Stock assessment of albacore tuna in the Indian Ocean for 2014 using Stock Synthesis

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Abstract: A stock assessment for albacore tuna in the Indian Ocean was developed using Stock Synthesis version 3. The model included catch data from 1952 to 2012. A Stock Synthesis assessment was run in 2012, and this assessment makes a number of changes and documents their effects on the results. Size data were analyzed and the spatial structure of the fisheries was changed to improve the consistency of sizes within the fisheries. Sensitivity runs were carried out with alternative parameters for natural mortality, growth, selectivity, steepness, and spatial structure. Alternative values of biological parameters were explored, given that the different tuna-RFMOs use different assumptions in their stock assessments, in some cases with little evidence, and there are substantial data gaps for Indian Ocean albacore. We examined conflicts among different sources of data and assumptions by down-weighting the different data sources. The sensitivity of management advice to the above explorations was used to identify priority areas for further research. The inferred structural uncertainty, including interactions, was included in the management advice. The assessment incorporates projections for 10 years and provides a Kobe II Strategy Matrix decision table. The preliminary stock status using a reference base case assessment contradicts results obtained in 2012, indicating that the stocks is in a healthy status and is not experiencing overfishing or is in an overfished status. The only scenario that contradicts this conclusion is a low steepness value, with a very low natural mortality rate that is highly unlikely given the life history of Albacore.

Contents

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 respectively. Driftnets were employed in the albacore fishery from the early-1980s until 1992 when an international ban on driftnet 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 driftnet fishery there has been no significant targeting of small fish.

Assessment of the Indian Ocean albacore stock has 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), and the age-structured production model ASPM (Nishida *et al.* 2012), and Stock Synthesis (Kitakado *et al.* 2012).

During the fourth Working Party on temperate tunas (WPTmT4) in 2012, the first assessment using Stock Synthesis (Kitakado *et al.* 2012) was carried out, using data up to 2010. Results suggested overfishing is occurring on the stock, though the stock is 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 abundance trend, given issues such as target change; and some of the influential biological parameters had not been estimated for Indian Ocean albacore. While the time –series of catch for albacore has also changed after the assessment in 2012, following a review of the catches of albacore in Indonesia for the period 2003-12 (IOTC Secretariat 2013), marked changes to the catches were only recorded in 2008 and, to a lesser extent, 2009. These changes are not considered influential to the assessment. The stock status in 2012 was determined by combining the results of different methods. Most results suggested that the stock was experiencing higher than optimal fishing mortality, and the end result indicated that overfishing was occurring on the stock, but the stock was not yet overfished.

2. Methods

2.1. Model

The model used was the most recent version of Stock Synthesis, version: SSv3.23f.

2.2. Data compilation

2.2.1. Fishery structure:

A total of 8 fisheries were defined based on the fishing method, the flag, and the location of the fishery. Details of the fishery definitions are presented in Table 1 below. Annual catches from the individual fisheries are presented in Appendix 1. More details on the fisheries are provided below.

Japan composite longline and other assimilated fleets (Fishery 1: JP_LL_N; Fishery 5: JP_LL_S).

These fisheries, referred to as Japanese composite longline, are made up by the deep-freezing longline fisheries of Japan, the Republic of Korea, and Thailand. The majority of the catches of albacore over the time series have been reported by Japan (80% of the total) in the earlier part of the catch record, especially between the mid-1950s and the late 1960s. Note, the Republic of Korea reported high catches of albacore in the 1970s, accounting for 70% of the total catches during that period.

Taiwan,China longline and other assimilated fleets (Fishery 2: TW_LL_N; Fishery 6:TW_LL_S)

Currently, Taiwan,China longline and other assimilated fleets (Fishery 2: TW_LL_N; Fishery 6:TW_LL_S) is the most important fishery for ALB. These fisheries, referred to as Taiwan,China longline, include various deep-freezing and fresh-tuna longline fisheries, in particular Taiwan,China longline (both deep-freezing and fresh-tuna) and Indonesia fresh-tuna longline fisheries. While the majority of the catches of albacore over the time series have been reported by Taiwan,China (72% of the total), in recent years Indonesia has reported high catches of albacore, accounting for over 30% of the total catches during 2003-07.

Taiwan,China driftnet fishery (Fishery 3: Driftnet_S)

This fishery was made up exclusively by driftnet vessels flagged to Taiwan,China, which operated in the southern waters of the Indian Ocean between 1982 and 1992, the year in which the UN adopted a worldwide ban on driftnets.

Purse seine (Fishery 3: PS_N).

While the purse seine fishery is made up of various fleets 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 fisheries of Iran, Japan, Mauritius, Thailand, and the Republic of Korea are also included here.

Other (Fishery 4: Other N).

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. Indonesia has reported over 90% of the total catches of albacore under this component with remaining catches reported by Mauritius, Reunion and Mayotte (EU), Comoros, Australia, South Africa, and East Timor. Table 1 shows the difference in the fishery structure used in the previous and current assessments, and the relative importance of each fishery in the current assessment, over the entire time-series (1950-2012), and in recent years (2008-12) (below)

Table 1: Fishery structure in 2012 and 2014 assessments and relative importance of fisheries in the present assessment

2012 fishery structure	2014 fishery structure	Time-series catch Albacore (%)	Catch Albacore (% 2008-12)
1. JPN LL	1. JPN LL N	10	1
	5. JPN LL S	14	9
2. TWN LL	2. TWN LL N	17	26
	6. TWN LL S	47	55
3. Driftnet	7. Driftnet S	7	0
4. PS	3. PS N	2	2
5. Other	4. Other N	2	6

The most significant difference in fishery structure between the 2012 and the current assessments was the spatial separation of northern and southern fisheries at latitude 20 ^{o}S in the updated assessment. This separation had the primary aim of stratifying by size. Consistency of size distribution within fisheries is very important in models like Stock Synthesis, and albacore caught in the northern area are on average considerably larger than those caught further south. A further advantage of splitting the fisheries is that albacore is a bycatch species in the north, but more often a target in the south (Figure 3), which allows CPUE standardizations to include more consistent effective effort.

2.2.2. *Catch*

Longline fisheries

Figure 3 and Figure 4 show total estimated catches of albacore from all industrial longline fleets over the entire time-series, by five degree square area.

Albacore is likely to be a target of longline fisheries in southern waters, between latitudes 15 and 35 South and longitudes 50 and 80 East (Figure 3). Figure 4 represents an attempt to show the seasonality of the longline fisheries for albacore, by area:

- Latitude 10-25 South (other than South Indonesia): the bulk of albacore catches are taken during the 4th quarter, with also important catches during the 1st quarter.
- Latitude 25-35 South and South Indonesia: the bulk of albacore catches are taken during the 3rd quarter, with also important catches during the 2nd quarter.
- Beyond latitude 35 South: the bulk of albacore catches are taken during the 1st and 2nd quarters, with also catches during the 3rd quarter, especially in waters off-South Africa.

The Japanese composite longline fishery operates throughout the Indian Ocean although catches are concentrated in the equatorial region. Targeting has varied through time with a transfer of effort from albacore and Southern Bluefin tuna towards targeting bigeye tuna and yellowfin tuna in the

1970s, followed by a return of part of the fleet to the southern Indian Ocean to target albacore since 2000, in particular from 2007 due to increased piracy in off-Somalia. However, the main consequence of piracy has been a major drop in fishing effort in the Indian Ocean as a whole. While catches of albacore by these fisheries account for 24% of the total catches of albacore in the Indian Ocean, over the entire time-series, in recent years (2008-12) their contribution has decreased to as little as 10% of the total catches (Figure 7). Annual catches from the JPN LL N fishery steadily increased from the early 1950s to reach peaks in 1961, at 8,700 mt, and 1967, at 7,700 mt. Catches between 1968 and 1981 ranged between over 1,000 mt and 5,500 mt and, since then, catch levels have been low, with catches below 1,000 mt during most years. In 2012 the catches of albacore were very low, amounting to less than 200 mt (Figure 3). Annual catches from the JPN LL S fishery also increased markedly between the onset of the fishery in the South, in 1954 (30 mt) and the high catches recorded in 1962, 1964 (both over 11,000 mt), and 1967 (12,600 mt). Since the mid-1970s albacore catches have been below 4,000 mt, lower than 2,000 mt during most years. As indicated before, catches of albacore increased in the late 2000s, especially since 2008, due to piracy off-Somalia.

Longline vessels flagged in Taiwan,China have operated in the Indian Ocean since 1954, covering the majority of the IOTC region, as it is the case with other longline fleets. A more or less stable component of the deep-freezing Taiwan,China fleet has operated in Southern waters of the Indian Ocean to target albacore. Fresh-tuna longliners from Indonesia and, to a lesser extent, Taiwan,China and other flags, have also targeted albacore in the Southern waters of the Indian Ocean in recent years (since the mid-2000s). These fisheries have reported the highest catches of albacore both over the time-series (64% of the total catches from all fisheries), and in recent years (82%). However, the contribution of the different fleets to total catches within this component has changed substantially over the years, especially in recent years, in which the majority of the catches of albacore come from fresh-tuna longliners flagged in Indonesia, Taiwan,China, and other flags. Piracy off-Somalia also led to large drops in the fishing effort exerted by Taiwan,China deep-freezing longliners in the Indian Ocean between 2007 and 2012. Annual catches from the TWN LL N fishery steadily increased from the mid-1950s to levels between 2,000 and 5,000 mt between the early 1970s and late 1990s. Since 1998 albacore catches have been between 5,000 and 13,500 mt, with the highest catches recorded in 2007 and 2010. Fresh tuna longline fleets, in particular Indonesia, are responsible for the increase in catches. Annual catches from the TWN LL S fishery also increased markedly between the onset of the fishery in the South, in 1954 (8 mt) and the high catches recorded since 1968, over 5,000 mt. Since the early-1990s albacore catches have been almost always over 15,000 mt, with the highest catches of albacore ever recorded in 2001, at over 33,000 mt, and catches between 20,000 and 25,000 mt in recent years. As indicated before, catches of albacore increased in the late 2000s, due to increased targeting of albacore by fresh-tuna longliners, and since 2008, due to piracy off-Somalia.

Driftnet Fishery

The driftnet fishery 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 (7% of the total catches of albacore over the entire time-series, Figure 7). This fishery stopped operating in 1992, following a UN ban on high seas driftnets. The majority of the catches of albacore by driftnets occurred during the 1st and 4th quarters each year, with minor catches also recorded during the 2nd quarter (Figure 5). No catches at all were recorded during the 3rd quarter.

Purse Seine Fishery

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, Table X). Purse seine catches of albacore have never been high, with peak catches recorded in 1992, at 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 (Figure 6). A very minor amount of albacore was taken by purse seiners in waters south of 20 ^{o}S.

Other Fisheries

The majority of the catches of albacore under this component have been reported by Indonesia, and they relate to the activities of coastal longliners based in Bali, that operate in the waters between Indonesia and Australia. These fisheries have increased in importance in recent years (2008-12) in which they have accounted for 6% of the total catches of albacore (they account for 2% of the total catches over the entire time-series).

2.2.3. Size

Longline fisheries

Longline fisheries catch adult or sub-adult albacore (length 60-120 cm).

Size frequency data are available for both Japan's longline fisheries (JPN LL N and JPN LL S) from 1965 to 2012. 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 have been 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 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 to 2012 (TWN LL N and TWN LL S). In recent years, length data are also available from other fleets and periods (e.g. Indonesia fresh-tuna longline, Seychelles, etc.). Length frequency data from all sources were aggregated to provide a composite length composition for each year/quarter. Prior to the mid-2000s the length compositions are dominated by sampling from the Taiwanese deep-freezing longline fleet, while in the subsequent period the size data comes from various sources, as indicated above. 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).

Driftnet fishery

Driftnets catch juvenile or sub-adult albacore. However, there is a complete lack of length frequency data in the Indian Ocean, which makes it difficult to assess the sizes that were taken by this fishery. While the average weights estimated from the numbers and weights in the catch-and-effort data available for the driftnet fishery of Taiwan,China are around 9 kg, this value is well above those estimated for the fisheries that operated in the Pacific Ocean, which are around 6 kg. A likely explanation is that numbers were underreported in comparison to weights in the Indian Ocean driftnet data.

Purse seine fishery

Purse seine fisheries catch adult albacore, as a by catch (90-120cm), in the western central Indian Ocean. Albacore lengths are measured in port, by enumerators, during the unloading of purse seiners flagged in the EU and Seychelles.

Other fisheries

This component includes various artisanal fisheries, especially coastal longlines and, to a lesser extent, trolling. The sizes of albacore caught are poorly known, due to the lack of length samples available. Considering the fishing area and the fact that the main fishery involved is a longline fishery it is assumed that the length distributions are similar to those reported by longliners in the North.

2.2.4. CPUE

Standardised CPUE indices were included in the model for the Japanese (Matsumoto *et al.* 2014) and Taiwanese (Lee *et al.* 2014) longline fleets. The Japanese indices were available between 1975 and 2012, and the Taiwanese indices ran from 1981-2012 (Figure 12). The individual CPUE indices included estimated coefficients of variation (c.v.) derived from observation error, averaging around 10% in the case of the southern Taiwanese longline fishery. CPUE indices represent the primary index of stock abundance in the assessment model and the resulting estimates of stock abundance should be generally consistent with these indices.

Previous work has indicated that vessels in the Japanese longline fishery have changed target species through time, changing to target bigeye and yellowfin tuna for the sashimi market, and switching back to albacore given piracy concern in areas close to Somalia. Since targeting in the Japanese longline fishery has varied strongly through time, the CPUE is considered unlikely to reflect albacore abundance trends, but to be strongly affected by changes in albacore fishing power. The Taiwanese longline fishery north of 20S also catches a proportion of other species that varies through time, and targeting of bigeye tuna is thought to have increased in the 1990s and 2000s. The indices may therefore not fully represent albacore abundance trends.

The Taiwanese longline fishery south of 20S has been the most consistent in catching mostly albacore for most of the fishery's history, and is thought to be the fishery most likely to represent albacore abundance trends. This fishery has therefore been used as the primary index of abundance for the stock assessment. However in recent years, and particularly since 2010, the proportion of 'other' species has increased considerably, potentially introducing some bias towards the end of the time series. Modelling approaches that account for target change are recommended in order to improve the relationship between standardized CPUE and abundance (Hoyle *et al.* 2014).

Depending on the approach used, standardization of the CPUE data may account to some extent for changes in the performance of the longline fishery over time. However, a range of technological improvements in the operation of the fleet are not accounted for in the analysis. These relate to the replacement of older vessels with increasingly efficient vessels equipped with an array of electronic communication and fish detection equipment. The development of the fleet is likely to have increased the overall catchability of the fleet, particularly with respect to the main target species. The extent of any increase in the catchability has not been adequately quantified, although failure to account for this process is likely to introduce a positive bias in the stock assessments that are dependent on longline CPUE indices as the primarily index of relative abundance. The final range of assessment models considered two catchability options: 1) no increase in catchability (TW_LL_S) and 2) including a 1% per annum (compounded) increase in catchability over the entire period of the CPUE time series (1980-2012) (TW_LL_S_q1). The second catchability assumption was applied to derive a modified series of CPUE indices (from the original, base CPUE indices). The catchability increase represents a 37% increase in the effective longline effort over the time-series, corresponding to a 27% reduction in the base CPUE at the end of the time-series (Figure 12).

2.3. Biological parameters

2.3.1. Stock structure

Single.

2.3.2. 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 change in sex ratio at older ages.

2.3.3. Growth equation

Growth curves are particularly influential in stock assessments that used length-based models such as Stock Synthesis. Modelling of albacore growth in the Indian Ocean has been limited, with no published investigations of ageing using otoliths, or of growth differences by sex or by location within 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 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 (Figure 1). 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.

Sampling design is an important consideration for the data used in growth curves. Sampling needs to be appropriately stratified across sources of variation. The models usually used to estimate growth fit length as a function of age, and implicitly assume that age is known. The probability distribution of length at age is assumed to be the same in all samples, and to be representative of the population. However the sampling process used to collect fish includes length-based effects at several levels, which need to be considered when modelling. First, albacore tend to distribute themselves by length with larger fish nearer the equator, so the younger fish captured in lower latitudes are more likely to be fast growing fish. Second, fishing is size-selective, with longline fisheries tending to catch fish over 80cm. Third, many ageing exercises structure their sampling and ageing by length, with targets for sample numbers by each length class. Ideally then, growth should be estimated inside the assessment in order to take size selectivity into account, and the growth likelihood should fit to age at length.

If using a single-sex model it is necessary to estimate an average growth rate for both sexes. However, catchability may increase with length, and males may live longer than females, more males will be sampled than females and the proportions of each sex will change with length. Therefore estimating a curve from pooled otoliths will result in a biased estimate. A better approach is to estimate separate male and female growth curves, and interpolate a curve between the two.

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 was used in the assessment, initially as a combined sex model, but differentiated by sex in the final set of models (Figure 13). Several sensitivity analyses were also run in which growth was estimated.

2.3.4. 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.

We used a value of M=0.3, as applied in the north Pacific and the north Atlantic. Values of 0.2 and 0.4 were applied as sensitivity analyses and as part of the grid. We also investigated variable natural mortality at age as a sensitivity analysis (Figure 14).

2.3.5. Length-weight relationship

We apply the Penney 1994 relationship from the south Atlantic, as proposed by Nishida et al (2014). However we note that the assumption of allometry may not be reliable for albacore, and there is likely to be spatial and seasonal variation in fish condition. A length-weight relationship for the stock assessment should be derived from longline data, which comprise the main fisheries in the assessment. However, catches in all fisheries are recorded in weights, and there are no weight frequency data in the model, so changing this relationship may make little difference to the final results.

2.3.6. Maturity-at-age

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 15).

2.3.7. Plus group age (last age)

The age of the plus group in length-based models is determined by different criteria than the age in virtual population analysis models. The limit at the upper end is determined by computing power, since adding more age classes increases the processing requirements. The limit at the lower end is determined by the growth curve and the total mortality, since fish aggregated into an age class are all assumed to be the same size. The easiest way to select an appropriate age is to increase the plus group age until the model estimates stop changing. Setting the age a little older than this point will provide some insurance that the plus group age will not affect the results under any plausible scenario. Increasing the age further will not affect results, but the model will take longer to run. We used a plus group age of 14 years.

2.3.8. *Initial conditions*

We assumed that at the start of the time series the population had experienced minimal fishing mortality, and estimated initial conditions assuming zero catch and equilibrium recruitment. The model estimated recruitment deviations from 1950 to allow non-equilibrium age structure at the start of period with size and CPUE data.

3. Model structure and assumptions

The model population structure included 14 annual age classes, the first age class representing fish aged 1 year and the last age class accumulating all fish age 14+ quarters. Although there are very limited sex specific data available, the model population age structure was differentiated by sex. The model commenced in 1950 and extended to the end of 2012 configured in quarterly intervals.

3.1. Recruitment

The model was set for recruitment to occur in the fourth quarter of each year, reflecting the summer spawning season. Recruitment was estimated as deviates from the BH stock recruitment relationship (SRR), with deviates estimated for each year in the model. 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.

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. Selectivity

For all fisheries, selectivity was estimated as a size based process. The northern Taiwanese longline fishery (F2_TW_LL_N) was estimated as an asymptotic form using a double normal function with the selectivity for the largest fish fixed at 1. Selectivities for all other fisheries were estimated using double normal functions, since these fisheries did not tend to catch fish as large as the northern TW longline fishery (other than the PS Fishery).

Selectivity for the 'Other' fishery (F4_Other_N) was fixed to be the same as selectivity for the northern Japanese composite longline fishery (F1_JP_LL_N), since the size data for this fishery were deemed to be unreliable. Limited size data are available from the "Other" fisheries. Initial attempts to estimate independent selectivities for these fisheries were not successful, partly due to the variability in the length composition between samples, with samples in only 3 year, and no overlap in sizes between one of the years and the other two. Furthermore the size samples were considered too small to be representative of a fishery north of 20S, given that small albacore are rarely caught in tropical and subtropical waters. A sensitivity analysis was carried out in which the selectivity estimated from the available data was assumed to apply to the fishery.

Selectivities for the Japanese composite northern longline fishery and both Taiwanese longline fisheries were split into two time periods. There was strong variation in size through time in these fisheries, and these changes were more likely to reflect changes in the fishery (in the case of the Japanese composite size data) or the size sampling (in the case of the Taiwanese fisheries) than changes in the population. Size data for the Japanese composite fishery are larger on average after 1978 than before (Figure 10 and Figure 16), possibly reflecting movement of fishing effort further north, and/or a change in targeting practices. With no other data in the assessment for the early period apart from catch, this change in size effected a large change in biomass estimates if selectivity was assumed to be constant.

Taiwanese size data showed a substantial change in distribution in about 2003 (Figure 10), as has been previously documented for albacore and other species (Geehan and Hoyle 2013). Similar changes were not observed at the same time in other fisheries targeting the same stock, which suggests that the population was not changing. Similarly, nor were similar changes observed in mean sizes estimated by comparing catch weights with catch numbers in the Taiwanese longline fishery (Geehan and Hoyle 2013), suggesting that the catch size composition was not changing. The observed change in the size sampling data is therefore most likely to be due to changes in sampling methodology.

On the assumption that the true selectivity of the fishery had not changed, the F6_TW_LL_S fishery was split into two parts, an early period prior to 2003, and a late period beginning in 2003. In the final set of runs, the CPUE index for the entire period (1980-2012) was associated with the selectivity in the early longline fishery. Some models in the run sequence were carried out in which the large change in selectivity estimated in 2003 was assumed to apply to the CPUE series, and this significantly affected the biomass trend.

3.3. Fishery dynamics

Fishing mortality was modelled using the hybrid method in which the model estimates the harvest rate using the Pope's approximation and then converts it to an approximation of the corresponding fishing mortality (Methot and Wetzel 2013). The CPUE indices are linked to the selectivity of the F6_TW_S_early fishery. The catchability of the CPUE indices was temporally invariant.

3.4. Likelihood function

The total likelihood is composed on a number of components, including the abundance indices (CPUE), length frequency data and catch data. There are also contributions to the total likelihood from the recruitment deviates and (very weak) 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 and Wetzel 2013).

The statistical weight (or likelihood weight, or effective sample size) given to different components of the stock assessment can be very influential for the final results. The model will fit more closely to a data component if it is given a higher statistical weight. In Stock Synthesis the weights can be adjusted in several ways: via lambdas, via effective sample sizes (for size data), and via standard errors (for survey data). The overall weights given to, for example, the length frequency data for a fishery, can be adjusted by changing the lambda parameter for that fishery and data type from its default value of 1. Adjustments can be made at a finer scale by changing the effective sample sizes for individual time periods.

Determining the appropriate levels for the relative likelihood weights has been the subject of recent research. As advised by Francis (2011), we give primacy to the information in the indices of abundance. Length frequency data is permitted to be informative about selectivity and relative year class strengths, but given the likely process errors such as change in selectivity through time, is not thought to contain reliable information about abundance levels.

For all fisheries, effective sample sizes for the individual length frequency observations were assigned as follows. The number of samples was set to the smaller of 1000 and the number of fish measured, and then divided by 100. This gave a maximum effective sample size (ESS) of 10, which down-weights these data in the overall likelihood. Alternative length frequency data weightings were examined as a sensitivity analysis.

3.5. Stepwise changes towards 2014 reference case

The model used the 2012 stock synthesis assessment as a base, and proceeded to the 2014 reference case via a series of stepwise changes. We describe each change and present figures showing the effects of each change on the biomass and recruitment time series. Although this process is not equivalent to running sensitivity analyses from the reference case, it nevertheless helps to clarify the influence of each change on the final result. This approach is recommended for presenting stock assessments (Ianelli *et al.* 2012).

3.5.1. Rerun 2012 assessment

We reran the input files for the 2012 assessment with updated version of Stock Synthesis.

3.5.2. Plus group 20+

We changed the age of the plus group from 10 to 20.

3.5.3. Update catch and size data and change fishery structures

We updated the size and age data to the data supplied in 2014 (noting that the assessment used catch at size data, with number of fish per length class bin raised to total catch, while this assessment just used the samples at length). Effective sample sizes for the length frequency data were set to a maximum of 10. We also changed the fishery structures to divide fisheries into north and south, to reflect size distributions. CPUE index data were not updated.

3.5.4. S. Pacific driftnet sizes

There were no size data for the driftnet fishery in Indian Ocean. Data from the south Pacific were copied in and fitted with a low effective ample size of 10 per quarter.

3.5.5. Update TW S CPUE

The CPUE time series provided by Japan and Taiwan were included in the model. The Taiwan,China time series designated 'IOTC' was associated with the F6_TW_LL_S fishery. The lambdas for all other indices were set to 0, so that the model fitted only to the TW_LL_S index.

3.5.6. Growth Chen 2012

The growth curve was changed from the curve used in 2012 to a curve based on the work of Chen et al (2012). We estimated lengths at age intermediate between the values in the male and female growth curves, fitted a curve that supplied these lengths at age, and applied this growth curve in the model.

3.5.7. M=0.3

Natural mortality was changed from 0.2207 to 0.3.

3.5.8. Size comp

WeChanged the constant added to the length composition data from 0.0001 to 0.001. This was in order to make the length composition estimation more robust and to reduce the influence of the outliers.

3.5.9. Maturity

The maturity ogive was changed from the approach used in 2012 to the updated ogive, as described earlier.

3.5.10. Plus group age 14

The plus group age was changed from 20 years to 14 years, in order to speed up the running of the model.

3.5.11. Rec deviates 1970

Recruitment deviates were estimated from 1970 rather than starting in 1980.

3.5.12. Rec deviates 1950

Recruitment deviates were estimated from the start of the model in 1950. This approach allows the model to respond to patterns in length frequency data by adjusting relative year class strength rather than by changing the overall average recruitment.

3.5.13. Year end recruitments

Recruitment deviates ere estimated all the way to the end of the time series rather than truncating in 2008.

3.5.14. Recruitment bias adjustment

We approximated the approach to recruitment bias adjustment recommended by Methot and Taylor (2011), with bias adjustment beginning in 1970, reaching 100% in 1980, and declining from 2007. Further adjustments were made in later runs.

3.5.15. Variance adjustment index
We added a variance adjustment factor to the fit to the CPUE index, on top of the existing observation error which was fixed at 0.1, resulting in CV of 0.2 for each index value. This was lower than the model's estimated full CV of 0.31.

3.5.16. Time dependent selectivity
Time-dependent selectivity was included in the F1_JP_LL_N, F2_TW_LL_N, and F6_TW_LL_S fisheries, as described earlier.

3.5.17. Remove F4_Other sizes
The very limited size data associated with the F4_Other fishery were removed, and the selectivity of the fishery was linked to that of the F1_JP_LL_N fishery.

3.5.18. Remove F4_Other catch
This was run as a sensitivity analysis only, with the changes not applied to subsequent model runs. All catches associated with the F4_Other fishery were set to zero.

3.5.19. Recruitment bias estimate
The recruitment bias adjustment was changed so that the maximum adjustment was 60% of the total adjustment for the assumed uncertainty in recruitment, and the first recent year of no adjustment was changed from 2013 to 2009.

3.5.20. Adjust selectivity limits
Selectivity estimates were being constrained by upper limits of peak selectivity at 130 cm, so these were adjusted to 139 cm so that the model could fit to the size data better.

3.5.21. Sex dependent growth
The growth model was changed so that males and females had different growth curves, using the growth curves estimated by Chen et al (2012). Sex ratio in the population remained fixed at 50%.

3.5.22. Recruitment penalty
The expected variability in recruitment was changed from a CV of 0.4 to 0.6, which is a more commonly used assumption about the level of variability in recruitment.

3.5.23. Split T LL S
The fishery F6_TW_LL_S, which is associated with the primary index of abundance, was split into two fisheries, F6_TW_LL_S_early and F8_TW_LL_S_late. The index of abundance was associated with the F6 fishery for the whole time period. As described earlier, this was done to avoid a change in the selectivity associated with the index.

3.5.24. Asymptotic selectivity
Selectivity for the F2_TW_LL_N fishery was made asymptotic, both before and after the split in selectivity.

3.5.25. Update CPUE index
The CPUE index associate with the F6_TW_LL_S fishery was updated with a new index provided by Taiwan.

3.6. Sensitivity analyses

In addition to the stepwise changes described, we ran a number of sensitivity analyses to identify the effects on model results.

3.6.1. Estimate the effective sample size

Effective sample sizes were assigned using an alternative method. Stock Synthesis derives estimates of effective sample size following the method of McAllister and Ianelli (1997), based on the fit between the data and the model. These estimates were taken from the fitted reference case and a regression was fitted for each fishery to the relationship between observed and effective sample size. We used the regressions to predicted effective sample sizes for each time period, and applied these predicted effective sample sizes to the sensitivity analysis model.

3.6.2. Downweight length frequency likelihood

We modelled a scenario in the length frequency data was allowed to contribute to estimating selectivity, but given no influence on the abundance. The model was run as normal and then restarted from the final fit, with selectivities fixed and length frequency lambdas set to zero.

3.6.3. Estimate growth

Four alternative approaches were applied to the growth curves, since stock assessments are sensitive to growth estimates, and curve used in the reference case is based on north Pacific data. First, all growth parameters were estimated. Second, the asymptotic length and variance of length were estimated, but the growth coefficient and length at age 1 were held constant, in order to maintain the shape of the curve. Third, the south Pacific albacore was used as a starting point in order to apply the shape of this growth curve, and the parameters for asymptotic length and the variance of length at age were estimated. Fourth, the south Pacific albacore was used as a starting point, and only the parameter for asymptotic length was estimated.

3.6.4. Gradually increase fishing power

As describe in section 2.2.4, we modelled a scenario in which the catchability increased by 1% each year.

3.6.5. Alternative natural mortality

We modelled scenarios with natural mortality set to 0.2 and 0.4, rather than the reference case level of 0.3.

3.6.6. Alternative steepness

We modelled scenarios with steepness set to 0.7 and 0.9, rather than the reference case level of 0.8.

3.7. Uncertainty grid

An uncertainty grid was run with all combinations of the following options, making a total of 36 options.

a) Natural mortality set to 0.2, 0.3, or 0.4
b) Steepness set to 0.7, 0.8, or 0.9
c) Fishing power constant or increasing at 1% per year

d) Effective population size of length frequency data at the reference case level, or entirely downweighted in the final phase with growth and selectivity fixed

3.8. Projections

The model was projected forward for 10 years, with constant recruitment and with catch in each fishery fixed at the 2012 level. Additional projections were run with catch increased by 10%, and reduced by 10%.

4. Model results

4.1. Stepwise changes

The effects on estimates of spawning biomass and recruitment of the various changes in the model towards the 2014 assessment are presented in Figure 17 to Figure 24. The overall differences between the 2012 and 2014 assessments are shown in Figure 25.

The sequential changes and their consequences on the Biomass trajectories are outlined below:

4.1.1. Rerun 2012 assessment

Updating the model with the new version of stock synthesis did not significantly change the model outcomes.

4.1.2. Plus group 20+

Changing the age of the plus group from 10 to 20 made only a very small difference to the biomass trend.

4.1.3. Update catch and size data and change fishery structures

As expected, updating the size and age data and fishery structures substantially changed the model outcomes. These changes had multiple causes. The 2 changes with the greatest influence were a) changing the fishery structure to include north and south fisheries, and b) changing the length frequency data effective sample size from the previous levels (estimated in the model after a run with nominal levels) to a maximum of 10 per quarter.

4.1.4. S. Pacific driftnet sizes

Including driftnet size data in the F7_Driftnet fishery substantially changed the selectivity for this fishery, which was now estimated based on data. In previous runs it was estimated but without data, resulting in some instability. There was a small effect on the abundance trend.

4.1.5. Update TW S CPUE

Fitting to the CPUE time for the F6_TW_LL_S fishery had a significant effect on the abundance trend, as expected, and also resulted in higher average abundance.

4.1.6. Growth Chen 2012

Changed the curve to one based on the work of Chen et al (2012) changed the productivity of the population and consequently changed both the abundance trend and the average abundance.

4.1.7. M=0.3

Similarly changing natural mortality from 0.2207 to 0.3 increased the productivity of the stock, and changed both the spawning biomass trend and the average abundance.

4.1.8. Size comp

Changing the constant added to the length composition data from 0.0001 to 0.001 changed the abundance level somewhat, suggesting that outliers in the size data had been affecting the fit of the model. Outliers may continue to have some effect.

4.1.9. Maturity

Changing the maturity ogive had a relatively small effect on the recruitment but significantly increased the spawning biomass. Note that at this stage in the run sequence the sexes are still assumed to have the same growth curve.

4.1.10. Plus group age 14

Changing the plus group age from 20 to 14 had very little effect on model parameters.

4.1.11. Rec deviates 1970

4.1.12. Rec deviates 1950

Estimating recruitment deviates in 1970 rather than 1980 greatly increased the overall estimate of model biomass, but taking recruitment further back to 1950 had only a small additional effect. It appears likely that greater flexibility in the recruitment deviates improved the fit to the size data between 1970 and 1980 (note the large deviates in 1970 and 1978), reducing bias on the overall population level due to lack of fit to the size data.

4.1.13. Year end recruitments

Similarly, estimating recruitment deviates to 2012 resulted in a slight change to the average biomass presumably due to improved fit.

4.1.14. Recruitment bias adjustment

Applying the first part if the Methot and Taylor (2011) recommended approach to recruitment bias adjustment slightly increased the average recruitment and spawning biomass in parts of the time series.

4.1.15. Variance adjustment index

Adding a variance adjustment factor to the fit to the CPUE index reduced the priority given to the CPUE index, and as expected significantly changed the biomass trend and level.

4.1.16. Time dependent selectivity

Time-dependent selectivity in the F1_JP_LL_N, F2_TW_LL_N, and F6_TW_LL_S fisheries was a significant change to the model which substantially improved the fit to the size data, and reduced the average abundance level. It also changed the population trajectory at the end of the time series.

4.1.17. Remove F4_Other catch

4.1.18. Remove F4_Other sizes

Removing the very limited size data associated with the F4_Other fishery, and linking the selectivity linked to that of the F1_JP_LL_N fishery, had a relatively small effect on the model. Similarly, removing the catch associated with this fishery (as a sensitivity analysis) had a very minor effect on the model.

4.1.19. *Recruitment bias estimate*
Further changing the recruitment bias adjustment had almost no further effect on the model.

4.1.20. *Adjust selectivity limits*
Adjusting the selectivity limits substantially affected the biomass level, indicating that size data remain very influential in their effects on the stock assessment. It was apparent that the model was struggling to predict the sizes of the larger fish observed.

4.1.21. *Sex dependent growth*
Changing the growth model to a two-sex model reduced the average abundance even further. The model was now able to predict larger fish and provide a better fit to the size data.

4.1.22. *Recruitment penalty*
Assuming greater variability in recruitment effectively reduced the penalty applied to the recruitment deviates, and made a small difference to the average biomass.

4.1.23. *Split T LL S*
Splitting the F6_TW_LL_S fishery allowed the CPUE index to be associated with the same selectivity throughout the time series. This represented a change in the period after 2003, and the biomass trend now followed the index downwards rather than increasing

4.1.24. *Asymptotic selectivity*
Requiring the TW_LL_N fishery selectivity to be asymptotic made little difference to the model in this case, since the selectivity was already close to asymptotic. However it represented a more reasonable assumption about the selectivity of the fishery, and was likely to stabilise outcomes across other models such as sensitivity analyses and the grid.

4.1.25. *Update CPUE index*
The updated CPUE series had a different population trajectory, which as expected changed the model outcomes.

4.2. Final model set
The final set of models included two alternative sets of CPUE indices (TW_LL_S_IOTC and TW_LL_S_IOTCq1), three natural mortality schedules (adult M of 0.2, 0.3, and 0.4), three alternative levels of steepness (0.7, 0.8 and 0.9) for the SRR, and two approaches to weighting the size data (maximum of 10, and downweighted entirely in the final phase). The set of models encompassing all combinations of these options (2x3x3x2) comprised 36 alternative models. The WPTmT 5 identified a subset / considered that there was no compelling information to identify a preferred sub-set from the range of models or exclude any specific model options. Thus, xxx model combinations were retained in the final set of models.

The range of model options have broadly similar characteristics regarding the fit to the main data sets and model parameterisation. For presentation purposes, a single reference model was selected

(M=0.3, IOTC TW_LL_S index, ESS=10, and steepness 0.8) to describe the main features of the assessment. Significant differences amongst the range of models are highlighted.

There is a reasonable fit to the general trend in the CPUE indices (Figure 27), as expected given the priority given to these indices in the model weights. There are some minor patterns in the CPUE residuals, with largely positive residuals from 1999-2007. Overall, the variation in the residuals (RMSE approx. 0.33) is a little higher than the average assumed c.v. for the CPUE indices (0.20). We chose to apply a tighter c.v. in order to prioritise the fit to the abundance index (Francis 2011)

The length-specific selectivity functions are presented in Figure 28. Given the size variation among fleets, only the northern Taiwanese longline fleet could be given asymptotic selectivity. For this fleet prior to 2003, selectivity began at about 70cm and continued to increase up to about 115 cm. After 2003 the proportion of small fish reduced considerably with selectivity beginning at about 90 cm and increased until 120 cm. For Japanese composite longliners in the north, the selectivity curve was very narrow. Before the split in 1978 selectivity increased from about 90cm and dropping away after peaking at a little over 100 cm. After 1978, selectivity in the northern Japanese composite longline fishery shifted to slightly larger sizes. Selectivity of the purse seine fishery was similar to or slightly larger than the Japanese composite longline fishery, possibly reflecting its different location in the west, and with a lower proportion of the catch in the south of the northern area.

Overall there was a good fit to the aggregated length frequency data for the main fisheries with comprehensive sampling (Figure 29). However, examination of the model residuals from the individual observations reveal a poor fit to the data from key fisheries during certain time periods (Figure 30). Fit to the F1_JPN_LL_N fishery is good up until the mid-1990s, but the subsequent period is significantly worse. For F2_TWN_LL_N some very large residuals are apparent particularly during the early period, though the fit was considerably improved by splitting the selectivity in 2003. Size data for the purse seine fishery F3_PS_N are relatively consistent with a narrow size range and only a few fish caught at uncharacteristic sizes. This reflects the relatively restricted spatial distribution of the fishery, in an area where fish are expected to be large. Fit to the F4_Other fishery is as expected very poor, since the model does not attempt to fit to this fishery – these residuals are not included in the likelihood. The southern Japanese composite longline fishery has the largest residuals of all fisheries due to a number of outliers, with very noisy data, but the selectivity curve appears reasonable. Data from the southern Taiwan,China longline fisheries F6_TW_LL_S_early and F8 TW_LL_S_late fit reasonably well, which was not the case until the fishery was split in 2003.

Some inconsistency between the fishery-specific length frequency data and the CPUE indices was also evident in the derived values of effective sample size from the model (following McAllister and Ianelli 1997) (Figure 31). The values are the ESS required for each sample to enable the observed proportions at length to approximate the predicted proportions. Large ESSs were computed for most of the individual samples although there was also considerable variability in the ESS over the respective time-series.

The time-series of recruitment deviates for the sensitivity analyses related to size data (Figure 32) showed that downweighting the size data with growth and selectivity fixed did not greatly change the biomass series. However, increasing the effective sample sizes to the levels estimated in the model (see Figure 31) considerably changed the model trajectory, away from the CPUE trend.

Including effort creep in the abundance trend had a relatively small impact on the abundance trend. The impact was felt during the period from 1981 to 2012 with a greater decline during this period. However the biomass in 1950 was almost unchanged.

When growth was estimated the biomass trend and biomass level changed considerably (Figure 33). Using the south Pacific growth curve, with its different shape but with asymptotic length estimated, resulted in particularly large changes. However, the growth curve estimates were quite unstable and may not have been realistic.

Alternative values of natural mortality made a large difference to the recruitment estimates, and smaller differences to the spawning biomass trends (Figure 34). Lower natural mortality resulted in a steeper decline in biomass, while higher M resulted in a flatter trajectory.

In general, there was a moderate variability in the recruitment deviates, with some larger recruitments contributing to strong year classes in the fishery. There was a consistent temporal trends in the recruitment time series with a decline on average through the time series.

The estimate of fishing mortality on small fish was very high for the driftnet fishery in the late 1980s early 1990s (Figure 35). After that period the fishing mortality in other fisheries steadily increased, as biomass declined.

The relationship between spawning stock size and estimated recruitments differed somewhat from the relationship predicted by the SRR, with lower recruitments than predicted at the low stock sizes in in recent years (Figure 36).

4.3. Structural uncertainty grid

The distribution of outcomes in the structural uncertainty grid is presented on a Kobe plot (Figure 39). The majority of model runs indicate neither overfishing nor an overfished state, but about one quarter of the model runs indicate overfishing and a few of these also indicate an overfished state. Natural mortality had the most effect on F/F_{MSY}, SB/SB_{MSY}, and the estimate of MSY (Figure 40). Steepness was also influential, particularly for SB/SB_{MSY}. The assumption of increasing catchability had a moderate effect on F/F_{MSY} and SB/SB_{MSY}, but did not affect MSY. Downweighting the length frequency data in the final phase had only a minor effect on F/F_{MSY}, and no effect on the other management parameters.

4.4. Projections (WILL BE UPDATED)

5. Discussion

5.1. State of current knowledge, and potential improvements

The results of this assessment provide a view of the current status. The majority of model runs indicate neither overfishing nor an overfished state, but about one quarter of the model runs indicate overfishing and a few of these also indicate an overfished state. The status is therefore uncertain, which is expected given the relatively limited information available to assess the albacore stock.

The estimated stock status in this assessment differs from the previous assessment, which was the first application of an integrated analysis approach to this stock. We used the 2012 assessment as a starting point and progressed by changing one feature at a time, in order to understand how each change affected the assessment. A number of changes significantly affected model outcomes, and these can be grouped as changes affecting the fit to the size data, the productivity, and the index of abundance. Changes affecting the fit to the size data included restructuring of fisheries into north and south regions to reflect the size patterns; changing the growth curve to a two-sex curve based on the north Pacific curve (Chen *et al.* 2012); reducing the effective sample sizes to prevent size data affecting abundance trends; adding time-dependent selectivity to reflect features observed in the data; and estimating recruitment deviates for the whole time series so as to improve the fit to the size data. Changes affecting productivity included changing the growth curve based on recent research in other oceans, and adjusting natural mortality to reflect the range of values assumed in other albacore assessments. Changes affecting the CPUE series included introducing an updated CPUE series based on the Taiwan,China southern longline fishery; and adjusting the c.v. applied to the CPUE series. We consider that these changes are reasonable and represent improvements, although there is uncertainty about some aspects.

The drivers of the uncertainty that remains in the assessment can be classed according to their significance for stock status, and how easy it is to resolve them. When considering the significance for stock status, in addition to the grid we look at the sensitivity analyses and runs in the sequence from the 2012 to 2014 models, since the grid considered only a few sources of uncertainty.

The source of uncertainty that may be easiest to address is the CPUE series. We fitted the model closely to the CPUE, and the run sequence demonstrated that changing the CPUE series can significantly change the biomass trajectory. All of the CPUE series available for the Indian Ocean albacore assessment are likely to be affected by target change, and resolving this issue may significantly improve the assessment. The best CPUE indices are based on operational data and include vessel effects, and we encourage development of such indices. A reliable CPUE series that started earlier than 1981 may significantly reduce uncertainty and improve model results. This may be achievable through additional careful analysis of the long term catch and effort data available from the Japanese longline fleet.

Another potentially tractable source of uncertainty, although more difficult than CPUE to address, is the growth curve. Sensitivity analyses demonstrated that changing the growth curve significantly changed the stock assessment outcomes. Reliable growth curves require well-stratified sampling across a wide range of sizes based on an understanding of the species biology, ageing using otoliths and the most reliable methods, and appropriate statistical analysis, preferably within the stock assessment.

A well-designed programme of otolith collection may also provide a way to address uncertainties about natural mortality and total mortality, and differences between the sexes. The shape of the Indian Ocean albacore growth curve may turn out to be similar to the south Pacific albacore growth curve, which shows slow growth post-maturity. If this is the case then size data will contain little information about total mortality, and data on age structure may be required to determine stock status. Albacore growth may also vary spatially, be density dependent, and be affected by environmental conditions. Otolith data would both allow better understanding of these issues and provide an independent source of information about total mortality.

The size data from the Taiwan,China longline fishery is also a source of some uncertainty. There was a contemporaneous change in the size data, but not catch weight data, towards larger fish and away from smaller fish across multiple species and across many locations, with similar patterns seen in other oceans (Geehan and Hoyle 2013). Uncertainty remains about what caused these changes, but in this assessment we have assumed that the selectivity of the fishery itself did not change. As indicated by the progression of changes in the run sequence, different causes have different implications for biomass trajectory and for stock status. Resolving this issue is a high priority.

The least tractable source of uncertainty is the steepness of the stock recruitment relationship. Estimating the stock recruitment relationship within stock assessments is increasingly thought to be impractical (e.g. Lee *et al.* 2012). The standard approach is to accept the uncertainty and estimate stock status across a range of options (ISSF 2011). Underestimating rather than overestimating the steepness of the stock recruitment relationship may provide higher yields on average in the long term, together with lower fishing costs due to higher catch rates (Zhu *et al.* 2012).

5.2. Individual model components

Some inconsistency between the fishery-specific length frequency data and the CPUE indices was evident in the derived values of effective sample size from the model. Prior to 1981 there were no CPUE data to conflict with the size data from the Japanese composite longline fisheries, so it is not surprising that the ESS are generally high for this period. However, for time periods without CPUE data, allocating the estimated ESS to the size data would give them undue influence on the abundance trend.

The time-series of recruitment deviates for the sensitivity analyses related to size data (Figure 32) show that the low weight given to the size data was appropriate, since it was sufficient to allow the estimation of selectivity, but did not substantially affect biomass or the biomass trend, given the assumed growth curve. The biomass series was not affected by downweighting the size data with growth and selectivity fixed. However, increasing the effective sample sizes considerably changed the model trajectory and caused conflict with the CPUE trend.

Including effort creep in the abundance trend had a relatively small impact on the abundance trend and little influence on the average biomass level, apparently because the change in trend was relatively small. Results from the grid suggested that the greatest effect of assuming effort creep was on the parameter SB/SB_{MSY}.

The divergent results when growth was estimated show the great influence of the (comparatively unknown) growth curve on the stock assessment. The shape of the growth curve was influential, given the impact of using the south Pacific growth curve with asymptotic length estimated. However, these estimates cannot be seen as definitive since the model had little information with which to estimate growth, and the estimates were quite unstable. Changing the growth curve without estimating it also significantly changed the biomass trajectory.

6. Overall Conclusions

Based on the analysis done (the reference case) and the set of grids run (the median trajectory of all runs), the stock appears to be in healthy status (not overfished, nor experiencing overfishing) and is the green quadrant (Figure 37). Only a few runs indicate when natural mortality is low, and steepness is low that the stock is overfished or overfishing is occurring on the stock (Figures 38 & 39). In the grid based runs analysed, 2 (5.6%) runs indicate the stock is overfished, 8 (22.4%) indicate that the stock is experiencing overfishing, i.e.~ 28% of the runs examined have a feasible stock trajectory that may indicate that overfishing is occurring on the stock, and only in a very minor set (~5%) that the stock is at overfished status. Even, though there is considerable uncertainty in the stock dynamics, the stock is likely in a healthy status (~72%) in the majority of the runs examined. More emphasis needs to be placed on examining basic biological data (growth) and natural mortality (M) that is specific to Indian Ocean Albacore. While, considerable uncertainty exists on the stock, the stock is currently in a healthy status and is probably not experiencing overfishing, nor is in an overfished status. Due to the considerable uncertainty, it is not recommended catch levels exceed the 2012 levels till better information is available.

7. Acknowledgements

Simon Hoyle's participation in the assessment was funded by the Indian Ocean Tuna Commission. The staff of the IOTC provided support and assistance with the project. Thanks to Kevin Piner, HuiHua Lee, and Adam Langley for valuable advice on the use of Stock Synthesis. Discussions during the WPTmT 5 contributed significantly to the final assessment.

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9. Tables

Table 1: Definitions of the individual fisheries in the model.

Code	Fishing method	Area	Flag	Notes
F1_JPN_LL_N	Longline	North	Japan	Selectivity changed in 1990
F2_TWN_LL_N	Longline	North	Taiwan	Selectivity changed in 2003
F3_PS_N	Purse seine	North	All	
F4_Other_N	Mixed	North	All	Selectivity linked to F1
F5_JPN_LL_S	Longline	South	Japan	
F6_TWN_LL_S_early	Longline	South	Taiwan	Separated into early and late stages to address changes in selectivity
F7_Driftnet_S	Driftnet	South	Driftnet	Size data sourced from the south Pacific driftnet fleet
F8_TWN_LL_S_late				

Table 2: Maximum posterior density estimates of the main model status indicators.

Downwt LF	hh	LLq	M	SB_0	SB_{MSY}	SB_{2012}	SB_{2012}/SB_0	SB_{2012}/SB_{msy}	F_{2011}/F_{MSY}	MSY	Total likelihood	Survey Likelihood	L frq Likelihood
0	0.7	0	0.2	209626	55065	39902	0.1903	0.7246	1.2854	30693	1345.54	-8.265	-1.169
0	0.7	1	0.2	215374	56535	33584	0.1559	0.5940	1.4182	31516	1350.54	-5.953	-1.144
0	0.8	0	0.2	198123	43593	39339	0.1986	0.9024	1.0460	33872	1345.29	-8.205	-1.281
0	0.8	1	0.2	203959	44836	33249	0.1630	0.7416	1.1486	34848	1350.59	-5.788	-1.018
0	0.9	0	0.2	189931	31752	39086	0.2058	1.2310	0.8313	37784	1345.19	-8.131	-1.277
0	0.9	1	0.2	195829	32699	33179	0.1694	1.0147	0.9088	38930	1350.74	-5.629	-0.805
0	0.7	0	0.3	232195	57112	73493	0.3165	1.2868	0.6155	48143	1336.86	-10.600	-0.816
0	0.7	1	0.3	232599	57278	59374	0.2553	1.0366	0.7124	48365	1339.5	-9.666	0.330
0	0.8	0	0.3	224945	44841	73630	0.3273	1.6420	0.4873	55266	1337.15	-10.552	-0.592
0	0.8	1	0.3	225235	44964	59804	0.2655	1.3300	0.5602	55471	1340.05	-9.548	0.758
0	0.9	0	0.3	220124	31275	74077	0.3365	2.3686	0.3756	64439	1337.4	-10.499	-0.386
0	0.9	1	0.3	220664	31413	60615	0.2747	1.9296	0.4286	64713	1340.53	-9.432	1.143
0	0.7	0	0.4	311274	72191	136109	0.4373	1.8854	0.3369	82508	1342.8	-11.197	0.837
0	0.7	1	0.4	298196	69194	106205	0.3562	1.5349	0.4035	79221	1344.95	-10.763	2.545
0	0.8	0	0.4	308176	56487	138612	0.4498	2.4539	0.2669	98290	1343.12	-11.146	1.059
0	0.8	1	0.4	293726	53894	108077	0.3680	2.0054	0.3191	93880	1345.54	-10.653	2.936
0	0.9	0	0.4	305973	48855	140565	0.4594	2.8772	0.2270	117762	1343.39	-11.097	1.231
0	0.9	1	0.4	291119	48971	109913	0.3776	2.2444	0.2770	111705	1346.01	-10.552	3.250
1	0.7	0	0.2	206957	54531	34916	0.1687	0.6403	1.2924	30414	1261.72	-8.274	-1.336
1	0.7	1	0.2	212369	55936	28860	0.1359	0.5160	1.4231	31216	1266.65	-6.085	-1.349
1	0.8	0	0.2	194911	43058	34207	0.1755	0.7944	1.0500	33435	1261.26	-8.264	-1.502
1	0.8	1	0.2	200359	44239	28376	0.1416	0.6414	1.1501	34373	1266.49	-5.980	-1.273
1	0.9	0	0.2	186300	31305	33844	0.1817	1.0811	0.8329	37162	1261.03	-8.225	-1.527

Downwt LF	hh	LLq	M	SB_0	SB_{MSY}	SB_{2012}	SB_{2012}/SB_0	SB_{2012}/SB_{msy}	F_{2011}/F_{MSY}	MSY	Total likelihood	Survey Likelihood	L frq Likelihood
1	0.9	1	0.2	191759	32202	28186	0.1470	0.8753	0.9080	38249	1266.51	-5.861	-1.081
1	0.7	0	0.3	222007	54702	62486	0.2815	1.1423	0.6264	46117	1252.96	-10.371	-1.084
1	0.7	1	0.3	223242	55066	50202	0.2249	0.9117	0.7180	46523	1255.34	-9.519	0.031
1	0.8	0	0.3	214423	42828	62498	0.2915	1.4593	0.4947	52760	1253.2	-10.339	-0.848
1	0.8	1	0.3	215458	43095	50444	0.2341	1.1705	0.5631	53163	1255.84	-9.421	0.476
1	0.9	0	0.3	209303	29803	62799	0.3000	2.1071	0.3805	61337	1253.43	-10.297	-0.626
1	0.9	1	0.3	210301	30008	50942	0.2422	1.6976	0.4306	61763	1256.31	-9.322	0.882
1	0.7	0	0.4	294368	68289	117377	0.3987	1.7188	0.3373	78065	1258.98	-10.864	0.590
1	0.7	1	0.4	283047	65702	91118	0.3219	1.3868	0.3998	75252	1260.92	-10.478	2.284
1	0.8	0	0.4	290223	53215	119016	0.4101	2.2365	0.2676	92605	1259.3	-10.821	0.820
1	0.8	1	0.4	277973	51027	92470	0.3327	1.8122	0.3161	88904	1261.49	-10.380	2.688
1	0.9	0	0.4	287428	46691	120431	0.4190	2.5793	0.2295	110499	1259.57	-10.778	1.001
1	0.9	1	0.4	274832	47232	93835	0.3414	1.9867	0.2771	105274	1261.96	-10.287	3.013

10. Figures

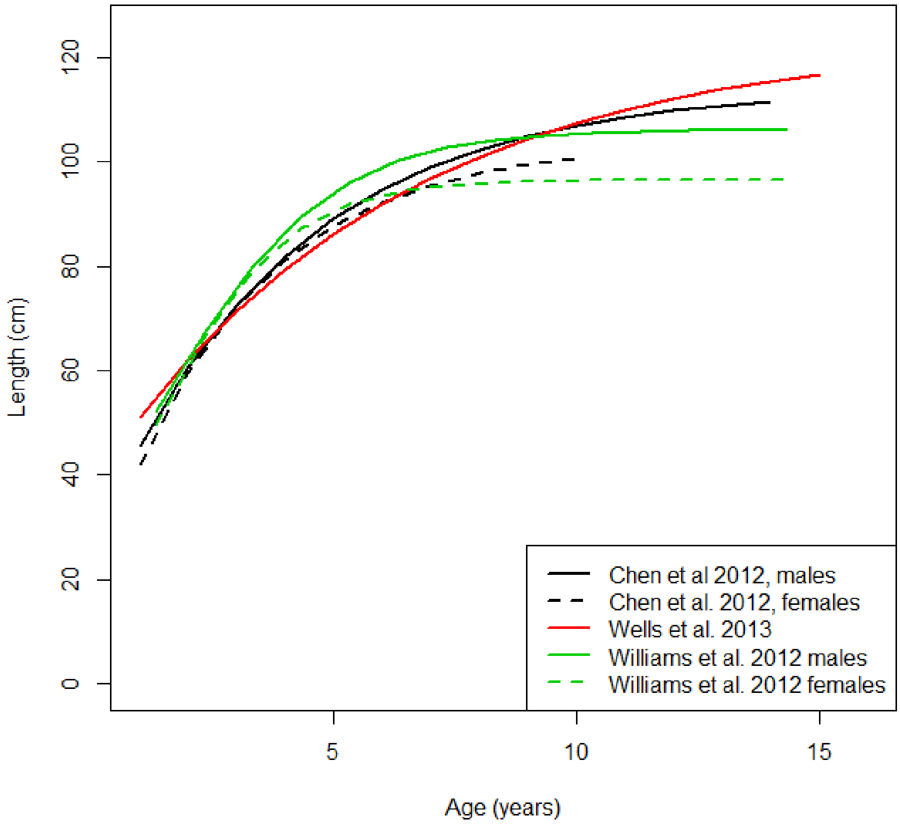


Figure 1: Growth curves based on ageing with otoliths for the north Pacific (Chen et al 2012 and Wells et al 2013) and south Pacific (Williams et al 2012).

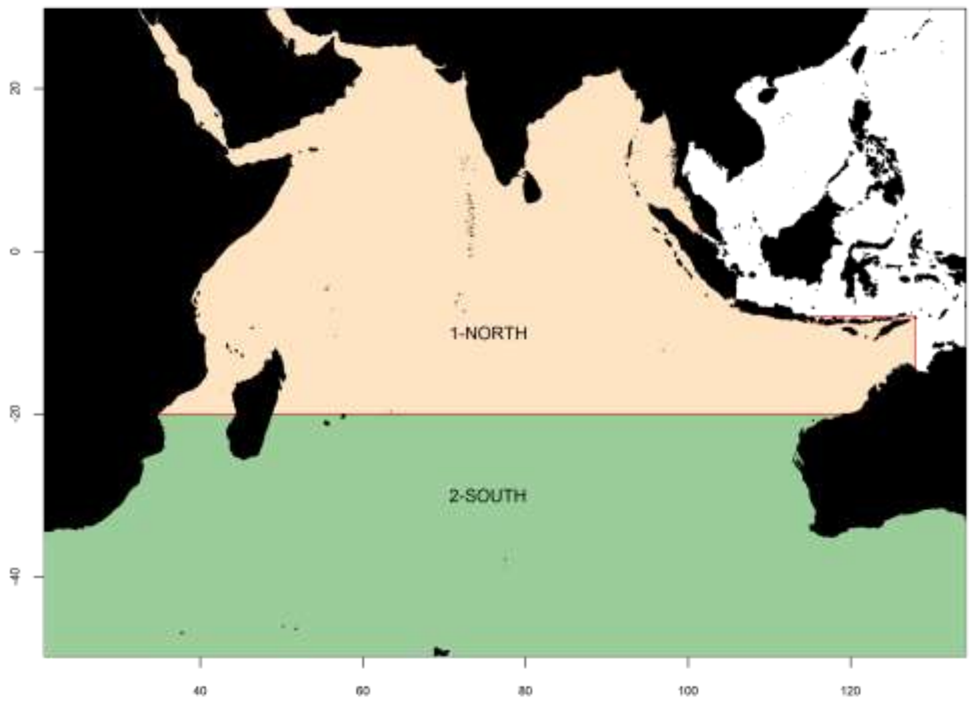


Figure 2: The spatial structure used to define the model fisheries.

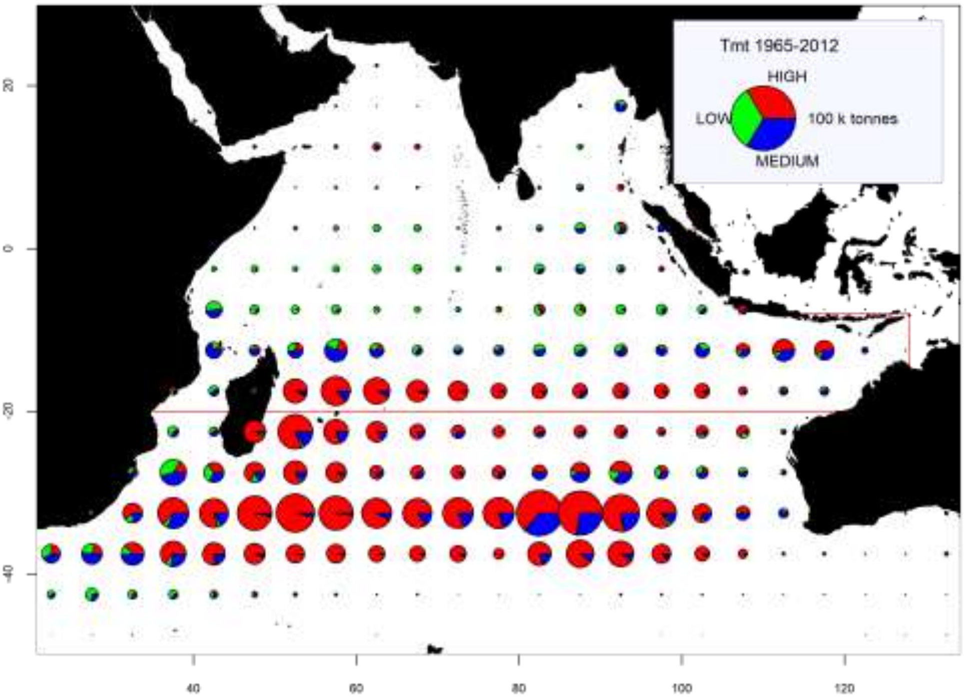


Figure 3: Catches of albacore from all industrial longline fleets over the period 1965-2012, by 5 degree square grid, and relative importance of albacore in each 5 degree square grid and quarter:

HIGH (red): Catches of albacore from each grid and quarter stratum were assigned to the category high when they represented 50% or more of the total combined catches of ALB-SBF-BET-YFT-SWO;
MEDIUM (blue): Catches of albacore represented between 15% and 50% of the total combined catches of ALB-SBF-BET-YFT-SWO;
LOW (green): Catches of albacore represented less than 15% of the total combined catches of ALB-SBF-BET-YFT-SWO.

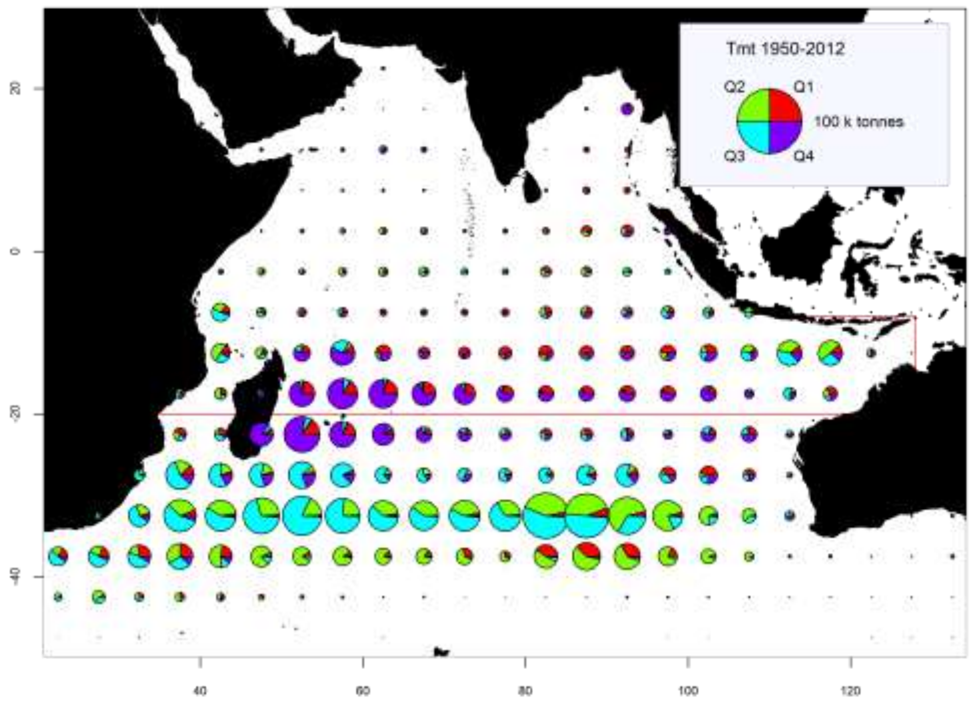


Figure 4: Catches of albacore from all industrial longline fleets over the entire time-series of catch, by 5 degree square grid and quarter:

Q1 (red): Jan-Mar;
Q2 (green): Apr-Jun;
Q3 (blue): Jul-Sep;
Q4 (purple): Oct-Dec.

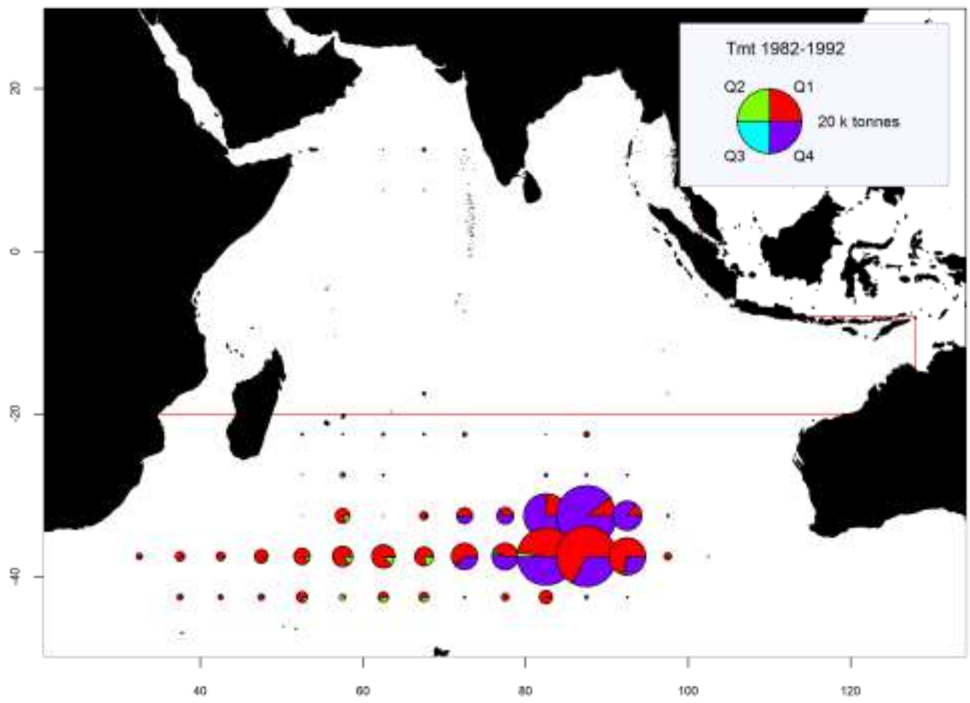


Figure 5: Catches of albacore for the driftnet fishery of Taiwan,China, by 5 degree square grid and quarter:

Q1 (red): Jan-Mar;
Q2 (green): Apr-Jun;
Q3 (blue): Jul-Sep;
Q4 (purple): Oct-Dec.

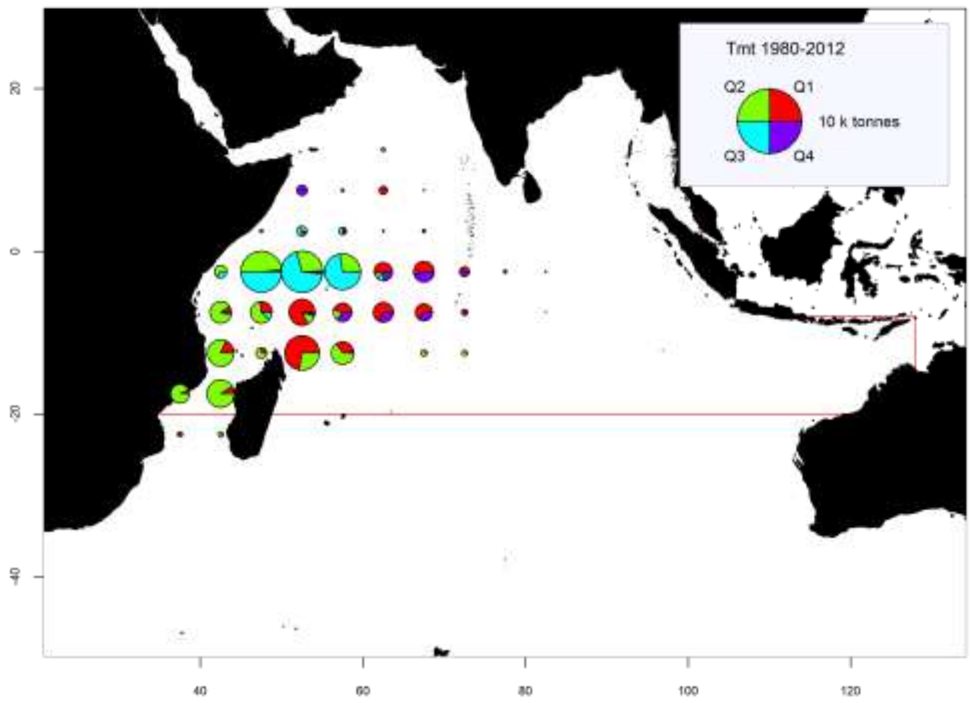


Figure 6: Catches of albacore from all industrial purse seine fisheries, by 5 degree square grid and quarter:

Q1 (red): Jan-Mar;
Q2 (green): Apr-Jun;
Q3 (blue): Jul-Sep;
Q4 (purple): Oct-Dec.

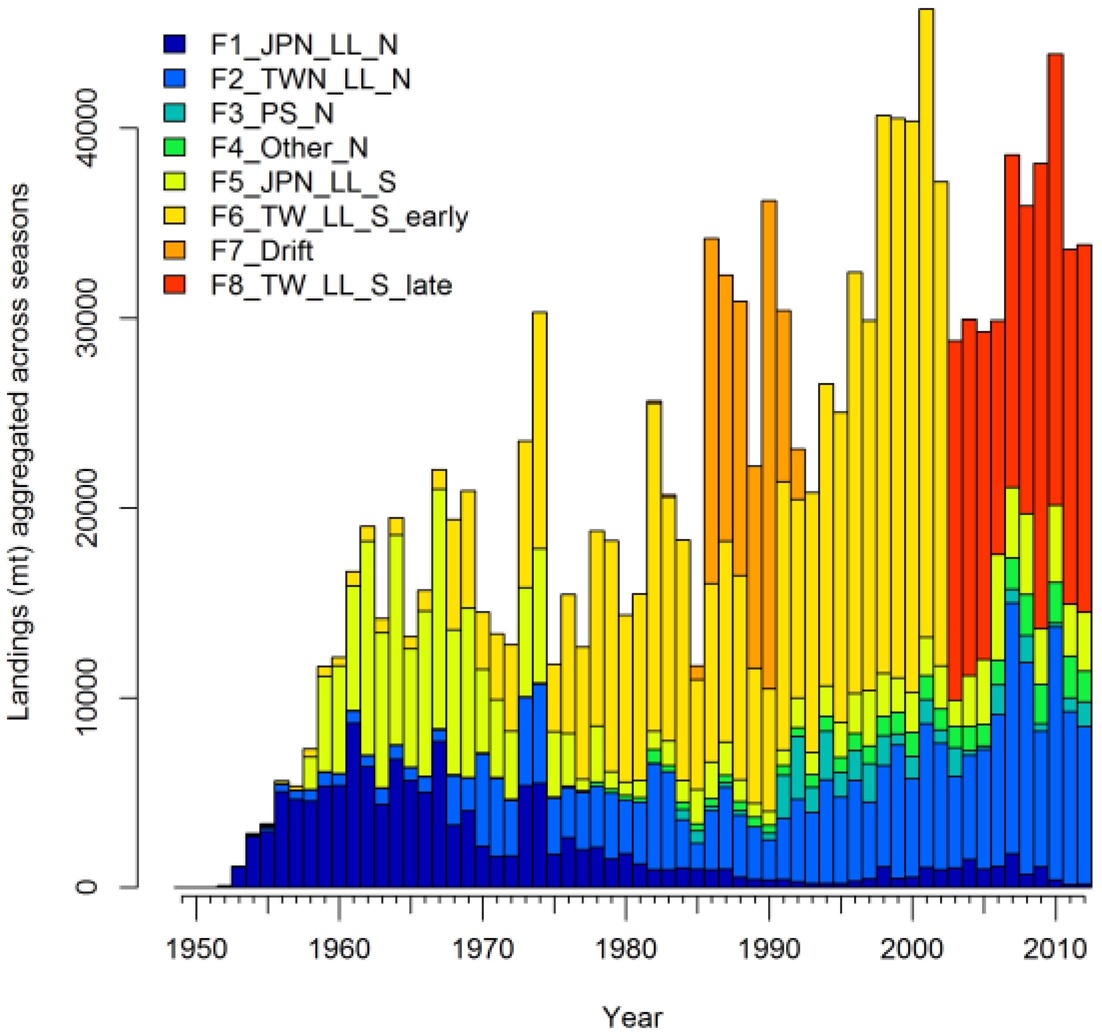


Figure 7: Annual catches by fishery, 1950-2012.

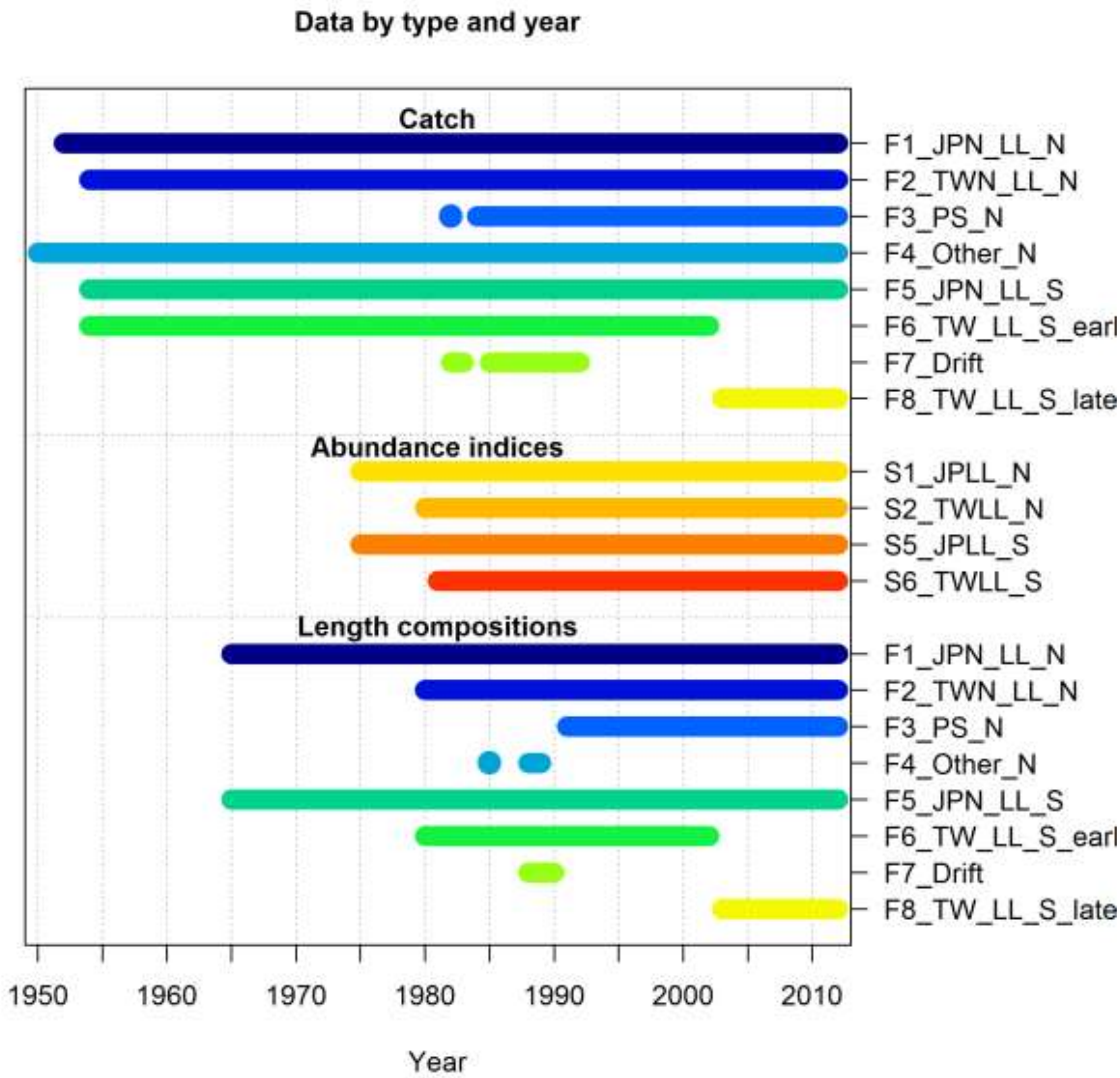


Figure 8: Distribution of data availability by fishery and data type, through time.

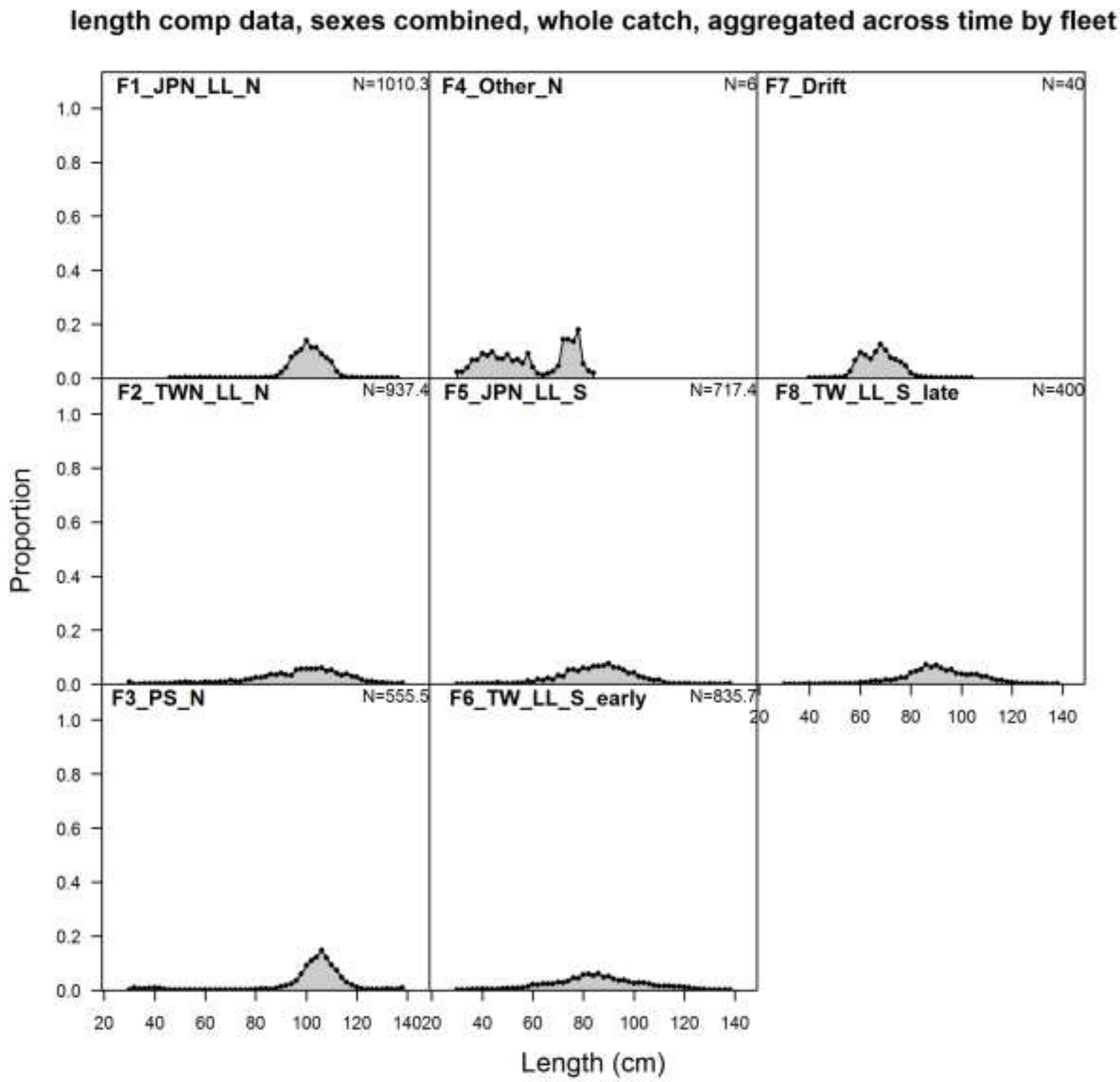


Figure 9: Length data by fleet, aggregated across all years

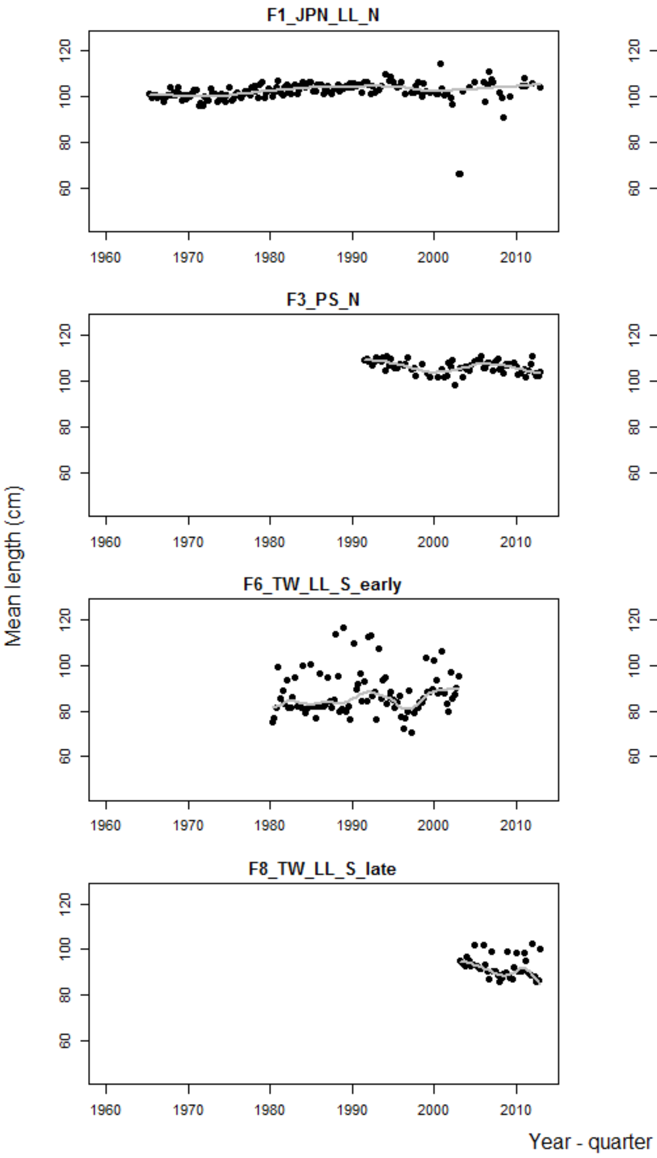


Figure 10: Average length of albacore in the quarterly samples from each fishery. The grey line is a loess smoothed trend.

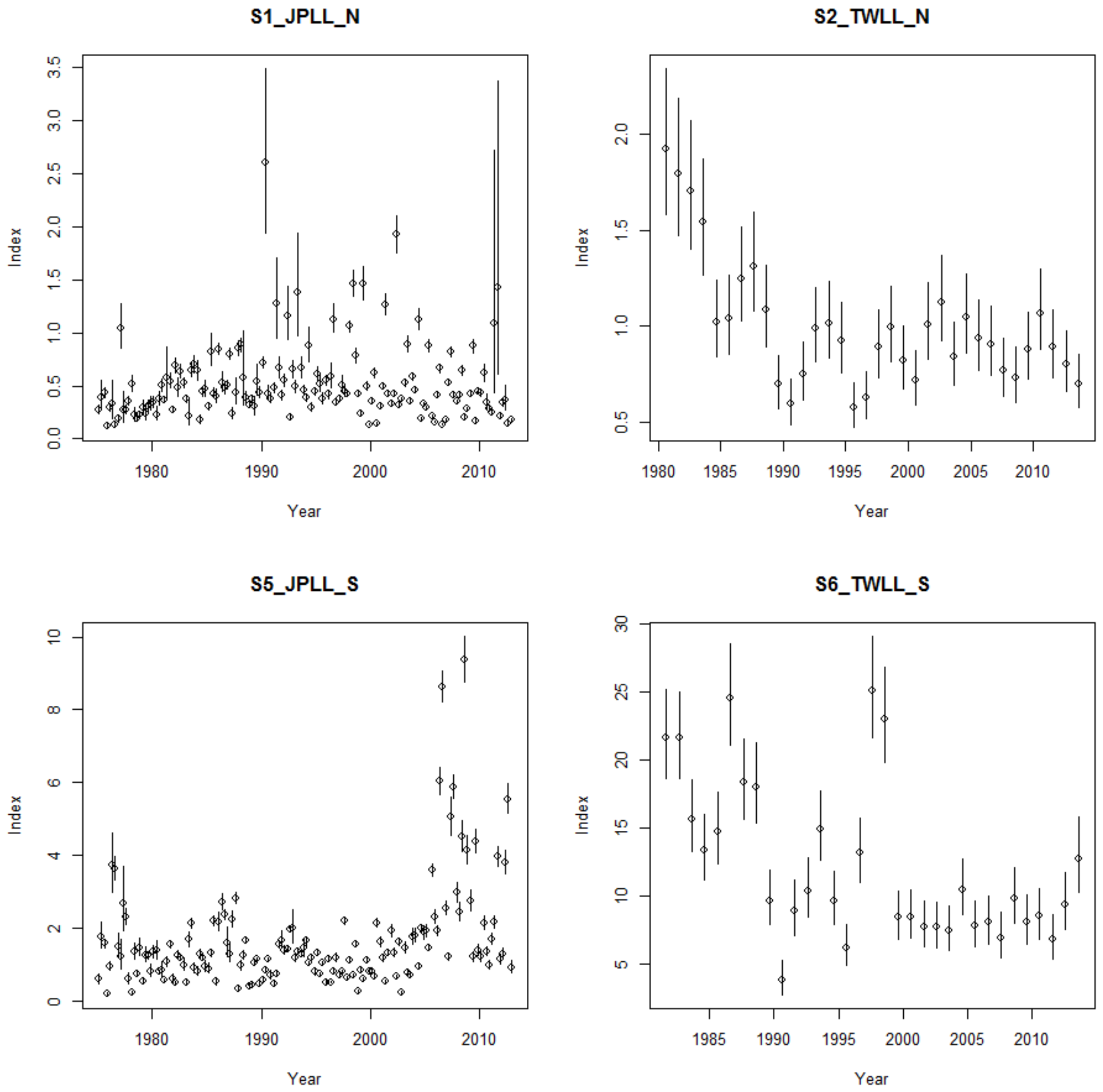


Figure 11: CPUE indices for the Japanese (left) and Taiwanese (right) longline fisheries to the north (above) and south (below) of the latitude 20 degrees south.

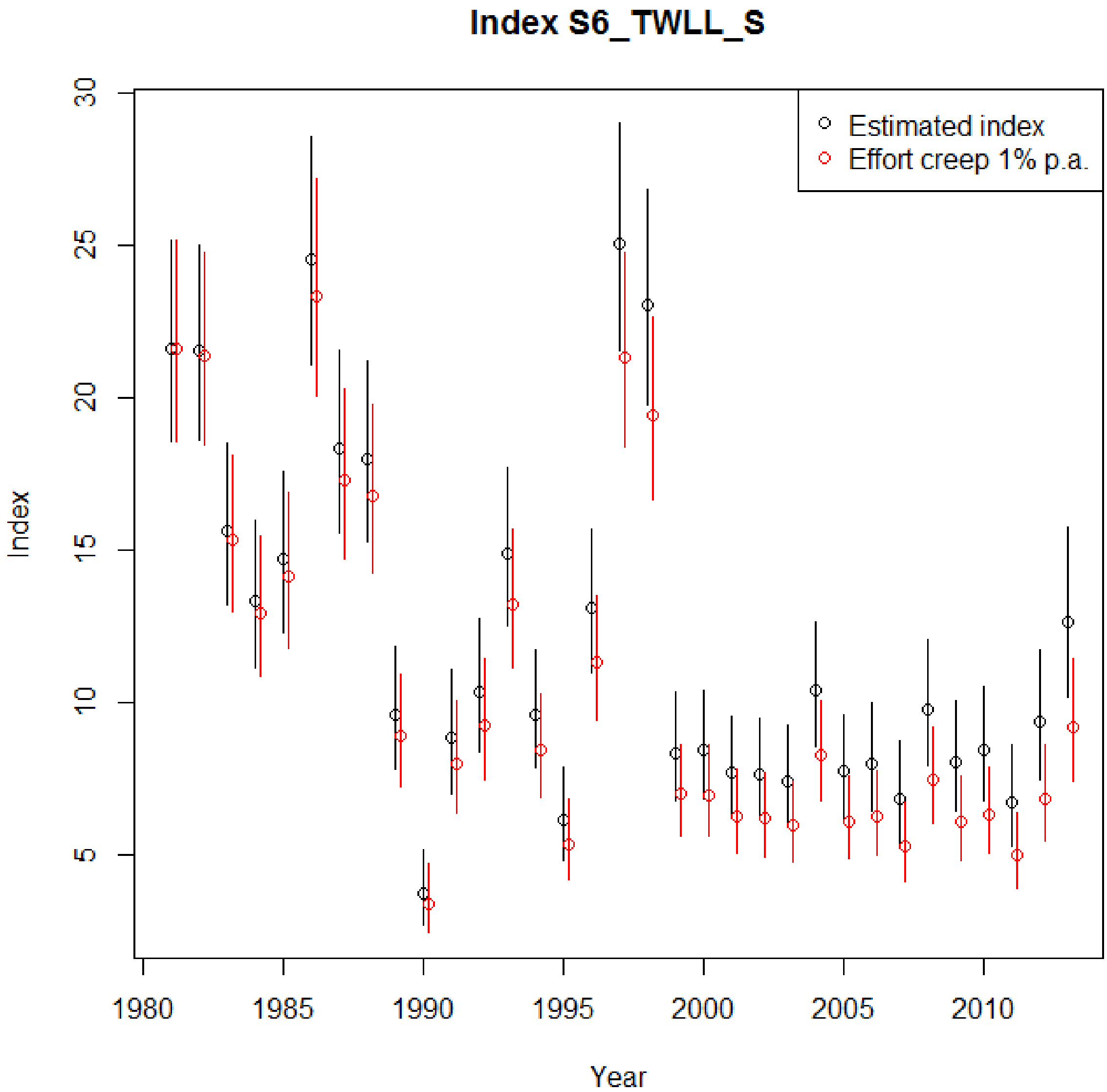


Figure 12: Standardized annual CPUE indices for the Taiwanese southern longline fishery, including indices adjusted for hypothesized levels of effort creep.

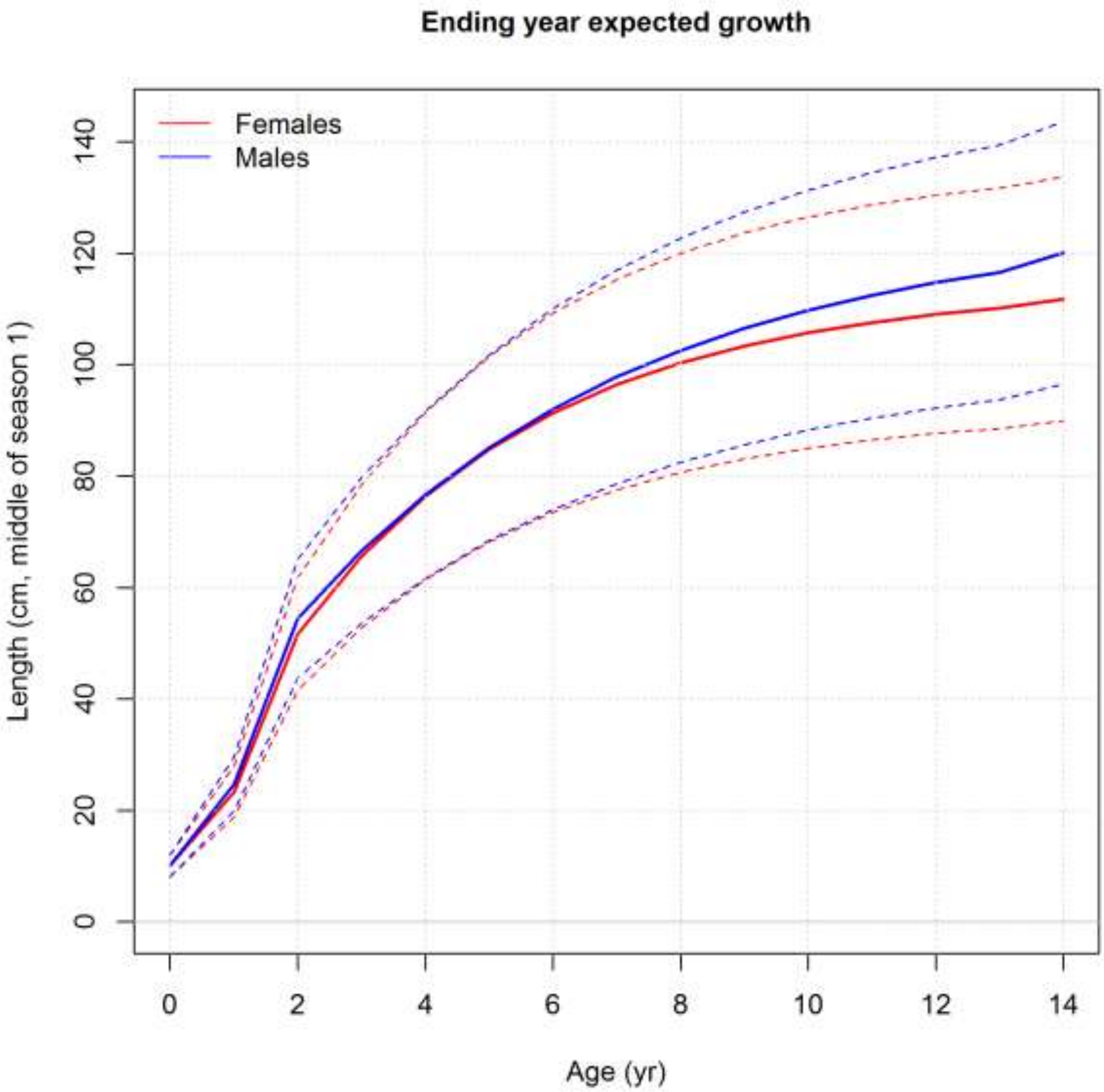


Figure 13: Growth curve assumed for Indian Ocean albacore tuna, based on growth of north Pacific albacore tuna (Chen at al 2012). The red curve with lower maximum length is female growth, and the blue curve is male growth.

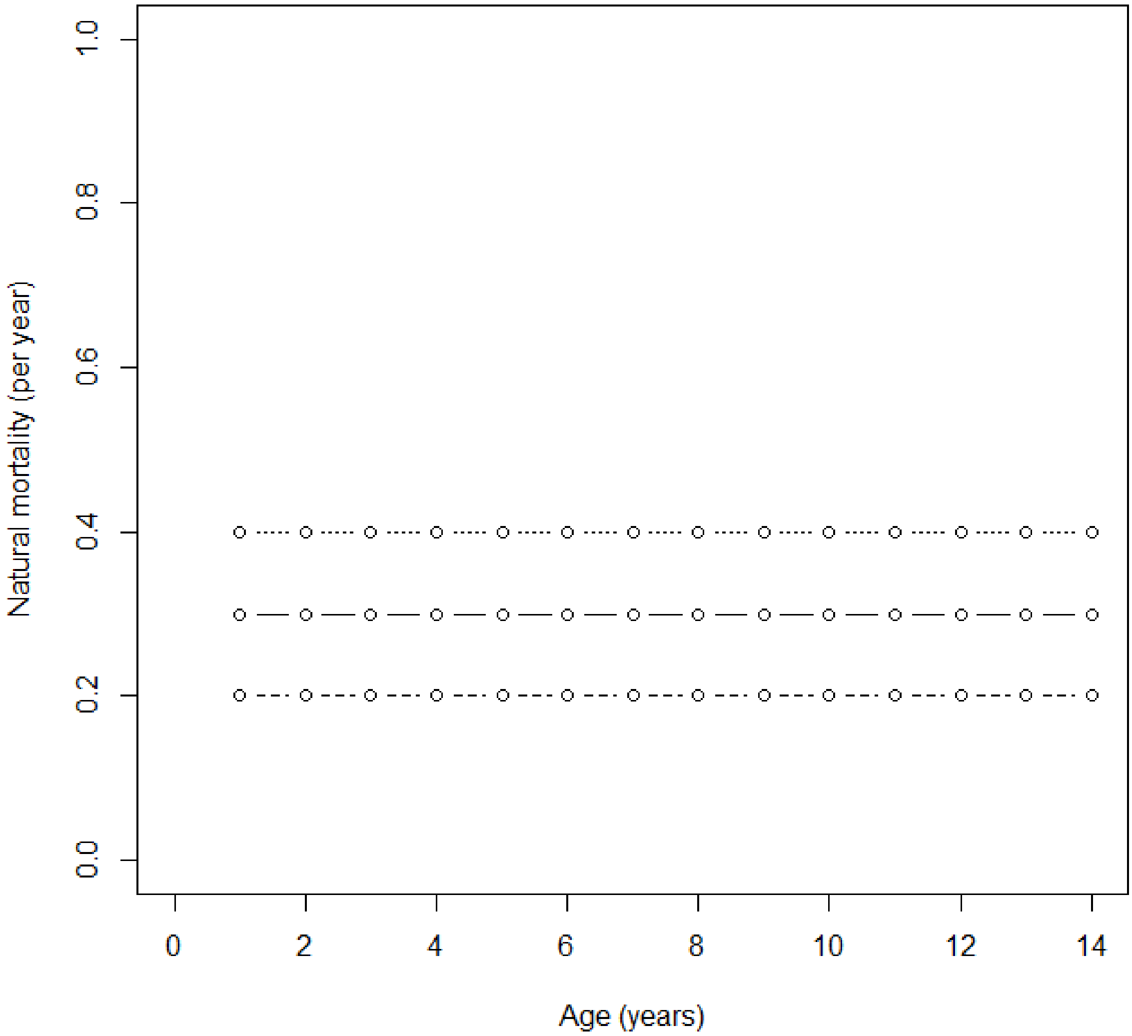


Figure 14: Natural mortality (per year) applied in the three model options.

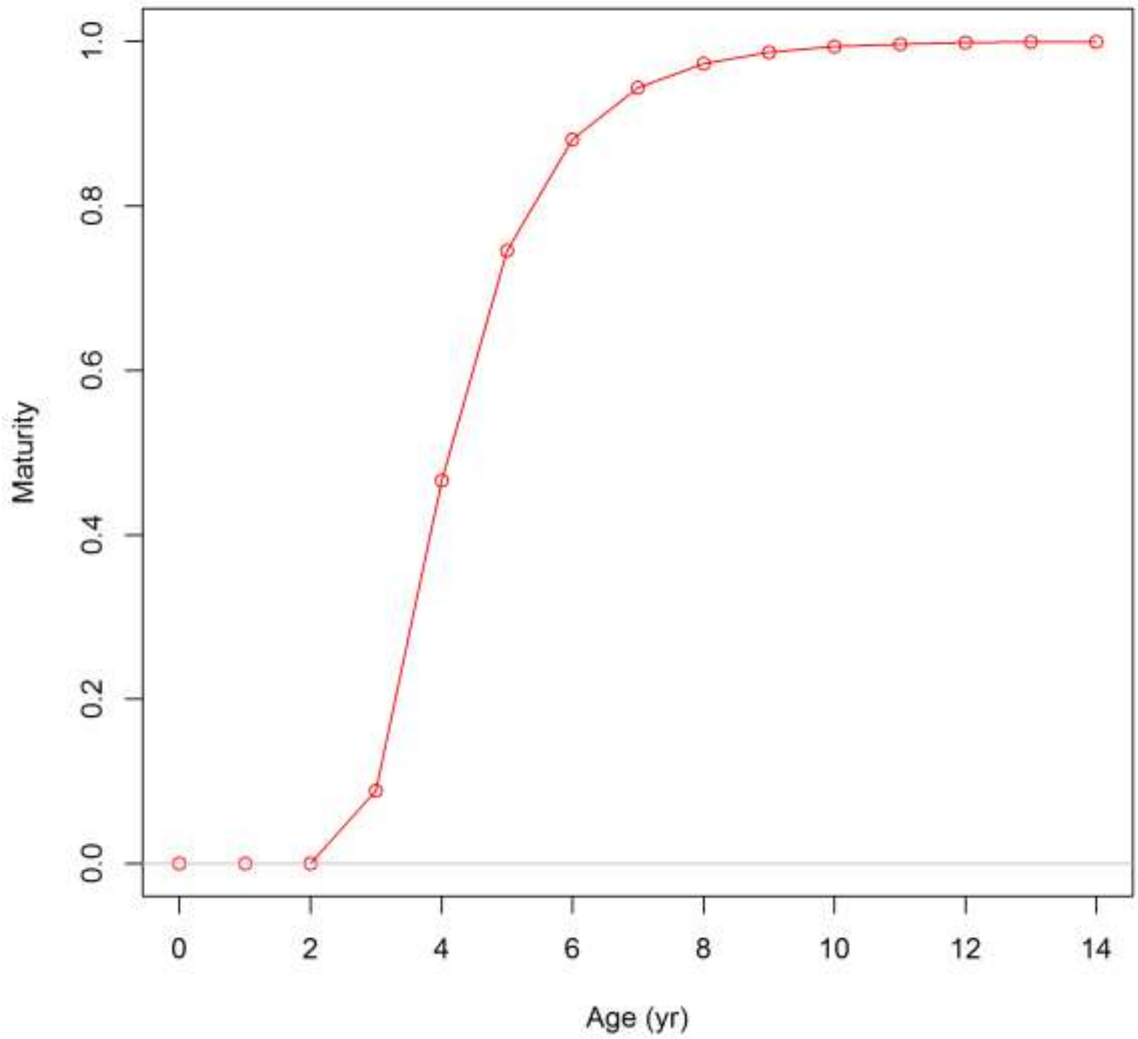


Figure 15: Maturity ogive, based on maturity for south Pacific albacore.

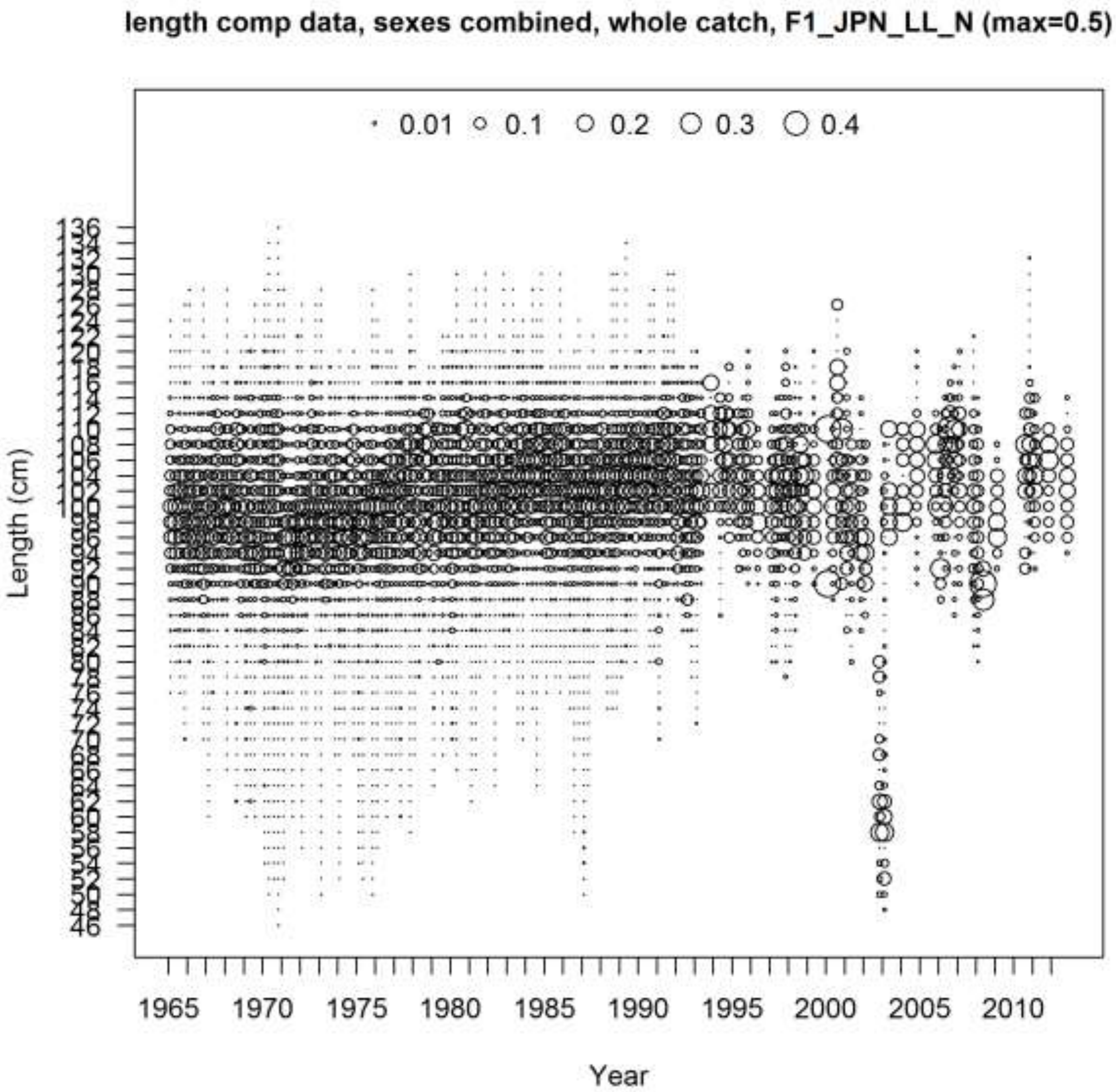
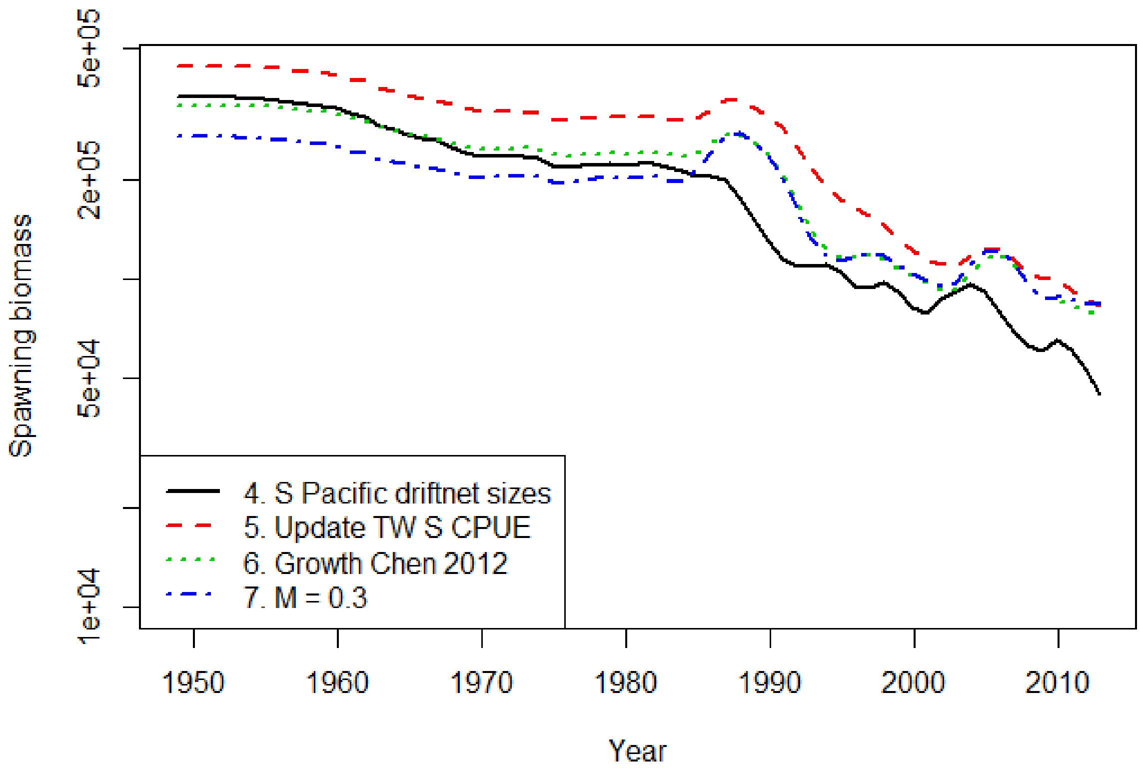
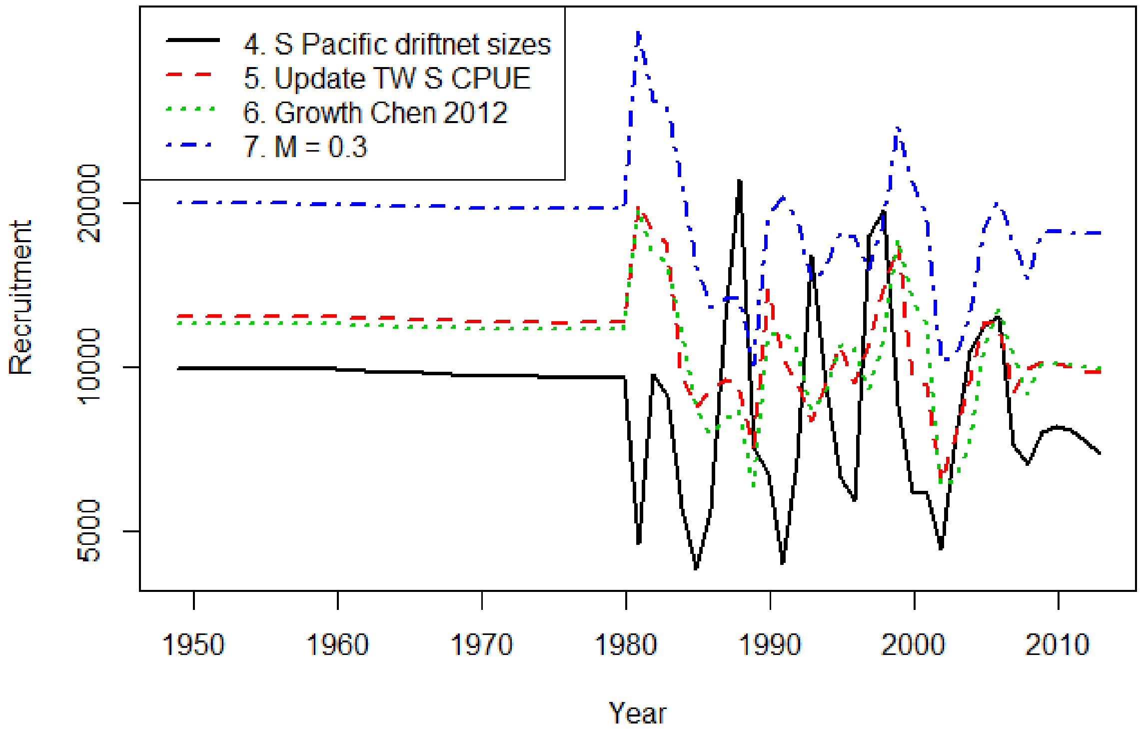


Figure 16: Bubble plot of length frequency for the Japanese composite northern longline fishery.

Figure 17


Spawning biomass
5e+05
2e+05
5e+04
1e+04
4. S Pacific driftnet sizes
5. Update TW S CPUE
6. Growth Chen 2012
7. M = 0.3
1950
1960
1970
1980
1990
2000
2010
Year


Recruitment
20000
10000
5000
4. S Pacific driftnet sizes
5. Update TW S CPUE
6. Growth Chen 2012
7. M = 0.3
1950
1960
1970
1980
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2000
2010
Year

Figure 18

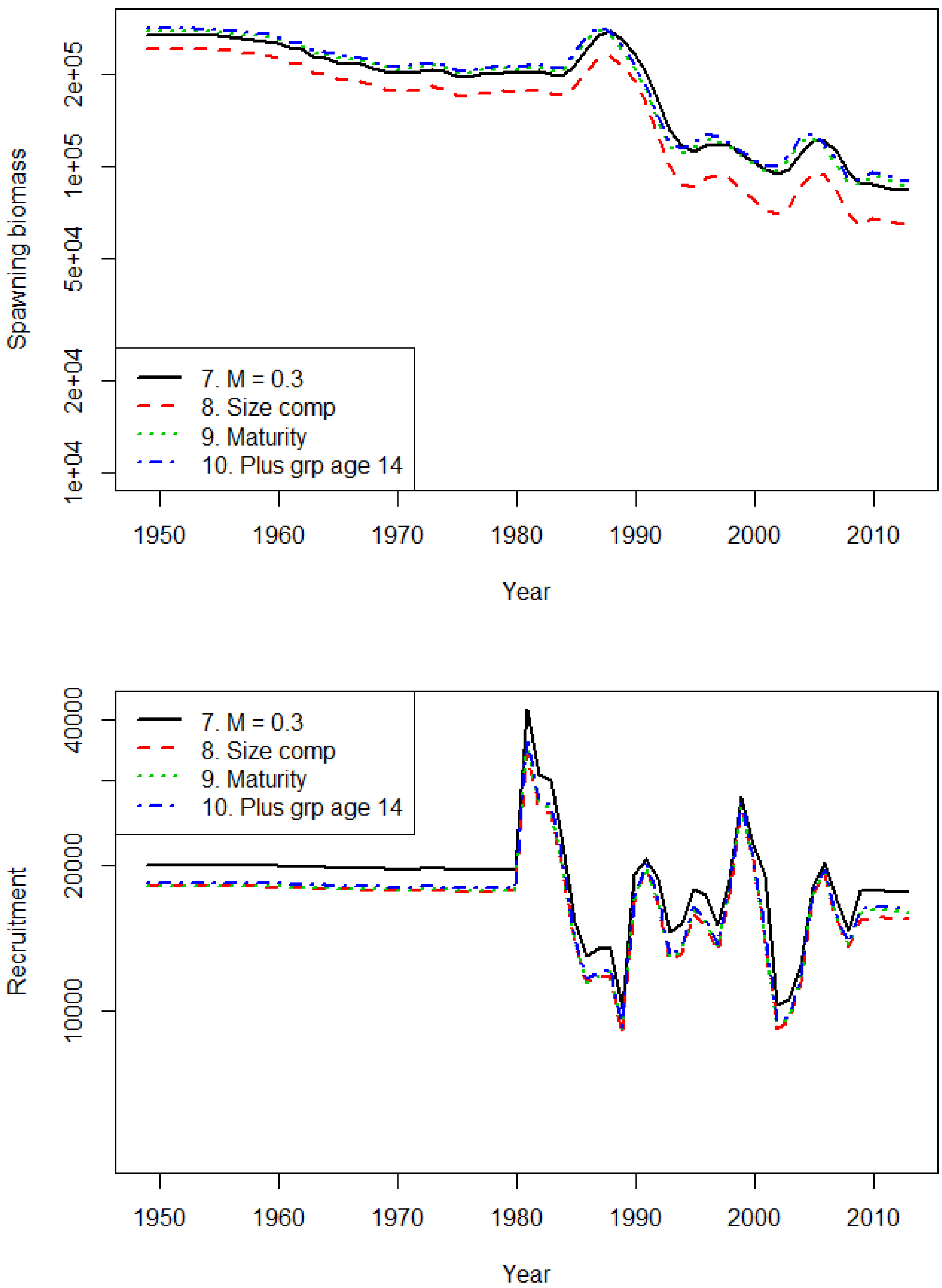
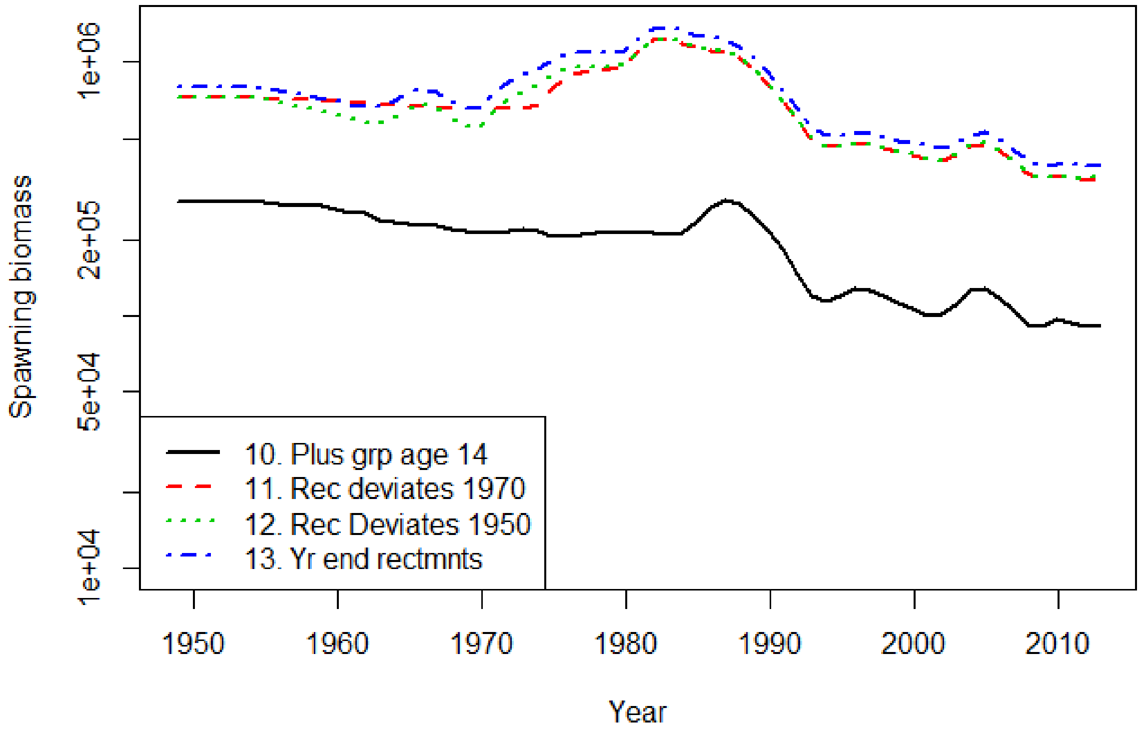

Spawning biomass
2e+05
1e+05
5e+04
2e+04
1e+04
7. M = 0.3
8. Size comp
9. Maturity
10. Plus grp age 14
1950
1960
1970
1980
1990
2000
2010
Year
Recruitment
40000
20000
10000
7. M = 0.3
8. Size comp
9. Maturity
10. Plus grp age 14
1950
1960
1970
1980
1990
2000
2010
Year

Figure 19


Spawning biomass
1e+06
2e+05
5e+04
1e+04
10. Plus grp age 14
11. Rec deviates 1970
12. Rec Deviates 1950
13. Yr end rectmnts
1950
1960
1970
1980
1990
2000
2010
Year

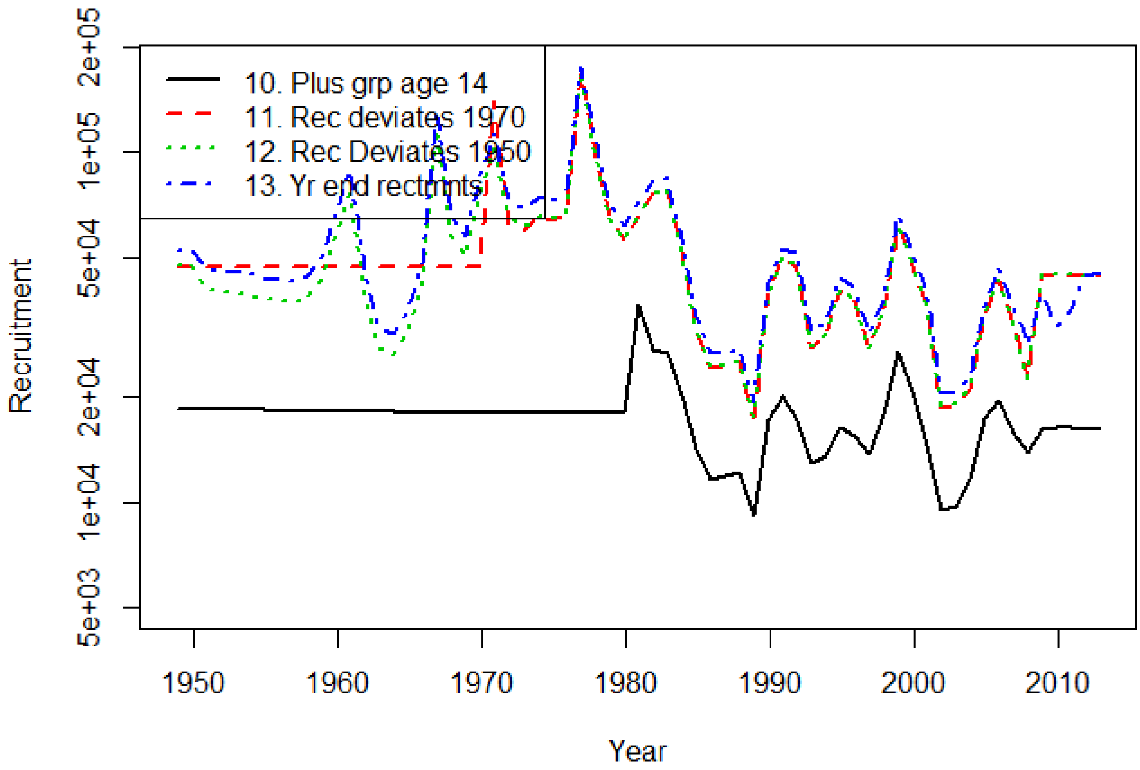

Recruitment
2e+05
1e+05
5e+04
2e+04
1e+04
5e+03
10. Plus grp age 14
11. Rec deviates 1970
12. Rec Deviates 1950
13. Yr end rectmnts
1950
1960
1970
1980
1990
2000
2010
Year

Figure 20

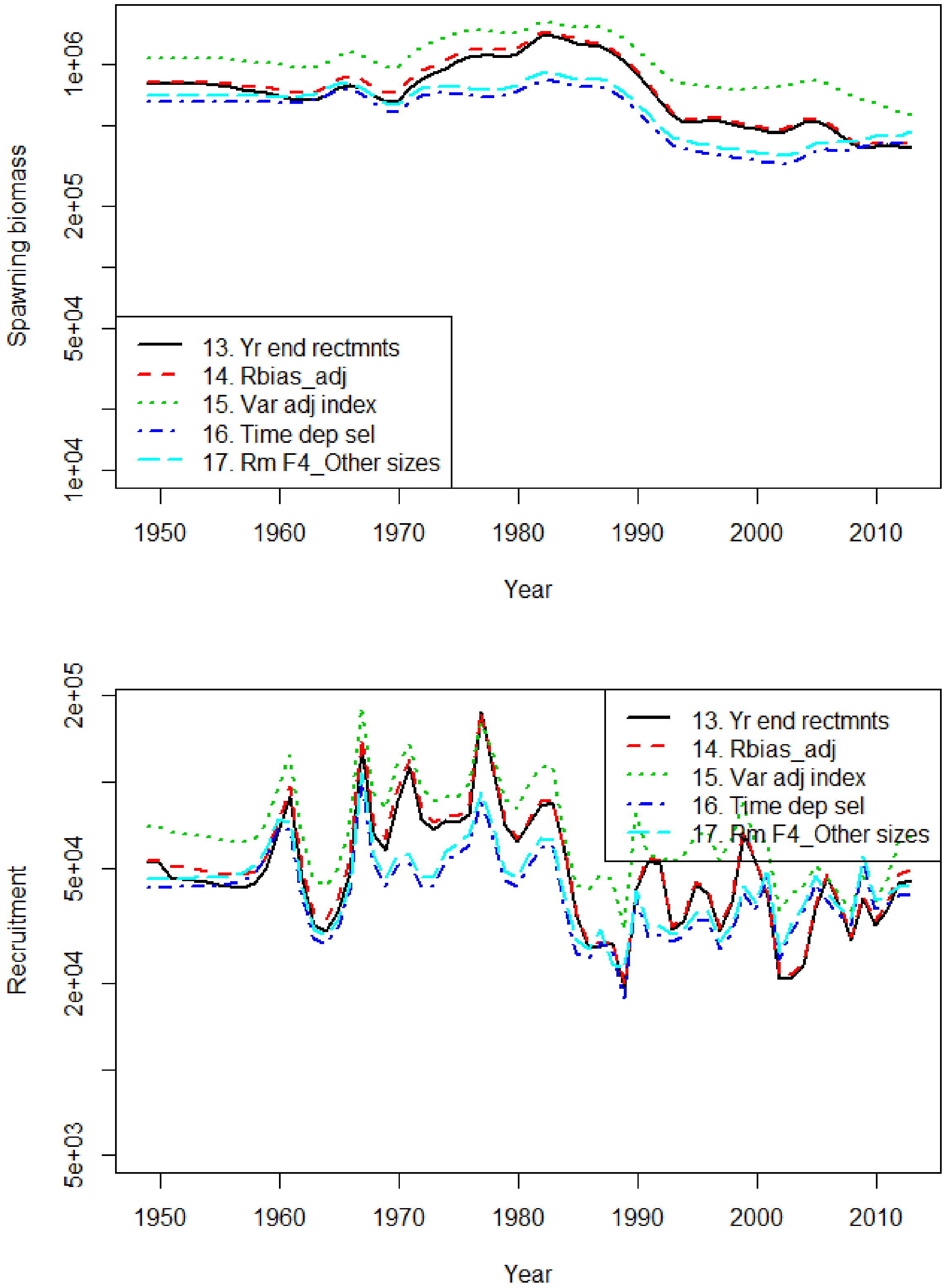
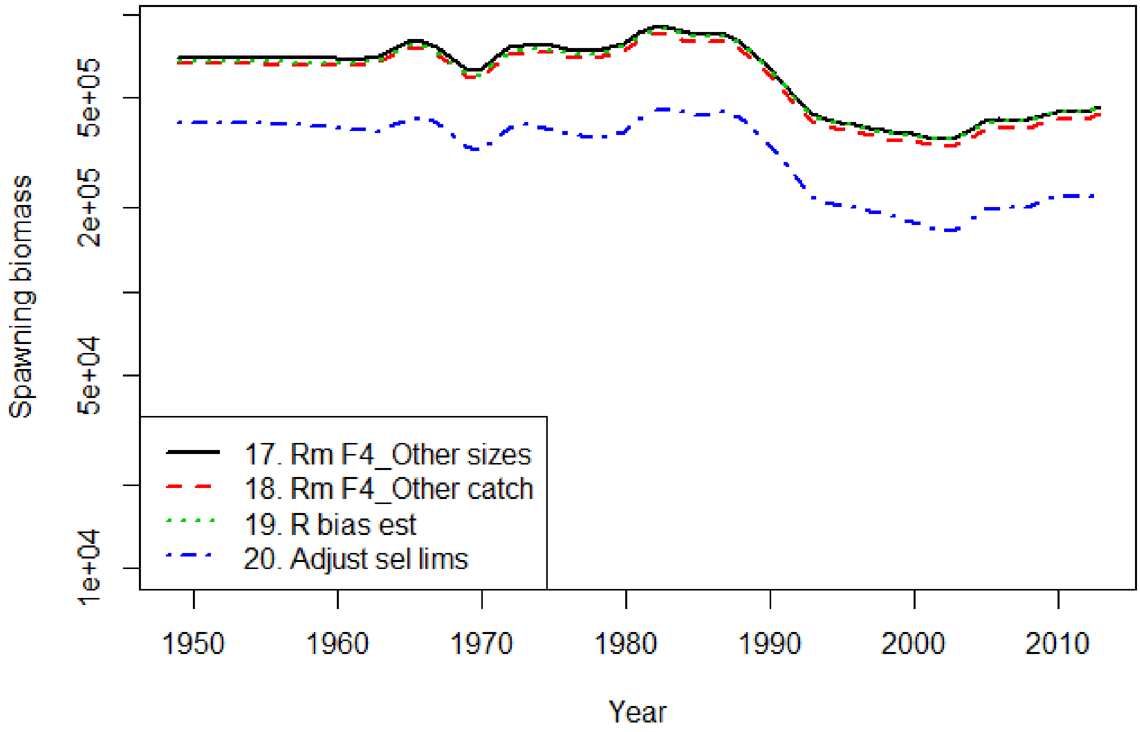

Spawning biomass
1e+06
2e+05
5e+04
1e+04
13. Yr end rectmnts
14. Rbias_adj
15. Var adj index
16. Time dep sel
17. Rm F4_Other sizes
1950
1960
1970
1980
1990
2000
2010
Year
Recruitment
2e+05
5e+04
2e+04
5e+03
13. Yr end rectmnts
14. Rbias_adj
15. Var adj index
16. Time dep sel
17. Rm F4_Other sizes
1950
1960
1970
1980
1990
2000
2010
Year

Figure 21


Spawning biomass
1e+04
5e+04
2e+05
5e+05
1950
1960
1970
1980
1990
2000
2010
Year
17. Rm F4_Other sizes
18. Rm F4_Other catch
19. R bias est
20. Adjust sel lims

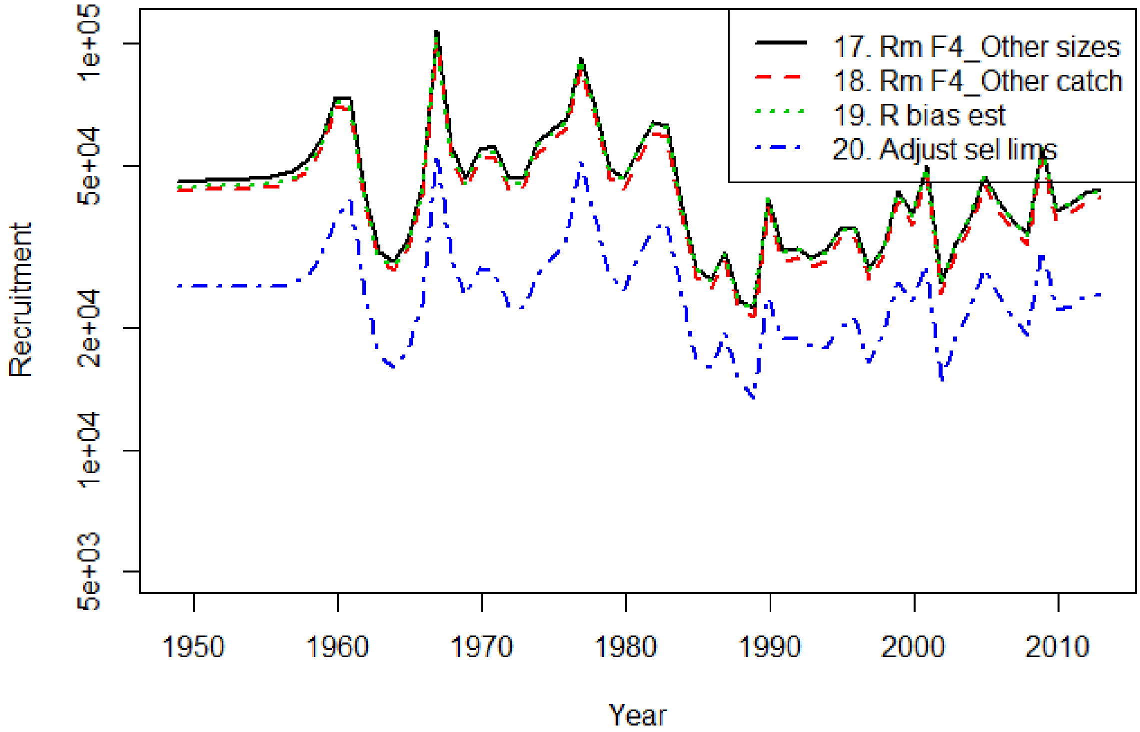

Recruitment
5e+03
1e+04
2e+04
5e+04
1e+05
1950
1960
1970
1980
1990
2000
2010
Year
17. Rm F4_Other sizes
18. Rm F4_Other catch
19. R bias est
20. Adjust sel lims

Figure 22

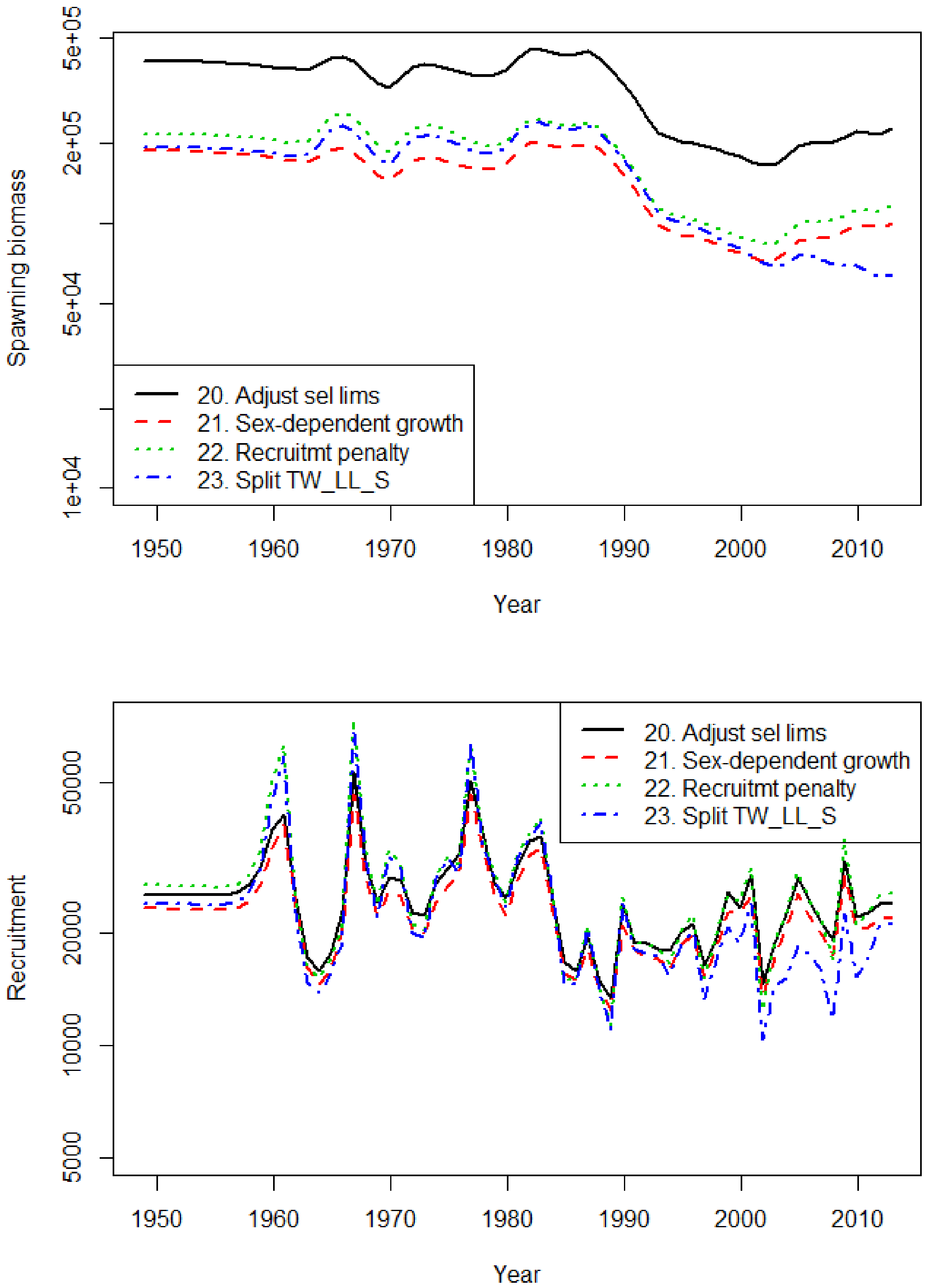
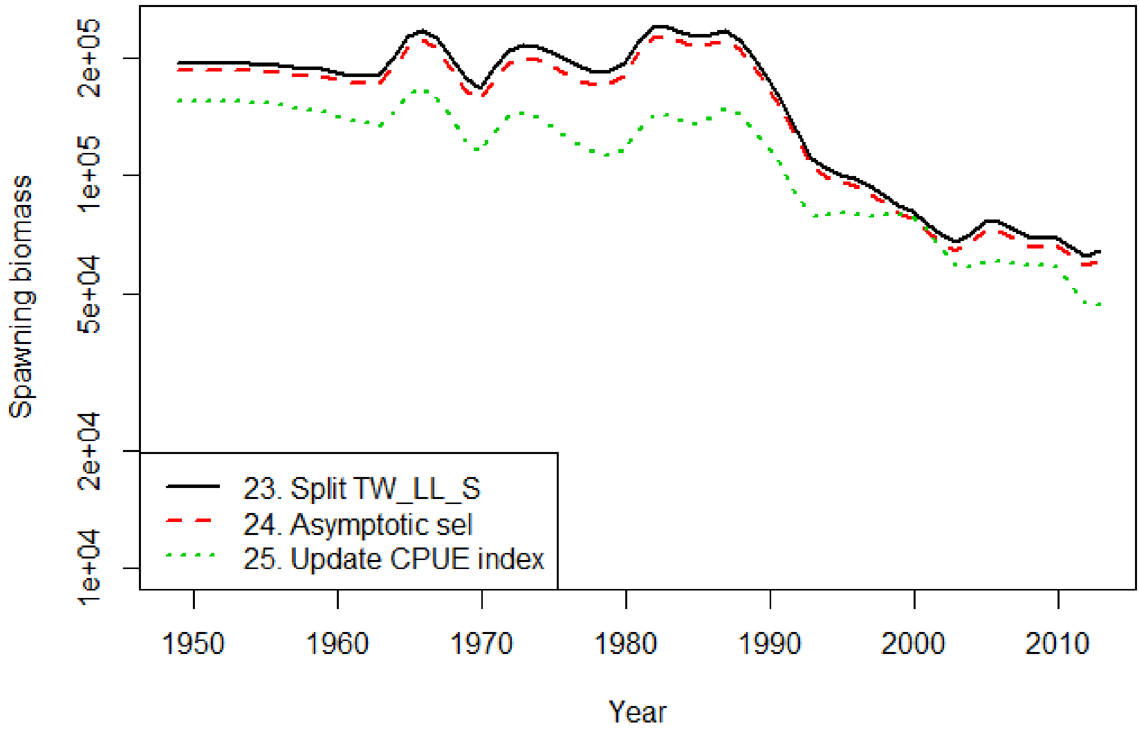

Spawning biomass
5e+05
2e+05
5e+04
1e+04
20. Adjust sel lims
21. Sex-dependent growth
22. Recruitmt penalty
23. Split TW_LL_S
1950
1960
1970
1980
1990
2000
2010
Year
Recruitment
50000
20000
10000
5000
20. Adjust sel lims
21. Sex-dependent growth
22. Recruitmt penalty
23. Split TW_LL_S
1950
1960
1970
1980
1990
2000
2010
Year

Figure 23


Spawning biomass
1e+04
2e+04
5e+04
1e+05
2e+05
1950
1960
1970
1980
1990
2000
2010
Year
23. Split TW_LL_S
24. Asymptotic sel
25. Update CPUE index

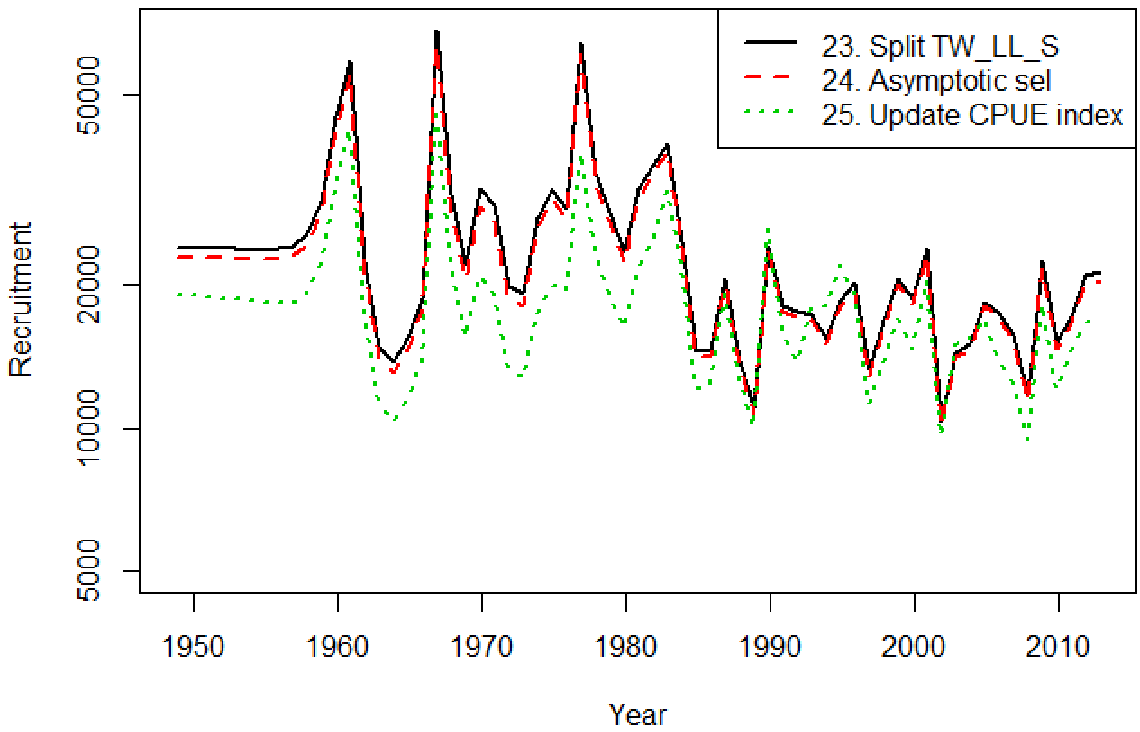

Recruitment
5000
10000
20000
50000
1950
1960
1970
1980
1990
2000
2010
Year
23. Split TW_LL_S
24. Asymptotic sel
25. Update CPUE index

Figure 24

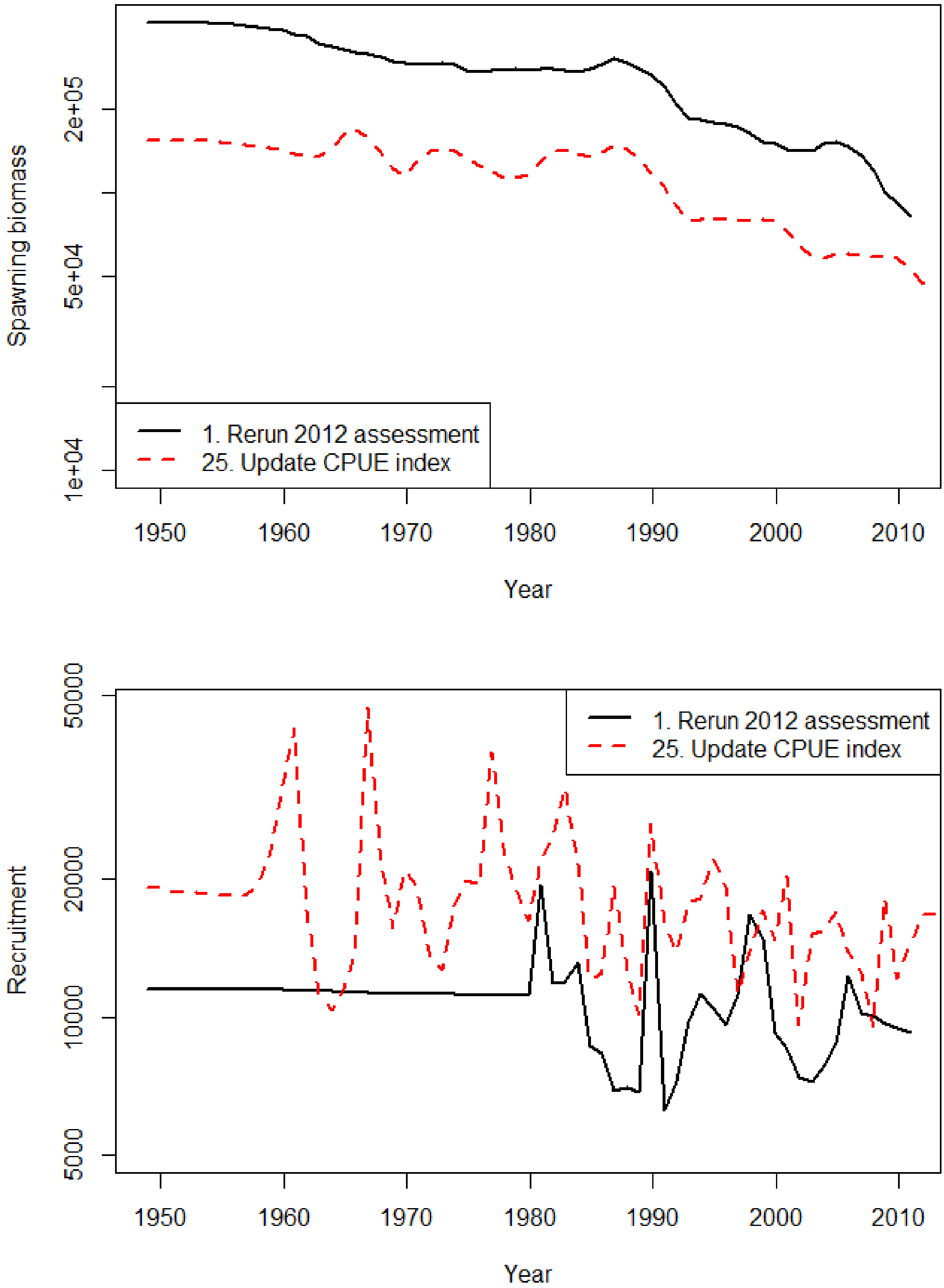

Spawning biomass
2e+05
5e+04
1e+04
1. Rerun 2012 assessment
25. Update CPUE index
1950
1960
1970
1980
1990
2000
2010
Year
Recruitment
50000
20000
10000
5000
1. Rerun 2012 assessment
25. Update CPUE index
1950
1960
1970
1980
1990
2000
2010
Year

Figure 25

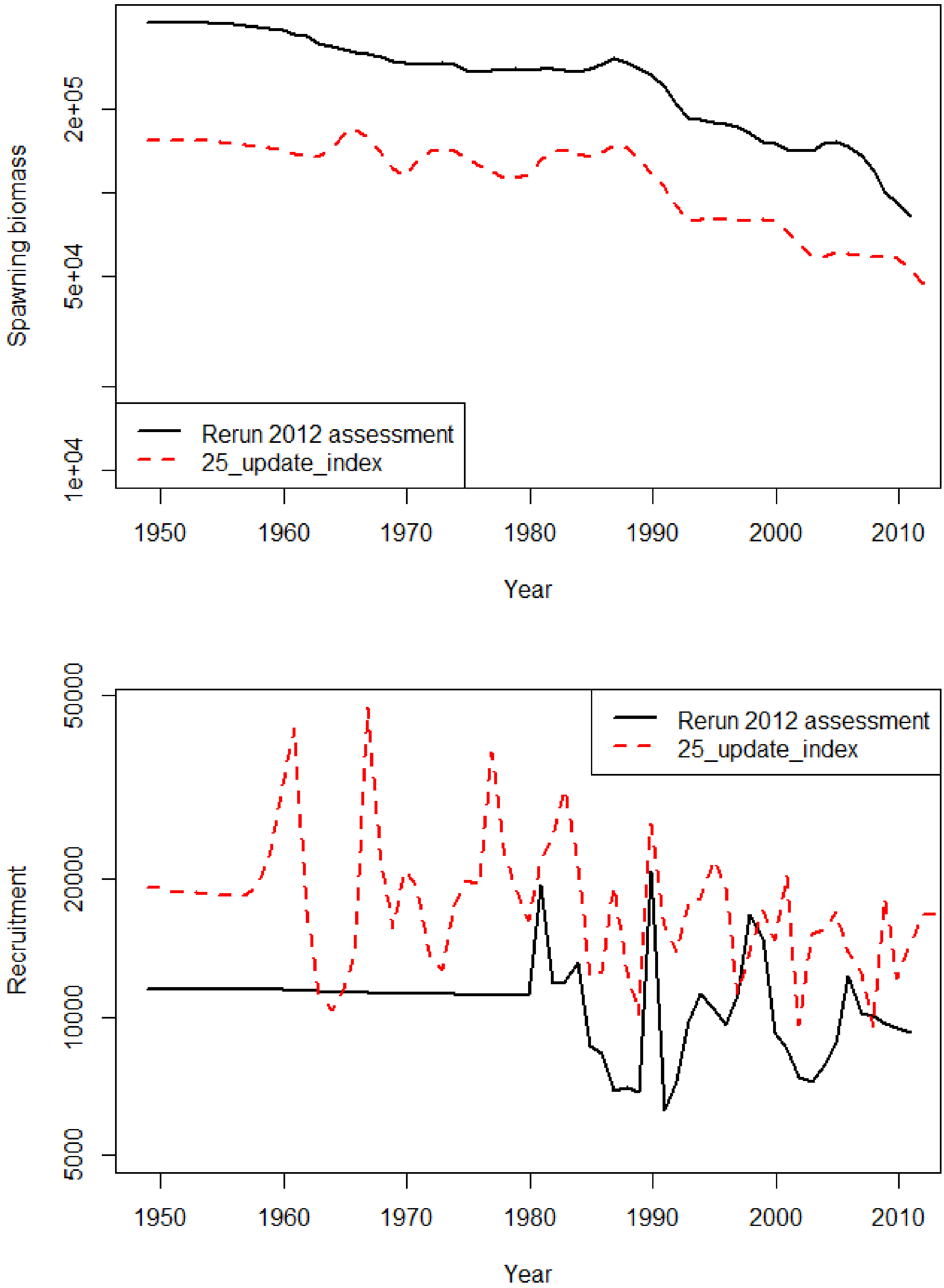
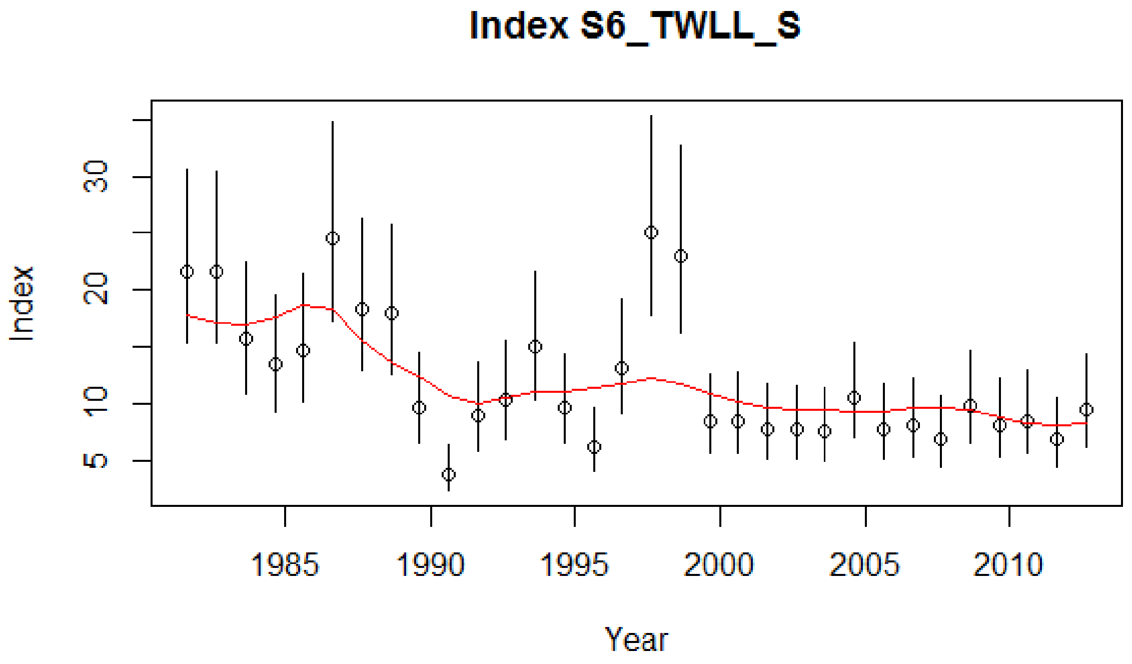

Spawning biomass
2e+05
5e+04
1e+04
Rerun 2012 assessment
25_update_index
1950
1960
1970
1980
1990
2000
2010
Year
Recruitment
50000
20000
10000
5000
Rerun 2012 assessment
25_update_index
1950
1960
1970
1980
1990
2000
2010
Year

Figure 26



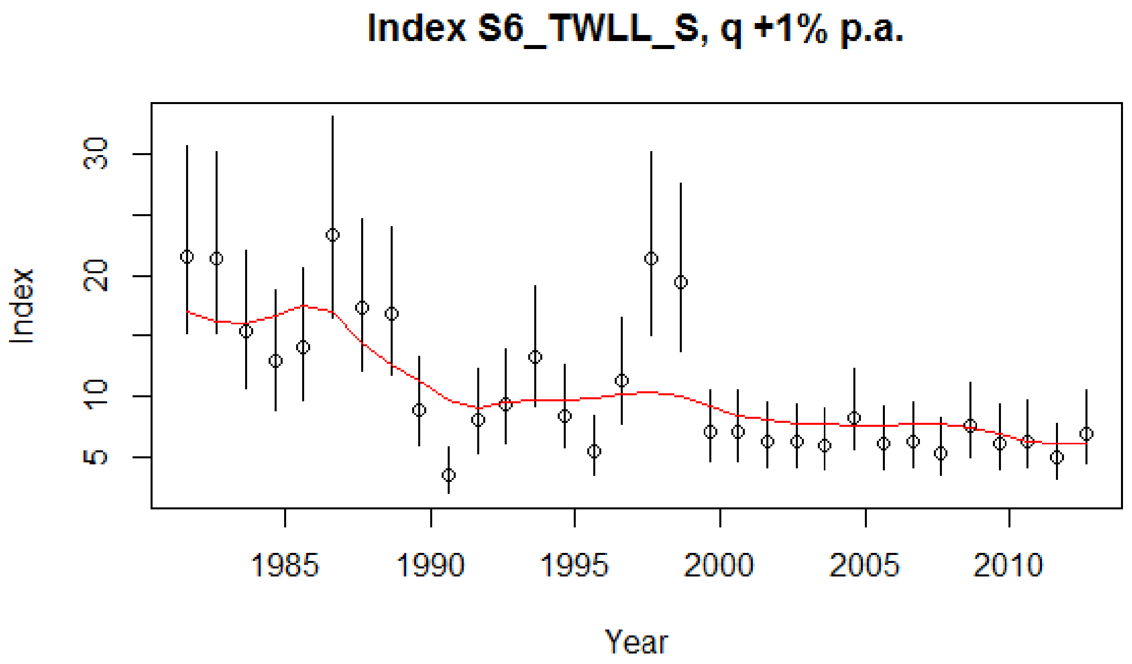


Figure 27: Fit to the southern Taiwanese longline CPUE index: the reference case CPUE indices,(left) and the CPUE indices with an assumed increase in catchability.

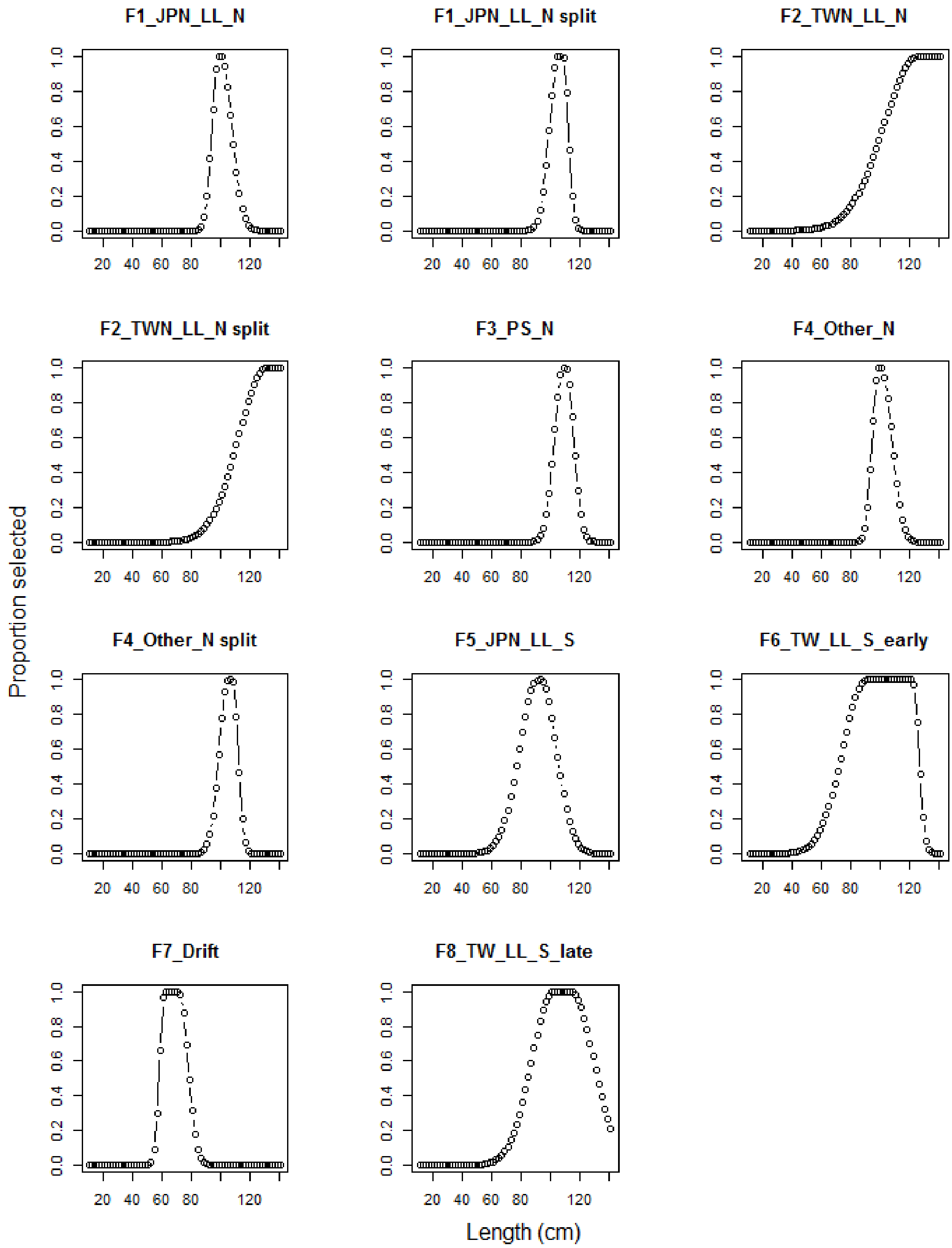


Figure 28: Selectivity at length for the individual fisheries in the reference case model. For fisheries that have split selectivity (F1_JP_LL_N, F2_TW_LL_N, and F4_Other_N) the later period is labelled 'split'.

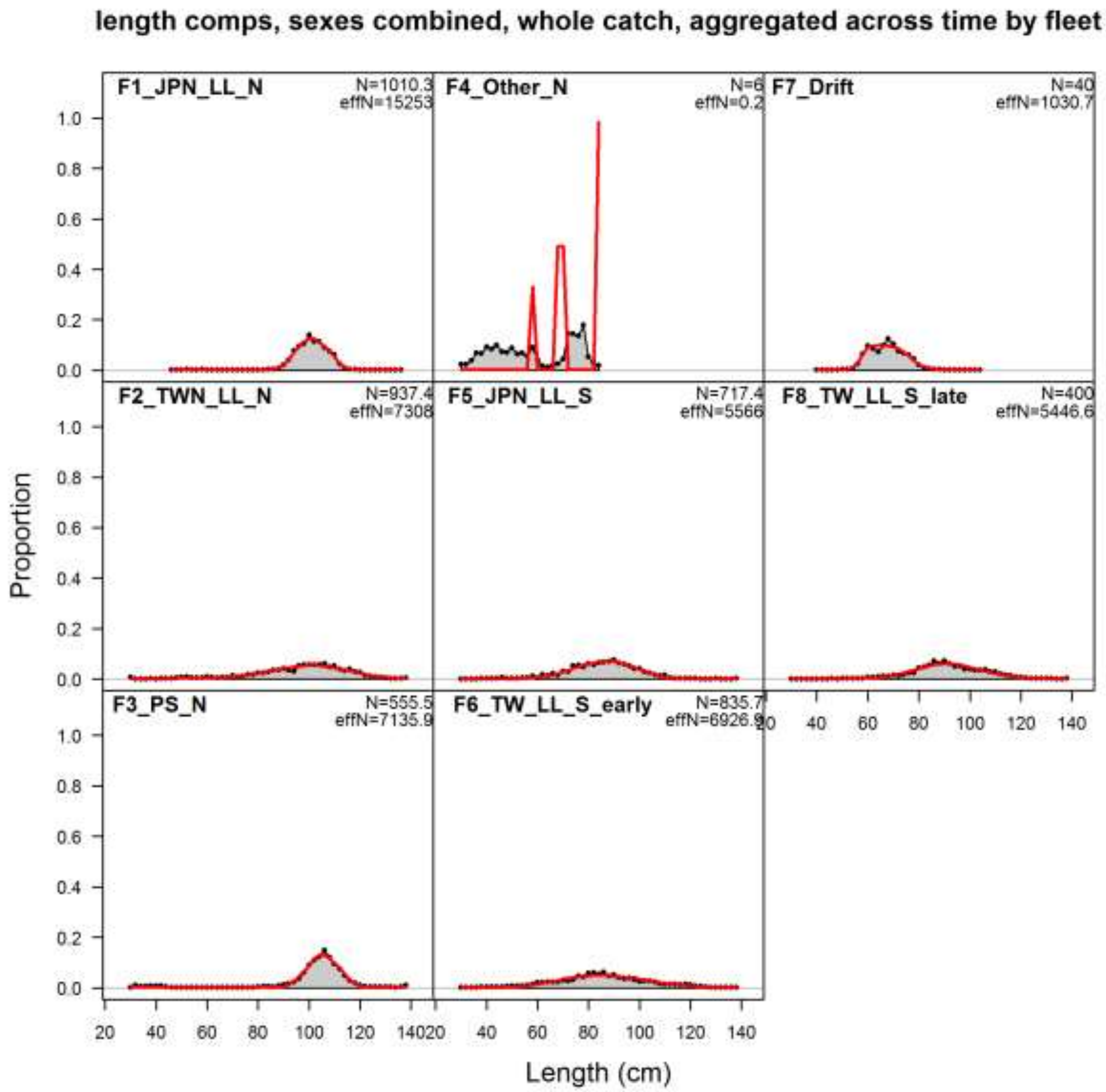


Figure 29: the observed (grey polygon) and predicted (red line) aggregated length compositions for the main fisheries with length frequency data from the reference case model.

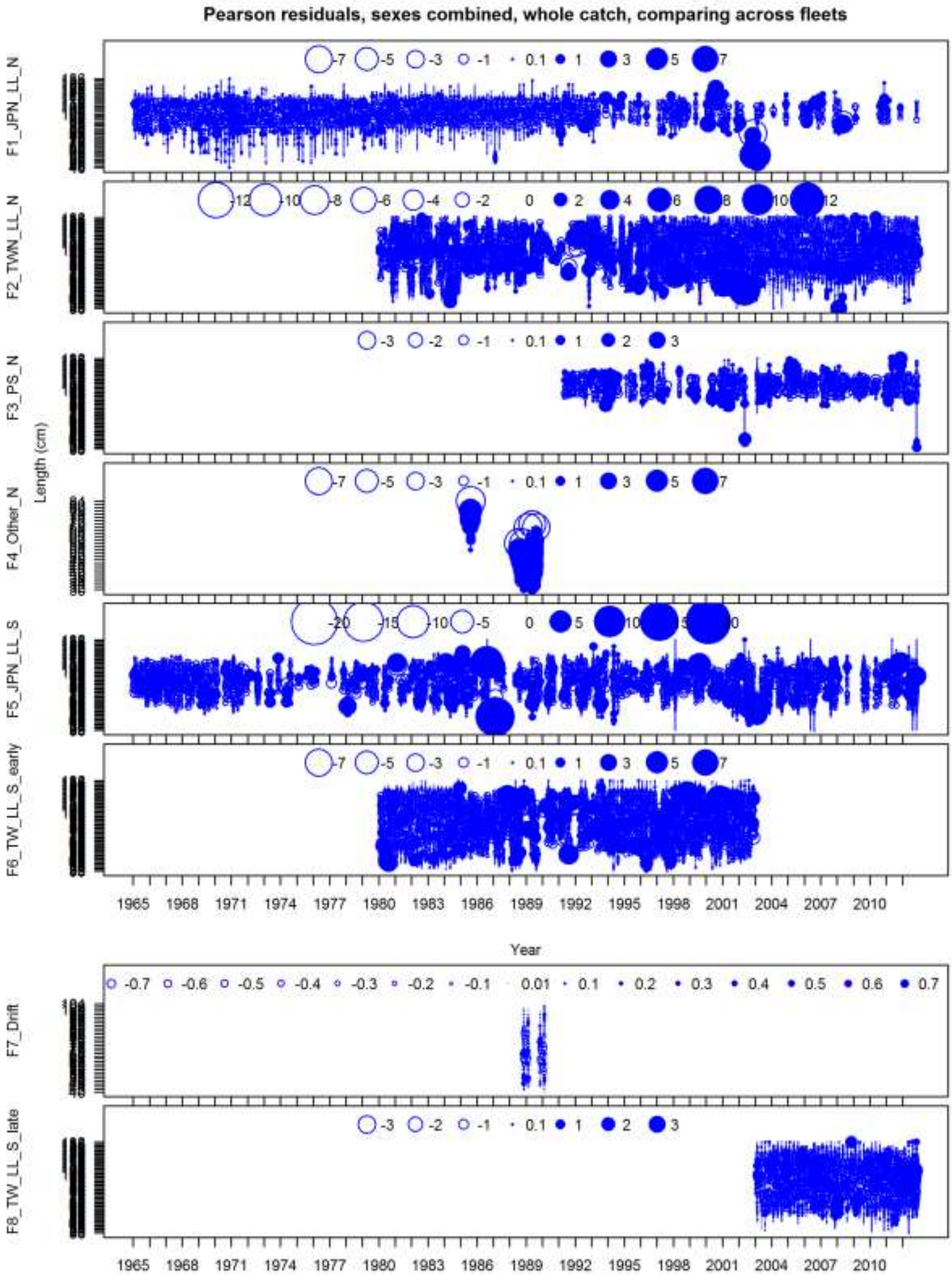


Figure 30: Residuals from the fit to the length data from the reference case model.

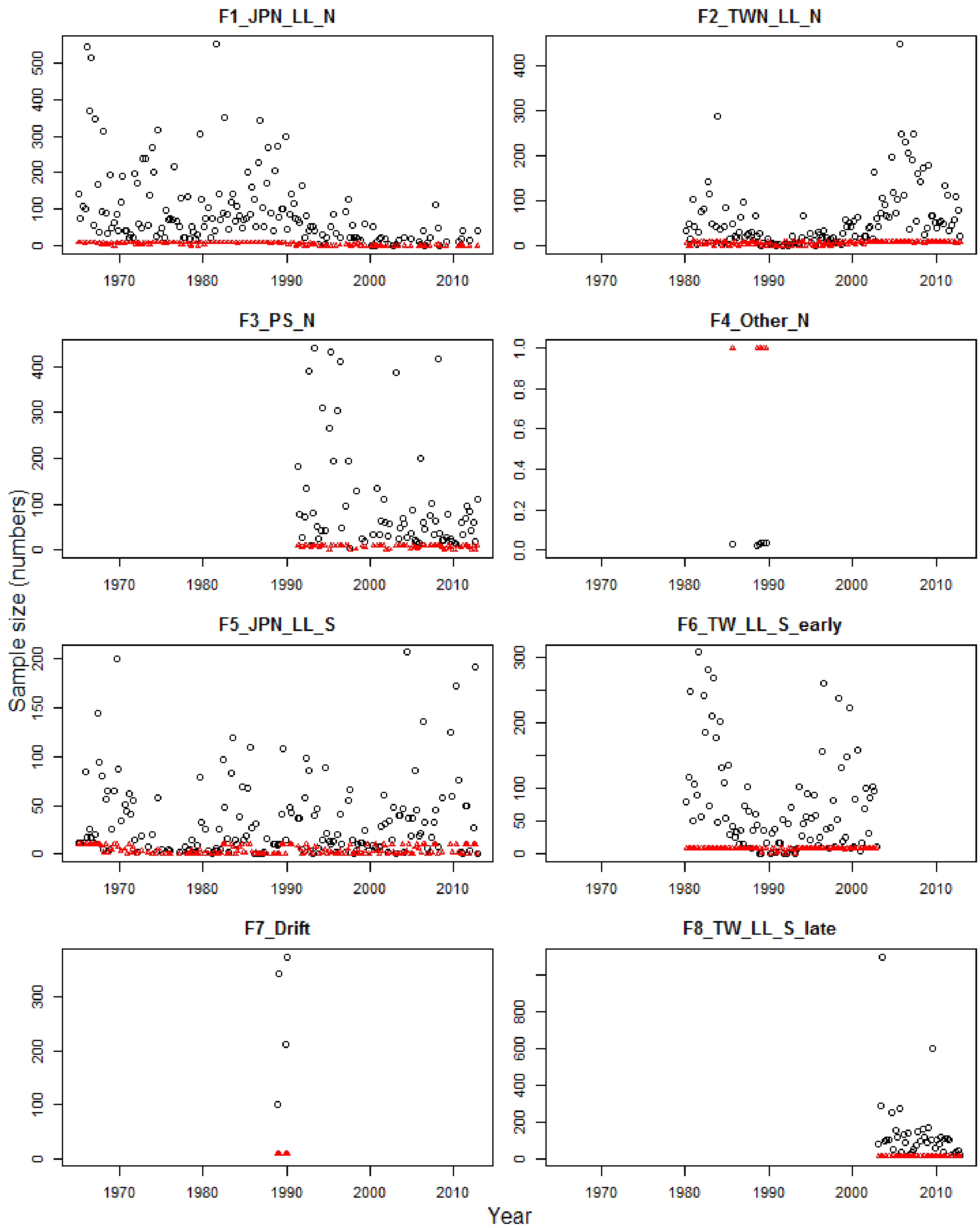


Figure 31: The estimated (black circles) and applied (red triangles) effective samples size applied to the length frequency data in the reference case model.

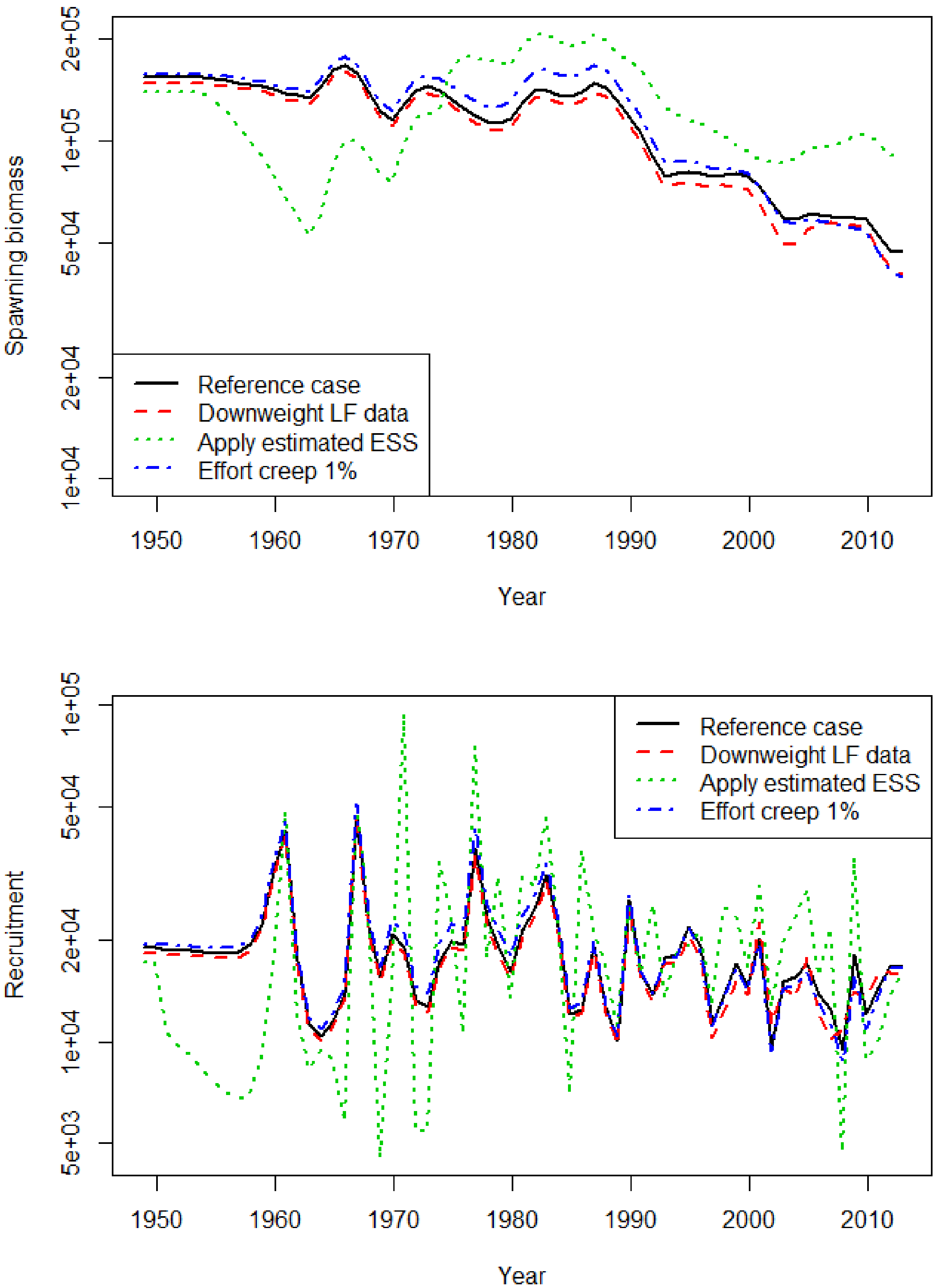

Spawning biomass
2e+05
1e+05
5e+04
2e+04
1e+04
Reference case
Downweight LF data
Apply estimated ESS
Effort creep 1%
1950
1960
1970
1980
1990
2000
2010
Year
Recruitment
1e+05
5e+04
2e+04
1e+04
5e+03
Reference case
Downweight LF data
Apply estimated ESS
Effort creep 1%
1950
1960
1970
1980
1990
2000
2010
Year

Figure 32:

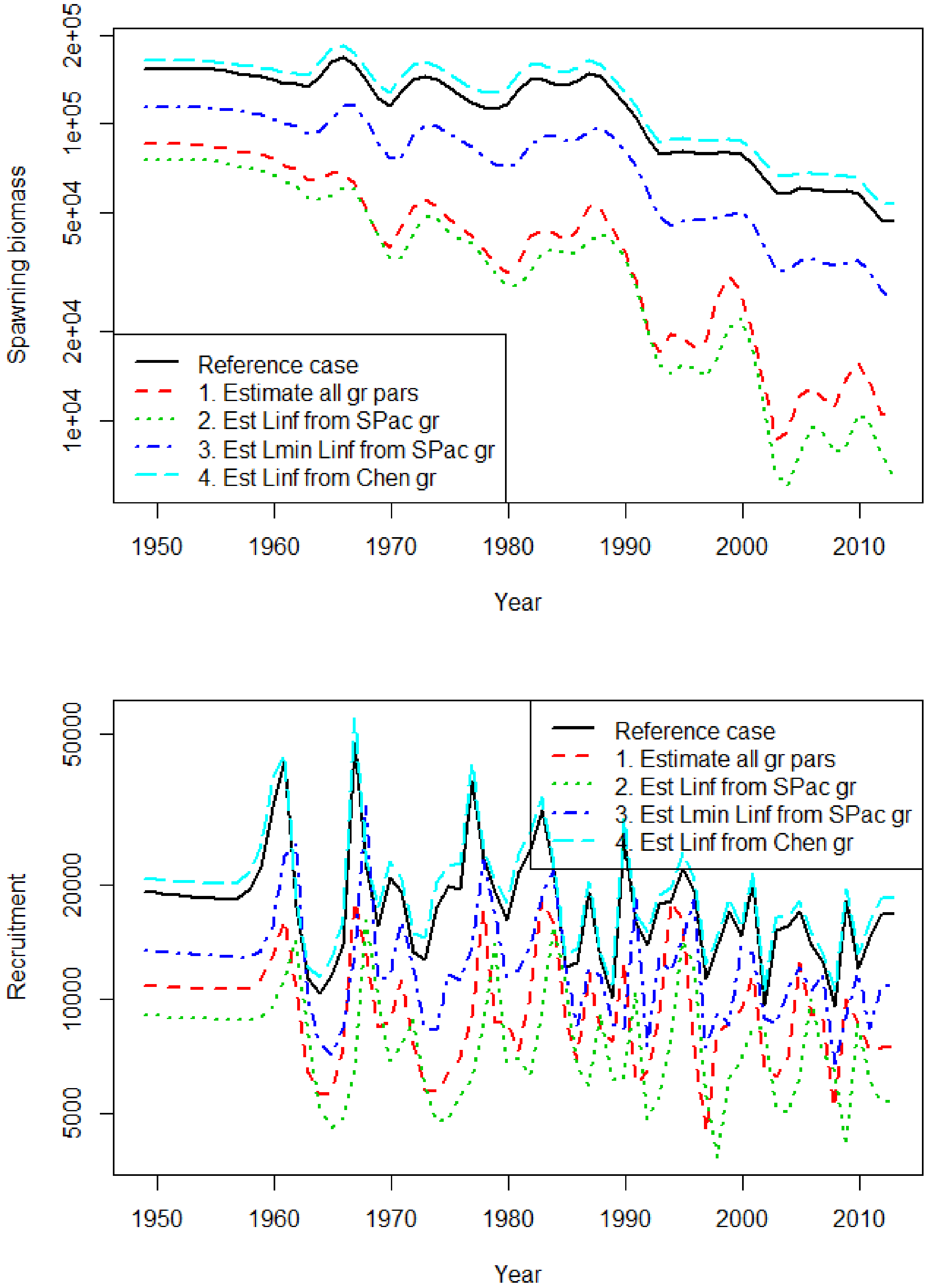
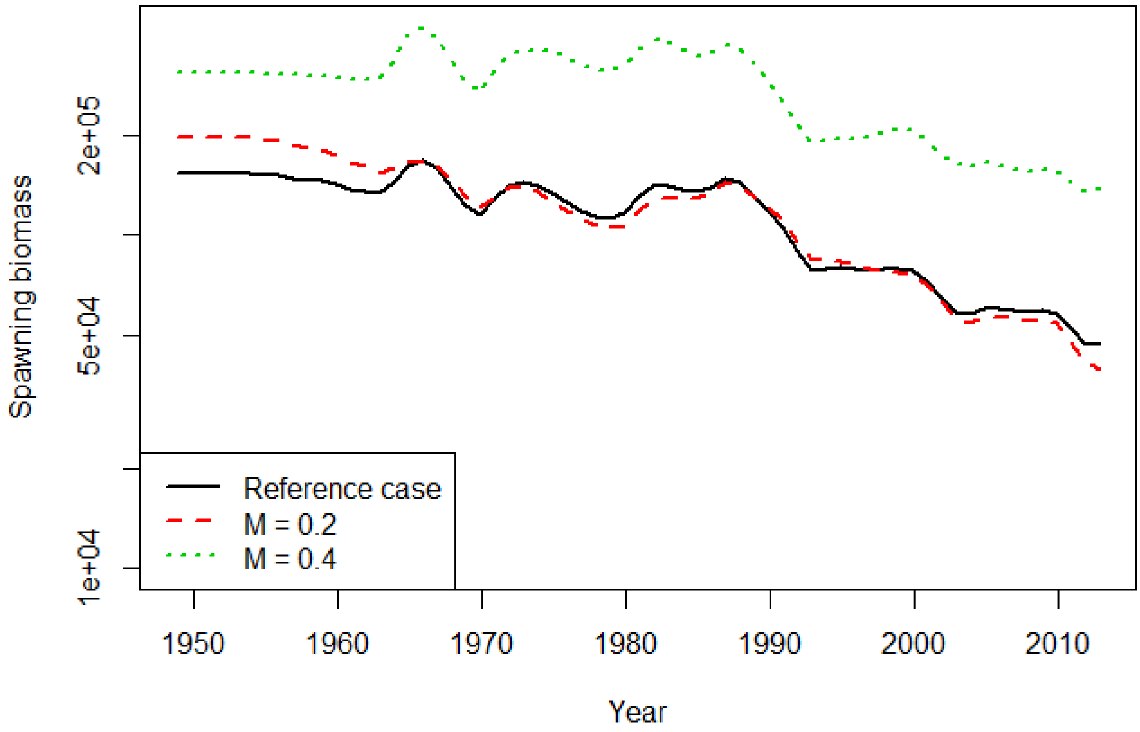

Spawning biomass
1e+04
2e+04
5e+04
1e+05
2e+05
1950
1960
1970
1980
1990
2000
2010
Year
Reference case
1. Estimate all gr pars
2. Est Linf from SPac gr
3. Est Lmin Linf from SPac gr
4. Est Linf from Chen gr
Recruitment
5000
10000
20000
50000
1950
1960
1970
1980
1990
2000
2010
Year
Reference case
1. Estimate all gr pars
2. Est Linf from SPac gr
3. Est Lmin Linf from SPac gr
4. Est Linf from Chen gr

Figure 33


Spawning biomass
1e+04
5e+04
2e+05
Reference case
M = 0.2
M = 0.4
1950
1960
1970
1980
1990
2000
2010
Year

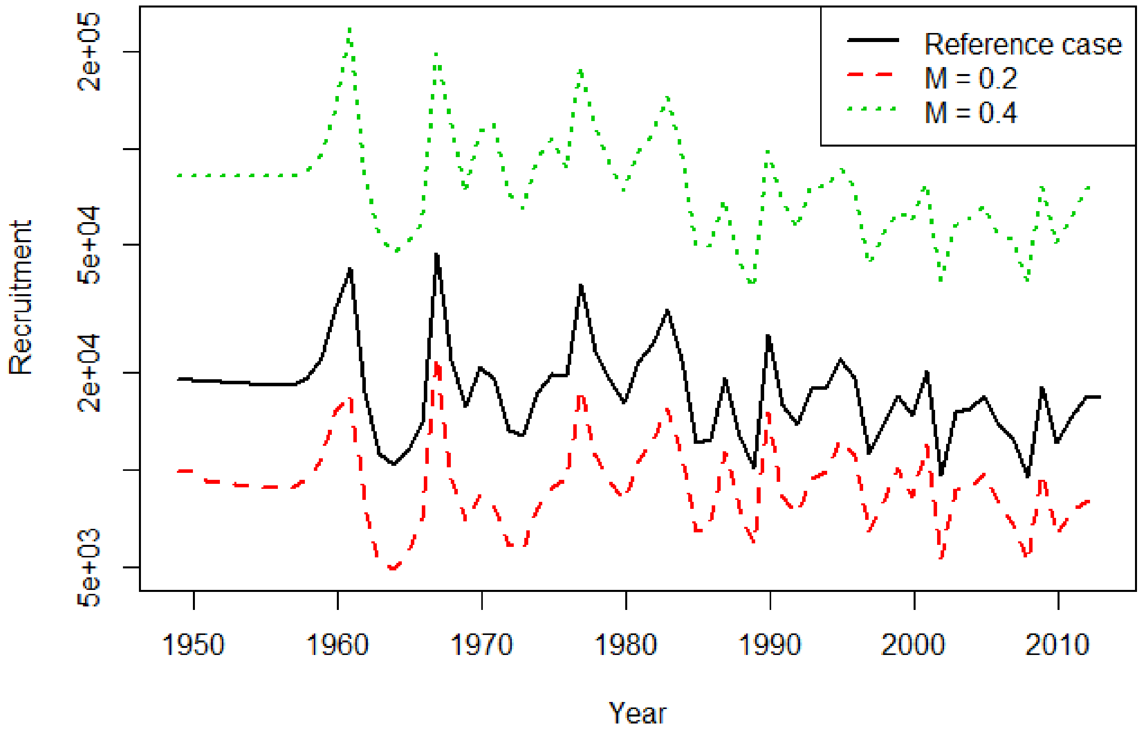

Recruitment
5e+03
2e+04
5e+04
2e+05
Reference case
M = 0.2
M = 0.4
1950
1960
1970
1980
1990
2000
2010
Year

Figure 34

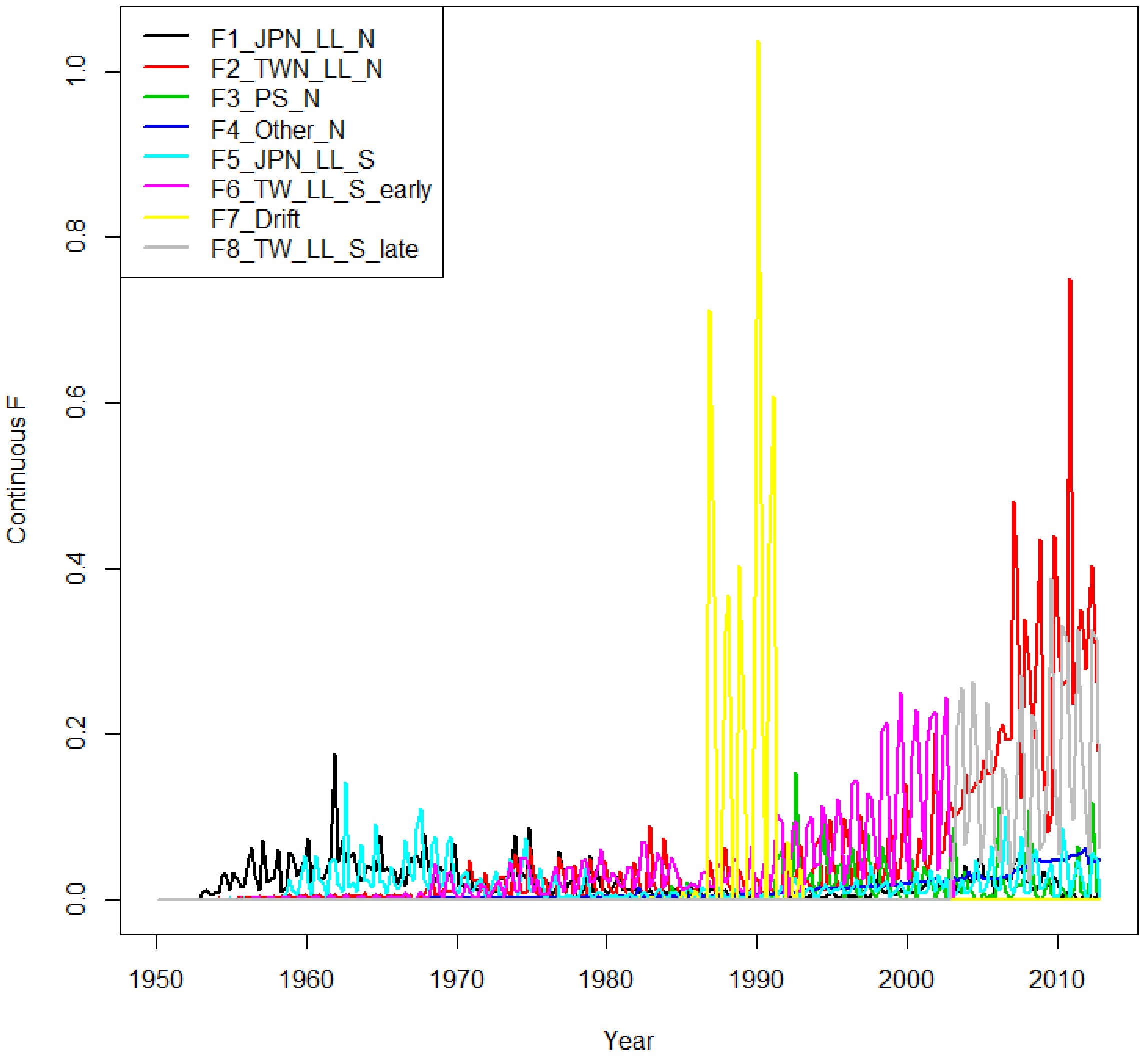


Figure 35: Estimates of fishery specific fishing mortality by fishery region from the reference case model.

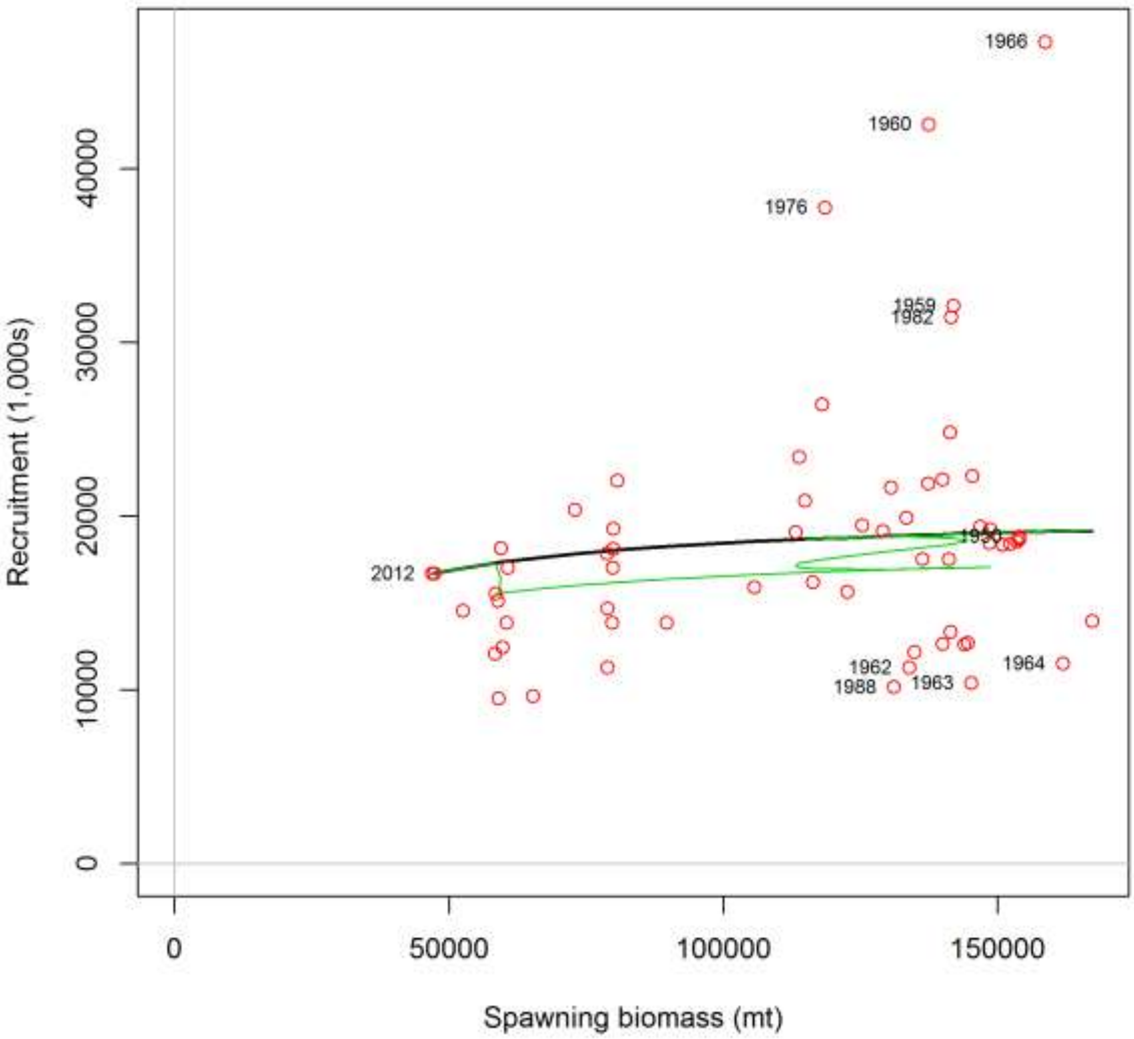


Figure 36: The relationship between spawning biomass and recruitment from the reference model (steepness of the SRR equal to 0.8).

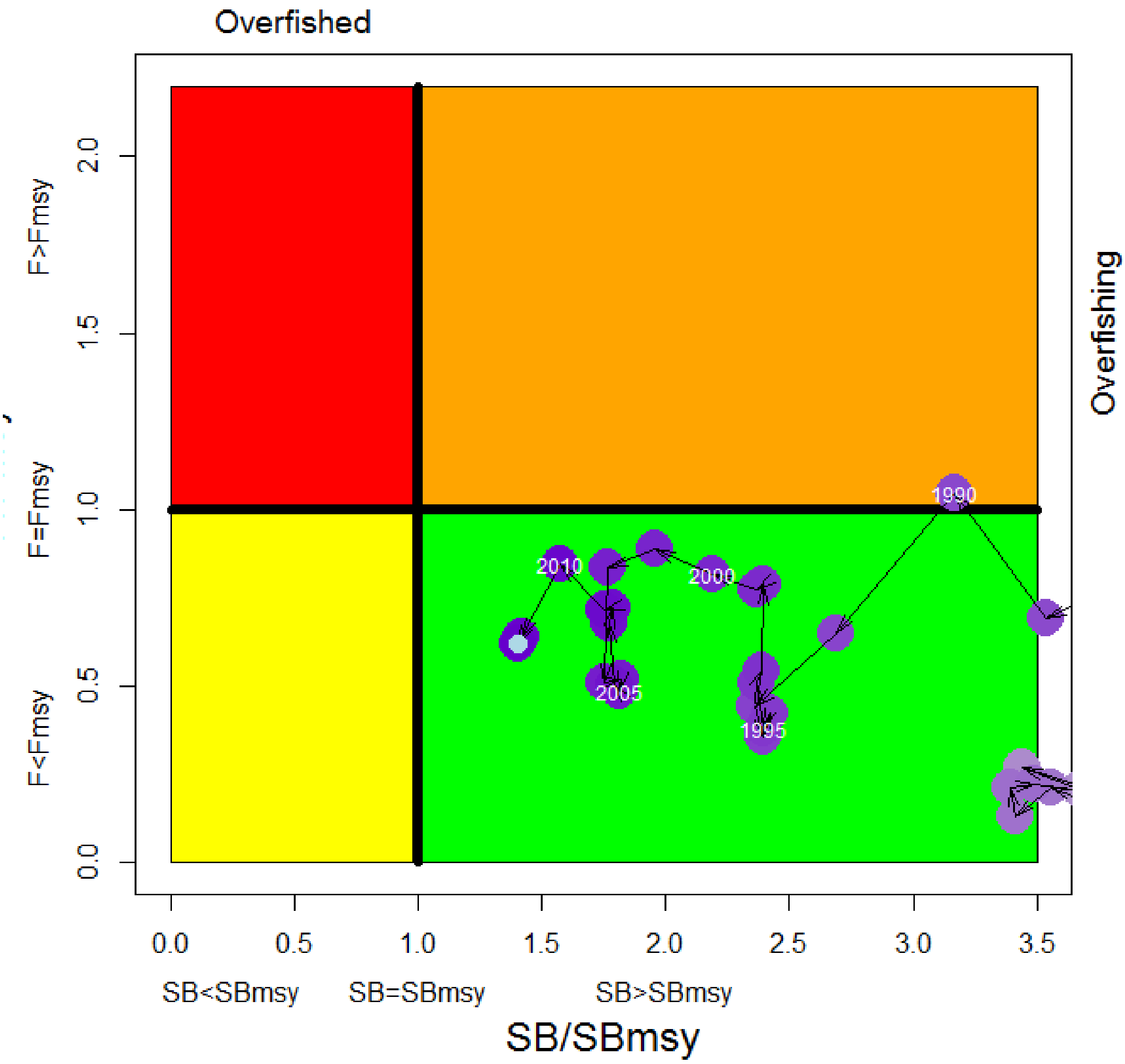


Figure 37: Kobe plot for the reference case. The arrows are the trajectories from the individual model options and the light blue point represents the terminal year (2012).

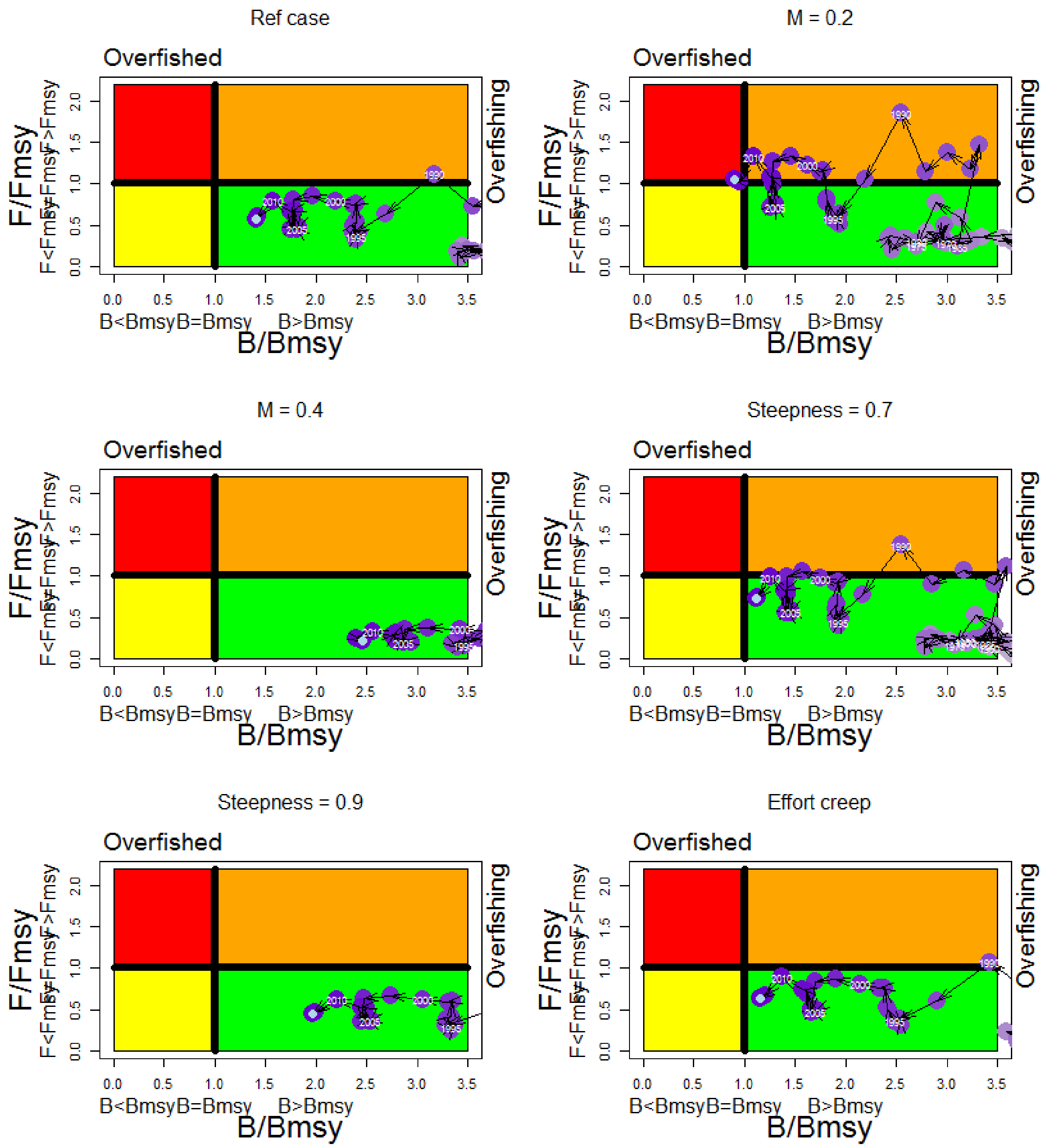


Figure 38: Kobe plots for the reference case and sensitivity analyses. The arrows are the trajectories from the individual model options and the light blue points represent the terminal year (2012) of the individual models.

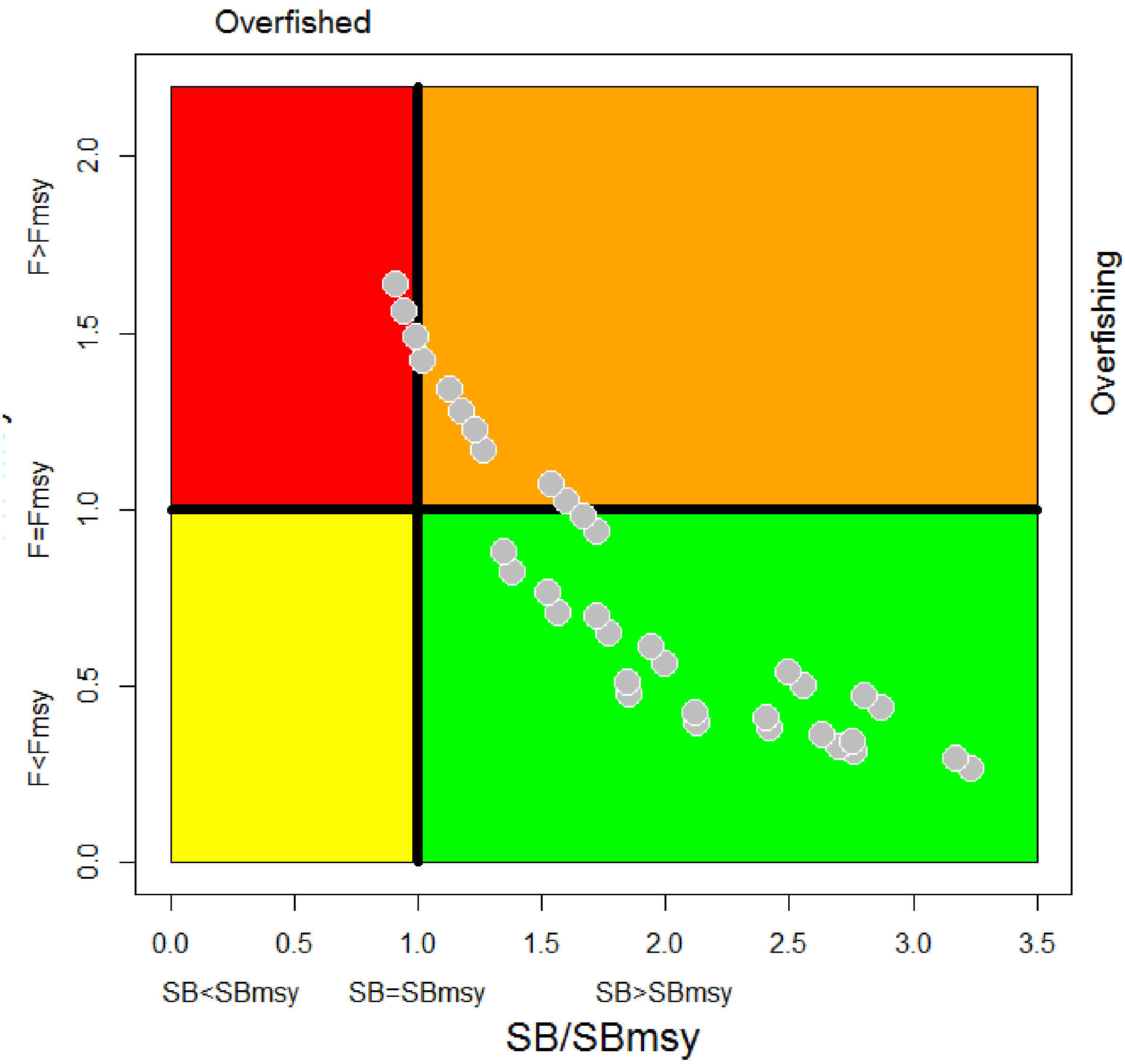


Figure 39: Kobe plot for the grid, including the 36 model options.

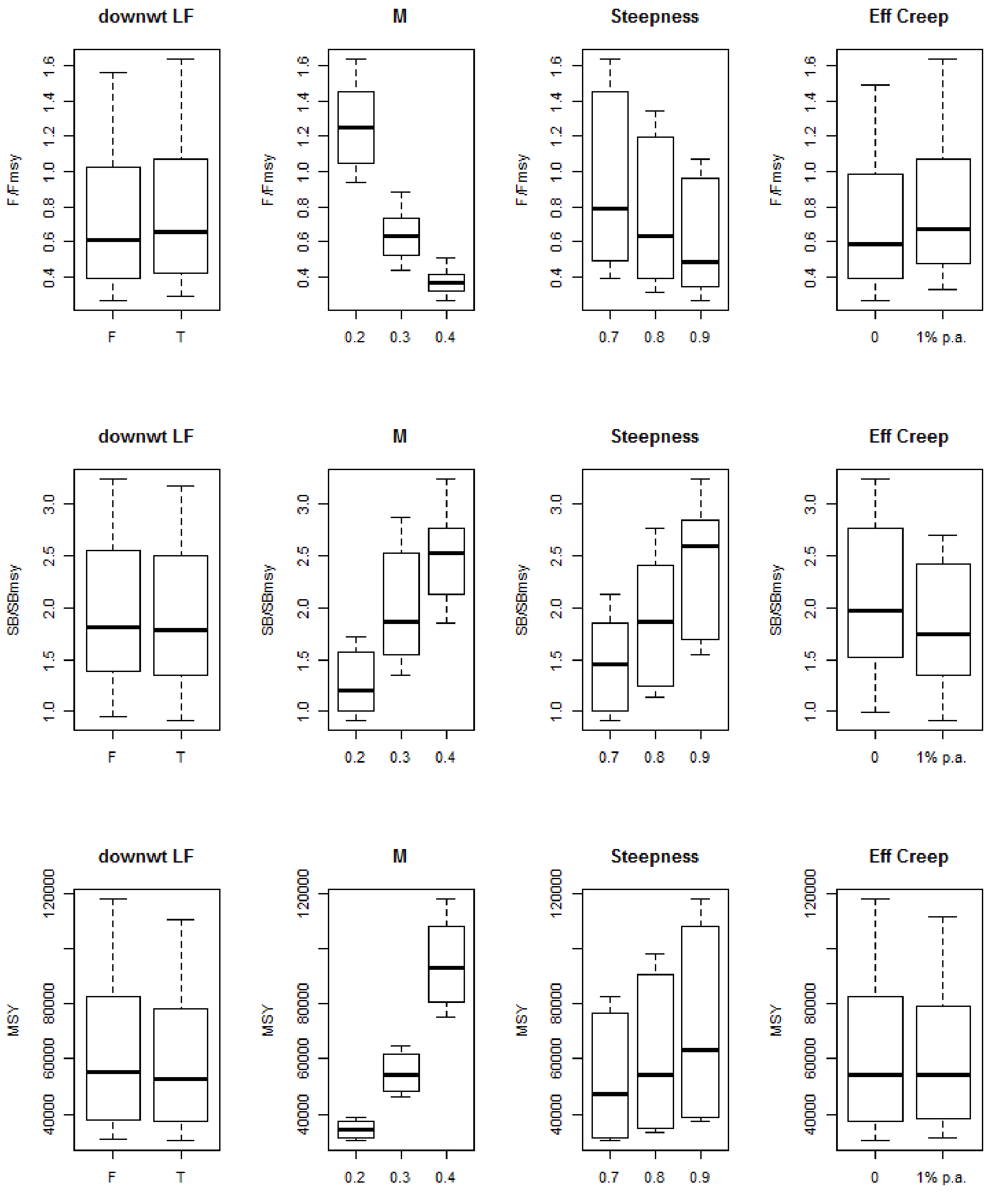


Figure 40: Boxplots of the main MSY based stock status indicators relative to the four model factors included in the grid of models (natural mortality, steepness and longline catchability)

11. Appendix 1: Catch data

Table 3: Annual catch (mt) of albacore tuna, by fishery, included in the stock assessment model.

Year	F1	F2	F3	F4	F5	F6	F7	F8
	JPN_LL_N	TWN_LL_N	PS_N	Other_N	JPN_LL_S	TW_LL_S_ early	Drift	TW_LL_S_ late
1950	0	0	0	8	0	0	0	0
1951	0	0	0	20	0	0	0	0
1952	61	0	0	20	0	0	0	0
1953	1094	0	0	20	0	0	0	0
1954	2701	82	0	24	34	7	0	0
1955	2970	178	0	24	89	98	0	0
1956	5057	368	0	24	17	162	0	0
1957	4658	461	0	24	4	195	0	0
1958	4565	580	0	24	1720	409	0	0
1959	5347	718	0	24	5065	509	0	0
1960	5382	605	0	24	5680	457	0	0
1961	8682	619	0	24	6558	764	0	0
1962	6365	576	0	28	11283	761	0	0
1963	4398	841	0	28	8162	749	0	0
1964	6767	719	0	28	11047	908	0	0
1965	5636	673	0	32	6258	636	0	0
1966	5012	829	0	36	8694	1074	0	0
1967	7704	615	0	40	12620	1040	0	0
1968	3309	2597	0	48	7652	5774	0	0
1969	4040	1720	0	48	8911	6185	0	0
1970	2167	4876	0	50	4413	2983	0	0
1971	1642	4101	0	57	4118	3471	0	0
1972	1664	2917	0	62	3590	4574	0	0
1973	5392	4627	0	53	5710	7732	0	0
1974	5493	5227	0	61	7053	12466	0	0
1975	1766	2952	0	68	3437	3564	0	0
1976	2631	2642	0	76	2791	7289	0	0
1977	1987	3029	0	81	606	6980	0	0
1978	2133	3213	0	221	2966	10262	0	0
1979	1529	3466	0	209	901	12154	0	0
1980	1792	2833	0	229	720	8786	0	0
1981	1236	3254	0	249	907	9811	0	0
1982	952	5586	12	719	991	17256	118	0
1983	955	5155	0	339	1296	12824	128	0
1984	1030	2546	527	392	1169	12643	0	0

1985	966	1364	673	348	1810	5812	721	0
1986	940	3114	247	388	1927	9392	18175	0
1987	960	4340	225	396	1751	10558	14026	0
1988	556	3264	244	482	1129	10745	14441	0
1989	432	2761	7	520	719	7136	10621	0
1990	402	2119	342	435	719	6459	25703	0
1991	442	3224	2246	525	823	14118	9001	0
1992	306	4358	3299	454	1585	10455	2643	0
1993	221	3748	1334	663	1168	13671	0	0
1994	217	5455	2578	778	1602	15905	0	0
1995	229	4553	1296	786	1829	16328	0	0
1996	339	5312	1584	892	2107	22154	0	0
1997	456	4048	2030	938	2904	19476	0	0
1998	1091	5341	1570	1027	2266	29376	0	0
1999	486	7051	556	1144	1829	29463	0	0
2000	543	5202	1165	1262	2142	30054	0	0
2001	1052	7584	1267	1260	2026	33084	0	0
2002	944	6674	702	1090	2282	25465	0	0
2003	1028	4849	1496	1106	1386	0	0	18944
2004	1495	5487	232	1288	2661	0	0	18772
2005	985	6311	164	1146	3430	0	0	17267
2006	1120	8010	1548	1306	5549	0	0	12337
2007	1780	13200	726	1652	3724	0	0	17506
2008	700	11158	1424	2137	4265	0	0	16233
2009	1087	7150	393	2105	2902	0	0	24497
2010	405	13350	206	2118	4049	0	0	23787
2011	149	9135	724	2203	2696	0	0	18708
2012	177	8309	1296	1650	3056	0	0	19376

Page **74** of **74**