Stock assessment of yellowfin tuna in the Indian Ocean using MULTIFAN-CL.

IOTC-2011-WPTT13 Meeting Report

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1 Introduction

This paper presents the stock assessment of yellowfin tuna (*Thunnus albacares*) in the Indian Ocean (IO) using the MULTIFAN-CL software (Fournier et al. 1998; Hampton and Fournier 2001; Kleiber et al. 2003; http://www.multifan-cl.org) which implements a size-based, age- and spatially-structured population model. Parameters of the model are estimated by maximizing an objective function consisting both of likelihood (data) and prior information components.

MULTIFAN-CL is routinely used to conduct the stock assessment of tuna stocks of the western and central Pacific Ocean, including yellowfin tuna (e.g., Langley et al. 2011). For the Indian Ocean, stock assessments of yellowfin tuna conducted before 2008 had used more traditional methods such as VPA and production models (Nishida & Shono 2005 & 2007). MULTIFAN-CL has the functionality to integrate data from tag release/recovery programmes and, thereby, utilise the information collected from the large-scale tagging programme conducted in the Indian Ocean in recent years. For this reason, the IOTC Working Party on Tagging Data Analysis held in June–July 2008 recommended conducting an assessment of the IO yellowfin tuna stock using MULTIFAN-CL software (IOTC 2008a).

A preliminary stock assessment of IO yellowfin tuna using MULTIFAN-CL was conducted in 2008 (Langley et al. 2008). The assessment was reported to the IOTC 10th Working Party on Tropical Tunas (WPTT) and the assessment was refined during that meeting (IOTC 2008b). The assessment was subsequently updated in 2009 and 2010 (Langley *et al.* 2009 & 2010) and further refined during the corresponding IOTC WPTT meetings (IOTC 2009, 2010).

An update of the yellowfin tuna stock assessment was conducted in advance of the 13th WPTT meeting (Langley et al 2011). The preliminary analysis included the refinements in model structure and assumptions that were recommended and implemented during the 12th WPTT and a range of additional model sensitivities related to the spatial structure of the model and assumptions regarding the treatment of the tagging data (mixing phase).

Further model options were considered during the 13th WPTT and this report documents the final model options agreed by the WPTT. These model options formed the basis for the management advice from IOTC 13th WPTT (IOTC 2010).

2 Background

2.1 Biology

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

The tag recoveries of the RTTP-IO provide evidence of large movements of yellowfin tuna, thus supporting the assumption of a single stock for the Indian Ocean. Fisheries data indicate that medium sized yellowfin concentrate for feeding in the Arabian Sea, that dispersion not being yet reflected in the present set of tag recovery data.

Longline catch data indicates that yellowfin are distributed continuously throughout the entire tropical Indian Ocean, but some more detailed analysis of fisheries data suggests that the stock structure may be more complex. A study of stock structure using DNA was unable to detect whether there were subpopulations of yellowfin tuna in the Indian Ocean.

Spawning occurs mainly from December to March in the equatorial area (0-10°S), with the main spawning grounds west of 75°E. Secondary spawning grounds exist off Sri Lanka and the Mozambique

Channel and in the eastern Indian Ocean off Australia. Yellowfin size at first maturity has been estimated at around 100 cm, and recruitment occurs predominantly in July. Newly recruited fish are primarily caught by the purse seine fishery on floating objects and the pole-and-line fishery in the Maldives. Males are predominant in the catches of larger fish at sizes larger than 150 cm (this is also the case in other oceans).

Tag data of the RTTP-IO clearly support a two-stanza growth pattern for yellowfin but more work is needed to achieve an appropriate integration of otolith and tagging data and agree on a growth model to be used in the assessment of this stock.

There are no direct estimates of natural mortality (*M*) for yellowfin in the Indian Ocean. In previous IO stock assessments, estimates of *M* at length based on those from other oceans have been used. These were then converted to estimates of M at age using two growth curve models. This indicated a higher *M* on juvenile fish than for older fish.

Before the RTTP-IO, there was little information on yellowfin movement patterns in the Indian Ocean, and what information there was came from analysis of fishery data, which can produce biased results because of their uneven coverage. However, there is good evidence that medium sized yellowfin concentrate for feeding in the Arabian Sea. Feeding behaviour is largely opportunistic, with a variety of prey species being consumed, including large concentrations of crustacea that have occurred recently in the tropical areas and small mesopelagic fishes which are abundant in the Arabian Sea.

2.2 Fisheries

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

Prior to 1980, annual catches of yellowfin tuna remained below about 80,000 mt. Annual catches increased markedly during the 1980s and early 1990s, mainly due to the development of the purse-seine fishery as well as an expansion of the other established fisheries (fresh-tuna longline, gillnet, baitboat, handline and, to a lesser extent, troll). A peak in catches was recorded in 1993, with catches over 400,000 mt, the increase in catch almost fully attributable to longline fleets, in particular longliners flagged in Taiwan, which reported exceptional catch rates of yellowfin tuna in the Arabian Sea. Catches declined in 1994, to about 350,000 mt, remaining at those levels for the next decade then increasing sharply to reach a peak of about 500,000 mt in 2004/2005 driven by a large increase in catch by all fisheries, especially the purse-seine (free school) fishery. Total annual catches declined sharply from 2004 to 2007 and remained at about 300,000 mt during 2007-2010. The total catch in 2009-2010 were estimated to be 275,000-294,000 mt (Table 2), representing the lowest catch for the species since the early 1990s.

In recent years (2008–2010), purse seine and gillnet have been the dominant fishing method, harvesting 60% - 30% each - of the yellowfin tuna catch (by weight), with the longline, and handline fisheries comprising 17% and 8% of the total catch, respectively. A smaller component of the catch was taken by the regionally important baitboat (6%) and troll (6%) fisheries.

The purse-seine catch is generally distributed equally between free-school and associated (log and FAD sets) schools, although the large catches in 2003–2005 were dominated by fishing on free-schools. Conversely, in the last two years (2009–2010) the purse-seine catch has been dominated (65%) by the associated fishery.

Most of the yellowfin catch is taken from the western equatorial region of the IO (47%; region 2, see Figure 1) and, to a lesser extent, the Arabian Sea (21%), the eastern equatorial region (25%, region 5) and the Mozambique Channel (8%; region 3). The purse-seine and baitboat fisheries operate almost exclusively within the western equatorial region, while catches from the Arabian Sea are principally by handline, gillnet, and longline (Figure 2). Catches from the eastern equatorial region (region 5) were dominated by longline and gillnet (around Sri Lanka and Indonesia). The southern Indian Ocean (region 4) accounts for a small proportion of the total yellowfin catch (1%) taken exclusively by longline (Figure 2).

In recent years (2008-10), due to the threat of piracy, the bulk of the industrial purse seine and longline fleets have moved to the eastern waters of Region 2, or left the area altogether, to avoid the coastal and off-shore waters off Somalia, Kenya and Tanzania. This represents a significant change in the fishery as catches in the western side of Region 2 are usually important throughout the year. The effect of piracy is particularly important for freezing longline fleets, for which the levels of effort and catch in the western tropical Indian Ocean (Area 2) have been decreasing markedly since 2007. The total catches of freezing longliners estimated for 2010 amount to as little as 2,000 mt, or more than a 10-fold decrease with respect to the catches recorded before the onset of piracy in the area (2- and 3-fold decrease in 2008 and 2009, respectively). On the contrary, purse seine catches, though reduced, have remained more or less stable during 2008-2010, at around 75% of the average catch levels recorded in the area in years before the onset of piracy (2000-02).

3 Data compilation

The data used in the yellowfin tuna assessment consist of catch, effort, and length-frequency data for the fisheries defined in the analysis, and tag release-recapture data. The details of these data and their stratification are described below. More details relating to the compilation of these data are provided in Herrera & Pierre (2011).

3.1 Spatial stratification

The geographic area considered in the assessment is the Indian Ocean, defined by the coordinates 40°S–25°N, 20°E–150°E. Within this overall area, a five-region spatial stratification was adopted for the assessment (Figure 1). The rationale for this stratification was to separate the tropical area, where both surface and longline fisheries occur year-round, from the higher latitudes, where the longline fisheries occur more seasonally. The spatial stratification is also designed to minimise the spatial heterogeneity in the magnitude and trend in longline CPUE and the size composition of the longline catch.

3.2 Temporal stratification

The time period covered by the assessment is 1972–2010. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec).

Fishery data (catch, effort and size data) are available prior to 1972 and longline CPUE indices have been derived from 1960 onwards. However, there is a strong decline in the CPUE indices during the early period (1960–1971). At the 10th WPTT, it was agreed that the decline in the CPUE indices was unlikely to be solely due to changes in stock abundance. On that basis, the early data were excluded from the assessment and the model initiated in 1972. From the mid 1950s to 1972, annual catches were about 50,000 t principally caught by the longline method.

3.3 Definition of fisheries

MULTIFAN-CL requires the definition of “fisheries” that consist of relatively homogeneous fishing units. Ideally, the fisheries so defined will have selectivity and catchability characteristics that do not vary greatly over time (although in the case of catchability, some allowance can be made for time-series variation). Twenty-five fisheries have been defined for this analysis on the basis of region, time period, gear type, and, set type in the case of purse seine, or type of vessel in the case of longline fleet (Table 1).

For the purposes of the present assessment, the longline fishery was broken into two separate components:

Freezing longline fisheries, or all those using drifting longlines for which one or more of the following three conditions apply: (i) the vessel hull is made up of steel; (ii) vessel length overall of 30m or greater; (iii) the majority of the catches of target species are preserved frozen or deep-frozen. A composite longline fishery was defined in each region (LL 1–5) aggregating the longline catch from all freezing longline fleets (principally Japan and Taiwan).

Fresh-tuna longline fisheries, or all those using drifting longlines and made of vessels (i) having fibreglass, FRP, or wooden hull; (ii) having length overall less than 30m; (iii) preserving the catches of target species fresh or in refrigerated seawater. A composite longline fishery was defined aggregating the longline catch from all fresh-tuna longline fleets (principally Indonesia and Taiwan) in region 5 (LF 5), which is where the majority of the fresh-tuna longliners have traditionally operated. The catches of yellowfin tuna recorded in regions 1 to 4 for fresh-tuna longliners, representing only a 3% of the total catches over the time series, were assigned to area 5.

The main reasons for segregating the two fisheries was to reduce potentially sources of bias in the LL 5 CPUE index due to concern over the reliability of the estimates of average fish size (and hence estimates of catch expressed in numbers of fish) for the fresh tuna component and differences in the length composition of the catch between the two sectors. The sources of bias could be significant given the large increase in the relative scale of the fresh tuna fishery over the last two decades.

The purse-seine catch and effort data were apportioned into two separate method fisheries: catches from sets on associated schools of tuna (log and drifting FAD sets; PS LS) and from sets on unassociated schools (free schools; PS FS). Purse-seine fisheries operate within regions 1, 2, 3 and 5 and separate purse-seine fisheries were defined in regions 2, 3 and 5, with the limited catches, effort and length frequency data from region 1 reassigned to region 2.

The region 2 purse-seine fisheries (log and free-school) were divided into three time periods: pre 2003, 2003-2006 and post 2006. This change was implemented due to the apparent change in the length composition of the catch from the purse-seine fisheries during the 2000s. The length of fish caught by the FAD fishery was generally smaller from 2007 onwards, while a higher proportion of smaller fish were caught by the free-school fishery prior to 2003. Separate selectivity functions were estimated for each fishery/time period.

A single baitboat fishery was defined within region 2 (essentially the Maldives fishery). As with the purse-seine fishery, a small proportion of the total baitboat catch and effort occurs on the periphery of region 2, within regions 1 and 5. The additional catch and effort was assigned to the region 2 fishery.

Gillnet fisheries were defined in the Arabian Sea (region 1), including catches by Iran, Pakistan, and Oman, and in region 5 (Sri Lanka and Indonesia). A very small proportion of the total gillnet catch and effort occurs in region 2, with catches and effort reassigned to area 1.

Three troll fisheries were defined, representing separate fisheries in regions 2 (Maldives), 3 (Comoros and Madagascar) and 5 (Sri Lanka and Indonesia). Moderate troll catches are also taken in regions 1 and 4, the catch and effort from this component of the fishery reassigned to the fisheries within region 2 and 5, respectively.

A handline fishery was defined within region 1, principally representing catches by the Yemenese fleet. Moderate handline catches are also taken in regions 2, 3 and 5, the catch and effort from these components of the fishery were reassigned to the fishery within region 1.

For regions 1 and 5, a miscellaneous (“Other”) fishery was defined comprising catches from artisanal fisheries other than those specified above (e.g. trawlers, small purse seines or seine nets, sport fishing and a range of small gears).

3.4 Catch and effort data

Catch and effort data were compiled according to the fisheries defined above. The catches for longline fisheries were expressed in numbers of fish while the catches for other fisheries were expressed in tonnes (Figure 3).

Limited effort data were available for the fresh-tuna longline (LF 5), handline (HD 1), gillnet (GN 1 and 5), other (OT 1 and 5) and the troll (TR 3 and 5) fisheries and, for records with no effort, effort was set to “missing”. A low penalty weight was specified for effort and (temporal) catchability deviations to minimise the influence of these effort data on the model results.

Effort data units for the two purse seine fisheries are defined as the total days fishing and/or searching by the purse-seine fleet; i.e., the effort data has not been allocated between the two set types and essentially the equivalent effort series is used for the two fisheries. Effort data for the handline, baitboat, gillnet, and troll fisheries were defined as number of fishing trips.

For the 2011 assessment, there were changes to the catch history for the TR 5 and OT 5 fisheries resulting from major revisions of the Indian and Indonesia catch by fishing gear.

The time-series of catch-per-unit-effort (CPUE) for all fisheries are shown in Figure 7. For the longline fisheries (LL 1–5), effective (or standardised) effort was derived using generalized linear models (GLM) from the Japanese longline fleet (2–5) (Okamoto 2011) and for the Taiwanese longline fleet in region 1 (Yeh Y.M. & Chang S.T. 2011) (Figure 8). Standardised longline CPUE indices for the Taiwanese fleet were available for 1979–2008. The GLM analysis used to standardise the Japanese longline CPUE indices was refined for the

2011 assessment to include a spatial (latitude*longitude) variable (Okamoto 2011). The resulting CPUE indices were generally comparable to the indices derived from the previous model and were adopted as the principal CPUE indices for the 2011 assessment.

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

The approach used was to determine regional scaling factors that incorporated both the size of the region and the relative catch rate to estimate the relative level of exploitable longline biomass among regions. This approach is similar to that used in the WCPO regionally disaggregated tuna assessments. The scaling factors were derived from the Japanese longline CPUE data from 1960–75, essentially summing the average CPUE in each of the 5*5 lat/longitude cells within a region. The relative scaling factors thus calculated for regions 1–5 are 0.21, 1.00, 0.55, 0.15, and 0.85, respectively.

For each of the principal longline fisheries, the GLM standardised CPUE index was normalised to the mean of the GLM index from 1960–75 — the equivalent period for which the region scaling factors were derived. The normalised GLM index was then scaled by the respective regional scaling factor to account for the regional differences in the relative level of exploitable longline biomass between regions. Standardised effort was calculated by dividing the quarterly catch by the quarterly (scaled) CPUE index (Figure 8).

Within the model, effort for each fishery was normalised to an average of 1.0 to assist numerical stability. The principal longline fisheries were grouped to share common catchability parameters in the various analyses. For such grouped fisheries, the normalisation occurred over the group rather than for the individual fisheries so as to preserve the relative levels of effort among the fisheries.

3.5 Length-frequency data

Available length-frequency data for each of the defined fisheries were compiled into 95 2-cm size classes (10–12 cm to 198–200 cm). Each length frequency observation for purse seine fisheries represents the number of fish sampled raised to the sampling units (sets in the fish compartment) while for fisheries other than purse seine each observation consisted of the actual number of yellowfin tuna measured. A graphical representation of the availability of length samples is provided in Figure 9. The data were collected from a variety of sampling programmes, which can be summarized as follows:

Purse seine: Length-frequency samples from purse seiners have been collected from a variety of port sampling programmes since the mid-1980s. The samples are comprised of very large numbers of individual fish measurements.

Longline freezing: Length and weight data were collected from sampling aboard Japanese commercial, research and training vessels. Weight frequency data collected from the fleet have been converted to length frequency data via a processed weight-whole weight conversion factor and a weight-length key. Length frequency data from the Taiwanese longline fleet are also available from 1980–2010. Overall, the average length of yellowfin caught by the longline fleet is comparable among the five regions and there are no strong temporal trends in the length of fish caught, with the exception of a shift to significantly smaller fish in most regions during the 1990s (Figure 10). In recent years, length data are also available from other fleets and periods (e.g. Seychelles).

Longline fresh: Length data are available from 1998, with no length data available at all for the period 1973-1997. Length and weight data were collected in port, during unloading of catches, for several landing locations and time periods, especially on fresh-tuna longline vessels flagged in Indonesia and Taiwan/China (IOTC-OFCF sampling). In addition, in 2011 Taiwan-China provided for the first time length frequency data for its fresh-tuna longline fleet, including individual lengths by time-period and area for the year 2010.

Gillnet: Length data are available from both GN 1 and 5 fisheries.

Baitboat: Size data are available from the fishery from 1983 to 2009.

Troll: No size data are available from the TR 2 and 3fisheries. The troll fishery in region 5 was sampled during two periods: 1985–1990 (Indonesian fishery) and 1994–2004 (Sri Lankan fishery).

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

Other: Length samples are available from the “Other” fishery in region 5 (OT 5) fishery and limited data are available from the “Other” fishery in region 1 (OT 1) (2009 only).

Changes to the length frequency data sets from the 2010 assessment include the preparation of separate datasets for the fresh-tuna and freezing longline fisheries and adding or updating of datasets relating to recent years for most of the fisheries

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

3.6 Tagging data

A considerable amount of tagging data was available for incorporation into the MULTIFAN-CL analysis. The data used consisted of yellowfin tuna tag releases and returns from the Indian Ocean Tuna Tagging Programme (IOTTP), and mainly from its main phase, the Regional Tuna Tagging Project-Indian Ocean (RTTP-IO) conducted during 2005–2009. The IOTC has been compiling all the data from the RTTP-IO and the complementary small-scale programmes in a single database in order for all the tagging information to be incorporated into the different stock assessments. However, the data from the small-scale programme has not been fully analysed, and the number of yellowfin released, and especially recovered during these operations is limited in comparison to the RTTP-IO. Therefore, the integration in the model of these additional data is more difficult and the small-scale data was not included in the present assessment.

Most of the tag releases of the RTTP-IO occurred within the western equatorial region (region 2) and a high proportion of these releases occurred in the second and third quarters of 2006 (see IOTC 2008a for further details) (Figure 4). Limited tagging also occurred within regions 1 and 3. The model included all tag recoveries up to the end of 2010. The spatial distributions of tag releases and recoveries are presented in Figure 5 and Figure 6, respectively.

For incorporation into the MULTIFAN-CL analyses, tag releases were stratified by release region, time period of release (quarter) and the same length classes used to stratify the length-frequency data. A total of 54,393 releases were classified into 15 tag release groups in this way.

The returns from each size class of each tag release group were then classified by recapture fishery and recapture time period (quarter). The results of associated tag seeding experiments, conducted during 2005–2008, have revealed considerable temporal variability in tag reporting rates from the IO purse-seine fishery (Hillary *et al.* 2008). Reporting rates were lower in 2005 (57%) compared to 2006 and 2007 (89% and 94%). This large increase overtime was the result of the development of publicity campaign and tag recovery scheme raising the awareness of the stakeholders, *i.e.* stevedores and crew. MULTIFAN-CL assumes a constant fishery-specific reporting rate for each fishery (or fishery group). To account for the temporal change in reporting rate, the number of tag returns from the purse-seine fishery in each stratum (tag group, year/quarter, and length class) were corrected using the respective estimate of the annual reporting rate. A reporting rate of 94% was assumed for the correction of the 2008, 2009 and 2010 tag recoveries.

In total, 9,961 tag recoveries (corrected for reporting rate) could be assigned to the fisheries included in the model. Almost all of the tags released in region 2 were recovered in the home region, although some recoveries occurred in adjacent regions, particularly regions 1 and 3. A small number of tags were recovered in region 5 (from tags released in region 2) and there were no tags recovered from region 4 (Table 3).

A significant proportion (35%) of the tag returns from purse seiners were not accompanied by information concerning the set type and, consequently, these returns could not be linked to a specific purse seine fishery. To enable these tags to be incorporated within the model, it was necessary to aggregate the tag-return data across set types for the purse seine fisheries in each region. The population dynamics model was in turn configured to predict equivalent estimated tag recaptures by these grouped fisheries.

For the purse-seine fisheries, the tag dataset was corrected for reporting rates (as described above) and the reporting rates were essentially fixed at a value of 0.81 to account for initial tag retention rates (0.9) (Gaertner and Hallier 2008) and the proportion of the total purse-seine catch examined for tags (0.9). No information is available regarding tag reporting rates from the other (non purse-seine) fisheries some of which returned a substantial number of tags.

4 Model description – structural assumptions, parameterisation, and priors

The model can be considered to consist of several components, (i) the dynamics of the fish population; (ii) the fishery dynamics; (iii) the dynamics of tagged fish; (iv) observation models for the data; (v) parameter estimation procedure; and (vi) stock assessment interpretations. Detailed technical descriptions of components (i) – (iv) are given in Hampton and Fournier (2001) and Kleiber et al (2003) and are not repeated here. Rather, brief descriptions of the various processes are given, including information on structural assumptions, estimated parameters, priors and other types of penalties used to constrain the parameterisation. For convenience, these descriptions are summarized in Table 4. In addition, we describe the procedures followed for estimating the parameters of the model and the way in which stock assessment conclusions are drawn using a series of reference points.

4.1 Population dynamics

The spatially aggregated model partitions the population into five regions and 28 quarterly age-classes. The first age-class has a mean fork length of around 22 cm and is assumed to be approximately three months of age based on ageing studies of yellowfin tuna in other oceans (e.g. Lehodey and Leroy 1999). The last age-class comprises a "plus group" in which mortality and other characteristics are assumed to be constant. For the purpose of computing the spawning biomass, we assume a fixed maturity schedule (Table 4) consistent with the observations of Itano (2000). No published maturity data are available for yellowfin tuna in the Indian Ocean.

The population is "monitored" in the model at quarterly time steps, extending through a time window of 1972–2009. The main population dynamics processes are as follows:

4.1.1 Recruitment

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

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

Spatially-aggregated recruitment was assumed to have a weak relationship with the spawning biomass via a Beverton and Holt stock-recruitment relationship (SRR). The SRR was incorporated mainly so that yield analysis could be undertaken for stock assessment purposes. We therefore opted to apply a relatively weak penalty for deviation from the SRR so that it would have only a slight effect on the recruitment and other model estimates (see Hampton and Fournier 2001, Appendix D). Typically, fisheries data are not very informative about SRR parameters and three alternative values of steepness (h) were considered (0.7, 0.8 and 0.9).

4.1.2 Initial population

The population age structure in the initial time period in each region was assumed to be in equilibrium and determined as a function of the average total mortality during the first 20 quarters. This assumption avoids having to treat the initial age structure, which is generally poorly determined, as independent parameters in the model. The initial age structure was applied to the initial recruitment estimates to obtain the initial populations in each region.

4.1.3 Growth

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

For the current assessment, growth parameters were fixed at values that replicated the growth curve derived by Fonteneau (2008) (Figure 11). The non-von Bertalanffy growth of juvenile yellowfin tuna is evident, with slow growth for young age classes and near-linear growth in the 60–110 cm size range. Growth in length is estimated to continue throughout the lifespan of the species, attenuating as the maximum is approached. The estimated variance in length-at-age was assumed to increase with increasing age (Figure 11).

4.1.4 Movement

Movement was assumed to occur instantaneously at the beginning of each quarter through movement coefficients connecting regions sharing a common boundary. However, fish can move between non-contiguous regions in a single time step due to the “implicit transition” computational algorithm employed (see Hampton and Fournier 2001; Kleiber et al. 2003 for details). Movement is parameterised as the proportion of fish in a given region that move to the adjacent region. There are six inter-regional boundaries in the model with movement possible across each in both directions. Four seasonal movements were allowed, each with their own movement coefficients. Thus there is a need for 2×6×4 = 48 movement parameters. The seasonal pattern of movement persists from year to year with no allowance for longer-term variation in movement. The movement coefficients are invariant with respect to age.

4.1.5 Natural mortality

Natural mortality was variable with age with the relative trend in age-specific natural mortality based on the values applied in the Pacific Ocean (western and central; eastern) yellowfin tuna stock assessments. The overall level of natural mortality was fixed at the lower level (Figure 12). This level of natural mortality is consistent with the estimated age-specific natural mortality for the range of age classes with a reasonable number of tag recoveries (2-15 quarters).

4.2 Fishery dynamics

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

4.2.1 Selectivity

Selectivity is assumed to be fishery-specific and time-invariant. For the non longline fisheries, selectivity was modelled using a cubic spline interpolation to estimate age-specific selectivity. This is a form of smoothing, but the number of parameters for each fishery is the number of cubic spline “nodes” that are deemed to be sufficient to characterise selectivity over the age range. We chose five nodes, which seems to be sufficient to allow for reasonably complex selectivity patterns.

For the longline fisheries (LL 1-5) a single selectivity is estimated that is shared among the five regional fisheries. Two alternative parameterisations were considered for defining the longline selectivity function: 1) the cubic spline parameterisation that has the flexibility to estimate a decline in the selectivity of the older age classes and 2) a logistic selectivity function that constrains the older age classes to be fully selected (“flat top”).

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

No length frequency data are available for the “Other” fishery in region 1, while limited data are available from the OT 5 fishery. Similarly, size data were available from the troll fishery in region 5, but not from the fisheries in regions 2 and 3. The selectivity of the “Other” fisheries was assumed to be equivalent among the two regions (1 and 5), while a common selectivity was assumed for the troll fisheries in regions 2 and 5.

4.2.2 Catchability

For the non longline fisheries, catchability was allowed to vary slowly over time (akin to a random walk) using a structural time-series approach. Random walk steps were taken every one or two years, and the deviations were constrained by prior distributions of mean zero and variance specified for the different fisheries according to our prior belief regarding the extent to which catchability may have changed.

A number of fisheries have limited or no effort data (HD 1, GN 1 & 5, OT 1 & 5, TR 3 & 5 and LF 5). In the absence of effort data, MFCL assumes a notional value for the effort. For these fisheries, the variance on the catchability deviations was high (approximating a CV of about 0.7), thereby, allowing catchability changes (as well as effort deviations) to predict the observed effort without the assumed effort series influencing the trend in stock abundance. For the other fisheries with time-series variability in catchability, the catchability deviation priors were assigned a variance approximating a CV of 0.10.

The principal longline fisheries (LL 1-5) were grouped for the purpose of initial catchability, and time-series variation was assumed not to occur in this group. As noted earlier, this assumption is similar to assuming that the CPUE for these fisheries indexes the exploitable abundance both among areas and over time.

Catchability for all fisheries was allowed to vary seasonally.

4.2.3 Effort deviations

Effort deviations, constrained by prior distributions of zero mean, were used to model the random variation in the effort – fishing mortality relationship. For the non longline fisheries, the variance was set at a moderate level (approximating a CV of 0.2). For the main longline fisheries (LL 1-5), the variance was set at a lower level (approximating a CV of 0.1) because the effort had been standardised in prior analyses and these longline fisheries provide wide spatial coverage of the respective areas in which they occur.

4.3 Dynamics of tagged fish

4.3.1 Tag mixing

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

The release phase of the tagging programme was essentially restricted to region 2. To date, the distribution of tags throughout the wider IO appears to be relatively limited. This is evident from the low number of tag recoveries from the fisheries beyond region two, although these data are unlikely to significantly inform the model regarding movement rates given the lack of information concerning tag reporting rates from many of these fisheries (see below).

4.3.2 Tag reporting

In principal, tag-reporting rates can be estimated internally within the model. In practice, experience has shown that independent information on tag-reporting rates for at least some fisheries tends to be required for reasonably precise estimates to be obtained. We provided reporting rate priors for all fisheries that reflect our prior opinion regarding the reporting rate and the confidence we have in that opinion. For the purse-seine fisheries, the tag dataset was corrected for reporting rates (from the tag seeding experiments) and the reporting rates were essentially fixed at a value of 0.81 to account for initial tag retention rates (0.9) and the proportion of the total purse-seine catch examined for tags (0.9).

For the other fisheries, we have no auxiliary information with which to estimate reporting rates, so relatively uninformative priors were used for those fisheries. All reporting rates were assumed to be stable over time. The proportions of tag returns rejected from the analysis because of insufficient data were incorporated into the reporting rate priors.

4.4 Observation models for the data

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

The probability distributions for the length-frequency proportions are assumed to be approximated by robust normal distributions, with the variance determined by the effective sample size and the observed length-frequency proportion.

The size frequency data is assigned an effective sample size lower than the actual number of fish sampled. Reduction of the effective sample size recognises that (i) length frequency samples are not truly random (because of clumping in the population with respect to size) and would have higher variance as a result; and (ii) the model does not include all possible process error, resulting in further under-estimation of variances.

The length frequency data were considered to be uninformative regarding current stock status and were given an according weighting in the likelihood function; individual length frequency distributions were assigned an effective sample size of 0.01 times the actual sample size, with a maximum effective sample size of 10.

A log-likelihood component for the tag data was computed using a negative binomial distribution in which fishery-specific variance parameters were estimated from the data. The negative binomial is preferred over the more commonly used Poisson distribution because tagging data often exhibit more variability than can be attributed by the Poisson. We have employed a parameterisation of the variance parameters such that as they approach infinity, the negative binomial approaches the Poisson. Therefore, if the tag return data show high variability (for example, due to contagion or non-independence of tags), then the negative binomial is able to recognise this. This should then provide a more realistic weighting of the tag return data in the overall log-likelihood and allow the variability to impact the confidence intervals of estimated parameters. A complete derivation and description of the negative binomial likelihood function for tagging data is provided in Hampton and Fournier (2001).

4.5 Parameter estimation and uncertainty

The parameters of the model were estimated by maximizing the log-likelihoods of the data plus the log of the probability density functions of the priors and smoothing penalties specified in the model. The maximization was performed by an efficient optimization using exact derivatives with respect to the model parameters. Estimation was conducted in a series of phases, the first of which used arbitrary starting values for most parameters.

The Hessian matrix computed at the mode of the posterior distribution was used to obtain estimates of the covariance matrix, which was used in combination with the Delta method to compute approximate confidence intervals for parameters of interest.

4.6 Stock assessment interpretation methods

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

4.6.1 Fishery impact

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

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

4.6.2 Yield analysis

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

For the standard yield analysis, the F_a are determined as the average over some recent period of time. In this assessment, we use the average over the period 2006–2009. The most recent year (2010) is not included in the average as fishing mortality tends to have high uncertainty for the terminal data year of the analysis.

The MSY based reference points were also computed using the average annual F_a from each year included in the model (1972–2010). This enabled temporal trends in the reference points to be assessed and a consideration of the differences in MSY levels under historical patterns of age-specific exploitation.

5 Results

Overall, six model options were agreed by the WPTT. These model options include the two alternative parameterisations of the longline selectivity each with the three alternative values of steepness for the SRR. No single model was promoted as a preferred option and the main stock assessment-related results are summarised for the range of model options. Nonetheless, for illustrative purposes detailed results are presented for a single model option - the model that incorporates the cubic spline selectivity function for the longline fisheries and the intermediate value of steepness (fixed at 0.80).

5.1 Fit statistics and convergence

A summary of the fit statistics for a selected range of model options is given in Table 5.

The fit statistics are not directly comparable between the two sets of models with different assumptions regarding longline selectivity. The cubic spline parameterization provides greater flexibility in the fitting to the length frequency data and, hence, results in a lower likelihood for these data and the total likelihood (Table 5).

5.2 Fit diagnostics

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

- The log total catch residuals by fishery are shown in Figure 13. The magnitude of the residuals is in keeping with the model assumption (CV=0.05) and they generally show even distributions about zero.
- For most fisheries, there is good fit to the length frequency data revealed from a comparison of the observed and predicted length data aggregated over time (Figure 14). However, the model tends to underestimate the proportion of fish in the larger length classes sampled from purse-seine free-school fisheries in region 2 and the longline fisheries in regions 1 and 2. The poor fit to the length data from the “other” fisheries in region 1 (OT 1) probably reflects the limited data available from the fishery.
- For most fisheries, the size composition of individual length samples is generally consistent with the temporal trend in the size composition of the fishery-specific exploitable component of the population (Figure 15). However, there are a number of fisheries that exhibit considerable shifts in the length composition of the catch. Notable examples include the recent increase in the length of fish caught from the hand-line fishery in region 1 (HD 1), the smaller size of fish caught by the longline fisheries in regions 2

and 5 during the 1990s (Figure 16), the larger fish caught by the free school purse-seine fishery in region 2 (PS FS 2) since the early 2000s, and the larger fish caught by the gillnet fishery in region 5 in recent years. These observations are indicative of significant changes in the overall selectivity of these fisheries and warrant further refinement of the fishery definitions and/or a more rigorous analysis of the individual data sets. Further, a number of fisheries have considerable variability in the size frequency data (for example, PS FS 2 (pre 2003), PS FS 3 & 5 and TR 5) which may be partly due to sampling error.

- Most of the tag returns are from the purse-seine fishery in region 2. The fits of the model to the tagging data compiled by calendar time and by time at liberty are shown in Figure 17 and Figure 18, respectively. Overall, the model predicts the number of tag recoveries very well, with the exception of a considerable underestimation of the number of tags recovered in the first quarter of 2007 from the purse-seine fishery – fishery specific recoveries by quarter are presented in Figure 19. Tag recoveries from the non purse-seine fisheries are not considered to be informative and the model has the flexibility to freely estimate reporting rates for these fisheries. However, it is worth noting that the model generally fits the temporal trend in tag recoveries from a number of the other fisheries, particularly in region 2 (BB2, TR2 and OT1) indicating the assumption of a constant reporting rate, albeit low (except for TR 2), may be reasonable for these fisheries.
- The model predicts tag attrition reasonably well (Figure 18). Most of the tag recoveries are from fish at liberty for up to about three years largely reflecting the period of release (most tags were released during 2006) as well as the relatively high fishery-specific mortality by the purse-seine fleet. The decline in tag recoveries for extended periods at liberty is partly related to the cumulative effect of natural and fishery induced mortality on the younger age classes and the lower reporting rates of tags by the longline fleets.
- The observed age-specific tag recoveries for the composite purse-seine fishery in region 2 are comparable to the tag recoveries predicted by the model (Figure 20). Almost all the recoveries occurred during 2007-2010 and the selectivity estimated for the two purse-seine fisheries (PS LS post 2006 and PS FS post 2006) is clearly consistent with the age-specific tag recoveries.
- Most of the tag recoveries occurred in the region of release. However, there were also movements of tagged fish to areas adjacent to the region of release, primarily from region 2 to regions 1 and 3. The estimated movement parameters are consistent with the observed movement of tags between these regions (Figure 21).
- The overall consistency of the model with the observed effort data can be examined in plots of effort deviations against time for each fishery (Figure 22). If the model is coherent with the effort data, we would expect an even scatter of effort deviations about zero. On the other hand, if there was an obvious trend in the effort deviations with time, this may indicate that a trend in catchability had occurred and that this had not been sufficiently captured by the model. For the principal longline fisheries in regions 2-5 (LL 2-5), there are no strong trends evident in the effort deviations (Figure 22) and there is a reasonable fit to the CPUE indices over the model period (Figure 23). The effort deviations are more variable for LL 1 partly due to the lack of standardised effort data for considerable periods prior to 1992 and the high variability in the CPUE indices in the subsequent period (Figure 23).
- A number of fisheries have limited or no effort data. For these fisheries, the model tends to fit the catch through the effort deviations (rather than temporal variation in catchability). Hence, for a number of fisheries (GI 1 & 5, HD 1, LF 5 and TR 3 & 5) there are strong trends in the effort deviations (Figure 22). However, given the low penalty associated with the effort deviations these observations are not influential in the model fit (the effort deviations associated with missing effort are excluded from the likelihood).

5.3 Model parameter estimates

5.3.1 Movement

Two representations of the movement estimates are shown in Figure 24 and Figure 25. The estimated movement coefficients for adjacent model regions are shown in Figure 24. Coefficients for some region boundaries are close to zero, while overall, most movement rates are low. Movement rates are generally highest between region 2 and adjacent regions, although a relatively high level of movement is also estimated from region 4 to region 5 in the second quarter.

The distribution of regional biomass by source region derived from a simulation using the movement coefficients is presented in Figure 25. The simulation indicates that most biomass within a region is sourced from recruitment within the region, although significant mixing occurs between regions 2 and 3 and region 2 providing a source of recruitment to region 4. Regional fidelity is highest in regions 1 and 5 most of the regional biomass sourced from recruitment within the region (Figure 25).

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

5.3.2 Selectivity

The cubic spline selectivity option yields a common selectivity for the principal longline fisheries (LL 1-5) that attains full selectivity at age 13 quarters and has a considerably lower selectivity (0.40) for the oldest age classes (Figure 26). The fresh tuna fishery (LF 5) is estimated to have a higher selectivity for older fish than the principal longline fisheries.

The associated purse-seine and baitboat fisheries have a high selectivity for juvenile fish, while the free-school purse-seine fishery selects substantially older fish. For the region 2 associated purse-seine fisheries, there are differences in the selectivities estimated for the three time intervals, while the selectivities for the free-school fisheries are more comparable over the three intervals (Figure 26).

Limited or no size data were available for a number of fisheries, specifically the artisanal fisheries (OT 1 & 5) and the troll fishery in regions 2 and 3 (TR 2 & 3). Consequently, selectivity for these fisheries is poorly estimated or, in the absence of size data, assumed equivalent to a fishery with the same gear code in another region.

5.3.3 Catchability

For the principal longline fisheries, catchability was assumed to be constant over time (Figure 27), with the exception of seasonal variation (not shown in figure).

Time-series changes in catchability are evident for several other fisheries; there is evidence of a general increase in catchability for the baitboat fishery (BB 2) and the purse seine fisheries, particularly the associated sets fishery (PS LS 2, 3, and 5). However, given that the purse-seine effort data are not separated by set type, these trends may partly reflect a shift in the proportion of associated sets in the aggregated purse-seine effort data.

For many of the non industrial scale fisheries, reliable effort data are not available. For these fisheries, the trends in catchability are meaningless. Instead, the trends in catchability provide a mechanism for the model to fit the catch data, in conjunction with the effort deviations, given the notional effort. The constraints on temporal trends in catchability are relaxed for these fisheries so that the effort data has very limited influence on the total likelihood.

5.3.4 Tag-reporting rates

Tag reporting rates for the purse-seine fisheries (combined within a region for the estimation of tag recoveries) were fixed in the analysis (Figure 28). For all other fisheries, no information was available regarding tag reporting rates and fishery-specific reporting rates were estimated with virtually no constraints. For those fisheries with tag recoveries, the estimated reporting rates were generally low (less than 30%), with the exception of the artisanal fishery in region 1 (OT 1) and the troll fisheries in regions 2 and 3 (TR 2 & 3) (may relate to a lack of effort data for the recovery period?).

5.4 Stock assessment results

5.4.1 Recruitment

The base-case recruitment estimates (aggregated by year for ease of display) for each region and the entire IO are shown in Figure 29. The regional estimates display large inter-annual variability and variation on longer time scales, as well as differences among regions. For the aggregated estimates, recruitment is estimated to be relatively stable during 1972–2003 and then declines sharply from 2003 to 2006. Recruitment is estimated to have recovered during the subsequent years but remains below (80%) the long-term average level in the most recent years (2008-2010).

Overall, total historical recruitment was dominated by recruitment in region 2, 5 and, to a lesser extent region 3 (Figure 29). However, there are considerable differences in the temporal trends in recruitment among regions. Recruitment is estimated to have steadily declined in region 5, while recruitment in region 3 was highest prior to 1982 (Figure 29). The recent trends in the overall level of recruitment are largely driven by recruitment in region 2.

For the entire IO, recruitment estimates for early period of the model (prior to 1990) are considerably more uncertain than the subsequent period (Figure 29).

For the model options with logistic longline selectivity, the overall level of recruitment is considerably lower than derived from the cubic spline model options, particularly during the early model period (Figure 30). Both model options estimate a similar level of recruitment during the last decade, including the period of very low recruitment during 2003-06 (Figure 30).

5.4.2 Biomass

The estimated biomass trajectory for each region and for the entire IO is shown in Figure 31 and Figure 32 for the base-case analysis. Adult and total biomass is estimated to have declined rapidly since the late 1980s. This trend is largely driven by the decline in biomass within regions 2, 3 and 5 — historically these regions accounted for the most of the IO biomass.

There are very narrow confidence intervals around the time-series of estimated biomass for each region (Figure 31). These confidence intervals do not accurately reflect the true level of uncertainty as they are predicated on the high precision associated with the longline CPUE indices and the fixed biological parameters.

A comparison of total biomass trends for the two longline selectivity options is shown in Figure 33. The magnitude of the total biomass estimated from the logistic selectivity model is considerably lower than the cubic spline model although the relative trend in biomass is comparable.

5.4.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age classes increased strongly from the early 1980s for the two main model options (Figure 34). However, the extent of the increase is considerably higher for the model options with logistic longline selectivity.

Recent fishing mortality rates, for the period used in the computation of references points (2006–2009), were highest in regions 1, 2 and 5, particularly for the younger age classes (3–10) (Figure 35).

5.4.4 Fishery impact

We measure fishery impact at each time step as the ratio of the estimated biomass to the biomass that would have occurred in the historical absence of fishing. This is a useful variable to monitor, as it can be computed both at the region level and for the IO as a whole. The two trajectories are plotted in Figure 36. Impacts are highest in regions 1, 2 and 3, while the strong declines in biomass in regions 4 and 5 are only partly attributable to the effect of fishing. The fishery impact in region 2 accounts for a high proportion of the reduction in total IO biomass that is attributable to fishing.

The biomass ratios are plotted in Figure 37. These figures indicate higher levels of fishery depletion (50–70% reduction) of yellowfin tuna in regions 1, 2 and 5. For the entire IO, recent levels of fishing have resulted in about a 40% reduction in total biomass. The fishery impact is estimated to be considerably higher for the longline logistic selectivity model (approximately 55% reduction in total IO biomass).

5.4.5 Yield analysis

Symbols used in the following discussion are defined on Table 6. The yield analysis incorporates the SRR into the equilibrium biomass and yield computations with three alternative values of steepness assumed for the SRR (0.70, 0.80 and 0.90). There is no strong evidence from the model estimates of spawning biomass and recruitment to select a specific value of steepness (Figure 38).

For each model option, the reference points $F_t \big/ \tilde{F}_{MSY}$, $B_t \big/ \tilde{B}_{MSY}$ and $SB_t \big/ \widetilde{SB}_{MSY}$ were computed for each year (*t*) included in the model (1972–2010). These computations incorporated the overall fishery selectivity in year *t*. This enables trends in the status of the stock relative to these reference points to be followed over the model period (Figure 40). Estimates of statistical uncertainty were not determined for the range of model options. The very large number of parameters estimated for the models precludes the estimation of statistical uncertainty using MCMC approaches. Further, likelihood profiling of the key stock status metrics was not practicable due to time constraints of the WPTT 13. Instead, the WPTT agreed to express the uncertainty of the assessment results by applying the range of the six model options to determine the plausible range of the key stock status indicators. A simple average of the model options was used to express the central tendency of the range of values.

Exploitation rates were low from 1972 to 1990, while total and adult biomass remained well above $\tilde{B}_{MSY}$ and $S\tilde{B}_{MSY}$. Since the early 1990s, $F_t/\tilde{F}_{MSY}$ steadily increased while the relative biomass levels ($B_t/\tilde{B}_{MSY}$ and $SB_t/S\tilde{B}_{MSY}$) declined (Figure 40). For most model options, recent fishing mortality rates remain below the F_{MSY} level while total biomass and adult biomass have approached the $\tilde{B}_{MSY}$ and $S\tilde{B}_{MSY}$ thresholds in the two most recent years (Figure 40). One model option (logistic longline selectivity and steepness of 0.7) estimated that current fishing mortality rates were higher than the F_{MSY} level (Table 7b).

The WPTT agreed to adopt the stock status in 2009 as the best indicator of current stock status. The 2010 year was discounted due to uncertainty associated with the catch estimates for some fisheries in the most recent year, the lower precision of the Japanese longline CPUE indices for region 2 in 2010 and imprecise estimates of the recruitment for the most recent year (2010).

Equilibrium yield and biomass (spawning and total) are computed as a function of multiples of the 2006–09 average fishing mortality-at-age (Figure 39). Estimates of *MSY* for the model options with logistic longline selectivity were 290,000–339,000 mt (Table 7b), whereas, the cublic spline model options estimated considerably higher values of *MSY* (364,000–436,000 mt) (Table 7a). The *MSY* estimates are based on the long-term average level of recruitment. However, for the cubic spline model, average recruitment over the last 15 years has been considerably lower (80%) than the long-term average. *MSY* estimates derived for the cubic spline model options based on the recent period of recruitment were approximately 300,000 mt. This level is comparable with the recent level of catch from the fishery (averaging about 285,186 mt in 2009–10).

6 Discussion and conclusions

The first application of MULTIFAN-CL to the assessment of the Indian Ocean yellowfin tuna stock was presented and further refined at the WPTT meeting in 2008. The 2008 assessment was the first attempt to integrate the tag release/recovery data available from the recent IO-RTTP within a statistical framework that incorporates the other available sources of data from the fishery (catch, effort and length frequency data). The assessment was considerably more complex than previous assessments as it was configured to reflect the spatial dynamics of stock and the principal region-specific fisheries.

The current assessment incorporates a range of refinements and recommendations arising from the subsequent (10-13th) meetings of the WPTT. These refinements have included some substantial changes to the structural assumptions of the model and the various model data sets. There has also been considerably more attention given to the understanding of the interaction between the various sources of data incorporated in the model.

In general, the diagnostics reveal that the model provides a good fit to the main data sets included in the assessment. Nevertheless, a range of issues were identified that require further consideration. These issues are not unique to the current MFCL assessment and, in many cases, are of direct relevance to assessments conducted using other methodologies and the assessment of yellowfin tuna in other oceans. Key issues most directly relevant to the current assessment are as follow.

i. The standardized CPUE indices from the longline fisheries represent the principal index of stock abundance in the model and, hence, are highly influential in the stock assessment. For region 2, the longline CPUE indices were very low during the mid-late 2000s, resulting in the low recent estimates of recruitment and stock biomass for the region and the overall IO stock. During this period, the total yellowfin longline catch and the proportion of yellowfin tuna in the total longline catch declined substantially and longline fishing effort has been very limited in the region over the last few years. It is unclear whether these declines represent a decline in the yellowfin tuna stock or are due to changes in the operation of the longline fishery (attributable to the increased risk of piracy in the area).

ii. Historically, regions 2, 3 and 5 collectively accounted for most of the total stock biomass (29%, 28%, 48%, respectively). Catches from region 3 and 5 have been low relative to the level of historical biomass. Nonetheless, regional biomass, as indexed by the longline CPUE, has declined substantially. The model attributes most of the decline in regional biomass to a strong decline in recruitment in the two regions; however, the length frequency data are relatively uninformative and hence there are limited data available to reliably estimate the trend in historical recruitments. Further attention should be given to determine the reliability of the relative abundance indices in these two regions and the areal weighting factors applied to determine the relative catchability of the longline fisheries among regions (the relatively high historical CPUE for these two regions attracts high region specific weighting factors).

iii. Limited or no size frequency data are available for several significant fisheries. Consequently, selectivities for these fisheries are poorly determined or unknown and assumed to be equivalent to other fisheries using similar methods. More representative sampling is required for key fisheries, for example the principal longline fisheries. Currently, the length frequency data are given a relatively low weighting (sample size of 10) to reduce the influence of these data on the biomass trajectory. However, some of the fishery specific data sets may be more informative regarding recruitment and exploitation rates and may warrant a higher level of influence in the assessment model. Further refinement of the fishery definitions may be justified if there are substantial differences in the length composition of the catches from the individual constituents (e.g the handline fishery in region 1). In this regard, some progress was made in the current assessment with the separation of the distant-water and fresh tuna longline fisheries within region 5.

iv. Over the last decade, there appear to have been changes in the selectivity of the purse-seine fisheries within region 2. These have been addressed in the current stock assessment through the separating the purse-seine fisheries into three time periods. As a result, there has been an improvement to the fit of the tagging data. However, there remains a poor fit to the adult mode of the length frequency distribution of the catch. This indicates a conflict between the length frequency data and the tagging data and further examination of the assumptions regarding selectivity and growth is warranted.

v. The spatially disaggregated Indian Ocean model relies on a single longline CPUE index derived for the entire stock. The individual region-specific CPUE indices differ somewhat among regions with respect to the rate and timing of the decline in CPUE. It is unclear as to whether or not the global CPUE index reliably integrates the biomass trend over the five regions to provide a composite index of the total stock. Conversely, some of the assumptions regarding the relative weighting of the individual region-specific CPUE indices in the spatially disaggregated model should be further investigated.

vi. For all oceans, there is limited information available regarding natural mortality and maturity at age. The current assessment has adopted values of natural mortality that are considerably lower than those used in the Pacific Ocean assessments of yellowfin tuna. The tagging data has the potential to inform the assessment models regarding the level of natural mortality and the current assessment indicates that a relatively low level of natural mortality is more consistent with the tagging data. Further research is required to refine the biological parameters for the IO stock.

vii. There is a conflict between the estimates of growth from MFCL (Langley 2009) and external estimates of growth. Further studies are required to refine the current estimates of growth, incorporating direct data from ageing (otoliths) and tag growth increment data.

It is envisaged that some of the above issues will be further investigated prior and during the 13th meeting of the WPTT.

Key issues of more general nature, of relevance to other yellowfin tuna stocks, are as follow.

i. The range of assessment models assumes a constant catchability of yellowfin by the longline fisheries, as indexed by the Japanese and Taiwanese standardized CPUE indices. However, the CPUE standardization is unlikely to account for a range of variables that may have increased (or decreased) the efficiency of the longline fleet with respect to yellowfin tuna. The sensitivity of the model to this assumption should be investigated. More detailed information regarding gear technology and fishing strategy is necessary to investigate changes in longline catchability over the model period.

ii. The assessment also assumes that the selectivity of most of the fisheries have remained constant throughout the model period. There are some indications that this assumption may not be valid for some key fisheries. It may be possible that changes in the composition of the fleet and/or targeting behaviour, for example the increased targeting of bigeye tuna by the longline fleet, have resulted in a change in the size selectivity of some fisheries.

iii. The SRR is a key component of the computation of the *MSY*-based reference points. However, model estimates of recruitment and adult biomass are unlikely to be informative in the estimation of parameters of the SRR, particularly at low biomass levels. For this reason, WPTT 10 agreed to adopt a range of default values of steepness. Consideration should also be given to adopting a range of reference points that are less dependent on assumptions relating to SRR.

Many of the issues identified above require the collection of additional biological and fishery related data and/or an investigation of the sensitivity to a number of the key structural assumptions. A number of sensitivity analyses were included in the recent assessments; however, a more thorough examination of the model uncertainty should be undertaken.

Despite the issues identified above, a number of key observations and conclusions are evident from the results of the current assessment.

1. The model estimates that total biomass has declined rapidly since the late 1980s. The decline in biomass has been largest in regions 2, 3 and 5. These trends are generally consistent with the trends in the longline CPUE indices. However, catches in regions 3 and 4 have been relatively low (compared to historical biomass) and the model attributes most of the reduction in regional biomass to a strong decline in recruitment.
2. For the cubic spline longline selectivity models, exploitation rates and fishery impacts are relatively high in regions 1, 2 and 5 resulting in a 50–70% reduction in regional biomass and a 40% reduction in overall Indian Ocean biomass. Fishery impacts are considerably higher for the logistic selectivity model options.
3. For the cubic spline longline selectivity model, total recruitment is estimated to have declined throughout the model period and recruitment over the last 15 years is estimated to be 80% of the long-term average. Recruitment was particularly low during 2003-06. The logistic longline selectivity models estimate long-term average levels of recruitment that are considerably lower than the cubic spline models although recent recruitment levels (last 15 years) are comparable for the two model options.
4. Recent (2006–2009 average) exploitation rates are at historically high levels. The *MSY*-based reference points, and the resulting stock status, are influenced by the value of steepness assumed for the SRR. The values included in the assessment encompass the plausible range of steepness for yellowfin tuna. For most model options, current exploitation rates remain below the level *MSY*-based reference level. Nonetheless, fishing mortality rates have continued to increase over recent years and, for the lower productivity model options (lower steepness), have approached or exceeded the *MSY* based threshold.
5. For most model scenarios, recent (2006–2009) average adult and total biomass remained above the respective *MSY*-based reference points ($\tilde{B}_{MSY}$ and $S\tilde{B}_{MSY}$). However, biomass is estimated to have declined rapidly over the last five years and for many of the model options adult and total biomass is estimated to have approached the respective reference point ($\tilde{B}_{MSY}$ and $S\tilde{B}_{MSY}$) in the most recent year (2010).
6. For most model options, *MSY* is estimated to be between 300,000 and 400,000 mt. Recent (2009–2010) annual catches are below this range (averaging about 285,000 mt in 2009–10) following a period of (very) low recruitment. The higher *MSY* estimates were derived from the cubic spline selectivity model options. However, these models estimate recent recruitment levels that are considerably lower than the long-term average. If recruitment remains at the recent level, then yields at the lower range of the *MSY* values are more appropriate.
7. During 2003–2006, annual catches reached a peak of about 500,000 mt — a level substantially higher than the *MSY*. Catches of this magnitude were not maintained in the subsequent years. Some of the decline in catch may be, at least partly, attributable to the recent operational constraints of the purse-seine and longline fleets due to piracy off the Somali coast.

7 Acknowledgements

The authors would like to thank Hiroaki Okatomo and Yu-Min Yeh for providing the Japanese and Taiwanese longline CPUE indices, respectively. Alejandro Anganuzzi, David Wilson and Hilario Murua provided guidance and support and comments on a draft version of the report.

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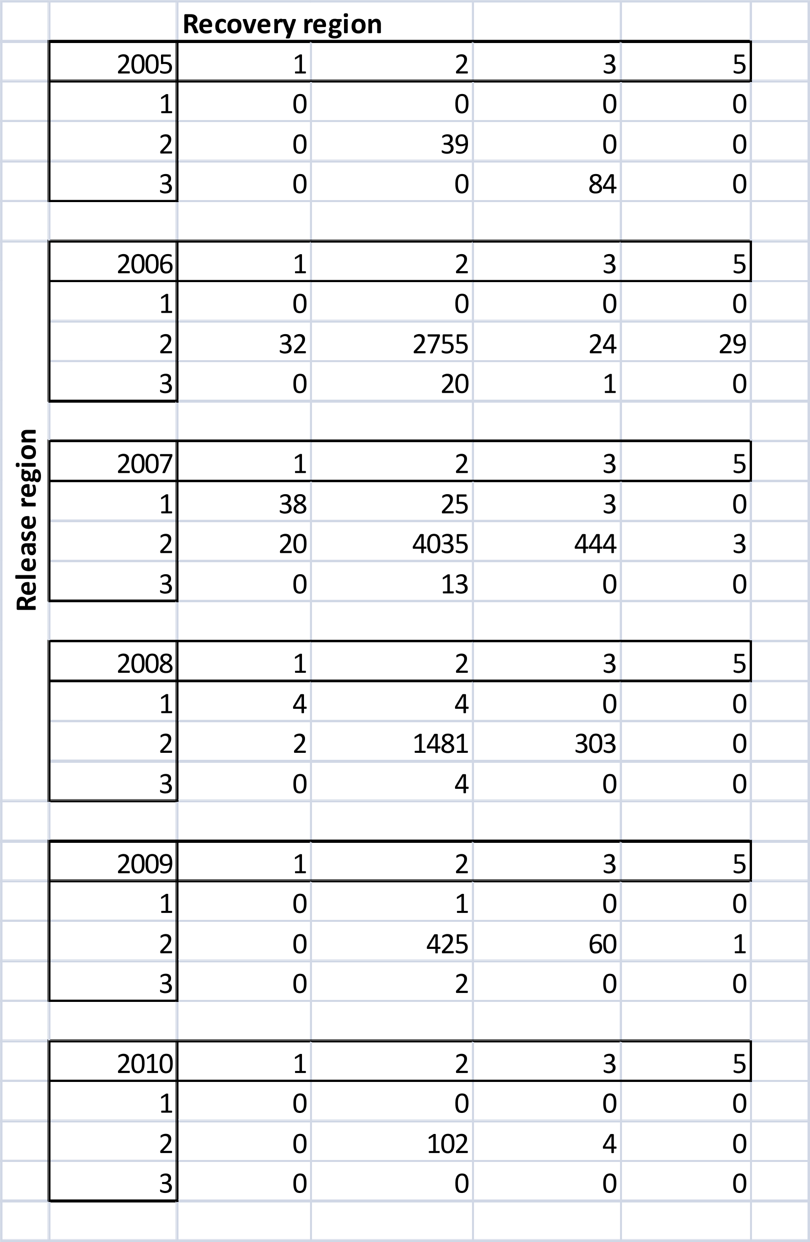
Table 1. Definition of fisheries for the five-region MULTIFAN-CL analysis of yellowfin tuna.

Fishery	Nationality	Gear	Region
1. GI 1	All	Gillnet	1
2. HD 1	All	Handline	1
3. LL 1 post 1972	All	Longline	1
4. OT 1	All	Other	1
5. BB 2	All	Baitboat	2
6. PS FS 2 2003-06	All	Purse seine, school sets	2
7. LL 2 post 1972	All	Longline	2
8. PS LS 2 2003-06	All	Purse seine, log/FAD sets	2
9. TR 2	All	Troll	2
10. LL 3 post 1972	All	Longline	3
11. LL 4 post 1972	All	Longline	4
12. GI 5	All	Gillnet	5
13. LL 5 post 1972	All	Longline (distant water)	5
14. OT 5	All	Other	5
15. TR 5	All	Troll	5
16. PS FS 3	All	Purse seine, school sets	3
17. PS LS 3	All	Purse seine, log/FAD sets	3
18. TR 3	All	Troll	3
19. PS FS 5	All	Purse seine, school sets	5
20. PS LS 5	All	Purse seine, log/FAD sets	5
21. PS FS 2 pre 2003	All	Purse seine, school sets	2
22. PS LS 2 pre 2003	All	Purse seine, log/FAD sets	2
23. PS FS 2 post 2006	All	Purse seine, school sets	2
24. PS LS 2 post 2006	All	Purse seine, log/FAD sets	2
25. LF 5	All	Longline (fresh tuna)	5

Table 2: Recent yellowfin tuna catches (mt) by fishery included in the stock assessment model. The annual catches are presented for 2009 and 2010 and the average annual catch is presented for 2006-09.

Fishery	Time period		
	2006-09	2009	2010
1. GI 1	34,565	31,765	39,729
2. HD 1	28,696	23,933	20,461
3. LL 1 post 1972	11,002	6,456	4,334
4. OT 1	850	431	379
5. BB 2	18,177	18,523	12,781
6. PS FS 2 2003-06	20,507	0	0
7. LL 2 post 1972	15,132	5,700	1,792
8. PS LS 2 2003-06	17,517	0	0
9. TR 2	2,986	1,889	2,315
10. LL 3 post 1972	8,794	5,380	4,043
11. LL 4 post 1972	699	433	500
12. GI 5	44,136	50,741	61,526
13. LL 5 post 1972	5,902	3,754	4,626
14. OT 5	455	504	504
15. TR 5	2,400	2,625	2,625
16. PS FS 3	3,169	3,104	1,519
17. PS LS 3	4,401	7,947	8,091
18. TR 3	13,551	13,188	13,184
19. PS FS 5	652	917	176
20. PS LS 5	1,148	1,010	602
21. PS FS 2 pre 2003	0	0	0
22. PS LS 2 pre 2003	0	0	0
23. PS FS 2 post 2006	37,704	31,897	28,332
24. PS LS 2 post 2006	28,486	42,983	62,475
25. LF 5	28,184	23,138	24,058
Total	329,111	276,318	294,053

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



		Recovery region			
Release region	2005	1	2	3	5
	1	0	0	0	0
	2	0	39	0	0
	3	0	0	84	0
	2006	1	2	3	5
	1	0	0	0	0
	2	32	2755	24	29
	3	0	20	1	0
	2007	1	2	3	5
	1	38	25	3	0
	2	20	4035	444	3
	3	0	13	0	0
	2008	1	2	3	5
	1	4	4	0	0
	2	2	1481	303	0
	3	0	4	0	0
	2009	1	2	3	5
	1	0	1	0	0
	2	0	425	60	1
	3	0	2	0	0
	2010	1	2	3	5
	1	0	0	0	0
	2	0	102	4	0
	3	0	0	0	0

Table 4. Main structural assumptions of the yellowfin tuna base-case analysis and details of estimated parameters, priors and bounds. Note that the number of estimated parameters shown is substantially greater than the effective number of parameters in a statistical sense because of the effects of priors, bounds and smoothing penalties.

Category	**Assumptions**	**Estimated parameters** (ln = log transformed parameter)		**Prior**		**Bounds**	
				μ	**σ**	**Low**	**High**
Observation model for total catch data	Observation errors small, equivalent to a residual SD on the log scale of 0.07.	None		na	na	na	na
Observation model for length-frequency data	Normal probability distribution of frequencies with variance determined by effective sample size and observed frequency. Effective sample size assumed to be 0.01 times actual sample size for all fisheries with a maximum effective sample size of 10.	None		na	na	na	na
Observation model for tagging data	Tag numbers in a stratum have negative binomial probability distribution, with estimated variance parameters for fishery groups.	Variance parameters		-	-	0	100
Tag reporting	Common tag reporting rate for all PS fisheries. All reporting rates constant over time. PS tag reporting rates are fixed (see text for details).	PS		-	-	0.001	0.9
		Other fisheries		0.5	0.7	0.001	0.9
Tag mixing	Tags assumed to be randomly mixed at the model region level four quarters following the quarter of release.	None		na	na	na	na
Recruitment	Occurs as discrete events at the start of each quarter. Spatially-aggregated recruitment is weakly related to spawning biomass in the prior quarter via a Beverton-Holt SRR (fixed steepness).The spatial distribution of recruitment in each quarter is allowed to vary with a small penalty on deviations from the average spatial distribution. Steepness values of 0.7, 0.8 and 0.9 were assumed.	Average spatially aggregated recruitment (ln)		-	-	-20	20
		Spatially aggregated recruitment deviations (ln)					
		Average spatial distribution of recruitment		-	-	0	1
		Time series deviations from average spatial distribution (ln)		0	1	-3	3
Initial population	A function of the initial recruitment and equilibrium age structure in each region, which is in turn assumed to arise from the total mortality estimated for 1972–75 and movement rates.	Initial recruitment scaling (ln)		-	-	-8	8
Age and growth	28 quarterly age-classes, with the last representing a plus group. Mean length at age fixed at values determined by Fonteneau (2008). SD of	None					

	length-at-age are log-linearly related to the mean length-at-age. Mean weights (W_j) computed internally by estimating the distribution of weight-at-age from the distribution of length-at-age and applying the weight-length relationship $W = aL^b$ (a= 1.585e-05, b= 3.045, source Nishida and Shono 2007 IOTC-2007-wptt-12).						
Selectivity	Constant over time. Coefficients for the last 4 age-classes are constrained to be equal. Longline fisheries share selectivity parameters. OT 1 & 5 and TR 2 & 5 also share selectivity parameters. For longline fisheries, selectivity is parameterised with 5-node cubic spline. Longline selectivity parameterized using cubic spine or logistic depending on model option.			-	-	0	1
Catchability	Constant over years and among regions for principal longline fisheries (effort data are scaled to reflect different region sizes). Seasonal variation for all fisheries. Other fisheries have structural time-series variation, with random steps (catchability deviations) taken every 2 years or every year (GI1, OT1, OT5, TR5).	Average catchability coefficients (ln)		-	-	-15	1
		Seasonality amplitude (ln)		0	2.2	-	-
		Seasonality phase		-	-	-	-
		Catchability deviations biennial (ln)		0	0.7	-0.8	0.8
		Catchability deviations annual (ln)		0	0.1	-0.8	0.8
Fishing effort	Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.1 for LL 1–5 and SD 0.22 for other fisheries at the average level of effort for each fishery. SD inversely proportional to the square root of effort.	Effort deviations LL (ln)		0	0.10	-6	6
		Effort deviations other (ln)		0	0.22	-6	6
Natural mortality	Age-dependent but constant over time and among regions. All parameters are specified (see Figure 12).	Average natural mortality (ln)		-	-	-	-
		Age-specific deviations (ln)		-	-	-	-
Movement	Age-independent and variant by quarter but constant among years. No age-dependent variation.	Movement coefficients		0	0.32	0	3
		Age-dependent component (ln)		0	0.32	-4	4
Maturity	Age-dependent and specified – age-class 0-8: 0; 9: 0.25; 10: 0.5; 11: 0.75; 12-28: 1.0	None		na	na	0	1

Table 5. Details of objective function components for the range of stock assessment models with different assumptions related to longline selectivity and steepness (h).

Objective function component	**Cubic spline** **h=0.7**	**h=0.8**	**h=0.9**
Total catch log-likelihood	222.01	221.96	221.89
Length frequency log-likelihood	-313,105.02	-313,104.91	-313,104.78
Tag log-likelihood	2,865.15	2,865.06	2,865.06
Penalties	3,202.33	3,202.95	3,203.47
Total function value	-306,815.53	-306,814.94	-306,814.29
Number of parameters	4,543	4,543	4,543

Objective function component	**Logistic** **h=0.7**	**h=0.8**	**h=0.9**
Total catch log-likelihood	27.74	27.73	27.74
Length frequency log-likelihood	-312,924.49	-312,924.26	-312,926.26
Tag log-likelihood	2,931.79	2,931.80	2,932.35
Penalties	3,520.55	3,714.35	3,715.70
Total function value	-306,250.26	-306,250.37	-306,250.48
Number of parameters	4,511	4,511	4,511

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

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2006–2009
F_{MSY}	Fishing mortality-at-age producing the maximum sustainable yield (*MSY*)
$\tilde{Y}_{F_{current}}$	Equilibrium yield at $F_{current}$
$\tilde{Y}_{F_{MSY}}$ (or *MSY*)	Equilibrium yield at F_{MSY}, or maximum sustainable yield
$\tilde{B}_0$	Equilibrium unexploited total biomass
$\tilde{B}_{F_{current}}$	Equilibrium total biomass at $F_{current}$
$\tilde{B}_{MSY}$	Equilibrium total biomass at MSY
$S\tilde{B}_0$	Equilibrium unexploited adult biomass
$S\tilde{B}_{F_{current}}$	Equilibrium adult biomass at $F_{current}$
$S\tilde{B}_{MSY}$	Equilibrium adult biomass at MSY
$B_{current}$	Average current (2006–2009) total biomass
$SB_{current}$	Average current (2006–2009) adult biomass
B_{year}	Average total biomass in *year*
SB_{year}	Average adult biomass in *year*
$B_{current,F=0}$	Average current (2006–2009) total biomass in the absence of fishing.

Table 7a. Estimates of management quantities for the stock assessment model options with **cubic spline selectivity parameterisation** for the longline fisheries and three levels of steepness. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading).

Management quantity	**Units**	***h* 0.70**	***h* 0.80**	***h* 0.90**
$\tilde{Y}_{F_{current}}$	mt per year	352,720	372,960	386,960
$\tilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	363,600	400,800	435,600
$\tilde{B}_0$	mt	7,622,000	7,548,000	7,489,000
$\tilde{B}_{F_{current}}$	mt	3,397,000	3,580,000	3,706,000
$\tilde{B}_{MSY}$	mt	2,714,000	2,509,000	2,295,000
$\tilde{SB}_0$	mt	6,903,000	6,836,000	6,783,000
$\tilde{SB}_{F_{current}}$	mt	2,894,000	3,049,000	3,156,000
$\tilde{SB}_{MSY}$	mt	2,265,000	2,056,000	1,839,000
$B_{current}$	mt	3,738,021	3,723,370	3,712,708
$SB_{current}$	mt	3,389,156	3,374,632	3,363,992
SB_{2009}		2,612,093	2,601,283	2,593,462
$B_{current,F=0}$	mt	6,397,738	6,383,746	6,373,946
$B_{current}/\tilde{B}_0$		0.490	0.493	0.496
$B_{current}/\tilde{B}_{F_{current}}$		1.100	1.040	1.002
$B_{current}/\tilde{B}_{MSY}$		1.354	1.459	1.590
$B_{current}/B_{current,F=0}$		0.584	0.583	0.582
$SB_{current}/\tilde{SB}_0$		0.491	0.494	0.496
$SB_{2009}/\tilde{SB}_0$		0.378	0.381	0.382
$SB_{current}/\tilde{SB}_{F_{current}}$		1.171	1.107	1.066
$SB_{current}/\tilde{SB}_{MSY}$		1.470	1.613	1.798
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.446	0.474	0.495
$\tilde{SB}_{F_{current}}/\tilde{SB}_0$		0.419	0.446	0.465
$\tilde{B}_{MSY}/\tilde{B}_0$		0.356	0.332	0.306
$\tilde{SB}_{MSY}/\tilde{SB}_0$		0.328	0.301	0.271
$F_{current}/\tilde{F}_{MSY}$		0.791	0.677	0.582
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		1.252	1.427	1.615
$\tilde{SB}_{F_{current}}/\tilde{SB}_{MSY}$		1.278	1.483	1.716
$\tilde{Y}_{F_{current}}/MSY$		0.970	0.931	0.888
$B_{current}/B_{2000}$		0.674	0.674	0.674
SB_{2009}/SB_{2000}		0.535	0.535	0.536

Table 7b. Estimates of management quantities for the stock assessment model options with **logistic selectivity parameterisation** for the longline fisheries and three levels of steepness. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading).

Management quantity	Units	***h*** **0.70**	***h*** **0.80**	***h*** **0.90**
$\tilde{Y}_{F_{current}}$	mt per year	287,680	314,880	333,240
$\tilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	289,640	315,320	338,960
$\tilde{B}_0$	mt	5,186,000	5,086,000	4,996,000
$\tilde{B}_{F_{current}}$	mt	1,676,000	1,828,000	1,921,000
$\tilde{B}_{MSY}$	mt	1,880,000	1,732,000	1,584,000
$\tilde{SB}_0$	mt	4,697,000	4,606,000	4,525,000
$\tilde{SB}_{F_{current}}$	mt	1,372,000	1,496,000	1,571,000
$\tilde{SB}_{MSY}$	mt	1,558,000	1,407,000	1,257,000
$B_{current}$	mt	2,104,292	2,094,939	2,078,442
$SB_{current}$	mt	1,816,744	1,807,156	1,790,964
SB_{2009}		1,436,719	1,430,221	1,417,621
$B_{current,F=0}$	mt	4,829,326	4,821,196	4,806,084
$B_{current} / \tilde{B}_0$		0.406	0.412	0.416
$B_{current} / \tilde{B}_{F_{current}}$		1.256	1.146	1.082
$B_{current} / \tilde{B}_{MSY}$		1.100	1.189	1.290
$B_{current} / B_{current,F=0}$		0.436	0.435	0.432
$SB_{current} / \tilde{SB}_0$		0.387	0.392	0.396
$SB_{2009} / \tilde{SB}_0$		0.306	0.311	0.313
$SB_{current} / \tilde{SB}_{F_{current}}$		1.324	1.208	1.140
$SB_{current} / \tilde{SB}_{MSY}$		1.144	1.259	1.397
$\tilde{B}_{F_{current}} / \tilde{B}_0$		0.323	0.359	0.385
$\tilde{SB}_{F_{current}} / \tilde{SB}_0$		0.292	0.325	0.347
$\tilde{B}_{MSY} / \tilde{B}_0$		0.363	0.341	0.317
$\tilde{SB}_{MSY} / \tilde{SB}_0$		0.332	0.305	0.278
$F_{current} / \tilde{F}_{MSY}$		1.109	0.949	0.818
$\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$		0.891	1.055	1.213
$\tilde{SB}_{F_{current}} / \tilde{SB}_{MSY}$		0.881	1.063	1.250
$\tilde{Y}_{F_{current}} / MSY$		0.993	0.999	0.983
$B_{current} / B_{2000}$		0.674	0.674	0.675
SB_{2009} / SB_{2000}		0.535	0.536	0.536

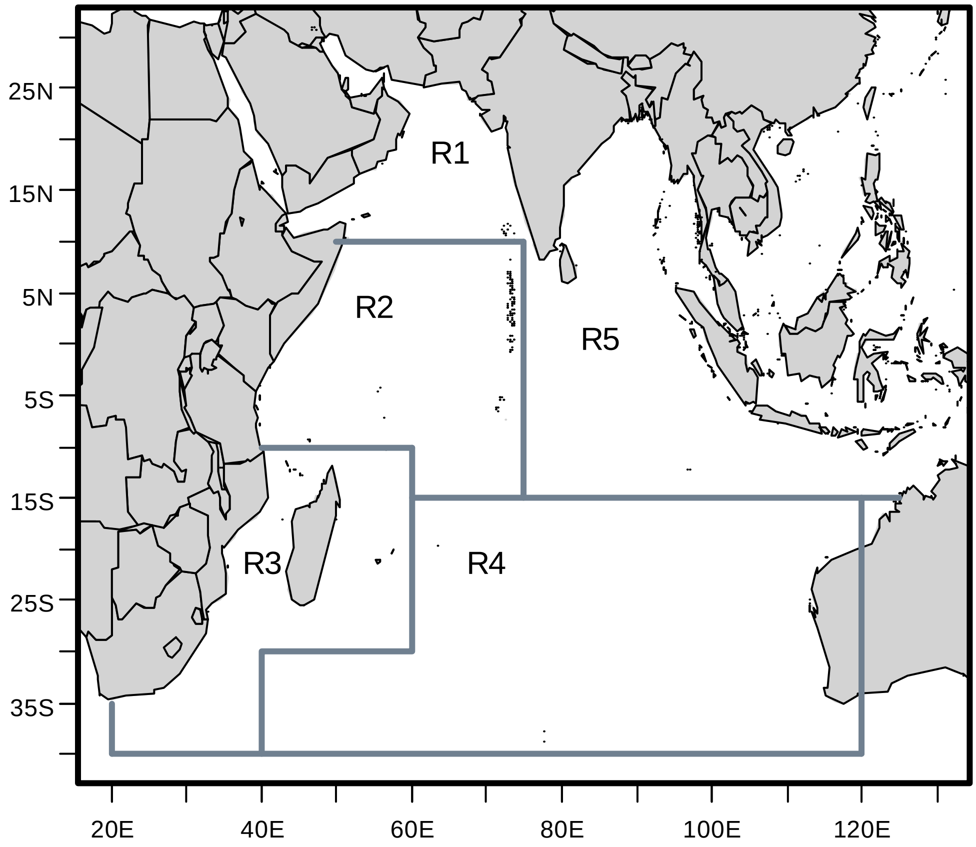


Figure 1. Spatial stratification of the Indian Ocean for the MFCL assessment model.

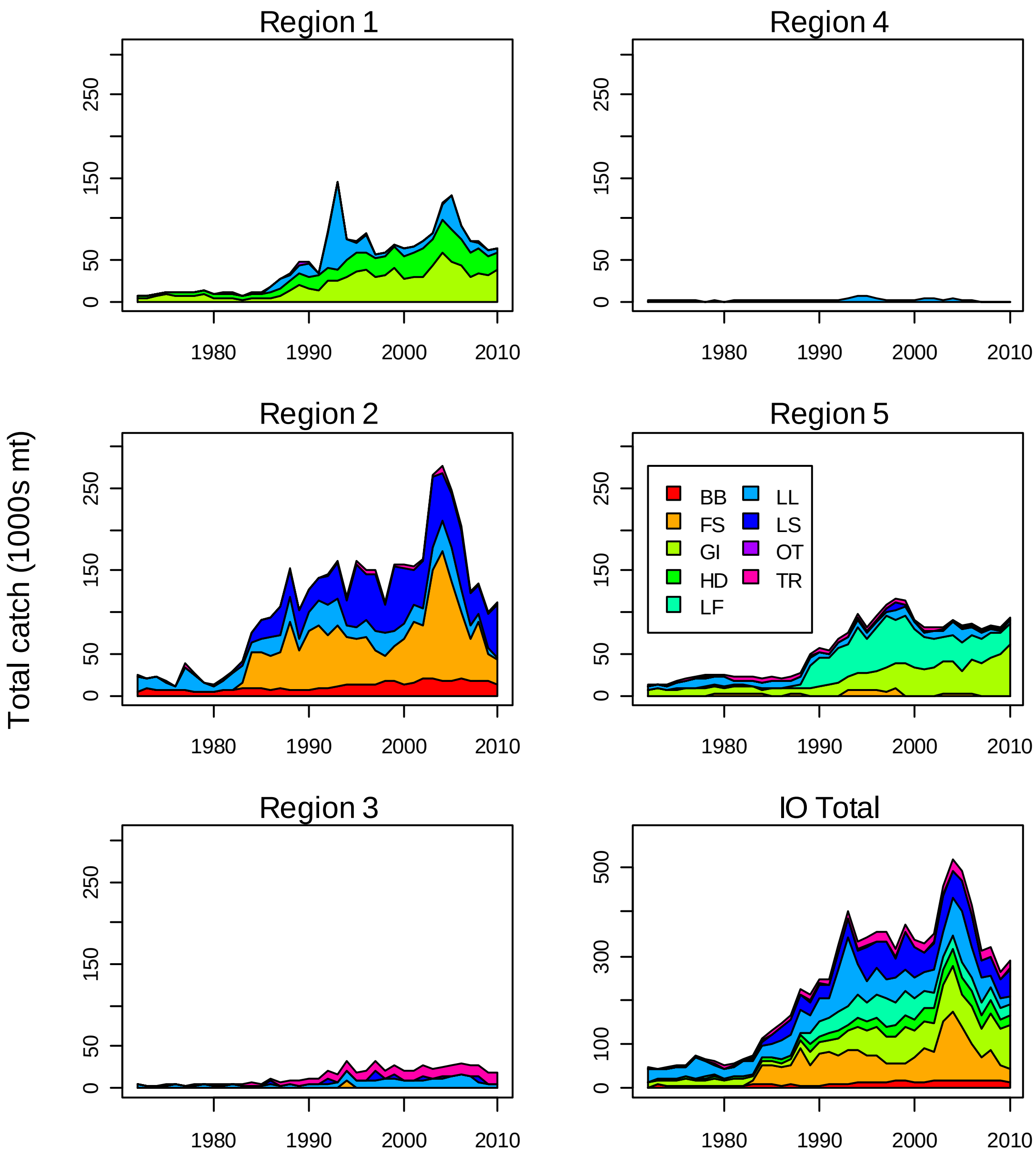


Figure 2. Total annual catch (1000s mt) of yellowfin tuna by fishing method and MFCL region from 1972 to 2009 (BB, baitboat; FS, purse-seine, free schools; GI, gillnet; HD, handline; LF, fresh tuna longline; LL, distant water longline; LS, purse-seine, log sets; OT, other; TR, troll).

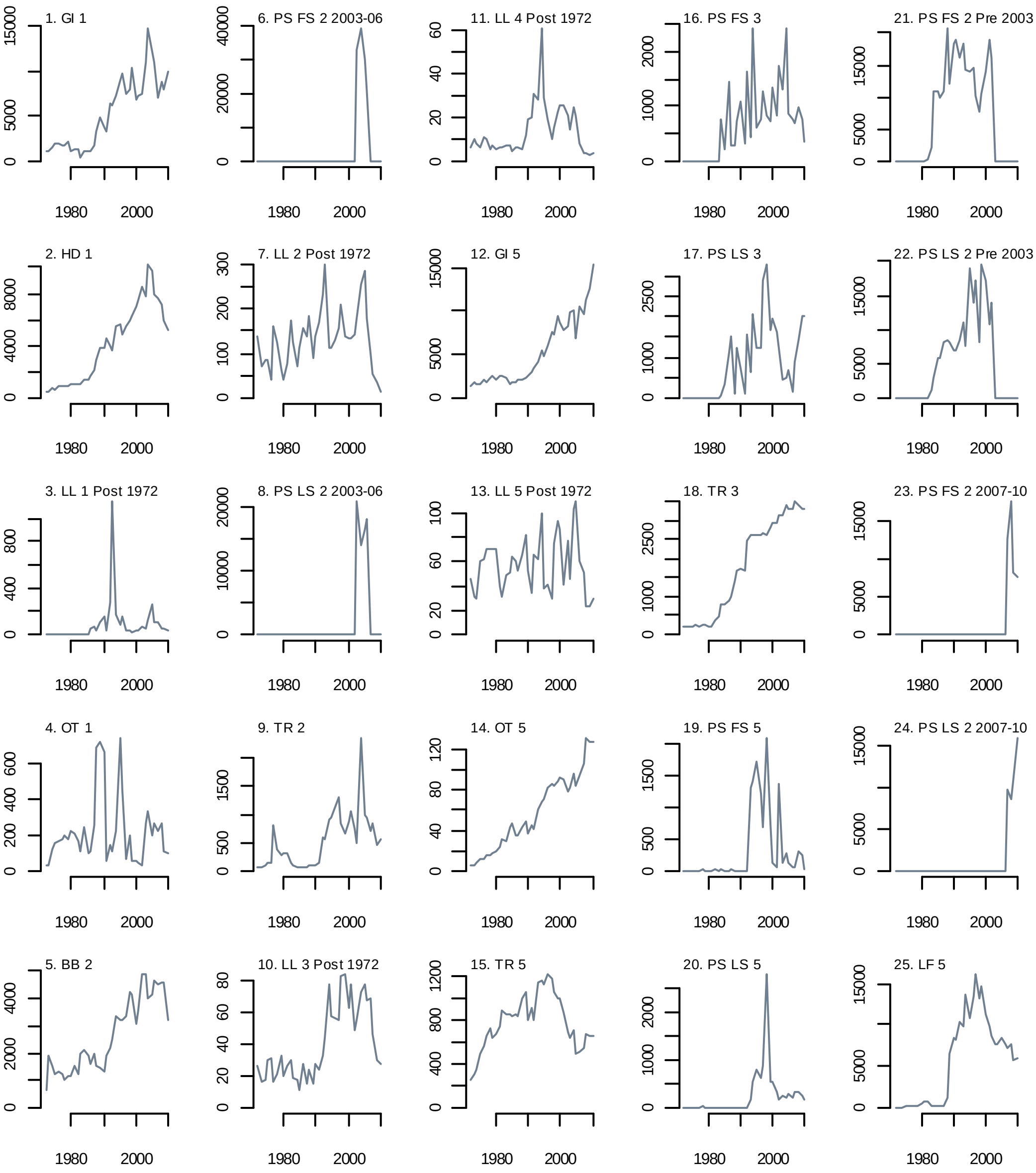


Figure 3. Quarterly catches, by fishery. Catches are in weight (tonnes) except for the longline fisheries (number, thousands of fish). Note the y-axis differs among plots.

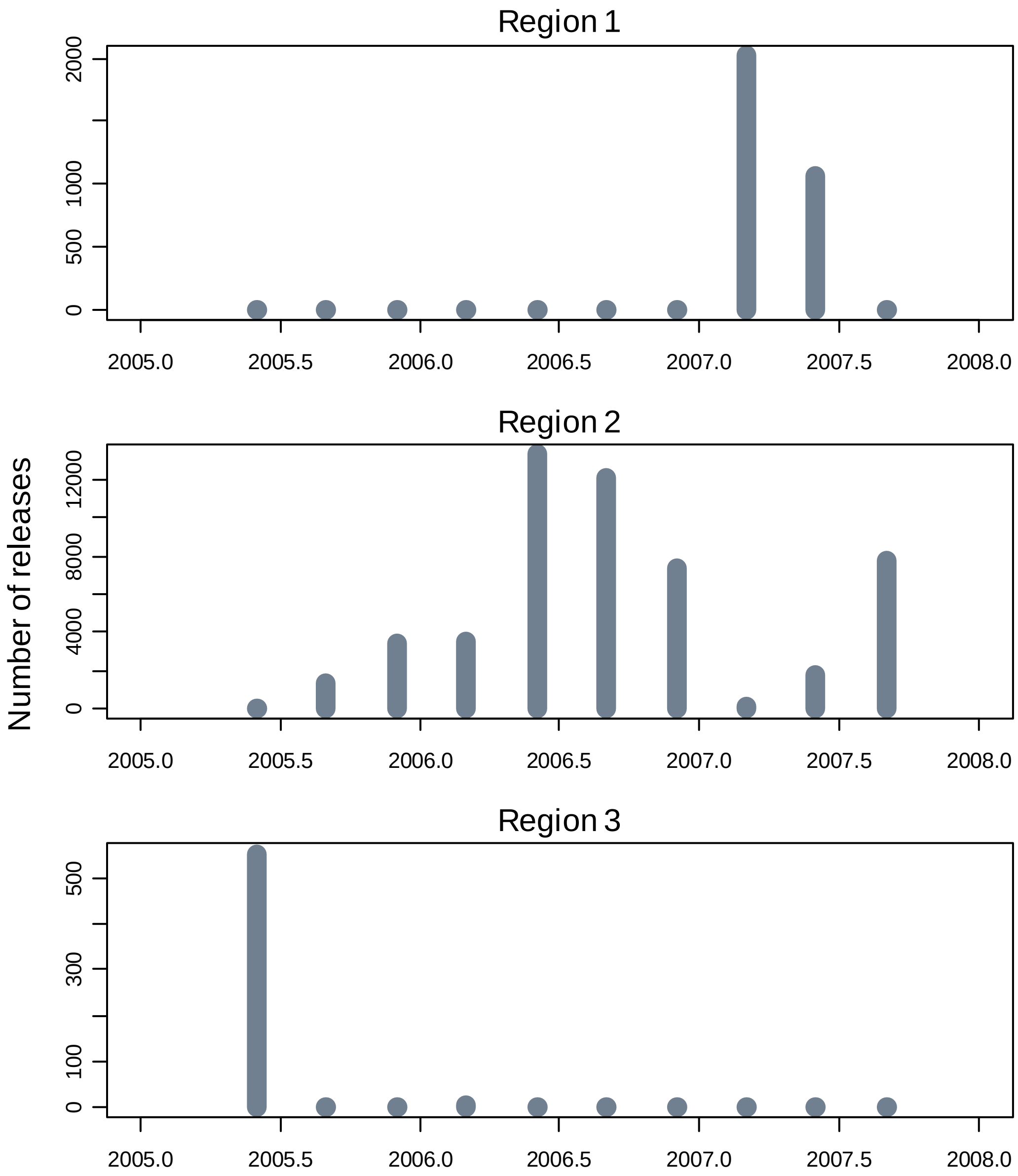


Figure 4. Number of tag releases by region and quarter included in the MFCL data set. No tag releases occurred in regions 4 and 5.

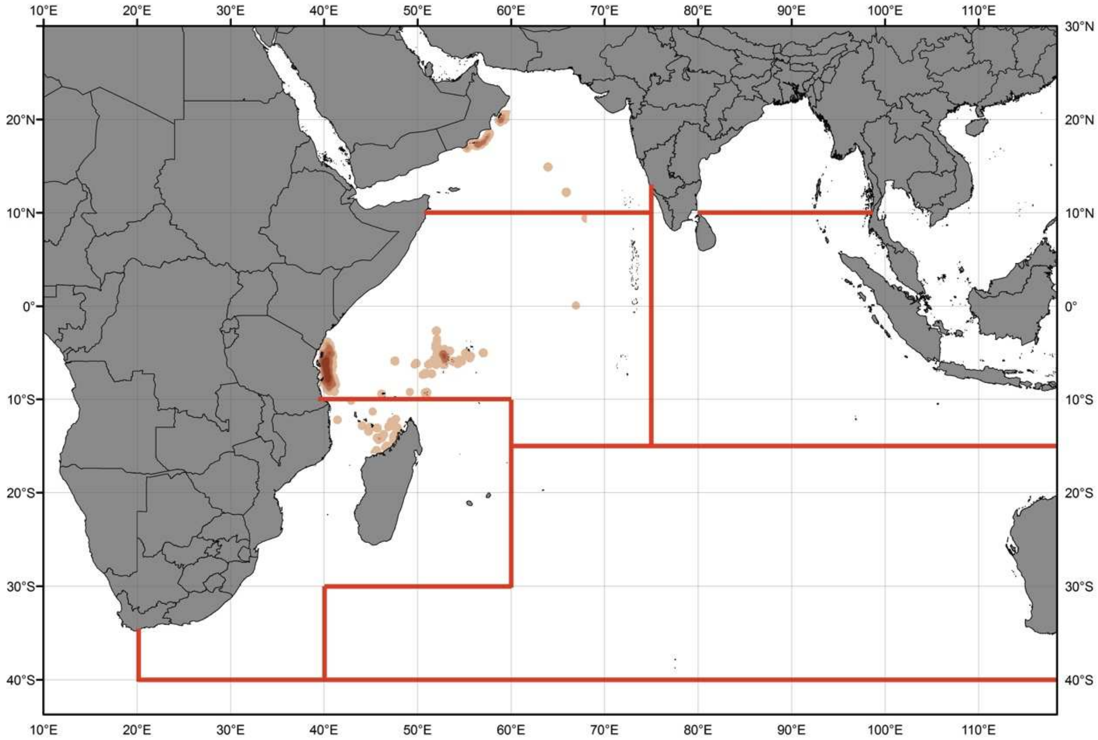


Figure 5. Density of RTTP-IO tag releases.

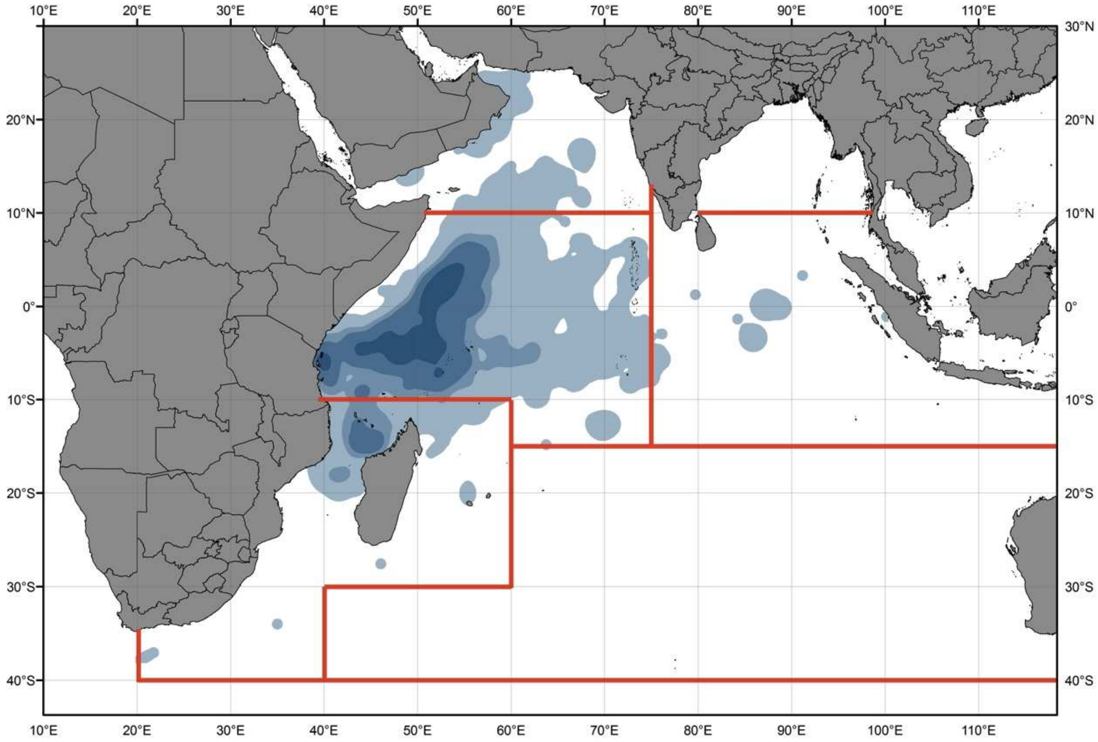


Figure 6. Density of RTTP-IO tag recoveries.

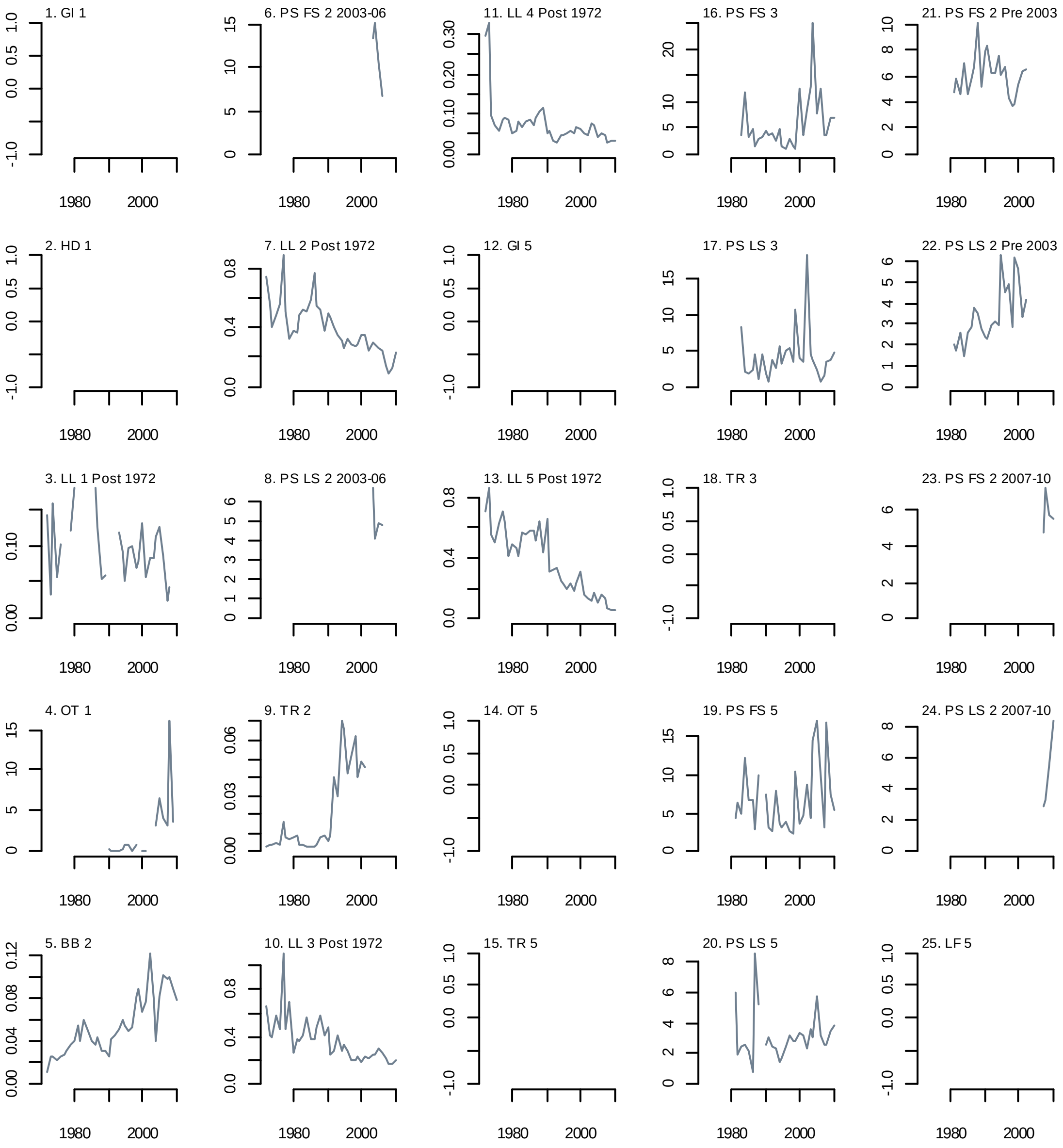


Figure 7. Quarterly catch-per-unit-effort (CPUE) by fishery. Units are catch (number) per GLM-standardised effort (fisheries LL 1–5), catch (number) per day fished/searched (PS fisheries) and catch (number) per trip. Note that CPUE for “Other” and troll fisheries is arbitrary and not based on data (see discussion on catchability and effort deviation constraints for these fisheries).

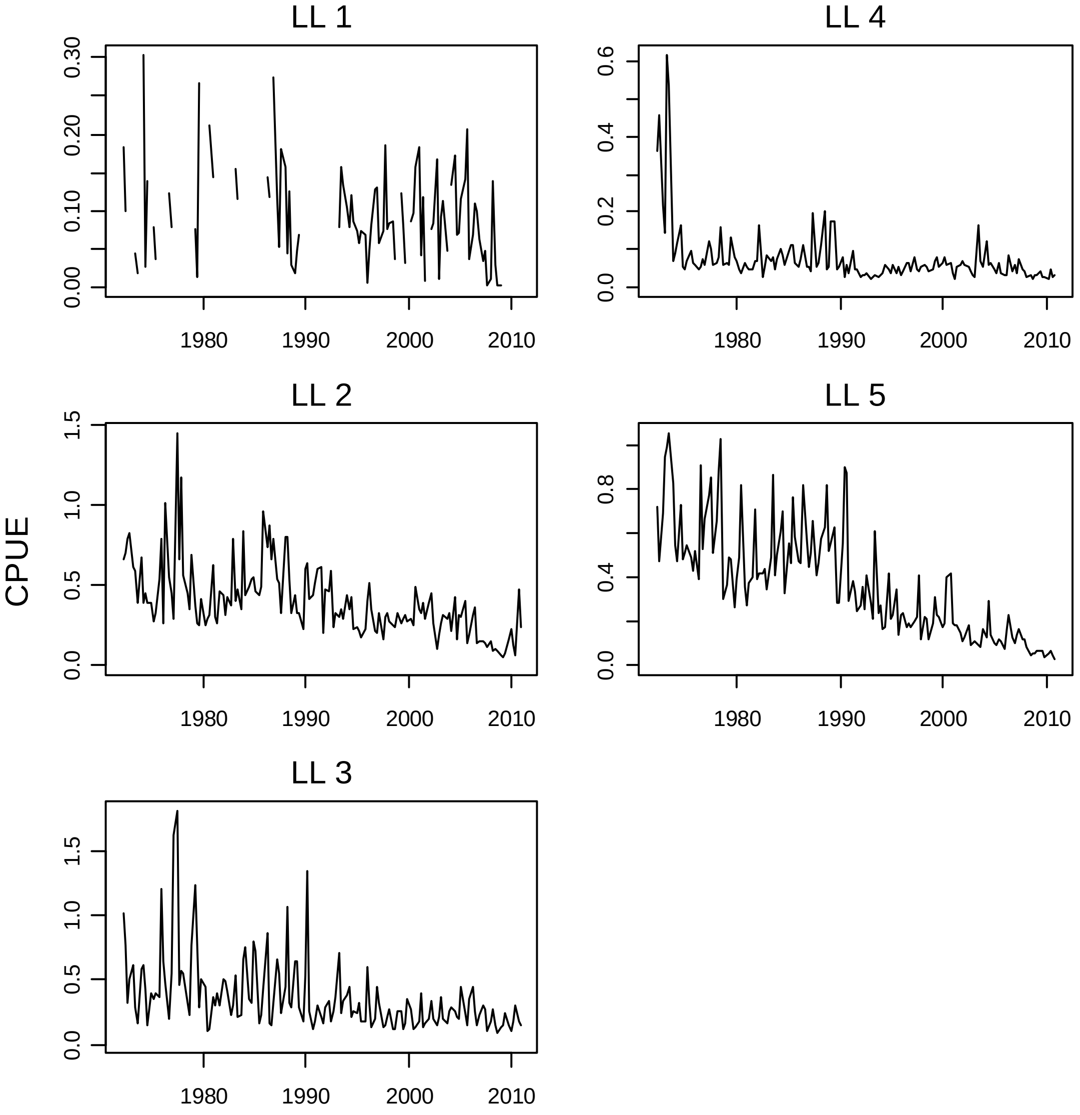


Figure 8. Annualised GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL 1–5) scaled by the respective region scalars.

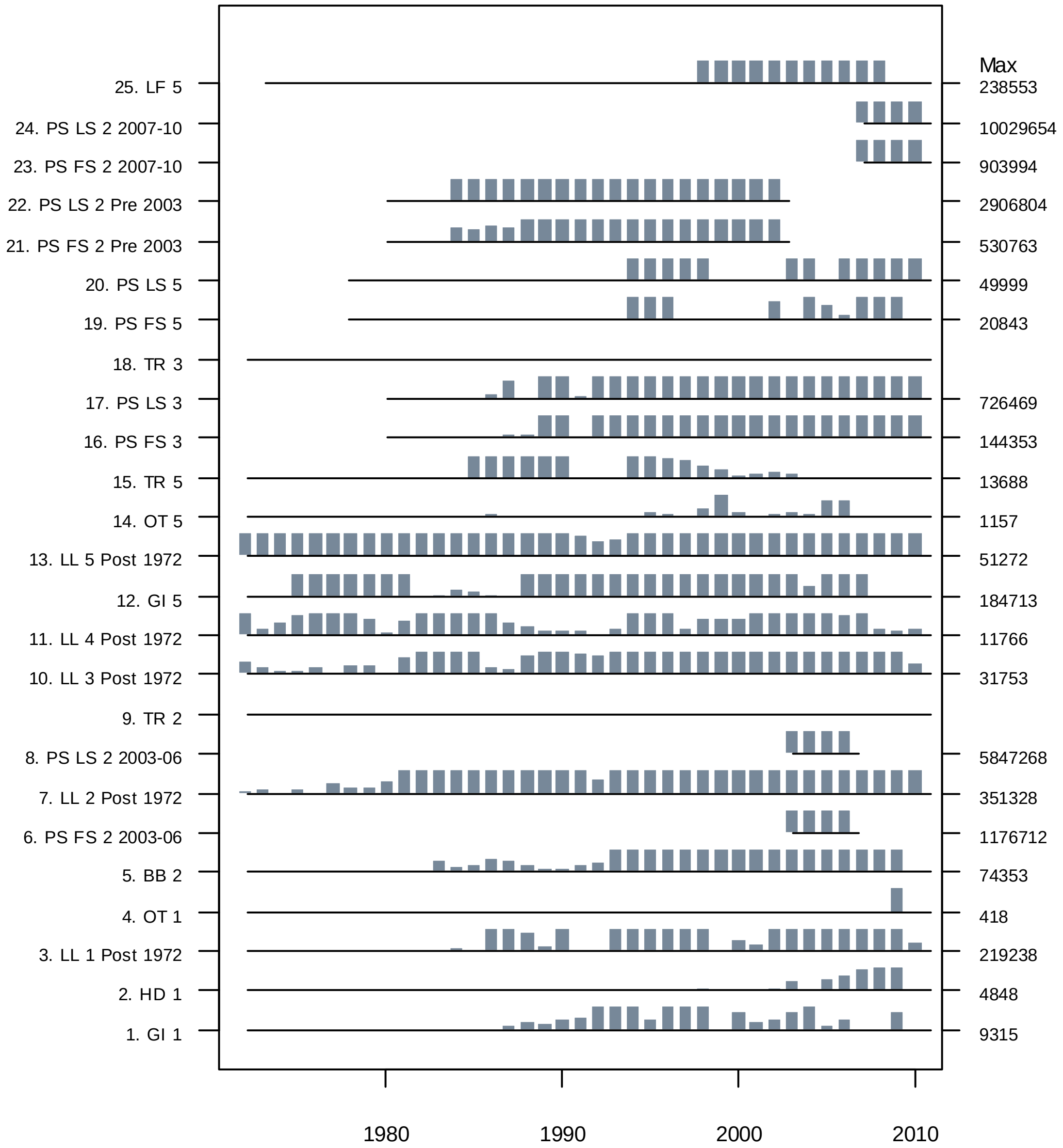


Figure 9. Number of fish length measurements by year for each fishery. The height of the bar is proportional to the maximum sample size, up to a maximum of 4000 fish per annum. The maximum annual sample size for each fishery is given on the right-hand side. The extent of the horizontal lines indicates the period over which each fishery occurred.

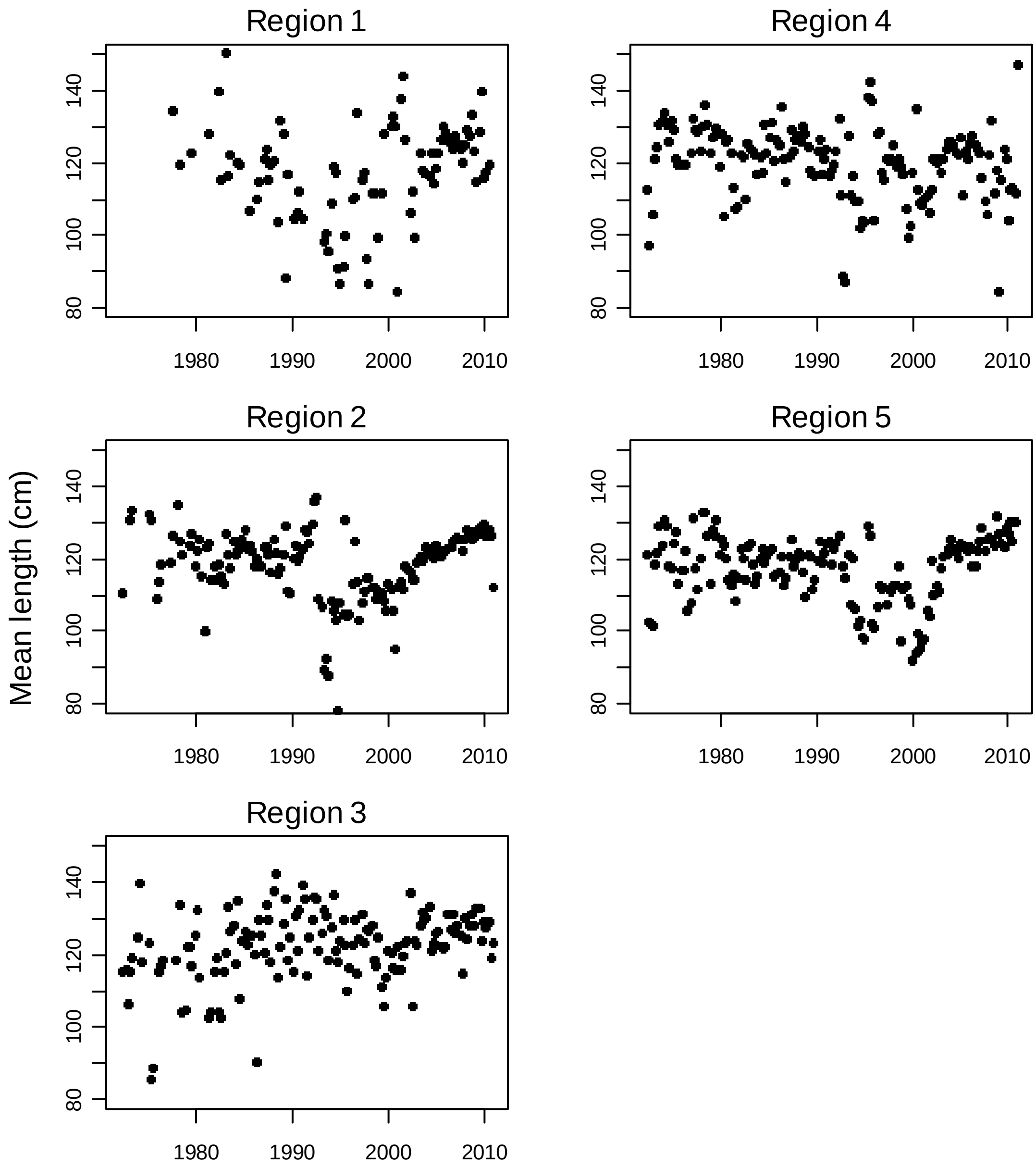


Figure 10. Mean length (fork length, cm) of yellowfin sampled from the principal longline fisheries (LL 1-5) by quarter.

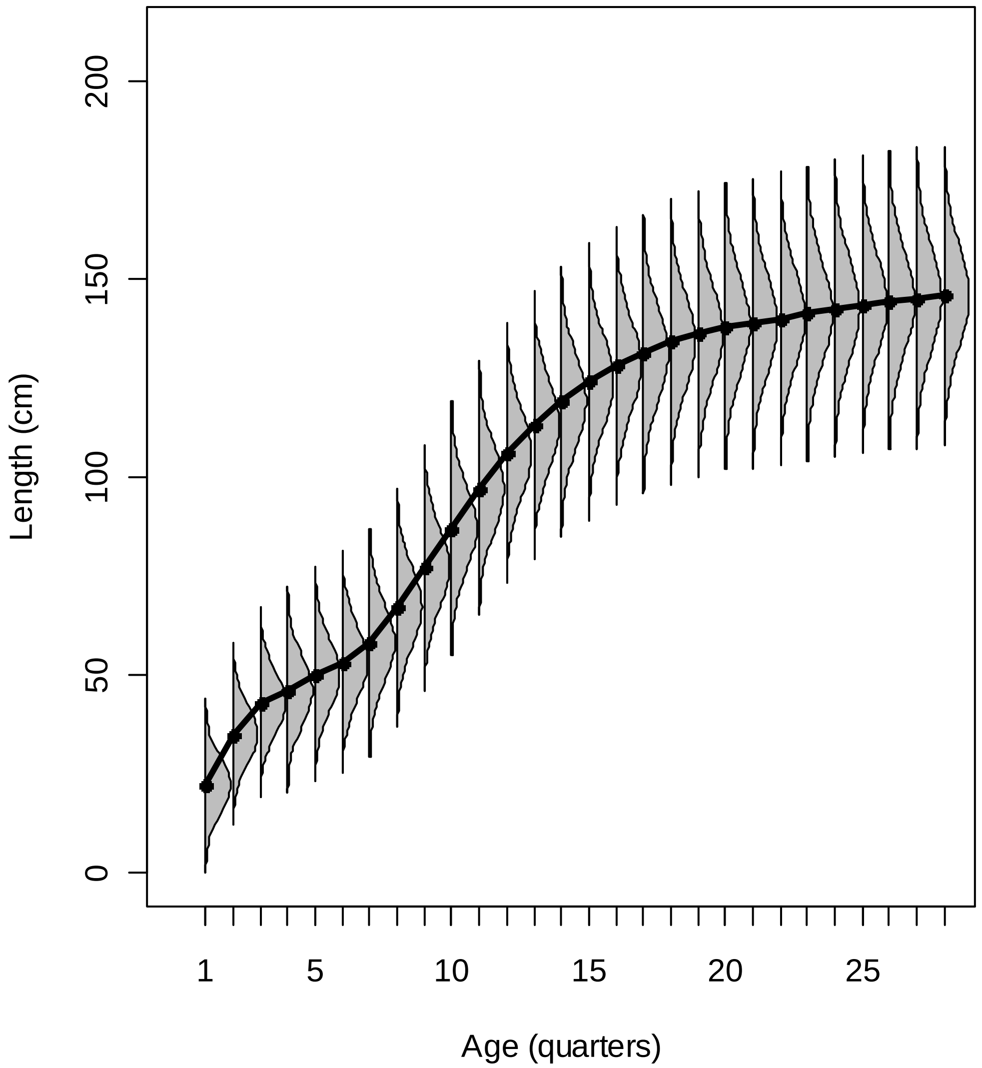


Figure 11. Fixed growth function for yellowfin tuna (following Fonteneau 2008). The black line represents the estimated mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age.

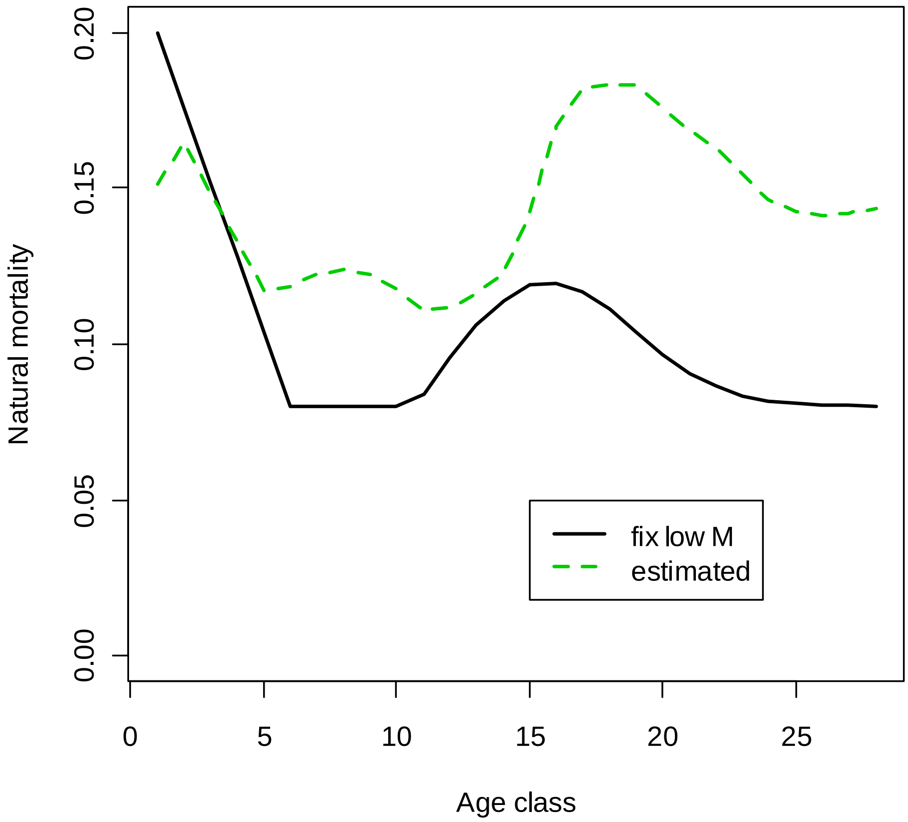


Figure 12. Age-specific natural mortality assumed for the assessment and the estimated level of natural mortality.

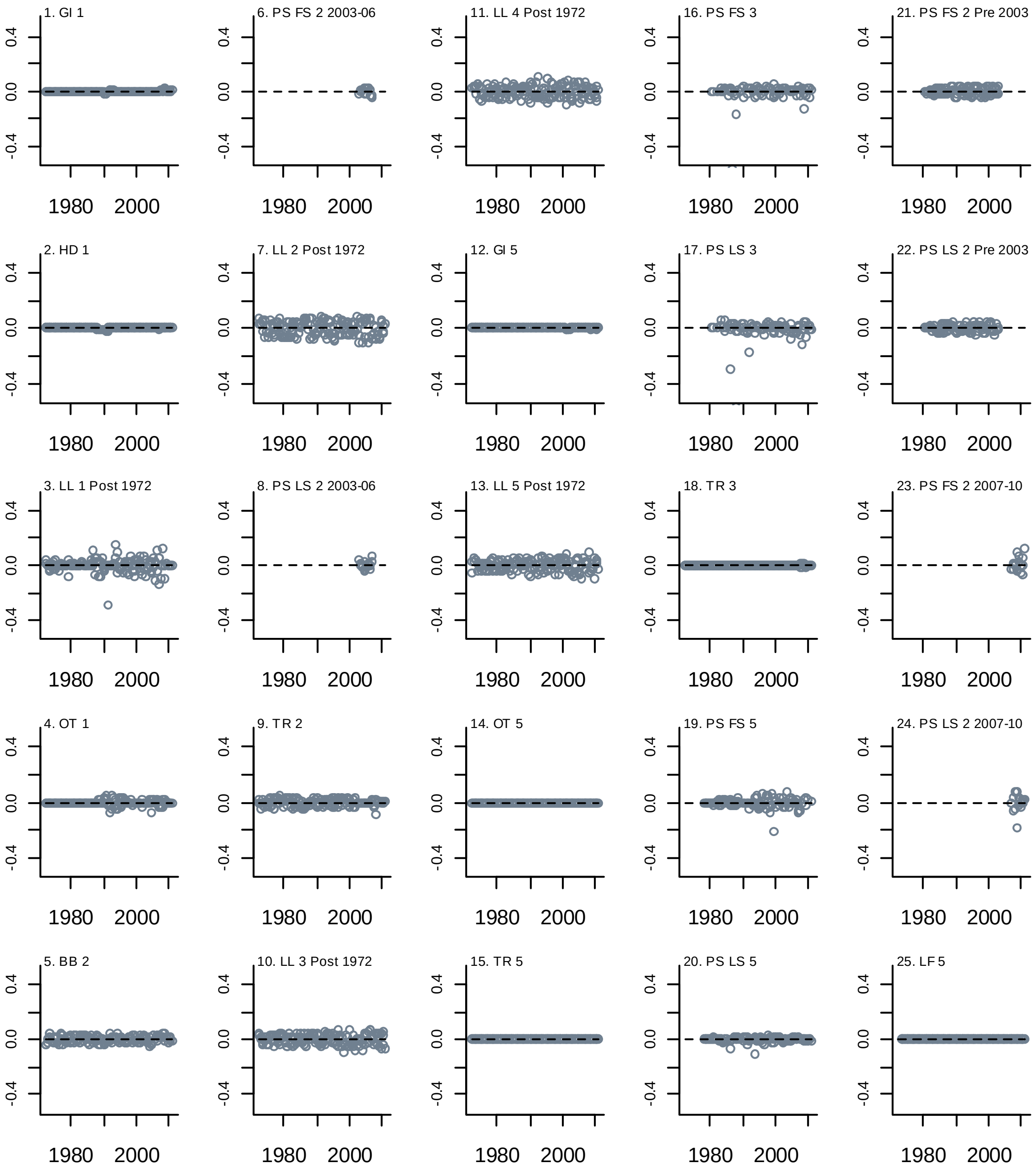


Figure 13. Residuals of ln (total catch) for each fishery.

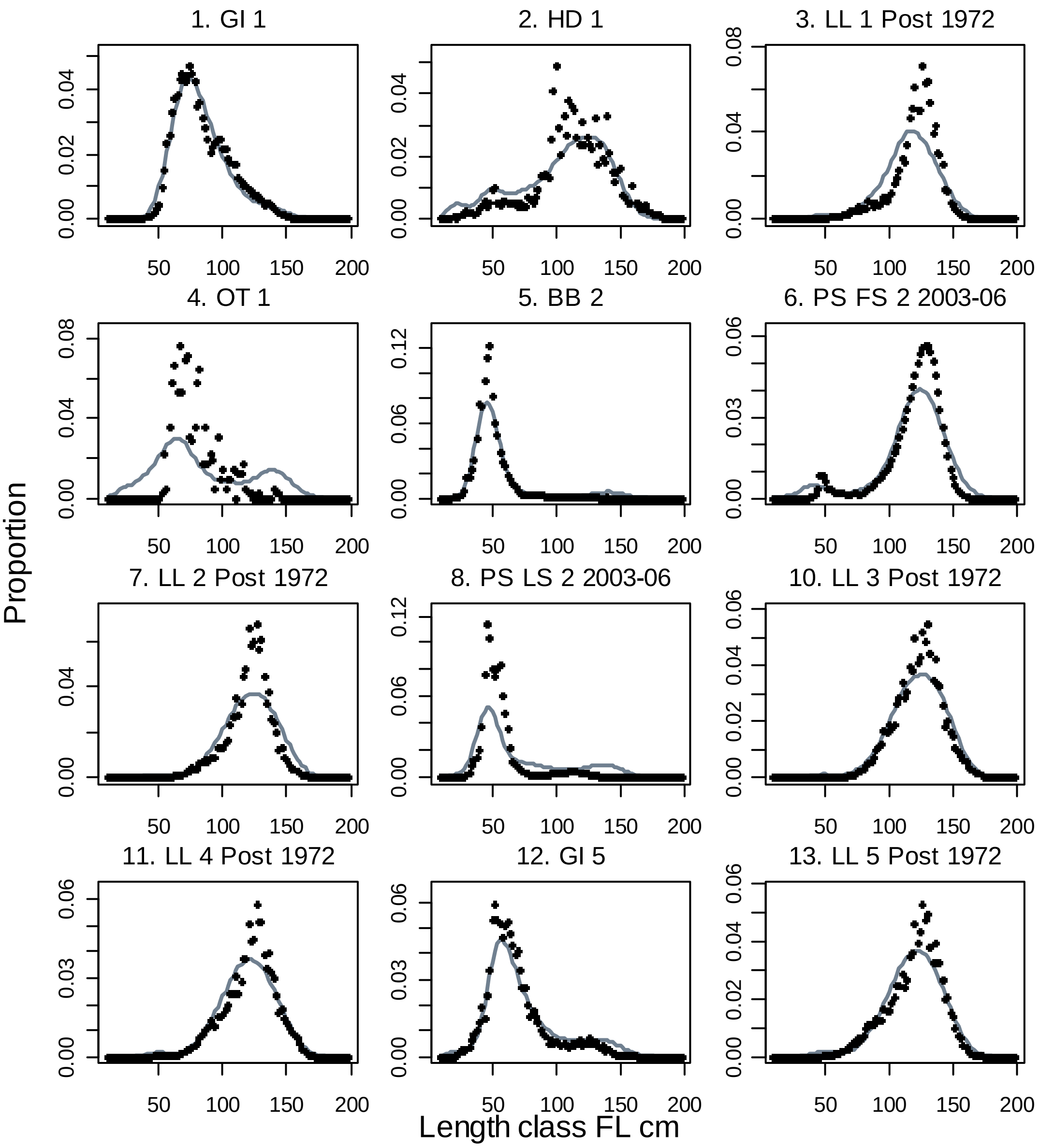


Figure 14. Observed (points) and predicted (line) length frequencies (in cm) for each fishery aggregated over time.

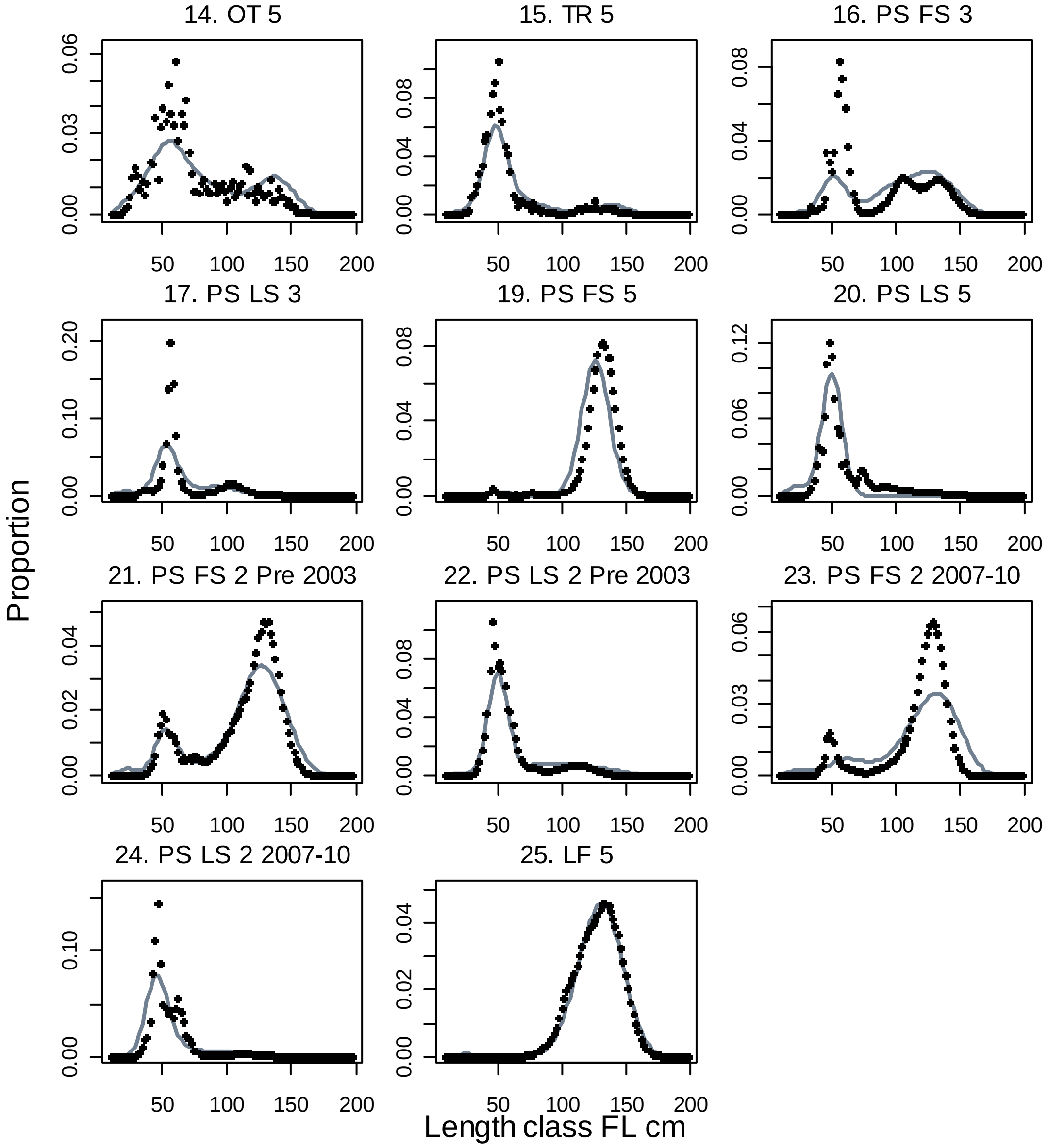


Figure 14 continued

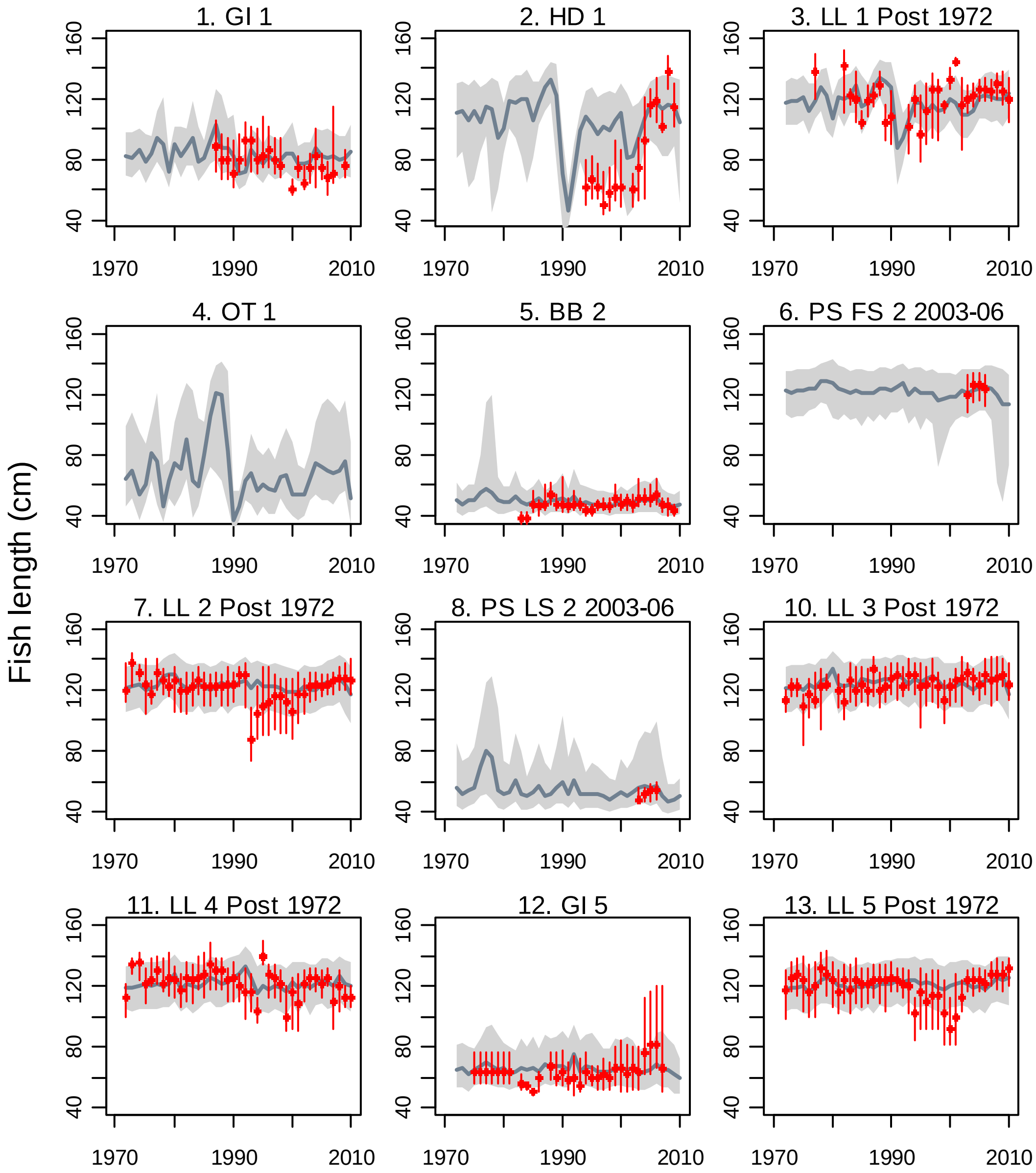


Figure 15. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of yellowfin tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

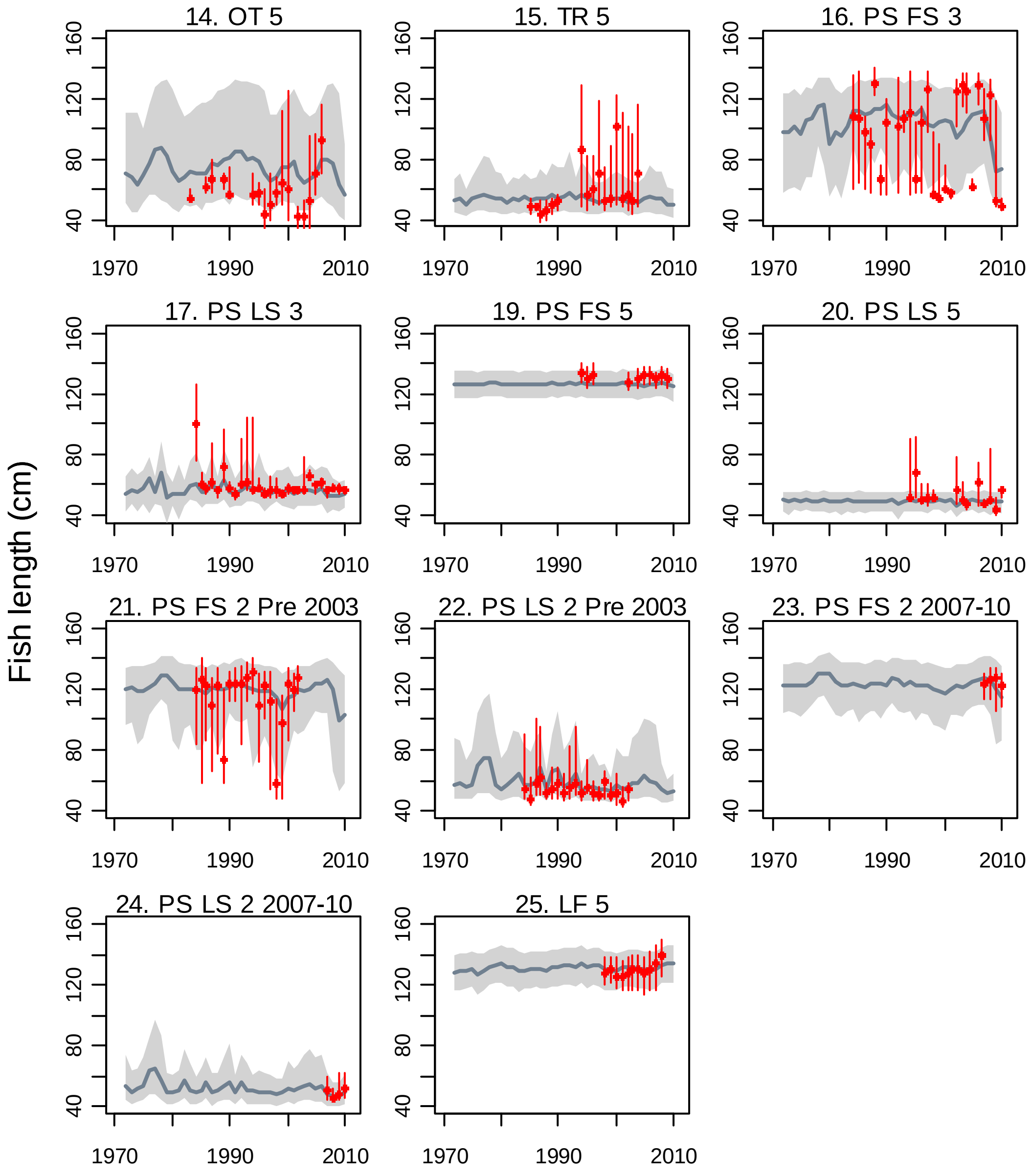


Figure 15 continued.

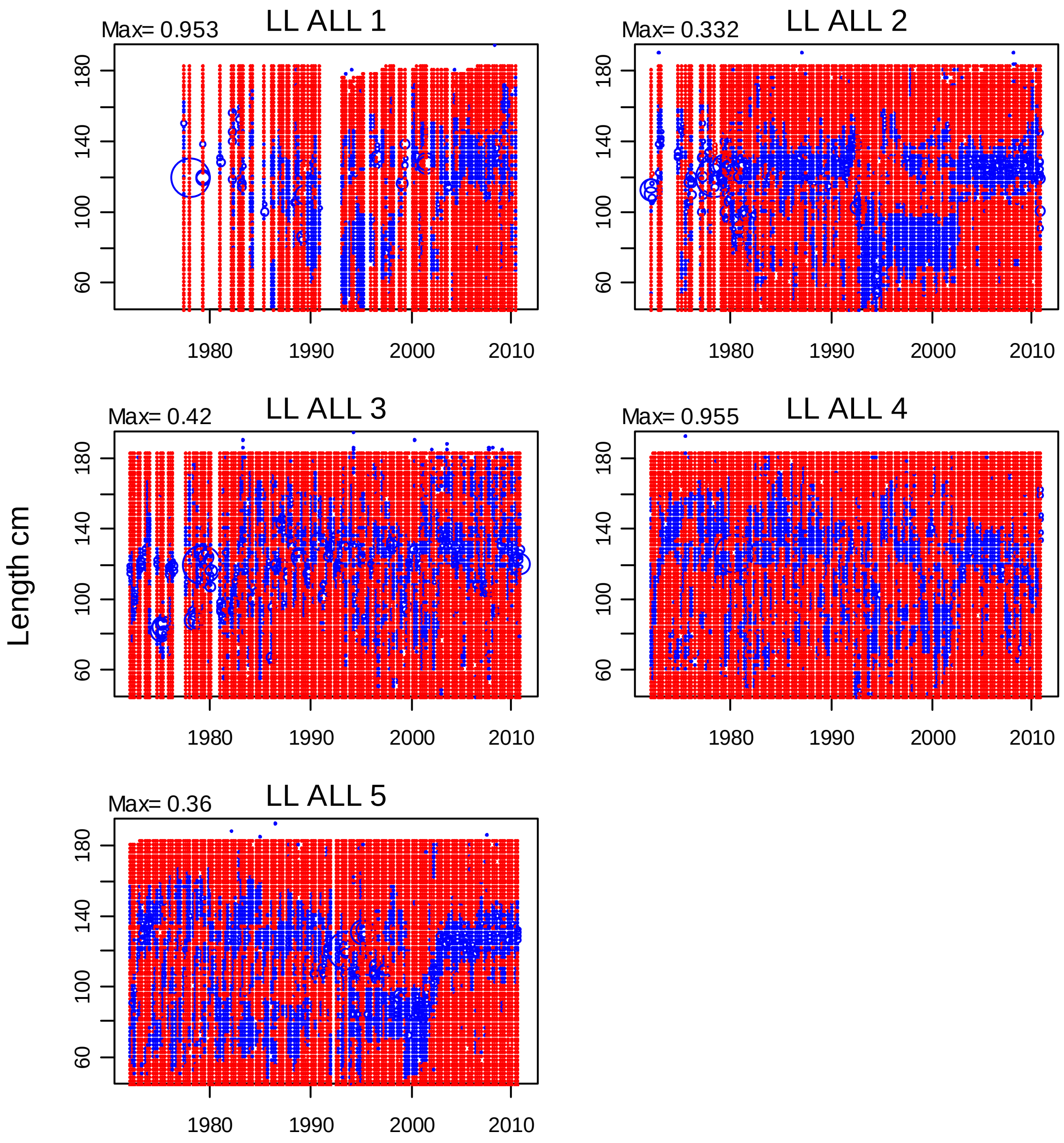


Figure 16: Residuals (observed – predicted proportions) of the fit to the length frequency data from each of the principal longline fisheries. The size of the circle is proportional to the residual; blue circles are positive residuals, red circles negative residuals. The maximum residual is given for each fishery.

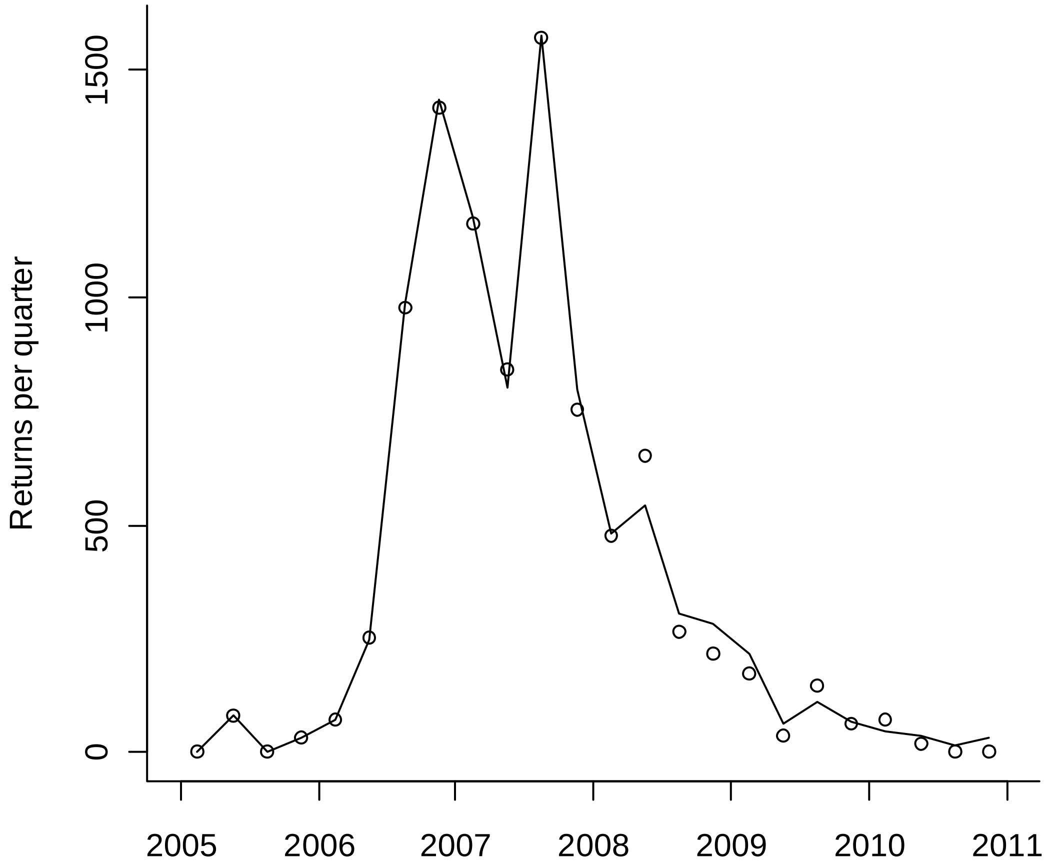


Figure 17. Number of observed (points) and predicted (line) tag returns by recapture period (quarter). Observed tag returns have been corrected for the purse-seine reporting rate (see text for details). The data includes tags recovered during the mixing phase.

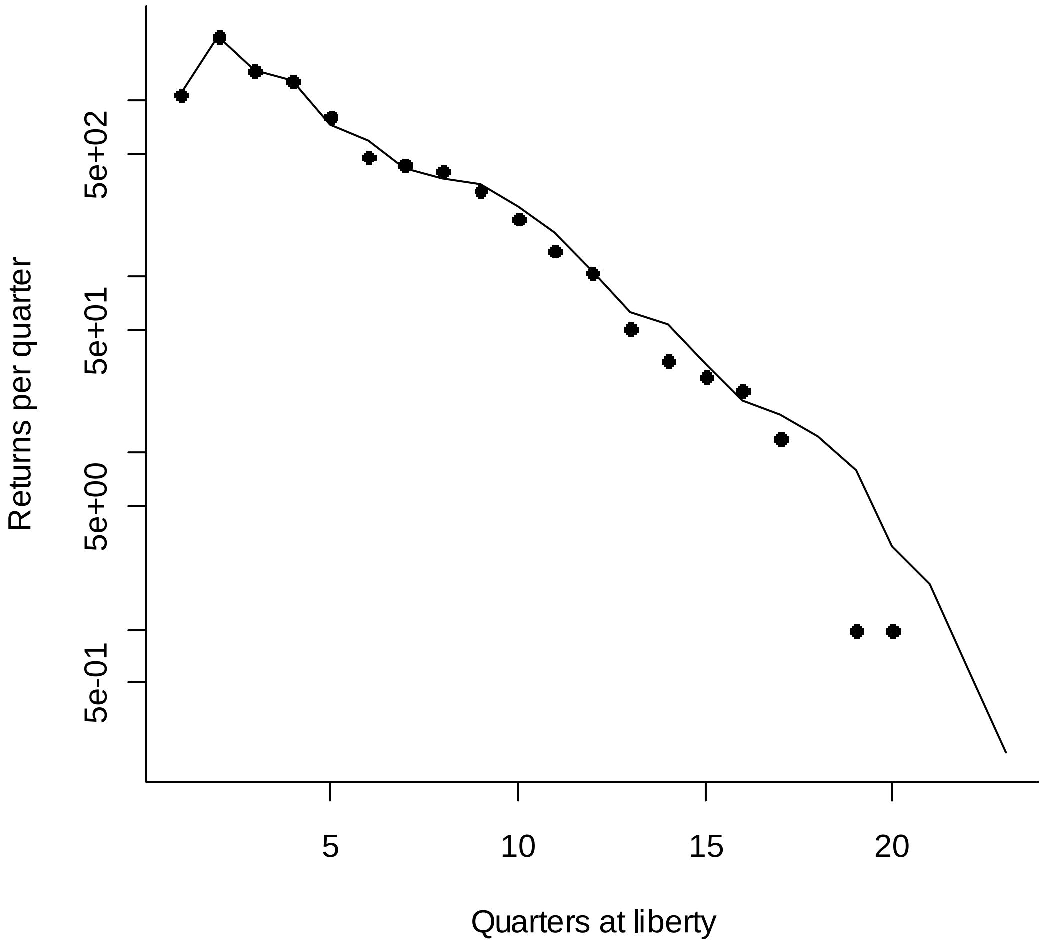


Figure 18. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters). Observed tag returns have been corrected for the purse-seine reporting rate (see text for details). The first four quarters are considered to represent the mixing phase and these data are not included in the model fit.

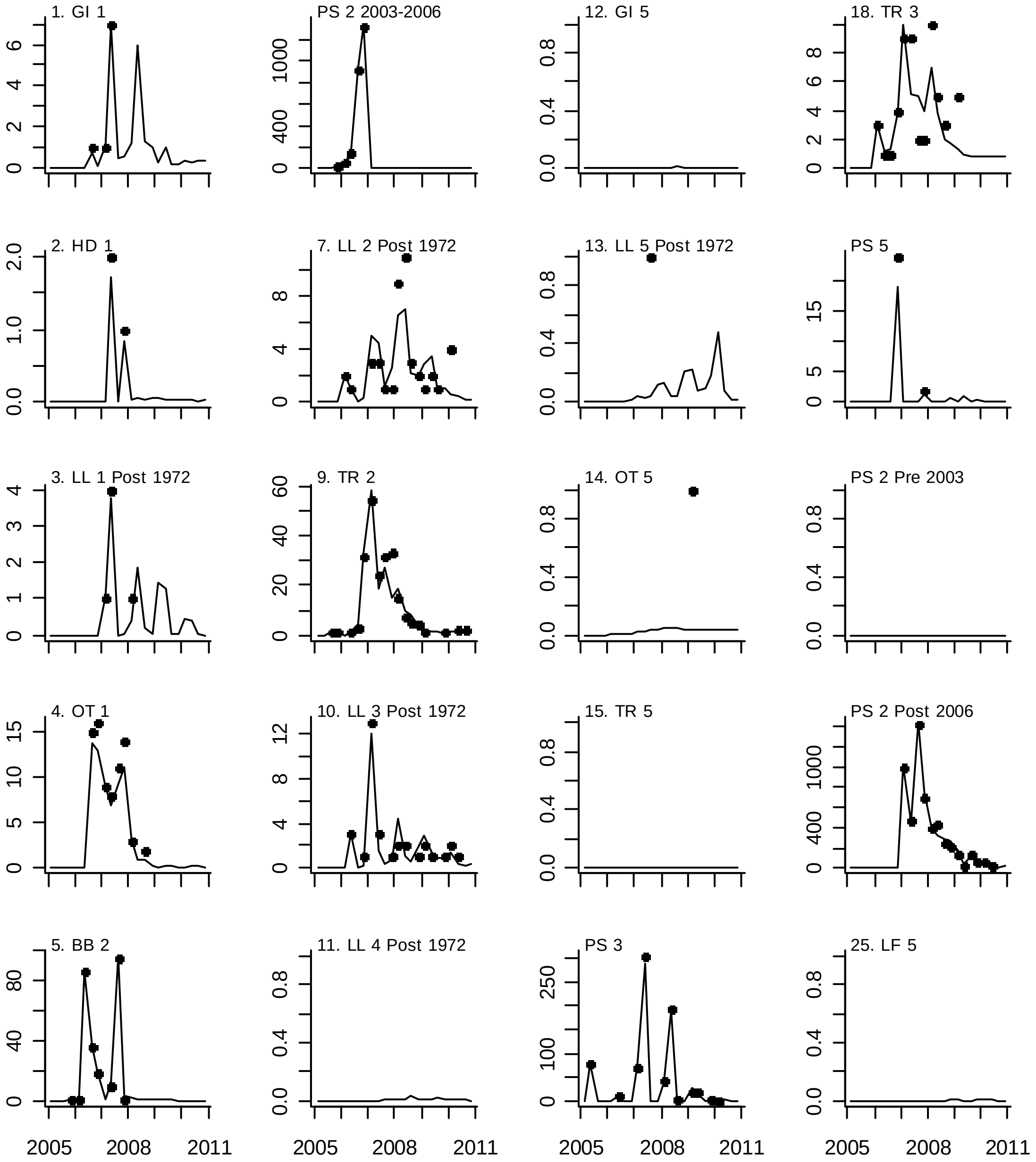


Figure 19. Number of observed (points) and predicted (line) tag returns by recapture period (quarter) for the various fisheries (or groups of fisheries) defined in the model. Observed tag returns have been corrected for the purse-seine reporting rate (see text for details).

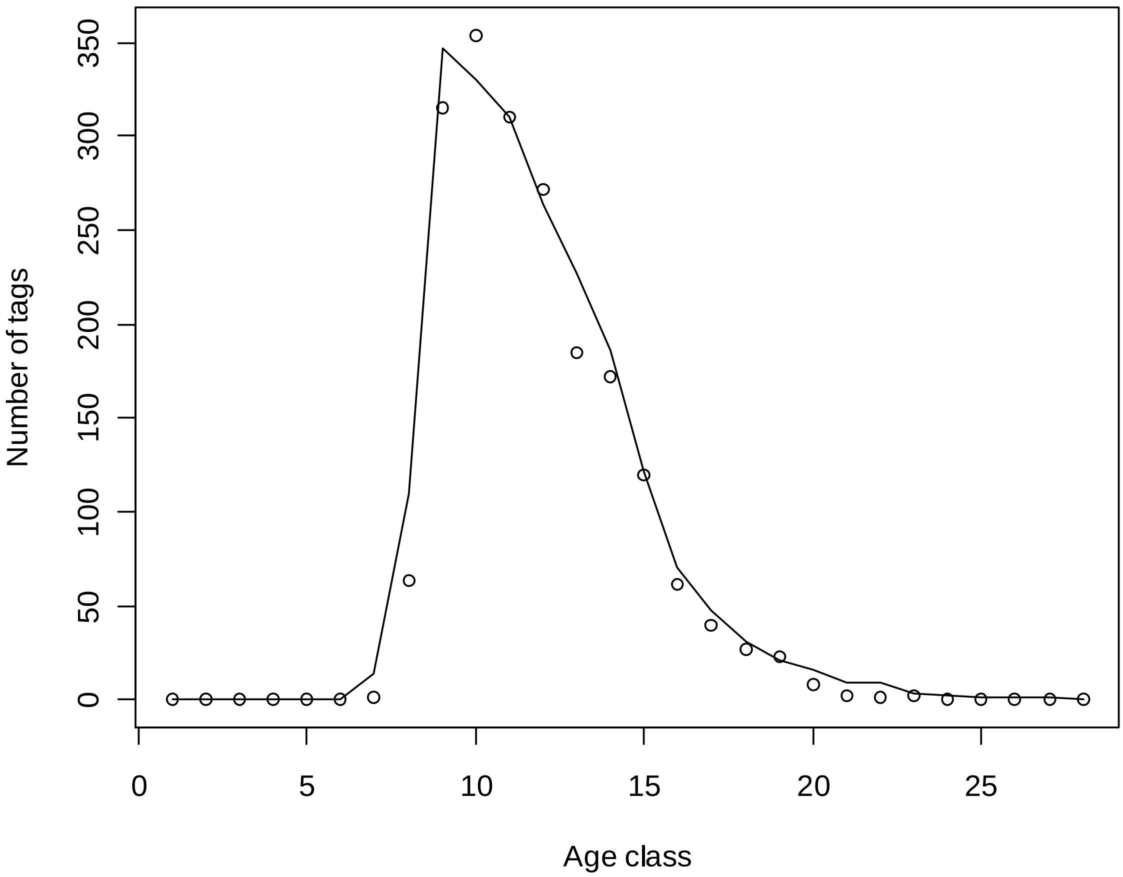


Figure 20. Observed (points) and predicted (line) number of tag recoveries by quarterly age class for the aggregated purse seine fisheries in region 2 (excludes mixing period).

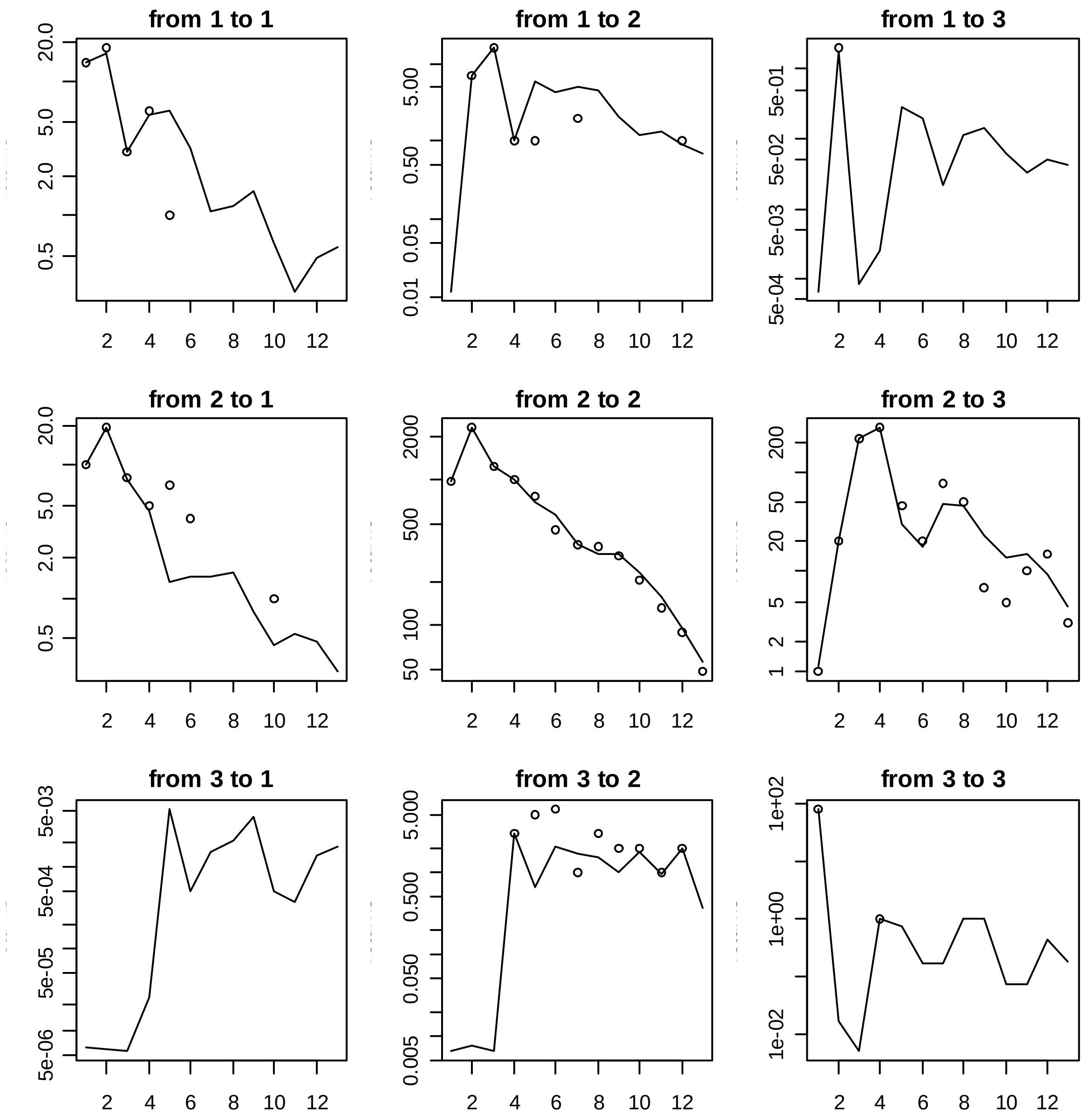


Figure 21. Observed (points) and predicted (line) number of tags recovered from releases in a specific region (from *regionx*) and recoveries in a specific region (to *regiony*) by quarter at liberty. Only release/recovery combinations with a least three recovered tags are presented.

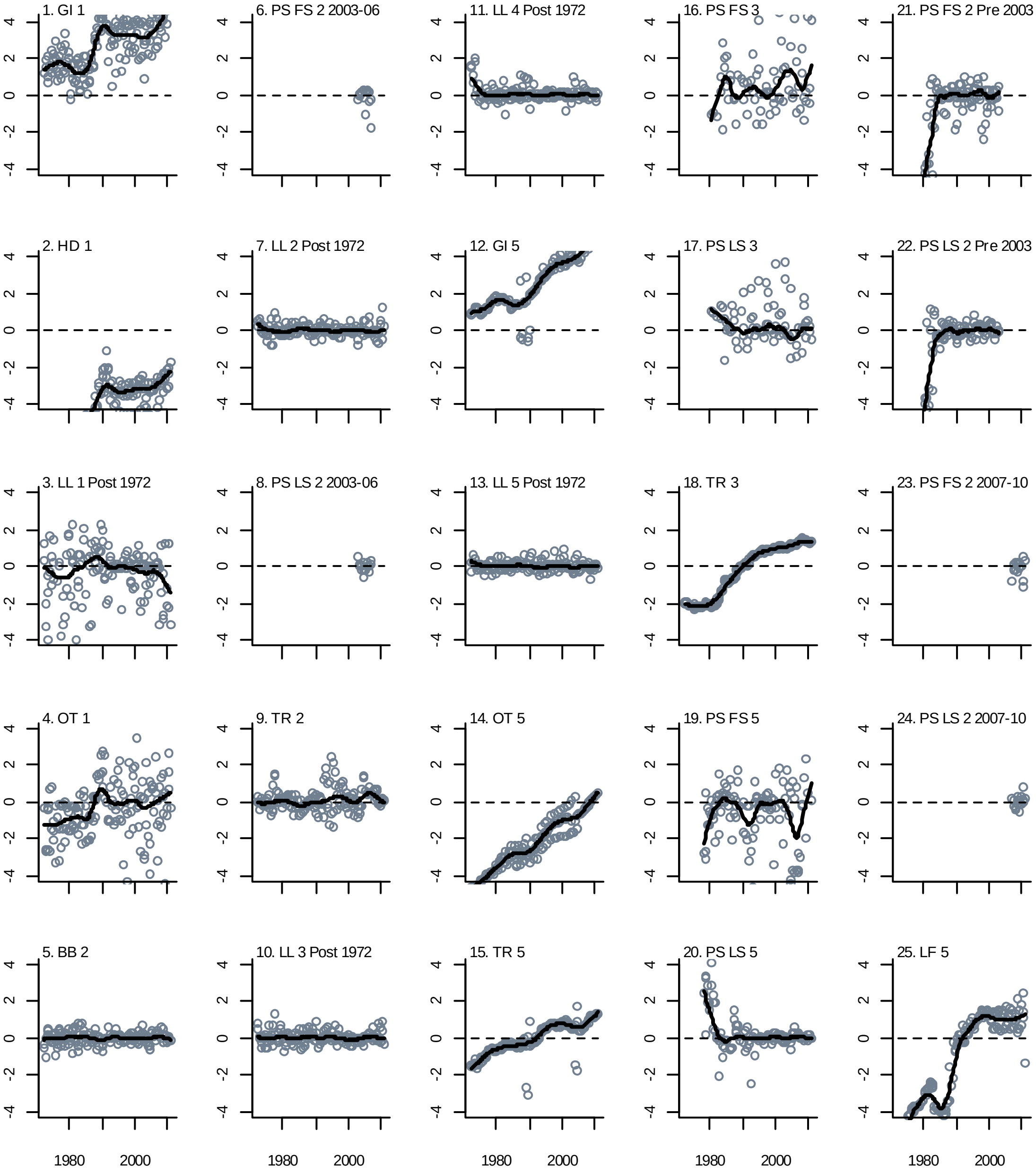


Figure 22. Effort deviations by time period for each fishery. The solid line represents a lowess fit to the data.

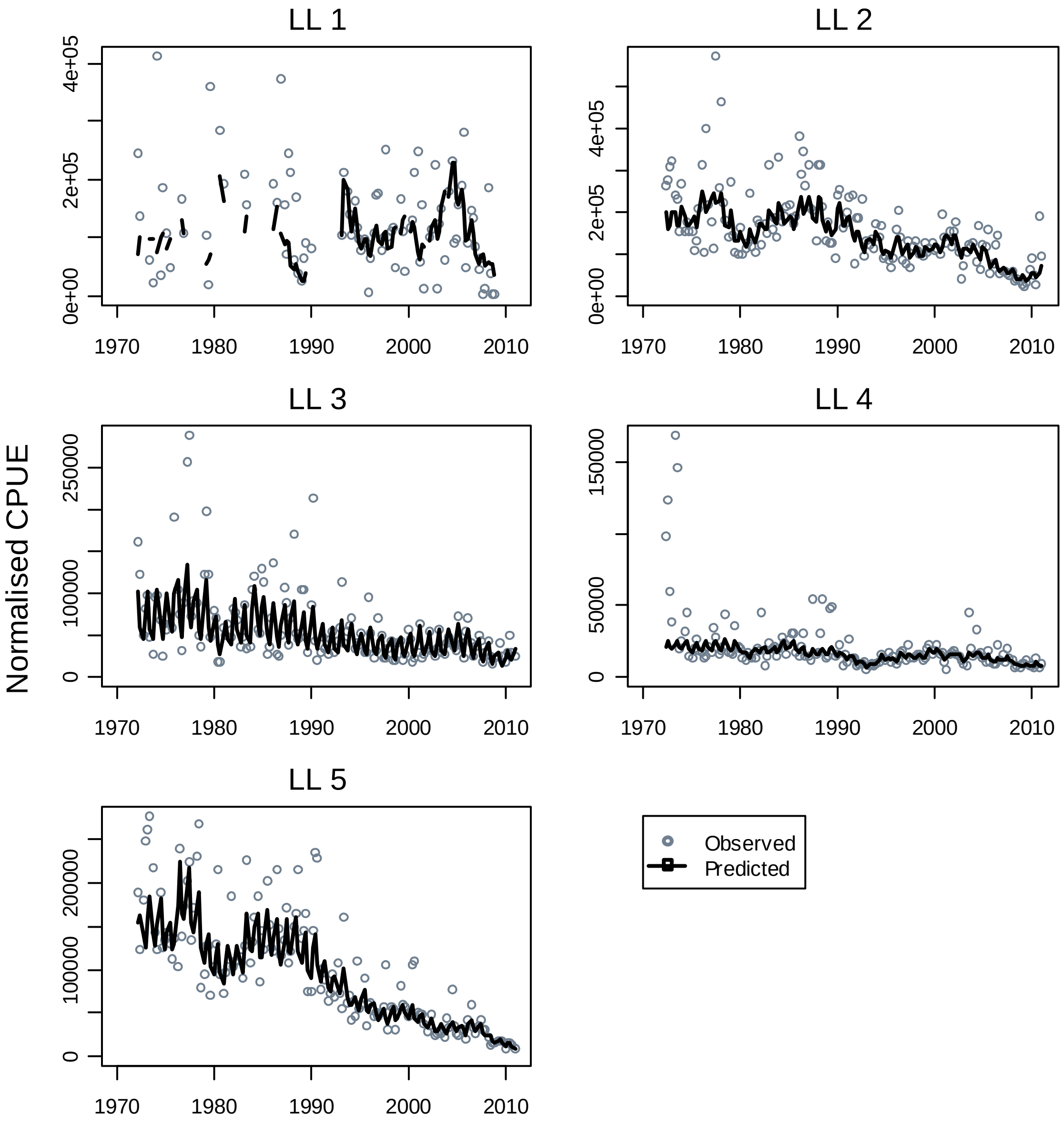


Figure 23. A comparison of longline exploitable biomass by quarter and region (predicted) and the quarterly standardised CPUE indices (observed) for the fisheries.

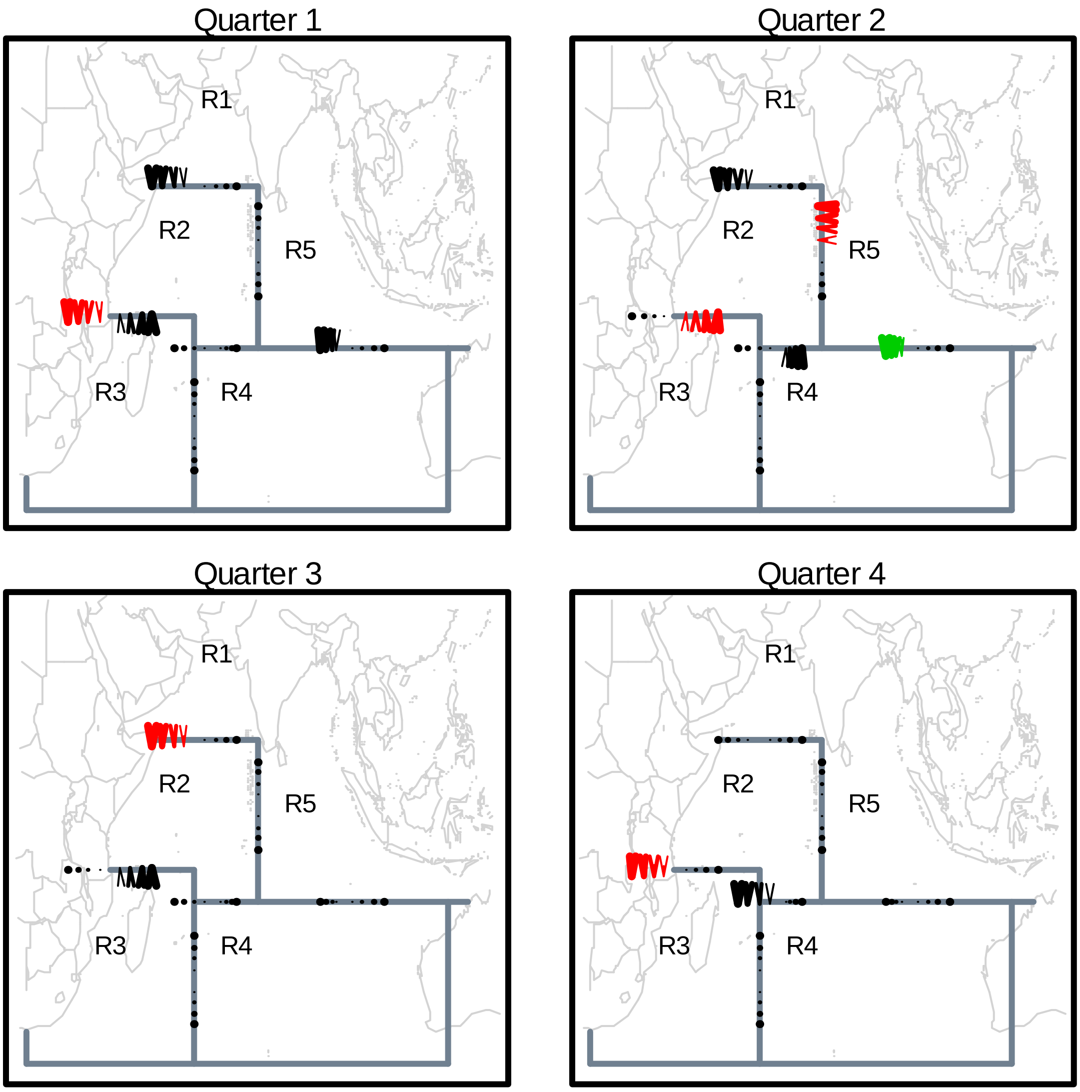


Figure 24. Estimated quarterly movement coefficients at age (1, 7, 15, 25 quarters) from the base-case model. The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age. The maximum movement (quarter 2, region 4 to region 5) represents movement of 12.8% of the fish at the start of the quarter. Movement rates are colour coded: black, 0.5–5%; red 5–10%; green >10%.

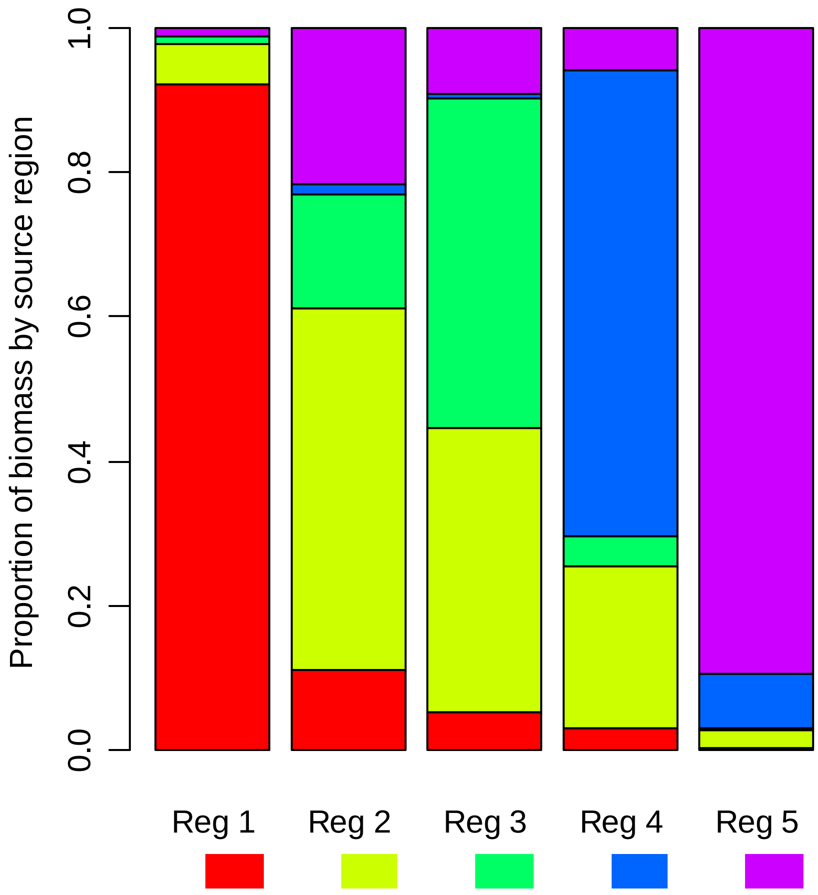


Figure 25. Proportional distribution of total biomass (by weight) in each region (Reg 1–5) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment among regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

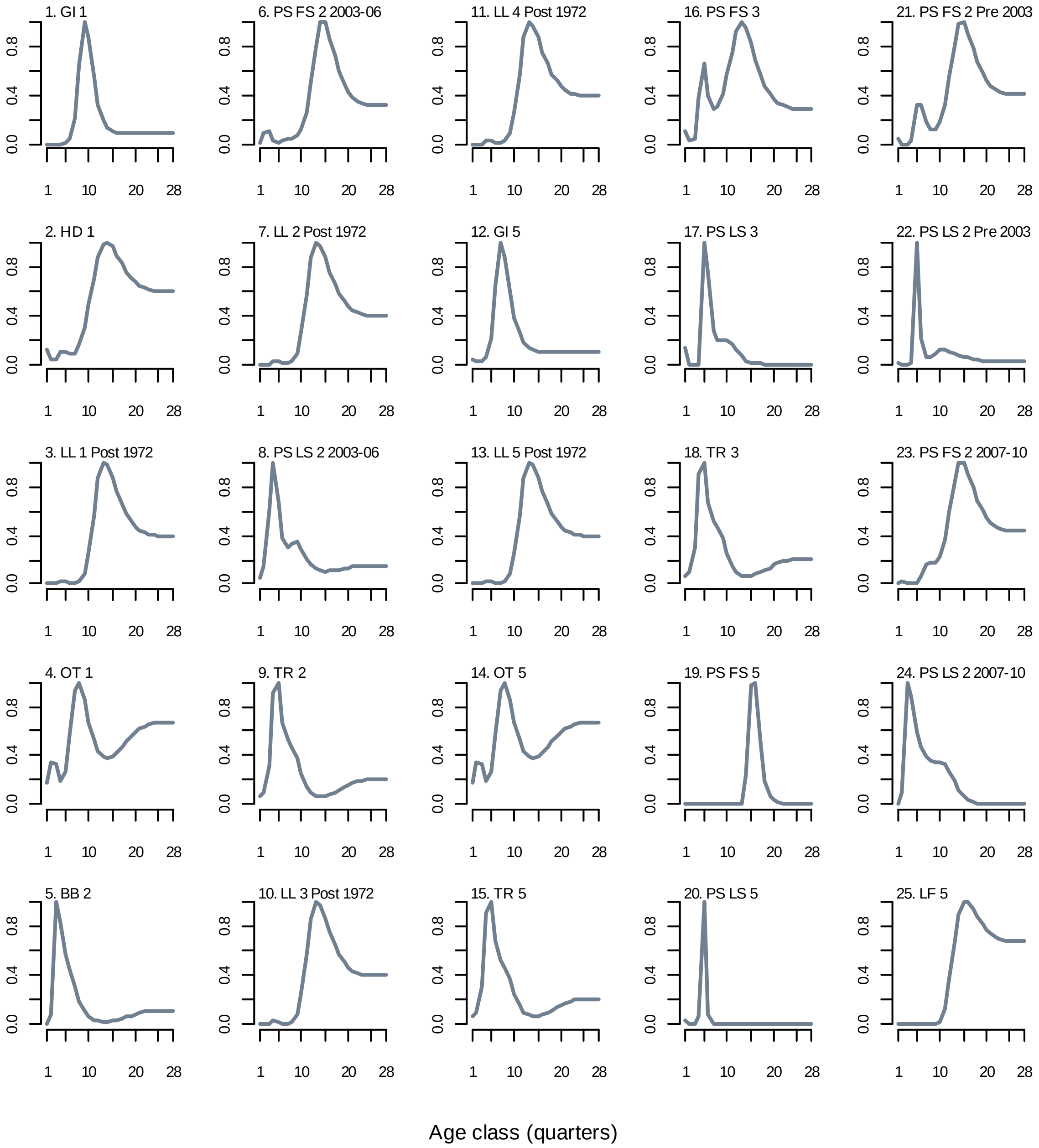


Figure 26. Selectivity coefficients, by fishery.

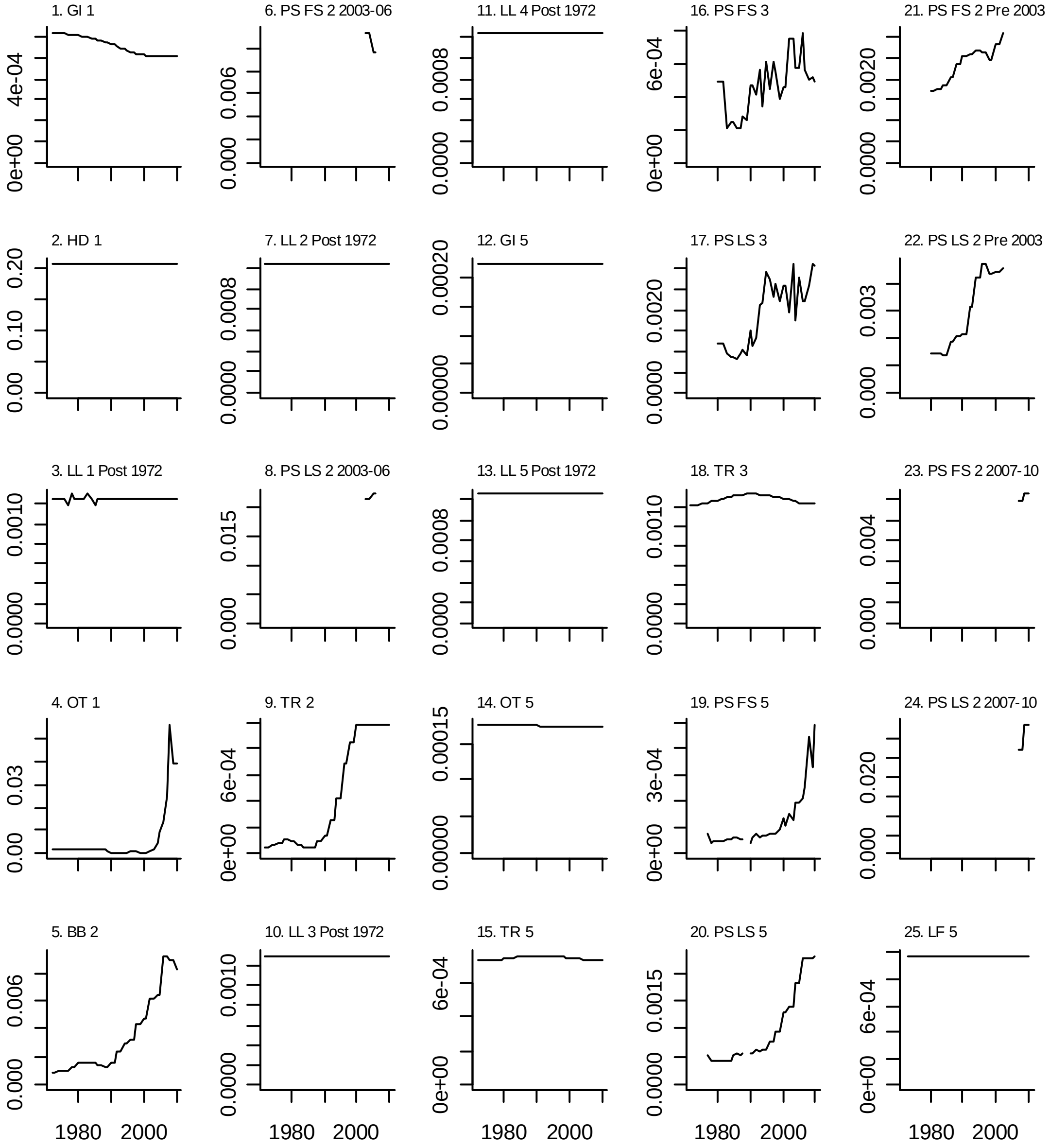


Figure 27. Average annual catchability time series, by fishery.

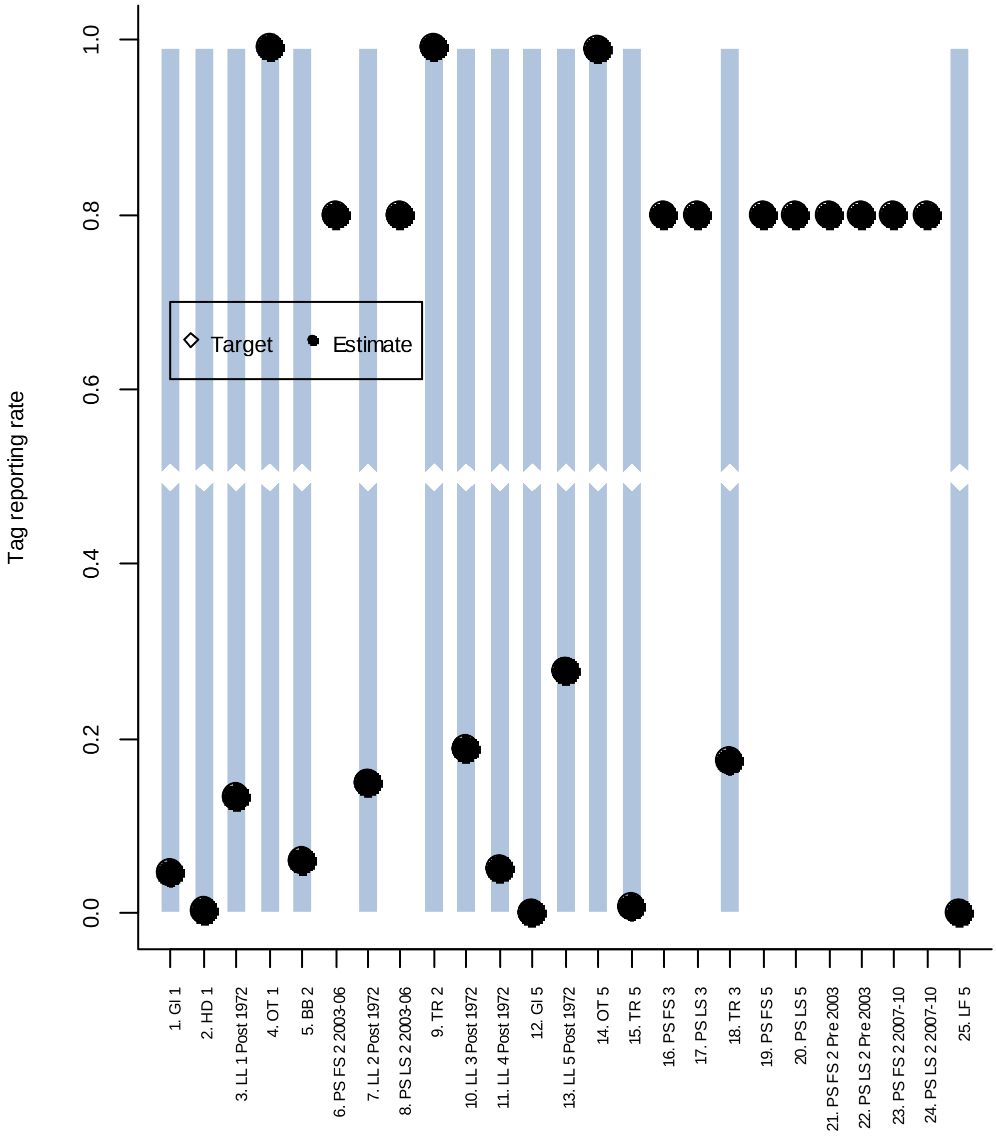


Figure 28. Estimated tag-reporting rates by fishery (black circles). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars indicate a range of ±1 SD. The reporting rates for the purse-seine fishery were fixed.

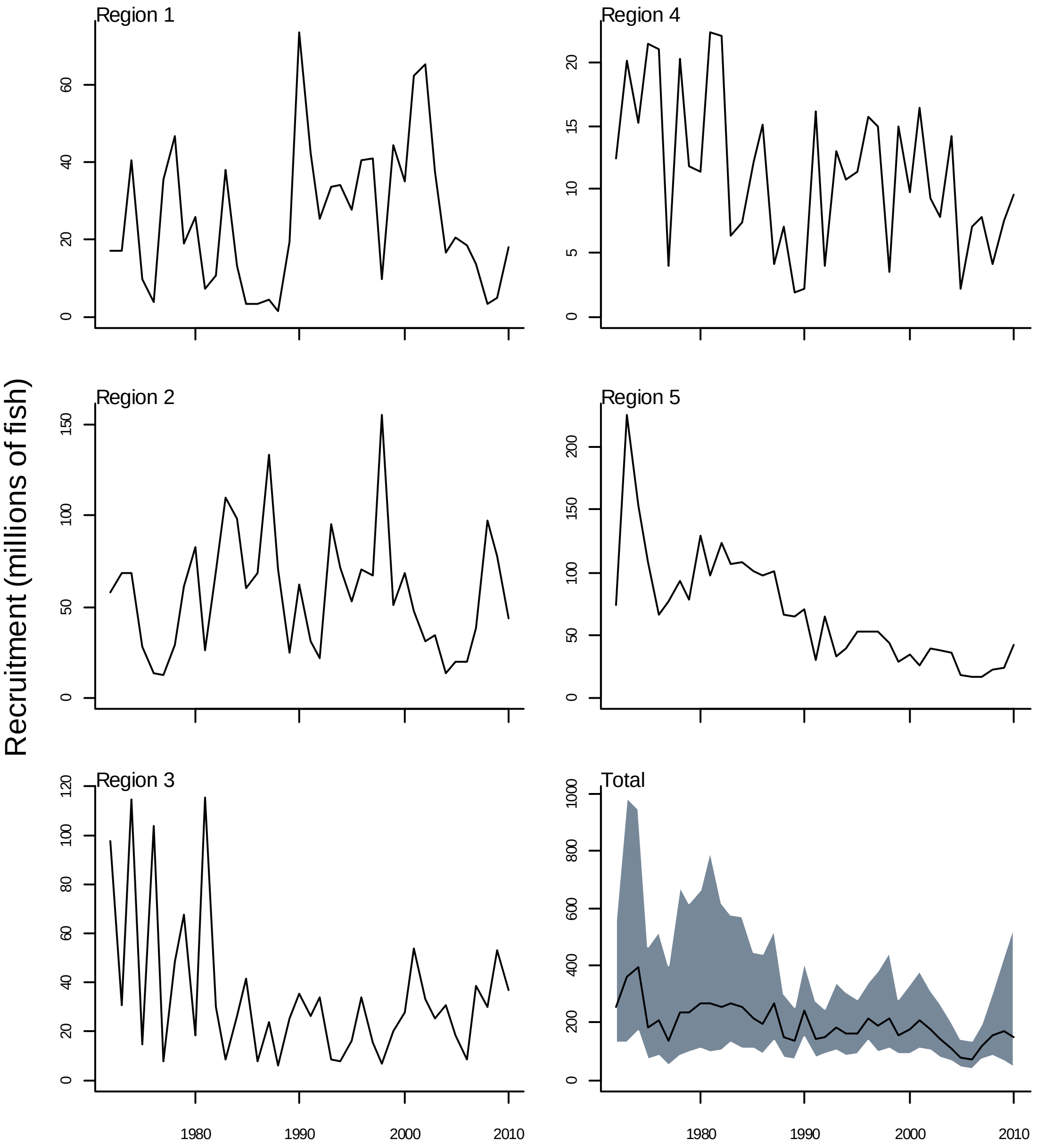


Figure 29. Estimated annual recruitment (millions of fish) by region and for the IO. The shaded area for the IO indicates the approximate 95% confidence intervals.

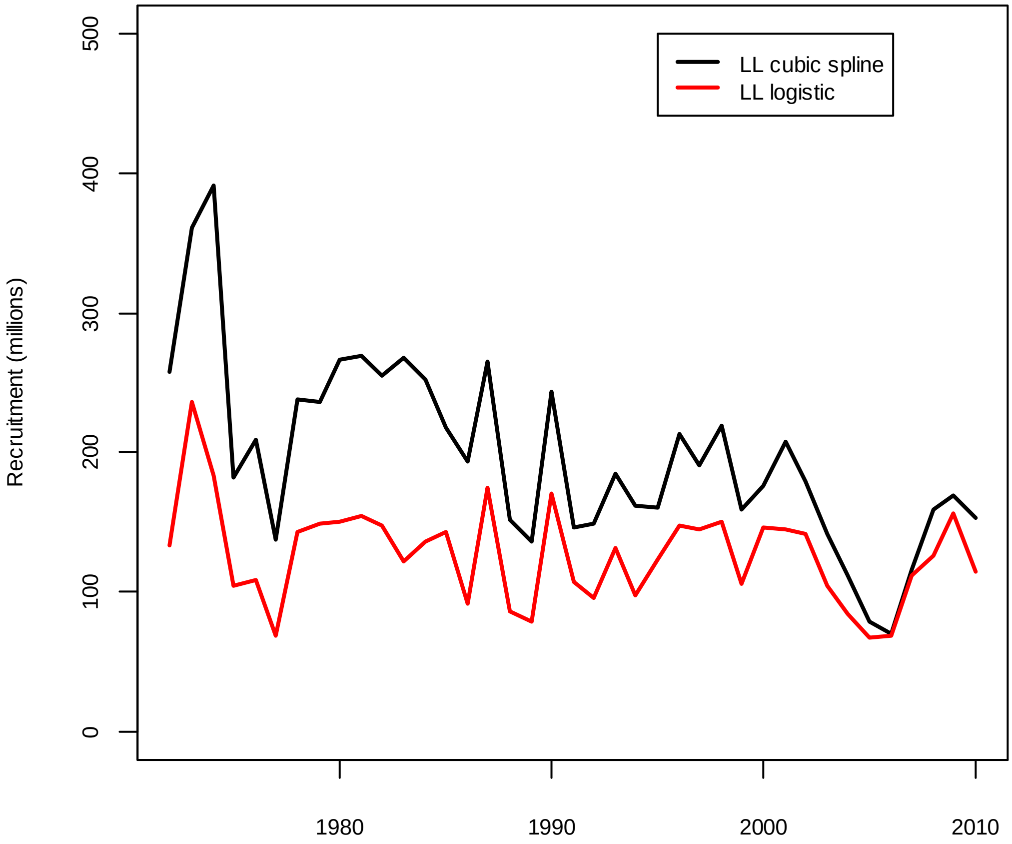


Figure 30. Estimated annual recruitment (millions of fish) for the IO from the two model options with different assumptions regarding longline selectivity.

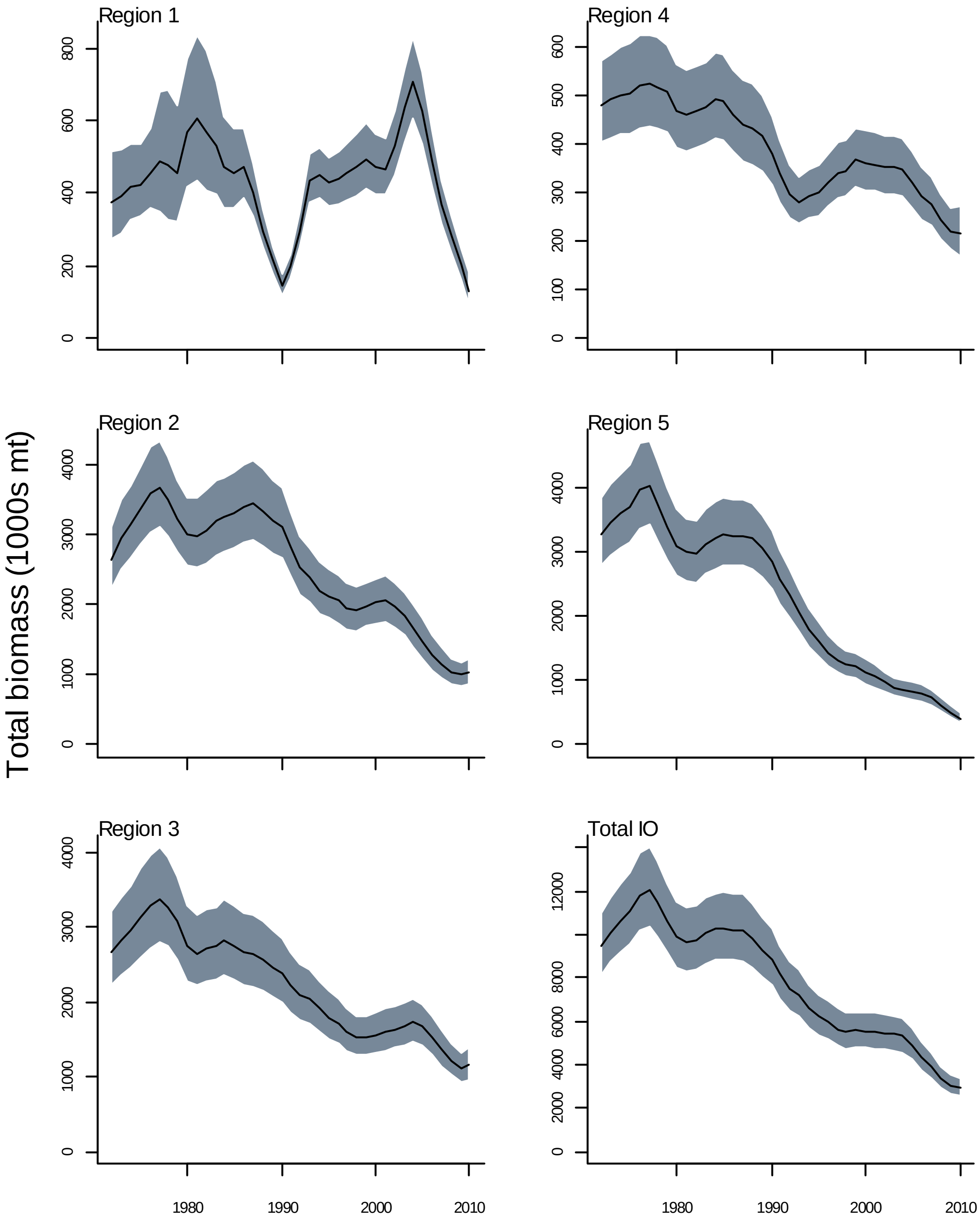


Figure 31. Estimated annual average total biomass (thousand mt) by region and for the IO for the base-case analysis. The shaded areas indicate the approximate 95% confidence intervals.

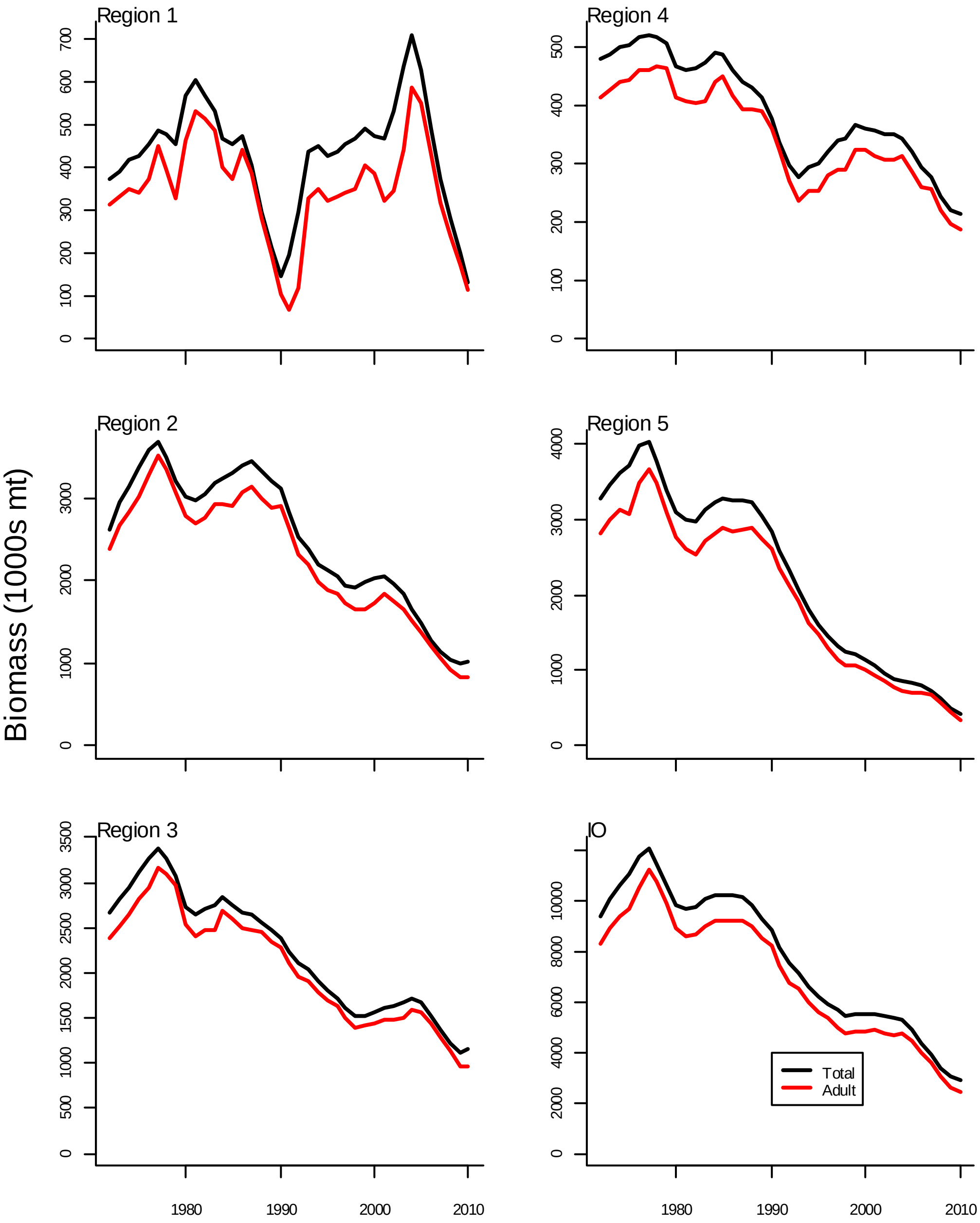


Figure 32. Temporal trend in total and adult biomass (1000s mt) by region and for the entire IO from the base-case assessment.

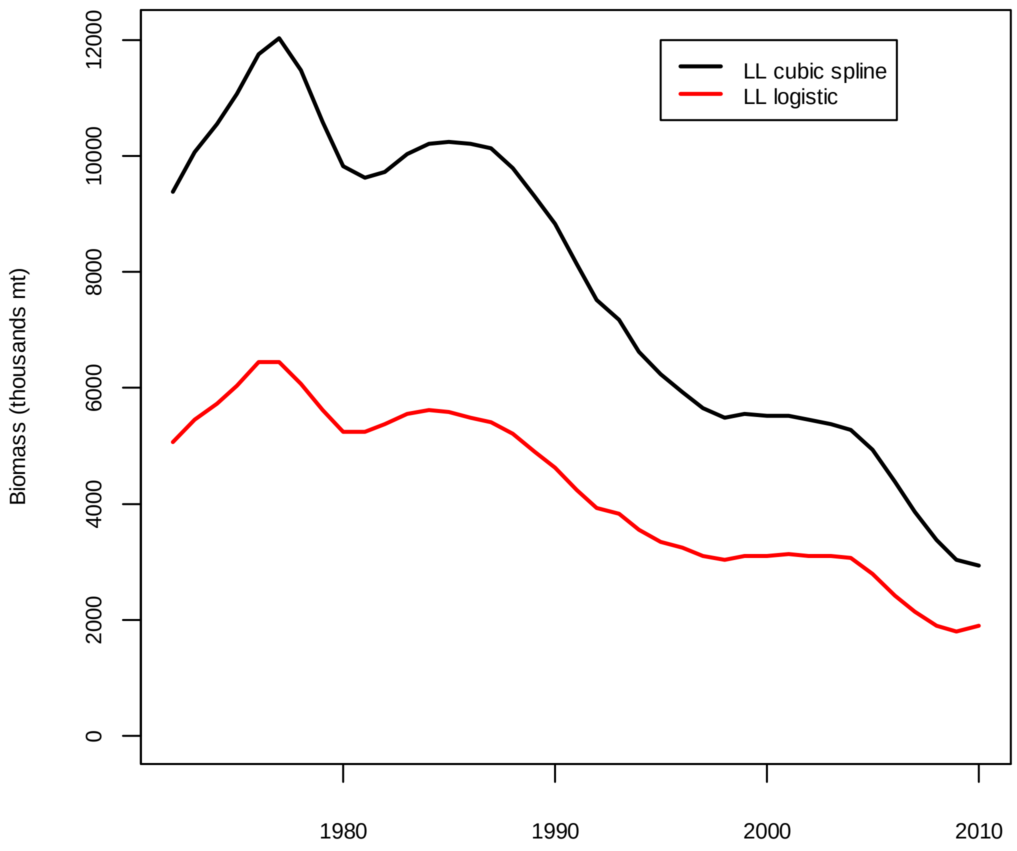


Figure 33a. Estimated annual average total biomass (thousands mt) for the IO from the two model options with different assumptions regarding longline selectivity.

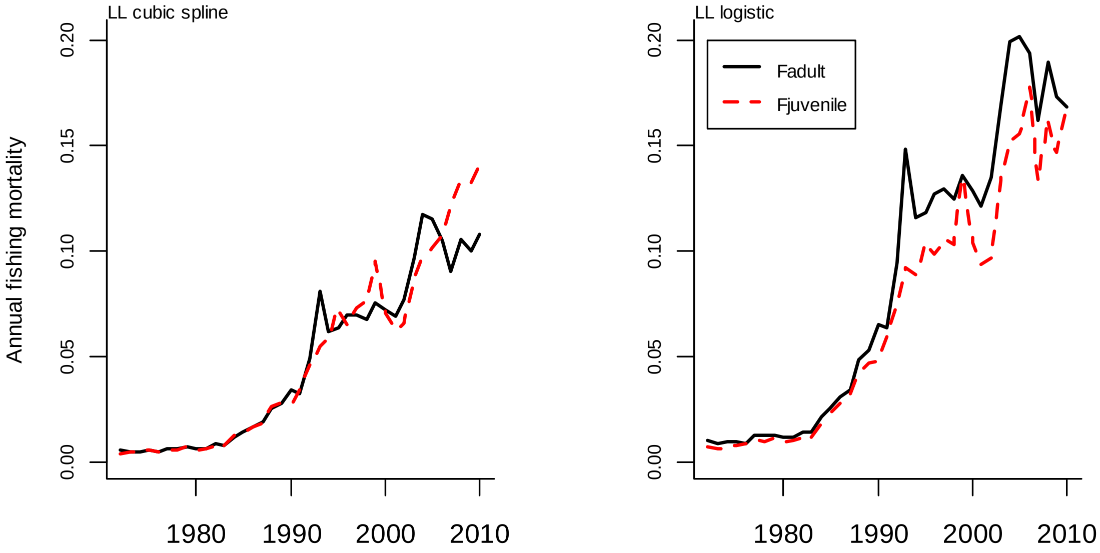


Figure 34. Estimated annual average juvenile and adult fishing mortality for the IO obtained from the separate model options.

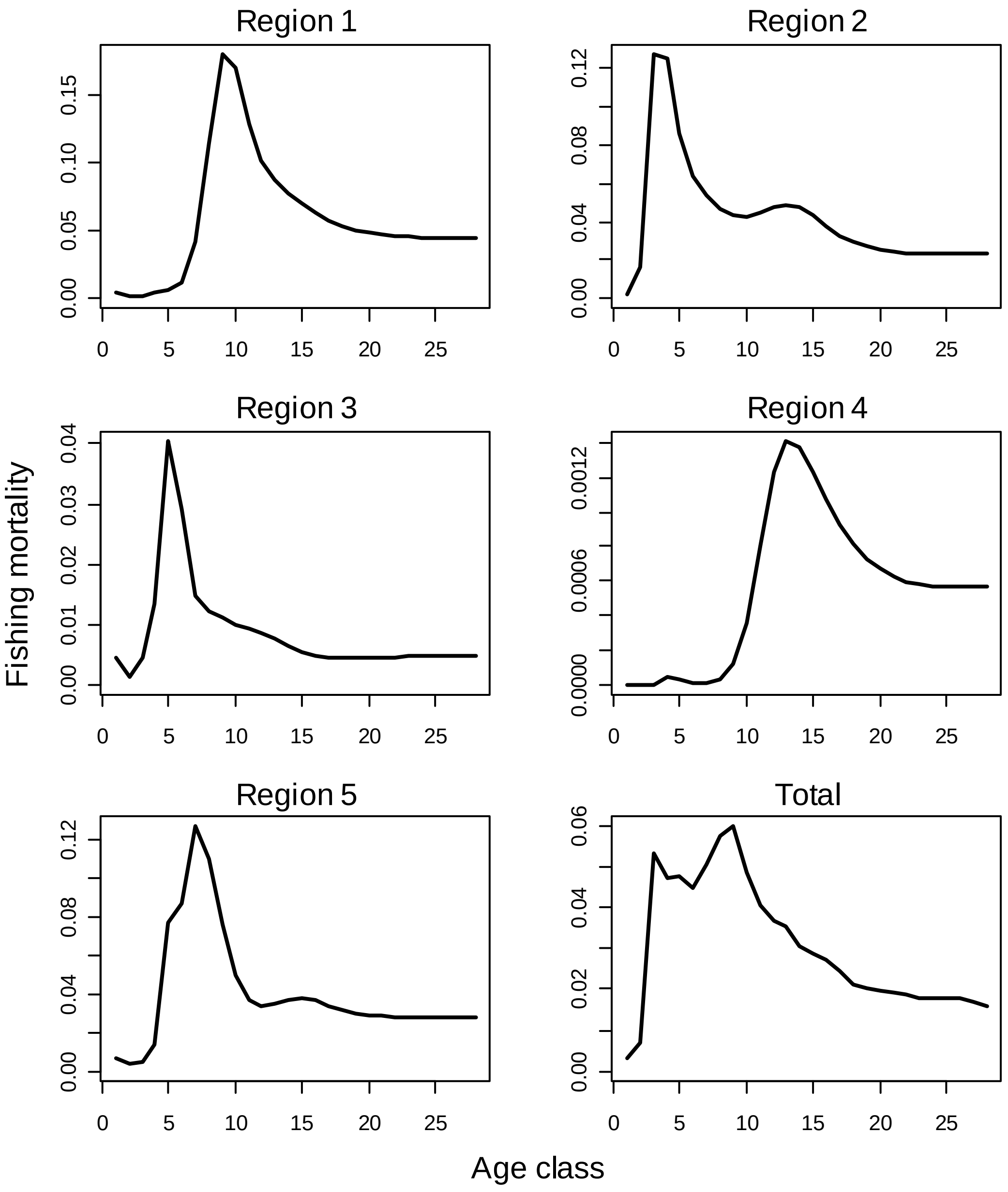


Figure 35. Fishing mortality (quarterly, average) by age class and region for the period used to determine the total F-at-age included in the calculation of MSY based reference points (2006–09). Note that the y-axis varies between plots.

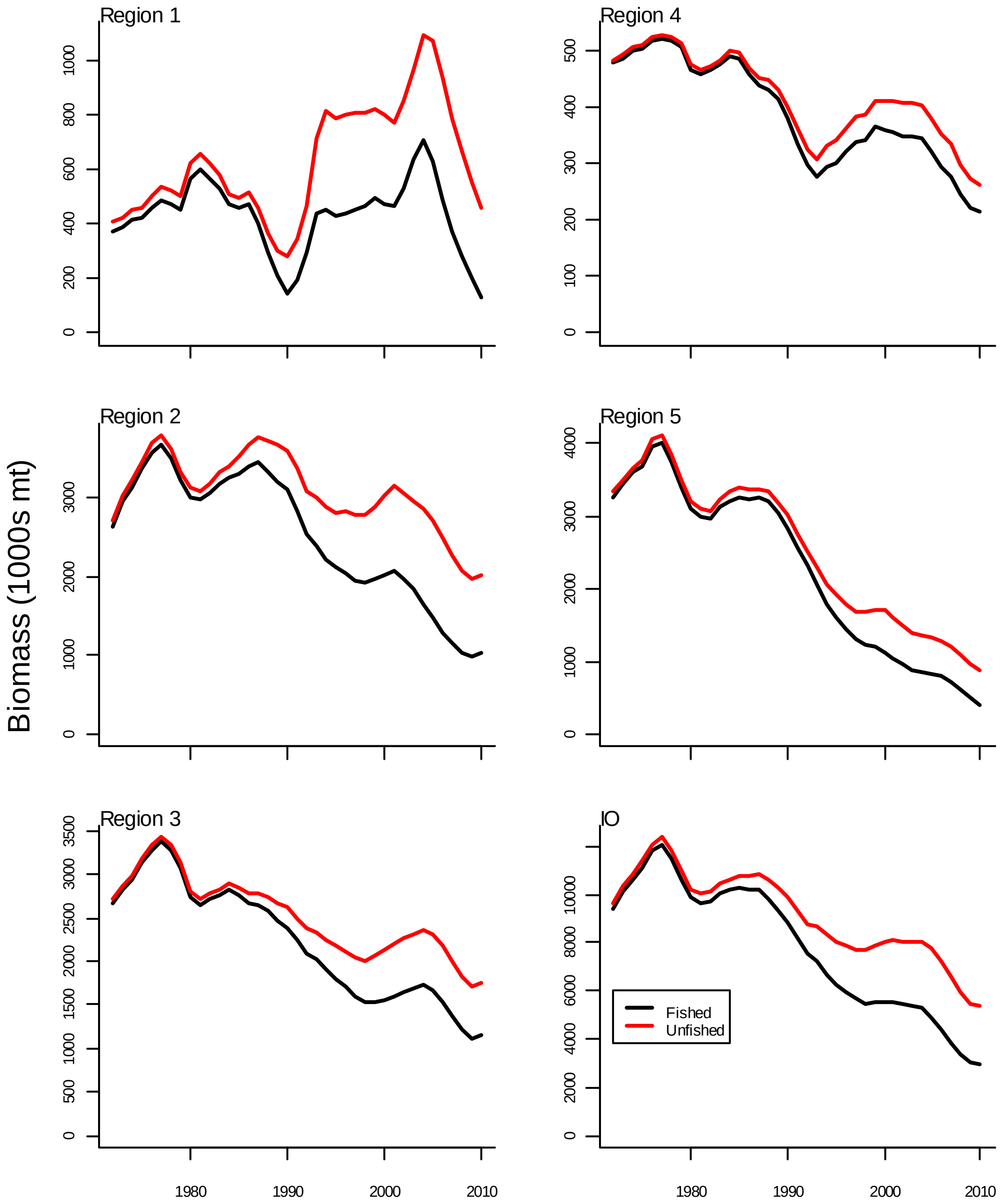


Figure 36. Comparison of the estimated total biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper thin lines) for the base-case model for each region and for the IO.

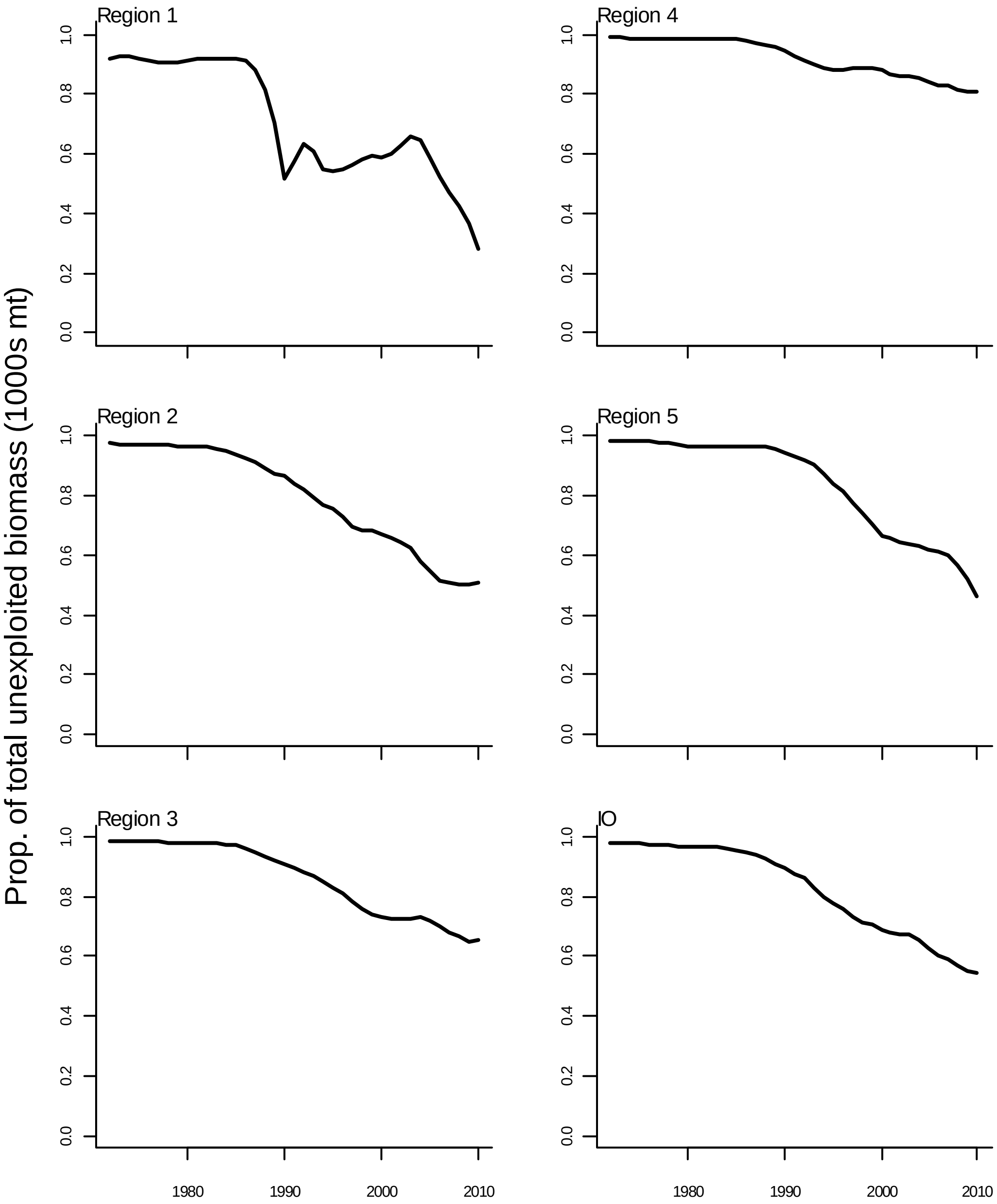


Figure 37. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the IO.

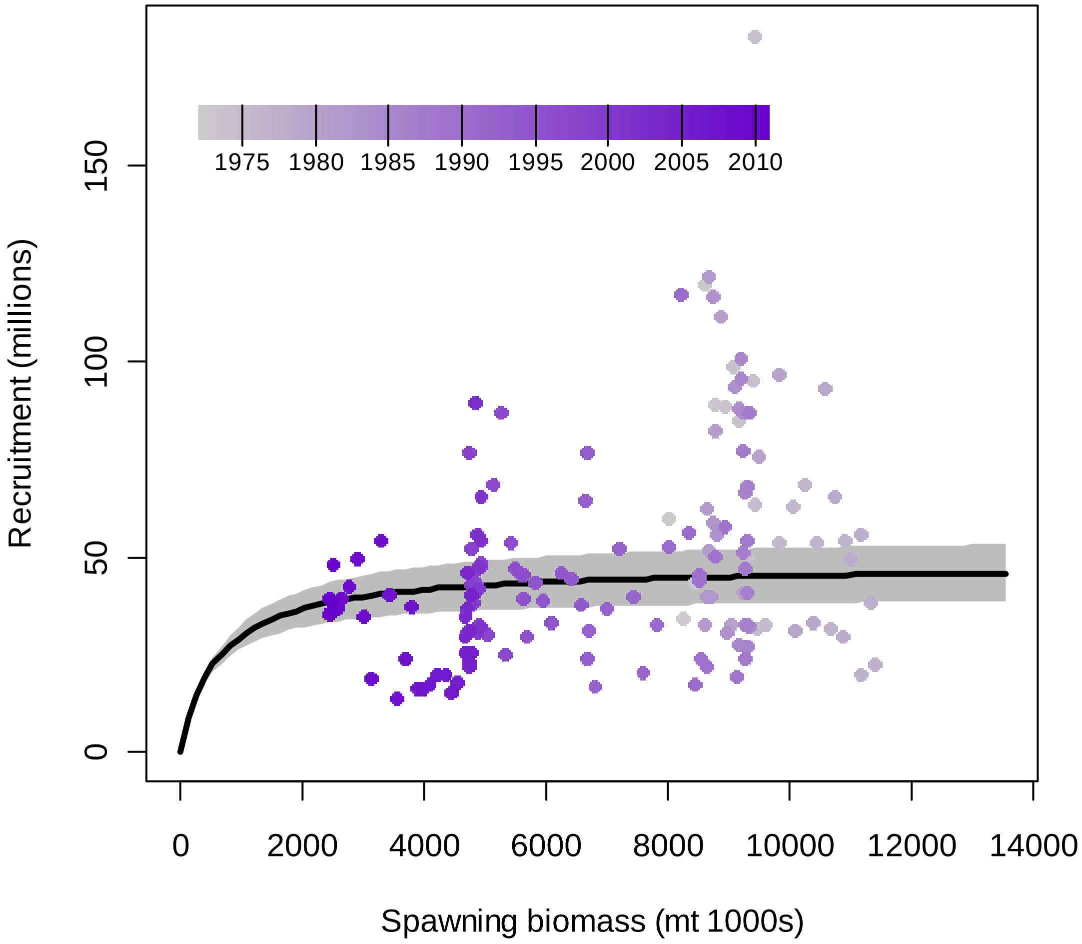


Figure 38. Relationship between equilibrium recruitment and equilibrium spawning biomass for the base-case with steepness of the SRR is fixed at 0.80 (black line). The grey area indicates the 95% confidence region. The points represent the estimated recruitment-spawning biomass and the colour of the points denotes the time period from which the estimate was obtained (see legend).

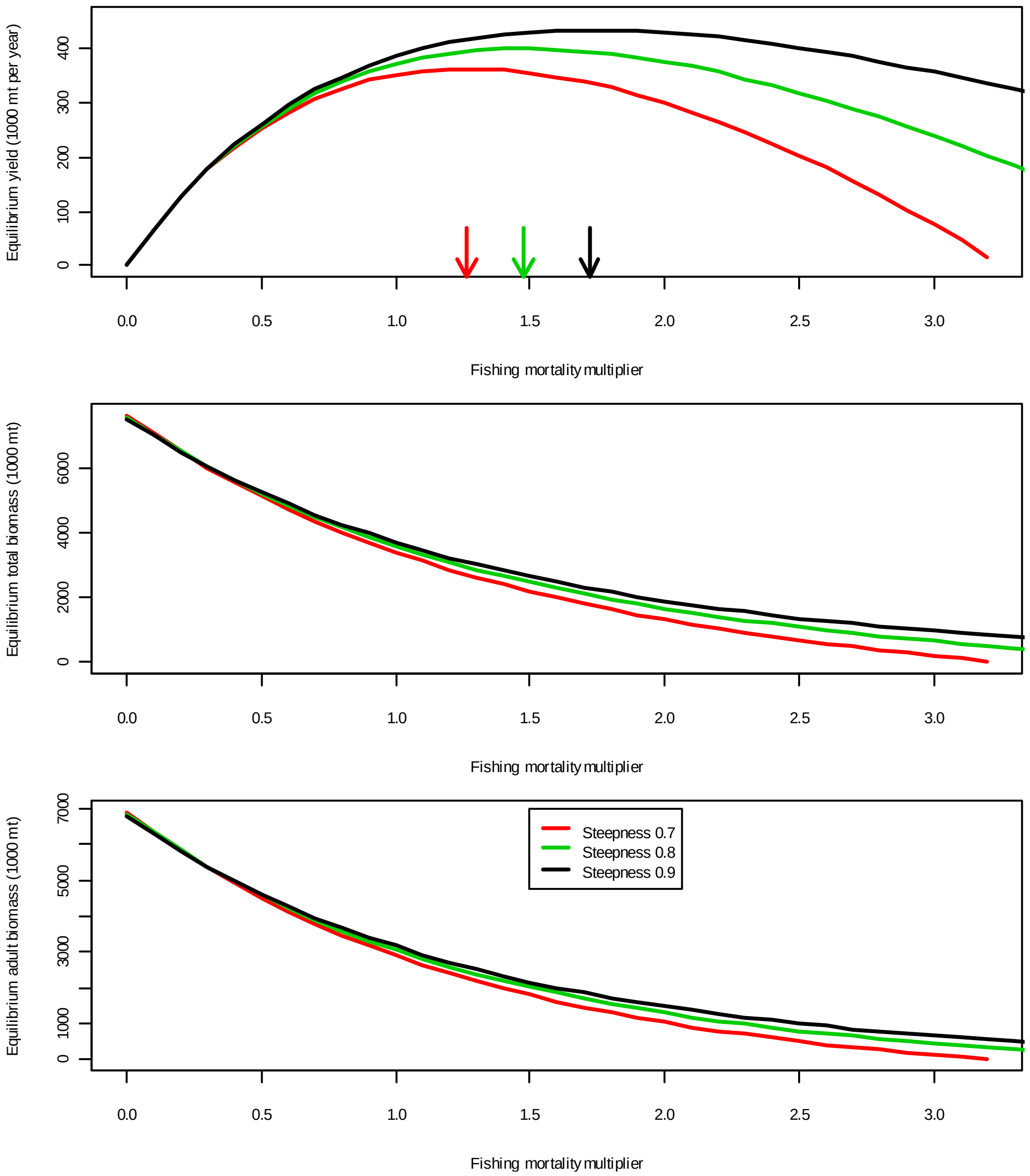


Figure 39a. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier obtained from the *cubic spline longline selectivity* model with three different values for steepness. In the upper panel, the arrows indicate the value of the fishing mortality multiplier at maximum yield.

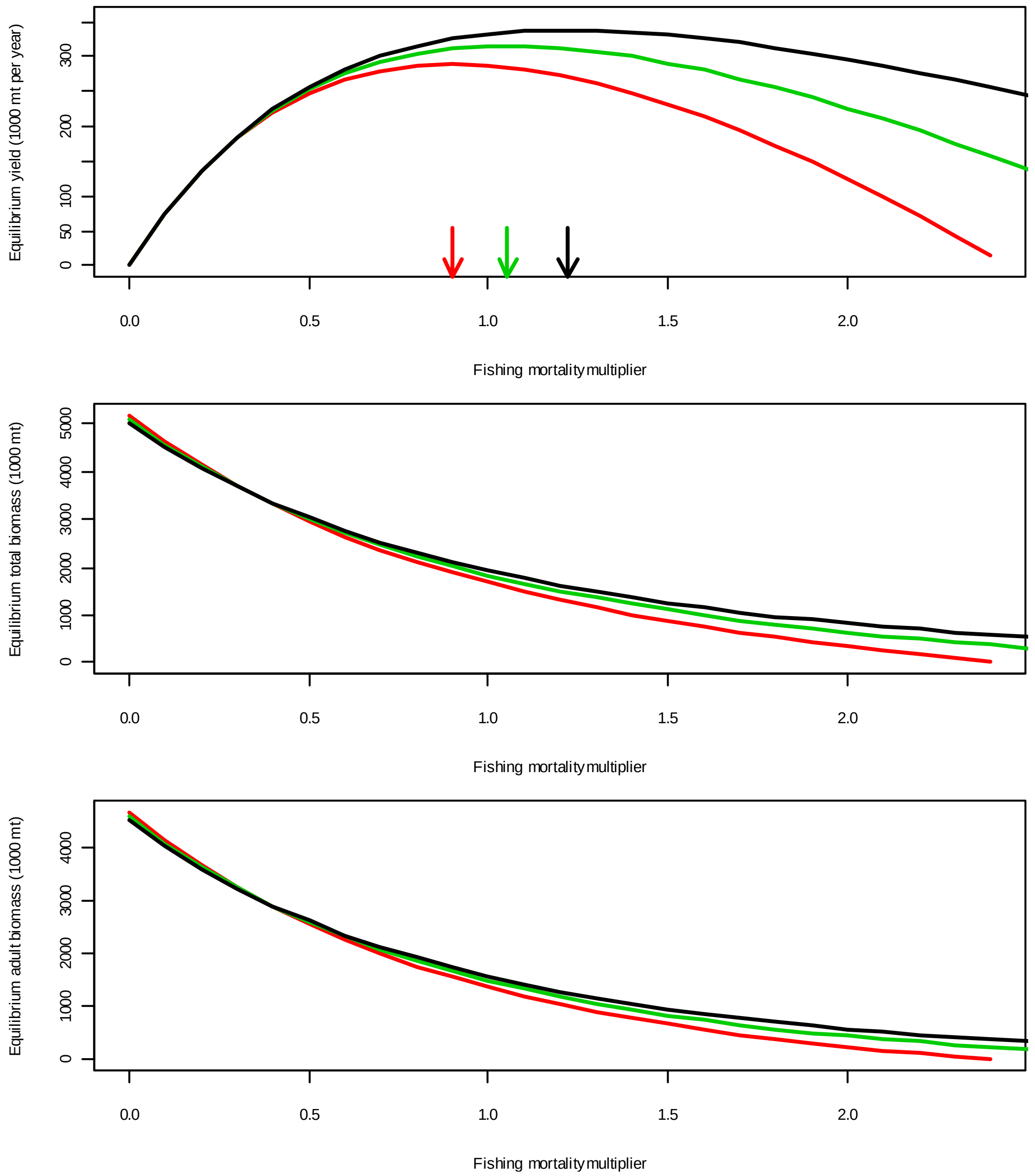


Figure 39b. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier obtained from the *logistic longline selectivity* model with three different values for steepness. In the upper panel, the arrows indicate the value of the fishing mortality multiplier at maximum yield.

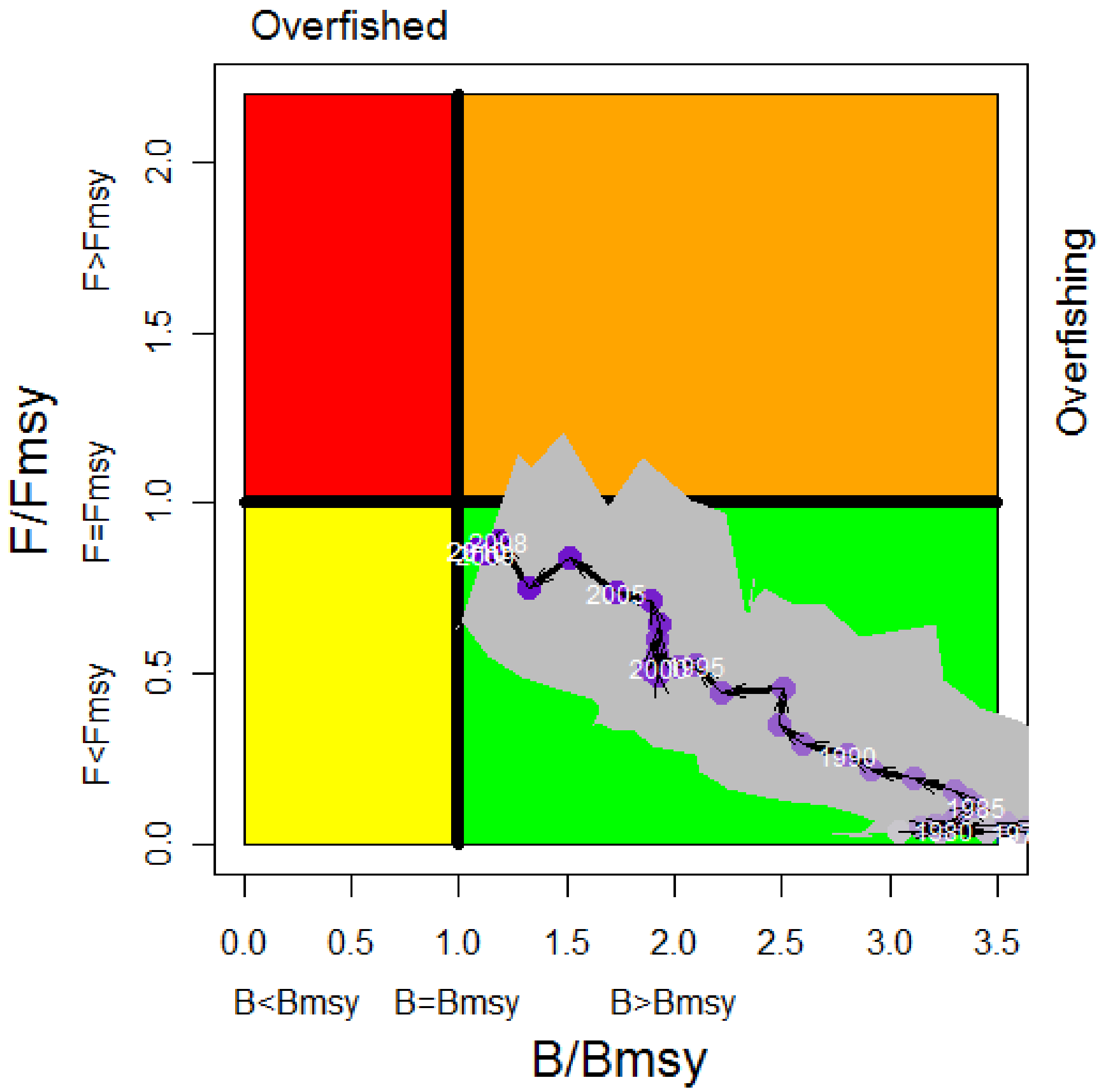


Figure 40. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period. The grey envelope encompasses the range for the six model options and the points represent the average annual values from the six model options.