DRAFT: STOCK ASSESSMENT PAPERS

The material in this publication is a DRAFT stock assessment developed by the authors for the consideration of the relevant subsidiary body of the Commission. Its contents will be peer reviewed at the upcoming Working Party meeting and may be modified accordingly.

Based on the ensemble of Stock Assessments to be presented and debated during the meeting, the Working Party will develop DRAFT advice for the IOTC Scientific Committee's consideration, which will meet later this year.

It is not until the IOTC Scientific Committee has considered the advice, and modified it as it sees fit, that the Assessment results are considered final.

Received: 16 September 2015

Stock assessment of yellowfin tuna in the Indian Ocean using Stock Synthesis.

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1 Introduction

This paper presents the stock assessment of yellowfin tuna (*Thunnus albacares*) in the Indian Ocean (IO) using the Stock Synthesis software (Methot 2013, Methot & Wetzel 2013) to implement an age- and spatially-structured population model.

Prior to 2008, Indian Ocean yellowfin tuna was assessed using methods such as VPA and production models (Nishida & Shono 2005 & 2007). In 2008, a preliminary stock assessment of IO yellowfin tuna was conducted using MULTIFAN-CL (Kleiber et al 2003, Langley et al. 2008) enabling the integration of the tag release/recovery data collected from the large-scale tagging programme conducted in the Indian Ocean in the preceding years (Langley et al. 2008). The MULTIFAN-CL assessment was revised and updated in the following years (Langley *et al.* 2009, 2010 and 2011, Langley 2012).

For the 17th WPTT meeting, the IOTC specified that the yellowfin stock assessment be conducted using the Stock Synthesis (SS) modelling platform. Conceptually, the SS modelling framework is very similar to MFCL including the facility to integrate tag release/recovery data. Previously, preliminary trials comparing the application of the two platforms to the modelling of spatially structured tuna populations have yielded similar results.

For the 17th WPTT meeting, the IOTC also requested that a range of model sensitivities be conducted to investigate a range of structural assumptions, specifically natural mortality, growth, selectivity, steepness and spatial structure. This report documents the results of the assessment for presentation to WPTT17.

2 Background

2.1 Biology

Yellowfin tuna *(Thunnus albacares)* is a cosmopolitan species distributed mainly in the tropical and subtropical oceanic waters of the three major oceans, where it forms large schools. The sizes exploited in the Indian Ocean range from 30 cm to 180 cm fork length. Smaller fish (juveniles) form mixed schools with skipjack and juvenile bigeye tuna and are mainly limited to surface tropical waters, while larger fish are found in surface and sub-surface waters. Intermediate age yellowfin are seldom taken in the industrial fisheries, but are abundant in some artisanal fisheries, mainly in the Arabian Sea.

Longline catch data indicates that yellowfin are distributed continuously throughout the entire tropical Indian Ocean, but some more detailed analysis of fisheries data suggests that the stock structure may be more complex. Studies of stock structure using DNA techniques have indicated that there may be genetically discrete subpopulations of yellowfin tuna in the north western Indian Ocean (Dammannagoda et al 2008) and within Indian waters (Kunal et al 2013). However, there has been no comprehensive study that encompasses the entire ocean basin. The tag recoveries of the RTTP-IO provide evidence of large movements of yellowfin tuna within the western equatorial region, although there are very few observations of large scale transverse movements of tagged yellowfin. This may indicate that the western and eastern regions of the Indian Ocean support relatively discrete sub-populations of yellowfin tuna.

Spawning occurs mainly from December to March in the equatorial area (0–10°S), with the main spawning grounds west of 75°E. Secondary spawning grounds exist off Sri Lanka and the Mozambique Channel and in the eastern Indian Ocean off Australia. Yellowfin size at first maturity has been estimated at around 60-70 cm (Zudaire et al 2013) and recruitment occurs predominantly in July. Newly recruited fish are primarily caught by the purse seine fishery on floating objects and the pole-and-line fishery in the Maldives. Males are predominant in the catches of larger fish at sizes larger than 150 cm (this is also the case in other oceans).

Medium sized yellowfin concentrate for feeding in the Arabian Sea. Feeding behaviour is largely opportunistic, with a variety of prey species being consumed, including large concentrations of crustacea that have occurred recently in the tropical areas and small mesopelagic fishes which are abundant in the Arabian Sea.

2.2 Fisheries

Yellowfin tuna, an important component of tuna fisheries throughout the IO, are harvested with a diverse variety of gear types, from small-scale artisanal fisheries (in the Arabian Sea, Mozambique Channel and waters around Indonesia, Sri Lanka and the Maldives and Lakshadweep Islands) to large gillnetters (from Oman, Iran and Pakistan operating mostly but not exclusively in the Arabian Sea) and distant-water longliners and purse seiners that operate widely in equatorial and tropical waters. Purse seiners and gillnetters catch a wide size range of yellowfin tuna, whereas the longline fishery takes mostly adult fish.

Prior to 1980, annual catches of yellowfin tuna remained below about 80,000 mt. Annual catches increased markedly during the 1980s and early 1990s, mainly due to the development of the purse-seine fishery as well as an expansion of the other established fisheries (fresh-tuna longline, gillnet, baitboat, handline and, to a lesser extent, troll). A peak in catches was recorded in 1993, with catches over 400,000 mt, the increase in catch almost fully attributable to longline fleets, in particular longliners flagged in Taiwan, which reported exceptional catches of yellowfin tuna in the Arabian Sea.

Catches declined in 1994, to about 350,000 mt, remaining at that level for the next decade then increasing sharply to reach a peak of about 520,000 mt in 2004/2005 driven by a large increase in catch by all fisheries, especially the purse-seine (free school) fishery. Total annual catches declined sharply from 2004 to 2007 and remained at about 300,000 mt during 2007–2011. In 2012, total catches increased to about 400,000 mt and were maintained at about that level in 2013 and 2014 (Table 2).

In recent years (2011–2013), purse seine has been the dominant fishing method harvesting 34% of the total IO yellowfin tuna catch (by weight), with the longline, handline and gillnet fisheries comprising 18%, 19% and 15% of the catch, respectively. A smaller component of the catch was taken by the regionally important baitboat (5%) and troll (7%) fisheries. The recent increase in the total catch has been attributable to an increase in catch from all the major fisheries.

The purse-seine catch is generally distributed equally between free-school and associated (log and FAD sets) schools, although the large catches in 2003–2005 were dominated by fishing on free-schools. Conversely, during 2011–2013 the purse-seine catch was dominated (64%) by the associated fishery.

Historically, most of the yellowfin catch is taken from the western equatorial region of the IO (47%; region 1b, see Figure 1) and, to a lesser extent, the Arabian Sea (21%), the eastern equatorial region (25%, region 4) and the Mozambique Channel (8%; region 2). The purse-seine and baitboat fisheries operate almost exclusively within the western equatorial region, while catches from the Arabian Sea are principally by handline, gillnet, and longline (Figure 2). Catches from the eastern equatorial region (region 4) were dominated by longline and gillnet (around Sri Lanka and Indonesia). The southern Indian Ocean (region 3) accounts for a small proportion of the total yellowfin catch (1%) taken exclusively by longline (Figure 2).

In recent years (2008–2012), due to the threat of piracy, the bulk of the industrial purse seine and longline fleets moved from the western waters of Region 1b to avoid the coastal and off-shore waters off Somalia, Kenya and Tanzania. The threat of piracy was particularly affected the freezer longline fleet and levels of effort and catch decreased markedly from 2007. The total catch by freezing longliners declined to about 2,000 mt in 2010, a 10-fold decrease in catch from the years before the onset of piracy. Purse seine catches also dropped in 2008–2010 but rapidly recovered to the earlier level. Piracy off the Somali coast was almost eradicated by 2013 although longline catches have not recovered.

3 Data compilation

The data used in the yellowfin tuna assessment consist of catch and length composition data for the fisheries defined in the analysis, longline CPUE indices and tag release-recapture data. The details of the configuration of the fishery specific data sets are described below.

3.1 Spatial stratification

The geographic area considered in the assessment is the Indian Ocean, defined by the coordinates 40°S–25°N, 20°E–150°E. Previous yellowfin stock assessments have adopted a five region spatial structure (see Langley 2012). Preliminary analyses conducted during the current assessment highlighted a number of issues related to the five region model structure. There have been no CPUE abundance indices available from the Arabian Sea region (region 1) since 2010 although the area has yielded very high catches from the handline and gillnet fisheries during recent years. The preliminary models estimated exceptionally high levels of fishing mortality in those years. The models failed to estimate *MSY* bench marks seemingly due to the magnitude of the fishing mortality rates in Region 1.

For the Arabian Sea region, the Taiwanese longline CPUE indices represent the primary series of abundance indices from 1979 onwards (Yeh Y.M. & Chang S.T. 2012). While there has also been some concern regarding the reliability of these CPUE indices, the general trend in the CPUE indices is comparable to the Japanese longline CPUE indices in the western equatorial region (LL1b). During the current assessment, preliminary modelling was conducted comparing the previous five region model structure and an alternative four region structure that amalgamated the Arabian Sea and western equatorial regions (formerly regions 1 and 2). The results indicated that recent trends in stock abundance from 2010 were sensitive to the model structure with the five region model providing a more optimistic stock trajectory. The increase in stock biomass was principally within the Arabian Sea region. Given the lack of a regional abundance index during that period it was considered that these results were unlikely to provide a reliable indication of current stock status. For that reason, the five region model was abandoned in favour of the four region model structure.

The base assessment model adopted the four region model structure, combining the Arabian Sea (region 1a) and western equatorial region (region 1b) (Figure 1), although the two sub regions were retained for the definition of spatially distinct fisheries that operate in each area. The spatial structure retains two regions that encompass the main year-round fisheries in the tropical area and two austral, subtropical regions where the longline fisheries occur more seasonally. The sensitivity of the stock assessment model to the assumptions regarding spatial structure is further evaluated in the current assessment (see Section 5).

3.2 Temporal stratification

The time period covered by the assessment is 1950–2014 representing the period for which catch data are available from the commercial fishing fleets. This differs from previous MFCL assessments which commenced in 1972 (assuming unexploited equilibrium conditions). For the current assessment, preliminary model results indicated that the assessment results were not sensitive to the early catches from the model (pre 1972) and commencing the model in 1950 or 1972 yielded very similar results.

Within this model period, the annual data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec) (representing a total of 260 time steps). The time steps were used to define model "years" (of 3 month duration) enabling recruitment to be estimated for each quarter to approximate the continuous recruitment of yellowfin in the equatorial regions. The quarterly time step precluded the estimation of seasonal model parameters, particularly the movement parameters. There is a strong indication of seasonal movement of yellowfin to the higher latitudes during the summer period.

3.3 Definition of fisheries

The assessment adopted the equivalent fisheries definitions used in the previous MULTIFAN-CL stock assessment. These "fisheries" represent relatively homogeneous fishing units, with similar selectivity and catchability characteristics that do not vary greatly over time. Twenty-five fisheries were defined based on location (region), time period, fishing gear, purse seine set type, and type of vessel in the case of longline fleet (Table 1).

The longline fishery was partitioned into two main components:

Freezing longline fisheries, or all those using drifting longlines for which one or more of the following three conditions apply: (i) the vessel hull is made up of steel; (ii) vessel length overall of 30 m or greater; (iii) the majority of the catches of target species are preserved frozen or deep-frozen. A composite longline fishery was defined in each region (LL 1–4) aggregating the longline catch from all freezing longline fleets (principally Japan and Taiwan).

Fresh-tuna longline fisheries, or all those using drifting longlines and made of vessels (i) having fibreglass, FRP, or wooden hull; (ii) having length overall less than 30 m; (iii) preserving the catches of target species fresh or in refrigerated seawater. A composite longline fishery was defined aggregating the longline catch from all fresh-tuna longline fleets (principally Indonesia and Taiwan) in region 4 (LF 4), which is where the majority of the fresh-tuna longliners have traditionally operated. The catches of yellowfin tuna recorded in regions 1 to 3 for fresh-tuna longliners, representing only a 3% of the total catches over the time series, were assigned to area 4.

The purse-seine catch and effort data were apportioned into two separate method fisheries: catches from sets on associated schools of tuna (log and drifting FAD sets; PS LS) and from sets on unassociated schools (free schools; PS FS). Purse-seine fisheries operate within regions 1a, 1b, 2 and 4 and separate purse-seine fisheries were defined in regions 1b, 2 and 4, with the limited catches, effort and length frequency data from region 1a reassigned to region 1b.

The region 1b purse-seine fisheries (log and free-school) were divided into three time periods: pre 2003, 2003–2006 and post 2006. This temporal structure was implemented due to the apparent change in the length composition of the catch from the purse-seine fisheries during the 2000s. The length of fish caught by the FAD fishery was generally smaller from 2007 onwards, while a higher proportion of smaller fish were caught by the free-school fishery prior to 2003.

A single baitboat fishery was defined within region 1b (essentially the Maldives fishery). As with the purse-seine fishery, a small proportion of the total baitboat catch and effort occurs on the periphery of region 1b, within regions 1a and 4. The additional catch was assigned to the region 1b fishery.

Gillnet fisheries were defined in the Arabian Sea (region 1a), including catches by Iran, Pakistan, and Oman, and in region 4 (Sri Lanka and Indonesia). A very small proportion of the total gillnet catch and effort occurs in region 1b, with catches and effort reassigned to area 1a.

Three troll fisheries were defined, representing separate fisheries in regions 1b (Maldives), 2 (Comoros and Madagascar) and 4 (Sri Lanka and Indonesia). Moderate troll catches are also taken in regions 1a and 3, the catch and effort from this component of the fishery reassigned to the fisheries within region 1b and 4, respectively.

A handline fishery was defined within region 1a, principally representing catches by the Yemenese fleet. Moderate handline catches are also taken in regions 1b, 2 and 4, the catch and effort from these components of the fishery were reassigned to the fishery within region 1a.

For regions 1a and 4, a miscellaneous (“Other”) fishery was defined comprising catches from artisanal fisheries other than those specified above (e.g. trawlers, small purse seines or seine nets, sport fishing and a range of small gears).

3.4 Catch data

Catch data were compiled based on the fisheries definitions. The catches for longline fisheries were expressed in numbers of fish while the catches for other fisheries were expressed in metric tonnes (mt) (Figure 3). For the 2012 assessment, there were changes to the catch history for the TR 4 and OT 4 fisheries resulting from major revisions of the Indian and Indonesia catch by fishing gear (Herrera & Pierre 2012). For the current assessment, there were changes to the catch history relating to the coastal fisheries of Pakistan, Indonesia, Sri Lanka, India and Maldives (Geehan et al. 2013).

3.5 CPUE indices

Standardised CPUE indices were derived using generalized linear models (GLM) from Japanese longline catch and effort data (Regions 1b & 2–4) (Ochi et al 2015). The Japanese longline fleet did not operate within region 1b during 2011 due to the threat of piracy and, consequently, CPUE indices are not available.

Standardised longline CPUE indices for the Taiwanese fleet were available for 1979–2011 (Yeh Y.M. & Chang S.T. 2012). For previous assessments, these CPUE indices were the primary abundance indices for the Arabian Sea fishery (formerly Region 1); however, these indices were not used in the current four region assessment model.

Quarterly CPUE indices are available for the Japanese longline fleet from 1963, although following previous assessments the CPUE indices from 1963–72 were not included in the assessment model. The CPUE indices from the earlier period are considerably higher than for the remainder of the 1970s. The decline in CPUE indices during the late 1960s–early 1970s is inconsistent with the relatively low level of catch taken during this period. The inclusion of the earlier CPUE indices in previous stock assessment models resulted in stock dynamics that were considered unrealistic, especially the high initial stock biomass levels and declining biomass attributable to a decline in recruitment during the 1960s (see Langley et al 2008). At the 10th WPTT, it was agreed that the decline in the CPUE indices was unlikely to be solely due to changes in stock abundance. On that basis, the early data were excluded from the assessment and the model was initiated in 1972.

For the regional longline fisheries, a common catchability coefficient (and selectivity) was estimated in the assessment model, thereby, linking the respective CPUE indices among regions. This significantly increases the power of the model to estimate the relative (and absolute) level of biomass among regions. However, as CPUE indices are essentially density estimates it is necessary to scale the CPUE indices to account for the relative abundance of the stock among regions. For example, a relatively small region with a very high average catch rate may have a lower level of total biomass than a large region with a moderate level of CPUE.

The approach used was to determine regional scaling factors that incorporated both the size of the region and the relative catch rate to estimate the relative level of exploitable longline biomass among regions. This approach is similar to that used in the WCPO regionally disaggregated tuna assessments. The scaling factors were derived from the Japanese longline CPUE data from 1963–75, essentially summing the average CPUE in each of the 5*5 lat/longitude cells within a region. The relative scaling factors thus calculated for regions 1–4 are 1.21, 0.55, 0.15, and 0.85, respectively.

For each of the principal longline fisheries, the GLM standardised CPUE index was normalised to the mean of the GLM index from 1963–75 — 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 among regions.

A number of important trends are evident in the CPUE indices from the four regions (**Error! Reference source not found.**).

- The CPUE indices from regions 1, 2, and 4 show similar fluctuating trends during 1972–95 with peaks in CPUE in 1972–73, 1976–78 and 1985–88 and a decline in CPUE during 1988–95.
- From 1995, the CPUE indices from regions 1, 2, and 4 declined, although the timing and extent of the decline differed amongst the three regions.
- The CPUE indices from region 1 remained relatively stable during 1995–2005 and then dropped sharply in late 2006 and remained low until late 2009. The drop in CPUE occurred before the peak in the number of piracy incidents in the western Indian Ocean (2008–2011). The low CPUE indices followed the period of exceptionally high catches from the purse seine fishery in region 1 during 2003–2005. Since 2010, the CPUE indices have been variable; CPUE indices were high in late 2010 and relatively low during 2012–14. No CPUE indices are available for region 1 from 2011 due to the restrictions on the operation of the longline fleet in the area due to the risk of piracy.
- The CPUE indices for region 2 followed a similar trend to the CPUE indices from region 1 until the mid-2000s. During the last decade, the CPUE indices for region 2 remained relatively stable, in contrast to the the general decline in the region 1 CPUE indices.
- From 1995, the CPUE indices from region 4 generally declined and have been very low from 2008 onwards. The recent decline in CPUE in this region is consistent with a decline in the proportion of yellowfin in the combined tuna catch from the Japanese longline fleet in the eastern Indian Ocean (see Figure 44 from Hoyle et al 2015). It is unclear whether the change in species proportion is related to a decline in the abundance of yellowfin in the region (relative to the other species) or a regional change in the targeting of the fishing fleet. However, there is an indication that there has been a differential shift towards deeper longline gear (greater HBF) in the eastern Indian Ocean since 2000 and this may indicate a changing in shift in targeting toward bigeye tuna in this region (Hoyle pers. comm. additional JP LL analyses). Such factors may not be adequately accounted for in the standardisation of the yellowfin CPUE data.
- There is considerable variability in the R1 and R4 CPUE indices between quarters. During the late 1970s to mid-1990s, there were contradictory patterns in the quarterly CPUE between the two regions; i.e. when CPUE increased in one region there was a corresponding decline in CPUE in the other region. The magnitude of the variation in CPUE in R1 was generally higher than R4.
- The CPUE indices from region 3 are low compared to the other three regions reflecting the low regional scaling factor. However, the overall trend in the CPUE indices is broadly comparable to the other regions with relatively high CPUE during the late 1980s, relatively stable CPUE during 1995–2007 and a sharp drop in 2008. The CPUE indices have been variable during the last five years; higher in 2011 and very low in late 2014.
- The CPUE indices for region 2 are strongly seasonal with highest catch rates typically occurring during the first quarter of the year and lowest catch rates during the third quarter. However, the duration of the period of higher catch rates varies between years.

3.6 Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 95 2-cm size classes (10–12 cm to 198–200 cm). Each length frequency observation for purse seine fisheries represents the number of fish sampled raised to the sampling units (sets in the fish compartment) while for fisheries other than purse seine each observation consisted of the actual number of yellowfin tuna measured. A graphical representation of the availability of length samples is provided in Figure 5. The data were collected from a variety of sampling programmes, which can be summarized as follows:

Purse seine: Length-frequency samples from purse seiners have been collected from a variety of port sampling programmes since the mid-1980s. The samples are comprised of very large numbers of individual fish measurements. The length frequency samples are available by set type with log sets catches typically composed of smaller fish than free school catches. However, there is also a considerable catch of smaller fish taken during free school fishing operations, particularly in the Mozambique Channel area (Chassot 2014).

Longline freezing: Length and weight data were collected from sampling aboard Japanese commercial, research and training vessels. Weight frequency data collected from the fleet have been converted to length frequency data via a processed weight-whole weight conversion factor and a weight-length key. Length frequency data from the Taiwanese longline fleet from 1980–2003 are also included in the length frequency data set, although data from the more recent years were excluded due to concerns regarding the reliability of these data (Greehan & Hoyle 2013). Comparisons between size data collected from Taiwanese vessels by observers and logbooks since 2003 revealed that the vessel masters reported considerably larger fish (Simon Hoyle pers. comm.). In recent years, length data are also available from other fleets (e.g. Seychelles).

Overall, the average length of yellowfin caught by the longline fleet is generally comparable among the regions. However, there is considerable temporal variation in the length of fish caught (Figure 6). For all longline fisheries there was a marked decline in the size of fish caught during the 1950s and 1960s, while the size of fish caught stabilised during the 1970s and 1980s. The longline fisheries tended to catch smaller fish during the late 1990s and early 2000s, although the size of fish caught has increased in the subsequent years.

Longline fresh: Length data are available from 1998–2008. Length and weight data were collected in port, during unloading of catches, for several landing locations and time periods, especially on fresh-tuna longline vessels flagged in Indonesia and Taiwan/China (IOTC-OFCF sampling).

Gillnet: Length data are available from both GN 1 and 4 fisheries.

Baitboat: Size data are available from the fishery from 1983 to 2011.

Troll: No size data are available from the TR 1b and 2 fisheries. The troll fishery in region 4 was sampled during two periods: 1985–1990 (Indonesian fishery) and 1994–2004 (Sri Lankan fishery).

Handline: Limited sampling of the handline fishery was conducted over the last decade. Samples are available for the Maldivian handline fisheries for this period.

Other: Length samples are available from the "Other" fishery in region 4 (OT 4) fishery and limited data are available from the "Other" fishery in region 1a (OT 1a) (2009–2014).

Changes to the length frequency data sets from the 2012 assessment primary relate to the exclusion of the data from the Taiwanese longline fleet for 2003 onwards and the fresh tuna longline fleet from 2010. All other data sets were updated to include the most recent years (2011–2014).

Length data from each fishery/quarter were simply aggregated assuming that the collection of samples was broadly representative of the operation of the fishery in each quarter.

3.7 Tagging data

A considerable amount of tagging data was available for inclusion in the assessment model. The data used consisted of yellowfin tuna tag releases and returns from the Indian Ocean Tuna Tagging Programme (IOTTP), and mainly from its main phase, the Regional Tuna Tagging Project-Indian Ocean (RTTP-IO) conducted during 2005–2009. The IOTC has continued to compile all the release and recovery data from the RTTP-IO and the complementary small-scale programmes in a single database.

Most of the tag releases of the RTTP-IO occurred within the western equatorial region (region 1b) and a high proportion of these releases occurred in the second and third quarters of 2006 (see IOTC 2008a for further details) (Figure 7). Limited tagging also occurred within regions 1a and 2. The model included all tag recoveries up to the end of 2014. The spatial distributions of tag releases and recoveries are presented in Figure 8 and Figure 9, respectively.

For incorporation into the assessment model, tag releases were aggregated in release groups defined by release region, time period of release (quarter) and quarterly age class. The age at release was assumed based on the fish length at release and the average length-at-age from the yellowfin growth function (see Section 4.1.2). Fish aged 15 quarters and older were aggregated in a single age group. Tag releases in regions 1a and 1b were stratified in separate release groups due to the spatial separation of the individual release events. A total of 54,392 releases were classified into 131 tag release groups. Most of the tag releases were in the 5−8 quarter age classes (Figure 7).

The returns from tag release group were then classified by recapture fishery and recapture time period (quarter). The results of associated tag seeding experiments, conducted during 2005–2008, have revealed considerable temporal variability in tag reporting rates from the IO purse-seine fishery (Hillary *et al.* 2008). Reporting rates were lower in 2005 (57%) compared to 2006 and 2007 (89% and 94%). This large increase over time was the result of the development of publicity campaign and tag recovery scheme raising the awareness of the stakeholders, *i.e.* stevedores and crew. SS assumes a constant fishery-specific reporting rate. To account for the temporal change in reporting rate, the number of tag returns from the purse-seine fishery in each stratum (tag group, year/quarter, and length class) were corrected using the respective estimate of the annual reporting rate. A reporting rate of 94% was assumed for the correction of the 2008−2014 tag recoveries.

In total, 10,474 tag recoveries (corrected for reporting rate) could be assigned to the fisheries included in the model. Almost all of the tags released in region 1 were recovered in the home region, although some recoveries occurred in adjacent regions, particularly region 2. A small number of tags were recovered in region 4 (from tags released in region 1b) and there were no tags recovered from region 3 (Table 3). Most of the tag recoveries occurred between mid-2006 and mid 2008 (Figure 10). The number of tag recoveries started to attenuate in 2009 although small numbers of tags have been recovered up to the end of 2014.

Most of the tags were recovered by the purse seine fishery within region 1b (Figure 10). A significant proportion (35%) of the tag returns from purse seiners were not accompanied by information concerning the set type. These tag recoveries were assigned to either the free-school or log fishery based on the expected size of fish at the time of recapture; i.e. fish larger than 80 cm at release were assumed to be recaptured by the free-school fishery; fish smaller than 80 cm at release and recaptured within 18 months at liberty were assumed to be recovered by the log set fishery; fish smaller than 80 cm at release and recaptured after 18 months at liberty were assumed to be recovered by the free-school fishery.

For the purse-seine fisheries, the tag dataset was corrected for reporting rates (as described above) and the reporting rates were essentially fixed at a value of 0.81 to account for initial tag retention rates (0.9) (Gaertner and Hallier 2008) and the proportion of the total purse-seine catch examined for tags (0.9). No information is available regarding tag reporting rates from the other (non purse-seine) fisheries some of which returned a substantial number of tags. Tag recoveries were also corrected for long-term tag loss (tag shedding) based on an update of the analysis of Gaertner and Hallier (unpublished). Tag loss for yellowfin was estimated to be approximately 20% at 2000 days at liberty.

Additional tag release/recovery data are available from a number of small-scale tagging programmes. The data set included a total of 7,828 tags released during 2002-08, primarily within regions 1b (70%) and 4 (28%). A total of 366 tag recoveries were reported, predominantly from the baitboat fishery in region 1a. There has been no comprehensive analysis of these data results and there is no information available concerning the fishery specific reporting rate of these tags. The tag release/recovery data from the SS tagging programmes were not incorporated in the current range of assessment models. However, these data were included in a model sensitivity (*tagAll*) in the preliminary modelling conducted prior to the WPTT14 meeting (Langley et al 2012a). This analysis indicated that the stock assessment results were relatively insensitive to the inclusion of these data.

3.8 Environmental data

A range of environmental indices were configured to characterise seasonal and temporal variation in the oceanographic conditions in the Indian Ocean. These indices were primarily defined to investigate the potential for environmental covariates to be incorporated in the estimation of the movement of fish between adjacent model regions.

Regional environmental indices were determined using NOAA NCEP EMC CMB GODAS monthly current (*u* and *v* component) and sea temperature data (Behringer & Xue 2004). The model data are resolved by month and a grid of 1 degree longitude and 0.33 degree of latitude and available from January 1980.

Five sets of indices were included in the stock assessment modelling: three sets of SST indices from the Mozambique Channel (*SST1*), southern Indian Ocean (*SST3*) and eastern Indian Ocean (*SST4*) (Figure 11) and two sets of current indices from the central Indian Ocean (E/W *u* vector *Current5*) and northern Mozambique Channel (N/S *v* vector *Current7*) (Figure 12). The indices were derived by computing the average of the values within the specified area for each quarter (1980-2014). Each index was then normalised as deviations from the overall average for the time series.

The *SST1* and *SST3* indices display a strong seasonal trend with highest values in quarters 1 and 4 corresponding to the austral summer (Figure 13). There are no strong temporal trends in either set of indices. The *SST4* index is similar in formulation to the Dipole Index. The indices exhibit a relatively weaker seasonal trend and a higher degree of interannual variability compared to the other two sets of SST indices (Figure 13). The *Current5* indices exhibit an interannual trend that is generally comparable to the *SST4* index derived from an overlapping area in the central Indian Ocean, although the indices indicate that the since the late 1990s there has been a more persistent eastward flow compared to the preceding decade (Figure 13). This may provide an explanation for the lower longline CPUE in the eastern Indian Ocean (LL4 CPUE index) during the latter period (and the shift to deeper setting of longline gear).

The longer term trend in the *Current7* indices is similar to the *Current5* index with northward currents tending to prevail from the late 1990s (Figure 13). There are some corresponding trends in the environmental variables and fishery performance, as follow.

- There is a strong seasonal trend in the longline CPUE indices from R2 and R4 that corresponds to the seasonal variation in SST in each area (*SST1* and *SST3*).
- Seasonal patterns in LL CPUE between R1 and R2 are generally contrary; higher CPUE in R2 during quarters 1 and 4 and lower CPUE in R2 during the corresponding period. A similar pattern is evident between the CPUE in R4 and R3.
- Relative longline CPUE in Region 1b tended to higher than Region 2 (CPUE R1/CPUE R2) when the *SST1* index was positive for a sustained period.
- Relative longline CPUE in Region 1b tended to higher than Region 4 (CPUE R1/CPUE R4) when the *SST4* index was positive (both seasonally and interannually).
- Highest PSFS catches in Region 1b have tended to follow peaks in the *SST4*; i.e. warmer SST conditions in the eastern Indian Ocean and eastward current flow.
- PSFS catches in Region 2 generally peak in the second quarter of the year. Highest PSFS catches in Region 2 have tended to occur during periods when the *SST1* index was negative for a sustained period; i.e. SST in Mozambique Channel lower than average.

4 Model structural and assumptions

4.1 Population dynamics

The spatially dissaggregated model partitions the population into four regions. The population in each region is comprised of 28 quarterly age-classes both sexes combined. The first age-class has a mean fork length of around 22 cm and is assumed to be approximately three months of age based on ageing studies of yellowfin tuna (Fonteneau 2008). The last age-class comprises a “plus group” in which mortality and other characteristics are assumed to be constant. Insufficient sex-specific data are available to configure a two sex population model.

The model commences in 1950 at the start of the available catch history. The initial population age structure in each region was assumed to be in an unexploited, equilibrium state.

4.1.1 <u>Recruitment</u>

Recruitment occurs in each quarterly time step of the model. Recruitment was derived from a BH stock recruitment relationship (SRR) and variation is recruitment was estimated as deviates from the SRR. Recruitment deviates were estimated for 1972 to mid-2014 (170 deviates), representing the period for which longline CPUE indices are available. Recruitment deviates were assumed to have a standard deviation (σ_R) of 0.6. For 1950-1969, recruitment was derived directly from the SRR. The base model assumed a level of steepness (*h*) of 0.8 for the SRR, an intermediate value within the plausible range of steepness values generally adopted in the tuna assessments by other tuna RFMOs (0.7, 0.8 and 0.9) (Harley 2011).

Recruitment was assumed to occur in the two equatorial regions only (region 1 and 4). This assumption was based on the temperature preference for the spawning of yellowfin tuna and a minimum temperature for larval survival of about 24°C (Suzuki 1993). The constraint precluded large recruitments occurring within the subequatorial regions as evident in previous assessments (see Langley 2012).

The overall proportion of the quarterly recruitment allocated to region 1 and region 4 was estimated (*RecrDist_Area* parameters). The base model estimated 64% and 36% of the recruitment occurred in the respective regions. Variation in the regional distribution of recruitment was included by estimating temporal deviates of the *RecrDist_Area* parameters for 1977 to mid-2014 (2*150 deviates) (assuming a standard deviation of 1.0 for the deviates).

4.1.2 Growth and maturation

Previous assessments of IO yellowfin tuna using MFCL have attempted to estimate the growth parameters during the fitting procedure (Langley et al. 2008, 2009). However, the resulting estimates of mean length-at-age were considerably higher than growth parameters estimated externally of the assessment model (Fonteneau 2008, Gaertner et al. 2009). Further examination of the data indicated that the growth parameters in the MFCL were being strongly influenced by the modal progression in the length frequency data from the fisheries in region 1a. This may indicate that growth rates in the Arabian Sea are higher than for the tropical fishery.

For the current assessment, growth parameters were fixed at values that replicated the growth curve derived by Fonteneau (2008) (Figure 14). The non-von Bertalanffy growth of juvenile yellowfin tuna is evident, with slow growth for young age classes and near-linear growth in the 60–110 cm size range. Growth in length is estimated to continue throughout the lifespan of the species, attenuating as the maximum is approached. The estimated variance in length-at-age was assumed to increase with increasing age (Figure 14).

Tag based estimates of mean length at age from Eveson et al. (2012) and Dortel et al. (2012) are comparable to the values currently incorporated in the assessment model; however, for the older age classes the estimates of the standard deviation of length at age are considerably higher than the values previously assumed.

Length based maturity OGIVEs for Indian Ocean yellowfin are available from Zudaire et al (2013). The paper presents two alternative maturity OGIVEs based on either the cortical alveolar or vitellogenic stages of ovarian development. The two length based OGIVEs were converted to age based OGIVEs assuming an equilibrium population age-length structure (derived from age-specific natural mortality, growth function and the assumed variation of length-at-age).

The maturity OGIVE based on cortical alveolar stage development indicates the onset of maturity occurs at about age 5 quarters and full maturity is attained at about 12 quarters (Figure 15). The maturity OGIVE based on vitellogenic stage development is offset by about 3 quarters. The former OGIVE was used in the base model and the alternative (older) OGIVE was used in a model sensitivity during preliminary modelling.

4.1.3 Natural mortality

Natural mortality is variable with age with the relative trend in age-specific natural mortality based on the values applied in the Pacific Ocean (western and central; eastern) yellowfin tuna stock assessments.

For the 2012 stock assessment (Langley 2012), the overall average level of natural mortality was initially fixed at a level comparable to a preliminary estimate of age-specific natural mortality from the tagging data (see IOTC 2008b). However, the overall level of natural mortality is low compared to the level of natural mortality used in the stock assessments of other regional yellowfin stocks (WCPO, EPO and Atlantic) (Maunder & Aires-da-Silva 2012). The WPTT considered that the IO tag data set was likely to be reasonably informative regarding the overall level of natural mortality and for the final model options the overall (average) level of natural mortality estimated, while maintaining the relative age-specific variation in natural mortality (Langley 2012). The estimated level of natural mortality intermediate between the initial level and the level of natural mortality adopted for the WCPFC and IATTC yellowfin stock assessments (Maunder & Aires-da-Silva 2012).

The resulting age-specific natural mortality has been used as the base level of natural mortality for the current stock assessment, while the lower level of natural mortality is included in a model sensitivity (*Mlow*)

(Figure 16). Further evaluation of the utility of the tagging data set for the estimation of natural mortality was conducted during the preliminary modelling phase.

4.1.4 Movement

For the four region model, reciprocal movement was assumed to occur between adjacent model regions, specifically R1-R2, R1-R4, R3-R4 (3x2) (Figure 1). Movement is parameterised as the proportional redistribution of fish amongst regions, including the proportion remaining in the home region. The redistribution of fish occurs instantaneously at the end of each model time step.

Movement was parameterised to estimate differential movement for young (2–8 quarters) and old (≥9 quarters) fish to approximate potential changes in movement dynamics associated with maturation. Thus, for each movement transition two separate movement parameters were estimated. Fish did not commence moving until the end of age 2 quarters.

There is no seasonal structure in the assessment model due to the quarterly time step and consequently it was not possible to directly estimate seasonal movements. The seasonal variation in the longline CPUE indices and the purse-seine catches, particularly in region 2, indicate that there are likely to be significant seasonal changes in the regional abundance of yellowfin. Preliminary modelling results identified that it was necessary to incorporate seasonal movement dynamics to adequately account for the magnitude of the variation in the CPUE indices and catches.

To incorporate seasonal movement dynamics, a range of environmental covariates were included in the movement parameterisation. These environmental covariates were based on quarterly SST and current flow specific to the transitional areas between regions (defined in Section 3.8). The individual metrics were associated with the specific movement parameters as defined in the following Table. The movements of mature (≥9 quarters) fish were linked to SST based metrics, while the movements of juvenile fish were linked to current based metrics. The environmental covariates were assigned to the preceding quarter to facilitate movement in advance of the fishery (movement is configured to occurs at the end of each quarter).

The rationale for linking juvenile movements to current flow was based on an analysis of the IO tag release and recovery location data. The analysis indicated that the location of spatially aggregated tag recoveries could be approximated based on the passive movement of fish from the tag release location.

Transition	**Life stage**	**Covariate**	**Link parameter (estimated)**
R1 to R2	Immature	*Current7*	1.267
R1 to R2	Mature	*SST1*	0.050
R1 to R4	Immature	*Current5*	-0.011
R1 to R4	Mature	*SST4*	-0.182
R2 to R1	Immature	*Current7*	2.529
R2 to R1	Mature	*SST1*	0.166
R3 to R4	Immature	*SST3*	-0.927
R3 to R4	Mature	*SST3*	-0.389
R4 to R1	Immature	*Current5*	0.020
R4 to R1	Mature	*SST4*	0.217
R4 to R3	Immature	*SST3*	0.314
R4 to R3	Mature	*SST3*	1.406

The movement parameterisation incorporates the environmental covariate by modifying the base movement parameter by multiplying the exponentiated product of the link parameter and the environmental index; i.e., *parm'(y) = parm * exp(link * env(y,g))* where *link* is the environmental link parameter, *parm* is the base parameter being adjusted, *parm'* is the value after adjustment, and *env(y,g) is* the value of the environmental input g in year (Methot 2013).

4.2 Fishery dynamics

Fishery selectivity is assumed to be age-specific and time-invariant. For the longline fisheries (LL 1a, 1b, 2, 3 and 4) a single selectivity is estimated that is shared among the five fisheries. The selectivity is also shared by the four sets of LL CPUE indices. The longline selectivity was parameterised with a logistic function that constrains the constrains the older age classes to be fully selected ("flat top"). The selectivity of the fresh tuna longline fishery (LF4) was estimated using a separate logistic function.

The free-school (FS) and FAD (LS) purse seine fisheries within region 1b were divided into three time periods (pre 2003, 2003−2006 and post 2006) based on the observation that the size of fish caught differed between these periods. Earlier stock assessments had estimated separate selectivities for each time period (and fishery). However, the stock assessment results were relatively insensitive to the temporal changes in selectivity and, for simplicity, a single selectivity was estimated for each method (FS and LS) for the three time periods. The corresponding purse-seine method selectivities were also shared with the purse-seine fisheries in region 2 and region 4.

The two purse seine selectivities (FS and LS) were formulated using a cubic spline interpolation with five nodes. The nodes were specified to approximate the main inflection points of the selectivity function. This formulation was sufficiently flexible to provide a reasonable representation of the modal structure of the length composition of the catch from the two purse seine methods.

For the other fisheries, selectivity was parameterised using a double-normal function (Methot 2013). No length frequency data are available for the "Other" fishery in region 1a, while limited data are available from the OT 4 fishery. Similarly, size data were available from the troll fishery in region 4, but not from the fisheries in regions 1b and 2. The selectivity of the "Other" fisheries was assumed to be equivalent among the two regions (1a and 4), while a common selectivity was assumed for the troll fisheries in regions 1b and 4.

Fishing mortality was modelled using the hybrid method that the harvest rate using the Pope's approximation then converts it to an approximation of the corresponding *F* (Methot & Wetzel 2013).

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

An analysis of the tag recovery data was undertaken to determine an appropriate mixing period for the tagging programme (Langley & Million 2012). The analysis revealed that the tag recoveries from the FAD purse-seine fishery were not adequately mixed, at least during the first 6 months following release. Conversely, the free-school tag recoveries indicate a higher degree of mixing within the fished population. Most of the tagged yellowfin were in the length classes that are not immediately selected by the free-school fishery (< 90 cm). A mixing period of about 6−12 months is of sufficient duration for most tagged fish to recruit to free-school fishery (> 90 cm) and no longer be vulnerable to the FAD fishery. On that basis, it was considered that a mixing period of three quarters was sufficient to allow a reasonable degree of dispersal of tagged fish amongst the yellowfin tuna population within the primary region of release.

The release phase of the tagging programme was essentially restricted to the western equatorial region. The distribution of tags throughout the wider IO appears to have been relatively limited as is evident from the low number of tag recoveries from the fisheries beyond region 1b. Tag recoveries from beyond region 1 and 2 are unlikely to significantly inform the model regarding movement rates given the lack of information concerning reporting rates of tags for these fisheries (see below).

4.3.2 Tag reporting

Estimates of tag reporting rates from the purse seine fishery were available from tag seeding trials. These estimates were applied to correct the number of tags included in the recovery dataset for the purse seine fisheries (within region 1b and region 2) and the fishery specific tag reporting rates were fixed at a value of 0.81 to account for initial tag retention rates (0.9) and the proportion of the total purse-seine catch examined for tags (0.9).

For the other fisheries, there is very limited information is available to indicate the tag reporting rates and fishery specific reporting rates were estimated based on uninformative priors. All fishery reporting rates were assumed to be temporally invariant.

4.4 Observation models for the data

The total likelihood is composed of a number of components, including the fit to the abundance indices (CPUE), tag recovery data, fishery length frequency data and catch data. There are also contributions to the total likelihood from the recruitment deviates and priors on the individual model parameters. The model is configured to fit the catch almost exactly so the catch component of the likelihood is very small. There are two components of the tag likelihood: the multinomial likelihood for the distribution of tag recoveries by fleets over time and the negative binomial distribution of expected total recaptures across all regions. Details of the formulation of the individual components of the likelihood are provided in Methot & Wetzel (2013).

Previous MFCL yellowfin assessments had assigned the regional CPUE indices a weighting that corresponded to a CV of 0.1 (10%). The high weighting was intended to ensure that the stock biomass trajectories were consistent with the regional CPUE indices, although it was generally considered that the weighting did not reflect the overall precision of the CPUE indices.

For the current assessment, the weighting of the CPUE indices followed the approach of Francis (2011). An initial model was implemented that down weighted all the length composition and tag release/recovery data sets. The RMSE of the resulting fit to each set of CPUE indices was determined as a measure of the magnitude of the variation of each set of indices CPUE indices. The resulting RMSEs were relatively high (0.40–0.50), although a significant proportion of this variation is related to the relatively high seasonal variation in CPUE in most regions. On that basis, a CV of 0.3 was assigned to each set of CPUE indices, representing an intermediate level of precision that ensured the stock biomass trajectories were broadly consistent with the CPUE indices while allowed for a moderate degree of variability in fitting to the indices.

The weighting of the tag component of the likelihood was conducted following Francis & McKenzie (in prep.). The relative weighting of the tagging data was controlled by the magnitude of the over-dispersion parameters assigned to the individual tag release groups. The value of the over-dispersion parameter was determined using an iterative approach. From an initial model run, the residuals of the fit to the tag recovery data were determined (observed – expected number of tags recovered). The variance of the standardised residuals represents the variability in the tag-recapture data and the over-dispersion parameter should reflect this level of variability. For the initial model, the variance of the standardised residual was 6.8 and, on that basis, the over-dispersion parameters for all tag release groups were set at 7.0 (for all model options).

The reliability of the length composition data is variable across fisheries and over time periods. For that reason, it was considered that the length composition data should not be allowed to dominate the model likelihood and directly influence the trends in stock abundance. For each fishery, an overall effective sample size (ESS) was determined following the weighting procedure of Francis (2011) resulting in low ESS (3–8) for most fisheries, with the exception of the PSLS fishery in region 1b (ESS approx. 30). On that basis, an ESS of 5 was assigned to all length composition observations (all fisheries, all time periods) essentially giving the entire length composition data set a relatively low weighting in the overall likelihood. Nonetheless, due to the magnitude of the length composition data, these data were sufficiently informative to provide reasonable estimates of fishery selectivity and provide some information regarding recruitment trends. In general, the trends in the average fish size predicted by the model were generally consistent with the specific trends in the fishery data sets.

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.

5 Preliminary modelling

The initial modelling phase investigated a range of model options examining assumptions related to the spatial structure, biological parameters and the influence of key data sets. The initial modelling was primarily based on the model specified in Table 4. These model trials were completed prior to the finalisation of the catch data for 2014 and fishery catches for that year were assumed to be equivalent to the 2013 catches. The conclusions of the preliminary modelling were not sensitive to the catches in the terminal year (2014).

A description of the range of alternative model options considered is presented in the following Table.

Option	**Configuration (relative to base option)**	**Rationale and comments**
Base	As per Table 4	Initial model for comparative purposes.
Mlow	Relative age-specific natural mortality equivalent to base model. Overall level of *M* approximately 60% of the base level.	Lower overall level of natural mortality used as a sensitivity in previous assessment (see Figure 16).
Mscale	Constant *M* for all age classes; *M* parameter estimated (no prior).	To compare magnitude of estimated value of *M* with scale of base *M* estimated in 2012 IO yellowfin assessment (Figure 16).
MestAge	Estimate natural mortality at 4 ages (3, 6, 10 and 15 quarters) and interpolate between these break points.	The *Mscale* model resulted in a considerable improvement in the overall fit without any variation in *M* at age. This model incorporates additional variation in *M* by estimating at four specified ages and interpolating between the ages (see Figure 16). Estimates of *M* for the 6–10 age classes were very low.
OGIVEmaturity	Female maturity OGIVE sensitivity.	Maturity OGIVE derived based on maturation of female fish at a larger size (from Zudaire et al 2013). (see Figure 15).
TwoSex	Base model reconfigured with two sexes. Differential *Linfinity* growth parameter for female fish. High natural mortality for older age classes of female fish.	Model accounts for sex specific difference in biological parameters that provide an explanation for the observed differences in sex ratio of larger fish in catch; the increasing proportion of male fish in length classes greater than about 110 cm. Model run time is considerably longer (almost double). Spawning biomass represents female biomass only, while other model options include mature biomass for all fish.
3region	Three region model amalgamating region 1 (1a & 1b) and region 2. Fishery configuration equivalent to base model (25 fisheries); LL2 CPUE index excluded; all tag releases assigned to single region (1). LL1 CPUE indices for quarters 2 and 3 only.	Base model estimates a substantial biomass in Region 2 (Moz Channel) throughout the year, despite strong seasonal pattern in catch and, to a lesser extent, CPUE. This biomass may be considered to be “cryptic” as probably not reliably monitored by LL2 CPUE during quarters 2 & 3. Amalgamated regions monitored using LL1 CPUE indices from quarters 2&3 only as most of biomass likely to be available to LL1 fishery during that period

		(i.e. biomass has moved northward to equatorial region).
5region	Five region model structure equivalent to 2012 assessment.	Approximates 2012 base assessment model.
AreaScaleCatch	Reweighting of the LL regional CPUE indices by the relative catch from the region during 1960–1975 (rather than weighted by relative CPUE)	An alternative weighting scheme that increases the relative weighting to Region 1 (area scalars 1.00, 0.20, 0.05, 0.45).
MoveFix	Constrain movements between Regions 1 and 2. Covariate on region 2 to 1 movement to force juvenile and adult biomass to move northwards at the end of the first quarter.	Base model estimates a substantial biomass in Region 2 (Moz Channel) throughout the year, despite strong seasonal pattern in catch and, to a lesser extent, CPUE. This biomass may be considered to be "cryptic" as probably not reliably monitored by LL2 CPUE during quarters 2 & 3. Movement constraints were applied in an attempt to reduce the level of biomass in Region 2 during quarters 2 & 3 to mimic seasonal variation in catch and CPUE. Approach was not entirely successful but considerably reduced overall biomass level in R2.
RecruitR2	Distribute annual recruitment amongst regions 1, 2, and 4 (rather than regions 1 and 4 only). Estimate regional variation in recruitment distribution for the three regions also.	Sensitivity to examine the effect of estimating recruitment in the two equatorial regions only (as per base model option).
LLqSplit	Estimate separate catchability coefficients for the four sets of LL CPUE indices.	Sensitivity to examine the assumption of equivalent LL catchability amongst the four model regions, scaled to account for differences in the size of the model regions and the relative density of yellowfin (area scalars) (as per base model option).
TagMix10Q	Extend the tag mixing period from three to 10 quarters.	Sensitivity analysis to examine the effect of substantially down weighting the overall influence of the tagging data set.
CPUEcv01	Decrease the CV for all LL CPUE indices from 0.3 to 0.1.	Increase the relative influence of the LL CPUE indices. A CV of 0.1 was assumed in the 2012 assessment.
CPUEoperational	LL CPUE indices for regions 1 and 4 substituted with the CPUE indices derived from the operational data (Hoyle et al 2015). CPUE indices included for the 1972–2014 period. CPUE indices for Regions 2 and 3 equivalent to the base model.	Alternative set of CPUE indices for the two equatorial regions incorporate individual vessel effects. These CPUE indices are slightly more pessimistic than the base indices.
CPUEallYears2	LL CPUE indices for regions 1 and 4 derived from the operational data (Hoyle et al 2015) from 1952–2014. CPUE indices for Regions 2 and 3 include years prior to 1972 (1963–2015). Power function for relationship between LL CPUE and abundance (estimate single parameter). Temporal variation (deviates) in LL selectivity logistic parameter for age of 50% selectivity for 1955–1972. Increase weighting on pre 1972 LL size data (from 5 to 200). Equilibrium recruitment pre 1972 (as per base model).	The base model excludes the CPUE indices from the period prior to 1972, as per previous assessments. Previous model options that included these indices estimated substantial stock depletion during the period when the overall level of catch was low. The size of fish caught by the longline fisheries declined considerably during the 1950s and 1960s. This may suggest that the selectivity of the fishery changed during that period and, consequently, that the pre 1972 CPUE indices are not monitoring a constant component of the stock. This *CPUEallYears2* model option is an attempt to incorporate all the available data and provide a potential explanation for the apparent conflict between

		the catch and CPUE indices during the earlier years of the model.
LL4cpueSplit	LL4 CPUE indices from 1998 onwards partitioned from other LL CPUE indices (i.e. as a separate CPUE index). Separate base catchability estimated for new index (LL4recent) and catchability allowed to vary using random walk (std dev 0.1). LL4recent selectivity was assumed to be equivalent to the generic LL selectivity.	Prior to the late 1990s, the trend in the LL4 CPUE indices was comparable to the other regions. From about 1998, the LL4 CPUE indices declined sharply. This occurred during a period when there was a shift to deeper longline sets (higher HBF) in the eastern IO (Hoyle et al 2015). The partitioning of the latter CPUE indices was an attempt to explain the change in the CPUE as a shift in catchability (as opposed to regional variation in stock abundance). The temporal variation in LL catchability estimated for LL4 recent was generally consistent with the change in HBF of the longline fleet. Catchability declined by approximately 50% during the early 2000s and then stabilised at the lower level for the remained of the period.
Steep70	B-H stock recruitment, fixed steepness 0.70	Lower value of steepness.
Steep90	B-H stock recruitment, fixed steepness 0.90	Higher value of steepness.
RecruitVar	SigmaR increase to 1.0 (from 0.6) and commence period of the deviates of the regional regional recruitment in 1972.	Relax the constraints on the recruitment variability.

The biomass trajectory for each model option is presented in Figures A1–3 (Appendix 1). The main observations from preliminary modelling are as follow.

- The three region model (*3region*) is considerably more pessimistic than the base model with a greater level of stock depletion and higher current fishing mortality rates. This is due to the amalgamation of the two regions (1 and 2) and the resulting effect of removing the relatively high level of biomass in region 2 that was not vulnerable to the fishery during the austral winter (quarters 2 and 3). The fixed movement model (*MoveFix*) that reduced the biomass in region 2 produced an intermediate result between the *base* and *3region* models.
- Changing the relative scaling of the regional longline CPUE indices did not fundamentally change the biomass trajectory from the base model.
- The five region model (*5region*) converged but *MSY* benchmarks could not be determined due to exceptionally high fishing mortality rates for Arabian Sea in the recent years (equilibrium recruitment unable to sustain catches). Recent trend in biomass is more optimistic than for the base model. This may relate to the lack of CPUE indices from the Arabian Sea region from 2010.
- The *LLqSplit* model indicates that the assessment is relatively insensitive to the assumptions regarding the scaling of the LL CPUE indices amongst regions (area scalars). This is despite the estimates of LL catchability amongst the regions being considerably different from the area scaling factors with region 2 having a catchability coefficient substantially higher than region 1. These differences effectively counter the scaling of the biomass between the two areas using the scaling factors estimating a similar magnitude of LL vulnerable biomass in the two areas. This result is not considered credible, especially during the winter period. On that basis, it is proposed to retain the relative scaling amongst areas and the constant catchability assumption.
- Including the estimation of temporal varying recruitment within region 2 (*RecruitR2*) did not change the results relative to the *base* model.
- The *Mlow* option yielded a considerably more pessimistic stock status than the *base* model, while the *Mscale* option yielded an intermediate estimate of stock status. The *Mscale* option does not incorporate age-specific variation in natural mortality. The *Mscale* model provided a considerably better fit to the model data sets compared to the base model (total likelihood 12063.6 compared to 12184.7),

particularly the tag and length composition components. The estimate of overall *M* from the *Mscale* model is intermediate between the two other levels of *M* and is considerably lower than the peak level of *M* in the 13–18 age classes for the *base* model.

- The *MestAge* model estimated an independent value of natural mortality at each of the specified ages (3, 6, 10, 15 quarters). The estimates of *M* at the first three break points were very low and approached zero for age classes 6 and 10. The estimate of *M* at the oldest age is comparable to the level of the base *M* schedule. The *MestAge* model represented a substantially improved fit to the tag, length composition and CPUE data sets (total LL 11,862.1 compared to 12,184.7). The low estimates of *M* for the younger age classes could be attributable to inadequate dispersal of tags through the population within Region 1 during the mixing period (three quarters following release). Most of the improvement in the tag likelihood was for release groups in the 3–8 age classes. The very low values of *M* for young fish are not considered credible when compared to established values of *M* for the species; however, the overall scale of *M* used in the base model was also determined from essentially the same data sets. On that basis, the base level of *M* may not be reliably determined and a range of sensitivities about the overall magnitude of *M* should be considered, particularly lower levels of *M*.
- The alternative maturity OGIVE (*OGIVEmaturity*) model estimates a lower SB_{MSY} level corresponding to the small proportion of the biomass that has reach maturity. Current stock status relative to the *MSY* based reference points is also slightly more pessimistic than the base model.
- The alternative values of steepness (0.7 and 0.9) resulted in stock status that differed predictably from the *base* model.
- *TwoSex* model spawning biomass is substantially lower than the other model options because it represents female biomass only (whereas the one sex models represent the biomass of all mature fish). The model produces the expected trend in sex ratio for the larger length classes (shifting towards male fish above 110 cm). The level of stock depletion (in 2014) is lower for the other models, probably due to the higher depletion of male fish in the two sex model (and lower depletion of female fish). This is based on the assumption that the selectivity of the two sexes is equivalent for all fisheries. There is very limited data available to investigate this assumption. The *TwoSex* model resulted in a substantial deterioration in fit to tag and length composition data sets and a slight improvement in fit to the CPUE indices. It was also not possible to derive *MSY* based reference points for the *TwoSex* model; this appears to be related to the very high total mortality (Z) for the older age classes of female fish. These high values of Z are primarily due to the high values of differential *M* assigned to female fish to achieve the observed variation in the sex ratio for the larger size classes. The current sex specific natural mortality is not based on direct observations and the analysis may be refined, particularly if sufficient data are available from the tagging programme. The model is considered preliminary at this stage and is not recommended for the provision of stock assessment advice.
- The *CPUEoperational* model yielded a similar result to the *base* model. This reflects the similarity between the two sets of LL CPUE indices (aggregated and operational) for the regions 1 and 4.
- Down weighting the tagging data (*TagMix10Q*) resulted in a higher overall stock biomass and *MSY*. Current biomass (relative to SB_{MSY}) was comparable to the base model although fishing mortality was lower (relative to F_{MSY}).
- The *base* model estimates a declining trend in recruitment within region 4 from the mid-1990s to fit the stronger decline in CPUE for this region during 1998–2014. The declining trend in recruitment is moderated in the *LL4cpueSplit* model as the decline in CPUE is attributed to a decline in catchability during the early 2000s (correlated with increasing HBF in the longline fishery). Thus, this model provides a plausible alternative to the interpretation of the CPUE data to the *base* model. The estimates of stock biomass from the two models are comparable from the late 1990s, although the *LL4cpueSplit* model estimates a slightly lower virgin biomass and very similar current stock status.
- The higher weighting of the LL CPUE indices (CPUEcv01) resulted in a lower initial biomass and a lower overall decline in biomass. Current stock status (relative to SB_{MSY}) did not differ markedly from the base model (Table A1).
- The *CPUEallYears2* model estimated a general shift in the LL selectivity function during 1955–1972 with the age of 50% selectivity shifting from 14 to 12 quarters over the period. This result was

consistent with the observed decline in the size of fish sampled from the regional LL fisheries. The model estimated a relatively weak negative coefficient (-0.046) for the power function that relating catchability to vulnerable biomass (i.e. catchability was lower when biomass was high). The model provided a reasonable fit to the CPUE indices from regions 2 and 3 for which indices are available from 1963. However, the earlier (1952–1962) CPUE indices for the equatorial regions (1 and 3) are substantially higher and decline considerably during the earlier period. The *CPUEallYears2* model was unable to fit the high early CPUE indices. The *CPUEallYears2* model does not provide any new insights into the relationship between stock abundance and LL CPUE during the earlier period of the fishery and is not considered a credible alternative model.

The preliminary modelling phase investigated the influence of a wide range of assumptions related to structure and parameterisation of the assessment model. Overall, the results revealed that the estimates of stock status and yield were relatively insensitive to the structural assumptions of the model, particularly related to the spatial configuration of the model; i.e., regional recruitment distribution, movement parameterisation and LL CPUE catchability (Appendix 1, Table A1). Although the three region model (*3region*) was more pessimistic than the base, four region model option. The model results were also sensitive to the key biological parameters that define the productivity of the stock, especially natural mortality and SRR steepness (Appendix 1, Table A1); the lower productivity assumptions resulted in considerably more pessimistic estimates of stock status.

6 Model results – base model and sensitivities

6.1 Model selection

From the results of the preliminary modelling, a base model and a number of alternative model options and sensitivities were selected. The base model retained the four region spatial structure and included the environmental covariates in the movement parameterisation. The regional structure partitions the distribution of the main fisheries, particularly in the western equatorial region, and accommodates the seasonal variation in the fisheries in the southern regions of the Indian Ocean (especially Region 2). Inclusion of the environmental covariates in the movement parameterisation substantially improved the overall fit to the CPUE indices (Table 5).

For the base model configuration, management advice was formulated using a range of values for the SRR steepness (0.70, 0.80 and 0.90). For presentation purposes, detailed results were presented for the intermediate value of steepness only.

Model sensitivities were limited to three main options:

a) The *NoEnviroMove* option was included as this model represents a simpler parameterisation of the movement dynamics that is more consistent with the previous yellowfin stock assessments. However, the model does not incorporate any seasonal variation in movement and consequently the fit to the LL CPUE indices is considerably worse than the base model option (Table 5). The preliminary modelling results indicated that the overall assessment was unlikely to be sensitive to the different movement parameterisations.
b) The three region model (*3region*) amalgamates the two western regions and the stock abundance in the region is indexed by the LL 1b CPUE indices. Previous assessments and the current modelling have produced results that allocate a substantial proportion of the stock biomass to region 2 despite this region having a relatively low overall catch. This is likely to be related to the spatial partitioning of the model and the trends in longline catch and CPUE in region 2. There is concern that the regional partitioning of this area is inflating the level of current biomass and resulting in a more optimistic estimate of the current stock status.
c) The *Mlow* model option was also retained as a sensitivity. The alternative level of natural mortality is substantially lower than base level and is substantially lower than the level of natural mortality adopted for yellowfin tuna assessments by other tuna RFMOs. However, there is some suggestion from the results of the IO tag release/recovery data that natural mortality of fish younger than about 12 quarters may be lower than the base level. The *Mlow* option also represented the best overall fit to the data sets, improving the fit to the overall length composition data set and the time series of tag recoveries (tag negbin component) (Table 5). Nonetheless, the reliability of the estimates of natural mortality from the tagging data will also be influenced by assumptions related to tag

mixing, selectivity (i.e. age-specific fishing mortality), and movement. On balance, the *Mlow* natural mortality schedule is considered to represent the lower bound for the range of credible values of natural mortality.

6.2 Fit diagnostics – base model

The performance of the model was evaluated by examining the fit to the three predicted data classes – the CPUE indices, the tag recovery data and the length composition data.

- The model provides a reasonable fit to the overall trend in the CPUE indices for each region (Figure 17). However, the CPUE indices exhibit a high degree of seasonal variability that is not estimated by the model. Consequently, the residuals from the fit to the regional CPUE indices have a higher RMSE (between 0.40 and 0.50) than the variance assumed for the CPUE indices (CV 0.30). There are appreciable temporal trends in the residuals from the fit to the CPUE indices for region 2 and region 4. For region 2, the residuals tended to be positive during 2005–2015, while there is a general decline in the LL4 residuals over the data period (Figure 18). This decline appears to primarily relate to the poor fit to the higher CPUE indices during 1972–1980 (Figure 17).
- Most of the tag returns were from the purse-seine fishery in region 1b and, to a lesser extent, region 2 (Figure 19). A comparison of the observed and predicted numbers of tags recovered from each fishery (excluding recoveries during the three quarter mixing period) by quarterly time period are presented in Figure 19. Overall, the model provides a reasonable fit to the tag recoveries during the main recovery period (2007–2009) although there are a number of quarters when the model substantially underestimates the number of tag recoveries from both regional purse seine fisheries. These were the first three quarters of 2007 and the second quarter of 2008. These quarters correspond to the first quarter following the three quarter mixing period for the large releases of tags in 2006 (quarters 2, 3 and 4) and 2007 quarter 3 (see Figure 7). The lack of fit to the recoveries in those quarters suggests that the three quarter mixing period may not be sufficient to allow for adequate dispersal of tagged fish in the population.
- Tag recoveries from the non purse-seine fisheries are not considered to be very informative and the model has the flexibility to freely estimate reporting rates for these fisheries. Of these fisheries, only the LL fisheries in region 1b and region 2 recovered moderate numbers of tags during the period following the three quarter mixing phase. The numbers of tags recovered from these fisheries was low relative to the purse-seine fishery and the fishery specific tag reporting rates were estimated to be very low (6% and 8%, respectively). The model provided a reasonable approximation of the temporal trend in the number of tags recovered from the two longline fisheries (Figure 19).
- For most fisheries, there is a reasonable overall fit to the length composition data (Figure 20). However, the model tends to underestimate the proportion of fish in the smaller length mode from purse-seine FAD fisheries, while over estimating the proportion of fish in the 70–100 cm length range. Conversely, the model tends to underestimate the proportion of fish in the larger length classes sampled from purse-seine free-school fisheries in region 1a in 2003–06 and 2006–2014. There is a reasonable fit to the five longline fisheries which are constrained to share a common selectivity among regions. The poor fit to the length data from the handline and "other" fisheries in region 1a (OT 1) reflects the limited and variable length composition data available from these fisheries (Figure 20).
- For the main longline fisheries (LL1a, 1b, 2–4), the model does not fit the observed decline in fish size during the 1950s and 1960s (Figure 21). However, the more recent trends in average size are evident in the predicted size composition from the model, specifically the sharp decline in fish size during the early 1990s and the recovery in fish size from the late 1990s. These trends are associated with lower recruitment during the early 1990s followed by higher recruitment in the late 1990s and early 2000s (see Section 6.4.1).
- The other main sets of length frequency data included in the model are from the purse seine fisheries in region 1a and region 2. The average size of fish sampled from the PSFS fishery is variable amongst quarters, probably due to size related schooling behaviour of adult yellowfin tuna (Figure 22). However, the recent trends in the predicted average fish size for the PSFS1b and PSFS2 fisheries is broadly consistent with the sampling data with larger fish caught during the mid-2000s and smaller fish from 2010 onwards. There is a marked decline in the average size of fish sampled from the purse seine FAD fisheries in both region 1b and region 2 (Figure 22), particularly during the mid-1990s. This trend is not evident in the predicted average fish size derived from the model. The decline in fish size in the mid-1990s coincided with

a sharp increase in the catch from the fishery, indicating a significant change in the operation of the fishery at that time. This change appears to have resulted in a decline in the relative proportion of fish in the secondary mode of the length composition (90–130 cm).

- There are a number of other fisheries that exhibit considerable shifts in the length composition of the catch. Notable examples include the recent increase in the length of fish caught from the hand-line fishery in region 1a (HD 1) and the OT4 and TR4 fisheries (Figure 21). There has also been a marked increase in the length of fish sampled from the LF4 fishery in the last few years. These observations are indicative of significant changes in the overall selectivity of these fisheries and warrant further refinement of the fishery definitions and/or a more rigorous analysis of the individual data sets.

6.3 Model parameter estimates

6.3.1 Selectivity

A common logistic selectivity function is estimated for the principal longline fisheries (LL 1a, 1b, 2–4) that attains full selectivity at age 17 quarters (Figure 23). The fresh tuna fishery (LF 4) is estimated to have a relatively similar selectivity to the principal longline fisheries, albeit skewed towards older fish.

The associated purse-seine and baitboat fisheries have a high selectivity for juvenile fish, while the free-school purse-seine fishery selects substantially older fish. For all regions and time blocks, the selectivity of the free school and associated purse-seine fisheries was held constant among the method fisheries (Figure 23). The selectivity of associated purse-seine method is relatively broad compared to the modal structure of the length frequency data. The selectivity function encompasses the full range of age classes, including the older age classes, albeit with a relatively low selectivity.

Limited or no size data were available for a number of fisheries, specifically the artisanal fisheries (OT 1a & 4) and the troll fishery in regions 1b and 2 (TR 1b & 2). Consequently, selectivity for these fisheries is poorly estimated or, in the absence of size data, assumed equivalent to a fishery with the same gear code in another region. The handline fishery in region 1a has a broad selectivity to accommodate the wide variation in the size of fish caught (Figure 23).

6.3.2 Tag-reporting rates

Tag reporting rates for the purse-seine fisheries within regions 1b and 2 were fixed at the prior value (0.81) (Figure 24). For the other fisheries, limited information was available regarding tag reporting rates and fishery-specific reporting rates were estimated with virtually no constraints. The estimated tag reporting rates are for the period following the initial tag mixing phase (i.e. for tags at liberty for at least three quarters). The tag reporting rates estimated for the purse seine fishery in region 4 were comparable to the base reporting rate of the main purse seine fisheries, although the reporting rates were very poorly determined.

For the other fisheries, the estimated reporting rates were generally low (less than 10%) or close to zero reflecting the small number of tags reported from these fisheries (post dispersal period). The main exception was the troll fishery in region 2 (TR 2) with a reporting rate of 26%. The moderate reporting rate for the LL 3 represents the prior value as there were no tag recoveries from the fishery (or region). Similarly, reporting rates from the other fisheries in region 4 (LL4 and OT4) were informed by a very small number of tag recoveries from a small population of tagged fish.

The estimates of fishery-specific tag reporting rates differ somewhat from those estimated by Carruthers et al (2015). These differences are likely to be primarily due to the different assumptions included in the two modelling approaches, especially related to the spatial stratification of the fisheries, spatial structure of the tag releases, and the duration of the tag mixing period.

6.3.3 Recruitment parameters

The model estimates 64% and 36% of the total annual recruitment is assigned to regions 1 and 4, respectively. The proportion of total recruitment assigned to either region varies temporally during the estimation period (1977–2014) and, overall the proportion of recruitment allocated to region 1 during the estimation period is higher than the base level (and vice versa for region 4) (Figure 25).

The quarterly recruitment deviates indicate recruitment varies seasonally with higher recruitment generally occurring during the third quarter and lower recruitment in the first quarter (Figure 26). Recruitment deviates were low during 2004–2006, especially during 2005. This immediately followed the exceptionally large catches taken by the PSFS fishery during 2004–2006. Correspondingly, the LL CPUE for region 1 (1b) and region 4 were lower during the late 2000s.

6.3.4 Movement

The base model estimates that there is a high degree of connectivity between the two western regions (R1 and R2) and between the eastern regions (R3 and R4) but trivial longitudinal movement between regions 1 and 4 (Figure 27 and Figure 28). Recruitment is restricted to regions 1 and 4. There is a very high movement rate estimated for juvenile fish from region 1 to region 2, with a lower reciprocal rate of movement (Figure 27a).

Similarly, there is a high level of movement of juvenile fish between region 4 and region 3 (Figure 27b). These movements are strongly correlated with the seasonal variation in SST in region 3 (*SST3* covariate) as is the northward movement of adult fish from region 3 (to region 4), presumably reflecting the seasonal variability in LL CPUE in region 3 (Figure 27b). There is also considerable seasonal variation in the northward movement of adult fish from region 2 to region 1 correlated with the SST in region 2 (*SST1* covariate). Overall, the environmental covariates do not have a strong longer term temporal effect on the realized migration coefficients.

6.4 Stock dynamics

6.4.1 Recruitment

Recruitment is parameterised to occur in region 1 and 4 only. Recruitment within the western region (R1) is characterised by relatively high recruitment during the mid-1980s and late 1990s–early 2000s and lower recruitment during the early 1990s and particularly low recruitment during 2004–2006 (Figure 29). Recruitment in Region 1 was above average during 2009–2014. These trends in recruitment also drive the trend in total recruitment for the Indian Ocean.

Recruitment in region 4 fluctuated about the equilibrium level during 1972–1986 but was considerably lower during the subsequent years, particularly 2005–2012 (Figure 29).

6.4.2 Biomass

Total spawning biomass for the IO stock is estimated to have remained relatively high throughout the 1950s, 1960s and early 1970s (Figure 30) corresponding with the relatively low levels of catch during the period and the assumption of equilibrium recruitment. Total spawning biomass declined rapidly during the late 1980s to mid 1990s, recovered slightly during the late 1990s and early 2000s before declining to a low level in 2008–2009 (Figure 30). Total spawning biomass recovered slightly during 2009–2011 and then steadily declined to a low level in 2014. Current (2014) total spawning biomass is estimated to be at an historically low level.

There are very narrow confidence intervals associated with the time-series of total spawning biomass (Figure 30). The high level of precision is likely to be a function of the key assumptions of the model, especially constant catchability and selectivity associated with the LL CPUE indices and the fixed biological parameters.

Relative trends in spawning biomass are broadly comparable for the four model regions (Figure 31), although the overall magnitude of the decline in biomass is substantially higher in Region 4. The biomass in this region declined steadily throughout the 1990s and 2000s following the trend in the regional LL CPUE indices. For the most recent years, region 4 biomass is estimated to be at a very low level (Figure 31).

The model estimates that a substantial proportion (approximately a third) of the total spawning biomass is within Region 2, despite the region accounting for a relatively small proportion of the total catch (less than 10%) (Figure 31). There is a strong linkage between Region 1 and Region 2 and the model estimates that a high proportion of the juvenile biomass (recruited in Region 1) resides in Region 2. In turn, these juvenile and adult fish return to Region 1 where they become available to the main equatorial fisheries.

The creation of a "refuge" for fish in Region 2 may indicate that the model is not adequately accounting for seasonal trends in the availability and/or abundance of fish in either region. Preliminary modelling that attempted to constrain the level of biomass within Region 2 did not substantially change the estimated stock dynamics. For this reason, a model sensitivity was conducted that amalgamated the two regions (1 and 2) in a three region model. The *3region* model, increased the PSLS selectivity of older (10–14 quarter) fish suggesting that the sharing of the fishery selectivity between the two regions could be partly responsible for the spatial dynamics of the base model. However, an additional model option that estimated separate PSLS selectivities for the two regions did not fundamentally change the spatial dynamics from the base model.

Further, reassigning the Region 2 PS fisheries to Region 1 did not fundamentally change the result either. This strongly suggests that the population dynamics in Region 2 are largely determined by the magnitude of catch and CPUE indices from the longline fishery. The relatively high CPUE from the fishery requires sufficient adult biomass to be available to the fishery and the model uses the movement dynamics to provide sufficient adult fish to support the fishery. Since the mid-1990s, the magnitude of the catch from the LL2 fishery has broadly comparable to the LL1 fishery, while trends in the CPUE indices were similar for the two regions.

Overall, the trend in total stock biomass from 2012 to 2014 from the *3region* was considerably more pessimistic than the base model (Figure 36) reflecting the higher recent catches in Region 1b and the relatively low CPUE indices in the region.

6.4.3 Fishing mortality

Fishing mortality rates for each fishery are defined as apical fishing mortality rates; i.e. the fishing mortality for the fully selected age class (or age classes). The fishing mortality rates are an approximation of the Baranov continuous *F* (Methot & Wetzel 2013). Relatively high recent fishing mortality rates have been estimated for a number of fisheries in Region 1, specifically PSLS1b, PSFS1b, GI1, HD1 and BB1b (Figure 32). Fishing mortality rates for the PSLS1b fishery increased sharply in 2013 corresponding to relatively high catches from the fishery in the last two quarters of 2013.

In Region 4, recent fishing mortality rates from the LF4 fishery were very high (Figure 32), although annual catches from the fishery have remained relatively stable during the last 10 years. The very high fishing mortality rates correspond to the sharp decline in model biomass from the late 2000s and are also related to the selectivity of the fishery, with full selection occurring at age 18 quarters. The GI4 and the TR4 fisheries represent the other main sources of fishing mortality in Region 4 (Figure 32). Fishing mortality rates are estimated to be very low in both Region 2 and Region 3 (Figure 32).

Spatially aggregated, age-specific fishing mortality rates are derived for each model time period (Methot & Wetzel 2013). Average total fishing mortality rates were derived for the last two years of the assessment model (2013 and 2014) and the resulting age specific mortality schedule was applied in the computation of the *MSY* reference points. Aggrregate fishing mortality rates increased for the younger age classes and were highest at age 9 quarters (Figure 33). Fishing mortality rates were also relatively high for age classes 14–18 and are somewhat lower for the oldest (22–28) age classes.

7 Stock status

7.1 Current status and yields

Current (2014) stock status was defined relative to the *MSY* based biomass (SB_{MSY}) and fishing mortality (F_{MSY}) reference points. For the base model structure, the yield analysis incorporates the SRR into the equilibrium biomass and yield computations with three alternative values of steepness assumed for the SRR (0.70, 0.80 and 0.90). For comparative purposes, the model sensitivities (*Mlow*, *3region* and *NoEnviroMove*) assumed the intermediate value of steepness (0.80). The time-series of model estimates of spawning biomass and recruitment are poorly correlated and do not provide any indication of the most appropriate value of steepness (Figure 34).

Equilibrium yield and biomass (spawning) were computed as a function the 2013–2014 average fishing mortality-at-age (Figure 33). Estimates of *MSY* for the model options with the base level of natural mortality were 402,000–438,000 mt (Table 6). This level of yield is somewhat higher than the average level of catch from 1995–2014 (376,000 mt). The estimate of *MSY* is considerably lower for the model sensitivity with lower natural mortality (*MSY* 318,000 mt) (Figure 33).

For the base model option, the annual trends in $F_t/\tilde{F}_{MSY}$ and $SB_t/\tilde{SB}_{MSY}$ were computed for each year (t) included in the model (1950–2014) (Figure 35). Prior to 1990, exploitation rates were low and adult biomass remained well above $\tilde{SB}_{MSY}$. In the early 1990s, $F_t/\tilde{F}_{MSY}$ increased and biomass levels declined before stabilising during the mid-1990s–early 2000s (Figure 35). Overall fishing mortality rates increased sharply in 2005 in line with the large increase in catches during 2004/2005. Adult biomass declined considerably in the subsequent years, attributable to a period of very low recruitment during 2004–2006, and declined below the SB_{MSY} level in 2008. The stock remained below the SB_{MSY} level throughout 2008–2014.

Fishing mortality rates increased and exceeded the F_{MSY} level in 2012 following the recent increase in annual catch (Figure 35). The estimate of current fishing mortality is not well determined although there is only a small probability that fishing mortality is below the F_{MSY} level (for the base model) (Figure 35 and Table 6).

For the base model, adult biomass is estimated to be at 66% of the the SB_{MSY} level and current fishing mortality rates are 34% higher than the F_{MSY} level (Table 6). The other model options also estimated that the stock is in an overfished state (SB/SB_{MSY} < 1.0) and that overfishing is occurring (F/F_{MSY} > 1.0), although the extent of the stock depletion varies considerably amongst the model options (SB/SB_{MSY} 0.42–0.71).

Potential yields for 2015 were estimated based on fishing mortality at the F_{MSY} level (Table 6). The resulting estimates of yield (122,000–296,000 mt) are substantially lower than recent catches (410,000 mt). This reflects the extent of the reduction in fishing mortality required to achieve the F_{MSY} level (reductions of 14–63%) and the low level of current biomass. However, given the uncertainty associated with the estimate of current fishing mortality (relative to F_{MSY}) these yields should be considered to be indicative only.

For the *3region* and *Mlow* model sensitivities, current stock status is estimated to be considerably more pessimistic than the corresponding base model option (steepness 0.8) (Table 6).

7.2 Projections

Stock projections were conducted for the base model and the two alternative steepness options (0.70 and 0.9) and the *Mlow* and *3region* models. The projections were conducted for a 10 year period (2015–2024) at a constant level of catch set as a multiple of the fishery catches in 2014. Three levels of catch were investigated representing 100% (415,000 mt), 80% (332,000 mt) and 60% (249,000 mt) of the 2014 catch level. Recruitment during the projection period was at the equilibrium level. The uncertainty associated with the projected biomass was derived from the covariance matrix. For each stock scenario, the probability of the biomass being below the SB_{MSY} level was determined after 3 years (2017), 5 years (2019) and 10 years (2024).

The uncertainty associated with the projected biomass promulgates rapidly reflecting the uncertainty associated with the equilibrium recruitment level (Figure 37). For the base model, current (2014) levels of catch exceed the equilibrium surplus production and the stock biomass is projected to reach extinction in about 5 years (i.e. projected catches exceeding vulnerable biomass) (Table 7). At 80% of the current catch level, the outcome of the stock projections varies in response to the level of SRR steepness; for the lower value of steepness (0.70) the stock is projected to remain stable at about 55% of SB_{MSY} while for the base level of steepness (0.80) the stock rebuilds slowly and approximates the SB_{MSY} level at the end of the 10 year projection period, although there is still a high probability (50%) of the stock being below the SB_{MSY} level (Table 7). For the higher steepness scenario (0.90), there is considerably more certainty that the stock will be above the SB_{MSY} level at the end of the projection period.

For the base model configuration, stock projections at 60% of the current catch all have a high probability of achieving SB_{MSY} at the end of the projection period, while there is a relatively high probability of achieving the benchmark in 5 years for the two more productive stock scenarios (steepness 0.8 and 0.9) (Table 7).

The *Mlow* and *3region* model options are considerably less optimistic than the base model with the corresponding level of steepness (0.80). Under all levels of catch, the biomass declines during the projection period and reaches extinction in about 5 years (Table 7). This reflects the very low level of current biomass estimated for these two model scenarios (SB/SB_0 0.17 and 0.15, respectively) and the correspondingly depressed level of equilibrium recruitment.

8 Discussion and conclusions

Previous stock assessments of Indian Ocean yellowfin tuna have been implemented using MULTIFAN-CL. This assessment represents the first time that Stock Synthesis has been applied to assess the IO yellowfin stock and represents one of the more complex assessments conducted using the software. The comparison of the current SS assessment and previous (2012) MFCL assessment provides a good opportunity to evaluate the relative strengths of the two frameworks. Overall, SS has considerably more flexibility in the formulation of key model parameters, in particularly recruitment. This enables a greater level of control in the regional distribution of recruitment and the period of estimation of deviates from average recruitment compared to MFCL.

SS assessment models are typically implemented with an annual temporal structure. For simplicity, the current assessment defined a model "year" to be three months in duration to be consistent with the quarterly model structure of the previous MFCL assessment. This approach enabled recruitment to be estimated quarterly rather than as part of an annual cycle. However, adopting a quarterly time step (model "year") meant that seasonal variation could not be explicitly incorporated in the current assessment model. This limited the ability to estimate seasonal movement dynamics that may have enabled seasonal variation in catch and CPUE to be more adequately modelled, especially for the sub-equatorial fisheries. Future development of the current assessment model should investigate the potential to adopt an annual/seasonal model structure. This will require the apportionment of annual recruitment amongst seasons and probably require fishery selectivity to be modelled using a length based process. There are also likely to be issues related to the allocation of tags to age specific release groups. Considerable model testing will be required to ensure the model results are relatively insensitive to these changes.

8.1 Comparison with 2012 MFCL assessment results

The current assessment is considerably less optimistic than the previous MFCL stock assessment (Langley 2012). The 2012 assessment derived MSY based reference points using two difference assumptions regarding equilibrium recruitment: a) the recruitment level that corresponded to the unexploited equilibrium biomass level (SB_0) and b) the average recruitment level from the last 15 years of the model. The second option was adopted because the assessment model estimated recent recruitment levels that were substantially lower than the equilibrium level. The equilibrium based option estimated long-term yields that were considered too high for the stock (*MSY* of 425,000 mt) while yields from the recent recruitment option were considerably lower (344,000 mt). The equilibrium recruitment option estimated the that the biomass in 2010 was at the *MSY* level (SB/SB_{MSY} = 1.0), while fishing mortality was below the F_{MSY} level (F/F_{MSY} = 0.69). By comparison, the recent recruitment option estimated the that the biomass in 2010 was above the *MSY* level (SB/SB_{MSY} = 1.24), while fishing mortality was equivalent (F/F_{MSY} = 0.69).

For the current assessment, the main model assumptions are similar to the previous (2012) assessment. The main data sets are also very similar, with the exception of the additional three years of data included in the current assessment (2012–2014). The 2014 stock status derived from the current assessment (based on equilibrium recruitment) estimates biomass is below SB_{MSY} (SB/SB_{MSY} = 0.66) while fishing mortality is above the F_{MSY} reference level (F/F_{MSY} = 1.34). The deterioration in stock status in the intervening years is primarily attributable to an overall increase in yellowfin catch (by approximately one third) while stock abundance (as indexed by longline CPUE) declined. As a result fishing mortality is estimated to have increased considerably from 2010 to 2014 (by approximately 45%).

The *MSY* reference level for the current assessment (SB_{MSY}/SB_0 = 0.35) is also somewhat higher than derived for the previous assessment (0.30). This difference is presumably related to the difference in the age specific fishing mortality schedule used in the determination of the *MSY* reference points. For the current assessment, there is a higher relative level of fishing mortality associated with fish at ages 9 and 14–17 quarters compared to the previous assessment.

There are a number of more subtle differences between the two assessments that also influence the final estimates of stock status. The revised maturity OGIVE reduced the age of 50% maturity to age 9 quarters compared to 10 quarters for the MFCL assessment. Comparative model options revealed that this change resulted in a slightly more optimistic estimate of stock status.

Overall, the MFCL assessment model estimated a substantially higher level of stock biomass in 1972 compared to the current assessment (Figure 38), although the recent (2005–2010) level of biomass was very similar, probably due to the scaling effect of the tag release/recovery data. Superficially, the amalgamation of the western equatorial region and the Arabian Sea in the current assessment model appears to have been influential in reducing the overall level of biomass in the preceding period. However, a direct comparison of the four region and five region (*5region*) models from the preliminary modelling phase revealed no substantive change in the overall stock size during the 1970s and 1980s (Figure A2 Appendix 1). The model sensitivity that was most comparable to the 2012 assessment was the option that substantially relaxed the constraints on the annual recruitment deviates (increasing SigmaR from 0.60 to 1.00) (*RecruitVar*). This model estimated biomass levels in the mid-1970s that were comparable to the MFCL assessment model, although the biomass trajectories declined sharply from this level from the late 1970s (Figure 38).

The *RecruitVar* model estimated a substantially higher level of equilibrium recruitment (Figure 39) and, correspondingly, an implausibly high *MSY* (Table A1 Appendix 1). Clearly, the stock status is sensitive to the assumed value of sigmaR. For the MFCL assessment model, the overall regional recruitment deviates had a small penalty (recruitment deviations penalty 10, region recruit penalty 0.1). The low penalty on the recruitment deviates gave the model the flexibility to estimate the substantially higher level of recruitment in the eastern equatorial region (previously region 5) during the period prior to 1987 (Figure 39). In turn, this contributed to the higher biomass in the western equatorial region due to the relatively high level of movement estimated from region 5 to region 2 (Langley 2012).

8.2 Current assessment results

In general, the current assessment models provides a good fit to the main data sets included in the assessment. This indicates that the various data sets are relatively consistent with the trends in the LL CPUE indices (from 1972 onwards). These CPUE indices represent the primary source of information regarding abundance in the assessment model and, consequently, the main conclusions of the assessment are dependent on the reliability of these indices. Recent analysis of the detailed catch and effort data from the Japanese longline fishery did not result in a substantive reevaluation of the CPUE indices for the two equatorial regions (Hoyle et al 2015).

The trends in the CPUE indices are broadly comparable amongst the model regions, although the overall decline in the CPUE indices from the mid-1990s is more pronounced in the eastern equatorial region. There is some suggestion of a change in the availability of yellowfin and/or the operation of the longline fishery in that region, possibly in response to a deepening of the thermocline. Attempts to account for these changes in the assessment model (*LL4cpueSplit*) did not fundamentally change the overall assessment conclusions.

The longline CPUE indices for 2008–2014 were derived from limited data due to the reduction of fishing effort in response to the risk of piracy during 2008–2011. Incidents of piracy off the Somali coast had been almost eradicated by 2013 although there has been no appreciable recovery of the longline fishery in subsequent years. Regional longline CPUE indices have tended to be low from 2009 onwards and it is unknown whether the changes in the overall operation of the longline fishery have substantially affected the abundance indices.

Recent trends in stock abundance and fishing mortality derived from the assessment model are consistent with the recent trends in annual catch. The stock assessment model attributes the recent (2008–2009) drop in spawning biomass to a period of very low recruitment during the preceding period (2004–2006). The decline in recruitment corresponded to the period of very high catches during 2004/05 especially by the purse seine free-school fishery. The period of lower recruitment may be a direct consequence of high catches of adult fish, although it may be also be an artefact of the structural assumptions of the model, particularly the assumption of constant (temporally invariant) fishery selectivity for the purse-seine free school fishery.

The average length of fish sampled from the PSFS fishery increased markedly during 2004–2006. The estimation of low recruitment during 2004–2006 is consistent with this observation in conjunction with a similar increases in the size of fish sampled from the longline fisheries and the decline in the CPUE indices during the same period (late 2000s). Thus, the model interprets the low 2008–2009 biomass to be attributable to lower recruitment rather than a direct result of the higher levels of catch during the peak period. The estimates of recent levels of fishing mortality and recruitment is likely to be considerably more uncertain than the estimation of the overall change in stock abundance.

The main assessment model option has retained a regional structure that partitions the south-western Indian Ocean in a separate model region. The assessment estimates a substantial proportion of the stock biomass resides in that region despite a relatively low seasonal catch from the area. This result was consistent with the previous MFCL stock assessment and appears to be related to the comparable trends in longline catch and CPUE indices between the equatorial and subequatorial regions (regions 1b and 2). It is unclear if the Region 2 LL CPUE indices adequately reflect the seasonal variation in the abundance of yellowfin in the region and, correspondingly, the assessment model does not estimate a strong seasonal pattern in the movement of fish between regions 1 and 2.

Consequently, juvenile and adult biomass tends to accumulates in region 2 and the associated fishing mortality on this component of the stock is estimated to be relatively low. This is apparent from the comparison between the base model configuration and the *3region* model that amalgamates the two regions. The current stock status for the latter option is considerably more pessimistic with a higher level of fishing mortality and lower current biomass (Table 6).

Therefore, the regional structure of the base model may understate the overall extent of the stock decline. However, the LL CPUE indices from Region 2 do not exhibit the extent of the decline in CPUE that is evident in region 1b and, conversely, the *3region* model may overstate the degree of depletion in the wider, amalgamated region. In future, the most appropriate approach may be to amalgamate the two regions and derive a composite CPUE index for the larger region.

As in previous assessments, longline CPUE indices from the period prior to 1972 were not included in the final range of model options. The CPUE indices decline sharply during the 1960s and the magnitude of the decline is not consistent with the overall level of catch during the period. There is also a decline in the size of fish in the longline catch during the period that may indicate a shift in the selectivity of the longline fishery during the period. However, this would be expected to lead to an increase in the proportion of the population vulnerable to the longline fishery (and result in a corresponding increase in CPUE). Attempts to account for these somewhat conflicting trends during the preliminary model development were not successful. There appear to be more complex temporal trends in the operation of the longline fishery that are not adequately explained by the static assumptions of the assessment model (constant selectivity and catchability).

The assessment results are also sensitive to the key productive assumptions, especially SRR steepness and natural mortality. The overall level of natural mortality included in the *base* assessment model is broadly comparable to the level of natural mortality assumed for other regional yellowfin tuna stocks (Maunder & Aires-da-Silva 2012). However, there are somewhat conflicting information from the data from the Indian Ocean tagging programme regarding the overall magnitude of natural mortality of yellowfin tuna. A recent tag recovery (EE31536) was from a fish that was aged at approximately 12 (11.8) years at recapture. A maximum age of 12 years yields a monthly total mortality rate of 0.086 using the equation of Hoenig (1983). This level of total mortality is reasonably consistent with the lower level of natural mortality that was incorporated in the *Mlow* sensitivity. However, the total mortality estimate was derived from a period of high catches and, therefore, also includes a significant component of fishing related mortality.

The higher *base* level of fishing mortality was, in part, informed by the previous stock assessments which estimated the overall scale of natural mortality. The incorporation of tag release/recovery data provides the model with some information to estimate natural mortality although the estimation of natural mortality is likely to be sensitive to the tag mixing assumptions and other key structural assumptions of the model (especially regional structure and movement dynamics). This is evident from the variable level of age-specific natural mortality estimated during the preliminary modelling conducted in the current assessment (*MestAge*), especially the very low level of natural mortality estimated for the 6–10 age classes; i.e. the age classes that accounted for most of the tag releases.

The current assessment also assumes that natural mortality is equivalent for both sexes. The differential sex ratio of the larger fish in the population indicates that natural mortality rates for older female fish are likely to be higher than for male fish. Currently, there is insufficient information available to derive sex specific estimates of natural mortality and an overall level of natural mortality derived for male fish is likely to under-estimate the aggregate level of natural mortality (both sexes combined).

Clearly, there remains considerable uncertainty associated with the overall level of natural mortality. The values assumed in the *base* and *Mlow* assessment models probably represents a reasonable range to reflect the uncertainty associated with natural mortality. The *Mlow* model option yields a considerably more pessimistic estimate of current stock status compared to the *base* model options.

Overall, the general stock assessment conclusions are comparable for the range of model options considered; i.e, the stock is over fished (SB/SB_{MSY} 0.42–0.71), overfishing is occurring (F/F_{MSY} 1.16–2.71) and the current (2014) level of catch will not allow the stock biomass to recover (i.e., 2014 catch is greater than current yield at F_{MSY}).

Stock projections were conducted to evaluate the impact of the alternative levels of catch relative to 2014 catches. The projections are not intended to provide a reliable prediction of future stock status due to the simplifying assumptions of equilibrium recruitment (from SRR), constant catch and unlimited fishing mortality.

Instead, the projections are provided to give an indication of the relative performance of the stock at different levels of catch.

Recent (2012–2014) catches from the fishery have been relatively high and appear to have been partly supported by above average recruitment in Region 1 during 2009–2013. For all model options, projected catches at the 2014 level resulted in a collapse of the stock in less than five years. For the two most optimistic model scenarios (base model, steepness 0.80 or 0.90), the stock slowly recovered to SB_{MSY} at a catch level of 80% of the 2014 catch. However, for the most pessimistic model options (*Mlow* and *3region* models), a catch reduction of 40% was not sufficient to prevent the stock from collapsing, due to the current low level of spawning biomass (0.42 and 0.48 SB_{MSY}, respectively).

9 Acknowledgements

The stock assessment was funded by FAO and IOTC. The IOTC Secretariat especially James Greehan, Lucia Pierre and Miguel Herrera (formerly IOTC) provided the initial data sets. I would also like to thank Daisuke Ochi and Takayuki Matsumoto for the timely provision of the Japanese longline CPUE indices. David Wilson, Dale Kolody and Emmanuel Chassot provided useful advice during the development of the assessment.

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Table 1. Definition of fisheries for the four-region assessment model for yellowfin tuna.

Fishery	Nationality	Gear	Region
1. GI 1a	All	Gillnet	1a
2. HD 1a	All	Handline	1a
3. LL 1a	All	Longline	1a
4. OT 1a	All	Other	1a
5. BB 1b	All	Baitboat	1b
6. PS FS 1b 2003-06	All	Purse seine, school sets	1b
7. LL 1b	All	Longline	1b
8. PS LS 1b 2003-06	All	Purse seine, log/FAD sets	1b
9. TR 1b	All	Troll	1b
10. LL 2	All	Longline	2
11. LL 3	All	Longline	3
12. GI 4	All	Gillnet	4
13. LL 4	All	Longline (distant water)	4
14. OT 4	All	Other	4
15. TR 4	All	Troll	4
16. PS FS 2	All	Purse seine, school sets	2
17. PS LS 2	All	Purse seine, log/FAD sets	2
18. TR 2	All	Troll	2
19. PS FS 4	All	Purse seine, school sets	4
20. PS LS 4	All	Purse seine, log/FAD sets	4
21. PS FS 1b pre 2003	All	Purse seine, school sets	1b
22. PS LS 1b pre 2003	All	Purse seine, log/FAD sets	1b
23. PS FS 1b post 2006	All	Purse seine, school sets	1b
24. PS LS 1b post 2006	All	Purse seine, log/FAD sets	1b
25. LF 4	All	Longline (fresh tuna)	4

Table 2: Recent yellowfin tuna catches (mt) by fishery included in the stock assessment model. The annual catches are presented for 2013 and 2014 and the average annual catch is presented for 2011-13.

Fishery	Time period		
	2011-13	2013	2014
1. GI 1a	44,926	46,287	58,295
2. HD 1a	70,288	73,970	77,786
3. LL 1a	1,994	1,952	1,675
4. OT 1a	1,092	1,182	1,106
5. BB 1b	17,876	24,120	23,596
6. PS FS 1b 2003-06	0	0	0
7. LL 1b	5,794	5,417	5,264
8. PS LS 1b 2003-06	0	0	0
9. TR 1b	1,074	434	1,513
10. LL 2	4,467	4,349	3,626
11. LL 3	499	504	503
12. GI 4	12,248	10,556	7,485
13. LL 4	2,944	259	1,729
14. OT 4	7,023	7,052	7,063
15. TR 4	23,313	28,627	22,625
16. PS FS 2	3,420	4,388	4,189
17. PS LS 2	7,902	7,957	8,613
18. TR 2	1,944	1,944	2,182
19. PS FS 4	284	0	0
20. PS LS 4	793	750	726
21. PS FS 1b pre 2003	0	0	0
22. PS LS 1b pre 2003	0	0	0
23. PS FS 1b post 2006	41,464	30,069	51,055
24. PS LS 1b post 2006	72,881	93,199	84,404
25. LF 4	51,303	55,699	64,044
Total	373,530	398,714	427,477

Table 3. Tag recoveries by year of recovery (box), region of release (vertical), and region of recovery. Region of recovery is defined by the definitions of the fisheries included in the model.

Recovery year	Release region	Recovery region		
		1	2	4
2005	1	36	-	-
	2	7	83	-
2006	1	2,758	29	23
	2	22	5	-
2007	1	4,348	427	3
	2	13	2	-
2008	1	1,580	286	3
	2	5	-	-
2009	1	480	61	1
	2	3	-	-
2010	1	173	5	-
	2	-	-	-
2011–2014	1	106	11	2
	2	-	-	-

Table 4. Main structural assumptions of the yellowfin tuna base analysis and details of estimated parameters.

Category	Assumptions	Parameters
Recruitment	Occurs at the start of each quarter as 0 age fish. Recruitment is a function of Beverton-Holt stock-recruitment relationship (SRR). Regional apportionment of recruitment to R1 and R4 only. Temporal recruitment deviates from SRR, 1972–2013. Temporal deviates on proportion of recruitment allocated to R1 and R4, 1977–2013.	R_0 Norm(10,2); *h* = 0.80 *PropR1* Norm(1.5,0.25); *Prop R4* Norm(0.5,0.25) *SigmaR* = 0.6. 170 deviates. Deviates Norm(0,1), 300 deviates.
Initial population	A function of the equilibrium recruitment in each region assuming population in an unexploited state prior to 1950. Initial fishing mortality fixed at zero for all fisheries.	
Age and growth	28 quarterly age-classes, with the last representing a plus group. Growth based on VonBert growth model with age-specific *k* to approximate the mean length at age determined by Fonteneau (2008). SD of length-at-age based on a constant coefficient of variation of average length-at-age. Mean weights (W_j) from the weight-length relationship $W = aL^b$ (source WPDCS IOTC-2014-WPDCS10-INF02).	*Linfinity* = 145cm, *k* (base) = 0.455, *k* deviates for ages 2–13. CV =0.10 *a* = 1.7665e-05, *b* = 3.03542
Natural mortality	Age-specific. Relative variation amongst ages based on WCPO yellowfin assessment and overall scale of natural mortality estimated in 2012 IO yellowfin assessment (see Figure 16). Constant over time and among regions.	
Maturity	Age-dependent, specified. Derived from length based maturity OGIVE in Zudaire et al (2013). Mature population includes both male and female fish (single sex model).	age-class 0-4: 0; 5: 0.1; 6: 0.15; 7: 0.2; 8: 0.5; 9: 0.5; 10: 0.7; 11: 0.9; 12-28: 1.0
Movement	Age-dependent with two blocks; age classes 2-8 and 9-28. Constant among quarters. Correlated with oceanographic covariates.	10 movements * 2 age blocks. Norm(0,4). 12 parameters Norm(0,1).
Selectivity	Age specific, constant over time. Principal longline fisheries share logistic selectivity parameters. Common selectivitiy for all PSLS fisheries. Common selectivitiy for all PSLS fisheries. LF4 fishery logistic selectivity. All other fisheries: double normal selectivity. OT 1a & 4 and TR 1b & 4 share selectivity parameters.	Logistic *p1* Norm(14,1), *p2* Norm(4,1) Five node cubic spline Five node cubic spline

Catchability	Constant over years and among regions for LL CPUE indices (CPUE indices are scaled to reflect different region sizes). No seasonal variation in catchability for LL CPUE. LL CPUE indices have CV of 0.3 for all regions.	Unconstrained (nuisance) parameter *LLq*
Fishing mortality	Hybrid approach (method 3, see Methot & Wetzel 2013).	
Tag mixing	Tags assumed to be randomly mixed at the model region level three quarters following the quarter of release. Accumulation after 16 quarters	
Tag loss	Chronic tag loss represents tag shedding of 20% over 2000 days (Gaertner & Hallier). Applied to all tag release groups.	Parameter -3.5
Tag reporting	All (corrected) reporting rates constant over time. Common tag reporting rate fixed for all PS fisheries. Non PS tag reporting rates uninformative priors.	 PS RR 0.81 Other fisheries
Tag variation	Over dispersion parameter of 7.0. Applied to all tag release groups.	Tag OD 7.0
Length composition	Multinomial error structure, all length samples assigned ESS of 5.0.	

Table 5. Details of objective function components for the final set of stock assessment models and main sensitivities.

Component	*Base*	*Steep70*	*Steep90*	*Mlow*	*NoEnviroMove*	*3region*
LIKELIHOOD	12177.4	12174.0	12180.4	12101.4	12213.6	12291.0
CPUE	-94.5	-97.3	-92.2	-98.2	-24.5	-65.6
Length_comp	5011.2	5009.1	5012.6	4988.5	4964.5	5030.4
Tag_comp	5197.4	5197.7	5197.2	5226.1	5223.9	5312.7
Tag_negbin	2009.8	2011.2	2008.9	1911.8	1996.0	1966.6
Recruitment	-45.4	-45.3	-45.2	-37.4	-48.5	-44.7
Parm_priors	78.0	77.8	78.1	89.9	84.7	68.6
Parm_devs	20.8	20.7	20.9	20.7	17.5	22.9
Catch	0.152	0.147	0.156	0.080	0.128	0.037
Parm_softbounds	0.010	0.010	0.010	0.012	0.008	0.008

Table 6. Estimates of management quantities for the stock assessment model options and model sensitivities. Current yield (mt) represents yield in 2015 corresponding to fishing mortality at the F_{MSY} level. The 95% confidence intervals for the current stock status metrics are provided for the base model.

Option	SB_0	SB_{MSY}	SB_{MSY}/SB_0	SB_{2014}	SB_{2014}/SB_0	SB_{2014}/SB_{MSY}	F_{2014}/F_{MSY}	*MSY*	*Current Yield*
base	3,448,810	1,216,510	0.35	799,560	0.23	0.66 (0.54–0.77)	1.34 (0.82–1.81)	421,304	256,591
Steep70	3,600,250	1,335,660	0.37	801,428	0.22	0.60	1.59	402,192	216,838
Steep90	3,338,770	1,116,820	0.33	798,424	0.24	0.71	1.16	438,264	296,248
3region	3,707,110	1,343,250	0.36	563,552	0.15	0.42	1.75	432,128	167,788
Mlow	4,546,050	1,611,410	0.35	772,718	0.17	0.48	2.71	318,203	121,715
NoEnviroMove	3,296,290	1,192,370	0.36	776,673	0.24	0.65	1.47	407,896	265,030

Table 7. Projected stock status relative to SB_{MSY} and the probability of being below SB_{MSY} in 3-, 5- and 10 years for three alternative levels of catch (relative to 2014) for the range of model options with different assumed levels of steepness for the SRR and *Mlow* and *3region* model options. A value of zero for SB/SB_{MSY} indicates that catches exceeded the stock biomass and the stock crashed.

Model option	Catch	3 years (2017)		5 year (2019)		10 year (2024)	
		SB/SB_{MSY}	$Pr(SB<SB_{MSY})$	SB/SB_{MSY}	$Pr(SB<SB_{MSY})$	SB/SB_{MSY}	$Pr(SB<SB_{MSY})$
Steepness							
0.8	100%	0.507	0.988	0.000	1.000	0.000	1.000
	80%	0.695	0.906	0.799	0.733	0.984	0.500
	60%	0.881	0.690	1.175	0.290	1.674	0.040
Steepness							
0.7	100%	0.381	1.000	0.000	1.000	0.000	1.000
	80%	0.550	0.986	0.548	0.930	0.000	1.000
	60%	0.717	0.912	0.913	0.620	1.387	0.157
Steepness							
0.9	100%	0.642	0.925	0.000	1.000	0.000	1.000
	80%	0.849	0.706	1.051	0.433	1.356	0.204
	60%	1.054	0.441	1.435	0.124	1.897	0.009
Mlow	100%	0.000	1.000	0.000	1.000	0.000	1.000
	80%	0.164	1.000	0.000	1.000	0.000	1.000
	60%	0.321	1.000	0.000	1.000	0.000	1.000
3region	100%	0.507	0.486	0.000	1.000	0.000	1.000
	80%	0.546	0.633	0.000	1.000	0.000	1.000
	60%	0.601	0.487	0.000	1.000	0.000	1.000

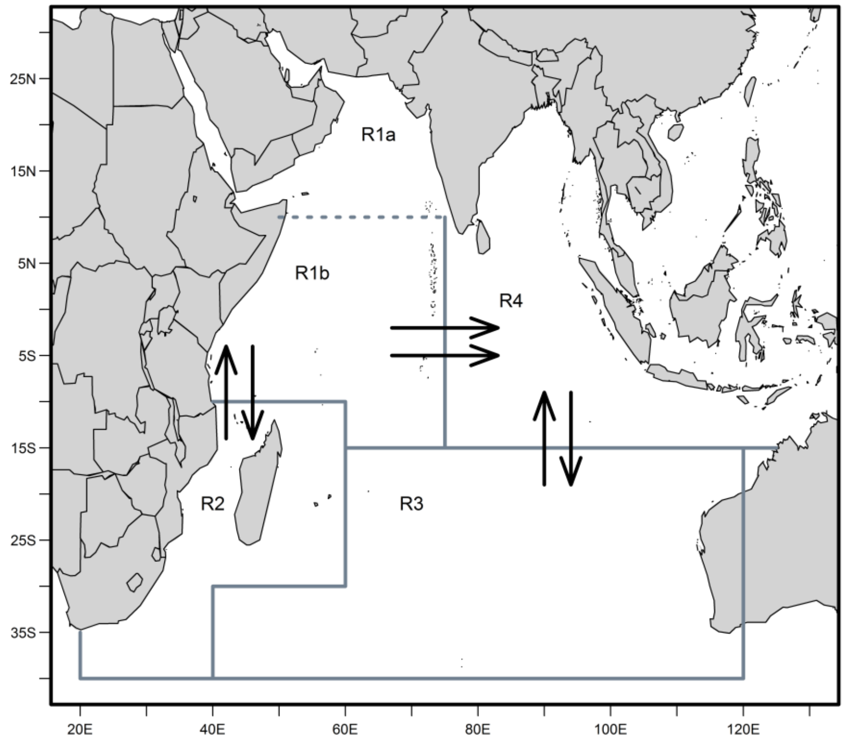


Figure 1. Spatial stratification of the Indian Ocean for the four region assessment model. The black arrows represent the configuration of the movement parameterisation of the base assessment model.

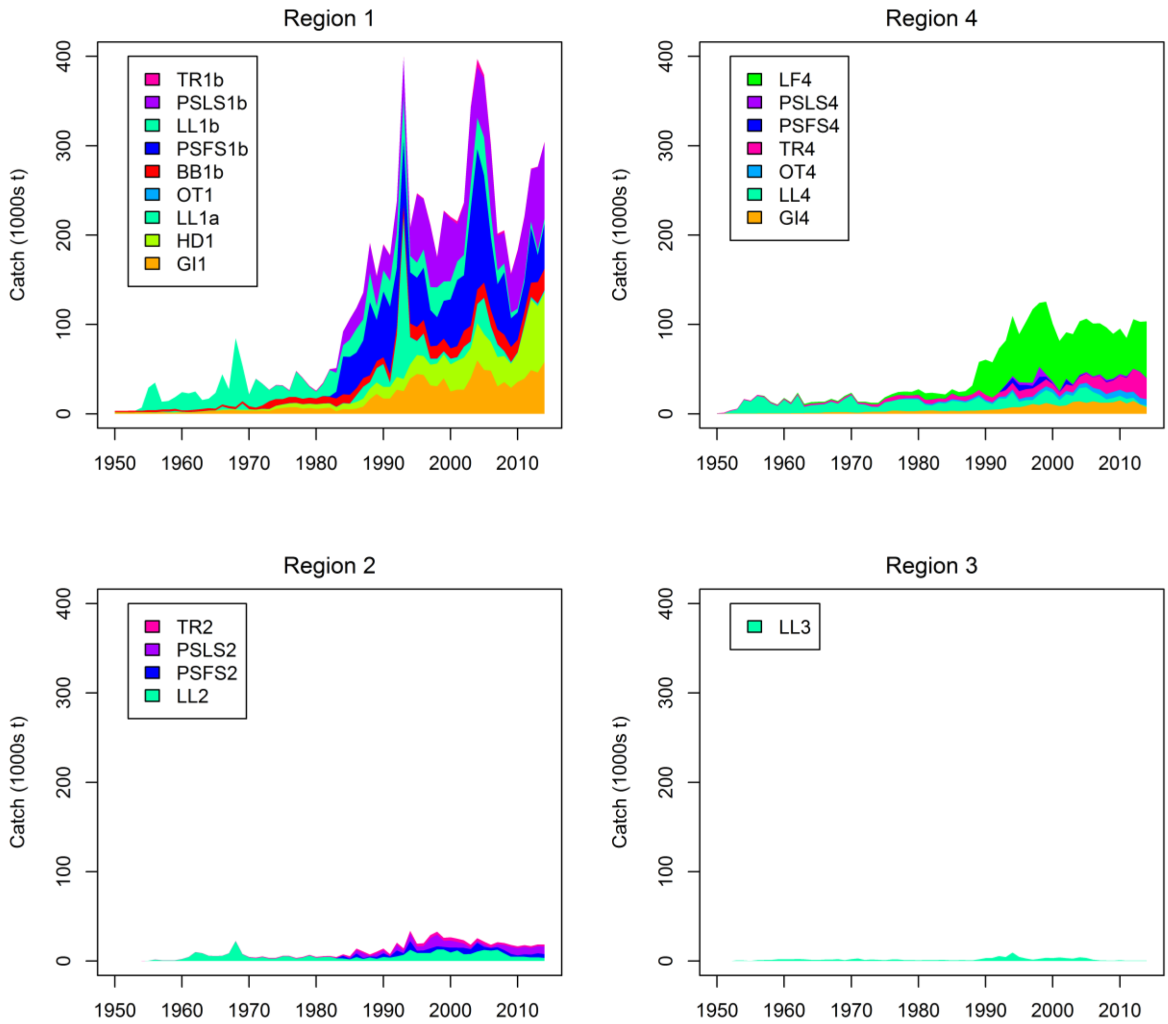


Figure 2. Total annual catch (1000s mt) of yellowfin tuna by fishing method and region from 1950 to 2014 (BB, baitboat; FS, purse-seine, free schools; GI, gillnet; HD, handline; LF, fresh tuna longline; LL, distant water longline; LS, purse-seine, log sets; OT, other; TR, troll).

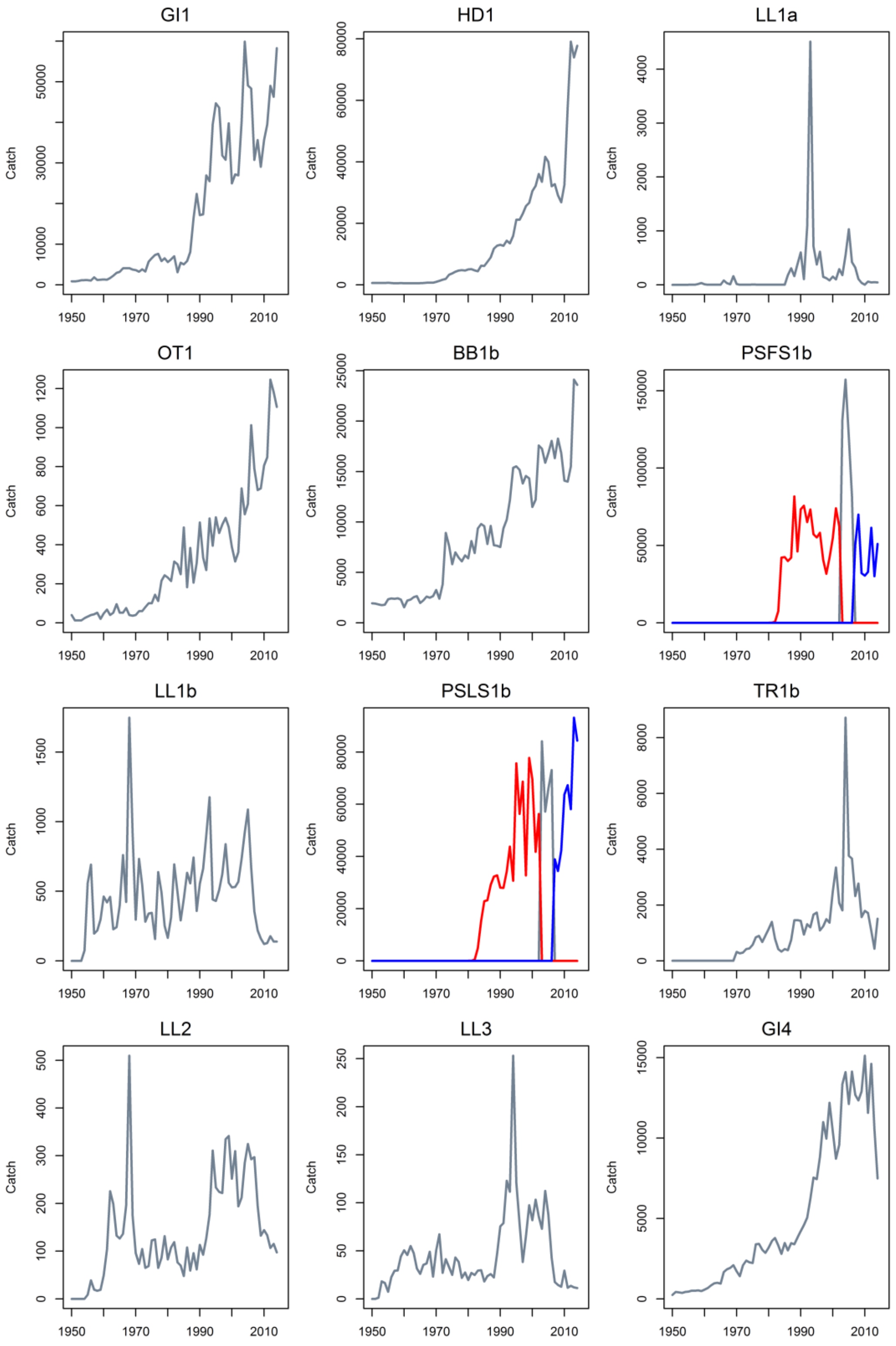
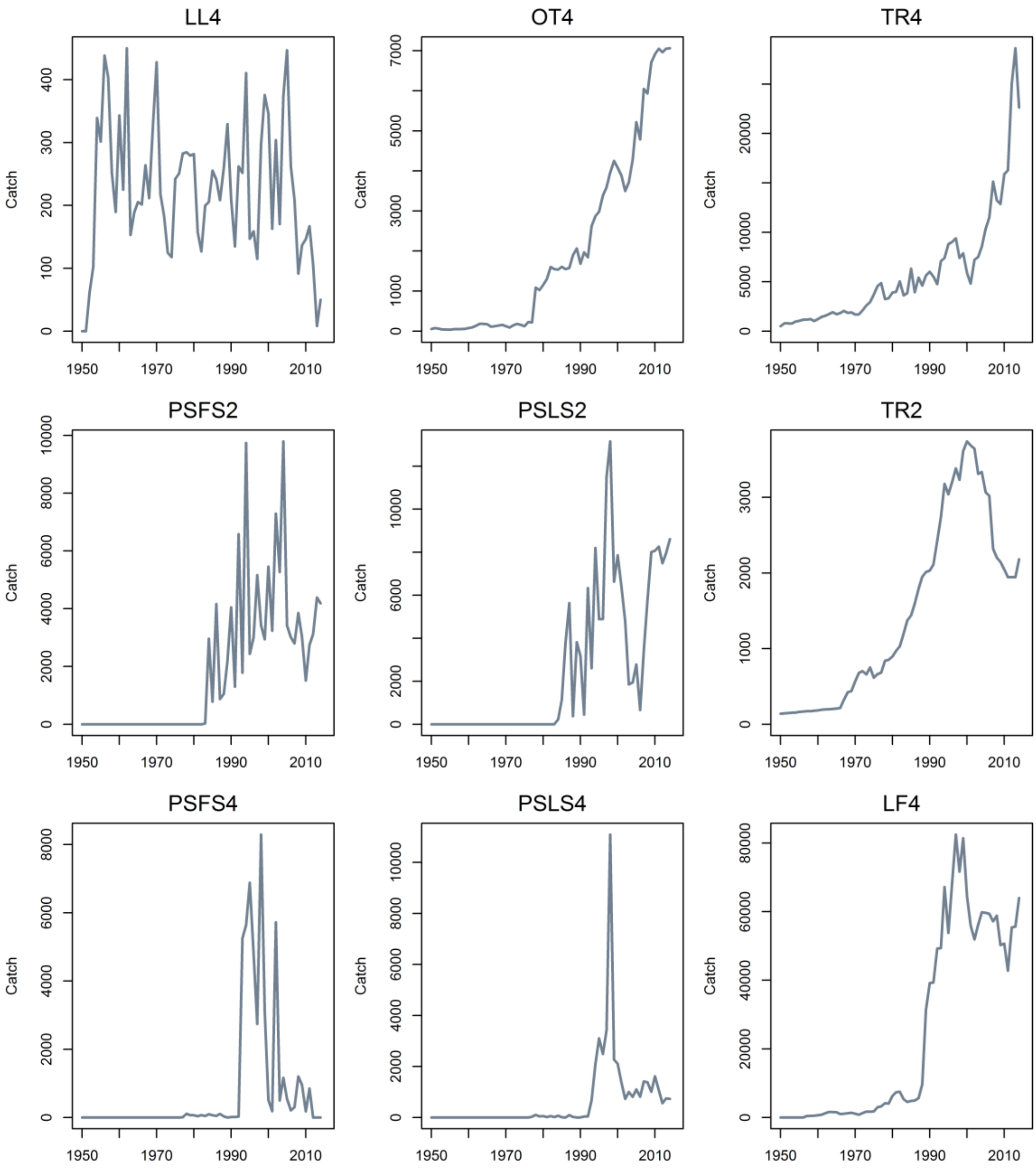


Figure 3. Fishery catches aggregated by year. Catches are in weight (tonnes) except for LL1-4 longline fisheries (number, thousands of fish). Note the y-axis differs among plots.



LL4
OT4
TR4
PSFS2
PSLS2
TR2
PSFS4
PSLS4
LF4
Catch
1950
1970
1990
2010

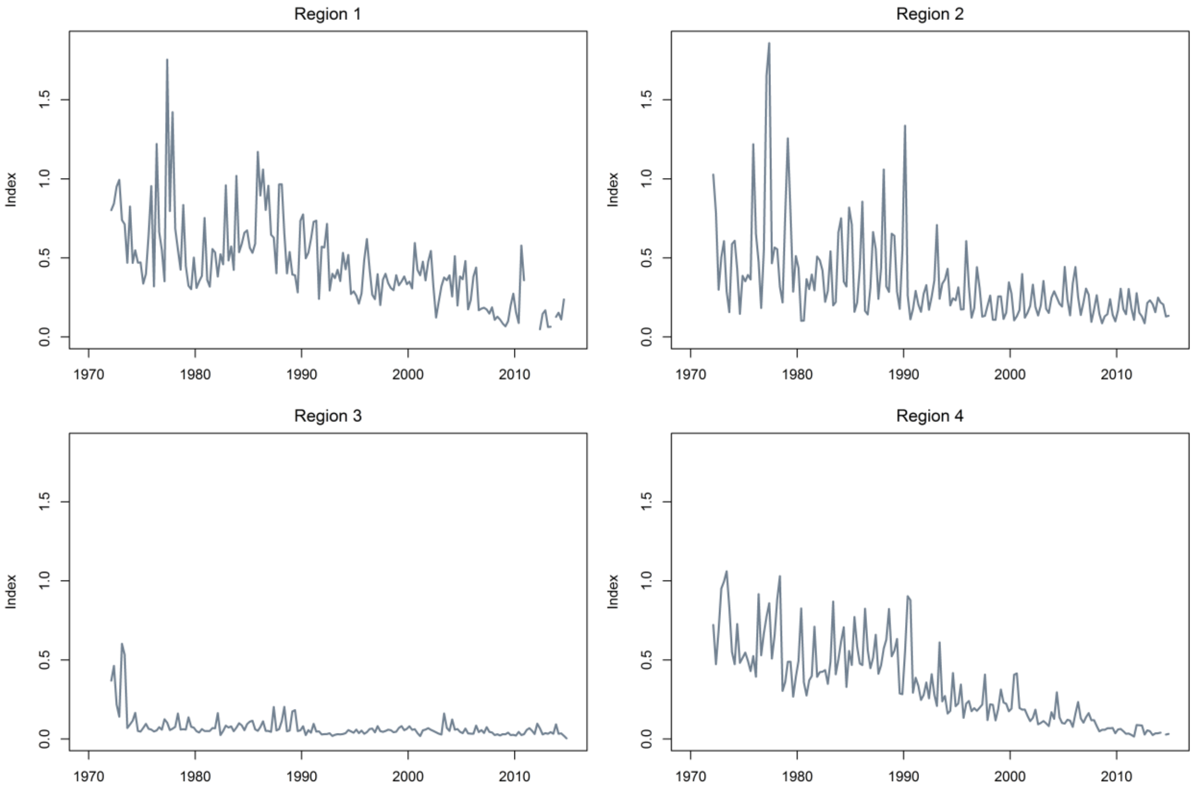


Figure 4. Quarterly GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL 1–4) scaled by the respective region scalars.

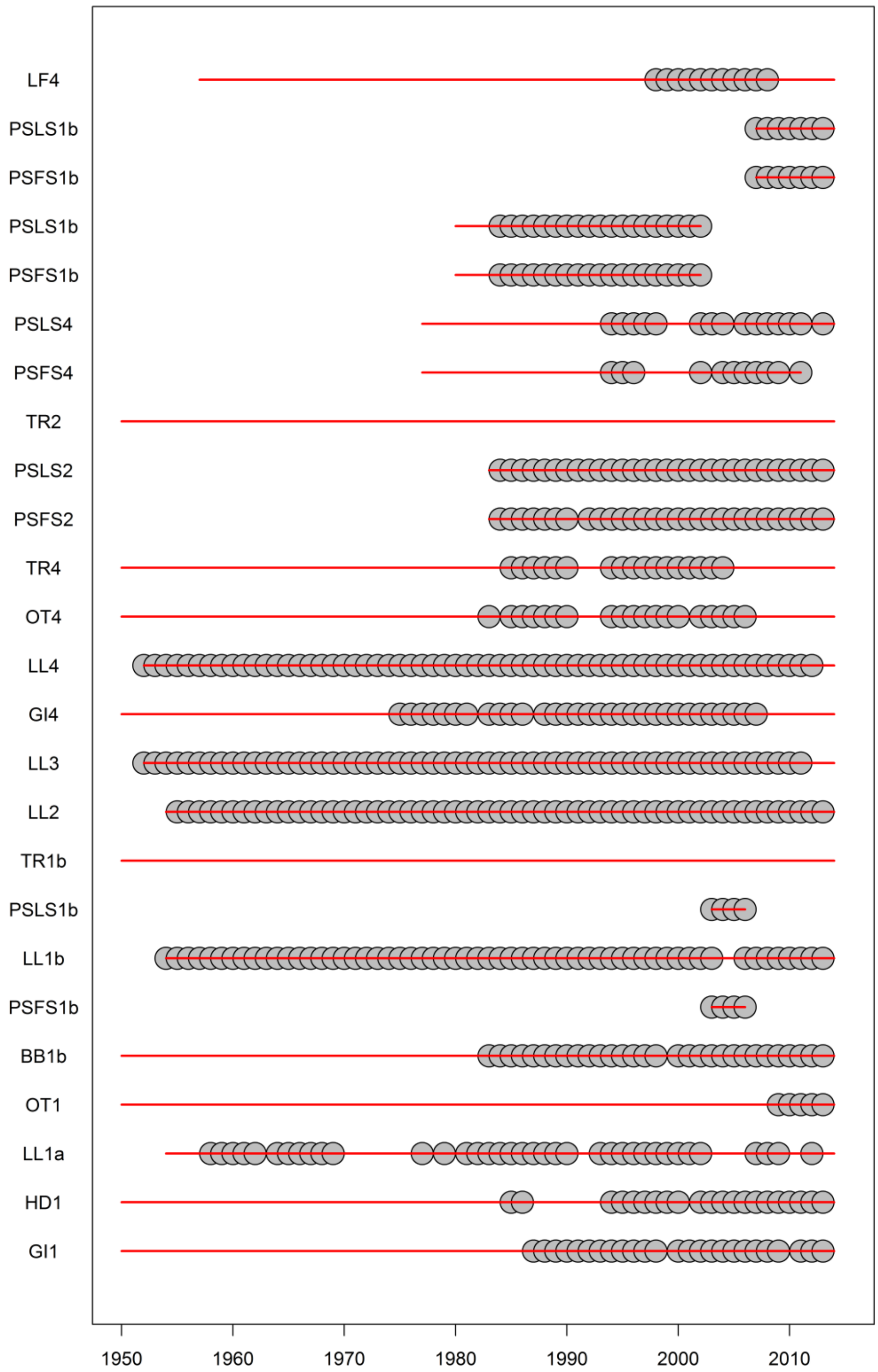


Figure 5. The availability of length sampling data from each fishery by year. The grey circles denote the presence of samples in a specific year. The red horizontal lines indicate the time period over which each fishery operated.

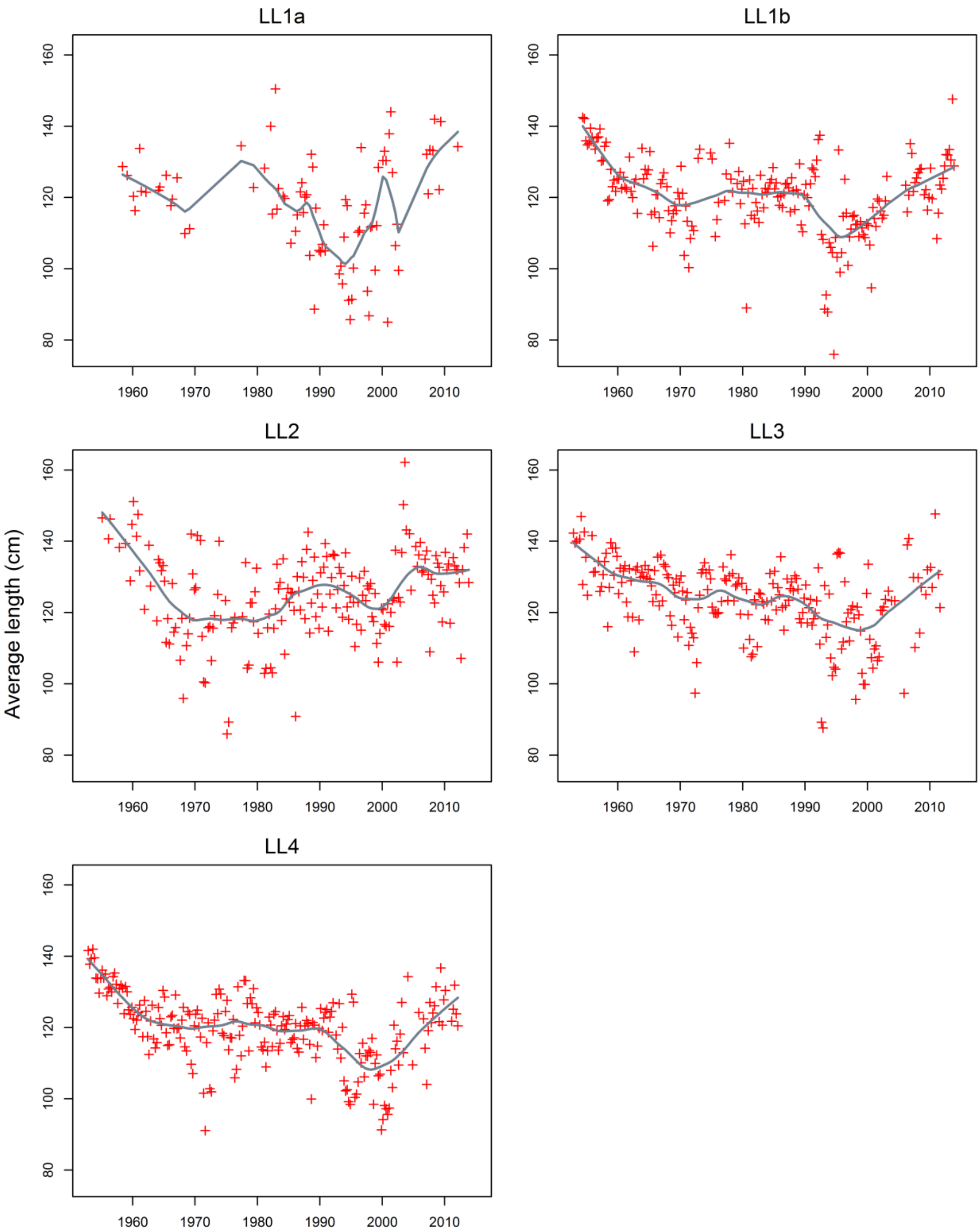


Figure 6. Mean length (fork length, cm) of yellowfin sampled from the principal longline fisheries (LL 1a-4) by quarter. The grey line represents the fit of a lowess smoother to each data set.

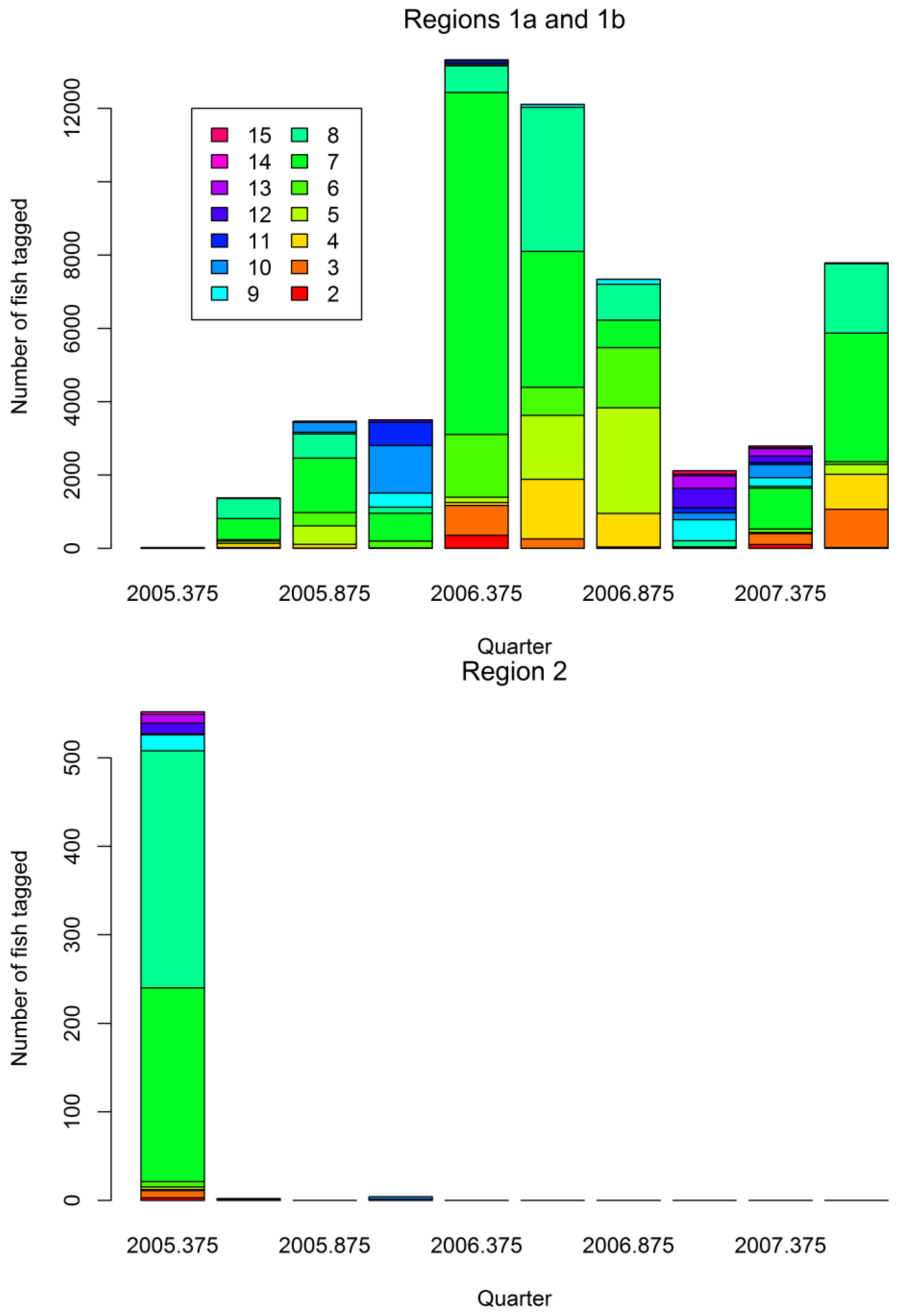


Figure 7. Number of tag releases by region and quarter and age class included in the assessment data set. No tag releases occurred in regions 3 and 4.

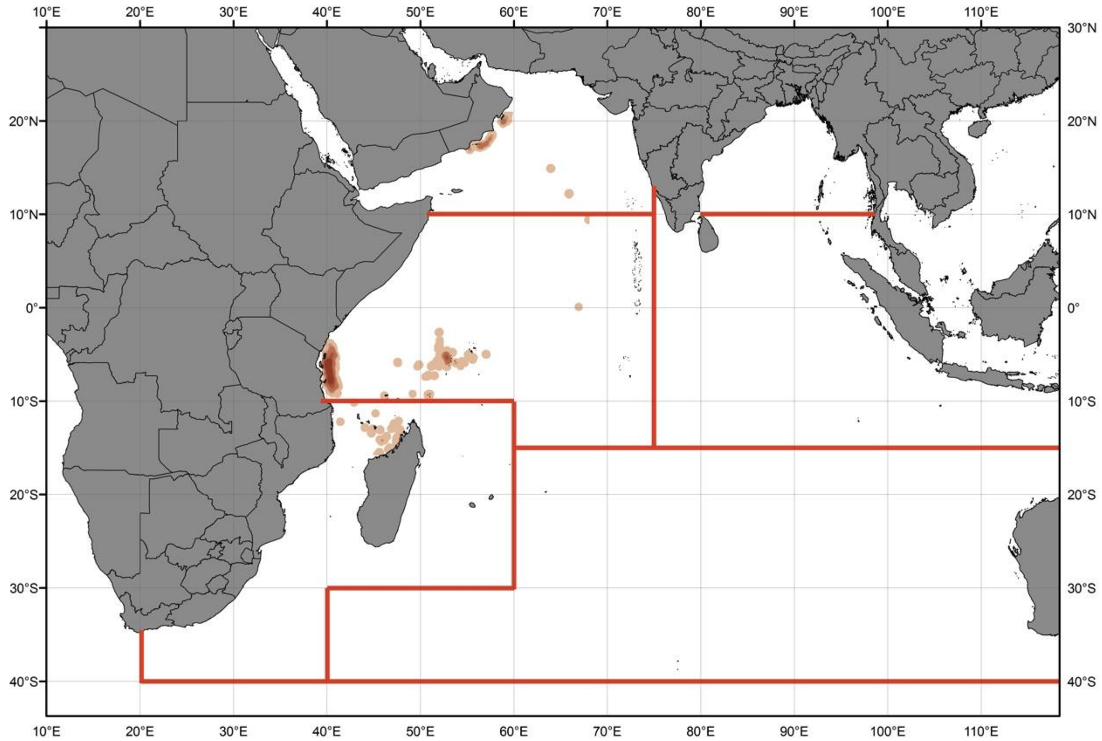


Figure 8. Density of RTTP-IO tag releases.

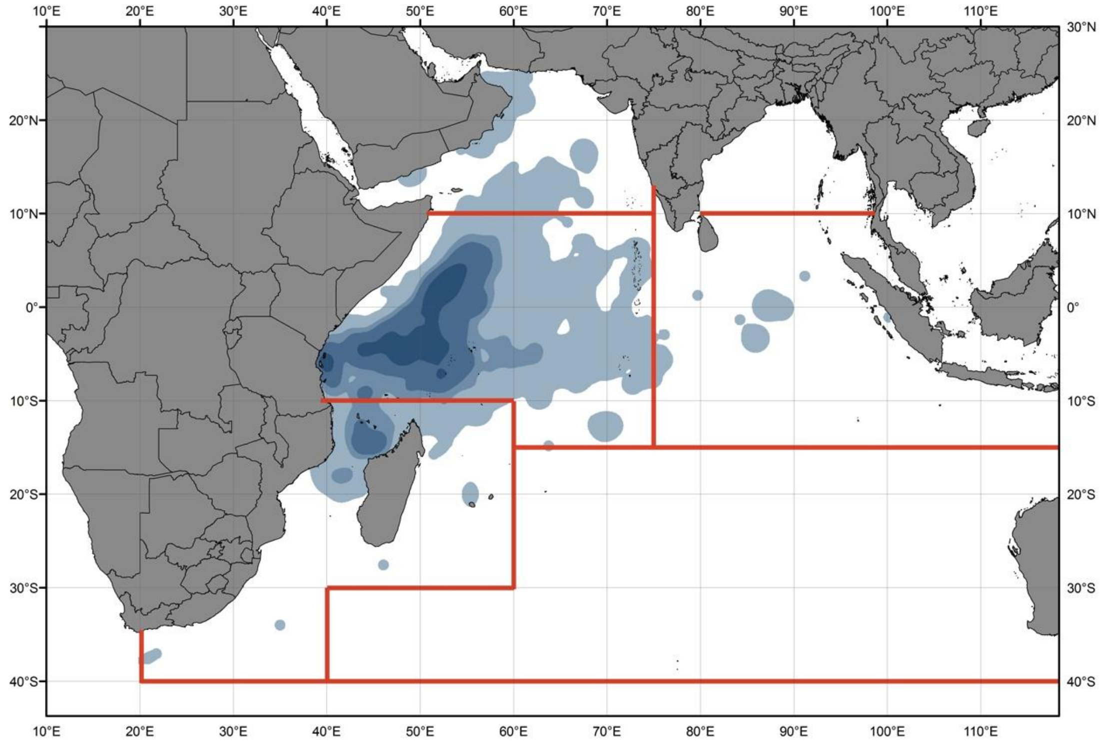


Figure 9. Density of RTTP-IO tag recoveries.

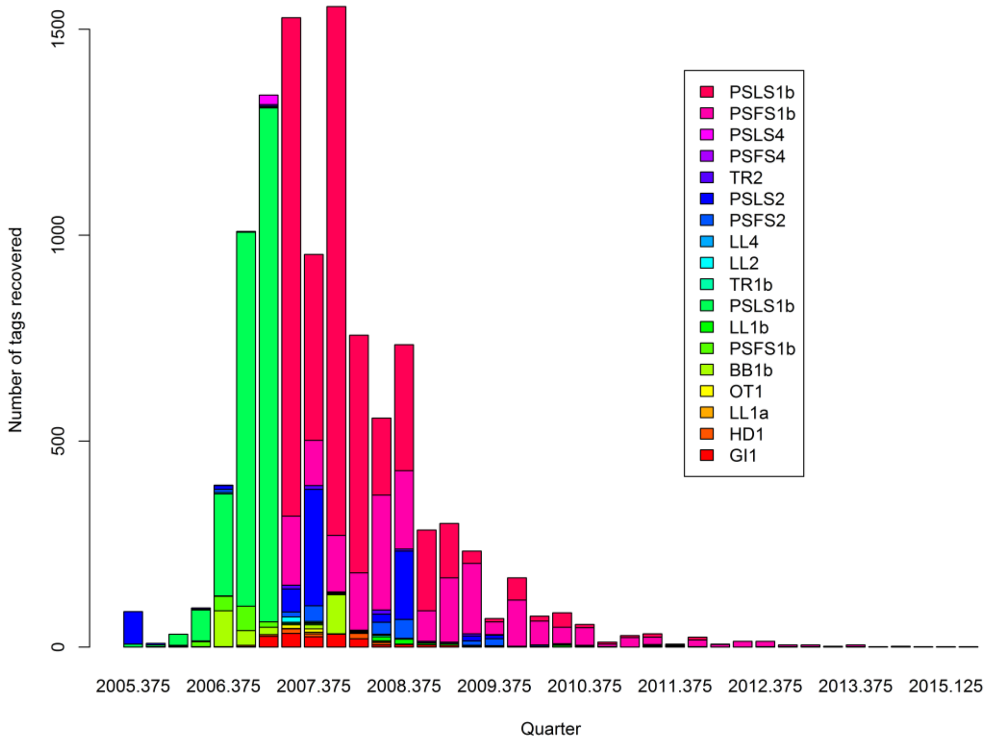


Figure 10. Yellowfin tag recoveries by year/quarter and fishery included in the assessment model. Purse seine tag recoveries have been corrected for reporting rate.

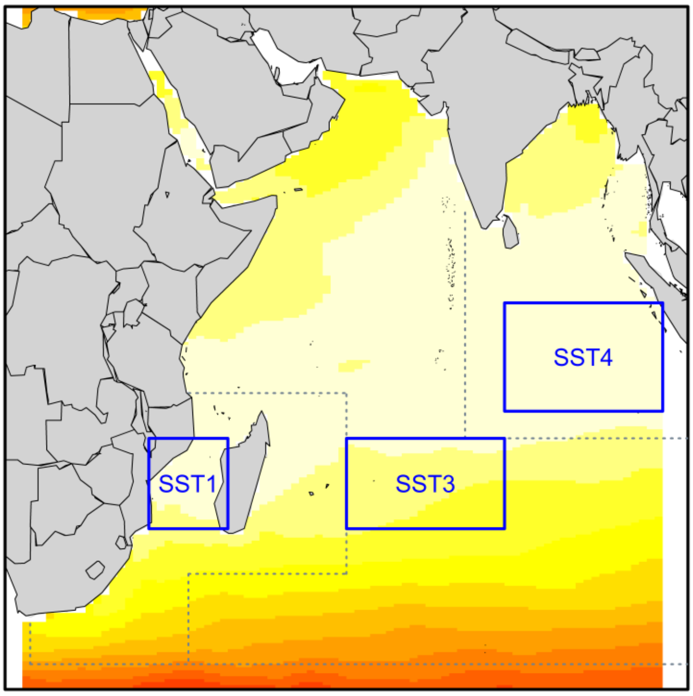


Figure 11. Definition of the areas used to derive the SST environmental indices.

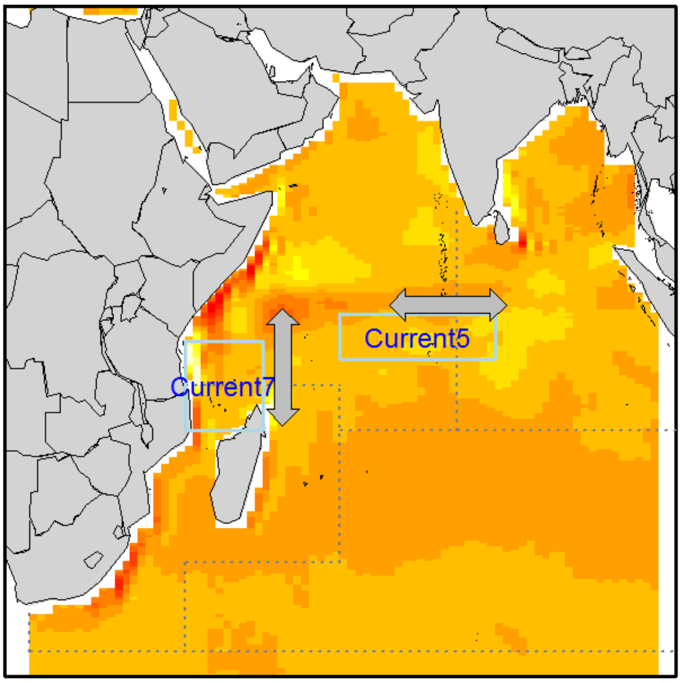


Figure 12. Definition of the areas used to derive the current environmental indices.

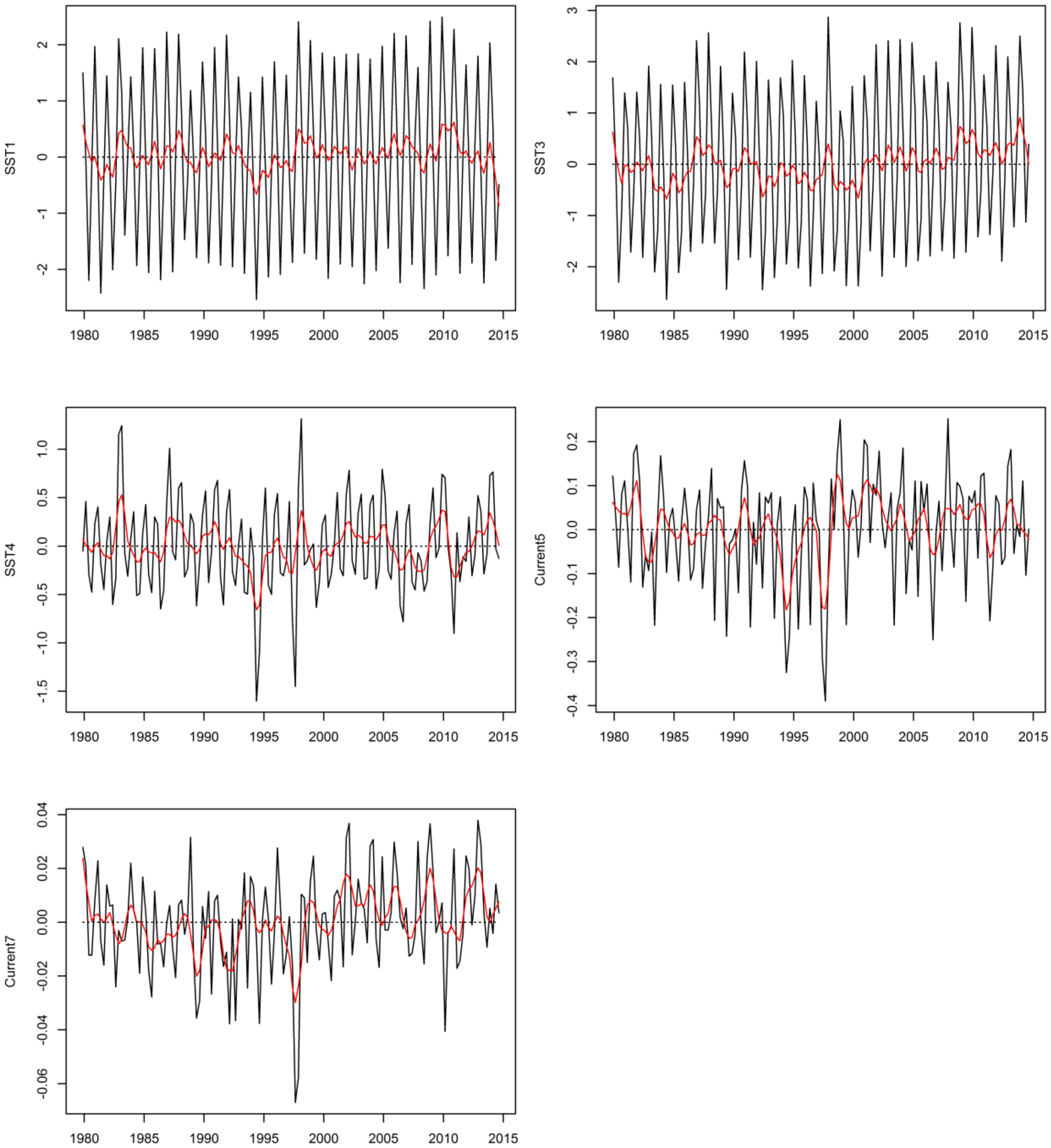


Figure 13. Quarterly indices for each environmental index (black lines) and a lowess smoothed trend for the indices (red line).

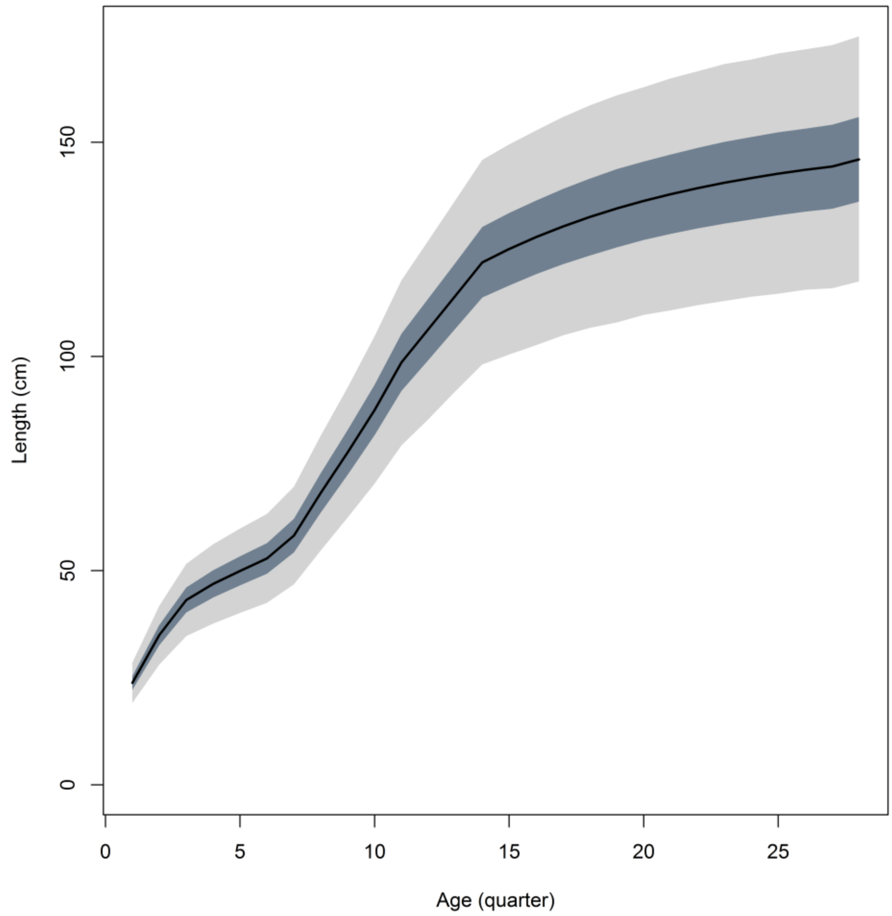


Figure 14. Fixed growth function for yellowfin tuna (following Fonteneau 2008). The black line represents the estimated mean length (FL, cm) at age and the grey area represents the assumed distribution of length at age.

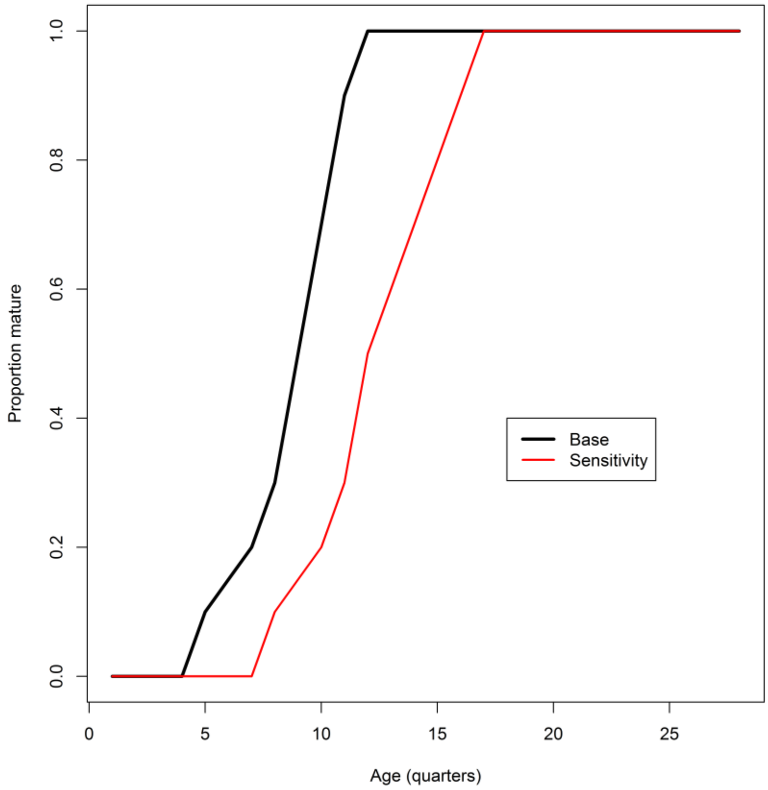


Figure 15. Age based maturity OGIVEs for Indian Ocean yellowfin tuna (derived from Zudaire et al 2013).

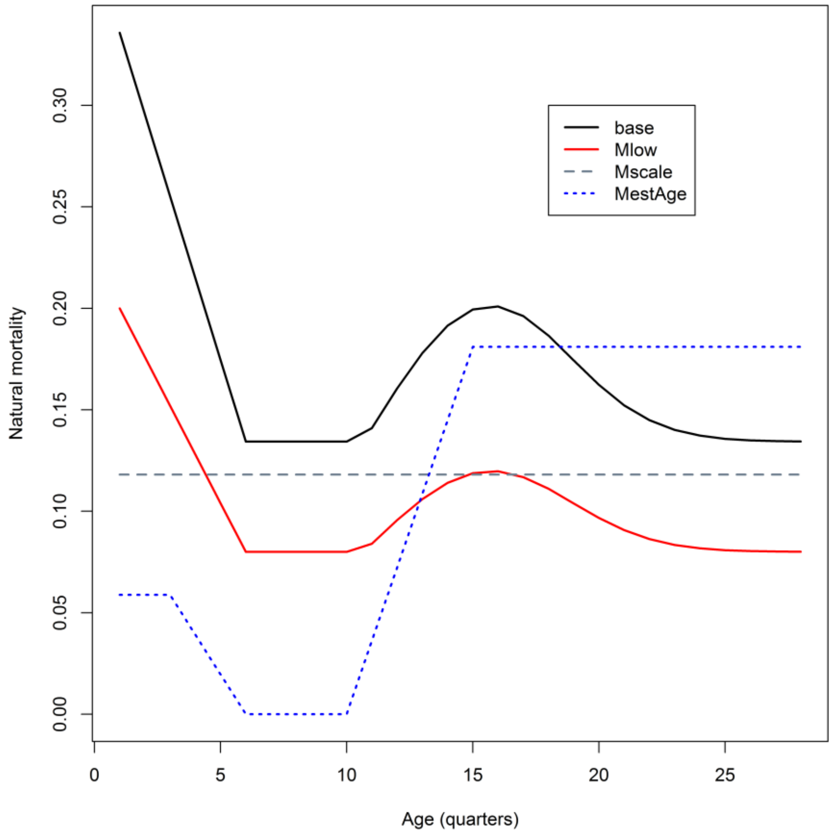


Figure 16. The age-specific natural mortality schedule assumed for the assessment model (*Base*) and other age-specific *M* schedules from various model options (see text for details).

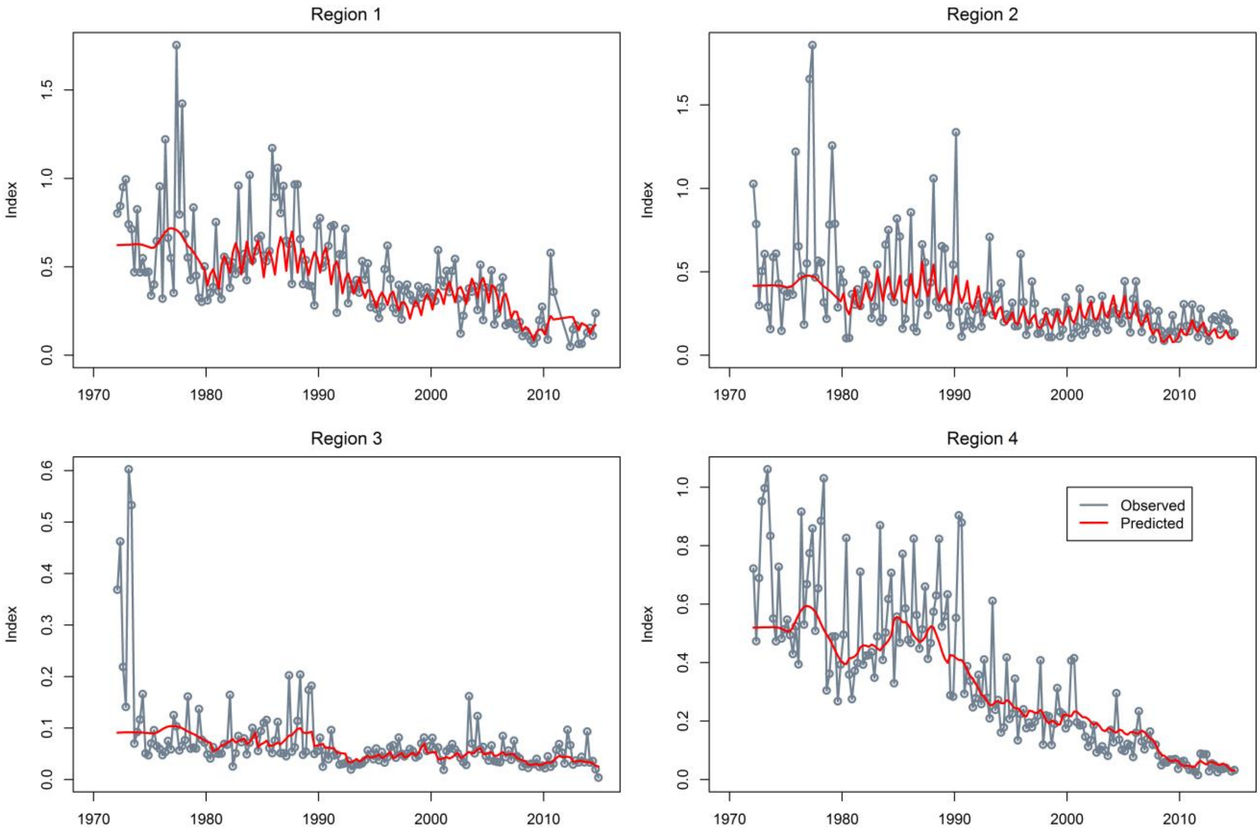


Figure 17. Fit to the regional longline CPUE indices, 1972–2014.

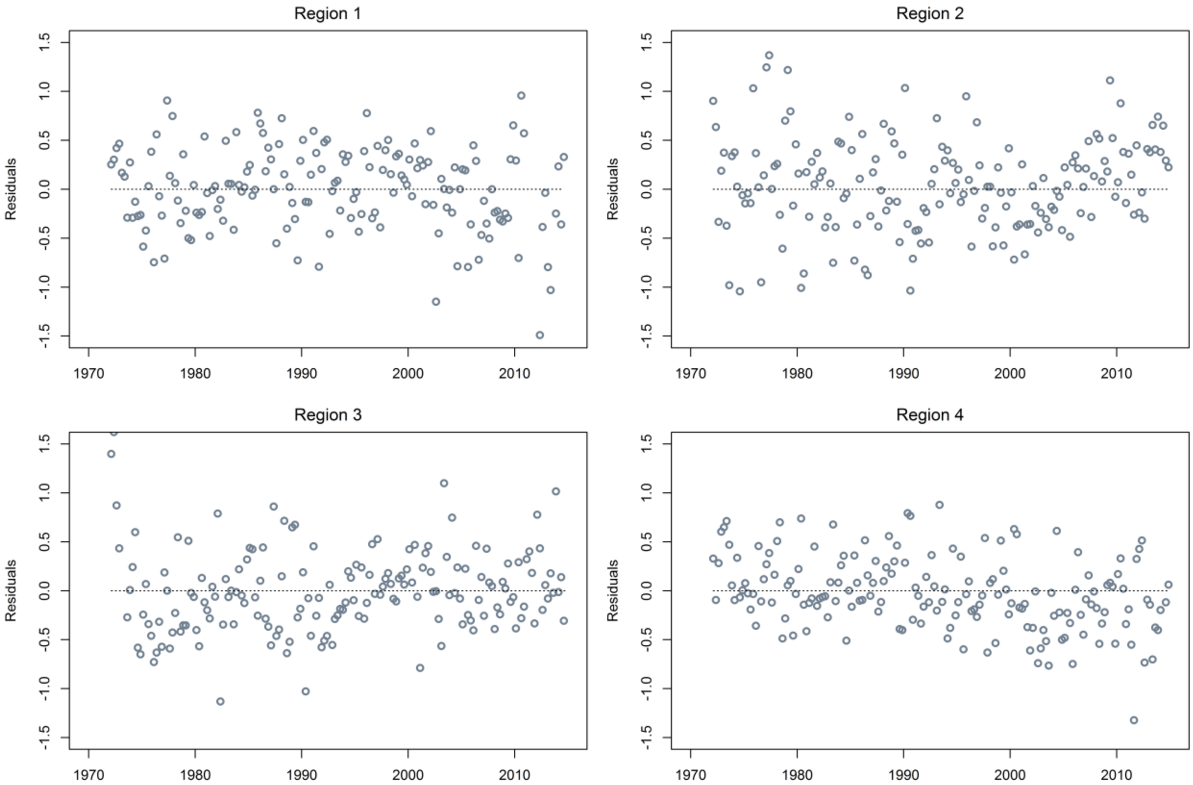


Figure 18. Residuals (observed – expected) from the fit to the CPUE indices in each region.

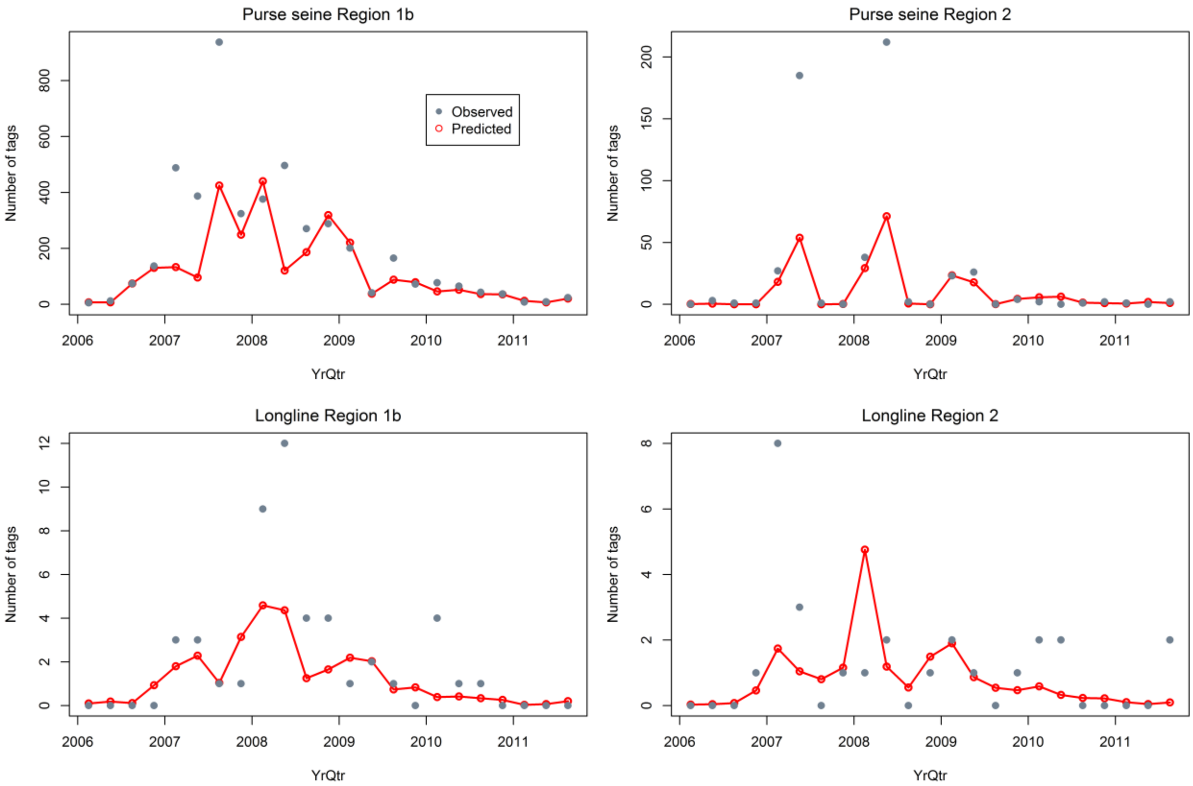


Figure 19. Observed and predicted number of tags recovered by quarter for the main method, region fisheries recovering tags. Only tags at liberty after the three quarter mixing period are included. Tag recoveries are aggregated from the regional purse seine free-school and log fisheries.

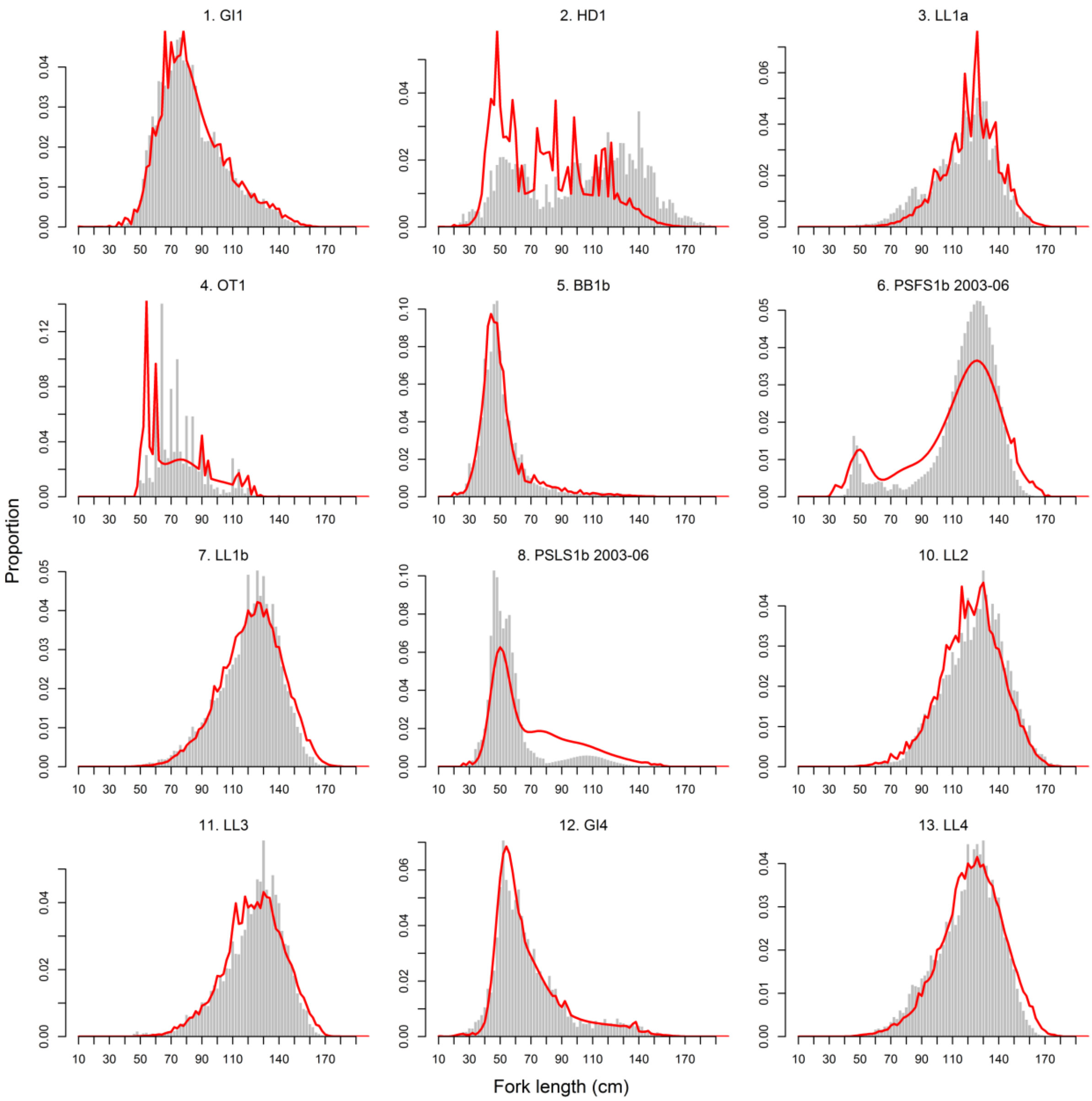


Figure 20. Observed (grey bars) and predicted (red line) length compositiobs (in 2 cm intervals) for each fishery aggregated over time.

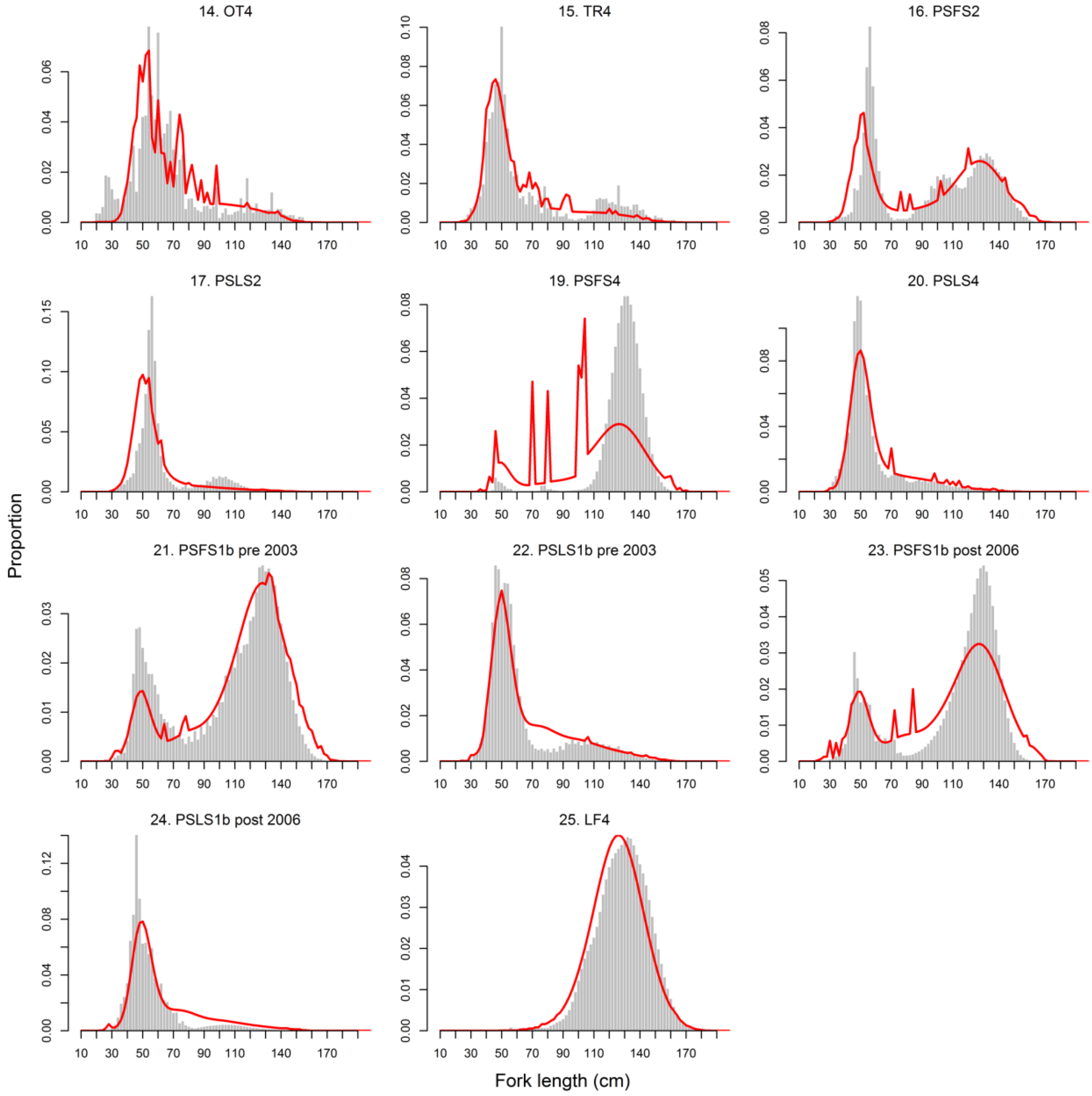


Figure 20 continued

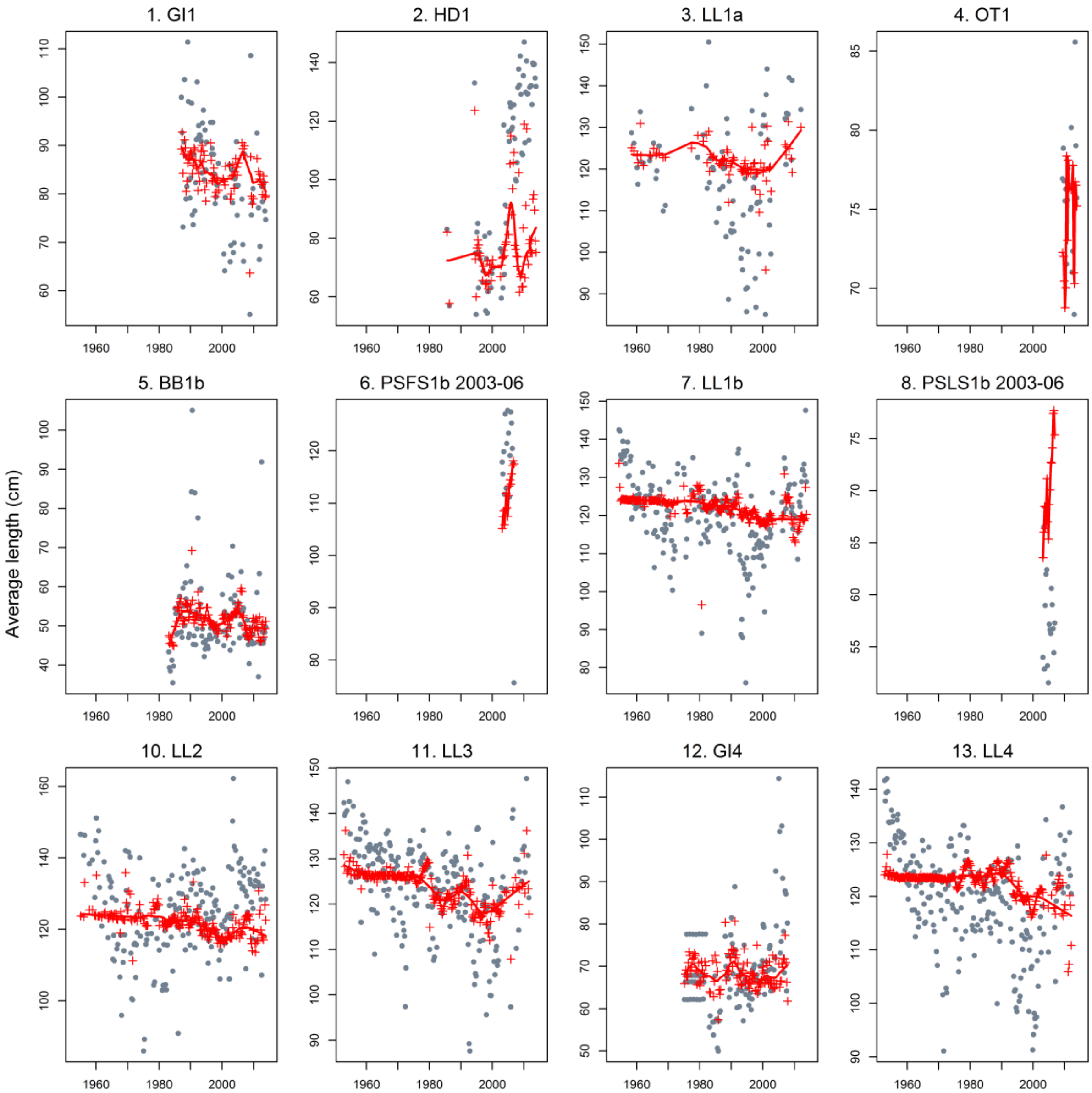


Figure 21. A comparison of the observed (grey points) and predicted (red points and line) average fish length (FL, cm) of yellowfin tuna by fishery for the main fisheries with length data. The red line represents a lowess smoother fit to the predicted average lengths.

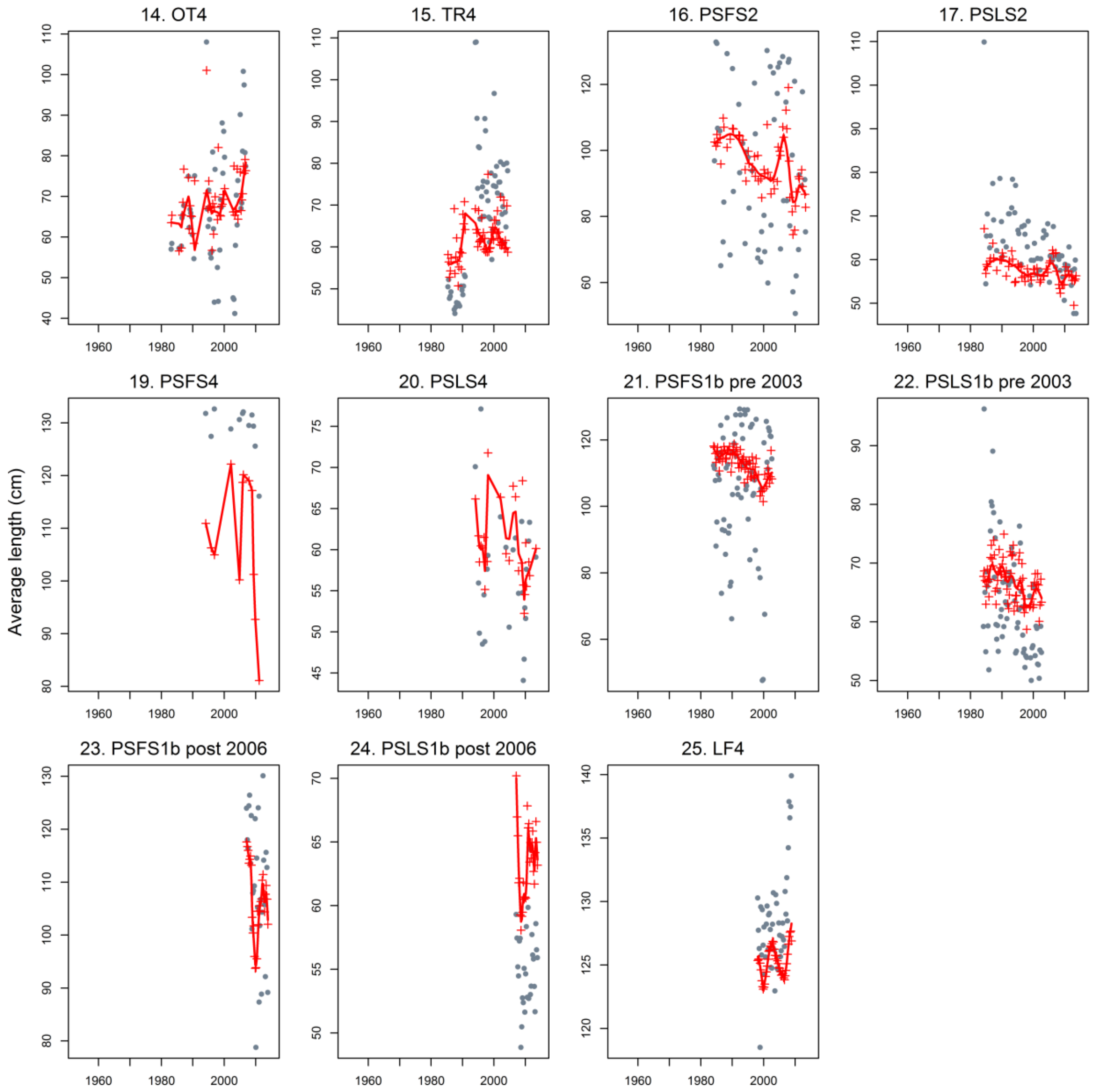


Figure 21 continued.

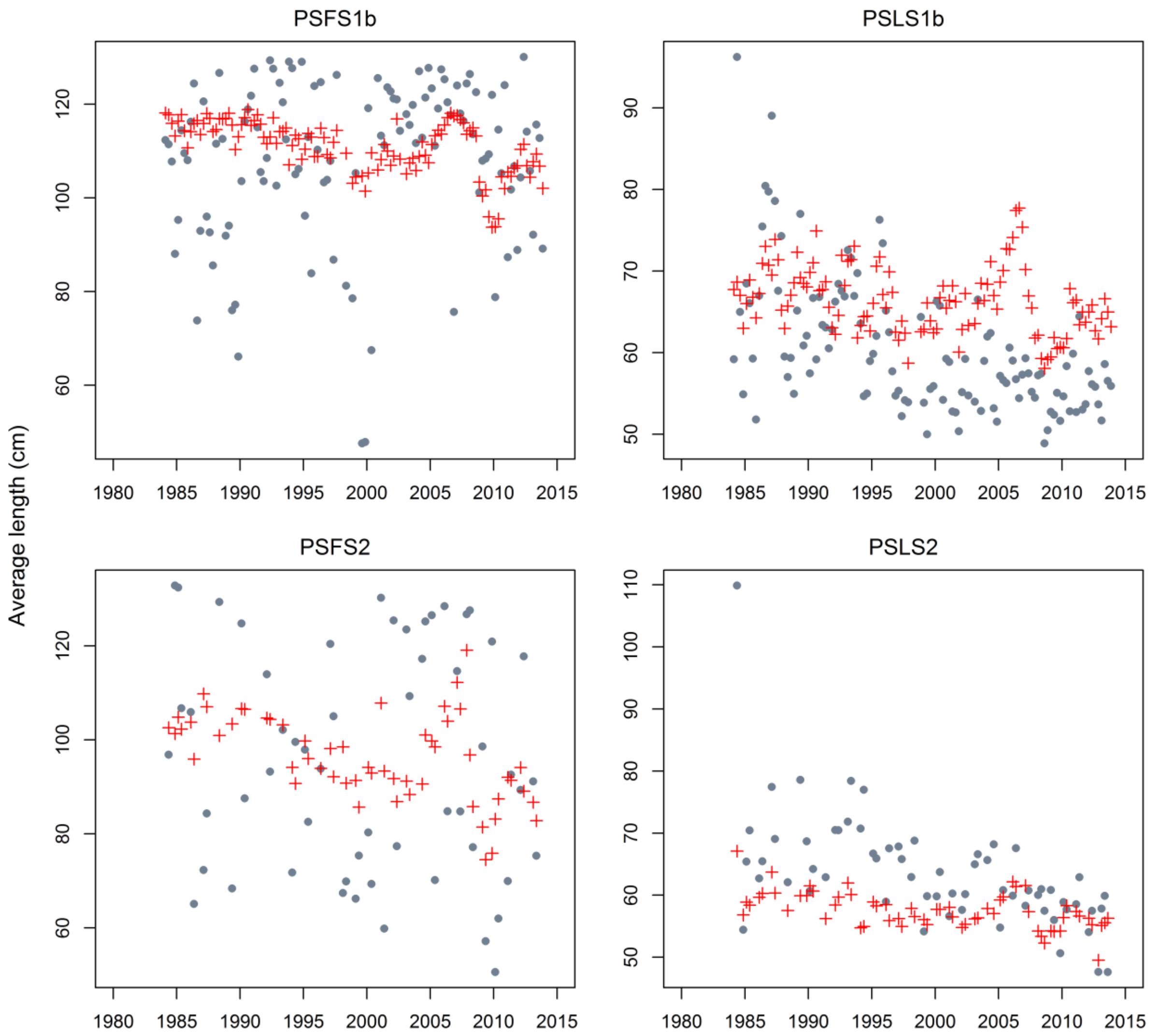


Figure 22: A comparison of the observed (grey points) and predicted (red points) average fish length (FL, cm) of yellowfin tuna by fishery for the main purse seine fisheries.

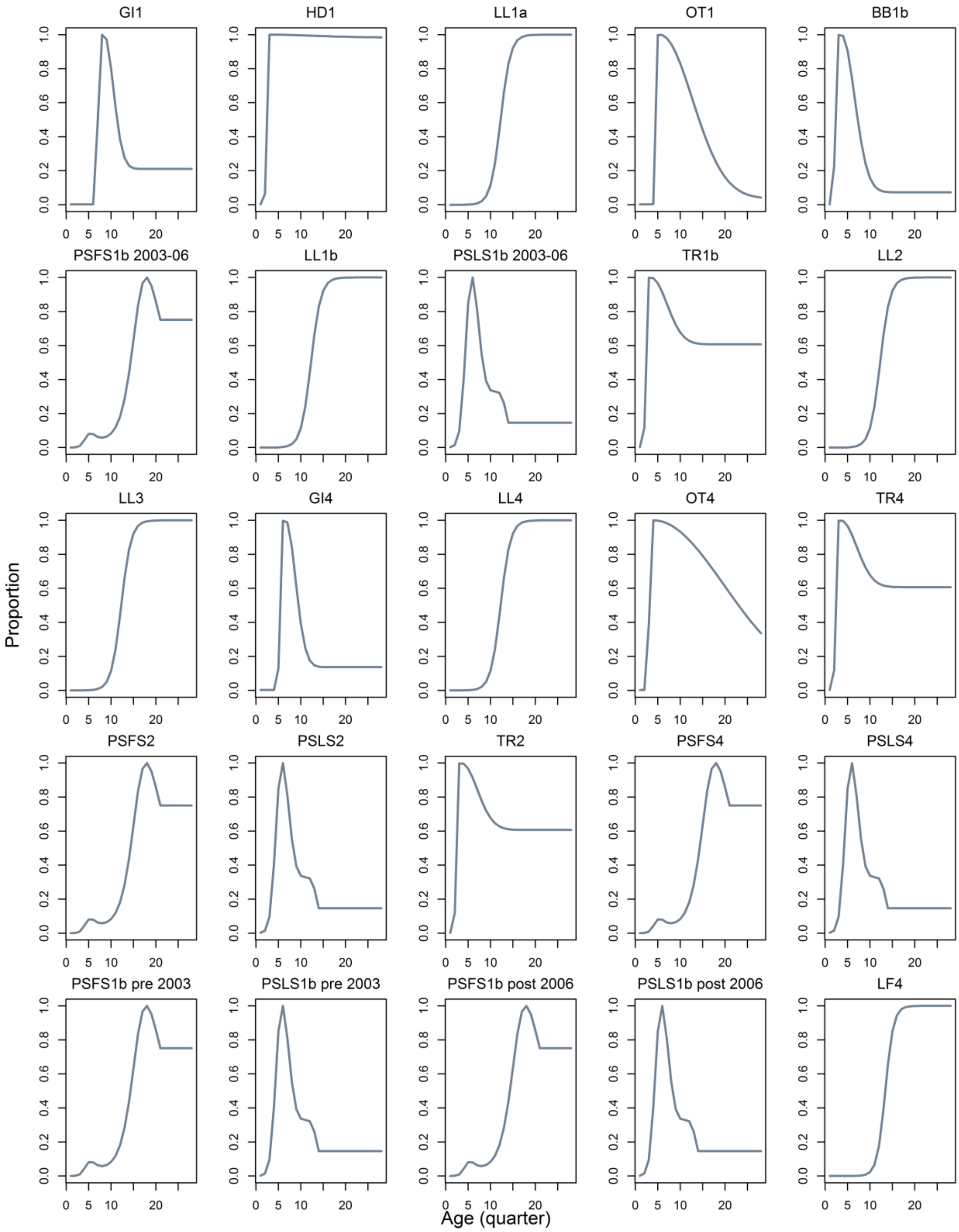


Figure 23. Age specific selectivity by fishery.

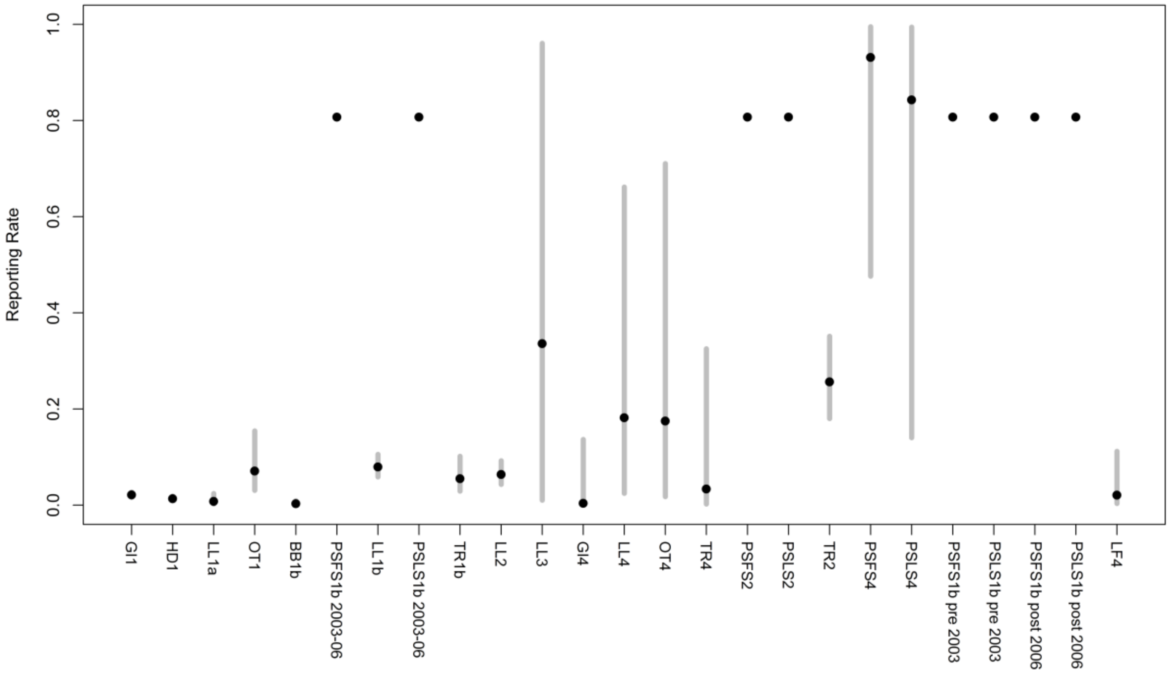


Figure 24. Tag-reporting rates by fishery (black circles) and 95% confidence intervals for the estimated fishery reporting rates. The reporting rates for the purse-seine fisheries in regions 1 and 2 were fixed.

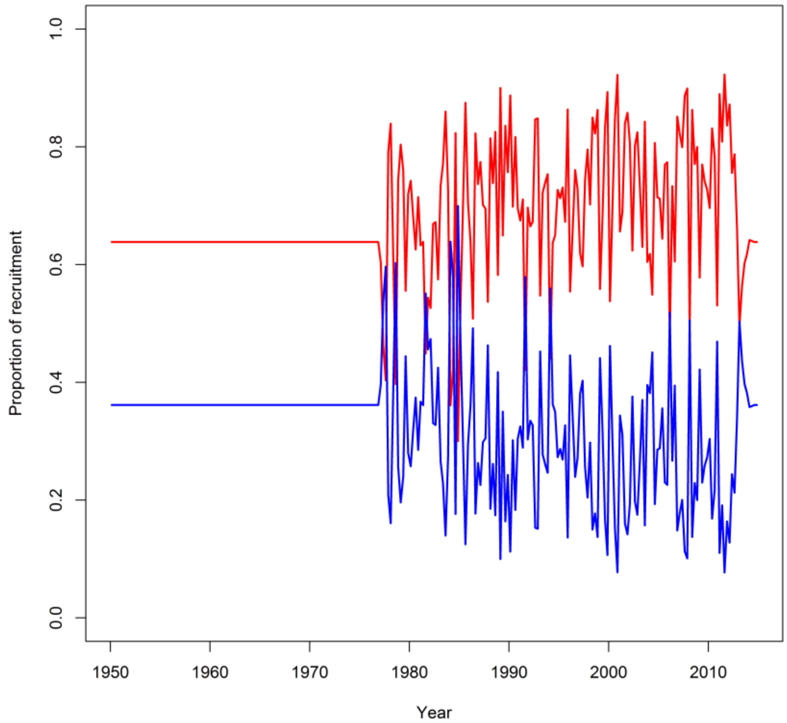


Figure 25. Proportion of the total quarterly recruitment assigned to region 1 (red) and region 4 (blue).

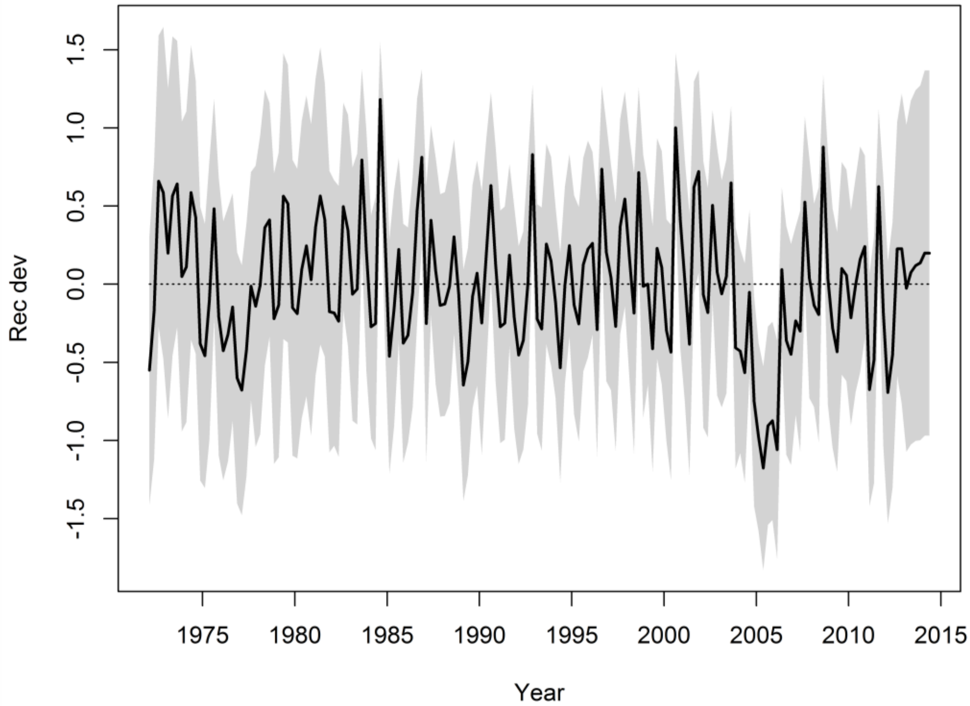


Figure 26. Recruitment deviates from the SRR and the associated 95% confidence interval.

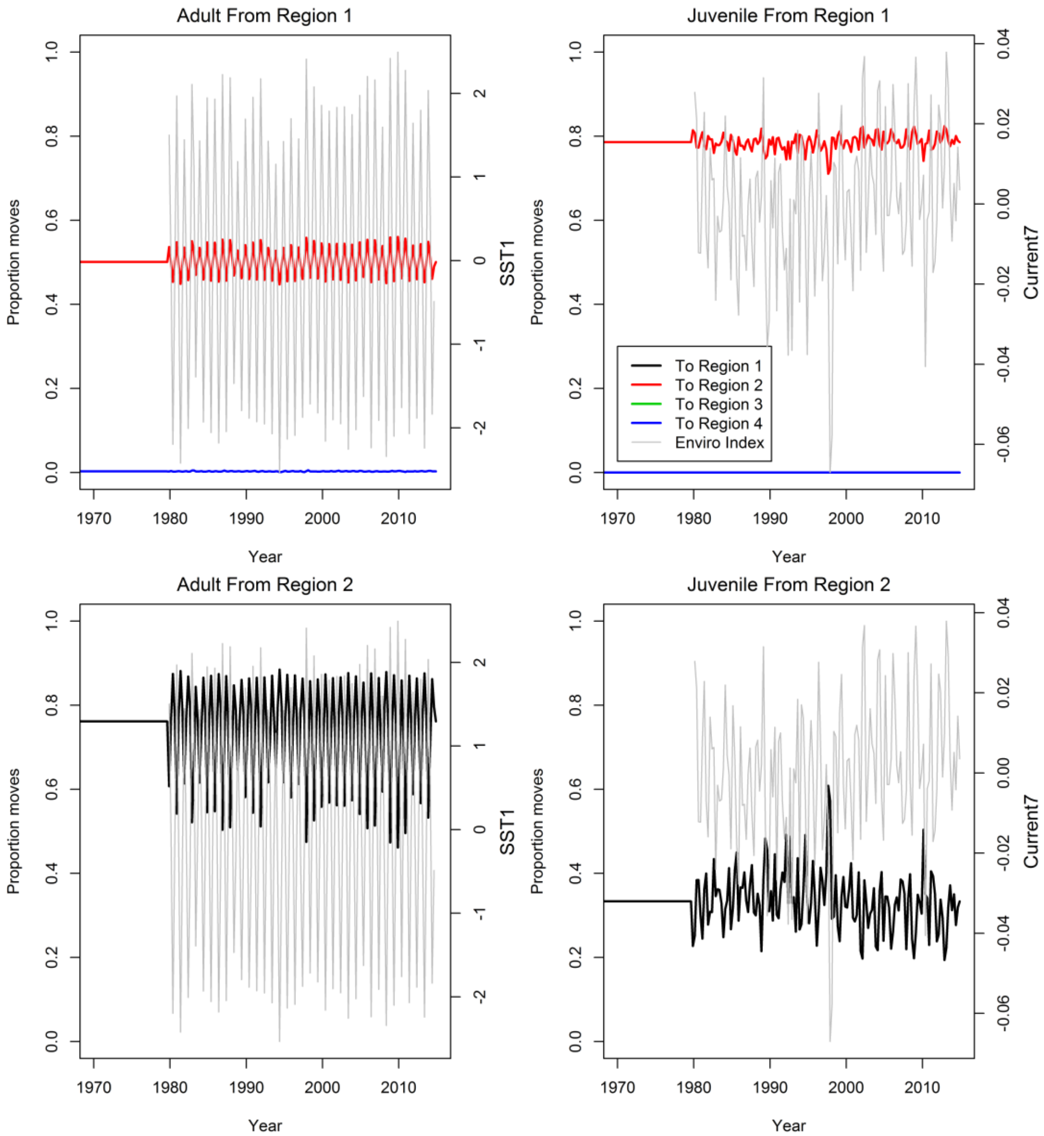


Figure 27. Quarterly movement coeficients and the corresponding environmental covariate (grey line).

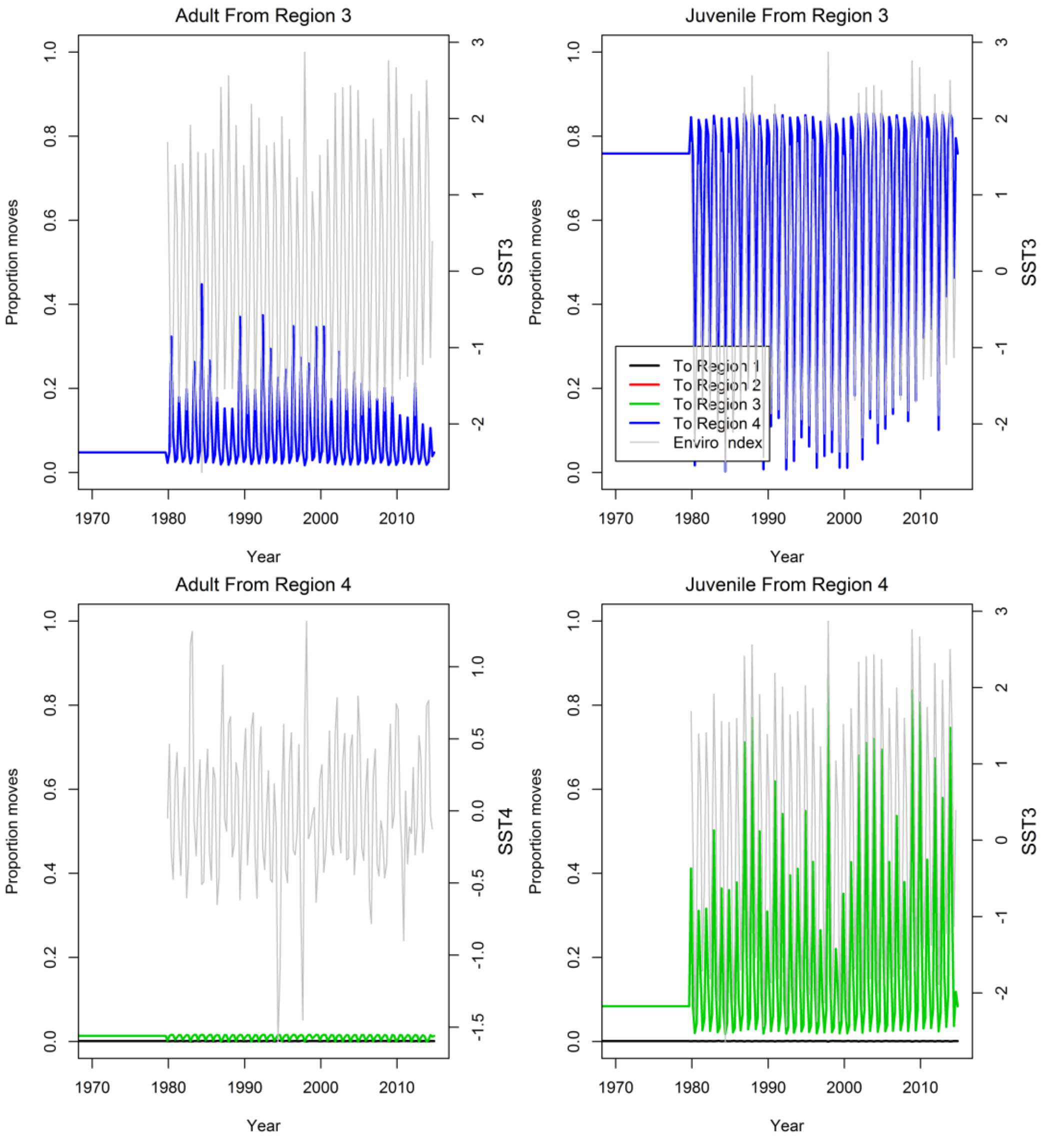


Figure 27 contd.

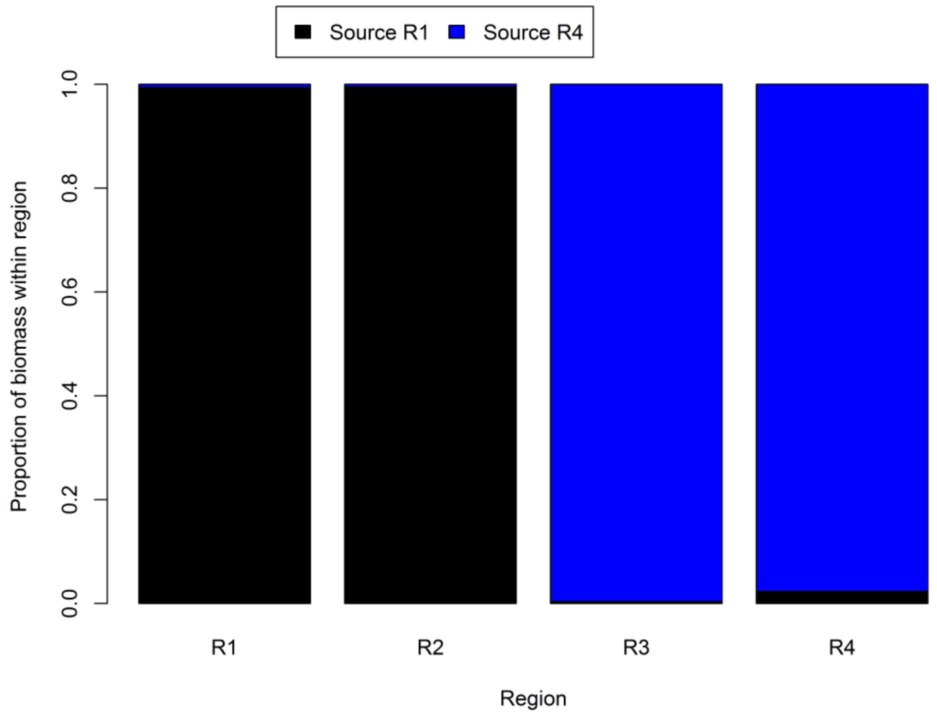


Figure 28. Simulated proportion of the biomass in each region attributable to each source region of recruitment (regions 1 and 4).

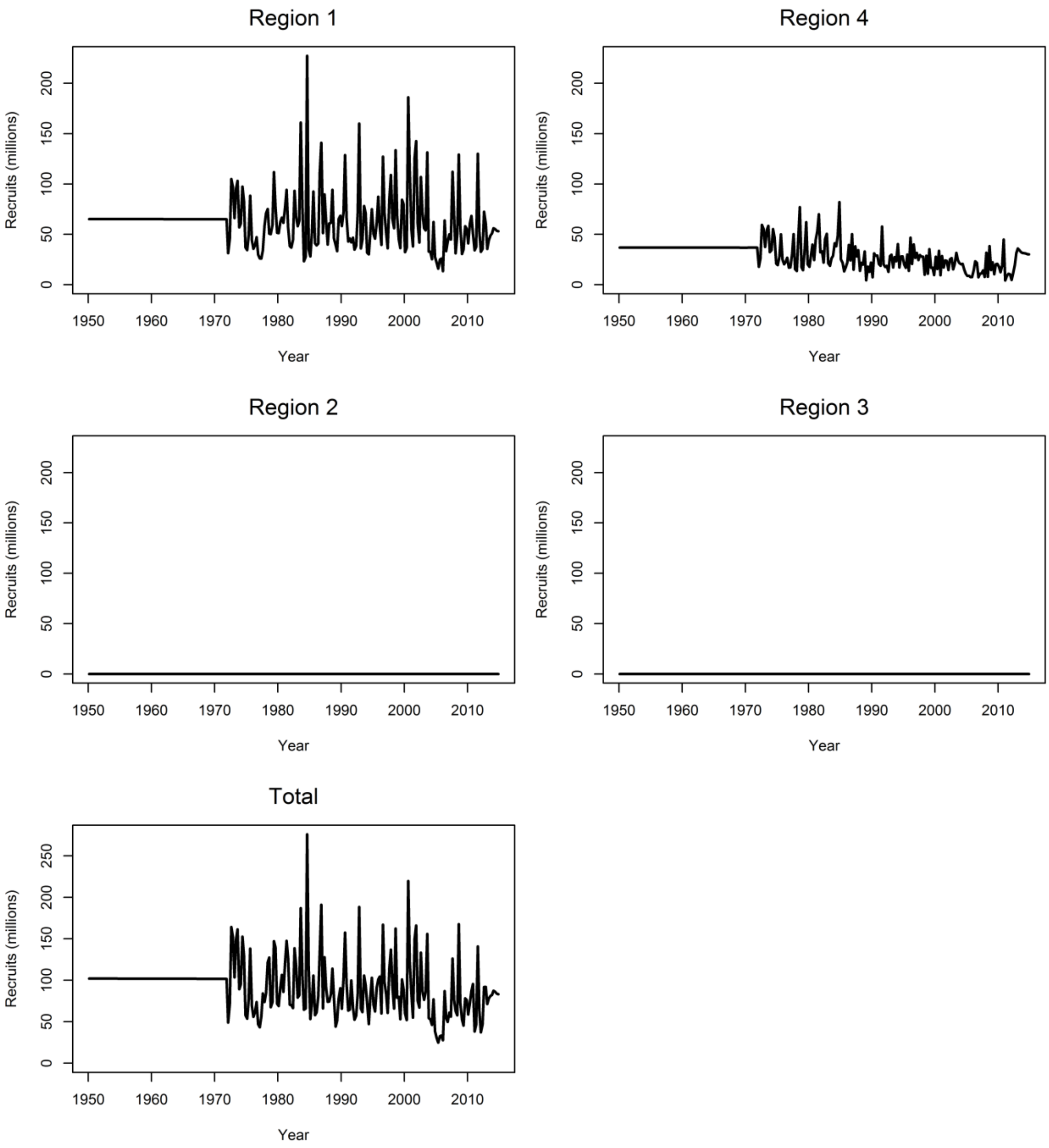


Figure 29. Estimated quarterly recruitment by region and for the entire IO.

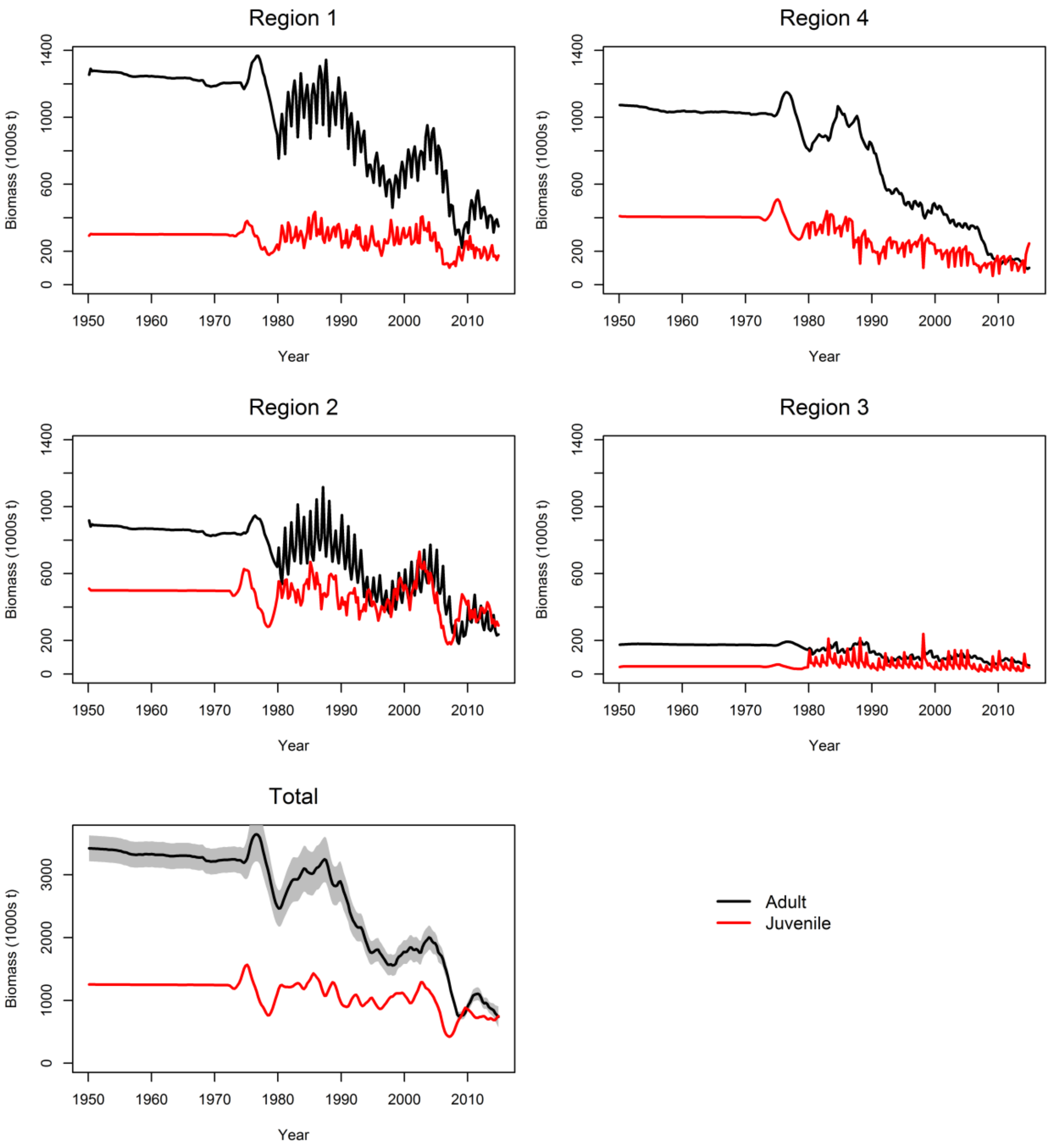


Figure 30. Spawning and juvenile biomass (thousand mt) by region and for the IO for the base-case analysis. The shaded areas indicate the approximate 95% confidence interval.

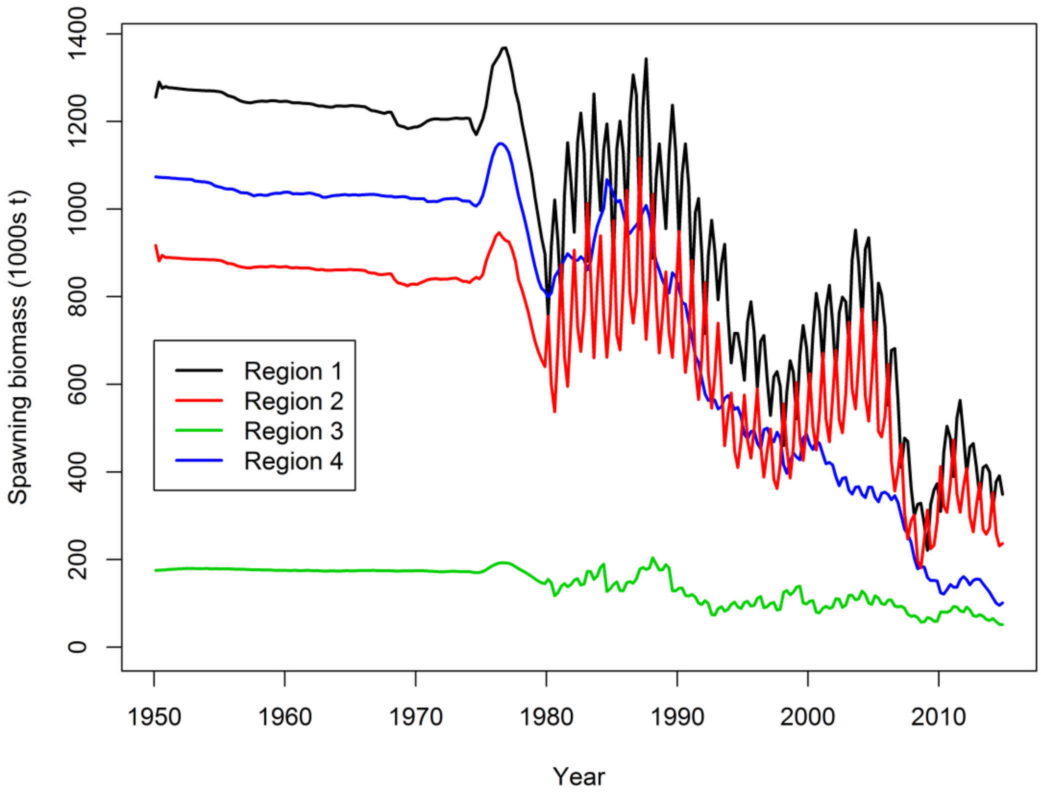


Figure 31. A comparison of the spawning biomass trajectory for the individual model regions.

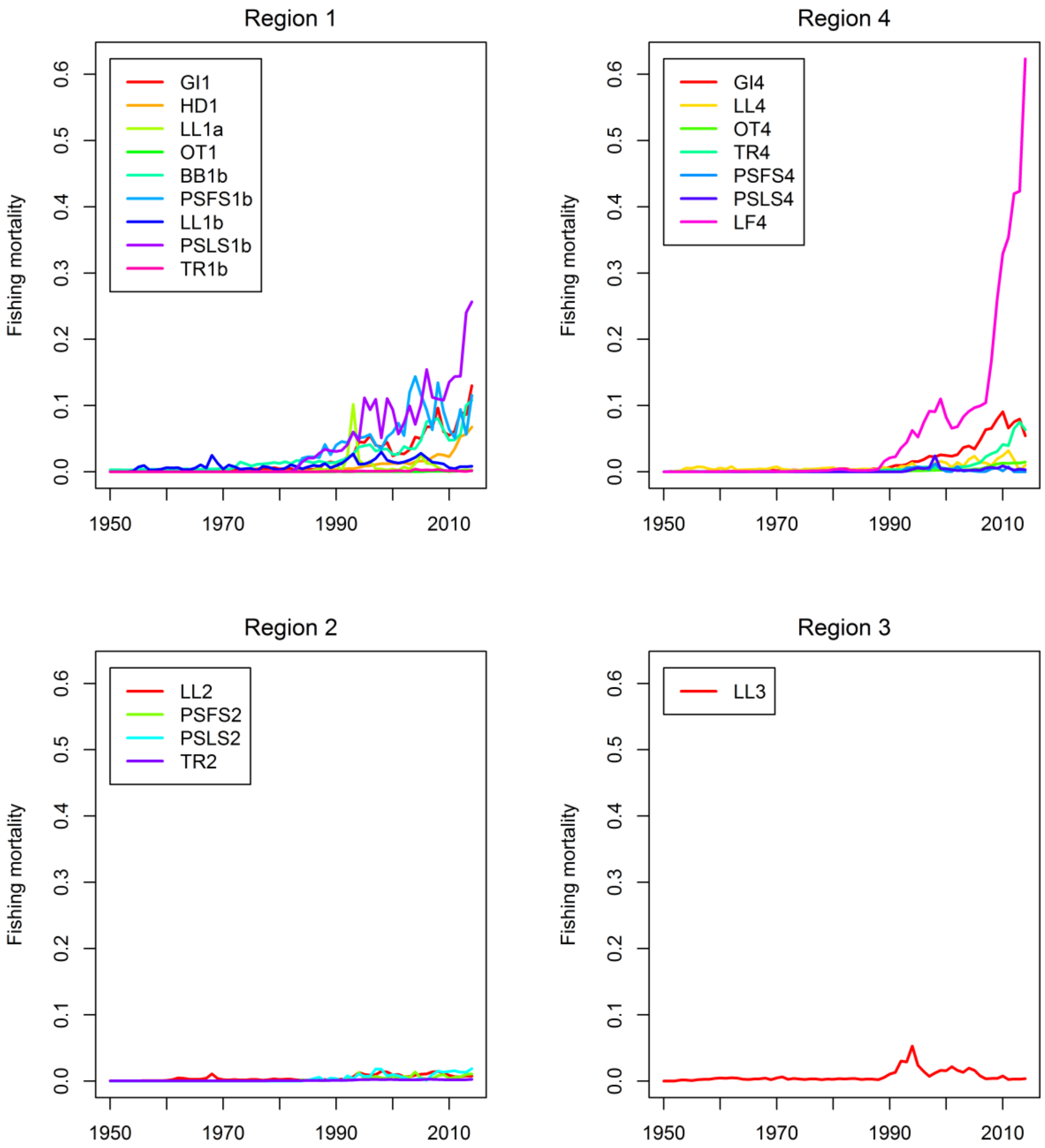


Figure 32. Trends in fishing mortality by fleet.

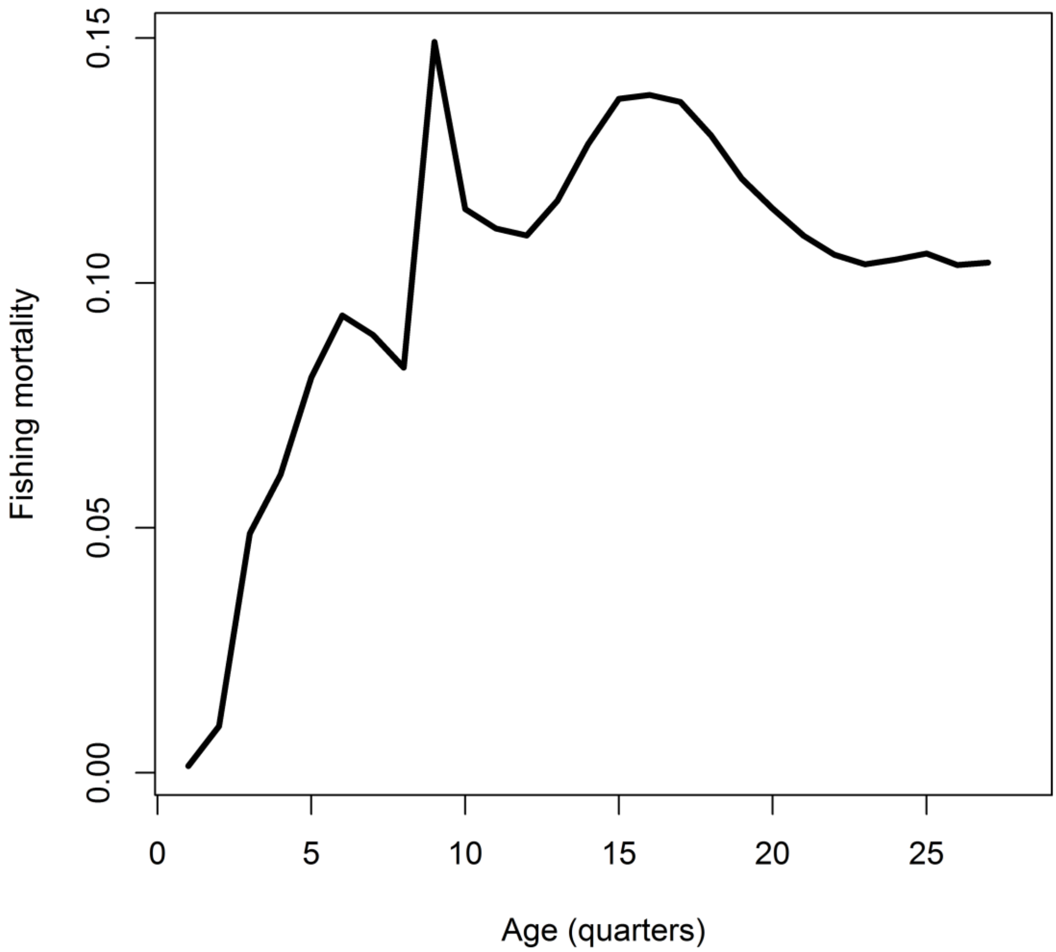


Figure 33. Fishing mortality (quarterly, average) by age class and region for the period used to determine the total F-at-age included in the calculation of MSY based reference points (2013 and 2014).

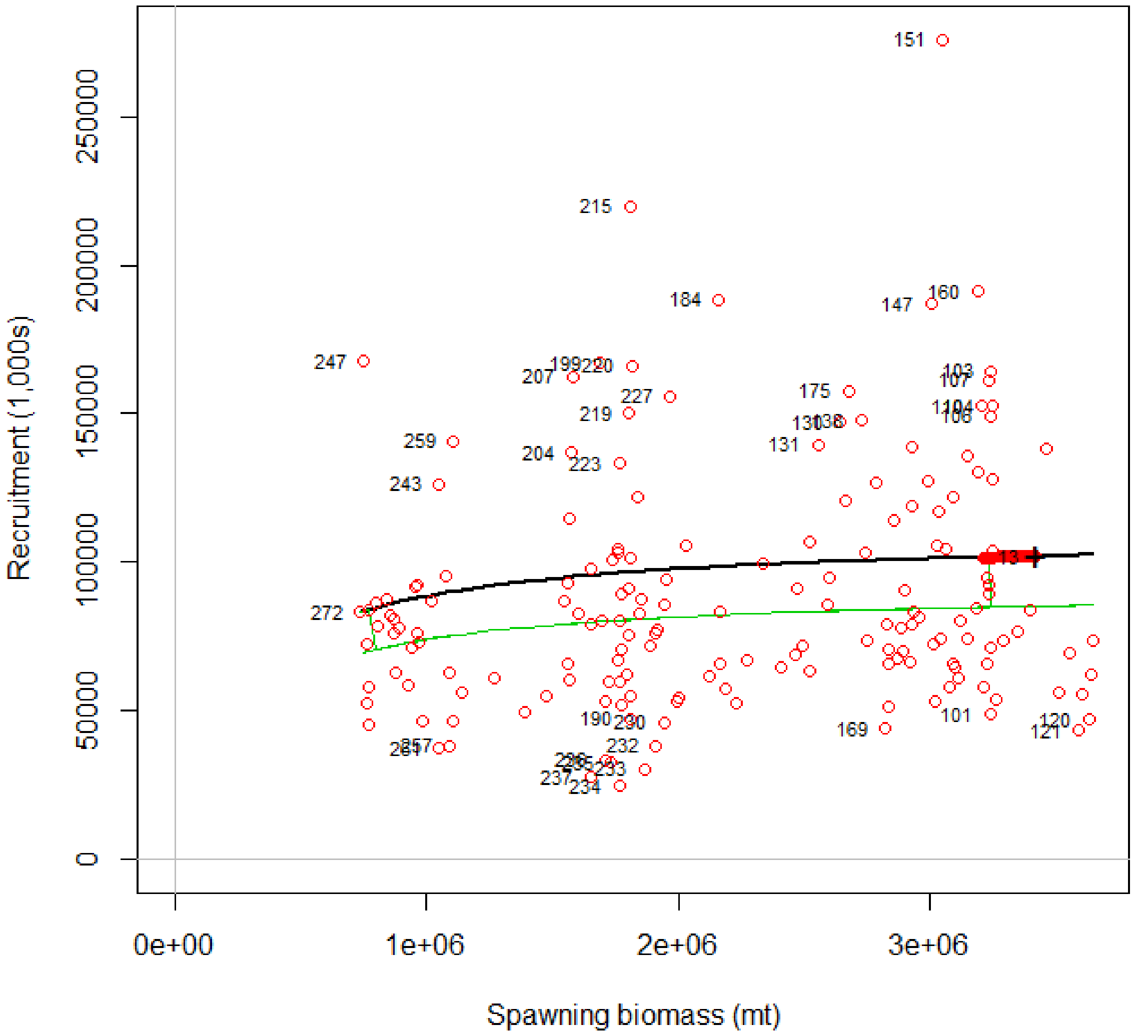


Figure 34. Relationship between equilibrium recruitment and equilibrium spawning biomass for the base-case with steepness of the SRR is fixed at 0.80 (black line). Year 101 = 1972, quarter 1.

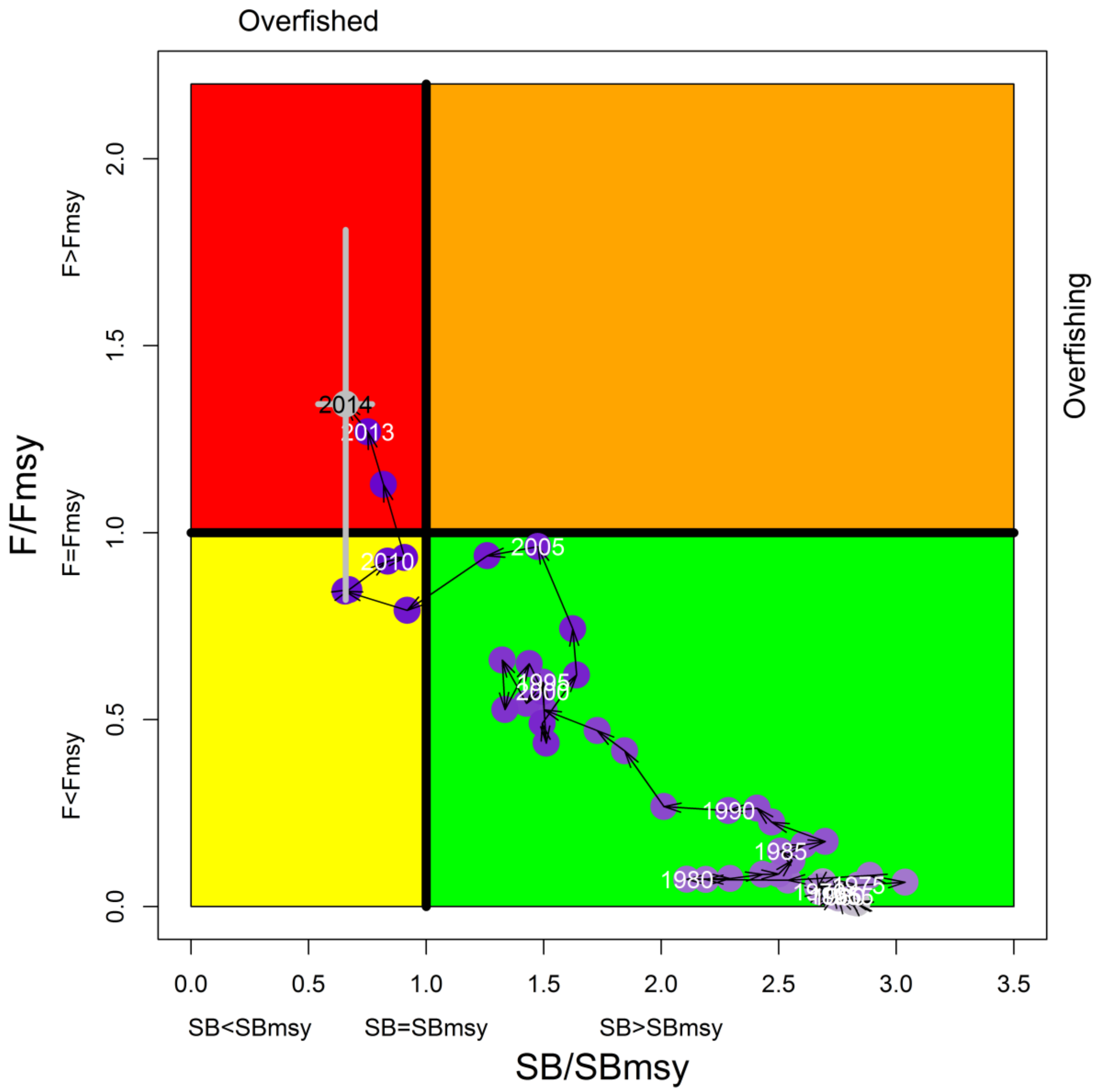


Figure 35. Annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points for the base model. The grey lines represent the 95% confidence interval associated with the 2014 stock status.

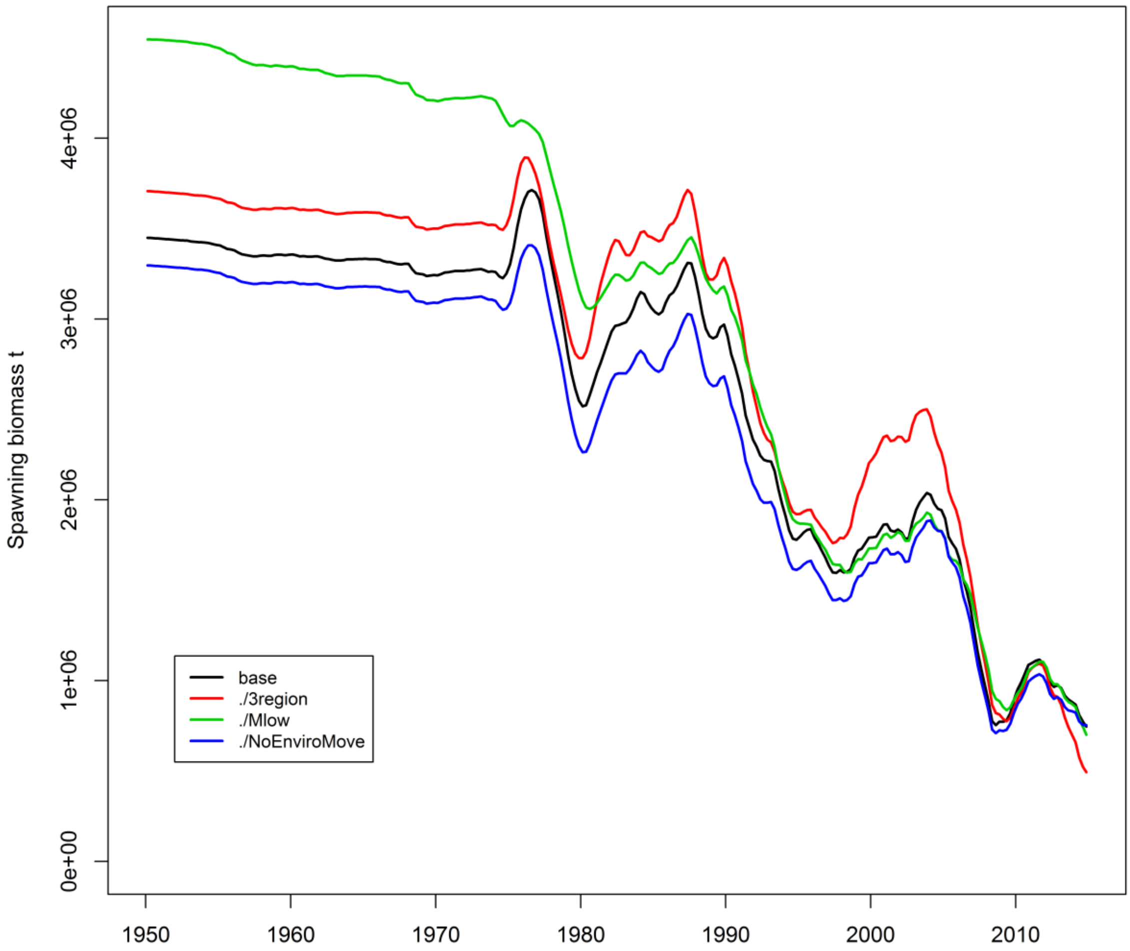


Figure 36. A comparison of the biomass trajectories from the base case model and main sensitivities.

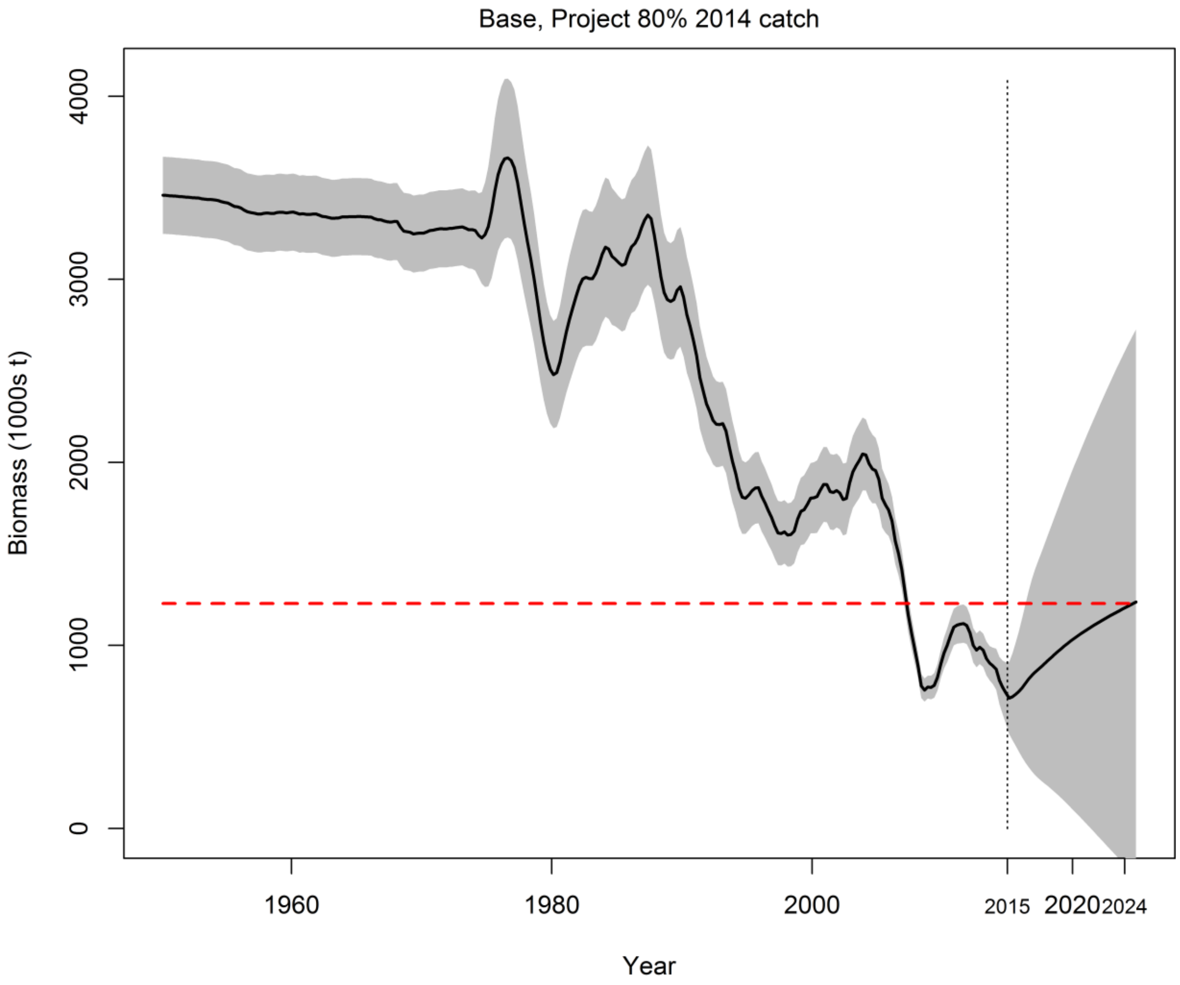


Figure 37. Spawning biomass trajectory for the base model option with a 10 year projection (2015-2024) assuming a constant level of catch at 80% of the 2014 catch level. The grey area represents the 95% confidence interval. The red horizontal line represents the SB_{MSY} level.

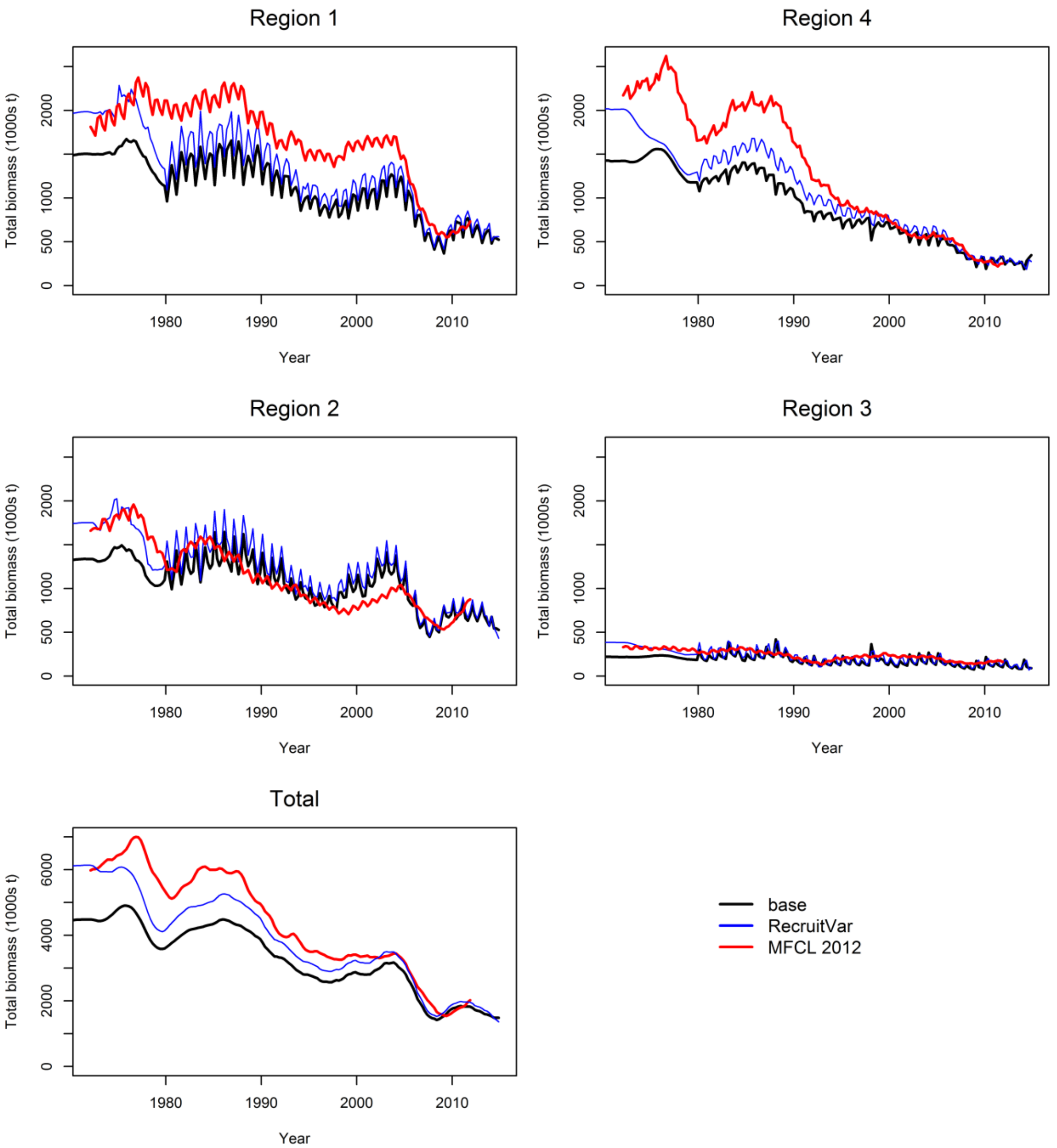


Figure 38: A comparison of the total biomass trajectories from the 2012 MFCL stock assessment and the current assessment (base) from 1972 onwards. For comparative purposes, biomass from regions 1 and 2 of the 2012 assessment is amalgamated in region 1 of the current assessment. The biomass trajectory from the *RecruitVar* preliminary model is also presented.

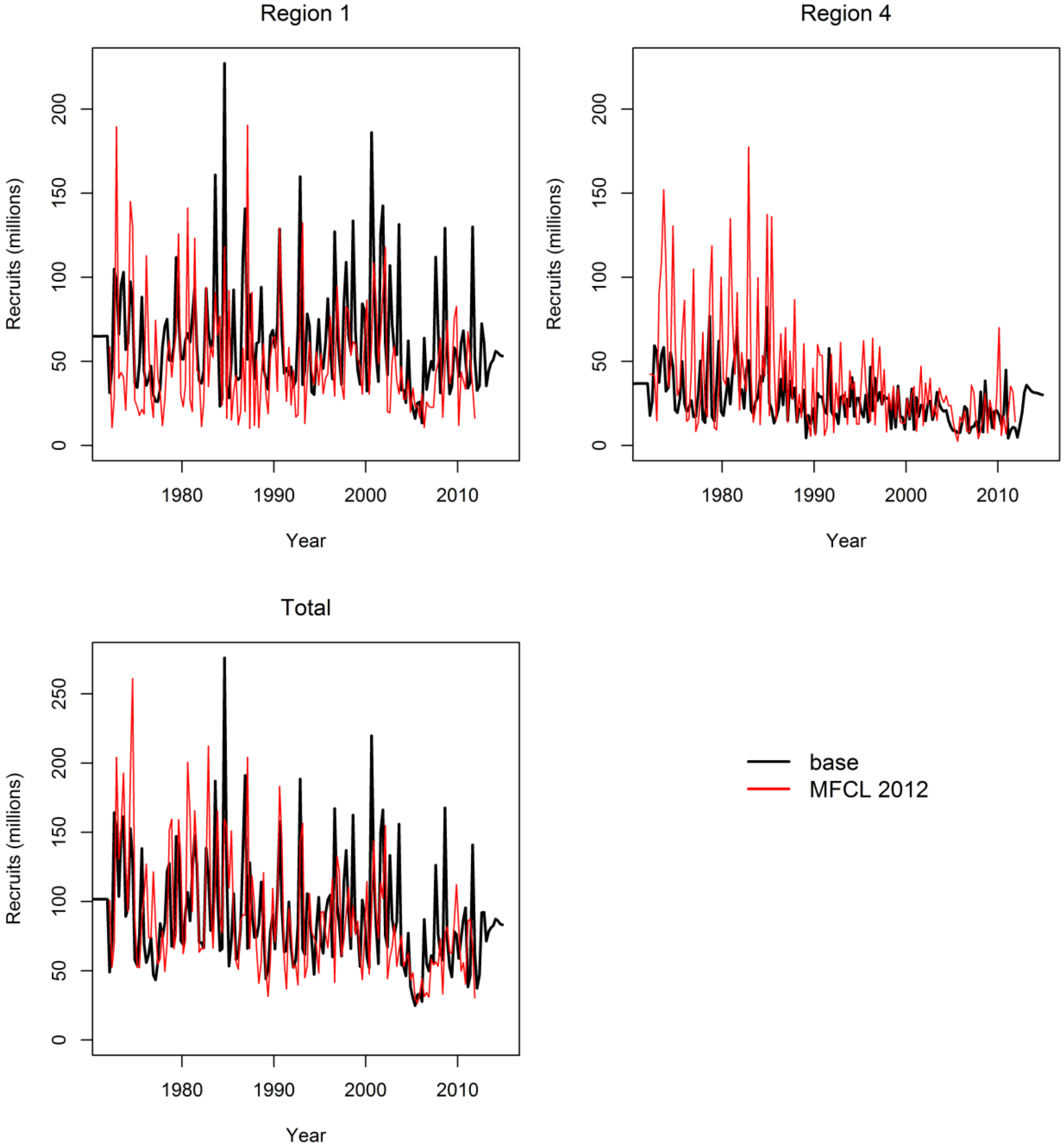


Figure 39: A comparison of recruitment from the 2012 MFCL stock assessment and the current assessment (base) from 1972 onwards. For comparative purposes, recruitments from regions 1-3 and 4-5 of the 2012 assessment are amalgamated in regions 1 and 4 of the current assessment.

APPENDIX 1. RESULTS FROM THE PRELIMINARY PHASE OF THE STOCK ASSESSMENT MODELLING

Table A1. Maximum Posterior Density (MPD) estimates of the main stock status indicators from the preliminary model option.

	SB_0	SB_{MSY}	SB_{MSY}/SB_0	SB_{2014}	SB_{2014}/SB_0	SB_{2014}/SB_{MSY}	F_{2014}/F_{MSY}	MSY
base	3,421,080	1,199,010	0.35	786,721	0.23	0.66	1.31	401,980
MestAge	4,485,590	1,714,900	0.38	854,541	0.19	0.50	2.28	353,439
Mlow	4,481,000	1,594,490	0.36	759,983	0.17	0.48	2.81	309,058
Mscale	3,914,000	1,397,670	0.36	747,101	0.19	0.53	2.13	348,051
OGIVEmaturity	2,492,110	751,359	0.30	457,707	0.18	0.61	1.46	390,570
OGIVEmaturityMFCL	3,088,090	1,012,860	0.33	641,301	0.21	0.63	1.42	400,380
RecruitVar	4,627,560	1,648,480	0.36	860,924	0.19	0.52	1.46	530,672
TwoSex	1,005,960	na	na	323,216	0.32	na	na	na
steep70	3,606,500	1,337,020	0.37	813,870	0.23	0.61	1.54	386,679
steep90	3,362,220	1,126,050	0.33	797,728	0.24	0.71	1.03	411,260
3region	3,624,160	1,291,290	0.36	544,680	0.15	0.42	1.82	418,828
5region	3,573,170	na	na	930,825	0.26	na	na	na
AreaScaleCatch	3,519,310	1,228,430	0.35	814,143	0.23	0.66	1.31	402,520
LLqSplit	3,473,010	1,222,990	0.35	718,222	0.21	0.59	1.40	414,988
MoveFix	3,627,490	1,269,950	0.35	740,438	0.20	0.58	1.41	410,900
NoEnviroMove	3,273,730	1,153,430	0.35	629,349	0.19	0.55	1.55	384,968
RecruitR2	3,471,210	1,225,950	0.35	810,852	0.23	0.66	1.31	404,096
CPUEcv01	3,101,330	1,115,240	0.36	777,772	0.25	0.70	1.00	369,121
CPUEoperational	3,479,290	1,228,920	0.35	889,933	0.26	0.72	1.15	403,752
LL4cpueSplit	3,228,030	1,118,640	0.35	735,328	0.23	0.66	1.41	373,870
TagMix10Q	4,231,000	1,483,810	0.35	1,008,800	0.24	0.68	1.01	458,284

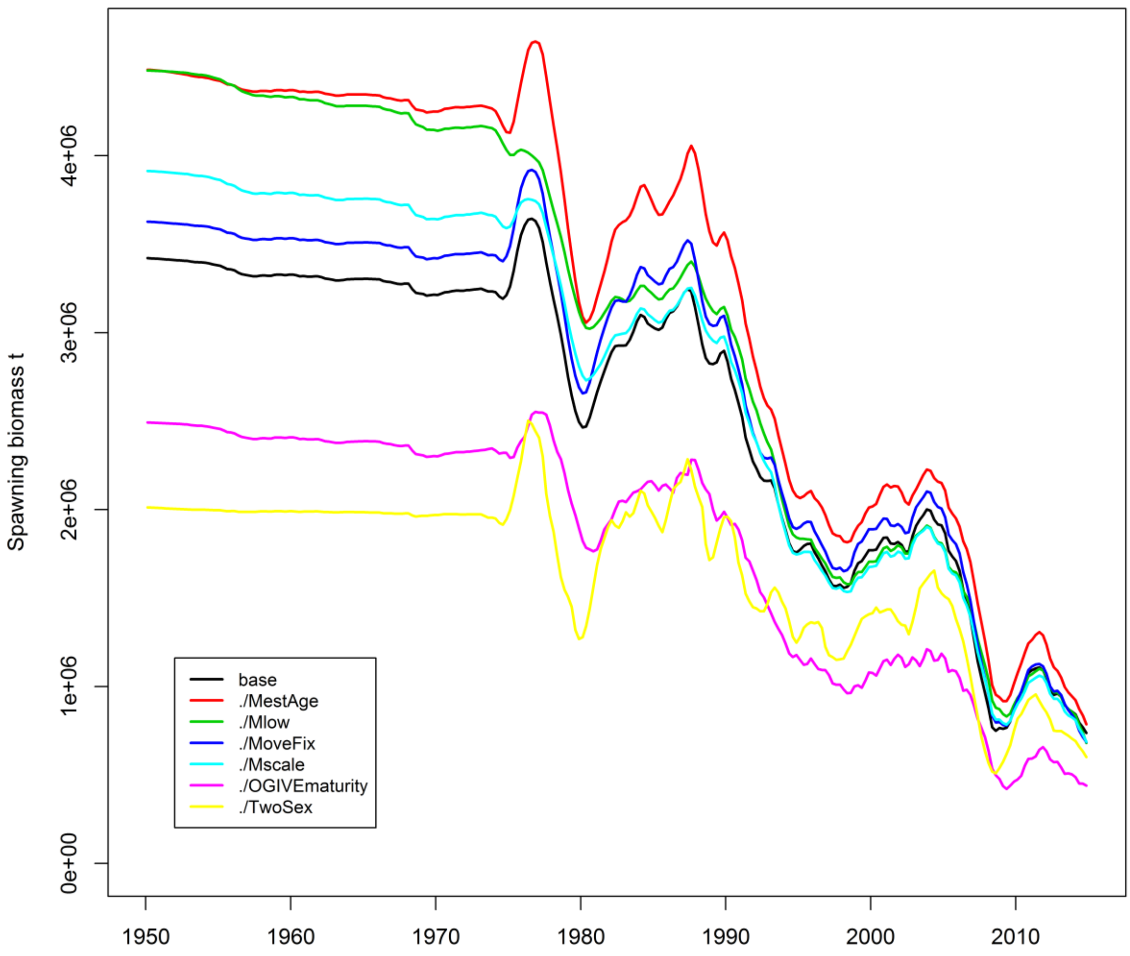


Figure A1. Spawning biomass trajectories from the preliminary base model and a range of preliminary model sensitivities related to the biological parameters. The spawning biomass for the two sex model represents the female mature biomass only, while for the other model options spawning biomass represents total mature biomass.

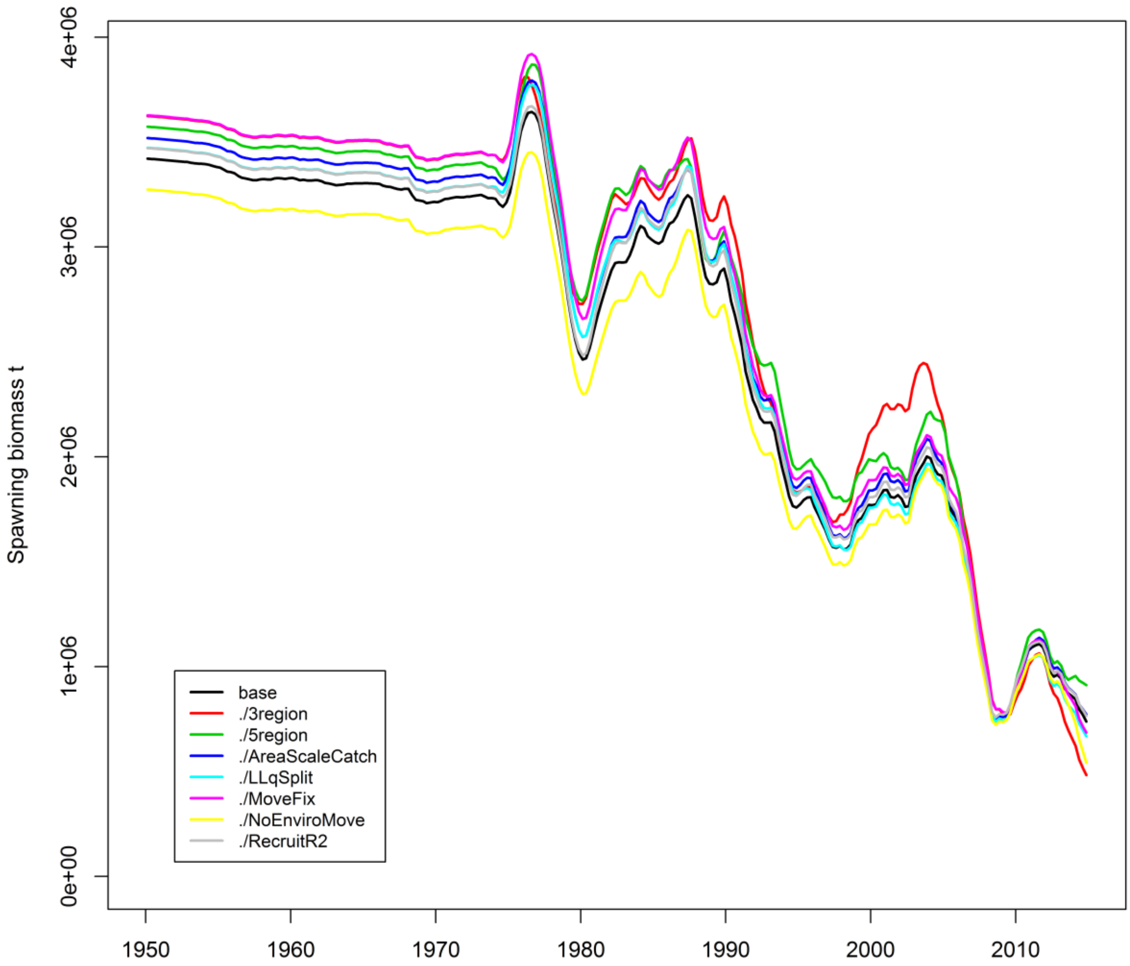


Figure A2. Spawning biomass trajectories from the preliminary base model and a range of preliminary model sensitivities related to the main spatial structural assumptions.

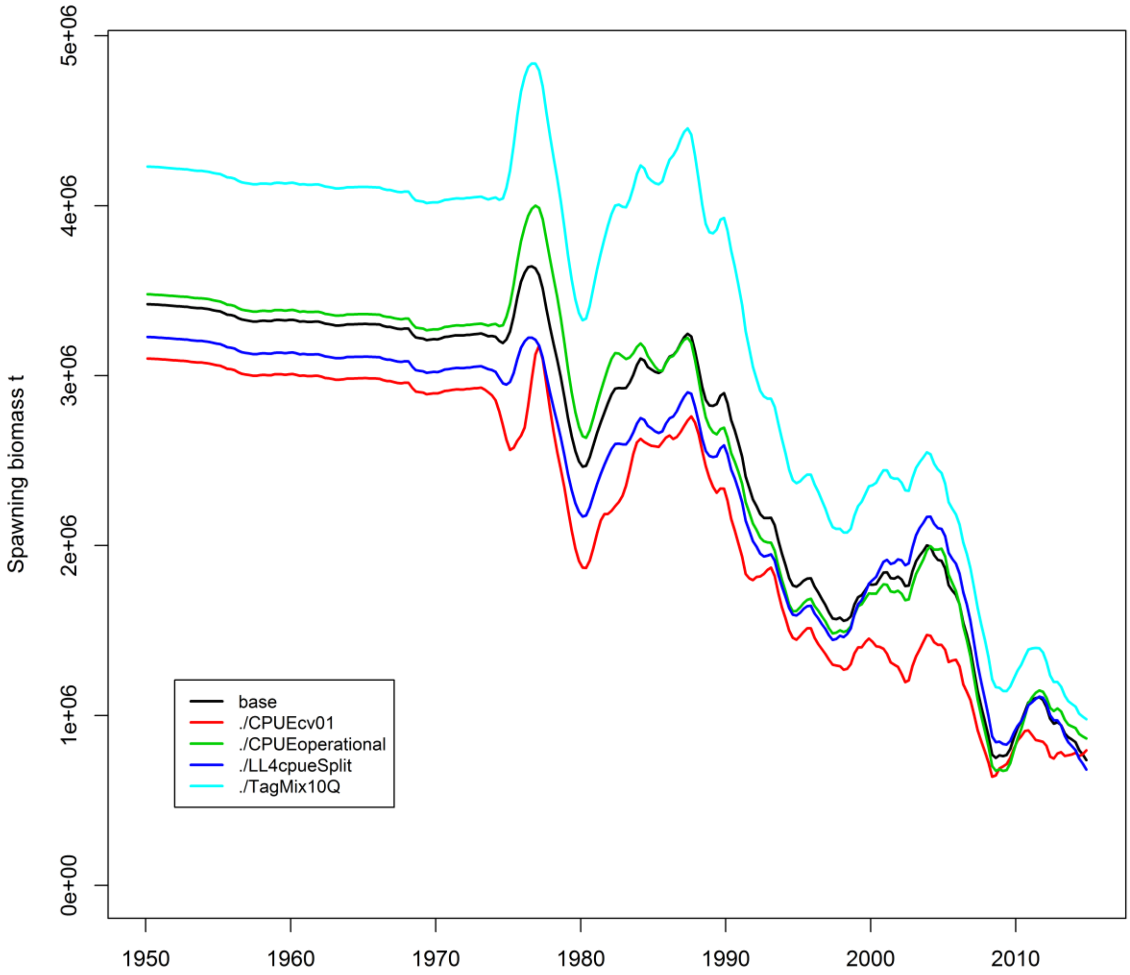


Figure A3. Spawning biomass trajectories from the preliminary base model and a range of preliminary model sensitivities related to the ket input data sets.