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Stock assessment of bigeye tuna in the Indian Ocean for 2012.

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1 Introduction

The distant-water longline fishery commenced operation in the Indian Ocean during the early 1950s. Bigeye tuna represented a significant component of the total catch from the longline fishery and catches increased steadily over the subsequent decades, reaching a peak in the late 1990s-early 2000s. The purse-seine fisheries and fresh-chilled longline fisheries developed from the mid 1980s and total bigeye tuna catches peaked at about 150,000 mt in the late 1990s. Since the mid 2000s, the total annual bigeye catch has declined considerably, primarily due to a decline in the longline catch in the western equatorial region in response to the threat of piracy off the Somali coast. The total annual catch declined to 87,235 mt in 2010 and then subsequently recovered to 115,793 in 2012 (Herrera et al 2013). A detailed description of the Indian Ocean bigeye tuna fishery and available fishery data are presented in Herrera et al (2013).

Recent assessments of the Indian Ocean bigeye tuna stock have been conducted using Stock Synthesis (Kolody et al. 2010 and Shono et al. 2009) and ASPM (Nishida & Rademeyer 2011) software. The two most recent assessments (2010 SS3 and ASPM 2011) form the basis for the current management advice for bigeye tuna (IOTC 2011). Both assessments methodologies estimated that recent fishing mortality rates were below the F_{MSY} reference level ($F_{current}/F_{MSY} < 1$) and that the stock was not overfished ($SB_{current}/SB_{MSY} > 1$). However, Kolody et al. (2010) conducted a thorough examination of the sensitivity of the assessment to a range of the key model assumptions. The resulting model scenarios highlighted the high level of uncertainty associated with the stock assessment, encompassing a range of contrasting estimates of stock status.

Langley et al. (2013) updated the IO bigeye assessment, extending the model time period to 2011. The modelling investigated a wide range of model sensitivities particularly regarding the spatial configuration of the model, the treatment of the available tagging data and the relative influence of the individual length frequency data sets. The assessment was updated again during the WPTT15 meeting, including catch, CPUE indices and size frequency data to the end of the 2012 year. This report documents the updated assessment of the Indian Ocean bigeye tuna stock. The assessment formed the basis for the bigeye tuna management advice from WPTT15.

2 Preliminary modelling

A considerable amount of exploratory modelling was conducted during the development phase of the assessment (Langley et al. 2013). These analyses highlighted a number of key structural uncertainties, conflicts amongst a number of the main data sets and sensitivities to key parameters. The main conclusions of the analyses are as follow.

1. Model spatial structure. Two alternative spatial structures were considered: 1) a single region encompassing the entire Indian Ocean and 2) a spatial structure that subdivides the Indian Ocean into three regions. The spatially disaggregated (3 region) models yielded large estimates of stock biomass, mainly due to the magnitude of biomass apportioned to the southern region. This region represents a relatively small proportion of the total catch and the relative level of biomass estimated for the region was considered implausible. This was reflected in the other population dynamics estimated by the model (recruitment distribution, movement dynamics and very high exploitation rates estimated for the main fishery area). It was considered that these model characteristics were driven by the considerably difference in

the CPUE indices from the southern region (compared to the equatorial region) and the lack of data to inform the model regarding movement of fish amongst the three regions.

2. Tagging data. One of the main reasons for implementing a spatially structured model was to enable the RTTP tag release/recovery data to be incorporated in the stock assessment (see Langley et al. 2013). Various analyses of the IO bigeye tagging data have revealed that the dispersal of tagged fish is inadequate to achieve adequate mixing of tags at the IO basin scale during a time period (1–2 years) that is sufficient to enable a reasonable number of tags to be recovered from the population. The spatial structure of the disaggregated model was configured to include a region that encompassed all of the tag releases and most of the tag recoveries. The partitioning of the model was intended to reduce the sensitivity of the model to the basin-scale tag mixing assumptions.

3. Length frequency data. The preliminary modelling highlighted a considerable conflict between the main length frequency data sets and the longline CPUE indices. The length frequency data from the main longline and purse-seine fisheries are more consistent with a lower stock biomass (lower R_0, lower SB_0 and lower *MSY*) than the CPUE indices. However, there is considerable uncertainty regarding the reliability time-series of the length frequency data from the main longline fisheries (LL 1–3), especially the more recent sampling data from the fisheries (Greehan & Hoyle 2013). It was concluded that these data should be down-weighted so that the data were not influential in the final assessment model.

These three main conclusions guided the formulation of the main stock assessment models considered in Langley et al. (2013) and in the final stock assessment models adopted by WPTT 15. The base models adopted the single region model structure (spatially aggregated) due to implausible stock dynamics of the spatially disaggregated model and, as a consequence, the tag release/recovery data were not included in the final models due to inadequate mixing of tagged fish at the basin-scale. The length frequency data from most of the fisheries, with the exception of the main purse-seine fisheries, were down-weighted to the extent that these data were not unduly influencing the resulting biomass estimates.

3 Data compilation

The available data included fishery specific catch and length frequency data, and CPUE indices from the Japanese longline fishery. The tag release/recovery data from the RTTP were not included in the final models. The stock assessment was implemented in Stock Synthesis (version V3.24j) and data were configured in accordance with the structure of the model and the SS data structure.

Bigeye tuna catches (in mt) and length frequency data were compiled by fishery and year/quarter. The length-frequency data for each of the defined fisheries were compiled into 95 2-cm size classes (10–12 cm to 198–200 cm). Each length frequency observation for purse seine fisheries represents the number of fish sampled raised to the sampling units (sets in the fish compartment) while for fisheries other than purse seine each observation consisted of the actual number of fish measured.

3.1 Fishery data

A total of 12 fisheries were defined based on the fishing method and location of the fishery. The specific fishery definitions are presented in Table 1. The spatial demarcation of the individual fisheries was equivalent to the regional structure used in the spatially disaggregated models (Figure 1). Annual catches from the individual fisheries are presented in Appendix 1. The available data from each fishery is described below.

Longline, distant-water (LL 1–3). The longline fishery operates throughout the Indian Ocean although catches are concentrated in the equatorial region (Figure 2). Catches are primarily from the Japanese, Korean and Taiwanese distant-water longline fleets. Most of the catch has been taken from the western equatorial region and annual catches from the LL1 fishery steadily increased from the early 1950s to reach a peak of 70,000 mt in 2004. Catches of about 55,000 mt were maintained during 2005–07, declined rapidly to about 15,000 mt in 2010–2011 and then recovered to about 50,000 mt in 2012 (Figure 3). Annual catches from the LL2 fishery remained relatively stable at about 15,000 mt from 1975–2011.

Annual longline catches from the southern area were comparatively low, averaging about 3,000 mt, from 1960 to 1990 (Figure 3). Catches then increased to a peak of 20,000 mt in 1995, declined steadily to about 3,000 mt in 2007 and remained at that level over subsequent years.

Size frequency data are available for the LL1–3 fisheries 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 have been converted to length frequency data via a processed weight-whole weight conversion factor and a weight-length key. Length frequency data from the Taiwanese longline fleet are also available from 1980–2012. In recent years, length data are also available from other fleets and periods (e.g. Seychelles).

Length frequency data from all sources were aggregated to provide a composite length composition for each year/quarter. Prior to 1995, the length compositions are dominated by sampling from the Japanese longline fleet, while in the subsequent period the size data is increasingly dominated by the data collected from the Taiwanese distant-water longline fleet.

The length composition of the sampled longline catch is dominated by fish in the 90–150 cm length range (Figure 5). The length composition is comparable for the three regions although fish in the southern region are somewhat smaller than the fish sampled from the equatorial regions. The average length of fish in the sampled catch from LL1 and LL2 fluctuated over the study period (Figure 6). For both regions, average fish length declined during the 1990s and then recovered during the early 2000s. These trends were not evident in the LL3 fishery.

It is unknown whether the temporal trends in the length composition of samples from LL1 and LL2 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 level of length sampling from the Taiwanese fleet, while the average fish weight from the Taiwanese catch (total weight of catch/total number of fish) revealed no corresponding increase. Furthermore, the limited length data available from the Japanese longline fishery revealed no strong trend in the size of fish caught during the period. On that basis, it appears more likely that the observed trends in length composition of the LL1 and LL2 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).

Longline, fresh tuna fleet (FL2). The fishery developed in the late 1980s and annual catches rapidly increased to reach a peak of about 30–35,000 mt in the late 1990s-early 2000s. Catches declined sharply in 2003 and since then have averaged about 15–20,000 mt per annum (Figure 3).

Length data are available from 1998 onwards; however, no length data are available from the earlier period of the fishery (1973−1997) (Figure 4). Length and weight data were collected during the unloading of catches at several ports, primarily from fresh-tuna longline vessels flagged in Indonesia and Taiwan/China (IOTC-OFCF sampling).

The composite length composition of the catch is similar to the distant water longline fleet (Figure 5) and remained relatively stable over the sampling period (Figure 6).

Purse seine (PSFS1, PSFS2, PSLS1, PSLS2). Almost all of the industrial purse-seine catch is taken within the western equatorial region (Figure 2) and catches are dominated by the fishery on associated schools (PSLS1) (Figure 3). Annual catches from the PSLS1 fishery reached a peak of about 30,000 mt in the late 1990s and have fluctuated at 15–25,000 mt over the last decade before dropping sharply in 2012 to about 10,000 mt. Since the late 1980s, annual catches from the purse-seine free school fishery (PSFS1) have averaged about 5,000 mt

Relatively minor catches were taken by the associated purse-seine fishery in the eastern equatorial region (PSLS2) (Figure 3).

Length-frequency samples from purse seiners have been collected from a variety of port sampling programmes since the mid-1980s. The samples are comprised of very large numbers of individual fish measurements and represent comprehensive sampling coverage of the main period of the fishery (Figure 4). Limited size data are available from the purse-seine fishery within region 2.

The associated purse-seine fishery primarily catches smaller bigeye tuna, while the size composition of the catch from the free school fishery is bimodal comprised of the smaller size range of bigeye and a broad mode of larger fish (Figure 5). There was a general decline in the average length of fish caught by the PSLS1 fishery from 1990 to 2010 (Figure 6). The average size of fish sampled from the free school fishery was variable among quarters, although fish tended to be smaller during the late 2000s, increased during the early–mid 2000s and declined in more recent years. It is unknown whether the trends in the length composition of the purse seine catch are representative of the population or reflect changes in the operation of the fishery.

Baitboat (BB1). Bigeye catches from the Maldives baitboat fishery are estimated to have increased steadily from a minimal level in the late 1970s to about 6-7,000 mt in recent years (Figure 3). Limited length samples are available from the fishery (Figure 4) and the sampled catch was dominated by fish in the smaller length classes (50–70 cm) (Figure 5 and Figure 6).

Line (LINE2). The LINE2 fishery includes small scale fisheries using handlines, small longlines and the gillnet/longline combination fishery of Sri Lanka. Annual catches are estimated to have increased steadily from a minimal level in the 1970s to about 7,000 mt in recent years (Figure 3). Negligible length frequency data are available from the composite fisheries although the available data indicate that the catch is predominantly composed of larger fish (Figure 5).

Other (OT1 and OT2). The “Other” fisheries include gillnet, trolling and other minor artisanal gears. The fisheries are aggregated by region for the two equatorial areas. Within the western region the OT1 fishery is primarily comprised of the Iranian driftnet fishery operating in the high seas. Total catches were negligible prior to 2005 but since then annual catches have been about 1,500 mt (Figure 3). Length samples are not available from the driftnet fishery. Instead, the available OT1 length samples were collected from the other fisheries that operated prior to 2005 (Figure 4). The aggregate length samples encompass a broad length range (Figure 5).

For the Other 2 (OT2) fishery, recent catches were mainly from trolling and, to a lesser extent, gillnets, with most of the catch from Indonesian fleets. Recent annual catches of about 5,000 t were considerably higher the catches from the preceding period (Figure 3). The limited length samples were all collected from the from Indonesian small purse seine and troll fisheries (Figure 4). The aggregate length frequency data available include two size modes from the small scale purse seine samples (Figure 5). This is probably due to different sizes of fish taken by different modes of fishing (e.g. fishing at night with light, around anchored FADs, etc.).

3.2 CPUE indices

Standardised CPUE indices for the entire Indian Ocean IO were determined for the Japanese longline fleet using a generalized linear model (GLM) (Matsumoto et al. 2013). The indices were computed by year/quarter for 1960–2012 (212 quarterly indices) (Figure 7).

The individual CPUE indices were assigned a coefficient of variation (c.v.) of 10%. This high level of precision was ascribed to the CPUE indices on the basis that these indices represent the primary index of stock abundance in the assessment model and that the resulting estimates of stock abundance should be generally consistent with these indices.

The CPUE standardization procedure incorporates a number of factors, including changes in gear configuration, that may account for changes in the performance of the longline fishery over time. However, there are a range of other technological improvements in the operation of the fleet that are not accounted for in the analysis. These specifically relate to the replacement of older vessels with increasingly more 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 (*LLq0*) and 2) including a 1% per annum (compounded) increase in catchability over the entire time period of the CPUE time series (1960-2012) (*LLq1*). 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 68% increase in the effective longline effort over the time-series, corresponding to a 40% reduction in the base CPUE at the end of the time-series (Figure 7).

3.3 Tag release/recovery data

As discussed above, the tag release/recovery data were not included within the final assessment models. A detailed description of the available tag data and incorporation of these data in the range of preliminary models is provided in Langley et al (2013).

4 Biological parameters

Recent estimates of Indian Ocean bigeye tuna growth derived from otolith age data and tag release/recovery are available from Eveson et al. (2012). Growth estimates are available for both sexes combined. The quarterly growth deviates from a von Bertalanffy growth function with considerably lower growth for quarterly age classes 4–8 (Figure 8). Maximum average length (L_∞) was estimated by Eveson et al. (2012) at 150.9 cm (fork length). The growth model was unable to reliably estimate the standard deviation of length-at-age; however, the most appropriate level of variation in length for all age classes was considered to be represented by a coefficient of variation of 0.10 (P. Eveson, pers. comm.).

The growth function was implemented in SS using age-specific deviates on the k growth parameter. This feature has only recently been implemented in SS and is currently not documented.

The size of sexual maturity was equivalent to that applied by Shono et al (2009) and Kolody et al. (2010). Female fish were assumed to attain sexual maturity from 100 cm (F.L.) with full sexual maturity at about 125 cm.

The length-weight relationship was equivalent to that previously used by Shono et al (2009) and Kolody et al. (2010) and was originally derived by Nakamura and Uchiyama (1966). Fish weight = $a$length^b , a = 3.661 x 10^{-5} , b = 2.901 where weight is in kilograms and length is in centimetres.

Age specific natural mortality was equivalent to the schedule used by Shono et al (2009) and Kolody et al. (2010) (Figure 9). The levels of natural mortality are comparable to IATTC and WCPFC bigeye tuna stock assessments with relatively high natural mortality for the younger age classes and natural mortality of about 0.1 per quarter for the adult age classes.

An alternative natural mortality schedule was proposed based on a Lorenz curve analysis (A. Fonteneau pers. comm.) with a lower natural mortality for the adult age classes (0.0625 per quarter) (Figure 9).

5 Model structure and assumptions

The model population structure included 40 quarterly age classes; the first age class represents fish aged 3–6 months and the last age class accumulates all fish age 40+ quarters. There are very limited sex specific data available and, hence, the model population age structure was aggregated by sex. The model commenced in 1952 and extended to the end of 2012 configured in quarterly intervals. The population age structure at the start of the model was assumed to be in an equilibrium, unexploited state.

5.1 Recruitment

Recruitment occurs in each quarterly time step of the model. Recruitment was estimated as deviates from the BH stock recruitment relationship (SRR), although deviates were estimated for 1964–2010 only (188 deviates). Recruitment deviates were not estimated for the earlier period of the model due to the lack of longline CPUE indices prior to 1960 and the lack of length frequency data prior to 1965. Recruitment deviates were not estimated for the last 8 quarters in the model as the relative abundance of these recruitments is not monitored by the model abundance index (longline CPUE). Recruitment deviates are assumed to have a standard deviation (σ_R) of 0.6.

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 bigeye tuna and are routinely adopted in tuna assessments conducted by other tuna RFMOs.

5.2 Fishery dynamics

For all fisheries, selectivity was estimated as an age based process. Initially, the selectivity of the main longline fishery (LL1) was estimated as an asymptotic form using a logistic function. A logistic selectivity was also assumed for the FL2 longline fishery. For the other two main longline fisheries (LL2 and LL3), double normal selectivity functions were estimated.

The selectivities of the PSLS and BB fisheries were estimated using a double normal functional form. To account for the bimodal length composition of the catch from the PSFS fishery, the selectivity was modelled using a cubic spline with 6 nodes. Limited data were available to estimate the selectivity of either the PSLS2 or PSFS2 fisheries. The selectivity of these fisheries was constrained to be equivalent to the corresponding fishery selectivity in the western region.

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. In aggregate, the length compositions are bimodal and similar to the length composition from the PSFS fishery. On that basis, the selectivities for the two “Other” fisheries

(OT1 and OT2) were assumed to be equivalent to the PSFS fishery. Similarly, limited length data are available for the LINE2 fishery and the selectivity was assumed to be equivalent to the main longline fishery.

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

The CPUE indices are linked to the selectivity of the LL1 fishery. The catchability of the CPUE indices (base and LLq1) was temporally invariant in the assessment model framework.

5.3 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 (in prep.).

For all fisheries, with the exception of the PSLS1 and PSFS1 fisheries, the individual length frequency observations were assigned an effective sample size (ESS) of 10, down-weighting these data in the overall likelihood. For the PSLS1 and PSFS1 fisheries an ESS of 100 was assigned to all length observations.

6 Model results

The final set of models included two alternative sets of CPUE indices (LLq0 and LLq1), two natural mortality schedules (high M and low M) and three alternative levels of steepness (0.7, 0.8 and 0.9) for the SRR. The set of models encompassing all combinations of these options (2x2x3) resulting in 12 alternative models. The WPTT 15 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, all 12 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 (LLq0, high M and steepness 0.8) to describe the main features of the assessment. Significant differences amongst the range of models are also highlighted.

There is a reasonable fit to the general trend in the CPUE indices, although the model does not account for the seasonal variability in the CPUE indices (Figure 10). There are some persistent patterns in the CPUE residuals, with persistent positive residuals during the 1960s, positive residuals during the late 1970s and early 1980s when there was a strong peak in the CPUE indices and negative residuals during the early 2000s. Overall, the variation in the residuals (RMSE approx. 0.2) is considerably higher than the assumed c.v. for the CPUE indices (10%).

The age-specific selectivity functions are presented in Figure 11. For the main logline fisheries, full selectivity is attained at about age 20 (quarters). For the LL2&3 fisheries, selectivity is estimated to be lower for the older (25+ quarters) age classes. Conversely, for the PSFS fisheries a comparatively high selectivity is estimated for these older age classes. Peak selectivity for the PSLS fishery occurs at ages 5–8 quarters.

Overall, there is a good fit to the aggregated length frequency data for the main fisheries with comprehensive sampling (Figure 12). However, an examination of the model residuals from the individual observations reveal a poor fit to the data from key fisheries during certain time periods. Most notably is the poor fit to the data from LL 1 during the late 1970s–early 1980s (coinciding with the early peak in the CPUE indices) and the mid–late 1990s and mid 2000s (Figure 13). The latter two periods coincide with the periods when smaller and larger fish were sampled from the longline catch (see Figure 6).

The inconsistency between the fishery-specific length frequency data and the CPUE indices is also evident from the derived values of effective sample size from the model (following McAllister and Ianelli 1997) (Figure 14). The values are the ESS required for each sample to enable the observed proportions at length to approximate the predicted proportions. For the longline fisheries, large ESSs were computed for most of the individual samples although there was also considerable variability in the ESS over the respective time-series, especially for LL1 and LL2 (Figure 14).

The time-series of recruitment deviates for the four main model options (M and catchability) are comparable (Figure 15). For the mid 1980s onwards, there is a strong seasonal pattern in the recruitment deviates with higher recruitment in the second and third quarters and low recruitment in the first and fourth quarters. This period corresponds to the availability of length frequency data from the purse-seine fisheries, indicating that these data are highly informative in the estimation of the recruitment deviates. There are some notable temporal trends in the recruitment time series with relatively higher recruitment during the late 1990s, lower recruitment in the mid 2000s, and higher recruitment in more recent years (Figure 15).

The trends in spawning biomass are broadly comparable among the four main model options (natural mortality and longline catchability options). For all model options, there is an increase in spawning biomass during the late 1970s–early 1980s that follows the trend in the CPUE indices (Figure 16). Biomass tends to decline relatively steadily until about 2010 followed by a slight recovery in spawning biomass during the last 2-3 years.

The estimates of fishing mortality for the LL1 and PSLF1 fisheries increased during the 1990s and declining from 2007 to 2010. Fishing mortality rates for the LL1 fishery increased again in 2012. Fishing mortality rates for the other fisheries are relatively low.

7 Stock status

Stock status was determined based on the range of 12 final model options. No preference was given to any subset of these models and all were included in the formulation of management advice by WPTT15.

MSY based reference points were derived for the final model options based on the average F-at-age matrix for the period 2008–11. The period was considered representative of the recent average pattern of exploitation from the fishery, while including a sufficient period to reduce the variability in the pattern of exploitation, particularly associated with the variation in the operation of the purse seine fishery (i.e. the relative component of FS and LS catch). For the final model options, a range of values for the steepness (0.7, 0.8 and 0.9) of the Beverton-Holt stock-recruitment relationship was assumed. There is no evidence from the assessment models to infer an appropriate level of steepness for the SRR (Figure 18).

The resulting annual trends in fishing mortality and biomass relative to the associated *MSY* based benchmarks (F_{MSY} and B_{MSY}) for each model option are presented in Figure 19. The 12 model trajectories exhibit similar trends in both dimensions, although the extent of the trajectory differs considerably among the 12 model options. Fishing mortality rates increased considerably during the 1990s, stabilised during the late 2000s and then decreased markedly from 2009 to 2010 and have remained relatively low over the last few years. Spawning biomass declined in response to the increase in fishing mortality, reaching the lowest level in about 2010 and is estimated to have increased in the subsequent years, although the extent of the increase varies amongst models. Model options with lower values of steepness and natural mortality and the increasing trend in longline catchability exhibit higher levels of fishing mortality and stock depletion and vice versa (Table 2 and Figure 20). The lower productivity scenarios have lower associated estimates of *MSY* (Figure 20).

For all model options, 2012 fishing mortality rates are estimated to be considerably lower than the F_{MSY} level (F/F_{MSY} median 0.43, range 0.21–0.80) (Table 2), while spawning biomass is estimated to be above the SB_{MSY} level for most of the model options (SB/SB_{MSY} median 1.44, range 0.87–2.22). The two exceptions are the model options with lower steepness (0.7 and 0.8), lower natural mortality and increasing longline catchability. The estimates of *MSY* from all models range from 98,000–207,000 mt with a median value of 132,000 mt (Table 2).

It was considered appropriate to characterise the uncertainty in the current stock status by encompassing the range from the 12 model scenarios. This structural uncertainty in the model is considerably greater than the statistical uncertainty of the individual model estimates. This was evident from previous estimates of statistical uncertainty obtained using a MCMC approach (Langley et al 2013). The relatively high precision of the individual models related to the high precision assigned to the CPUE indices (c.v. 10%) and the constrained (fixed) biological parameters, especially natural mortality and steepness.

8 Discussion

Overall, the results of the current assessment are generally consistent with the previous assessment conducted by Kolody et al. (2010). The earlier assessment was based on a single region Indian Ocean model and explored a range of assumptions, including the relative weighting of the various data sets. The range of model options yielded contrasting estimates of *MSY* ('minMSY' = 89,000 t to 'maxMSY' = 183,000 t). The relative weighting of the length frequency data was an influential factor with higher estimates of *MSY* associated with a lower ESS. However, other factors were more influential; lower *MSY* values were associated with lower values of natural mortality and lower values of SRR steepness, lower *MSY* values were also associated with the constraint on the estimation of recruitment deviates ($\sigma_R = 0$) and the inclusion of an increase in longline catchability. The estimates of *MSY* from the current study encompass a similar range that that of Kolody et al. (2010) and the individual model options exhibit similar patterns for the key variables examined by Kolody.

Langley et al. (2013) highlighted that the length frequency data as a key source of model uncertainty. These data are potentially highly influential due, in part, to the other model constraints (fixed growth parameters, especially L_∞ and the std dev of length-at-age, fixed natural mortality and logistic selectivity for the longline fishery); however, there is considerable uncertainty associated with the collection and compilation of these data, particularly for the longline fisheries. The data sets are in conflict, to some degree, with the CPUE indices which are considered to represent the prime indicator of stock abundance.

On that basis, the longline length frequency data were assigned a low relative weighting in the preferred assessment model option. Nonetheless, this approach is unsatisfactory and it should be a priority of future assessments to address the conflict between the main data sources. In the first instance, this would involve a detailed analysis of the length frequency data from the longline fishery (specifically Chinese Taipei and Japan) resulting in the compilation of a time-series of length data that are representative of the operation of the fishery (e.g. sampling from the commercial fleet rather than from training vessels) and identification of potential sources of variability and bias in the collection of the sampling data (e.g. changes in spatial distribution of data collection, changes in targeting behaviour and changes in fleet nationality). This analysis is likely to generate a more consistent time-series of length data from the fishery and/or identify structure in the data set that can be accounted for in the configuration of the assessment model (e.g. temporal variation in selectivity).

Once these data issues are addressed, it may be more appropriate to adopt a length-based selectivity for some of the key fisheries, particularly for the fisheries primarily catching a distinct length mode of small bigeye (especially the PSLS fishery), although the current assessment provides a good fit to the length data from these fisheries, facilitated by the quarterly age structure of the population and the implementation of the new growth parameterisation in SS (i.e., the age specific *k* parameters).

A related issue is the lack of reliable length frequency data from the "Other" fisheries (OT1 & 2). These fisheries accounted for approximately 5,000 mt of bigeye catch in recent years. In the absence of reliable length data, these fisheries were assumed to have a selectivity equivalent to the PSFS fishery, reflecting the bimodality in the length compositions from the two fisheries.

The current models incorporate the entire catch history (from 1952) and assumes initial unexploited conditions (in 1951) and a considerable period of equilibrium recruitment (prior to 1964). An alternative approach is to commence the model at later time and estimate the initial level of exploitation and the associated initial age structure. The latter approach was initially discounted due to the lack of available information to reliably inform the model regarding the population age structure at the start of the model. Nonetheless, Langley et al (2013) investigated several model options that initialized the model in 1975 based on the estimated fishery specific exploitation rates in the initial model period. These models estimated low exploitation rates for the longline fisheries operating during the 1970s and estimates of initial (1975) biomass that were comparable to the main assessment models. The absolute biomass trajectory and trends in the key *MSY* based stock status indicators were also similar. Thus, future stock assessments may reconsider the need to include the entire catch history period in the assessment models.

The current assessment does not incorporate the available IO bigeye tag release/recovery data. This is a potentially highly informative data set; however, a range of model options developed during the preliminary modelling phase (Langley et al 2013) highlighted a range of issues that precluded these data being included in the final assessment models. These issues primarily relate to the inability of the current modelling framework to adequately encapsulate the spatial dynamics of the entire IO stock, including the dispersal of tagged fish, regional recruitment processes and movement dynamics. Further model development is urgently required to adequately utilise the tagging data in the IO bigeye stock assessment. Nonetheless, a number of model sensitivities were conducted that incorporated the tagging data within the final single region IO model. These models yielded more conservative estimates of stock status, although these results do not differ sufficiently to alter the current conclusions regarding the status of the stock.

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10 References

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Table 1. Definitions of the individual model fisheries.

Code	Method	Region	Flag	Notes
FL2	Longline, fresh tuna fleets	2	All	
LL1	Longline, distant water	1	All	
LL2	Longline, distant water	2	All	
LL3	Longline, distant water	3	All	
PSFS1	Purse seine, free school	1	All	
PSFS2	Purse seine, free school	2	All	
PSLS1	Purse seine, associated sets	1	All	
PSLS2	Purse seine, associated sets	2	All	
BB1	Baitboat and small scale encircling gears (PSS, RN)	1	All	Primarily catch from the Maldives baitboat fishery. Predominantly catching small bigeye.
LINE2	Mixed gears (hand-line, gillnet/longline combination)	2	All	Gears grouped on the basis that primarily catch large bigeye.
OT1	Other (trolling, gillnet, unclassified)	1	All	
OT2	Other (trolling, gillnet, unclassified)	2	All	

Table 2. Maximum Posterior Density (MPD) estimates of the main stock status indicators from the final set of model options with alternative values of steepness (*h*), longline catchability (LLq, q0 no increase; q1 increasing catchability) and natural mortality (M1 = higher M; M2 = lower M). The reference model option is highlighted. The total model likelihood and the main likelihood components are also presented.

h	LLq	M	SB_0	SB_{MSY}	SB_{2012}	SB_{2012}/SB_0	SB_{2012}/SB_{MSY}	F_{2011}/F_{MSY}	*MSY*	Model likelihood		
										Total	Survey	LF
0.8	**q0**	**M1**	**1,674,570**	**464,949**	**894,600**	**0.53**	**1.92**	**0.25**	**187,596**	**11505.6**	**-70.4**	**11532.0**
0.8	q1	M1	1,230,490	344,059	450,253	0.37	1.31	0.43	143,632	11663.5	-11.5	11651.8
0.8	q0	M2	2,068,550	597,346	903,960	0.44	1.51	0.42	122,541	11593.3	-67.1	11606.9
0.8	q1	M2	1,669,190	482,316	466,429	0.28	0.97	0.68	105,543	11709.8	-22.8	11701.6
0.7	q0	M1	1,703,280	526,637	902,982	0.53	1.71	0.30	169,410	11505.2	-71.9	11533.1
0.7	q1	M1	1,264,770	392,389	455,438	0.36	1.16	0.51	131,920	11650.3	-19.0	11646.1
0.7	q0	M2	2,125,490	676,530	926,092	0.44	1.37	0.49	112,232	11591.6	-68.1	11605.7
0.7	q1	M2	1,738,530	553,032	480,561	0.28	0.87	0.80	97,842	11700.9	-27.8	11696.8
0.9	q0	M1	1,661,680	401,872	892,933	0.54	2.22	0.21	206,976	11509.1	-68.7	11533.9
0.9	q1	M1	1,203,630	295,291	446,657	0.37	1.51	0.36	155,743	11672.7	-5.0	11654.2
0.9	q0	M2	2,026,550	519,441	888,004	0.44	1.71	0.36	132,555	11594.7	-66.2	11607.9
0.9	q1	M2	1,618,690	416,289	456,742	0.28	1.10	0.58	113,100	11717.2	-18.4	11705.2

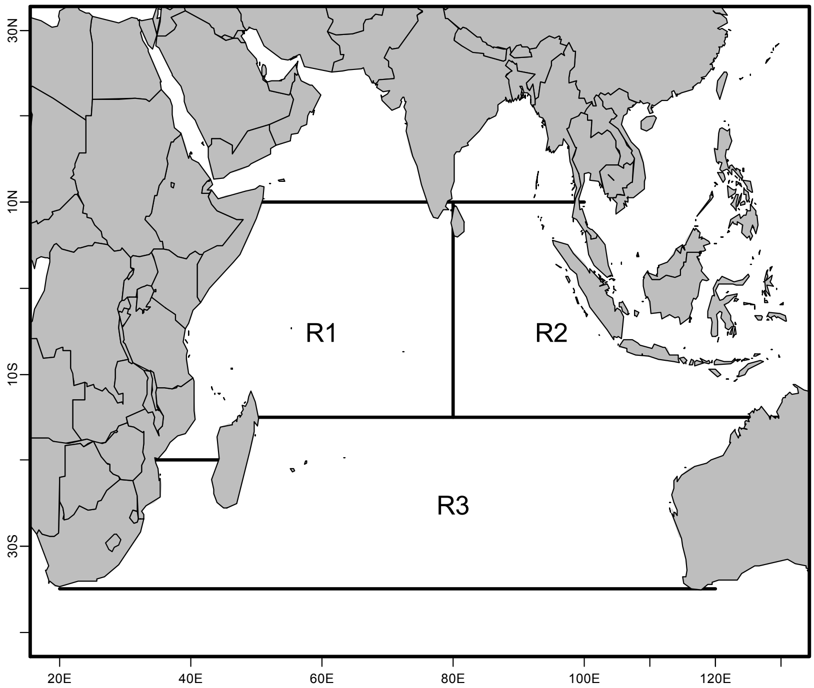

Figure 1. The spatial structure applied to define the model fisheries.

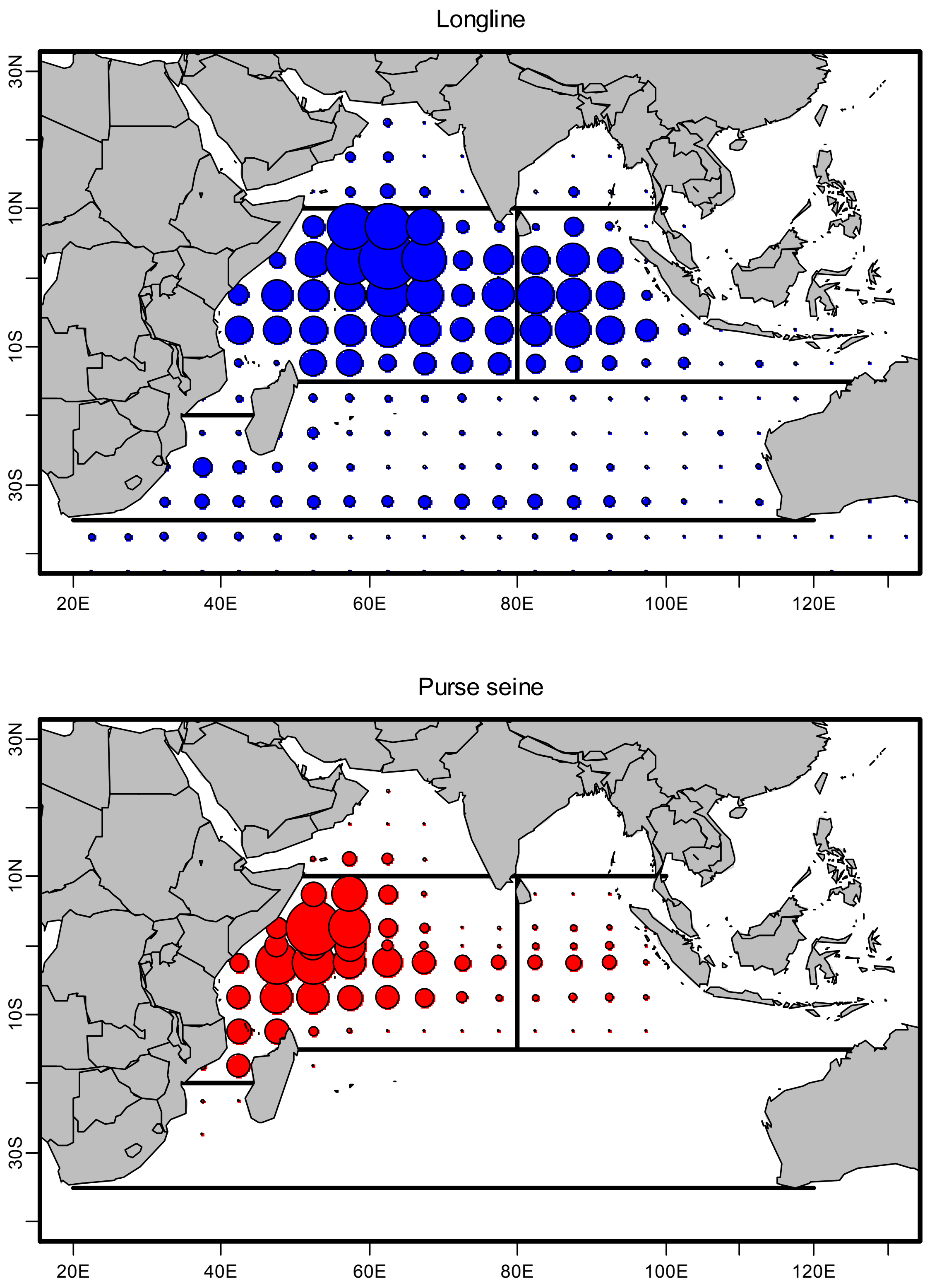

Figure 2. Aggregate LL and PS catch (max bet catch in 5 deg cell aggregated over time 70159.62 mt)

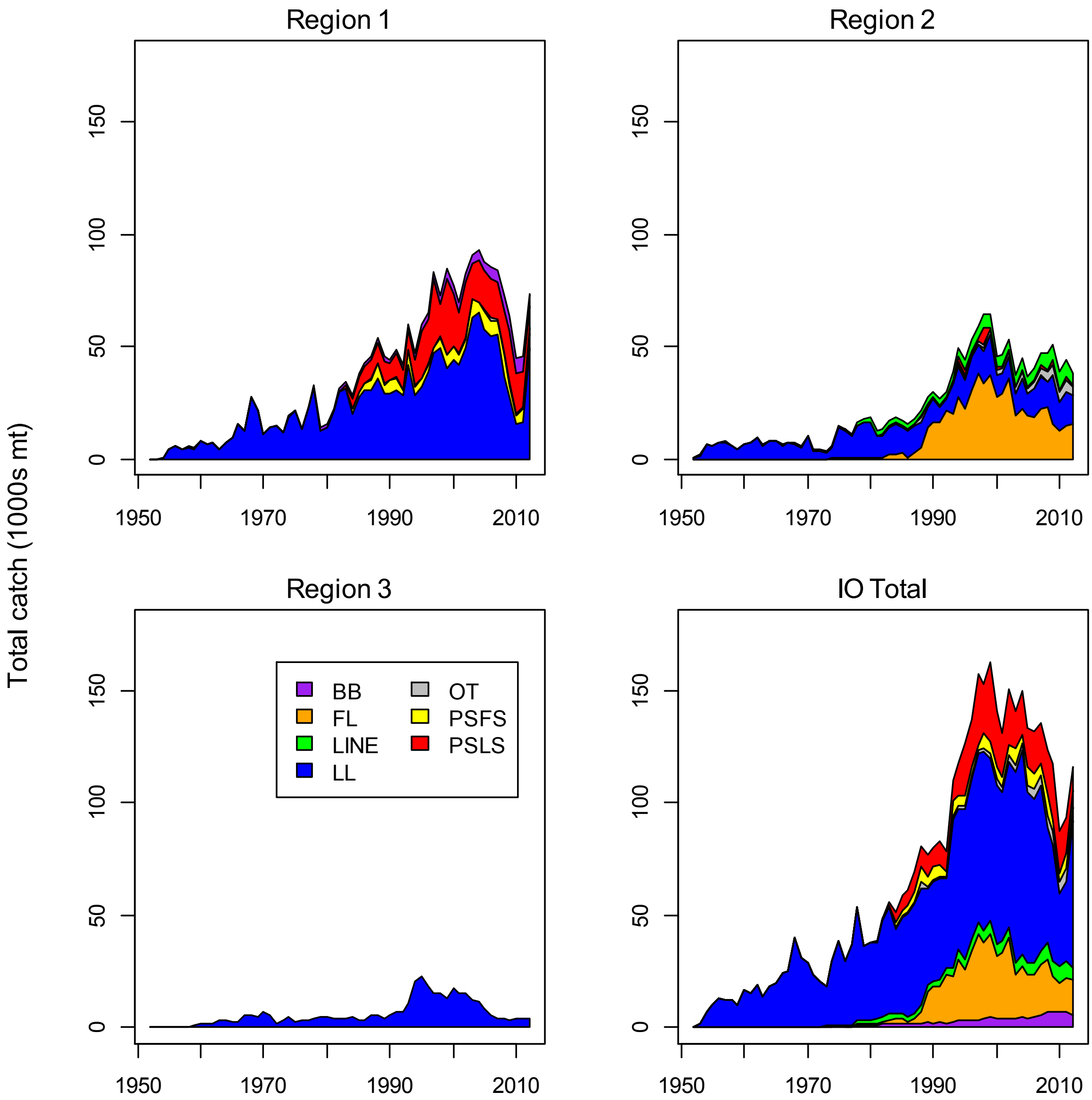

Figure 3. Annual catches by fishery and region 1952-2012.

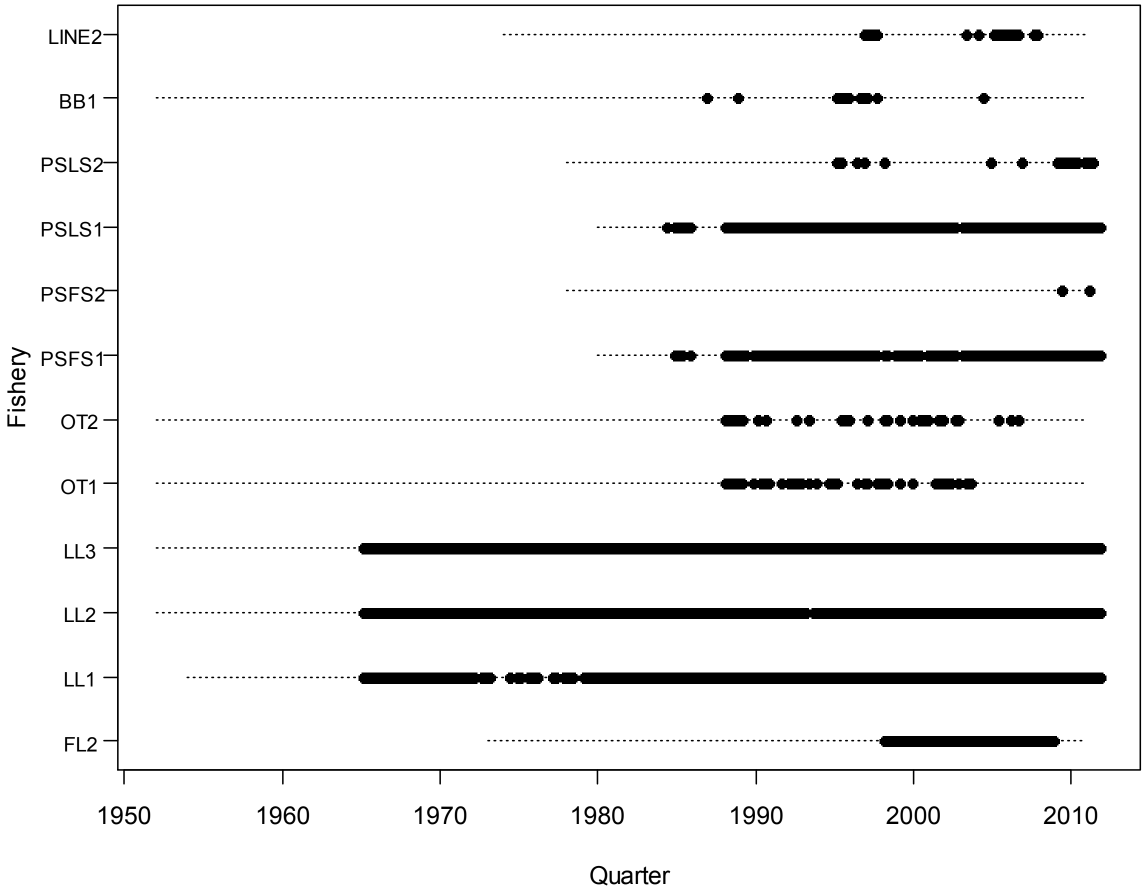

Figure 4. The quarterly distribution of length samples (points) from each fishery. The dashed line spans the time period of catch from the individual fishery.

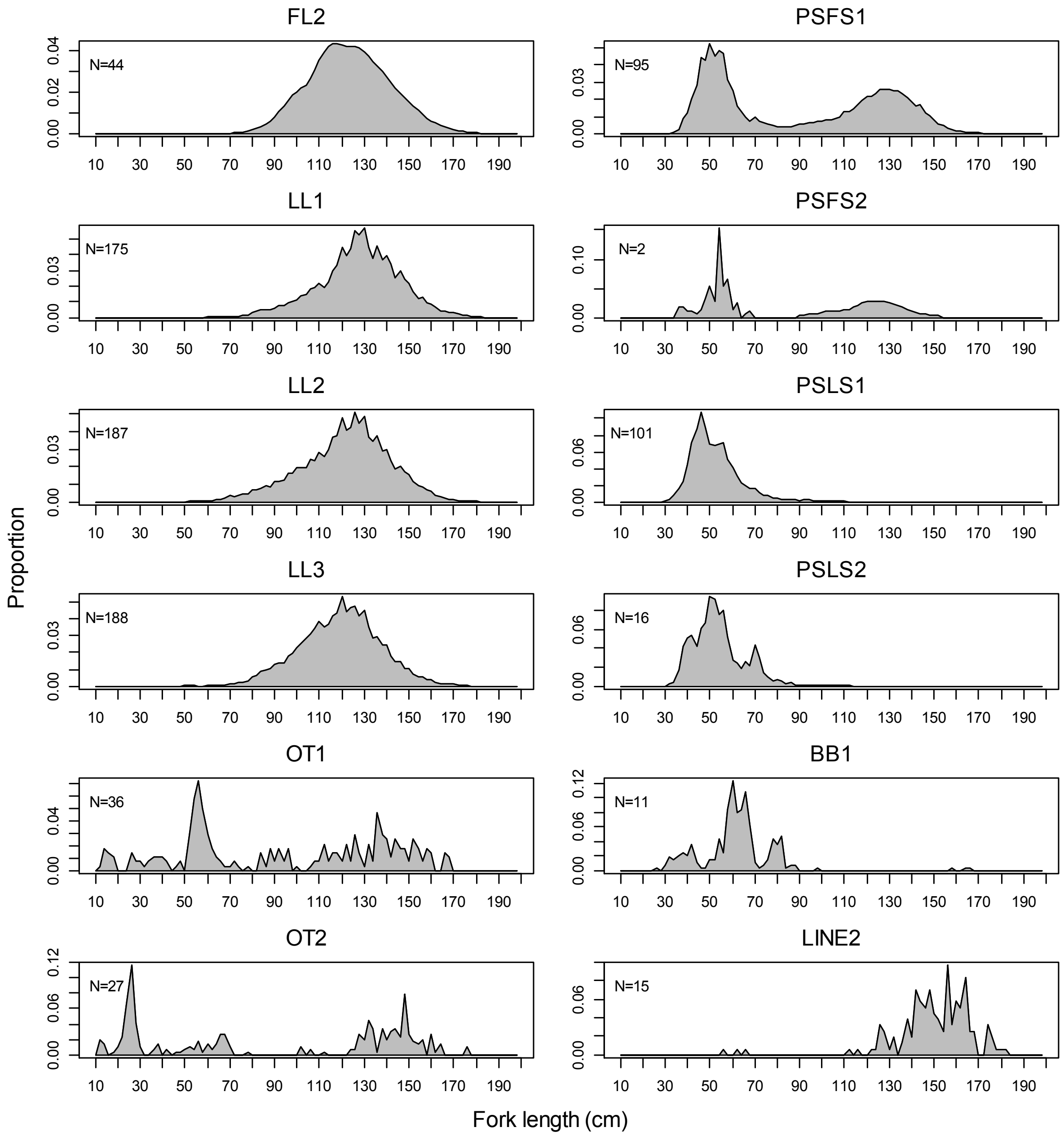

Figure 5. Length compositions of bigeye tuna samples aggregated by fishery. N represents the number of quarterly samples.

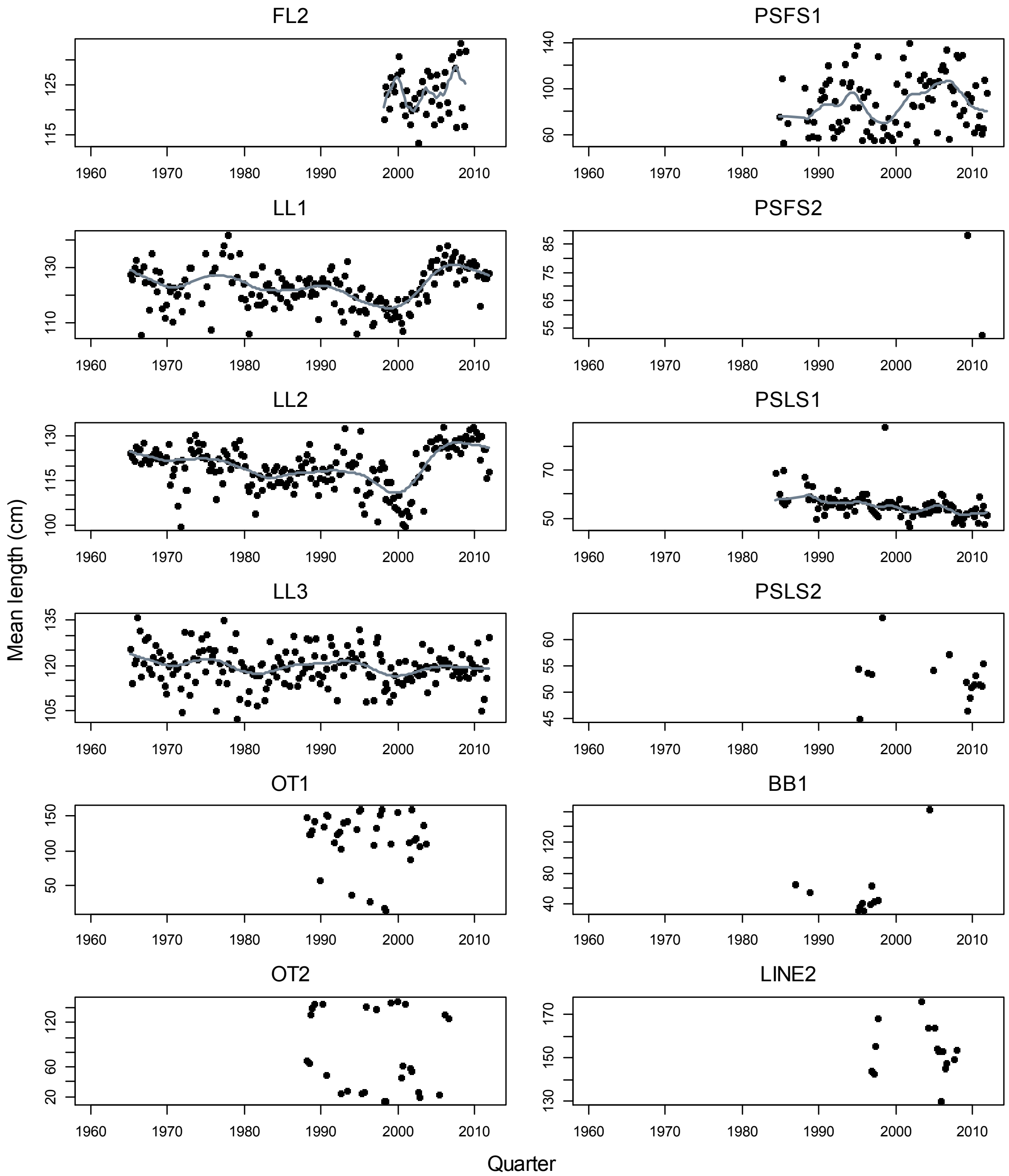

Figure 6. The average length (fork length, cm) of bigeye in the individual samples from each fishery. The grey line represents a lowess smoothed trend. The y-axis differs among the individual plots.

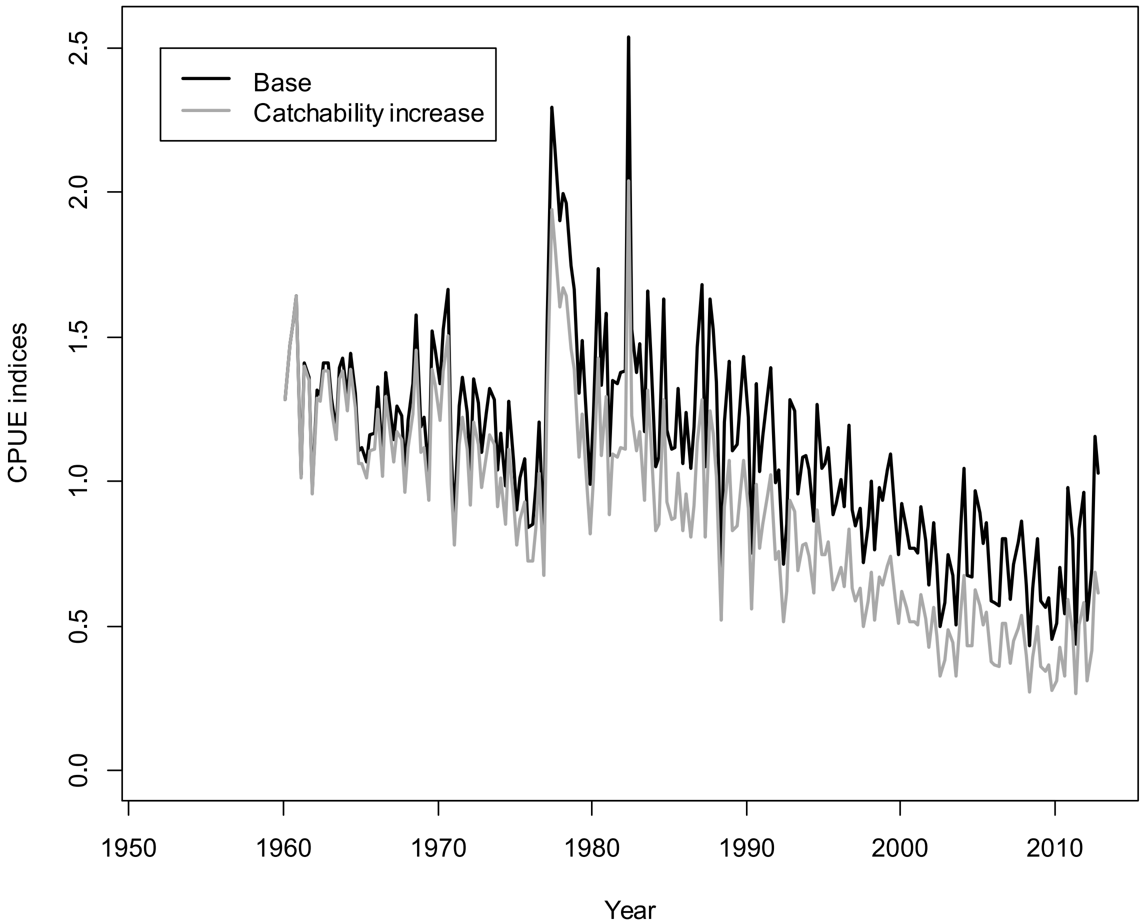

Figure 7. Standardised quarterly longline CPUE indices for the entire Indian Ocean and indices with an assumed increase in catchability (LLq1).

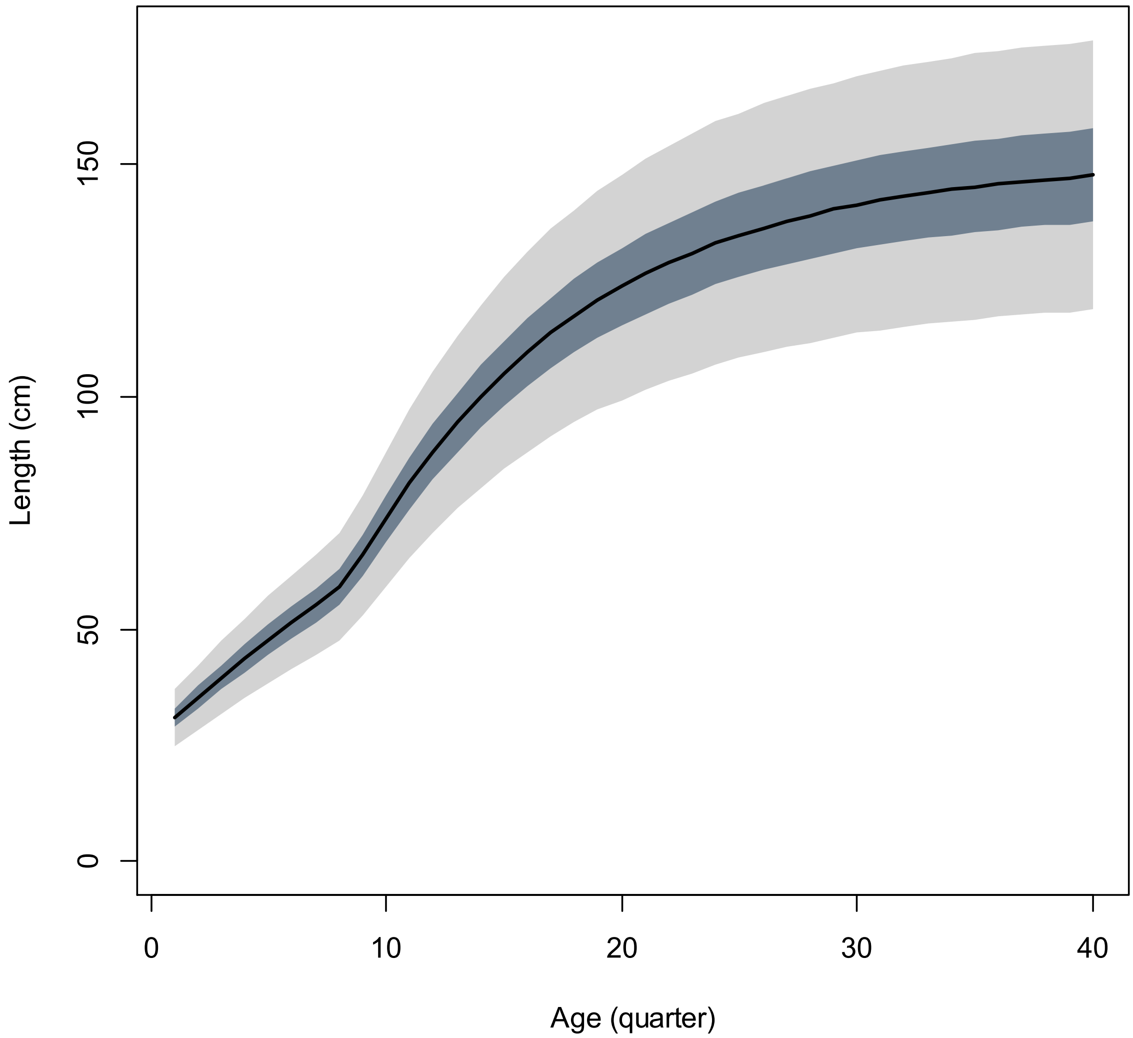

Figure 8. Growth of Indian Ocean bigeye tuna (following Everson et al 2012). The dark grey region represents the quartile range of the distribution of length-at-age and the light grey region represents the 95% confidence interval.

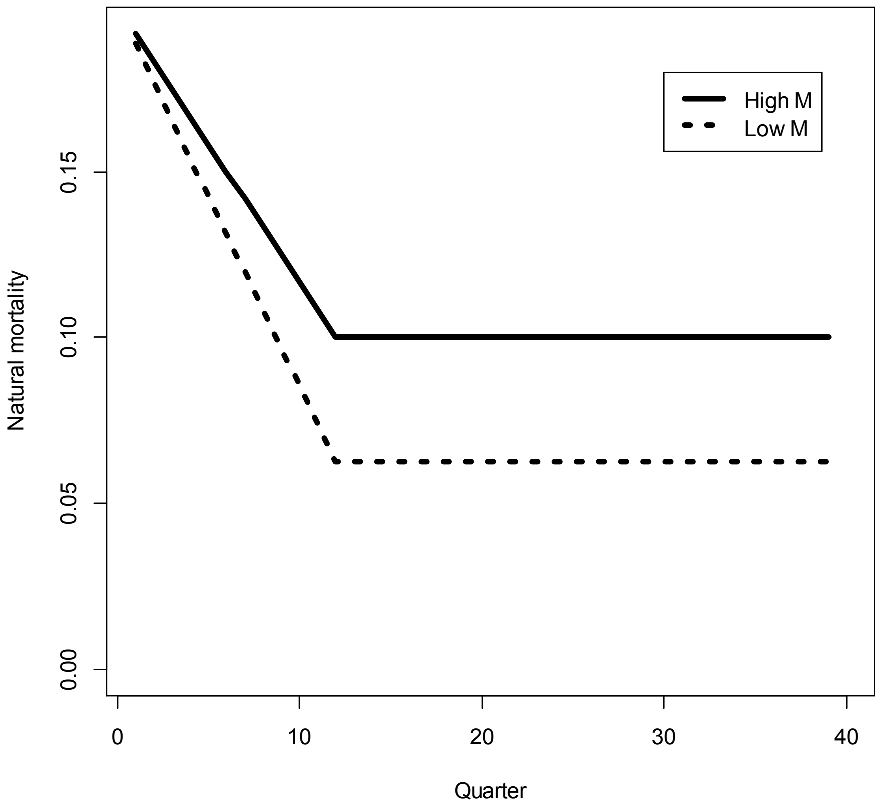

Figure 9. Age specific natural mortality (per quarter) patterns assumed for the highM and lowM assessment model options.

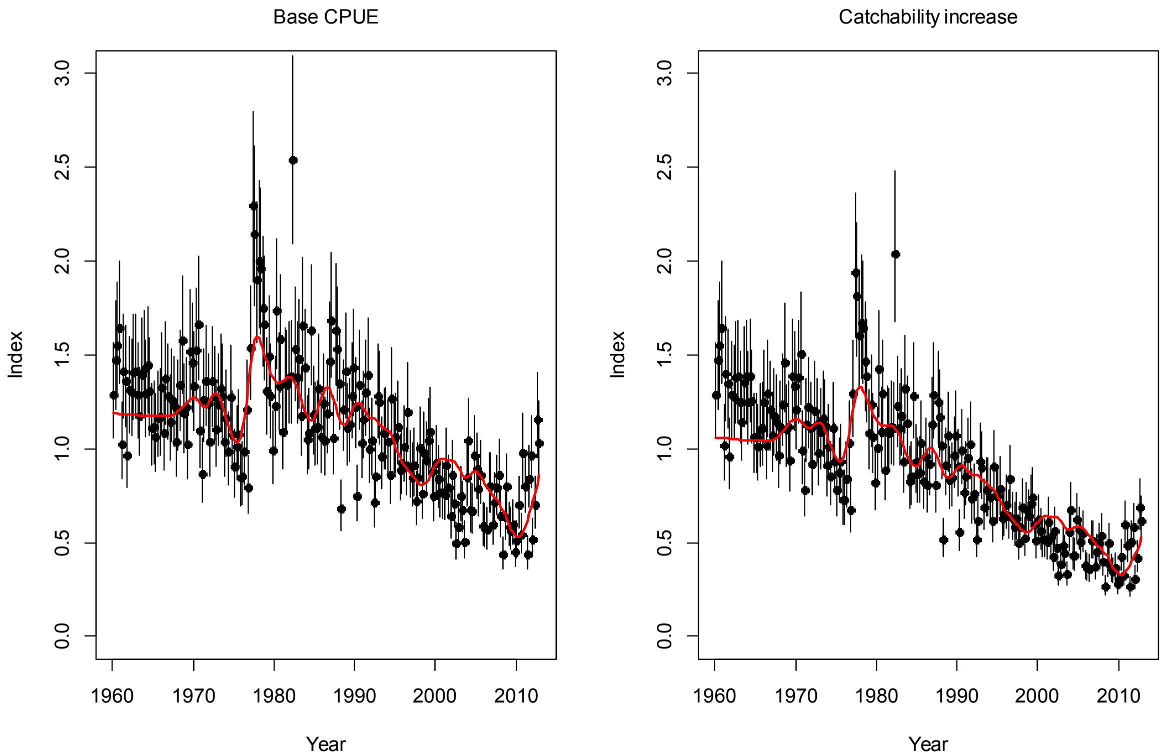

Figure 10. The fit to the IO wide CPUE indices from model options with the base CPUE indices (left) and CPUE indices including an assumed increase in catchability.

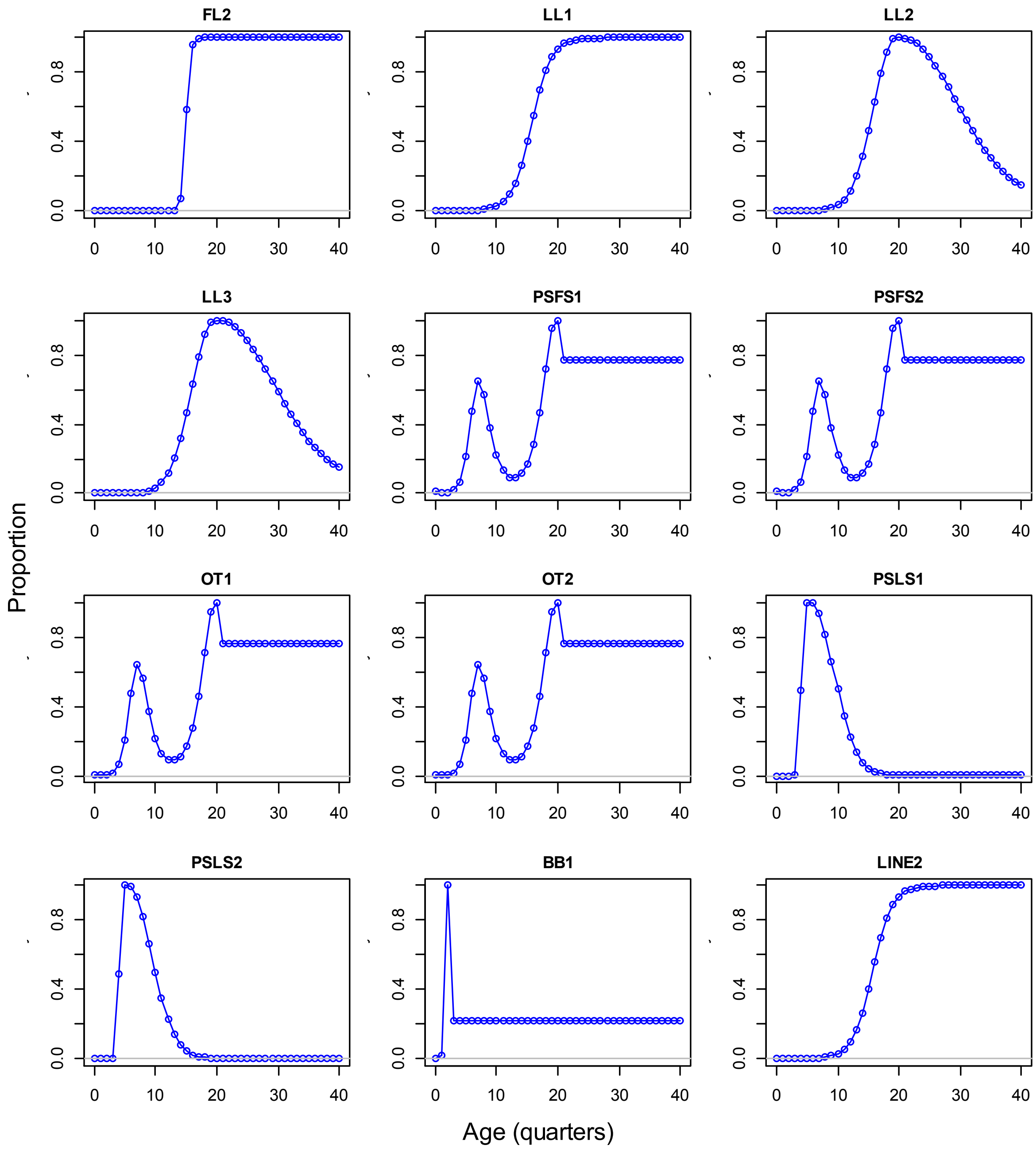

Figure 11. Selectivity for the individual fisheries for the reference model (high M and base longline CPUE).

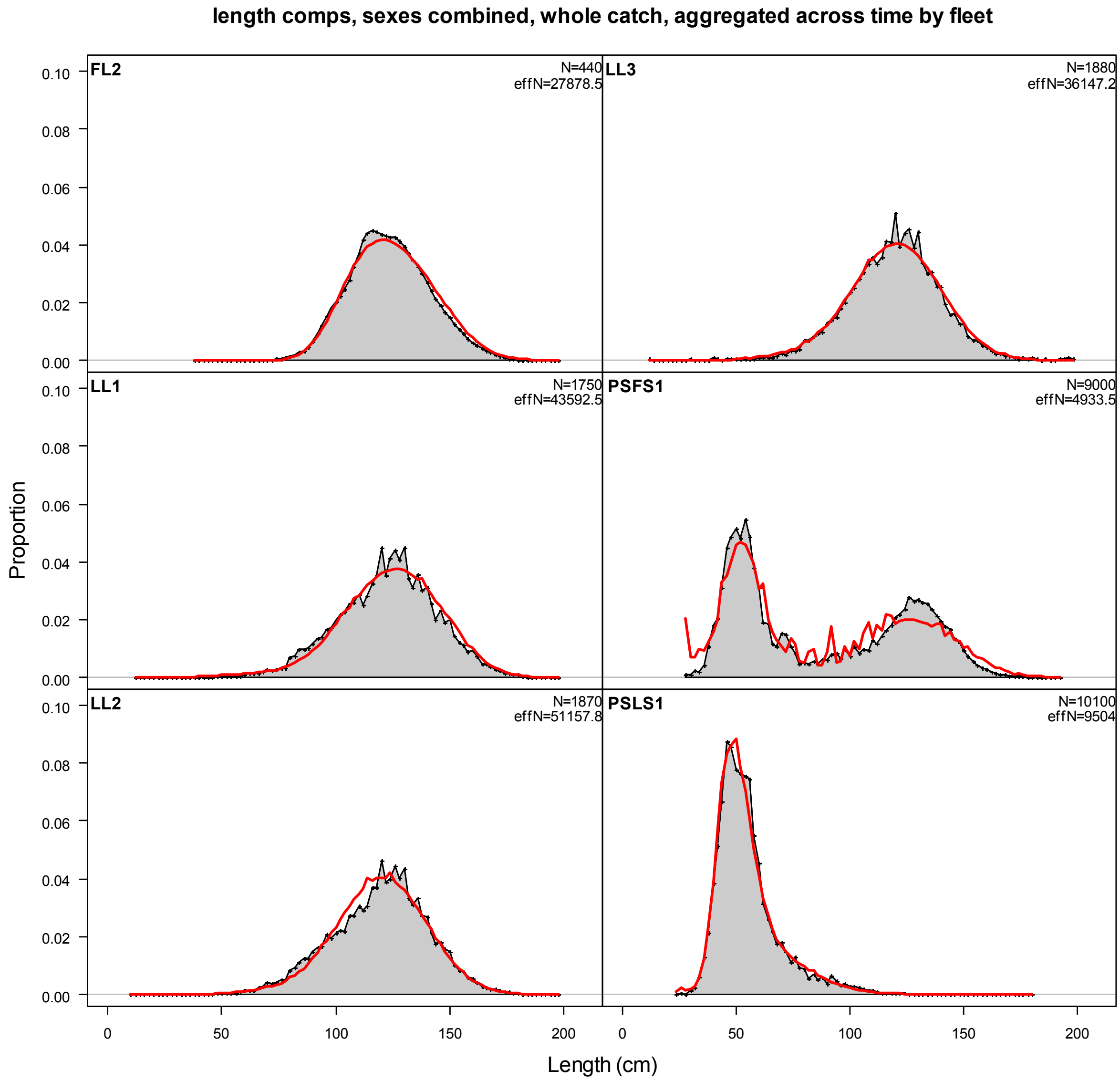

Figure 12. The observed (grey polygon) and predicted (red line) aggregated length compositions for the main fisheries with length frequency data from the reference model.

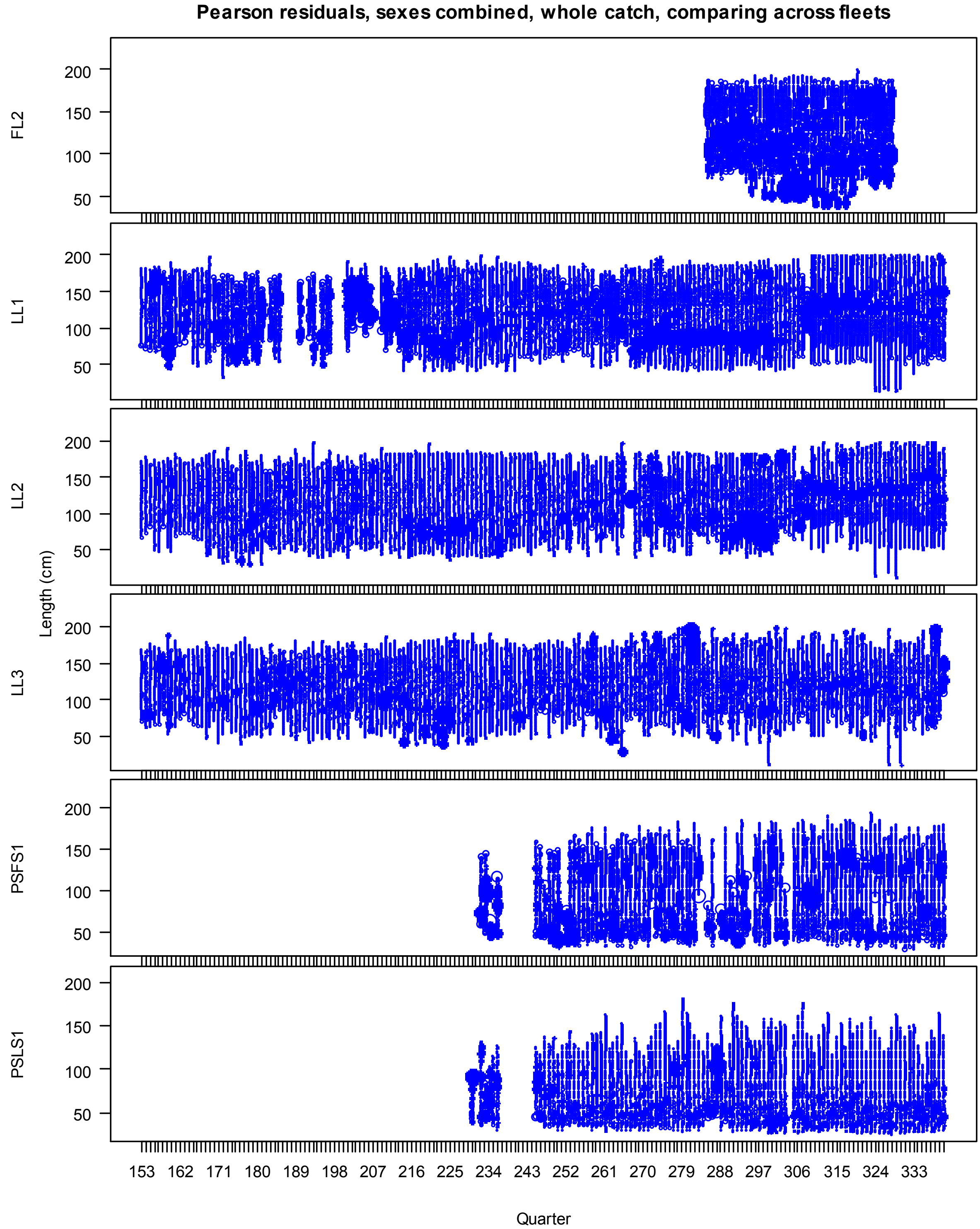

Figure 13. Residuals from the fit to the length data from the main fishery data sets from the reference model (high M, base CPUE) by quarter (quarter 153 = 1965 Q1).

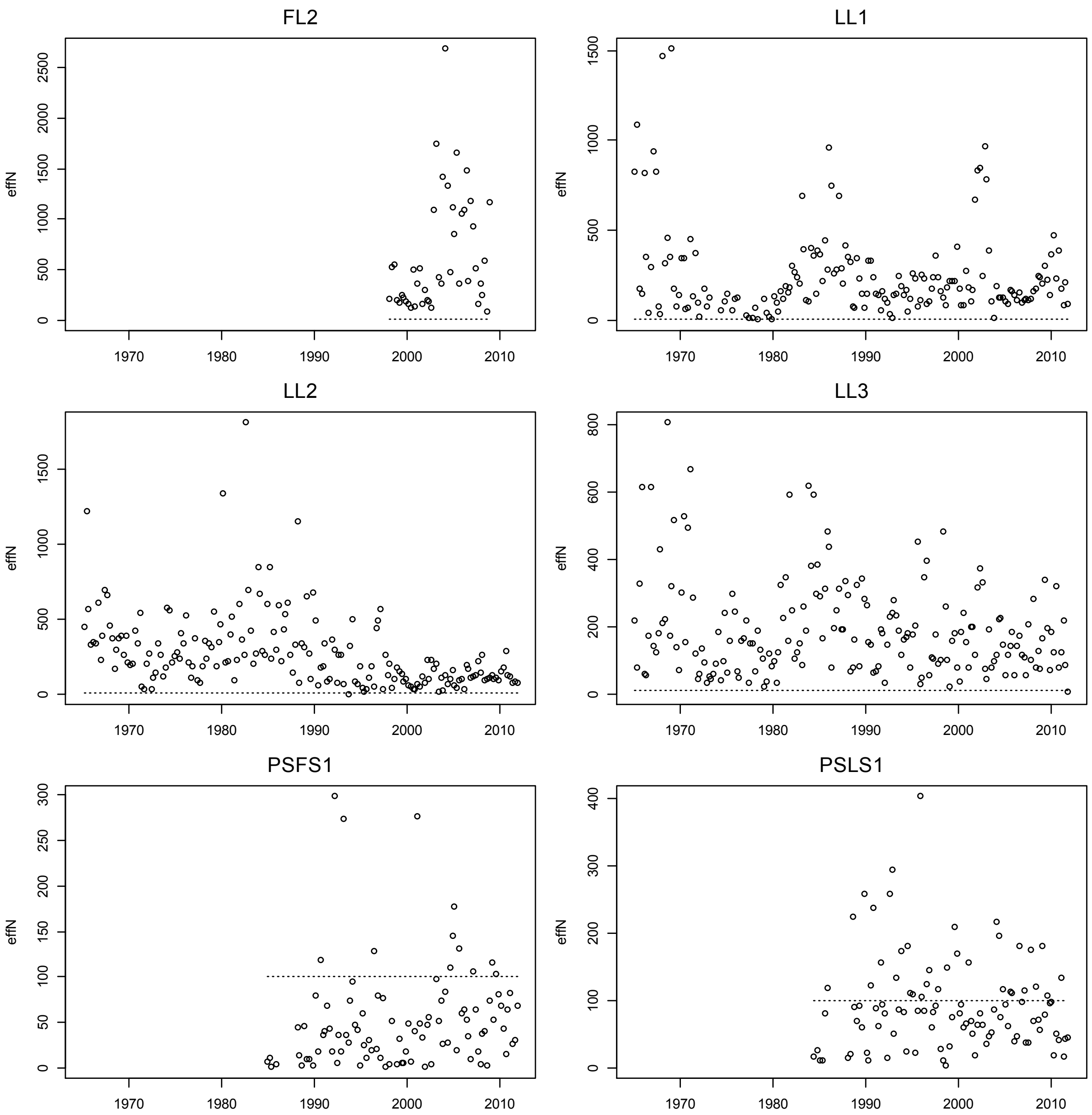

Figure 14. The estimated Effective Sample Size (effN) from the reference model (following McAllister and Ianelli 1997). The dashed line represents the ESS value applied to the fishery length data over the model period (LL ESS=10, PS ESS = 100).

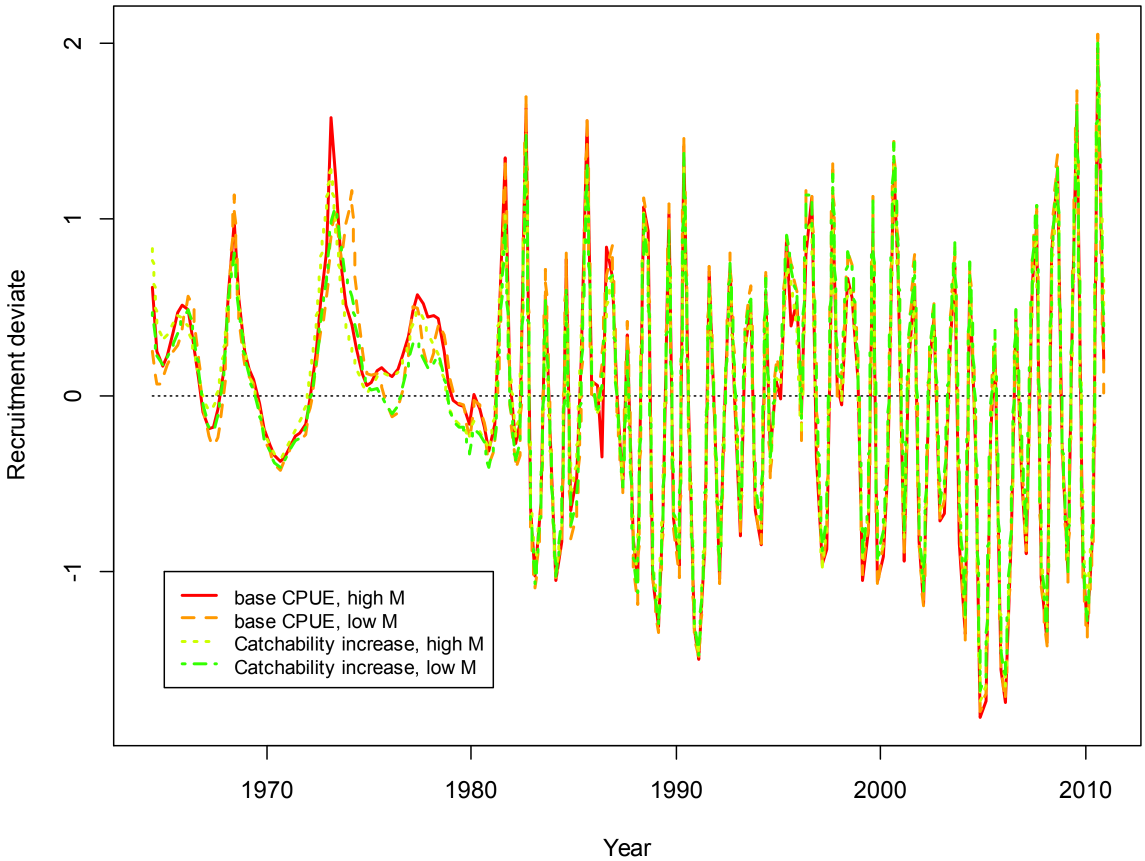

Figure 15. Quarterly recruitment deviates for the four main model options (steepness 0.8).

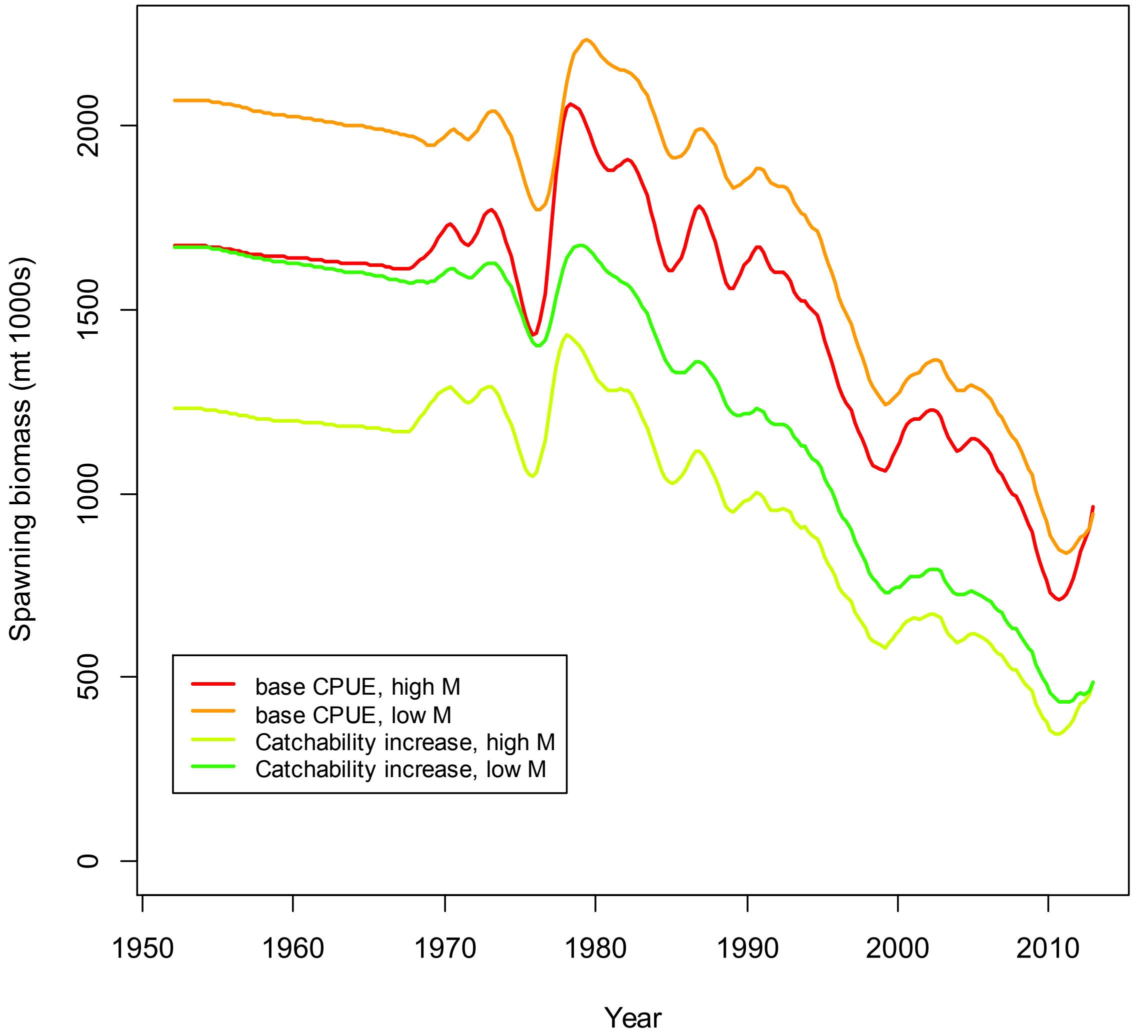

Figure 16. Spawning biomass (mature, female) trajectories for the four main model options (steepness = 0.8).

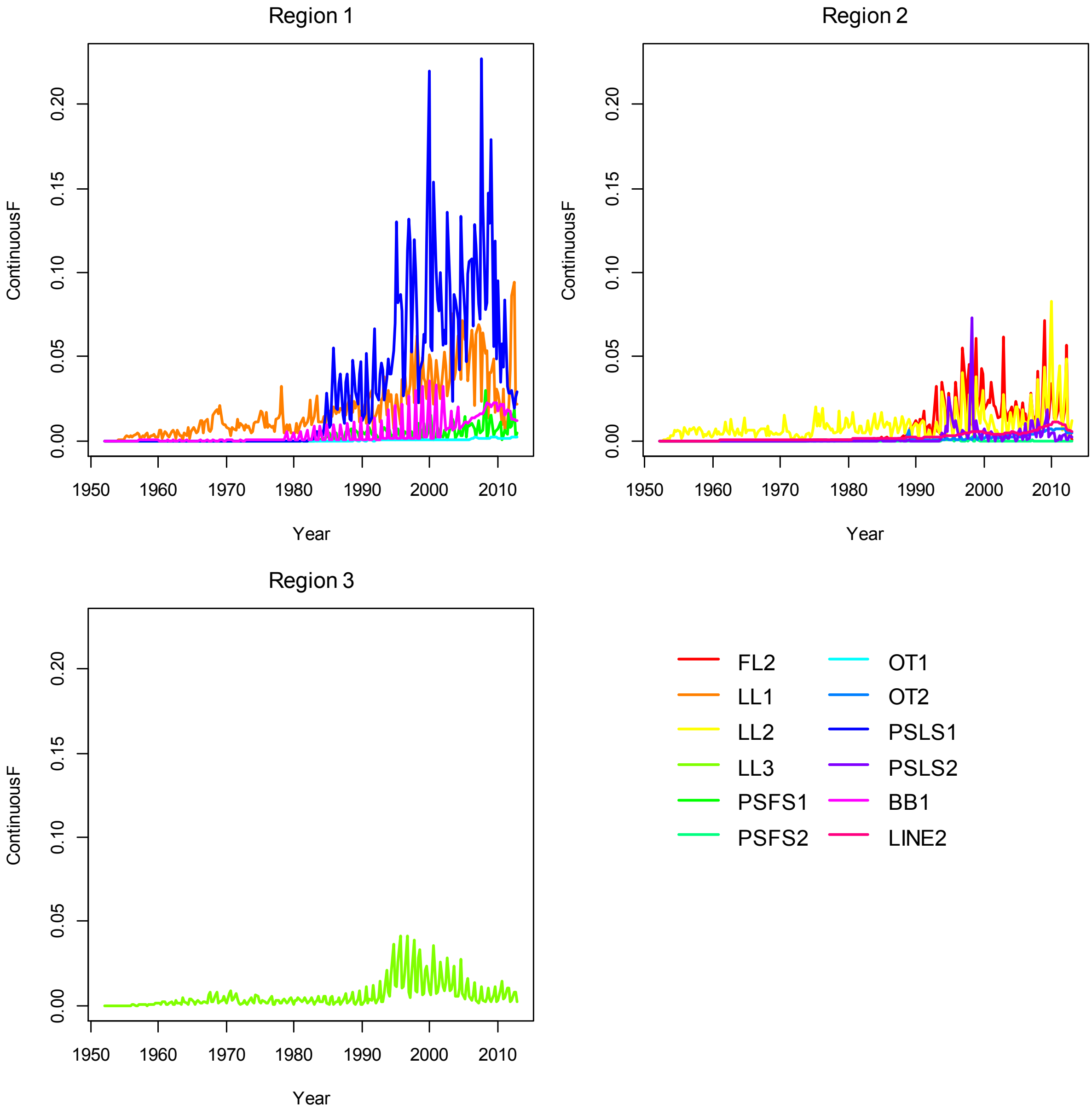

Figure 17. Estimates of fishery specific fishing mortality by fishery region from the reference model (high M, base CPUE).

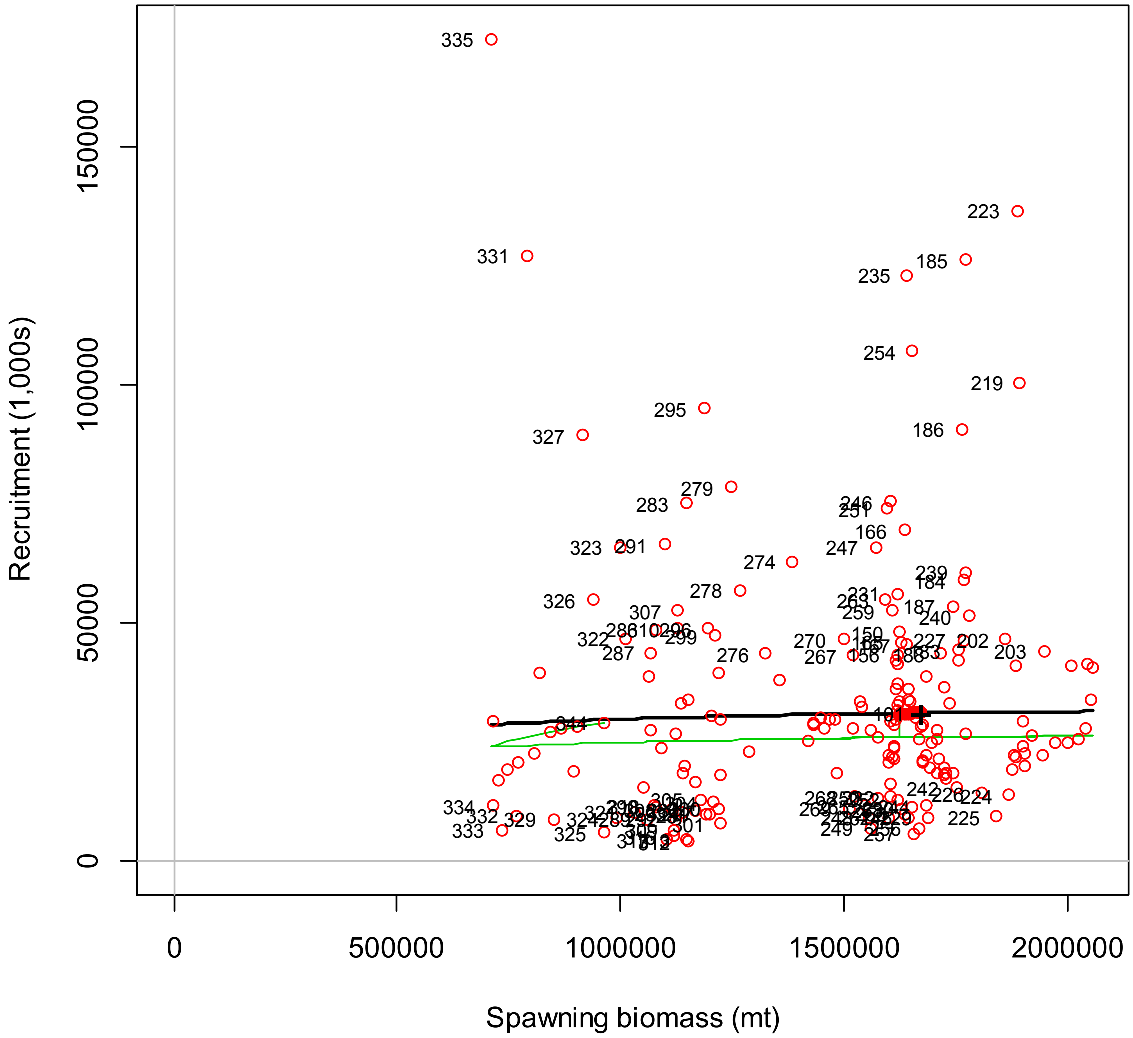

Figure 18. The relationship between spawning biomass and quarterly recruitment from the reference model (steepness of the SRR equal 0.80). The labels represent the quarters in the model period (quarter 101 represents 1952, first quarter).

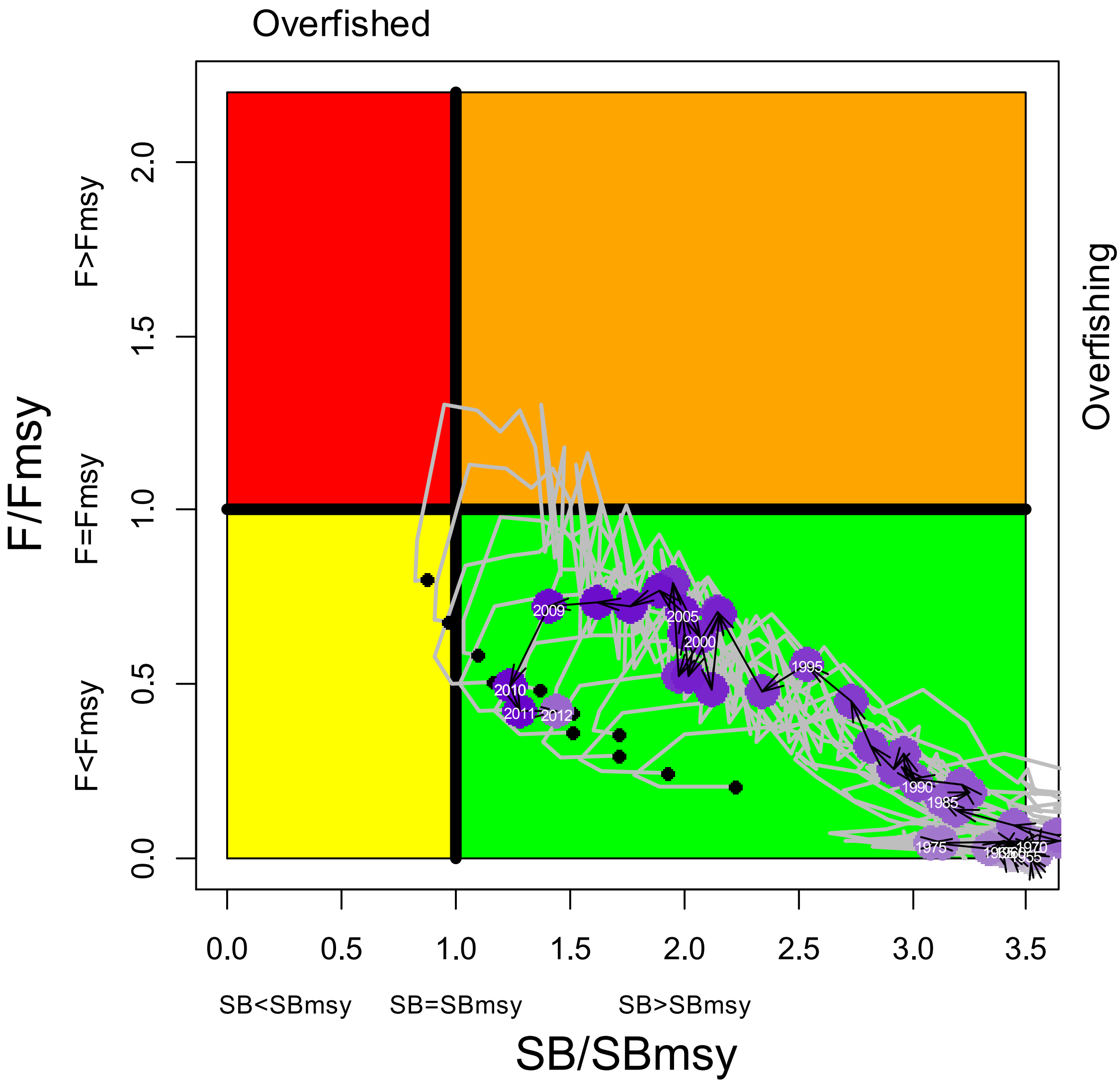

Figure 19. Kobe plot for the 12 alternative model options. The grey lines are the trajectories from the individual model options and the black points represent the terminal year (2012) of the individual models. The purple points represent the median of the individual model options.

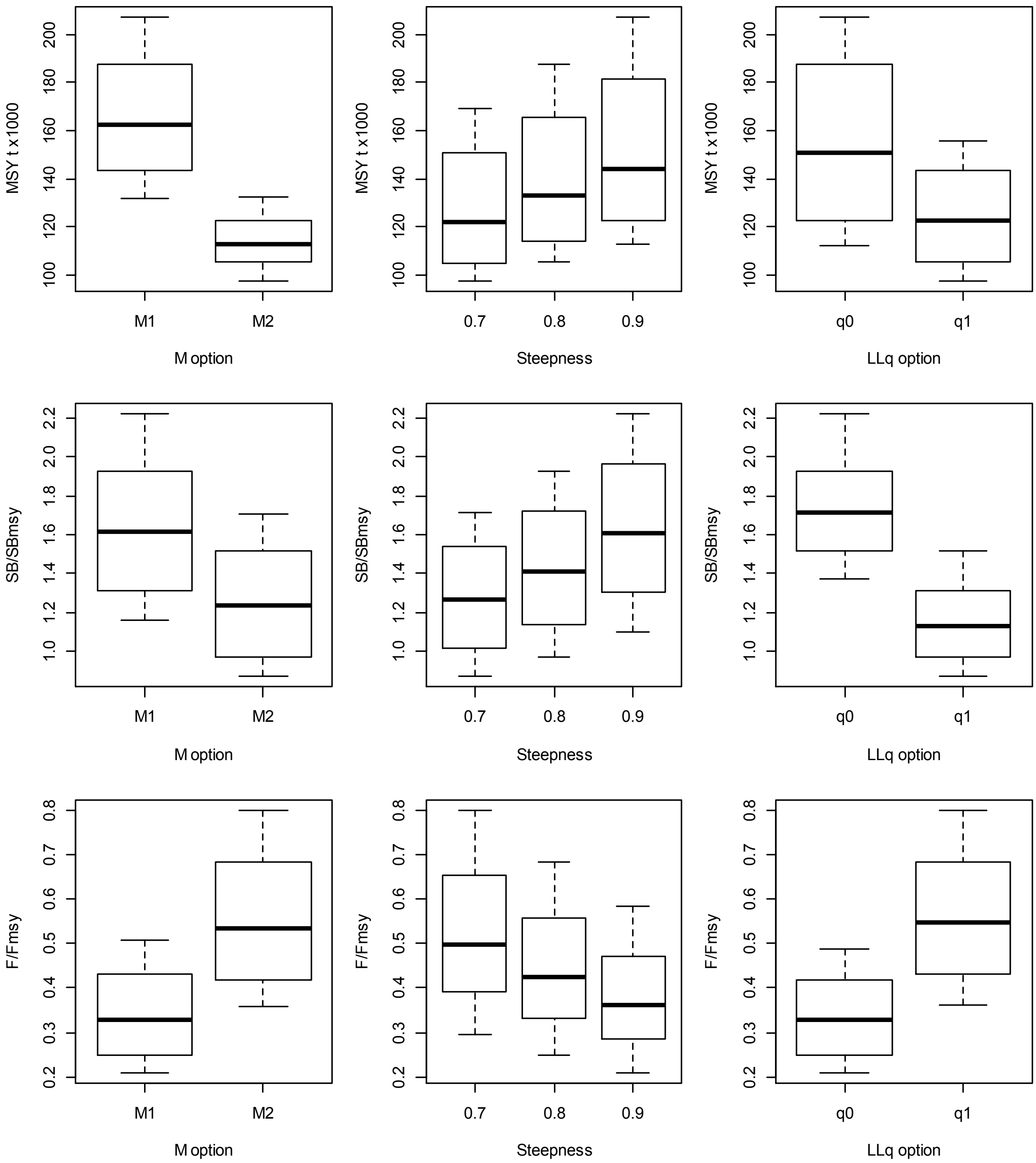

Figure 20. Boxplots of the main MSY based stock status indicators relative to the three model factors included in the grid of models (natural mortality, steepness and longline catchability).

Appendix 1. Annual catch (mt) of bigeye tuna, by fishery, included in the stock assessment model.

Year	Fishery												Total
	FL2	LL1	LL2	LL3	PSFS1	PSFS2	OT1	OT2	PSLS1	PSLS2	BB1	LINE2	
1952	0	0	272	8	0	0	3	32	0	0	0	7	322
1953	0	0	1,608	46	0	0	3	32	0	0	0	7	1,695
1954	0	600	6,186	65	0	0	3	40	0	0	0	7	6,900
1955	0	4,117	5,579	44	0	0	3	40	0	0	0	13	9,796
1956	0	5,713	6,979	154	0	0	4	42	0	0	0	13	12,905
1957	0	4,155	7,601	236	0	0	4	40	0	0	68	109	12,213
1958	0	5,369	5,932	354	0	0	4	40	0	0	68	118	11,885
1959	0	4,587	4,169	1,112	0	0	4	40	0	0	68	126	10,107
1960	0	8,023	6,292	1,800	0	0	4	40	0	0	34	162	16,356
1961	0	6,388	7,209	1,355	0	0	4	43	0	0	52	198	15,247
1962	0	7,478	9,269	1,735	0	0	4	53	0	0	51	294	18,886
1963	0	4,493	5,948	2,863	0	0	5	54	0	0	51	392	13,806
1964	0	7,112	7,917	3,022	0	0	5	55	0	0	51	379	18,541
1965	0	9,552	7,744	2,293	0	0	5	58	0	0	34	366	20,054
1966	0	15,851	6,142	2,183	0	0	5	67	0	0	51	244	24,543
1967	0	12,456	7,095	5,236	0	0	6	68	0	0	58	267	25,188
1968	0	27,480	6,643	5,639	0	0	7	68	0	0	58	304	40,200
1969	0	21,252	5,015	4,306	0	0	8	71	0	0	62	338	31,052
1970	0	11,048	10,290	6,684	0	0	10	62	0	0	81	285	28,460
1971	0	14,156	3,894	5,146	0	0	11	60	0	0	51	235	23,553
1972	0	14,713	3,470	2,001	0	0	12	75	0	0	58	377	20,706
1973	29	11,415	2,814	3,336	0	0	14	86	0	0	130	463	18,287
1974	239	18,847	5,012	4,441	0	0	15	98	0	0	124	436	29,213
1975	428	21,723	13,725	2,117	0	0	13	142	0	0	100	386	38,635
1976	310	12,944	12,477	3,026	0	0	13	159	0	0	142	615	29,685
1977	319	23,146	9,966	2,818	0	0	14	187	0	0	160	611	37,221

1978	438	32,090	14,123	4,160	0	1	15	326	0	4	920	1,624	53,701
1979	420	12,797	15,742	4,581	0	0	15	311	0	1	898	1,546	36,311
1980	528	14,280	15,790	4,431	5	2	16	346	9	6	956	1,737	38,105
1981	459	21,358	9,461	3,666	4	0	24	386	21	1	1,180	1,944	38,505
1982	815	29,518	9,538	3,598	44	5	47	552	189	17	1,373	2,549	48,244
1983	1,939	31,038	12,372	4,258	272	2	57	538	1,624	7	1,431	2,452	55,990
1984	2,359	20,033	13,210	4,349	2,097	9	69	544	4,628	43	1,647	2,314	51,300
1985	2,403	27,403	11,799	3,306	2,664	1	77	583	6,628	3	1,648	2,427	58,941
1986	725	30,892	11,802	3,259	2,770	0	90	565	7,439	0	1,504	2,342	61,386
1987	2,417	30,823	12,592	5,428	4,566	12	115	656	8,529	45	1,639	2,379	69,200
1988	5,128	35,641	11,210	5,074	6,938	6	129	2,587	9,187	21	1,920	2,749	80,590
1989	13,890	29,065	9,549	4,131	4,014	0	146	1,067	10,156	0	2,066	2,951	77,034
1990	16,318	28,869	10,188	5,132	5,947	0	182	887	7,793	0	1,664	2,575	79,554
1991	16,192	30,954	6,731	7,087	5,274	0	209	746	10,351	2	2,098	2,954	82,599
1992	21,609	28,477	5,049	6,626	2,227	0	179	657	9,037	0	1,859	2,884	78,604
1993	19,960	41,636	13,693	10,942	6,993	89	190	931	8,685	256	2,687	3,833	109,893
1994	27,348	28,285	14,080	20,372	4,135	575	190	1,042	11,698	2,475	2,908	4,134	117,241
1995	22,603	31,966	12,493	22,491	4,013	777	250	1,199	20,952	2,641	2,918	4,396	126,699
1996	30,757	38,614	14,574	18,432	3,499	289	209	1,243	19,701	1,040	3,447	4,877	136,682
1997	37,854	47,089	13,072	15,059	2,294	144	248	1,322	30,381	1,148	3,474	5,295	157,378
1998	33,330	49,214	14,437	15,540	5,053	1,299	217	1,955	14,266	7,714	4,040	5,844	152,910
1999	37,099	40,622	18,131	13,254	5,453	171	229	1,986	33,915	1,119	4,584	5,993	162,556
2000	27,772	44,143	9,559	17,222	5,689	2	234	2,515	23,152	1,015	3,993	5,128	140,422
2001	29,170	42,142	9,024	14,897	4,477	17	218	2,457	18,516	748	4,261	4,796	130,723
2002	35,967	49,072	9,759	14,981	4,434	15	356	2,270	24,614	509	4,046	4,486	150,509
2003	19,431	63,230	9,963	12,010	7,915	0	387	2,382	15,315	603	4,103	5,037	140,377
2004	22,366	65,365	13,692	11,565	4,097	0	382	2,753	18,771	524	4,519	5,595	149,629
2005	19,637	57,716	9,407	8,740	8,484	0	716	2,382	16,772	785	4,119	4,735	133,493
2006	18,788	55,027	12,435	5,470	6,405	1	1,584	2,997	17,490	1,032	4,822	5,372	131,422
2007	22,451	55,685	14,503	3,982	5,628	44	789	3,414	16,950	1,154	5,274	5,898	135,772
2008	23,323	36,778	11,094	3,720	9,646	0	975	4,147	18,870	1,007	6,731	7,323	123,611

2009	15,810	27,305	21,180	3,068	5,284	18	1,552	4,742	22,671	2,038	6,770	7,231	117,667
2010	12,759	15,505	12,811	3,936	3,792	0	868	4,500	17,824	662	6,782	7,796	87,235
2011	14,667	16,125	15,493	4,176	6,222	0	880	5,105	15,418	969	6,963	7,692	93,709
2012	15,774	49,039	12,428	4,187	7,180	0	2,013	3,938	9,892	543	5,217	5,583	115,794