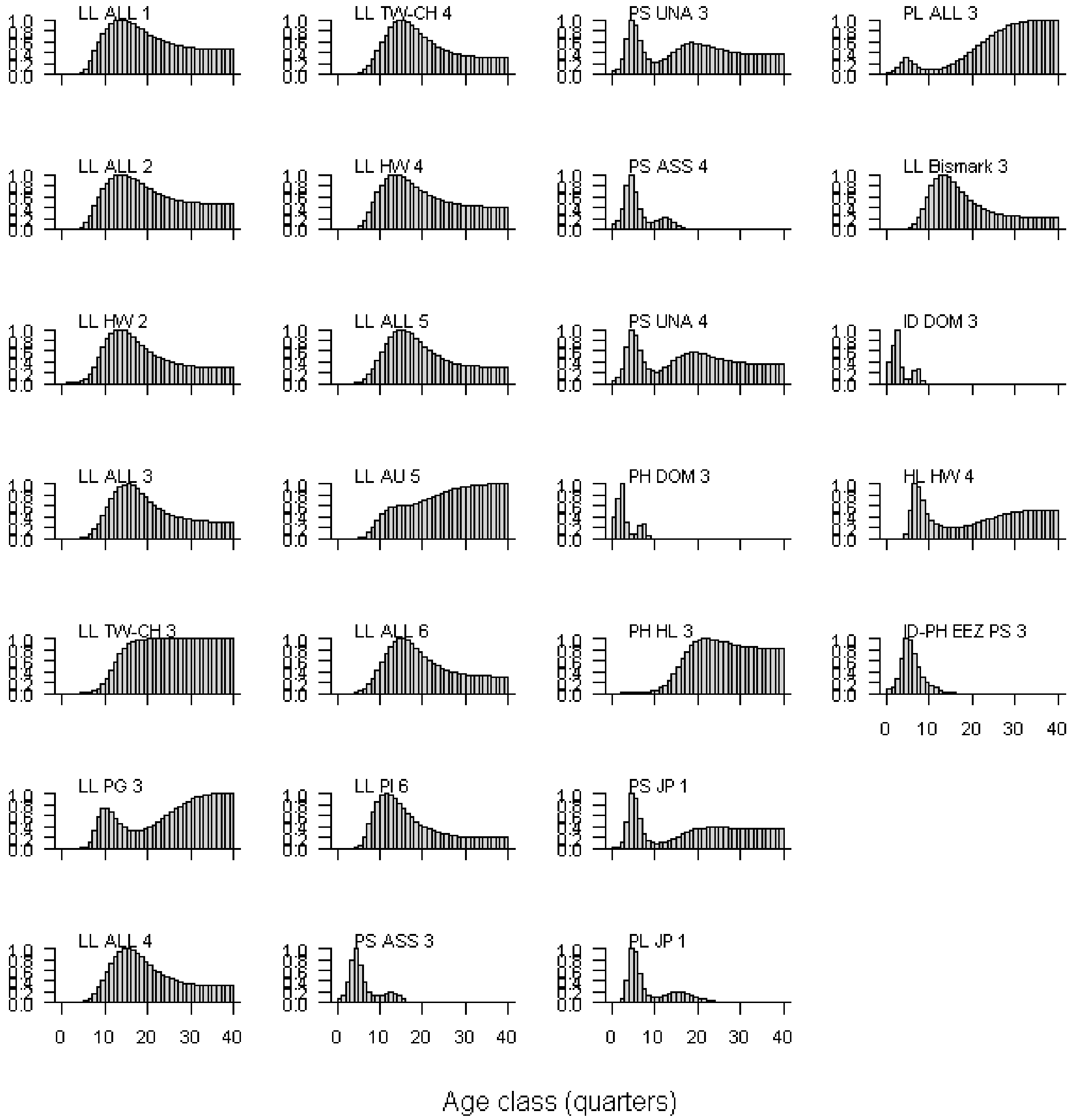


Figure 31. Selectivity coefficients by fishery.

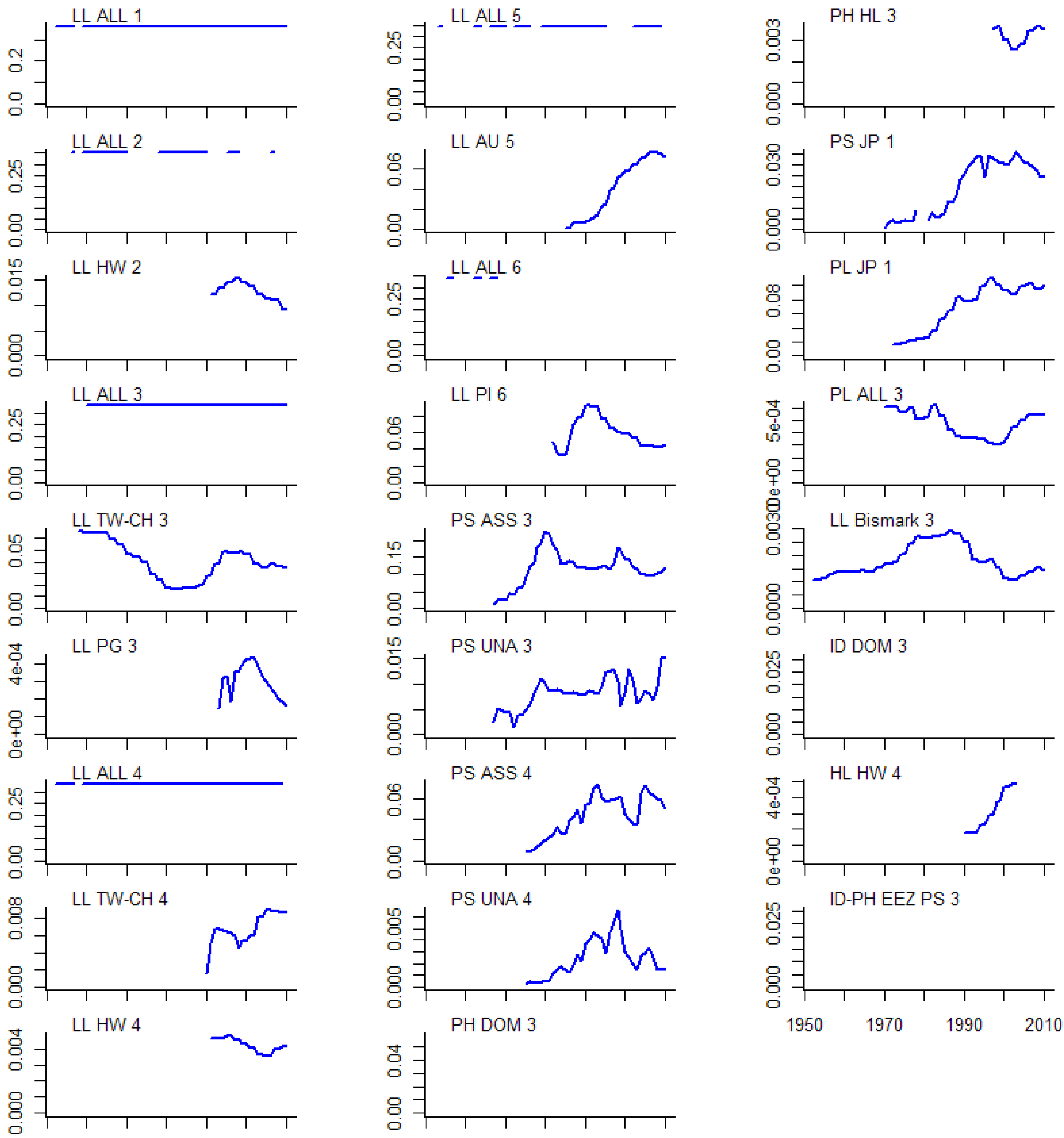


Figure 32. Average annual catchability time series, by fishery.

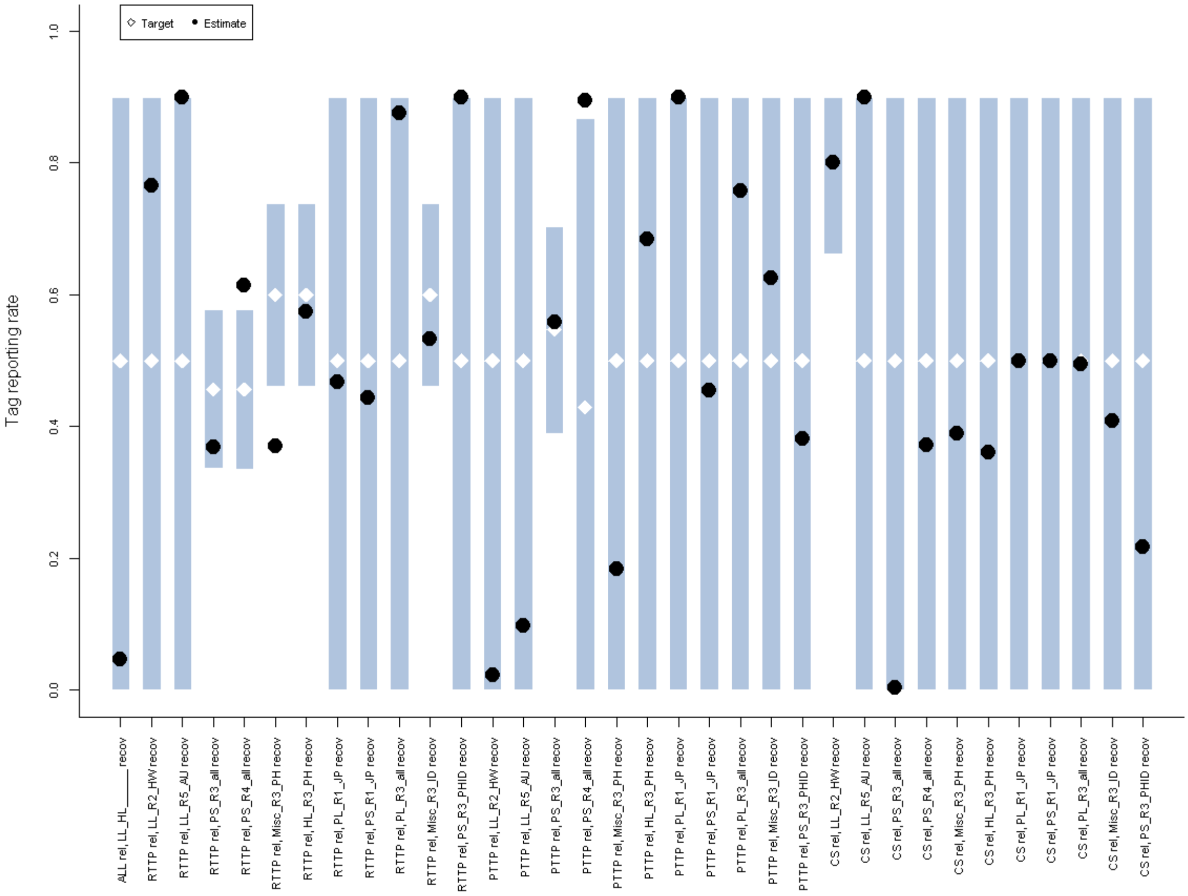


Figure 33. Estimated reporting rates for Run3j – Ref.case specific to each release program (RTTP, PTTP and CS) and recapture fishery group (histograms). Certain estimates are grouped over release programs and over recapture fisheries, (e.g. LL-ALL and HL fisheries: ALL rel.LL_HL___recov). The prior mean ±1.96 SD is also shown for each fishery.

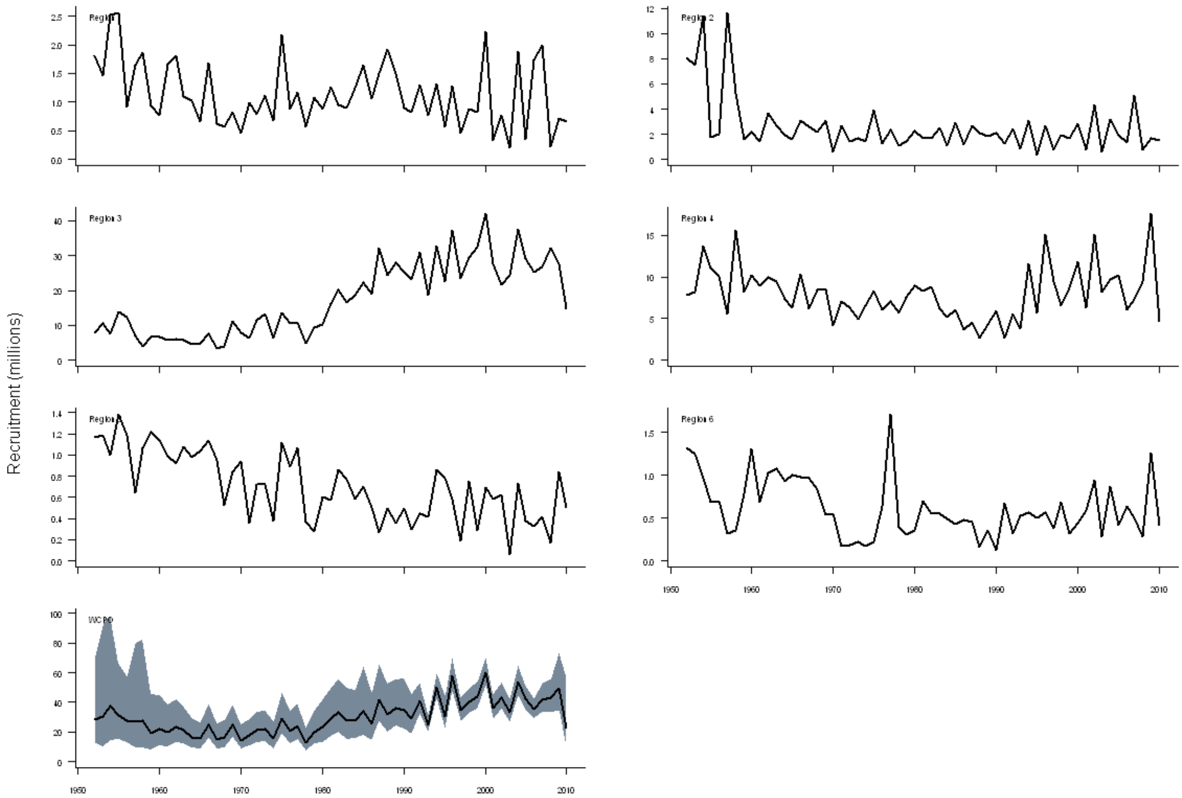
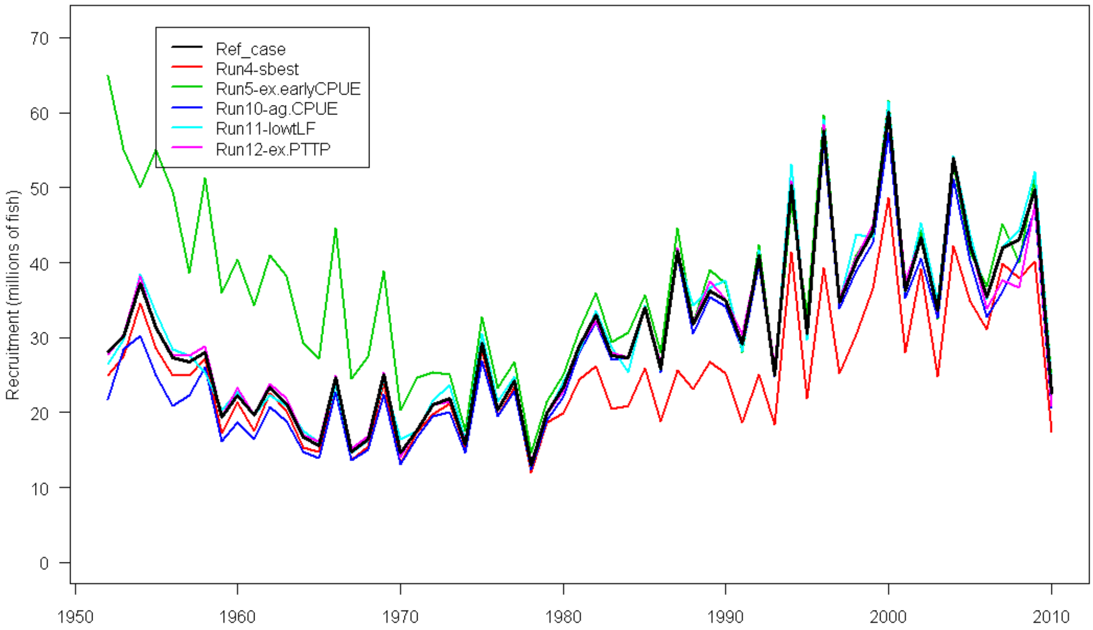


Figure 34. Estimated annual recruitment (millions) by region and for the WCPO. The shaded areas indicate the approximate 95% confidence intervals.



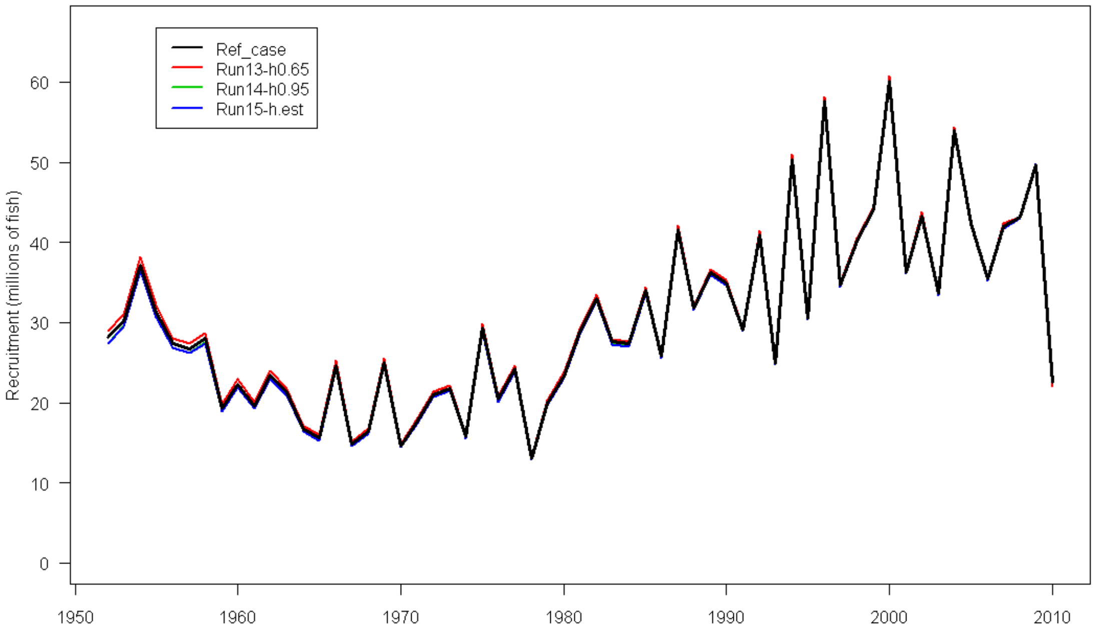


Figure 35. Estimated annual recruitment (millions of fish) for the WCPO obtained from the Ref.case and one-off sensitivity model runs.

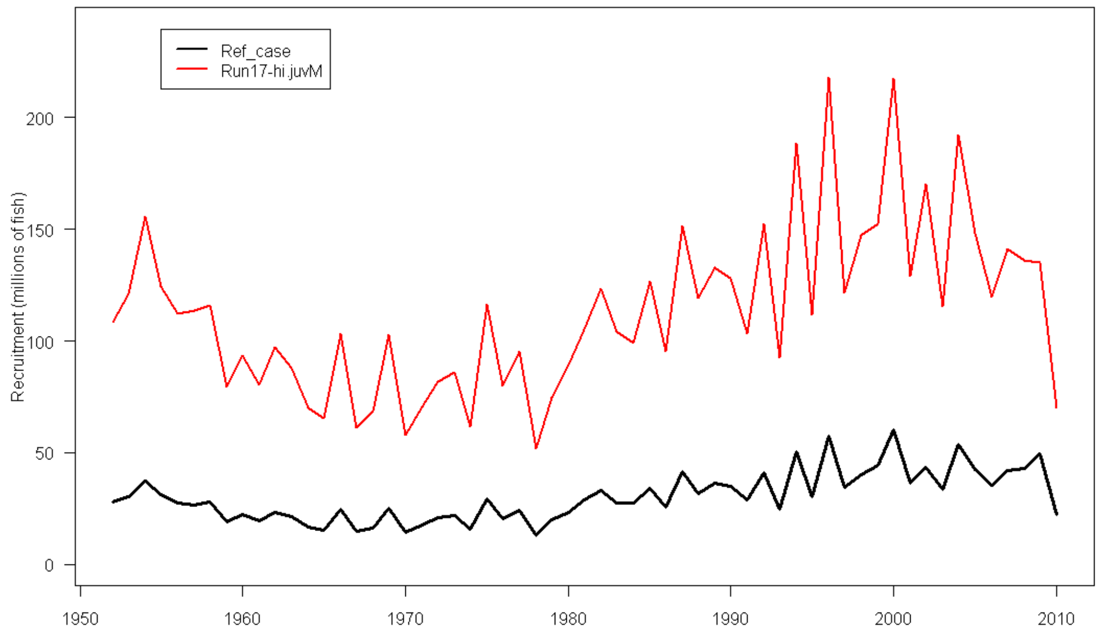


Figure 35 cont.. Estimated annual recruitment (millions of fish) for the WCPO obtained from the Ref.case and one-off sensitivity model runs.

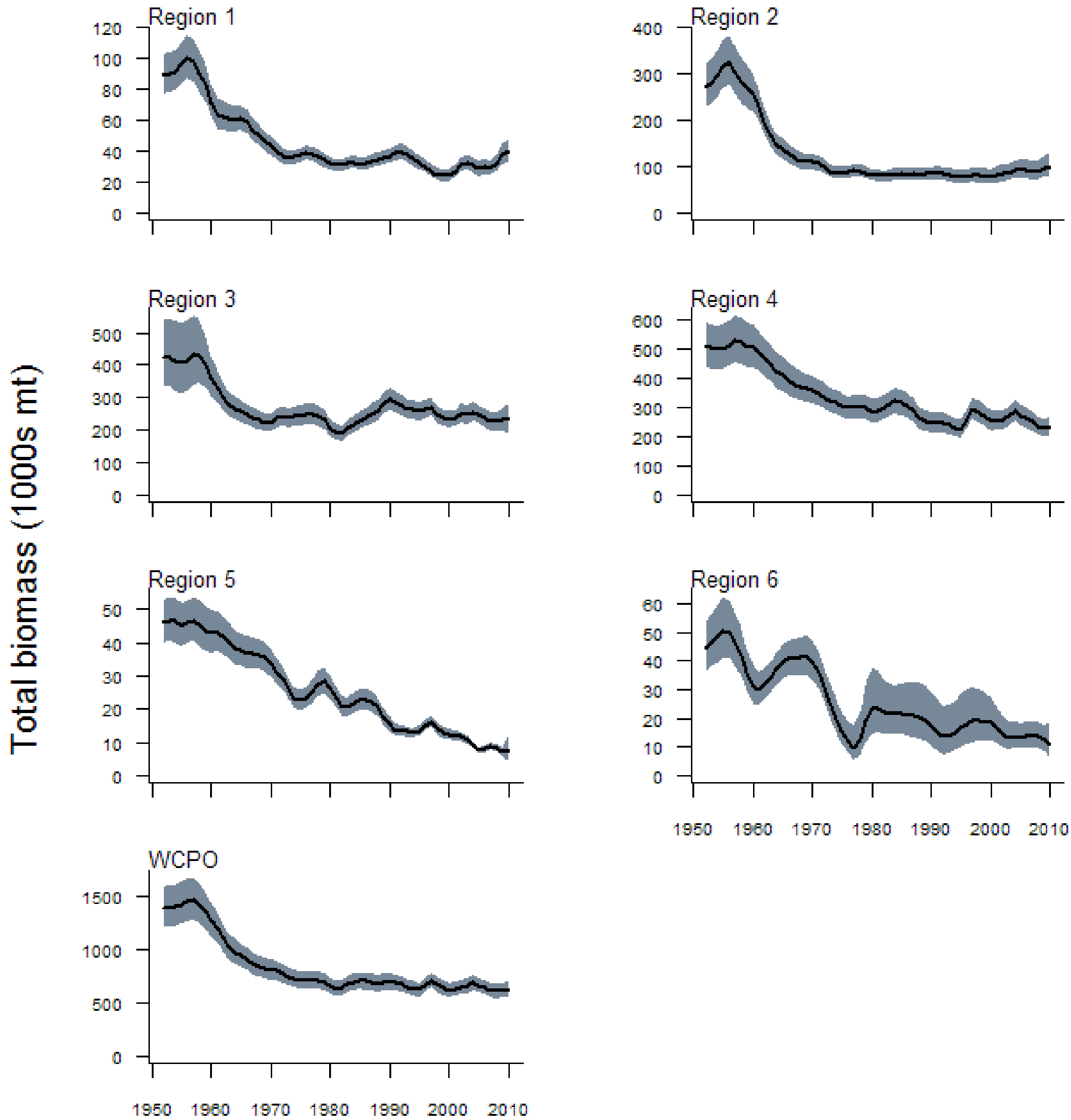


Figure 36. Estimated annual average total biomass by region and for the WCPO. The shaded areas indicate the approximate 95% confidence intervals.

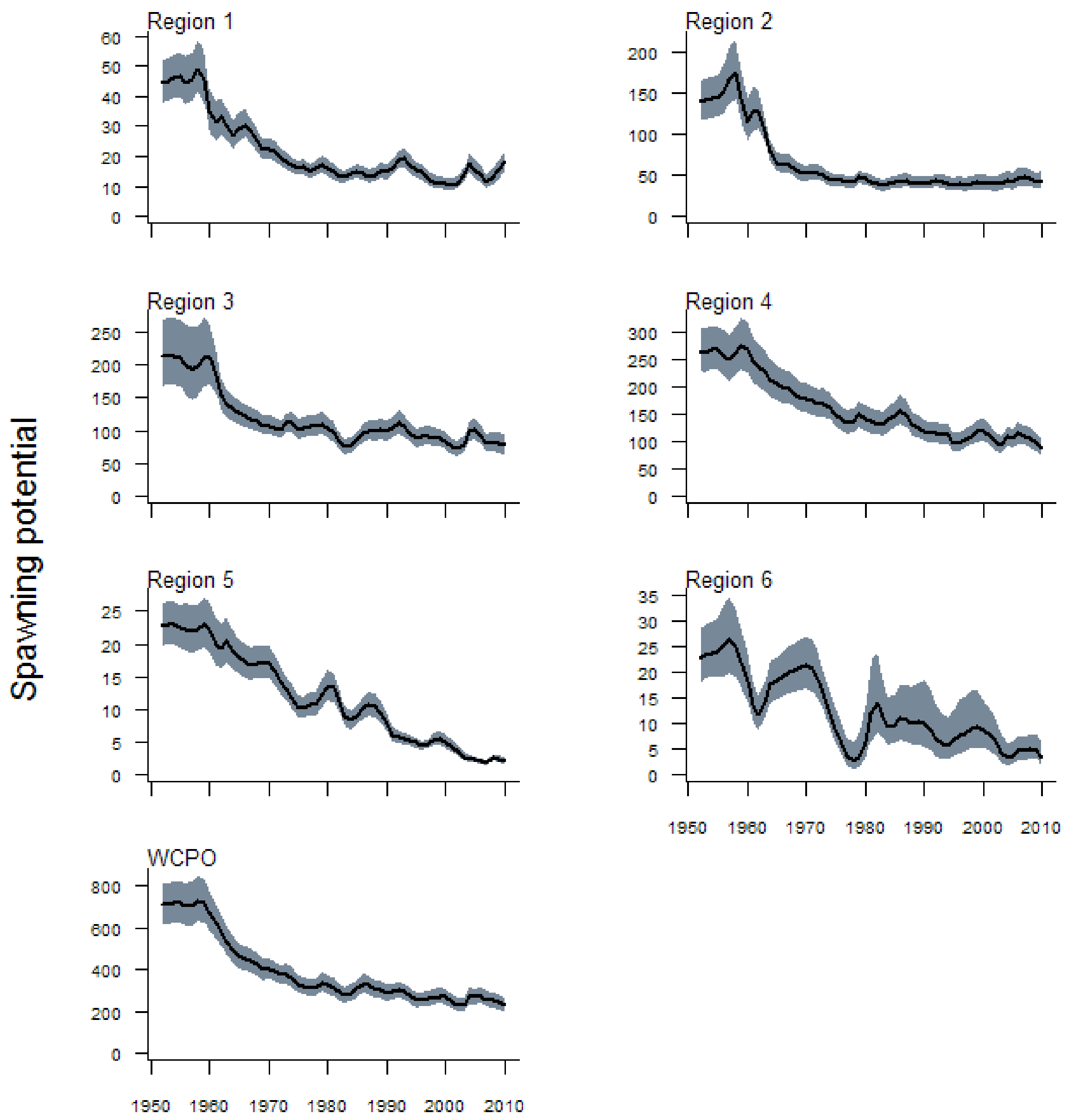
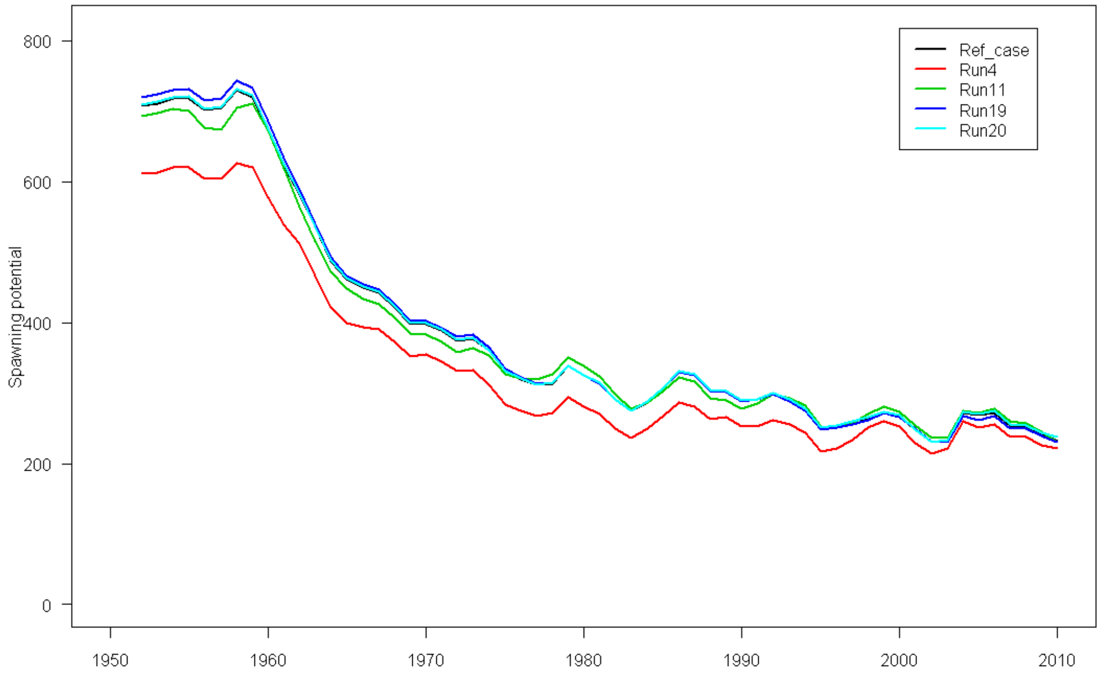


Figure 37. Estimated annual average spawning potential by region and for the WCPO. The shaded areas indicate the approximate 95% confidence intervals.



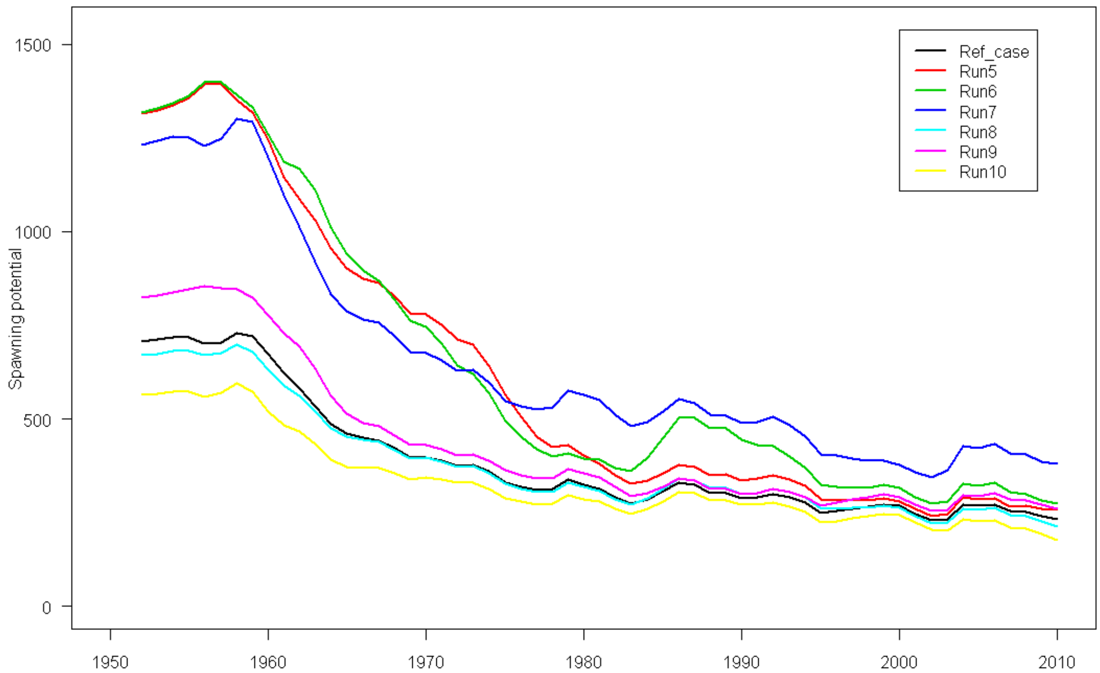
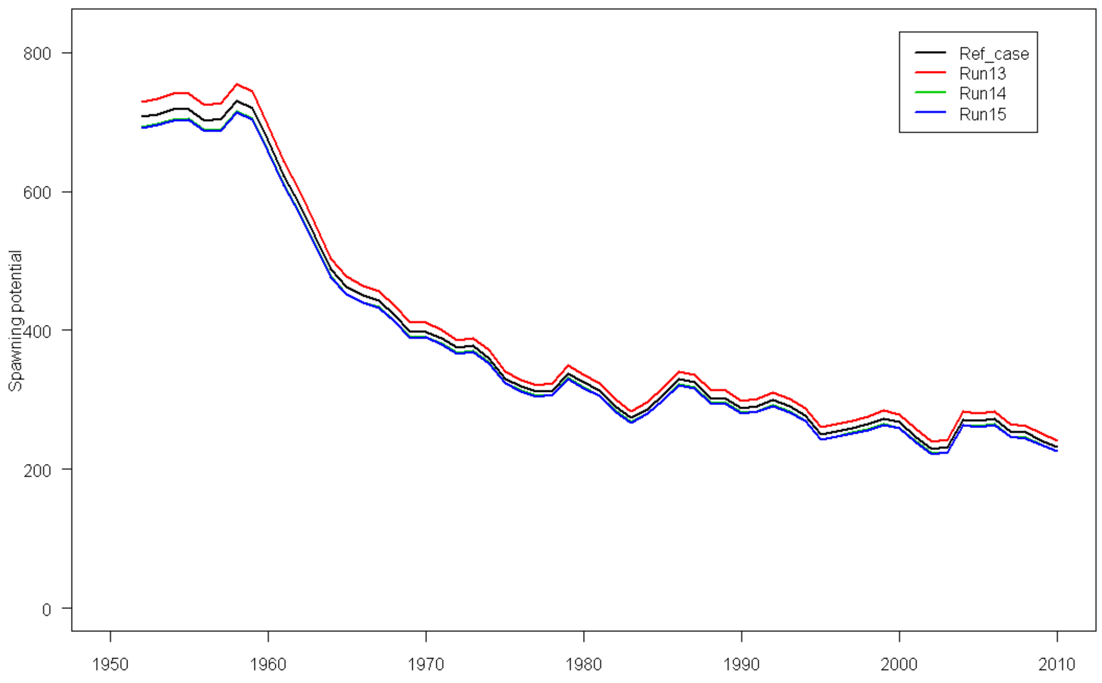


Figure 38. Estimated average annual spawning potential for the WCPO obtained from the one-off sensitivity model runs to the Ref.case in respect of catch and size data (top), and CPUE (bottom).



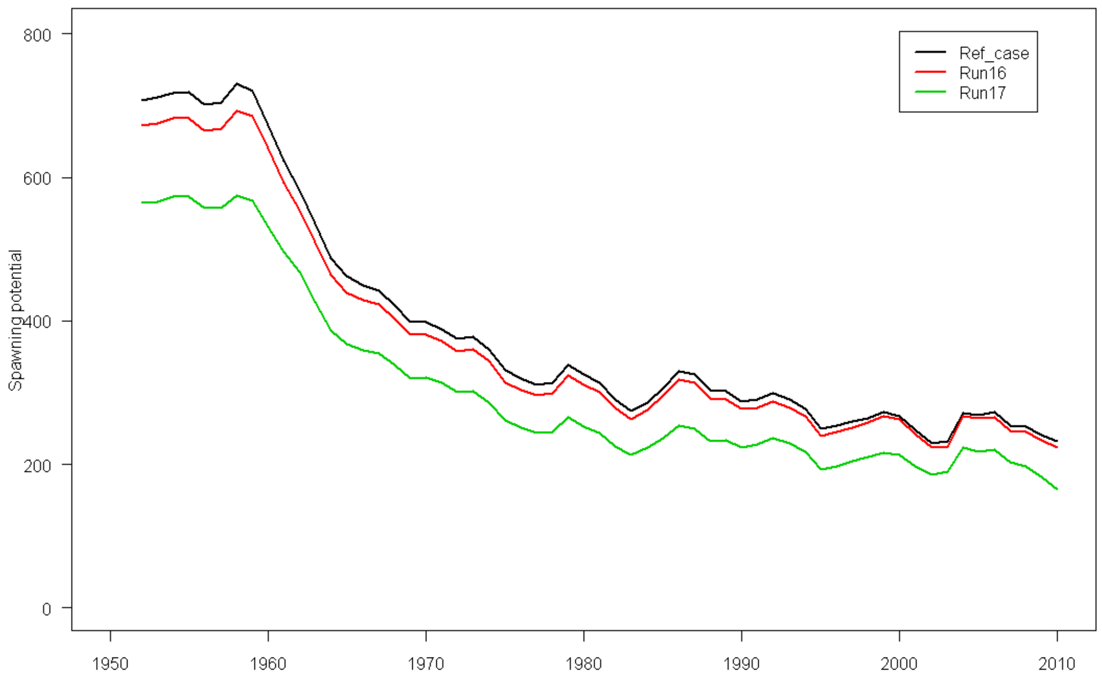


Figure 38 cont. Estimated average annual spawning potential for the WCPO obtained from the one-off sensitivity model runs to the Ref.case in respect of the assumptions for the spawning stock recruitment relationship steepness value (top) and juvenile natural mortality (bottom).

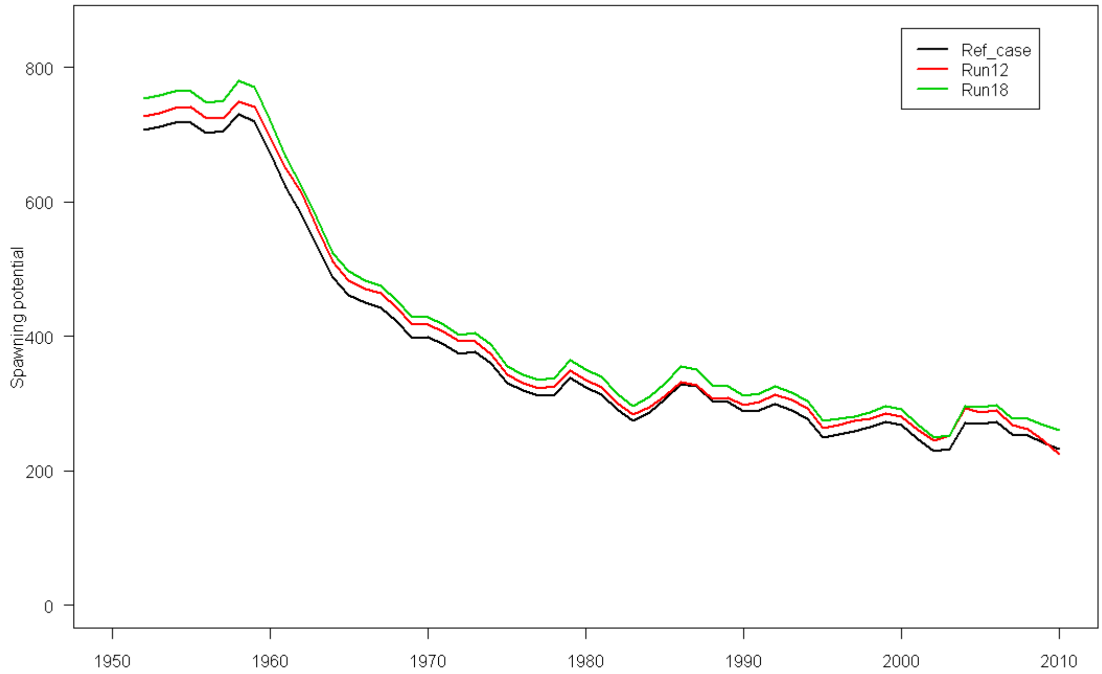
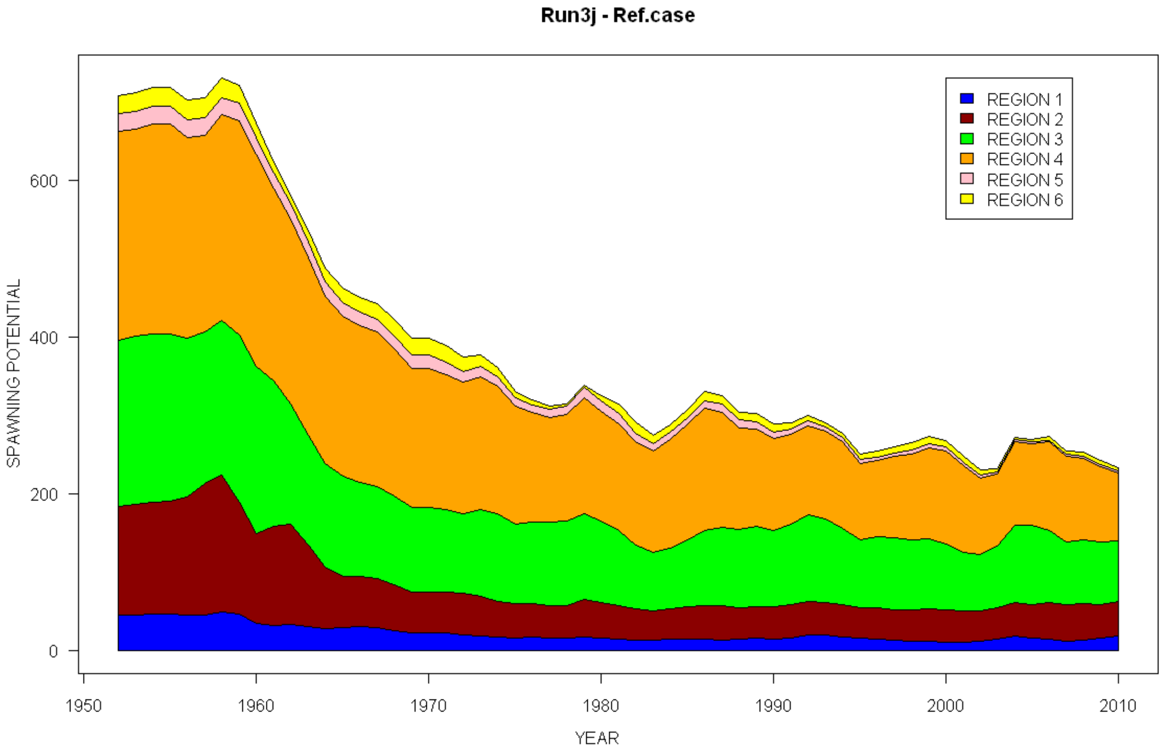


Figure 38 cont. Estimated average annual spawning potential for the WCPO obtained the one-off sensitivity model runs to the Ref.case in respect of the assumptions relating to the PTTP and mixing period for tagged fish.



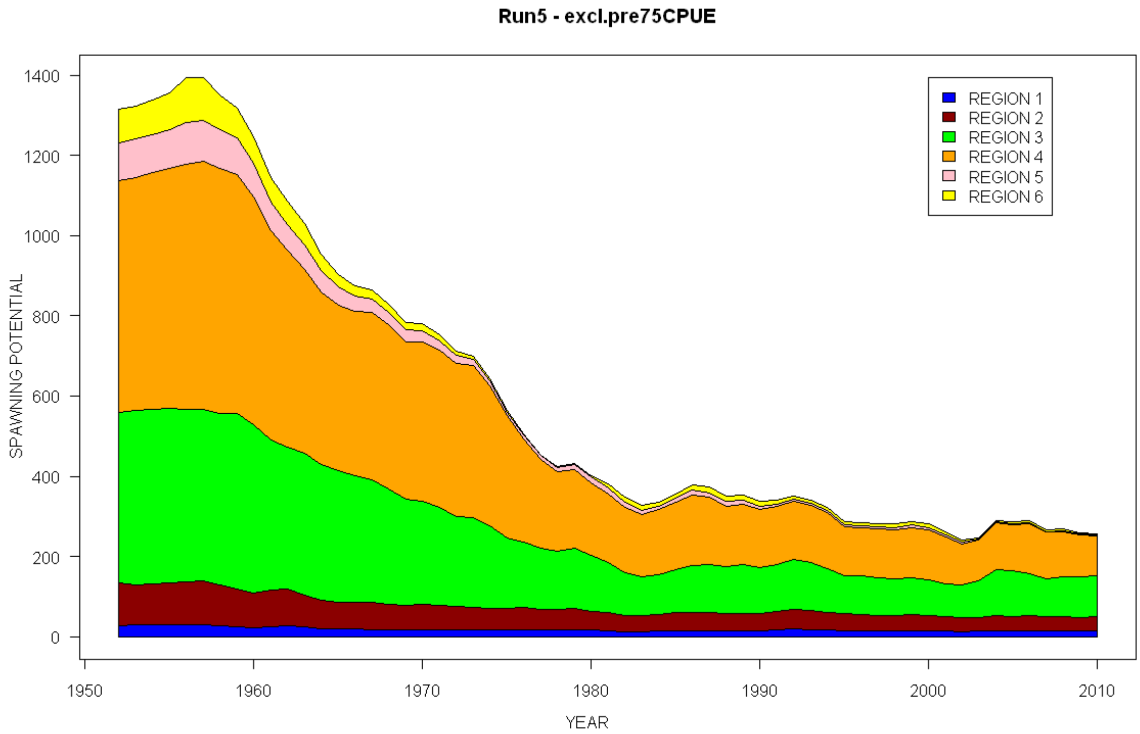


Figure 39. Estimated average annual spawning biomass by model region for Run3j (Ref.case – top) and Run5 (excl.pre75CPUE – bottom).

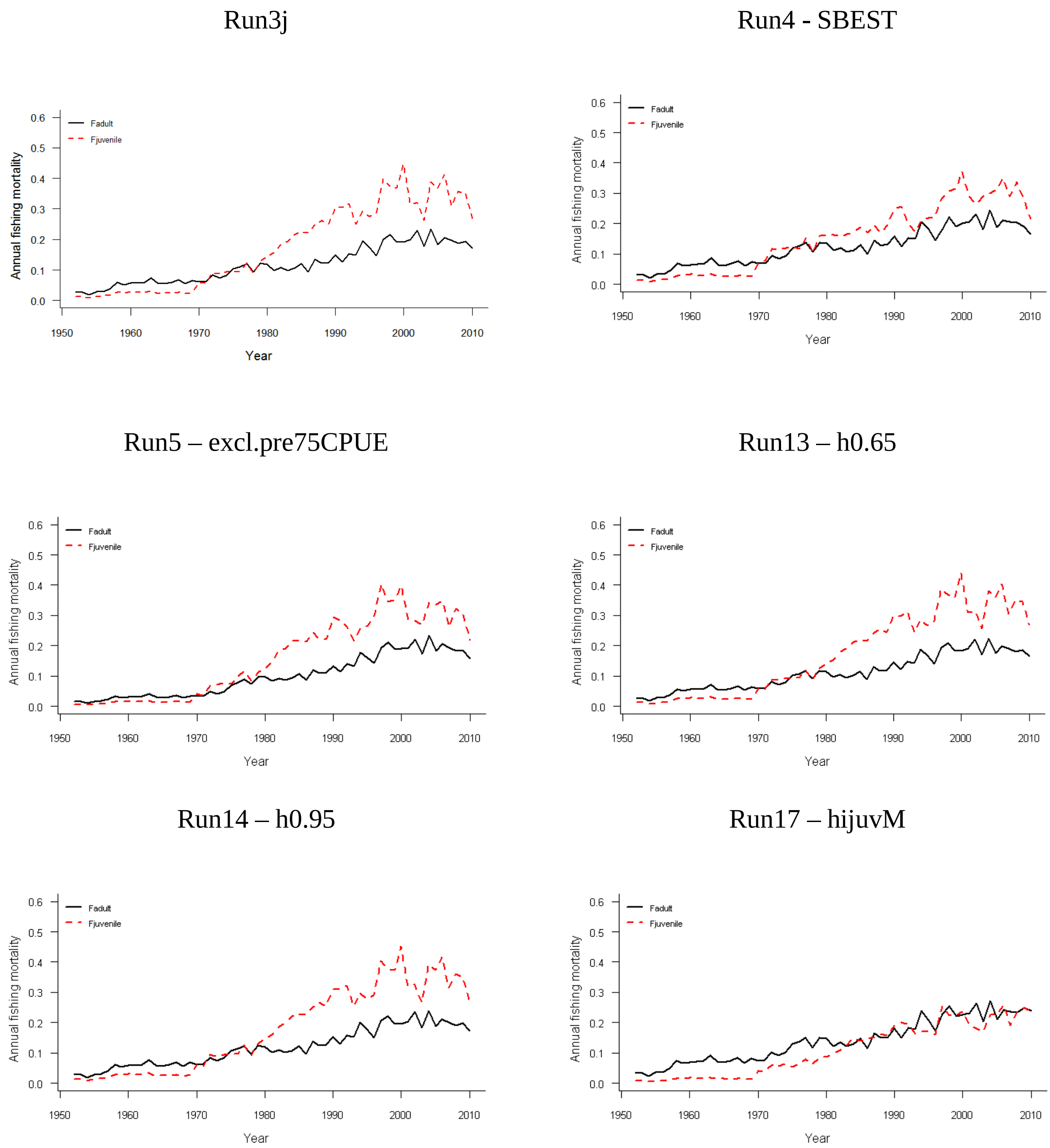


Figure 40. Estimated annual average juvenile and adult fishing mortality for the WCPO obtained from key model runs.

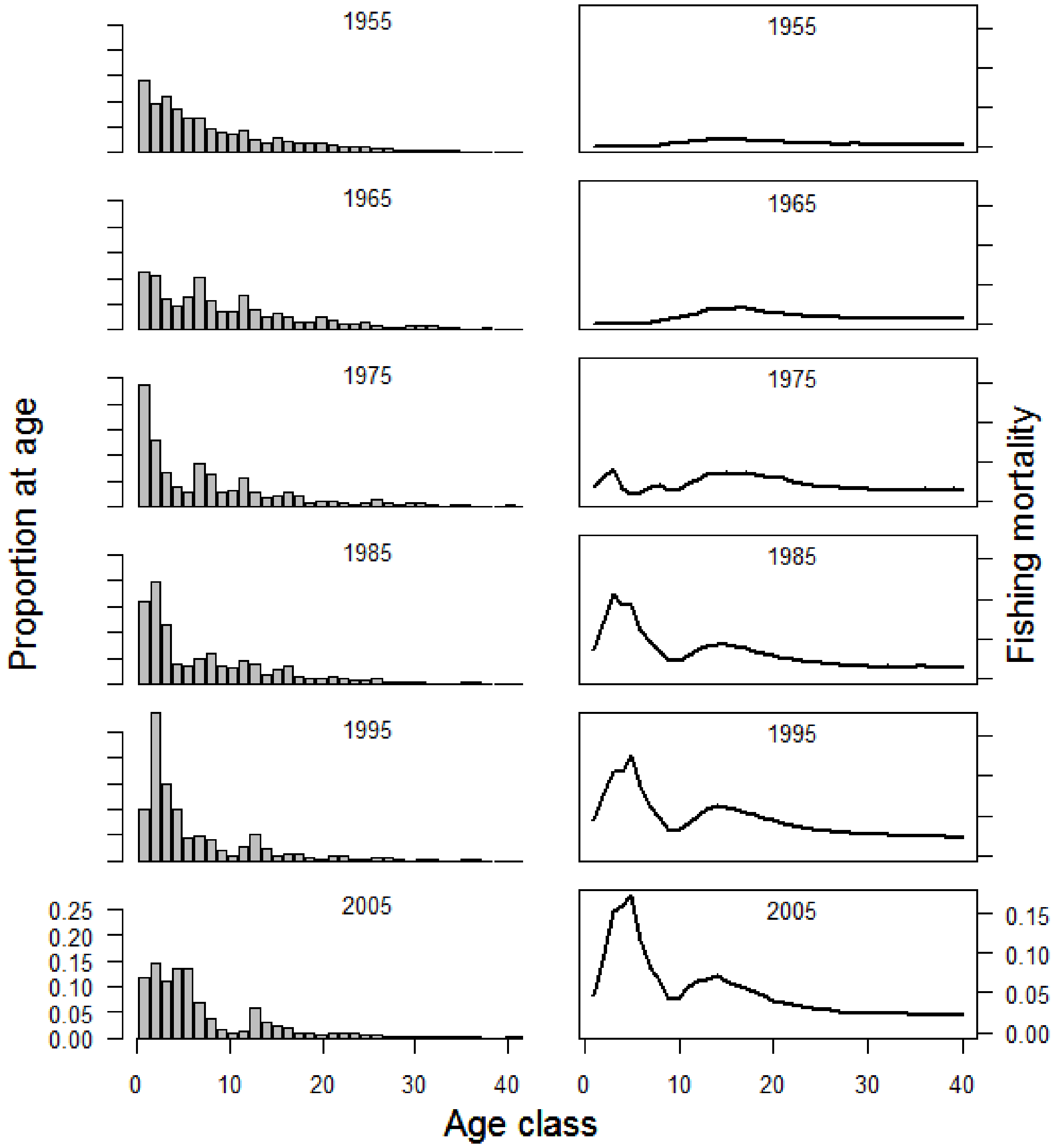


Figure 41. Estimated proportion at age (quarters) for the WCPO bigeye population (left) and fishing mortality at age (right) by year at decade intervals.

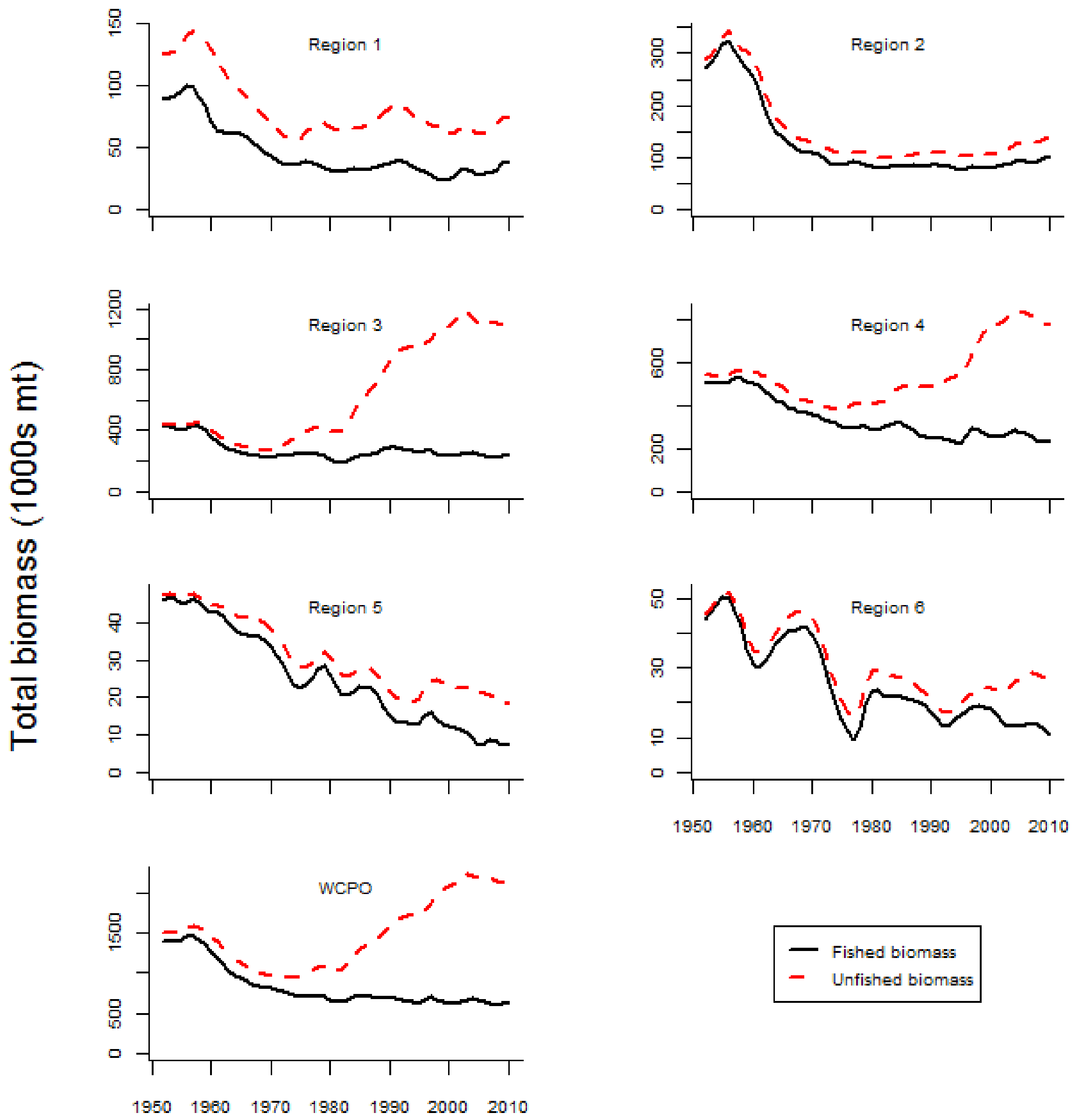


Figure 42. Comparison of the model Run3j – Ref.case estimated total biomass trajectories (black lines) with biomass trajectories that would have occurred in the absence of fishing (red dashed lines) for each region and for the WCPO.

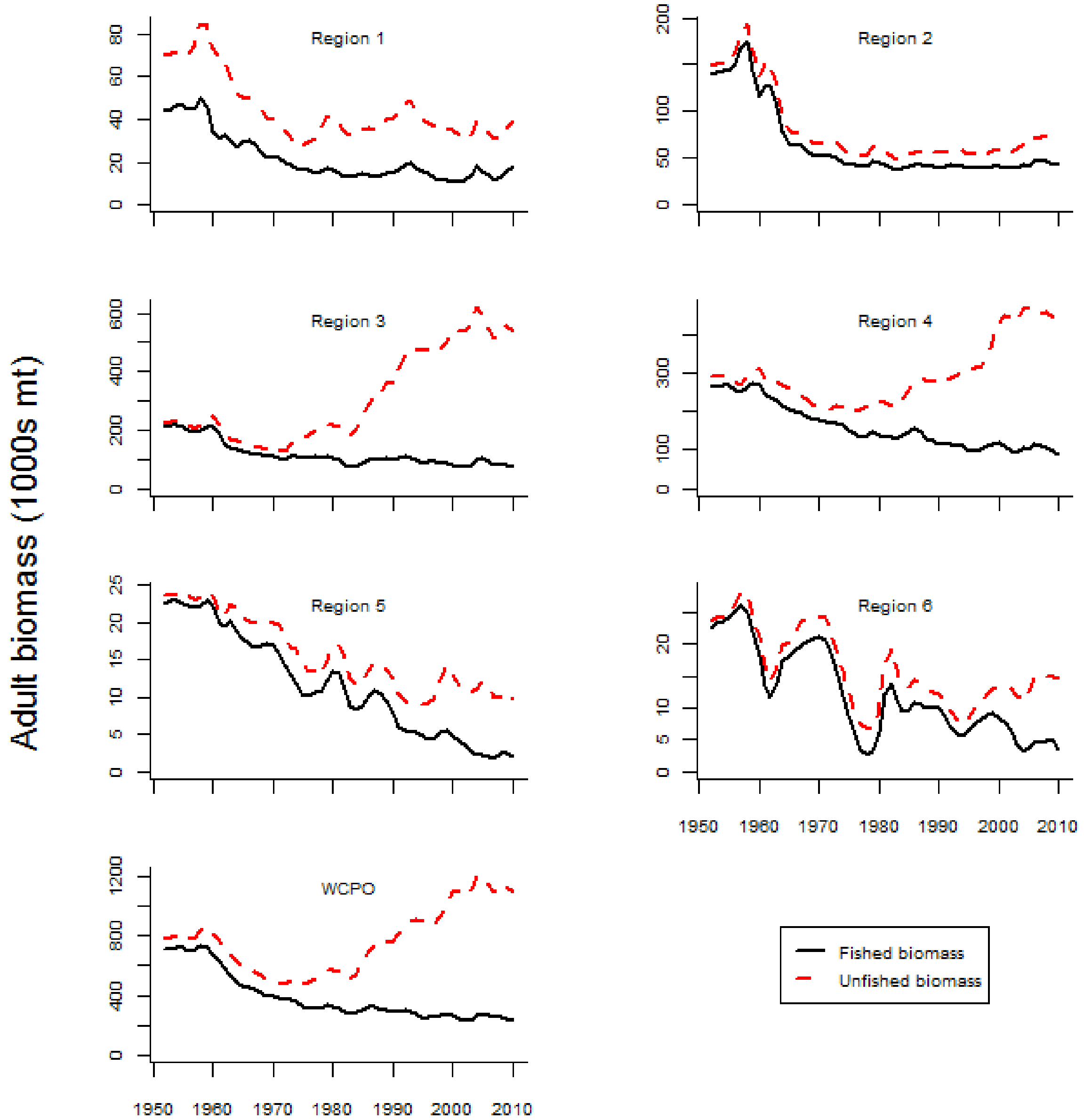


Figure 43. Comparison of the estimated adult biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper dashed lines) for each region and for the WCPO (Run3j – Ref.case).

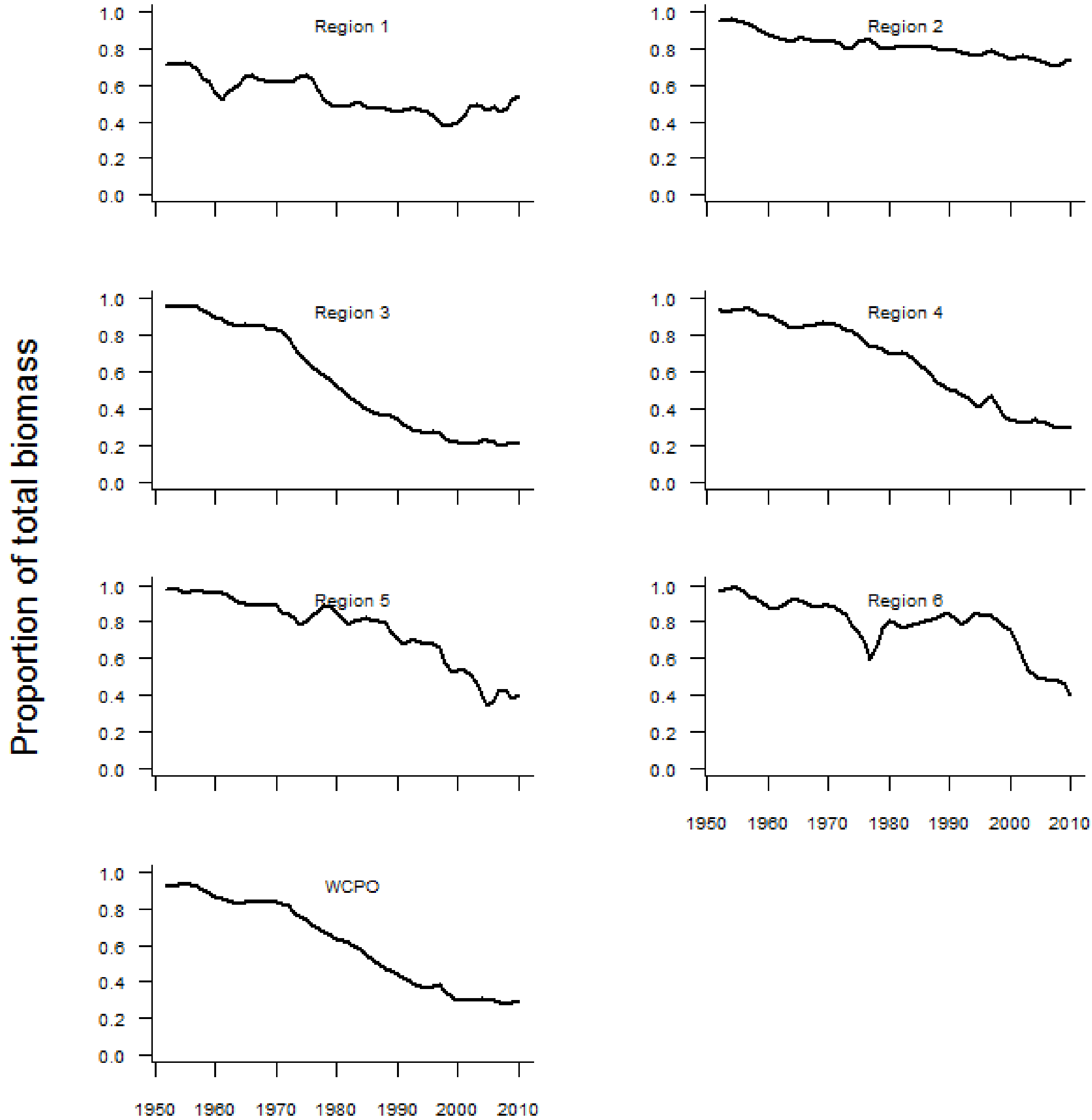


Figure 44. Ratios of exploited to unexploited total biomass $B_t/B_{t_{F=0}}$ for each region and the WCPO (Run3j – Ref.case).

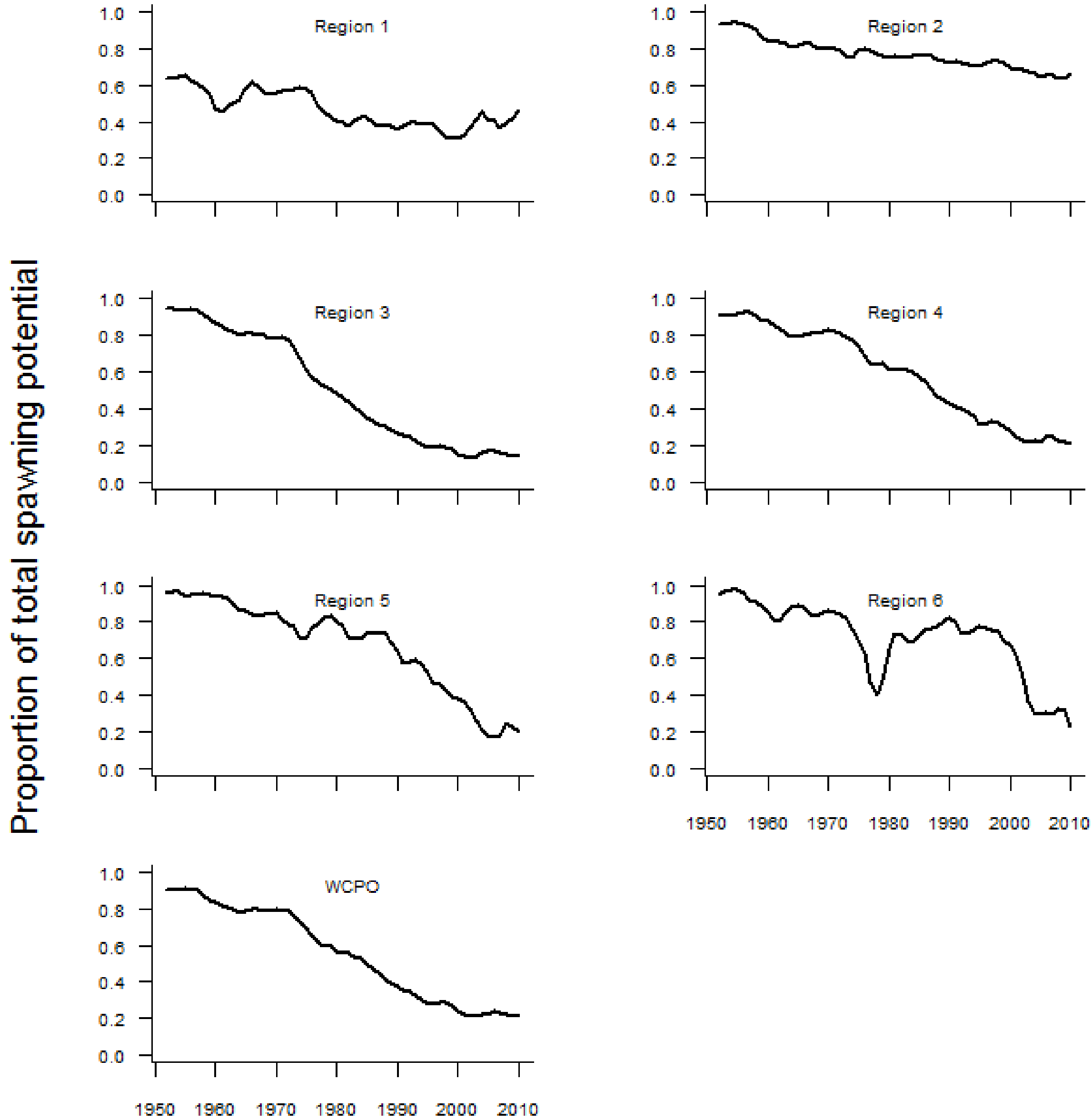
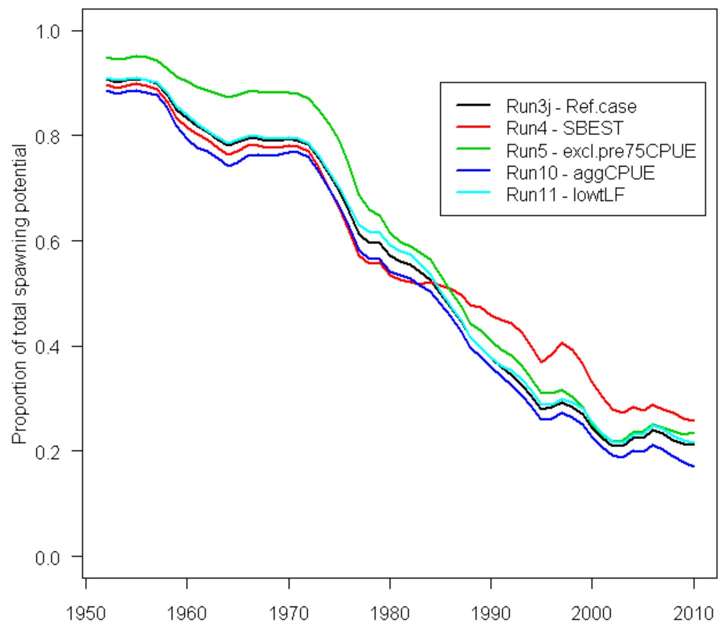


Figure 45. Ratios of exploited to unexploited spawning potential $SB_t/SB_{t_{F=0}}$ for each region and the WCPO (Run3j – Ref.case).



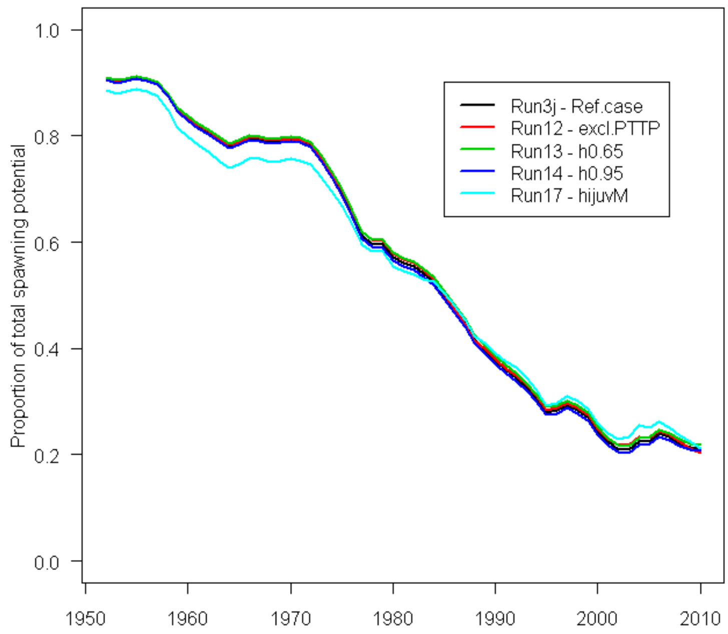


Figure 46. Ratios of exploited to unexploited spawning potential, $\boldsymbol{SB_t/SB_{t_{F=0}}}$, for the WCPO obtained from the key model runs.

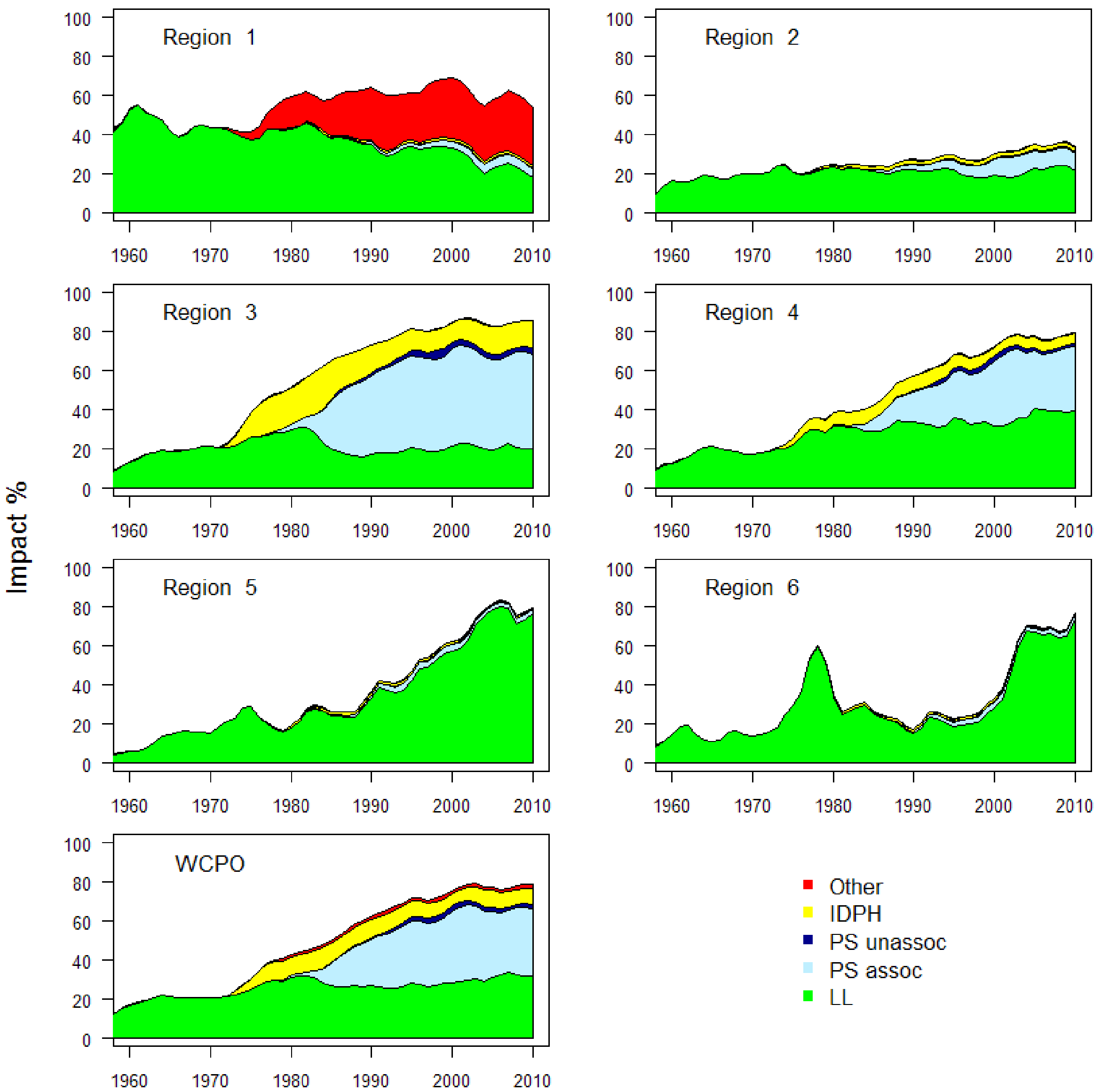


Figure 47. Estimates of reduction in spawning potential due to fishing (fishery impact = $\mathbf{1 - SB_t / SB_{t_{F=0}}}$) by region and for the WCPO attributed to various fishery groups (Run3j – Ref.case). LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine log and FAD sets; PS unassoc = purse seine school sets; Other = pole and line fisheries and coastal Japan purse-seine.

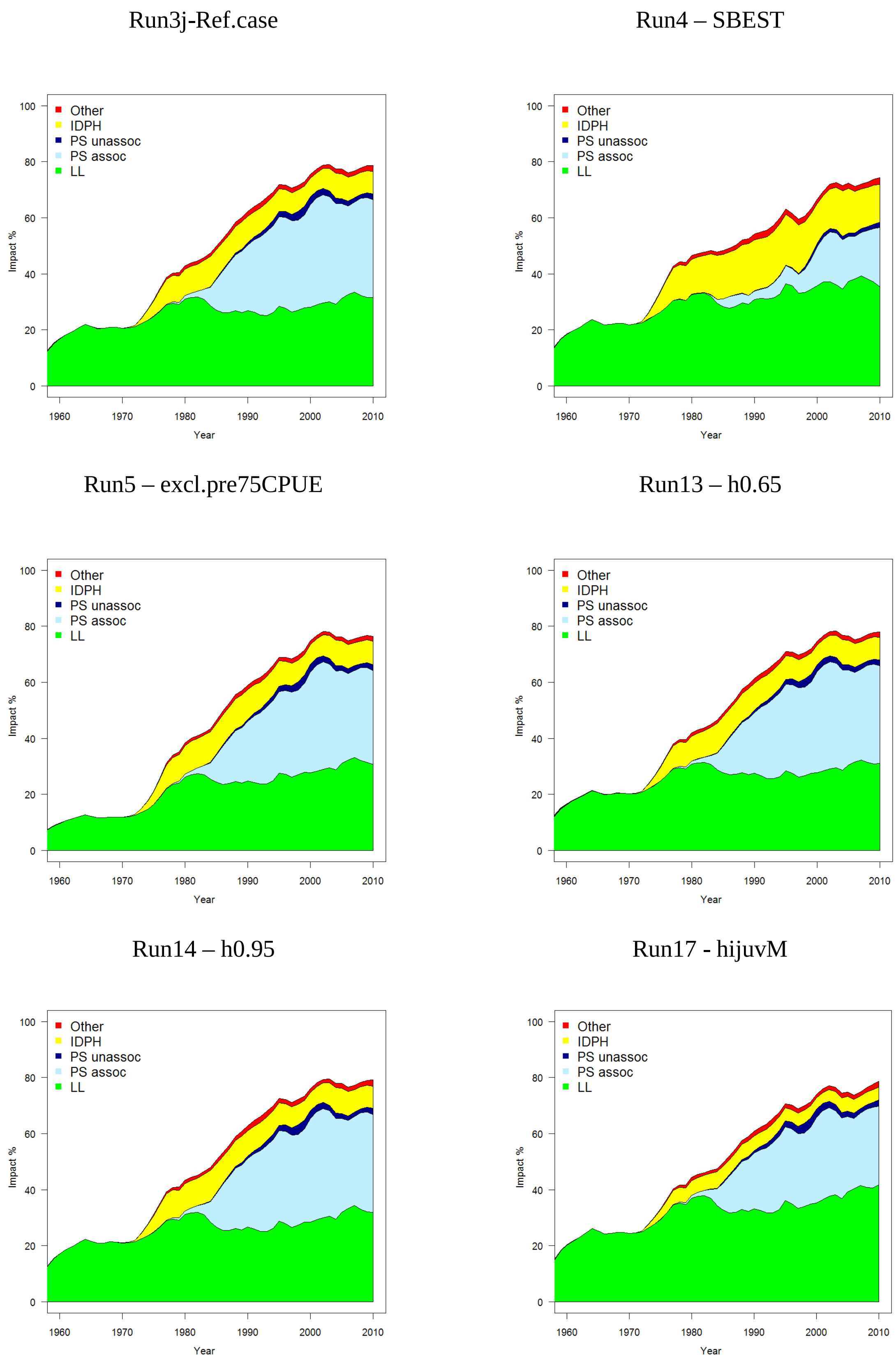


Figure 48. Estimates of reduction in WCPO spawning potential due to fishing (fishery impact = $\mathbf{1 - SB_t / SB_{t_{F=0}}}$) attributed to various fishery groups for the key model runs. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine log and FAD sets; PS unassoc = purse seine school sets; Other = pole and line fisheries and coastal Japan purse-seine.

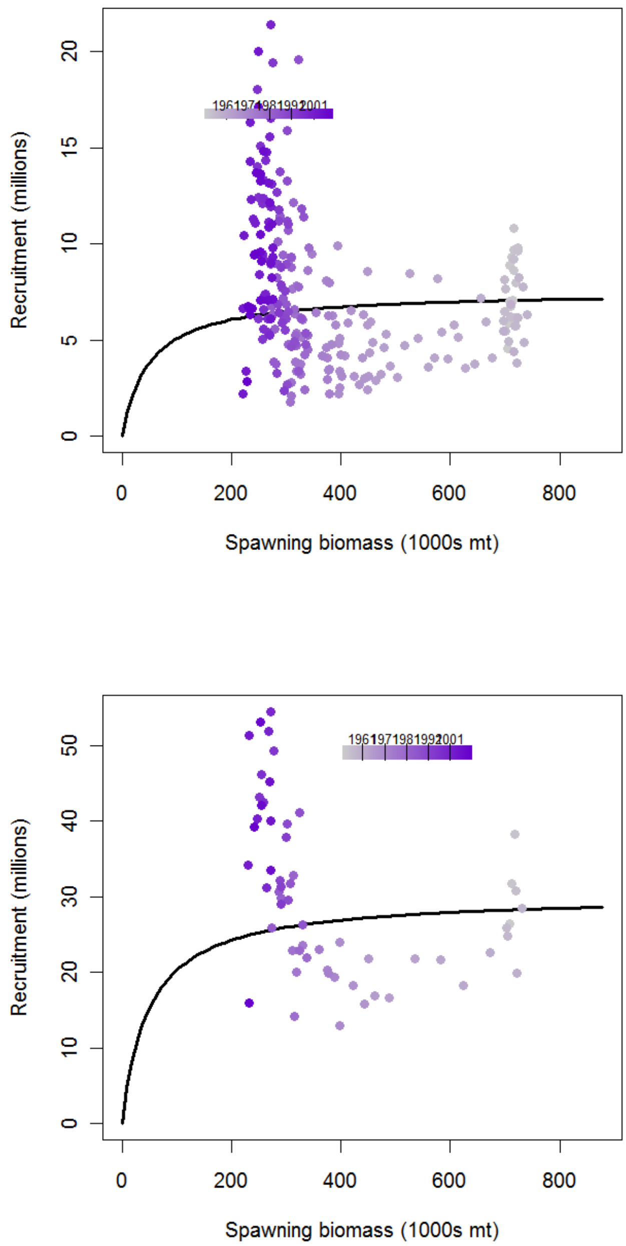


Figure 49. Estimated relationship between equilibrium recruitment and equilibrium spawning biomass based on quarterly (top) and annual (bottom) values.

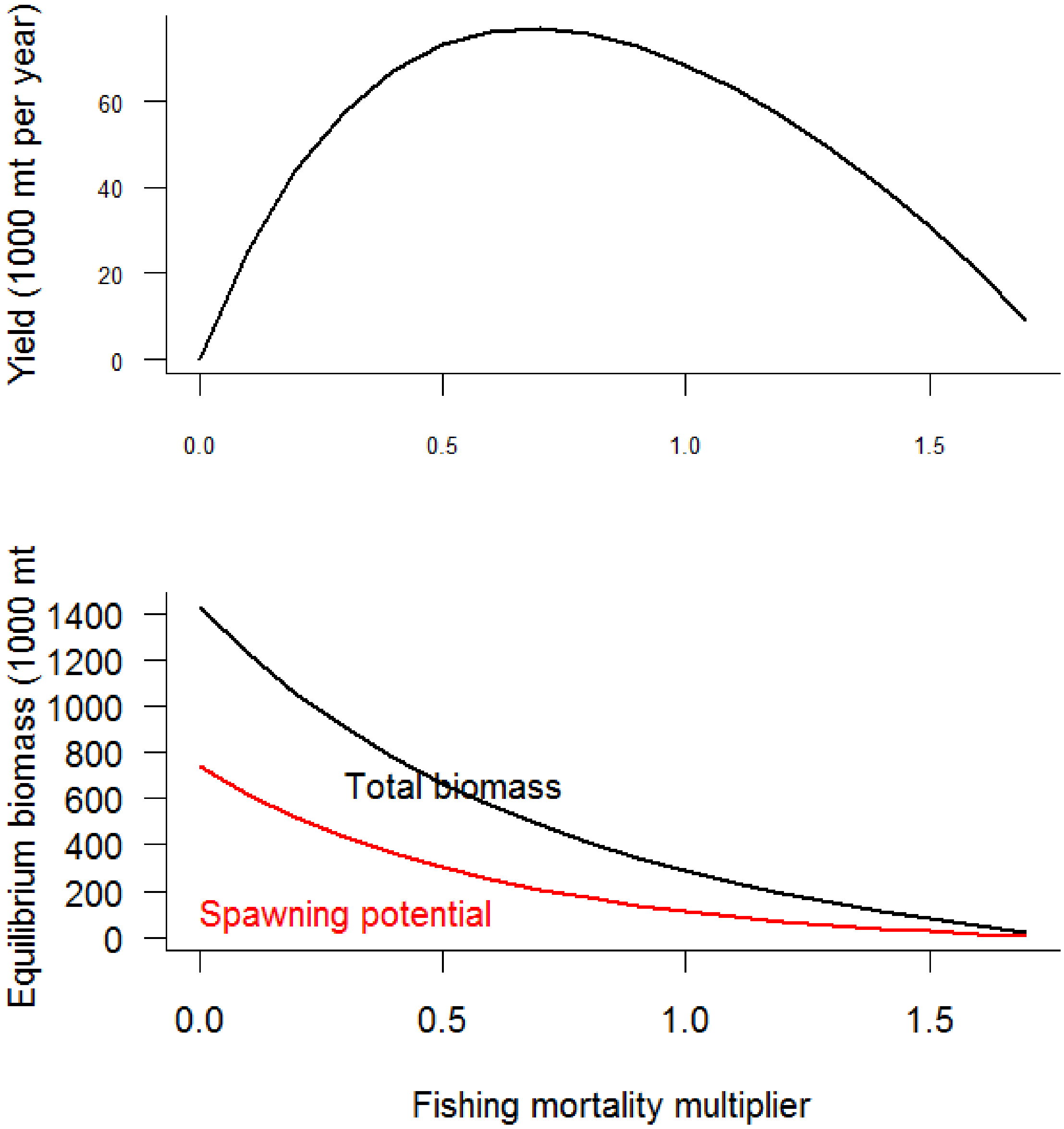


Figure 50. Yield (top), equilibrium total biomass and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier.

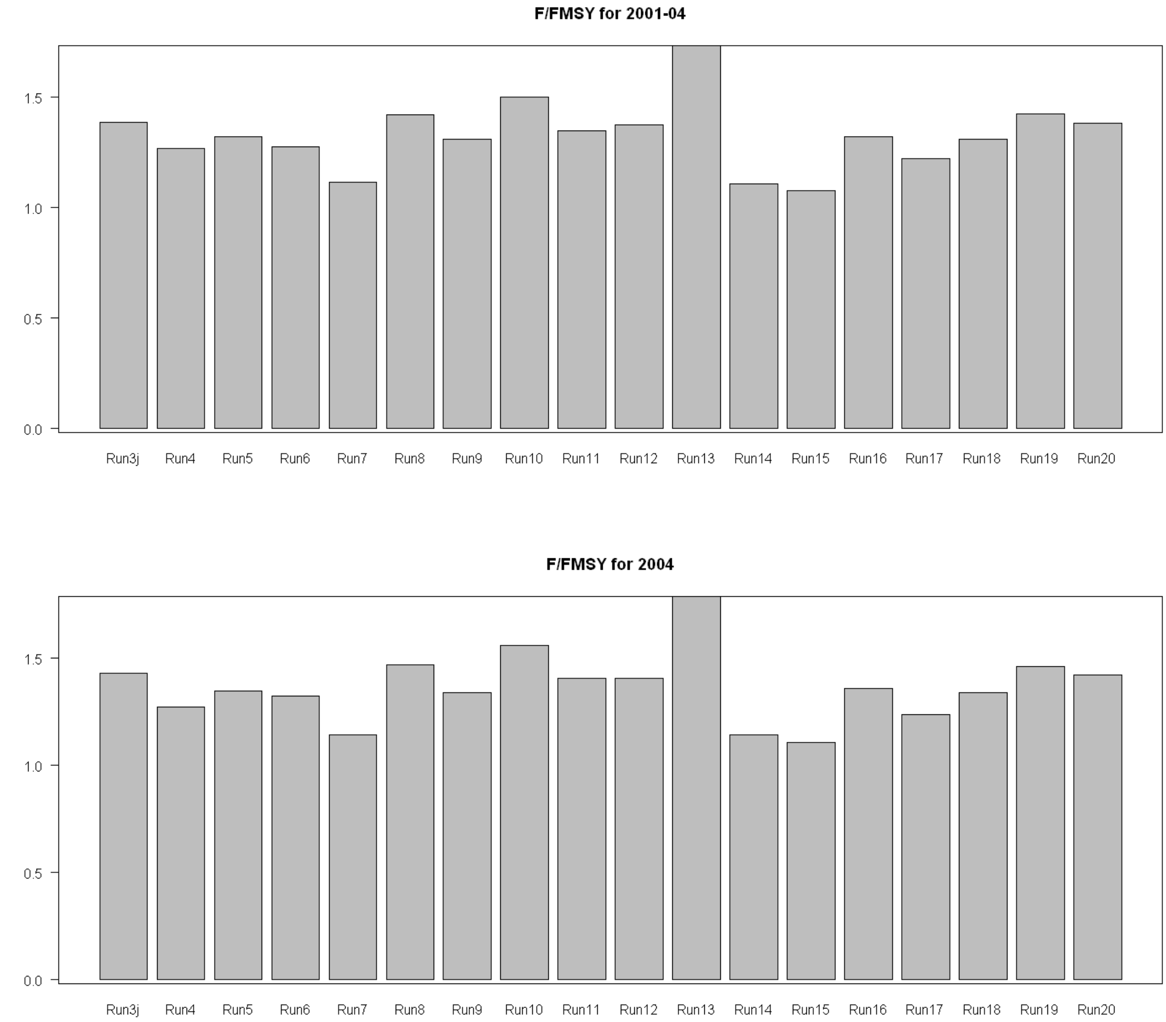


Figure 51. A comparison of $F_{current}/F_{MSY}$ for the model runs from Table 3 based on *MSY* estimation windows of 2001-04 (top) and 2004 (bottom).

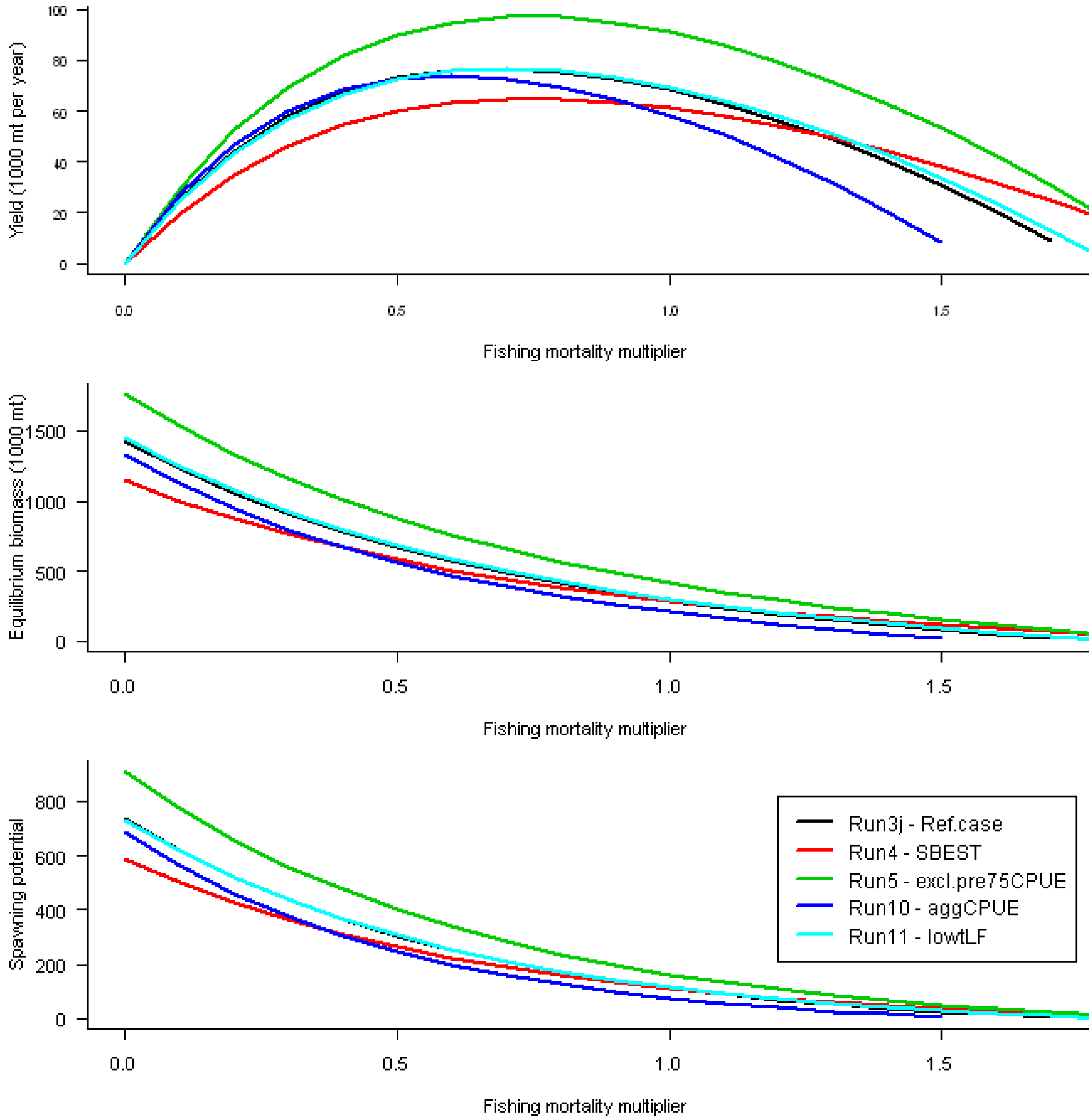


Figure 52. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier ($\boldsymbol{F_{mult}}$) obtained from the key model runs.

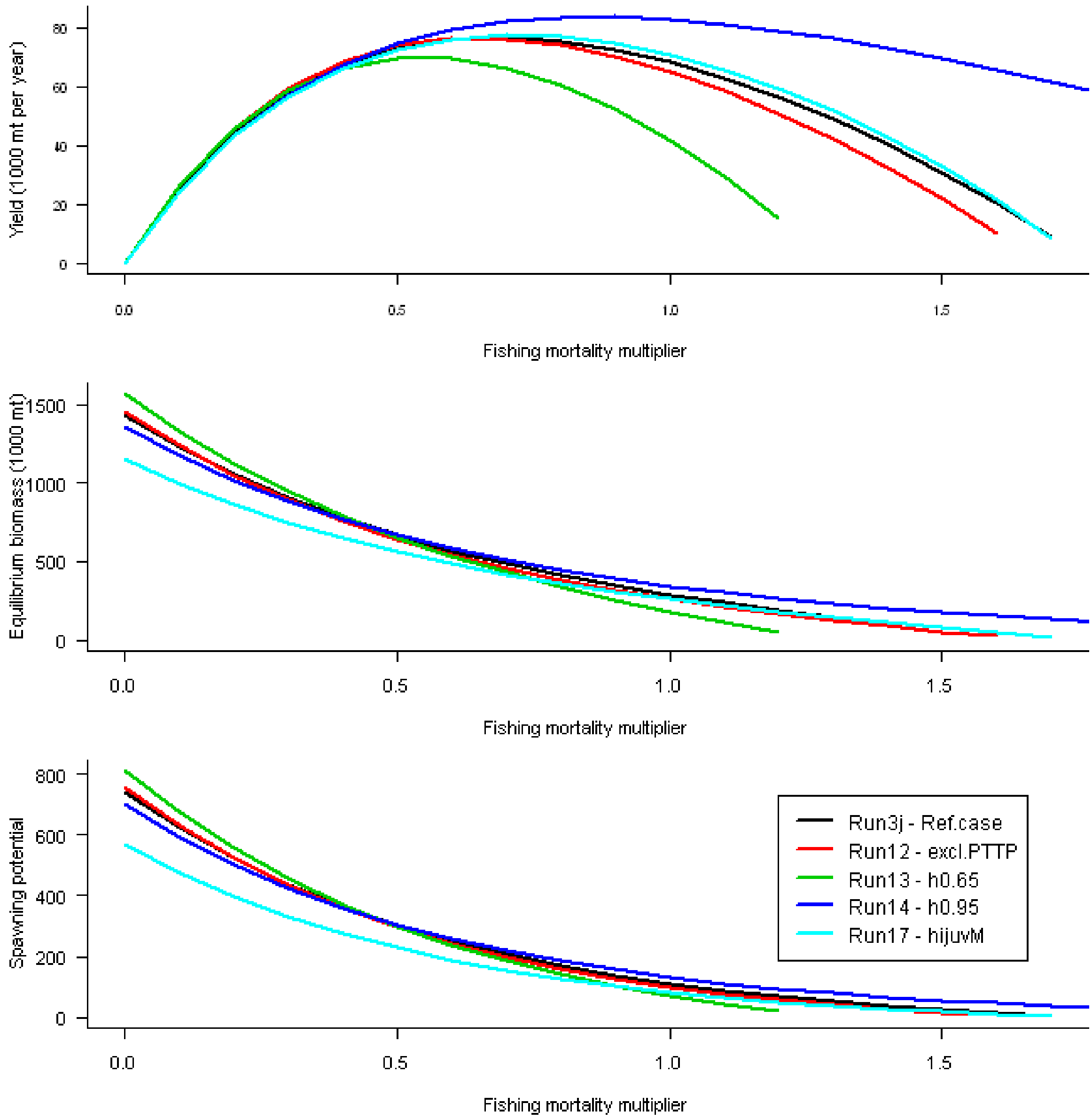


Figure 52 cont. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier (F_{mult}) obtained from the key model runs.

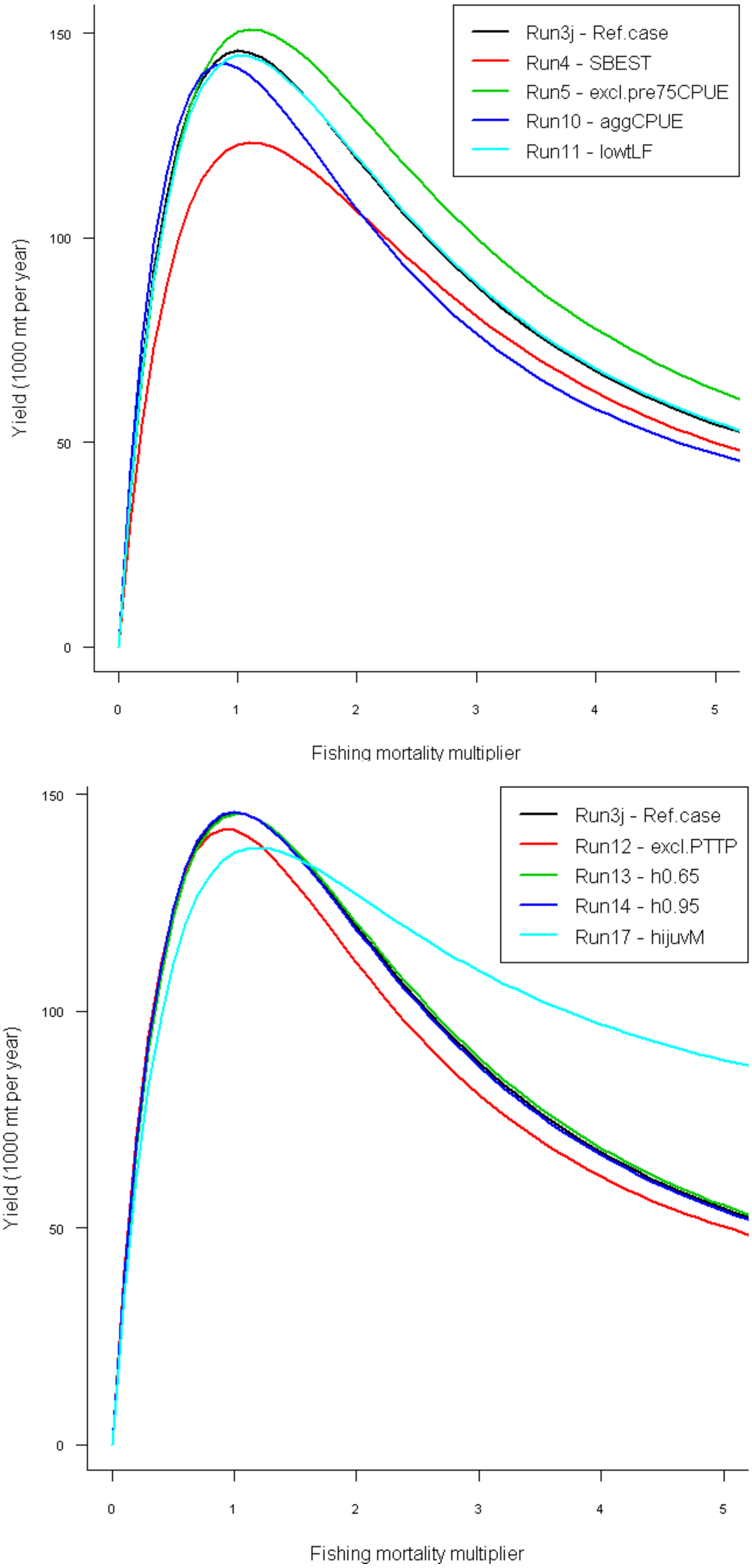


Figure 53. Yield curves based on 2000–2009 average recruitment for the key model runs.

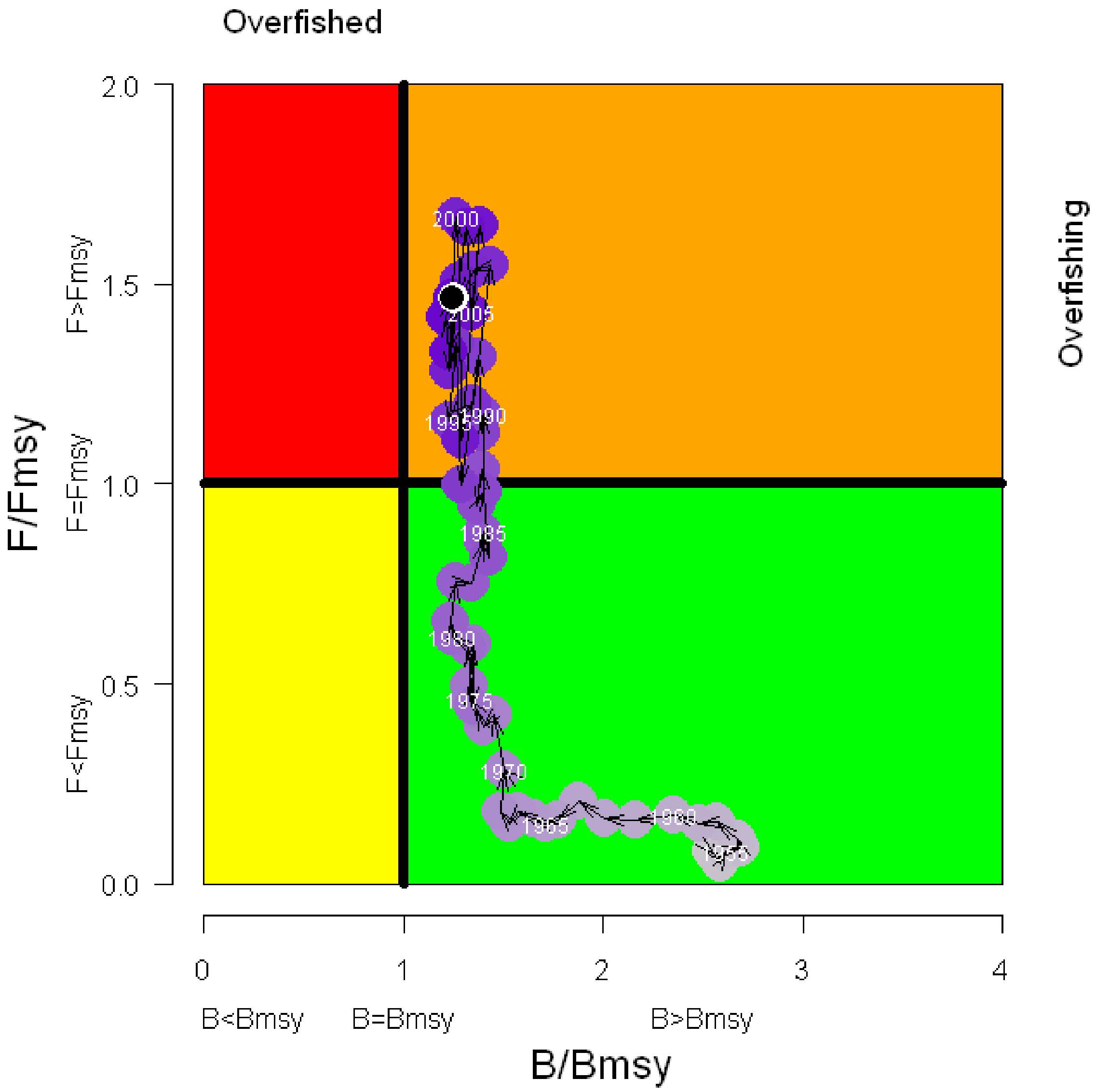


Figure 54. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the period 1952–2009 from Run3j – Ref.case. The colour of the points is graduated from mauve (1952) to dark purple (2009) and the points are labelled at 5-year intervals. The white circle represents the average for the period 2006-09 and the black circle the 2009 values.

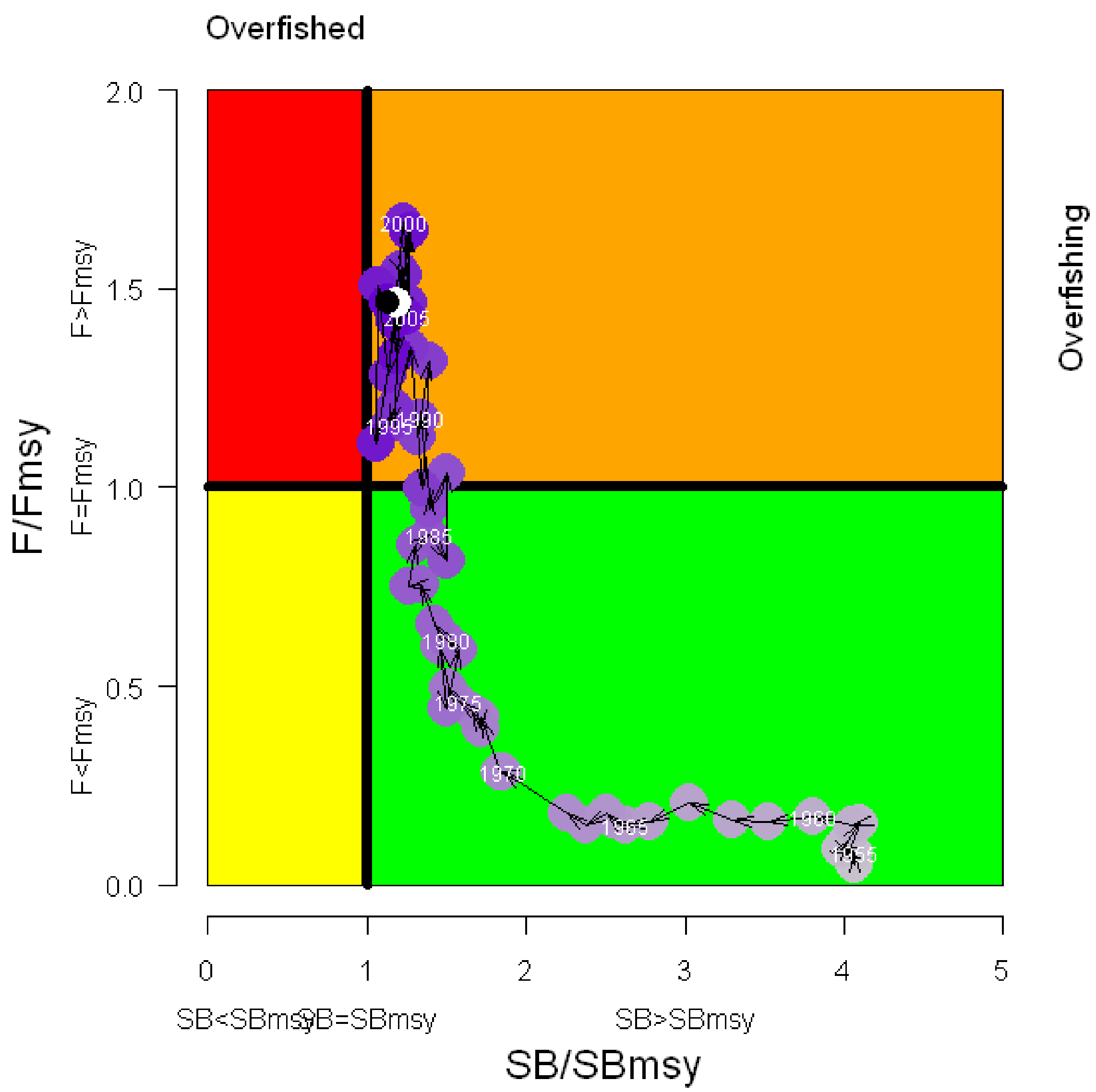


Figure 55. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the period 1952–2009 from Run3j – Ref.case. The colour of the points is graduated from mauve (1952) to dark purple (2009) and the points are labelled at 5-year intervals. The white circle represents the average for the period 2006-09 and the black circle the 2009 values.

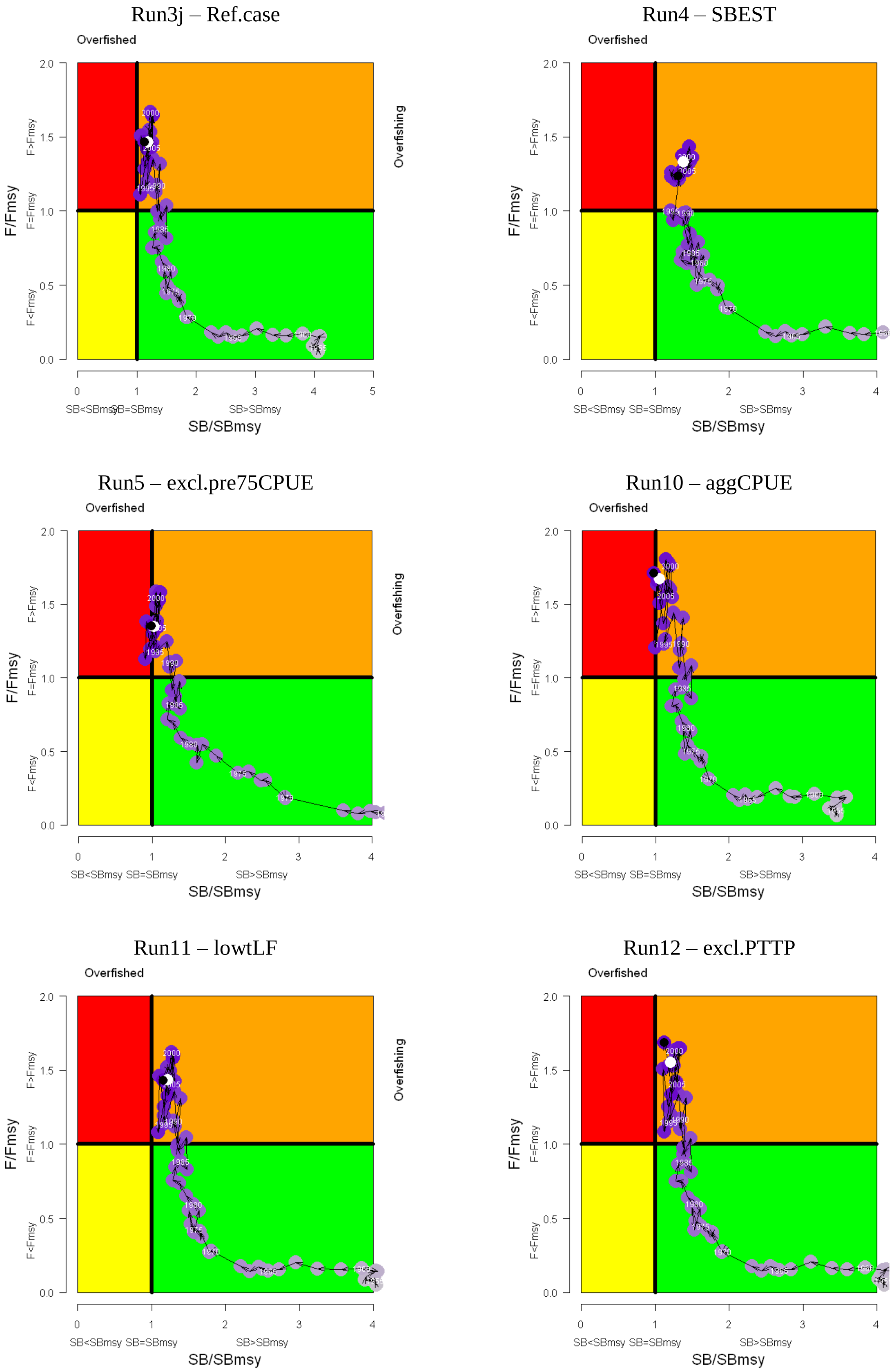


Figure 56. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points for the Ref.case and key model runs.

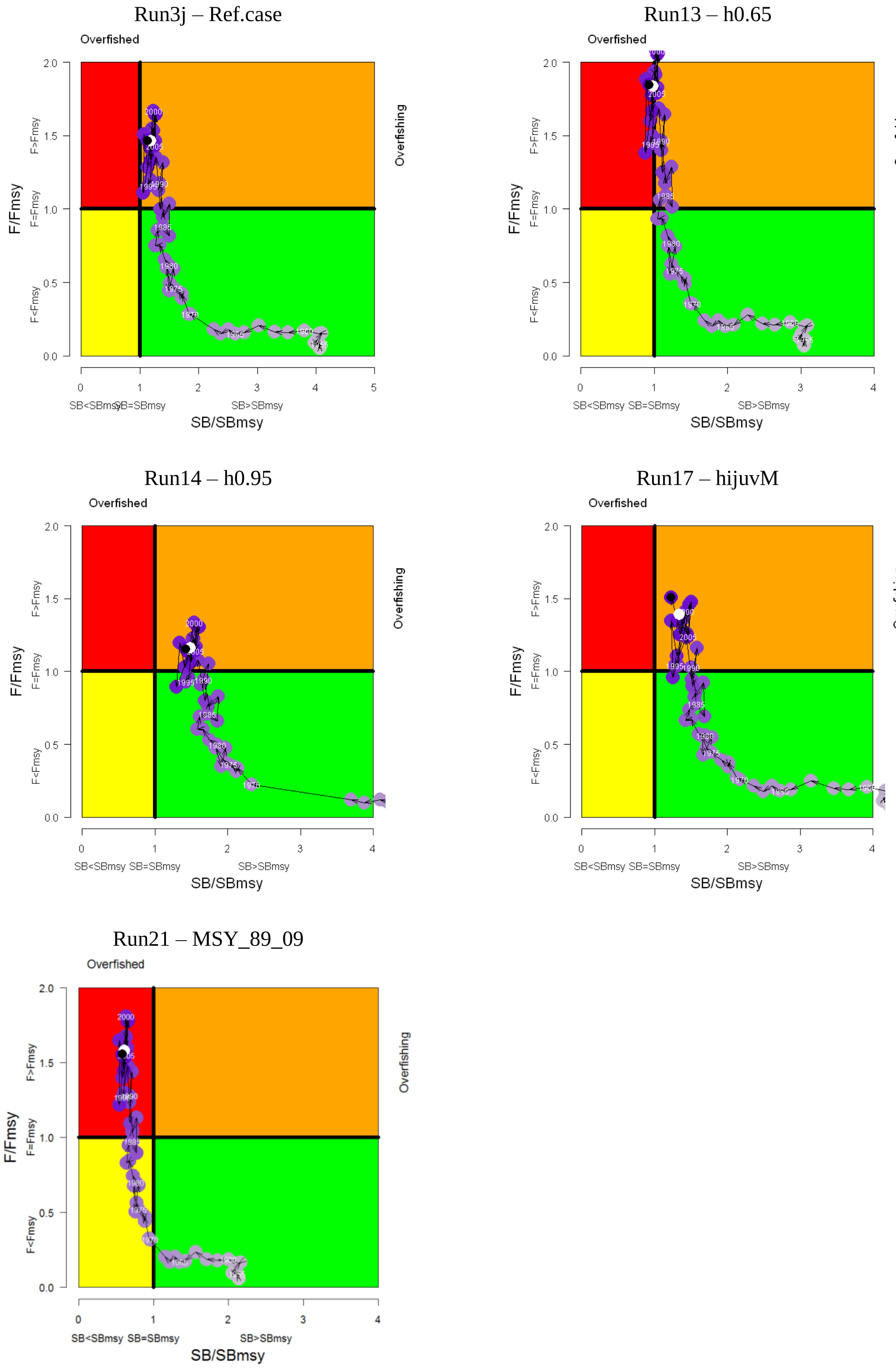


Figure 56. cont.. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points for the Ref.case and key model runs.

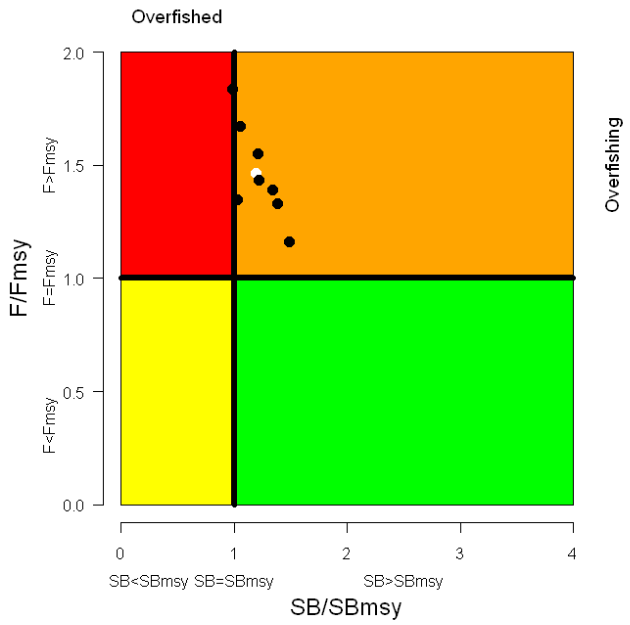


Figure 57. Summary of current stock status (based on 2006-09) for the key model runs. The white circle represents Run3j - Ref.case.

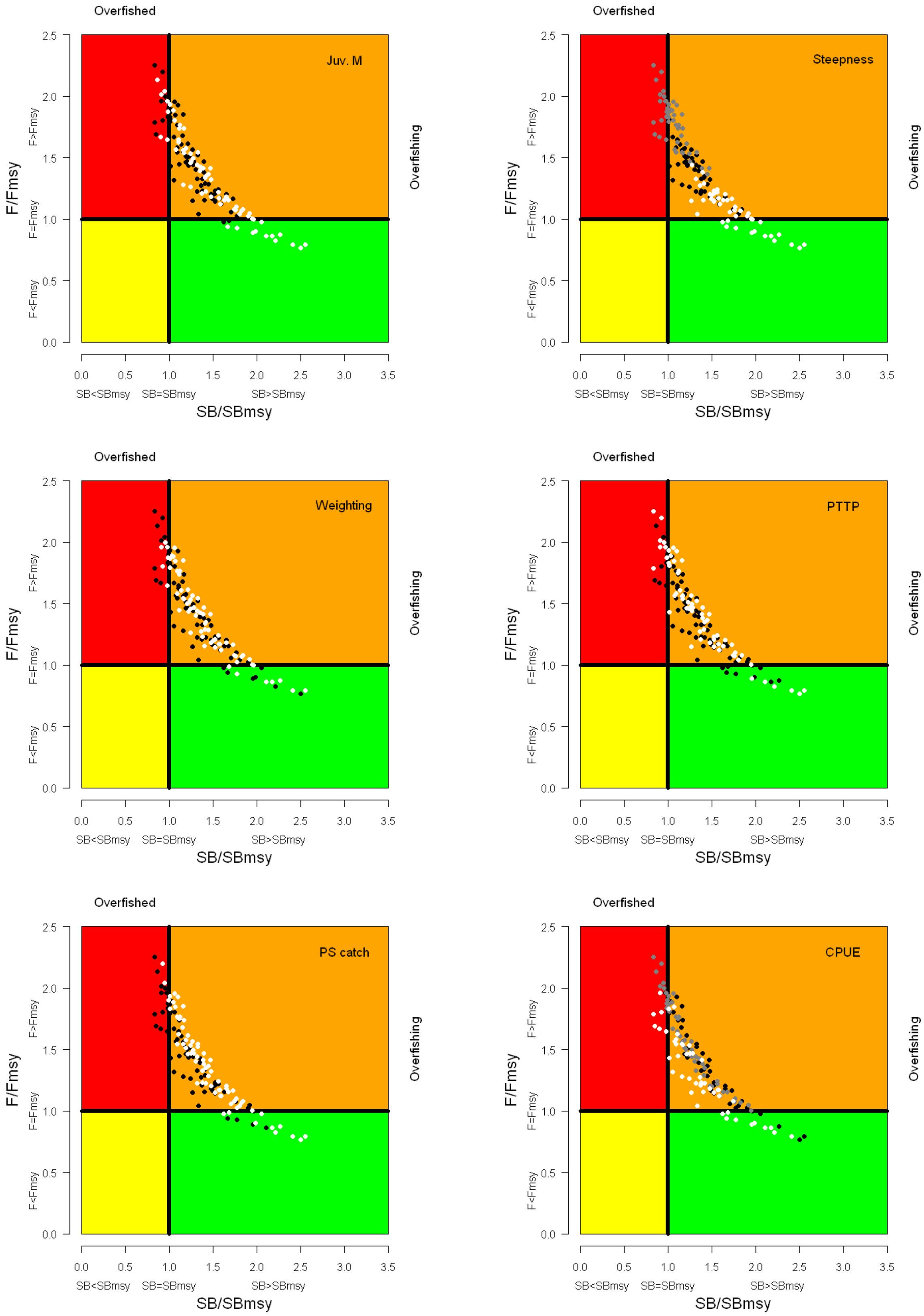
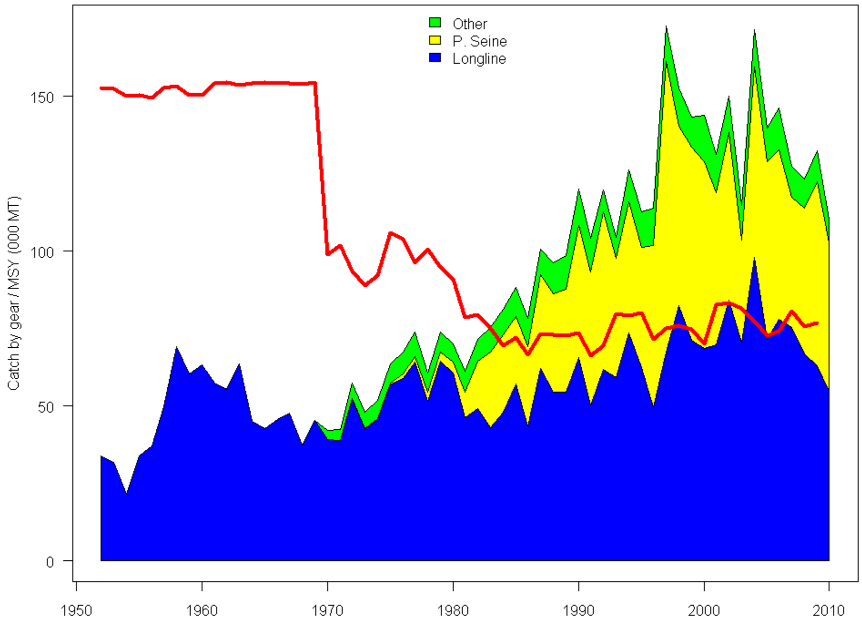


Figure 58. Plot of $SB_{current}/SB_{MSY}$ versus $F_{current}/F_{MSY}$ for the 144 model runs undertaken for the structural uncertainty analysis. The runs reflecting the Run3j – Ref.case assumption are denoted with black circles while the runs with the alternative assumption are denoted with white circles. For the steepness panel the labels are as follows: 0.95 (white), 0.65 (grey), and 0.8 (black), and for the CPUE panel they are operational (black), aggregate (grey), and exclude pre-75 operational (white).



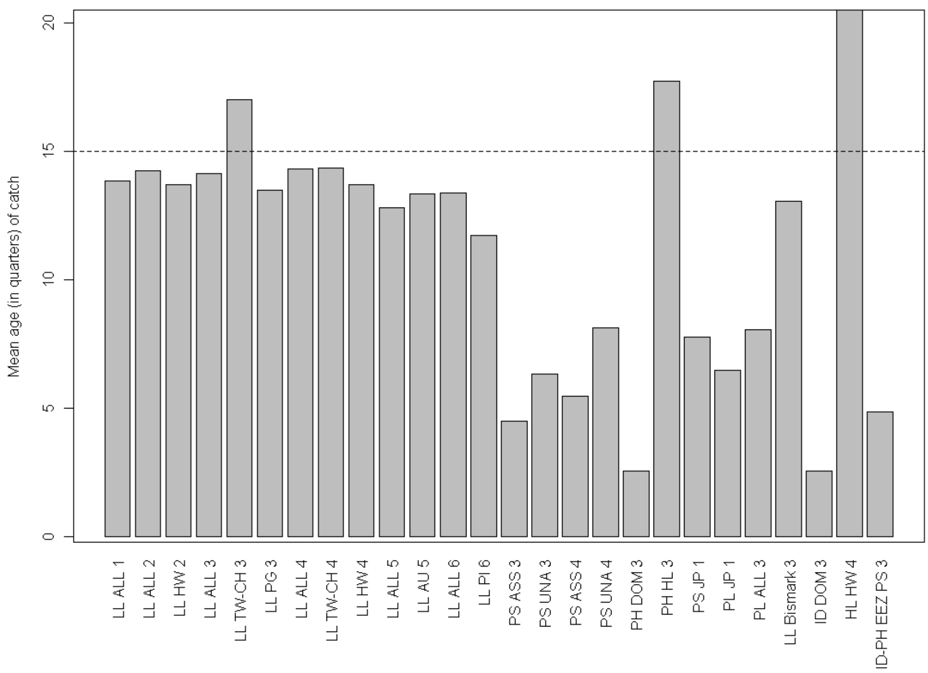


Figure 59. Two plots displaying various aspects of utilization. History of the annual estimates of *MSY* (top) compared with annual catch split into four sectors. Estimates of the mean age of harvest for the fisheries defined in the assessment (bottom)**.**

Appendix A: *doitall.bet (for run3j)*

```
#!/bin/sh
cd $_CONDOR_SCRATCH_DIR
export PATH=.:$PATH
export ADTMP1=.

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

if [ ! -f 00.par ]; then
  nice $MFCL bet.frq bet.ini 00.par -makepar
fi
#
#  ------------------------
#  PHASE 1 - initial par
#  ------------------------
#
if [ ! -f 01.par ]; then
  nice $MFCL 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
  2 116 70        # default value for rmax in the catch equations
  -999 49 20      # divide LL LF sample sizes by 20 (default=10)
  -999 50 20      # divide LL WF sample sizes by 20 (default=10)
  -26 49 100      # new fishery for 2011 assessment; except for PH/ID PS
fishery - lower confidence in these length data
#  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 3
   -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
  -26 24 18  # new fishery for 2011 assessment
# 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
  -26 29 21       # new fishery for 2011 assessment
   -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
  -26 60 21       # new fishery for 2011 assessment
# 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
   -26 32 23        # new fishery for 2011 assessment
# 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
```

```
   -26 34 23        # new fishery for 2011 assessment
# 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
   -26 35 50        # new fishery for 2011 assessment
# 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
   -26 36 60        # new fishery for 2011 assessment
# 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 1
  -2 13 1
  -4 13 1
  -7 13 1
  -10 13 1
  -12 13 1
  -18 13 3
  -23 13 -3
  -24 13 3
  -26 13 3
## use time varying effort weight for LL fisheries
  -1 66 1
  -2 66 1
  -4 66 1
  -7 66 1
  -10 66 1
  -12 66 1
# sets penalties for catchability deviations
   -18 15 1       # low penalty for PH.ID MISC.
   -24 15 1
   -26 15 1       # new fishery for 2011 assessment
  -999 33 1       # estimate tag-reporting rates
  1 33 90         # maximum tag reporting rate for all fisheries is 0.9
  2 96 30
  2 162 0
PHASE1
fi
#  ---------
#   PHASE 2
#  ---------
if [ ! -f 02.par ]; then
  nice $MFCL bet.frq 01.par 02.par -file - <<PHASE2
  1 149 100       # set penalty on recruitment devs to 400/10
  -999 3 37       # all selectivities equal for age class 37 and older
  -999 4 4        # possibly not needed
  -999 21 4       # possibly not needed
  1 189 1         # write length.fit and weight.fit
  1 190 1         # write plot-xxx.par.rep
  1 1 200         # set max. number of function evaluations per phase to
200
  1 50 -2         # set convergence criterion to 1E-02
  -999 14 10      # Penalties to stop F blowing out
  2 35 10          # Set effdev bounds to +- 10 (need to do AFTER phase 1)
  -18 16 2
  -18 3 12
  -24 16 2
  -24 3 12
  -14 15 1
  -15 15 1
  -16 15 1
  -17 15 1
  -5 50 1000
  -5 49 1000
  -4 49 20
  -1 49 20
  -2 49 20
  -7 49 20
  -10 49 20
  -12 49 20
  -23 49 1000
  2 198 1
```

```
  2 144 100000
PHASE2
fi
#  ---------
#
recruitmentConstraints 02.par 0.8
#
#   PHASE 3
#  ---------
if [ ! -f 03.par ]; then
  nice $MFCL 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
  nice $MFCL bet.frq 03.par 04.par -file - <<PHASE4
  2 68 1          # estimate movement coefficients
PHASE4
fi
#  ---------
#   PHASE 5
#  ---------
if [ ! -f 05.par ]; then
  nice $MFCL 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
  nice $MFCL 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
  -26 10 1        # new fishery for 2011 assessment
  -999 23 23      # and do a random-walk step every 23+1 months
```

```
PHASE6
fi
#  ---------
#   PHASE 7
#  ---------
if [ ! -f 07.par ]; then
  nice $MFCL 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
  -26 44 3         # new fishery for 2011 assessment
 -999 43 1         # estimate a for all fisheries
PHASE7
fi
#  ---------
#   PHASE 8
#  ---------
if [ ! -f 08.par ]; then
  nice $MFCL 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
  nice $MFCL 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
  nice $MFCL 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
  nice $MFCL bet.frq 10.par 11.par -file - <<PHASE11
  2 145 1        # use SRR parameters - low penalty for deviation
  2 146 1        # estimate SRR parameters
  2 163 0        # use steepness parameterization of B&H SRR
  1 149 0    # negligible penalty on recruitment devs
  2 147 1    # time period between spawning and recruitment
  2 148 20       # period for MSY calc - last 20 quarters
  2 155 4    # but not including last year
  2 153 31   # beta prior for steepness
  2 154 16       # beta prior for steepness
  1 1 500     #maximum of 1000 function evaluations for the final phase -
TO BEGIN WITH
  1 50 -3       #convergence criteria of 10^-3
  -999 55 1
  2 193 1
PHASE11
fi
```

Appendix B: *bet.ini*

```
# ini version number
1
# number of age classes
40
# tag fish rep
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.4567371 0.4567371
0.4566566 0.4566566 0.6 0.6 0.5 0.5 0.5 0.5 0.6 0.5 0.5
0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5469201 0.5469201
0.4297457 0.4297457 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5 0.5
```

```
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0.255818526902294  0.392823118863806  0.563563999511659  0.737564543664718
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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
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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
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0.0164061088045999      -0.0263041869763792      -0.0357131347138716      -
0.0446335543122571 -0.0530696422103984 -0.0610287749575805
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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
# ML2
173 140 200
# K (per year)
0.075 0 0.3
# Length-weight parameters
1.9729e-05 3.0247
# sv(29)
0.9
# 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
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