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

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1 Introduction

Commercial fisheries for albacore tunas have operated in the Indian Ocean since the early 1950s. The earliest known exploitation was by the Japanese longline fishery in the 1950s, followed by the Korean and Taiwanese longline fisheries in the mid and late 1950s (Kim *et al.* 2010; Chen 2009). Drift nets were employed in the albacore fishery from the early-1980s until 1992 when an international ban on drift net fishing came into force. Taiwanese and Indonesian longline catch has recently accounted for around 70% of the total catch. Between 2008 and 2011, following the onset of piracy in waters off Somalia, part of the longline fleets that had traditionally targeted tropical tunas or swordfish in those waters moved towards albacore fishing grounds in the southern Eastern Indian Ocean.

Like albacore fisheries in other oceans, the Indian Ocean fishery is characterised by smaller fish at higher latitudes. Unlike other oceans however, there is no significant troll or pole and line fishery for albacore, and since the ban on the drift net fishery there has been no large-scale targeting of small fish.

Stock assessments of the Indian Ocean albacore stock have been conducted in the past using several different methods, including recently the non-equilibrium production model ASPIC (Chang *et al.* 2012, Matsumoto *et al.* 2012, Matsumoto *et al.* 2014), and the age-structured production model ASPM (Nishida *et al.* 2012), and Stock Synthesis (Kitakado *et al.* 2012, Hoyle *et al*. 2014).

During the fourth Working Party on temperate tunas (WPTmT4) in 2012, the first assessment using Stock Synthesis (SS) (Kitakado *et al.* 2012) was conducted, incorporating data up to 2010. The assessment results suggested overfishing was occurring on the stock, though the stock was not in an overfished state, but were uncertain and sensitive to the index of abundance and decisions about biological parameters. The index of abundance was in turn considered to be potentially unrepresentative of the abundance trends due to issues such as target change; and some of the influential biological parameters had not been estimated for Indian Ocean albacore.

For WPTmT5, Hoyle *et al* (2014) presented a new assessment using Stock Synthesis. The assessment investigated the interactions between the key data sets (CPUE indices and length compositions) and the uncertainty associated with the key biological parameters (natural mortality, SRR steepness and growth). The WPTmT5 adopted a subset of the SS model scenarios for the formulation of management advice and inferring the uncertainty of the stock status indicators from a grid of plausible model options.

The 2014 SS model results were relatively consistent with the results of complimentary assessment modelling conducted using ASPIC (Matsumoto *et al.* 2014) and both sets of model results were used to formulate the stock status of Indian Ocean albacore for 2014. WPTmT5 concluded that "*stock status in relation to the Commission's B_{MSY} and F_{MSY} target reference points indicates that the stock is not overfished and not subject to overfishing, although considerable uncertainty remains in the SS3 and ASPIC assessments, indicating that a precautionary approach to the management of albacore should be applied by reducing fishing mortality or capping total catch levels to those taken in 2012 (34,000 t)".*

A key source of uncertainty in the 2014 albacore assessment was the reliability of the longline CPUE indices as abundance indices for albacore. In the interim period a collaborative project between Japan, Taiwan, Korea, and the IOTC developed abundance indices using operational-level longline data from all three fleets (Hoyle *et al.* 2016). The authors used cluster analysis to address the effects of target change, and standardization models included vessel effects and 5° square spatial effects. The project built on a study applying similar methods to Indian Ocean bigeye and yellowfin tuna (Hoyle *et al.* 2015).

The resulting albacore CPUE indices are incorporated in the revised albacore SS assessment presented in this report. The current assessment further evaluates the influence of the key model data sets to formulate a range of assessment model options, incorporating the recommendations from the previous WPTmT5 meeting (see Table 12 in IOTC 2014). The assessment also addresses some of the main issues highlighted in an informal review of the 2014 albacore stock assessment (Fonteneau 2015).

2 Data compilation

The data used in the albacore tuna assessment consist of fishery specific catch and length composition data and standardised longline CPUE indices. The details of the configuration of the fishery specific data sets is described below.

2.1 Spatial stratification

The 2014 assessment partitioned the Indian Ocean into two regions (North and South) demarcated at 20°S latitude (Hoyle *et al.* 2014). The spatial stratification was primarily adopted to partition the longline fisheries by the size of fish caught; the longline fisheries in the southern area tend to catch albacore that are considerably smaller than the fisheries in the northern area. A similar latitudinal partition was adopted for the current assessment, although the latitudinal boundary was shifted southward to 25°S latitude. The revised boundary is considered to better reflect the transition in fish size between the north and south areas (see Geehan & Hoyle 2013, Nikolic et al 2013).

For the current assessment, the spatial stratification also included a longitudinal partition (Western and Eastern). There is no indication of a longitudinal trend in the size of albacore caught by the longline fisheries (Geehan & Hoyle 2013) and the overall distribution of the southern longline fishery is continuous throughout the southern region (Figure 1). However, during the history of the fishery there were periods when there was an appreciable separation between the operation of the longline fishery in the southwestern and south-eastern quadrants of the Indian Ocean, most notably during the 1960s and 1970s (Figure 2). To account for potential longitudinal variation in the key fishery data sets the northern and southern areas of the Indian Ocean were partitioned at 75°E longitude.

The four regions of the Indian Ocean were used to define the spatial domain of the model fisheries and define the region specific longline data sets for the CPUE analysis (Hoyle *et al* 2016). There are apparent differences in recent trends in albacore CPUE indices between the two southern areas during the last decade.

2.2 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. The model was further stratified by quarter of the calendar year (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec) and the various data sets were compiled accordingly.

2.3 Definition of fisheries

The spatial stratification was applied to define model fisheries based on region and fishing gear. These “fisheries” are considered to represent relatively homogeneous fishing units, with similar selectivity and catchability characteristics.

A total of eleven fisheries were defined, including a single aggregate longline fishery in each region (Table 1).

Longline northwest (LL1). The composite longline fishery in the north-western region was initially developed by the Japanese fleet in the mid 1950s. Data for the Taiwanese fleet are available from the late 1960s and the fleet has operated continuously since then. Japanese fishing effort declined in the early 1970s and remained relatively low until the mid 1990s. Fishing effort by the Japanese fleet recovered to a moderate level during the late 1990s and 2000s but was at a relatively low level from 2010. The composite longline fishery included effort by the Korean longline fleet during the late 1970s and 1980s. Limited albacore catches have been taken by other fleets, most notably the Chinese longline fleet operating during the last decade.

Longline northeast (LL2). The composite longline fishery in the north-eastern region has a similar composition to the LL1 fishery. The Japanese fleet was the dominant component of the fishery during 1953–1970 and continued to operate at a lower level over the subsequent years. Data for the Taiwanese fleet’s operations in the area are available from the late 1960s, while the Korean fleet primarily operated in the fishery during 1976–1987.

Longline southwest (LL3) . The composite longline fishery in the south-western region was dominated by the Japanese fleet from the inception of the fishery in the late 1950s until the introduction of the Taiwanese fleet in the mid-1960s. Since the early 1970s, most of the catch was taken by the Taiwanese fleet. There was a short period of higher Japanese catch during 2004–2008.

Longline southeast (LL4) . The composite longline fishery in the south-eastern region was dominated by the Japanese fleet from the inception of the fishery in the late 1950s until the introduction of the Taiwanese fleet in the early 1970s. During 1974–2006, most of the catch was taken by the Taiwanese fleet. Japanese longline catches increased from 2006 and in recent years considerable catches have also been taken by China and Korea.

Drift net fisheries. Drift net fisheries were defined for the south-western (DN3) and south-eastern (DN4) regions. These fisheries were comprised exclusively of drift net vessels flagged to Taiwan,China, which operated in the southern waters of the Indian Ocean from 1982 until 1992 when the UN adopted a worldwide ban on drift nets.

Purse seine. A single purse seine fishery (PS1) was defined as virtually all purse seine catch was taken within the north-western region. The purse seine fishery is made up of various fleets although the majority of the catches of albacore are reported by purse seiners flagged to the European Union and other fleets under EU ownership, including the Seychelles (86% of the total catches of albacore over the time series). The purse seine catches of Iran, Japan, Mauritius, Thailand, and the Republic of Korea are also included in the fishery.

Other. A miscellaneous ("Other") fishery was defined for each of the regions. The "Other" fisheries include various coastal longline, gillnet, trolling, hand lines and other minor artisanal gears, which are used in coastal countries of the Indian Ocean. Collectively, the "Other" fisheries account for a small proportion of the Indian Ocean albacore catch (2% of the entire catch). Most of the catch was reported by Indonesia with the remainder of the catches reported by Mauritius, Reunion and Mayotte (EU), Comoros, Australia, South Africa, and East Timor.

2.4 Catch data

Catch data were compiled by IOTC secretariat based on the fishery definitions (Version2 provided 19/5/2016). All catches were expressed in metric tonnes (mt). There were negligible changes in the gear specific catch history from the previous assessment (Hoyle *et al* 2014).

The longline fisheries for albacore developed from the mid 1950s and total annual catches averaged about 17,000 t during 1960–1980 (Figure 3). Catches increased during the period of drift net fishing in the late 1980s and early 1990s and continued to increase with the expansion of the longline fishery in the late 1990s to reach a peak in catch of 40–45,000 t in 1998–2001. Total catches declined to about 30,000 t in 2003–2006 and have since fluctuated between 33–43,000 t per annum (Figure 3). During the last decade, the longline fisheries have accounted for 95% of the total albacore catch apportioned amongst the regions as follows: northwest 17%, northeast 18%, southwest 30% and southeast 35%. Most of the catch from the southern longline fisheries occurs during the 2^{nd} and 3^{rd} quarter of the year, while catches from the north-western longline fishery are predominantly taken in the 4^{th} quarter.

Longline northwest (LL1). The longline catch was relatively low from the north-western region during the late 1980s and early 1990s immediately following the reduction in fishing by the Korean fleet and during a period of low catch by the Japanese fleet. The high catches in 2000 and 2001 were predominantly attributable to higher catches by the Taiwanese fleet in those years (Figure 4).

Longline northeast (LL2). The higher catches from the fishery in the late 2000s (2007 and 2008) are primarily attributable to higher catches by the Taiwanese fleet in 2007 and 2008 and the Indonesian longline fleet during 2009 and 2010.

Longline southwest (LL3) The high catches from the fishery during 1996–2001 are primarily attributable to a considerable increase in catch by the Taiwanese fleet during that period (Figure 4). The catch from the Taiwanese fleet was relatively low during 2006–2007 but has increased steadily in the more recent years resulting in an overall increase in the annual catch from the fishery.

Longline southeast (LL4) . Recent (2005–2014) longline catches from the south-eastern region have been at an historically high level of about 12,000 t. The higher level of catch during this period is primarily attributable to an increase in catch by the Japanese fleet since 2006.

Drift net fisheries. The drift net fleet of Taiwan,China operated in Southern waters of the Indian Ocean between 1982 and 1992, reporting catches of juvenile albacore of up to 26,000 mt in 1990 (Figure 3). Most of the drift net catch was taken in the south-eastern region of the Indian Ocean (Figure 4). Most of the catch of albacore by drift nets occurred during the 1st and 4th quarter of each year, with minor catches also recorded during the 2nd quarter. No catches at all were recorded during the 3rd quarter.

Purse seine. Industrial purse seiners have caught adult albacore in the western central Indian Ocean and Mozambique Channel, as a bycatch, since the early 1980s (2% of the total catches of albacore). Purse seine catches of albacore have never been high, with peak catches recorded in 1992 (3,300 mt) and catches during other years well below 3,000 mt. Albacore is caught over the entire year, mainly between the 2nd and 3rd quarter as a bycatch of purse seine fishing on free-schools, during the 1st and 2nd quarters in waters South of Seychelles, and off-North Madagascar, and, to a lesser extent, during the 1st and 4th quarters in waters to the East of the Seychelles. A very minor amount of albacore was taken by purse seiners in waters south of 20°S.

Other. Collectively, the "Other" fisheries account for a small proportion of the Indian Ocean albacore catch (2% of the entire catch) (Figure 3). Most of the catch was reported by Indonesia in the north-eastern region (Other2 fishery) with the remainder of the catches reported by Mauritius, Reunion and Mayotte (EU), Comoros, Australia, South Africa, and East Timor.

2.5 CPUE indices

Standardised CPUE indices were derived using generalized linear models (GLM) from operational longline catch and effort data provided by Japan, Korea, and Taiwan,China (Hoyle *et al* 2016). Cluster analyses of species composition data by vessel-month for each fleet were used to separate datasets into fisheries understood to target different species. Selected clusters were then combined and standardized using generalized linear models. In addition to the year-quarter, models included covariates for vessel identity, 5 square location, hooks, and cluster.

The resultant CPUE indices differ from the separate Japanese and Taiwanese CPUE indices included in the 2014 assessment (Hoyle *et al* 2014).

For the 2016 assessment, three sets of CPUE indices were derived based on different treatment of the fishing vessel variable in the CPUE modelling (Hoyle *et al* 2016). The assessment modelling incorporated the *boat_allyears* set of CPUE indices on the basis that the indices represented the longest time series (1952–2014) and incorporated vessel effects for the period when individual vessel identifiers were available (1979–2014).

The quarterly *boat_allyears* CPUE indices for each region of the Indian Ocean are presented in Figure 5. The CPUE indices do not provide a complete time series of abundance indices for each region and the series from the LL2 fishery is sparse from 1990 onwards. The indices from the northern longline fisheries (LL1 and LL2) commence from the mid-1950s, while the southern longline fisheries (LL3 and LL4) commence in the early 1960s.

The LL1–3 CPUE indices are each characterised by a large decline in the indices prior to 1970 (Figure 5). The magnitude of the decline is not consistent with the relatively low catches that were taken from each of these regions during the period. On that basis, it is generally accepted that the longline CPUE indices during the development phase of these fisheries are not indicative of trends in stock abundance.

The large decline in CPUE indices during the early period is not apparent in the LL4 fishery (Figure 5). Prior to 1970, the fishery in that region primarily caught southern bluefin tuna and a difference in target species may account for the lower CPUE indices for albacore compared to the other regions.

Preliminary model options excluded the CPUE indices from the period prior to 1970 based on the presumption that those indices do not represent a reliable index of stock abundance. Further evaluation of the CPUE indices from the 1970s highlighted concerns regarding the utility of these indices also. For this period, the CPUE indices were derived from a small number of logsheet records, due to the decline in the scale of the operation of the Japanese fleet and a shift in the targeting activity of the Japanese fleet from albacore to other species (yellowfin, bigeye and southern bluefin tuna) and a lack of logsheet data from the Taiwanese fleet. Consequently, LL1 and LL2 CPUE indices were sparse through the 1970s. There is also concern that the decline in the LL3 CPUE indices during the 1970s may have been primarily attributable to a shift in targeting behaviour (Figure 5).

For the final model options, the time series of each set of regional CPUE indices was restricted to 1979–2014. The CPUE indices from this period were generally considered to provide a more reliable index of stock abundance especially for the southern regions (LL3 & LL4) as there was a more consistent target fishery for albacore operating throughout the period (primarily the Taiwanese fleet). The CPUE modelling also incorporated the individual vessel effects during that period, enabling the CPUE indices to potentially account for changes in the efficiency of the longline fleet over time (Hoyle *et al* 2016).

A number of important trends are evident in the CPUE indices from the four regions (Figure 6).

- CPUE indices from the north-western region (LL1) tend to increase during the late 1980s, remained at a relatively high level during the early 1990s and generally declined over the subsequent period.
- There are limited CPUE observations from LL2 fishery and the CPUE indices exhibit a higher degree of variability compared to the other regions.
- Prior to the mid-2000s, there are broad similarities in the CPUE indices from the two southern fisheries (LL3 & LL4). Both sets of indices exhibit a marked decline during the late 1980s–early 1990s while both sets of indices remain relatively stable during the 1990s–early 2000s (Figure 14).
- The CPUE trends from the two southern fisheries (LL3 & LL4) differ considerably from the LL1 CPUE indices. The decline in the LL3 & LL4 CPUE indices during the late 1980s–early 1990s is not evident in the LL1 CPUE indices, while the declining trend in LL1 CPUE from the mid-1990s is not evident in the two southern regions (Figure 12).
- The general trends in the CPUE indices from the two southern regions deviate considerably during the late 2000s. The LL4 indices increase considerably from 2006 onwards, whereas the LL3 indices generally increase in 2007–2012 and then decline in the last two years (2013 and 2014) (Figure 6).

There is a strong seasonal trend in the southern longline CPUE indices with higher indices during the 2nd and 3rd quarters compared to the 1st and 4th quarters. Preliminary modelling investigated the sensitivity of incorporating seasonal variation in the fitting of the two sets of CPUE indices from the southern regions (by fitting each set of quarterly indices as separate series) (*CPUEseason* see Appendix 2). The model results were insensitive to the seasonal treatment of the CPUE indices and, to reduce model complexity, seasonal variation was not incorporated in the final model options.

A short time series of annual Taiwanese drift net CPUE indices is available from 1985–1992 (Chang & Liu 1995) (Figure 7). The indices exhibit a high degree of interannual variability with high CPUE indices for 1987 and 1990. The reliability of the indices as an index of albacore abundance is unknown, although the high variability may provide some indication of variation in year class strength during the period given that the drift net fisheries typically catch a relatively narrow length range of albacore (corresponding to fish of about 2–3 years old). The annual indices were assumed to represent the relative abundance in the first quarter of the year (corresponding to the peak season of DN catch).

2.6 Length-frequency data

Longline fishery

Size frequency data are available for the Japan longline fishery from 1965. Length and weight data were collected from sampling aboard Japanese commercial, research and training vessels. Weight frequency data collected from the fleet (as live weight) have been converted to length frequency data via a weight-length key. Levels of sampling aboard the Japanese composite longline fleet over time were uneven in terms of both the sampling platform (commercial and non-commercial vessels) and sampling source (fishermen, scientists, observers). While in recent years the majority of the samples available have come from scientific observers on commercial vessels, in the past samples came from training and research vessels (scientists), and commercial vessels (fishermen). Length frequency data from the Taiwanese longline fleet are also available from 1980. In recent years, length data are also available from other fleets and periods (e.g. Indonesia fresh-tuna longline, Seychelles, etc.).

Prior to the mid-2000s the length frequency data set is dominated by sampling from the Taiwanese deep-freezing longline fleet. Length samples from this component come from commercial vessels and include lengths recorded by fishermen and, to a lesser extent, lengths measured by scientific observers on some of those vessels, in recent years. A recent review of the Taiwanese length frequency data identified major differences in the length frequencies of albacore recorded before and after 2003, with the majority of the smaller albacore missing from the length distributions since that year (Geehan and Hoyle 2013). It is unknown whether the temporal trends in the length composition of samples represent changes in the underlying length structure of the population or are attributable to changes in sample collection over the study period. Nonetheless, the large increase in fish length in the early 2000s corresponded to a large increase in the reported level of length sampling from the Taiwanese fleet, indicating a change in sampling approaches. At the same time the average fish weight from the Taiwanese catch (total weight of catch/total number of fish) revealed no corresponding increase in any species. Furthermore, the limited length data available from the Japanese composite longline fishery revealed no strong trend in the size of albacore caught during the period. On that basis, it appears more likely that the observed trends in length composition of the Taiwanese longline fisheries are due to changes in the sampling of the fishery and may indicate unrepresentative sampling of the catch from the Taiwanese longline fleet (biased towards the sampling of larger fish).

For each quadrant of the Indian Ocean, temporal trends in albacore length were compared amongst the main fishing fleets (Appendix 1). For each area, the average length of albacore sampled was determined from the aggregated length observations from the entire fishery region and for a subset of the model region that represented the main area of the albacore catch (core area). The core areas for each region were defined as follows.

LL1	Latitude range 25–15° S
LL2	Latitude range 25–20° S
LL3	Latitude range 35–30° S
LL4	Latitude range 35–30° S

The core area definitions were used to define the length frequency data included for the individual longline fisheries. These data were considered to be more representative of the overall catches of albacore from each fishery. The main effect of applying the core area criteria was to exclude the Japanese length samples collected from the LL2 fishery. These samples were generally comprised of larger fish than sampled by Taiwanese fishery operating primarily in the core area (Appendix 1).

As in LL2, the core area length compositions from LL1 and LL4 were dominated by length composition data from the Taiwanese fleet, while the LL3 length composition dataset retained length samples from the Japanese fishery. In general, the average lengths of fish sampled by the two fleets in LL3 were broadly comparable, although there was considerable variability amongst individual samples especially from the Taiwanese fleet (Appendix 1).

For inclusion in the assessment model, the length-frequency data for each fishery were aggregated into 55 2-cm size classes (30–32 cm to 138–140 cm) by year/quarter. Length data are available from the four fisheries from about 1979 onwards with more sporadic sampling from the fisheries in the earlier years (Figure 8).

The overall length compositions from the two northern fisheries are dominated by considerably larger fish (90–100 cm) than the length compositions from the southern longline fisheries (65–85 cm) (Figure 9).

For the longline fisheries, there are strong temporal trends in the length composition, especially for the LL1 and LL2 fisheries (Figure 10). For LL1, considerably larger fish were sampled during the late 1980s–early 1990s and late 2000s. A similar general trend was evident in the LL2 length composition data.

Albacore sampled from the LL3 fishery do not reveal a strong trend over the study period, although there is a high degree of variation amongst the individual quarterly samples. In addition, the fish sampled from the early 2000s are slightly larger than the fish sampled in the preceding years. The length composition data from LL4 reveals more systematic variation over time than the data from the LL3 fishery (Figure 10).

In the assessment modelling, the individual longline length frequency observations were assigned a relative weighting based on the number of fish measured, up to a maximum of 2000 fish (nfish). The Effective Sample Size (ESS) was determined from the number of fish divided by 400 (nfish/400) giving a maximum ESS of 5.

Purse seine fishery

Purse seine fisheries catch adult albacore, as a by catch (90–120cm), in the western central Indian Ocean (Figure 9). Albacore lengths are measured in port, by enumerators, during the unloading of purse seiners flagged in the EU and Seychelles. Length samples are available from the fishery from 1990–2014 (Figure 8). The ESS of the individual samples was determined in the same manner as described for the longline fisheries.

Drift net fishery

Drift nets catch juvenile or sub-adult albacore. However, there are no length frequency data available from the Indian Ocean fishery. As in the 2014 assessment, a small quantity of length frequency data from the South Pacific drift net fishery were incorporated in the length composition data set. These data were included in the model to corroborate the assumptions regarding the selectivity of the drift net fishery.

Other fisheries

No length data are available from the four “Other” fisheries.

3 Model structure and assumptions

The assessment models were implemented using Stock Synthesis version 3.24Y. (Methot 2015, Methot & Wetzel 2013).

3.1 Population dynamics

The final model options were configured as a spatially aggregated (single region) model. The model population was structured by sex and age with age classes of 0–13 years and an aggregate age class of 14+ fish. The model commences in 1950 at the start of the available catch history. The initial population age structure was assumed to be in an unexploited, equilibrium state. The terminal year of the model estimation period is 2014. Model years are partitioned into four quarterly seasons.

3.1.1 Sex ratio

The patterns of sex ratio at recruitment and at older ages and larger sizes are likely to be caused by features of albacore biology that are consistent across all oceans. A large amount of data on sex ratio at length is available for the south Pacific, and there is strong trend towards male bias above the length of female maturity (Hoyle 2008). Similar trends have been observed in the Atlantic and Mediterranean (Karakulak *et al*. 2011). Such a trend could be explained by differential growth and/or differential mortality. Differential growth is well supported, since males have been shown to grow considerably larger than females in the north Pacific (Chen *et al*. 2012), south Pacific (Williams *et al*. 2012), north Atlantic (Santiago and Arrizabalaga 2005), and Mediterranean (Megalofonou 2000).

Differential mortality is a possibility, although age sampling in the north and south Pacific has not been sufficiently randomized or intensive to draw conclusions about the relative numbers at age of males and females. Maximum observed ages are higher for males in both the north and south Pacific, suggesting that males may on average experience lower natural mortality than females. However, these observations may have been biased by non-random sampling, or sampling of more males than females. We are not aware of any evidence for unbalanced sex ratio at the age of recruitment.

We therefore modelled sex ratio at recruitment as 1:1, and assumed no differences in natural mortality at older ages.

3.1.2 Growth and maturation

Determination of albacore growth in the Indian Ocean has been limited, with no published studies of ageing using otoliths, or of growth differences by sex or by location from the Indian Ocean. In addition, length frequency data from small fish are limited which makes it difficult to use modal progression methods. Therefore the primary sources of inferences about growth must be studies from other oceans. We consider the following aspects of growth models: 1) the structure of the model, which defines the shape of the curve (e.g. von Bertalanffy versus Richards versus logistic), and includes factors affecting growth such as sex, location, season, and environmental effects; and 2) the parameters of the curve. We suggest that the structure of the model is largely defined by the biology of the species and is likely to be consistent across oceans, whereas the parameterization is likely to vary between oceans, within oceans, and through time depending upon local productivity.

Growth of albacore has been estimated using a variety of hard parts including otoliths, dorsal spines, vertebrae, and scales. Ageing using otoliths has been validated for a variety of tuna species including albacore, across a range of ages (Farley *et al.* 2013), but ageing methods using dorsal spines, vertebrae, and scales have not been validated to the same degree. Dorsal spine ageing is also subject to bias due to reabsorption of the spine core in older fish, which may lead to underestimating age. Vertebral aging has been shown to be biased in southern bluefin tuna, underestimating ages of older fish (Gunn *et al.* 2008). Potential bias together with lack of validation is problematic, since underestimating the age of older fish will change the shape of the growth curve, reducing the rate at which growth rate decreases and therefore increasing the estimate of asymptotic length. Growth curves for the Indian Ocean have been based on ageing using scale patterns (Huang *et al.* 1991) and vertebrae (Lee and Liu 1992), and on size frequency data (Chang *et al.* 1993).

Differential growth of albacore by sex is well established in other oceans, since males have been found to grow considerably larger than females in the Atlantic, north and south Pacific, and Mediterranean (Megalofonou 2000, Santiago and Arrizabalaga 2005, Chen *et al.* 2012, Williams *et al.* 2012). Given these differences, growth analyses that have not differentiated between the sexes will be biased towards the sex with more samples. A number of studies where sex has been determined have sampled more males than females in older age classes. Similar patterns are likely to have been present in studies that did not determine sex. Ageing of samples that are unbiased for younger fish but biased towards males in older age classes will result in biased growth curves and tend to overestimate the asymptotic length. This problem may affect a number of published growth curves.

Longitudinal spatial variation in albacore length at age has been found within the south Pacific (Williams *et al.* 2012) and may also occur in the north Pacific (Xu *et al.* 2014). Such variation may result from spatially varying growth, selectivity, or size-dependent movement. In the south Pacific the magnitude of spatial variation was smaller than the difference between sexes, but sufficient to affect management advice from the stock assessment (Hoyle *et al.* 2012).

Latitudinal spatial variation in size distribution is observed in the Indian Ocean (Chen *et al.* 2005, Geehan and Hoyle 2013), as it is in other oceans (e.g. Bromhead *et al.* 2009), with larger fish found closer to the equator.

The shape of the growth curve in the south Pacific is quite flat following the age of maturity, with relatively slow growth resulting in significant overlap in the size distributions of different ages. This pattern results partly from the use of the logistic growth curve, which fitted the data better than other options including the von Bertalanffy. Growth curves estimated for the north Pacific (Chen *et al.* 2012, Wells *et al.* 2013) have a different shape, and show more growth after maturity than was observed in the south Pacific. One of these studies (Chen *et al.* 2012) used the von Bertalanffy growth curve and did not test alternatives. The other study (Wells *et al.* 2013) found that von Bertalanffy growth fitted the data better than the logistic and other curves, but was not sex-specific and appeared to be affected by selection of more large males in the central Pacific where fish are larger (Xu *et al.* 2014), which would change the shape of the growth curve.

There are two albacore growth curves that are based on otoliths and have been fitted separately to males and females: from the north Pacific (Chen *et al.* 2012) and the south Pacific (Williams *et al.* 2012). The south Pacific growth curve takes spatial variation into account, used a designed sampling plan across multiple locations and sets, and tested alternative growth curves, so its overall structure is preferred. However, the north Pacific growth curve suggests growth to a larger size than in the south Pacific, so the parameterization may be closer to the Indian Ocean. The north Pacific albacore growth curve, differentiated by sex, was used in the current assessment following Hoyle *et al.* (2014) (Figure 15).

We used the maturity at age estimated by Farley *et al.* (2013), Farley *et al.* (2014), as calculated for the south Pacific albacore stock assessment (Hoyle *et al.* 2012). This ogive takes into account sex ratio at age, maturity at age, spawning fraction at age, and fecundity at age, and so represents female reproductive output at age (Figure 16).

3.1.3 Natural mortality

There is little information about likely values for natural mortality. Approaches commonly used to estimate M such as catch curve methods can be affected by biases due to the lack of equilibrium, unrepresentative sampling biases, and unreliable ageing. Past assessments have used various values ranging from 0.2 in the Indian Ocean to 0.4 in the south Pacific, with sensitivity analyses up to 0.5.

Natural mortality can be expected to be higher for small fish and also for older fish due to senescence (Lorenzen 1996). When including these features in models it can be difficult to choose from the wide variety of possible configurations.

In the current assessment natural mortality was assumed to be 0.3, based on the value applied in the north Pacific and the north Atlantic albacore stock assessments. A lower value of 0.2207 was applied as sensitivity; the alternative level of natural mortality corresponds to a maximum age of about 20 years compared to the maximum age observed in any ocean, of 15 years from the South Pacific. We also investigated variable natural mortality at age as a sensitivity analysis (Figure 17).

3.1.4 Recruitment

Recruitment in the model occurs in the fourth quarter of each year, reflecting the summer spawning season. Recruitment was based on a BH stock recruitment relationship (SRR) and annual deviates were estimated for the "data rich" period of the model (1975−2012). Deviates were given a small penalty, so that recruitment estimates in periods with less data were estimated closer to the mean. The applied penalty was based on the assumption that the true standard deviation of recruitment deviates (σ_R) is 0.6. Imperfections in models and lack of full information in the data cause models to underestimate recruitment variability, and recruitment variability tends to change across the time series, as information availability changes.

Since recruitment variability is assumed to be lognormally distributed, mean recruitment is higher than median recruitment. Equilibrium recruitment is meant to represent the average recruitment through time, so the median value in the recruitment function must be bias-corrected upwards. Given this lognormal bias, underestimation of recruitment variability also implies the need for bias correction so that mean recruitment over a period is accurate. The degree of bias correction depends on how much the variability is underestimated. Following Methot and Taylor (2011), we adjusted the bias correction across the time series according to the relationship between the assumed and estimated recruitment variability.

In the final set of models recruitment deviates were estimated for 1975−2012. Preliminary modelling revealed that the length composition data were influential in estimation of the recruitment deviates in the earlier period (1950−1974) in the absence of any abundance (CPUE) indices for the period. The length composition data from the longline fishery are not considered to provide reliable information regarding annual recruitment, particularly in isolation of indicators of stock abundance. No information is available in the model to reliably estimate recruitment in 2013 and 2014 as these age classes had not recruited to the fishery in the terminal year of the model (2014).

The final model options included three (fixed) values of steepness of the BH SRR (h 0.7, 0.8 and 0.9). These values are considered to encompass the plausible range of steepness values for tuna species such as albacore tuna and are routinely adopted in tuna assessments conducted by other tuna RFMOs.

3.2 Fishery dynamics

Modelled fishery selectivity was assumed to be a function of fish length. For all fisheries, selectivity was parameterised using a double-normal function (Methot 2015). The two southern longline fisheries (LL3 & LL4) shared a common selectivity as the length composition of the sampled catches from the two regional fisheries were comparable. The length of fish sampled tends to be considerably smaller than from the northern longline fisheries. Thus, the parameterisation of the selectivity function for the southern longline fisheries was given considerable flexibility to estimate a lower selectivity for the larger length classes (declining right hand limb).

The length composition data from the two northern longline fisheries (LL1 & LL2) indicate that these fisheries catch very similar sizes of fish and a common selectivity was estimated for these two fisheries. Initial modelling results indicated that it was necessary to constrain the selectivity function to maintain full selectivity of the largest length classes; i.e. approximating a logistic selectivity function. Relaxing the selectivity constraint resulted in implausibly large estimates of stock size (see Appendix 2, Table A3).

There is considerable temporal variation in the length composition data from the northern longline fisheries. The scale of the variation in these length data is not consistent with the relatively stable length composition of sampled catches from the southern longline fisheries. Therefore, it is unlikely that the variation in length composition could be attributable to recruitment variation. A more plausible explanation for the observed variability in the length composition is a change in the selectivity of the fishery either attributable to a change in the availability of smaller fish to the longline fishery or related to a change in the target operation of the composite longline fishery. Alternatively, the variation may simply reflect a high level of sampling error and sustained periods of sampling bias.

To account for the temporal variation in the length composition in the modelling framework, the selectivity of the northern longline fisheries was allowed to vary during the more data rich period (1980−2014). This was implemented by estimating annual deviates for the selectivity parameter that determines the length of the peak selectivity (parameter 1). The deviates were assumed to be from a normal distribution with a standard deviation of 10 cm.

A separate double normal selectivity was estimated for the purse seine fishery (PS1).

No length frequency data are available from the Indian Ocean drift net fisheries (DN3 & DN4). Estimates of the length based selectivity of albacore by the fishing method were derived from experimental fishing in the Pacific Ocean (Bartoo & Holts 1993). The resulting selectivity functions indicate albacore become vulnerable to the drift net fishery from about 50 cm and are fully vulnerable at 55−72 cm. The selectivity declines for larger fish with fish over about 85 cm not selected by the fishery (Bartoo & Holts 1993). A selectivity function was parameterised using a double normal selectivity to approximate the published drift net selectivity function. The selectivity parameters for the two drift net fisheries were fixed in the assessment model (i.e. not estimated).

The assumed selectivity function is broadly consistent with the length composition of albacore sampled from the South Pacific drift net fishery during 1988−1990. These data were used in the previous albacore stock assessment to estimate the drift net selectivity in the initial phases of the modelling procedure (Hoyle *et al*. 2014).

No length frequency data are available for the four “Other” fisheries. The selectivity of the “Other” fisheries was assumed to be equivalent to the selectivity of the drift net fishery. Initial modelling indicated that the model results were not sensitive to the selectivity assumed for the four Other fisheries due to the small magnitude of the catch associated with each of these fisheries.

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).

3.3 Observation models for the data

The total likelihood is composed of three main components: the fit to the abundance indices (CPUE), 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. Details of the formulation of the individual components of the likelihood are provided in Methot & Wetzel (2013).

For the current assessment, the weighting of the CPUE indices followed the general approach of Francis (2011). An initial model was implemented that down weighted all the length composition data. 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 for the northern longline fisheries (LL1 RMSE 0.38 and LL2 0.54) and considerably lower for the southern longline CPUE indices (LL3 0.21 and LL4 0.26) while the drift net CPUE indices had an intermediate level of deviance (0.30). On that basis, a CV of 0.20 was assigned to the two sets of southern longline CPUE indices. Model options that included the northern longline CPUE indices were included to investigate the sensitivity of the model results to the inclusion of these data and, hence, the LL1 & LL2 indices were given sufficient weight to be influential (a CV 0.30). The drift net CPUE indices were assigned a CV of 0.30.

The reliability of the length composition data is likely to be variable amongst 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. The relative weighting of the length data sets was investigated during the preliminary modelling phase by examining the influence of the length composition data on the overall magnitude of the stock size (see Appendix 2). The results indicated that a maximum ESS of 5 (all fisheries, all time periods) ensured that the length composition data were sufficiently informative to provide reasonable estimates of fishery selectivity and, hence, reasonable fits to the length composition data but were not strongly influencing overall stock size or the stock trajectory.

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.

4 Preliminary modelling

4.1 Spatially stratification

Initially, exploratory modelling investigated the potential to develop a spatially stratified assessment model to account for differences in the length composition and CPUE trends amongst the four regional longline fisheries. The limited time-series of CPUE indices from the north-eastern areas (LL2) meant that it was not practicable to develop a four-region, spatially stratified model.

A two region model was configured that partitioned the Indian Ocean longitudinally combining areas 1 and 3 and combining areas 2 and 4. Differences in the longline size composition between the northern and southern areas were accounted for by estimating different selectivity functions for the two sets of longline fisheries. Movement between the two regions was assumed to occur annually at the end of the first quarter, i.e. immediately before the start of the main longline fishing season in the southern areas. Two sets of age based movement parameters were estimated for the movement between the two regions (2x2=4 parameters); movement coefficients were estimated for age classes 2−4 years and age classes 8−14 years and there was a linear interpolation (ramp) of the movement for the intermediate years (5−7 years). The model estimated the overall proportion of the total recruitment allocated to each region and temporal variation in regional recruitment was estimated as deviates from the overall regional recruitment distribution.

The two region model was able to provide a reasonable fit to the four sets of LL CPUE indices and, in particular was able to fit the contrasting trends in the LL3 and LL4 CPUE indices in the more recent period (2000 onwards). The increasing CPUE in the LL4 fishery was accounted for by increasing the overall proportion of recruitment allocated to the eastern region during the latter period. Typically, the two region models estimated a large proportion (approx. 85%) of the adult biomass to be within the eastern region. This appears to be related to the higher quantity of catch taken from the eastern region during the late 1980s−early 1990s when the LL3 and LL4 CPUE indices show a similar magnitude of decline. However, the differential in the magnitude of catch between the two regions is not maintained throughout the subsequent model period. Based on these observations and the lack of any information regarding fish movement, it was considered that the two region model was not sufficiently reliable for stock assessment purposes and was not progressed beyond the initial modelling phase.

4.2 Model development

Subsequent modelling was conducted based on a spatially aggregated model structure. The single region model retained the four sets of longline CPUE indices and the 11 spatially defined fisheries. The two northern longline fisheries (and associated CPUE indices) were assumed to share a common length based selectivity, while a separate common selectivity function was estimated for the two southern longline fisheries based on the similarity of the size of fish sampled from these two fisheries.

The parameterisation of the selectivity function for the southern longline fisheries allowed the estimation of declining selectivity of the larger length classes. In contrast, the selectivity for the northern longline fisheries was constrained to have a non-declining selectivity for the largest length classes. This constraint was applied to maintain the stock biomass within a credible upper limit. Preliminary model options with no selectivity constraint estimated levels of stock biomass that were in excess of an order of magnitude larger than model options with the selectivity constraint (i.e. *SB0* 2.6e7).

Preliminary modelling revealed a poor fit to the northern LL CPUE indices relative to the southern CPUE indices. The RMSE of the two sets of CPUE indices from the initial model runs was used to assign the respective weighting of these indices. Accordingly, the two northern LL CPUE indices were all assigned a CV of 0.3 while the two sets of southern LL CPUE indices were assigned a CV of 0.2. The higher relative weighting of the southern LL CPUE indices is considered justifiable as the area supports the main target longline fisheries for albacore and, consequently, the CPUE indices may be less sensitive to changes in species targeting compared to the northern longline fisheries.

The variation in the CPUE indices from the longline fisheries in the northern area may also relate to changes in the component of the albacore population that is being fished over time. Length samples from the LL1 and LL2 fisheries reveal considerable variation in the length composition of the catch during the 1980s and 1990s. To simultaneously improve the fit to both the northern CPUE indices and the associated length composition data, temporal variation was introduced to the northern longline selectivity function, allowing the length of full selectivity to vary annually during 1980−2014. This assumes that the observed variation in the length composition of the sampled catch more adequately represents the overall catch removals from the stock compared to a static selectivity function.

The general trends in the LL CPUE indices from the two southern areas (LL3 and LL4) are broadly comparable during 1979−2006. However, the two sets of CPUE indices diverge during the more recent period with the LL4 CPUE indices increasing considerably while the LL3 CPUE indices have remained relatively stable. The increase in the LL4 CPUE indices is partly attributed to fewer CPUE observations from the quarters that are typically characterised by lower CPUE (quarters 1 and 4) in the latter period as well as a relatively strong increase in CPUE in the second quarter.

The recent CPUE indices from LL4 may represent a less reliable index of stock abundance (compared to LL3) due to a recent increase in the targeting of albacore by the Japanese fleet following a decline in fishing effort in the SBT fishery. The divergence in the LL3 and LL4 CPUE indices was accommodated in several model options by estimating catchability deviates for the LL4 CPUE indices during the recent period (2006−2014).

The results of the preliminary modelling are presented in Appendix 2 and summarised briefly below. The range of model options highlighted that the overall magnitude of the stock biomass was most sensitive to the influence of the CPUE indices from the northern LL fisheries. Model options that excluded these indices resulted in considerably lower levels of stock biomass (see Figure A5). Given the influence of these data it was decided to conduct further preliminary model testing based on two alternative model formulations: a set of models that included all four sets of the CPUE indices (*CPUEall*) and a set of model option that excluded the northern CPUE indices (*CPUEsouth*).

A description of the range of preliminary *CPUEall* model options is presented in the following Table.

Option	**Configuration (relative to base option)**	**Rationale and comments**
Reference (CPUEall)	See Table A1.	Initial model for comparative purposes.
Region2	Two region spatial structure partitioning IO into western and eastern regions. Overall regional distribution of recruitment estimated with temporal variation in regional recruitment distribution during 1975−2000. Movement estimated between regions. Single annual movement at end of season 1. Movement age specific with transition between age 4 and 8 years.	More recent regional recruitment deviations not estimated as also estimating catchability coefficients for the LL4 CPUE indices (eastern region). Model estimates a high proportion of the recruitment to eastern region and consequently high proportion of the biomass is within the eastern region. Movement rates are relatively low. Scale of biomass in each region probably relates to magnitude of catch taken during period of largest decline in the CPUE indices.
CPUE1970	Include LL1−4 CPUE indices from 1970−78 and estimate recruitment deviates from 1965−2012.	Investigate influence of earlier CPUE indices.
CPUEsouthwest	Down weight (CV 1.3) LL4 CPUE indices. Retain relative weighting of LL1−3 CPUE indices as per reference model.	Examine the relative influence of the LL3 and LL4 CPUE indices.
CPUEsoutheast	Down weight (CV 1.3) LL3 CPUE indices. Retain relative weighting of LL1,3&4	As previous.

	CPUE indices as per reference model. Remove the temporal deviates in catchability for LL4.	
CPUEincreaseQ	Apply an increase in catchability of 1% per annum to each of the four sets of LL CPUE indices for 1979−2014.	Look at sensitivity of model to increases in LL efficiency not accounted for in the CPUE standardisation. A constant annual increase of 1% is considered to be an upper limit of the likely increase in catchability over the time period (1979−2014).
SelectNoVar	Remove the estimation of temporal deviates in the selectivity of the northern longline fisheries (LL1 and LL2).	Investigate sensitivity to temporal variation in selectivity.
LFupWt	Increase the effective sample size of all length observations by a factor of 2.	Investigate influence of length frequency data.
LFdownWt2	Decrease the effective sample size of all length observations by a factor of 2.	As previous
LFdownWt5	Decrease the effective sample size of all length observations by a factor of 5.	As previous
LFdownWt10	Decrease the effective sample size of all length observations by a factor of 10.	As previous
Mlow	Constant natural mortality of 0.2207	Lower overall level of natural mortality (see Figure 17).
Mhybrid	Natural mortality of 0.4 for juveniles and declining t0 0.2207 for adults (age 5+).	Alternative hybrid natural mortality similar to proposed in IOTC-2014-WPTmT05 (see Figure 17).
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.
RecruitDevZero	Exclude estimation of recruitment deviations for 1975-2012.	Investigate sensitivity of biomass trajectory to temporal variation in recruitment.
NoRecBiasAdj	Exclude bias adjustment for estimated recruitment period.	

The biomass trajectory for each *CPUEall* model option is presented in Figures A5–8 (Appendix 2). The main observations from preliminary modelling using the *CPUEall* reference model are as follow.

- Overall stock biomass was relatively insensitive to the relative weighting of the two sets of southern LL CPUE indices (*CPUEsoutheast* and *CPUEsouthwest*) although recent trends in stock abundance were more optimistic when the LL3 CPUE indices were down weighted (*CPUEsoutheast*).
- The model results were relatively insensitive to the inclusion of the earlier (1970−78) CPUE indices as the model compensated by increasing recruitment during the 1970s. This differed from initial model trials that were based on a two region model structure.
- The model option that incorporated an increasing trend in longline catchability (*CPUEincreaseQ*) accounted for the greater decline in the CPUE indices by increasing recruitment during the late 1980s.
- Increasing the weighting of the length composition data (doubling ESS) (*LFupWt*) resulted in a considerably lower overall stock size. Conversely, down weighting the length composition data tended to result in an increase in overall biomass, although markedly down weighting the length composition data (*LFdownWt10*) resulted in a level of biomass that was comparable to the base model. These somewhat contradictory results is related to the estimation of the temporal deviates in the selectivity of the northern longline fisheries. The lowest weighting of the length composition data enabled the temporal trend in the selectivity to vary considerably from the base level.

- The lower M options (*Mlow* and *Mhybid*) estimated a greater level of stock depletion compared to the base model. There is a deterioration in the fit to the length composition data with the lower levels of natural mortality for older age classes.
- Not accounting for the bias associated with the estimation of recruitment deviates resulted in an over estimation of the overall stock size.
- There are strong trends in the recruitment deviates for the base model with positive deviates in the 1980s, negative deviates in the early 1990s and an increasing trend in recruitment deviates from the early 1990s to mid-2000s. Removing the estimation of recruitment deviates (*RecruitDevZero*) obviously results in a marked deterioration in fit to the length composition and CPUE indices, while resulting in a lower overall estimate of stock size.

The second suite of preliminary model options was based on the *CPUEsouth* reference model. The CPUE indices from the southern areas (LL3 and LL4) are derived from the main target ALB fisheries within the Indian Ocean. These fisheries appear to target a more consistent size of fish over the model period (compared to the northern LL fisheries). On that basis, it may be assumed that the LL3 and LL4 CPUE indices represent more reliable sets of long-term abundance indices for the overall Indian Ocean stock (compared to the LL1 and LL2 CPUE indices). However, recent trends in the CPUE indices from the LL3 and LL4 longline fisheries differ somewhat, with a relatively strong increase in CPUE in the latter fishery from about 2006.

The *CPUEsouth* model was primarily used to investigate the relative influence of the assumptions regarding the southern CPUE indices. Examining the seasonal residuals of the fit to the two CPUE indices revealed strong recent temporal patterns in the residuals for some area:quarter indices: negative residuals for LL3,Q1 and positive residuals for LL3,Q2 and LL4,Q2. These trends may indicate an increase in the extent of targeting of albacore in the southern longline fisheries in quarter 2 since 2006 and/or a shift from targeting albacore in the southwestern area during quarter 1. Additional model options partitioned the southern LL CPUE indices by season, effectively increasing the number of sets of CPUE indices in the southern area from two to eight.

In addition, the *CPUEsouth* model was also applied to investigate the assumptions regarding model initial conditions (initial population age structure). A description of the range of preliminary *CPUEsouth* model options considered is presented in the following Table.

Option	**Configuration (relative to base option)**	**Rationale and comments**
Reference ***(CPUEsouth)***	See Table A1. Exclude LL CPUE indices from the two northern fisheries (LL1 and LL2). Estimate LL4 temporal catchability deviates for the recent period as per reference model.	Initial model for comparative purposes.
Mlow	Constant natural mortality of 0.2207	Lower overall level of natural mortality proposed in IOTC-2014-WPTmT05 (see Figure 17).
Mhybrid	Natural mortality of 0.4 for juveniles and declining t0 0.2207 for adults (age 5+).	Alternative hybrid natural mortality similar to proposed in IOTC-2014-WPTmT05 (see Figure 17).
CPUEsouthwest	Down weight (CV 1.3) LL4 CPUE indices.	Examine the relative influence of the LL3 and LL4 CPUE indices.
CPUEsoutheast	Down weight (CV 1.3) LL3 CPUE indices. Retain relative weighting of LL4 CPUE indices as per reference model. Remove the temporal deviates in catchability for LL4.	As previous.

CPUEincreaseQ	Apply an increase in catchability of 1% per annum to each the two sets of LL CPUE indices for 1979−2014.	Look at sensitivity of model to increases in LL efficiency not accounted for in the CPUE standardisation. A constant annual increase of 1% is considered to be an upper limit of the likely increase in catchability over the time period (1979−2014).
CPUEseason	Estimate independent quarterly catchability coefficients for LL3 and LL4 CPUE indices.	Investigate effect of different seasonal catchability of southern longline CPUE indices, especially decline in frequency of CPUE observations from Quarters 1 and 4 in LL4 in recent years.
CPUEseasonExQ2	Estimate independent quarterly catchability coefficients for LL3 and LL4 CPUE indices and exclude Q2 CPUE indices from LL3 and LL4.	CPUE season revealed high positive residuals for Q2 from LL3 and LL4 in recent years.
LFupWt	Increase the effective sample size of all length observations by a factor of 2.	Investigate influence of length frequency data.
LFdownWt2	Decrease the effective sample size of all length observations by a factor of 2.	As previous
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.
RecruitDevZero	Exclude estimation of recruitment deviations for 1975−2012.	Investigate sensitivity of biomass trajectory to temporal variation in recruitment.
Rec1952	Extend estimation of recruitment deviations to include earlier period (1952−2012).	Investigate performance of model to estimate early recruitments.
RecInitialConditionsVar	Estimate an additional parameter *SR_R1_offset* to allow recruitment at the start of the period to deviate from equilibrium, unexploited recruitment.	Allows model biomass to deviate from equilibrium conditions in 1950. However, initial conditions will only deviate from equilibrium for the period of a generation (approx. first 10 years).
Start1975	Commence model in 1975 with equilibrium, exploited conditions. Initial level of fishing mortality estimated based on initial equilibrium catch equivalent to average annual fishery catch from 1970−74.	Investigate sensitivity to assumptions regarding initial stock conditions.

The biomass trajectories from the range of *CPUEsouth* model options are presented in Figures A9–10 (Appendix 2). The main observations from preliminary modelling using the *CPUEsouth* reference model are as follow.

- The overall magnitude and trends in stock biomass was relatively insensitive to the treatment of the two sets of CPUE indices (LL3 and LL4). However, biomass trends deviate in the more recent years from about 2008; there is a marked increase in spawning biomass for model options that incorporate the LL4 CPUE indices (*CPUEsouth*, *CPUEsoutheast*, *CPUEseason*) and the increase is most pronounced for the option that uses LL4 CPUE as the main CPUE index (*CPUEsoutheast*). Model options that remove or reduce the influence of the LL4 CPUE indices (*CPUEsouthwest*, *CPUEseasonExQ2*) estimate a minor increase in biomass from 2008.
- The model option that incorporated an increasing trend in longline catchability (*CPUEincreaseQ*) accounted for the greater decline in the CPUE indices by increasing recruitment during the late 1980s.
- The base model assumes that spawning biomass is at an unexploited equilibrium when fishing began in 1950. Recruitment deviates are not estimated until 1975 and therefore the catches are taken as removals from the equilibrium level of biomass. The initial magnitude of the unexploited biomass will be

sensitive to the level of steepness. Higher levels of SRR steepness (*SteepHigh*) can sustain the earlier catches from a smaller level of overall stock biomass compared to model options with lower SRR steepness (*SteepLow*).

- The assumption of initial equilibrium conditions is unrealistic but, is largely a default assumption in the absence of information to reliably estimate initial stock conditions. One option is to estimate a deviation in the level of recruitment that produced the initial conditions (*RecInitialConditionsVar*). This resulted in a relatively small, short term reduction in biomass during the first 10 years of the model. However, the effect can only persist for a single generation as recruitment reverts to the equilibrium level in the first year of the model period.
- Another option is to commence the model later and assume the stock is in exploited conditions. This was implemented by commencing the model in 1975 and estimating the fishery specific fishing mortality rates (*Start1975*). The model estimated a very similar level of stock biomass and stock status to the base model.
- A markedly different stock trajectory was derived from the model option that estimated recruitment deviates for 1952−2012 (*Rec1952*). For the 1965−1974 period, there are no abundance indices and only limited length composition data from the longline fisheries. The variation in stock biomass during the early period appears to be driven by the length composition data from that period. We consider that these data are not informative about stock size and, consequently, present the model option for comparative purposes only (rather than as a credible model option).
- The model option that does not estimate recruitment deviates for the entire model period (*RecDevZero*) yields estimates of biomass that are relatively similar to the reference model. This indicates that there are no strong temporal trends in recruitment being estimated by the reference model.

5 Model results – reference model and sensitivities

5.1 Final model selection

The results of the preliminary modelling reveal that a key structural uncertainty is the treatment of the northern LL CPUE indices (inclusion or exclusion of these indices). There is some degree of conflict between the northern and southern LL CPUE indices that is partly mediated by estimating variation in the selectivity of the northern longline fishery.

On balance, it is considered that the southern longline indices (LL3 and LL4) are likely to represent a more reliable index of stock abundance: the CPUE indices are derived from the longline fisheries data that represent the main target longline fisheries for albacore, the two sets of southern CPUE indices exhibit similar trends throughout the majority of the time period, the length composition data associated with these fisheries are considerably less variable than for the northern longline fisheries, and the temporal (interannual and decadal) variation in the southern indices is generally lower than the northern CPUE indices.

On that basis, the *CPUEsouth* model was selected as the reference model, while the *CPUEall* model was retained as a sensitivity option. Very different recent biomass trajectories depend upon the relative weightings of the LL3 and LL4 CPUE indices. The *CPUEsouth* model includes both sets of indices but estimates catchability deviates for the LL4 CPUE indices for 2006−2014. To encompass the range of plausible trends in recent biomass both the *CPUEsouthwest* and *CPUEsoutheast* model options were retained as model sensitivities. The former option excludes the LL4 CPUE indices, while the latter option excludes the LL3 CPUE indices.

The model option that included an increase in longline catchability was also retained as a sensitivity (*CPUEincreaseQ*).

The two alternative parameterisations of natural mortality were also included within the suite of model sensitivities (primarily to satisfy the request of the WPTmT05).

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

5.2 Fit diagnostics – reference model

The performance of the model was evaluated by examining the fit to the two data components – the CPUE indices and the fishery-specific length composition data.

- The reference model provides a reasonable fit to the overall trends in the LL3 and LL4 CPUE indices (Figure 19). There is considerable variability in the CPUE indices that is not accounted for by the model and the RMSE of the CPUE indices approximates the CV assigned to the indices (CV 0.20). The magnitude of the residuals may be partly attributable to seasonal variation in CPUE in the LL3 and LL4 fisheries. However, estimating separate seasonal catchability coefficients for each CPUE series did not substantially improve the overall fit to the CPUE indices (*CPUEseason* model).
- The very good fit to the recent LL4 CPUE indices was achieved by estimating quarterly catchability deviates during 2006−2014 (Figure 20). The catchability coefficients vary during the 2006−2014, partly accounting for seasonal variation in the CPUE indices, although catchability coefficients in the most recent years tend to be higher, reflecting the higher CPUE indices from LL4 compared to LL3. Overall, the estimation of the temporal deviates in LL4 CPUE indices removed the strong temporal patterns in the model residuals that were evident from preliminary model options (Figure 21). However, there remained persistent positive residuals for the LL4 CPUE indices during the period when catchability deviates were being estimated. Additional modelling revealed that the positive residuals related to the relative weighting assigned the CPUE indices during the period (CV 0.2) and the magnitude of the variance assumed for the catchability deviates (relatively high). Substantially increasing the precision of the recent LL4 CPUE indices removed this pattern in the LL4 residuals. However, the improvement in fit was at the expense of the fit to the LL3 CPUE indices rather than being accounted for by the LL4 catchability deviates. The apparent conflicting trends in the CPUE indices are accounted for more thoroughly via the separate model sensitivities.
- The fit to the drift net CPUE indices (nobs=7) was poor for all model options (Figure 19). This relates to the strong decline in both the LL3 and LL4 CPUE indices during the late 1980s that dominates the estimated trend in stock abundance. The assessment model estimated that this abundance trend was partly attributable to a general decline in recruitment during the 1980s. In turn, this would have been expected to affect the magnitude of the stock biomass that was vulnerable to the drift net fishery. However, the trend in declining abundance was not evident in the DN CPUE indices (Figure 19).
- For the LL1−4 and PS 1 fisheries, there is a reasonable overall fit to the aggregated length composition data (Figure 22). However, there is a high degree of variation in the individual length samples that cannot be accounted for by the model. The high degree of variability is assumed to be indicative of a high degree of sampling error and consequently the length frequency data sets have each been assigned a relatively low weighting in the final model options (Figure 23).
- For the two northern LL fisheries, there appears to be some systematic temporal variation in the length composition of the sampled catch (Figure 23). This may indicate changes in the availability of smaller fish to the northern longline fishery and/or changes in the target operation of these fisheries over time. Some of the temporal variability was accounted for by the estimation of temporal variation in the selectivity of the northern longline fisheries, although the model was unable to fully account for the observed trends in the length composition.
- There are some persistent temporal trends in the residuals from the fit to the length composition data (Figure 24 to Figure 27). The model predicts a small decline (of approx. 2–3 cm) in the size of fish vulnerable to the southern longline fisheries from about 1990, while the observed average length of fish sampled from LL3 and LL4 fisheries was higher in the 2000s compared to the earlier period (Figure 26). There are also temporal trends in the length of fish sampled from the purse seine fishery (PS 1) that are not accounted for by the model (Figure 27).
- A small number of south Pacific drift net length samples were included in the model, although the samples were assigned a very low weight in the final model options (ESS = 0.5). The selectivity of the drift net fishery was fixed outside the model. The predicted average length of the drift net catch from the model was broadly consistent with the South Pacific length composition data, albeit comprised of slightly larger (about 5 cm) fish (Figure 23).

5.3 Model parameter estimates

5.3.1 Selectivity

A common double normal selectivity function was estimated for the southern longline fisheries (LL3 & LL4). The selectivity function estimates that fish are fully vulnerable over a relatively narrow length range of about 75–90 cm (Figure 28). Larger fish are estimated to have a considerably lower vulnerability to the southern longline fisheries.

A common selectivity function was estimated for the northern longline fisheries (LL1 & LL2). The selectivity function was parameterised using a double normal although it was constrained to maintain full selectivity for the largest length classes (Figure 28). Full selectivity was estimated from about 95 cm for the base selectivity function, although selectivity was allowed to vary during 1980–2014. The temporal variation in selectivity generally followed the observed trends in the length composition from the LL1 & LL2 fisheries. Selectivity was estimated to shift towards smaller fish during the 1990s and then to larger fish from the early 2000s (Figure 29).

The selectivity of the PS 1 fishery indicates the fishery catches the larger fish in the population with full vulnerability at about 100 cm. The selectivity declines sharply for larger fish although this partly reflects the low number of fish in the population in the length classes exceeding the length of full selectivity (based on the natural mortality rate, growth function and associated variation in length-at-age for the oldest age classes) and the selectivity of the larger length classes is likely to be poorly determined.

The selectivity function for the drift net fisheries were not estimated and was assumed to have a length based selectivity approximating the selectivity derived by Bartoo & Holts (1993)(Figure 28). The four "Other" fisheries were assumed to have a selectivity function that was equivalent to the drift net fisheries.

5.3.2 Recruitment parameters

Annual recruitment deviates from the SRR were estimated for 1975–2012 (Figure 30). The model assumes recruitment deviates are from a distribution with a standard deviation of 0.6 (*sigmaR*) while the realised variation in the recruitment deviates is considerably lower (standard deviation approx 0.3). The recruitment deviates are estimated with a relatively high level of uncertainty reflecting the limited data included in the model to inform regarding the strength of individual year classes. There is no strong temporal trend in the recruitment deviates although lower recruitment deviates tended to be estimated during the late 1980s and early 1990s compared to the subsequent period (Figure 30).

5.4 Stock dynamics

5.4.1 Recruitment

The assessment models are configured to constrain recruitment to be at the equilibrium level for 1950–1974 (Figure 31). The reference model and the other model options that include only the southern longline CPUE indices (LL3 and/or LL4) estimated a comparable level of equilibrium recruitment. The overall scale of recruitment is estimated to be considerably higher for the model option that incorporates the northern longline CPUE indices (LL1 & LL2) (*CPUEall*) (Figure 31).

All model options estimated a general decline in recruitment during the late 1980s and early 1990s followed by a period of higher recruitment in the mid 2000s (Figure 31). More recent estimates of recruitment are sensitive to the treatment of the LL3 and LL4 CPUE indices; fitting to the LL4 CPUE indices only (*CPUEsoutheast*) resulted in higher estimates of recent (2006–2012) recruitment compared to the other model options.

The model option with increasing longline catchability (*CPUEincreaseQ*) estimated slightly higher recruitment during the late 1970s and early 1980s.

The temporal trends in recruitment were comparable between the reference model and the alternative natural mortality and steepness options, although the low M option (*Mlow*) estimated a considerably lower overall magnitude of equilibrium recruitment.

5.4.2 Biomass

For the reference model, spawning biomass is estimated to have declined gradually during 1950–1989 (Figure 32). The spawning biomass then declined sharply during 1989–1994 following the high catches from the drift net fishery. Spawning biomass continued to decline, albeit at a lower rate, until 2003. These trends in stock abundance are comparable for the range of model options (Figure 32 and Figure 33) although the overall extent of the stock decline is lower for the model option that incorporates the northern longline CPUE indices (LL1 & LL2) (*CPUEall*).

The lower productivity options (*Mlow, Mhybrid, SteepLow*) estimated a higher level of stock depletion during the early period when recruitment was assumed to be at equilibrium levels (Figure 33).

Spawning biomass is estimated to have increased from the low level in 2003, although the extent of the increase is sensitive to the treatment of the south longline CPUE indices. The model options that emphasise the CPUE trend from the LL3 fishery (reference *CPUEsouth* and *CPUEsouthwest*) estimate a lower level of stock recovery compared to the model options that emphasise the CPUE trend from the LL4 fishery (*CPUEsoutheast*) (Figure 32).

For the reference model, there is a relatively high level of precision associated with the estimate of initial spawning biomass and the level of spawning biomass during the period prior to 1975 (Figure 34). The level of precision is a function of the assumption of equilibrium recruitment during the early period and the fixed level of steepness for the SSR. There is a higher level of uncertainty associated with the estimates of spawning biomass during main data period of the model (1975–2014) that includes the estimation period for the recruitment deviates.

5.4.3 Fishing mortality

Fishing mortality rates for each fishery are defined as apical fishing mortality rates; i.e. the fishing mortality for the fully selected length class (or length classes). The fishing mortality rates are an approximation of the Baranov continuous *F* (Methot & Wetzel 2013). Relatively high recent fishing mortality rates were estimated for the two drift net fisheries during the late 1980s and early 1990s (Figure 35).

Longline fishing mortality rates are estimated to be higher for the southern longline fisheries (LL3 & LL4) than the northern fisheries (LL1 & LL2). For LL4, fishing mortality rates have been maintained at a relatively stable level over the last decade, while LL3 fishing mortality rates are estimated to have been more variable (Figure 35). Fishing mortality rates for the “Other” fisheries were negligible throughout the model period.

Aggregated, age-specific fishing mortality rates were derived for the terminal year (2014) of the model (following Methot & Wetzel 2013). Aggregate fishing mortality rates were highest for age classes 3–6 years and decline for the older age classes (Figure 36). The aggregate, age-specific fishing mortality from 2014 is the basis for the derivation of the *MSY* based reference points.

6 Stock status

6.1 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 reference 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 range of model sensitivities (CPUE options and natural mortality options) 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 37).

Equilibrium yield and biomass (spawning) were computed as a function of the 2014 aggregate fishing mortality-at-age (Figure 36). Estimates of *MSY* from the range of model options that exclude the northern LL CPUE indices were 33,600–41,900 mt (Table 5). This level of yield is broadly comparable to the average annual catch from 2010–2014 (36,200 mt) (Table 2). The estimate of *MSY* was considerably higher for the model sensitivity that incorporated the northern CPUE indices (*MSY* 61,700 mt).

The *MSY* reference spawning biomass is estimated to be a relatively small proportion of the equilibrium unexploited spawning biomass i.e. SB_{MSY}/SB_0 of 0.205–0.215 for the 0.8 steepness options (Table 5). The relatively low SB_{MSY}/SB_0 ratio appears to be related to the lower vulnerability of the older, mature age classes.

For the reference model option, the spawning biomass is estimated to have remained above the SB_{MSY} level throughout the history of the fishery (1950–2014) (Figure 38). Prior to 1985, exploitation rates were low and spawning biomass remained well above SB_{MSY} (Figure 38 and Figure 39). Fishing mortality increased sharply in the late 1980s and exceeded the F_{MSY} level in 1990 and again in 2001. Correspondingly, the biomass declined during the 1990s–early 2000s, approaching the SB_{MSY} level in the early 2000s.

Fishing mortality rates during 2003–2012 were estimated to be lower than the preceding period 1998–2002 (Figure 39) and spawning biomass was estimated to increase during the more recent period. Current (2014) biomass is estimated to be above SB_{MSY} (SB_{2014}/SB_{MSY} 1.801, confidence interval 1.154–2.448) (Figure 40 and Table 5). Fishing mortality increased in 2014 approaching the F_{MSY} level (F_{2014}/F_{MSY} 0.846). There is considerable uncertainty associated with the estimate of current fishing mortality (confidence interval 0.421–1.271) and some probability that the current (2014) level of fishing mortality exceeded the F_{MSY} level ($Pr(F_{2014}/F_{MSY} >1) = 0.22$)) (Figure 40).

The range of model options all estimate that current spawning biomass is above the SB_{MSY} level (SB_{2014}/SB_{MSY} 1.35–2.99) while most model options estimate fishing mortality to be below F_{MSY} level (F_{2014}/F_{MSY} 0.421–1.09) (Table 5). The model options that incorporated lower natural mortality or increasing LL catchability were the least optimistic and estimated current fishing mortality levels approaching or exceeding the F_{MSY} level. The *CPUEall* model option was considerably more optimistic than the other models.

6.2 Projections

Stock projections were conducted for all model options. The projections were conducted for a 10 year period (2015–2024) with a constant level of catch equivalent to the fishery catches in 2014 (39,709 t). 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 34). For the reference model, current (2014) levels of catch exceed the equilibrium surplus production and the stock biomass is projected to decline over the first five years and then stabilize above the SB_{MSY} level (Figure 38, Figure 39 and Table 6) with fishing mortality levels below F_{MSY} (Figure 39 and Table 7).

The projections for most of the other model options reveal similar trends, with the notable exception of the two lower natural mortality options (*Mlow* and *Mhybrid*). For these two model options, the 2014 catch levels are in excess of the *MSY* yields and, consequently, the stock is further depleted throughout the projection period and is reduced below the SB_{MSY} level within the first 5 years.

7 Discussion and conclusions

7.1 Comparison with previous (2014) assessment results

There are considerable differences in model structure between the 2014 stock assessment (Hoyle et al 2014) and the current assessment that mean that it is not possible to make direct comparisons between the two sets of model results. These differences primarily relate to the changes in the spatial definition of the fishery data sets and the CPUE indices in the current assessment.

Nonetheless, the main input data sets are based on the same core data sets. Both models primarily utilize CPUE indices derived from the southern longline fishery which has been dominated by the Taiwanese fleet for the main period of the assessment. The overall fishery catches are virtually identical and, while both assessments assign a relatively low weighting to the length composition data, the models estimate similar fishery selectivity functions.

The range of model options presented in Hoyle et al. (2014) include models with comparable productivity parameters to the current assessment (e.g. natural mortality 0.3 and steepness 0.8). For The comparable model options estimated 2012 stock status SB_{2012}/SB_{MSY} of approximately 1.5 and F_{2012}/F_{MSY} approximately 0.5 (Hoyle et al 2014). These stock status indicators are broadly comparable to the estimates of stock status for the current reference model (SB_{2014}/SB_{MSY} 1.801 and F_{2014}/F_{MSY} 0.846).

However, there are considerable differences between the corresponding estimates of *MSY* between the current assessment model (38,800 t) and the previous assessment (53–55,000 t). The higher estimates of yield from the 2014 assessment appear to be partly related to the estimation of recruitment deviates for the period prior to the inclusion of the CPUE data in the model (pre 1980). In the previous assessment, extending the recruitment estimation period back from 1980 to commence in 1970 resulted in a considerable increase in the overall magnitude of equilibrium biomass and recruitment and is likely to have increased *MSY* accordingly. The estimation of a higher level of biomass appears to be driven by the length composition data from the early time period.

7.2 Current assessment results

The current assessment depends largely on the time series of CPUE indices and the catch history from the fishery. The influence of the CPUE indices is most apparent when comparing model options that include or exclude the northern LL CPUE indices. The higher level of stock biomass estimated for the former model option (*CPUEall*) appears to be related to the lack of a substantive decline in the LL1 CPUE indices during the 1979–2000 despite the relatively high catches taken from the stock during the period.

This is contrasted by the decline in the LL3 and LL4 CPUE indices during the late 1980s–early 1990s. It was presumed that the LL3 and LL4 CPUE indices from this period were highly influential in the overall estimates of stock size. However, additional model trials revealed that the decline in the CPUE indices during this period was not the main determinant of overall stock size. A trial that reduced the CPUE indices from 1979–1990 by 30%, effectively removing the main decline in the CPUE indices, resulted in a relatively small (less than 5%) reduction in both SB_0 and *MSY*. A separate trial that reduced the CPUE by 30% during 1990−2014 also had a negligible influence on estimates of SB_0 and *MSY*.

Estimates of initial stock size and *MSY* are clearly determined by the overall magnitude of catch, especially the relatively high catch maintained during 1990−2014 (average 33,000 t). The higher stock size estimated for the *CPUEall* model appears to relate to the lack of a substantive impact on the abundance of larger fish prior to about 2000 as indexed by the LL1 CPUE indices.

Obviously, recent trends in CPUE are highly influential in determining current stock status. However, there are conflicting trends in the recent CPUE indices from the southern longline fisheries (LL3 & LL4). The increase in albacore catch by the Japanese fleet in LL4 may indicate that the level of targeting of albacore has increased and may be positively biasing the LL4 CPUE indices, although further evaluation of the CPUE indices is required to evaluate the reliability of the two sets of CPUE indices (e.g. examination of trends in CPUE model residuals by fleet). An evaluation of the CPUE indices will then enable the WPTmT to select the most appropriate model option from the range of treatments of the southern CPUE indices.

The drift net CPUE indices have negligible influence in the assessment models due to the relatively low weighting assigned to the indices and the small number of indices relative to the number of LL3 & LL4 CPUE observations in the corresponding period. It is appropriate that the drift net CPUE indices are not overly influential, especially given the lack of information regarding the selectivity of the Indian Ocean drift net fishery. However, model options that attributed the drift net CPUE indices a high relative weighting (during model trials) did not appreciably change the relative trend in the stock trajectory, although the overall magnitude of the stock biomass (and estimate of *MSY*) was reduced by about 15–20%.

Most of the longline length composition data are derived from Taiwanese size frequency data. There is considerable uncertainty regarding the reliability of these data (Geehan and Hoyle 2013). Despite configuring the length composition data sets to represent the area of operation of the main albacore fisheries there is considerable variation in the length composition data. Some of the variation is likely to be attributable to sampling error although temporal trends in the length composition data are indicative of changes in the operation of the fishery and/or systematic biases in the collection of the size data. On that basis, the length composition data were down-weighted to the extent that these data did not substantially influence the estimates of stock abundance from the model. Nonetheless, an additional model trial that excluded all longline length frequency data from 2000 did result in change in a reduction in the recent level of stock biomass from the reference model (reducing SB_{2014}/SB_0 from 0.369 to 0.305).

Integrating the length composition data in the assessment model is also dependent on having reliable information regarding the growth of albacore. As previously noted, growth has not been determined for Indian Ocean albacore and the growth was assumed to be equivalent to the North Pacific albacore stock. The sensitivity of the model results to the assumed growth function was not investigated in the current assessment as no reasonable alternative growth model is currently available. However, the results of sensitivity modelling of Hoyle *et al* (2014) illustrate that the assessment results are likely to be sensitive to the assumed growth function. The IOTC secretariat has developed a research project to conduct ageing of Indian Ocean albacore and the results of this work will be available to incorporate in the next stock assessment.

The assessment results are also sensitive to the other key productive assumptions, especially SRR steepness and natural mortality. Estimates of natural mortality, such as those derived from observations of longevity, are not available for Indian Ocean albacore and have been based on the values used in the assessment of other albacore stocks. The value of natural mortality (M=0.3) included in the reference assessment model resulted in a considerably better fit to the length composition data compared to the model options with a lower level of natural mortality for adult fish (M=0.2207). This observation only provides a weak basis for preferentially selecting the higher M option because the fit to the length composition data also depends on the growth model assumed.

The current assessment also assumes that natural mortality is equivalent for both sexes. The differential sex ratio of the larger fish in the population may indicate 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).

Estimates of overall stock size are also likely to be influenced by assumptions regarding the population structure during the early period of the model. The range of model options are based on the assumption that the stock is at unexploited, equilibrium conditions at the start of the model (1950) and recruitment prior to 1975 is simply a function of the SRR. Model testing indicated that estimating recruitment during the earlier period (prior to 1975) may result in a different biomass trajectory during the early period, although the biomass trajectories from alternative models tended to converge during the late 1980s–early 1990s. The models can account for the higher catches during the subsequent years either by having a higher level of equilibrium biomass or by increasing recruitment immediately prior to the period of higher catch (early recruitment options). There is very limited information to inform the model about the population age structure during this crucial period due to the lack of information to inform the model about the age composition of the population at that period (due to the uninformative length composition data). Nonetheless, the estimation of the early recruitments may influence the overall level of equilibrium recruitment and, hence the estimates of the overall productivity of the stock.

Overall, the range of assessment models reveal considerable uncertainty in the estimates of stock status related to the treatment of the CPUE indices and the assumed productivity parameters. Individual model estimates of current stock status are also poorly determined especially for the reference model which incorporated both sets of southern LL indices. Nonetheless, the point estimates from the range of plausible model options indicate that the stock is not over fished (SB_{2014}/SB_{MSY} 1.35–2.40) and most model options indicate overfishing is not occurring (F_{2014}/F_{MSY} 0.66–0.99), with the exception of the lower M options for which fishing mortality is estimated to be slightly higher than the F_{MSY} level (F_{2014}/F_{MSY} 1.07 and 1.09). However, it is important to note that the *MSY* based reference points correspond to a low overall level of stock size relative to unexploited conditions (SB_{MSY} approximately 20% SB_0). The recent level of catch (2010–2014 average of 36,200 t) approximates the range of estimates of *MSY* for the stock (*MSY* 33,000–41,000 t).

Stock projections were conducted to evaluate the impact of current (2014) level of catch. 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 unconstrained fishing mortality. Instead, the projections provide an indication of future stock trends under different model assumptions. For the model options with the higher level of natural mortality, the stock is projected to remain above SB_{MSY} over the next 10 years, while the projections for the lower M options are less optimistic.

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Table 1. Definition of fisheries for the albacore assessment models.

Fishery	Nationality	Gear	Area
1. LL1	All	Longline	1
2. LL2	All	Longline	2
3. LL3	All	Longline	3
4. LL4	All	Longline	4
5. DN3	CN-TW	Drift net	3
6. DN4	CN-TW	Drift net	4
7. PS1	All	Purse seine	1
8. Other1	All	Other gears	1
9. Other2	All	Other gears	2
10. Other3	All	Other gears	3
11. Other4	All	Other gears	4

Table 2: Recent albacore 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 2010-14.

Fishery	Time period		
	2010-14	2013	2014
1. LL1	6,936.6	7,425.0	6,010.0
2. LL2	3,656.8	1,943.0	1,496.0
3. LL3	11,494.6	13,388.0	16,182.0
4. LL4	12,366.6	8,246.0	14,911.0
5. DN3	0.0	0.0	0.0
6. DN4	0.0	0.0	0.0
7. PS1	651.4	501.0	530.0
8. Other1	210.4	128.0	76.0
9. Other2	865.6	564.0	496.0
10. Other3	17.0	2.0	8.0
11. Other4	0.6	0.0	0.0
Total	36,199.6	32,197.0	39,709.0

Table 3. Main structural assumptions of the albacore tuna reference model and details of estimated parameters.

Category	Assumptions	Parameters
Spatial structure	Single region	
Recruitment	Occurs at the start of fourth quarter as 0 age fish. Recruitment is a function of Beverton-Holt stock-recruitment relationship (SRR). Temporal recruitment deviates from SRR, 1975–2012.	LNR_0 No prior; h = 0.80 *SigmaR* = 0.6. 38 deviates.
Initial population	A function of the equilibrium recruitment assuming population in an unexploited state prior to 1950. Initial fishing mortality fixed at zero for all fisheries.	
Age and growth	Two sexes with 14 age-classes, with the last representing a plus group. Growth parameterised using VonBert growth model. Male growth is parameterisaed as deviates from female growth parameters 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 $W = aL^b$.	*Lage1* = 45.4428, *Linfinity* = 114cm, *k* = 0.253. Male devs *Lage1* = 0.0792747, *Linfinity* = 0.0966268, *k* = -0.295556. CV =0.10 *a* = 1.3718e-05, *b* = 3.0973
Natural mortality	Invariant with age.	Fixed parameter 0.30
Maturity	Age-dependent, specified. Fecundity is directly related to female biomass (Wt) i.e. eggs=Wt*(a+b*Wt) with a=0 and b=1.	age-classes 0-14: 0, 0, 0, 0, 0.089, 0.466, 0.746, 0.881, 0.944, 0.973, 0.987, 0.994, 0.997, 0.999, 1.000
Selectivity	Length based selectivity, parameterised with double normal function. Southern LL fisheries LL 3 and LL 4 (and CPUE) share a common selectivity. Northern LL fisheries LL 1 and LL 2 (and CPUE) share a common selectivity. Constrained to approximate full selectivity for the largest length classes. Temporal	 5 estimated parameters, no priors. 4 estimated parameters, no priors. 35 temporal deviates (Sd 10)

	variation in selectivity for 1980-2014 (peak parameter). Drift net fisheries have common, fixed selectivity. Approximate Bartoo & Holts (1993) Purse seine double normal selectivity. Other (1-4) fisheries share drift net selectivity.	 Fixed 4 estimated parameters, no priors.
Catchability	Separate base catchability estimated for each LL CPUE. Catchability deviates for LL 4 CPUE indices for 2005-2014 No seasonal variation in catchability for LL CPUE. Southern LL CPUE indices have CV of 0.2. [Northern LL CPUE indices excluded from likelihood function]	4 base parameters 27 deviates (Sd = 3)
Fishing mortality	Hybrid approach (method 3, see Methot & Wetzel 2013).	
Length composition	Multinomial error structure. Length samples assigned an ESS of nfish/400 with a maximum ESS of 5. Nfish is the number of fish sampled.	

Table 4. Main objective function components for the set of stock assessment models. NA indicates that the data component was not included in the model likelihood.

Model	Total likelihood	Total LF Comp	CPUE indices				
			LLCPUE1	LLCPUE2	LLCPUE3	LLCPUE4	DNCPUE
Reference (*CPUEsouth*)	722.80	939.20	NA	NA	-136.70	-74.61	-5.02
./CPUEall	651.38	961.23	-82.38	-12.72	-136.16	-72.30	-4.71
./CPUEincreaseQ	724.57	940.88	NA	NA	-136.20	-74.81	-4.75
./CPUEsoutheast	890.52	940.32	NA	NA	NA	-45.04	-5.01
./CPUEsouthwest	789.43	933.75	NA	NA	-138.47	NA	-5.21
./Mhybrid	756.22	971.27	NA	NA	-137.10	-74.30	-5.06
./Mlow	757.92	972.45	NA	NA	-136.97	-74.20	-5.02
./SteepHigh	721.70	938.45	NA	NA	-136.59	-74.73	-5.06
./SteepLow	724.21	940.16	NA	NA	-136.82	-74.45	-4.97

Table 5. Estimates of management quantities for for the set of stock assessment models. The 95% confidence intervals for the current stock status metrics are provided for the reference model.

Model	SB_0	SB_{MSY}	SB_{MSY}/SB_0	SB_{2014}	SB_{2014}/SB_0	SB_{2014}/SB_{MSY}	F_{2014}/F_{MSY}	MSY
Reference (*CPUEsouth*)	146,434	30,030	0.205	54,089	0.37	1.801 1.154–2.448	0.846 0.421–1.271	38,812
./CPUEall	236,952	48,614	0.205	145,166	0.61	2.99	0.421	61,698
./CPUEincreaseQ	145,778	29,918	0.205	41,594	0.29	1.39	0.989	38,687
./CPUEsoutheast	153,762	31,591	0.205	63,927	0.42	2.02	0.657	41,120
./CPUEsouthwest	144,496	29,682	0.205	49,550	0.34	1.67	0.884	38,278
./Mhybrid	189,530	39,406	0.208	53,139	0.28	1.35	1.087	33,626
./Mlow	204,626	43,990	0.215	59,346	0.29	1.35	1.067	33,711
./SteepHigh	133,119	19,783	0.149	47,559	0.36	2.40	0.733	41,885
./SteepLow	164,839	41,374	0.251	63,843	0.39	1.54	0.926	36,903

Table 6. Projected stock status relative to SB_{MSY} and the probability of being below SB_{MSY} in 3-, 5- and 10 years for projections conducted using the 2014 level of catch for the range of model options. NA, not determined.

Model option	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($SB<SB_{MSY}$)
reference	1.415	0.138	1.304	0.276	1.273	0.365
./CPUEall	2.593	0.001	2.496	0.013	2.669	0.041
./CPUEincreaseQ	1.019	0.494	0.959	0.502	0.968	0.503
./CPUEsoutheast	2.254	0.006	2.078	0.045	1.831	0.105
./CPUEsouthwest	1.307	0.203	1.208	0.328	1.172	0.407
./Mhybrid	1.050	0.467	0.906	0.537	0.704	0.689
./Mlow	1.060	0.392	0.915	0.580	0.717	0.693
./SteepHigh	1.855	0.041	1.711	NA	1.739	NA
./SteepLow	1.238	0.235	1.143	0.386	1.088	0.444

Table 7. Projected fishing mortalityrelative to F_{MSY} and the probability of being above F_{MSY} in 3-, 5- and 10 years for projections conducted using the 2014 level of catch for the range of model options. NA, not determined.

Model option	3 years (2017)		5 year (2019)		10 year (2024)	
	F/F_{MSY}	Pr($F>F_{MSY}$)	F/F_{MSY}	Pr($F>F_{MSY}$)	F/F_{MSY}	Pr($F>F_{MSY}$)
reference	0.870	0.315	0.876	0.336	0.894	0.357
./CPUEall	0.418	0.000	0.410	0.000	0.399	0.001
./CPUEincreaseQ	1.004	0.508	1.007	NA	1.018	0.480
./CPUEsoutheast	0.678	0.043	0.698	0.077	0.733	0.322
./CPUEsouthwest	0.912	0.413	0.920	0.417	0.941	NA
./Mhybrid	1.157	0.554	1.206	0.657	1.362	0.636
./Mlow	1.162	0.700	1.209	0.663	1.365	0.732
./SteepHigh	0.750	0.133	0.748	NA	0.747	NA
./SteepLow	0.955	0.469	0.970	0.452	1.007	0.504

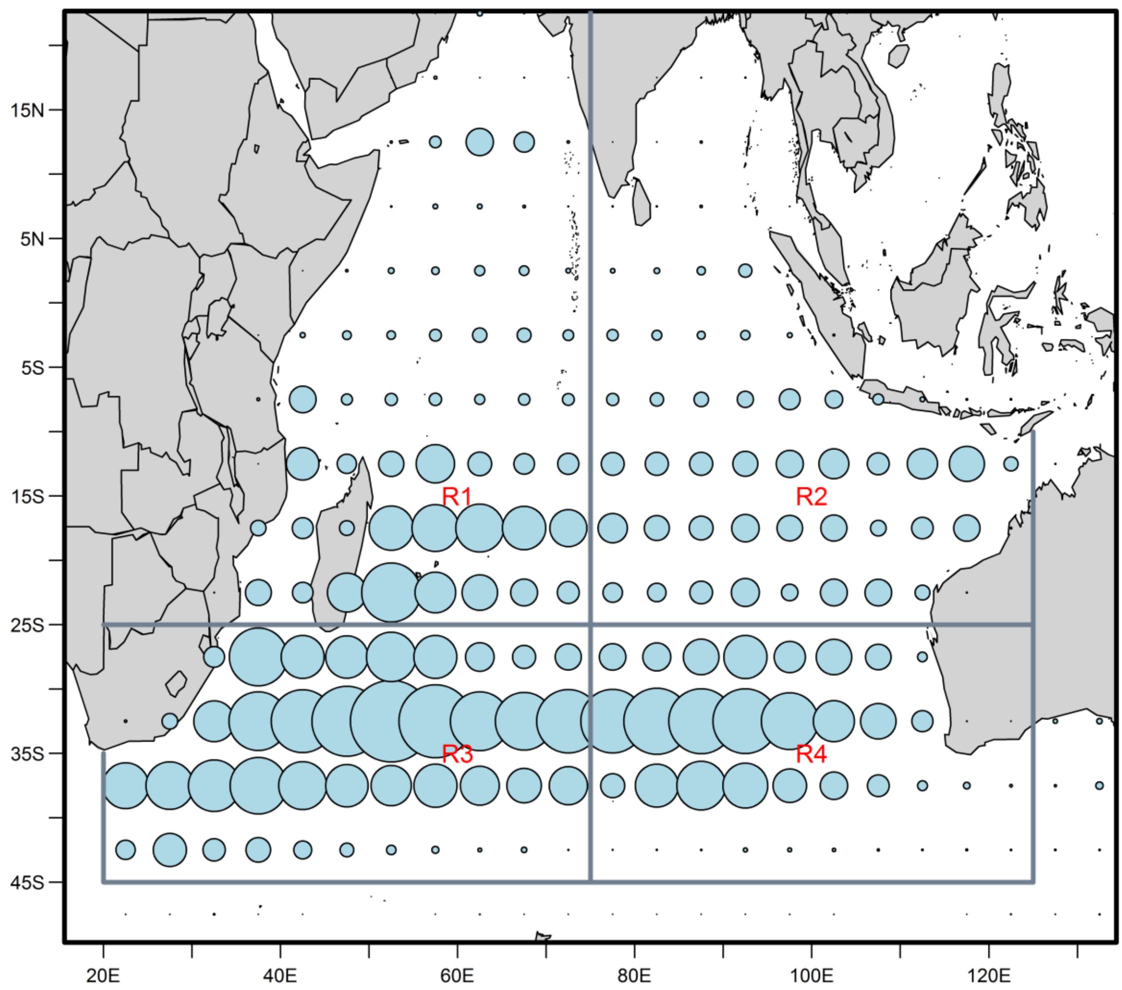


Figure 1. Spatial stratification of the Indian Ocean for the definition of the fisheries. The blue circles represent the aggregated Japanese and TW LL albacore catch (numbers of fish) by 5 degree cell from 1952-2014. The area of the circle is proportional to the magnitude of the catch (the largest circle represents a catch of 2137526 fish).

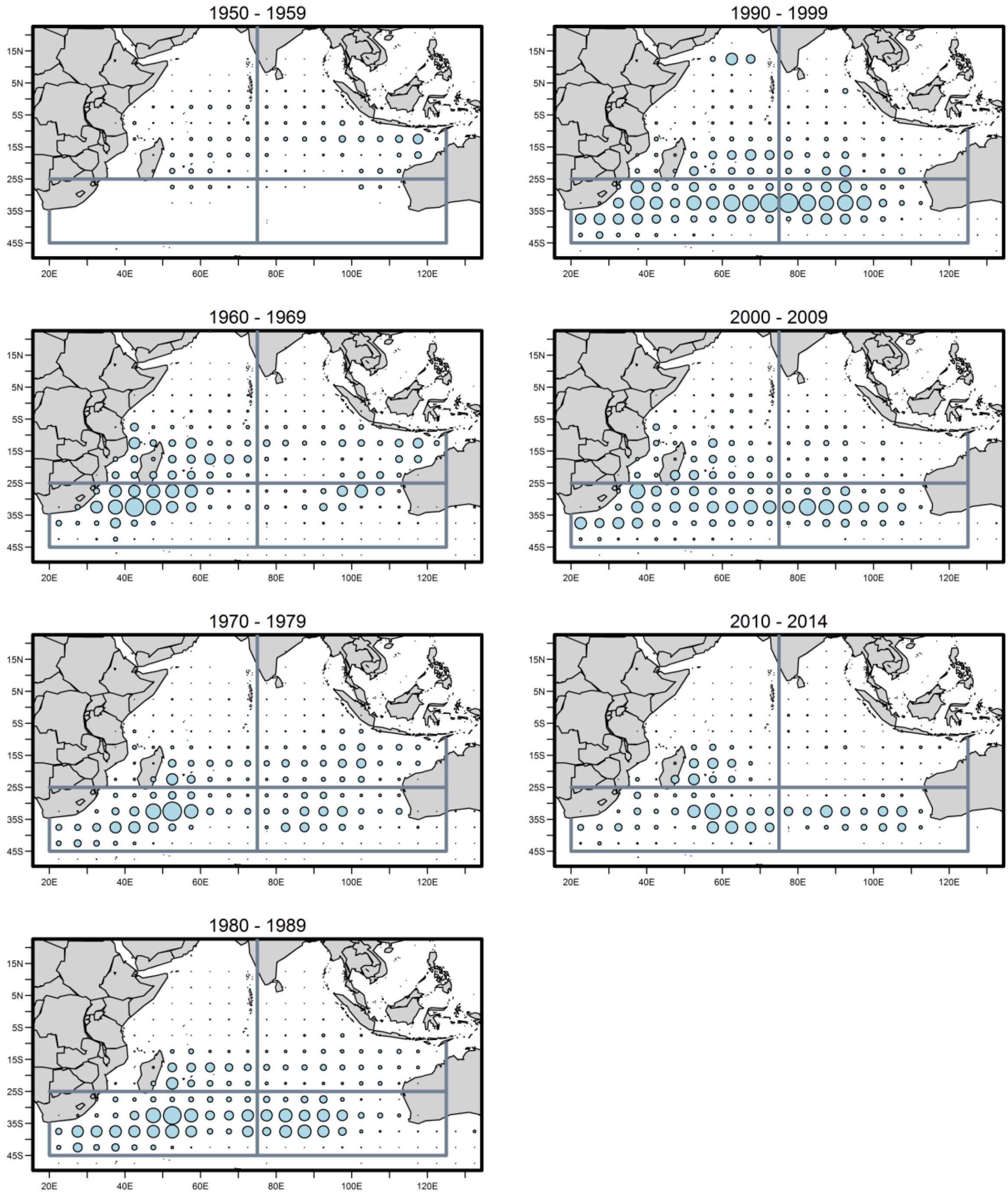


Figure 2. Distribution of Indian Ocean albacore longline catches by decade. The blue circles represent the aggregated Japanese and TW LL albacore catch (numbers of fish) by 5 degree cell. The area of the circle is proportional to the magnitude of the catch (the largest circle represents a catch of 621870 fish).

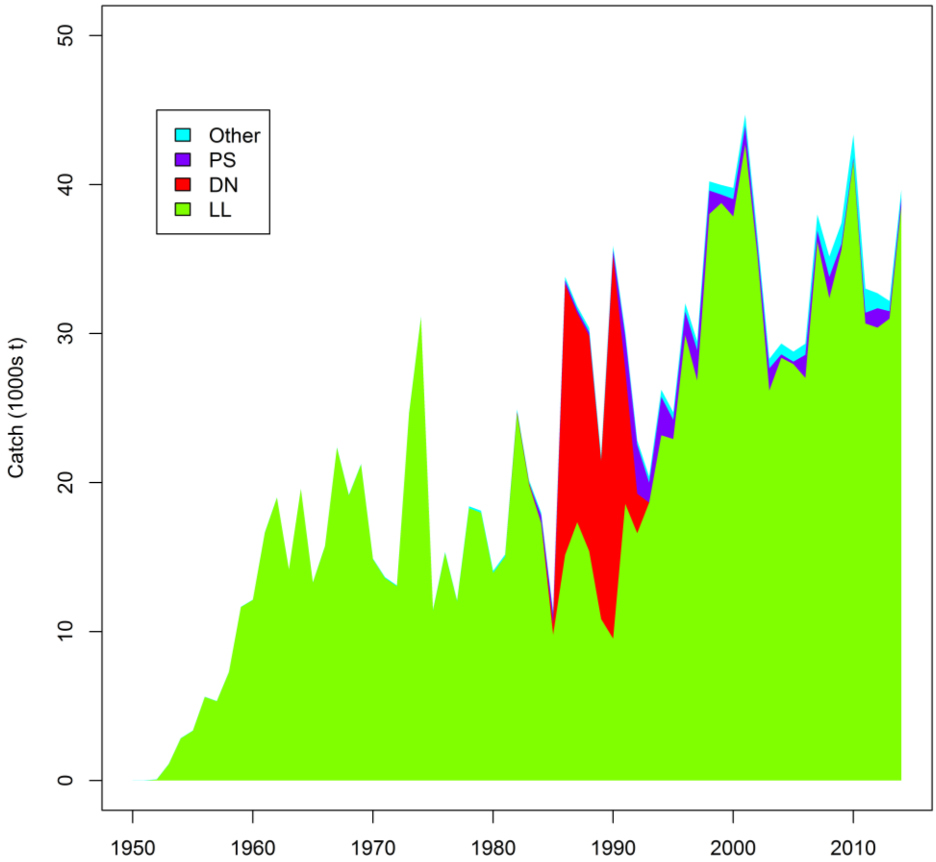


Figure 3. Total annual catch (1000s mt) of albacore tuna by fishing method from 1950 to 2014 (LL, longline; PS, purse-seine; OT, other; DN, drift net).

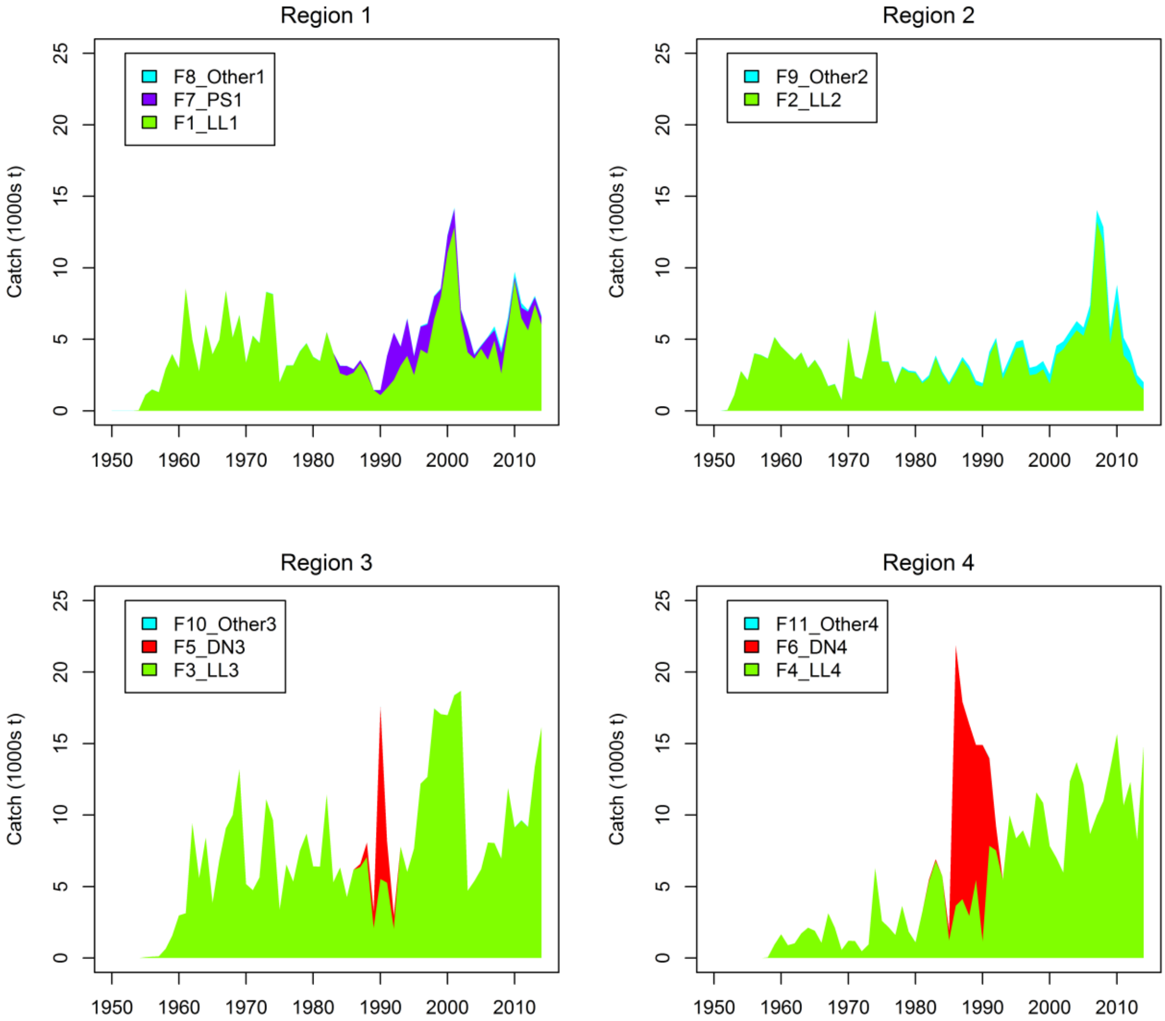


Figure 4. Total annual catch (1000s mt) of albacore tuna by fishing method and region from 1950 to 2014 (LL, longline; PS, purse-seine; OT, other; DN, drift net).

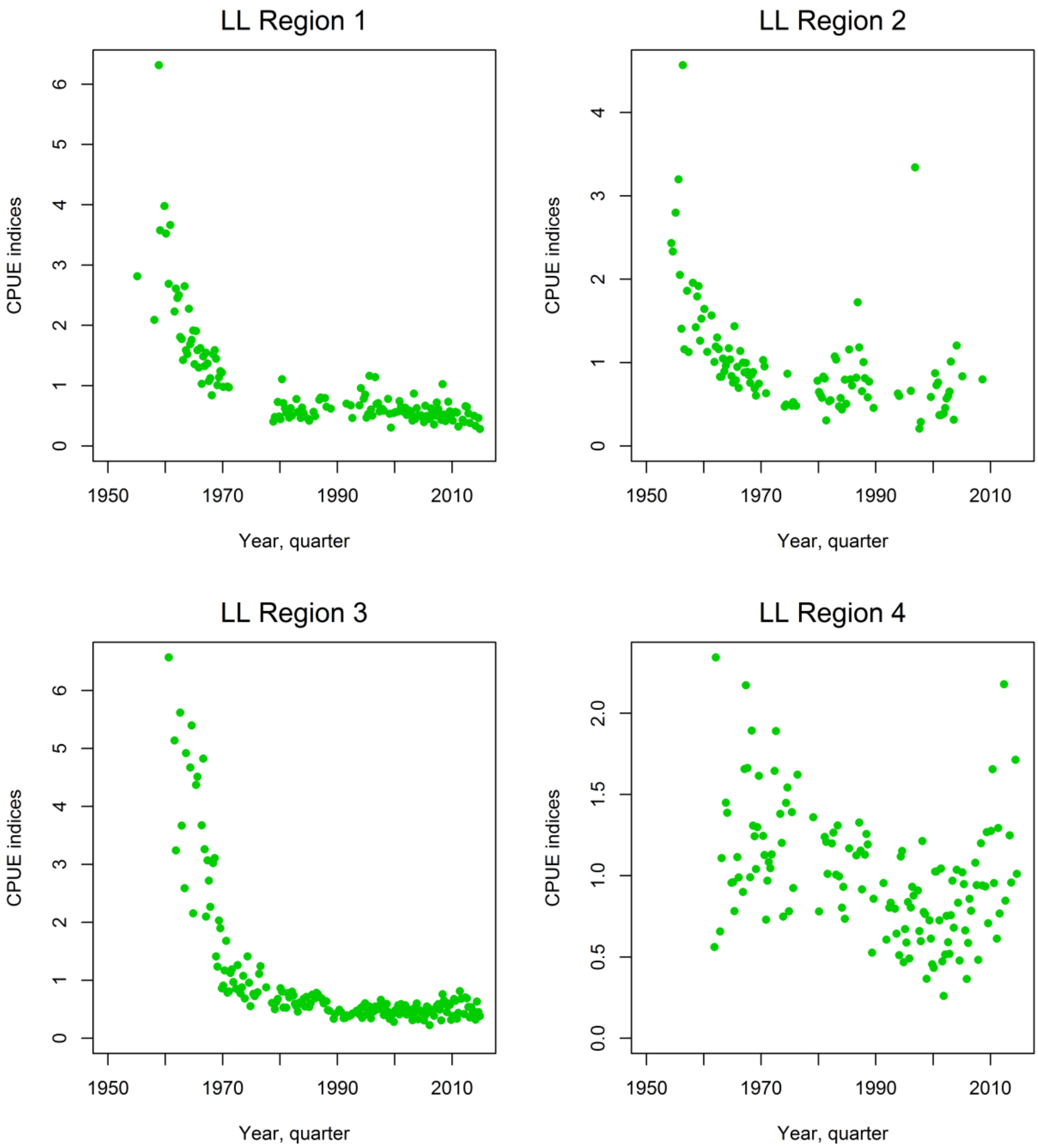


Figure 5. Quarterly GLM standardised catch-per-unit-effort (CPUE) for the longline fisheries (LL 1–4) (*boat_allyears* series). Each set of indices is normalised to the average of the series (source Hoyle et al 2016).

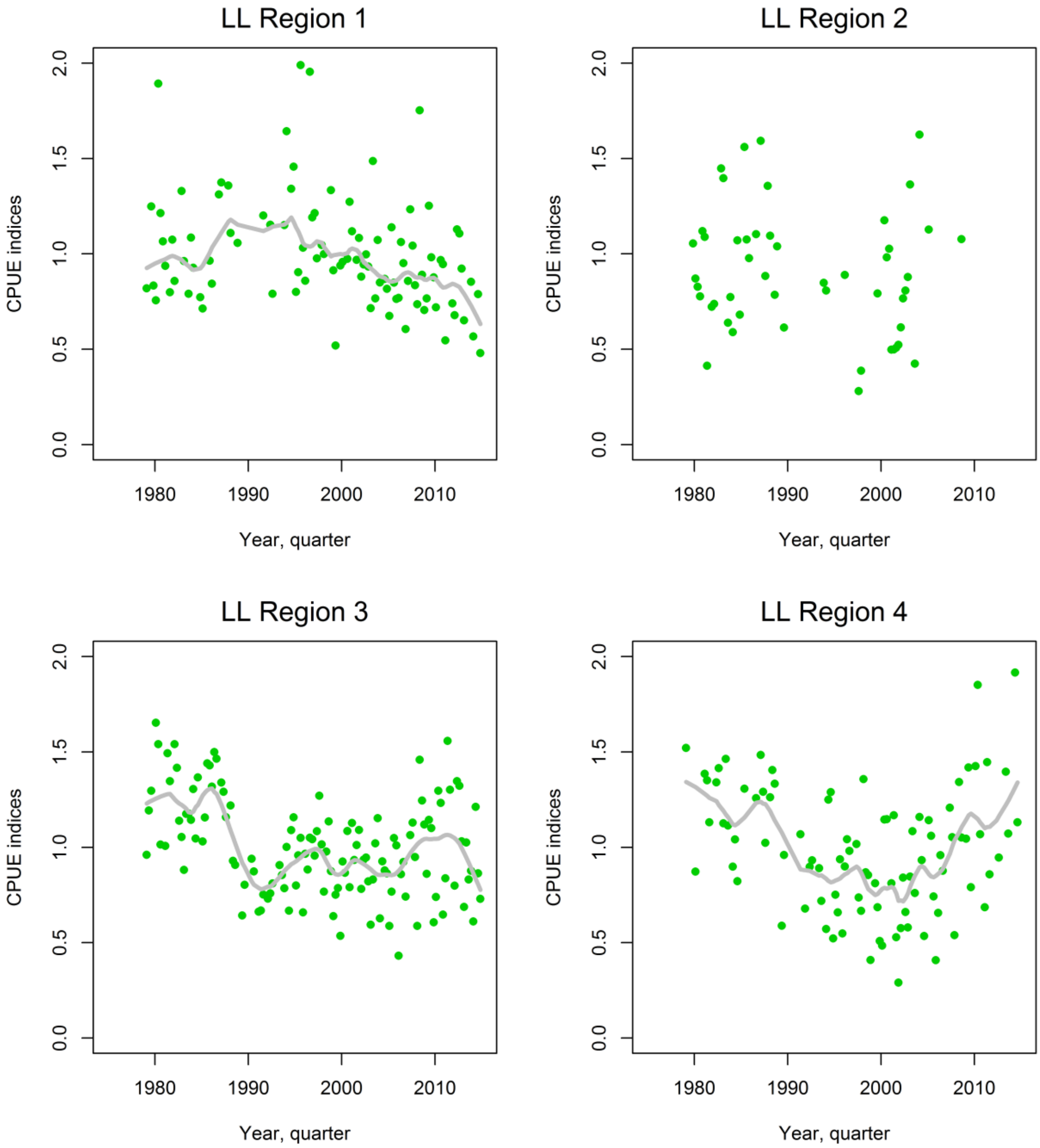


Figure 6. Quarterly GLM standardised catch-per-unit-effort (CPUE) for the longline fisheries (LL 1–4) from 1979-2014 (*boat_allyears* series). Each set of indices is normalised to the average of the entire series (source Hoyle et al 2016). The lines represent a lowess smooth fit to each set of indices.

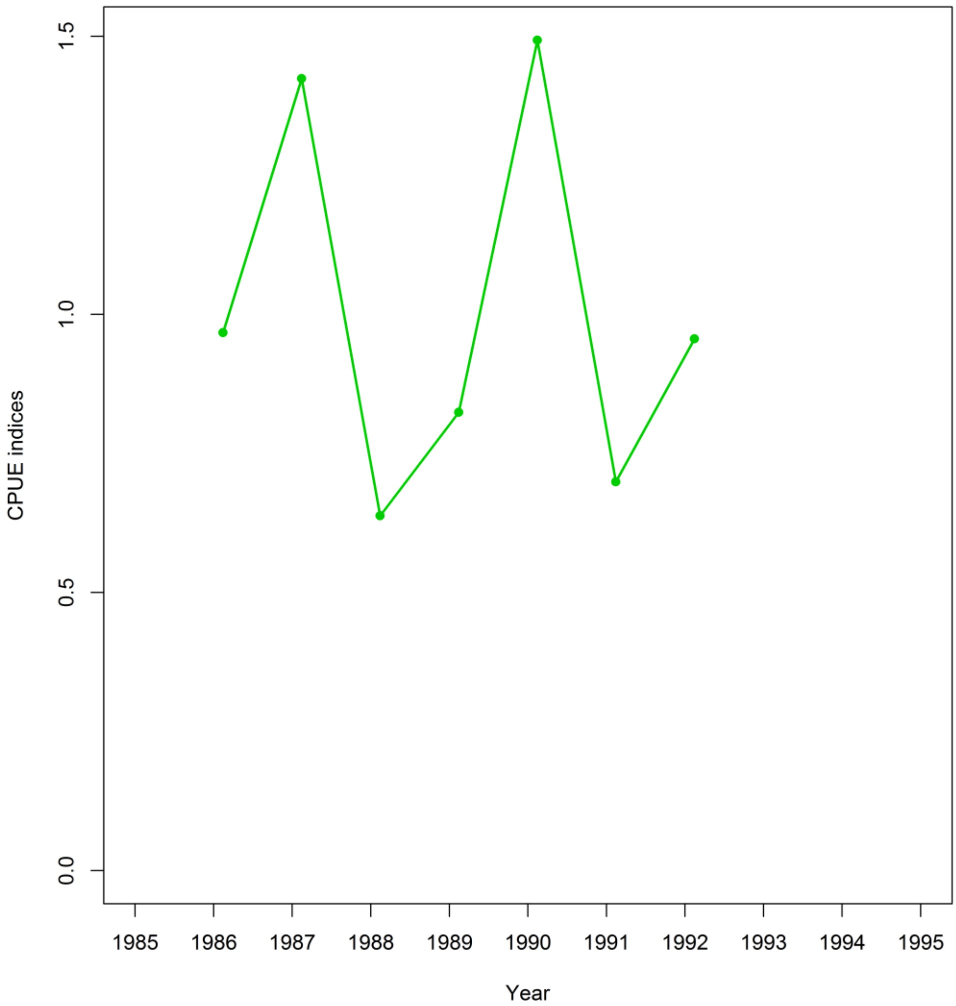


Figure 7. Annual drift net CPUE indices (source: Chang & Liu 1995).

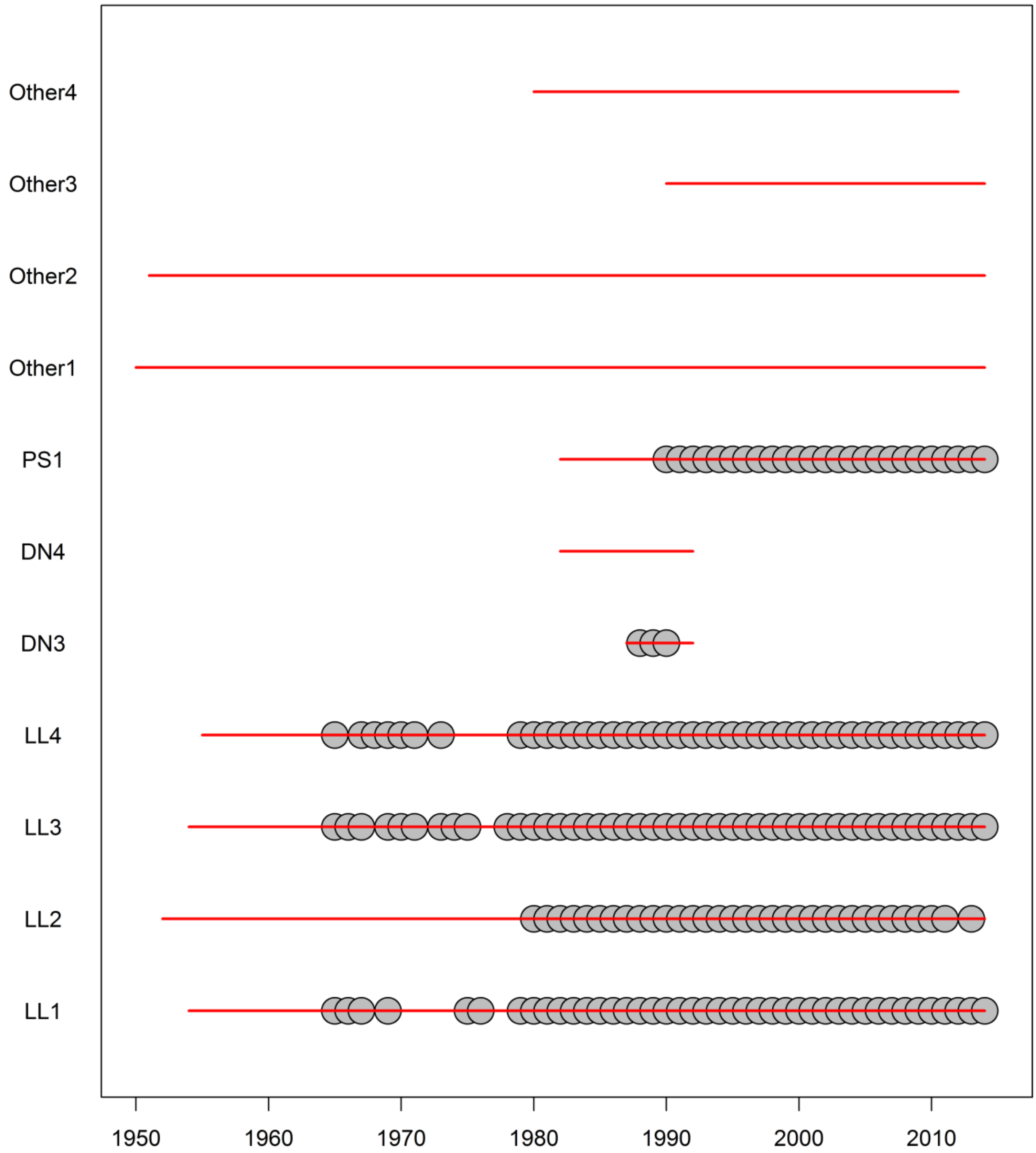


Figure 8. The availability of length sampling data from each fishery by year. The grey circles denote the presence of samples in a specific year. The red horizontal lines indicate the time period over which each fishery operated.

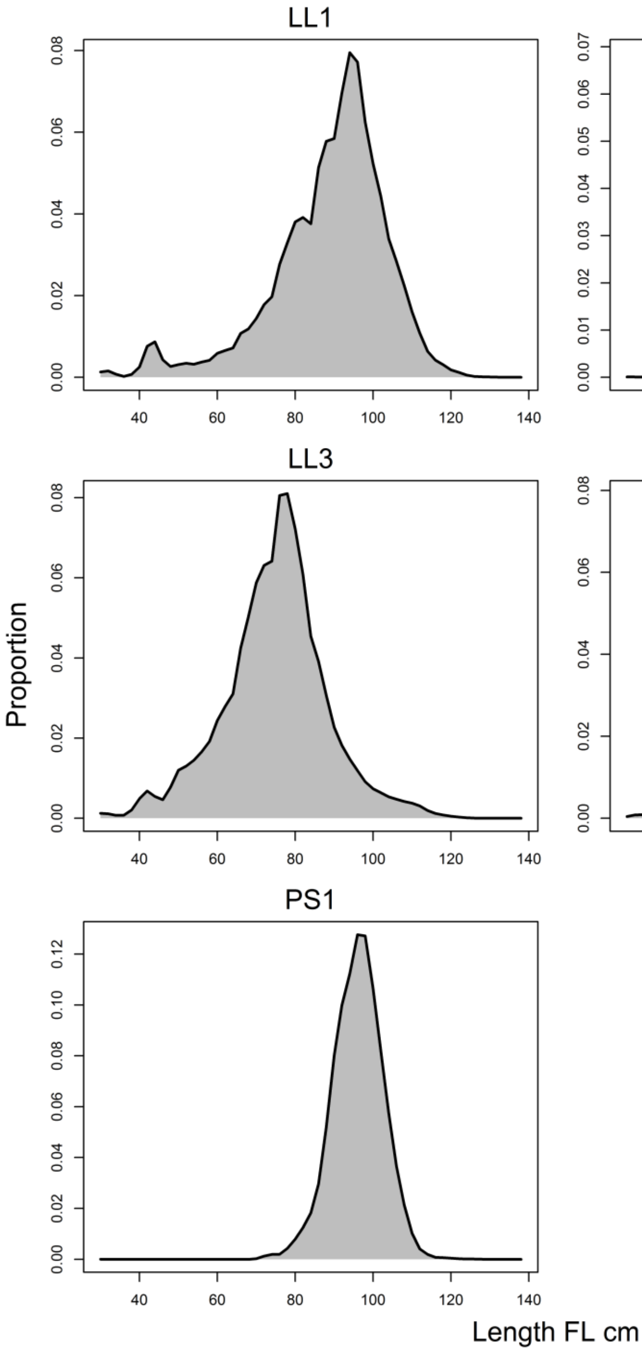


Figure 9. Aggregated length compositions of albacore sampled from the principal fisheries, all years combined.

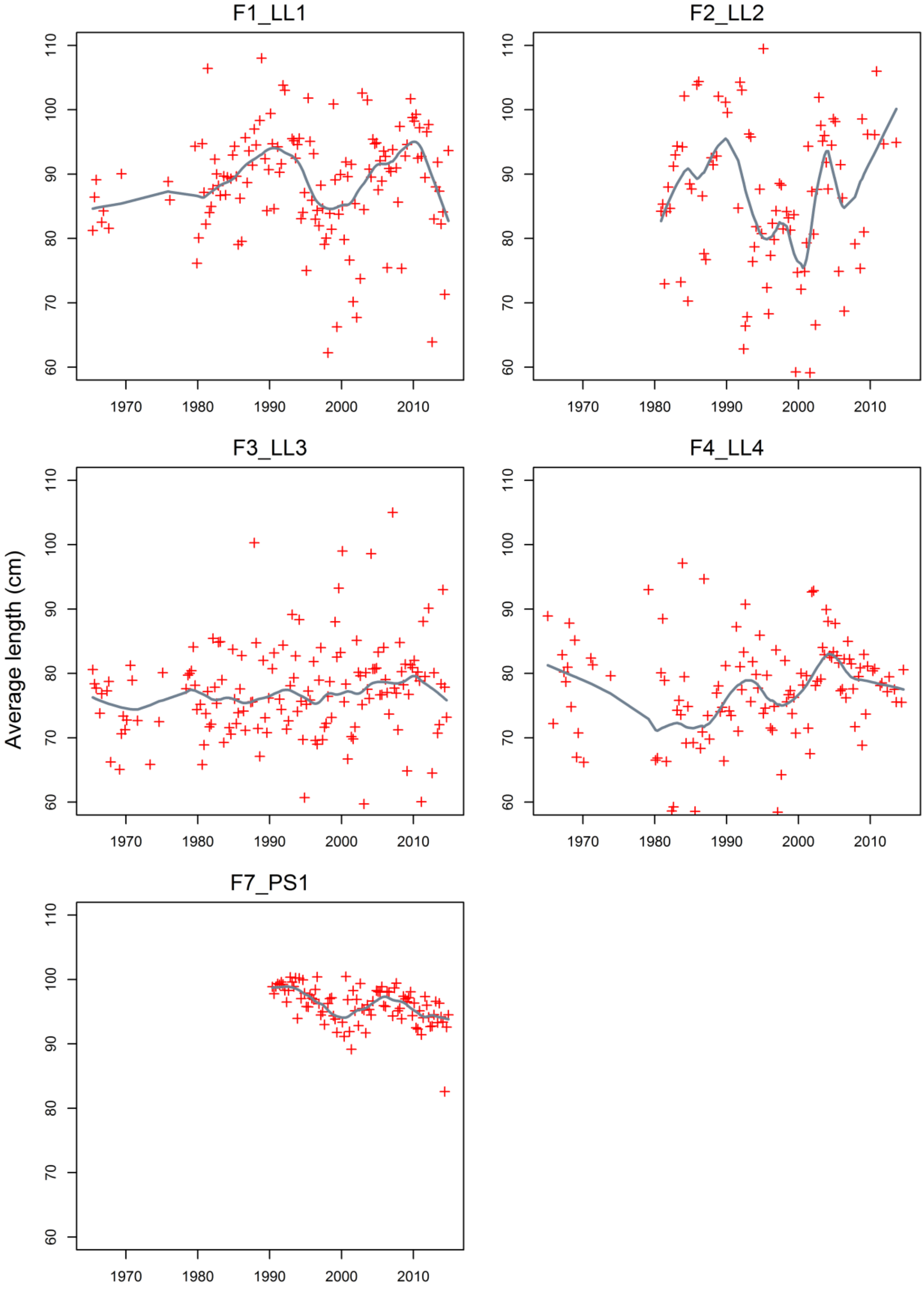


Figure 10. Mean length (fork length, cm) of albacore sampled from the principal fisheries by quarter. The grey line represents the fit of a lowess smoother to each data set.

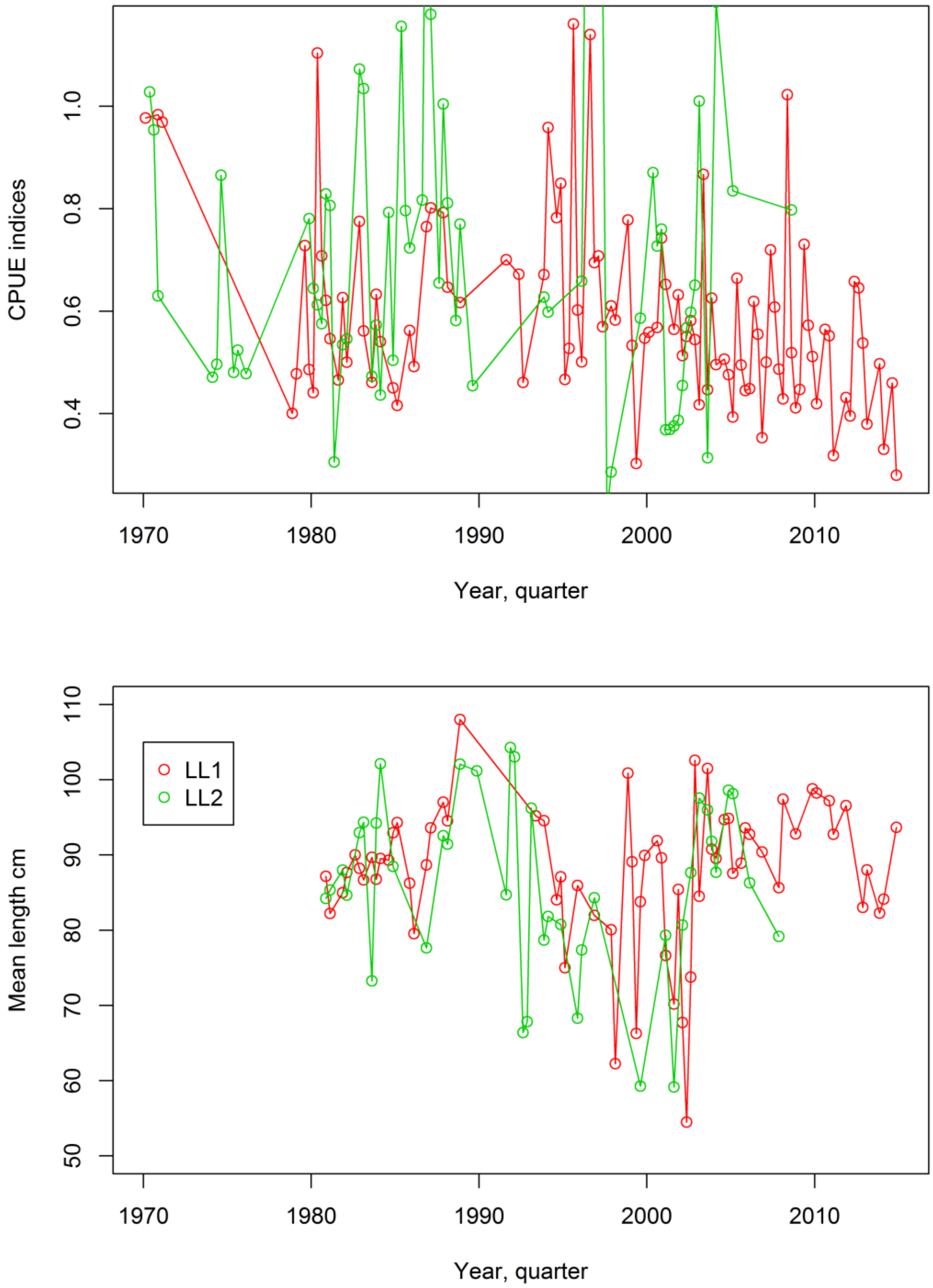


Figure 11. A comparison of the trends LL CPUE indices (top panel) and average length of albacore sampled from the longline fisheries (bottom panel) from the LL1 and LL2 fisheries.

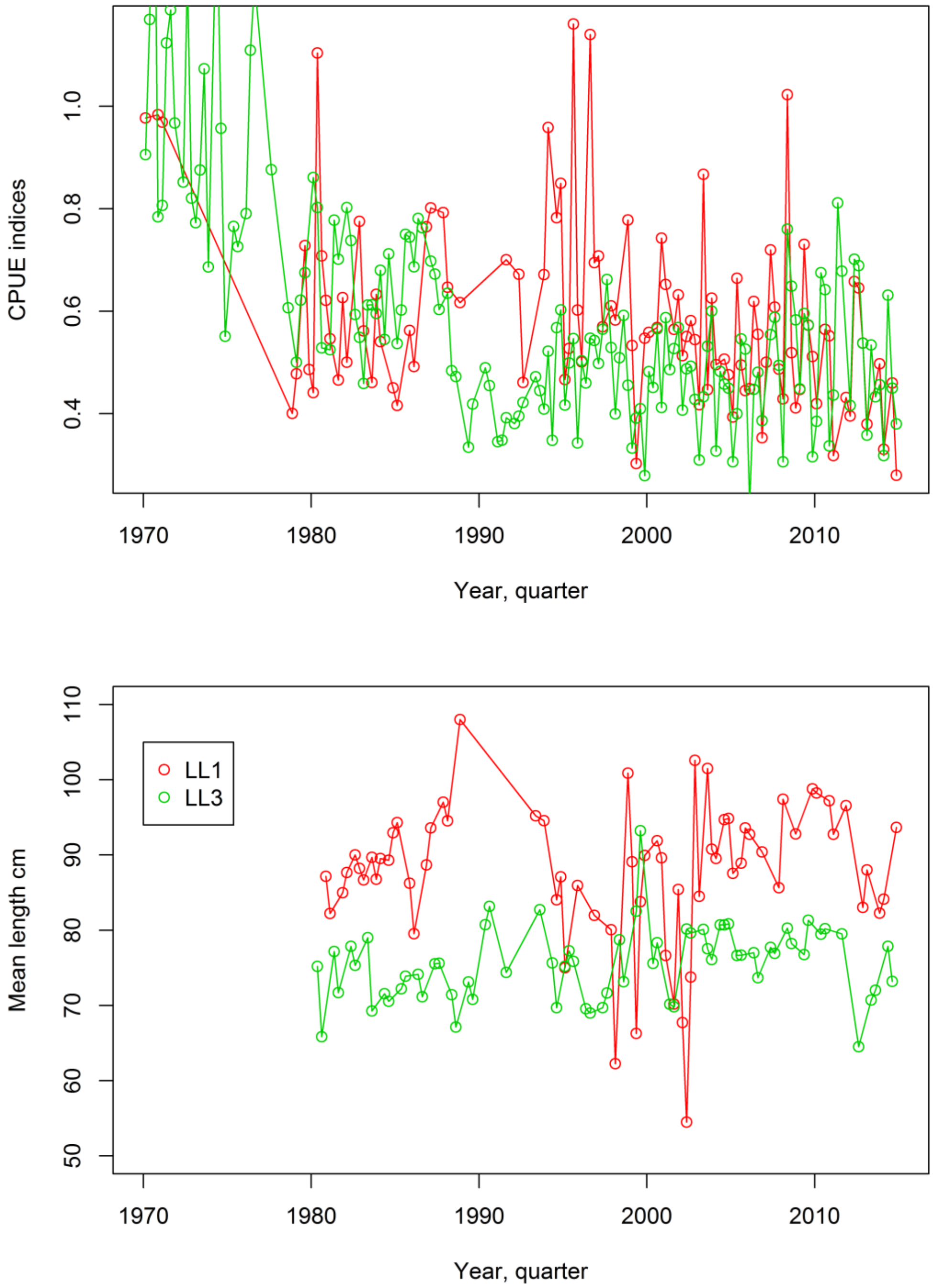


Figure 12. A comparison of the trends in LL CPUE indices (top panel) and average length of albacore sampled from the longline fisheries (bottom panel) from the LL1 and LL3 fisheries.

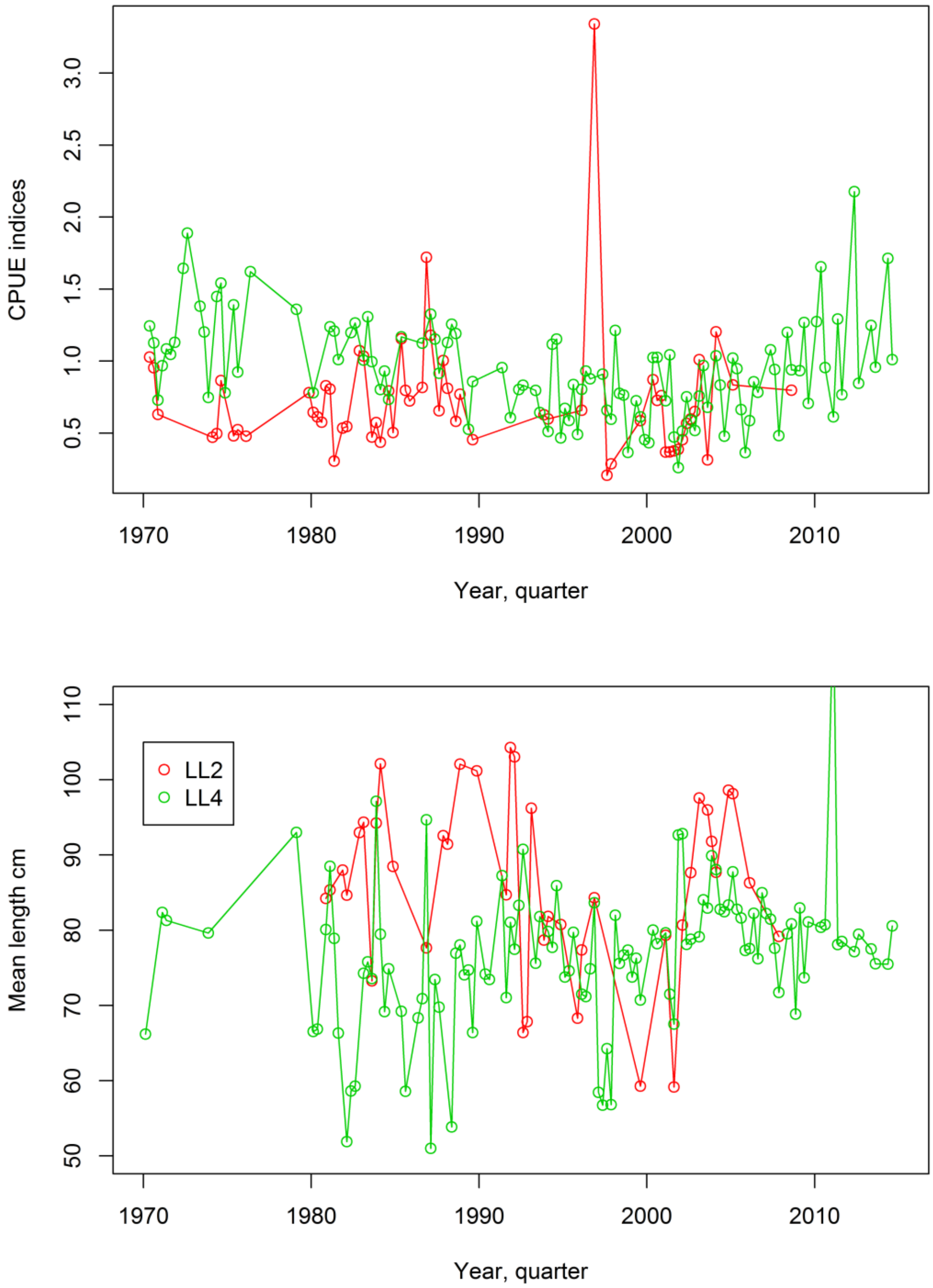


Figure 13. A comparison of the trends in LL CPUE indices (top panel) and average length of albacore sampled from the longline fisheries (bottom panel) from the LL2 and LL4 fisheries.

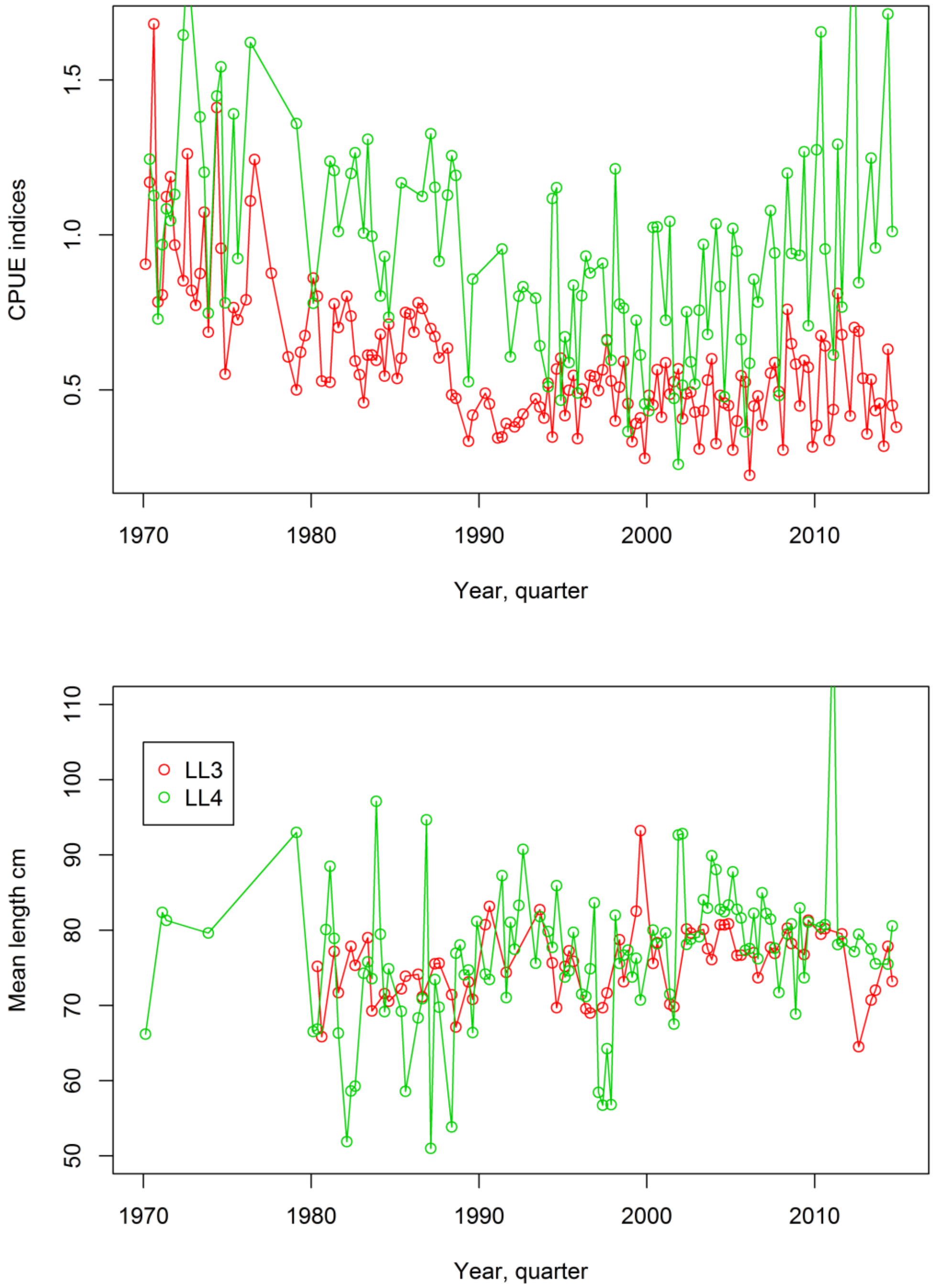


Figure 14. A comparison of the trends LL CPUE indices (top panel) and average length of albacore sampled from the longline fisheries (bottom panel) from the LL3 and LL4 fisheries.

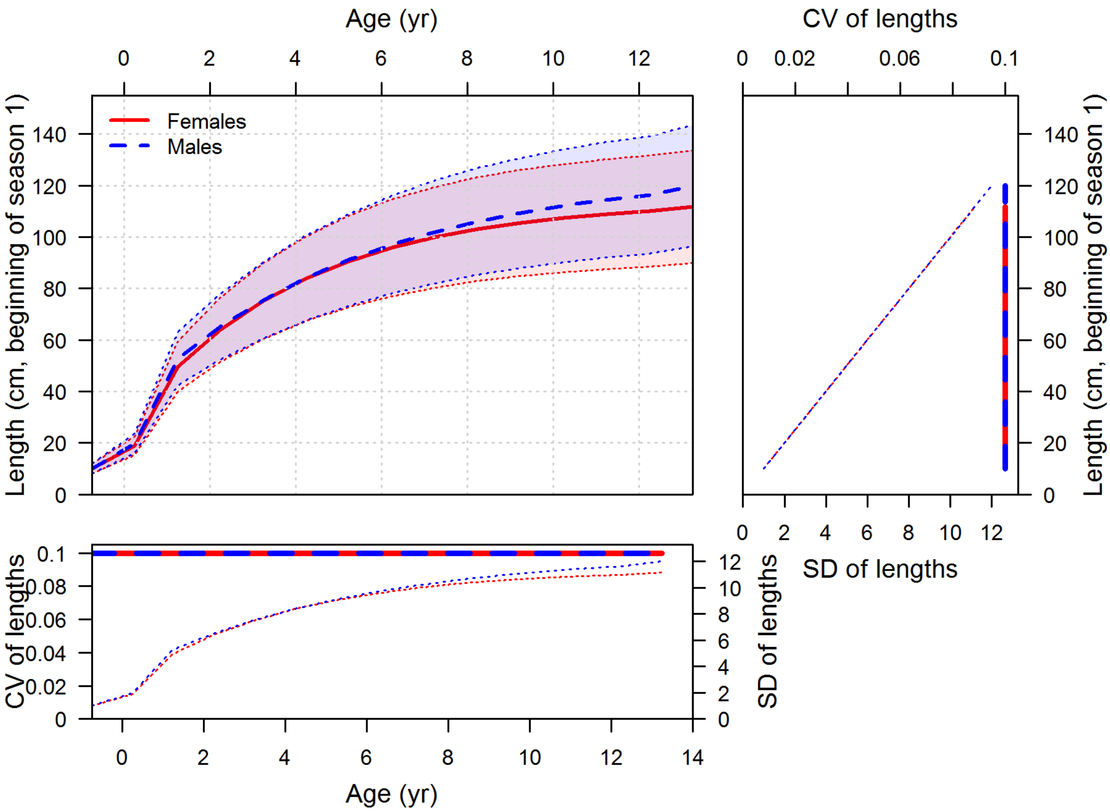


Figure 15. Growth function for female and male albacore.

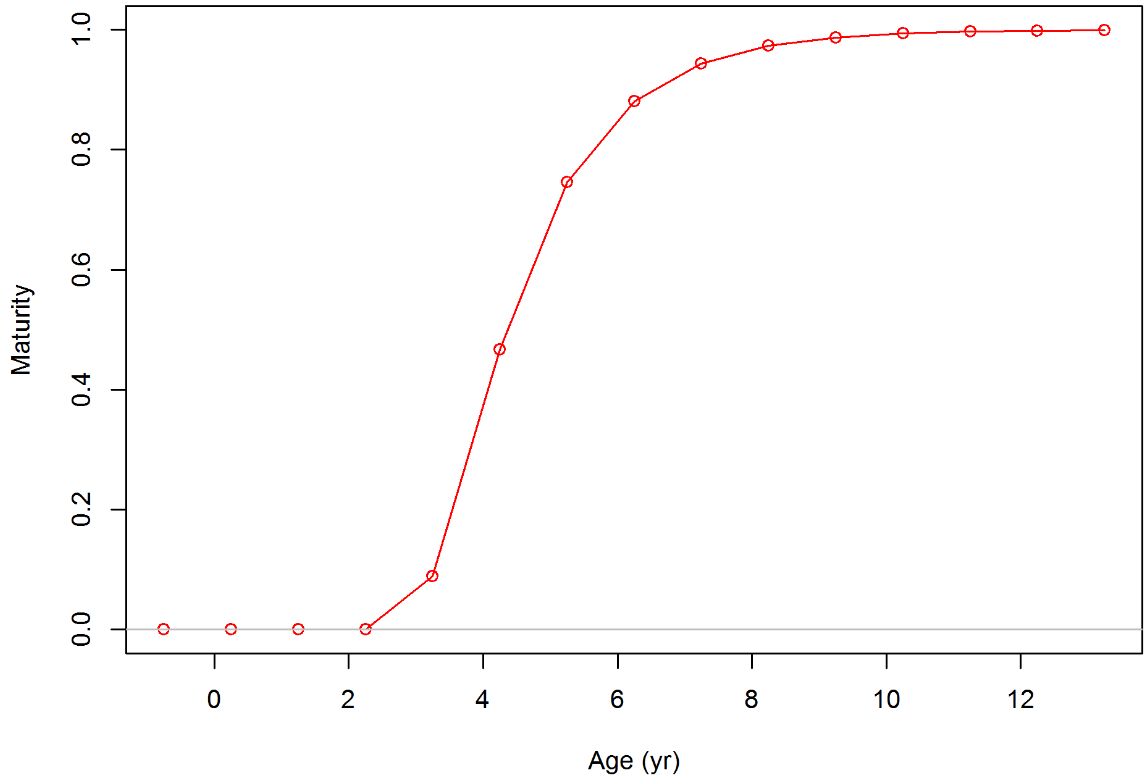


Figure 16. Maturity OGIVE for female albacore.

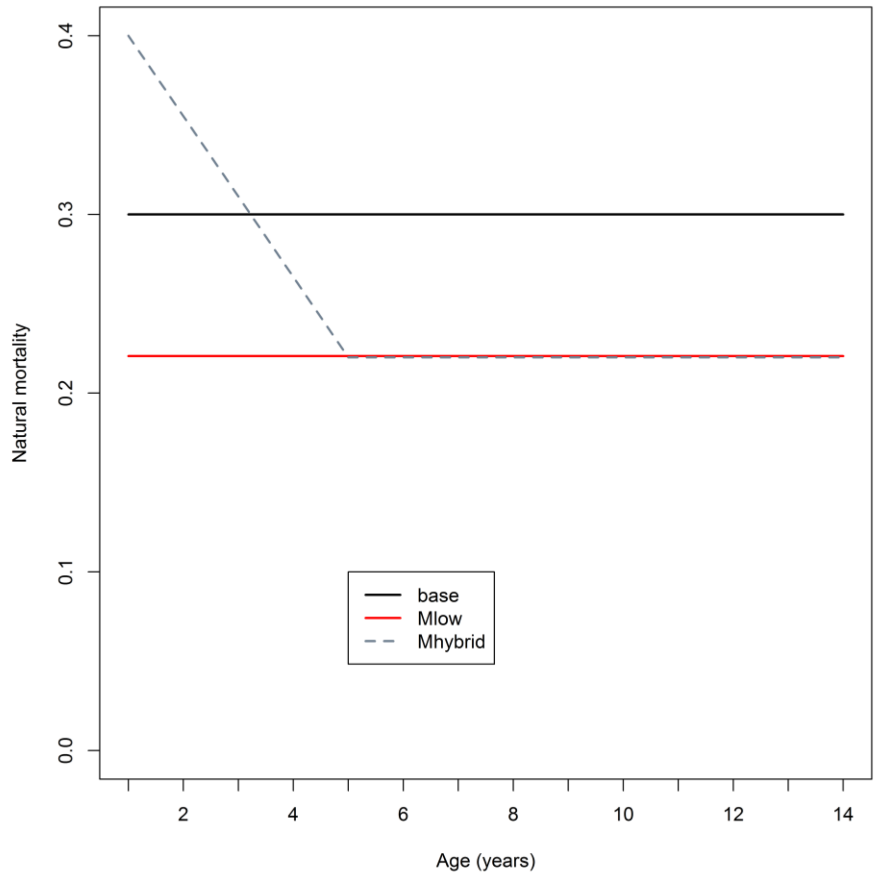


Figure 17. The age-specific natural mortality schedule assumed for the assessment model (*Base*) and other age-specific *M* schedules from various model options (see text for details).

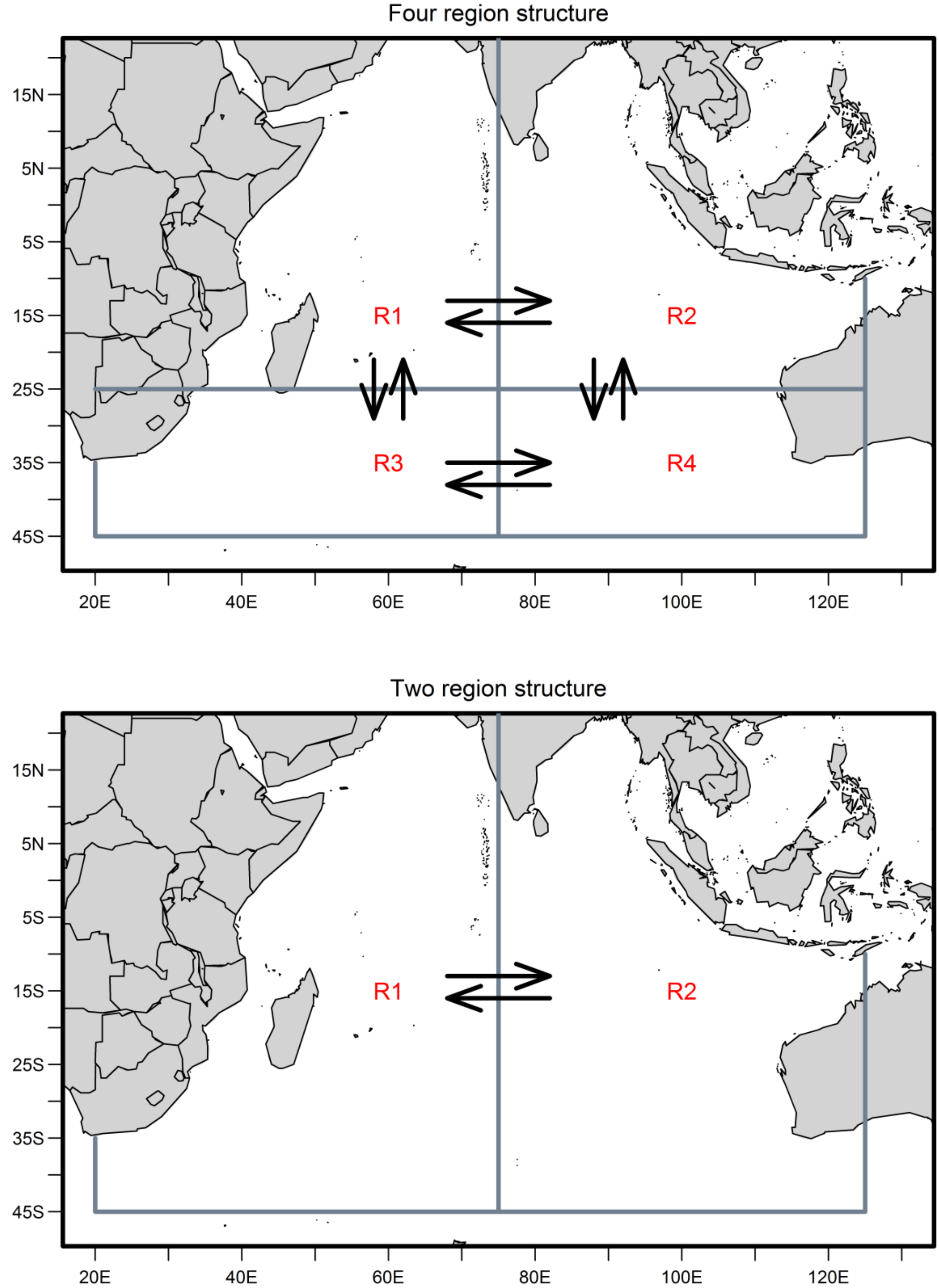


Figure 18. Alternative spatial structures investigated during the preliminary stock assessment modelling.

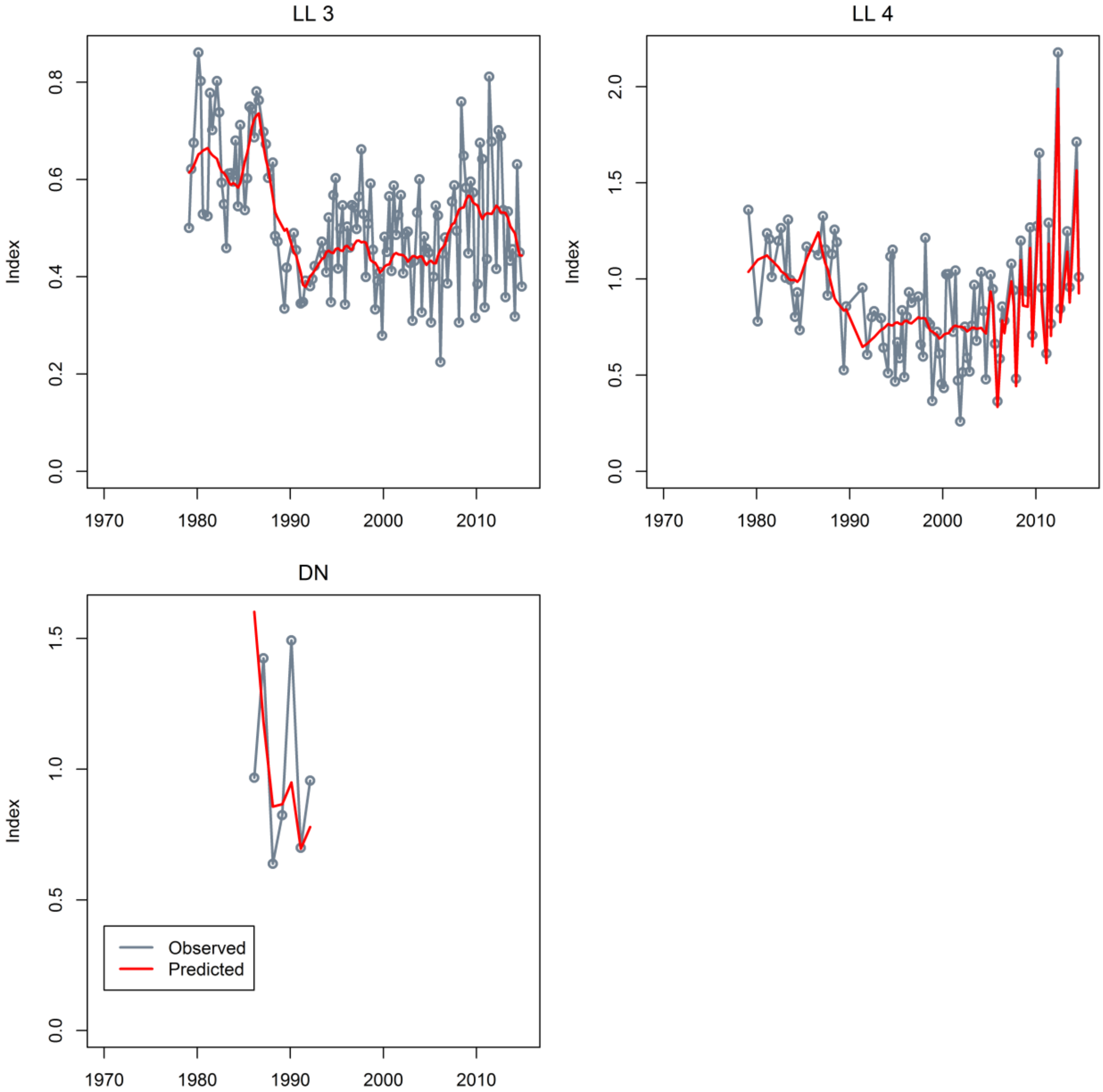


Figure 19. Fit to the longline and drift net (DN) CPUE indices for the reference model, excluding the northern LL CPUE indices.

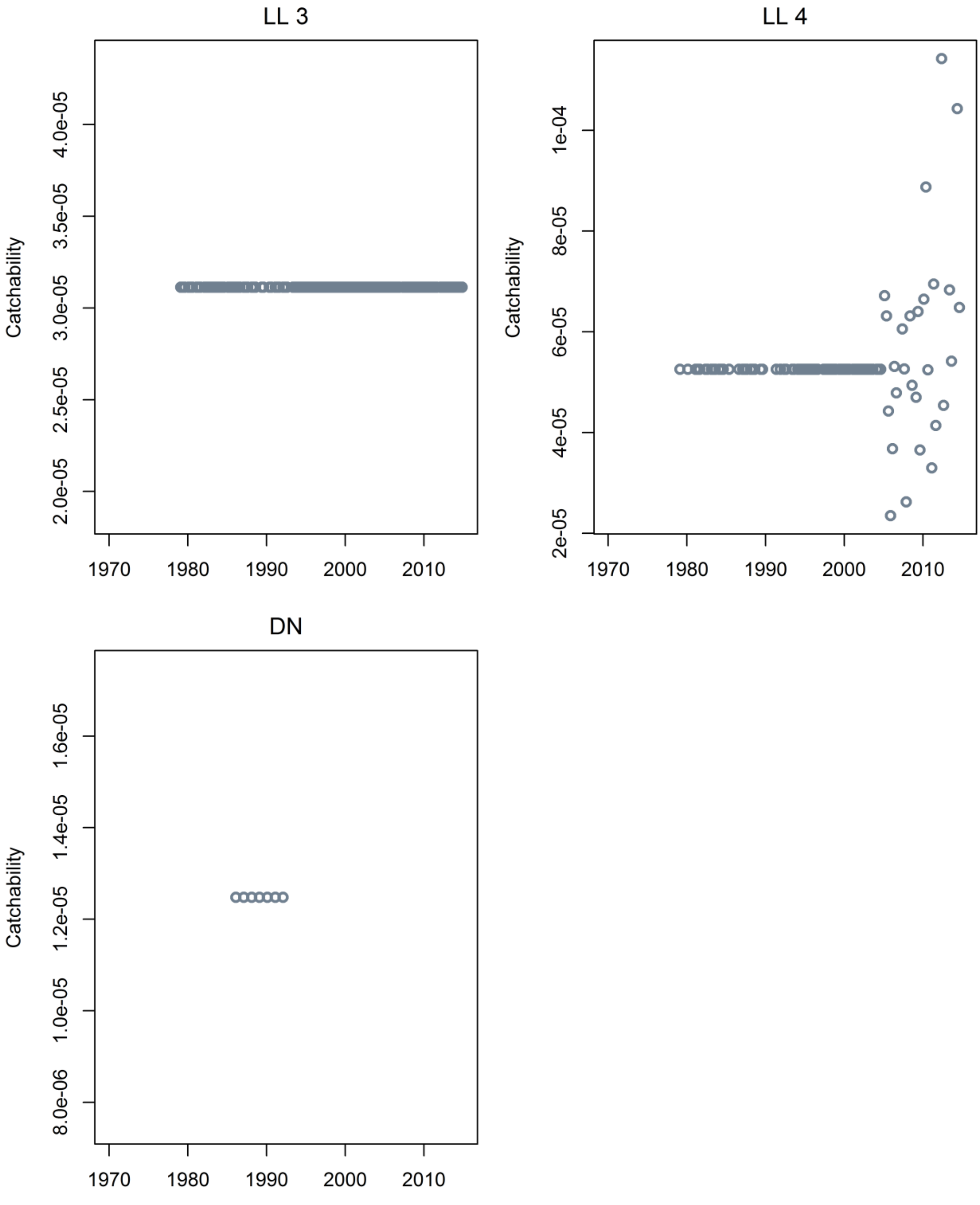


Figure 20. Quarterly catchability coefficients for the three sets of CPUE indices included in the reference model.

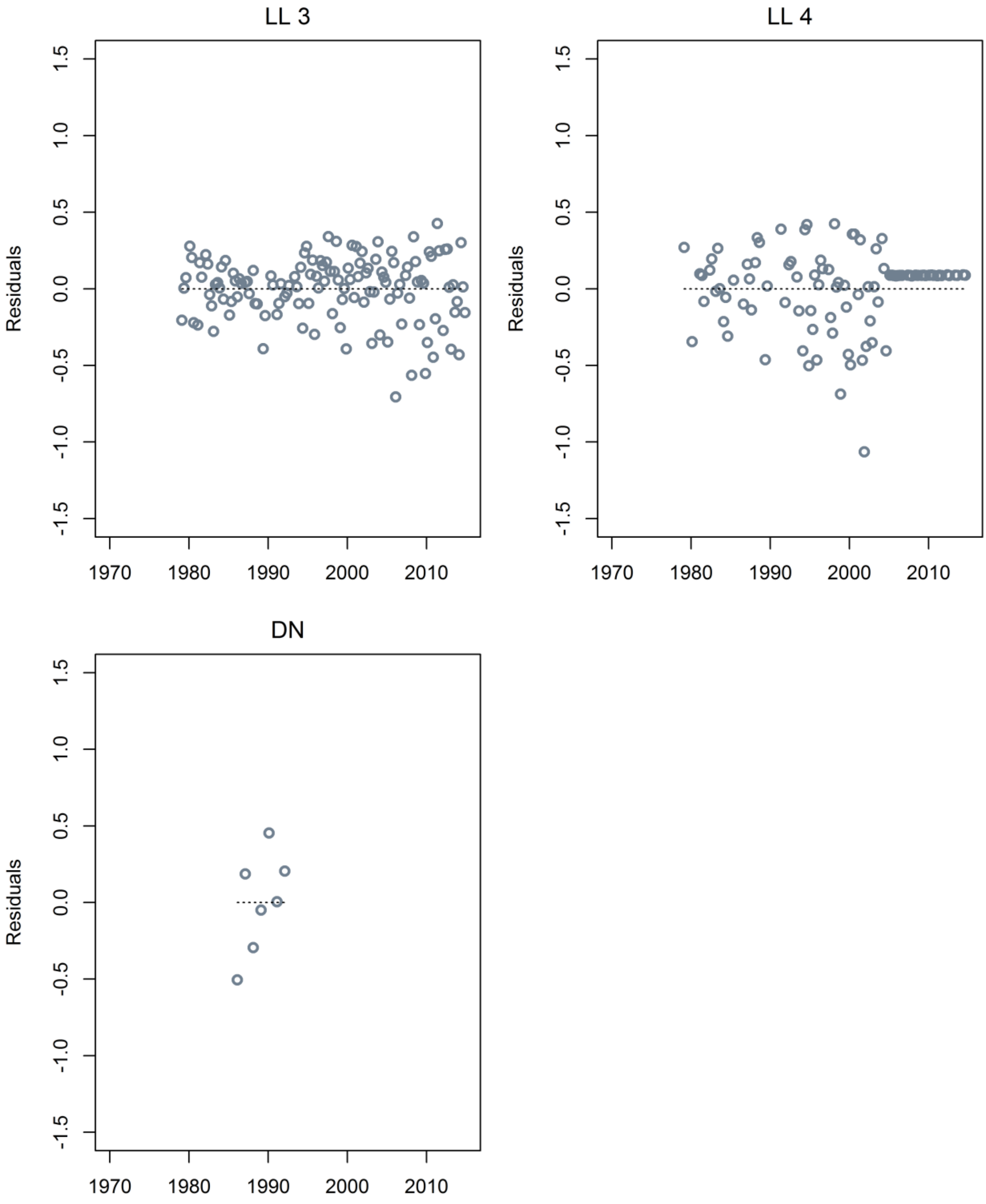


Figure 21. Residuals (observed – expected) from the fit to the longline and drift net (DN) CPUE indices for the reference model.

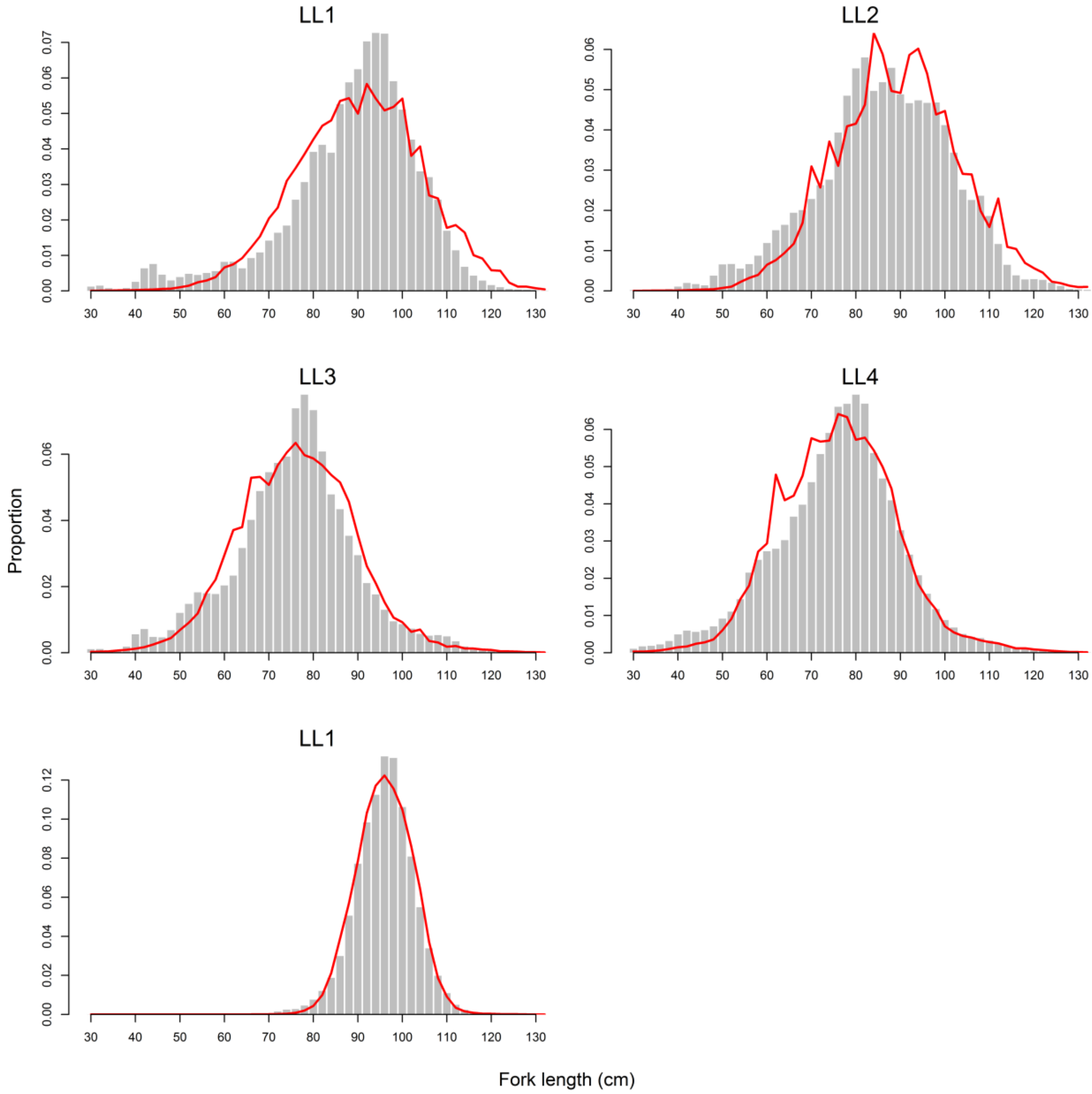


Figure 22. Observed (grey bars) and predicted (red line) length compositions (in 2 cm intervals) for each fishery aggregated over time.

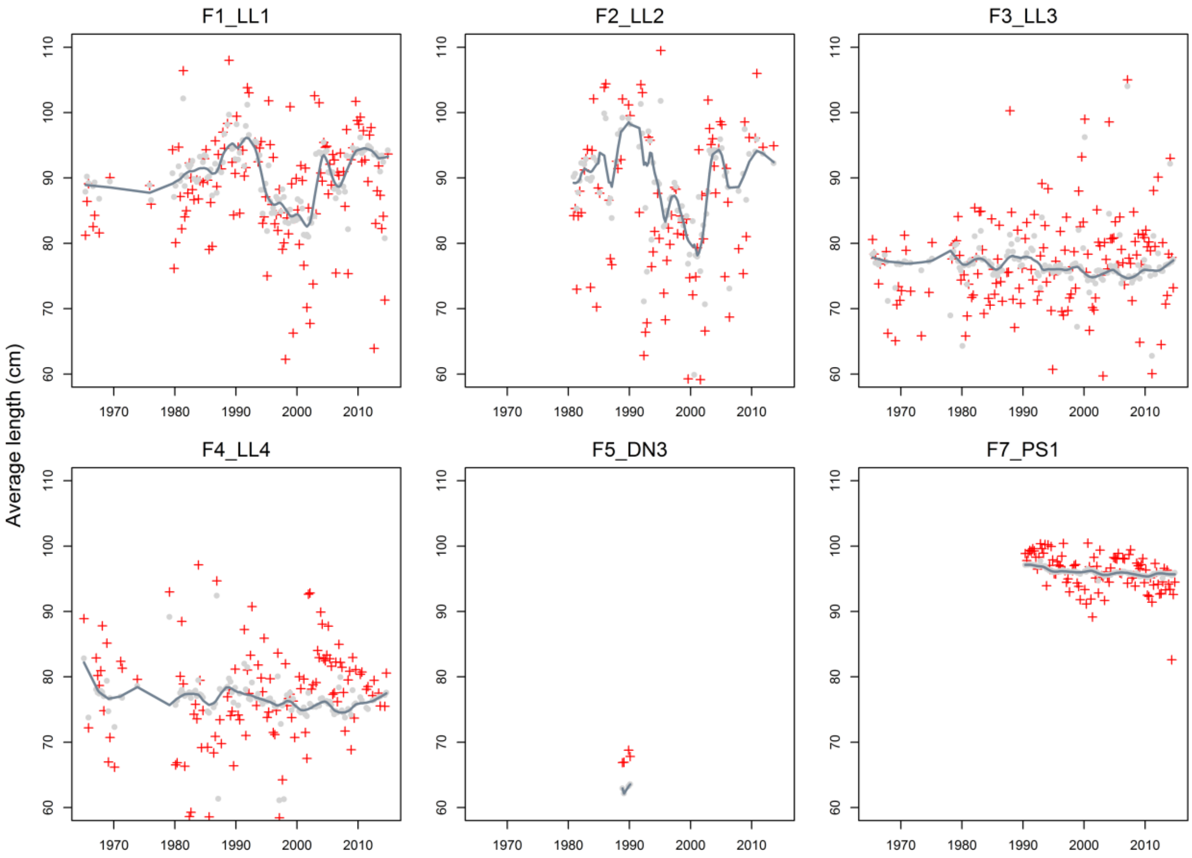


Figure 23: A comparison of the observed (red points) and predicted (grey points) average fish length (FL, cm) of albacore tuna by fishery (*CPUEsouth* model option).

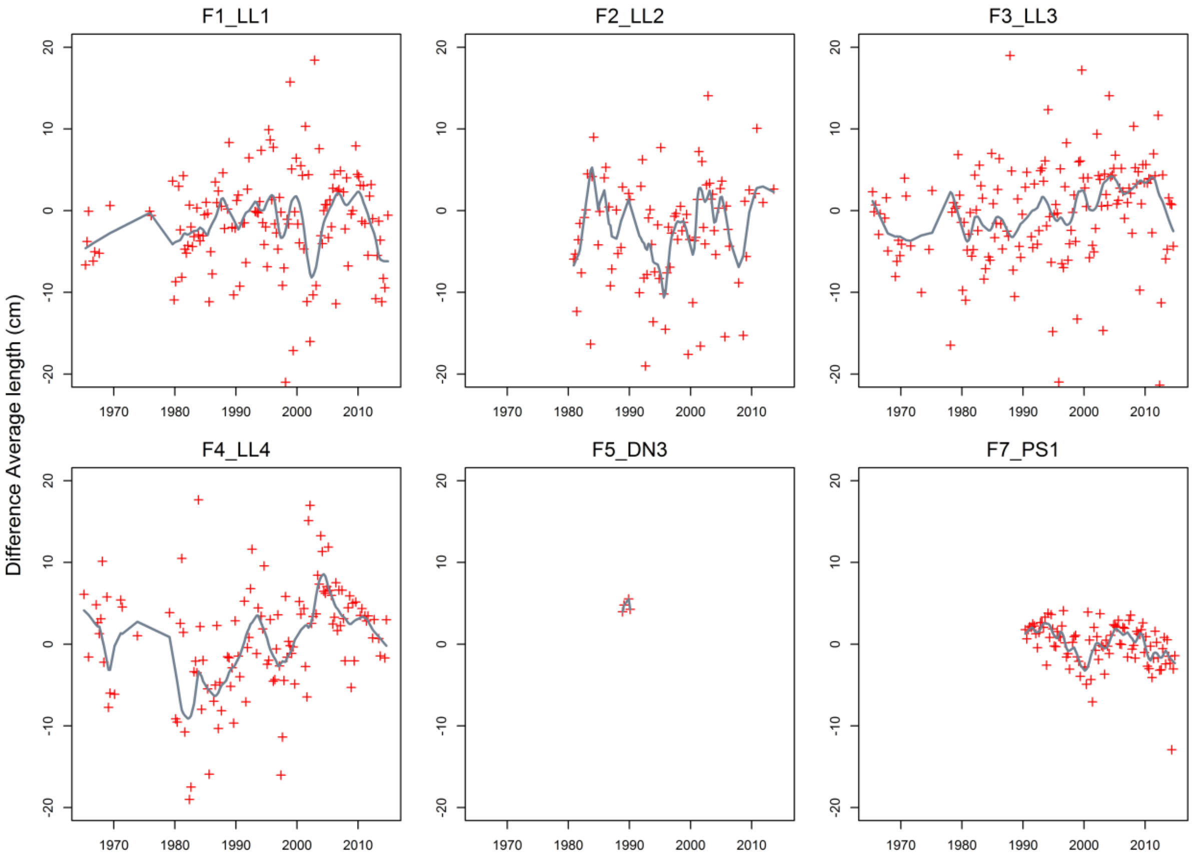
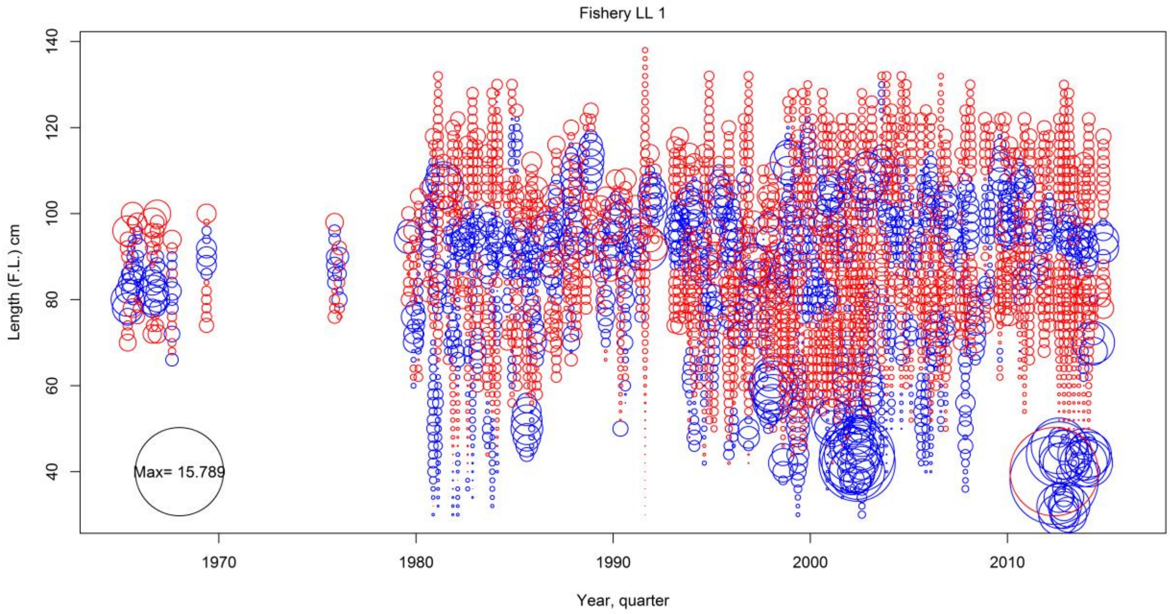


Figure 24: Trends in the difference between the observed (red points) and predicted (grey points) average fish length (FL, cm) of albacore tuna by fishery (*CPUEsouth* model option). The grey line represents a lowess smoothing fit the the data points.



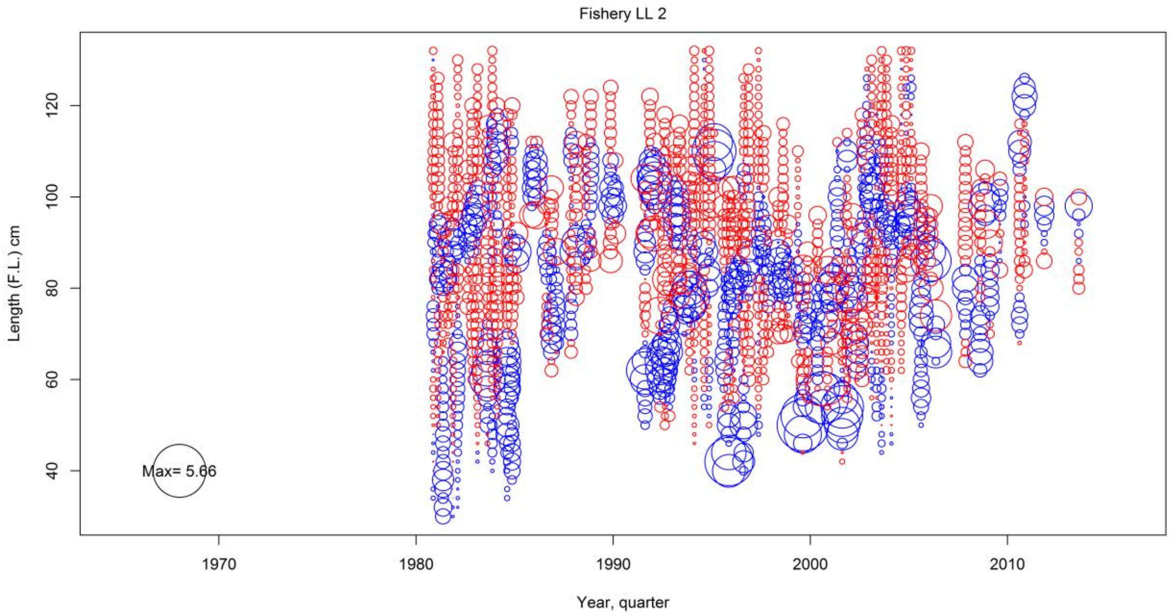
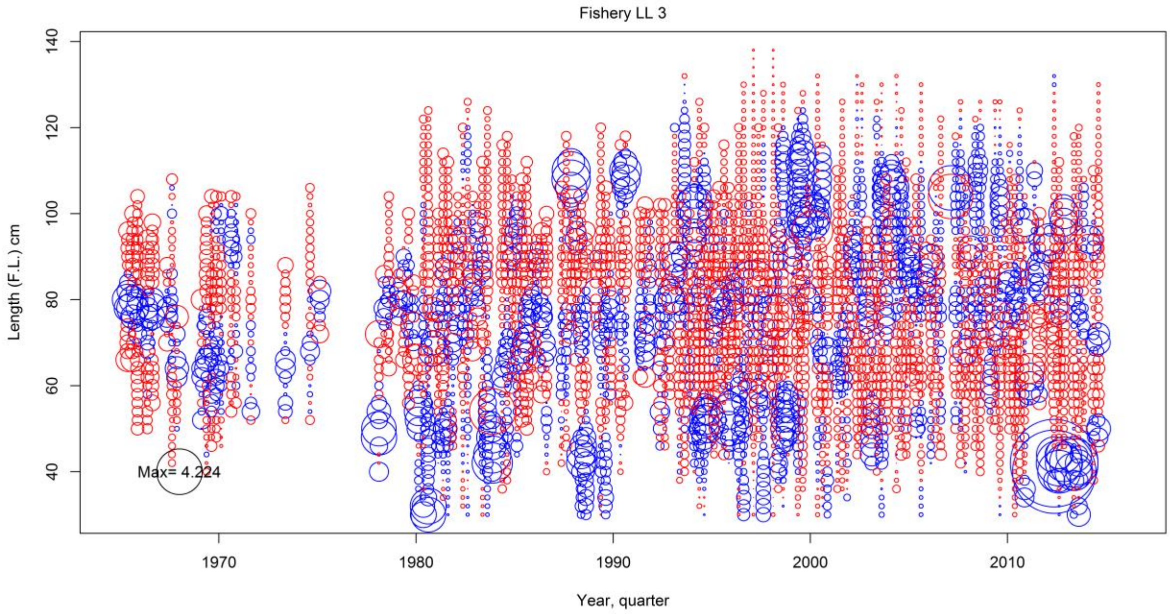


Figure 25. Pearson residuals from the fit to the length composition data from the LL1 and LL2 fisheries (reference model). Positive residuals are plotted as blue circles; negative residuals are plotted as red circles; the magnitude of the residual is proportional to the area of the circle.



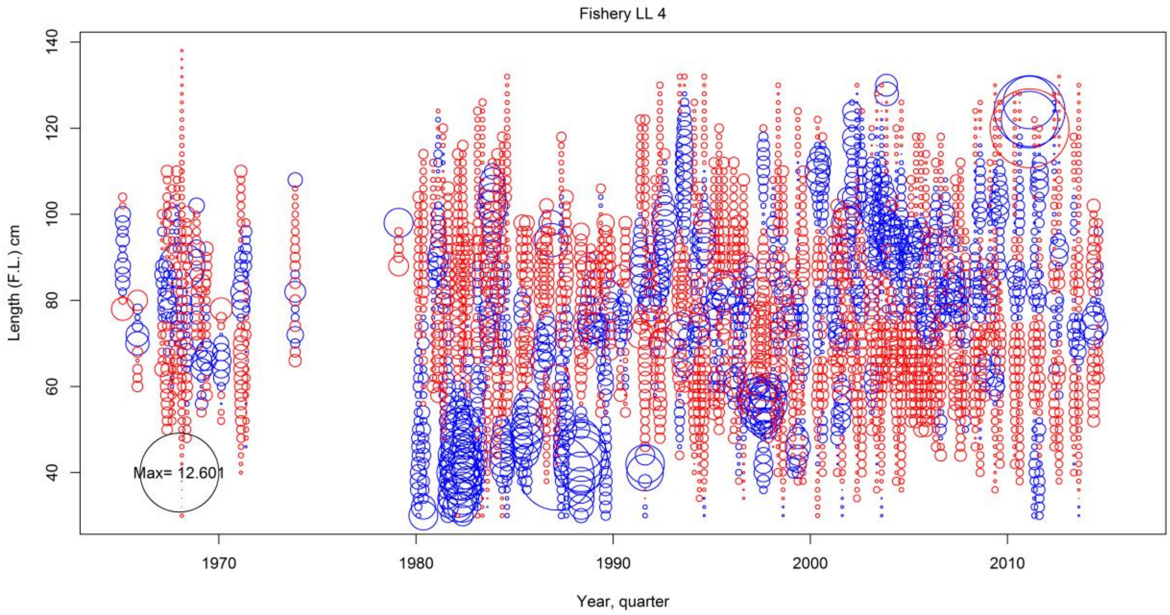


Figure 26. Pearson residuals from the fit to the length composition data from the LL3 and LL4 fisheries (reference model). Positive residuals are plotted as blue circles; negative residuals are plotted as red circles; the magnitude of the residual is proportional to the area of the circle.

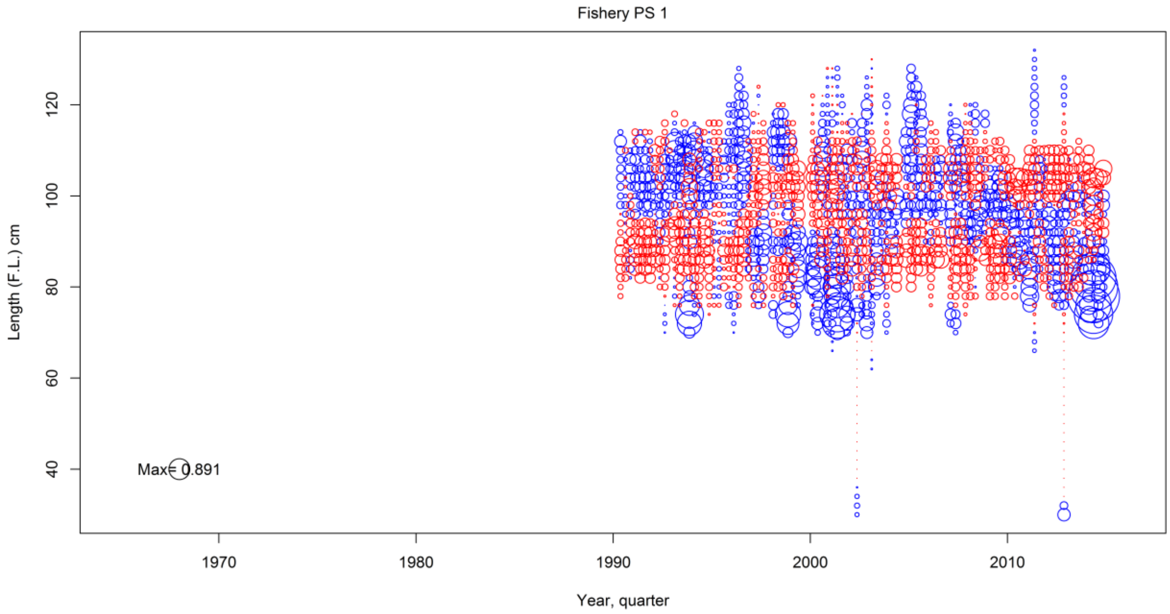


Figure 27. Pearson residuals from the fit to the length composition data from the PS1 fishery (reference model). Positive residuals are plotted as blue circles; negative residuals are plotted as red circles; the magnitude of the residual is proportional to the area of the circle.

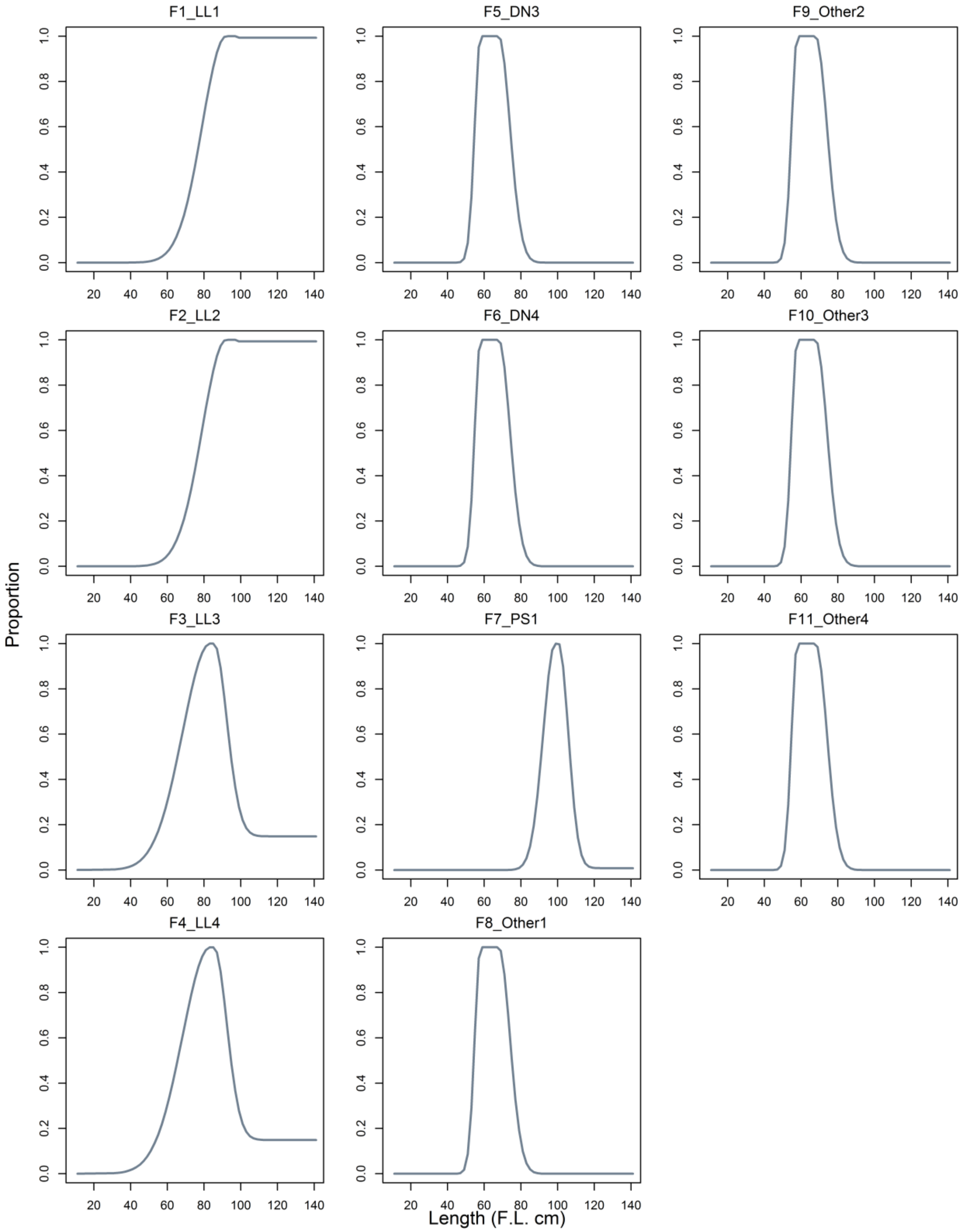


Figure 28. Length specific selectivity by fishery.

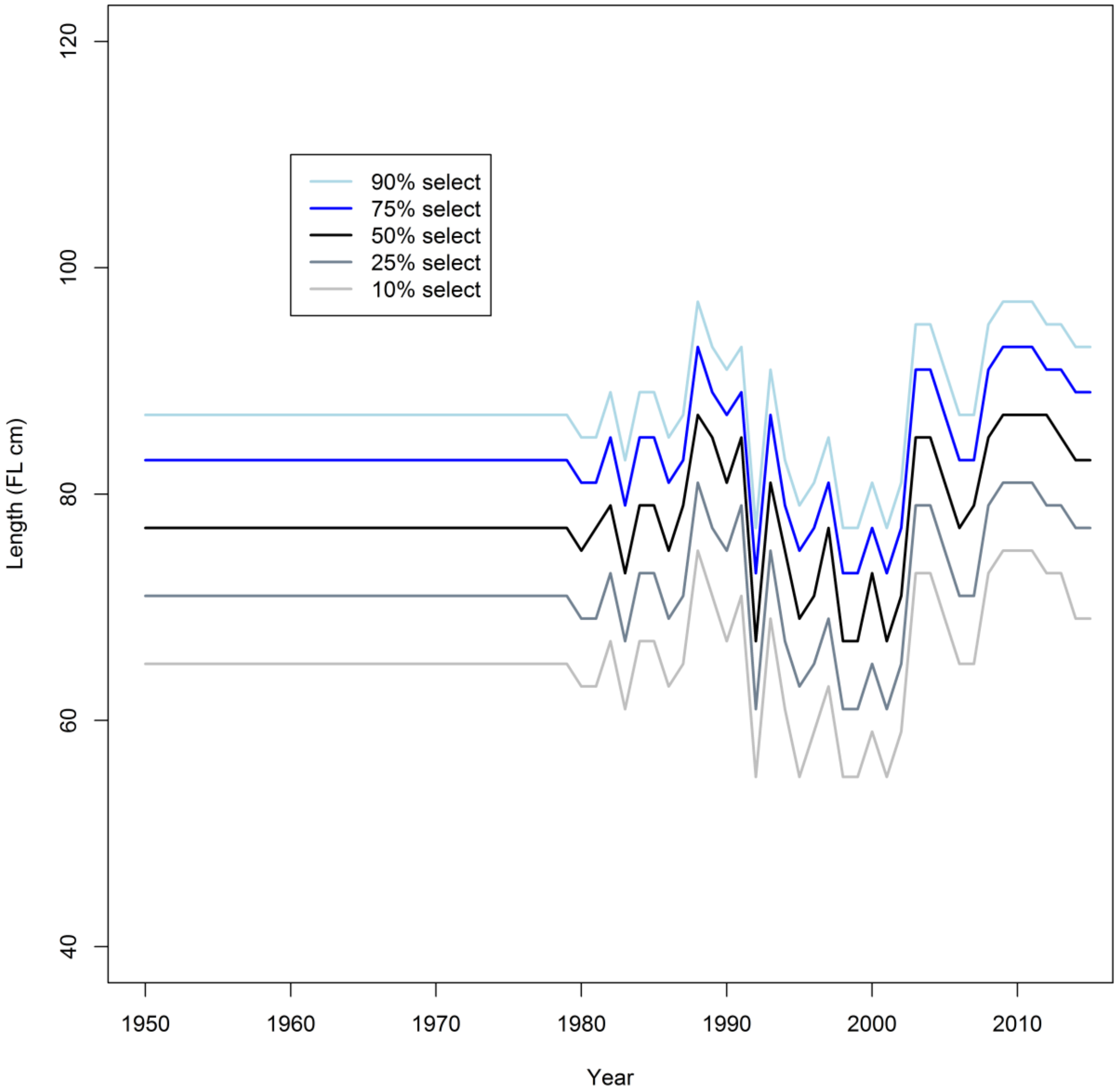


Figure 29: Temporal variation in the estimated selectivity for the northern longline fisheries (LL1 and LL2).

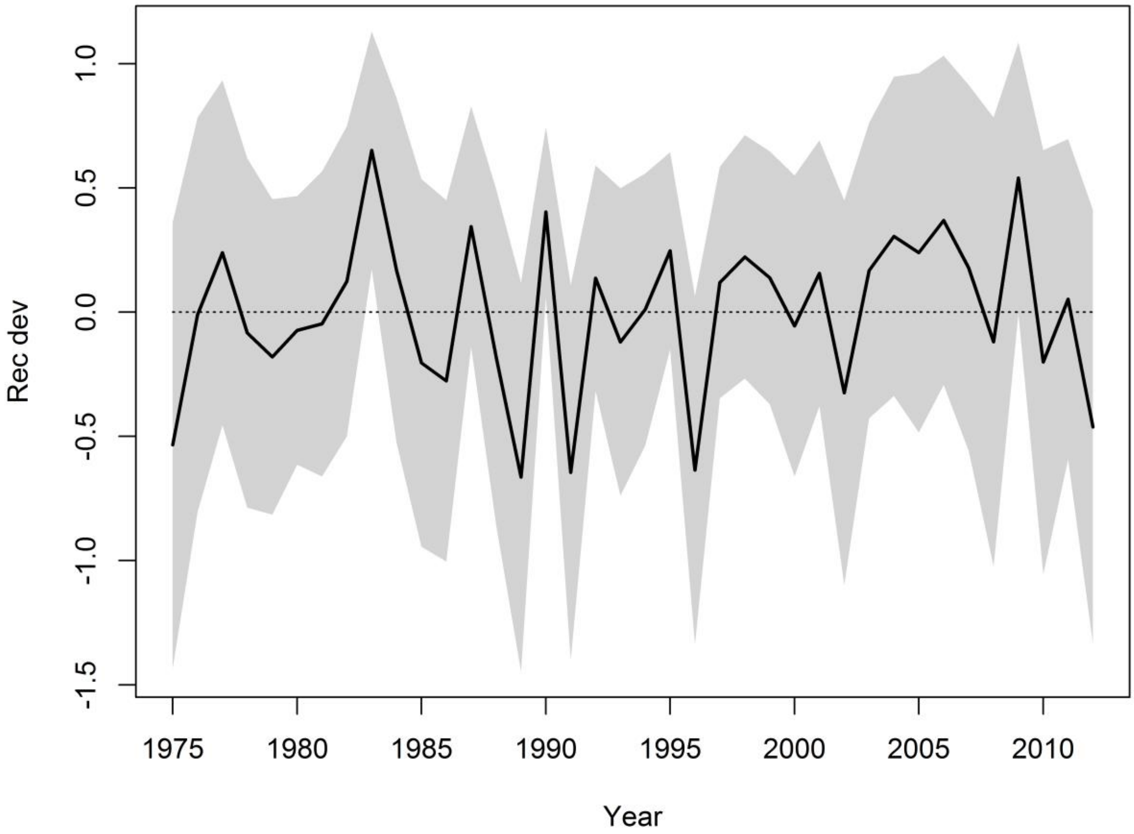


Figure 30. Estimated recruitment deviates and the associated 95% confidence interval for the *CPUEsouth* model.

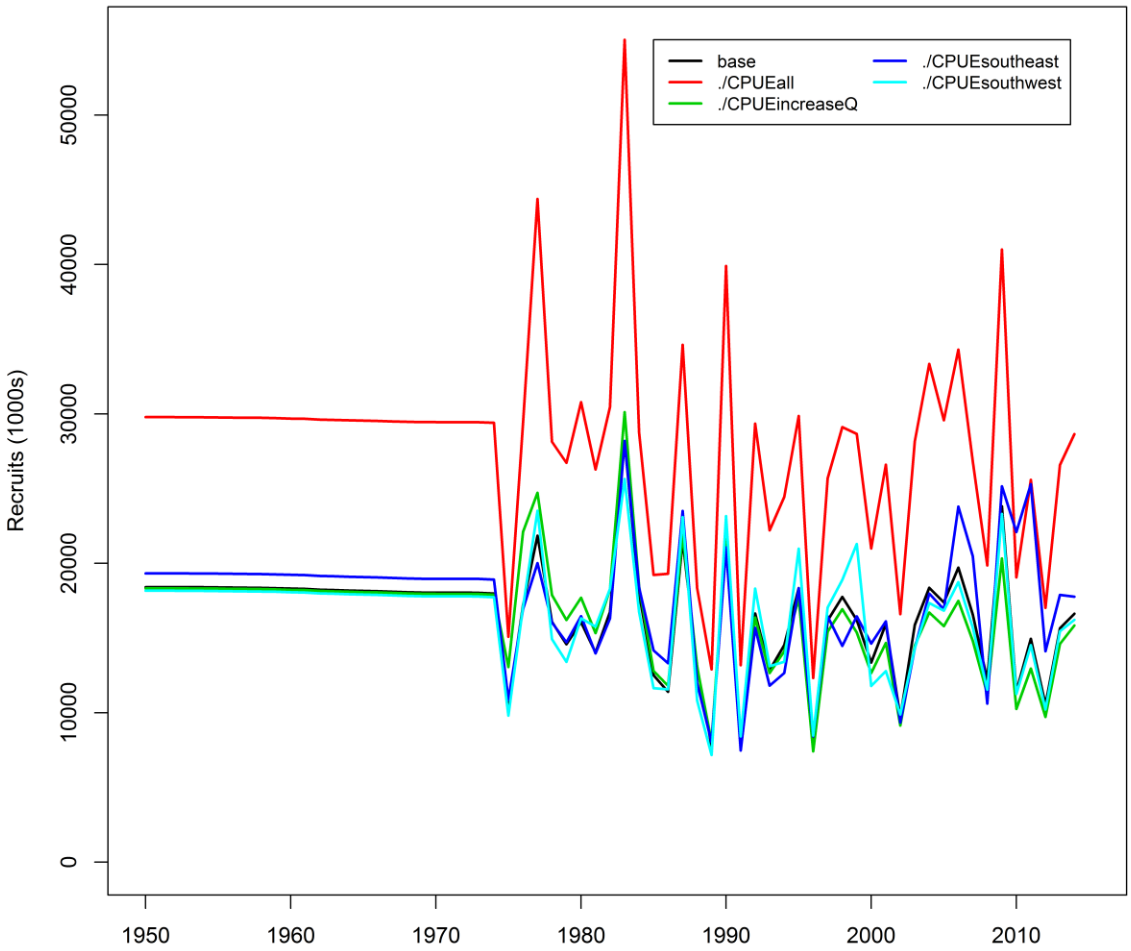


Figure 31. Estimated annual recruitment for the reference (base) model and alternative CPUE models.

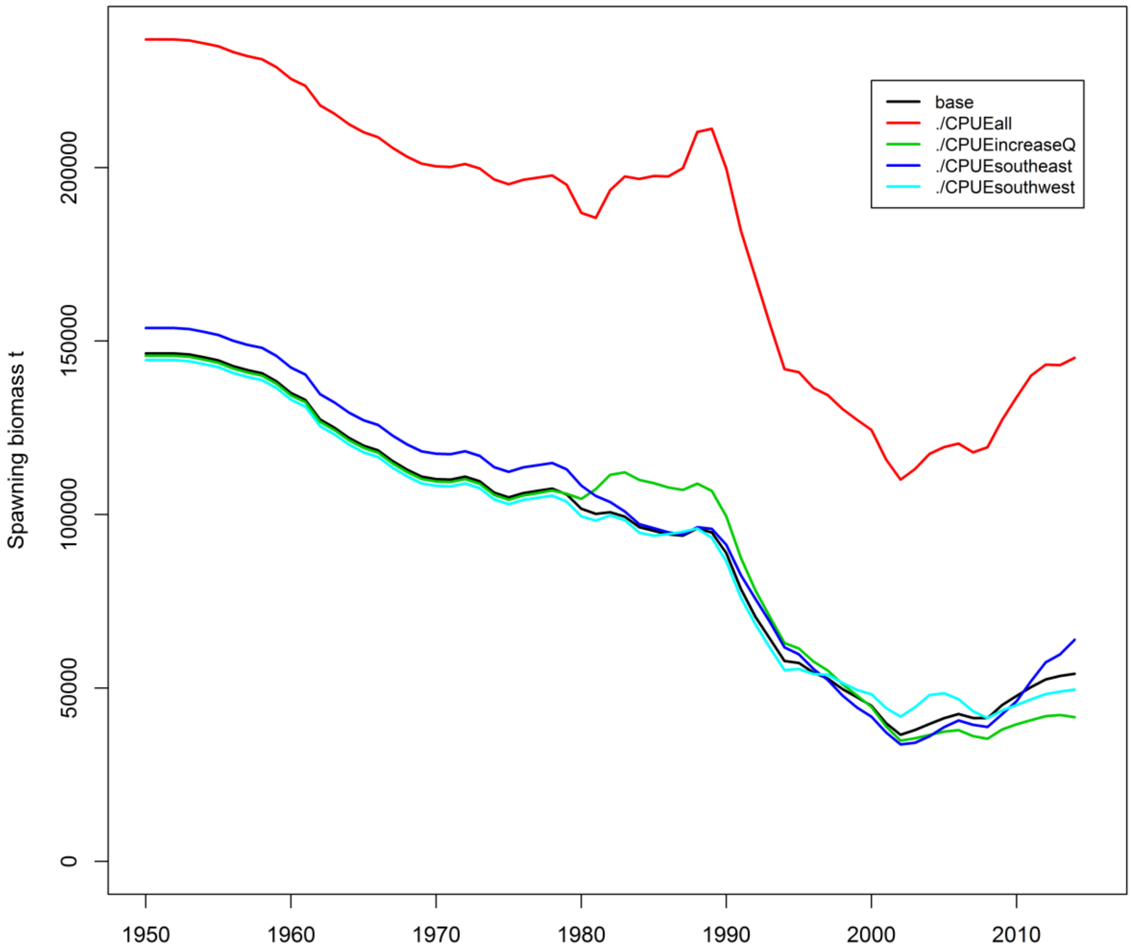


Figure 32. A comparison of the spawning biomass trajectory for the reference model and the alternative CPUE options.

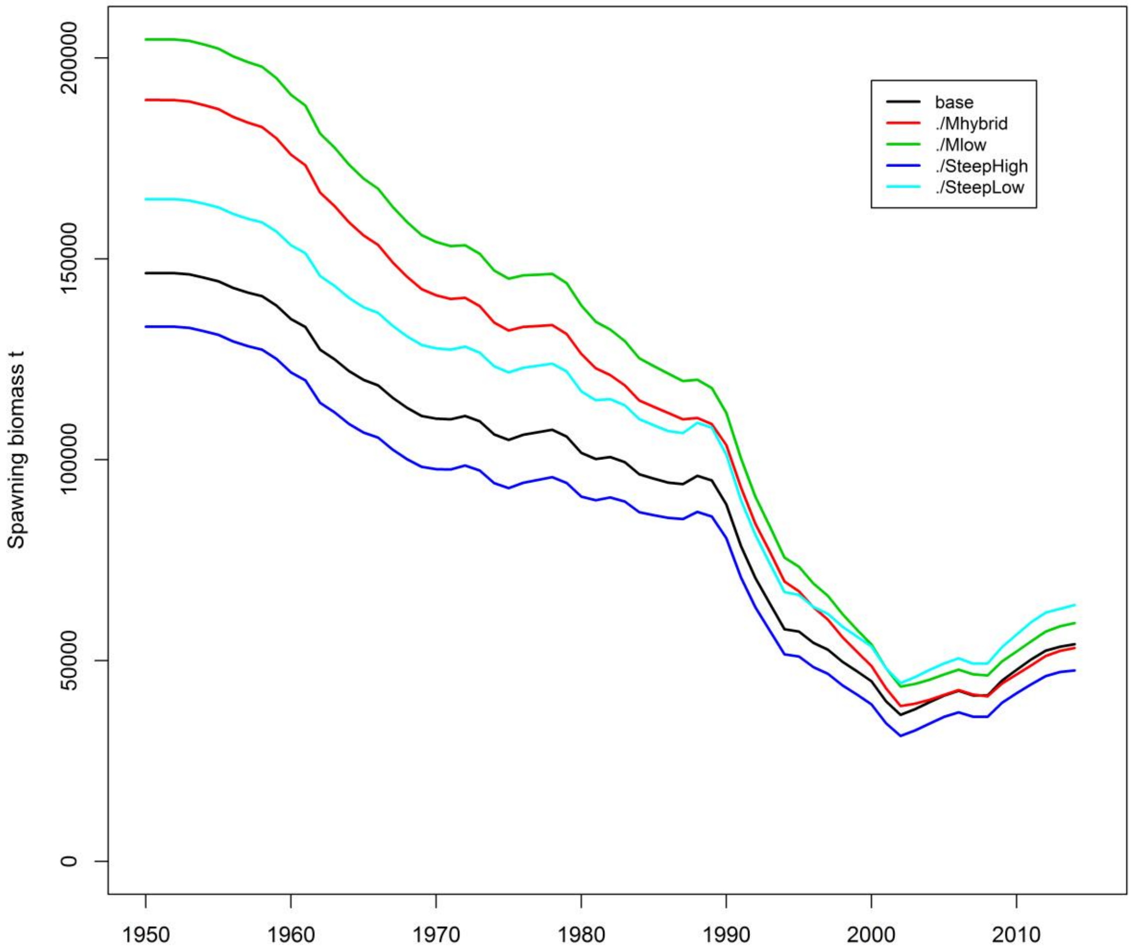


Figure 33. A comparison of the spawning biomass trajectory for the reference model and the model options with alternative biological parameters.

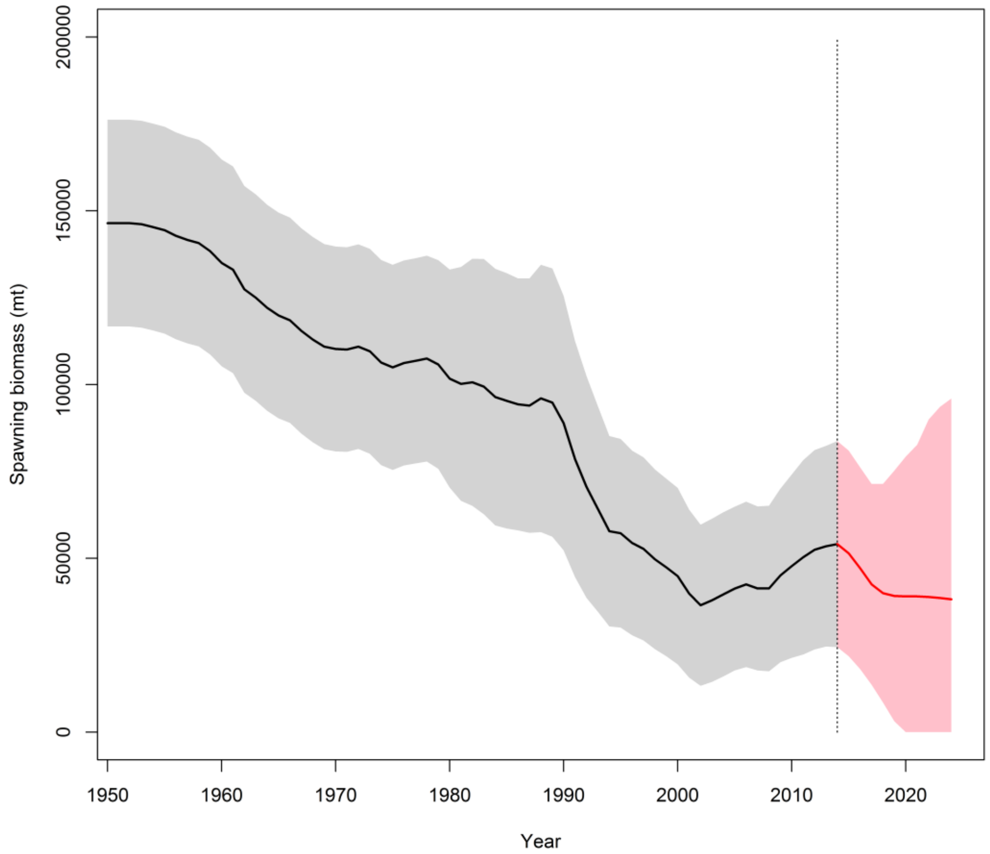


Figure 34. Spawning biomass trajectory and 95% confidence interval for the reference model (*CPUEsouth*) for the assessment period (black line) and the projection period (red line). The projection is based on the 2014 level of catch.

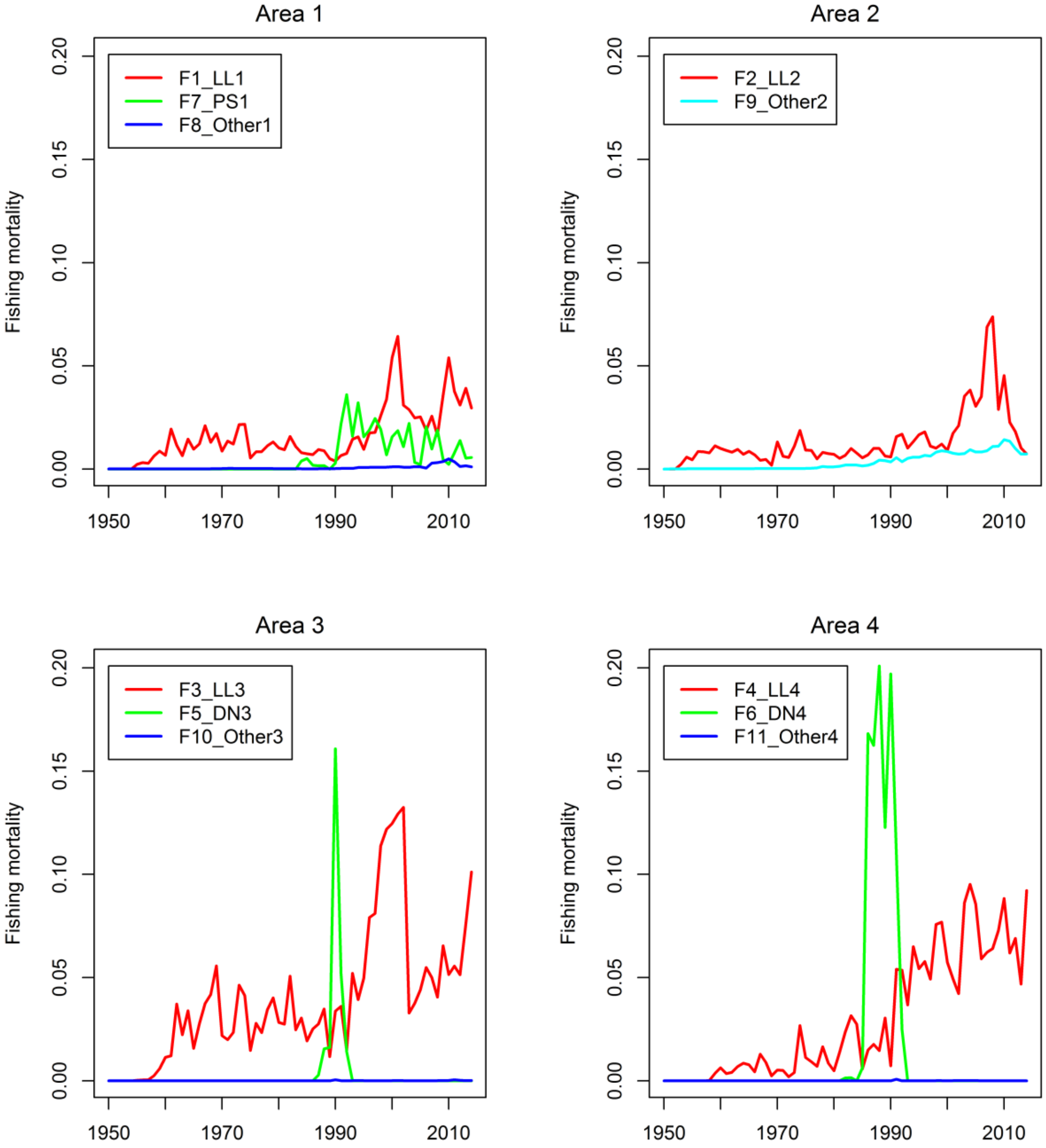


Figure 35. Trends in annual fishing mortality by fleet plotted by the area of operation of the fishery.

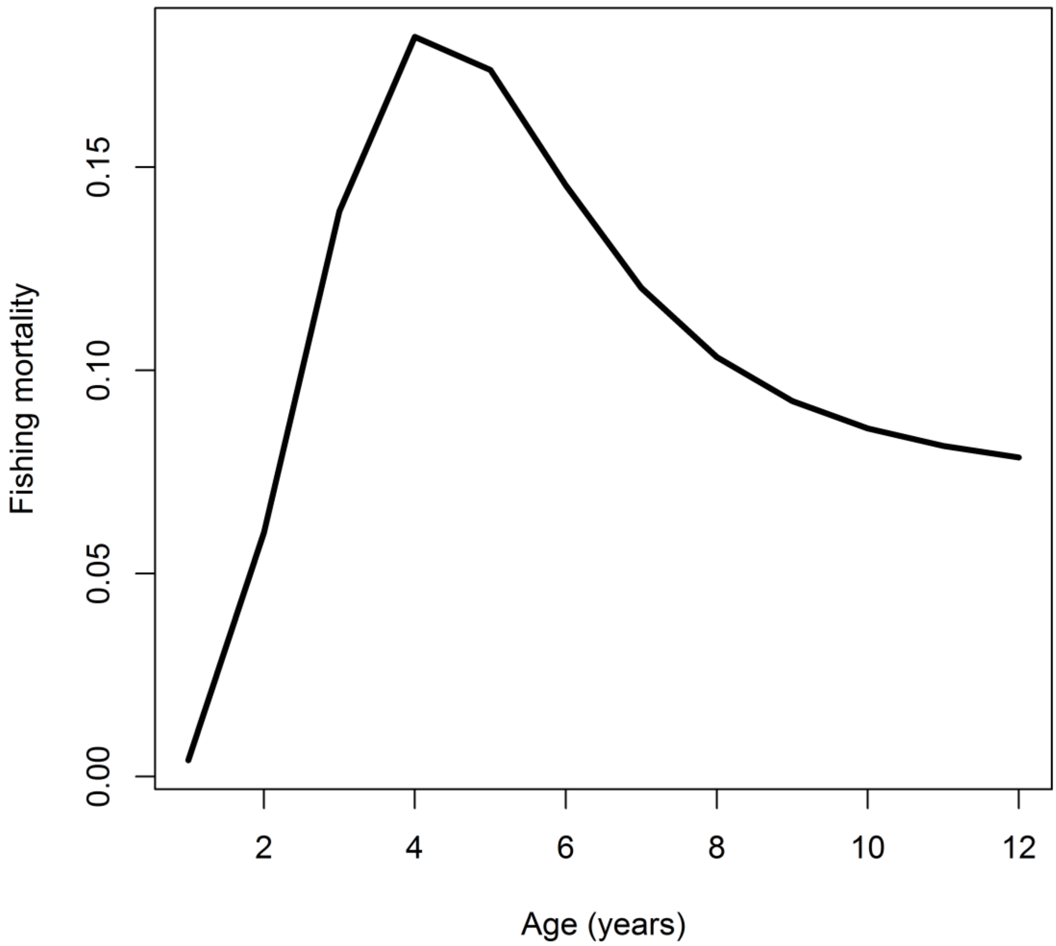


Figure 36. Composite fishing mortality by age class for the period used for the calculation of MSY based reference points (2014).

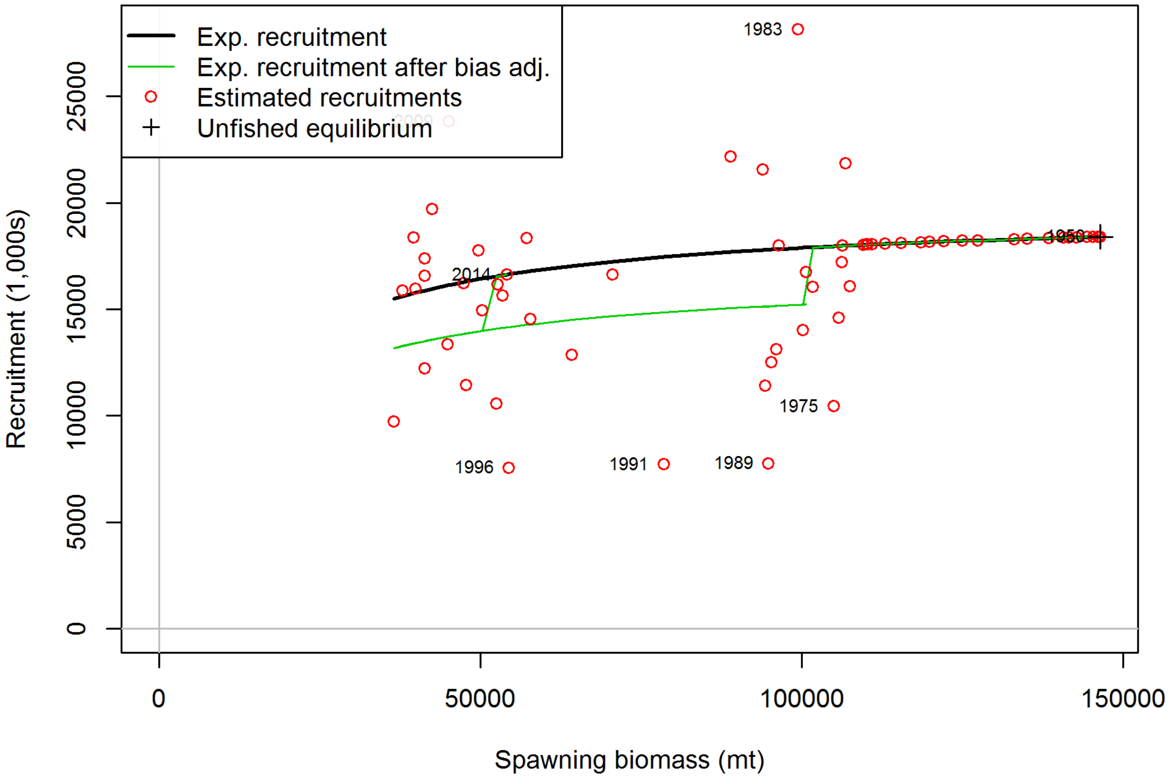


Figure 37. Relationship between equilibrium recruitment and equilibrium spawning biomass for the reference model with steepness of the SRR is fixed at 0.80 (black line).

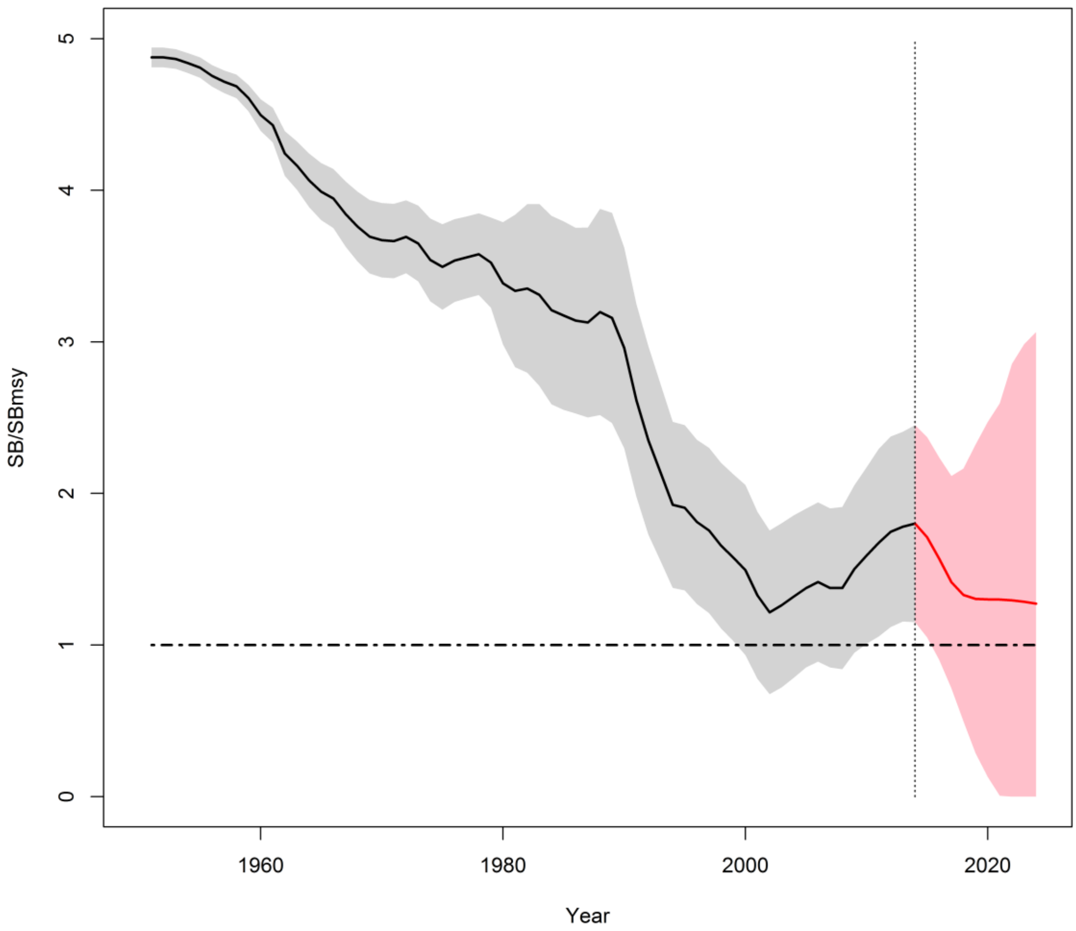


Figure 38. Annual spawning biomass relative to SB_{MSY} for the model period (black line) and the 10-year projection period (red line). The shaded area represents the 95% confidence interval. The horizontal dashed line represents the SB_{MSY} level. The projection assumes a constant level of catch equivalent to 2014.

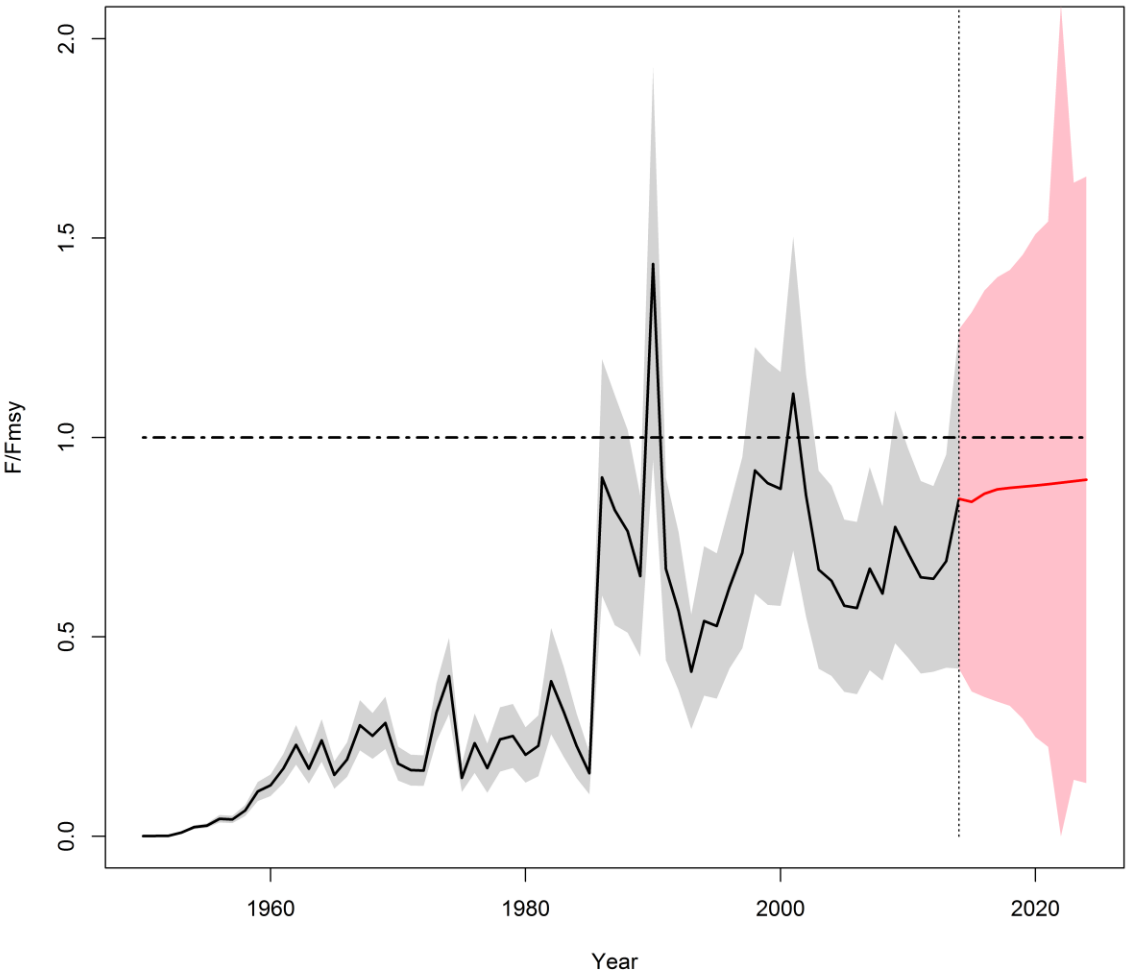


Figure 39. Annual fishing mortality relative to F_{MSY} for the model period (black line) and the 10 year projection period (red line). The shaded area represents the 95% confidence interval. The horizontal dashed line represents the F_{MSY} level. The projection assumes a constant level of catch equivalent to 2014.

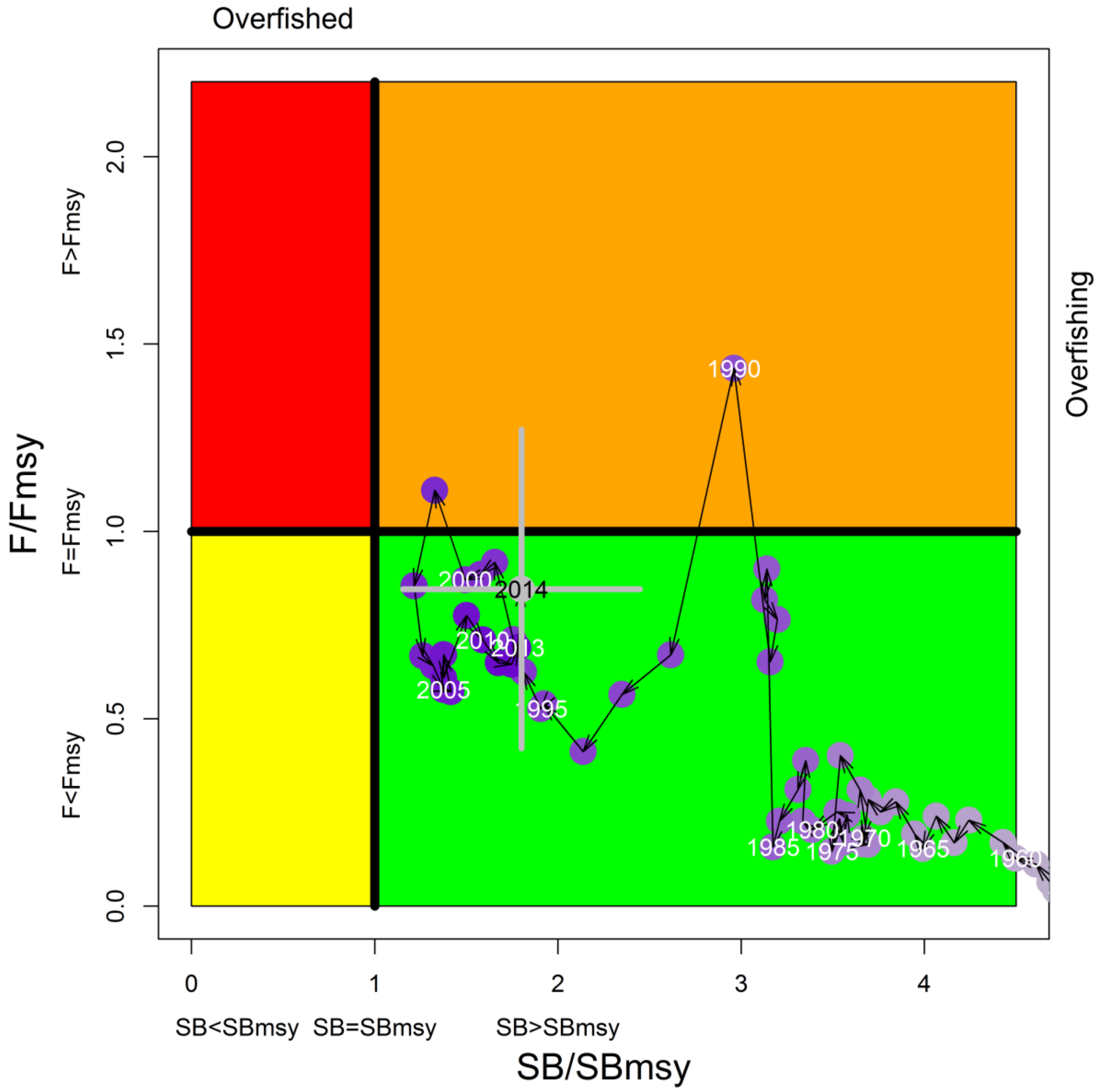
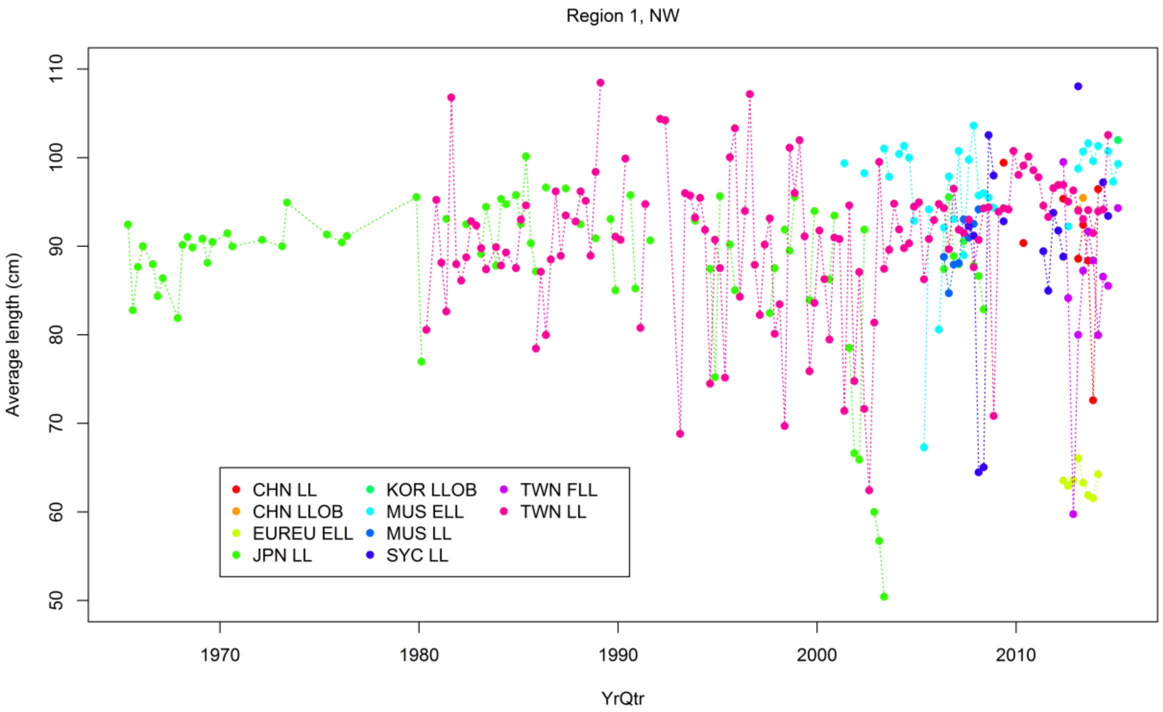


Figure 40. Annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points for the *CPUEsouth* reference model. The grey lines represent the 95% confidence interval associated with the 2014 stock status.

APPENDIX 1. ANALYSIS OF TRENDS IN ALBACORE LENGTH FREQUENCY DATA FROM THE INDIAN OCEAN LONGLINE FISHERIES



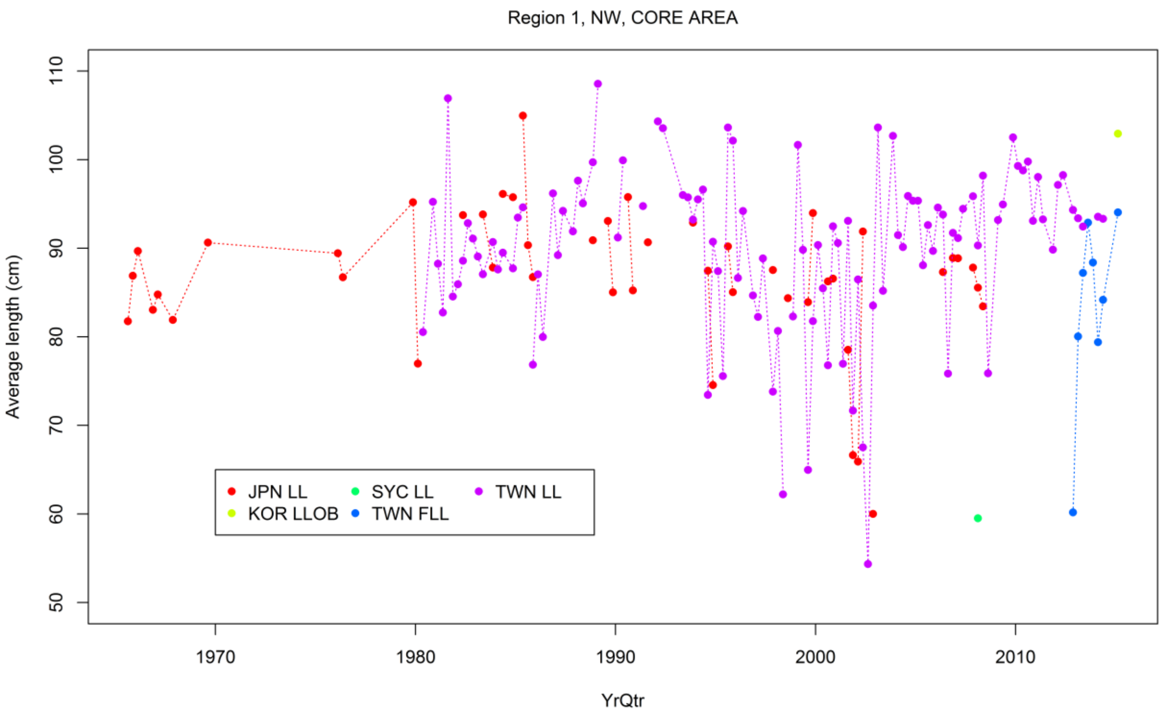
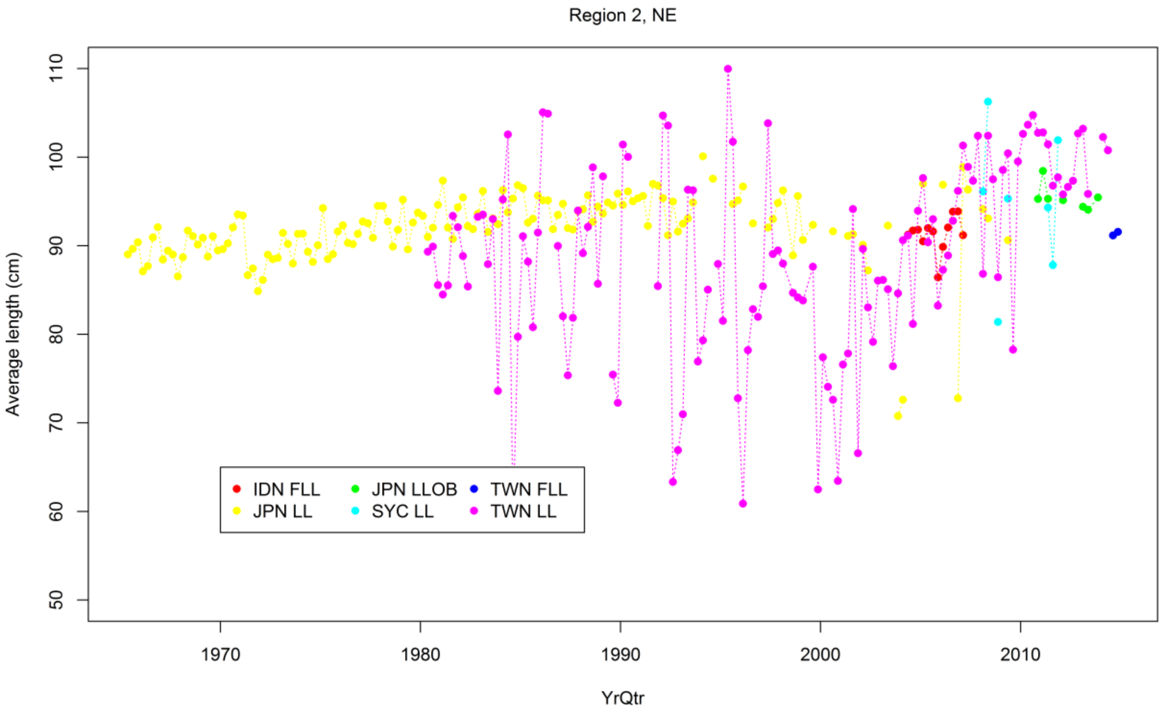


Figure A1: Average length (FL cm) of albacore sampled by year/quarter and longline fleet from the entire north-western area of the Indian Ocean (top panel) and from the sub-area of the NW area which accounts for most of the albacore longline catch (lower panel).



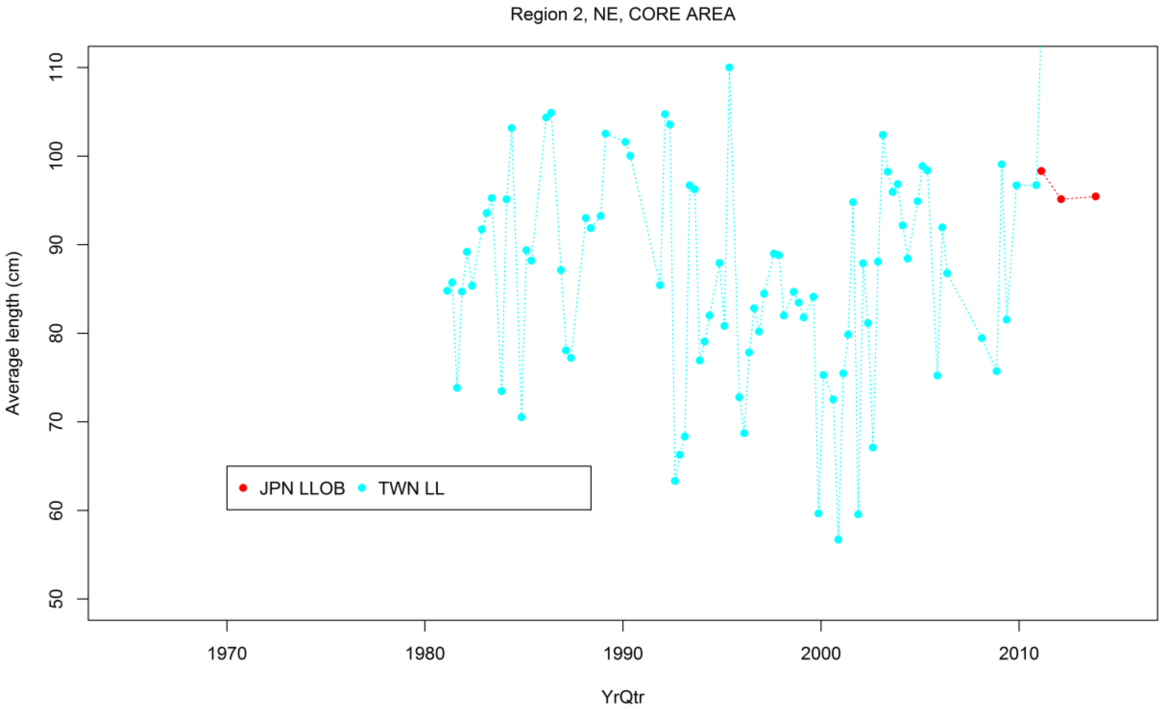


Figure A2: Average length (FL cm) of albacore sampled by year/quarter and longline fleet from the entire north-eastern area of the Indian Ocean (top panel) and from the sub-area of the NE area which accounts for most of the albacore longline catch (lower panel).

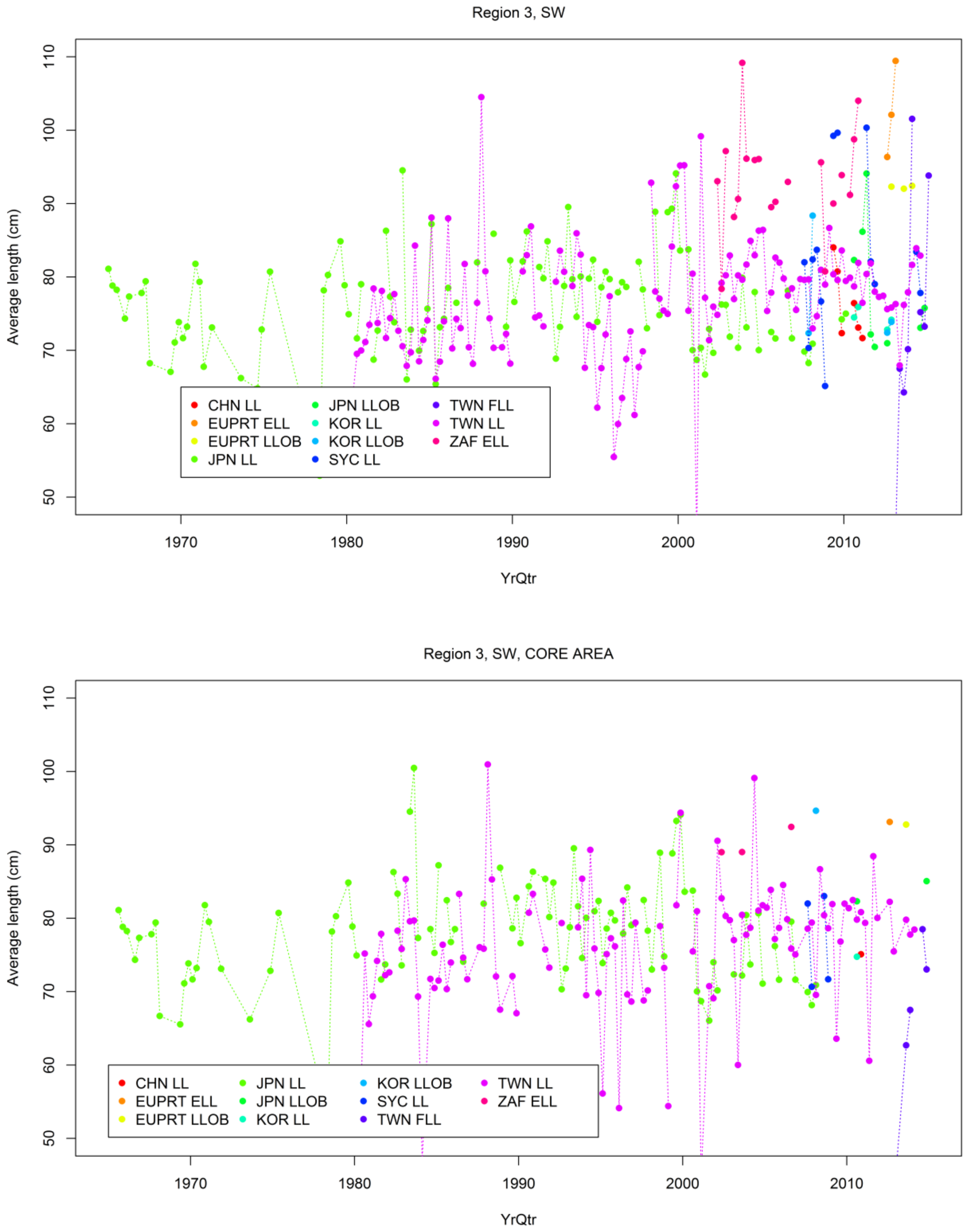
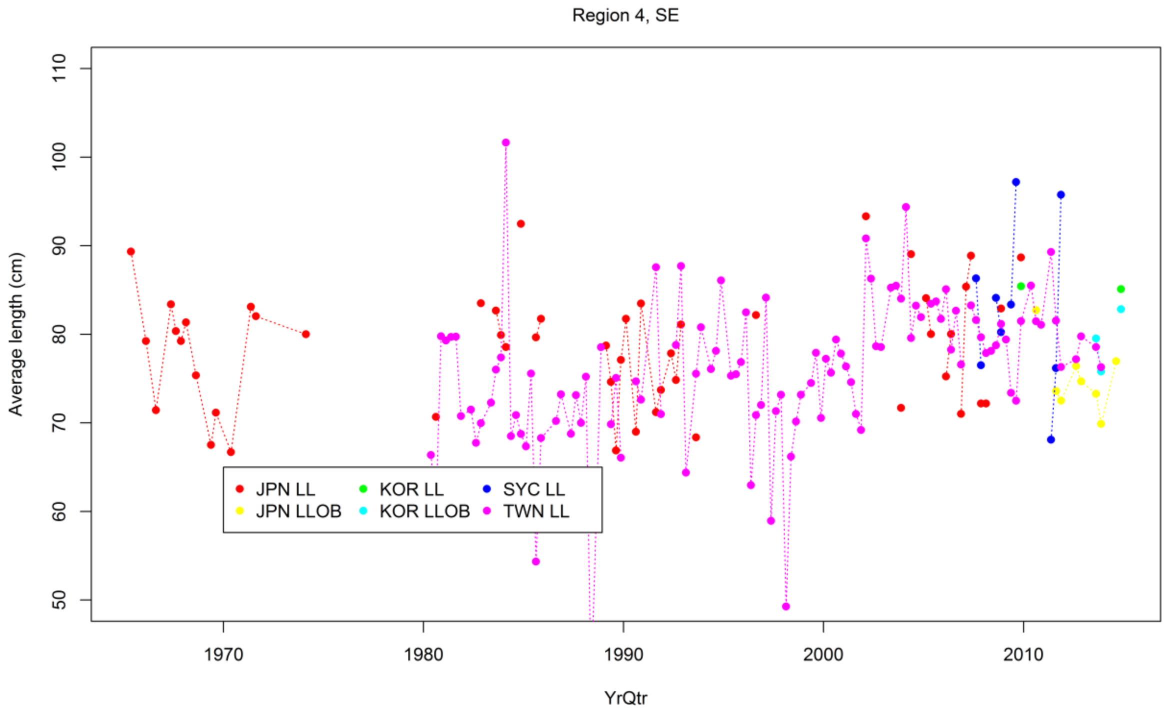


Figure A3: Average length (FL cm) of albacore sampled by year/quarter and longline fleet from the entire south-western area of the Indian Ocean (top panel) and from the sub-area of the SW area which accounts for most of the albacore longline catch (lower panel).



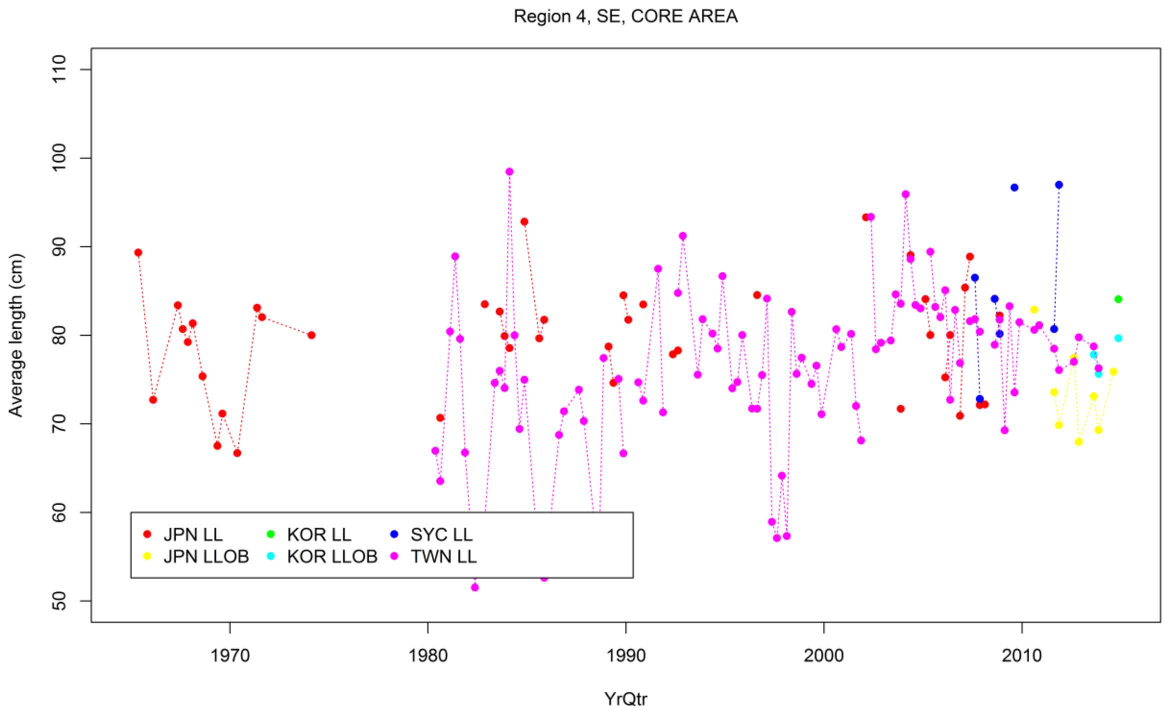


Figure A4: Average length (FL cm) of albacore sampled by year/quarter and longline fleet from the entire south-eastern area of the Indian Ocean (top panel) and from the sub-area of the SE area which accounts for most of the albacore longline catch (lower panel).

APPENDIX 2. RESULTS FROM THE PRELIMINARY PHASE OF THE STOCK ASSESSMENT MODELLING

Table A1. Main structural assumptions of the albacore tuna reference models used in the preliminary modelling phase.

Category	Assumptions	Parameters
Spatial structure	Single region	
Recruitment	Occurs at the start of fourth quarter as 0 age fish. Recruitment is a function of Beverton-Holt stock-recruitment relationship (SRR). Temporal recruitment deviates from SRR, 1975–2012.	LNR_0 No prior; *h* = 0.80 *SigmaR* = 0.6. 38 deviates.
Initial population	A function of the equilibrium recruitment assuming population in an unexploited state prior to 1950. Initial fishing mortality fixed at zero for all fisheries.	
Age and growth	Two sexes with 14 age-classes, with the last representing a plus group. Growth parameterised using VonBert growth model. Male growth is parameterisaed as deviates from female growth parameters 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 $W = aL^b$.	*Lage1* = 45.4428, *Linfinity* = 114cm, *k* = 0.253. Male devs *Lage1* = 0.0792747, *Linfinity* = 0.0966268, *k* = -0.295556. CV =0.10 *a* = 1.3718e-05, *b* = 3.0973
Natural mortality	Invariant with age.	Fixed parameter 0.30
Maturity	Age-dependent, specified. Fecundity is directly related to female biomass (Wt) i.e. eggs=Wt*(a+b*Wt) with a=0 and b=1.	age-classes 0-14: 0, 0, 0, 0, 0.089, 0.466, 0.746, 0.881, 0.944, 0.973, 0.987, 0.994, 0.997, 0.999, 1.000
Selectivity	Length based selectivity, parameterised with double normal function. Southern LL fisheries LL 3 and LL 4 (and CPUE) share a common selectivity. Northern LL fisheries LL 1 and LL 2 (and CPUE) share a common selectivity. Constrained to approximate full selectivity for the largest length classes. Temporal	 5 estimated parameters, no priors. 4 estimated parameters, no priors. 35 temporal deviates (Sd 10)

	variation in selectivity for 1980-2014 (peak parameter). Drift net fisheries have common, fixed selectivity. Approximate Bartoo & Holts (1993) Purse seine double normal selectivity. Other (1-4) fisheries share purse seine selectivity.	 Fixed 4 estimated parameters, no priors.
Catchability	Separate base catchability estimated for each LL CPUE. Catchability deviates for LL 4 CPUE indices for 2005-2014 No seasonal variation in catchability for LL CPUE. Southern LL CPUE indices have CV of 0.2. ***CPUEall*** Northern LL CPUE indices have CV of 0.3. ***CPUEsouth*** Northern LL CPUE indices have CV of 1.3.	4 base parameters 27 deviates (Sd = 3)
Fishing mortality	Hybrid approach (method 3, see Methot & Wetzel 2013).	
Length composition	Multinomial error structure. Length samples assigned an ESS of nfish/200 with a maximum ESS of 10. Nfish is the number of fish sampled.	

Table A2. Estimates of management quantities for for the set of stock assessment models that <u>incorporate LL CPUE indices for the northern fishery areas</u> (LL1 and LL2 CPUE).

Model	SB_0	SB_{MSY}	SB_{MSY}/SB_0	SB_{2014}	SB_{2014}/SB_0	SB_{2014}/SB_{MSY}	F_{2014}/F_{MSY}	MSY
Reference CPUEall	198,541	40,683	0.205	113,766	0.57	2.80	0.511	52,260
./CPUE1970	189,599	38,817	0.205	95,518	0.50	2.46	0.575	50,125
./CPUEincreaseQ	200,111	41,009	0.205	95,114	0.48	2.32	0.581	52,588
./CPUEsouth	141,015	28,932	0.205	52,693	0.37	1.82	0.859	37,708
./CPUEsoutheast	191,408	39,326	0.205	112,990	0.59	2.87	0.454	50,940
./CPUEsouthwest	174,780	35,847	0.205	88,413	0.51	2.47	0.614	46,114
./LFdownWt10	205,003	41,831	0.204	112,093	0.55	2.68	0.505	54,580
./LFdownWt10a	204,848	41,800	0.204	111,944	0.55	2.68	0.506	54,541
./LFdownWt2	229,907	47,060	0.205	138,675	0.60	2.95	0.436	60,393
./LFdownWt5	228,501	46,710	0.204	134,254	0.59	2.87	0.442	60,334
./LFupWt	153,994	31,619	0.205	76,125	0.49	2.41	0.681	40,864
./Mhybrid	211,375	43,169	0.204	96,702	0.46	2.24	0.740	39,069
./Mlow	234,095	50,253	0.215	108,535	0.46	2.16	0.736	38,226
./NoRecBiasAdj	215,038	44,050	0.205	120,772	0.56	2.74	0.500	56,528
./RecDevZero	152,825	31,371	0.205	66,768	0.44	2.13	0.697	40,667
./Region2	240,038	49,385	0.206	155,221	0.65	3.14	0.388	62,501
./SelectNorthernDoubleNormal	2.6E+07	5.3E+06	0.202	2.4E+07	0.94	4.65	0.003	6.6E+06
./SelectNoVar	192,224	39,251	0.204	101,964	0.53	2.60	0.562	50,325
./SteepHigh	183,819	27,295	0.148	103,336	0.56	3.79	0.442	57,352
./SteepLow	219,589	55,085	0.251	129,119	0.59	2.34	0.563	48,912

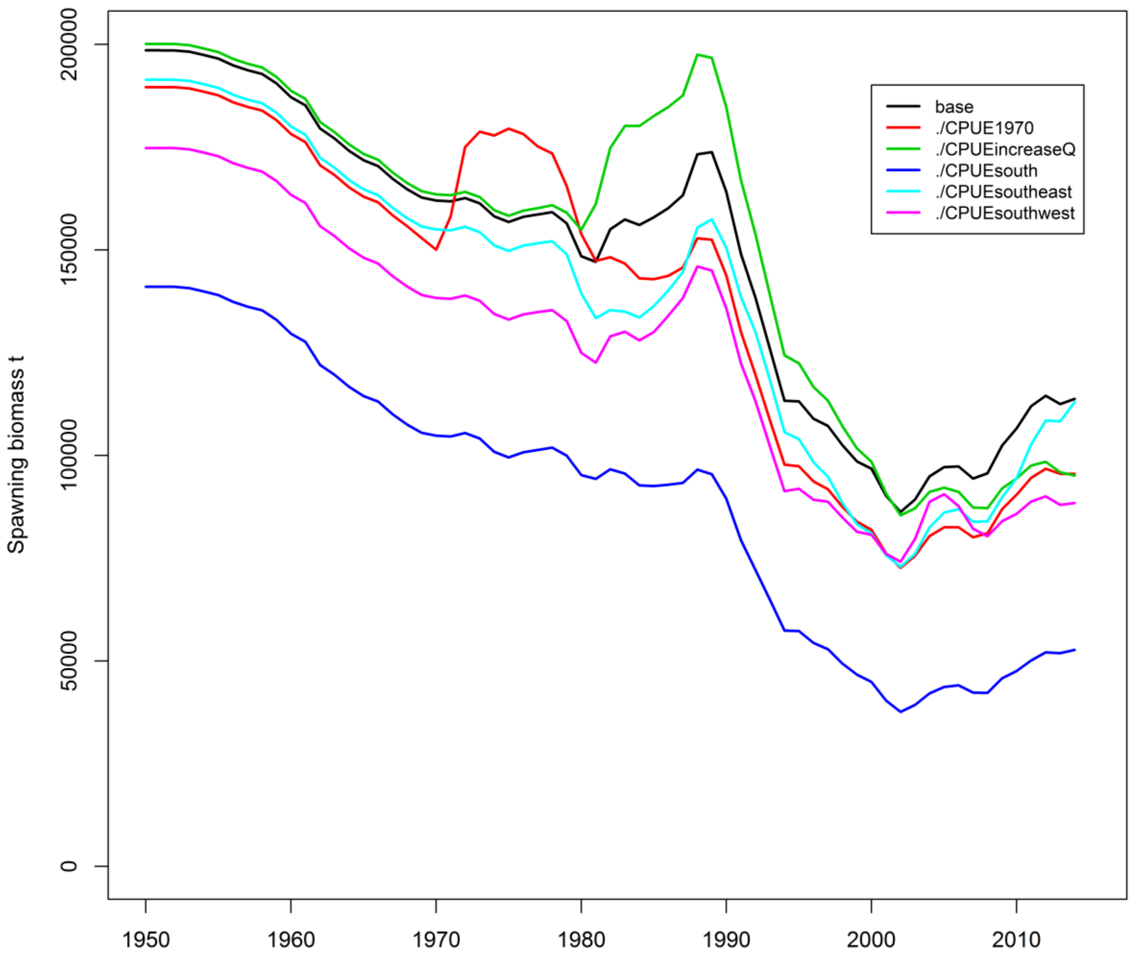


Figure A5. Spawning biomass trajectories from the preliminary *CPUEall* reference model and a range of preliminary model sensitivities related to the range of CPUE model options.

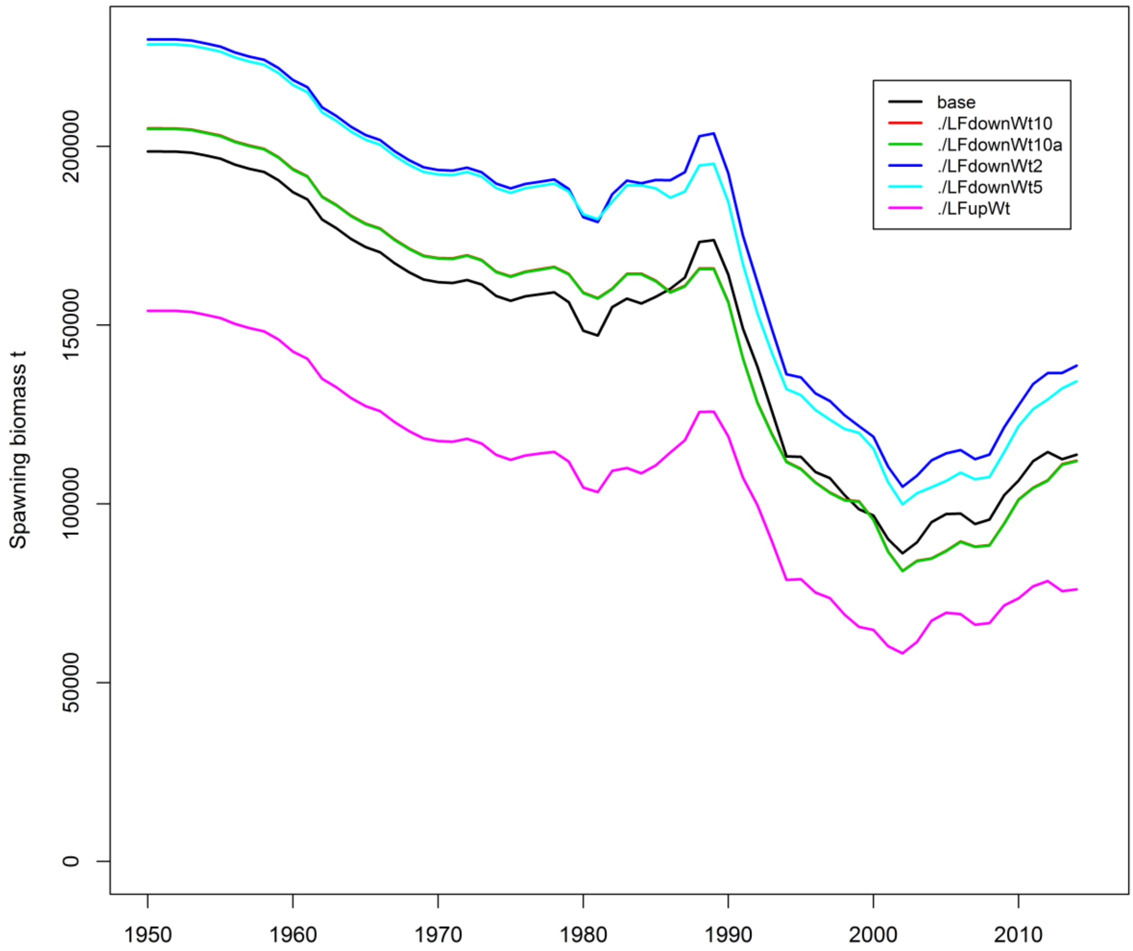


Figure A6. Spawning biomass trajectories from the preliminary *CPUEall* reference model and a range of preliminary model sensitivities related to the weighting of the length composition data.

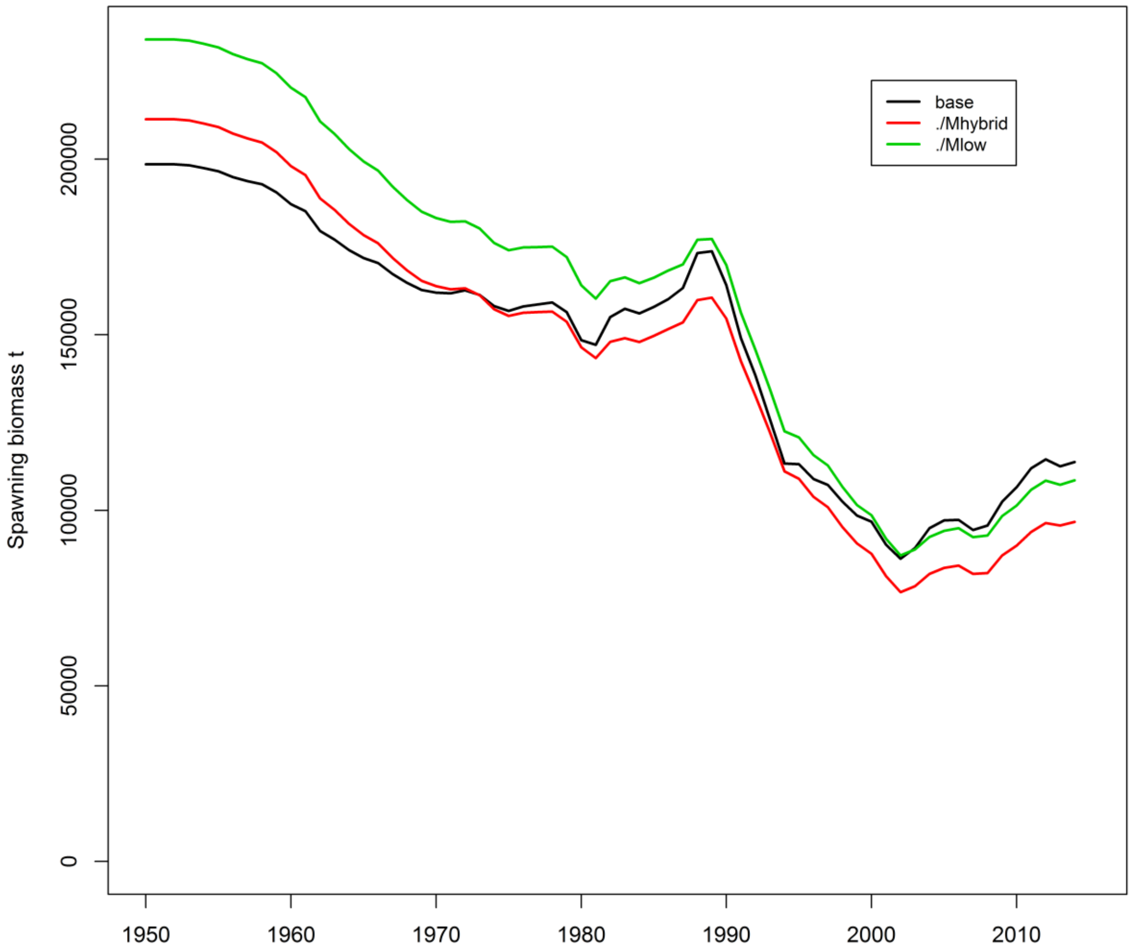


Figure A7. Spawning biomass trajectories from the preliminary *CPUEall* reference model and a range of preliminary model sensitivities related to natural mortality.

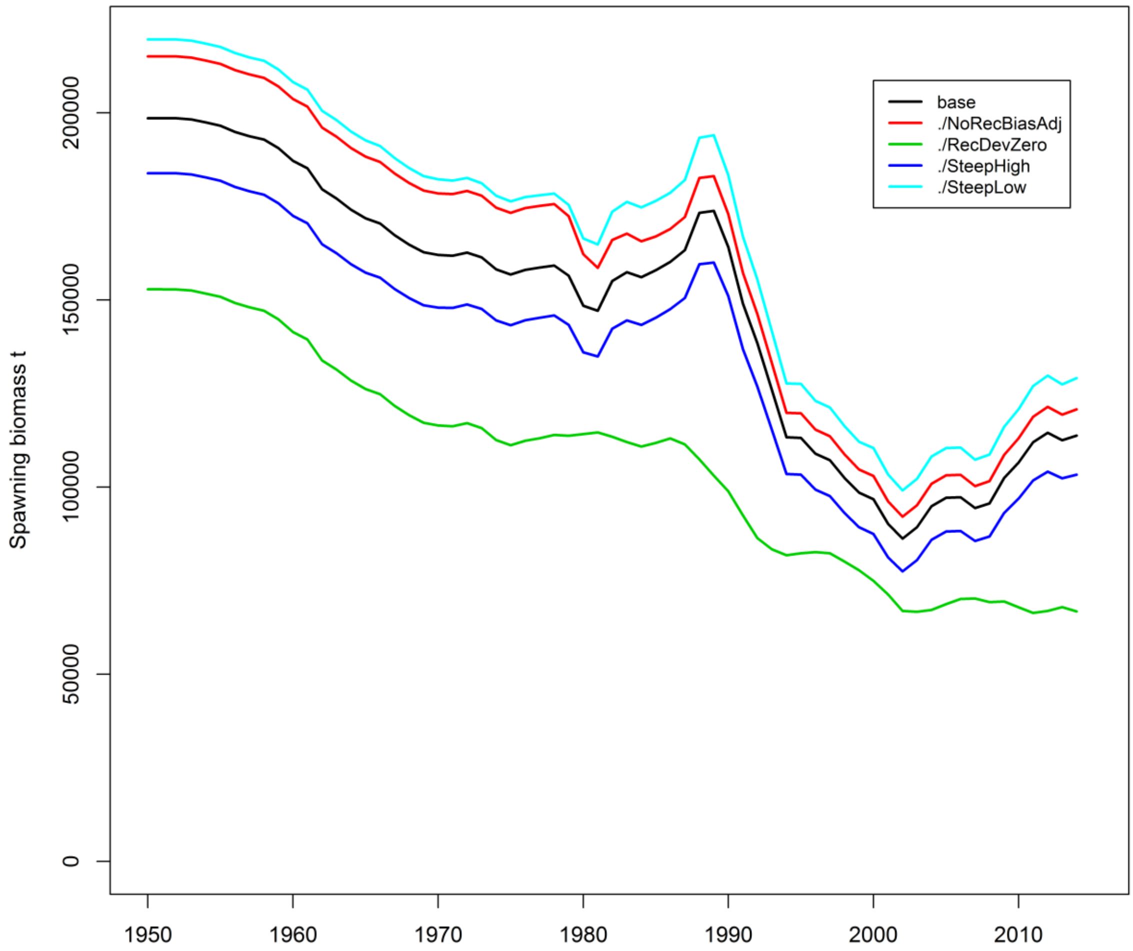


Figure A8. Spawning biomass trajectories from the preliminary *CPUEall* reference model and a range of preliminary model sensitivities related to recruitment.

Table A3. Estimates of management quantities for for the preliminary set of stock assessment models that exclude LL CPUE indices for the northern fishery areas (LL1 and LL2 CPUE) (*CPUEsouth*).

Model	SB_0	SB_{MSY}	SB_{MSY}/SB_0	SB_{2014}	SB_{2014}/SB_0	SB_{2014}/SB_{MSY}	F_{2014}/F_{MSY}	*MSY*
Reference (CPUEsouth)	141,015	28,932	0.205	52,693	0.37	1.82	0.859	37,708
./CPUEincreaseQ	142,914	29,347	0.205	42,502	0.30	1.45	0.978	38,205
./CPUEseason	142,966	29,363	0.205	54,460	0.38	1.85	0.819	38,276
./CPUEseasonExQ2	137,193	28,228	0.206	42,262	0.31	1.50	0.925	36,843
./CPUEsoutheast	146,965	30,235	0.206	62,169	0.42	2.06	0.676	39,630
./CPUEsouthwest	135,534	27,852	0.205	45,255	0.33	1.62	0.936	36,285
./LFdownWt2	157,870	32,291	0.205	66,199	0.42	2.05	0.741	41,982
./LFupWt	124,550	25,645	0.206	40,899	0.33	1.59	0.991	33,556
./Mhybrid	169,340	34,732	0.205	46,740	0.28	1.35	1.140	31,823
./Mlow	188,148	40,493	0.215	53,412	0.28	1.32	1.144	31,482
./Rec1952	106,009	21,874	0.206	38,000	0.36	1.74	1.084	28,694
./RecDevZero	131,903	27,111	0.206	44,181	0.33	1.63	0.893	35,410
./RecInitialConditionsVar	140,883	28,906	0.205	52,565	0.37	1.82	0.861	37,677
./Start1975	138,259	28,484	0.206	50,908	0.37	1.79	0.885	37,068
./SteepHigh	129,726	19,289	0.149	47,358	0.37	2.46	0.734	41,153
./SteepLow	156,548	39,308	0.251	60,562	0.39	1.54	0.958	35,381

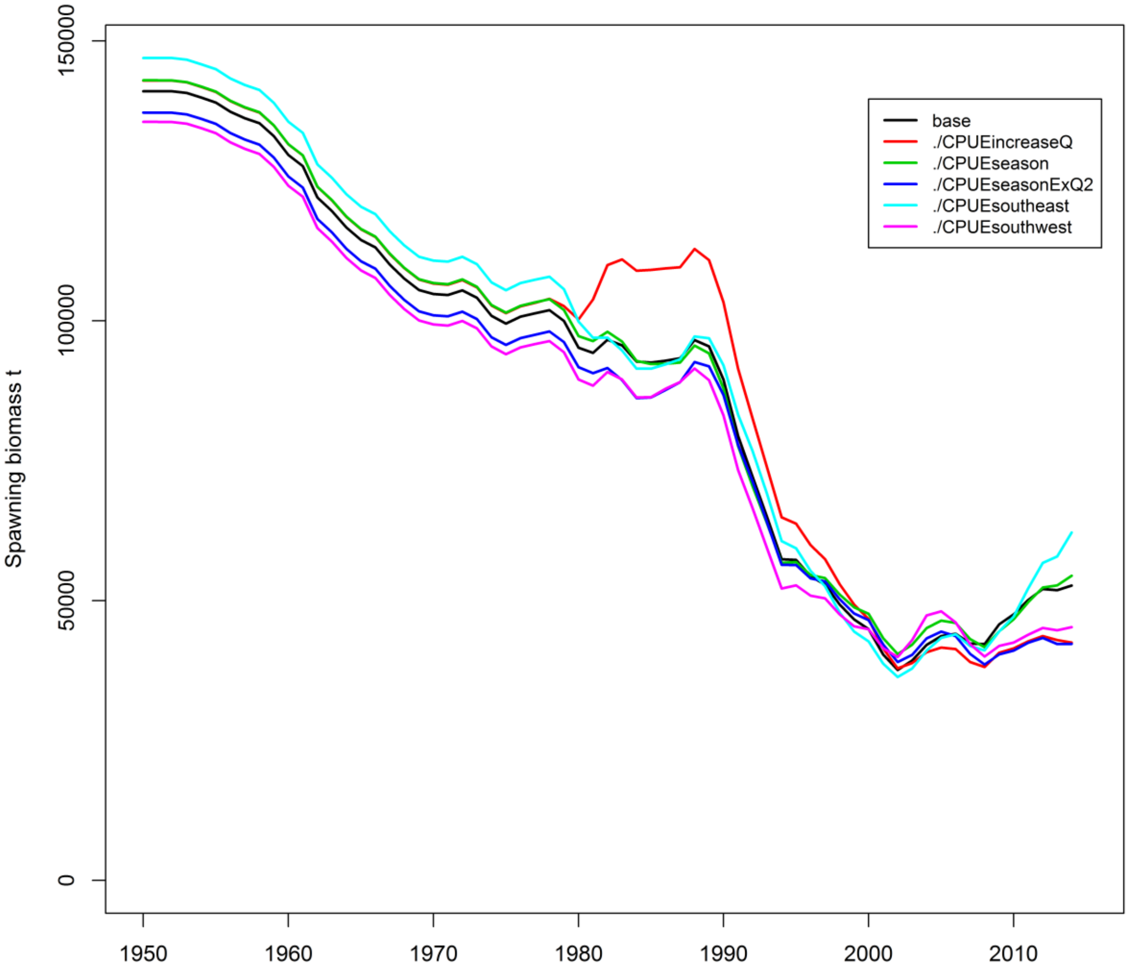


Figure A9. Spawning biomass trajectories from the preliminary *CPUEsouth* reference model and a range of preliminary model sensitivities related to the range of CPUE model options.

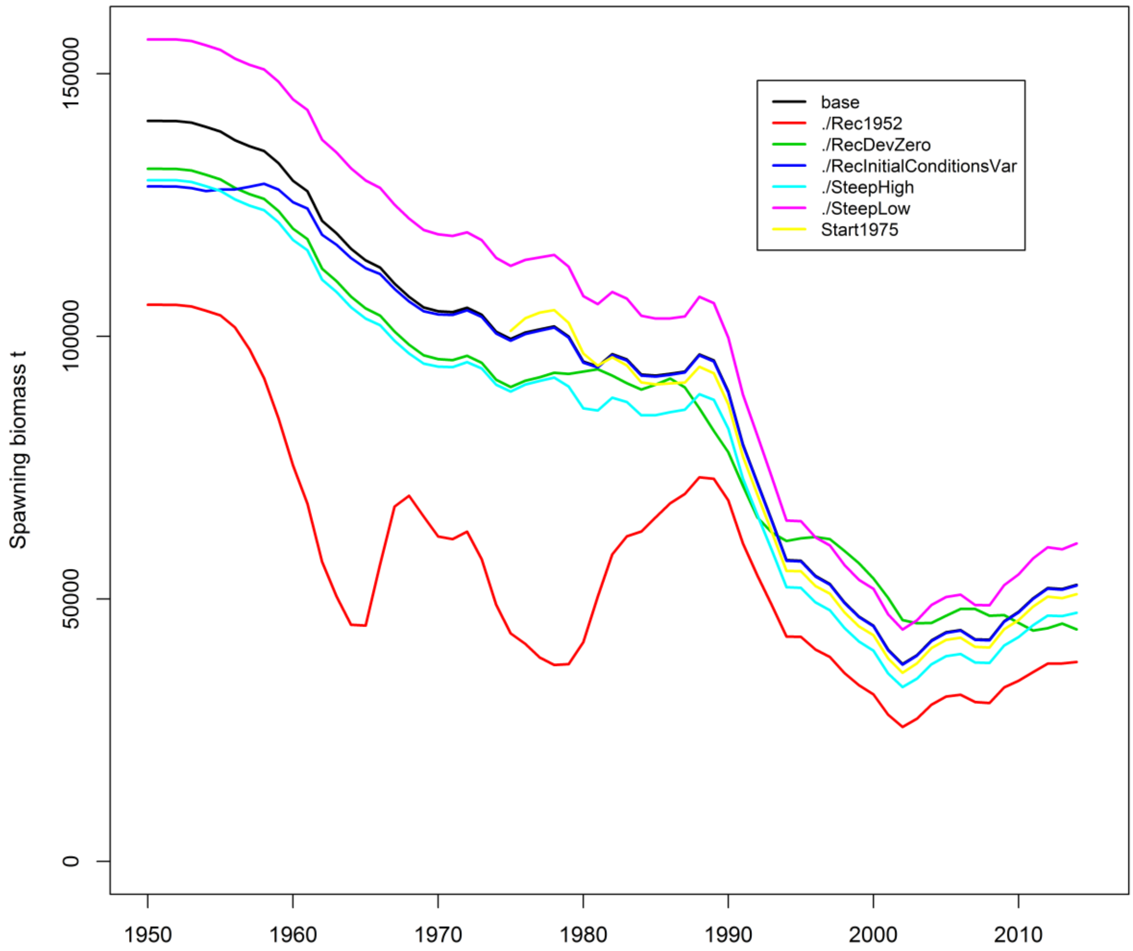


Figure A10. Spawning biomass trajectories from the preliminary *CPUEsouth* reference model and a range of preliminary model sensitivities related to recruitment and initial stock conditions.