SCIENTIFIC COMMITTEE
FOURTH REGULAR SESSION

11–22 August 2008
Port Moresby, Papua New Guinea

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

WCPFC-SC4-2008/SA-WP-1 Rev.1

30-Jul-08

Adam Langley[1], John Hampton[1], Pierre Kleiber[2] and Simon Hoyle[1]

[1] Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea, New Caledonia.

[2] Pacific Islands Fishery Science Center, National Marine Fisheries Service, Honolulu, Hawaii, USA.

Table of Contents

Executive summary

This paper presents the 2008 assessment of bigeye tuna in the western and central Pacific Ocean. The assessment uses the stock assessment model and computer software known as MULTIFAN-CL. The bigeye tuna model is age (40 age-classes) and spatially structured (6 regions) and the catch, effort, size composition and tagging data used in the model are classified by 25 fisheries and quarterly time periods from 1952 through 2007.

The catch, size and tagging data used in the assessment were updated from the 2006 assessment. It should be noted that, at the time the assessment was conducted, 2007 data were not complete for some fisheries, most notably the distant-water longline fisheries. The estimation of standardised effort for the main longline fisheries used the GLM approach as per the 2006 assessment. The current assessment included a number of additional fisheries (Japanese coastal pole-and-line and purse-seine and equatorial purse-seine) and reconfigured several main fisheries (Indonesia and Philippines domestic fisheries and the longline fishery within region 3). The revised fisheries structure was equivalent to the 2007 yellowfin assessment.

The sensitivity of the assessment model to a wide range of assumptions was examined, including the natural mortality-at-age schedule, steepness of the spawning stock-recruitment relationship, historical and current catch levels from the Philippines and Indonesian domestic fisheries, alternative catch history for the equatorial purse-seine fishery, the assumption of constant (versus increasing) catchability of the Japanese longline fleet, and structural assumptions related to recruitment distribution and movement. Of the sensitivity analyses, it was decided to focus on the results of the analyses which were considered more plausible, while still deviating significantly from the base-case analysis. Four sensitivities were selected for detailed examination.

- Lower steepness (run s11, h=0.75). The base-case estimates a high value of steepness (0.97); however, the model is not very informative about this parameter which is crucial in the determination of the MSY-based performance measures. Limited information is available to determine steepness for any tuna species or stock. A lower value of steepness is considered plausible and results in more conservative MSY-based reference points.

- Increasing longline catchability (run s7b, LL incr. q). The base-case model assumes that the GLM CPUE model accounts for all significant changes in the longline fishery that might have resulted in an increase in the efficiency (catchability) of the fleet. However, the CPUE model only includes a limited number of variables (location, gear configuration, and proportion of yellowfin in the catch) and does not consider the increase in efficiency of the longline fleet achieved from the adoption of a wide range of technological advances in fishing gear over the history of the fishery (see Ward 2008) or the increase in fisher knowledge and experience. A sensitivity analysis with increasing longline catchability is, therefore, a plausible alternative to the base-case assessment. The sensitivity formulated includes a 0.5% per annum increase prior to 1985 and a 2% per annum increase from 1985 onwards when bigeye was the main species targeted by the longline fleet. These values are considered to represent “best guesses” of the increase in fishing efficiency in the absence of any definitive quantitative study.

- Purse-seine revised catch. Current catches from the equatorial purse-seine fishery may be substantially under-estimated (Lawson 2008). The sensitivity incorporates an alternative bigeye tuna catch history, doubling the catch from 1980 onwards.

- Low catches from the Indonesian and Philippines domestic fisheries (run s5, low ID/PH). Historical and recent catches from these two fisheries are highly uncertain, particularly for the Indonesian fishery. A range of alternative catch histories were considered, of which the run with a 50% reduction in the level of catch from both fisheries represented a substantial improvement in the objective function of the model.

The main conclusions of the current assessment are as follows.

1. Recruitment in all analyses is estimated to have been high during 1995–2005. This result was very similar to that of previous assessments, although there are some indications that the high recruitment may be, at least partly, an artefact of the structural assumptions of the model. Recruitment in the most recent years is estimated to have declined to a level approximating the long-term average, although these estimates have high uncertainty.
2. For most of the analyses, total biomass for the WCPO is estimated to have declined to about half of its initial level by about 1970 and declined gradually over the subsequent period. Adult biomass has declined by about 20% over the last decade. Declines in biomass are more pronounced for the model with increasing longline catchability.
3. The biomass trends in the model are strongly driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. For some of the main longline fisheries, there is an apparent inconsistency between the trends in the size-frequency data and the trends in longline catch and effort; i.e., the two types of data are providing inconsistent information about the relative level of fishing mortality in the region. A number of approaches were applied to investigate the influence of the size data from the key longline fisheries. However, the stock status indicators were relatively insensitive to the treatment of these data.
4. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. For the models with higher purse-seine catch and increasing longline catchability, estimates of recent juvenile fishing mortality are considerably higher than for the base-case, while the opposite is the situation for the PH/ID low catch option.
5. The ratios $B_t / B_{t,F=0}$ provide a time-series index of population depletion by the fisheries. Overall, depletion is estimated to have been rapid, particularly since the mid-1980s. While total biomass has remained relatively stable since 1970, it appears to have been sustained by above average recruitment, particularly since 1995. The assessment indicates that recruitment may have returned to the long-term average level (although recent recruitment estimates have high uncertainty) and, if recruitment remains at that level, biomass would decline rapidly at current exploitation rates. The current level of biomass is 20–26% of the unexploited level ($B_{current} / B_{current,F=0}$ = 0.20–0.28) with higher depletion estimated from the model with increasing longline catchability. Depletion is more extreme for some individual model regions, notably region 1 (recent $B_t / B_{t,F=0}$ ratios around 0.25 in the base-case model) region 3 (0.20) and region 4 (0.25). Other regions are less depleted, with recent $B_t / B_{t,F=0}$ ratios of around 0.4 or greater.
6. The attribution of depletion to various fisheries or groups of fisheries indicates that the longline fishery has the greatest impact throughout the model domain. The purse seine and Philippines/Indonesian domestic fisheries also have substantial impact in region 3 and to a lesser extent in region 4. The Japanese coastal pole-and-line and purse-seine fisheries are also having a significant impact in their home region (region 1). For the sensitivity analysis with higher purse seine catch, the longline and purse seine fisheries are estimated to have approximately equal impact on total biomass.
7. The reference points that predict the status of the stock under equilibrium conditions are $\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$ and $S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$. For the base-case model, these ratios are 0.68 and 0.55, respectively, indicating that the long-term average biomass would fall below that capable of producing *MSY* at 2003–2006 average fishing mortality. For most of the analyses, current total biomass exceeds the biomass yielding *MSY* ($B_{current} / \tilde{B}_{MSY}$ > 1.0), with a high probability in the base-case assessment. On that basis, the bigeye stock in the WCPO is not in an overfished state due to above average recruitment. However, the situation is less optimistic with respect to adult biomass with $S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$ approaching or being below 1.0 for the principal analyses.

8. The estimate of $F_{current}/\tilde{F}_{MSY}$ reveals that **overfishing of bigeye is occurring in the WCPO** with high probability. While the stock is not yet in an overfished state with respect to total biomass ($B_{current}/\tilde{B}_{MSY}$ > 1), the situation is less optimistic with respect to adult biomass and a number of plausible model options indicate that adult biomass has been below the $S\tilde{B}_{MSY}$ level for a considerable period ($SB_{current}/S\tilde{B}_{MSY}$ < 1). Further, both the adult and total biomass are predicted to become over-fished at 2003–2006 levels of fishing mortality and long-term average levels of recruitment. For the base-case, there is also a significant probability (42.8%) that $SB_{2006}/S\tilde{B}_{MSY}$ is less than 1.0. This is consistent with a recent decline in biomass under increasing levels of fishing mortality resulting in an increase in the probability of the stock becoming overfished over time.

9. For both the fishing mortality and biomass based reference points, the stock status is considerably more pessimistic for the scenarios with increasing longline catchability or steepness of the SRR at a moderate level. Both of these scenarios are considered plausible alternative to the base-case assessment and indicate the adult component of the stock is in an overfished state ($SB_{current}/S\tilde{B}_{MSY}$ < 1).

10. Stock projections, using the base-case model, indicate significant reductions in fishery-specific effort are required to reduce fishing mortality below the F_{MSY} level. The target level of fishing mortality can be achieved via numerous configurations of fishery-specific effort; however, largest changes in the performance measure occur from changes in the multiplier applied to the longline fishing effort. This reflects the relatively high proportion of the total level of current fishing mortality attributable to this method throughout the WCPO. Significant reduction in fishing effort from at least one specific gear type is required to achieve F/F_{MSY} and larger reductions in some fisheries are required for scenarios that model an expansion of one of the other fisheries.

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). A comparison of results with those from a similarly-structured Pacific-wide analysis is given in a separate paper (Hampton and Maunder 2006). The overall objectives of the assessment are to estimate population parameters, such as time series of recruitment, biomass and fishing mortality, that indicate the status of the stock and impacts of fishing. We summarise stock status in terms of well-known reference points, such as the ratios of recent stock biomass to the biomass at maximum sustainable yield ($B_{current}/\tilde{B}_{MSY}$ and $SB_{current}/S\tilde{B}_{MSY}$) and recent fishing mortality to the fishing mortality at MSY ($F_{current}/\tilde{F}_{MSY}$). Likelihood profiles of these ratios are used to describe their uncertainty. The effects of the continuation of the current management arrangements for bigeye tuna, and an array of possible future arrangements, are investigated through stock projections.

The underlying methodology used for the assessment is that commonly known as MULTIFAN-CL (Fournier et al. 1998; Hampton and Fournier 2001; Kleiber et al. 2003; http://www.multifan-cl.org), which is software that implements a size-based, age- and spatially-structured population model. Parameters of the model are estimated by maximizing an objective function consisting of likelihood (data) and prior information components. A comparison of the results of this assessment with an analysis of equivalent data using the Stock Synthesis (V. 3) software (Methot 2005) is provided in a separate paper (Langley and Methot 2008).

2 Background

2.1 Biology

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

Bigeye tuna are relatively fast growing, and have a maximum fork length (FL) of about 200 cm. The growth of juveniles appears to depart somewhat from von Bertalanffy type growth with the growth rate slowing between about 40 and 70 cm FL (Lehodey et al. 1999) although this effect is not as marked as for yellowfin tuna. The natural mortality rate is likely to be variable with size, with the lower rates of around 0.5 yr^{-1} for bigeye >40 cm FL (Hampton 2000). Tag recapture data indicate that significant numbers of bigeye reach at least eight years of age. The longest period at liberty for a recaptured bigeye tuna tagged in the western Pacific at about 1–2 years of age is currently 14 years (SPC unpubl. data).

2.2 Fisheries

Bigeye tuna are an important component of tuna fisheries throughout the Pacific Ocean and are taken by both surface gears, mostly as juveniles, and longline gear, as valuable adult fish. They are a principal target species of both the large, distant-water longliners from Japan and Korea and the smaller, fresh sashimi longliners based in several Pacific Island countries. Prices paid for both frozen and fresh product on the Japanese sashimi market are the highest of all the tropical tunas. Bigeye tuna are the cornerstone of the tropical longline fishery in the WCPO; the catch in the SPC area had a landed value in 2006 of approximately US$504 million (Williams & Reid 2007).

From 1980 to 2000, the longline catch of bigeye tuna in the WCP-CA varied between about 50,000 and 60,000 mt (Figure 2). Catches increased in subsequent years, reaching a peak of about 100,000 mt in 2004. Longline catches have declined in the more recent years: 78,000 mt in 2005 and 84,000 mt in 2006 the most recent year for which complete catch data are available. Anecdotal information indicates that the annual catch declined further in 2007.

Since about 1994, there has been a rapid increase in purse-seine catches of juvenile bigeye tuna, first in the eastern Pacific Ocean (EPO) and since 1996, to a lesser extent, in the WCPO. In the WCPO, purse-seine catches of bigeye tuna are estimated to have been less than 20,000 mt per year up to 1996, mostly from sets on natural floating objects (Hampton et al. 1998). In 1997, the catch increased to 35,000 mt, primarily as a result of increased use of fish aggregation devices (FADs). High purse seine catches were also recorded in 1999 (38,000 mt) and 2000 (33,000 mt). During 2001-2005, annual purse seine catches remained at about 25,000 mt, while catches in 2006 were considerably lower (15,000 mt). However, there remains considerable uncertainty regarding the

[3] Efforts continue to develop a bigeye tuna model for the Pacific Ocean as a whole, incorporating spatial structure into the analysis to allow for the possibility of restricted movement between some areas. The results of the most recent Pacific-wide model are compared with the WCPO results and the results of the most recent IATTC assessment for the EPO in Hampton and Maunder (2006).

accuracy of the purse-seine catch and reported catches may significantly under-estimate actual catch levels (Lawson 2008).

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

The spatial distribution of WCPO bigeye tuna catch during 1990–2006 is shown in Figure 3. The majority of the catch is taken in equatorial areas, by both purse seine and longline, but with significant longline catch in some sub-tropical areas (east of Japan, north of Hawaii and the east coast of Australia). High catches are also presumed to be taken in the domestic artisanal fisheries of Philippines and Indonesia using a variety of gear types (e.g. pole-and-line, ringnet, gillnet, handline and seine net). These catches have exceeded 30,000 mt in recent years. The statistical basis for the catch estimates in Philippines and, in particular, Indonesia is weak; however, we have included the best available estimates in this analysis in the interests of providing the best possible coverage of bigeye tuna catches in the WCPO. The sensitivity of the stock assessment conclusions to the assumed levels of catch from these fisheries was examined.

3 Data compilation

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

3.1 Spatial stratification

The geographic area considered in the assessment is the WCPO, defined by the coordinates 40°N–35°S, 120°E–150°W. Within this overall area, a six-region spatial stratification was adopted for the assessment (Figure 3). The rationale for this stratification was to separate the tropical area, where both surface and longline fisheries occur year-round, from the higher latitudes, where the longline fisheries occur more seasonally. The stratification is equivalent to the regional structure adopted in the 2006 base case assessment, while the alternative seven-region stratification investigated in the 2006 assessment was not revisited.

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

3.2 Temporal stratification

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

3.3 Definition of fisheries

MULTIFAN-CL requires the definition of “fisheries” that consist of relatively homogeneous fishing units. Ideally, the fisheries so defined will have selectivity and catchability characteristics that do not vary greatly over time (although in the case of catchability, some allowance can be made for time-series variation). Twenty-five fisheries have been defined for this analysis on the basis of region, gear type and, in the case of purse seine, set type (Table 1). These fisheries definitions are equivalent to the fisheries included in the 2007 WCPO yellowfin stock assessment.

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

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

A spatio-temporal analysis of size data from the Japanese longline fishery revealed that bigeye caught within PNG waters, principally the Bismarck Sea, were consistently smaller than the fish caught in the remainder of Region 3 (Langley 2006c). Historically, this area accounted for a significant component of the total longline catch from Region 3 and, given the apparent difference in size selectivity, it was decided to separate this component of the fishery (LL BMK 3) from the principal longline fishery in Region 3 (LL ALL 3).

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

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

The domestic fisheries of the Philippines were grouped into two separate fisheries largely based on the size of fish caught: a hand-line fishery catching large fish (PH HL 3) and a surface fishery (ring net, small-scale purse-seine, etc) catching smaller fish (PH MISC 3). In previous assessments, the Indonesian domestic fishery was combined with the Philippines surface fishery. However, there is considerably greater uncertainty associated with the recent catch from the Indonesian fishery and it was decided to disaggregate the composite fishery to enable a more comprehensive investigation of the uncertainty related to the Indonesian catch. The Indonesian surface fishery includes catch by pole-and-line, purse-seine, ring net, and other methods (ID MISC 3).

Previous assessments have not included the bigeye catch from the seasonal purse-seine and pole-and-line fisheries operated by the Japanese coastal fleet within MFCL region 1. Catches of bigeye by the Japanese coastal surface fleet have averaged about 2,500 mt per annum since the mid 1980s. These fisheries were included separately in the current assessment (PS JP 1 and PL JP 1).

Further, an additional pole-and-line fishery was included within MFCL region 3 to incorporate catch and effort data from the Japanese distant-water pole-and-line fleet and the domestic pole-and-line fisheries (Solomon Islands and, historically, PNG) (PL ALL 3).

3.4 Catch and effort data

Catch and effort data were compiled according to the fisheries defined above. Catches by the longline fisheries were expressed in numbers of fish, and catches for all other fisheries expressed in weight. This is consistent with the form in which the catch data are recorded for these fisheries. Purse seine catches of bigeye are not reliably recorded on logsheets for most fleets, and must be estimated from sampling data. The method used to derive such estimates for the purse seine fishery is based on the two-variable (set type and year) analysis of variance described in Lawson (2005). A more recent analysis has revealed that this approach may be substantially underestimating the level of catch from the equatorial purse-seine fishery (Lawson 2008).

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

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

The technique for standardising longline effort was also applied to determine the relative scaling of longline effort among regions. These scaling factors incorporated both the effective size of the region and the relative catch rate to estimate the relative level of exploitable longline biomass between regions (see Langley et al. 2005 and Hoyle & Langley 2007). The scaling factors were derived from the Japanese longline CPUE data from 1960–86.

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

An alternative effort series was also formulated for the principal longline fisheries that incorporates a temporal increase in catchability with an increase in effective effort by assumed annual increases of 0.5% and 2.0% pre- and post 1985, respectively. This assumed increase is to account for increases in efficiency not incorporated in the GLM analysis (e.g. improvements in gear technology and fishing experience). The assumed increase in catchability results in a greater decline in the longline CPUE for each of the principal fisheries (Figure 7).

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

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.

3.5 Length-frequency data

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

<u>Philippines:</u> 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 (PHID MISC 3) under the National Stock Assessment Project (NSAP) were included in the current assessment.

<u>Indonesia:</u> 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 Philippines domestic fishery.

<u>Purse seine:</u> Length-frequency samples from purse seiners have been collected from a variety of port sampling and observer programmes since the mid-1980s. Most of the early data is sourced from the U.S. National Marine Fisheries Service (NMFS) port sampling programme for U.S. purse seiners in Pago Pago, American Samoa and an observer programme conducted for the same fleet. Since the early 1990s, port sampling and observer programmes on other purse seine fleets have provided additional data. Only data that could be classified by set type were included in the final data set. For each purse seine fishery, size samples were aggregated without weighting within temporal strata.

Longline: The majority of the historical data were collected by port sampling programmes for Japanese longliners unloading in Japan and from sampling aboard Japanese research and training vessels. This comprehensive set of data is available for the entire model period. In recent years, length data from longline catches have also been collected by OFP and national port sampling and observer programmes in the WCPO.

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

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

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

3.6 Weight-frequency data

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

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

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

3.7 Tagging data

A modest amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. The data used consisted of bigeye tuna tag releases and returns from the OFP’s Regional Tuna Tagging Project conducted during 1989–1992, and more recent (1995, 1999–2001) releases and returns from tagging conducted in the Coral Sea by CSIRO (Evans et al. in press). Tags were released using standard tuna tagging equipment and techniques by trained scientists and technicians. The tag release effort was spread throughout the tropical western Pacific, between approximately 120°E and 170°W (Kaltongga 1998; Hampton and Williams 2004).

The model does not include the tag release and recovery data from the 2006–08 tagging programme undertaken in PNG and Solomon Islands waters.

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

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

Tag returns that could not be assigned to recapture fisheries were included in the non-reported category and appropriate adjustments made to the tag-reporting rate priors and bounds. The returns from each size class of each tag release group were classified by recapture fishery and recapture time period (quarter). Because tag returns by purse seiners were often not accompanied by information concerning the set type, tag-return data were aggregated across set types for the purse seine fisheries in each region. The population dynamics model was in turn configured to predict equivalent estimated tag recaptures by these grouped fisheries.

4 Model description – structural assumptions, parameterisation, and priors

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

4.1 Population dynamics

The six-region model partitions the population into 6 spatial regions and 40 quarterly age-classes. The first age-class has a mean fork length of around 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. For the purpose of computing the spawning biomass, we assume a fixed maturity schedule (Table 2).

The population is "monitored" in the model at quarterly time steps, extending through a time window of 1952–2007. The main population dynamics processes are as follows:

4.1.1 Recruitment

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

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

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

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

4.1.2 Initial population

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

4.1.3 Growth

The standard assumptions made concerning age and growth are (i) the lengths-at-age are normally distributed for each age-class; (ii) the mean lengths-at-age follow a von Bertalanffy growth curve; (iii) the standard deviations of length for each age-class are a log-linear function of the mean lengths-at-age; and (iv) the distribution of weight-at-age is a deterministic function of the length-at-age and a specified weight-length relationship (see Table 2). As noted above, the population is partitioned into 40 quarterly age-classes.

4.1.4 Movement

Movement was assumed to occur instantaneously at the beginning of each quarter through movement coefficients connecting regions sharing a common boundary. Note however that fish can move between non-contiguous regions in a single time step due to the "implicit transition" computational algorithm employed (see Hampton and Fournier 2001 for details). There are seven inter-regional boundaries in the model with movement possible across each in both directions. Four seasonal movements were allowed, each with their own movement coefficients. Thus there is a need for 2×7×4 = 56 movement parameters. We did not incorporate age-dependent movement into this assessment, to avoid the addition of more parameters. Previous trials have indicated that this additional structure did not impact the overall results in a substantive way. The seasonal pattern of movement persists from year to year with no allowance for longer-term variation in movement.

4.1.5 Natural mortality

Natural mortality (M) was held fixed at pre-determined age-specific levels as applied in the 2005 assessment (MFIX model options). No attempt was made to estimate M-at-age in these assessments because previous trial fits estimating M-at-age produced biologically unreasonable results. M-at-age was determined outside of the MULTIFAN-CL model using bigeye sex-ratio data and the assumed maturity-at-age schedule. An identical procedure is used to determine fixed M-at-age for assessments in the EPO (Maunder 2005). Essentially, this method reflects the hypothesis that the higher proportion of males in sex-ratio samples with increasing length is due to the higher natural mortality of females after they reach maturity. The externally-estimated M-at-age is shown in Figure 10.

A range of sensitivities to the assumed M-at-age were investigated in the assessment. These are described in detail in Section 5.

4.1.6 Sexual maturity

The onset of sexual maturity is assumed to occur from 2.5 years and attain full maturity at 6 years. The sensitivity of the model to this maturity OGIVE was examined in Hoyle & Nicol (2008).

4.2 Fishery dynamics

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

4.2.1 Selectivity

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

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

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

In the 2005 assessment, the selectivity of the longline fisheries (which catch mainly adult bigeye) was assumed to increase with age and to remain at the maximum once attained. However, this assumption was relaxed in the 2006 and the current assessment for all longline fisheries, except for the Chinese/Taiwanese fisheries (LL TW-CH 3 and 4), thereby, allowing selectivity to decline for the older age classes. This is because the Chinese/Taiwanese fleet caught consistently larger fish than the other longline fleets in a comparable time period. There are operational differences between the longline fleets that may account for a higher selectivity of larger fish by the Chinese/Taiwanese fleet.

4.2.2 Catchability

Catchability was allowed to vary slowly over time (akin to a random walk) for all 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. We made the prior assumption that effort for these fisheries was proportional to catch, but set the variance of the priors to be high (approximating a CV of about 0.7), thus allowing catchability changes to compensate for failure of this assumption. For the other fisheries with time-series variability in catchability, the catchability deviation priors were assigned a variance approximating a CV of 0.10.

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

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

4.2.3 Effort deviations

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

4.3 Dynamics of tagged fish

4.3.1 Tag mixing

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

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

4.3.2 Tag reporting

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

4.4 Observation models for the data

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

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

The size frequency data is assigned an effective sample size lower than the actual number of fish sampled. Reduction of the effective sample size recognises that (i) length- and weight-frequency samples are not truly random (because of clumping in the population with respect to size) and would have higher variance as a result; and (ii) the model does not include all possible process error, resulting in further under-estimation of variances. The influence of the size frequency data in the model can be examined by varying the effective sample size in the model. The principal model runs were conducted using an effective sample size of 0.02 times the actual sample size, with a maximum effective sample size of 20. A range of alternative weighting schemes were investigated (see Section 5).

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) [4].

The Hessian matrix computed at the mode of the posterior distribution was used to obtain estimates of the covariance matrix, which was used in combination with the Delta method to compute approximate confidence intervals for parameters of interest. In addition, the likelihood profile method was used to generate probability distributions for the critical reference points $F_{current}/\tilde{F}_{MSY}$, $B_{current}/\tilde{B}_{MSY}$ and $SB_{current}/S\tilde{B}_{MSY}$. Likelihood profiles were generated by undertaking model runs with either $F_{current}/\tilde{F}_{MSY}$, $B_{current}/\tilde{B}_{MSY}$ or $SB_{current}/S\tilde{B}_{MSY}$ set at various levels (by applying a penalty to the likelihood function for deviations from the target ratio) over the range of possible

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

values. Similarly, likelihood profiles were constructed for the critical reference points for the each of the four years within the period used to define "current" conditions (2003-2006). The likelihood function values resulting from these runs were then used to construct a probability distribution for each ratio.

4.6 Stock assessment interpretation methods

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

4.6.1 Fishery impact

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

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

4.6.2 Yield analysis

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

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In this assessment, we use the average over the period 2003–2006. The last year in which catch and effort data are available for all fisheries is 2007. We do not include 2007 and subsequent years in the average as fishing mortality tends to have high uncertainty for the terminal data years of the analysis and the catch and effort data for this terminal year are usually incomplete (see Langley 2006a).

The assessments indicate that recruitment over the last two decades was higher than for the preceding period. Consequently, yield estimates based on the long-term equilibrium recruitment estimated from a Beverton and Holt SRR may substantially under-estimate the yields currently available from the stock under current recruitment conditions. For this reason, a separate yield analysis was conducted based on the average level of recruitment from 1997–2006.

5 Sensitivity analyses

There are three main differences in the configuration of the data set included in the current assessment compared to the 2006 assessment.

i. The inclusion of three new fisheries that were previously unaccounted in the model: the Japanese coastal pole-and-line and purse-seine fisheries in region 1 and the composite pole-and-line fishery in region 3.

ii. The separation of the composite Philippines and Indonesia domestic fishery (PHID MISC 3) into two separate national fisheries (PH MISC 3 and ID MISC 3).

iii. The separation of the LL ALL 3 fishery, the principal longline fishery in region 3, to include an additional historical distant-water longline fishery within an area approximating PNG national waters (LL BMK 3).

The additional fisheries were included to account for sources of catch previously not incorporated in the stock assessment and to maintain a fishery structure consistent with the WCPO yellowfin stock assessment. The three changes (above) were made in a step-wise manner to enable the effect of each change to be investigated relative to the fishery structure used in the 2006 bigeye stock assessment (denoted model runs 1–4, Table 3).

Three additional model runs investigated different approaches to configuring the size (length and weight) frequency data from the Japanese longline fleet and determining an appropriate weighting of these data in the assessment model. The approach used to compute the corresponding size frequency data in the 2007 yellowfin stock assessment was considered (run 6) as was determining the effective sample size based on the representativeness of the size frequency data relative to the distribution of the longline catch (run 8). The iterative reweighting approach to determining effective sample size, following McAllister and Ianelli (1997), was also investigated (run 9).

From the initial set of model runs a preferred model option was selected (run 4) and the sensitivity of this model to several assumptions was investigated (Table 4). These assumptions include the natural mortality-at-age schedule (Figure 10), steepness of the spawning stock-recruitment relationship, historical and current catch levels from the Philippines and Indonesian domestic fisheries (Figure 11), the assumption of constant (versus increasing) catchability of the Japanese longline fleet (Figure 12), and structural assumptions related to recruitment distribution and movement. Details of each of the sensitivity runs are presented in (Table 4). These sensitivities were largely determined from discussions held at a preparatory stock assessment meeting held in February 2008 and the rationale for the individual sensitivities is described in the report from the meeting (Langley & Hoyle 2008).

A recent paper by Lawson (2008) has highlighted the potential for considerable bias in the current estimates of the bigeye catch from the equatorial purse-seine fisheries and suggests that actual catches could be at least twice the assumed level. The effect of this potential bias on the current assessment conclusions was investigated via a sensitivity analysis that doubled the assumed level of catch from the four equatorial purse-seine fisheries (Figure 13).

6 Results

6.1 Model selection

A total of 24 model runs were completed, including 17 sensitivity analyses. It was decided to adopt run 4 as a nominal base-case on the basis that the model incorporated the catch from all fisheries in the WCPO and had a model configuration consistent with the 2007 yellowfin stock assessment. The principal model options with the reconfigured longline size data (runs 6 and 8) were discounted due to the high proportion of the bigeye size data that was excluded when the selection criteria were applied. The iterative reweighting approach was viewed as being somewhat experimental although it is interesting to note that it resulted in an overall reduction in the weighting of the longline size data, to about 40% of the base case, although the size data from recent years was downweighted even further, particularly in region 4.

Of the sensitivity analyses, it was decided to focus on the results of the analyses which were considered more plausible, while still deviating significantly from the base-case analysis. Four sensitivities were selected for detailed examination.

- Lower steepness (run s11, h=0.75). The base-case estimates a high value of steepness (0.97); however, the model is not very informative about this parameter which is crucial in the determination of the MSY-based performance measures. Limited information is available to determine steepness for any tuna species or stock. A lower value of steepness is considered plausible and results in more conservative MSY-based reference points.

- Increasing longline catchability (run s7b, LL incr. q). The base-case model assumes that the GLM CPUE model accounts for all significant changes in the longline fishery that might have resulted in an increase in the efficiency (catchability) of the fleet. However, the CPUE model only includes a limited number of variables (location, HBF, and proportion of yellowfin in the catch) and does not consider the increase in efficiency of the longline fleet achieved from the adoption of a wide range of technological advances in fishing gear over the history of the fishery (see Ward 2008) or the increase in fisher knowledge and experience. A sensitivity analysis with increasing longline catchability is, therefore, a plausible alternative to the base-case assessment. The sensitivity formulated includes a 1% per annum increase prior to 1985 and a 2% per annum increase from 1985 onwards when bigeye was the main species targeted by the longline fleet. These values are considered to represent “best guesses” of the increase in fishing efficiency in the absence of any definitive quantitative study.

- Purse-seine revised catch. As noted above, current catches from the equatorial purse-seine fishery may be substantially under-estimated (Lawson 2008). This sensitivity analysis incorporates an alternative catch history, doubling the catch from 1980 onwards.

- Low catches from the Indonesian and Philippines domestic fisheries (run s5, low ID/PH). Historical and recent catches from these two fisheries are highly uncertain, particularly for the Indonesian fishery. A range of alternative catch histories was considered, of which the run with a 50% reduction in the level of catch from both fisheries represented a substantial improvement in the objective function of the model (Table 5).

The results from the base-case and four sensitivity analyses are presented below. In the interests of brevity, some categories of results are presented for the base-case analysis only. However, we emphasize that the designation of the base-case model is notional and that each of the plausible sensitivity analyses should be considered for the interpretation of stock status and development of management advice. Therefore, the main stock assessment-related results are summarised for all analyses.

6.2 Fit statistics and convergence

A summary of the fit statistics for the base-case and four sensitivity analyses is given in Table 5. Due to differences in the catch and effort data sets and prior structure (h=0.75) the total likelihood values are not strictly comparable for all analyses. However, the values do provide some insights into the various model options. The lower Indonesian and Philippines catch resulted in a substantial improvement in the likelihood contributions for both sets of size data and the overall likelihood, while the converse was the case for the revised purse-seine catch sensitivity. The increasing catchability for the longline fishery improved the fit to the catch data and the weight frequency data but eroded the overall fit.

6.3 Fit diagnostics – base case (Run 4)

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

- The log total catch residuals by fishery are shown in Figure 14. The magnitude of the residuals is in keeping with the model assumption (CV=0.05) and they generally show even distributions about zero. One noteworthy exception is for LL ALL 3, which shows a group of negative residuals in the 1990s.
- There is some systematic lack of fit to the length data for the longline fisheries as revealed from a comparison of the observed and predicted length data aggregated over time (Figure 15). For some of the longline fisheries (LL ALL 2 and LL TW-CH 4) the model over-estimates the proportion of fish in the larger length classes and, correspondingly, under-estimates the proportion of fish in the smaller length classes. However, the fit to these data is superior to earlier assessments (Hampton et al. 2005) largely due to the refinement of the treatment of the weight frequency data (see Langley 2006a for details). These changes resolved much of the apparent conflict between the length- and weight-frequency data included in the model.
- For a number of the longline fisheries, the size composition of the catch is multimodal (LL ALL 1–2, LL HW 2, and LL PG 3); however, the overall fit to the size data is poor as the model is unable to predict the strong modal structure.
- The surface fisheries (the purse-seine fisheries, pole-and-line fisheries and PH MISC 3) reveal a similar discrepancy between the observed and predicted size composition. These fisheries principally catch small fish and there is a strong modal structure to the length frequency data. The predicted size composition does not adequately predict the magnitude of these modes and generally has a broader size distribution than observed. As for the longline data, this discrepancy appears to be partly due to an inconsistency between the estimated growth function and the observed modal structure of the length frequency samples.
- For most fisheries, the size composition of individual length samples is consistent with the temporal trend in the size composition of the fishery-specific exploitable component of the population (Figure 16). However, a number of the principal longline fisheries reveal substantial changes in the size composition of the sampled catch that are not predicted by the model. For example, the LL ALL 3 fishery length samples were comprised of significantly smaller fish during the 1980s than during the 1990s, while the model does not predict a strong temporal trend in the size composition (Figure 16). This was more pronounced in the 2006 bigeye assessment, although the separation of the fishery in the Bismarck Sea has transferred some of the inconsistent length data to that fishery.
- Similarly, there is a marked shift in the observed length-composition in the LL ALL 2 fishery in the late 1970s–early 1980s with significantly smaller fish sampled in the latter period. Such changes are indicative of temporal changes in the selectivity of individual fisheries and may be, at least partly, explained by temporal trends in the spatial distribution of fishing and sampling effort within a sub-region that exhibits spatial heterogeneity in size structure (see Langley 2006c).
- The length data from the pole-and-line fisheries and Japanese coastal purse-seine fishery are highly variable and not well described by the model dynamics (Figure 16).
- For most of the longline fisheries, there is a good fit to the aggregated weight frequency data (Figure 17). However, for a number of fisheries with a strong modal structure in the weight distribution, the model does not reliably predict the size composition. These fisheries include LL ALL 1, LL ALL 2, LL PG 3, and LL HW 4 for which the model tends to consistently under-estimate the magnitude of the stronger modes of the weight distribution. There is also a relatively poor fit to the weight data from those fisheries with limited size data, especially LL

TW-CH 4. This fishery is constrained to have a selectivity equivalent to that of the Chinese/Taiwanese longline fishery in region 3 (LL TW-CH 3). This assumption requires further examination.

- o In general, the model provides an excellent fit to the temporal trends in the weight data, although there are a number of deviations as observed for the length data, most notably for LL ALL 2 (Figure 18). The consistency in the trends between the length- and weight-frequency data for this fishery further supports the presumption of a temporal trend in the selectivity of these fisheries. The temporal trend observed in the fit to the LL ALL 3 length data is not evident for the weight frequency data. This may be partly explained by a difference in the spatial distribution of the collection of length- and weight-frequency data within this region (see Langley 2006c).
- o The fits of the model to the tagging data compiled by calendar time and by time at liberty are shown in Figure 19 and Figure 20, respectively. Overall, the model predicts tag attrition reasonably well. However, there is some lack of fit for individual fisheries, in particular the under-estimation of tag returns from the Australian longline fishery (see panel LL AU 5 of Figure 21). These returns were all from releases in the north-western Coral Sea and were recaptured over a long period of time in a relatively small area around the release site (some tags were recaptured from further a field, but these were relatively few). Therefore, the observed tag returns suggest a pattern of small-scale residency (or homing) that the relatively coarse spatial scale of the model is unable to capture completely (see Evans et al. *in press*). The model fit to the other fisheries is generally good for fisheries that returned large numbers of tags.
- o 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 22). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. On the other hand, if there was an obvious trend in the effort deviations with time, this may indicate that a trend in catchability had occurred and that this had not been sufficiently captured by the model. Of particular interest are the effort deviations for the LL ALL 1–6 longline fisheries, which were constrained to have the same average catchability and to have no year-to-year variation in the base-case model. For most of these fisheries, there are no strong patterns in the distributions of effort deviations, with the exception of negative effort deviations for the LL ALL 3 fishery in the last two decades (Figure 22). The effort deviations from the LL ALL 6 fishery are more variable than for the other fisheries. This does not imply a worse fit to the catch and effort data, rather it probably reflects the lower precision of the CPUE indices for this region.
- o The recent strong negative effort deviations from the LL ALL 3 fishery are removed when the size data from the Taiwanese-Chinese longline fishery (TW-CN LL 3) are down-weighted to the extent that they are no longer influential in the model (sensitivity downwtTWCN) (Figure 23). This result suggests there is a conflict between the size data from the TW-CN LL3 fishery and the CPUE indices from the principal longline fishery in region 3.
- o Effort deviations for the purse seine fisheries, particularly those in region 4, are highly variable and reveal short-term fluctuations (Figure 22). This observation indicates availability of bigeye to the purse-seine fishery is highly variable and may be related to short-term fluctuations in oceanographic conditions.

6.4 Model parameter estimates (run 4 base-case unless otherwise stated)

6.4.1 <u>Growth</u>

The estimated growth curve is shown in Figure 24. For the base-case model, growth in length is estimated to continue throughout the lifespan of the species, without the attenuation of length approaching a maximum level – the estimated mean length of the final age-class is 173.1 cm and the estimated L_∞ is 181.2 cm. The estimated variance in length-at-age is relatively low — much lower than estimated from the 2005 assessment (Hampton et al. 2005). For example, at age 20 the current assessment estimates a standard deviation at length of 10.2 cm compared to 19.1 cm from the 2005 assessment.

Comparisons of the estimated growth curve with length increments from tagging data and daily otolith readings (Lehodey et al. 1999) show some discrepancies (Figure 25). Most of the tagging length- and age-at-recapture observations are consistent with the estimated growth curve, although a subset of the tag recoveries exhibit considerably slower growth. These records may simply represent errors in the recorded length at recovery and should be examined more thoroughly.

The otolith length-age observations are generally consistent with the estimated growth curve up to age 12 (quarters). For older age classes the otolith data indicates higher growth rates than the estimated growth curve (Figure 25).

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

6.4.2 Natural mortality

As for the 2006 assessment, natural mortality was not estimated in any of the analyses and a fixed age-specific mortality function was applied (see Figure 10). Several alternative fixed *M*-at-age schedules were investigated. This issue may be re-visited in future assessments using biologically reasonable functional forms for *M*-at-age.

6.4.3 Movement

Two representations of movement estimates are shown in Figure 26 and Figure 27. The estimated movement coefficients for adjacent model regions are shown in Figure 26. Coefficients for some region boundaries are close to zero, while overall, movement rates are low. The highest movement rates occur from region 3 to region 4 (3%) and vice versa (4%) in the first quarter and from region 2 to region 1 in the second quarter (4%).

The distribution of regional biomass by source region derived from a simulation using the movement coefficients is presented in Figure 27. The simulation indicates that most biomass within a region is sourced from recruitment within the region, with the exception of region 1. The mixing between the equatorial regions results in a moderate (10–20% per generation) mixing of biomass between the two regions. Almost 40% of biomass within region 1 is sourced from fish recruited in region 2. Regional fidelity is highest in region 5 with virtually no transfer of biomass from this region and almost all biomass sourced from recruitment within the region (Figure 27).

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

6.4.4 Selectivity

Estimated selectivity coefficients are generally consistent with expectation with longline fisheries principally selecting larger, older fish and the associated purse-seine sets (FAD and log sets) catching smaller bigeye (Figure 28). The Philippines and Indonesia surface fisheries (PH and ID MISC 3) principally catch small fish; however, there are also some observations of larger fish in the catch (see Figure 15) that explain the high selectivity of older fish also. Similarly, the equatorial pole-and-line fishery (PL ALL 3) is estimated to have a high selectivity for the older age classes, despite catching few small large fish.

For the all the principal longline fisheries (LL ALL 1–6), selectivity is estimated to decline for the older age classes and the catch is predicted to be principally comprised of age 5–15 fish and selectivity of older fish is relatively low. This is consistent with the slightly smaller size of fish caught by these fisheries compared to the corresponding TW-CH fisheries. The functional form of the (common) selectivity of the latter fisheries is constrained to have full selectivity for the oldest age classes. Other longline fisheries are also estimated to have a high selectivity for the older age classes (LL PG 3, LL AU 5, and LL PI 6).

Selectivity functions are temporally invariant. However, for a number of fisheries there is a clear temporal change in the size-frequency data and an associated lack of fit to the predicted size composition (see Section 6.3). This is particularly evident for the LL ALL 1 fishery with a substantial change in size composition in the late 1970s.

6.4.5 Catchability

Time-series changes in catchability are evident for several fisheries (Figure 29). There is evidence of a general increase in catchability for the purse seine fisheries and some of the domestic longline fisheries (LL PG 3, LL AU 5, and PH HL 3). Catchability in the LL ALL 1–6 longline fisheries was assumed to be constant over time for the base-case, with the exception of seasonal variation (not shown in Figure 29).

6.4.6 Tag-reporting rates

Estimated tag-reporting rates by fishery are shown in Figure 30. Reporting rates vary widely among fisheries. Note that some reporting rates could reflect the fine-scale distribution of fishing effort and tag releases, as well as the propensity of the fisheries to return recaptured tags. For example, the high estimated reporting rate for LL AU 5 in part reflects the close proximity of tag releases to the operational area of this fishery. By contrast, the very low reporting rate for LL ALL 5 in parts reflects the fact that this fishery is distributed mainly to the east of the tag release locations in region 5.

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

6.5 Stock assessment results

6.5.1 Recruitment

The base-case recruitment estimates (aggregated by year for ease of display) for each region and the entire WCPO are shown in Figure 31. The regional estimates display large interannual variability and variation on longer time scales, as well as differences among regions. For the aggregated estimates, there is a decreasing trend to about 1970 and an increasing trend thereafter, with exceptionally high recruitment during 1995–2005, with a peak in recruitment in 2000. In recent years, recruitment is estimated to have declined to approximately the long-term average.

There are sharp initial declines in recruitment in several regions (1, 2, and 5), which are the model's response to the rapid declines in CPUE in these regions. The post-1970 increase in WCPO recruitment is due primarily to an increasing trend in the estimates for region 3 and, to a lesser extent, region 4. This trend, and its correspondence with increasing juvenile catch in the same region, has been noted in previous WCPO bigeye assessments and is investigated in detail in Langley & Hoyle (2008).

For the entire WCPO, recruitment estimates for the early period of the model (1952–1960) and the most recent years (2005–2007) are highly uncertain (Figure 31).

A comparison of WCPO recruitment estimates for the different analyses is provided in Figure 32. The five analyses reveal comparable trends in recruitment although there is some temporal variation in the magnitude of the trend in recruitment among analyses. For the sensitivity with increasing longline catchability, there is an increase in recruitment prior to 1980 and during the most recent decade. There is also a substantial increase in recruitment from the mid-1990s for the model option with increased purse-seine catch, while the converse is the case for the PH/ID low catch sensitivity (Figure 32).

6.5.2 Biomass

The estimated biomass trajectory for each region and for the entire WCPO is shown in Figure 33 for the base-case analysis. Biomass is estimated to decline during the 1950s and 1960s in all regions. In region 3, total biomass remained relatively stable from the mid 1970s to 2000 and declined sharply from 2003 onwards following a sharp decline in regional recruitment. Biomass levels are highest in region 4 and the biomass trend from this region dominates the overall trend in the WCPO; biomass declines rapidly during the 1950s and 1960s, is relatively stable through the 1970s and 1980s, and then declines steadily from 1990 onwards.

There are very narrow confidence intervals around the time-series of estimated biomass for each region (Figure 33). These confidence intervals do not accurately reflect the true level of uncertainty as they are predicated on the high precision of estimated recruitment time-series, which are conditioned on the assumption that natural mortality at age is known without error and other structural assumptions of the model.

The comparison of total biomass trends for the different analyses is shown in Figure 34 and Figure 35. The changes in the fishery configuration from the 2006 assessment (run 1) and the current assessment (run 4) resulted in a negligible increase in total biomass throughout the model period (Figure 34). Of the four sensitivities considered, only the run with the increasing longline catchability yielded a different trend in total biomass, with a significantly higher initial biomass and a steeper decline in total biomass throughout the model period (Figure 35).

A useful diagnostic is to compare model estimates of exploitable abundance for those longline fisheries with assumed constant catchability with the CPUE data from those fisheries. The time series comparison of these quantities (Figure 36) shows generally good correspondence between the model estimates and the data. The notable exception is the deviation between the trend in exploitable biomass and CPUE in region 3 from 1995 onwards, as previously noted from the examination of the effort deviates from the LL ALL 3 fishery. Also, the model estimates of exploitable abundance show very similar scaling among regions as the CPUE data (Figure 37). This indicates that model estimates are consistent with the CPUE data in terms of both time-series and spatial variability.

6.5.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increase strongly throughout the time series for all model runs (Figure 38). For the models with higher purse-seine catch and increasing longline catchability, estimates of recent juvenile fishing mortality are considerably higher than for the base-case, while the opposite is the situation for the PH/ID low catch option.

Changes in fishing mortality-at-age and population age structure are shown for decadal time intervals in Figure 39. Significant juvenile fishing mortality begins in the 1980s with the development of purse seining in the WCPO. There is also a significant increase in fishing mortality for the 15–25 age-classes from 1990 and a sharp increase in the juvenile fishing mortality in the last decade. Changes in age-structure are also apparent, in particular the decline in abundance of age-classes 20 and older (Figure 39).

6.5.4 Fishery impact

We measure fishery impact at each time step as the ratio of the estimated biomass to the biomass that would have occurred in the historical absence of fishing. This is a useful variable to monitor, as it can be computed both at the region level and for the WCPO as a whole. The two trajectories are plotted in Figure 40. Impacts are significant in all regions, but are particularly strong in the tropical regions 3 and 4, where most of the catch is taken. The patterns for these two regions therefore dominate the overall picture for the WCPO.

The biomass ratios are plotted in Figure 41. These figures indicate strong fishery depletion of bigeye tuna in regions 1, 3 and 4, and moderate levels of depletion in regions 5 and 6. Depletion in region 2 is slight by comparison. For the entire WCPO, recent levels of depletion are highest for the models with higher purse-seine catch and increasing longline catchability, while in all scenarios depletions is considerably higher for the adult component of the stock (Figure 42).

It is possible to ascribe the fishery impact, $1 - B_t / B_{0t}$, to specific fishery components in order to see which types of fishing activity have the largest impact on population biomass. Figures are presented for both adult (Figure 43) and total (Figure 44) biomass. In contrast with yellowfin tuna, the longline fishery has a significant impact on the bigeye tuna population in all model regions; it is the most significant component of overall fishery impact in regions 2 and 4–6 and is responsible for about half of the WCPO impact on total biomass and two-thirds of the impact on adult biomass in recent years. In region 3, the purse seine fisheries and the Indonesian and Philippines domestic fisheries also have high impact on both total and adult biomass. In region 4, purse seine impacts are significant. In region 1 the coastal pole-and-line and purse-seine fisheries have a significant impact on both adult and total biomass.

The level of fishery impact on WCPO total biomass that is attributable to the longline fishery is comparable between the five principal models (Figure 44 and Figure 46). The increased fishery impact in the model with increased purse-seine catch is directly attributable to the associated purse-seine fishery – in this analysis the impact of the longline and purse seine fisheries on total biomass is approximately equal. The impact of the Indonesian/Philippines fishery is substantially reduced in the model with a low catch for these fisheries (run s5). For the fishery with increasing longline catchability, most of the increase in fishery impact (compared to the base-case) is attributable to the Indonesian and Philippines fisheries, particularly in the last decade (Figure 46).

6.5.5 Yield analysis

Symbols used in the following discussion are defined in Table 6. The yield analyses conducted in this assessment incorporate the SRR (Figure 46) into the equilibrium biomass and yield computations. The estimated steepness coefficient is 0.97, indicating that there is little evidence of recruitment decline as a function of adult biomass. The high steepness is principally due, at least in part, to the very high estimates of recruitment obtained from the recent lower levels of adult biomass (Figure 46).

Equilibrium yield and biomass (spawning and total) are computed as a function of multiples of the 2003–2006 (denoted hereafter as "current") average fishing mortality-at-age (Figure 47). For the base-case model, a maximum yield (*MSY*) of 64,600 mt per annum is achieved at *fmult* = 0.69; i.e. at 69% of the current level of age-specific fishing mortality. This represents a ratio of $F_{current} / \tilde{F}_{MSY}$ equal to 1.44 (approximately 1/0.69); current exploitation rates are considerably higher than the exploitation rates to produce the *MSY*. The equilibrium biomass at *MSY* is estimated at 249,600 mt, approximately 30% of the equilibrium unexploited biomass (Table 7).

The approximate 95% confidence interval associated with the equilibrium yield curve is also presented in Figure 47. The narrow confidence interval across the range of fishing mortality rates suggests a high level of precision associated with the equilibrium yield estimates. This is attributable to the high precision associated with the SRR and the steepness coefficient in particular (Figure 46); i.e. there is apparent high certainty regarding equilibrium recruitment across a wide range of levels of equilibrium spawning biomass and, therefore, fishing mortality levels.

For each of the principal models, the reference points $F_t / \tilde{F}_{MSY}$, $B_t / \tilde{B}_{MSY}$ and $SB_t / S\tilde{B}_{MSY}$ were computed for each year (t) included in the model (1952–2007). These computations incorporated the overall fishery selectivity in year t. This enables trends in the status of the stock relative to these two reference points to be followed over the model period (Figure 48). For the base-case model, exploitation rates were low from 1952 to 1970, although total biomass declined rapidly relative to $\tilde{B}_{MSY}$. Over the subsequent 25 years, the biomass level ($B_t / \tilde{B}_{MSY}$) remained relatively constant while $F_t / \tilde{F}_{MSY}$ steadily increased. The increase in $F_t / \tilde{F}_{MSY}$ accelerated from the mid-1990s to recent years, exceeding 1.0 in 1997 and remaining above 1.0 in the subsequent years. During the same period, $B_t / \tilde{B}_{MSY}$ remained relatively constant, due to increased recruitment, and total biomass has remained above the overfished threshold ($\tilde{B}_{MSY}$) (Figure 48). For the base-case model, current (2003–2006) total biomass is estimated to be 37% higher than $\tilde{B}_{MSY}$ ($B_{current} / \tilde{B}_{MSY}$ = 1.37) (Table 7).

Similar trends are evident for the four other principal models, although the extent of overfishing ($F_t / \tilde{F}_{MSY}$ > 1) and the level of biomass depletion relative to $\tilde{B}_{MSY}$ is most pronounced in the models with increasing longline catchability (s7b) and lower steepness of the SRR (s11) (Figure 49).

For the base-case model, the level of depletion of the spawning biomass is higher than for the total biomass ($SB_{current} / S\tilde{B}_{MSY}$ = 1.19 compared to $B_{current} / \tilde{B}_{MSY}$ = 1.37) (Figure 50), while levels of depletion of adult biomass are substantially higher for the models with increasing longline catchability (s7b) and lower steepness of the SRR (s11) (Figure 51). In both cases, adult biomass is estimated to have been below the $S\tilde{B}_{MSY}$ level since 2001 and 2000, respectively.

For the base-case model, the maximum equilibrium yield (MSY_t) was also computed for each year (t) in the model. This analysis enables an assessment of the *MSY* level that would be theoretically achievable under the different patterns of age-specific fishing mortality observed through the history of the fishery (Figure 52). Prior to 1970, the WCPO bigeye fishery was almost exclusively conducted by the longline method, with a low exploitation of small bigeye. The associated age-specific selectivity resulted in a substantially higher level of *MSY* (100,000 mt per annum) compared to that estimated for the fishery based on the recent age-specific fishing mortality pattern (about 65,000 mt). The decline in the *MSY* over time follows the increased development of those fisheries that catch smaller bigeye, principally the surface fisheries (Figure 52).

Equilibrium yield and total biomass as functions of multiples of the 2003–2006 average fishing mortality-at-age are shown in Figure 53 for the various analyses. For the main runs considered, the value of *fmult* associated with *MSY* varies from 0.48 to 0.75 (i.e. $F_{current} / \tilde{F}_{MSY}$ of 1.33–2.09). The scenario with low steepness is the most pessimistic, with the lowest *fmult* and equilibrium yields predicted to decline rapidly at levels of fishing mortality exceeding F_{MSY} (Figure 53). For the range of scenarios, the equilibrium total and adult biomass at *MSY* are estimated to be 32–39% and 20–29% of the equilibrium unexploited total and adult biomass, respectively.

For the complete range of model runs investigated, most of the values of *fmult* and ($F_{current} / \tilde{F}_{MSY}$) were within the range for the principal scenarios (Table 10 and Figure 54) with scenarios with higher Philippines and/or Indonesian catch, lower natural mortality for adult fish (run s10 and seapodymM) or increasing longline catchability (runs s7a, s7b) at the lower (upper) end of the range of *fmult* ($F_{current} / \tilde{F}_{MSY}$). Only the run with no regional variation in recruitment deviates (s13) resulted in a value of $F_{current} / \tilde{F}_{MSY}$ (marginally) less than 1; however, this run was judged to be implausible because of the greatly degraded fit to the data.

The *MSY* estimates for all analyses range from about 55,000 mt to 75,000 mt per year (Table 10). These estimates of equilibrium yield are substantially less than recent catches, which have been of the order of 100,000–125,000 mt annually. This apparent anomaly results because the equilibrium computations use equilibrium recruitment determined from the SRR fitted to all of the recruitment time series. This equilibrium recruitment is close to the average recruitment over the time series and is much lower than the estimated recruitment post-1990. When yield is computed using the average recruitment from the past 10 years (1997–2006) rather than the equilibrium recruitment, we obtain a clearer picture of *MSY* under recent recruitment conditions (Figure 55). Under recent recruitment conditions, maximum yields are estimated to be 100,000–130,000 mt annually. However, there is an indication that recruitment in the most recent years has returned to long-term average levels and, in that case, these higher recent yields would not be sustainable.

6.5.6 Probability Distributions for Key Reference Points

A number of quantities of potential management interest associated with the yield analyses are provided in Table 7. In the top half of the table, absolute quantities are provided, while the bottom half of the table contains ratios of various biomass and fishing mortality measures that might be useful for stock monitoring purposes. It is useful to distinguish three different types of ratio: (i) ratios comparing a measure for a particular time period with the corresponding equilibrium measure (unshaded rows); (ii) ratios comparing two equilibrium measures (rows shaded grey); and (iii) ratios comparing two measures pertaining to the same time period (row shaded black). Several commonly used reference points, such as $B_{current}/\tilde{B}_{MSY}$, $SB_{current}/S\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ fall into the first category. These ratios are usually subject to greater variability than the second category of ratios because recruitment variability is present in the numerator but not in the denominator. The range of values observed in this and other assessments suggests that the category (ii) ratios are considerably more robust than those in category (i).

For the base-case model, profile likelihood-based estimates of the posterior probability distribution of $B_{current}/\tilde{B}_{MSY}$, $SB_{current}/S\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ were calculated. For the three reference points, likelihood profiles for also computed for each of the four years that constitute the period defined as representing *current* conditions (2003–2006). This enables recent trends in these metrics to be examined and, in the case of the $SB_{year}/S\tilde{B}_{MSY}$ metric, the latest year (2006) is likely to represent a more accurate indicator of the current status of the spawning stock.

The profile likelihood distribution for the base-case reveals that there is a zero probability that $B_{current}/\tilde{B}_{MSY}$ is below 1.0 and that the highest probability is at about the level of the point estimate from the model (1.37) (Figure 56, Table 8). However, there is a temporal trend in the mode of the probability distribution over the four years that are used to define current conditions and the mode of the $B_{2006}/\tilde{B}_{MSY}$ probability distribution is considerably lower than the composite $B_{current}/\tilde{B}_{MSY}$ with a small probability of the stock being overfished ($B_{2006}/\tilde{B}_{MSY}$ < 1) (Figure 56, Table 8).

There is a 10.3% probability that $SB_{current}/S\tilde{B}_{MSY}$, derived for the composite period 2003–2006, is below 1. However, the probability is substantially higher (42.8%) when the reference point is computed for the 2006 reference year only (Figure 57, Table 8). This is consistent with the point estimates from the principal model runs that reveal $SB_{2006}/S\tilde{B}_{MSY}$ to be lower than $SB_{current}/S\tilde{B}_{MSY}$ (Table 7) consistent with a sharp decline in adult biomass in the equatorial regions in the last few years.

The posterior probability distribution of $F_{current}/\tilde{F}_{MSY}$ is positively skewed with the mode of the distribution at about the point estimate of 1.44 and a 100% probability of $F_{current}/\tilde{F}_{MSY}$ exceeding 1.0 (Figure 58, Table 8). The broad upper tail of the distribution includes a high probability that $F_{current}/\tilde{F}_{MSY}$ exceeds 1.5. There is considerable inter-annual variation in the probability distribution of $F_{year}/\tilde{F}_{MSY}$ among the four constituent years with a considerably lower level of fishing mortality in 2003. The probability distributions for the other three years are comparable to the composite period (Figure 58, Table 8).

For the broader suite of model options considered, the scenarios with higher Philippines and/or Indonesian catch and lower natural mortality for adult fish resulted in a higher level of stock depletion with current total biomass approaching or falling below (run s10) the B_{MSY} level (Table 10 and Figure 54). Most of the other scenarios resulted in values of $B_{current}/\tilde{B}_{MSY}$ comparable to the base-case analysis (1.37).

For the main sensitivity analyses, there was considerable variation in the probability distributions of $B_{current}/\tilde{B}_{MSY}$ (Figure 59), $SB_{current}/S\tilde{B}_{MSY}$ (Figure 60) and $F_{current}/\tilde{F}_{MSY}$ (Figure 61), with considerably more pessimistic outcomes for the sensitivity analyses incorporating increasing longline catchability (s7b) and lower steepness (s11). A full suite of all likelihood profiles, including integrated profiles equally weighted across the base case and main sensitivity analyses, for $B_{current}/\tilde{B}_{MSY}$, $SB_{current}/S\tilde{B}_{MSY}$ and $F_{current}/\tilde{F}_{MSY}$ and their constituent years is provided in Appendix C.

6.6 Analyses of management options

Unlike previous assessments, no attempt has been made to assess specific management proposals in the context of the bigeye tuna stock assessment. However, the report endeavours to inform managers of the outcomes of a wide range of changes in fishery-specific effort which may serve to direct the formulation of potential management measures. Two approaches were taken using the base-case assessment (run 4):

1. Estimation of levels of fishing effort, relative to current effort, to ensure that the stock will remain at an agreed level above B_{MSY}; and
2. Conducting an array of model projections, applying the approach of Langley & Hampton (2006), to determine F/F_{MSY} and B/B_{MSY} from varying levels of longline, purse-seine associated, and Indonesian/Philippines fishing effort (70%, 80%, 90%, 100%, 110%, 120%, 130%) relative to a base-line level of fishing effort.

6.6.1 Fishing Effort and B_{MSY}

To investigate this question, we consider the equilibrium biomass in relation to B_{MSY} so that the effects of variable recruitment on future biomass need not be considered. This is appropriate as we are simply interested in a long-term average indicator of the relationship between fishing effort, resulting biomass and B_{MSY}. The yield analysis described above provides a basis for estimating levels of equilibrium biomass that would result at different levels of relative fishing effort, assuming maintenance of the 2003–2006 overall fishery selectivity and constant catchability and recruitment predicted from the estimated SRR. The former assumption means, *inter alia*, that the relative fishing effort of each fishery defined in the assessment model remains the same as the 2003–2006 average.

Table 9 provides estimates of fishing effort scalars (relative to the 2003–2006 average) that result in equilibrium total biomass at various levels above B_{MSY}. The fishing effort scalar consistent with B_{MSY} is 0.69. In other words, fishing effort would need to be reduced across the board by 31% to obtain an equilibrium biomass equal to B_{MSY}. Progressively lower fishing effort is required to achieve higher equilibrium biomass relative to B_{MSY}.

6.6.2 Stock Projections

The stock projections were constructed to simulate the application of the WCPFC-2 conservation and management arrangements as they apply to bigeye tuna. The CMAs with respect to bigeye tuna are contained in Attachment D of the WCPFC-2 report[5], and the pertinent paragraphs are:

> *1. Through the adoption of necessary measures, the total level of fishing effort for bigeye and yellowfin tuna in the Convention Area shall not be increased beyond current levels.*
>
> *8. CCMs shall take necessary measures to ensure that purse seine effort levels do not exceed either 2004 levels, or the average of 2001 to 2004 levels, in waters under their national jurisdiction, beginning in 2006.*

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

17. The [longline] *catch of bigeye for each CCM for the next 3 years shall not exceed the average annual bigeye catch for the years 2001-2004 or the year 2004* [the year 2004 applying only to China and the United States].

18. Paragraph 17 does not apply to CCMs that caught less than 2,000 tonnes in 2004. Each CCM that caught less than 2,000 tonnes of bigeye in 2004 shall ensure that their catch does not exceed 2,000 tonnes in each of the next 3 years.

To take account of the above, a base-line of fishing effort was defined as follows:

- o Purse seine effort levels for 2004 were assumed for the ten-year projection period (2008–2017). The distribution of effort among regions, quarters and set types was specified according to the average distributions for the period 2003–2006. The use of a multi-year average distribution reduces the risk of anomalous results arising from unusually high or low effort occurring in one of these strata in an individual year.
- o Longline effort levels averaged over 2001–2004 were assumed for the projection period, with the exception of the United States and Chinese fleets, which were assigned 2004 levels of effort. Because the extent to which CCMs catching less than 2,000 mt in 2004 might increase their catch is unknown, we did not incorporate catch increases through this provision into the projection; 2001–2004 average catches were used in these cases.
- o Relative effort levels for the Philippines and Indonesian domestic fisheries were assumed to continue through the projection period at 2006 levels.
- o For fisheries with estimated time-series variation in catchability, the estimated catchability for the last data year (2007) was assumed to continue through the projection period.
- o Recruitment during the projection period was predicted using the estimated SRR distributed among regions in accordance with the long-term proportional recruitment distribution.

For the three fishery groupings (longline, purse-seine associated, and Indonesian/Philippines), projections were undertaken using 7 multiples of the base-line fishing effort (70%, 80%, 90%, 100%, 110%, 120%, 130%). For each of the (7^3 = 343) effort scenarios, a stock projection was conducted and the F/F_{MSY} and B/B_{MSY} reference points computed at the end of the projection period (approximately equilibrium conditions). It is worth noting that during the projection period, recruitment is distributed according to the long-term distribution, resulting in an increased the level of recruitment in regions 1 and 2 in the projection period compared to recent years. Exploitation rates are lower in these two regions and, therefore, provide some buffer to the increasing *F*'s in the tropical region.

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

For each scenario, the resulting F/F_{MSY} is presented in Table 11. Projected fishing mortality below the F_{MSY} level can be achieved via many combinations of fishing effort; however, largest changes in the performance measure occur from changes in the multiplier applied to the longline fishing effort. This reflects the relatively high proportion of the total level of current fishing mortality attributable to this method throughout the WCPO. Significant reduction is fishing effort from at least one specific gear type are required to achieve F/F_{MSY} and larger reductions in some fisheries are required for scenarios that model an expansion of one of the fisheries. The changes in fishing effort to achieve outcomes that maintain equilibrium biomass above the B_{MSY} mirror the F/F_{MSY} outcomes (Table 12).

7 Discussion and conclusions

This assessment of bigeye tuna for the WCPO applied a similar modelling approach to that used in the 2006 assessment, although there were a number of important changes, notably:

- The separation of the LL ALL 3 fishery, the principal longline fishery in region 3, to include an additional historical distant-water longline fishery within an area approximating PNG national waters (LL BMK 3). A previous analysis revealed that the historical distant-water longline fishery in PNG waters caught considerably smaller fish than the fishery operating in other areas of region 3 (Langley 2006c). Up to the 1980s, the PNG area averaged approximately 20% of the distant-water longline catch from region 3; however, the proportion of the total catch was considerably lower (about 5%) through most of the model period. The selectivity of the PNG component of the fishery was estimated independently of the other principal longline fisheries.
- The inclusion of three new fisheries that were previously unaccounted in the model: the Japanese coastal pole-and-line and purse-seine fisheries in region 1 and the composite pole-and-line fishery in region 3 (excluding Indonesia). Since the mid 1970s, these fisheries collectively accounted for an average catch of 2,500 mt per annum.
- The separation of the composite Philippines and Indonesia domestic fishery (PHID MISC 3) into two separate national fisheries (PH MISC 3 and ID MISC 3). This was undertaken on the basis that, at least for recent years, the catch estimates from the Philippines domestic fisheries are considered to be more reliable than for the comparable Indonesian fisheries. The separation of the fisheries enabled a more comprehensive examination of the sensitivity to the model to the assumed magnitude of catch from the Indonesian fishery. However, in separating the fisheries, the paucity of size data from the Indonesian fishery is highlighted and, consequently, the selectivity for the fishery is likely to be poorly determined.
- The revision of the recent (2004 onwards) annual catch estimates from the Indonesian domestic fisheries.
- The addition of recent catch, effort, and size frequency data from most fisheries.
- The current assessment included a large number of sensitivity analyses, most notably assessing the implications of the assumed level of catch from the Philippines and Indonesian domestic fisheries and the equatorial purse-seine catch, natural mortality at age, and increased catchability of the principal longline fisheries. In addition, the sensitivity of the model to assumptions regarding the steepness parameter of the SRR was also investigated.

For the 2006 assessment, an alternative seven-region spatial stratification was also investigated. The rationale for the alternative regional stratification was to reduce the spatial heterogeneity in the CPUE and size data within each of the individual regions of the model, while also spatially segregating the Indonesian and Philippines fisheries from the other regions. However, the utility of the model was limited due to the lack of a reliable (fishery-dependent) index of abundance for this region during the latter period of the model. Some attempts were made to investigate potential sources of CPUE data for this region; however, no new data were forthcoming and, consequently, there was no opportunity to further develop the seven-region model.

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

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

- The lack of fit to the juvenile modes in the size frequency data from some fisheries may indicate a bias in the model estimates of growth for the youngest age classes. There is also some divergence between the model estimates of initial growth and length-at-age derived from otolith readings. The WCPFC has funded the development of a comprehensive research plan on Pacific-wide bigeye age, growth and reproductive biology. It is envisaged that the implementation of this plan would result in a considerable improvement of our understanding of age and growth of bigeye tuna. In addition, the research would improve our knowledge of sexual maturity and spawning dynamics, thereby, improving model estimates of spawning stock biomass and SRR.
- Residuals in the tag return data for the Australian longline fishery suggested that bigeye tuna may have patterns of long-term residency or homing that cannot be captured by the spatial resolution or movement parameterisation of this model.
- A significant discrepancy in the current model is the lack of fit to the principal longline CPUE index for region 3 during the last decade, as evident from the persistent negative effort deviations for the fishery. This is caused by a conflict between the CPUE index and the size frequency data from the Taiwanese-Chinese longline fishery. The presence of large and, it is assumed, old fish in the catch from this fishery is not consistent with the relatively high fishing mortality in region 3 and the lower CPUE from the principal longline fishery. To provide the best fit to these data (and other observations), the model estimates very high recruitment from 1995 onwards, thereby, ensuring sufficient large, old fish are in the model population (see Langley & Hoyle 2008 for further discussion). This issue was examined in more detail in a parallel stock assessment for bigeye tuna implemented in Stock Synthesis (SS) (Langley & Methot 2008). The results of SS model revealed that a significant improvement in fit was attained when the selectivity of the Taiwanese-Chinese longline fisheries was model based on a length-base rather than weight-based process and the temporal trend in recruitment is considerably reduced. Length-based selectivity parameterisation is not currently available within MFCL.

While not a failure of the model *per se*, the model did have some difficulty in interpreting the very strong declines in longline CPUE in regions 1 and 2 during the early 1950s. The model attempted to explain these CPUE trends by estimating very high initial recruitments in those regions. While high recruitment in the early 1950s is a possibility (and is in fact suggested by SEAPODYM simulations – see Lehodey 2005), there may be other explanations for the high initial longline CPUE, including short-term targeting of “hot-spots”, changes in the spatial distribution of effort within region, higher initial catchability by longline due to higher competition for food, and others. This is the subject of ongoing research.

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

The assessment results from the base-case model closely approximate the results from the 2006 assessment, with inclusion of the additional fisheries and changes in the fishery configurations. These changes are outlined above and represent refinements to the model rather than substantive changes to model structure and resulted in only minor changes to the biomass trajectories. The key conclusions of the models presented here are similar to the comparative model runs from the 2006 base-case assessment – depletions levels estimated in the 2006 (LOWSAMP) assessment (0.29) were similar to the current base-case (0.26), $F_{current}/\tilde{F}_{MSY}$ was more optimistic (1.32 for 2006 cf 1.44) and $B_{current}/\tilde{B}_{MSY}$ was lower (1.27 cf 1.37) while $SB_{current}/S\tilde{B}_{MSY}$ was comparable (1.20 cf 1.19). These metrics indicate that recent fishing mortality has continued to increase, although biomass levels have continued to be sustained by higher recruitment. However, the MSY-based reference points are not directly comparable as there has been a shift in the age-specific fishing mortality in recent years due to the recent decline in the longline catch.

A significant difference between the last two assessments is the higher level of depletion in region 1 in the current assessment due to the inclusion of the catch from the Japanese coastal pole-and-line and purse-seine fisheries. These fishery impacts are not significant at the WCPO scale but have increased fishery impacts in region 1 from about 50% in the 2006 assessment to about 80% in the current assessment.

A comprehensive range of sensitivities were conducted in the current assessment and in a parallel analysis (Hoyle et al. 2008). Additional sensitivities, focusing on the uncertainty regarding bigeye age, growth, and maturity, are presented in Hoyle & Nicol (2008). These analyses yielded comparable results and indicated that the MSY-based performance indicators derived from the model were sensitive to assumptions regarding natural mortality and steepness of the SRR.

A key assumption of the base-case model is that catchability of the Japanese longline fishery remained constant throughout the model period. However, given that the CPUE indices for the longline fishery do not account for increases in fishing efficiency from technological advances and fisher experience, it is reasonable to assume that catchability has increased through the history of the fishery. The sensitivity analysis including an increasing trend in longline catchability resulted in a more pessimistic stock status compared to the nominal base-case; biomass based reference points are lower ($B_{current}/\tilde{B}_{MSY}$ of 1.02 compared to 1.37; $SB_{current}/S\tilde{B}_{MSY}$ 0.76 cf 1.19), levels of depletion are higher (0.20 cf 0.26), and fishing mortality based reference points are higher ($F_{current}/\tilde{F}_{MSY}$ of 1.88 compared to 1.44).

The main conclusions of the current assessment are as follows.

1. Recruitment in all analyses is estimated to have been high during 1995–2005. This result was very similar to that of previous assessments, although there are some indications that the high recruitment may be, at least partly, an artefact of the structural assumptions of the model. Recruitment in the most recent years is estimated to have declined to a level approximating the long-term average, although these estimates have high uncertainty.
2. For most of the analyses, total biomass for the WCPO is estimated to have declined to about half of its initial level by about 1970 and declined gradually over the subsequent period. Adult biomass has declined by about 20% over the last decade. Declines in biomass are more pronounced for the model with increasing longline catchability.
3. The biomass trends in the model are strongly driven by the time-series of catch and GLM standardised effort from the principal longline fisheries. For some of the main longline fisheries, there is an apparent inconsistency between the trends in the size-frequency data and the trends in longline catch and effort; i.e., the two types of data are providing inconsistent information about the relative level of fishing mortality in the region. A number of approaches were applied to investigate the influence of the size data from the key longline fisheries. However, the stock status indicators were relatively insensitive to the treatment of these data.
4. Fishing mortality for adult and juvenile bigeye tuna is estimated to have increased continuously since the beginning of industrial tuna fishing. For the models with higher purse-seine catch and increasing longline catchability, estimates of recent juvenile fishing mortality are considerably higher than for the base-case, while the opposite is the situation for the PH/ID low catch option.
5. The ratios $B_t/B_{t,F=0}$ provide a time-series index of population depletion by the fisheries. Overall, depletion is estimated to have been rapid, particularly since the mid-1980s. While total

biomass has remained relatively stable since 1970, it appears to have been sustained by above average recruitment, particularly since 1995. The assessment indicates that recruitment may have returned to the long-term average level (although recent recruitment estimates have high uncertainty) and, if recruitment remains at that level, biomass would decline rapidly at current exploitation rates. The current level of biomass is 20–26% of the unexploited level ($B_{current}/B_{current,F=0}$ = 0.20–0.28) with higher depletion estimated from the model with increasing longline catchability. Depletion is more extreme for some individual model regions, notably region 1 (recent $B_t/B_{t,F=0}$ ratios around 0.25 in the base-case model) region 3 (0.20) and region 4 (0.25). Other regions are less depleted, with recent $B_t/B_{t,F=0}$ ratios of around 0.4 or greater.

6. The attribution of depletion to various fisheries or groups of fisheries indicates that the longline fishery has the greatest impact throughout the model domain. The purse seine and Philippines/Indonesian domestic fisheries also have substantial impact in region 3 and to a lesser extent in region 4. The Japanese coastal pole-and-line and purse-seine fisheries are also having a significant impact in their home region (region 1). For the sensitivity analysis with higher purse seine catch, the longline and purse seine fisheries are estimated to have approximately equal impact on total biomass.

7. The reference points that predict the status of the stock under equilibrium conditions are $\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$ and $S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$. For the base-case model, these ratios are 0.68 and 0.55, respectively, indicating that the long-term average biomass would fall below that capable of producing *MSY* at 2003–2006 average fishing mortality. For most of the analyses, current total biomass exceeds the biomass yielding *MSY* ($B_{current}/\tilde{B}_{MSY}$ > 1.0), with a high probability in the base-case assessment. On that basis, the bigeye stock in the WCPO is not in an overfished state due to above average recruitment. However, the situation is less optimistic with respect to adult biomass with $S\tilde{B}_{F_{current}}/S\tilde{B}_{MSY}$ approaching or being below 1.0 for the principal analyses.

8. The estimate of $F_{current}/\tilde{F}_{MSY}$ reveals that **overfishing of bigeye is occurring in the WCPO** with high probability. While the stock is not yet in an overfished state with respect to total biomass ($B_{current}/\tilde{B}_{MSY}$ > 1), the situation is less optimistic with respect to adult biomass and a number of plausible model options indicate that adult biomass has been below the $S\tilde{B}_{MSY}$ level for a considerable period ($SB_{current}/S\tilde{B}_{MSY}$ < 1). Further, both the adult and total biomass are predicted to become over-fished at 2003–2006 levels of fishing mortality and long-term average levels of recruitment. For the base-case, there is also a significant probability (42.8%) that $SB_{2006}/S\tilde{B}_{MSY}$ is less than 1.0. This is consistent with a recent decline in biomass under increasing levels of fishing mortality resulting in an increase in the probability of the stock becoming overfished over time.

9. For both the fishing mortality and biomass based reference points, the stock status is considerably more pessimistic for the scenarios with increasing longline catchability or steepness of the SRR at a moderate level. Both of these scenarios are considered plausible alternative to the base-case assessment and indicate the adult component of the stock is in an overfished state ($SB_{current}/S\tilde{B}_{MSY}$ < 1).

10. Stock projections, using the base-case model, indicate significant reductions in fishery-specific effort are required to reduce fishing mortality below the F_{MSY} level. The target level of fishing mortality can be achieved via numerous configurations of fishery-specific effort; however, largest changes in the performance measure occur from changes in the multiplier applied to the longline fishing effort. This reflects the relatively high proportion of the total level of current fishing mortality attributable to this method throughout the WCPO. Significant reduction in fishing effort

from at least one specific gear type is required to achieve F/F_{MSY} and larger reductions in some fisheries are required for scenarios that model an expansion of one of the other fisheries.

8 Acknowledgements

We are grateful to all fisheries agencies that have contributed data to the SPC and/or the WCPFC for this assessment. We also acknowledge the assistance of Peter Williams (SPC), Hiroaki Okamoto and Naozumi Miyabe (NRIFSF) in the compilation of the various data sets. We thank participants at the preparatory stock assessment workshop (Noumea, February 2008) for their contribution to the assessment.

9 References

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

Fournier, D.A., Hampton, J., and Sibert, J.R. 1998. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, *Thunnus alalunga*. *Can. J. Fish. Aquat. Sci.* **55**: 2105–2116.

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

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

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

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

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

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

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

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

Hampton, J., Langley, A., Harley, S., Kleiber, P., Takeuchi, Y., and Ichinokawa, M. 2005. Estimates of sustainable catch and effort levels for target species and the impacts on stocks of potential management measures. WCPFC-SC1 SA WP-10, Noumea, New Caledonia, 8–19 August 2005.

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

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

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

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

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

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

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

Kleiber, P., Hampton, J., and Fournier, D.A. 2003. MULTIFAN-CL Users' Guide. http://www.multifan-cl.org/userguide.pdf.

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

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

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

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

Langley A., Hampton J. 2006. Management options for yellowfin and bigeye tuna in the WCPO fishery. Pacific Economic Bulletin Volume 21 Number 3.

Langley, A., Hampton, J., Kleiber, P., Hoyle, S. 2007. Stock assessment of yellowfin tuna in the western and central Pacific Ocean, including an analysis of management options. WCPFC SC3 SA WP-1, Honolulu, Hawaii, 13–24 August 2007.

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

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

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

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

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

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

McAllister, M.K.; Ianelli, J.N. 1997. Bayesian stock assessment using catch-at-age data and the sampling-importance resampling algorithm. Can. J. Fish. Aquat. Sci. 54: 284-300.

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

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

Methot, R. D. 2005. Technical Description of the Stock Synthesis II Assessment Program Version 1.17, March 2005. Fisheries, N.O.A.A.

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

Ward, P. 2008. Empirical estimates of historical variations in the catchability and fishing power of pelagic longline fishing gear. Rev. Fish. Biol Fisheries on line.

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

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

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

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

Category	Assumptions	Estimated parameters (ln = log transformed parameter)	No.	Prior		Bounds	
				μ	σ	Low	High
Observation model for total catch data	Observation errors small, equivalent to a residual SD on the log scale of 0.07.	None	na	na	na	na	na
Observation model for length-frequency data	Normal probability distribution of frequencies with variance determined by effective sample size and observed frequency. Effective sample size assumed to be 0.02 times actual sample size for all fisheries with a maximum effective sample size of 20.	None	na	na	na	na	na
Observation model for weight-frequency data	Normal probability distribution of frequencies with variance determined by effective sample size and observed frequency. Effective sample size assumed to be 0.02 times actual sample size for all fisheries with a maximum effective sample size of 20.	None	na	na	na	na	na
Observation model for tagging data	Tag numbers in a stratum have negative binomial probability distribution, with estimated variance parameters for fishery groups.	Variance parameters	3	-	-	0	100
Tag reporting	Purse seine reporting rates constrained to be equal within regions. PH /ID fishery reporting rates constrained to be equal. All reporting rates constant over time.	LL 1–6, CH/TW LL, PNG LL, PI LL, LL BMK 3, PL 3, PL JP 1, PS JP 1	13	0.5	0.7	0.001	0.9
		AU LL, HW LL, HW HL	4	0.8	0.7	0.001	0.9
		PS	2	0.42	0.1	0.001	0.9
		PH, ID fisheries	3	0.6	0.1	0.001	0.9
Tag mixing	Tags assumed to be randomly mixed at the model region level two quarters following the quarter of release.	None	na	na	na	na	na
Recruitment	Occurs as discrete events at the start of each quarter. Spatially-aggregated recruitment is weakly related to spawning biomass in the prior quarter via a Beverton-Holt SRR (beta prior for steepness with mode at 0.85 and SD of 0.16, lower bound 0.2) .The spatial distribution of recruitment in each quarter is allowed to vary with a small penalty on deviations from the average spatial distribution.	Average spatially aggregated recruitment (ln)	1	-	-	-20	20
		Spatially aggregated recruitment deviations (ln)	224	SRR	0.7	-20	20
		Average spatial distribution of recruitment	5	-	-	0	1
		Time series deviations from average spatial distribution (ln)	1,110	0	1	-3	3

Initial population	A function of the initial recruitment and equilibrium age structure in each region, which is in turn assumed to arise from the total mortality estimated for 1952–56 and movement rates.	Initial recruitment scaling (ln)	1	-	-	-8	8
Age and growth	40 quarterly age-classes, with the last representing a plus group. Juvenile age-classes 1-8 have independent mean lengths constrained by a small penalty for deviation from the von Bertalanffy growth curve; adult age-class mean lengths constrained by VB curve. SD of length-at-age are log-linearly related to the mean length-at-age. Mean weights (W_j) computed internally by estimating the distribution of weight-at-age from the distribution of length-at-age and applying the weight-length relationship $W = aL^b$ (*a*=0.000019729, *b*=3.0247 independently estimated from available length-weight data, source N. Miyabe, NRIFSF).	Mean length age class 1	1	-	-	20	40
		Mean length age class 40	1	-	-	140	200
		von Bertalanffy *K*	1	-	-	0	0.3
		Independent mean lengths	7	0	0.7		
		Length-at-age SD	1	-	-	3	10
		Dependency on mean length (ln)	1	-	-	-1.00	1.00
Selectivity	Constant over time. Coefficients for the last 4 age-classes are constrained to be equal. Longline fisheries LL ALL 1–2 and LL ALL 3–6 share selectivity parameters. Purse-seine fisheries share selectivity among regions. For all fisheries, selectivity parameterised with 5-node cubic spline, except Taiwanese/Chinese longline selectivities with logistic function (non decreasing with age).	Selectivity coefficients (5 cubic spline nodes or 2 logistic parameters per fishery)	82	-	-	0	1
Catchability	Constant over years and among regions for longline fisheries (effort data are scaled to reflect different region sizes). Seasonal variation for all fisheries apart from Philippines and Indonesian fisheries. Non-longline fisheries and the Australian and Taiwanese/Chinese longline fisheries have structural time-series variation, with random steps (catchability deviations) taken every 2 years.	Average catchability coefficients (ln)	20	-	-	-15	1
		Seasonality amplitude (ln)	22	0	2.2	-	-
		Seasonality phase	22	-	-	-	-
		Catchability deviations PH/ID (ln)	54	0	0.7	-0.8	0.8
		Catchability deviations other (ln)	231	0	0.1	-0.8	0.8
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.1 for LL ALL 1–6 and SD 0.22 for other fisheries at the average level of effort for each fishery. SD inversely proportional to the square root of effort.	Effort deviations LL 1, 2, 4, 7, 10, 12 (ln)	1,310	0	0.16	-6	6
		Effort deviations PH, ID (ln)	444	0	0.22	-6	6
		Effort deviations other (ln)	1,799	0	0.22	-6	6
Natural mortality	Age-dependent but constant over time and among regions.	Average natural mortality (ln)	0	-	-	-	-
		Age-specific deviations (ln)	0	0	0.22	-5	5
Movement	Age-independent and variant by quarter but constant among years. No age-dependent variation.	Movement coefficients	56	0	0.32	0	3
		Age-dependent component (ln)	0	0	0.32	-4	4
Maturity	Age-dependent and specified – age-class 0-10: 0; 11: 0.05; 12: 0.1; 13: 0.2; 14: 0.4; 15: 0.6; 16: 0.7; 17: 0.8; 18: 0.85; 19: 0.9; 20: 0.95; 21-40: 1	None	na	na	na	0	1

Table 3. Summary of the principal model runs undertaken.

Run	Description	Size data configuration	Size data weighting
1	2006 model fisheries structure + additional and revised data (2 years).	As per 2006	n/20
2	As per 1 and split ID and PH dom.	As per 2006	n/20
3	As per 2. and split LL 3 (separate PNG and remainder of LL3).	As per 2006	n/20
4 (base case)	As per 3. and include JP coastal PL, PS and equatorial PL fisheries.	As per 2006	n/20
6	As per 4 and with change to JP LL size data compilation.	Reweighting scheme, 70% catch threshold.	n/20, n=total measured.
8	As per 4 and determine effective sample size for JP LL data based on representativeness of sampling.	As per 2006	n/20; for Jp LL n=1000 * proportion of catch covered by sampling
9	As per 4 and use iterative reweighting to determine effective sample size for JP LL data. Iterative reweighting by decade.	As per 2006	n/20; for Jp LL n=1000 * proportion of catch covered by sampling; iterative reweighting of JP LL by fishery/decade.

Table 4. Summary of the sensitivity analyses undertaken.

Run	Description	Details
S1	Low PH domestic catch – lower bound of probable recent/historic PH catch.	50% of base PH catch (see Figure 11).
S2	High PH domestic catch – upper bound of probable recent/historic PH catch.	150% of base catch (see Figure 11).
S3	Low ID domestic catch – lower bound of probable recent/historic ID catch.	50% of base catch (see Figure 11).
S4	High ID domestic catch – upper bound of probable recent/historic ID catch.	150% of base catch (see Figure 11).
S5	Low ID and low PH (S1 and S3).	50% of base catch (see Figure 11).
S6	High ID and high PH (S2 and S4).	150% of base catch (see Figure 11).
S7a	Increasing JP LL catchability.	Increase catchability for all JP LL fisheries; 1% pa over the entire period (see Figure 12).
S7b	Increasing JP LL catchability.	Increase catchability for all JP LL fisheries; pre 1985 0.5% pa, post 1985 2% pa (see Figure 12).
S8	JP LL Selectivity pre/post 1975.	Estimate separate selectivities/catchabilities for JP LL 3 fishery pre- and post 1975. Link post 1975 q to q's from other regions.
S9	Natural mortality – higher for young age classes.	Increase initial (age 1) M from 0.2 to 0.4, linear decline to age 5 (0.1) (see Figure 10).
S10	Natural mortality – reduce for older age classes.	Reduce M to 0.05 for all age classes > 12 quarters (see Figure 10).
S11	Steepness – lower (0.75) value of steepness than estimated (0.95).	
S12	Low movement between regions.	Fix movement to be low (<<1%) between all regions.
S13	Regional recruitment deviates not estimated (i.e. zero).	
seapodymM	Natural mortality - relative values of M-at-age from Seapodym (Lehody unpublished data). Scale value of M estimated (see Figure 10).	
downwtTWCN	Very low (n/10000) effective sample sizes for TWCN LL size data in regions 3 and 4.	
ps-revised	Alternative catch history for equatorial purse-seine fisheries with catch increased by 100% from 1980 onwards (see Figure 13).	

Table 5. Details of objective function components for the selected model runs.

Objective function component	Base-case (run4)	Steepness =0.75 (s11)	LL incr.q (s7b)	PS revised catch (doubled)	Low ID/PH (halved) (s5)
Total catch log-likelihood	646.95	646.64	636.55	665.25	647.86
Length frequency log-likelihood	-403,620.72	-403,632.54	-403,527.24	-403,592.30	-403,689.65
Weight frequency log-likelihood	-852,178.37	-852,164.85	-852,198.43	-852,171.16	-852,198.02
Tag log-likelihood	1,524.40	1,528.11	1,516.53	1,512.16	1,527.90
Penalties	7,452.22	7,450.49	7,448.64	7,592.49	7,427.16
Total function value	-1,246,175.52	-1,246,172.15	-1,246,123.95	-1,245,993.56	-1,246,284.75

Table 6. Description of symbols used in the yield analysis.

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2003–2006
F_{year}	Average fishing mortality-at-age in specified year
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (*MSY*)
$\tilde{Y}_{F_{current}}$	Equilibrium yield at $F_{current}$
$\tilde{Y}_{F_{MSY}}$ (or *MSY*)	Equilibrium yield at F_{MSY}, or maximum sustainable yield
$\tilde{B}_0$	Equilibrium unexploited total biomass
$\tilde{B}_{F_{current}}$	Equilibrium total biomass at $F_{current}$
$\tilde{B}_{MSY}$	Equilibrium total biomass at MSY
$S\tilde{B}_0$	Equilibrium unexploited adult biomass
$S\tilde{B}_{F_{current}}$	Equilibrium adult biomass at $F_{current}$
$S\tilde{B}_{MSY}$	Equilibrium adult biomass at MSY
$B_{current}$	Average current (2003–2006) total biomass
$SB_{current}$	Average current (2003–2006) adult biomass
B_{year}	Total biomass in specified year
SB_{year}	Adult biomass in specified year
$B_{current,F=0}$	Average current (2003–2006) total biomass in the absence of fishing.

Table 7. Estimates of management quantities for the selected stock assessment models. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading).

Management quantity	Units	Base-case (run4)	h=0.75 (s11)	LL incr.q (s7b)	PS revised catch	Low ID/PH (s5)
$\tilde{Y}_{F_{current}}$	mt per year	60,880	28,412	54,000	57,160	60,920
$\tilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	64,600	56,800	65,200	65,520	63,040
$\tilde{B}_0$	mt	755,327	825,900	869,700	842,400	690,600
$\tilde{B}_{F_{current}}$	mt	167,900	81,110	125,900	141,800	173,600
$\tilde{B}_{MSY}$	mt	249,600	321,900	282,800	272,600	231,400
$\tilde{SB}_0$	mt	488,924	533,000	561,800	544,000	446,000
$\tilde{SB}_{F_{current}}$	mt	54,900	27,130	37,800	44,970	56,990
$\tilde{SB}_{MSY}$	mt	100,600	154,500	125,000	118,500	90,880
$B_{current}$	mt	339,047	351,835	287,575	361,850	308,427
$SB_{current}$	mt	120,134	127,770	95,369	126,293	109,243
$B_{current,F=0}$	mt	1,270,652	1,260,504	1,399,944	1,711,661	1,086,108
$B_{current}/\tilde{B}_0$		0.45	0.42	0.33	0.43	0.44
$B_{current}/\tilde{B}_{F_{current}}$		2.00	4.30	2.27	2.53	1.76
$B_{current}/\tilde{B}_{MSY}$		1.37	1.09	1.02	1.33	1.33
$B_{current}/B_{current,F=0}$		0.26	0.28	0.20	0.21	0.28
$SB_{current}/\tilde{SB}_0$		0.25	0.24	0.17	0.23	0.24
$SB_{current}/\tilde{SB}_{F_{current}}$		2.19	4.71	2.52	2.81	1.92
$SB_{current}/\tilde{SB}_{MSY}$		1.19	0.83	0.76	1.07	1.20
$SB_{2006}/\tilde{SB}_{MSY}$		1.07	0.74	0.67	0.95	1.08
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.22	0.10	0.14	0.17	0.25
$\tilde{SB}_{F_{current}}/\tilde{SB}_0$		0.11	0.05	0.07	0.08	0.13
$\tilde{B}_{MSY}/\tilde{B}_0$		0.33	0.39	0.33	0.32	0.34
$\tilde{SB}_{MSY}/\tilde{SB}_0$		0.21	0.29	0.22	0.22	0.20
$F_{current}/\tilde{F}_{MSY}$		1.44	2.09	1.88	1.68	1.33
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		0.68	0.25	0.45	0.52	0.75
$\tilde{SB}_{F_{current}}/\tilde{SB}_{MSY}$		0.55	0.18	0.30	0.38	0.63
$\tilde{Y}_{F_{current}}/MSY$		0.94	0.50	0.83	0.87	0.97
$B_{current}/B_{1995}$		0.95	0.95	0.82	0.95	0.93
$SB_{current}/SB_{1995}$		0.79	0.80	0.60	0.78	0.79

Table 8. Probabilities of (a) $B_t / \widetilde{B}_{MSY}$ and (b) $SB_t / \widetilde{SB}_{MSY}$ being less than the reference level (1.0 corresponds to biomass at *MSY*) and probabilities of (c) $F_t / \widetilde{F}_{MSY}$ exceeding the reference level (1.0 corresponds to *F* at *MSY*) based on the likelihood profile of the base-case analysis. Probabilities are given for biomass and fishing mortality rations computed for 2003-2006 (current), and 2003, 2004, 2005 and 2006 individually. Probabilities greater than 0.2 are highlighted.

(a) $B_t / \widetilde{B}_{MSY}$

Reference level (*x*)	Probability				
	$\frac{B_{current}}{\widetilde{B}_{MSY}} < x$	$\frac{B_{2003}}{\widetilde{B}_{MSY}} < x$	$\frac{B_{2004}}{\widetilde{B}_{MSY}} < x$	$\frac{B_{2005}}{\widetilde{B}_{MSY}} < x$	$\frac{B_{2006}}{\widetilde{B}_{MSY}} < x$
0.5	0.00	0.01	0.00	0.00	0.00
0.6	0.00	0.01	0.00	0.00	0.00
0.7	0.00	0.01	0.00	0.00	0.00
0.8	0.00	0.01	0.00	0.00	0.00
0.9	0.00	0.01	0.00	0.00	0.00
1.0	0.00	0.01	0.00	0.00	0.04
1.1	0.01	0.01	0.02	0.03	0.22
1.2	0.09	0.01	0.10	0.17	0.61
1.3	0.34	0.09	0.34	0.50	0.92
1.4	0.70	0.31	0.70	0.84	0.99
1.5	0.93	0.63	0.93	0.98	1.00
1.6	0.99	0.89	0.99	1.00	1.00
1.7	1.00	0.98	1.00	1.00	1.00
1.8	1.00	1.00	1.00	1.00	1.00
1.9	1.00	1.00	1.00	1.00	1.00
2.0	1.00	1.00	1.00	1.00	1.00

(b) $SB_t / \widetilde{SB}_{MSY}$

Reference level (*x*)	Probability				
	$\frac{SB_{current}}{\widetilde{SB}_{MSY}} < x$	$\frac{SB_{2003}}{\widetilde{SB}_{MSY}} < x$	$\frac{SB_{2004}}{\widetilde{SB}_{MSY}} < x$	$\frac{SB_{2005}}{\widetilde{SB}_{MSY}} < x$	$\frac{SB_{2006}}{\widetilde{SB}_{MSY}} < x$
0.5	0.00	0.00	0.00	0.00	0.00
0.6	0.00	0.00	0.00	0.00	0.00
0.7	0.00	0.00	0.00	0.00	0.00
0.8	0.00	0.00	0.00	0.00	0.03
0.9	0.03	0.03	0.00	0.02	0.15
1.0	0.13	0.11	0.03	0.10	0.43
1.1	0.32	0.28	0.11	0.27	0.75
1.2	0.60	0.53	0.28	0.54	0.93
1.3	0.84	0.78	0.52	0.79	0.99
1.4	0.96	0.93	0.76	0.94	1.00
1.5	1.00	0.99	0.92	0.99	1.00
1.6	1.00	1.00	0.98	1.00	1.00
1.7	1.00	1.00	1.00	1.00	1.00
1.8	1.00	1.00	1.00	1.00	1.00
1.9	1.00	1.00	1.00	1.00	1.00
2.0	1.00	1.00	1.00	1.00	1.00

Table 8. Continued.

(c) F_t / F_{MSY}

Reference level (x)	Probability				
	$\frac{F_{current}}{\tilde{F}_{MSY}} > x$	$\frac{F_{2003}}{\tilde{F}_{MSY}} > x$	$\frac{F_{2004}}{\tilde{F}_{MSY}} > x$	$\frac{F_{2005}}{\tilde{F}_{MSY}} > x$	$\frac{F_{2006}}{\tilde{F}_{MSY}} > x$
0.5	1.00	1.00	1.00	1.00	1.00
0.6	1.00	1.00	1.00	1.00	1.00
0.7	1.00	1.00	1.00	1.00	1.00
0.8	1.00	1.00	1.00	1.00	1.00
0.9	1.00	0.99	1.00	1.00	1.00
1.0	1.00	0.80	1.00	1.00	1.00
1.1	1.00	0.47	1.00	1.00	1.00
1.2	1.00	0.23	1.00	1.00	0.99
1.3	0.95	0.10	1.00	1.00	0.96
1.4	0.76	0.03	1.00	0.96	0.82
1.5	0.51	0.01	0.94	0.82	0.61
1.6	0.30	0.00	0.77	0.59	0.40
1.7	0.17	0.00	0.55	0.38	0.24
1.8	0.08	0.00	0.36	0.22	0.13
1.9	0.05	0.00	0.21	0.12	0.07
2.0	0.02	0.00	0.12	0.06	0.04

Table 9. Fishing effort scalars relative to the 2003-2006 average required to produce equilibrium total biomass at various levels above B_{MSY}.

Equilibrium biomass relative to B_{MSY}	**Equilibrium biomass relative to $\tilde{B}_0$**	**Fishing Effort Scalar relative to 2001-2004 average**
1.00	0.33	0.69
1.05	0.35	0.66
1.10	0.36	0.62
1.15	0.38	0.59
1.20	0.40	0.56
1.25	0.41	0.53
1.30	0.43	0.51
1.35	0.45	0.48
1.40	0.46	0.46

Table 10. MSY based performance measures from the principal model runs and sensitivity analyses.

Run	$B_{current}$	B_{MSY}	*MSY*	Fmult	F/F_{MSY}	B/B_{MSY}	Obj. Fnt value	npars	gradient
1	323,866	240,800	63,840	0.68	1.46	1.34	1,138,187	4732	0.00021
2	336,332	243,700	64,240	0.71	1.40	1.38	1,137,778	4900	0.00067
3	336,201	249,000	64,320	0.70	1.43	1.35	1,219,795	5155	0.00080
4	339,047	249,600	64,600	0.69	1.44	1.36	1,246,176	5643	0.00008
6	395,054	282,300	73,840	0.81	1.23	1.40	767,337	5643	0.00044
8	396,167	281,200	72,120	0.80	1.25	1.41	1,102,289	5643	0.00095
9	403,669	288,100	74,000	0.81	1.23	1.40	1,008,462	5643	0.00087
S1	333,734	245,400	65,120	0.73	1.36	1.36	1,246,213	5643	0.01260
S2	313,806	254,300	57,080	0.54	1.85	1.23	1,246,146	5642	0.00090
S3	324,345	239,700	64,440	0.74	1.35	1.35	1,246,242	5643	0.00082
S4	311,299	250,200	56,320	0.53	1.88	1.24	1,246,133	5643	0.00054
S5	308,427	231,400	63,040	0.75	1.33	1.33	1,246,285	5643	0.00054
S6	312,240	255,800	55,760	0.50	1.99	1.22	1,246,113	5643	0.00077
S7a	301,807	279,400	65,520	0.56	1.77	1.08	1,246,143	5643	0.00037
S7b	287,575	282,800	65,200	0.53	1.88	1.02	1,246,124	5643	0.00049
S8	329,912	241,800	64,640	0.69	1.44	1.36	1,246,339	5652	0.00074
S9	342,601	247,600	65,880	0.72	1.39	1.38	1,246,140	5643	0.00024
S10	283,868	334,400	55,400	0.39	2.55	0.85	1,246,074	5643	0.00059
S11	351,835	321,900	56,800	0.48	2.09	1.09	1,246,172	5641	0.00096
S12	384,420	274,900	69,840	0.77	1.30	1.40	1,245,642	5587	0.90028
S13	489,398	334,600	83,920	1.03	0.97	1.46	1,243,473	4305	0.00050
seapodymM	286,718	264,300	61,840	0.55	1.82	1.08	1,246,009	5644	0.01782
downwtTWCN	359,132	261,700	66,400	0.75	1.33	1.37	1,153,778	5643	0.00086
ps-revised	361,850	272,600	65,520	0.60	1.68	1.33	1,245,994	5642	0.00091

Table 11. Predicted total fishing mortality relative to fishing mortality at MSY (F/F_{MSY}) for multiples of Indonesian/Philippines (each table), longline (rows), and purse-seine associated set (columns) fishing effort relative to a base-line fishing effort (see text for details). The shaded area of each table indicates scenarios that result in over-fishing (i.e. F/F_{MSY} **> 1)**.

PH/ID 0.7

		PS associated						
		0.7	0.8	0.9	1.0	1.1	1.2	1.3
Longline	0.7	0.81	0.83	0.85	0.87	0.89	0.91	0.92
	0.8	0.87	0.89	0.91	0.93	0.95	0.97	0.99
	0.9	0.93	0.95	0.97	0.99	1.01	1.03	1.05
	1.0	0.99	1.01	1.03	1.05	1.07	1.09	1.11
	1.1	1.05	1.07	1.09	1.11	1.13	1.15	1.17
	1.2	1.10	1.12	1.15	1.17	1.19	1.21	1.22
	1.3	1.16	1.18	1.20	1.22	1.24	1.26	1.28

PH/ID 0.8

		PS associated						
		0.7	0.8	0.9	1.0	1.1	1.2	1.3
Longline	0.7	0.84	0.85	0.87	0.89	0.91	0.93	0.94
	0.8	0.90	0.92	0.94	0.95	0.97	0.99	1.01
	0.9	0.96	0.98	1.00	1.01	1.03	1.05	1.07
	1.0	1.01	1.03	1.05	1.07	1.09	1.11	1.13
	1.1	1.07	1.09	1.11	1.13	1.15	1.17	1.19
	1.2	1.13	1.15	1.17	1.19	1.21	1.23	1.24
	1.3	1.18	1.20	1.22	1.24	1.26	1.28	1.30

PH/ID 0.9

		PS associated						
		0.7	0.8	0.9	1.0	1.1	1.2	1.3
Longline	0.7	0.86	0.87	0.89	0.91	0.93	0.94	0.96
	0.8	0.92	0.94	0.95	0.97	0.99	1.01	1.02
	0.9	0.98	1.00	1.01	1.03	1.05	1.07	1.08
	1.0	1.04	1.05	1.07	1.09	1.11	1.13	1.14
	1.1	1.09	1.11	1.13	1.15	1.17	1.19	1.20
	1.2	1.15	1.17	1.19	1.21	1.23	1.24	1.26
	1.3	1.20	1.22	1.24	1.26	1.28	1.30	1.32

Table 11. Continued.

PH/ID **1.0**

		PS associated						
		0.7	0.8	0.9	1.0	1.1	1.2	1.3
Longline	0.7	0.87	0.89	0.91	0.92	0.94	0.96	0.97
	0.8	0.94	0.95	0.97	0.99	1.00	1.02	1.04
	0.9	1.00	1.01	1.03	1.05	1.07	1.08	1.10
	1.0	1.05	1.07	1.09	1.11	1.13	1.14	1.16
	1.1	1.11	1.13	1.15	1.17	1.19	1.20	1.22
	1.2	1.17	1.19	1.21	1.22	1.24	1.26	1.28
	1.3	1.22	1.24	1.26	1.28	1.30	1.32	1.33

PH/ID **1.1**

		PS associated						
		0.7	0.8	0.9	1.0	1.1	1.2	1.3
Longline	0.7	0.89	0.91	0.92	0.94	0.96	0.97	0.99
	0.8	0.95	0.97	0.99	1.00	1.02	1.04	1.05
	0.9	1.01	1.03	1.05	1.07	1.08	1.10	1.11
	1.0	1.07	1.09	1.11	1.13	1.14	1.16	1.17
	1.1	1.13	1.15	1.17	1.18	1.20	1.22	1.23
	1.2	1.19	1.21	1.22	1.24	1.26	1.28	1.29
	1.3	1.24	1.26	1.28	1.30	1.32	1.33	1.35

PH/ID **1.2**

		PS associated						
		0.7	0.8	0.9	1.0	1.1	1.2	1.3
Longline	0.7	0.91	0.92	0.94	0.95	0.97	0.98	1.00
	0.8	0.97	0.99	1.00	1.02	1.03	1.05	1.06
	0.9	1.03	1.05	1.06	1.08	1.10	1.11	1.13
	1.0	1.09	1.11	1.12	1.14	1.16	1.17	1.19
	1.1	1.15	1.16	1.18	1.20	1.22	1.23	1.25
	1.2	1.20	1.22	1.24	1.26	1.27	1.29	1.31
	1.3	1.26	1.28	1.30	1.31	1.33	1.35	1.36

PH/ID **1.3**

		PS associated						
		0.7	0.8	0.9	1.0	1.1	1.2	1.3
Longline	0.7	0.92	0.94	0.95	0.97	0.98	1.00	1.01
	0.8	0.98	1.00	1.02	1.03	1.05	1.06	1.08
	0.9	1.04	1.06	1.08	1.09	1.11	1.12	1.14
	1.0	1.10	1.12	1.14	1.15	1.17	1.18	1.20
	1.1	1.16	1.18	1.20	1.21	1.23	1.24	1.26
	1.2	1.22	1.24	1.25	1.27	1.29	1.30	1.32
	1.3	1.28	1.29	1.31	1.33	1.34	1.36	1.38

Table 12. Predicted total biomass relative to total biomass at MSY (B/B_{MSY}) for multiples of Indonesian/Philippines (each table), longline (rows), and purse-seine associated set (columns) fishing effort relative to a base-line fishing effort (see text for details). The shaded area of each table indicates scenarios that result in an over-fished stock (i.e. B/B_{MSY} **< 1)**.

PH/ID 0.7

		PS associated						
		0.7	0.8	0.9	1.0	1.1	1.2	1.3
Longline	0.7	1.21	1.19	1.17	1.16	1.14	1.12	1.11
	0.8	1.14	1.12	1.11	1.09	1.07	1.05	1.04
	0.9	1.08	1.06	1.04	1.03	1.01	1.00	0.98
	1.0	1.03	1.01	0.99	0.97	0.96	0.94	0.93
	1.1	0.98	0.96	0.94	0.93	0.91	0.90	0.88
	1.2	0.93	0.92	0.90	0.88	0.87	0.86	0.84
	1.3	0.89	0.88	0.86	0.85	0.83	0.82	0.80

PH/ID 0.8

		PS associated						
		0.7	0.8	0.9	1.0	1.1	1.2	1.3
Longline	0.7	1.19	1.17	1.15	1.14	1.12	1.10	1.09
	0.8	1.12	1.10	1.09	1.07	1.05	1.04	1.02
	0.9	1.06	1.04	1.03	1.01	0.99	0.98	0.96
	1.0	1.01	0.99	0.97	0.96	0.94	0.93	0.91
	1.1	0.96	0.94	0.93	0.91	0.90	0.88	0.87
	1.2	0.92	0.90	0.88	0.87	0.86	0.84	0.83
	1.3	0.88	0.86	0.85	0.83	0.82	0.80	0.79

PH/ID 0.9

		PS associated						
		0.7	0.8	0.9	1.0	1.1	1.2	1.3
Longline	0.7	1.17	1.15	1.14	1.12	1.10	1.09	1.07
	0.8	1.10	1.08	1.07	1.05	1.04	1.02	1.01
	0.9	1.04	1.02	1.01	0.99	0.98	0.96	0.95
	1.0	0.99	0.97	0.96	0.94	0.93	0.91	0.90
	1.1	0.94	0.93	0.91	0.90	0.88	0.87	0.86
	1.2	0.90	0.88	0.87	0.86	0.84	0.83	0.82
	1.3	0.86	0.85	0.83	0.82	0.81	0.79	0.78

Table 12. Continued.

PH/ID **1.0**

Longline	PS associated 0.7	0.8	0.9	1.0	1.1	1.2	1.3
0.7	1.15	1.13	1.12	1.10	1.09	1.07	1.06
0.8	1.08	1.07	1.05	1.04	1.02	1.01	0.99
0.9	1.02	1.01	0.99	0.98	0.97	0.95	0.94
1.0	0.97	0.96	0.94	0.93	0.91	0.90	0.89
1.1	0.93	0.91	0.90	0.88	0.87	0.86	0.85
1.2	0.88	0.87	0.86	0.84	0.83	0.82	0.81
1.3	0.85	0.83	0.82	0.81	0.79	0.78	0.77

PH/ID **1.1**

Longline	PS associated 0.7	0.8	0.9	1.0	1.1	1.2	1.3
0.7	1.14	1.12	1.10	1.09	1.07	1.06	1.05
0.8	1.07	1.05	1.04	1.02	1.01	1.00	0.98
0.9	1.01	0.99	0.98	0.97	0.95	0.94	0.93
1.0	0.96	0.94	0.93	0.92	0.90	0.89	0.88
1.1	0.91	0.90	0.88	0.87	0.86	0.85	0.83
1.2	0.87	0.86	0.84	0.83	0.82	0.81	0.80
1.3	0.83	0.82	0.81	0.80	0.78	0.77	0.76

PH/ID **1.2**

Longline	PS associated 0.7	0.8	0.9	1.0	1.1	1.2	1.3
0.7	1.12	1.10	1.09	1.08	1.06	1.05	1.03
0.8	1.05	1.04	1.02	1.01	1.00	0.98	0.97
0.9	1.00	0.98	0.97	0.95	0.94	0.93	0.92
1.0	0.95	0.93	0.92	0.90	0.89	0.88	0.87
1.1	0.90	0.89	0.87	0.86	0.85	0.84	0.83
1.2	0.86	0.85	0.83	0.82	0.81	0.80	0.79
1.3	0.82	0.81	0.80	0.79	0.77	0.76	0.75

PH/ID **1.3**

Longline	PS associated 0.7	0.8	0.9	1.0	1.1	1.2	1.3
0.7	1.11	1.09	1.08	1.06	1.05	1.04	1.02
0.8	1.04	1.03	1.01	1.00	0.99	0.97	0.96
0.9	0.98	0.97	0.96	0.94	0.93	0.92	0.91
1.0	0.93	0.92	0.91	0.89	0.88	0.87	0.86
1.1	0.89	0.88	0.86	0.85	0.84	0.83	0.82
1.2	0.85	0.84	0.82	0.81	0.80	0.79	0.78
1.3	0.81	0.80	0.79	0.78	0.77	0.75	0.74

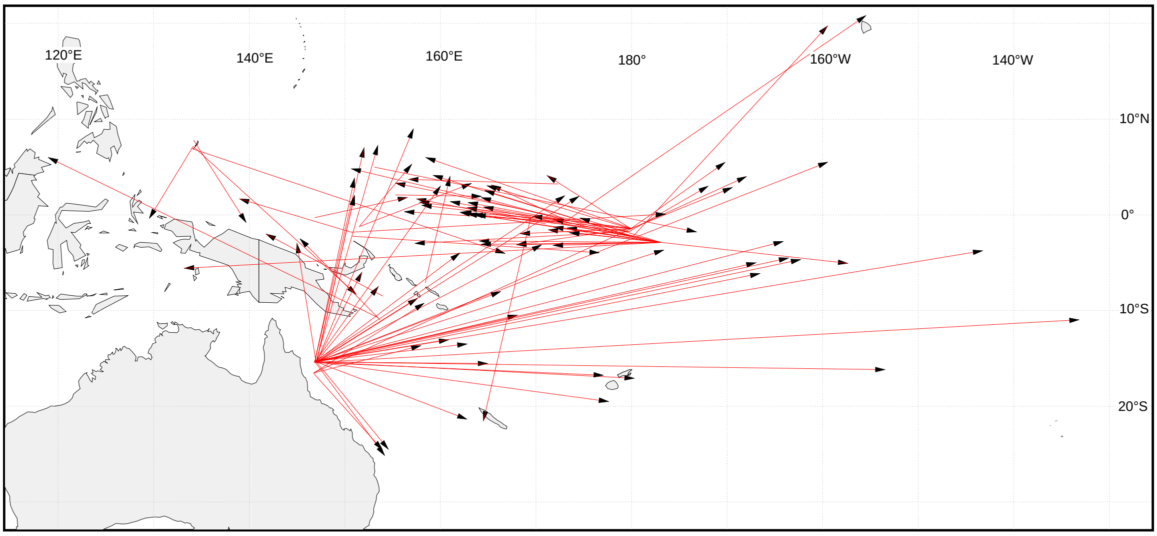


Figure 1. Long-distance (greater than 500 nmi) movements of tagged bigeye tuna.

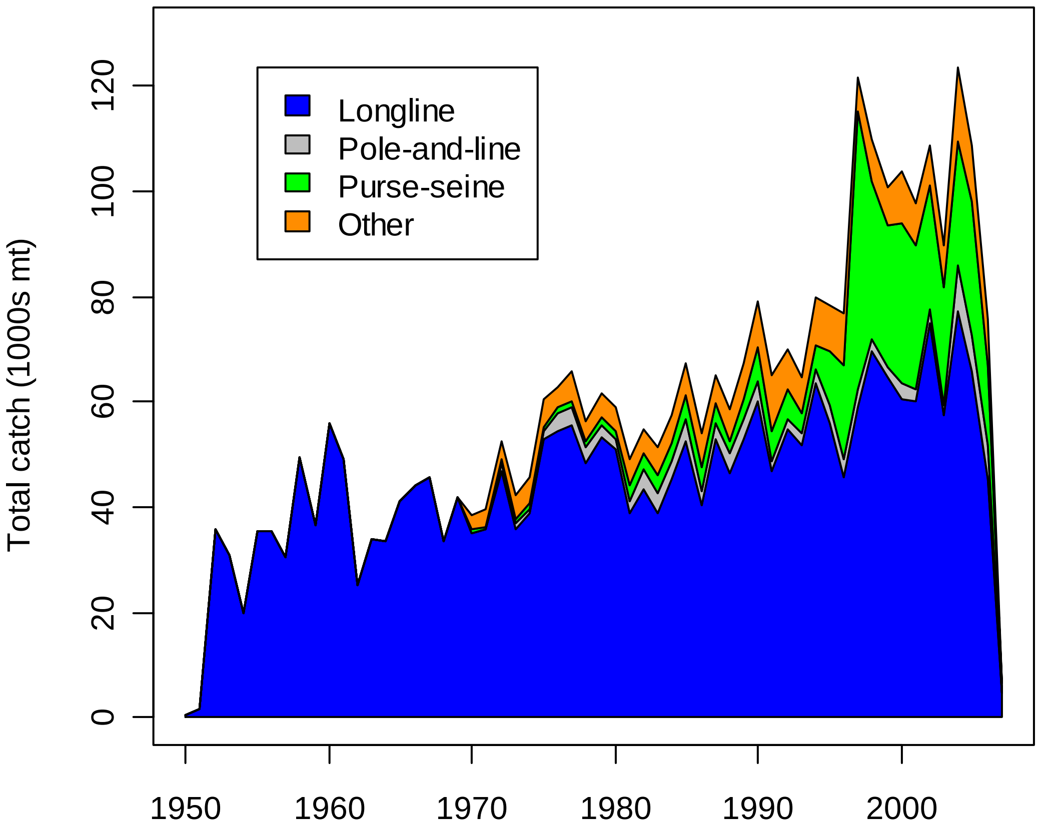


Figure 2. Total annual catch (1000s mt) of bigeye tuna from the WCPO by fishing method from 1952 to 2007. Data from 2007 are incomplete.

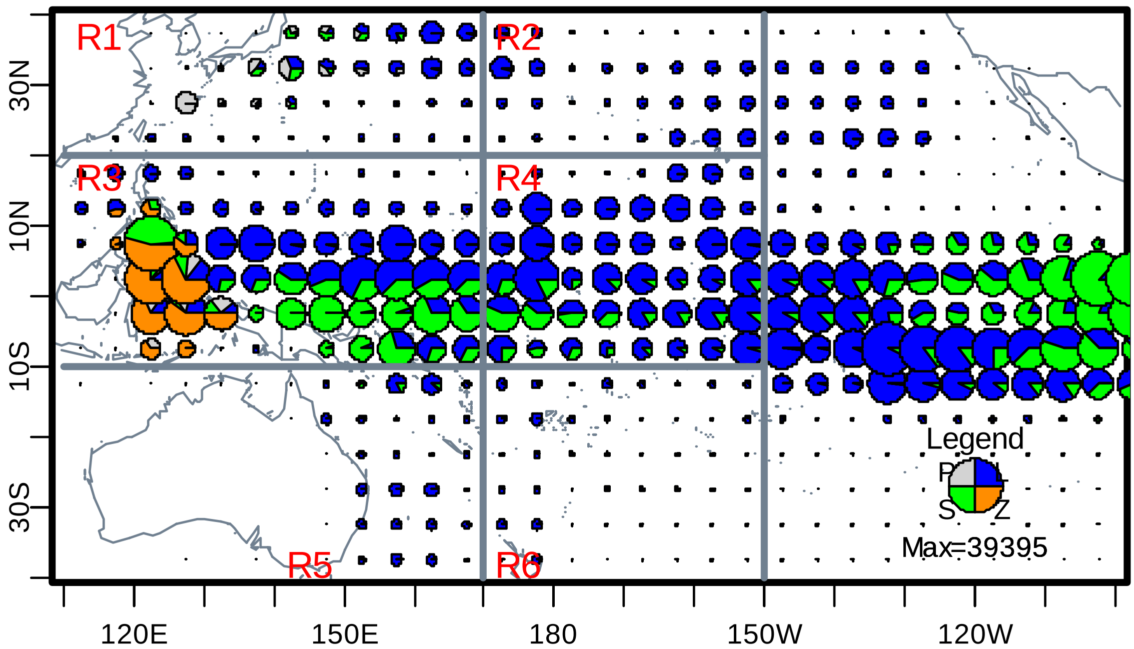


Figure 3. Distribution of cumulative bigeye tuna catch from 1990–2006 by 5 degree squares of latitude and longitude and fishing gear; longline (blue), purse-seine (green), pole-and-line (grey) and other (dark orange). The maximum circle size represents a catch of 40,000 mt. The grey lines indicate the spatial stratification of the six-region assessment model.

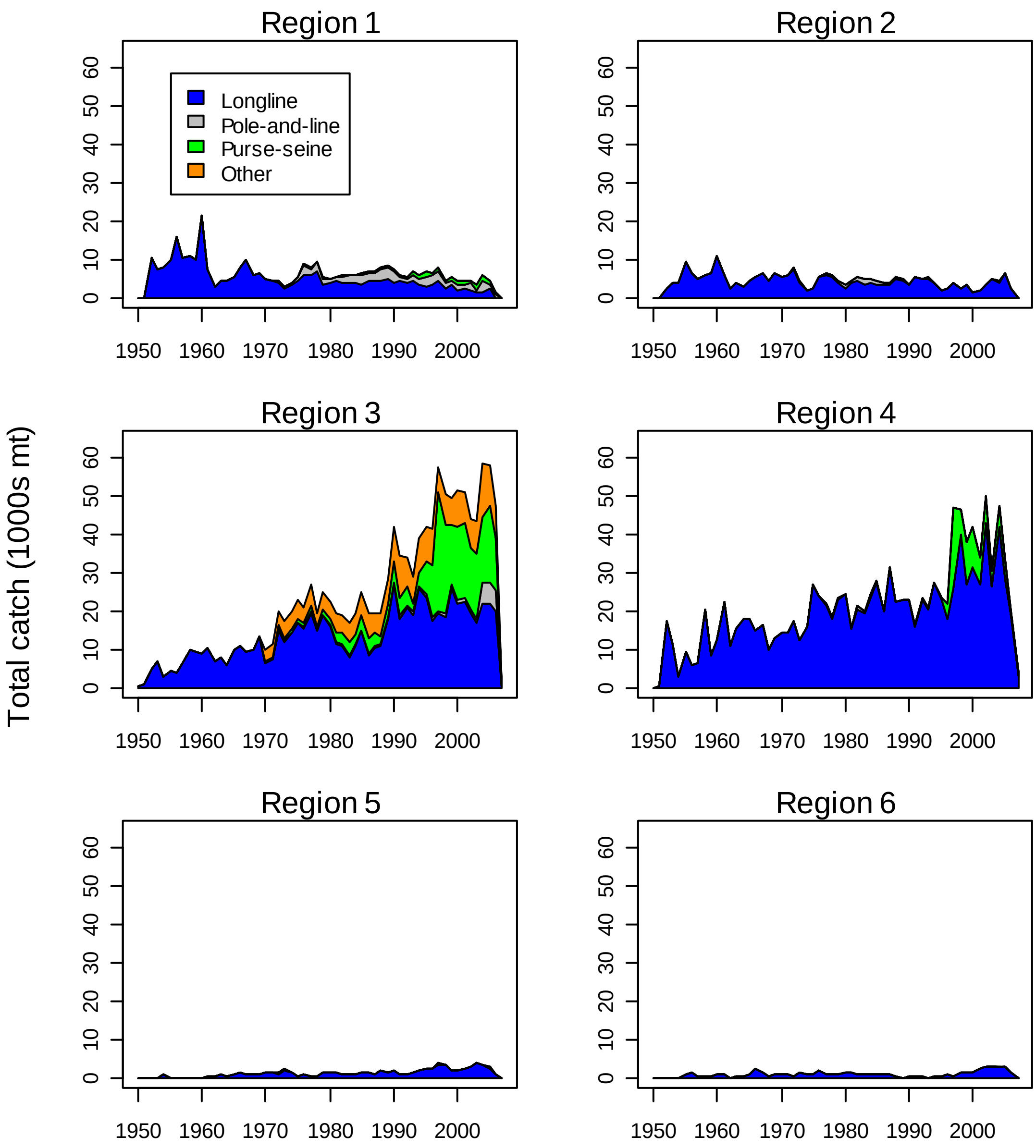


Figure 4. Total annual catch (1000s mt) of bigeye tuna by fishing method and MFCL region from 1952 to 2007. Data from 2007 are incomplete.

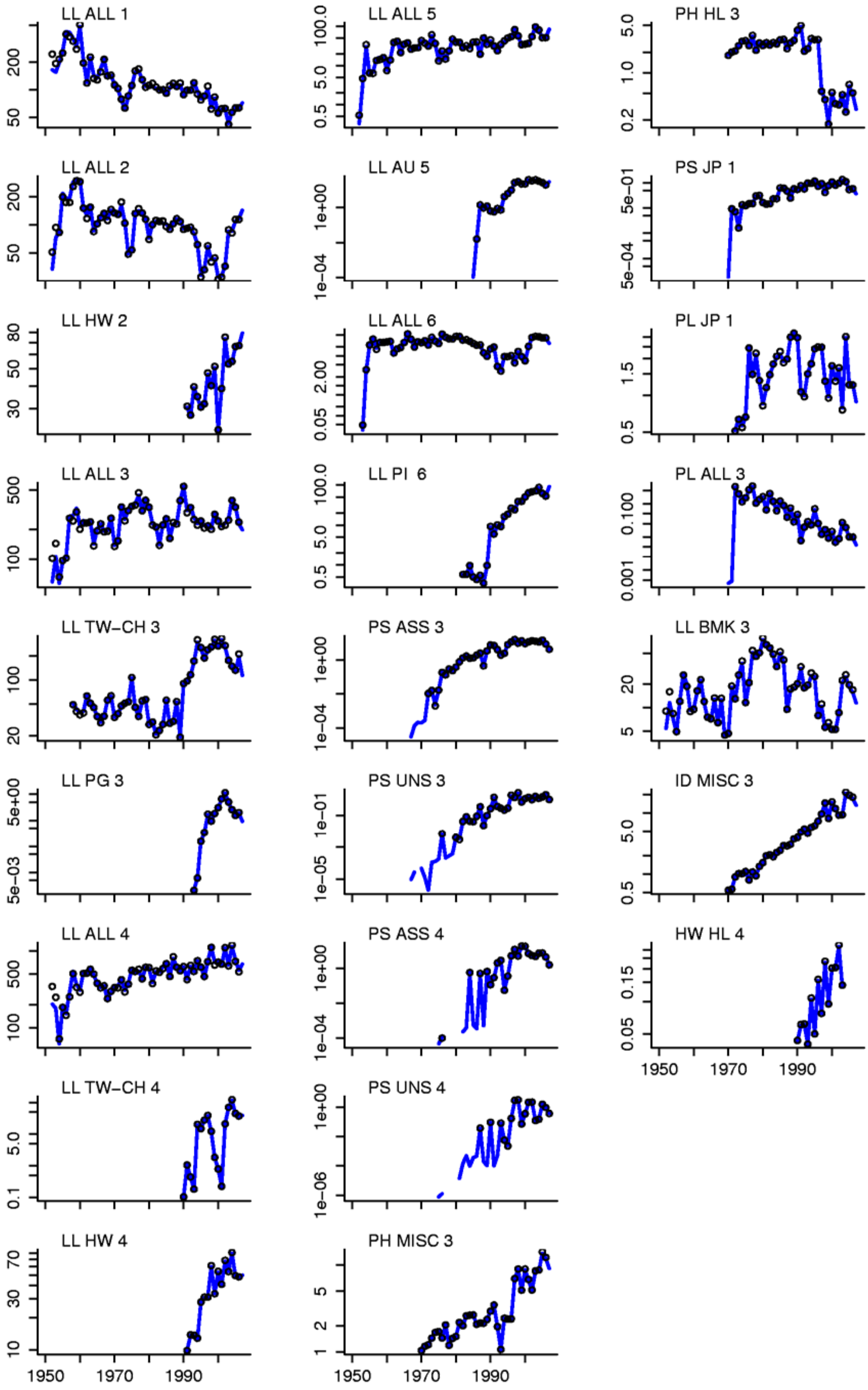


Figure 5. Annual catches by fishery. Circles are observed and the lines are model predictions. Units are catch number of fish (in thousands) for the longline fisheries and thousand metric tonnes for all other fisheries.

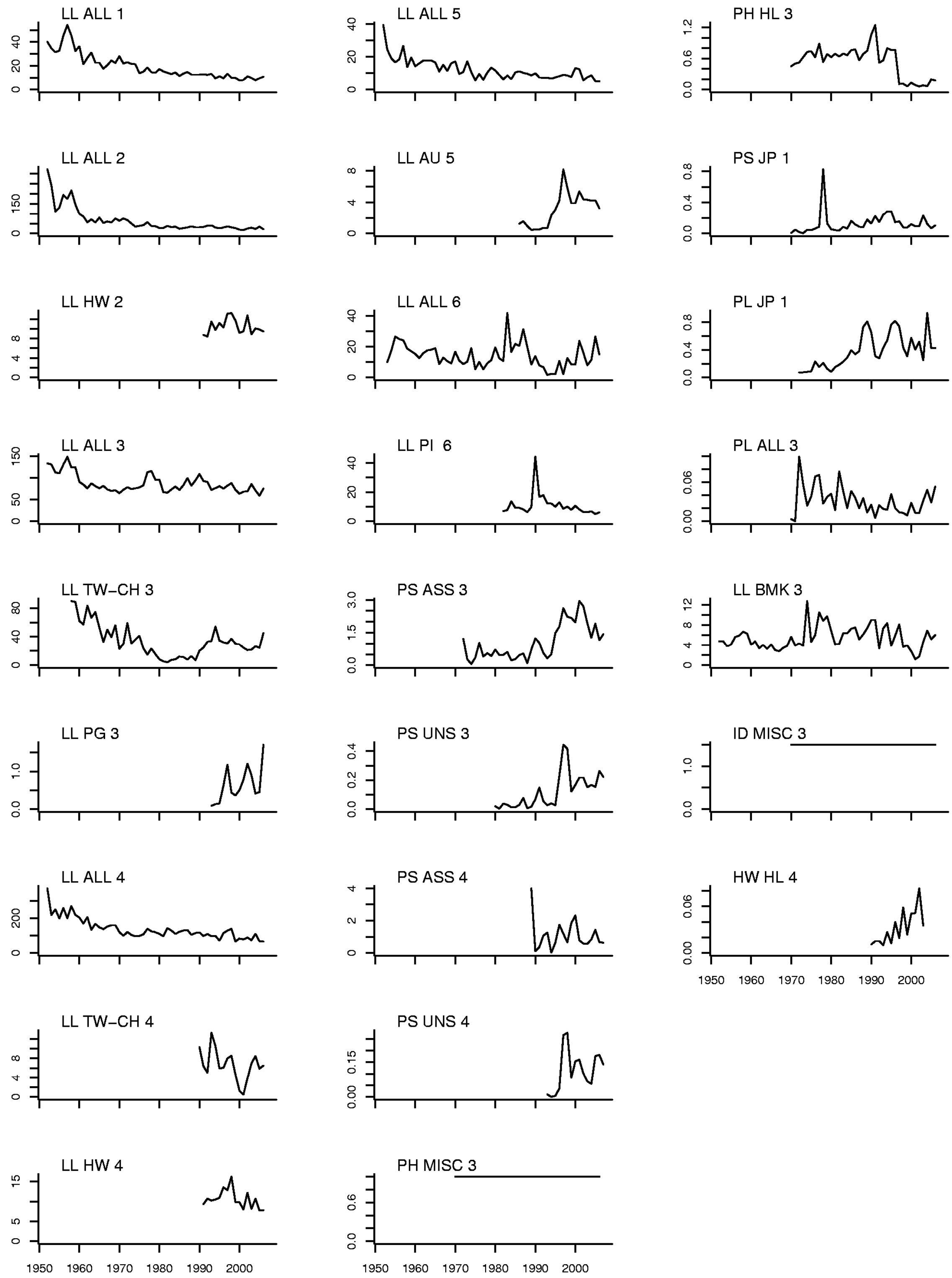


Figure 6. Catch-per-unit-effort (CPUE) by fishery. Units are catch number per GLM-standardised effort (fisheries LL ALL 1–LL ALL 6), catch number per 100 nominal hooks (LL HW, CH/TW LL, LL PI, LL PG, LL BMK) and catch (mt) per day fished/searched (all PS and PL fisheries). Note that CPUE for PH MISC,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

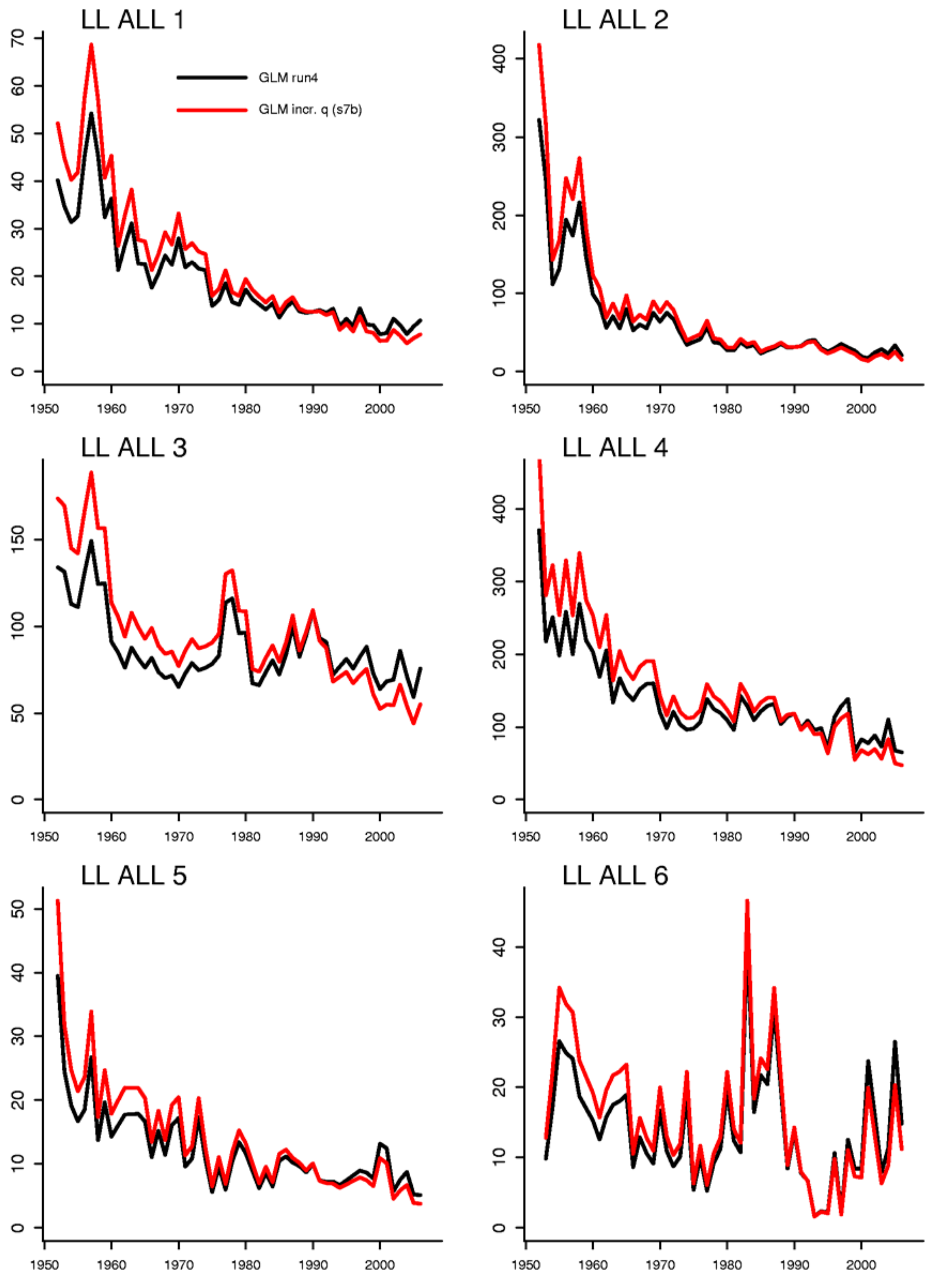


Figure 7. GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL ALL 1–6) scaled by the respective region scalars. The LL CPUE series with the assumption regarding increased longline catchability (sensitivity s7b) is also presented.

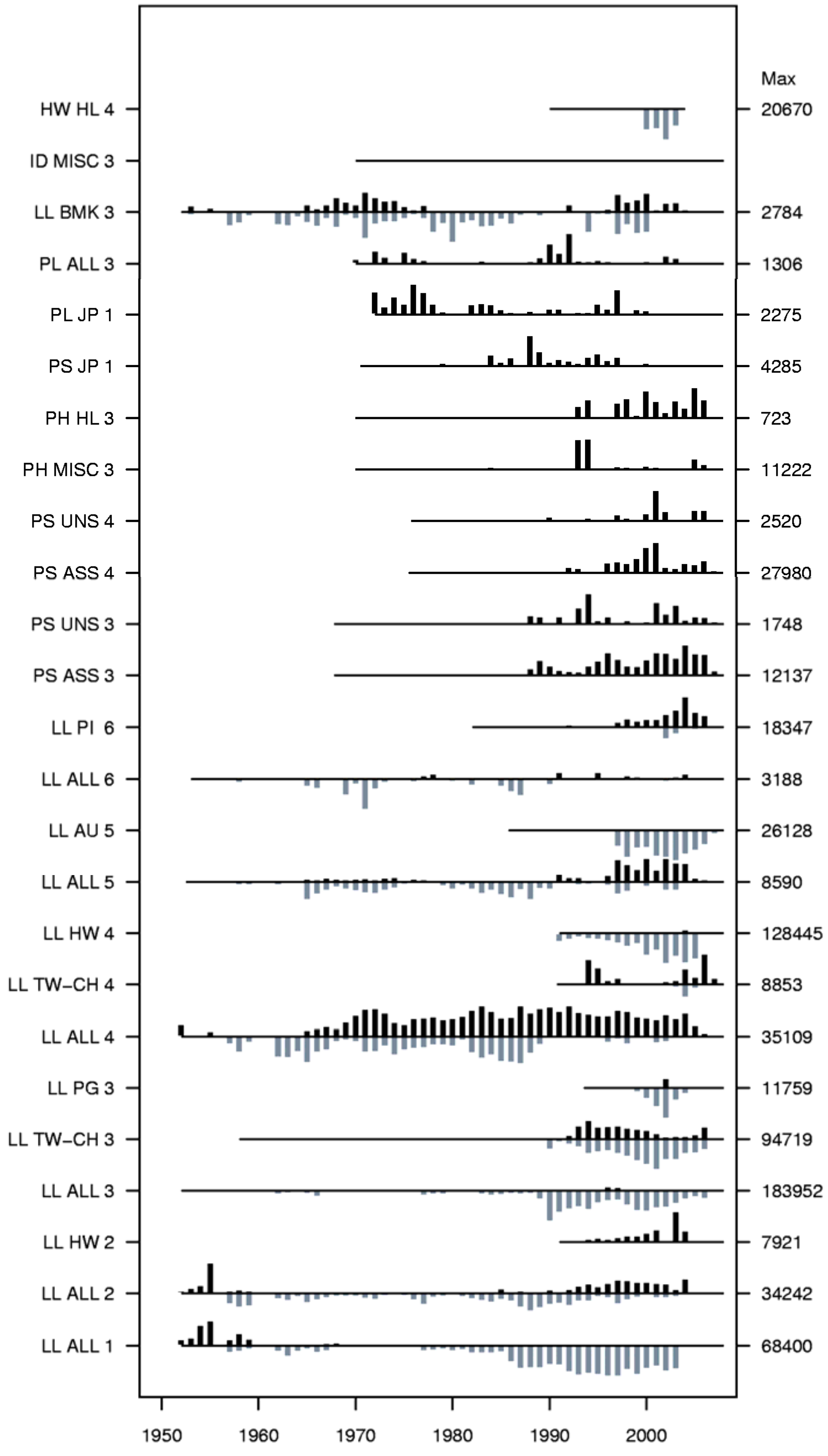


Figure 8. Number of fish size measurements by year for each fishery. The upper black bars represent length measurements and the lower grey bars represent weight measurements. The sample size corresponding to the maximum bar length for each fishery is given on the right-hand side. The extent of the horizontal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

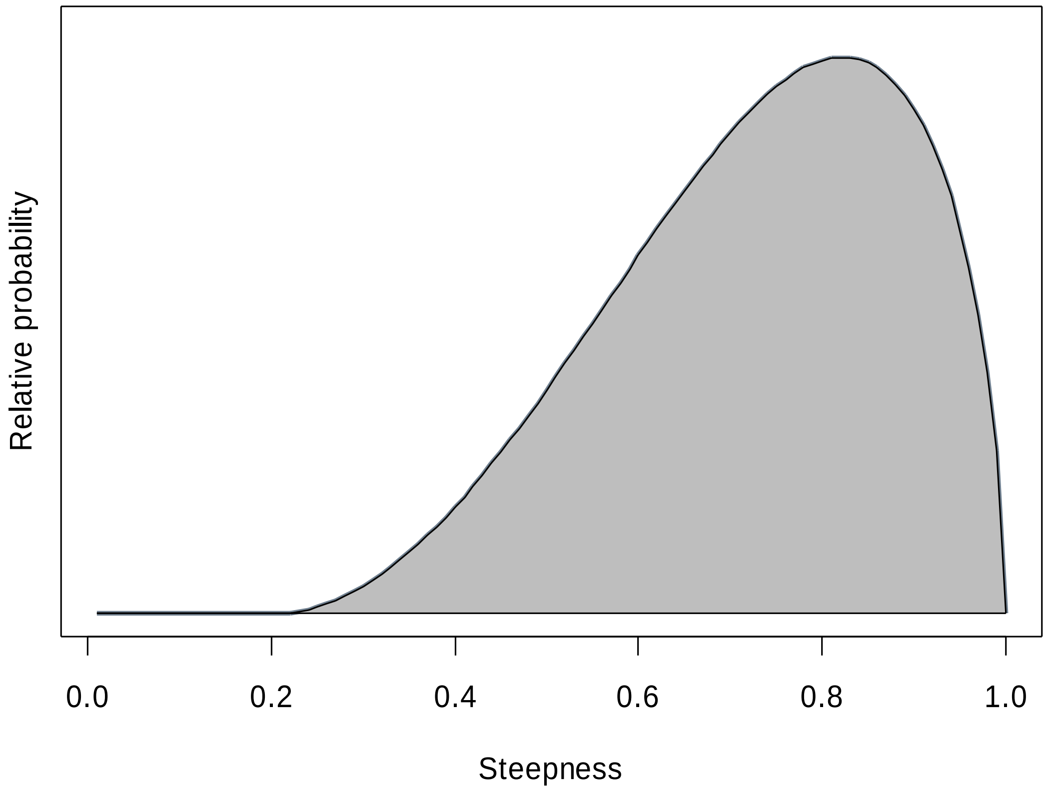


Figure 9. Prior for the steepness parameter of the relationship between spawning biomass and recruitment.

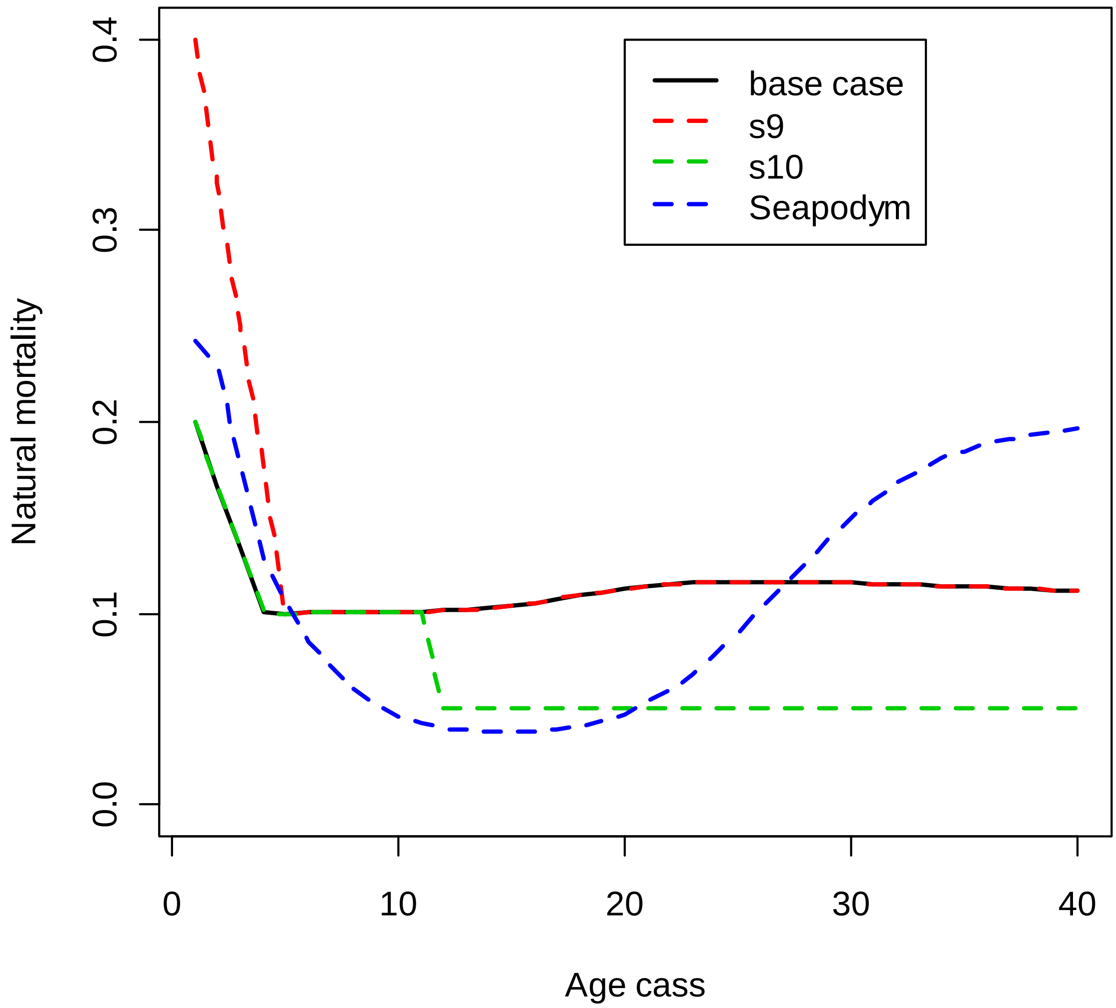
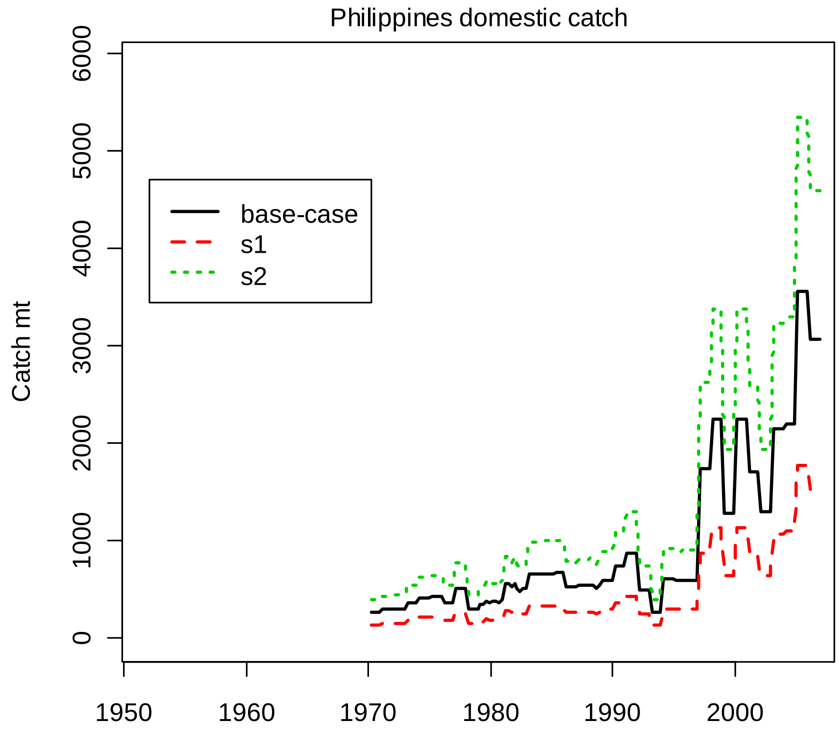


Figure 10. Natural mortality-at-age used in the assessment (base case) and the alternative age-specific natural mortalities considered in the sensitivity analyses.



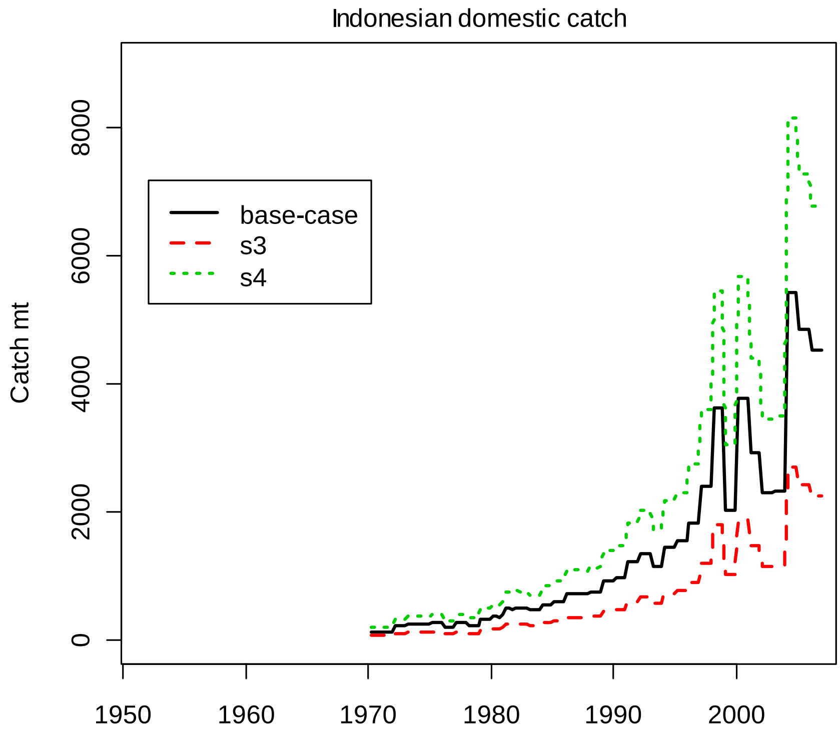


Figure 11. A comparison of the alternative catch histories for the Philippines (top) and Indonesian (bottom) domestic fisheries included in the sensitivity analyses.

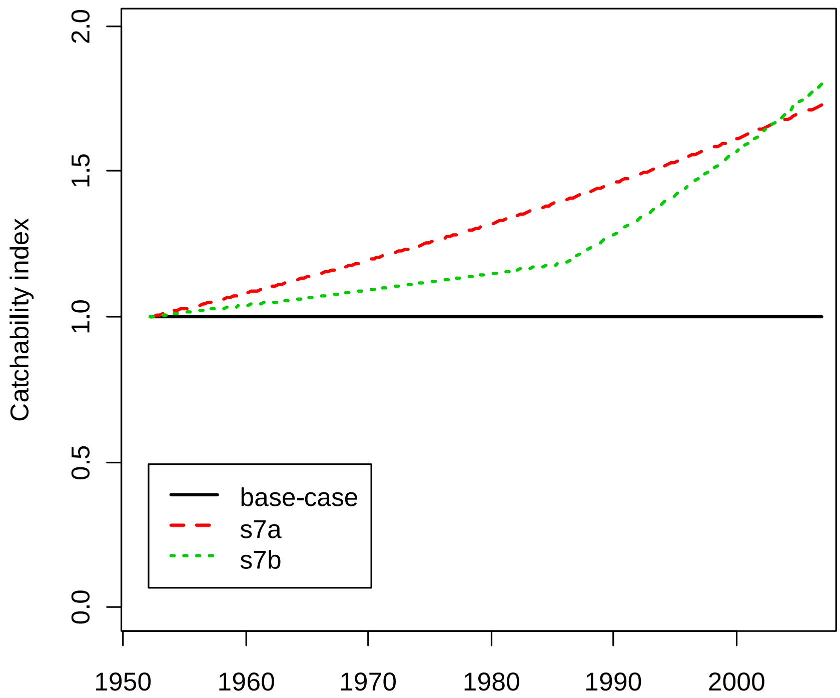


Figure 12. A comparison of the assumed trends in longline catchability for the principal longline fisheries included in the sensitivity analyses.

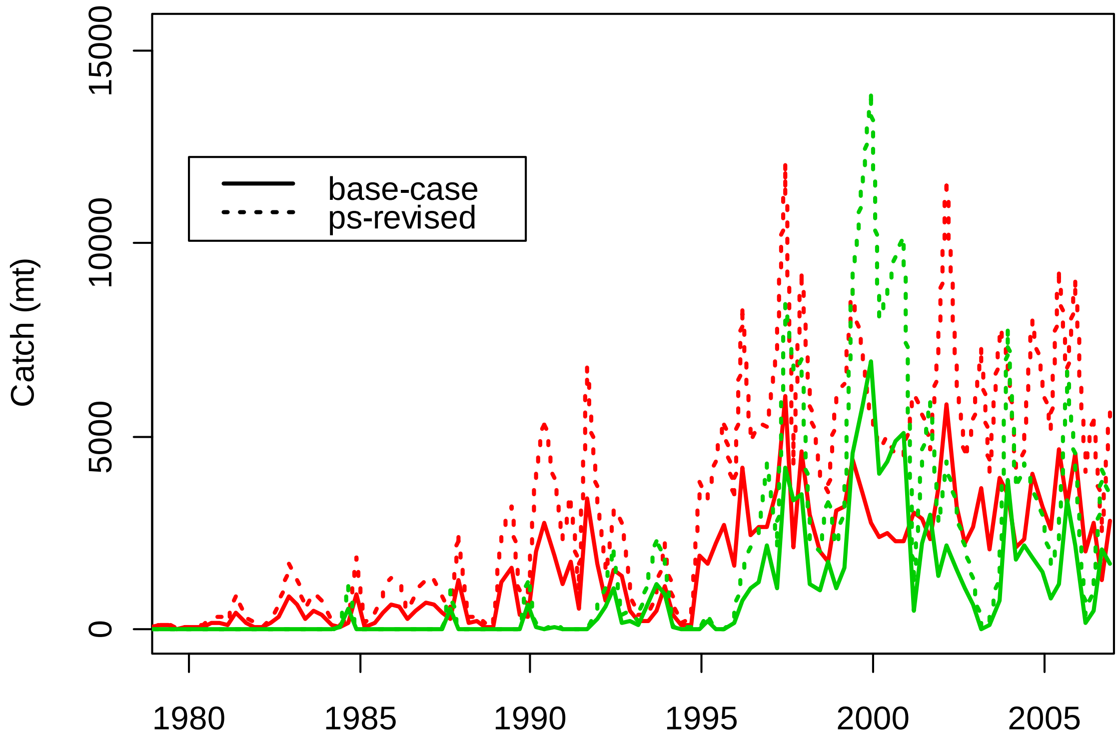


Figure 13. A comparison of the base-case (solid line) and alternative (dashed line; sensitivity ps-revised) catch histories for the purse-seine associated set fisheries in regions 3 (red) and 4 (green).

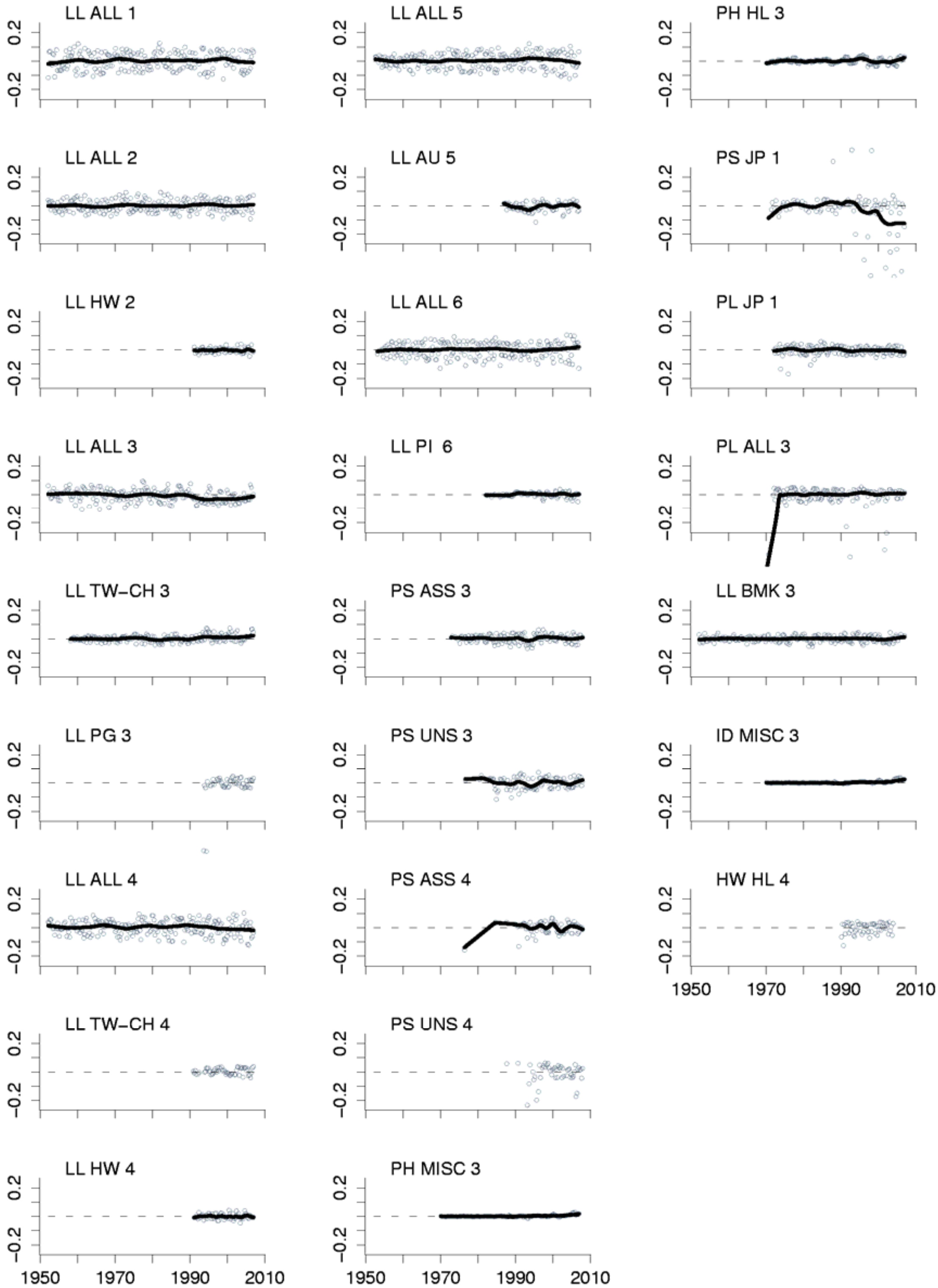


Figure 14. Residuals of ln (total catch) for each fishery (base-case model). The dark line represents a lowess smoothed fit to the residuals.

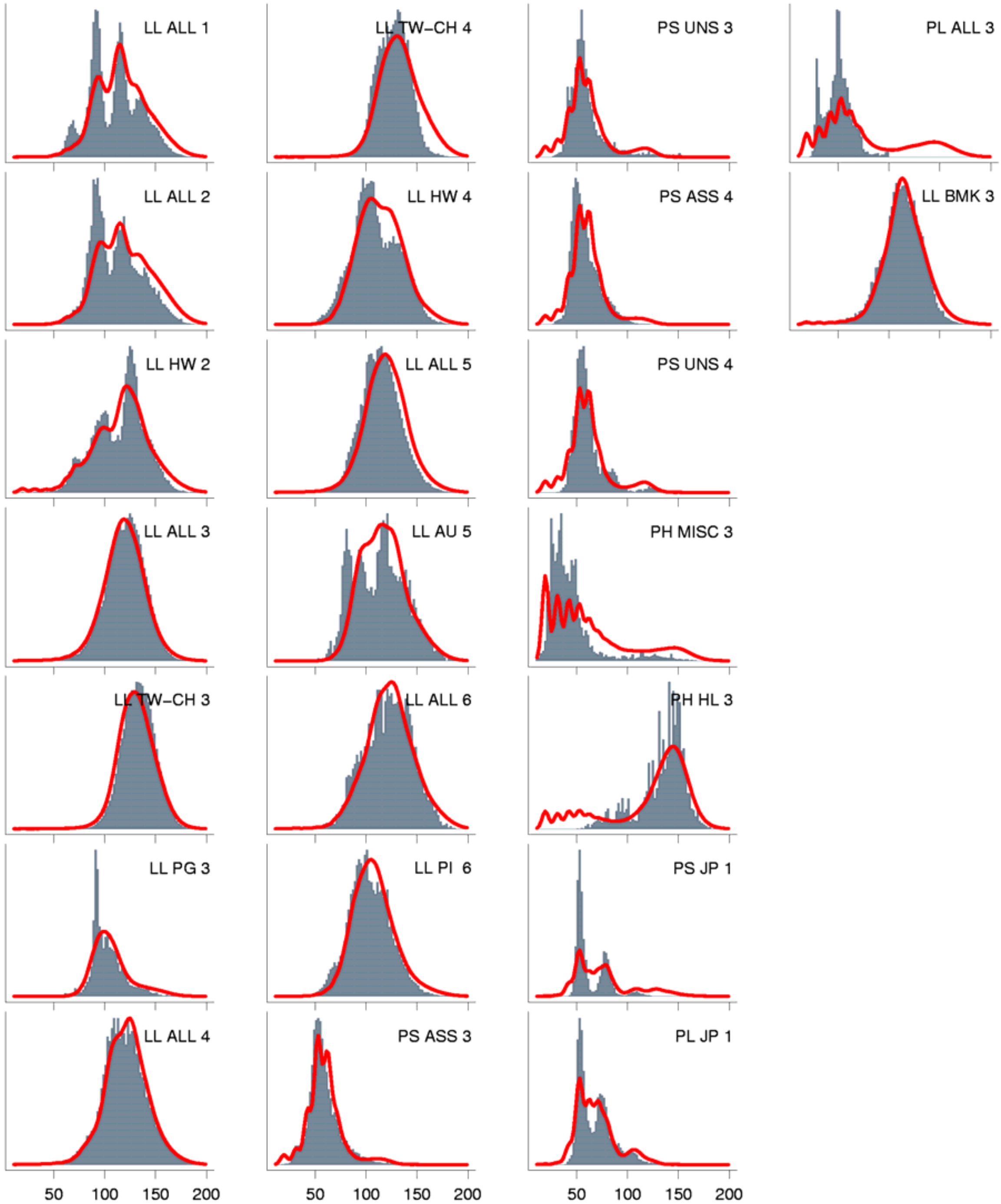


Figure 15. Observed (histograms) and predicted (line) length frequencies (in cm) for each fishery aggregated over time (base-case model).

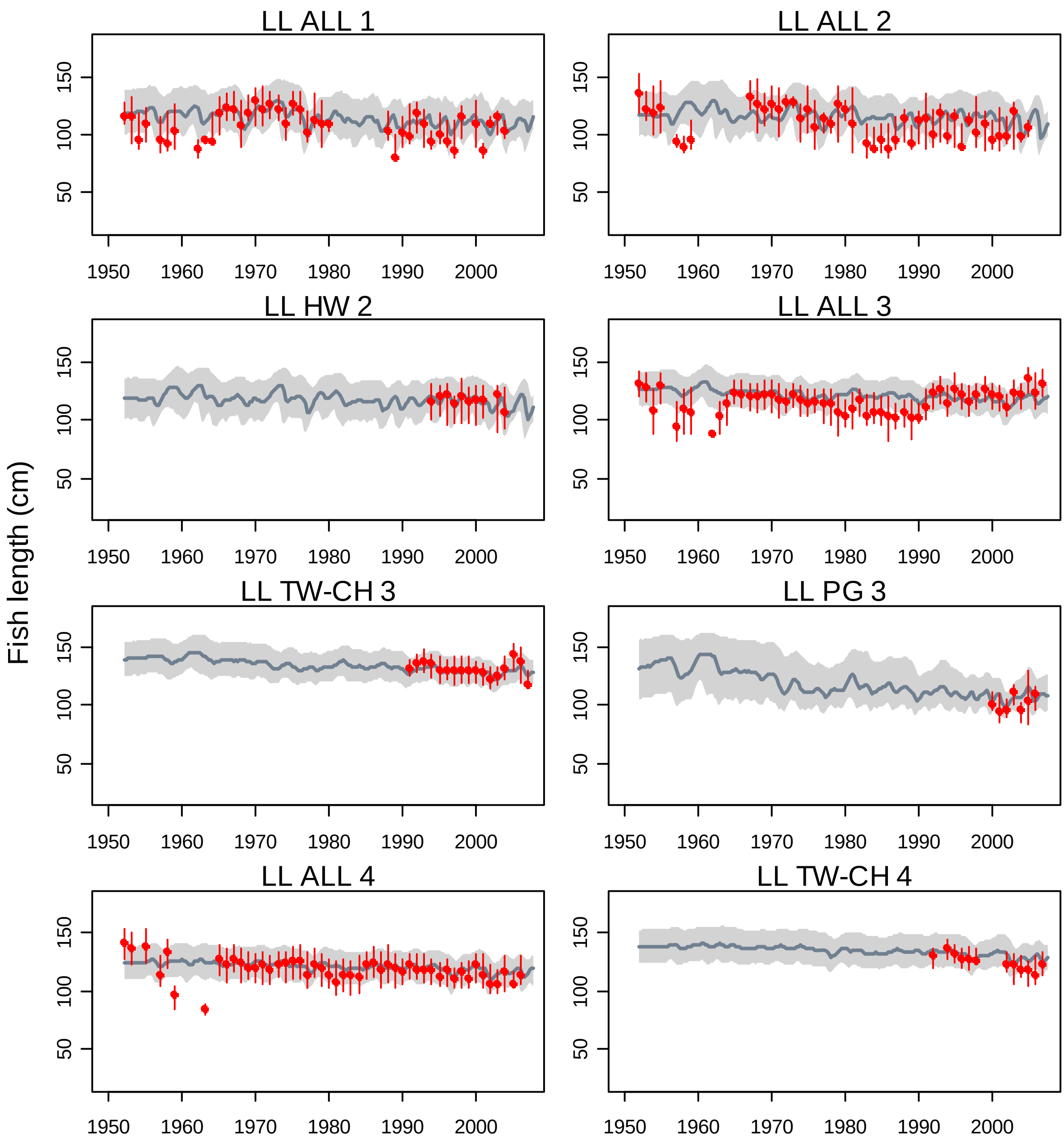


Figure 16. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of bigeye tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and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

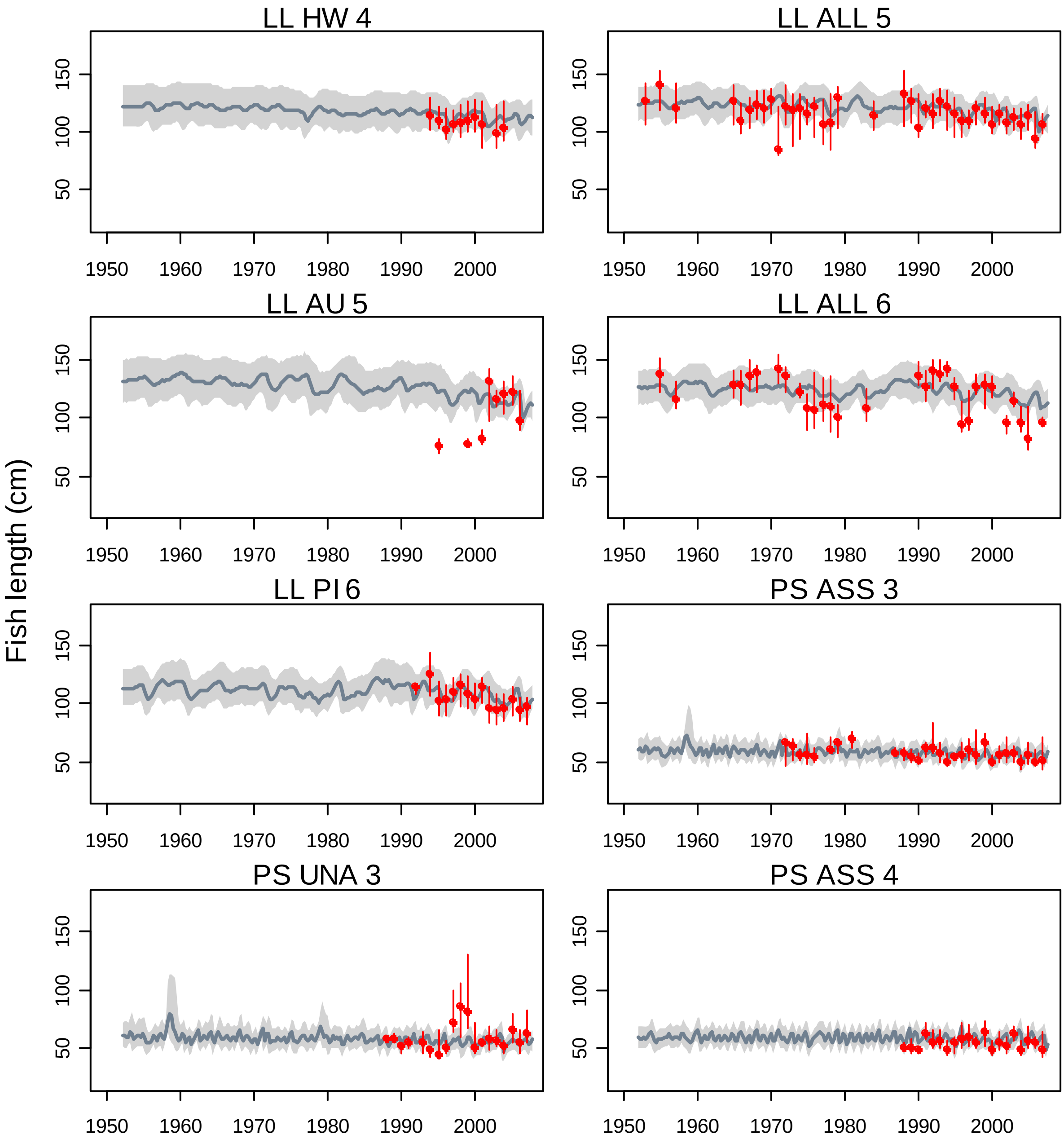


Figure 16 (continued)

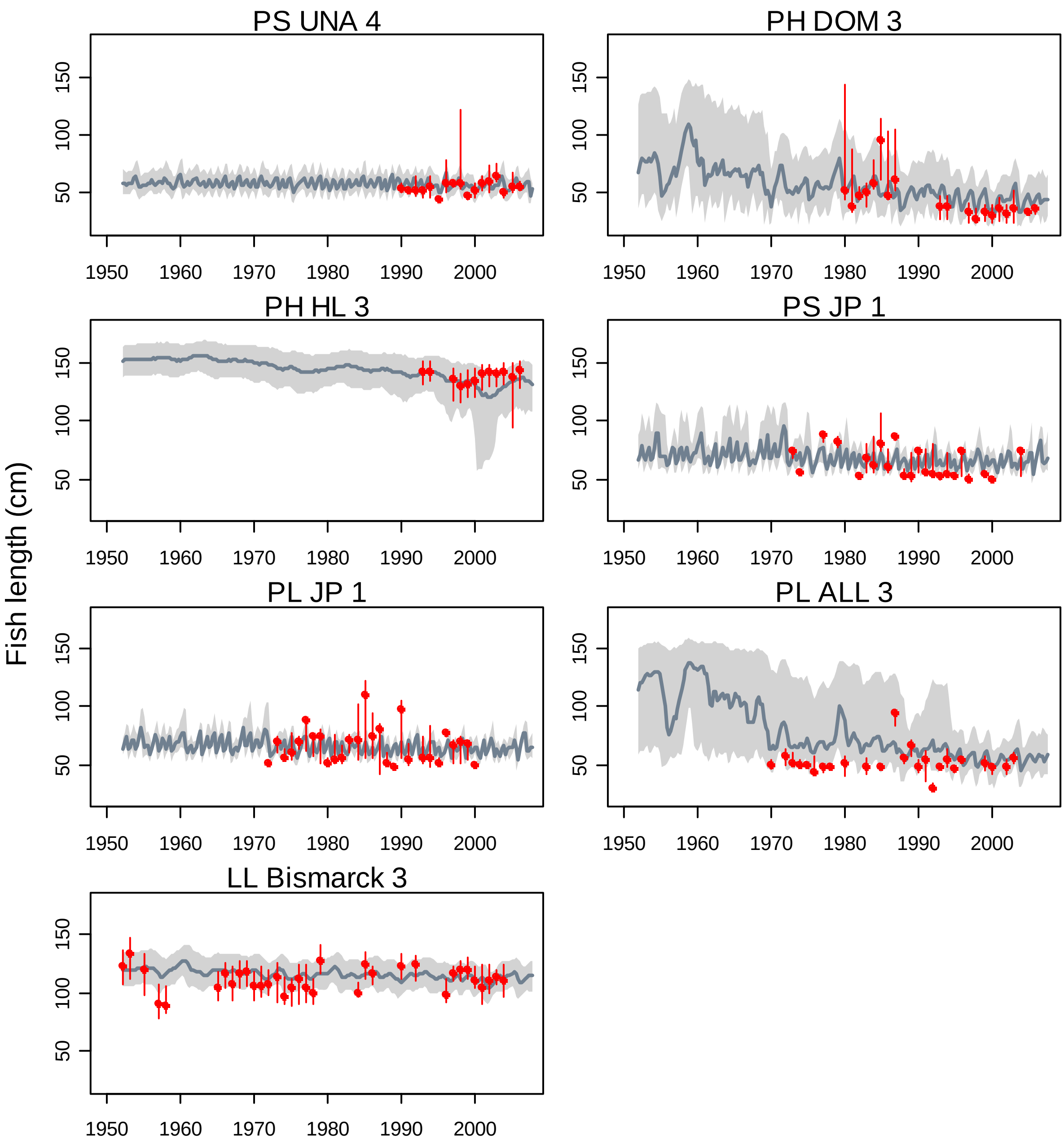


Figure 16. Continued.

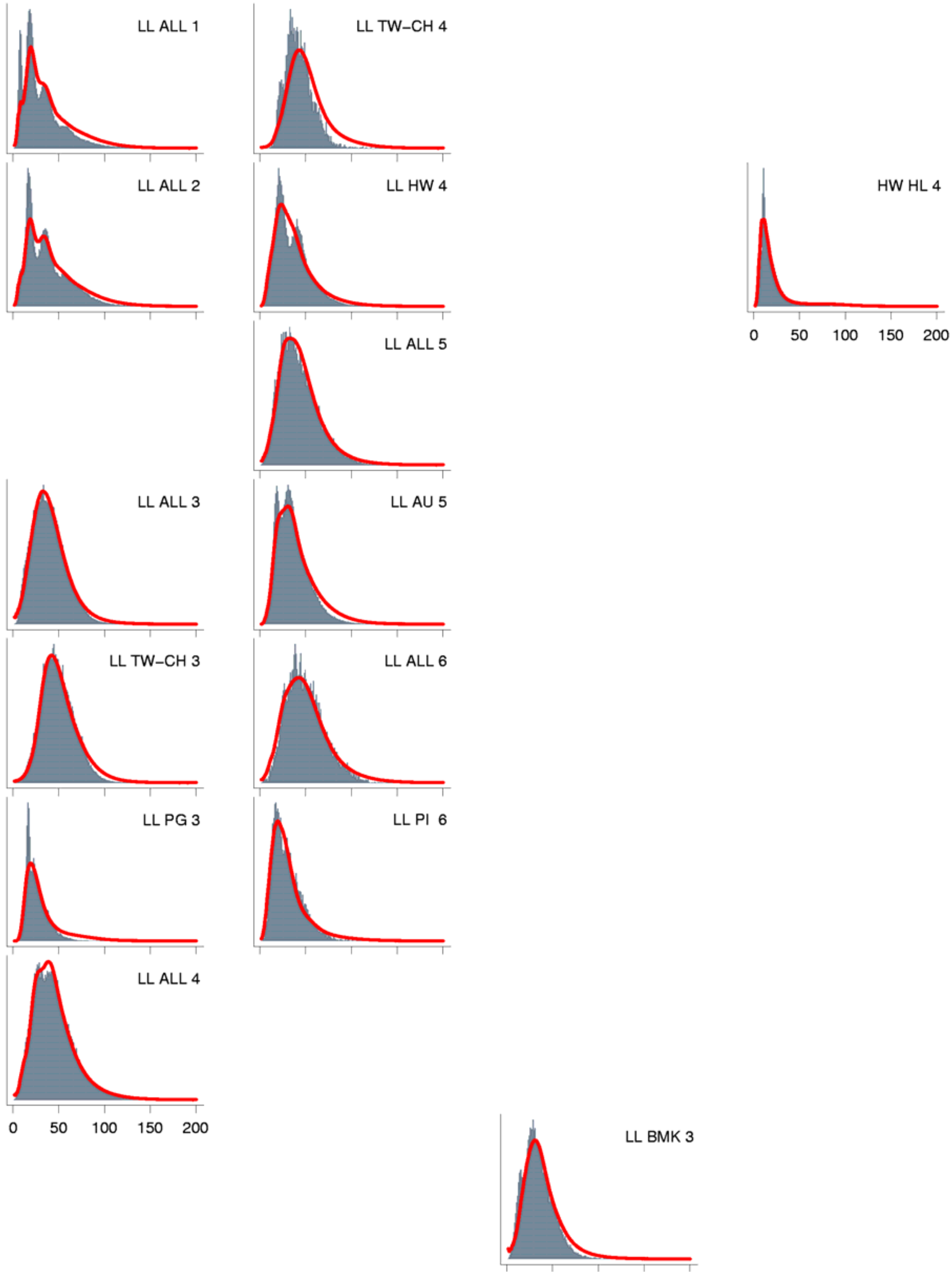


Figure 17. Observed (histograms) and predicted (line) weight frequencies (in kg) for each fishery aggregated over time (base-case model).

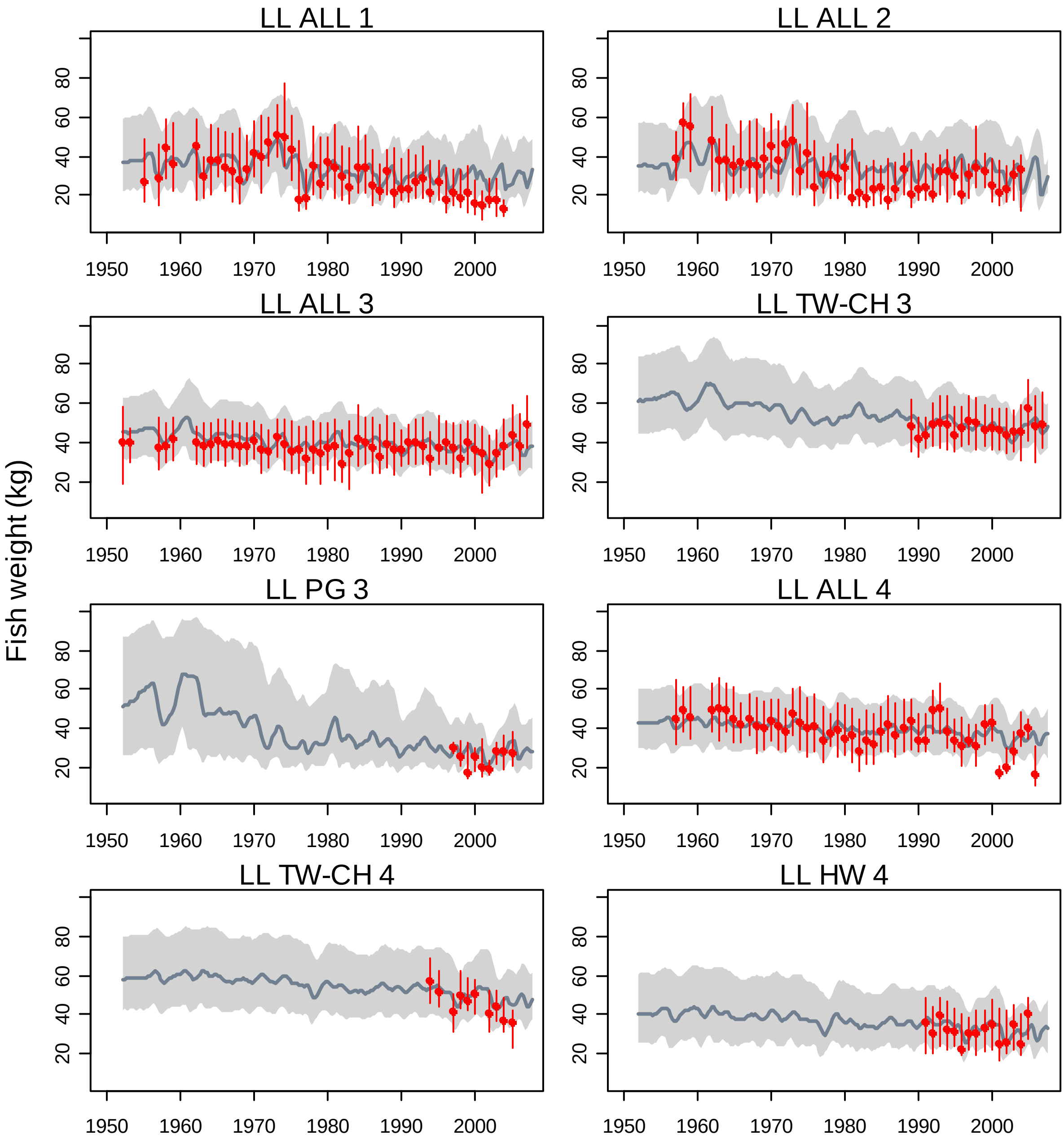


Figure 18. A comparison of the observed (red points) and predicted (grey line) median fish weight (whole weight, kg) of bigeye tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only weight samples with a minimum of 30 fish per year are plotted.

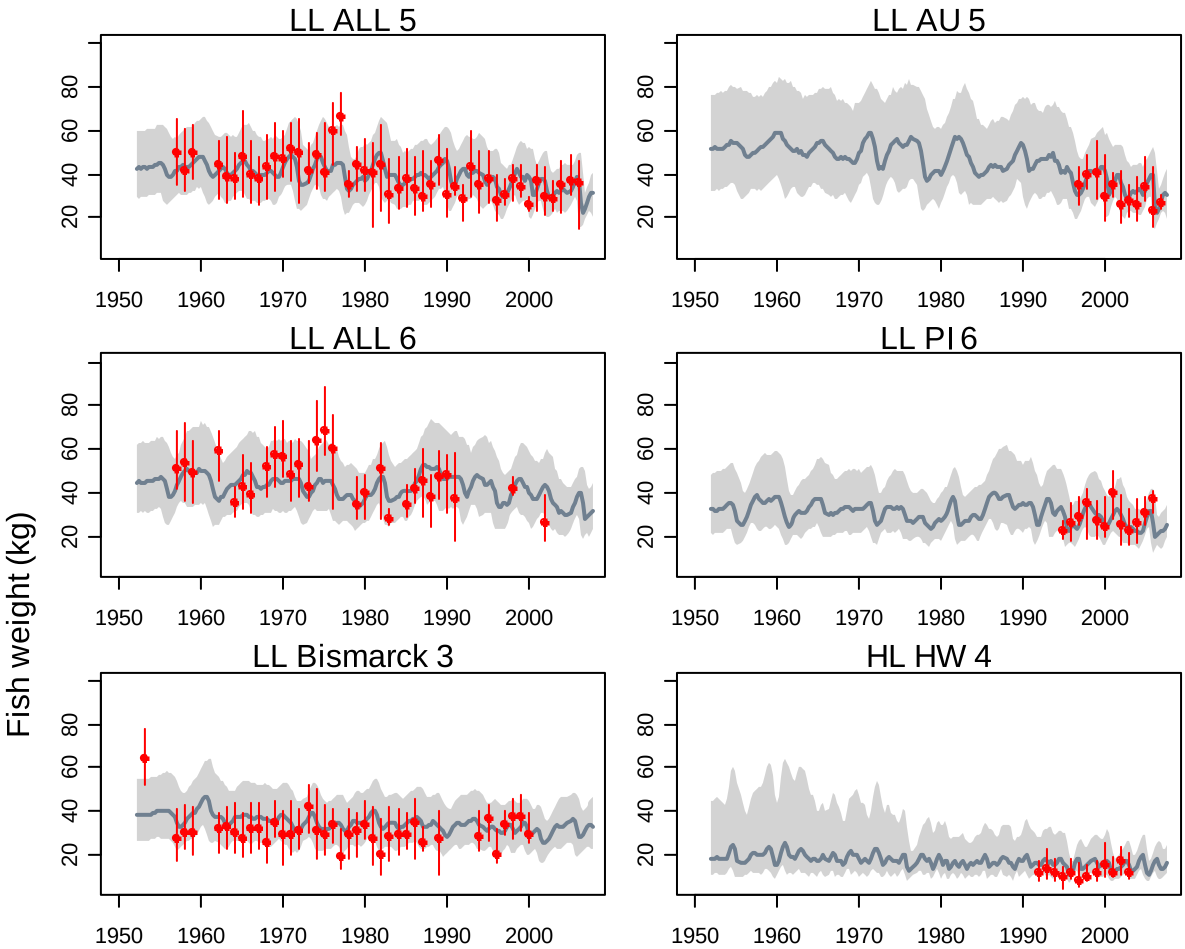


Figure 18. Continued.

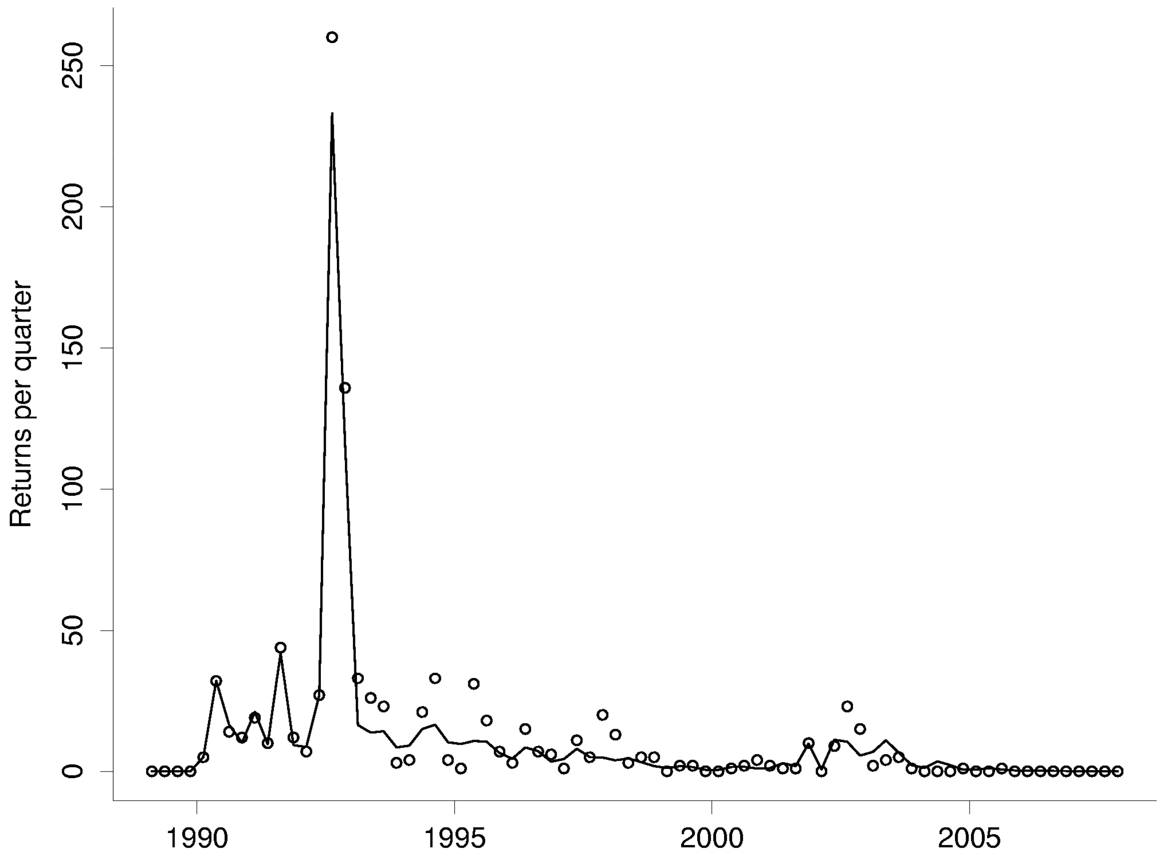


Figure 19. Number of observed (points) and predicted (line) tag returns by recapture period (quarter).

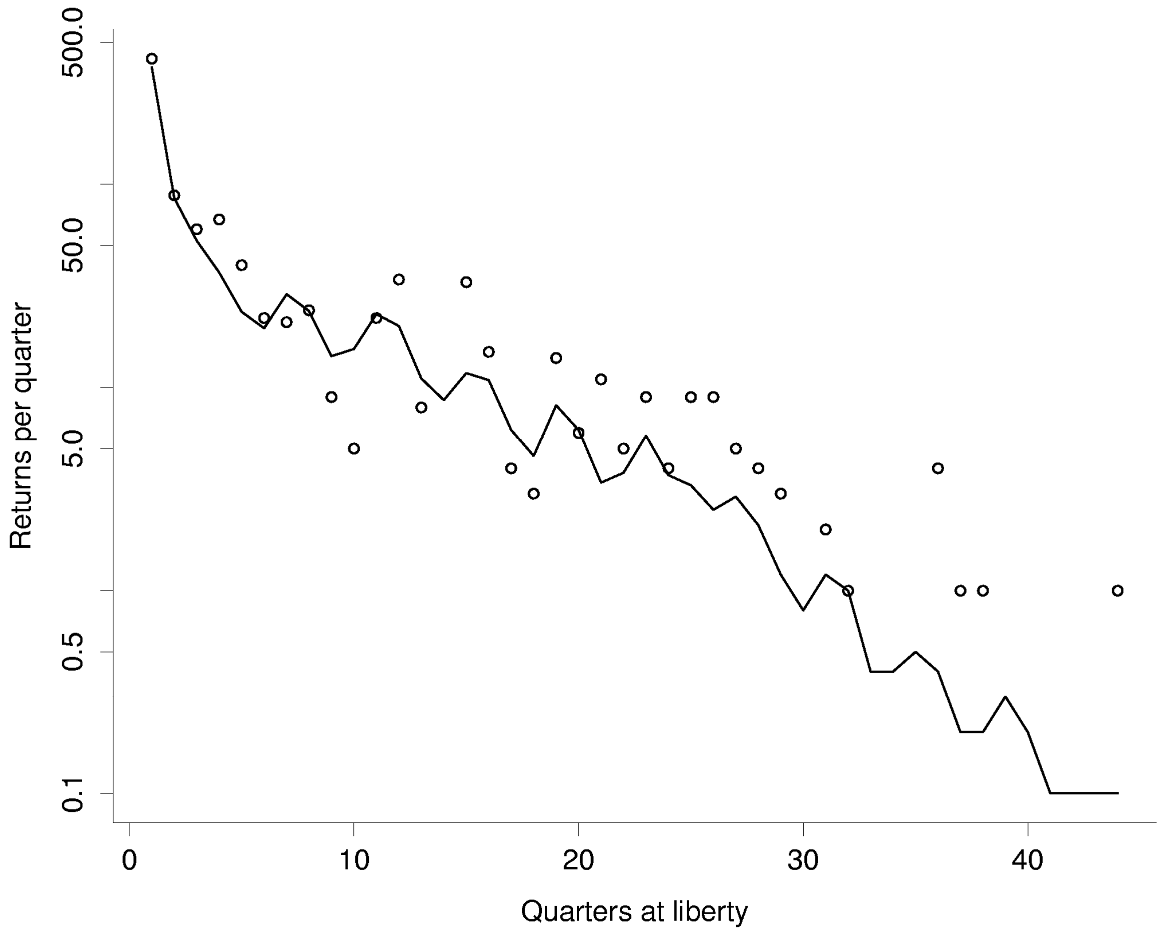


Figure 20. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters).

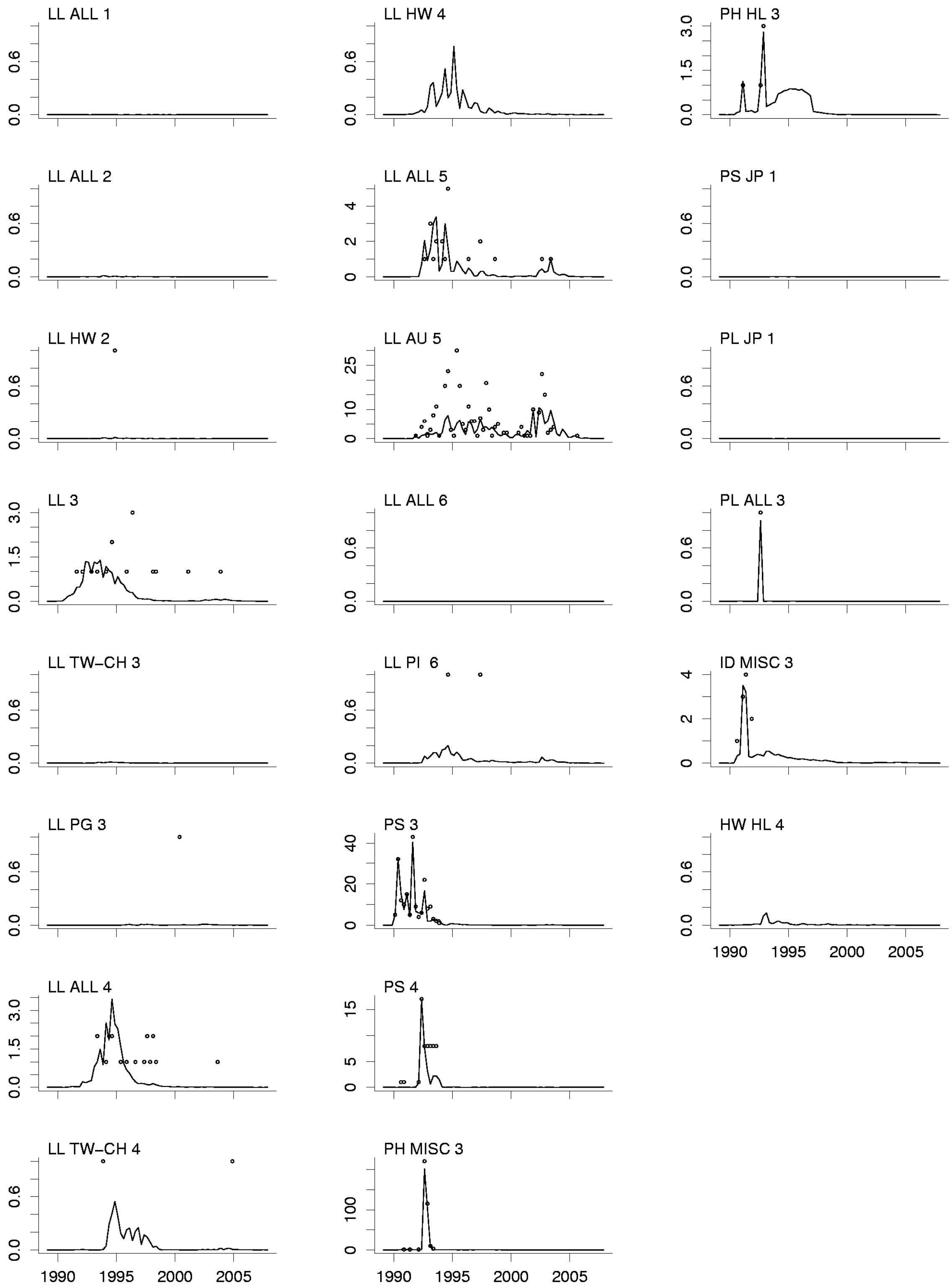


Figure 21. Number of observed (points) and predicted (line) tag returns by recapture period (quarter) for the various fisheries (or groups of fisheries) defined in the model.

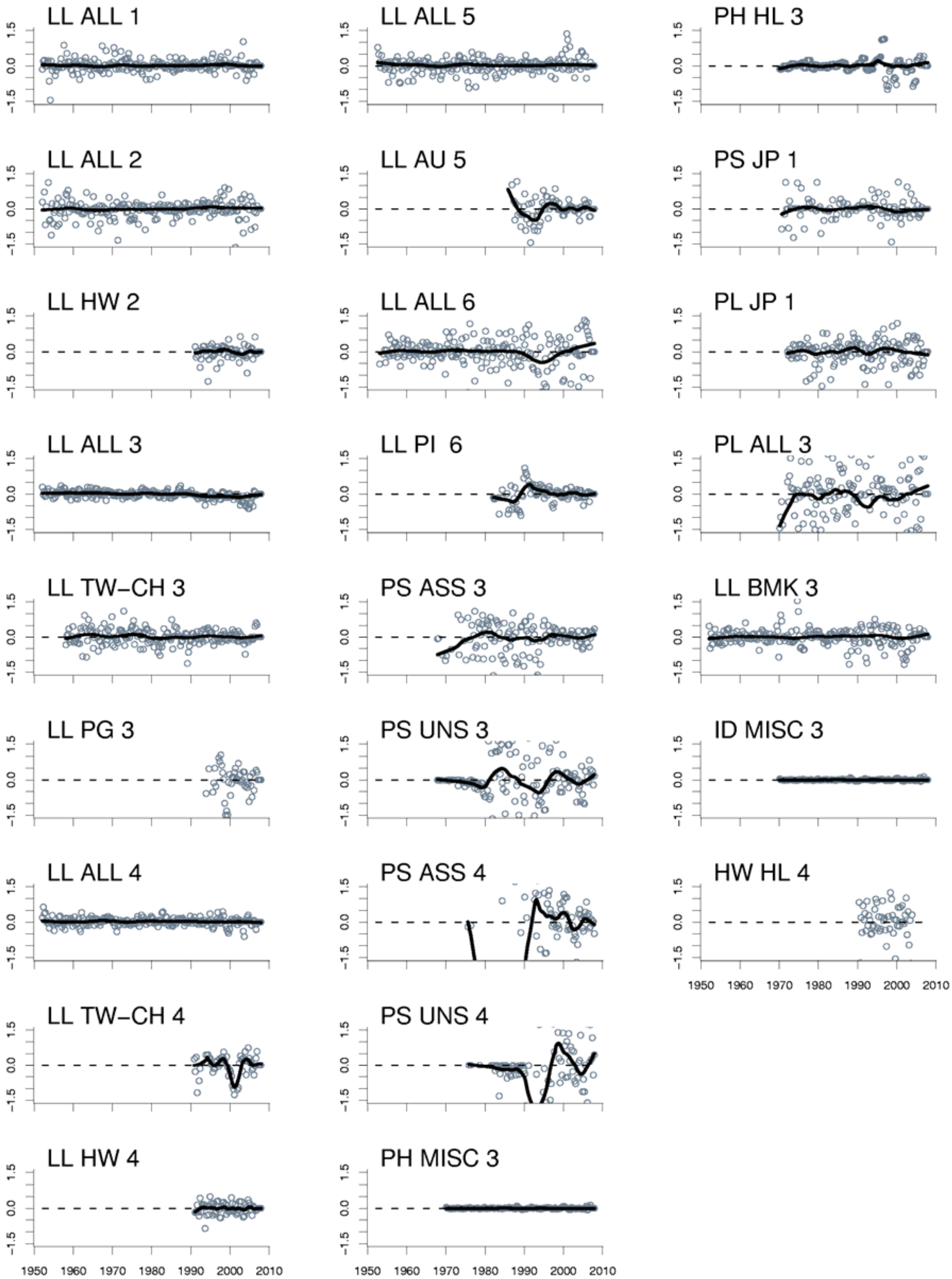


Figure 22. Effort deviations by time period for each fishery (base-case model). For fisheries with longer time series, the dark line represents a lowess smoothed fit to the effort deviations.

Figure 23. Temporal trend in the effort deviations from the principal longline fishery in region 3 (LL ALL 3) for the base case and the model with the down-weighted TW-CN size data. The solid line represents the lowess smoothed fit to the estimates.

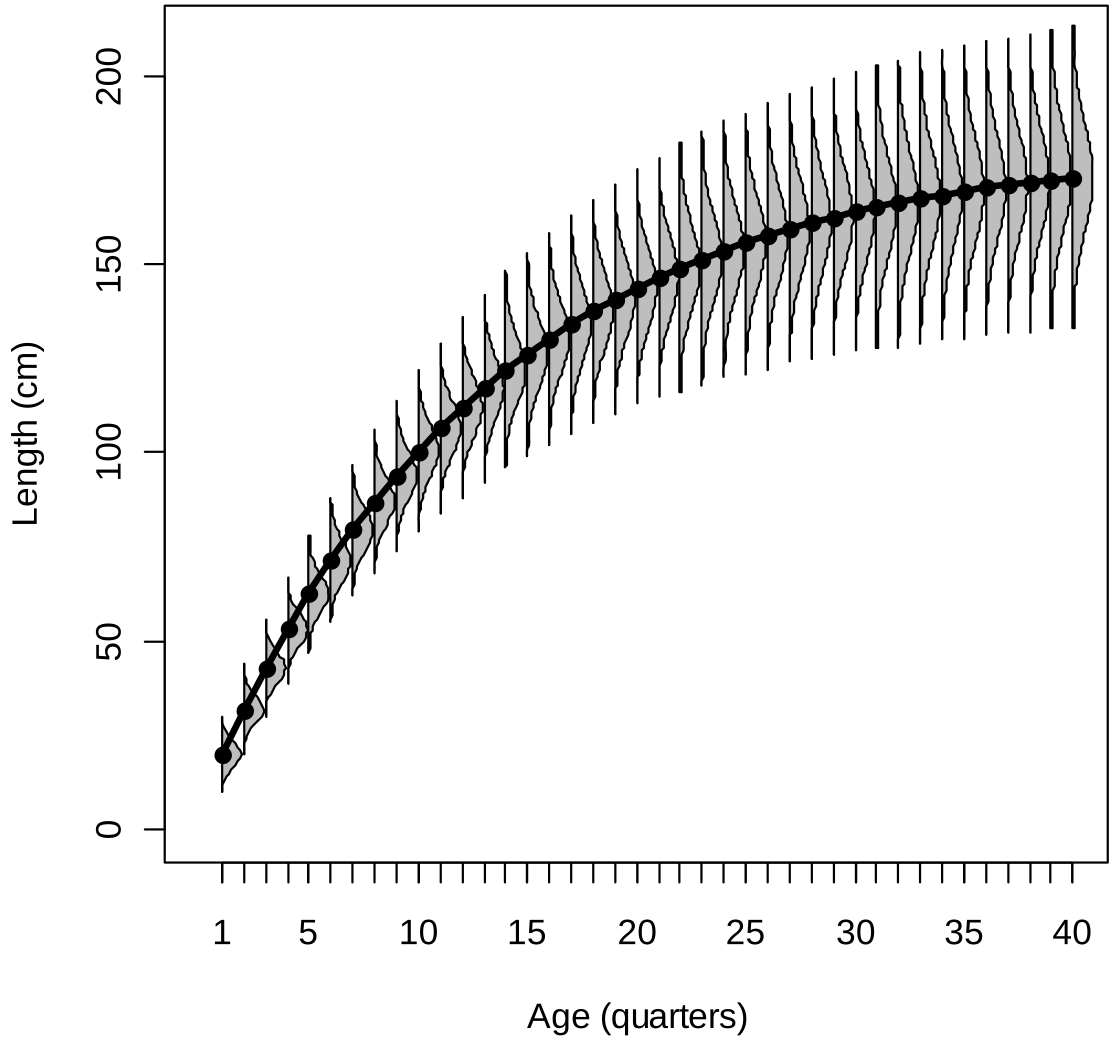


Figure 24. Estimated growth of bigeye derived from the assessment model. The black line represents the estimated mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age.

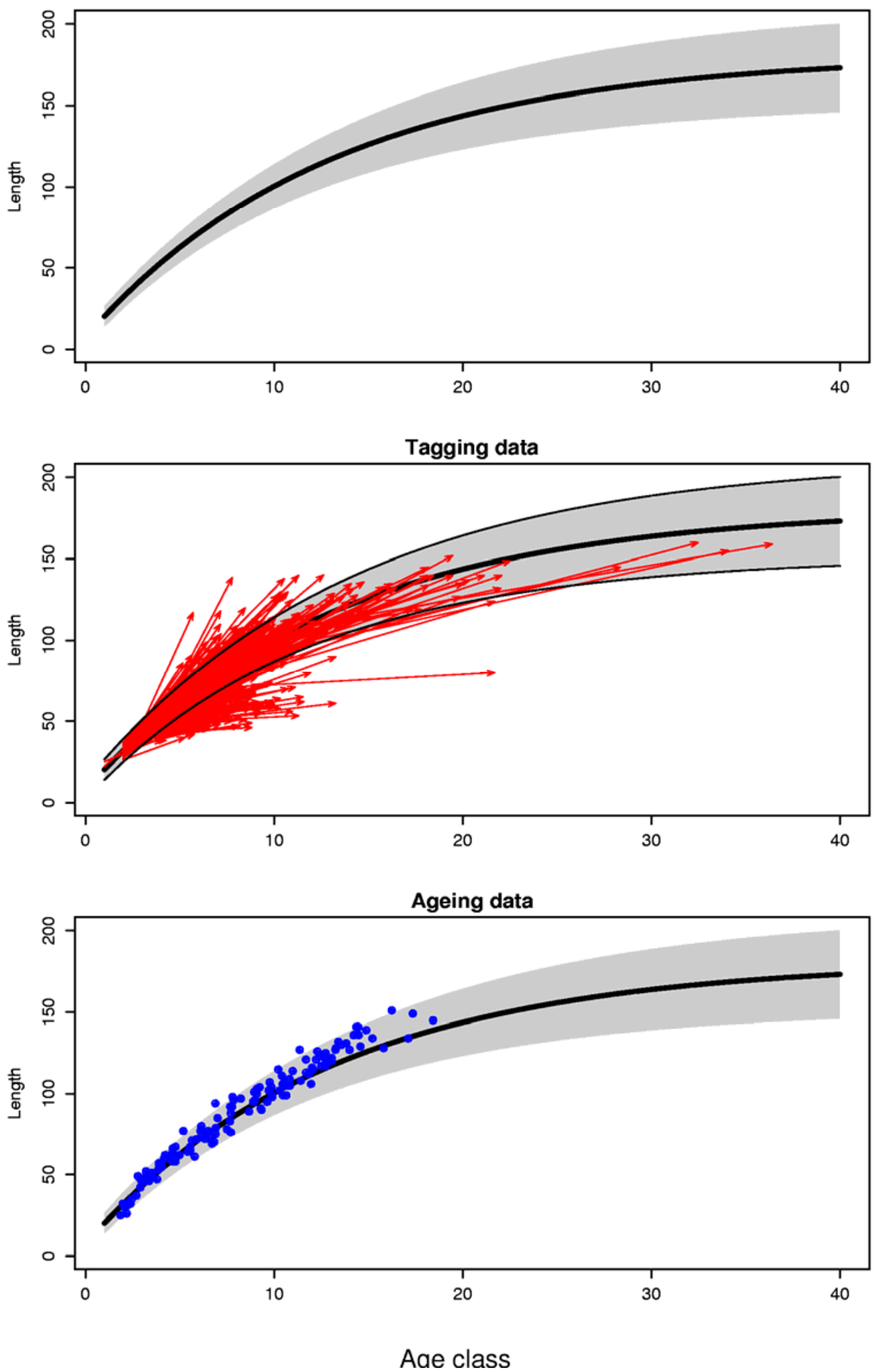


Figure 25. Estimated mean lengths-at-age (heavy line) and the variability of length-at-age (shaded area represents ± 2 SD). Age is in quarters and length is in cm. For comparison, length at age estimates are presented from tag release and recapture data (middle figure) and empirical age determination from otolith readings (bottom figure). The tagging data is presented as a linear growth vector (depicted as an arrow) from length at release to length at recovery. Only fish at liberty for at least 150 days are included. Age at release is assumed from the estimated growth function.

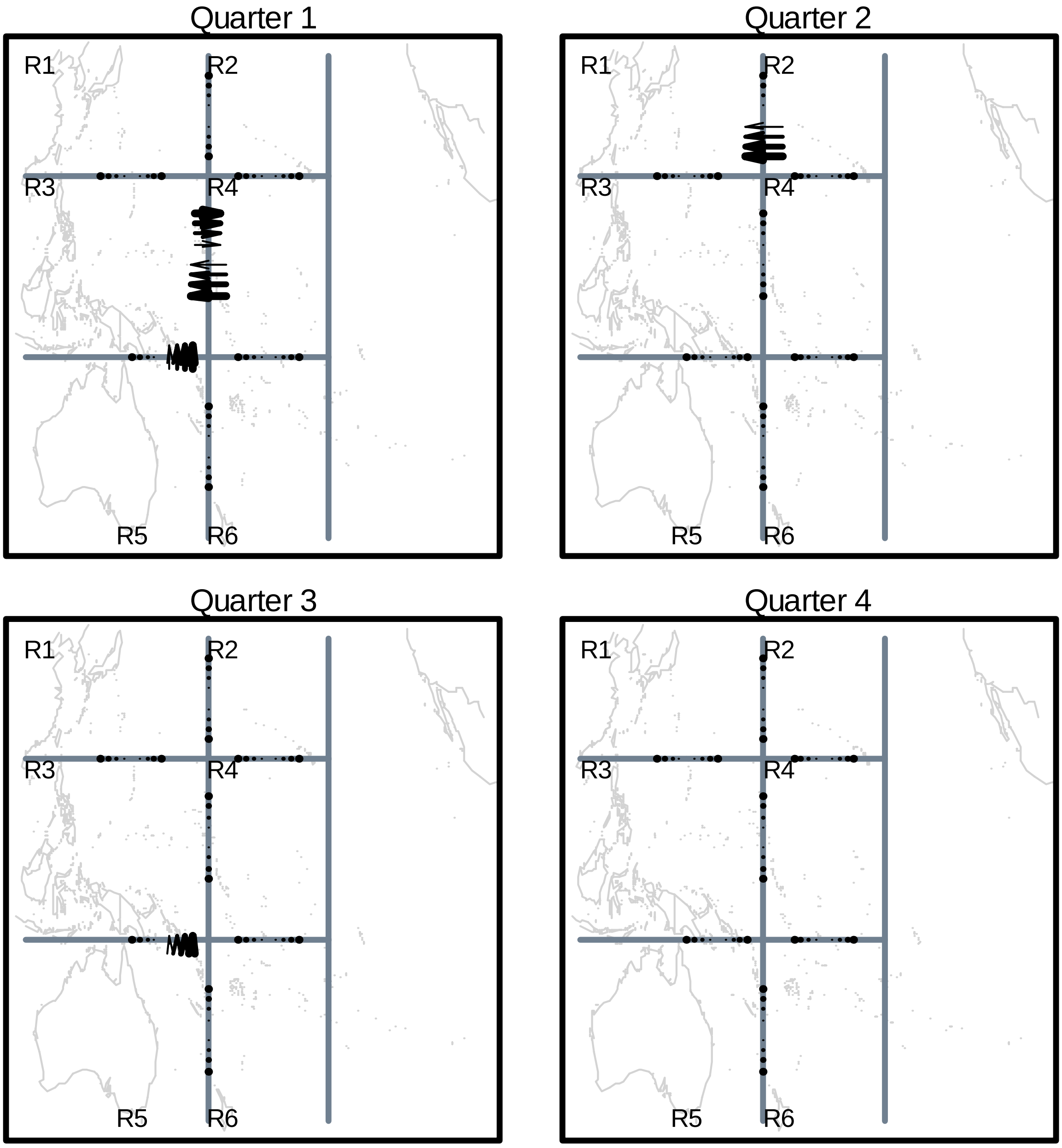


Figure 26. Estimated quarterly movement coefficients at age (1, 10, 20, 30 quarters). The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age. The maximum movement (quarter 2, region 2 to region 1) represents movement of 4% of the fish at the start of the quarter.

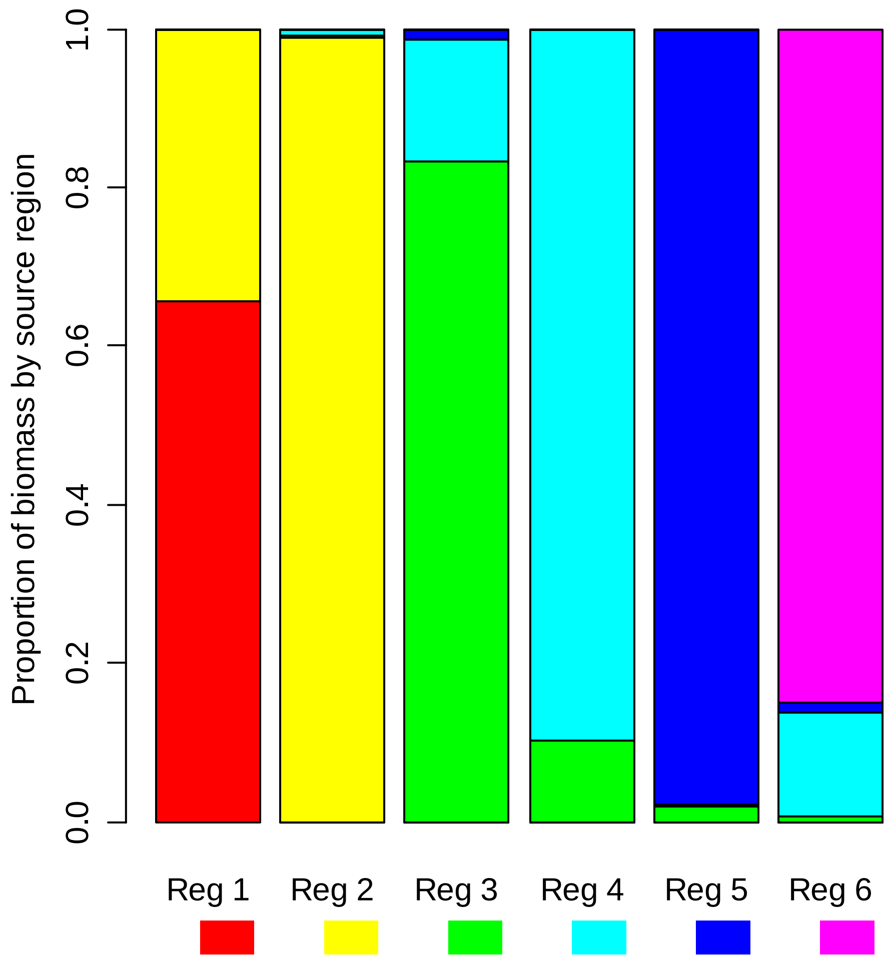


Figure 27. Proportional distribution of total biomass (by weight) in each region (Reg 1–6) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment between regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

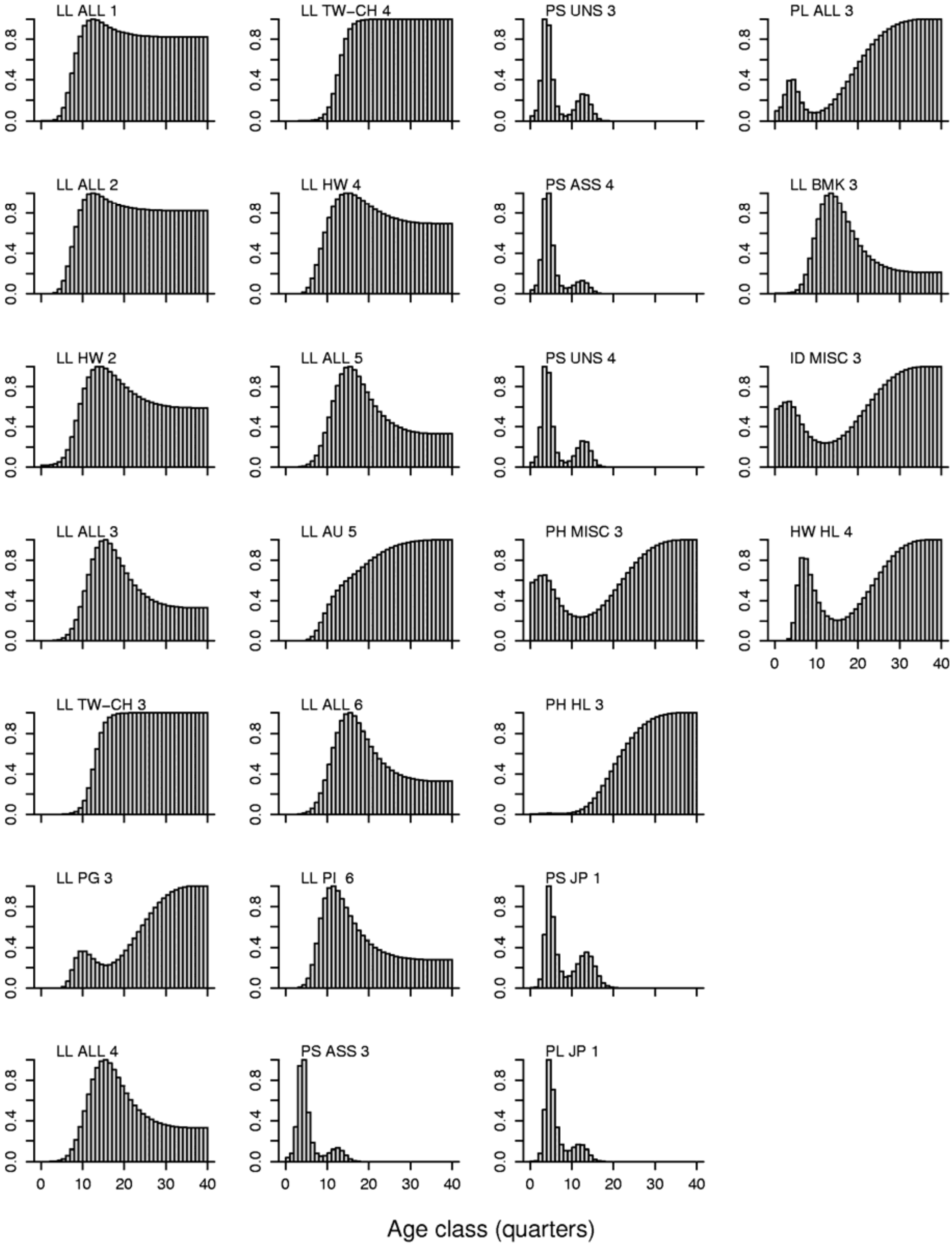


Figure 28. Selectivity coefficients, by fishery.

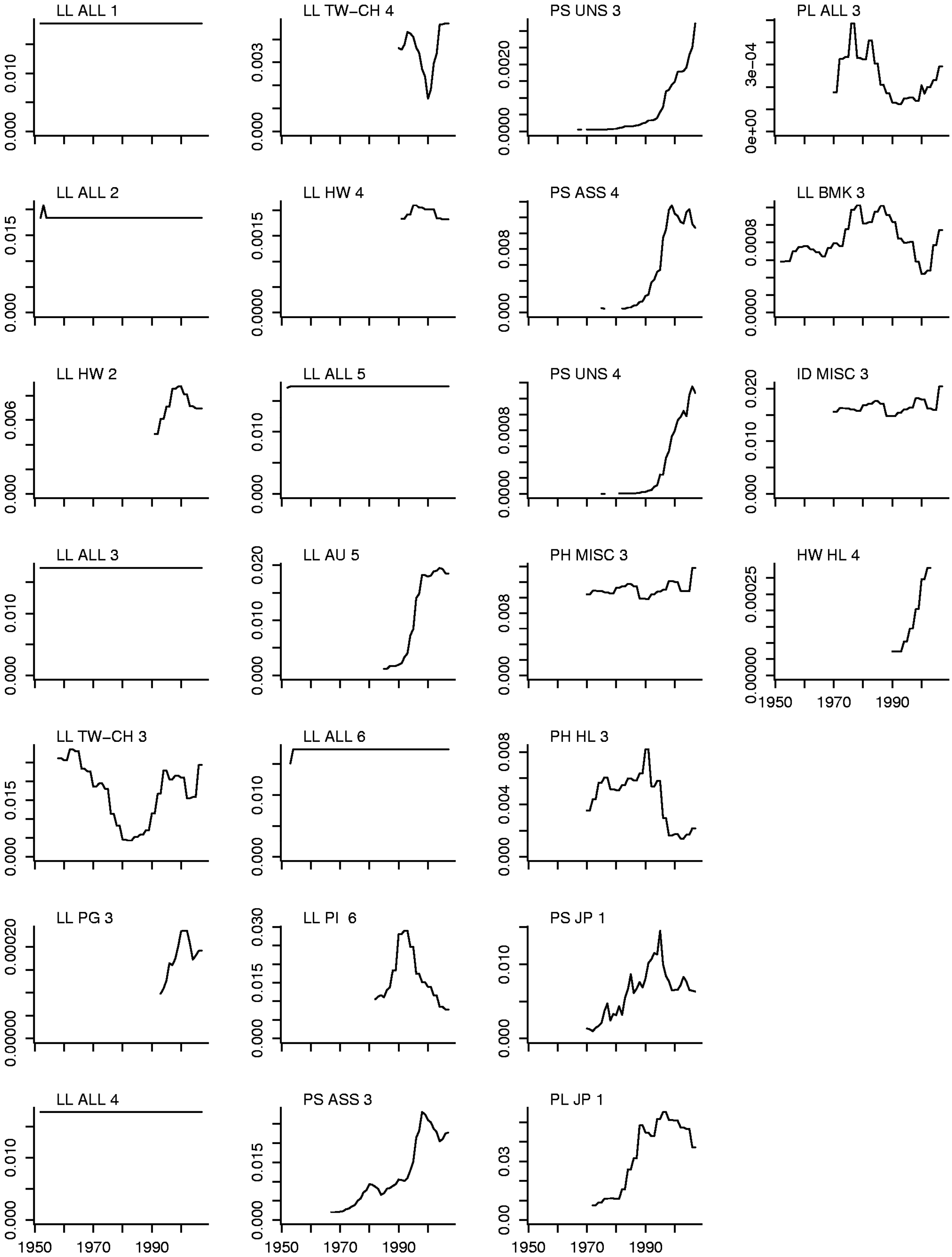


Figure 29. Average annual catchability time series, by fishery (base-case model).

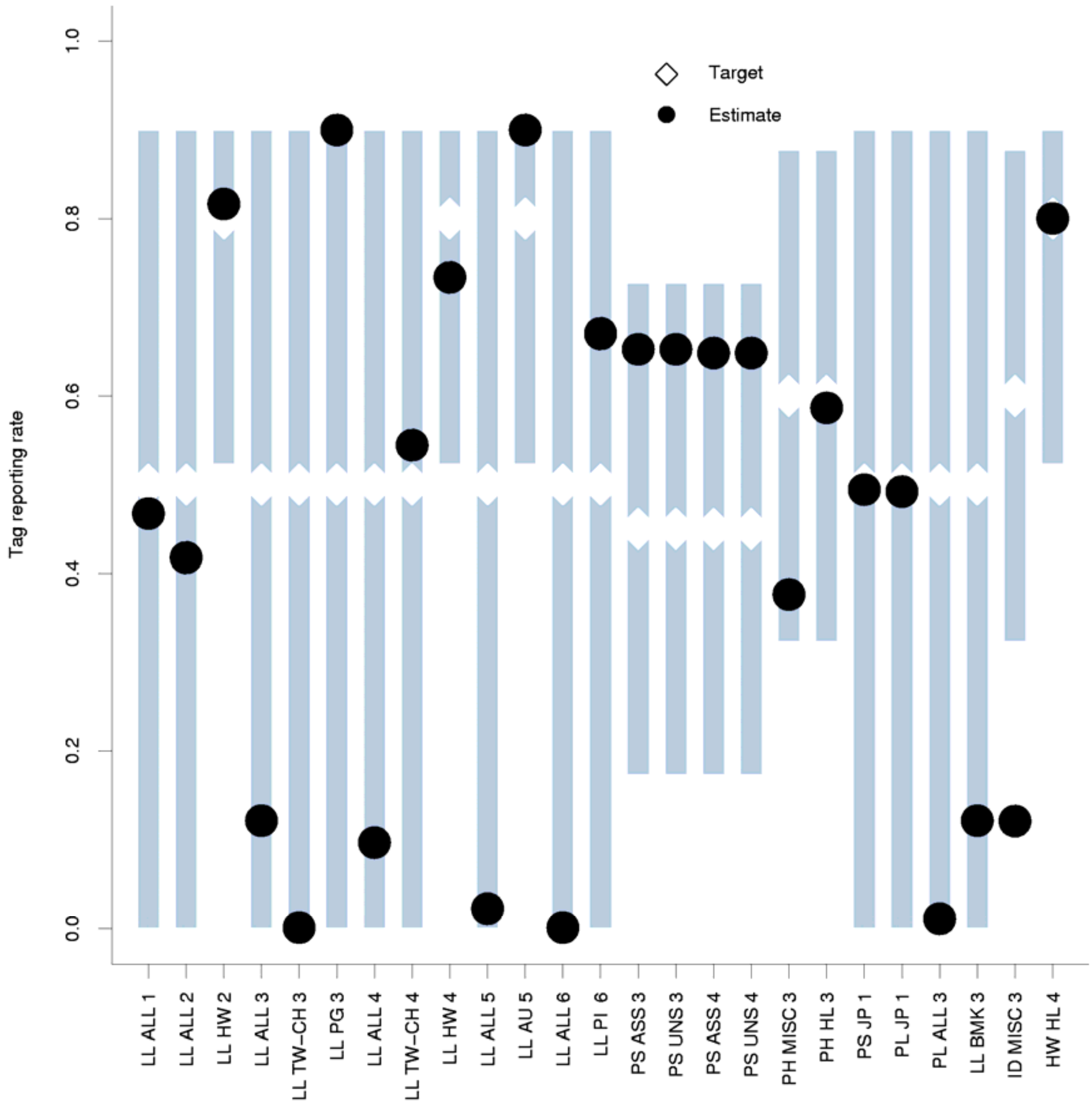


Figure 30. Estimated tag-reporting rates by fishery (black circles) (base-case model). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars (truncated at zero and 0.9, which were the bounds of the parameter estimates) indicate a range of ±1 prior SD.

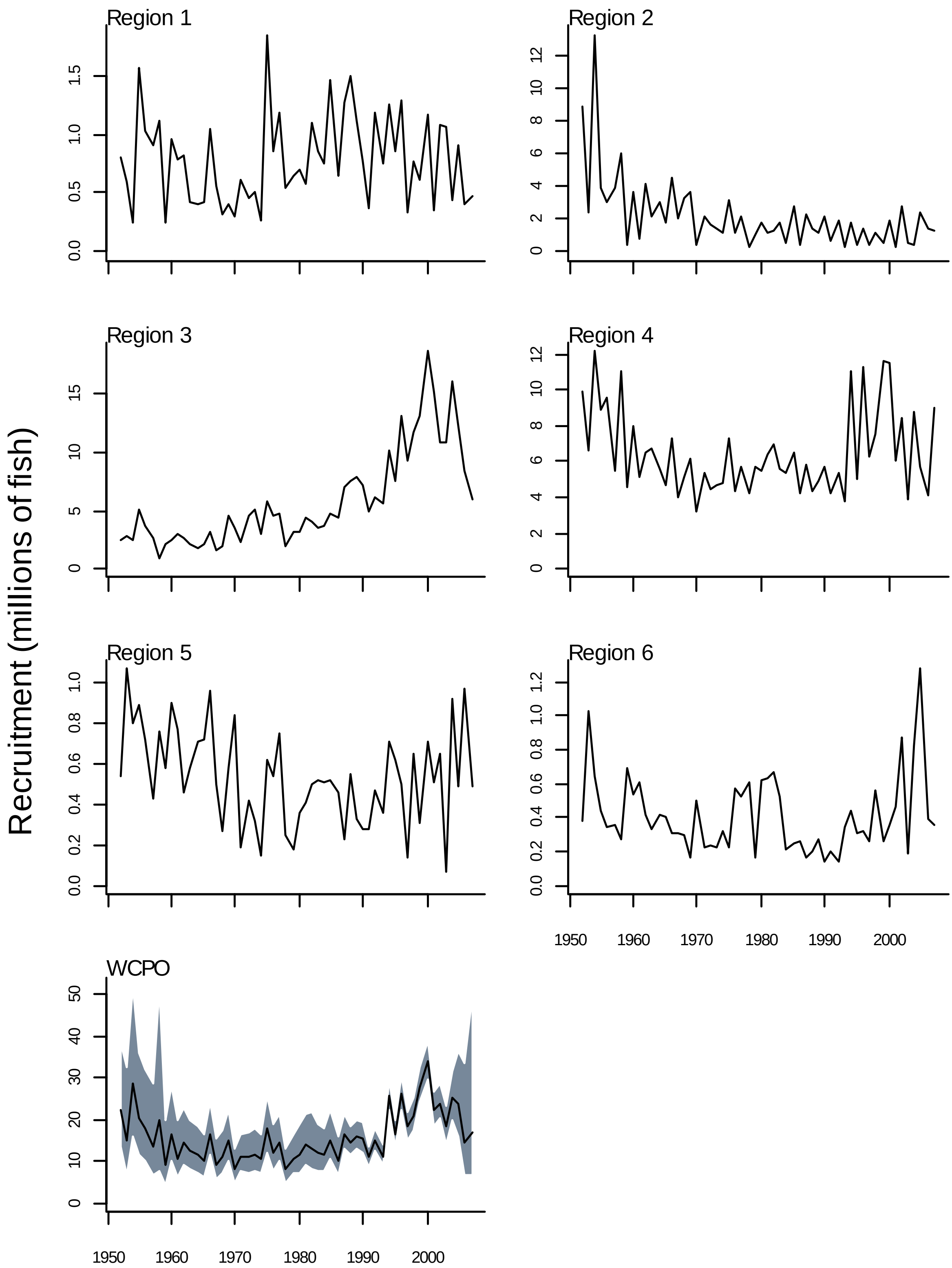


Figure 31. Estimated annual recruitment (millions) by region and for the WCPO. The shaded area for the WCPO indicates the approximate 95% confidence intervals.

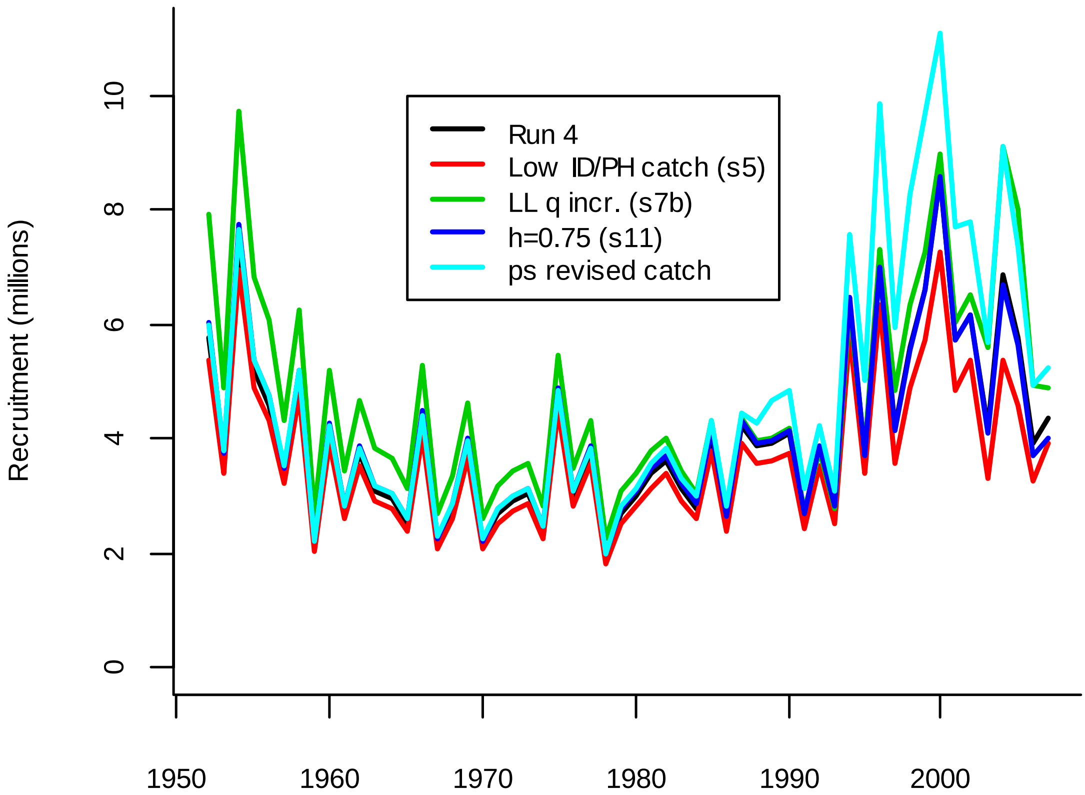


Figure 32. Estimated annual recruitment (millions of fish) for the WCPO obtained from five different model options.

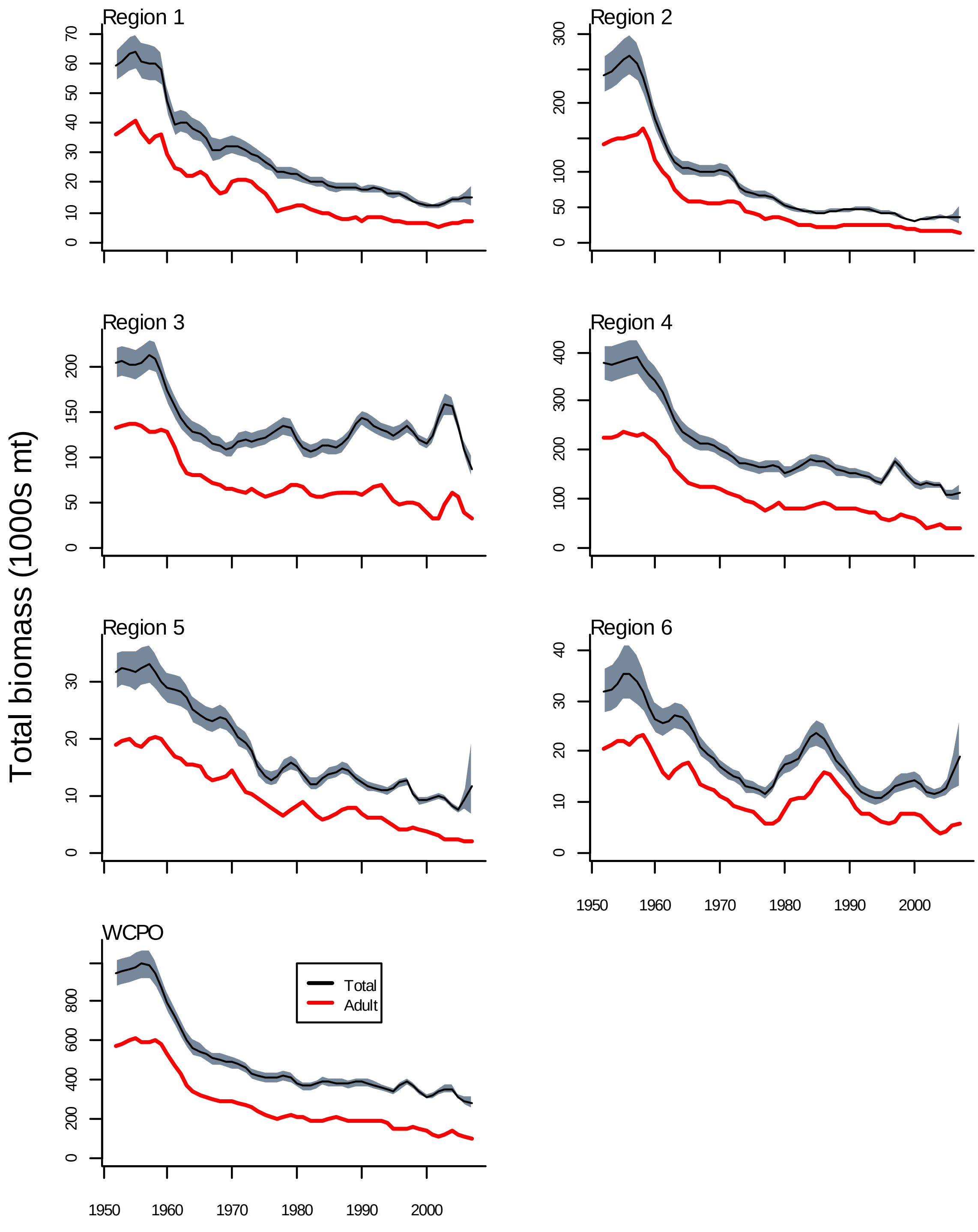


Figure 33. Estimated annual average total (black) and adult (red) biomass (thousand mt) by region and for the WCPO. The shaded areas around the total biomass indicate the approximate 95% confidence intervals.

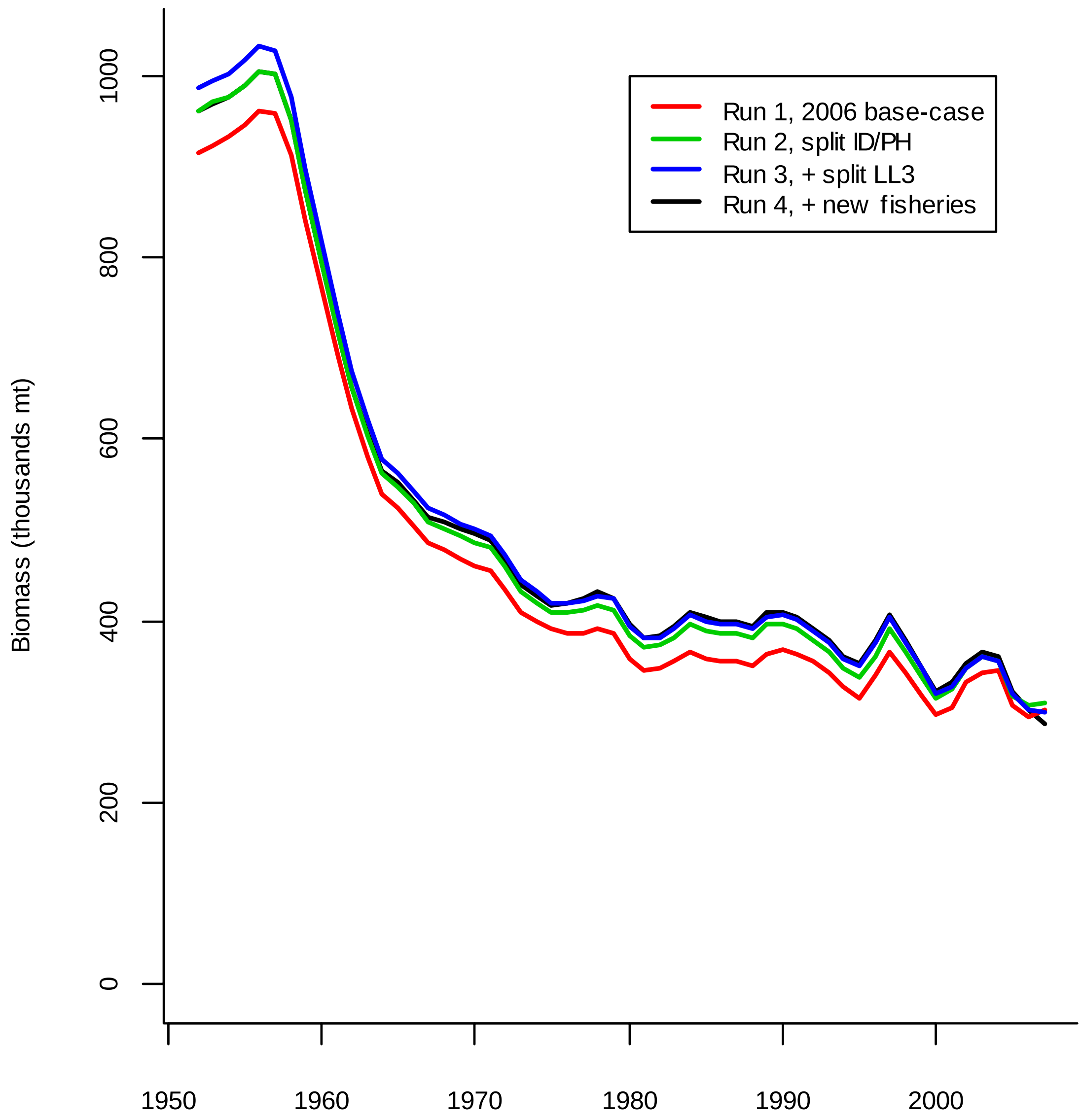


Figure 34. Estimated annual average total biomass (thousand mt) for the WCPO obtained from separate runs with different fishery configurations. Note: run 4 is obscured by run 3.

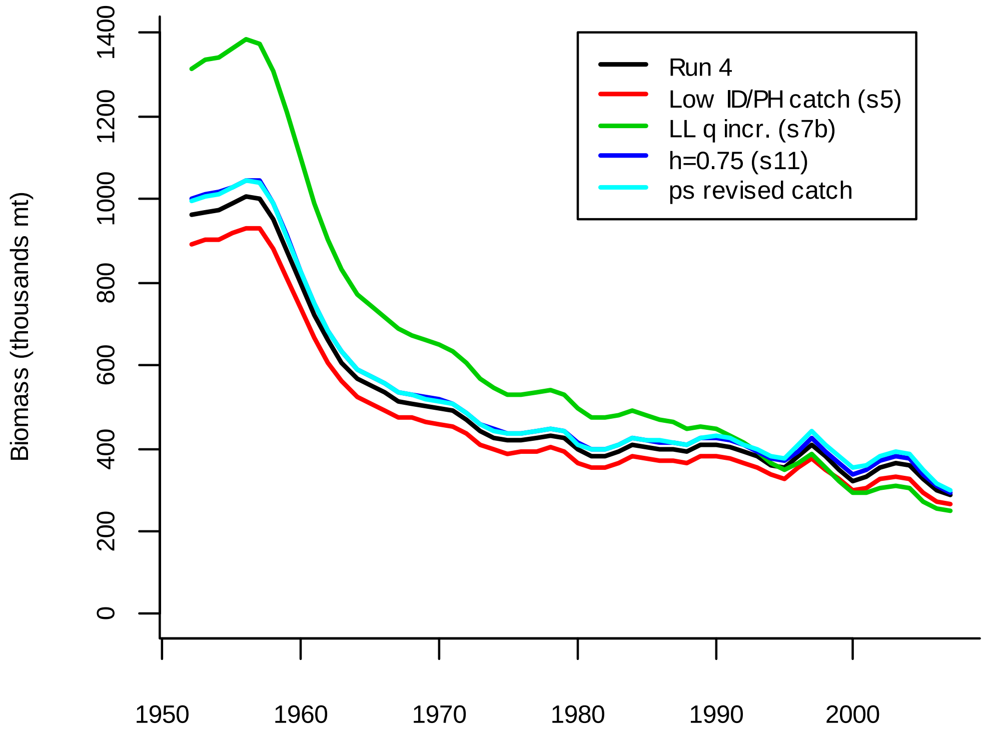


Figure 35. Estimated annual average total biomass (thousand mt) for the WCPO obtained from the separate analyses.

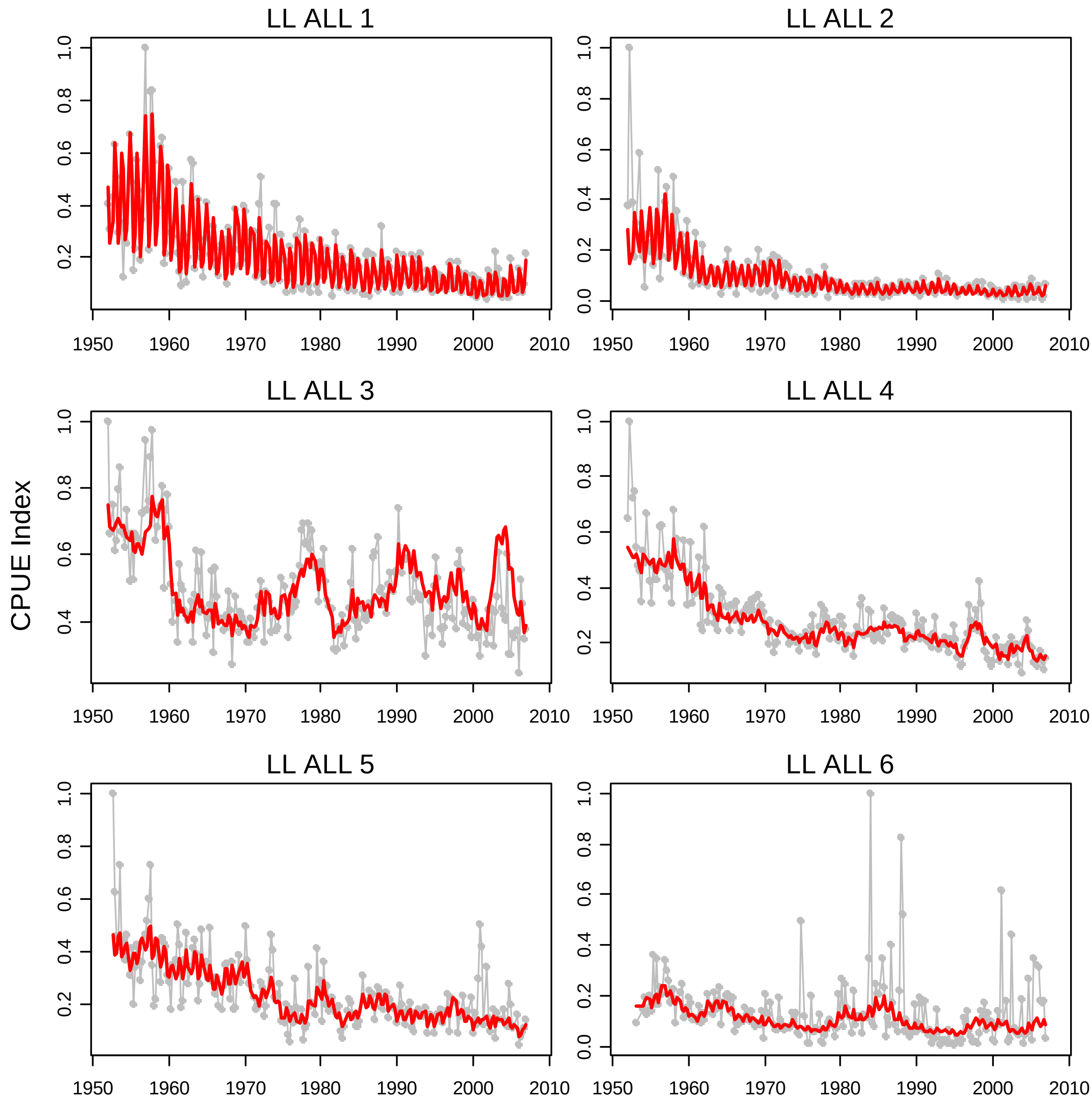


Figure 36. A comparison of longline exploitable biomass by quarter and region (red line) and the quarterly standardised CPUE indices for the fisheries.

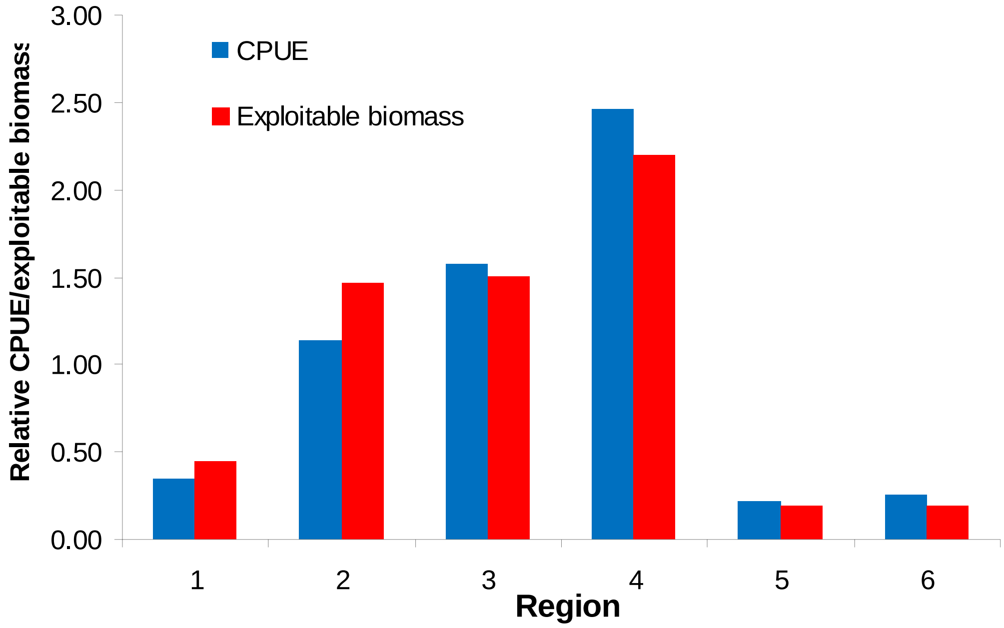


Figure 37. CPUE and exploitable abundance for LL ALL 1–6 averaged over all time periods. Values for each region are scaled relative to their averages across all regions.

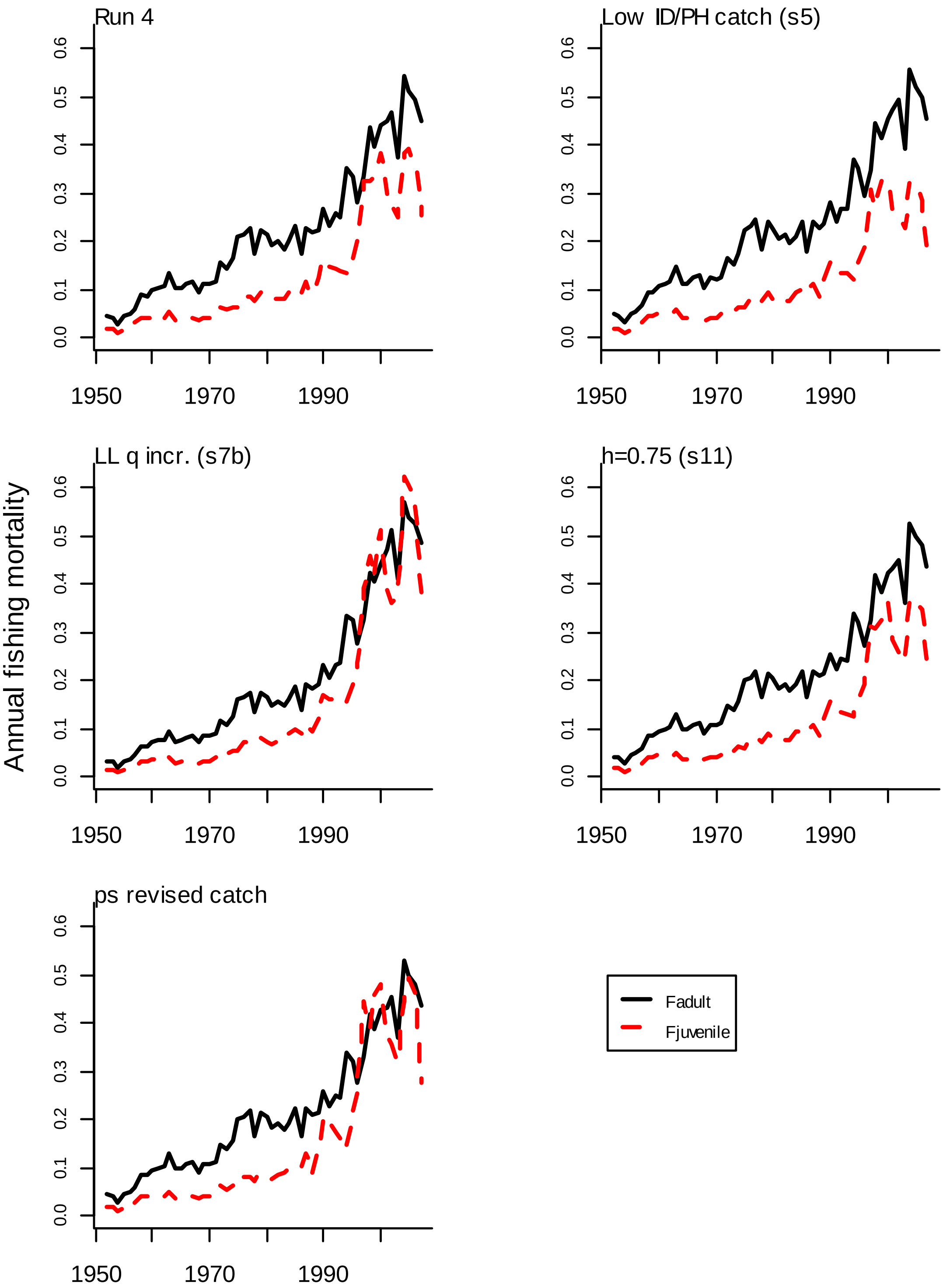


Figure 38. Estimated annual average juvenile and adult fishing mortality for the WCPO obtained from selected analyses.

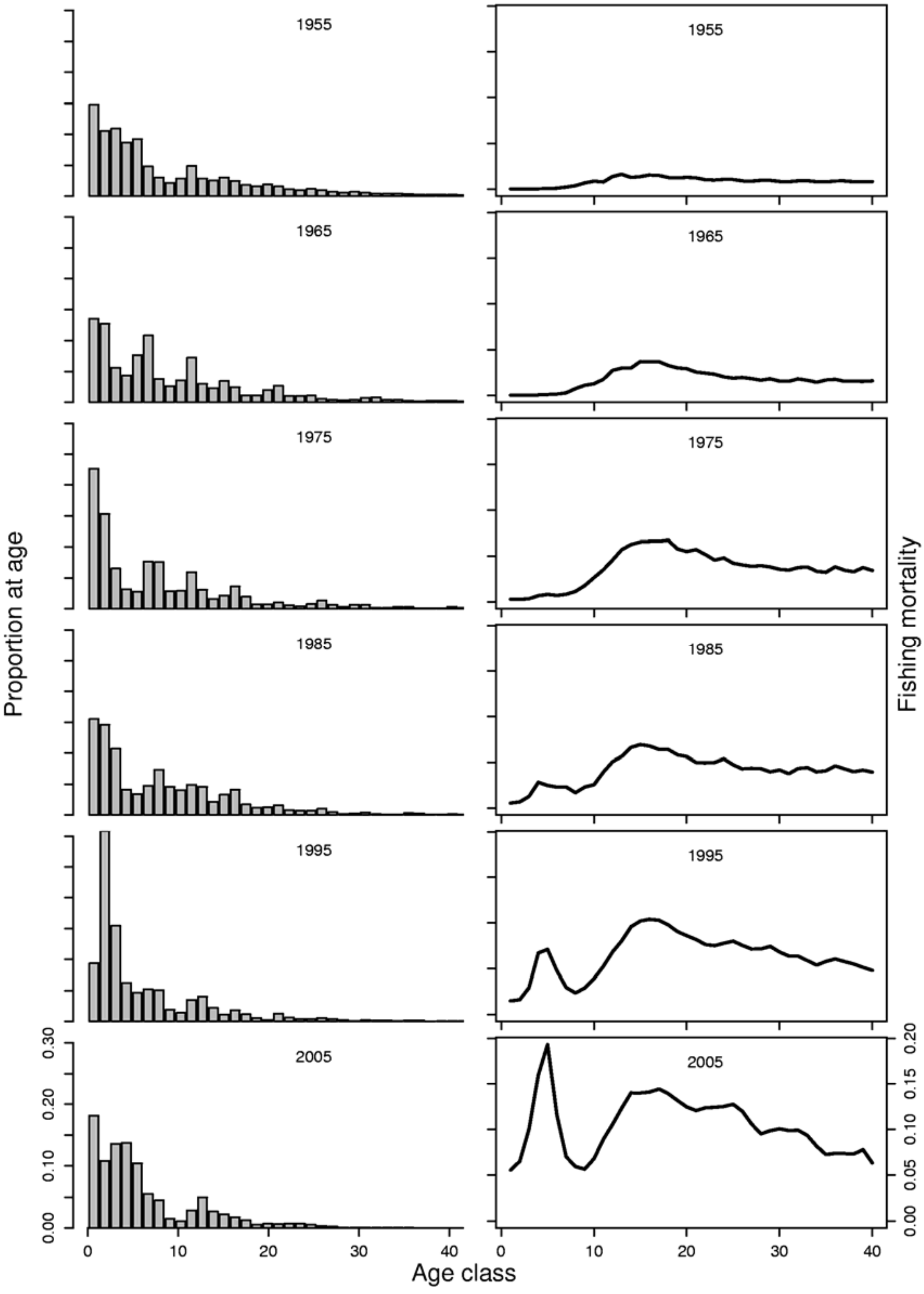


Figure 39. Estimated proportion at age (quarters) for the WCPO bigeye population (left) and fishing mortality at age (right) by year at decade intervals.

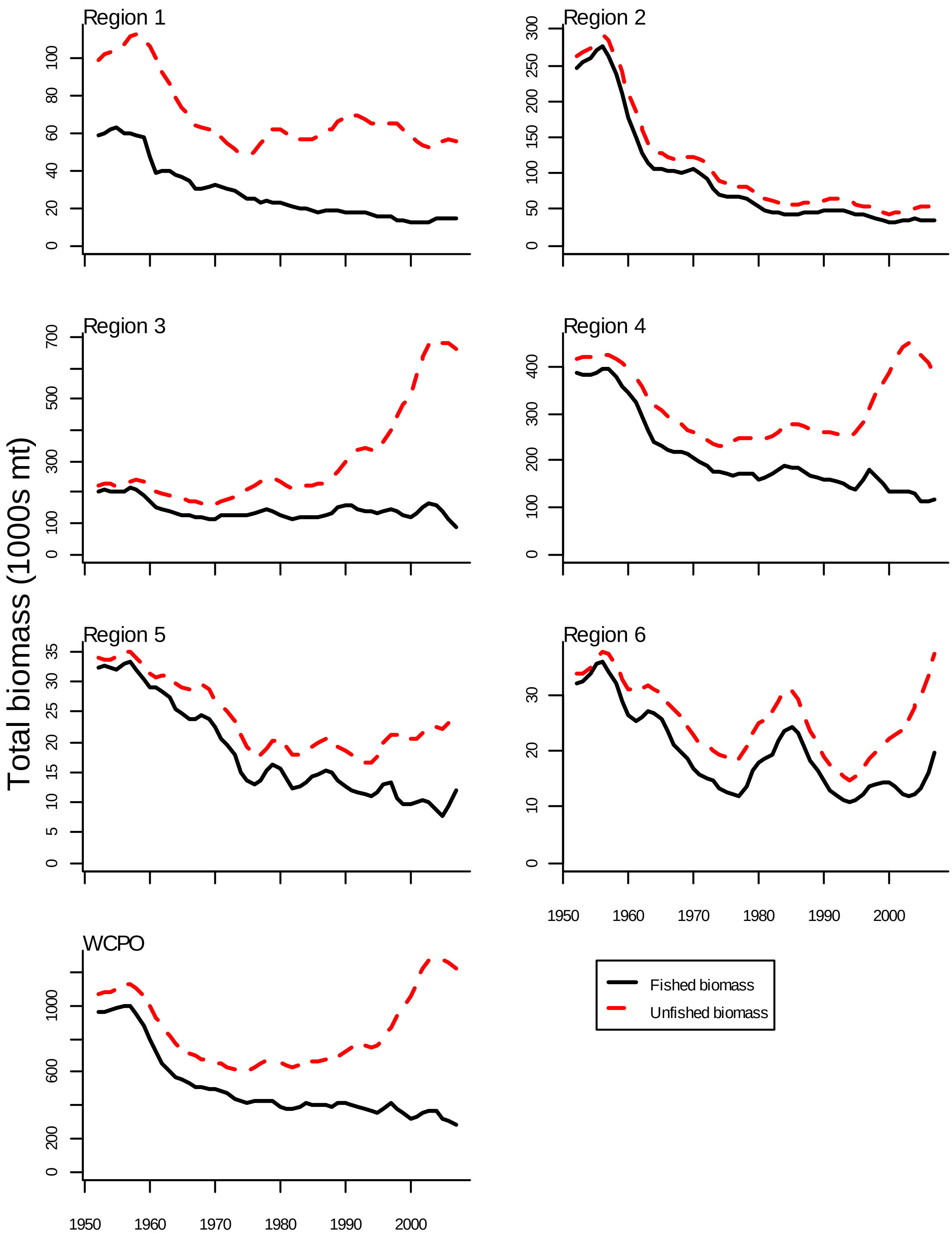


Figure 40. Comparison of the estimated biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper dashed lines) for each region and for the WCPO (base case model).

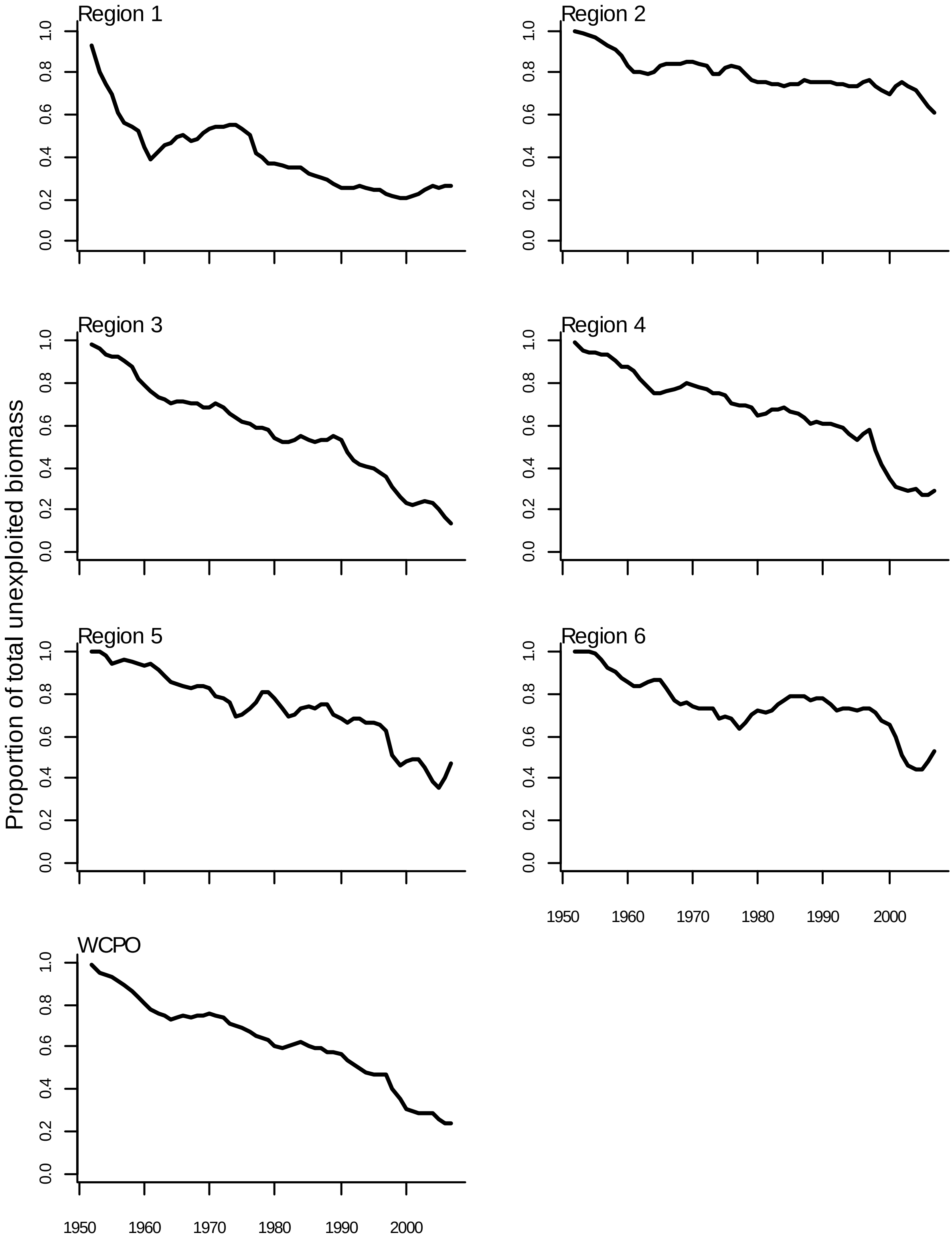


Figure 41. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the WCPO (base case model).

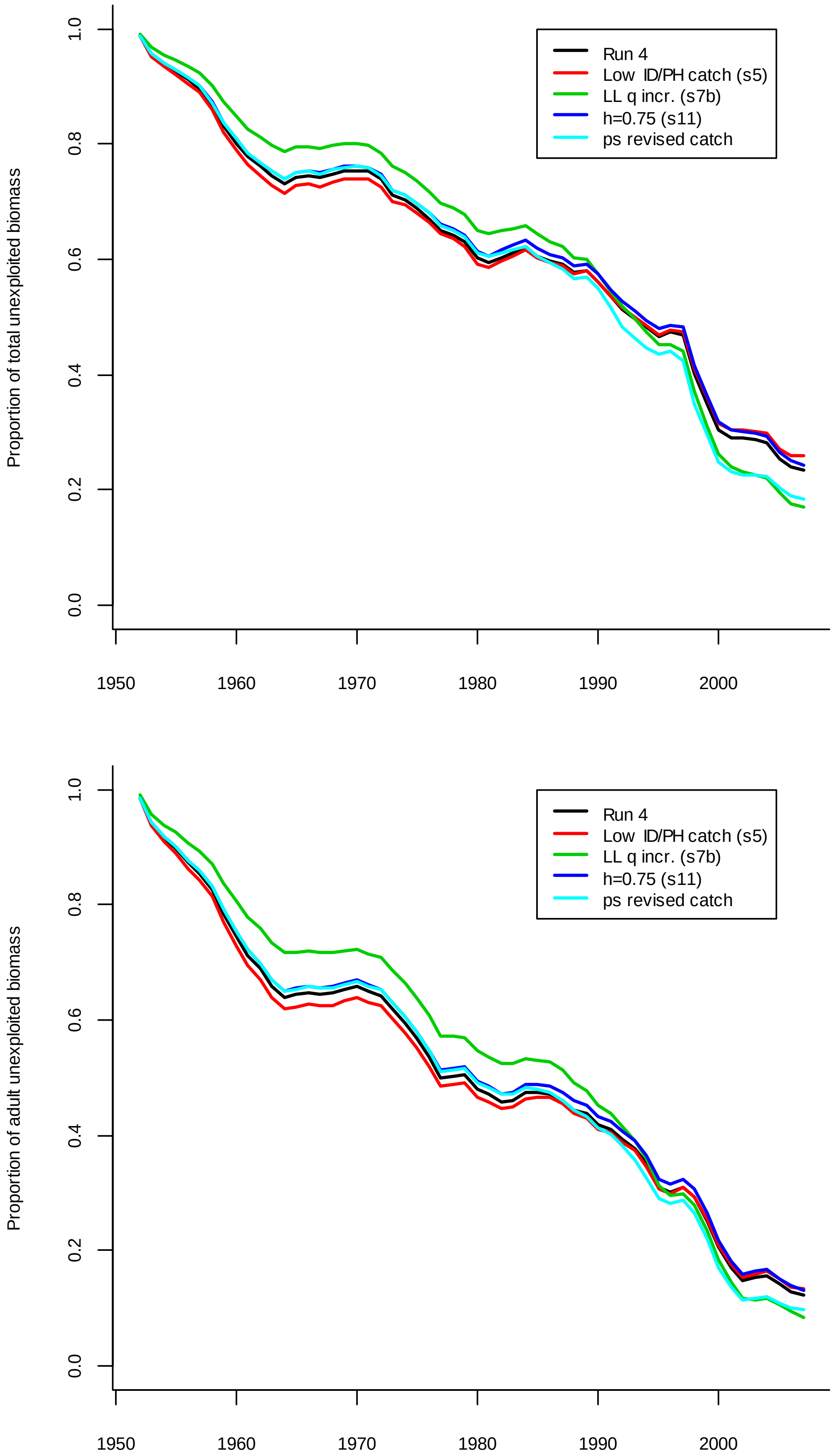


Figure 42. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) (top) and adult biomass ($SB_t/SB_{0,t}$) (bottom) for the WCPO obtained from the separate analyses.

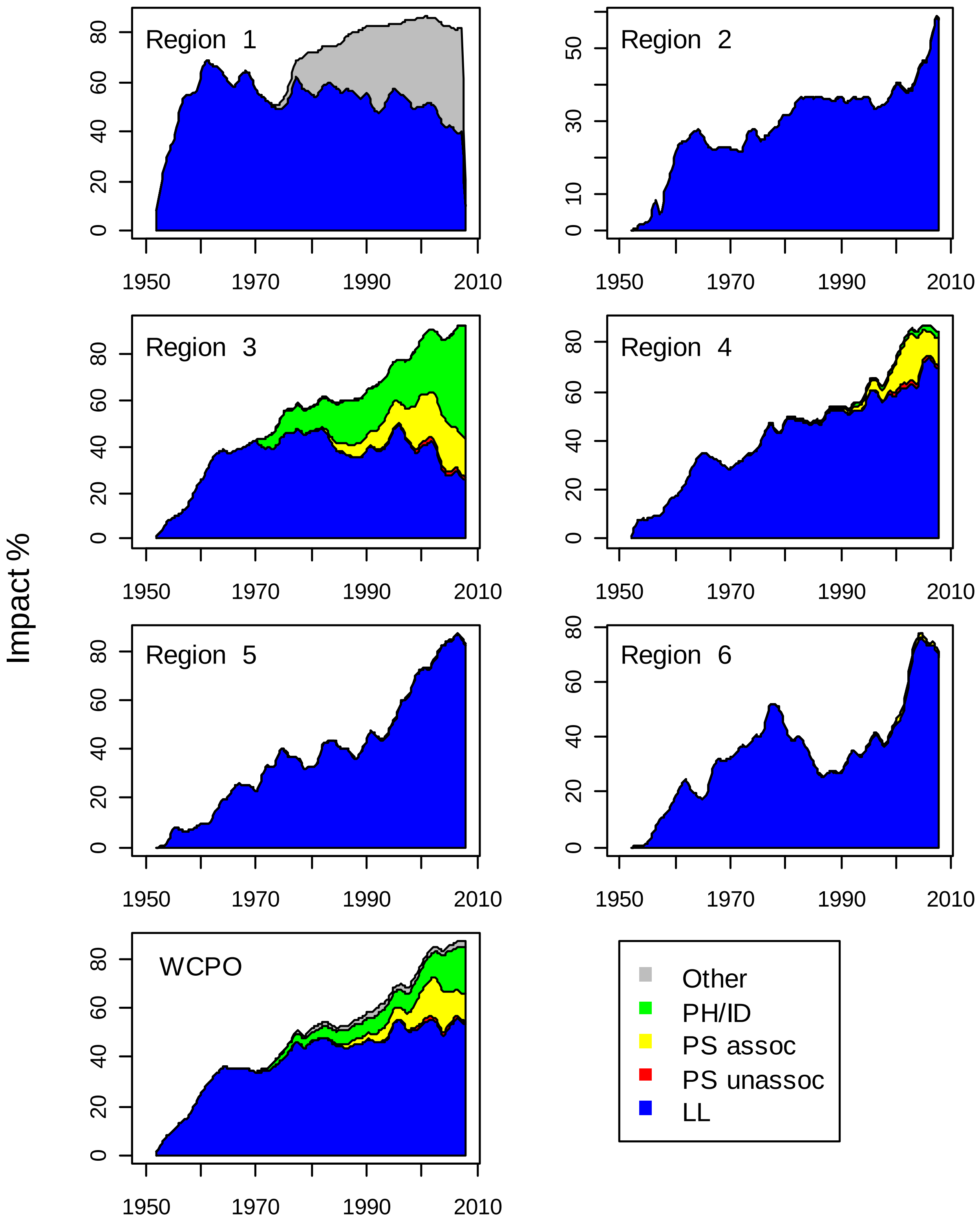


Figure 43. Estimates of reduction in spawning biomass due to fishing (fishery impact = 1-$SB_t/SB_{0,t}$) by region and for the WCPO attributed to various fishery groups (base case model). LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine log and FAD sets; PS unassoc = purse seine school sets; Other = pole and line fisheries and coastal Japan purse-seine.

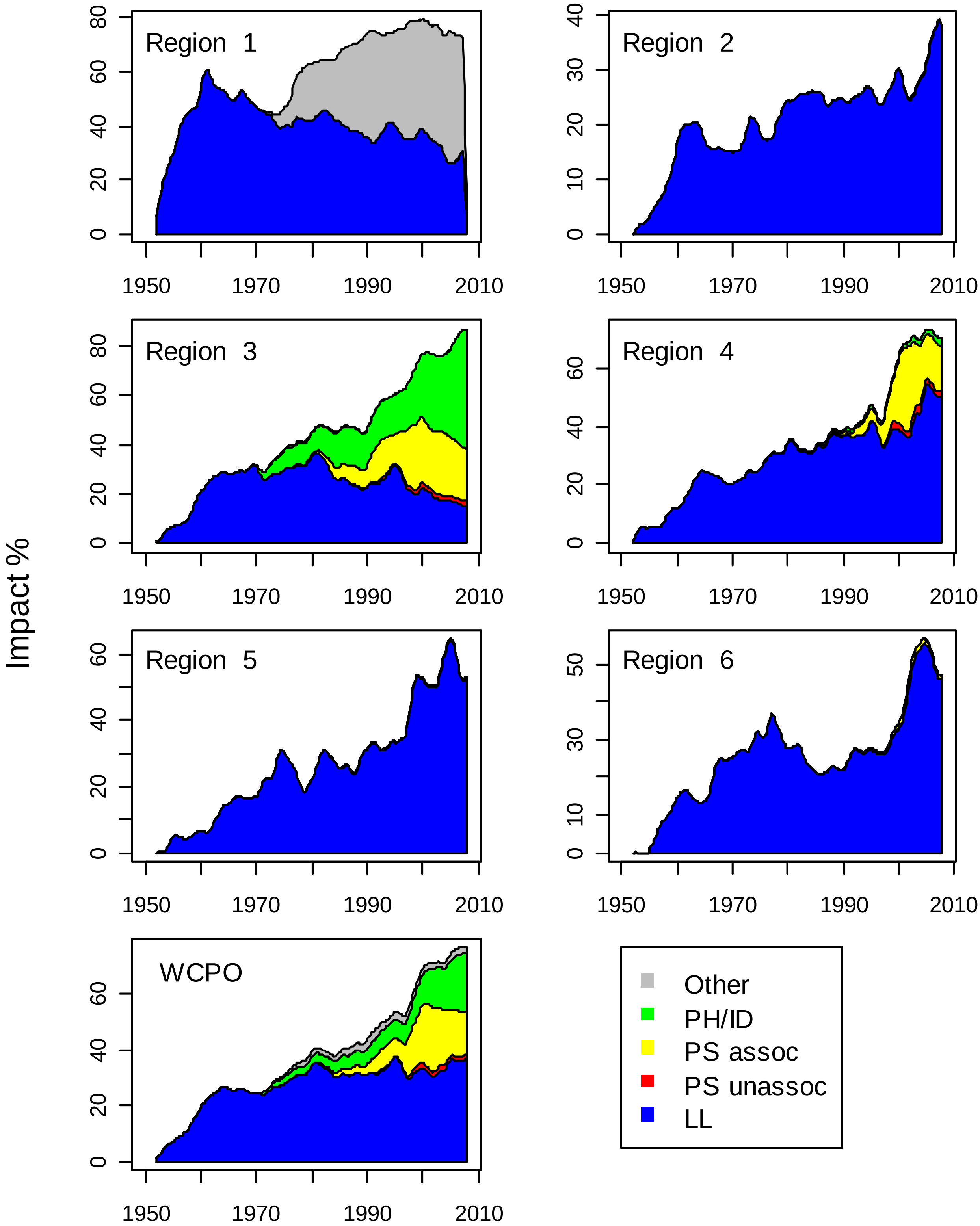


Figure 44. Estimates of reduction in total biomass due to fishing (fishery impact = 1-$B_t/B_{0,t}$) by region and for the WCPO attributed to various fishery groups (base case model). LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine log and FAD sets; PS unassoc = purse seine school sets; Other = pole and line fisheries and coastal Japan purse-seine.

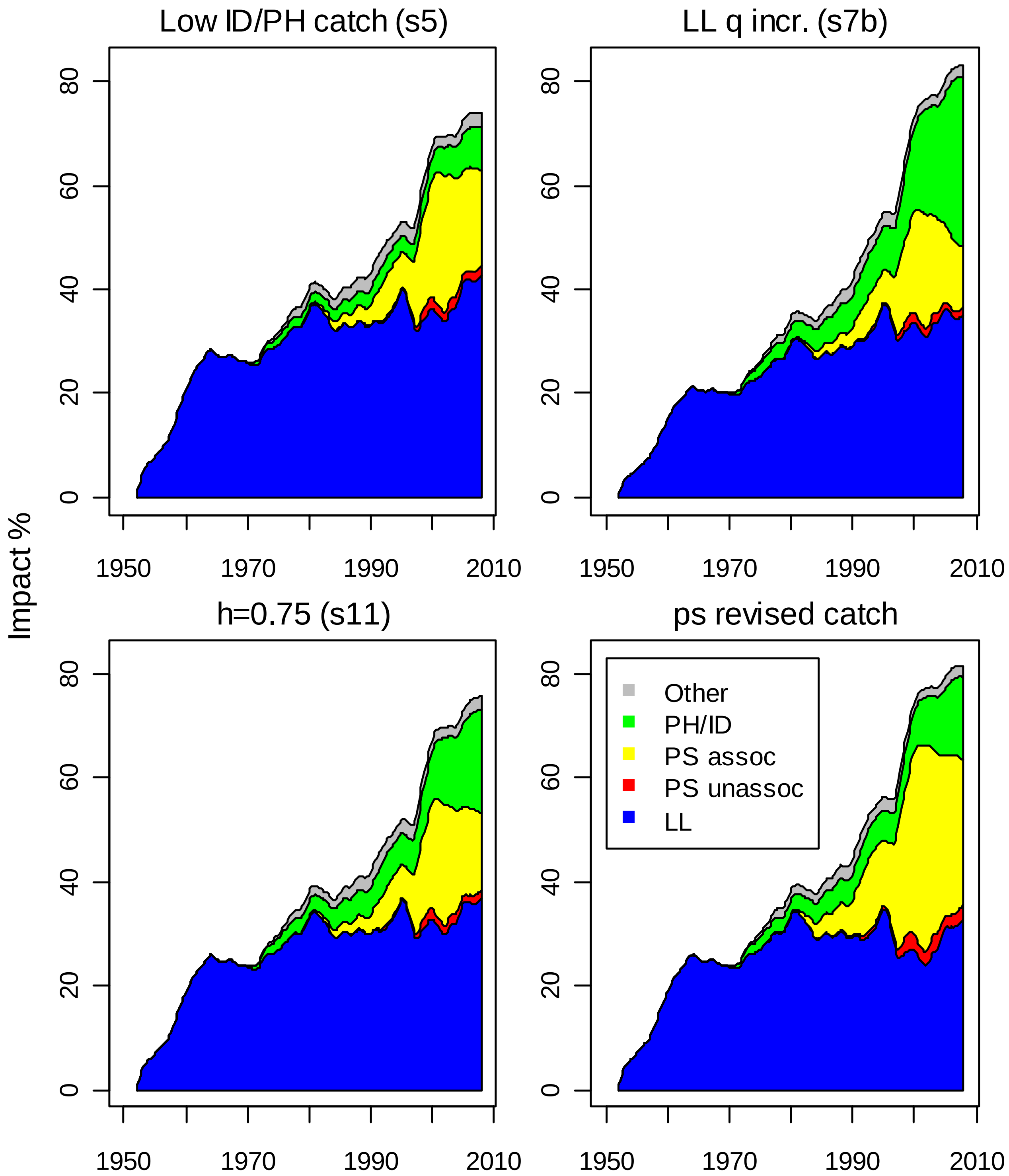


Figure 45. Estimates of reduction in WCPO total biomass due to fishing (fishery impact = 1-$B_t/B_{0,t}$) attributed to various fishery groups for the four main alternative models. LL = all longline fisheries; PH/ID = Philippines and Indonesian domestic fisheries; PS assoc = purse seine log and FAD sets; PS unassoc = purse seine school sets; Other = pole and line fisheries and coastal Japan purse-seine.

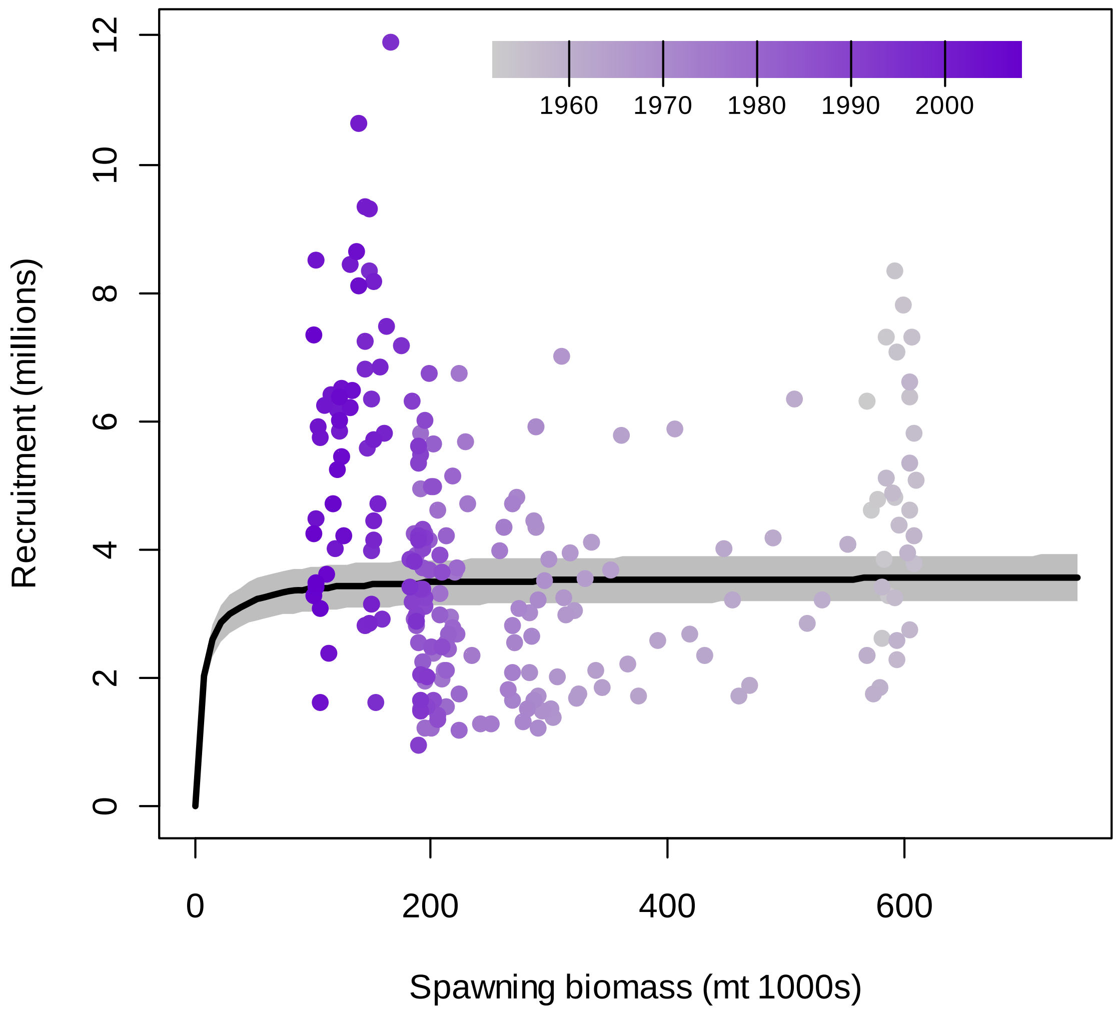


Figure 46. Estimated relationship between equilibrium recruitment and equilibrium spawning biomass. The grey area indicates the 95% confidence region. Estimated recruitment-spawning biomass points are plotted as points. The legend denotes the quarter of recruitment.

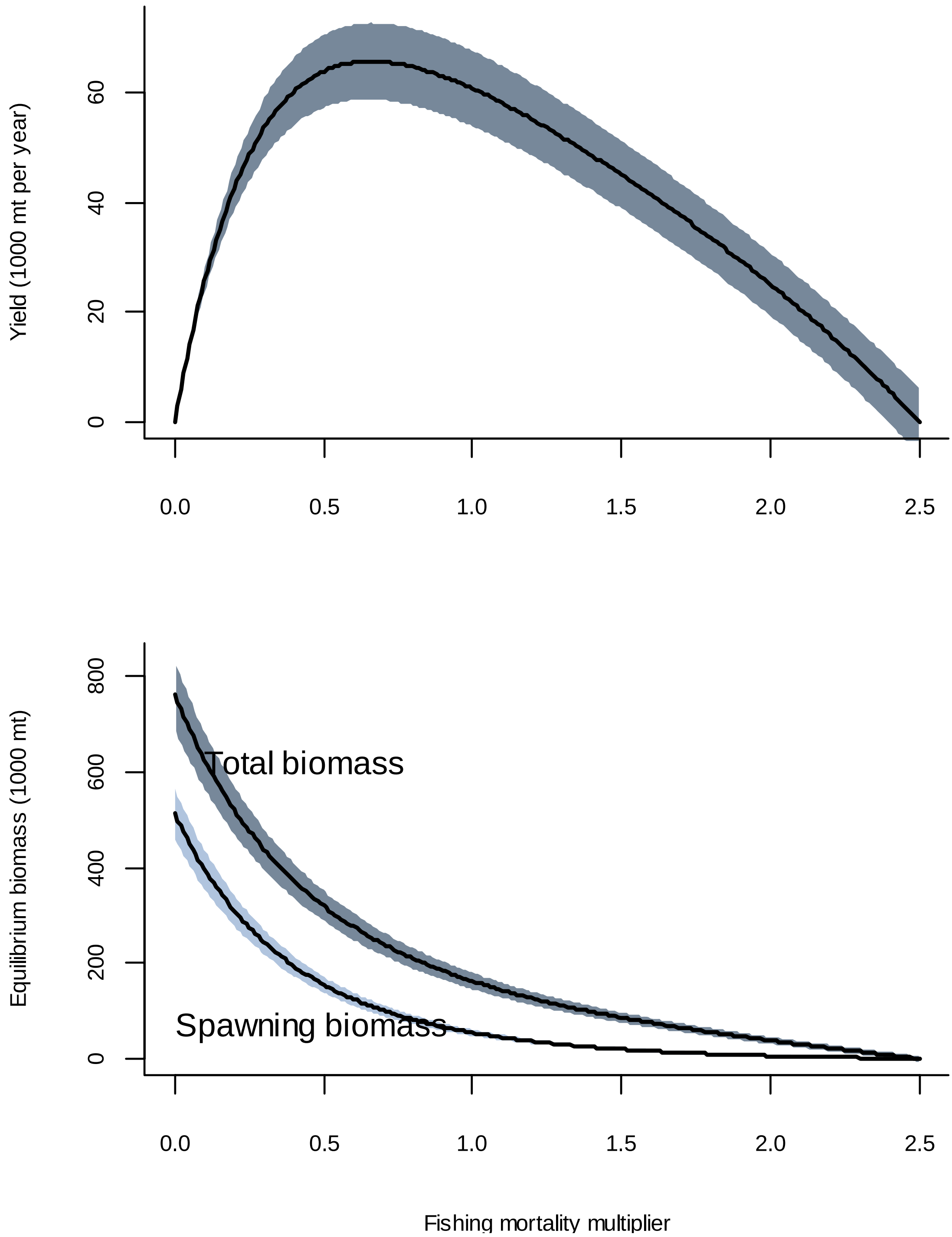


Figure 47. Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier. The shaded areas represent approximate 95% confidence intervals.

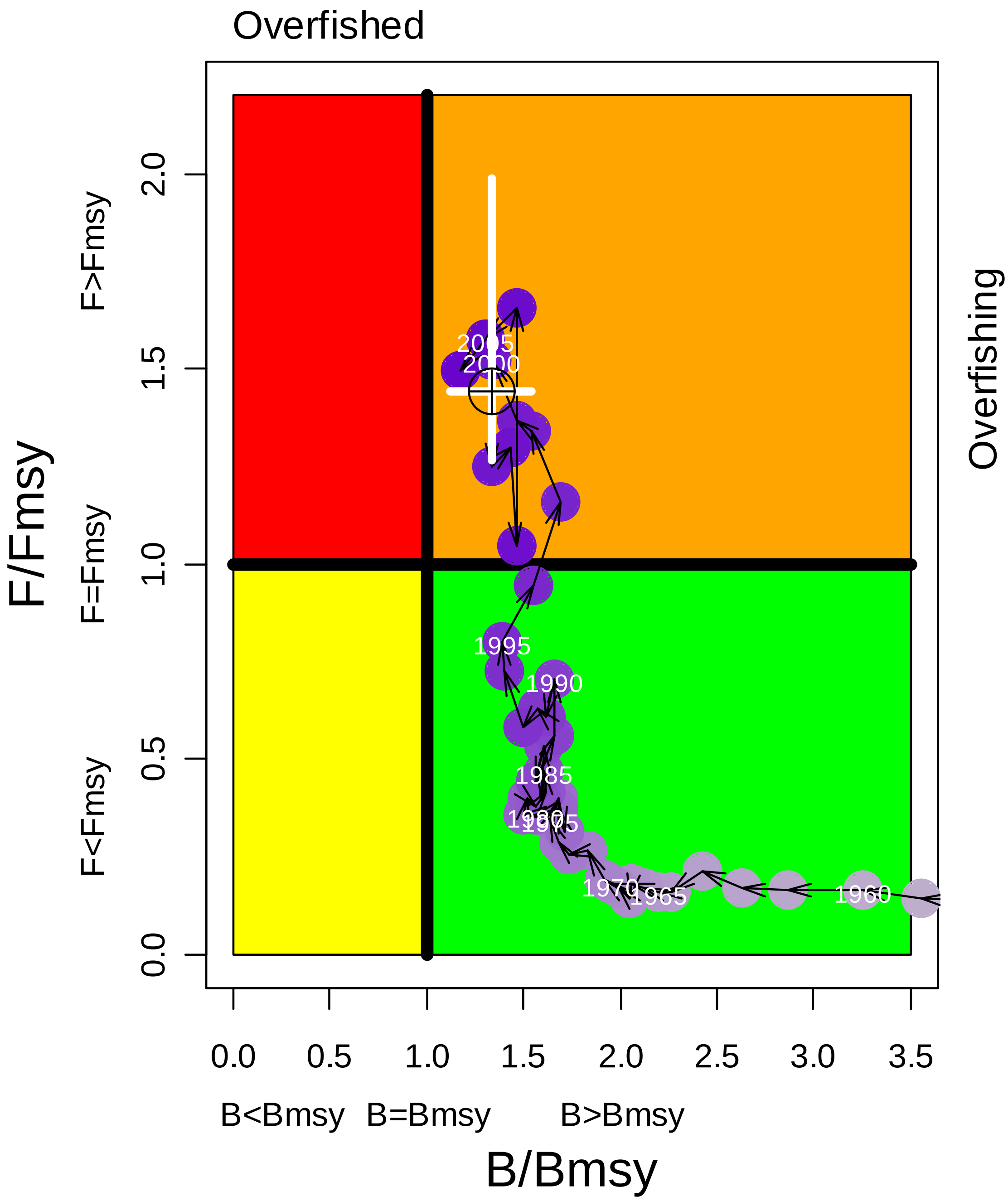


Figure 48. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1952–2006) from the base-case model (run 4). The colour of the points is graduated from mauve (1952) to dark purple (2006) and the points are labelled at 5-year intervals. The white lines represent the confidence interval of associated with F/F_{MSY} and B/B_{MSY}. The last year of the model (2007) is excluded as it is highly uncertain.

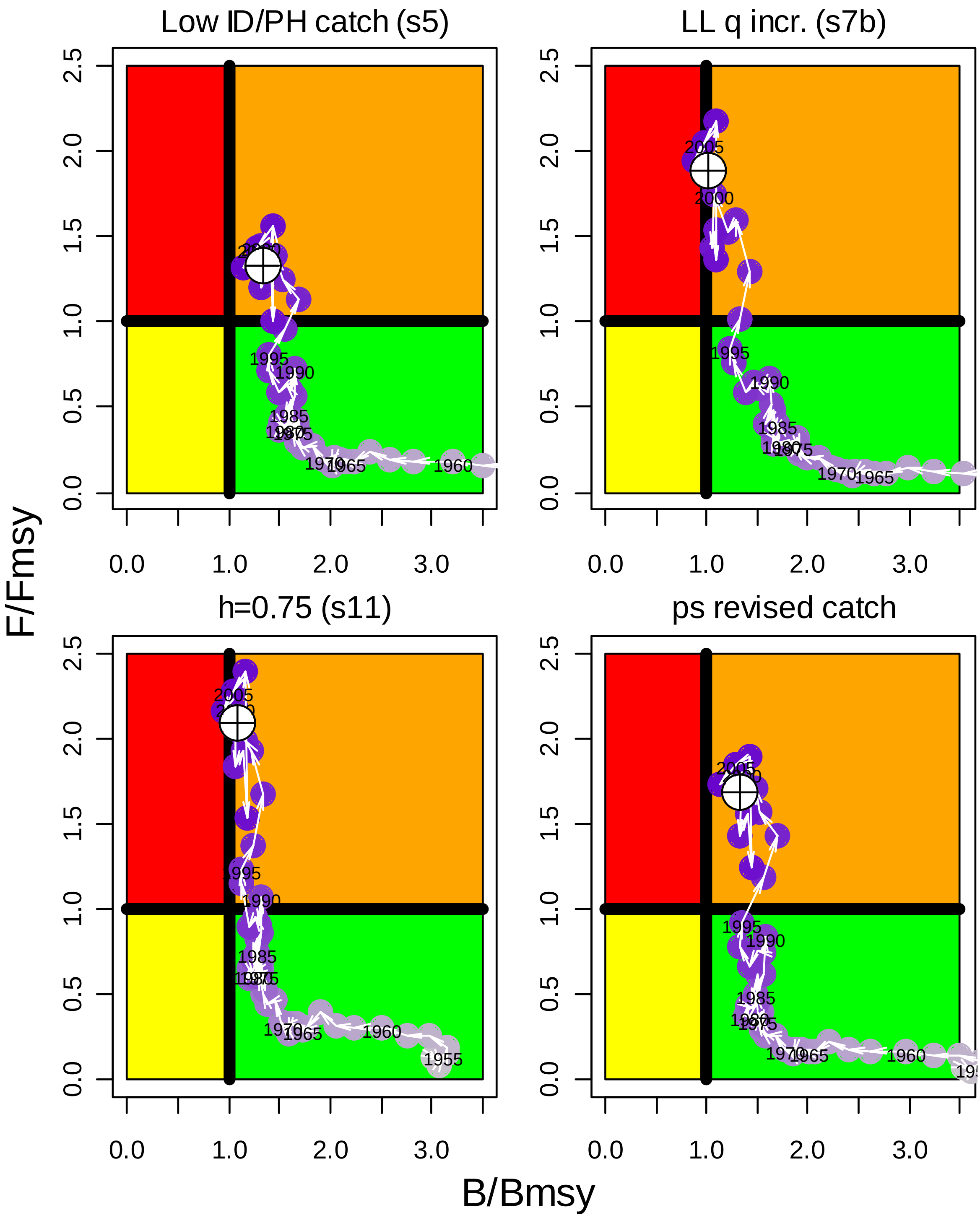


Figure 49. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1952–2006) for the four main alternative models. The colour of the points is graduated from mauve (1952) to dark purple (2006) and the points are labelled at 5-year intervals. The last year of the model (2007) is excluded as it is highly uncertain.

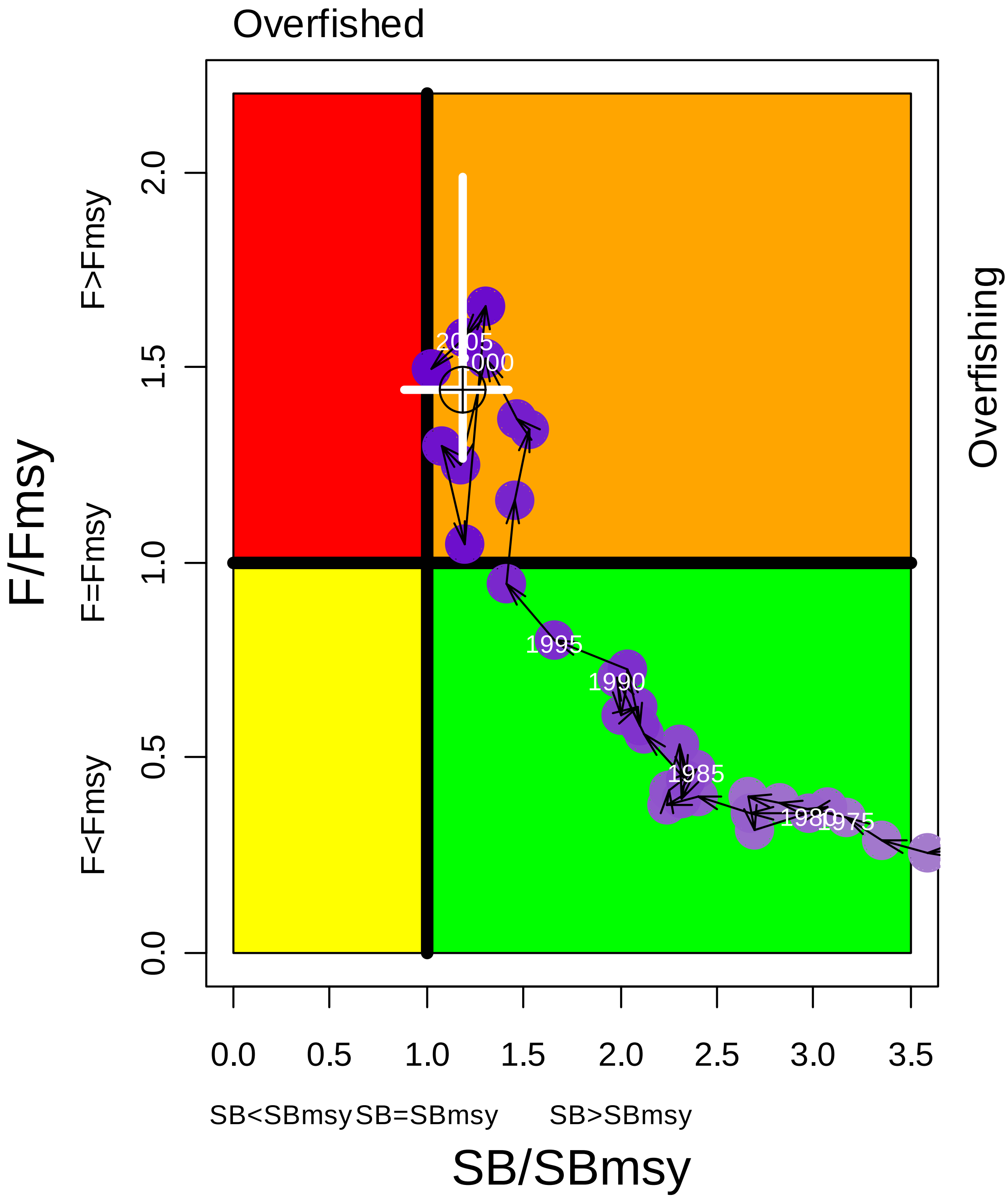


Figure 50. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1952–2006) from the base-case model (run 4). The colour of the points is graduated from mauve (1952) to dark purple (2006) and the points are labelled at 5-year intervals. The white lines represent the confidence interval of associated with F/F_{MSY} and SB/SB_{MSY}. The last year of the model (2007) is excluded as it is highly uncertain.

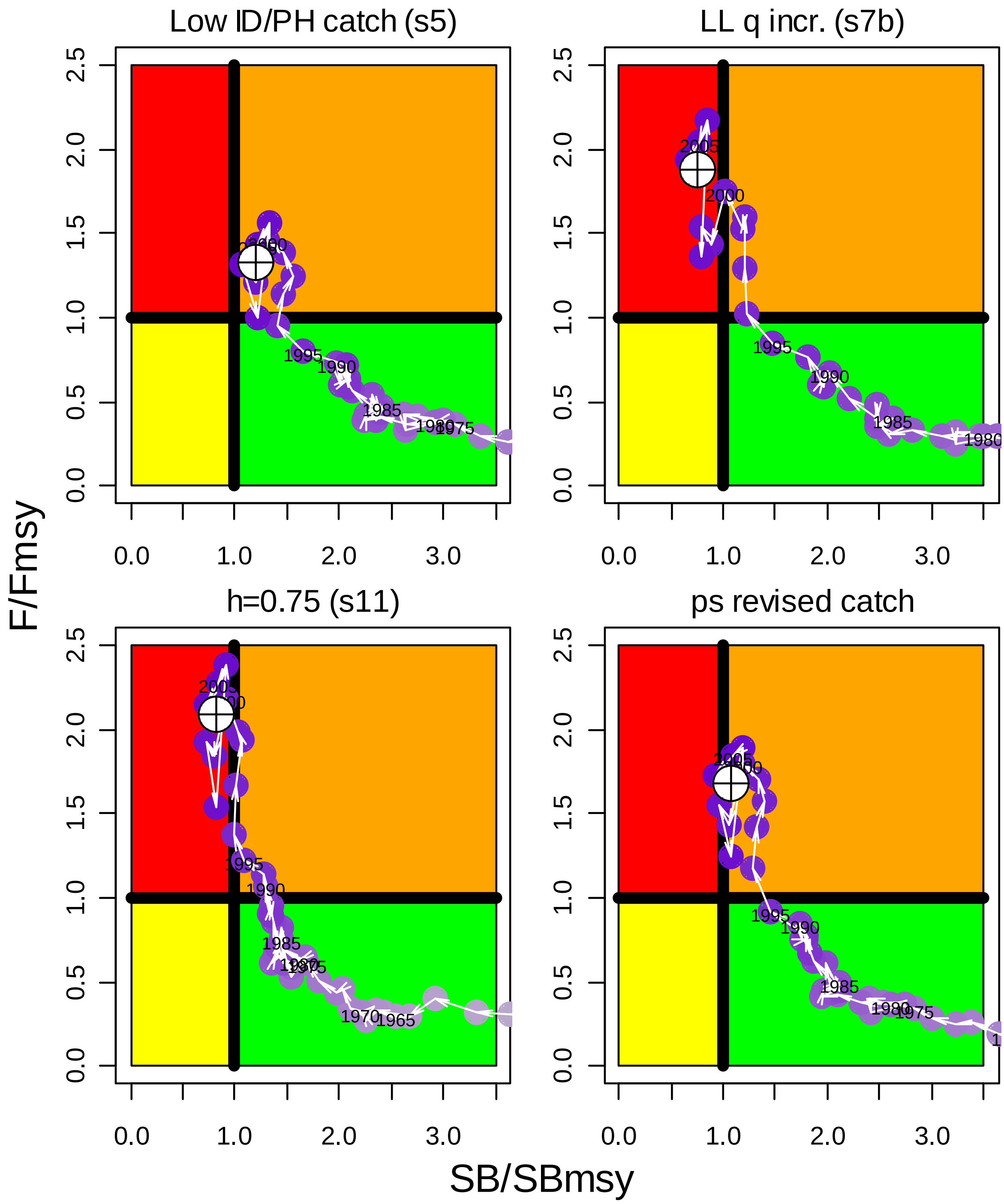


Figure 51. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period (1952–2006) for the four main alternative models. The colour of the points is graduated from mauve (1952) to dark purple (2006) and the points are labelled at 5-year intervals. The last year of the model (2007) is excluded as it is highly uncertain.

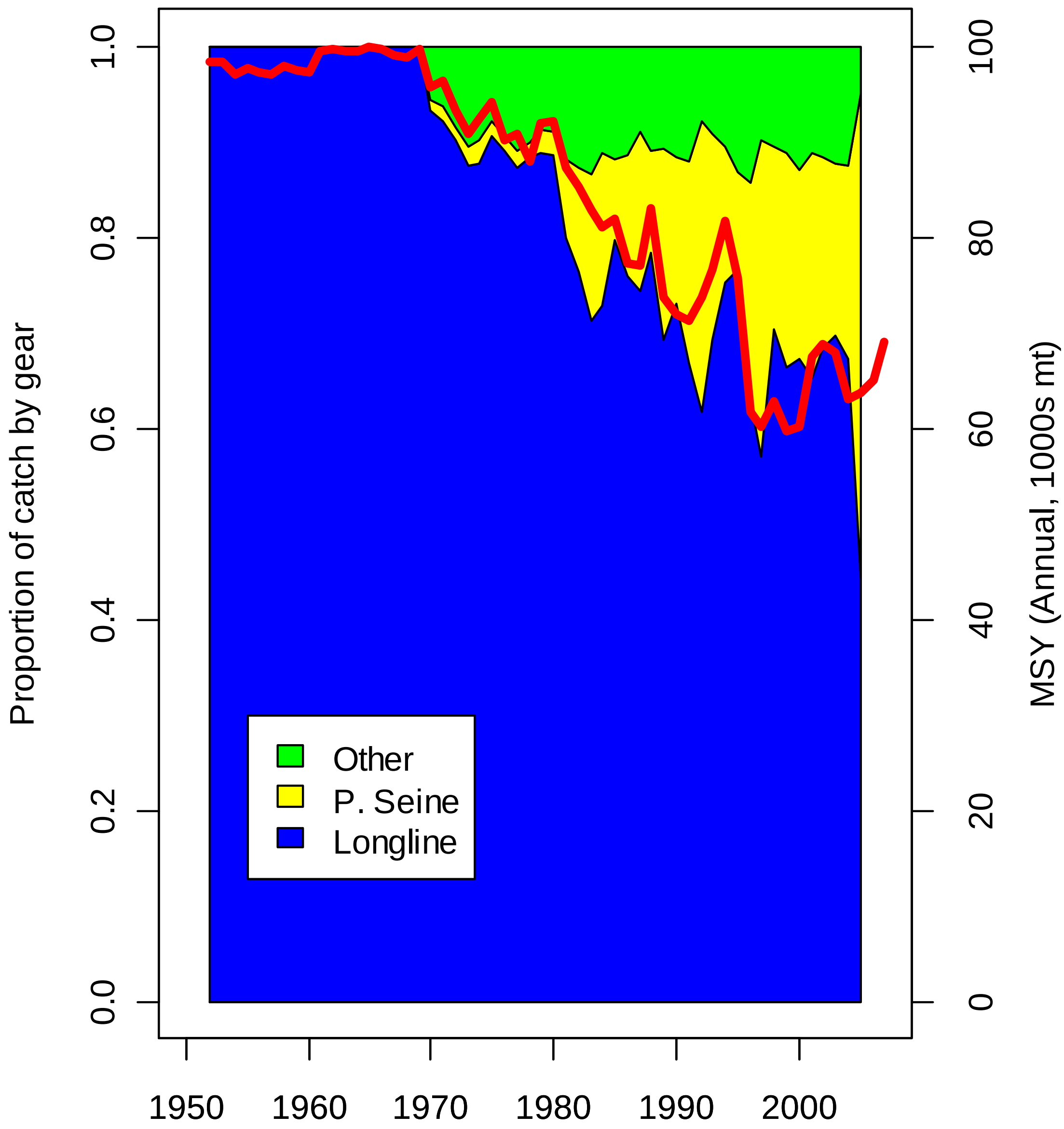


Figure 52. Temporal trend in annual Maximum Sustainable Yield (MSY) (red line) estimated for each year included in the bigeye stock assessment model. This is compared to the proportional distribution in the annual bigeye catch by main gear type for the entire WCPO.

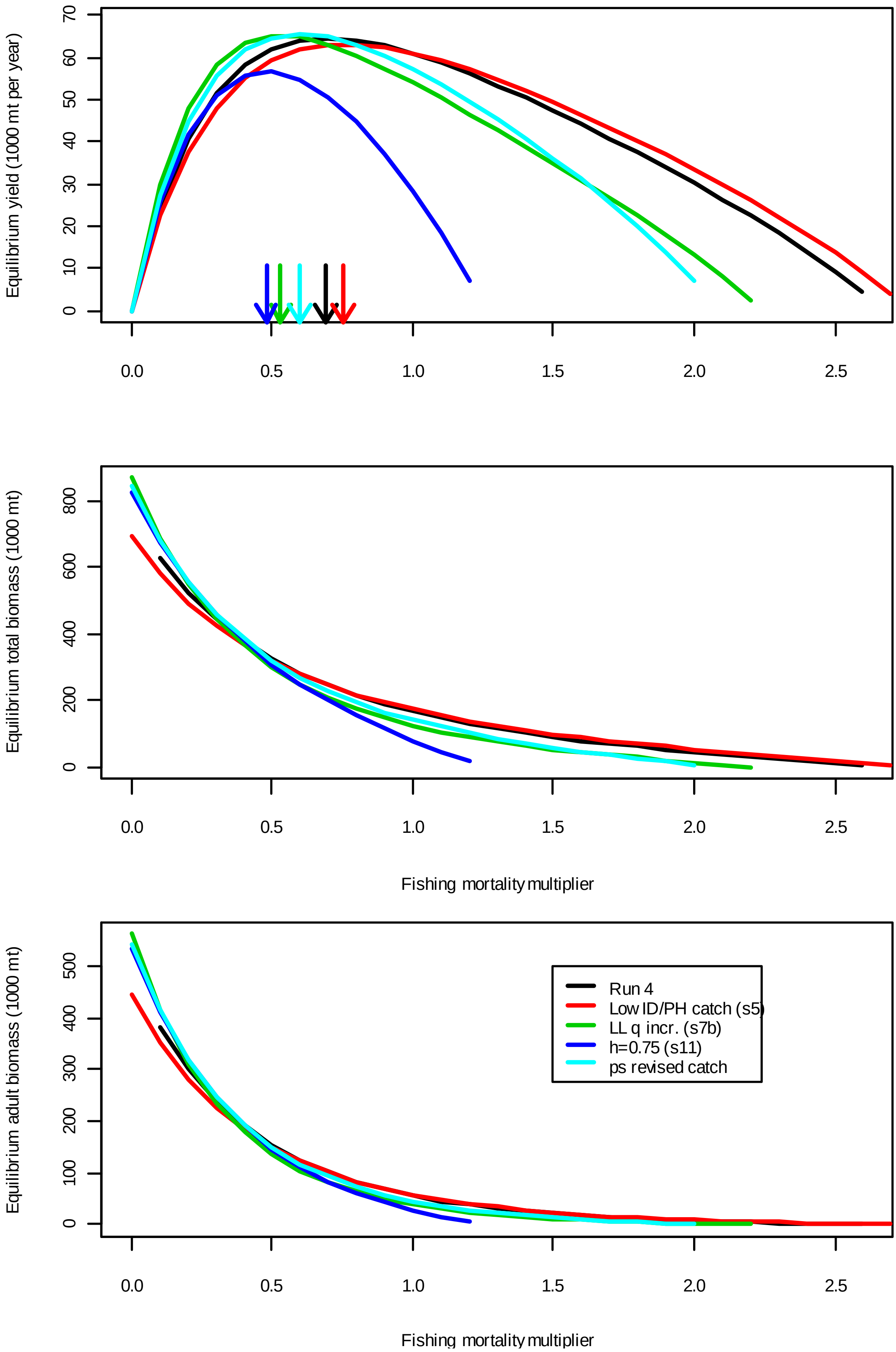


Figure 53. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier (*F*-mult) obtained from the separate analyses.

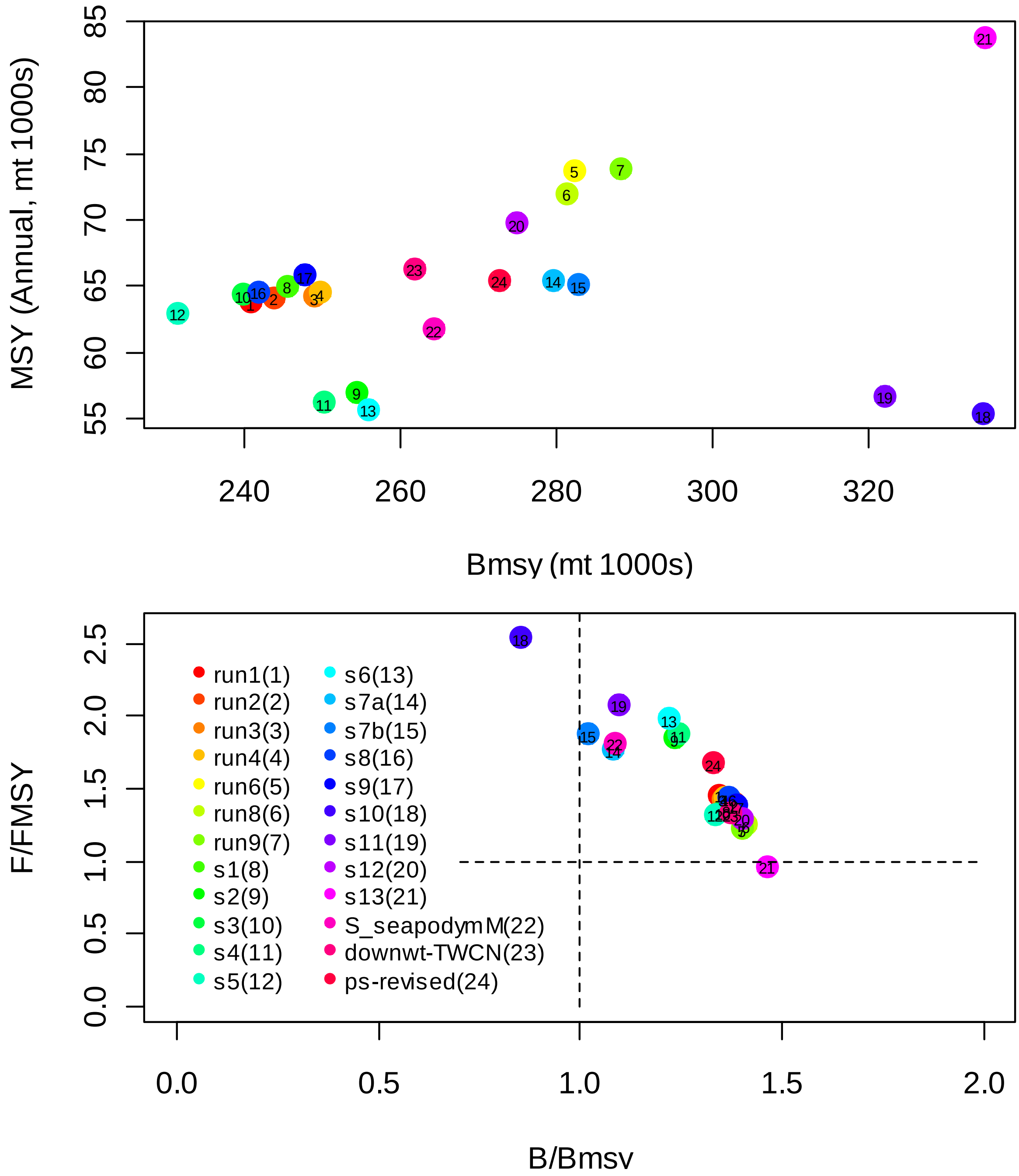


Figure 54. A comparison of MSY and B_{MSY} (top) and current exploitation rates and biomass levels relative to the MSY-based reference points (bottom) for the range of sensitivity analyses (see Table 3 and Table 4).

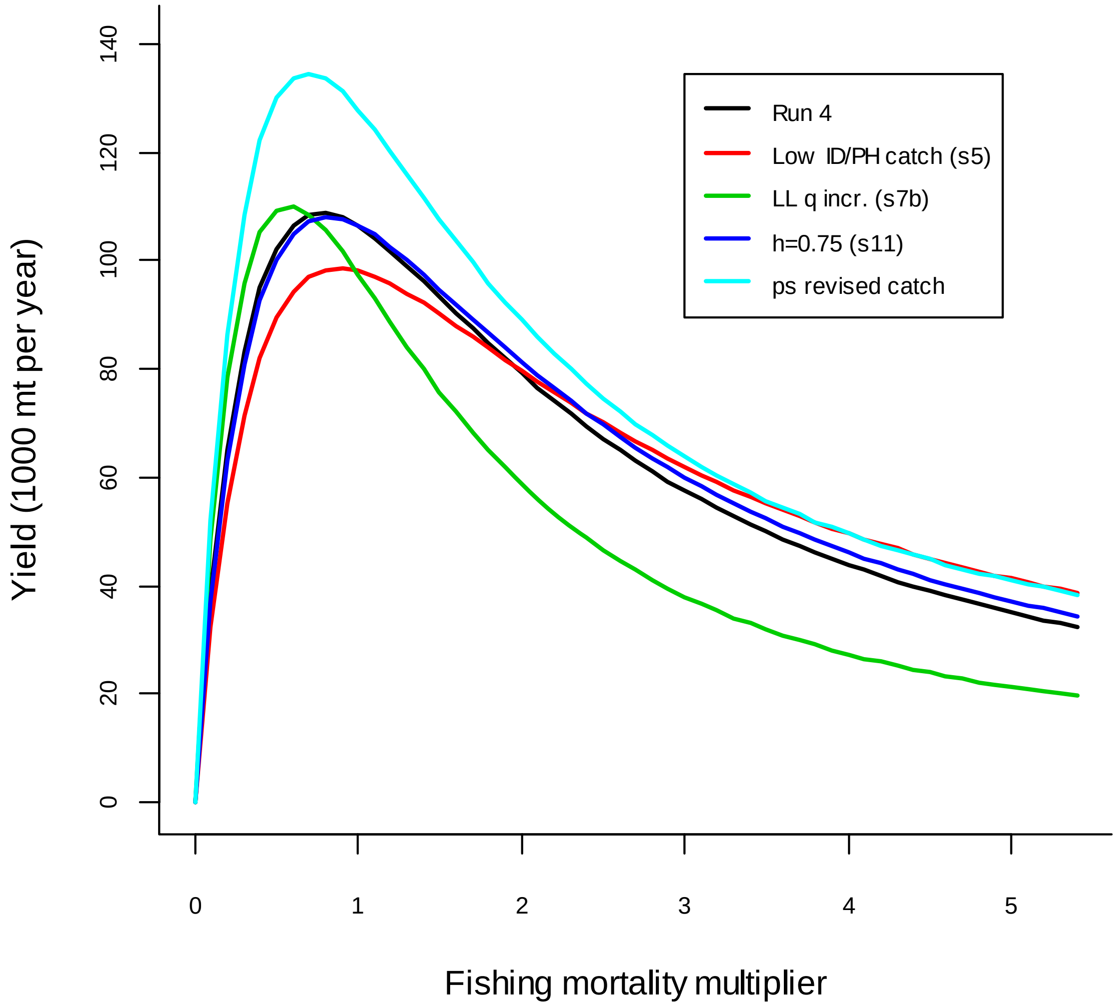


Figure 55. Yield curves based on 1997–2006 average recruitment.

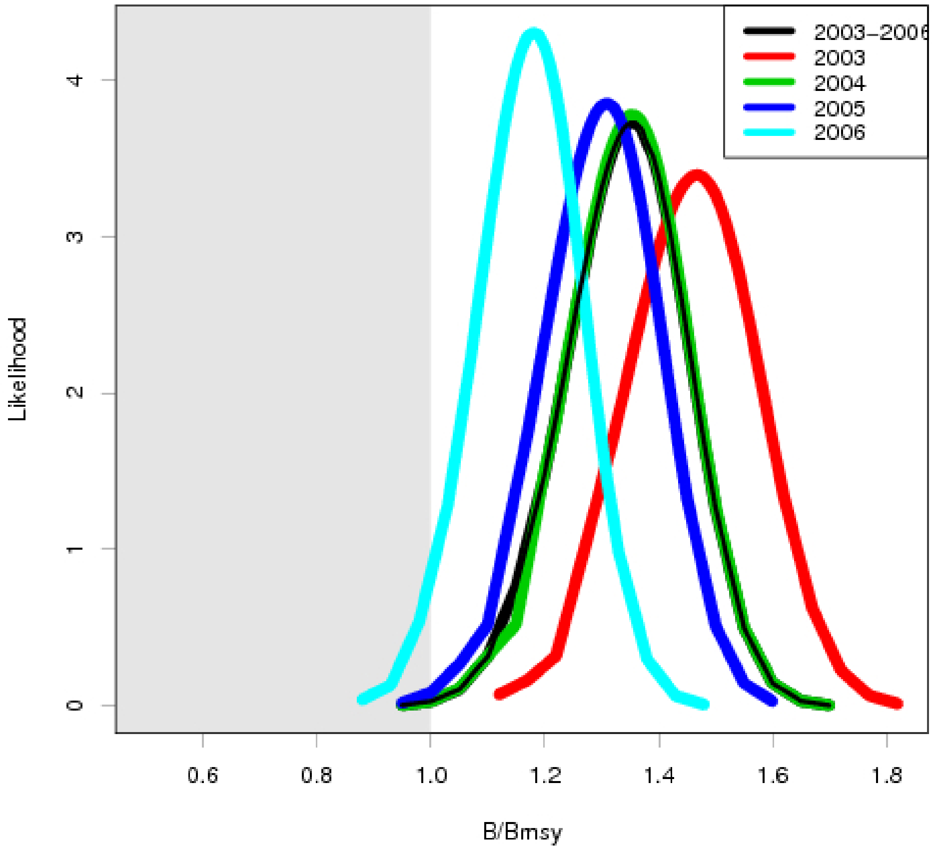


Figure 56. Probability distribution of $B_{current}/\tilde{B}_{MSY}$ and $B_{year}/\tilde{B}_{MSY}$ for the individual constituent years (2003–2006) based on the likelihood profile method for the base-case model. The probability of $B_{current}/\tilde{B}_{MSY} < 1$ (grey region) is negligible.

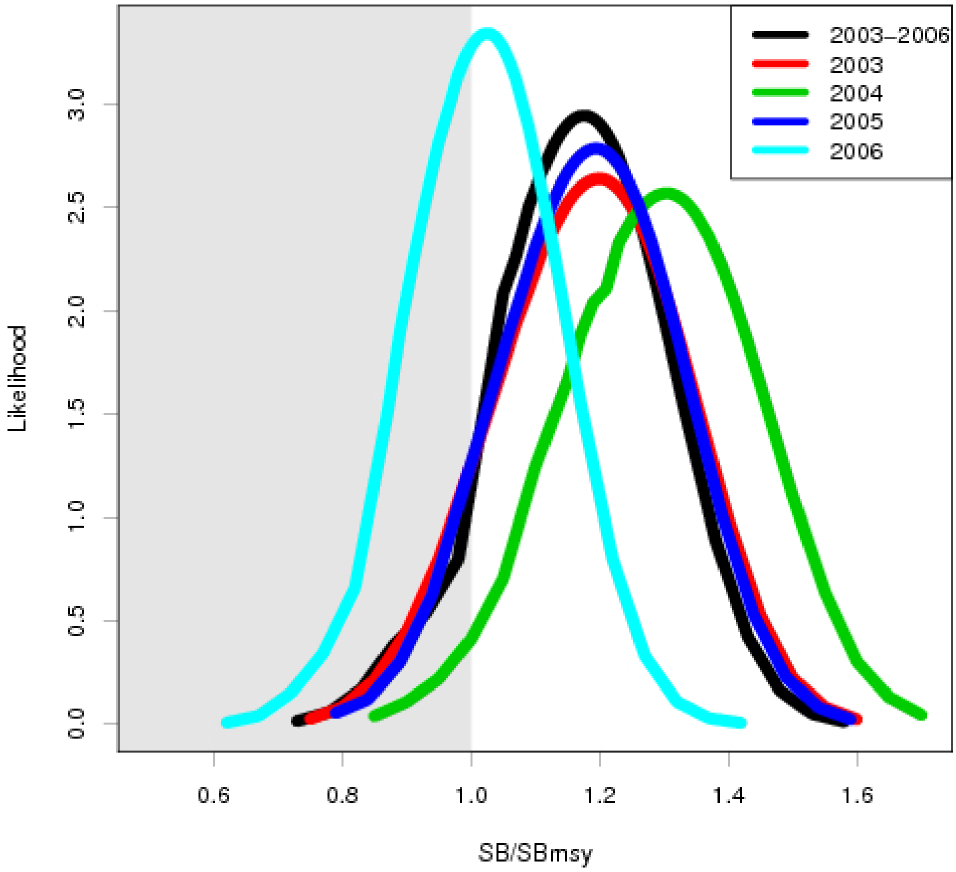


Figure 57. Probability distribution of $SB_{current} / \widetilde{SB}_{MSY}$ and $SB_{year} / \widetilde{SB}_{MSY}$ for the individual constituent years (2003–2006) based on the likelihood profile method for the base-case model. The probability of $SB_{current} / \widetilde{SB}_{MSY} < 1$ (grey region) is 10.3% and the probability of $SB_{2006} / \widetilde{SB}_{MSY} < 1$ is 42.8%.

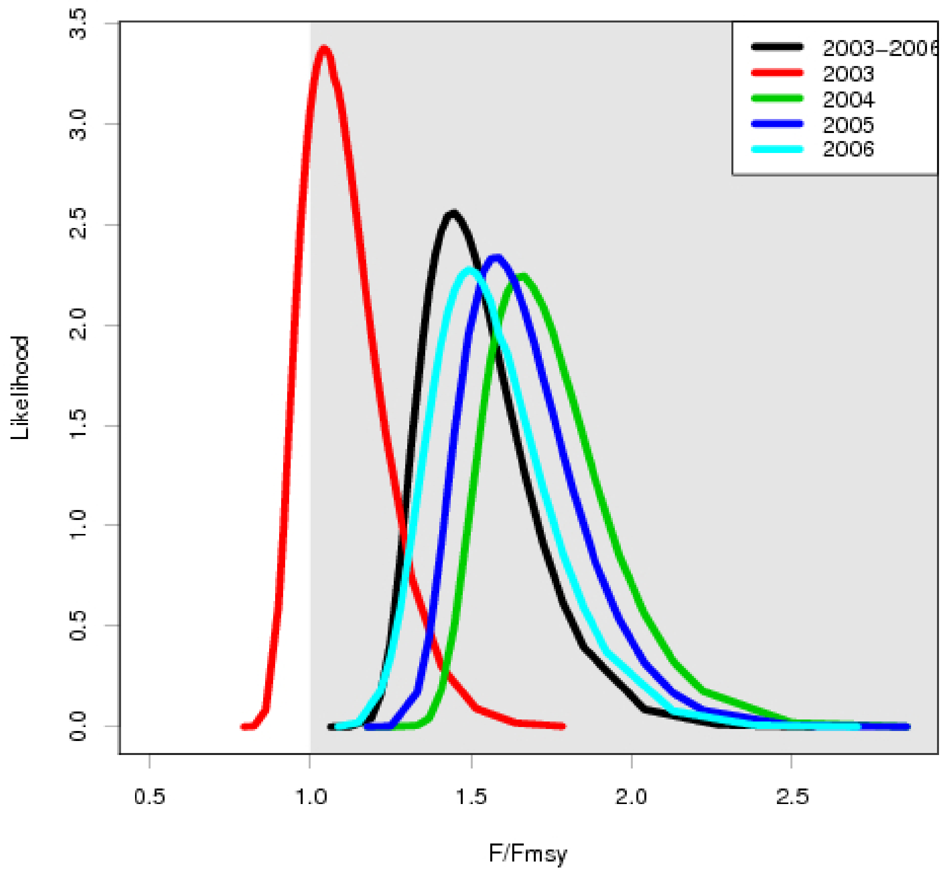


Figure 58. Probability distribution of $F_{current} / \tilde{F}_{MSY}$ and $F_{year} / \tilde{F}_{MSY}$ for the individual constituent years (2003–2006) based on the likelihood profile method for the base-case model. The probability of $F_{current} / \tilde{F}_{MSY} > 1$ (grey region) is 100% for all profiles except 2003.

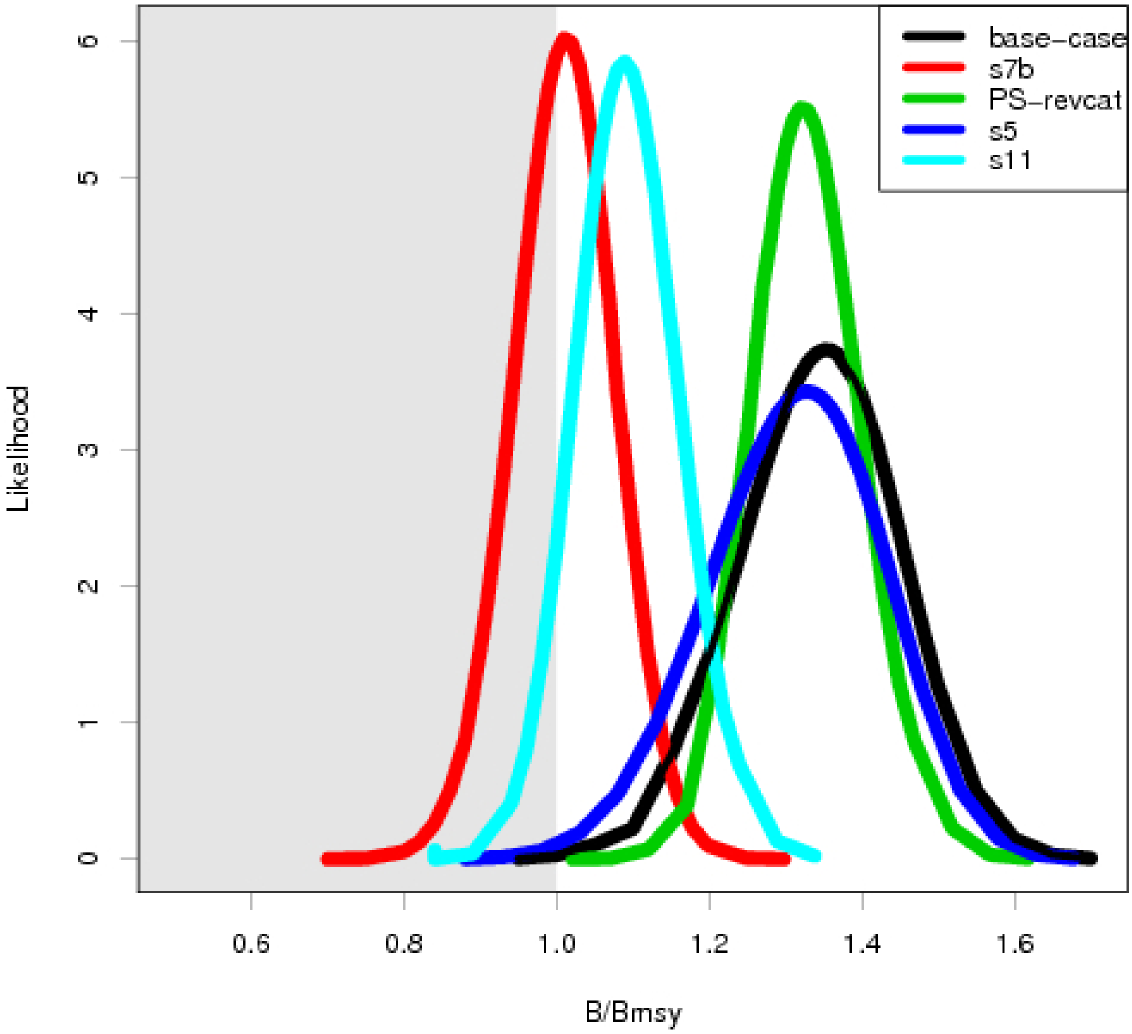


Figure 59. Probability distributions of $B_{current}/\tilde{B}_{MSY}$ based on the likelihood profile method for the base-case model and main sensitivity analyses.

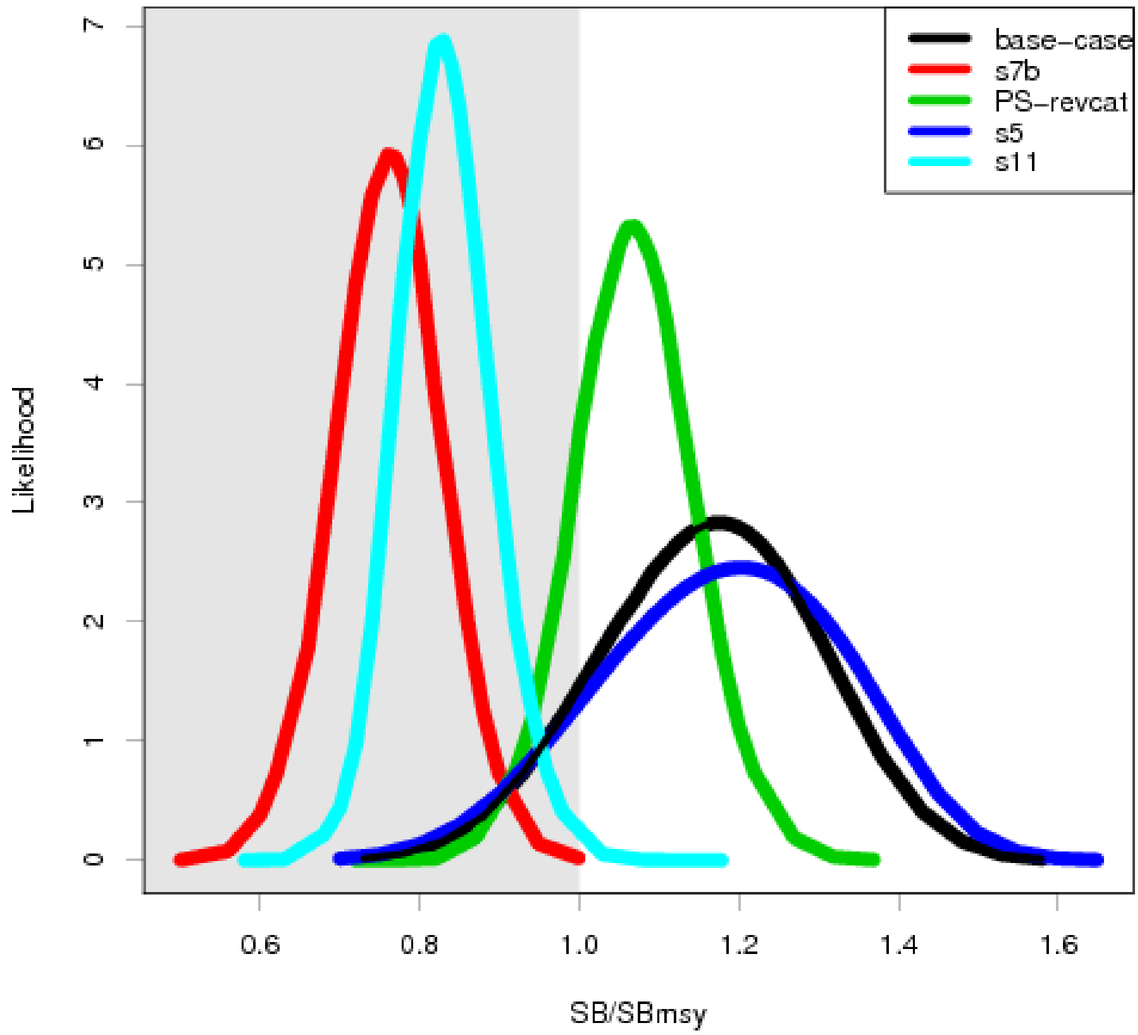


Figure 60. Probability distributions of $SB_{current} / S\tilde{B}_{MSY}$ based on the likelihood profile method for the base-case model and main sensitivity analyses.

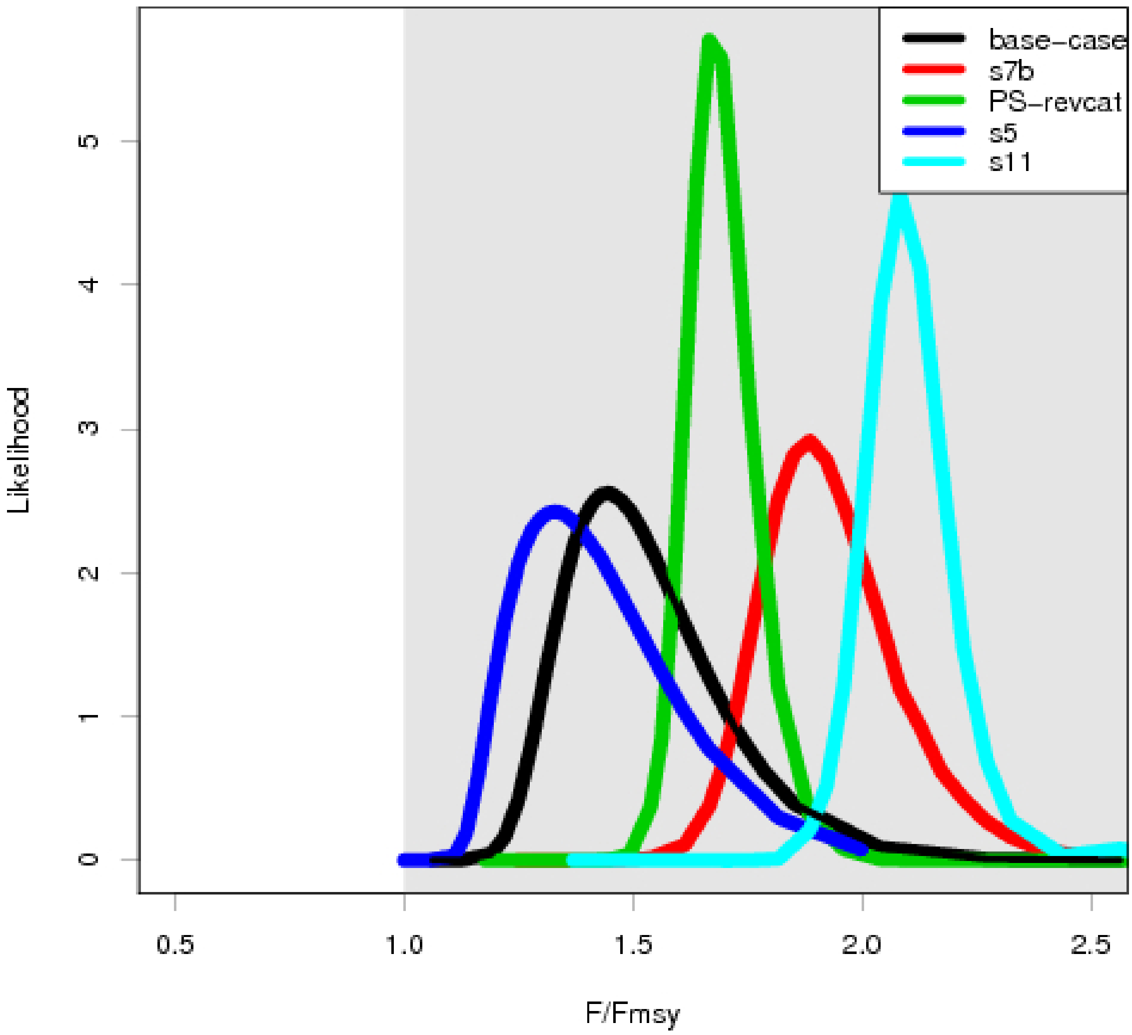


Figure 61. Probability distributions of $F_{current}/\tilde{F}_{MSY}$ based on the likelihood profile method for the base-case model and main sensitivity analyses.

Appendix A: *doitall.bet*

```
#!/bin/sh
#  ------------------------
#  PHASE 0 - create initial par file
#  ------------------------
#
if [ ! -f 00.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq bet.ini 00.par -makepar
fi
#
#  ------------------------
#  PHASE 1 - initial par
#  ------------------------
#
if [ ! -f 01.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 00.par 01.par -file - <<PHASE1
  1 149 100       # recruitment deviations penalty
  2 113 0         # scaling init pop - turned off
  2 177 1         # use old totpop scaling method
  2 32 1          # and estimate the totpop parameter
  -999 49 10      # divide LL LF sample sizes by 10 (default)
  -999 50 10      # divide LL WF sample sizes by 5 (default=10)
  1 32 2          # sets standard control
  1 111 4         # sets likelihood function for tags to negative binomial
  1 141 3         # sets likelihood function for LF data to normal
  2 57 4          # sets no. of recruitments per year to 4
  2 69 1          # sets generic movement option (now default)
  2 93 4          # sets no. of recruitments per year to 4 (is this used?)
  2 94 2 2 95 20  # initial age structure based on Z for 1st 20 periods
  -999 26 2       # sets length-dependent selectivity option
  -9999 1 2       # sets no. mixing periods for all tag release groups to 2
# sets non-decreasing (logistic) selectivity for longline fisheries
 -999 57 3        # uses cubic spline selectivity
 -999 61 3        # with 5 nodes for cubic spline
  -5 57 1         # logistic for TW-CN fisheries
  -8 57 1
# grouping of fisheries with common selectivity
   -1 24 1        # Longline fisheries have common selectivity in reg. 1, 2
   -2 24 1
   -3 24 2
   -4 24 3    # Longline fisheries have common selectivity in reg. 3, 4, 5,
6
   -5 24 4        # TW/CH longliners use night sets -> generally bigger
fish
   -6 24 5
   -7 24 3
   -8 24 4
   -9 24 6
  -10 24 3
  -11 24 7
  -12 24 3
  -13 24 8
  -14 24 9
  -15 24 10
  -16 24 9
  -17 24 10
  -18 24 11     #no size data for ID share with PH
  -19 24 12
```

```
  -20 24 13
  -21 24 14
  -22 24 15
  -23 24 16  # separate LL selectivity for smaller fish in PNG waters
  -24 24 11      # ID common with PH domestic
  -25 24 17
# grouping of fisheries with common catchability
   -1 29 1        # Longline fisheries grouped
   -2 29 1
   -3 29 2        # HI LL fishery different
   -4 29 1
   -5 29 3        # TW/CH LL fishery different
   -6 29 4
   -7 29 1        # AU LL fishery different
   -8 29 5        # JP LL in Aust. region 5 are targeting SBT in the south
   -9 29 6        # AU LL fishery different
  -10 29 1
  -11 29 7
  -12 29 1
  -13 29 8
  -14 29 9
  -15 29 10
  -16 29 11
  -17 29 12
  -18 29 13
  -19 29 14
  -20 29 15
  -21 29 16
  -22 29 17
  -23 29 18
  -24 29 19
  -25 29 20
   -1 60 1        # Longline fisheries grouped
   -2 60 1
   -3 60 2        # HI LL fishery different
   -4 60 1
   -5 60 3        # TW/CH LL fishery different
   -6 60 4
   -7 60 1        # AU LL fishery different
   -8 60 5        # JP LL in Aust. region 5 are targeting SBT in the south
   -9 60 6        # AU LL fishery different
  -10 60 1
  -11 60 7
  -12 60 1
  -13 60 8
  -14 60 9
  -15 60 10
  -16 60 11
  -17 60 12
  -18 60 13
  -19 60 14
  -20 60 15
  -21 60 16
  -22 60 17
  -23 60 18
  -24 60 19
  -25 60 20
# grouping of fisheries for tag return data
    -1 32 1
    -2 32 2
    -3 32 3
```

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

```
   -12 35 1
   -13 35 1
   -14 35 50        # WTP PS based on tag seeding
   -15 35 50
   -16 35 50
   -17 35 50
   -18 35 50        # PH/ID based on high recovery rate
   -19 35 50
   -20 35 1
   -21 35 1
   -22 35 1
   -23 35 1
   -24 35 50
   -25 35 50        # HI HL thought to be high rep. rate
# sets prior means for tag-reporting rates
    -1 36 50        # Mean of 0.5 and penalty of 1 -> uninformative prior
    -2 36 50
    -3 36 80        # HI LL
    -4 36 50
    -5 36 50
    -6 36 50
    -7 36 50
    -8 36 50
    -9 36 80
   -10 36 50
   -11 36 80        # AU LL region 4
   -12 36 50
   -13 36 50
   -14 36 45        # WTP PS based on tag seeding and discounted for unable
returns
   -15 36 45
   -16 36 45
   -17 36 45
   -18 36 60        # PH/ID
   -19 36 60        # PH HL
   -20 36 50
   -21 36 50
   -22 36 50
   -23 36 50
   -24 36 60
   -25 36 80        # HI HL
# sets penalties for effort deviations (negative penalties force effort
devs
# to be zero when catch is unknown)
 -999 13 -10      # higher for longline fisheries where effort is
standardized
   -1 13 -50
   -2 13 -50
   -4 13 -50
   -7 13 -50
  -10 13 -50
  -12 13 -50
  -18 13 10
  -23 13 -10
  -24 13 10
# sets penalties for catchability deviations
   -18 15 1       # low penalty for PH.ID MISC.
   -24 15 1
  -999 33 1       # estimate tag-reporting rates
  1 33 90         # maximum tag reporting rate for all fisheries is 0.9
PHASE1
```

```
fi
#  ---------
#   PHASE 2
#  ---------
if [ ! -f 02.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 01.par 02.par -file - <<PHASE2
  1 149 100       # set penalty on recruitment devs to 400/10
  -999 3 37       # all selectivities equal for age class 37 and older
  -999 4 4        # possibly not needed
  -999 21 4       # possibly not needed
  1 189 1         # write graph.frq (obs. and pred. LF data)
  1 190 1         # write plot.rep
  1 1 200         # set max. number of function evaluations per phase to
100
  1 50 -2         # set convergence criterion to 1E+01
  -999 14 10      # Penalties to stop F blowing out
  -999 62 2       # Add 2 more nodes to cubic spline
PHASE2
fi
#  ---------
#   PHASE 3
#  ---------
if [ ! -f 03.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 02.par 03.par -file - <<PHASE3
  2 70 1          # activate parameters and turn on
  2 71 1          # estimation of temporal changes in recruitment
distribution
PHASE3
fi
#  ---------
#   PHASE 4
#  ---------
if [ ! -f 04.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 03.par 04.par -file - <<PHASE4
  2 68 1          # estimate movement coefficients
PHASE4
fi
#  ---------
#   PHASE 5
#  ---------
if [ ! -f 05.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 04.par 05.par -file - <<PHASE5
  1 16 1          # estimate length dependent SD
PHASE5
fi
#  ---------
#   PHASE 6
#  ---------
if [ ! -f 06.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 05.par 06.par -file - <<PHASE6
  1 173 8         # estimate independent mean lengths for 1st 8 age classes
  1 182 10
PHASE6
fi
#  ---------
#   PHASE 7
#  ---------
if [ ! -f 07.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 06.par 07.par -file - <<PHASE7
  -999 27 1       # estimate seasonal catchability for all fisheries
  -18 27 0        # except those where
```

```
  -19 27 0         # only annual catches
  -24 27 0
PHASE7
fi
#  ---------
#   PHASE 8
#  ---------
if [ ! -f 08.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 07.par 08.par -file - <<PHASE8
  -3 10 1          # estimate
  -5 10 1          # catchability
  -6 10 1          # time-series
  -8 10 1          # for all
  -9 10 1          # non-longline
  -11 10 1         # fisheries
  -13 10 1
  -14 10 1
  -15 10 1
  -16 10 1
  -17 10 1
  -18 10 1
  -19 10 1
  -20 10 1
  -21 10 1
  -22 10 1
  -23 10 1
  -24 10 1
  -25 10 1
  -999 23 23       # and do a random-walk step every 23+1 months
PHASE8
fi
#  ---------
#   PHASE 9
#  ---------
if [ ! -f 09.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 08.par 09.par -file - <<PHASE9
  1 14 1           # estimate von Bertalanffy K
  1 12 1           # and mean length of age 1
PHASE9
fi
#  ---------
#   PHASE 10
#  ---------
if [ ! -f 10.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 09.par 10.par -file - <<PHASE10
# grouping of fisheries for estimation of negative binomial parameter a
   -1 44 1
   -2 44 1
   -3 44 1
   -4 44 1
   -5 44 1
   -6 44 1
   -7 44 1
   -8 44 1
   -9 44 1
  -10 44 1
  -11 44 1
  -12 44 1
  -13 44 1
  -14 44 2
  -15 44 2
```

```
  -16 44 2
  -17 44 2
  -18 44 3
  -19 44 3
  -20 44 1
  -21 44 1
  -22 44 2
  -23 44 1
  -24 44 3
  -25 44 4
 -999 43 1        # estimate a for all fisheries
PHASE10
fi
#  ---------
#   PHASE 11
#  ---------
if [ ! -f 11.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 10.par 11.par -file - <<PHASE11
  -100000 1 1     # estimate
  -100000 2 1     # time-invariant
  -100000 3 1     # distribution
  -100000 4 1     # of
  -100000 5 1     # recruitment
  -100000 6 1
PHASE11
fi
#  ---------
#   PHASE 12
#  ---------
if [ ! -f 12.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 11.par 12.par -file - <<PHASE12
  2 145 1        # use SRR parameters - low penalty for deviation
  2 146 1        # estimate SRR parameters
  2 162 1    # estimate steepness parameter
  2 163 0
  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 steepnes
  2 154 16
  1 1 1000
  1 50 -3
PHASE12
fi
cp plot.rep plot-12.rep
cp length.fit length-12.fit
cp weight.fit weight-12.fit
#  ----------
#   PHASE 13
#  ----------
if [ ! -f 13.par ]; then
  /home/mfcl/bin/mfclo32 bet.frq 12.par 13.par -file - <<PHASE13
  -999 49 20 # lower weighting for size data
  -999 50 20
PHASE13
fi
```

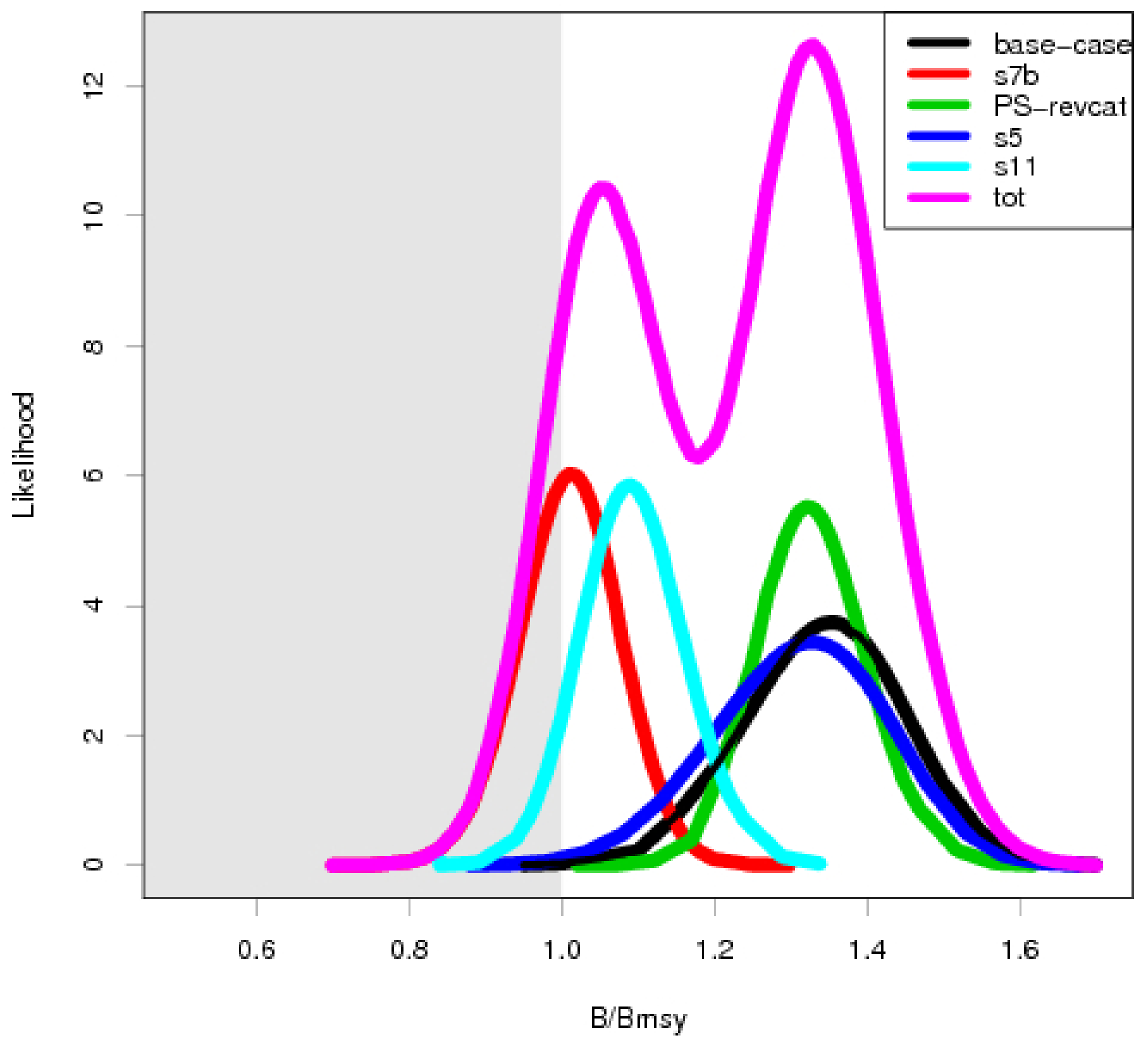
Appendix B: ***bet.ini***

```
# number of age classes
  40
# maturity at age
  0.0 0.0 0.0 0.0
  0.0 0.0 0.0 0.0
  0.0 0.0 0.05 0.1
  0.2 0.4 0.6 0.7
  0.8 0.85 0.9 0.95
  1.0 1.0 1.0 1.0
  1.0 1.0 1.0 1.0
  1.0 1.0 1.0 1.0
  1.0 1.0 1.0 1.0
  1.0 1.0 1.0 1.0
# natural mortality
0.112828307
# movement map
    1 2 3 4
# diffusion coffs
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
   0.01 0.01 0.01 0.01 0.01 0.01 0.01
# age_pars
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0.57270008   0.388151602   0.169824717   -0.109880777   -0.120429055   -0.120184071   -0.119736681   -
0.118950236   -0.117624734   -0.115488279   -0.112200121   -0.107371589   -0.100609865   -0.091587038   -
0.080133729 -0.06684202 -0.051242744 -0.034614946 -0.018129082 -0.00301803 0.009741098 0.019643201
0.026664669  0.031113414  0.033443002  0.034116377  0.033536898  0.032027915  0.029837148  0.027150142
0.024104578 0.020802649 0.017320587 0.013715783 0.010031876 0.006302492 0.00255379 -0.001193612 -
0.004923295 -0.008622116
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
  0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
# recruitment distribution
   0.05 0.06 0.40 0.35 0.05 0.09
# The von Bertalanffy parameters
28.000000000000  20.000000000000   40.000000000000
180.000000000000  140.000000000000   200.000000000000
0.075000000000   0   0.300000000000
# Length-weight coefficients
1.9729e-5 3.0247
# Variance parameters
6.000000000000  3.000000000000  12.000000000000
0.100000000000  -1.500000000000   1.500000000000
# The number of mean constraints
0
#7 99  1  20.000000000000   28.000000000000   0.100000000000   0.900000000000
#7 99  2  34.000000000000   40.000000000000   0.100000000000   0.900000000000
```

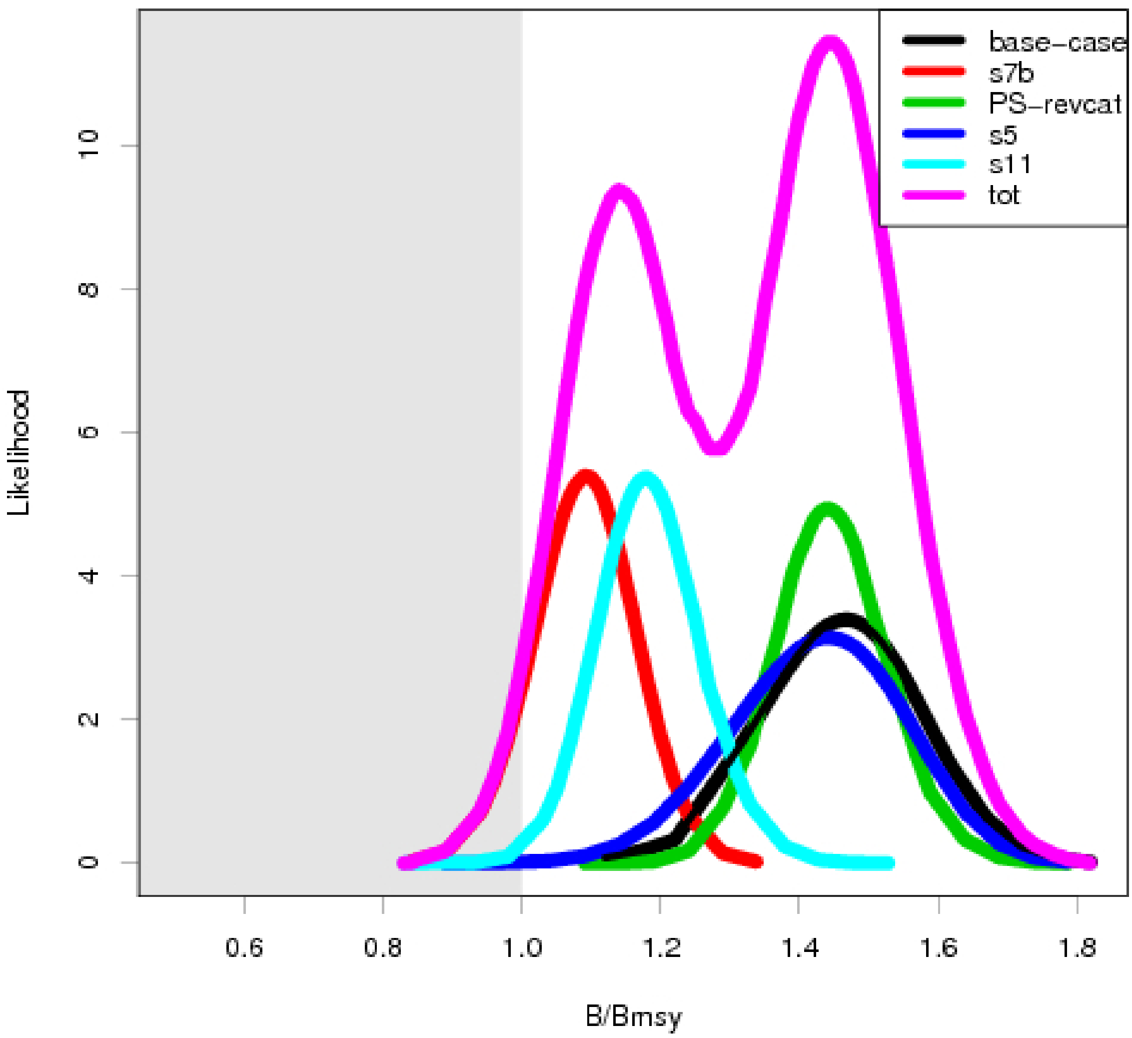
Appendix C: Likelihood profiles for B_t/B_{MSY}, SB_t/SB_{MSY} and F_t/F_{MSY}, for t = 2003-2006, 2003, 2004, 2005 and 2006. In each plot, profiles are shown for the base case and each of the main sensitivity analyses (see Table and text for definitions). The pink (upper) profile (entitled "tot" in the legend) is an unweighted sum of the individual profiles.

B_t/B_{MSY}

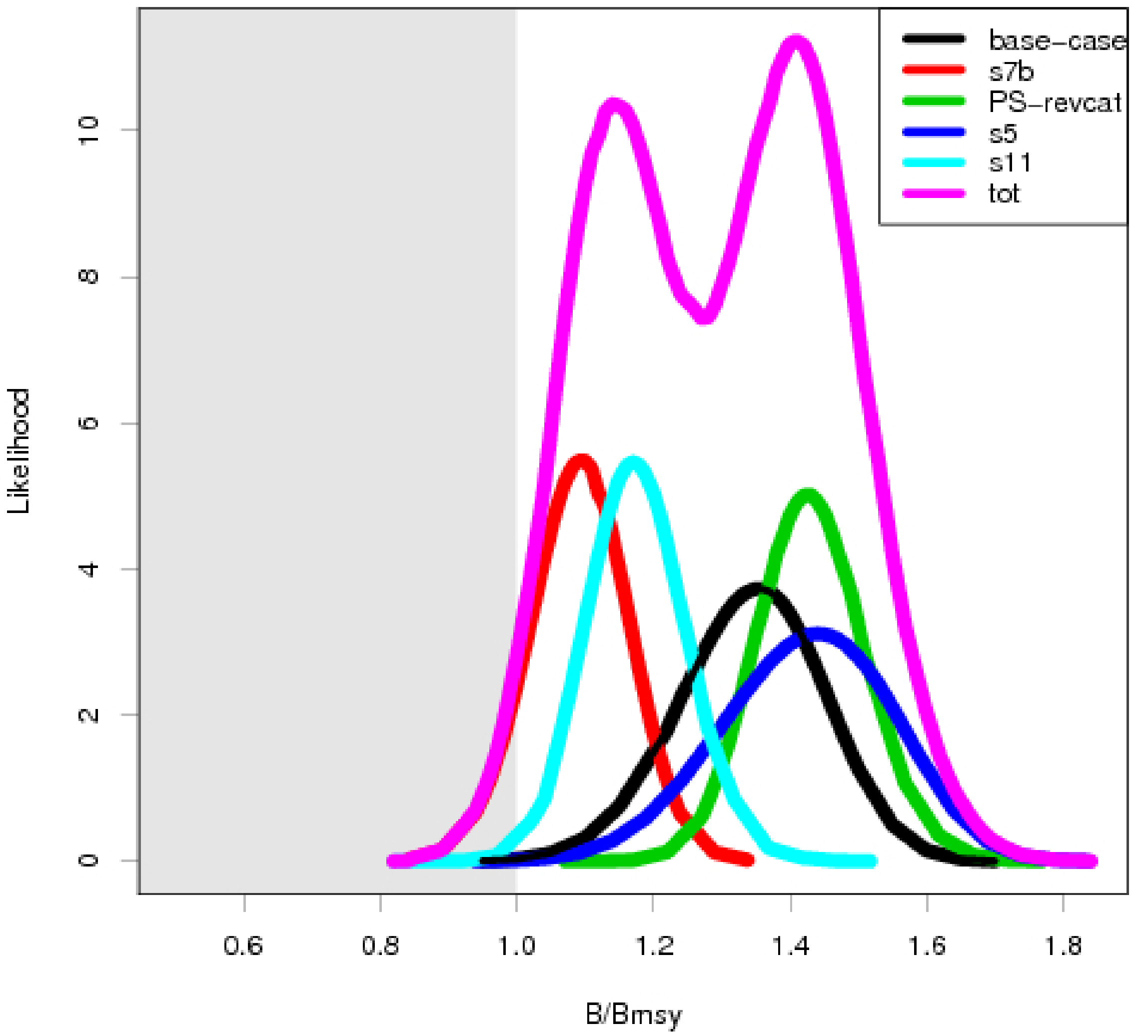
2003-2006



B_t/B_{MSY}
2003


base−case
s7b
PS−revcat
s5
s11
tot
Likelihood
0
2
4
6
8
10
0.6
0.8
1.0
1.2
1.4
1.6
1.8
B/Bmsy

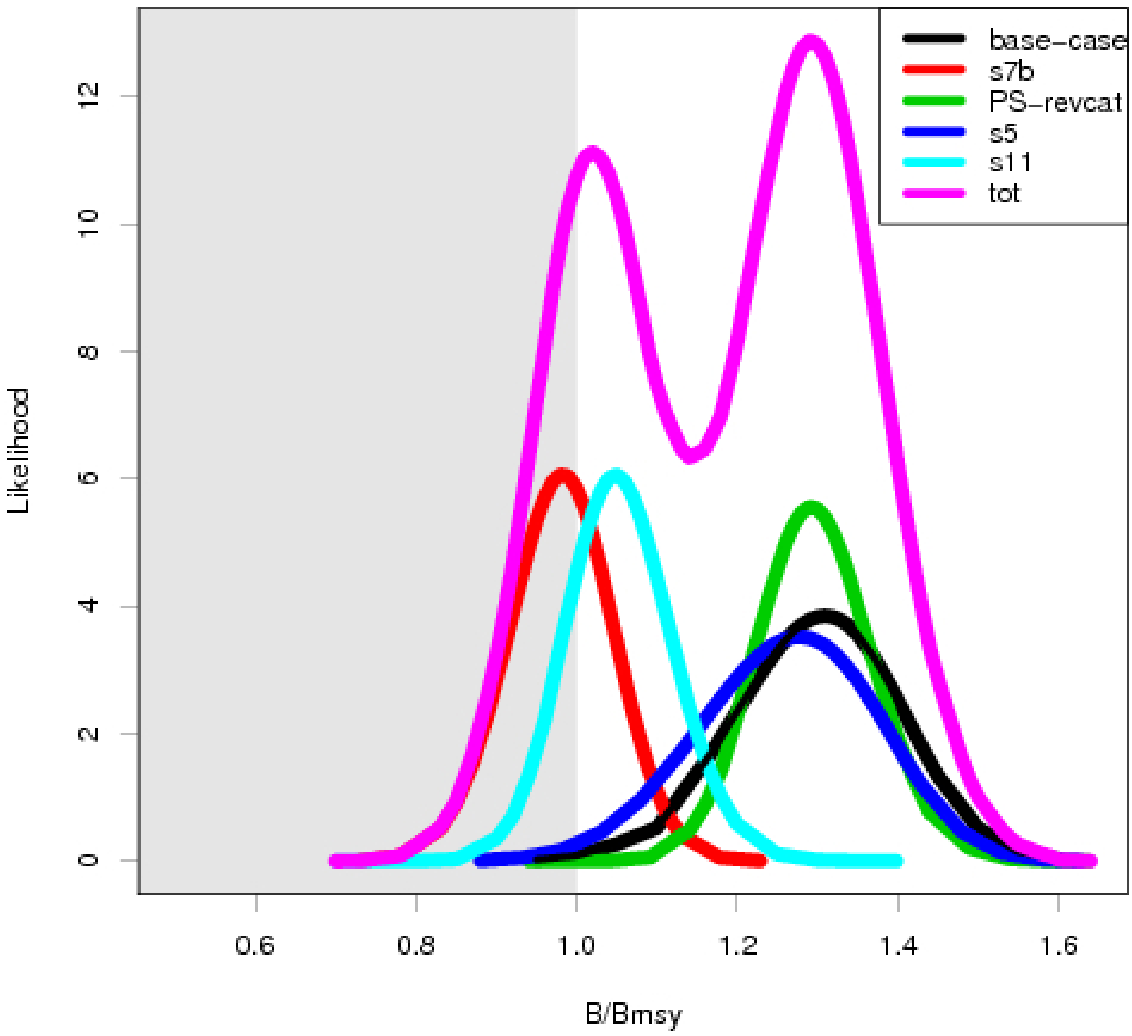
B_t/B_{MSY}
2004



base−case
s7b
PS−revcat
s5
s11
tot
Likelihood
0
2
4
6
8
10
0.6
0.8
1.0
1.2
1.4
1.6
1.8
B/Bmsy

B_t/B_{MSY}

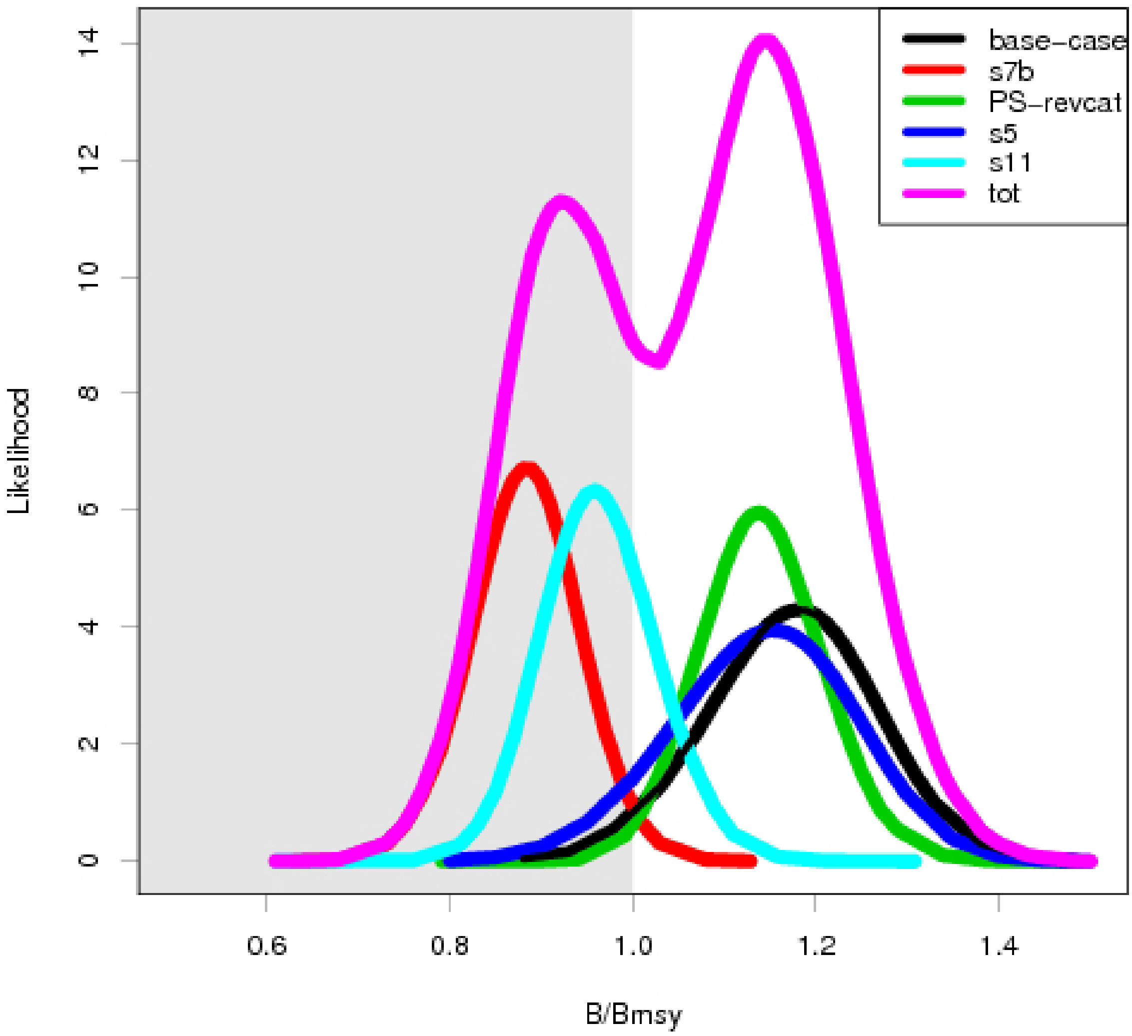
2005



base−case
s7b
PS−revcat
s5
s11
tot
Likelihood
B/Bmsy
0
2
4
6
8
10
12
0.6
0.8
1.0
1.2
1.4
1.6

B_t/B_{MSY}

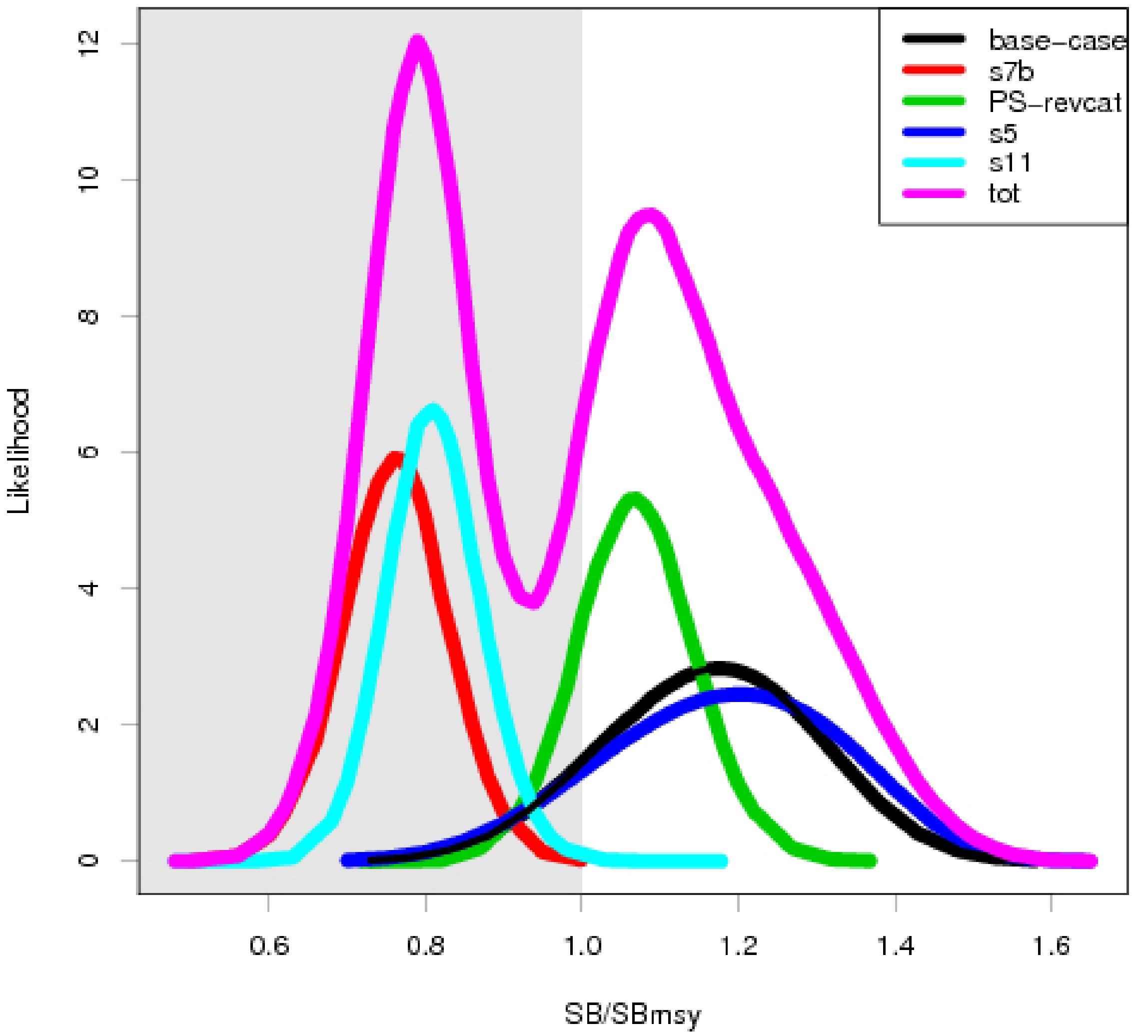
2006



base−case
s7b
PS−revcat
s5
s11
tot
Likelihood
0
2
4
6
8
10
12
14
0.6
0.8
1.0
1.2
1.4
B/Bmsy

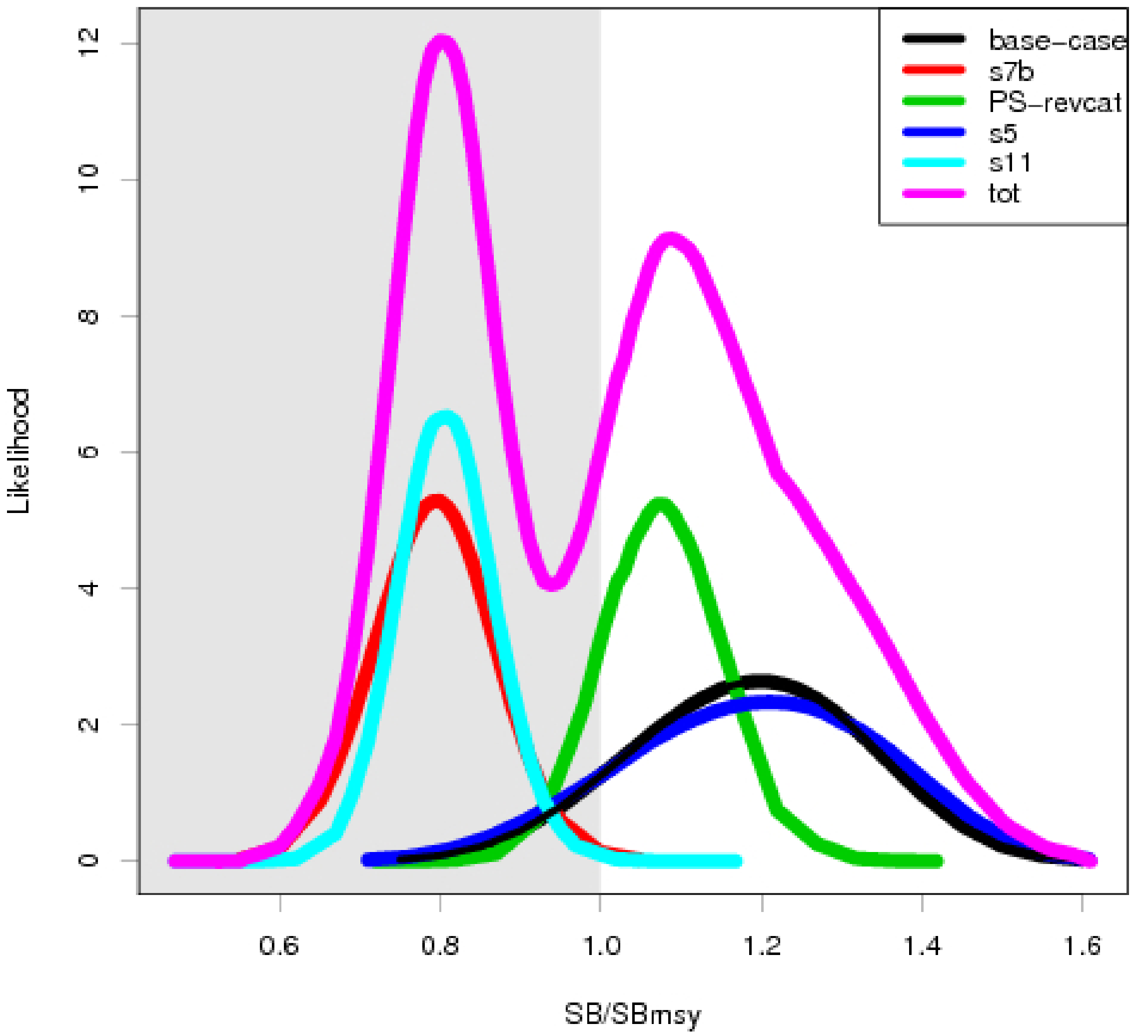
SB_t/SB_{MSY}

2003-2006



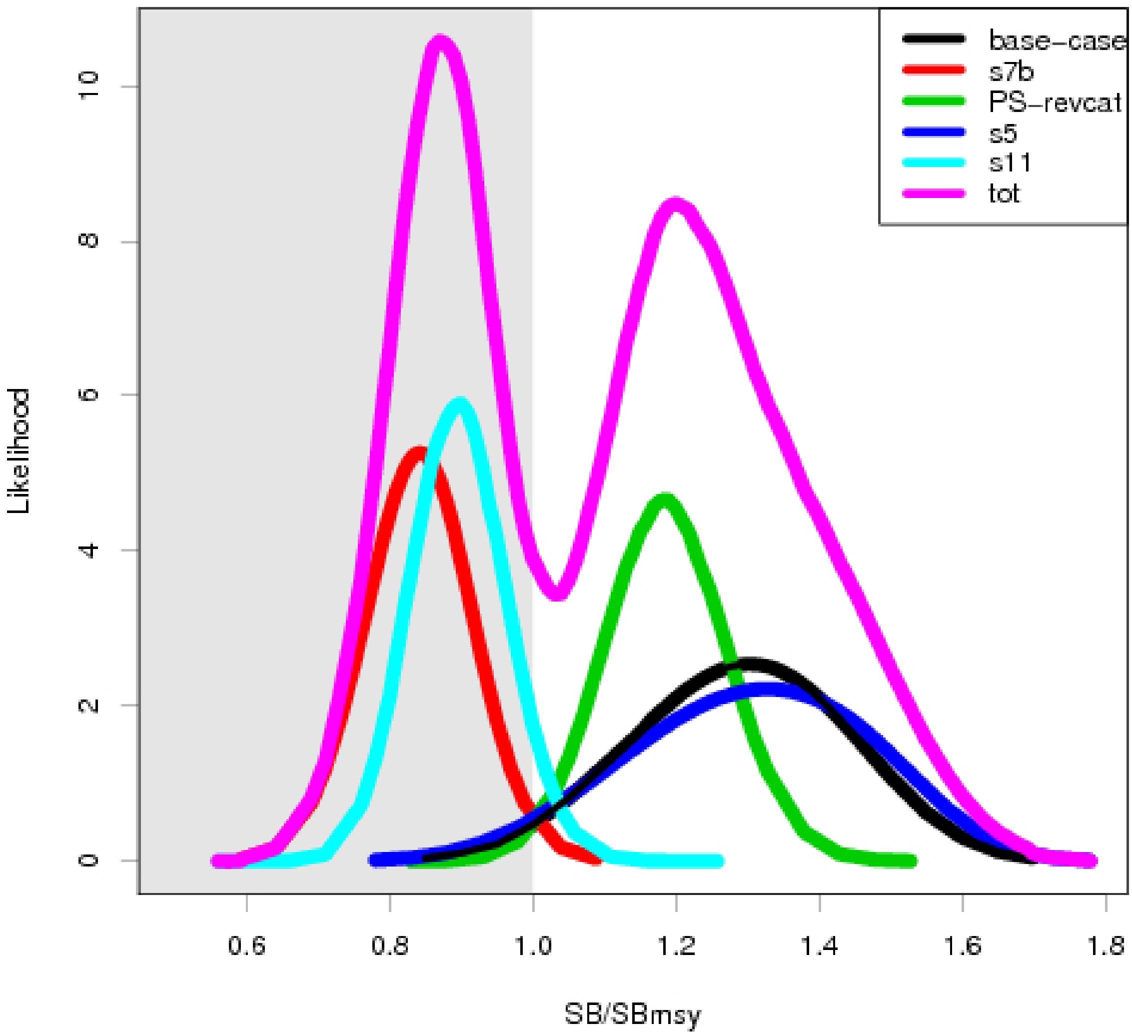
SB_t/SB_{MSY}

2003

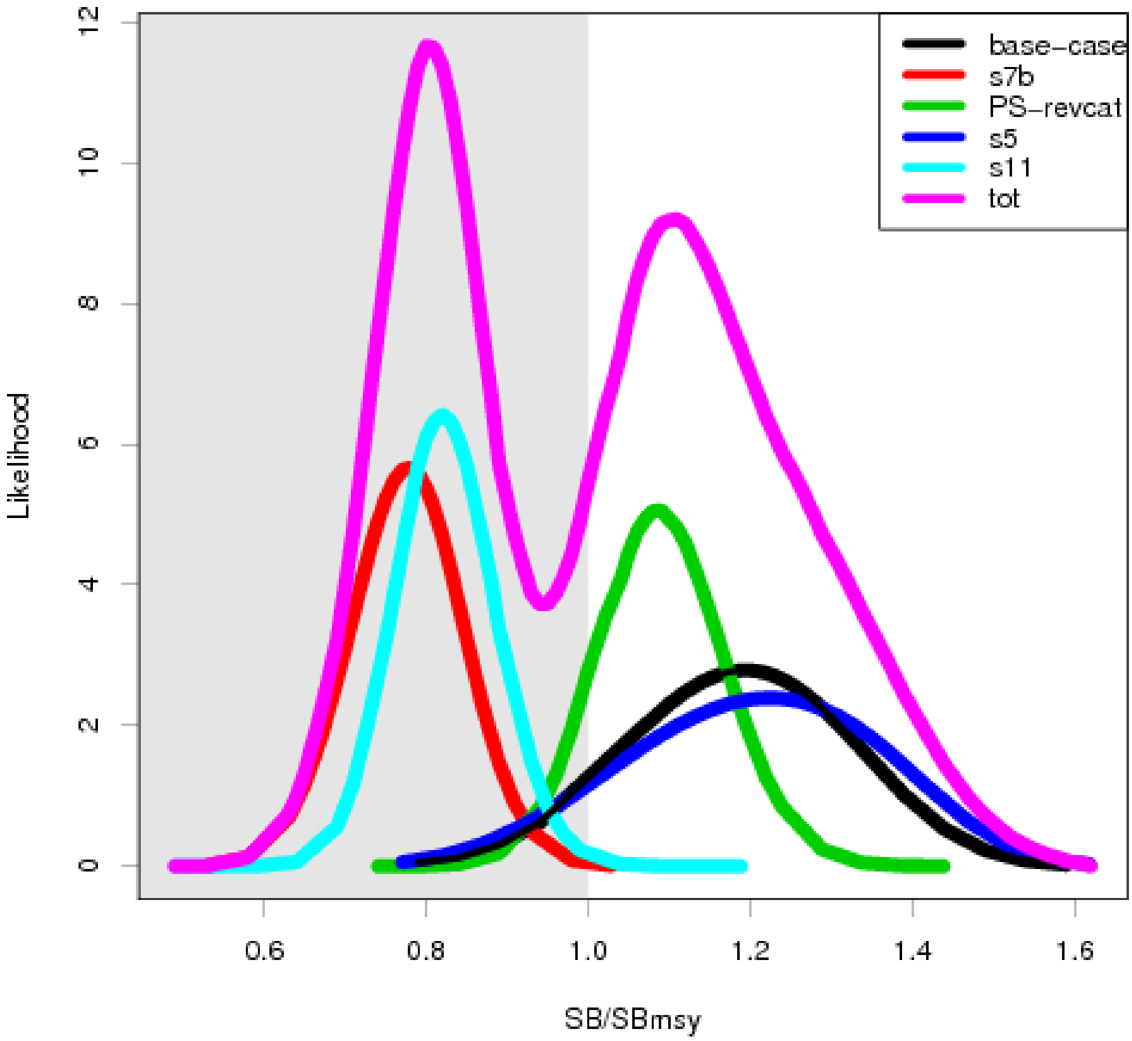


SB_t/SB_{MSY}

2004

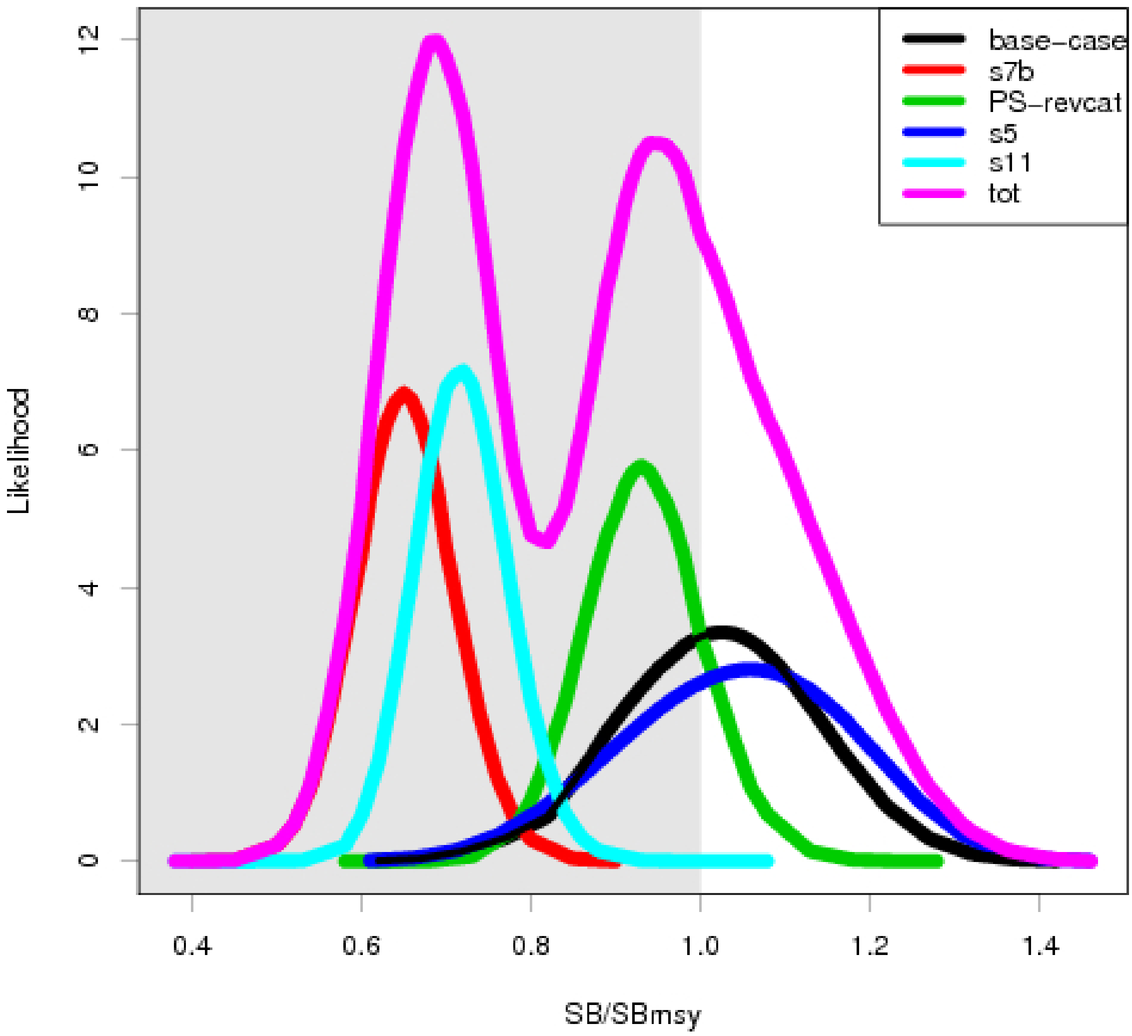


SB_t/SB_{MSY}
2005



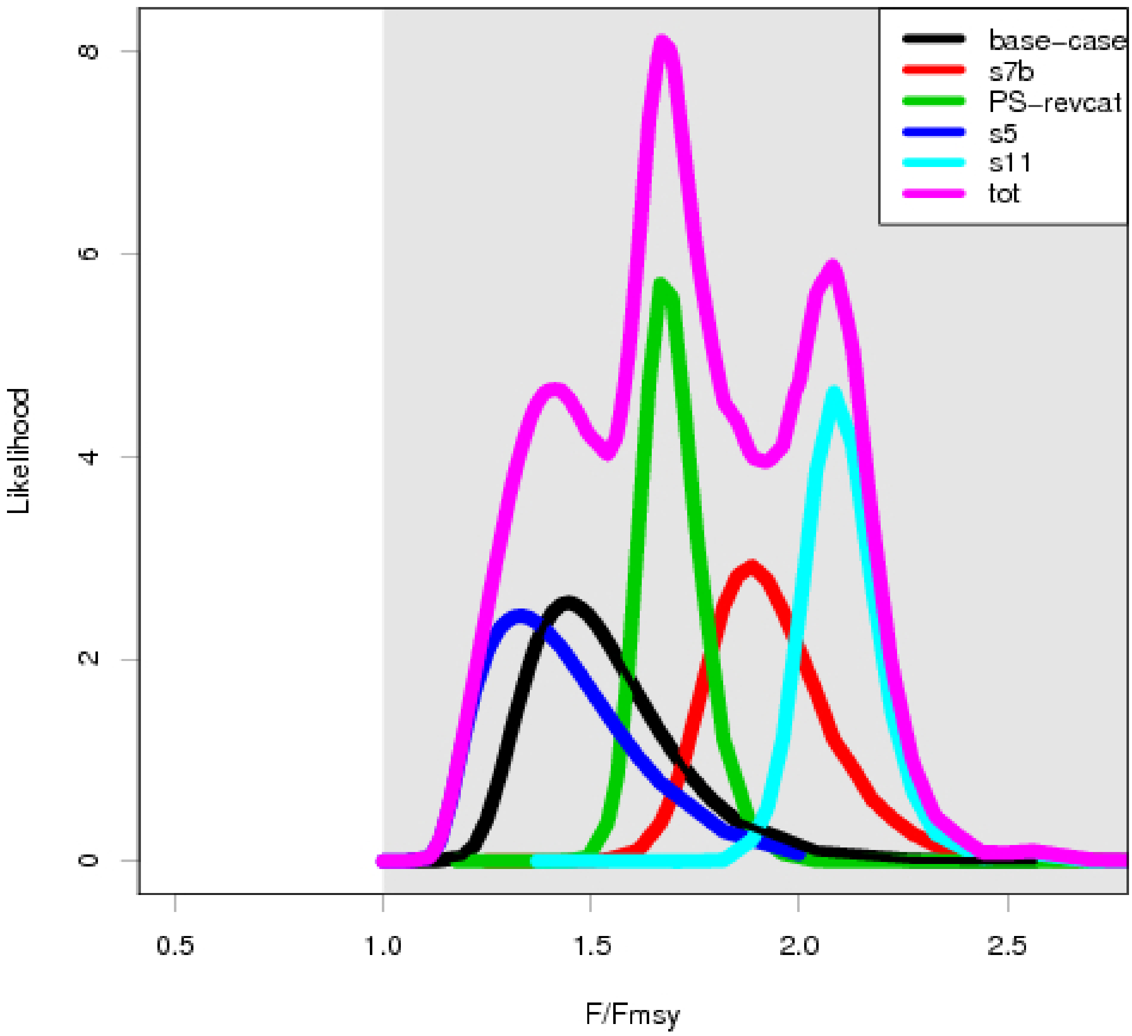
SB_t/SB_{MSY}

2006



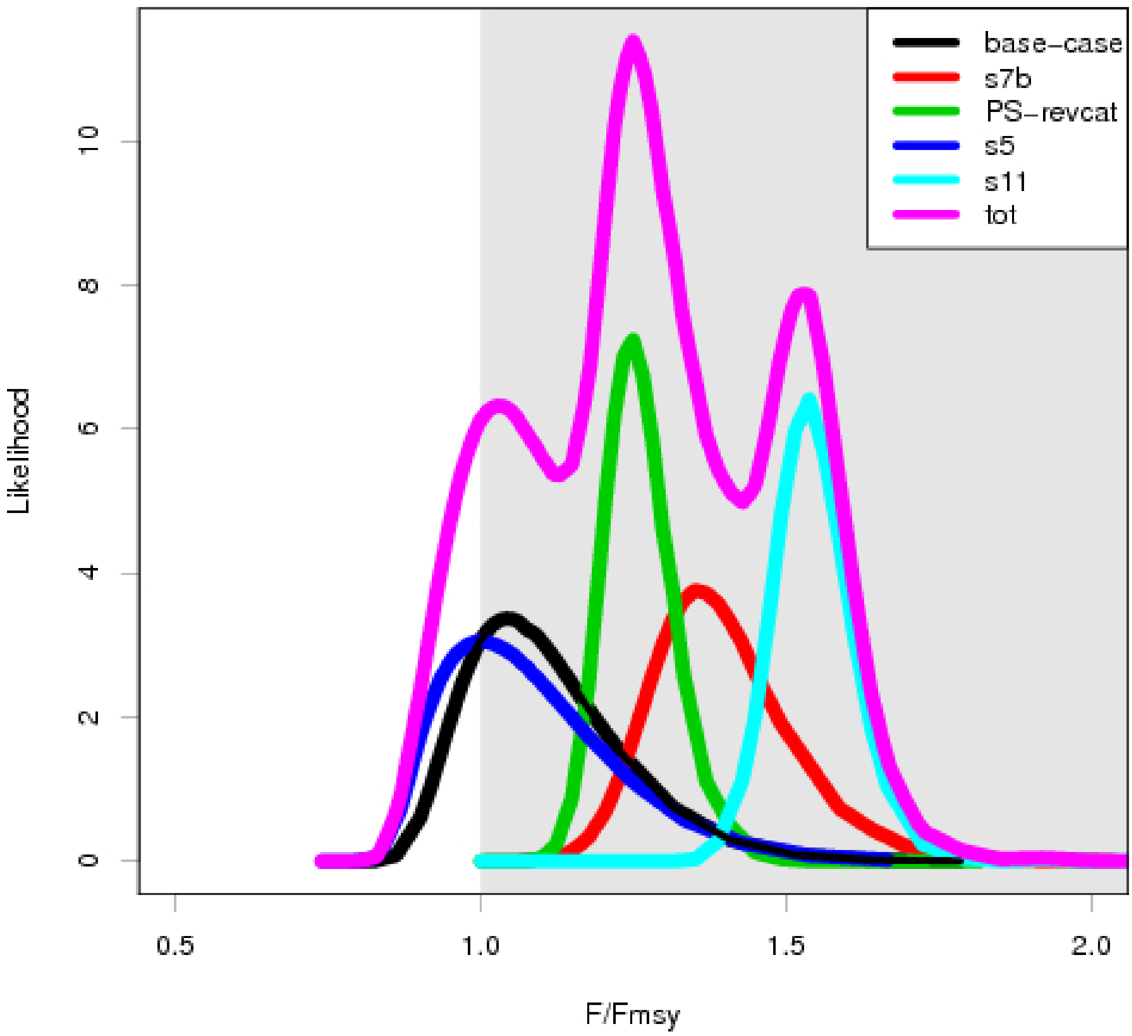
F_t/F_{MSY}

2003-2006



F_t/F_{MSY}

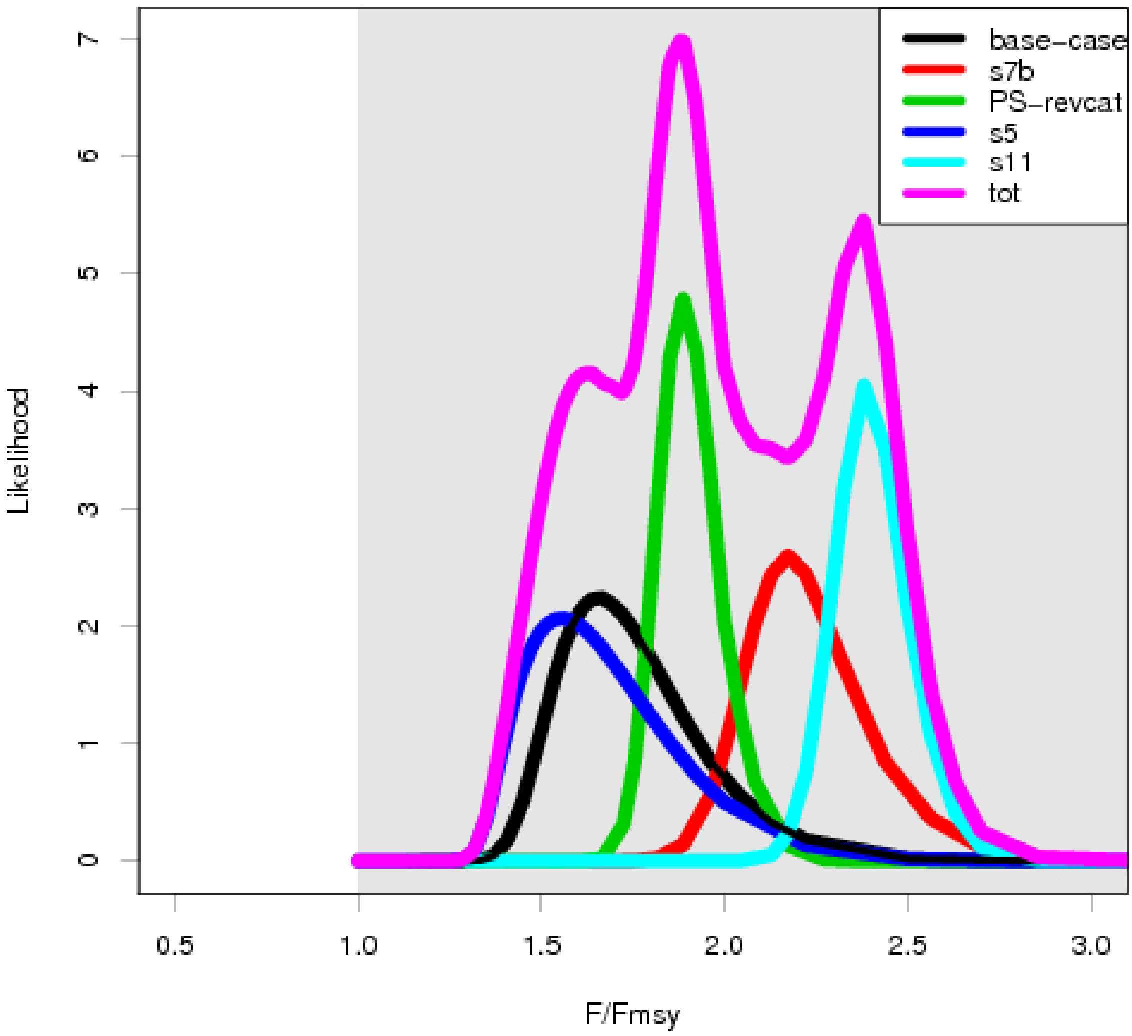
2003



base−case
s7b
PS−revcat
s5
s11
tot
Likelihood
0
2
4
6
8
10
0.5
1.0
1.5
2.0
F/Fmsy

F_t/F_{MSY}

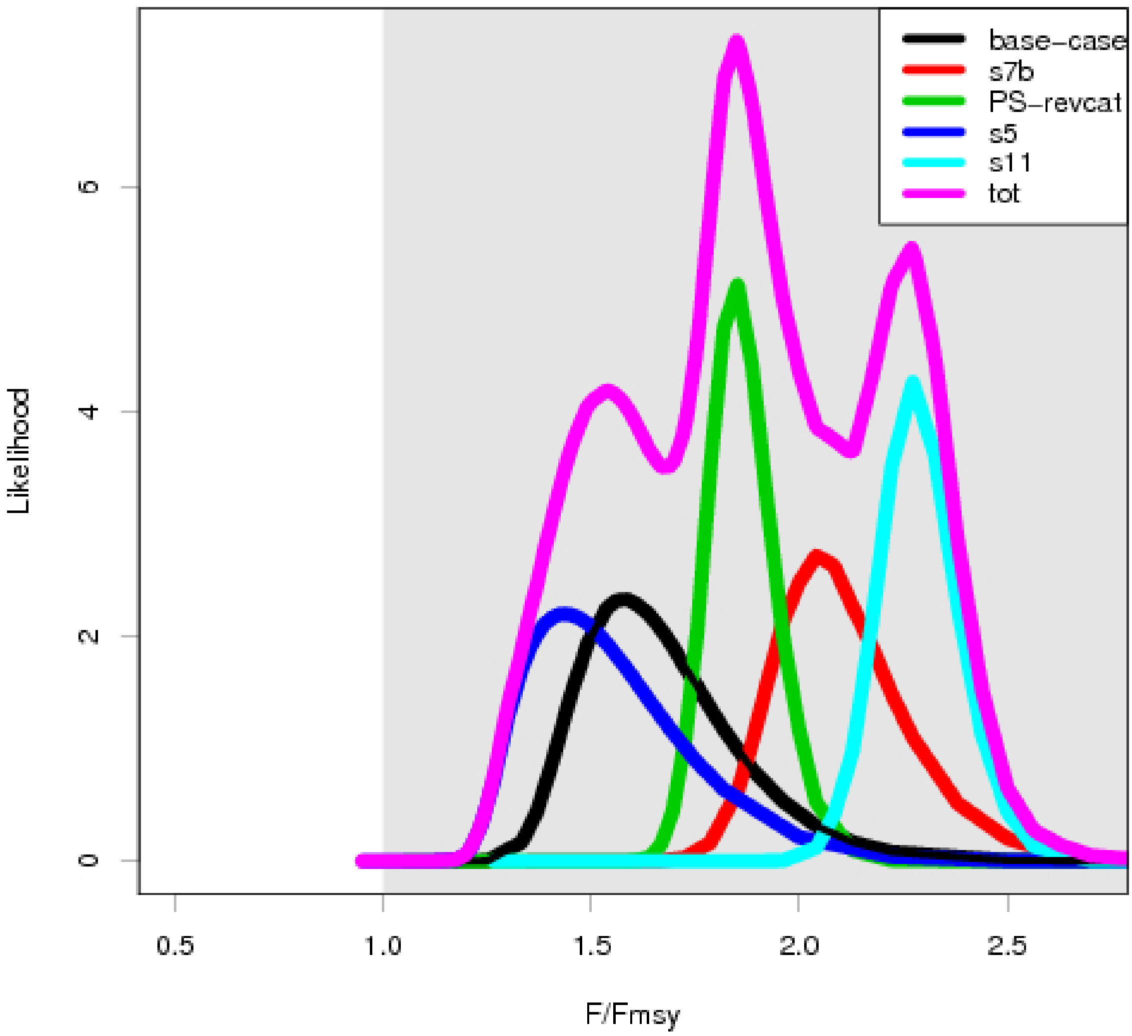
2004



base−case
s7b
PS−revcat
s5
s11
tot
Likelihood
F/Fmsy
0
1
2
3
4
5
6
7
0.5
1.0
1.5
2.0
2.5
3.0

F_t/F_{MSY}

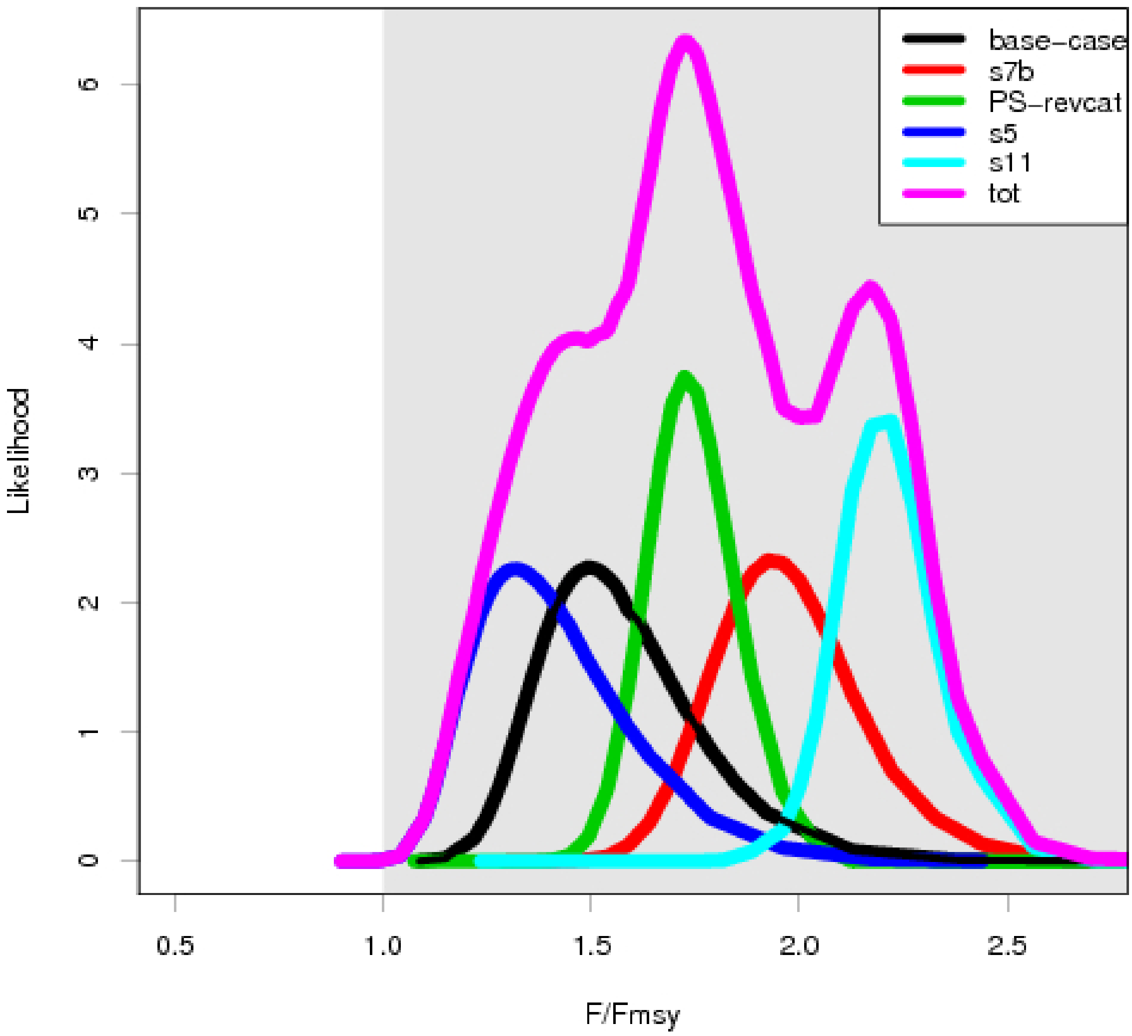
2005



base−case
s7b
PS−revcat
s5
s11
tot
Likelihood
0
2
4
6
0.5
1.0
1.5
2.0
2.5
F/Fmsy

F_t/F_{MSY}

2006



base−case
s7b
PS−revcat
s5
s11
tot
Likelihood
0
1
2
3
4
5
6
0.5
1.0
1.5
2.0
2.5
F/Fmsy