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

Adam Langley, Miguel Herrera and Julien Million

DRAFT 6 October 2010

1 Introduction

This paper presents the stock assessment of yellowfin tuna (*Thunnus albacares*) in the Indian Ocean (IO). The methodology used for the assessment is that commonly known as MULTIFAN-CL (Fournier et al. 1998; Hampton and Fournier 2001; Kleiber et al. 2003; http://www.multifan-cl.org), which is software that 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. 2007). For the Indian Ocean, stock assessments of yellowfin tuna conducted before 2008 had used more traditional methods such as VPA and production models (refs). 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 updated in 2009 (Langley et al. 2009) and further refined during the IOTC 11th WPTT (IOTC 2009).

This report presents the results of an updated assessment that includes an additional year of data (tag recoveries, length frequency, catch and effort) and incorporates the refinements in model structure and assumptions that were recommended by the 11th WPTT, including:

- starting the model in 1972, excluding the earlier data due to the large initial declines in the longline CPUE indices,
- additional new length frequency data from a number of fisheries,
- a minor revision of the regional boundaries (at the boundary of regions 3 and 4),
- estimation of logistic selectivity for the longline fisheries,
- a fixed growth function, derived from an external analysis (Fonteneau 2008),
- specify the catch of the non longline fisheries in terms of weight rather than number of fish (Herrera 2009),
- age specific natural mortality with three alternative levels of overall mean natural mortality (low, high and estimated),
- and three specified values of steepness in the SRR (0.6, 0.7, 0.8).

The overall objectives of the assessment are to estimate population parameters, such as time series of recruitment, biomass and fishing mortality that indicate the status of the stock and impacts of fishing. We also summarise stock status in terms of well-known reference points, such as the ratios of recent stock biomass to the biomass at maximum sustainable yield ($B_{current}/\tilde{B}_{MSY}$) and recent fishing mortality to the fishing mortality at MSY ($F_{current}/\tilde{F}_{MSY}$).

These stock assessment models approximate the analyses that formed the basis for the management advice from IOTC 11th WPTT (IOTC 2009). Nonetheless, it is considered that the model options presented in the report represent a starting point for the deliberations of 12th WPTT and the assessment will be further refined during the course of the meeting.

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).

Preliminary 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 (Oman, Iranian and Pakistani fleets 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, reaching about 350,000 mt, mainly due to the development of the purse-seine fishery as well as an expansion of the other established fisheries (longline, gillnet, baitboat, handline and, to a lesser extent, troll). Catches remained at about 350,000 mt for the next decade then increased 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. In subsequent years, total annual catches have declined sharply, although catches from the smaller fisheries (gillnet, handline, baitboat, and troll) tended to increase through the 2000s. The total catch in 2009 was estimated to be 277,000 mt.

In recent years (2007–2009), purse seine has been the dominant fishing method, harvesting 32% of the yellowfin tuna catch (by weight), with the longline, gillnet, and handline fisheries comprising 20%, 24% and 10% of the total catch, respectively. A smaller component of the catch was taken by the regionally important baitboat (5%) and troll (7%) fisheries. The purse-seine catch is generally distributed equally between free-school and associated (log and FAD sets) schools, with the exception of the large catches from free-schools in 2003–2005.

Most of the yellowfin catch is taken from the western equatorial region of the IO (46%; region 2, see Figure 1) and, to a lesser extent, the Arabian Sea (19%), the eastern equatorial region (23%, region 5) and the Mozambique Channel (9%; 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 (3%) taken exclusively by longline (Figure 2).

In recent years (2008-09), 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 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.

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 (2010).

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.

Following the recommendations of the WPTT, the regional structure was refined slightly from that used in the 2009 stock assessment with the extension of region 4 westward to include the area bounded by 30−40°S and 40–60°E previously encompassed within region 3 (Figure 1). The oceanographic conditions within this area are considered more comparable to the wider area of region 4 than the remainder of region 3.

3.2 Temporal stratification

The time period covered by the assessment is 1972–2009. 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, in the case of purse seine, set type (Table 1).

A composite longline fishery was defined in each region (LL 1–5) aggregating the longline catch from all fleets (principally Japan and Taiwan and, in region 5, Indonesia).

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 area 1 reassigned to region 2.

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 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 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.

The time-series of catch-per-unit-effort (CPUE) for all fisheries are shown in Figure 5. 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 san, 22/9/2010) and for the Taiwanese longline fleet in region 1 (Figure 6). Standardised longline CPUE indices for the Taiwanese fleet were available for 1979–2007.

For these 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 6).

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 7. The data were collected from a variety of sampling programmes, which can be summarized as follows:

<u>Purse seine:</u> 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.

<u>Longline</u>: 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 1980–2007. In recent years, length data are also available from other fleets and periods, especially fresh-tuna longline fleets from Indonesia and Taiwan/China (IOTC-OFCF sampling)

<u>Gillnet</u>: Length data are available from both GN 1 and 5 fisheries.

<u>Baitboat</u>: Size data are available from the fishery from 1983 to 2009.

<u>Troll</u>: 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).

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

<u>Other</u>: 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 2009 assessment include the inclusion of hand-line data from the Maldivian fishery (HD 1) for 2000–09 and a revision of the data from the baitboat fishery (BB 2), the inclusion of length frequency data from the Sri Lankan fisheries other than the gillnet and longline methods for 1994-2006 (OT 5) and the inclusion of data from the Other fishery in region 1 for 2009 only. There was also a revision to the approach used to determine the sample size of the length data collected from the purse-seine 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 IOTC Regional Tuna Tagging Project (RTTP) conducted during 2005–2007. Most of the tag releases 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). Limited tagging also occurred within regions 1 and 3. The model included all tag recoveries up to the end of 2009.

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%). 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 and 2009 tag recoveries.

In total, 9,853 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 2).

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 3. 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 five-region model partitions the population into 5 spatial 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 3) 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 <u>Recruitment</u>

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, following the recommendations of the WPTT, three alternative values of steepness (*h*) were considered (0.60, 0.70, and 0.80).

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

The standard assumptions made concerning age and growth are (i) the lengths-at-age are normally distributed for each age-class; (ii) the mean lengths-at-age follow a von Bertalanffy growth curve; (iii) the standard deviations of length for each age-class are a log-linear function of the mean lengths-at-age; and (iv) the probability distributions of weights-at-age are a deterministic function of the lengths-at-age and a specified weight-length relationship (see Table 3). These processes are assumed to be regionally invariant.

As noted above, the population is partitioned into 28 quarterly age-classes. The number of older age classes allows for the possibility of significantly older and possibly larger fish in the earlier years of the model when exploitation rates were relatively low.

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 8). 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 8).

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

Three alternative parameterisations of natural mortality (*M*) were considered. In all cases, 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 either a relatively high level (equivalent to the Pacific Ocean assessments) (*high M*), fixed at a lower level (as recommended by the WPTT 2008) (*low M*) or estimated (*est M*) during the fitting procedure (Figure 9).

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.

Previous assessments had applied a similar approach to the estimation of the selectivity of the longline fisheries. However, the change in model structure to commence the model in 1972 (adopted at 11th WPTT) resulted in a highly domed selectivity for these fisheries. The very low selectivity for the older age classes was considered implausible and resulted in a large proportion of the population that was not available to the fishery (“cryptic biomass”). In response, a logistic selectivity function was adopted for the longline fisheries. The five longline fisheries are assumed to have a common selectivity among fisheries and time periods.

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 and 5, OT 1 and 5 and TR 3 and 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 longline fisheries (1972 onwards) 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.

We assumed that tagged yellowfin mix fairly quickly with the untagged population at the region level and that this mixing process is complete by the end of the first 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.

For the initial model runs, the size data were considered to be moderately informative and were given an according weighting in the likelihood function; individual length frequency distributions were assigned an effective sample size of 0.05 times the actual sample size, with a maximum effective sample size of 50.

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) (Appendix C).

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 2005–2008. We do not include 2009 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 (1972–2009). 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 Sensitivity analyses

Preliminary analyses revealed that the models were most sensitive to the assumptions related to the relative weighting of the length frequency data and the inclusion of the tagging data. There was also a strong interaction between these structural assumptions and the level (assumed or estimated) of average natural mortality. Hence, three model sensitivities were conducted for each natural mortality assumption. In each case, the intermediate value of steepness (0.70) was assumed.

The analyses included:

i. Down weighting of the length frequency data from all fisheries to an assumed sample size of 10 (from 50).

ii. Excluding the tag release/recovery data (*no-tag*).

iii. The combination of (i) and (ii).

6 Results

No specific model was identified as a preferred option. However, for illustrative purposes the model with the estimated average value of natural mortality (estimated to be intermediate between the low and the high values) and the intermediate value of steepness (0.70) was selected as a notional "*base-case*". In the interests of brevity, some categories of results are presented for the *base-case* only. The main stock assessment-related results are also summarised for all analyses.

6.1 Fit statistics and convergence

A summary of the fit statistics for a selected range of model options is given in Table 4.

The model option with the lower value of overall natural mortality had a considerably weaker fit to the length frequency data than the models with the higher values of *M* (*est M* and *high M*). While the lower *M* model had a slightly better fit to the tagging data than the model with *M* estimated. The fit to the tagging data deteriorated with the higher level of natural mortality. Down weighting the length frequency data resulted in a considerable improvement to the fit to the tagging data without significantly changing the estimated level of natural mortality (relative to the *est M* model) (Table 4).

6.2 Fit diagnostics (base-case)

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 10. 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 11). However, the model tends to underestimate the proportion of fish in the larger length classes sampled from purse-seine free-school fishery 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) is due to 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 12). 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, 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, 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 13 and Figure 14, 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 15. 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 14). Most of the tag recoveries are from fish at liberty for up to about two 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 overall consistency of the model with the observed effort data can be examined in plots of effort deviations against time for each fishery (Figure 16). 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, there are no strong trends evident in the effort deviations.
- A number of fisheries have limited or no effort data. For these fisheries, the model tends to fit any trend in catch through the effort deviations (rather than temporal variation in catchability). Hence, for a number of fisheries (GI 1 & 5, HD 1 and TR 3 & 5) there are strong trends in the effort deviations (Figure 16). 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).

6.3 Model parameter estimates

6.3.1 Movement

Two representations of the movement estimates are shown in Figure 17 and Figure 18. The estimated movement coefficients for adjacent model regions are shown in Figure 17. Coefficients for some region boundaries are close to zero, while overall, most movement rates are low. Movement rates are highest between region 2 and adjacent regions with the highest movement rate of 8.7% (of all fish) occurring from region 3 to region 2 in the first quarter.

The distribution of regional biomass by source region derived from a simulation using the movement coefficients is presented in Figure 18. 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 (about 20% per generation) and region 5 is estimated to contribute to the biomass in region 2. Regional fidelity is highest in region 4 with very limited transfer of biomass from this region and almost all biomass sourced from recruitment within the region (Figure 18).

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".

6.3.2 Selectivity

The common selectivity of the longline fisheries, parameterised using a logistic function, achieves full selectivity at age 16 quarters (Figure 19). 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.

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.

6.3.3 Catchability

For the principal longline fisheries, catchability was assumed to be constant over time (Figure 20), 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 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, no reliable effort data were 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.

6.3.4 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 21). For all other fisheries, no information was available regarding tag reporting rates and fishery-specific reporting rates were estimated with virtually no constraint. 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).

6.4 Stock assessment results

6.4.1 Recruitment

The base-case recruitment estimates (aggregated by year for ease of display) for each region and the entire IO are shown in Figure 22. The regional estimates display large interannual 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 been low during the subsequent years (2007-2009).

There are considerable differences in the temporal trends in recruitment among regions. For regions 1 and 2, estimates of recruitment generally increased from 1980 to 2000, while the opposite trend is evident in regions 3 and 5. Recruitment is estimated to be minimal in region 4 (Figure 22). The recent decline in the overall level of recruitment is largely driven by declines in recruitment in regions 1 and 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 22).

A comparison of IO recruitment estimates for the different analyses is provided in Figure 23. The models with the low and high average levels of natural mortality (*low M* and *high M*) had correspondingly lower and higher overall levels of recruitment than the base-case that estimated an intermediate level of average natural mortality (Figure 23a). Excluding the tagging data from the model resulted in a higher estimate of average natural mortality and a level of recruitment akin to the *high M* model.

Down-weighting the length frequency data (*down-wt LF*) did not substantially influence the overall trend in recruitment from the model (with natural mortality estimated), although the relative weighting of the length frequency data was influential when the tagging data were excluded from the model. The resultant model was characterised by a high estimate of average natural mortality and a lower level of recruitment than the *no tag* model. There were also considerable differences in the selectivity functions for those fisheries with limited length frequency data.

The model with natural mortality fixed at a higher level (*high M)* was also highly sensitive to the inclusion of the tagging data set (Figure 23b). The exclusion of these data (*no tag*) resulted in a substantially higher level of average recruitment, although this change was countered by the down-weighting of the length frequency data (*no tag, down-wt LF*). The down-weighting of the length frequency data while maintaining the tagging data (*down-wt LF*) resulted in a slightly lower level of average recruitment compared to the *high M* base model (Figure 23b).

The models with natural mortality fixed at a lower level (*low M)* yielded a considerably different trend in recruitment compared to the models with higher natural mortality (*est M* and *high M*) (Figure 23c). For the low M models, recruitment tended to increase from the late 1970s to the early 2000s, declined rapidly in the early 2000s and then tended to remain at the lower level in the most recent years. The down-weighting of the length frequency data (*down-wt LF*) tended to moderate this trend by increasing the overall level of recruitment in 1972-1990 and in the most recent years. The exclusion of the tagging data (either with or without the down-weighting of the length data) yielded levels of recruitment that were comparable to the *low M* base model (Figure 23c).

6.4.2 Biomass

The estimated biomass trajectory for each region and for the entire IO is shown in Figure 24 and Figure 25 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 24). 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.

A useful diagnostic is to compare model estimates of exploitable abundance for those longline fisheries with assumed constant catchability with the CPUE data from those fisheries. The time series comparison of these quantities (Figure 26) shows generally good correspondence between the model estimates and the data.

The comparison of total biomass trends for the different analyses is shown in Figure 27. The relative trends in total biomass are generally comparable among model options, although the overall magnitude of the biomass varies relative to the level of natural mortality (assumed or estimated) (Figure 27a). The overall level of biomass is particularly sensitive to the influence of the tagging data set. Excluding these data (*no tag*) resulted in a considerably higher level of total biomass consistent with higher level of estimated recruitment (see Figure 23a) and the higher estimate of natural mortality. However, the models with the tag data excluded also estimate selectivity functions for some key fisheries (esp. PS LS 2) that differ considerably from the selectivities from the base-case analysis. This observation probably accounts for the higher levels of biomass estimated from the models (*est M*) with the tagging data excluded compared to the overall level of biomass from the *high M* model with tagging data included (Figure 27a).

This observation also accounts for the high level of total biomass estimated from the *high M* model with the tagging data excluded (*no tag*) (Figure 27b). However, the additional down-weighting of the length frequency data resulted in a biomass level that was more comparable to the *high M* model although there were marked differences in the selectivity functions for a range of fisheries for which only limited length data were available (most of the artisanal fisheries) (Figure 27b).

The tagging data are less influential in the *low M* model and the biomass trajectories are comparable regardless of whether or not the model includes the tagging data (Figure 27c). However, a lower relative weighting of the length frequency data incorporated in the *low M* model resulted in a higher level of initial biomass and a considerably larger decline in biomass over the model period (Figure 27c).

6.4.3 Fishing mortality

Average fishing mortality rates for juvenile and adult age-classes increased strongly from the early 1980s for most model options (Figure 28). For the most recent years (2006–2009), the period for which tag data are available, the model that excludes the tag data (*no-tag*) yields considerable lower estimates of overall fishing mortality for adult yellowfin compared to the base-case analysis (including tags). This is a function of both the higher estimated level of natural mortality for the *no tag* options and differences in the selectivity functions estimated for key fisheries.

Recent fishing mortality rates, for the period used in the computation of references points (2005–2008), were highest in regions 2 and 3, particularly for the younger age classes (1–6), and the older age classes in region 1 (Figure 29). In region 3, the exceptionally high fishing mortality rate for the youngest age classes is attributable to the troll fishery that is estimated to exclusively catch these age classes. There are no length data available from the fishery and the selectivity is derived solely from the tagging data.

6.4.4 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 30. 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 31. These figures indicate high levels of fishery depletion (60–70% reduction) of yellowfin tuna in regions 1, 2 and 3. For the entire IO, recent levels of fishing have resulted in about a 60% reduction in total biomass. Overall depletion levels varied considerably among the model options with different levels of natural mortality (assumed or estimated) (Figure 32).

6.4.5 Yield analysis

Symbols used in the following discussion are defined on Table 5. The yield analysis incorporates the SRR into the equilibrium biomass and yield computations with three alternative values of steepness assumed for the SRR (0.60, 0.70, and 0.80). There is no strong evidence from the model estimates of spawning biomass and recruitment to select a specific value of steepness (Figure 33). On that basis, the WPTT has considered that the three separate sets of *MSY*-based reference points are considered to be equally plausible indicators of stock status.

Equilibrium yield and biomass (spawning and total) are computed as a function of multiples of the 2005–08 average fishing mortality-at-age (Figure 34). For the base-case model and steepness fixed at 0.70, a maximum yield (*MSY*) of 235,640 mt per annum is achieved at *fmult* = 0.71; i.e. at 78% of the current level of age-specific fishing mortality. This represents a ratio of $F_{current}/\tilde{F}_{MSY}$ equal to 1.41 (approximately 1/0.71); current exploitation rates are **higher** than the exploitation rates to produce the *MSY*. The equilibrium biomass at *MSY* is estimated at 1,269,000 mt, approximately 40% of the equilibrium unexploited biomass (Table 6b). Equilibrium yield at the current level of fishing mortality ($\tilde{Y}_{F_{current}}$ = 217,000 mt) is considerably lower than the peak in total catches from the fishery (averaging about 456,000 mt in 2003–06) and lower than recent catches from the fishery (averaging about 298,000 mt in 2008–09). The lower equilibrium yields are due to the current high levels of fishing mortality reducing the equilibrium spawning biomass well below the $\tilde{SB}_{MSY}$ level ($\tilde{SB}_{F_{current}}/\tilde{SB}_{MSY}$ = 0.628) and, given the assumed value of steepness, substantially impacting on the equilibrium recruitment.

The results of the yield analysis are sensitive to the value of steepness assumed. The lower value of steepness (0.60) resulted in lower estimates of yield and lower reference levels of fishing mortality. Conversely, the higher value of steepness (0.80) resulted in higher estimates of yield and higher reference levels of fishing mortality (Figure 34). Nonetheless, for the three options of steepness, current exploitation rates are **higher** than the exploitation rates to produce the *MSY* ($F_{current}/\tilde{F}_{MSY} > 1$).

For the *base-case* analysis (and steepness fixed at 0.70), the reference points $F_t/\tilde{F}_{MSY}$, $B_t/\tilde{B}_{MSY}$ and $SB_t/\tilde{SB}_{MSY}$ were computed for each year (*t*) included in the model (1972–2009). 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 35 and Figure 36). For the base-case model, exploitation rates were low from 1972 to 1990, while total and adult biomass remained well above $\tilde{B}_{MSY}$ and $\tilde{SB}_{MSY}$. Since the early 1990s, $F_t/\tilde{F}_{MSY}$ steadily increased while the relative biomass levels ($B_t/\tilde{B}_{MSY}$ and $SB_t/\tilde{SB}_{MSY}$) declined. Fishing mortality rates exceeded the F_{MSY} level in the mid 2000s and continued to increase over recent years. Total biomass and adult biomass have followed this trend and are estimated to have declined below $\tilde{B}_{MSY}$ and $\tilde{SB}_{MSY}$ in the two most recent years (Figure 35 and Figure 36).

The estimates of equilibrium yield, total biomass and MSY based reference points for the range of model sensitivities to the natural mortality and steepness assumptions are presented in Table 6a-c. Model options that include the down-weighting of the length frequency data are also included, although model options that exclude the tagging data are not considered credible alternative models for the purpose of formulating management advice. Instead, these model options serve to illustrate the importance of the tagging data set in informing the model regarding a number of key parameters (natural mortality, selectivity and fishing mortality).

Equilibrium yield and total biomass, as a function of multiples of the 2005–2008 average fishing mortality-at-age, for the three alternative levels of natural mortality are shown in Figure 37. The assumption of a lower level of natural mortality yields considerably lower estimates of *MSY* and considerably more pessimistic estimates of the current stock status (Table 6a) than corresponding models that estimate a moderate average level of natural mortality (Table 6b). The down-weighting of the length frequency data results in a somewhat more optimistic stock status for the *low M* option (Table 6a).

Conversely, the models with an assumed high level of natural mortality (Table 6c) yield results that are considerably more optimistic than the models that estimate a moderate average level of natural mortality (Table 6b). The *high M* models estimate that recent (2005–2008) average fishing mortality rates were at or below the F_{MSY} level ($F_{current}/\tilde{F}_{MSY}$ > 1.0) and that recent catches were at or below the *MSY* level. For the *high M* model, the down weighting of the length frequency data resulted in slightly less optimistic estimates of stock status (Table 6c).

For the range of scenarios, the equilibrium total and adult biomass at *MSY* is estimated to be 35–46% and 31–37% of the equilibrium unexploited total and adult biomass, respectively (Table 6a-c).

7 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 10th and 11th meetings of the WPTT. These refinements include some large 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 need further consideration in future assessments. 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 have been very low since late 2006, 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 are 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. 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. 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).

iii. Further consideration needs to be given to the relative weighting of the individual data sets, particularly the length frequency data. The current assessment models assign a relatively high weight to the length frequency data (sample size of 50) and, hence, these data may be overly influential in the estimation procedure and thereby influencing the resultant biomass trends. However, for some fisheries these data may not be entirely representative of the length composition of the catch, particularly for the artisanal fisheries. Perhaps more crucially, there are indications that the length frequency data from some of the key fisheries may not be consistent over the time period of the fishery indicating either temporal change in the selectivity of the fisheries and/or bias in the collection of the length frequency data. Further consideration of the relative weighting of the various length frequency data sets is required.

iv. Where possible, purse-seine tag recoveries should be separated by set type (associated and unassociated sets). This would give the analysis more power to estimate fishery-specific exploitation rates, particularly given the significant difference in the age-specific selectivity of the two fisheries. There are indications that the treatment of the purse-seine tag recoveries (especially the tags where the purse-seine set type is unknown) is biasing the estimates of the selectivity of the purse-seine fisheries within region 2, particularly when the length frequency data are down weighted. Clearly, there is also some degree of conflict between the length frequency data and the tagging data (in conjunction with strong interactions between the length frequency data and the assumed level of natural mortality). The impact of these assumptions will be examined more thoroughly during the 12th meeting of WPTT.

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

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

vii. The current model options yields unreasonable estimates of selectivity for the troll fishery in region 3. No length data are available from this fishery and the model was reliant on the tagging data to estimate the selectivity function for the fishery. These data do not appear to be adequate and subsequent analyses (during the 12th WPTT) should adopt a more credible selectivity function for the fishery. Preliminary runs indicate that the assumption does not significantly influence the estimated biomass trajectory.

It is envisaged that some of the above issues will be further investigated prior and during the 12th meeting of the WPTT.

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

iv. 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.

v. The assessment also assumes that the selectivity of a fishery has 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.

vi. 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 current assessment; 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. These conclusions are generally consistent with the results of the assessment conducted by WPTT 11 for the corresponding model options (i.e., the overall level of natural mortality estimated) (IOTC 2009).

1. The model estimates that total biomass has declined rapidly since the late 1980s. The decline in biomass has been greatest in regions 2, 3 and 5. These trends are generally consistent with the trends in the longline CPUE indices.
2. Exploitation rates and fishery impacts are relatively high (resulting in a 60−70% reduction in biomass) in all regions except region 4.
3. The assessment estimates that there has been a strong decline in recruitment in recent years. As a consequence, total biomass has declined and recent (2007–2009) exploitation rates are at historically high levels, approximately 20% higher than the “current” (2005–2008 average) level of fishing mortality used in the computation of the *MSY*-based reference points. It is predicted that spawning biomass will also decline sharply over the next few years as the weaker cohorts reach the age of maturity.
4. 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 were considered by WPTT 10 to encompass the plausible range of steepness for yellowfin tuna. Model options with lower values of steepness yielded more pessimistic stock conclusions. However, regardless of the value of steepness assumed, all model options estimated levels of recent average fishing mortality that were in excess of the F_{MSY} level ($F_{current}/\tilde{F}_{MSY} > 1$). As mentioned in the previous paragraph, fishing mortality rates are estimated to have increased during the recent period and adopting the 2005–2008 average level will under-estimate fishing mortality rates in the most recent years.
5. For the model scenarios with the overall level of natural mortality estimated, recent (2005–2008) 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 declined below the respective reference point ($\tilde{B}_{MSY}$ and $S\tilde{B}_{MSY}$) in the most recent years (2008–2009).
6. *MSY* is estimated to be between 212,000 and 255,000 mt depending on the value of steepness assumed. Recent (2008–2009) annual catches are towards the upper end of this range (averaging about 298,000 mt in 2008−09) and have occurred following a period of lower than average recruitment. Catches of that magnitude may not be sustainable in the short-term if recruitment remains low. 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 most recent years (2008–2009) although the decline in catch may be, at least partly, attributable to the recent operational constraints of the purse-seine and longline fleets.

8 Acknowledgements

The authors would like to thank Hiroaki Okatomo and Eric Chang for providing the Japanese and Taiwanese longline CPUE indices, respectively. Alejandro Anganuzzi and Iago Mosqueira provided guidance and support and comments on a draft version of the report.

9 References

De Montaudoin, X., J.P. Hallier and S. Hassani 1991. Length-weight relationships for yellowfin (*Thunnus albacares*) and skipjack (*Katsuwonus pelamis*) from Western Indian Ocean. IPTP Coll. Vol. Work. Doc. 4: 47-65.

Francis, R.I.C.C. 1992. Use of risk analysis to assess fishery management strategies: a case study using orange roughy (*Hoplostethus atlanticus*) on the Chatham Rise, New Zealand. *Can. J. Fish. Aquat. Sci.* 49: 922–930.

Fonteneau, A. 2008. A working proposal for a Yellowfin growth curve to be used during the 2008 yellowfin stock assessment. IOTC-2008-WPTT-4.

Fournier, D.A., Hampton, J., and Sibert, J.R. 1998. MULTIFAN-CL: a length-based, age-structured model for fisheries stock assessment, with application to South Pacific albacore, *Thunnus alalunga*. *Can. J. Fish. Aquat. Sci.* **55**: 2105–2116.

Gaertner, D. and J.P. Hallier 2008. Tag Shedding by Tropical Tunas in the Indian Ocean: explanatory analyses and first results.

Gaertner, D., E. Chassot, A. Fonteneau, J.P. Hallier and F. Marsac 2009. Estimate of the non-linear growth rate of yellowfin tuna (*Thunnus albacares*) in the Atlantic and in the Indian Ocean from tagging data. IOTC-2009-WPTT-17.

Hampton, J., and Fournier, D.A. 2001. A spatially-disaggregated, length-based, age-structured population model of yellowfin tuna (*Thunnus albacares*) in the western and central Pacific Ocean. *Mar. Freshw. Res.* **52**:937–963.

Herrera, M. 2010. Preparation of data input files for the assessments of Indian Ocean yellowfin tuna stock using Multifan-CL IOTC-2010-WPTT-07.

Herrera, M. 2009. Preparation of data input files for the assessments of Indian Ocean yellowfin tuna stock using Multifan-CL IOTC-2009-WPTT-11.

Hillary, R.M., Million, J., Anganuzzi, A., Areso, J.J. 2008. Tag shedding and reporting rate estimates for Indian Ocean tuna using double-tagging and tag-seeding experiments. IOTC-2008-WPTDA-04.

Itano, D.G. 2000. The reproductive biology of yellowfin tuna (*Thunnus albacares*) in Hawaiian waters and the western tropical Pacific Ocean: project summary. SOEST 00-01 JIMAR Contribution 00-328. Pelagic Fisheries Research Program, JIMAR, University of Hawaii.

IOTC 2008a. Report of the First Session of the IOTC Working Party on Tagging Data Analysis, Seychelles, 30 June to 4 July 2008. IOTC-2008-WPTDA-R[E].

IOTC 2008b. Report of the 10th session of the IOTC Working Party on Tropical Tunas, Bangkok, Thailand, 23 to 31 October 2008. IOTC-2008-WPTT-R[E].

IOTC 2009. Report of the 11th session of the IOTC Working Party on Tropical Tunas, Mombasa, Kenya, 15-23 October 2009. IOTC-2009-WPTT-R[E].

Kleiber, P., Hampton, J., and Fournier, D.A. 2003. MULTIFAN-CL Users' Guide. http://www.multifan-cl.org/userguide.pdf.

Langley, A., Hampton, J., Kleiber, P., Hoyle, S. 2007. Stock assessment of yellowfin tuna in the western and central Pacific Ocean, including an analysis of management options. WCPFC SC3 SA WP-1, Honolulu, Hawai'i, 13–24 August 2007.

Langley, A., Hampton, J., Herrera, M., Million, J. 2008. Preliminary stock assessment of yellowfin tuna in the Indian Ocean using MULTIFAN-CL. IOTC-2008-WPTT-10.

Langley, A., Herrera, M., Hallier J.P., Million, J. 2009. Stock assessment of yellowfin tuna in the Indian Ocean using MULTIFAN-CL. IOTC-2009-WPTT-10.

McAllister, M.K.; Ianelli, J.N. 1997. Bayesian stock assessment using catch-at-age data and the sampling-importance resampling algorithm. Can. J. Fish. Aquat. Sci. 54: 284-300.

Maunder, M.N., and Watters, G.M. 2001. A-SCALA: An age-structured statistical catch-at-length analysis for assessing tuna stocks in the eastern Pacific Ocean. Background Paper A24, 2nd meeting of the Scientific Working Group, Inter-American Tropical Tuna Commission, 30 April – 4 May 2001, La Jolla, California.

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	All	Purse seine, school sets	2
7. LL 2 post 1972	All	Longline	2
8. PS LS 2	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	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

Table 2. 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	35	0	0
	3	0	7	75	0
	2006	1	2	3	5
	1	0	0	0	0
	2	38	2634	33	26
	3	0	0	0	0
	2007	1	2	3	5
	1	40	22	2	0
	2	27	4129	435	3
	3	0	14	1	0
	2008	1	2	3	5
	1	4	4	0	0
	2	2	1518	295	0
	3	0	5	0	0
	2009	1	2	3	5
	1	0	0	0	0
	2	0	435	63	2
	3	0	3	0	0

Table 3. 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 0.05 times actual sample size for all fisheries with a maximum effective sample size of 50.	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 two 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.	Average spatially aggregated recruitment (ln)		-	-	-20	20
		Spatially aggregated recruitment deviations (ln)		SRR	0.7	-20	20
		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 (XX). 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 De Montaudoin et al 1991).						
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. Logistic selectivity for longline fisheries. For all non longline fisheries selectivity is parameterised with 5-node cubic spline.	Selectivity coefficients (5 cubic spline nodes per fishery for non logline fisheries)		-	-	0	1
Catchability	Constant over years and among regions for longline fisheries from 1972 onwards (effort data are scaled to reflect different region sizes). Seasonal variation for all fisheries. Non-longline 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) Seasonality amplitude (ln) Seasonality phase Catchability deviations biennial (ln) Catchability deviations annual (ln)		- 0 - 0 0	- 2.2 - 0.7 0.1	-15 - - -0.8 -0.8	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 ALL 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) Effort deviations other (ln)		0 0	0.10 0.22	-6 -6	6 6
Natural mortality	Age-dependent but constant over time and among regions. All parameters are specified (see Figure 9).	Average natural mortality (ln) Age-specific deviations (ln)		- -	- -	- -	- -
Movement Maturity	Age-independent and variant by quarter but constant among years. No age-dependent variation. Age-dependent and specified – age-class 0-6: 0; 7: 0.25; 8: 0.5; 9: 0.75; 10-28: 1.0	Movement coefficients Age-dependent component (ln) None		0 0 na	0.32 0.32 na	0 -4 0	3 4 1

Table 4. Details of objective function components for a selection of the stock assessment models with different values of overall natural mortality (steepness of 0.70 in all cases).

Objective function component	**M low**	**M estimated**	**M high**	**M est, downwt LF**
Total catch log-likelihood	338.60	336.30	331.14	317.50
Length frequency log-likelihood	-376,344.02	-376,758.26	-376,758.22	-274,915.51
Tag log-likelihood	3,674.03	3,699.16	3,897.74	3,337.24
Penalties	3,873.74	3,783.66	3,866.75	3,391.20
Total function value	-368,457.65	-368,939.14	-368,662.58	-267,869.57
Number of parameters	4,175	4,176	4,175	4,176

Table 5. Description of symbols used in the yield analysis.

Symbol	Description
$F_{current}$	Average fishing mortality-at-age for 2005–2008
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 (2005–2008) total biomass
$SB_{current}$	Average current (2005–2008) adult biomass
B_{1999}	Average total biomass in 1999
SB_{1999}	Average adult biomass in 1999
$B_{current,F=0}$	Average current (2005–2008) total biomass in the absence of fishing.

Table 6c. Estimates of management quantities for the stock assessment models for the **low natural mortality** option. The highlighted rows are ratios of comparable quantities at the same point in time (black shading) and ratios of comparable equilibrium quantities (grey shading). For the h = 0.60 option, the current level of fishing mortality ($F_{currrent}$) is predicted to reduce the equilibrium spawning biomass and yields to zero.

Management quantity	Units	***h* 0.60**	***h* 0.70**	***h* 0.80**	***h* 0.70, down-wt LF**
$\tilde{Y}_{F_{current}}$	mt per year	0.000	87,320	142,680	140,000
$\tilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	173,840	186,160	197,360	226,440
$\tilde{B}_0$	mt	3,332,000	3,149,000	3,029,000	4,160,000
$\tilde{B}_{F_{current}}$	mt	0.000	249,100	406,100	468,300
$\tilde{B}_{MSY}$	mt	1,304,000	1,172,000	1,070,000	1,525,000
$\tilde{SB}_0$	mt	3,018,000	2,853,000	2,743,000	3,767,000
$\tilde{SB}_{F_{current}}$	mt	0.000	180,000	293,200	347,400
$\tilde{SB}_{MSY}$	mt	1,103,000	976,300	877,200	1,270,000
$B_{current}$	mt	1,133,809	1,130,036	1,127,459	1,368,687
$SB_{current}$	mt	949,897	945,971	943,277	1,144,061
SB_{2008}		646,789	644,044	642,145	832,185
$B_{current,F=0}$	mt	4,206,238	4,207,748	4,209,192	4,631,620
$B_{current}/\tilde{B}_0$		0.340	0.359	0.372	0.329
$B_{current}/\tilde{B}_{F_{current}}$		na	4.536	2.776	2.923
$B_{current}/\tilde{B}_{MSY}$		0.848	0.940	1.027	0.880
$B_{current}/B_{current,F=0}$		0.270	0.269	0.268	0.296
$SB_{current}/\tilde{SB}_0$		0.315	0.332	0.344	0.304
$SB_{2008}/\tilde{SB}_0$		0.214	0.226	0.234	0.221
$SB_{current}/\tilde{SB}_{F_{current}}$		na	5.255	3.217	3.293
$SB_{current}/\tilde{SB}_{MSY}$		0.839	0.944	1.048	0.883
$\tilde{B}_{F_{current}}/\tilde{B}_0$		0.000	0.079	0.134	0.113
$\tilde{SB}_{F_{current}}/\tilde{SB}_0$		0.000	0.063	0.107	0.092
$\tilde{B}_{MSY}/\tilde{B}_0$		0.391	0.372	0.353	0.367
$\tilde{SB}_{MSY}/\tilde{SB}_0$		0.365	0.342	0.320	0.337
$F_{current}/\tilde{F}_{MSY}$		2.698	2.266	1.951	1.971
$\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$		0.000	0.213	0.380	0.307
$\tilde{SB}_{F_{current}}/\tilde{SB}_{MSY}$		0.000	0.184	0.334	0.274
$\tilde{Y}_{F_{current}}/MSY$		0.000	0.469	0.723	0.618
$B_{current}/B_{1999}$		0.839	0.840	0.841	0.758
SB_{2008}/SB_{1999}		0.642	0.643	0.644	0.588

Table 6b. Estimates of management quantities for the stock assessment models for the **estimated natural mortality** option. 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* 0.60	*h* 0.70	*h* 0.80	*h* 0.70, down-wt LF
$\tilde{Y}_{F_{current}}$	mt per year	165,320	217,000	250,000	234,640
$\tilde{Y}_{F_{MSY}}$ (or MSY)	mt per year	212,640	235,640	255,360	257,080
$\tilde{B}_0$	mt	3,228,000	3,164,000	3,113,000	3,438,000
$\tilde{B}_{F_{current}}$	mt	648,900	849,900	977,800	881,600
$\tilde{B}_{MSY}$	mt	1,347,000	1,269,000	1,197,000	1,351,000
$S\tilde{B}_0$	mt	2,541,000	2,493,000	2,453,000	2,770,000
$S\tilde{B}_{F_{current}}$	mt	416,300	545,400	627,400	571,900
$S\tilde{B}_{MSY}$	mt	943,300	868,100	799,200	941,900
$B_{current}$	mt	1,499,276	1,496,058	1,493,076	1,443,587
$SB_{current}$	mt	1,157,482	1,155,006	1,152,359	1,096,226
SB_{2008}		721,576	720,030	718,491	711,579
$B_{current, F=0}$	mt	3,162,433	3,163,103	3,161,329	3,355,974
$B_{current} / \tilde{B}_0$		0.464	0.473	0.480	0.420
$B_{current} / \tilde{B}_{F_{current}}$		2.310	1.760	1.527	1.637
$B_{current} / \tilde{B}_{MSY}$		1.079	1.143	1.209	1.042
$B_{current} / B_{current, F=0}$		0.474	0.473	0.472	0.430
$SB_{current} / S\tilde{B}_0$		0.456	0.463	0.470	0.396
$SB_{2008} / S\tilde{B}_0$		0.284	0.289	0.293	0.257
$SB_{current} / S\tilde{B}_{F_{current}}$		2.780	2.118	1.837	1.917
$SB_{current} / S\tilde{B}_{MSY}$		1.189	1.289	1.397	1.135
$\tilde{B}_{F_{current}} / \tilde{B}_0$		0.201	0.269	0.314	0.256
$S\tilde{B}_{F_{current}} / S\tilde{B}_0$		0.164	0.219	0.256	0.206
$\tilde{B}_{MSY} / \tilde{B}_0$		0.417	0.401	0.385	0.393
$S\tilde{B}_{MSY} / S\tilde{B}_0$		0.371	0.348	0.326	0.340
$F_{current} / \tilde{F}_{MSY}$		1.678	1.413	1.218	1.427
$\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$		0.482	0.670	0.817	0.653
$S\tilde{B}_{F_{current}} / S\tilde{B}_{MSY}$		0.441	0.628	0.785	0.607
$\tilde{Y}_{F_{current}} / MSY$		0.777	0.921	0.979	0.913
$B_{current} / B_{1999}$		0.694	0.695	0.696	0.700
SB_{2008} / SB_{1999}		0.506	0.506	0.507	0.509

Table 6c. Estimates of management quantities for the stock assessment models for the **high natural mortality** option. 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* 0.60**	***h* 0.70**	***h* 0.80**	***h* 0.70, down-wt LF**
$\tilde{Y}_{F_{current}}$	mt per year	316,760	347,320	366,760	309,360
$\tilde{Y}_{F_{MSY}}$ (or *MSY*)	mt per year	317,120	356,520	391,680	309,400
$\tilde{B}_0$	mt	3,270,000	3,237,000	3,204,000	2,762,000
$\tilde{B}_{F_{current}}$	mt	1,565,000	1,716,000	1,810,000	1,242,000
$\tilde{B}_{MSY}$	mt	1,508,000	1,451,000	1,388,000	1,254,000
$\tilde{SB}_0$	mt	2,036,000	2,015,000	1,994,000	1,719,000
$\tilde{SB}_{F_{current}}$	mt	777,000	852,000	898,300	574,400
$\tilde{SB}_{MSY}$	mt	740,900	678,000	613,200	581,900
$B_{current}$	mt	1,692,468	1,691,543	1,689,228	1,352,267
$SB_{current}$	mt	1,098,625	1,097,545	1,095,595	790,487
SB_{2008}		614,655	614,083	612,851	444,368
$B_{current,F=0}$	mt	2,604,030	2,603,365	2,600,934	2,352,697
$B_{current} / \tilde{B}_0$		0.518	0.523	0.527	0.490
$B_{current} / \tilde{B}_{F_{current}}$		1.081	0.986	0.933	1.089
$B_{current} / \tilde{B}_{MSY}$		1.080	1.122	1.172	1.044
$B_{current} / B_{current,F=0}$		0.650	0.650	0.649	0.575
$SB_{current} / \tilde{SB}_0$		0.540	0.545	0.549	0.460
$SB_{2008} / \tilde{SB}_0$		0.302	0.305	0.307	0.259
$SB_{current} / \tilde{SB}_{F_{current}}$		1.414	1.288	1.220	1.376
$SB_{current} / \tilde{SB}_{MSY}$		1.427	1.558	1.720	1.313
$\tilde{B}_{F_{current}} / \tilde{B}_0$		0.479	0.530	0.565	0.450
$\tilde{SB}_{F_{current}} / \tilde{SB}_0$		0.382	0.423	0.451	0.334
$\tilde{B}_{MSY} / \tilde{B}_0$		0.461	0.448	0.433	0.454
$\tilde{SB}_{MSY} / \tilde{SB}_0$		0.364	0.336	0.308	0.339
$F_{current} / \tilde{F}_{MSY}$		0.954	0.784	0.657	1.012
$\tilde{B}_{F_{current}} / \tilde{B}_{MSY}$		1.038	1.183	1.304	0.990
$\tilde{SB}_{F_{current}} / \tilde{SB}_{MSY}$		1.049	1.257	1.465	0.987
$\tilde{Y}_{F_{current}} / MSY$		0.999	0.974	0.936	1.000
$B_{current} / B_{1999}$		0.595	0.595	0.596	0.637
SB_{2008} / SB_{1999}		0.421	0.421	0.421	0.418

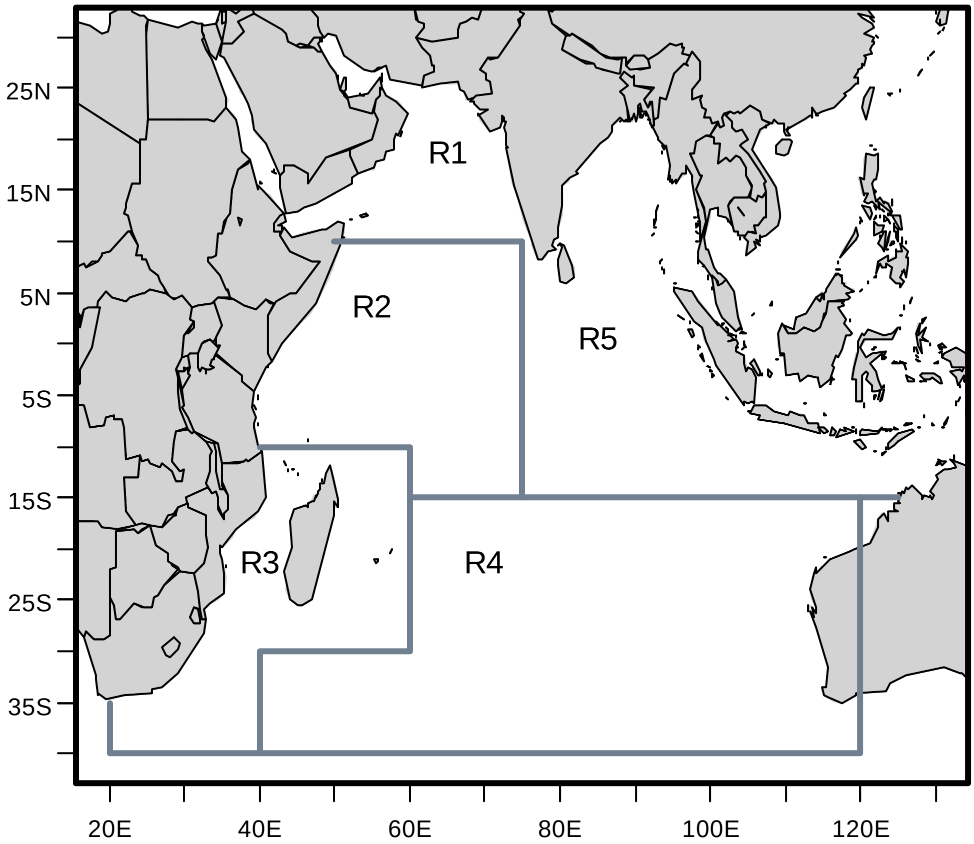

Figure 1. Spatial stratification of the Indian Ocean for the MFCL assessment model.

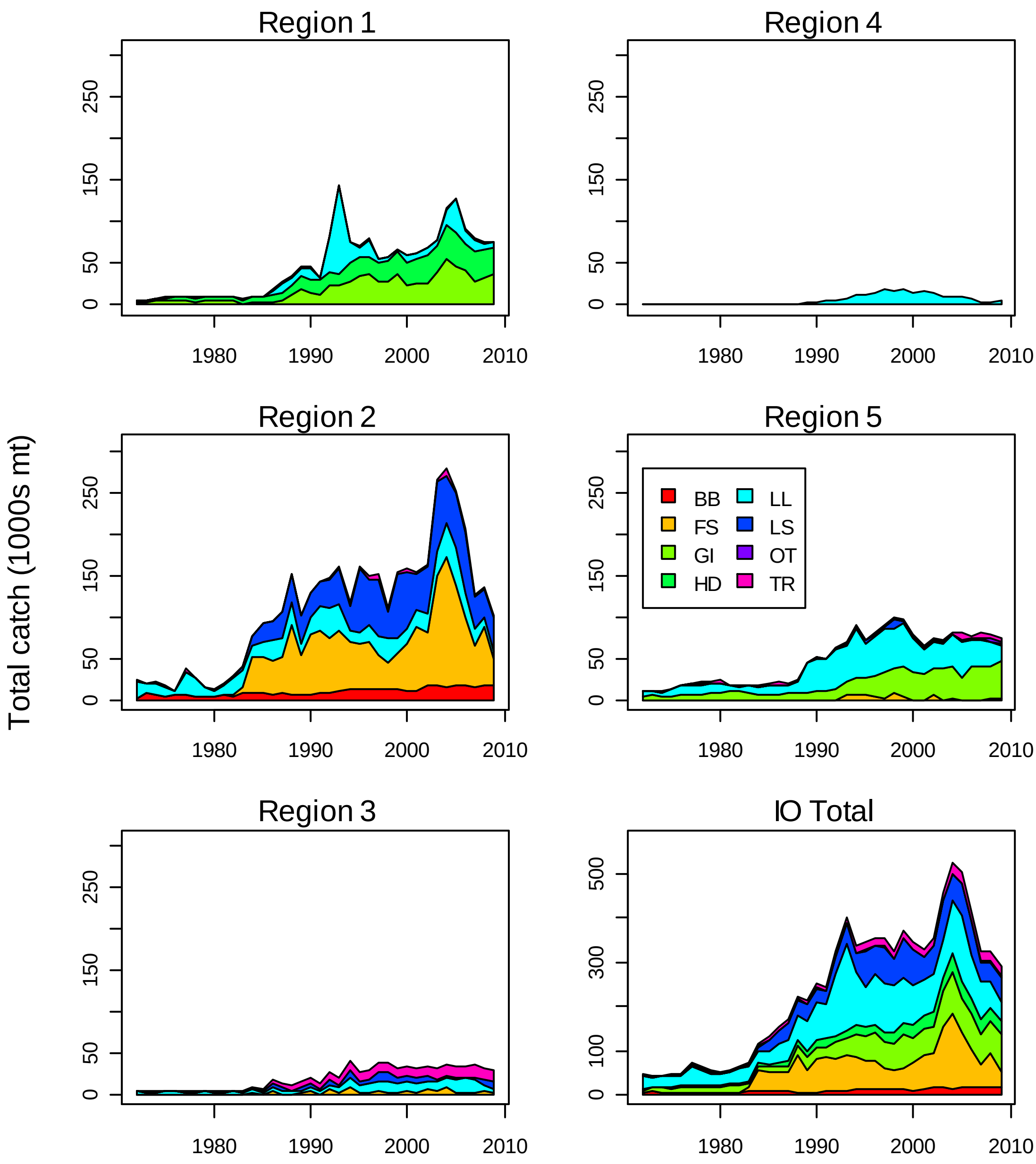

Figure 2. Total annual catch (1000s mt) of yellowfin tuna by fishing method and MFCL region from 1972 to 2009 (BB, baitboat; FS, purse-seine, free schools; GI, gillnet; HD, handline; LL, longline; LS, purse-seine, log sets; OT, other; TR, troll).

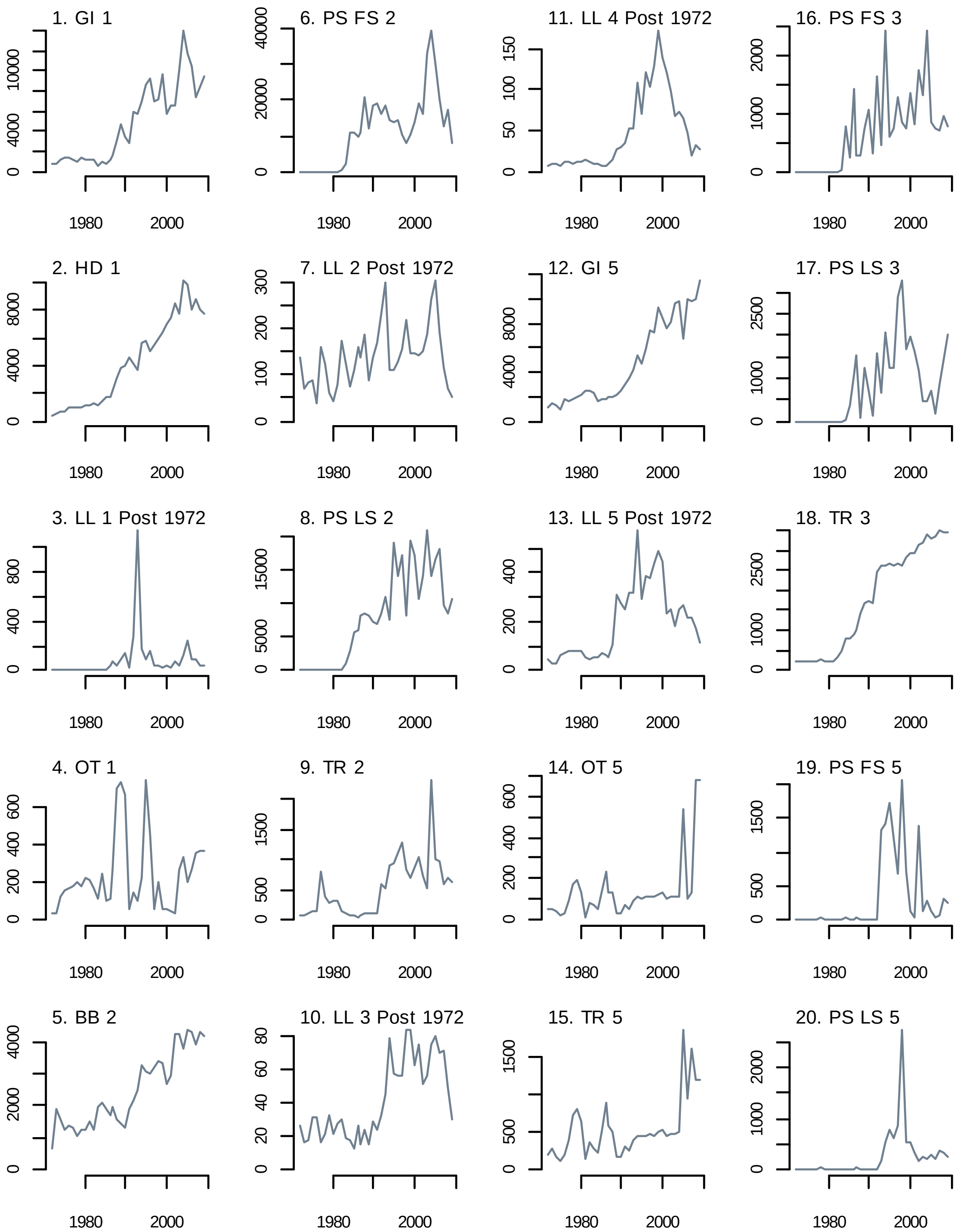

Figure 3. Quarterly catches, by fishery. Catches are in weight (tonnes) except for the longline fisheries (number, thousands of fish). Note the y-axis differs among plots.

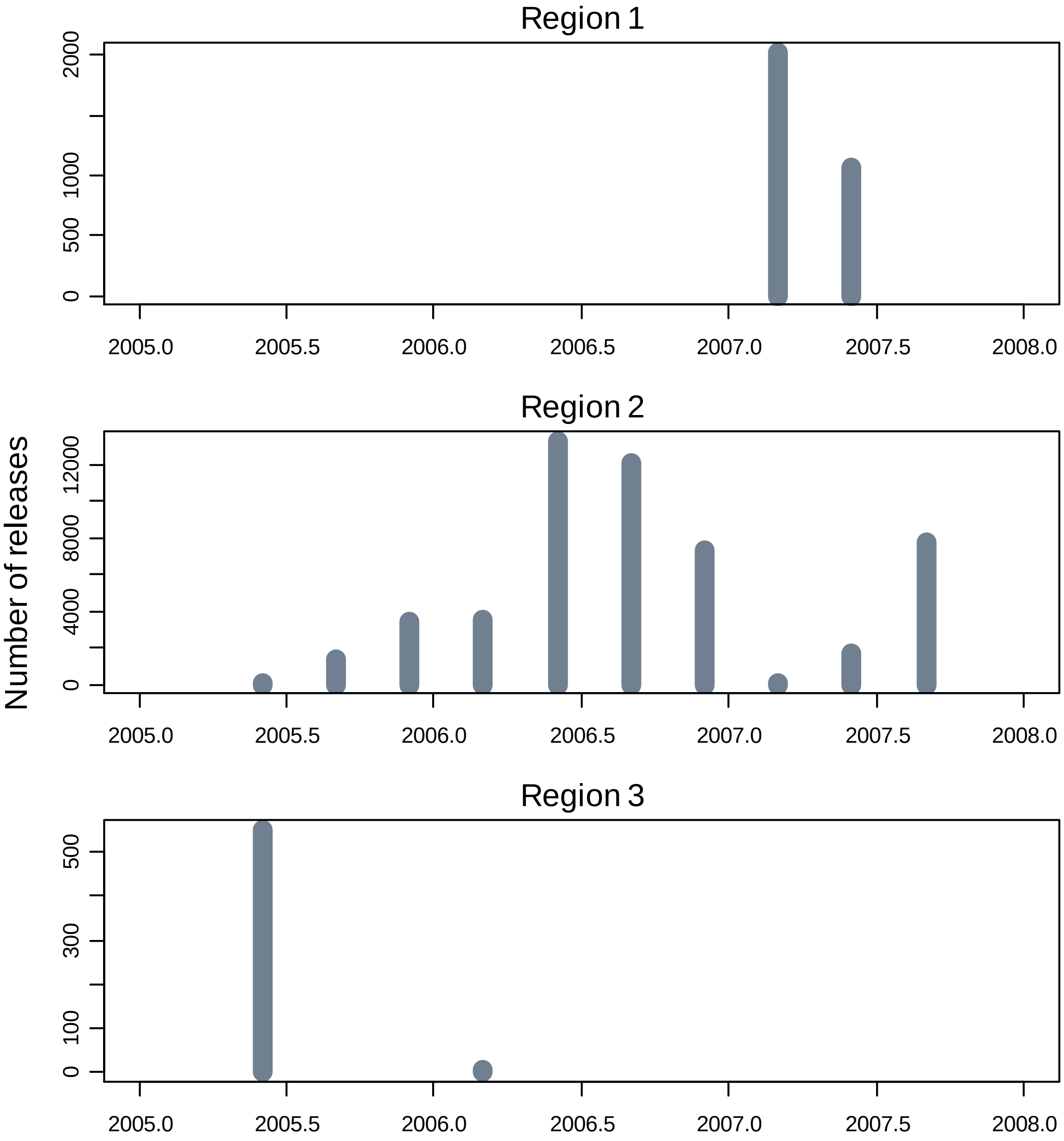

Figure 4. Number of tag releases by region and quarter included in the MFCL data set. No tag releases occurred in regions 4 and 5.

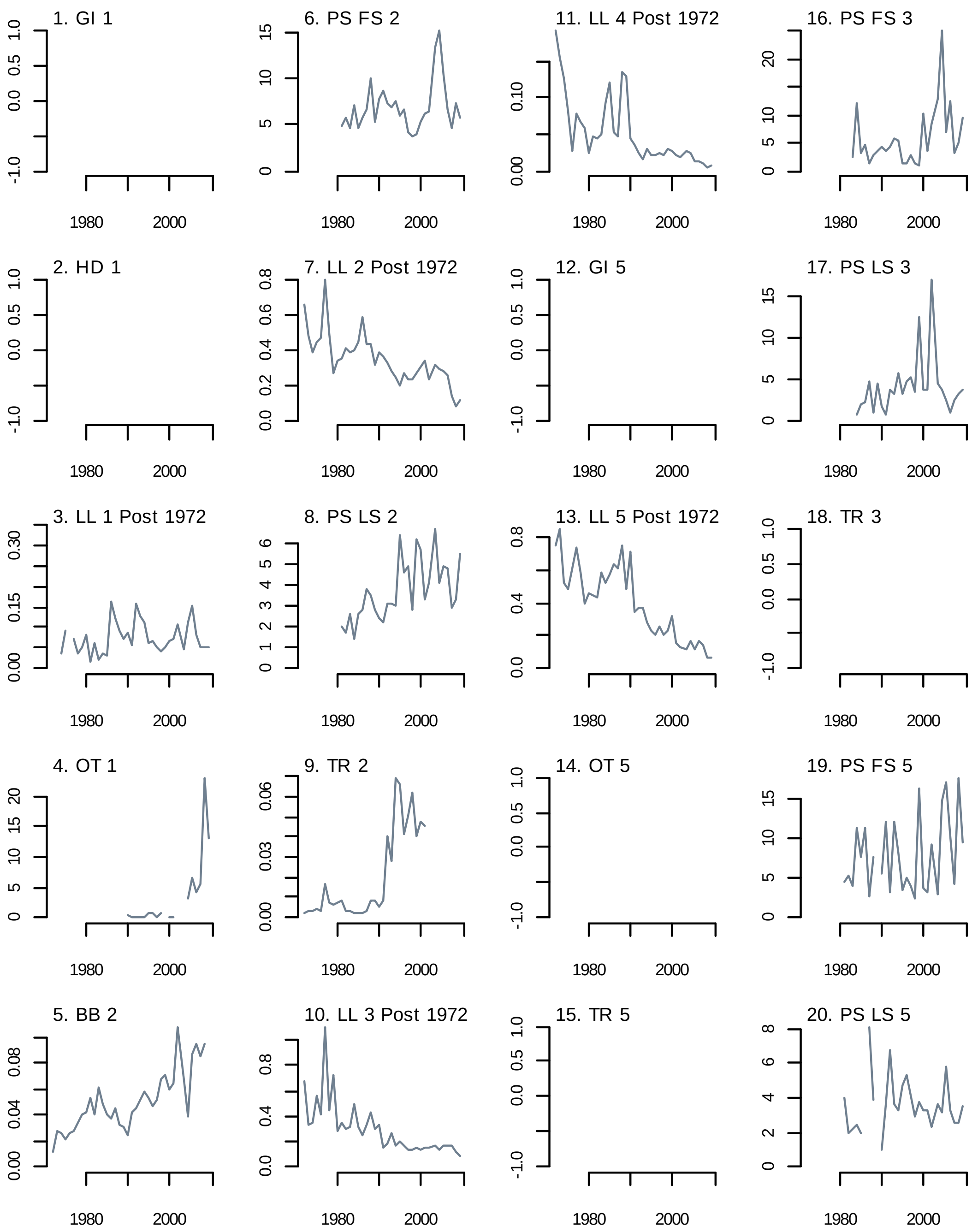

Figure 5. Quarterly catch-per-unit-effort (CPUE) by fishery. Units are catch (number) per GLM-standardised effort (fisheries LL 1–5), catch (number) per day fished/searched (PS fisheries) and catch (number) per trip. Note that CPUE for "Other" and troll fisheries is arbitrary and not based on data (see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

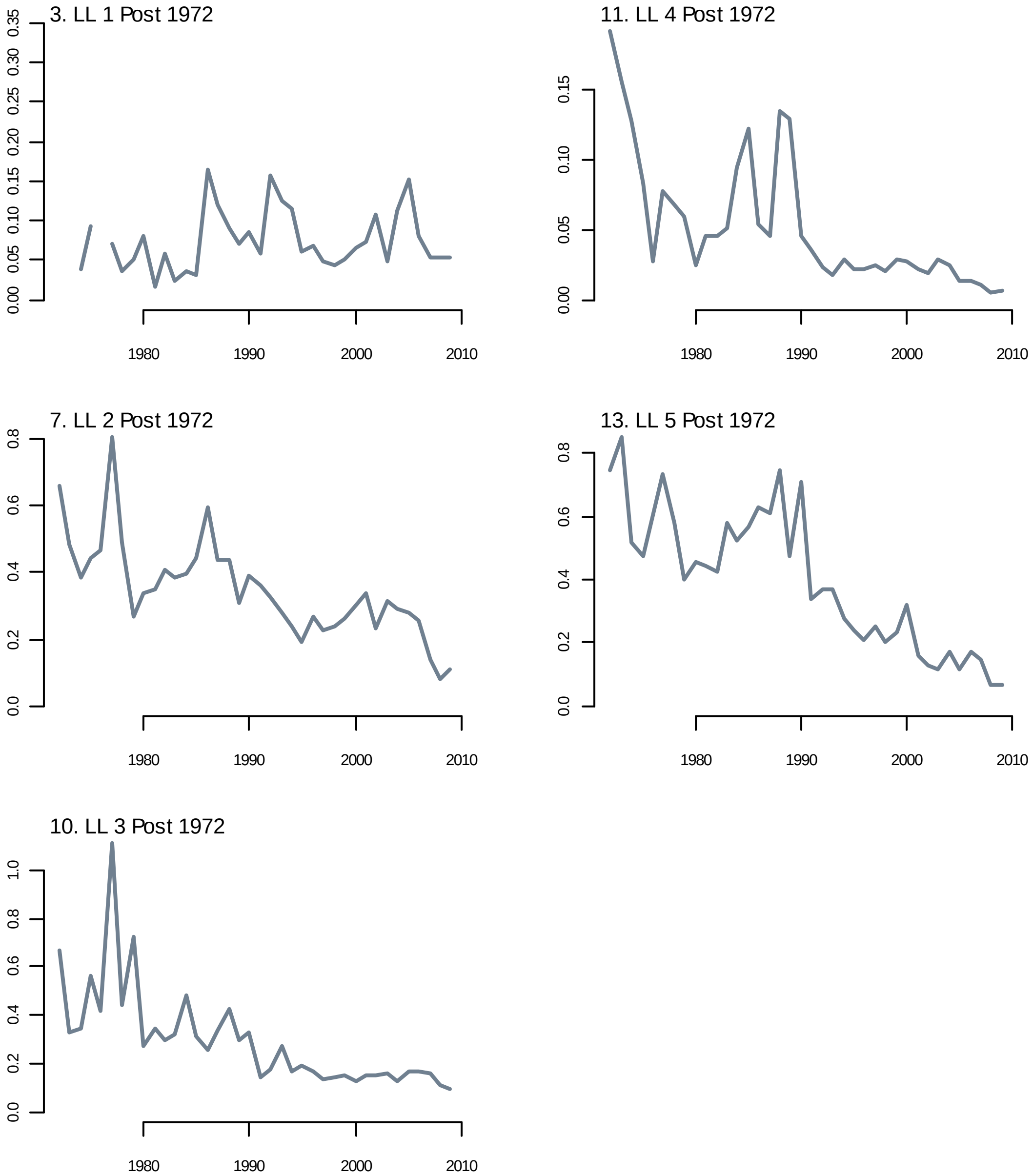

Figure 6. Annualised GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL ALL 1–5) scaled by the respective region scalars.

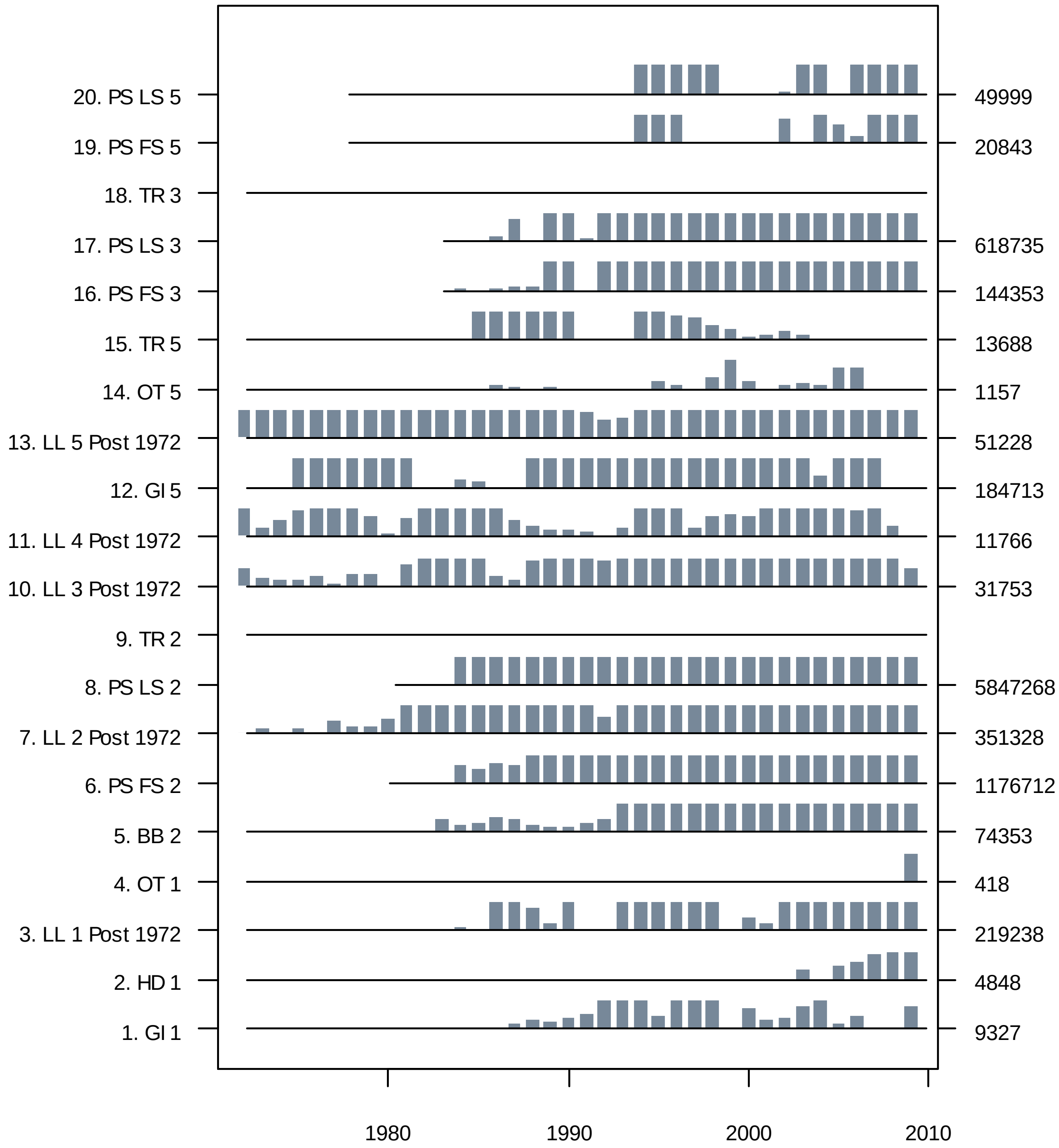

Figure 7. Number of fish length measurements by year for each fishery. The height of the bar is proportional to the maximum sample size, up to a maximum of 4000 fish per annum. The maximum annual sample size for each fishery is given on the right-hand side. The extent of the horizontal lines indicates the period over which each fishery occurred.

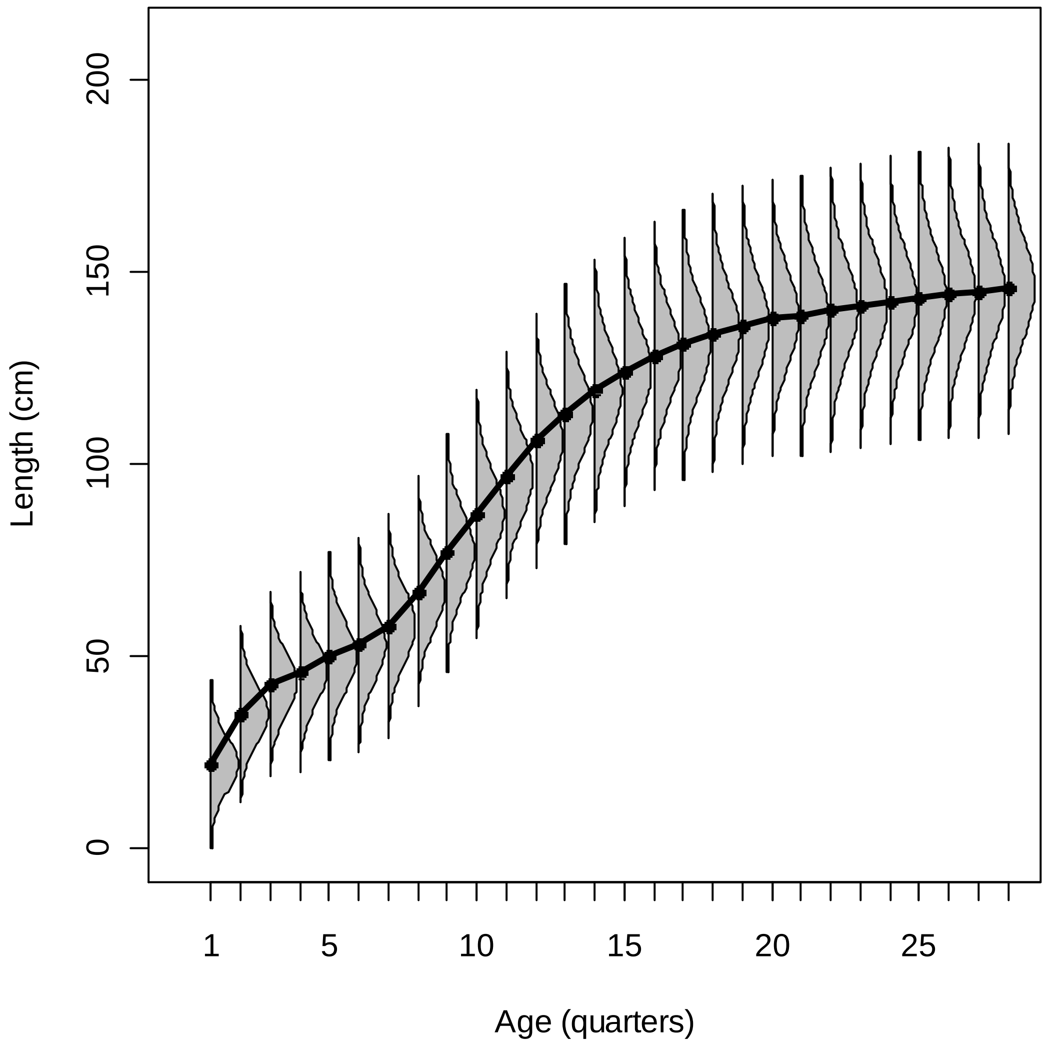

Figure 8. Fixed growth function for yellowfin tuna (following Fonteneau 2008). The black line represents the estimated mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age.

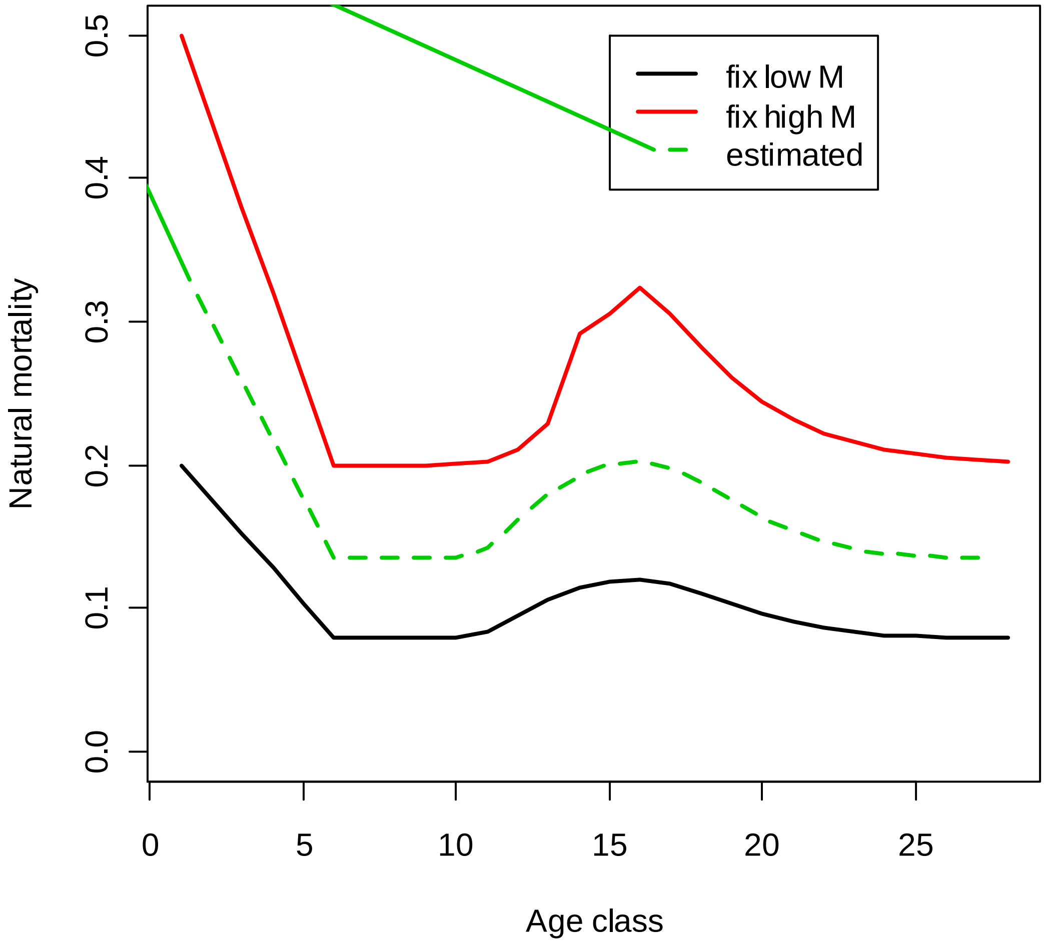

Figure 9. Age-specific natural mortality assumed for the assessment and the estimated level of natural mortality.

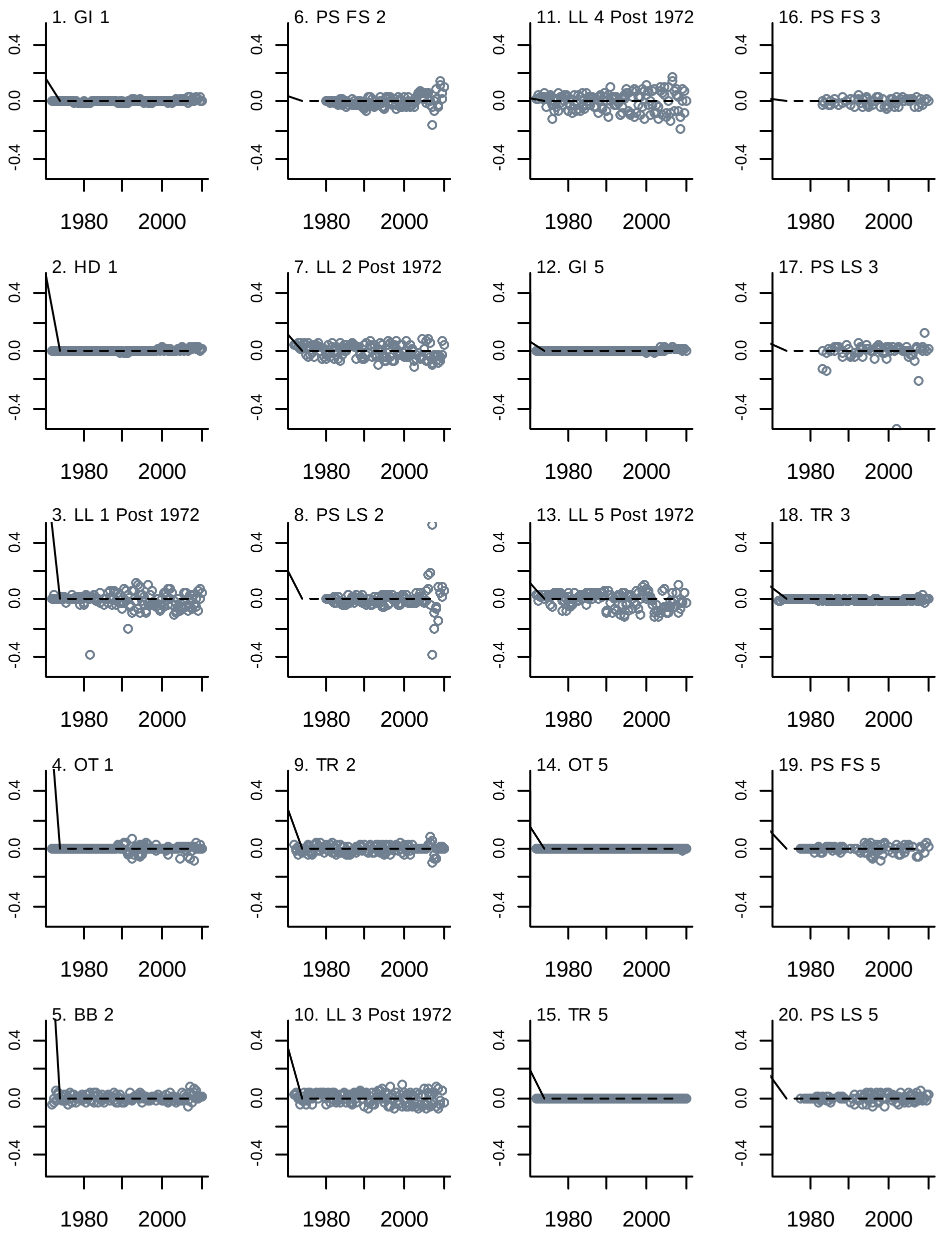

Figure 10. Residuals of ln (total catch) for each fishery.

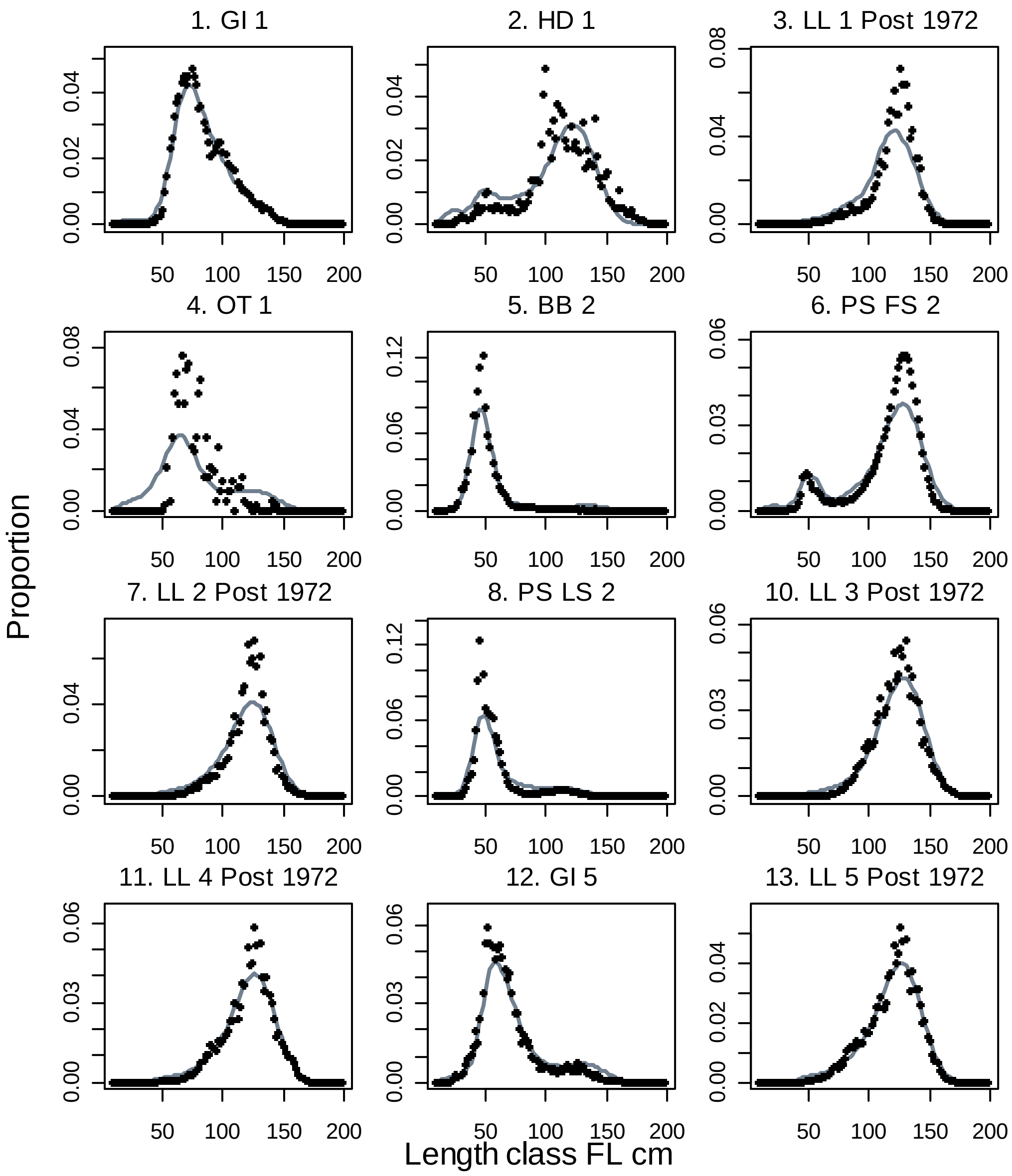

Figure 11. Observed (points) and predicted (line) length frequencies (in cm) for each fishery aggregated over time.

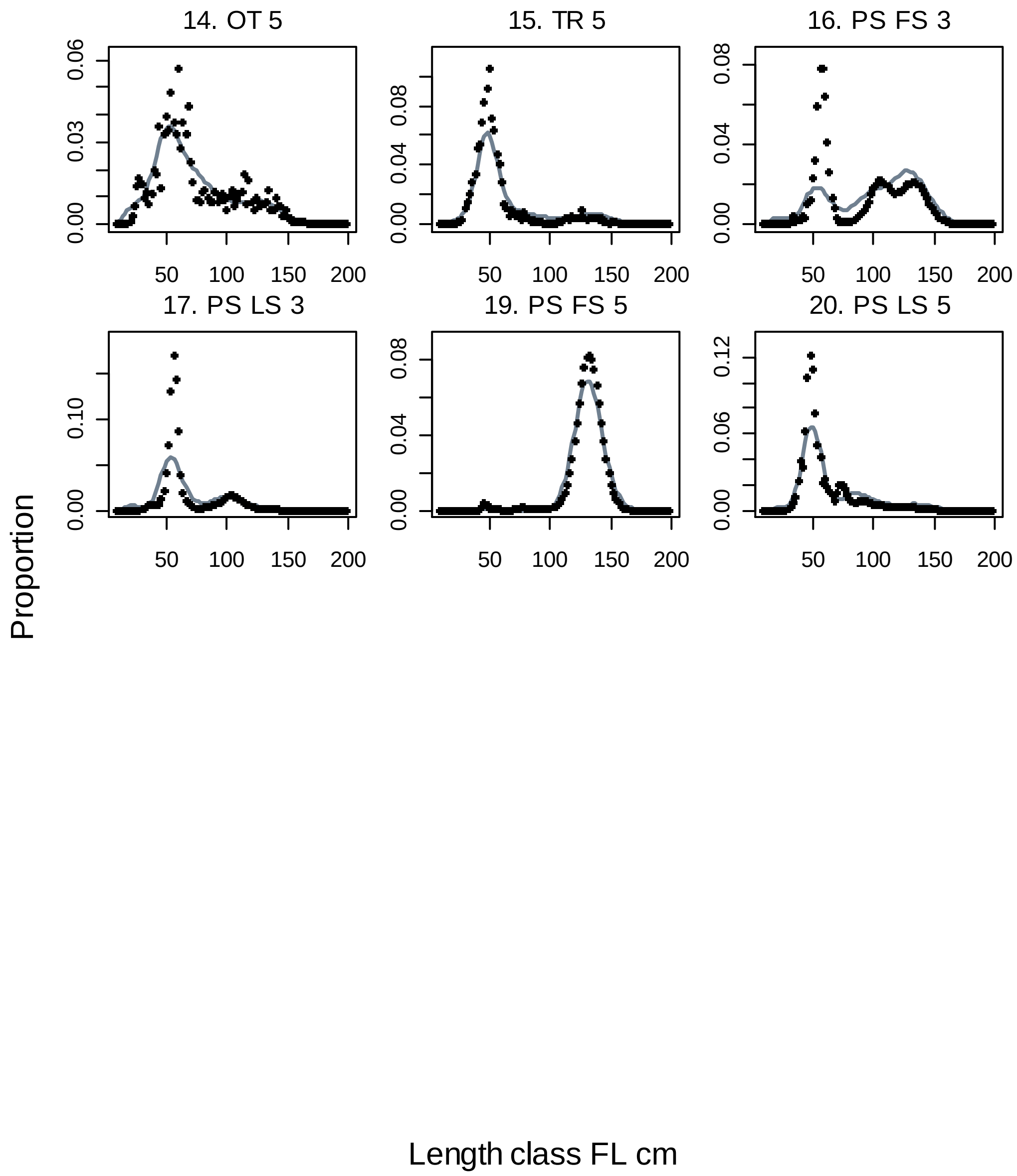

Figure 11 continued

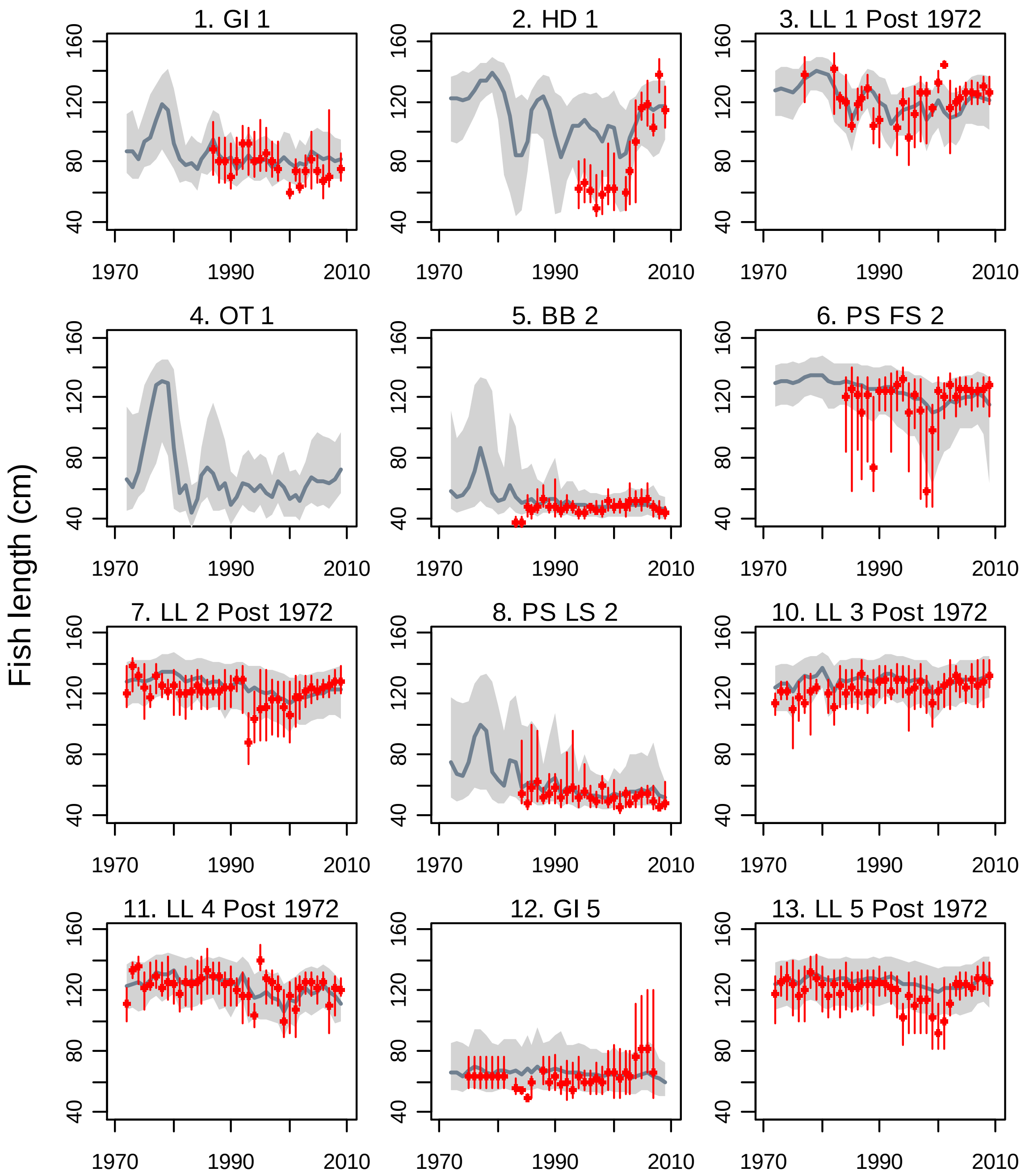

Figure 12. A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of yellowfin tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by year and only length samples with a minimum of 30 fish per year are plotted.

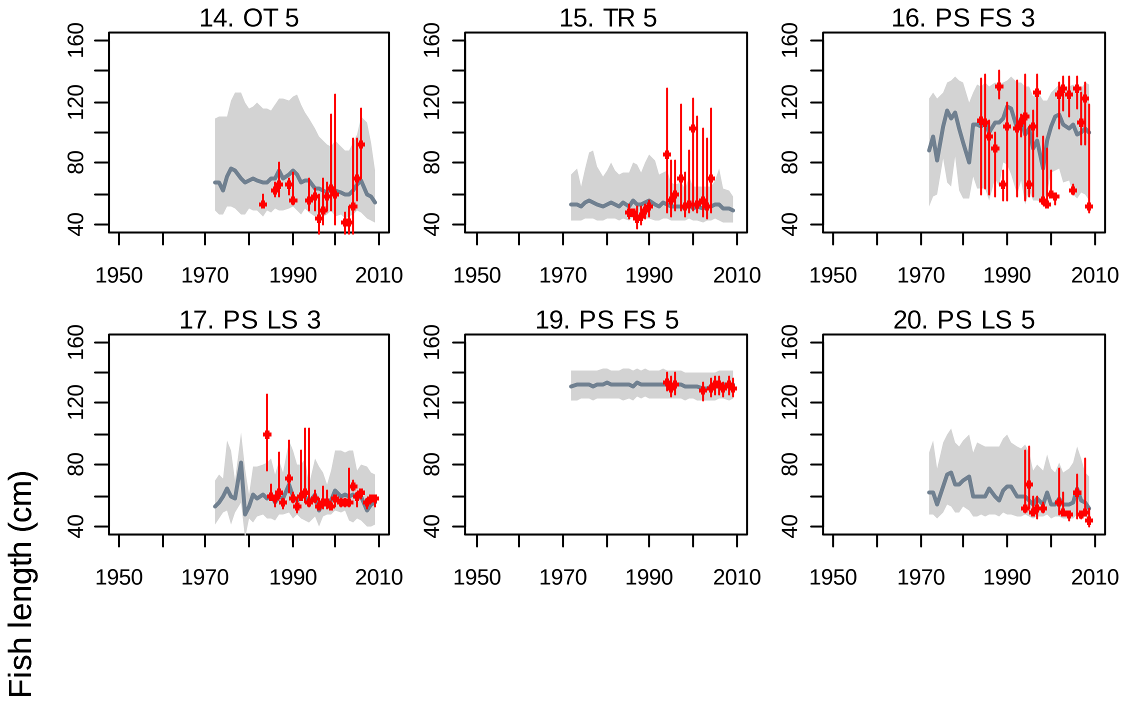

Figure 12 continued.

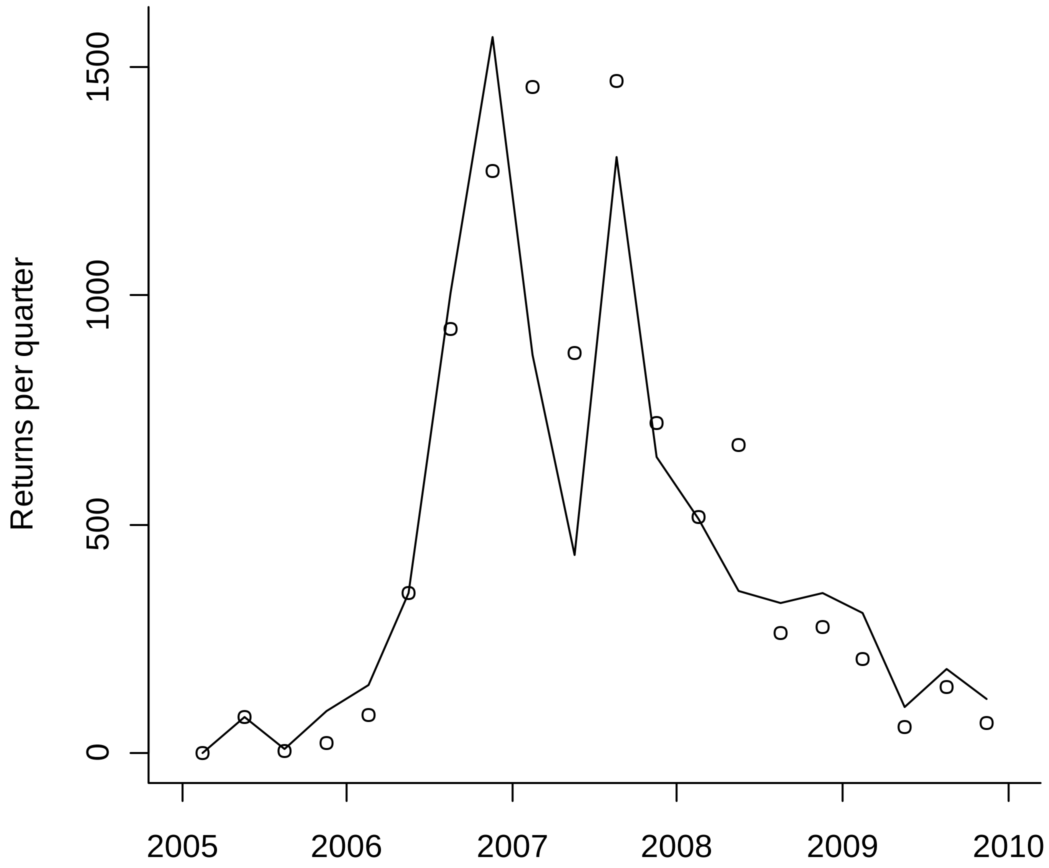

Figure 13. Number of observed (points) and predicted (line) tag returns by recapture period (quarter). Observed tag returns have been corrected for the purse-seine reporting rate (see text for details).

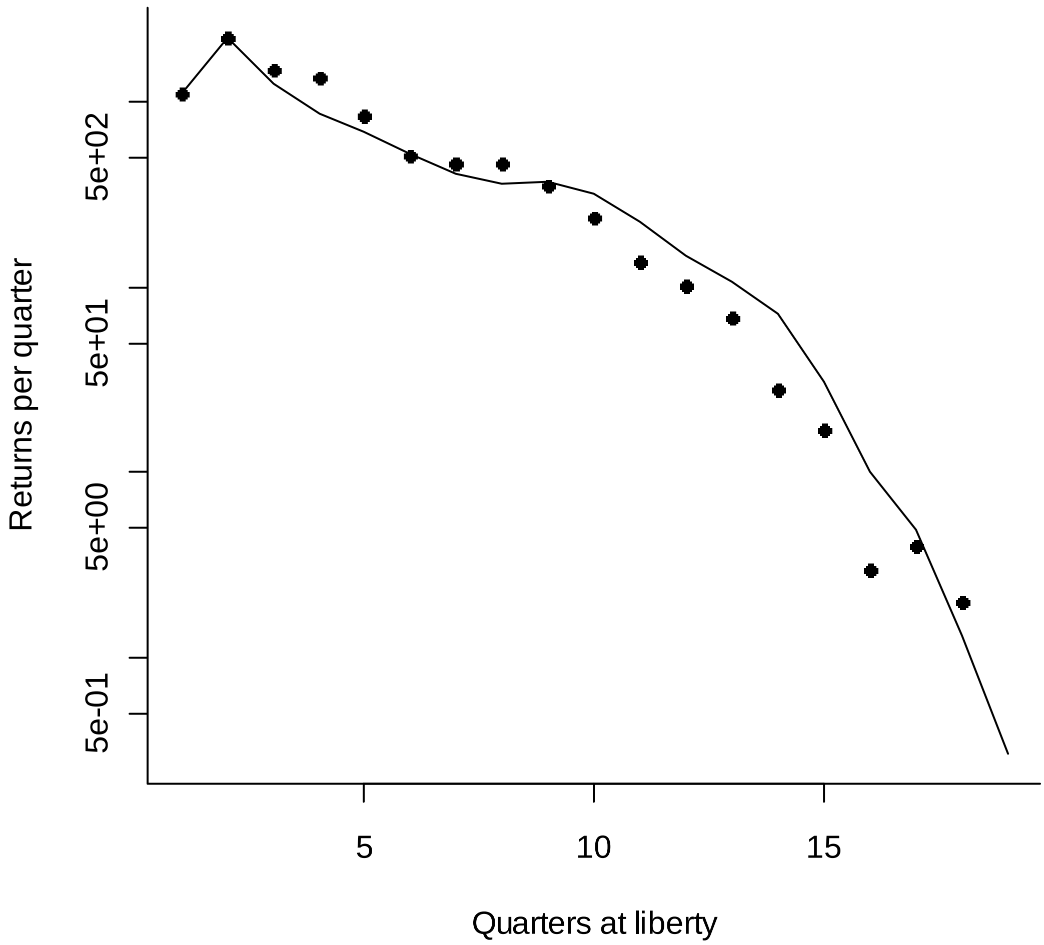

Figure 14. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters). Observed tag returns have been corrected for the purse-seine reporting rate (see text for details). The first quarter is considered to represent the mixing phase and these data are not included in the model fit.

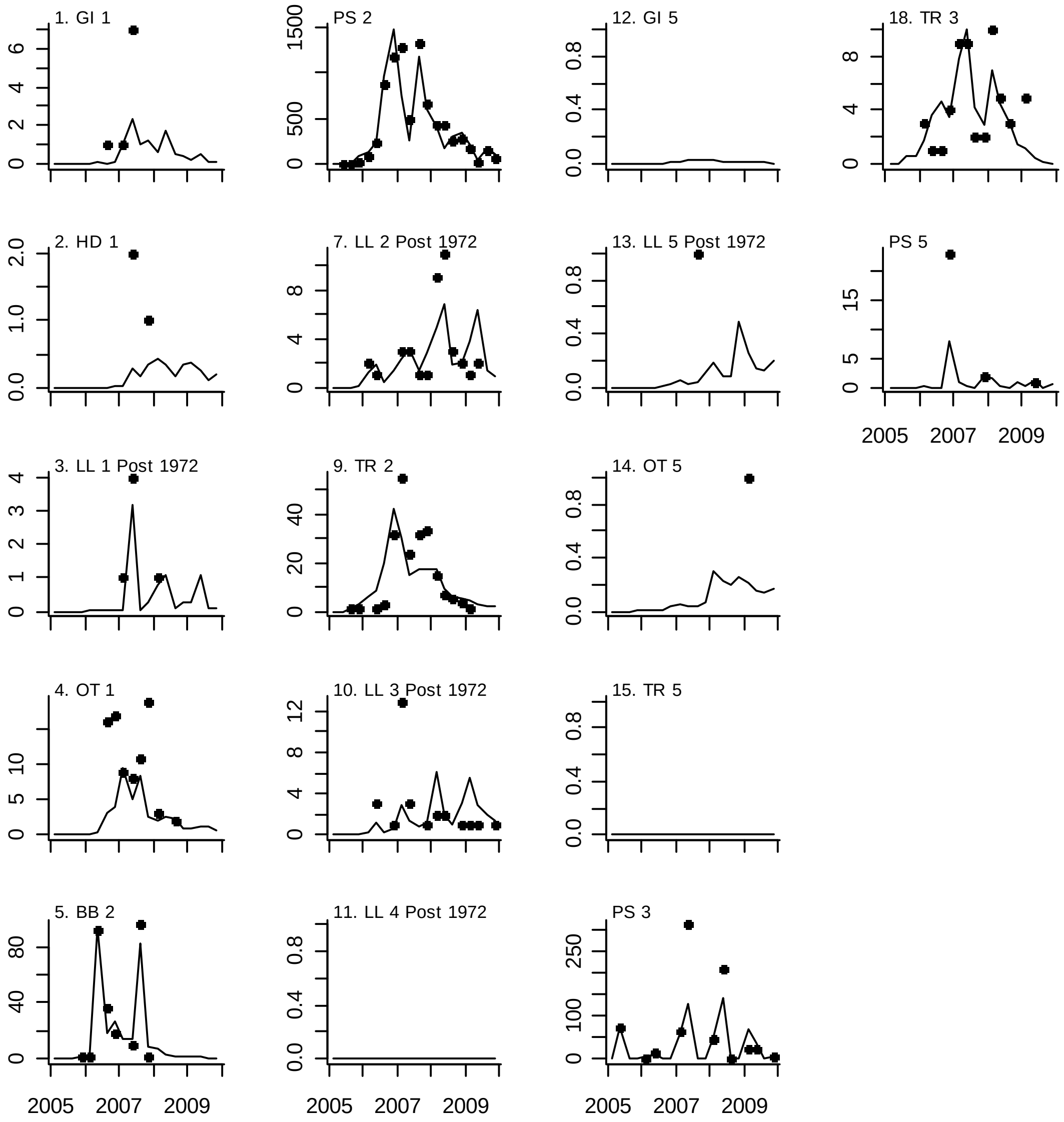

Figure 15. Number of observed (points) and predicted (line) tag returns by recapture period (quarter) for the various fisheries (or groups of fisheries) defined in the model. Observed tag returns have been corrected for the purse-seine reporting rate (see text for details).

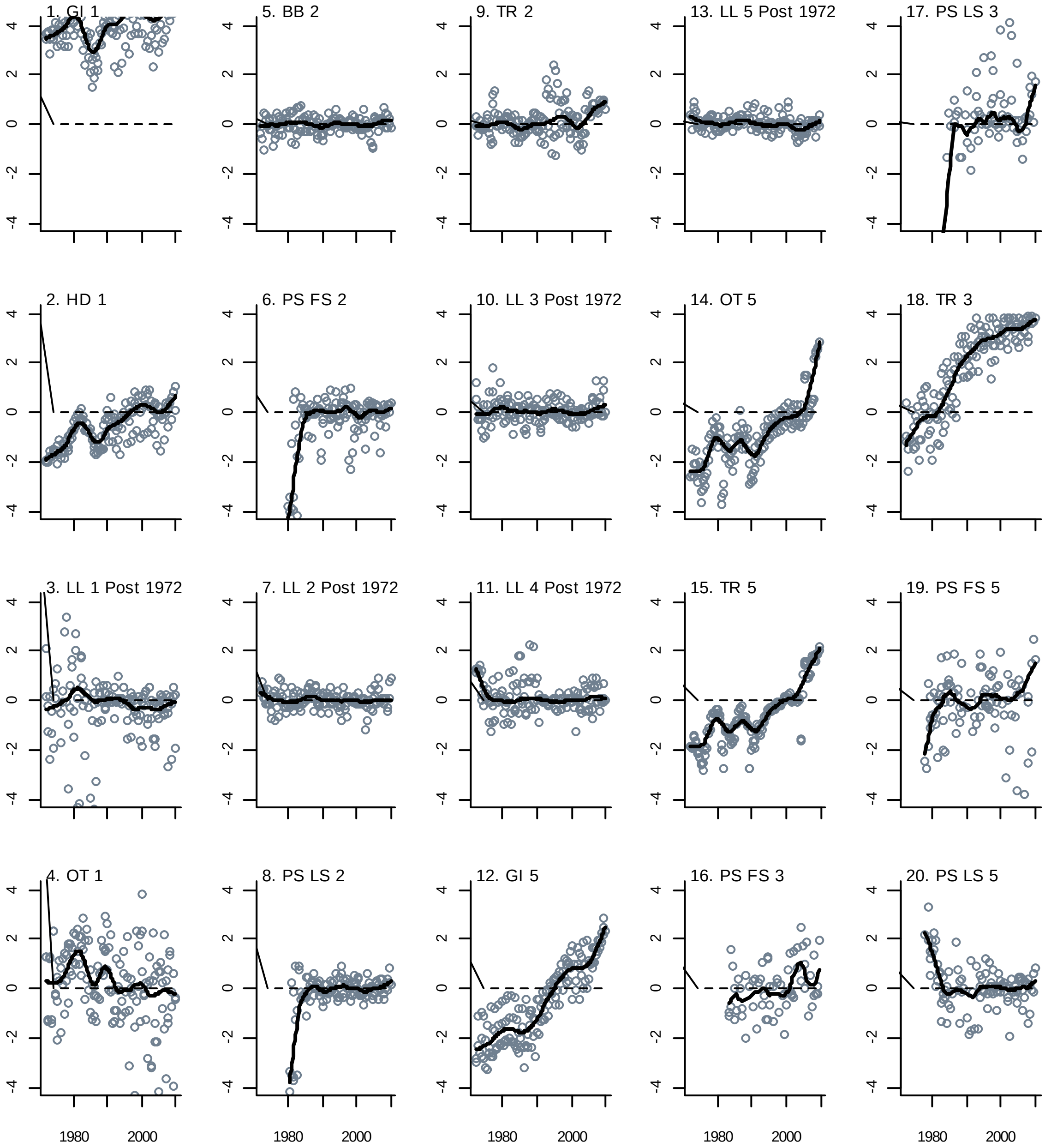

Figure 16. Effort deviations by time period for each fishery. The solid line represents a lowess fit to the data.

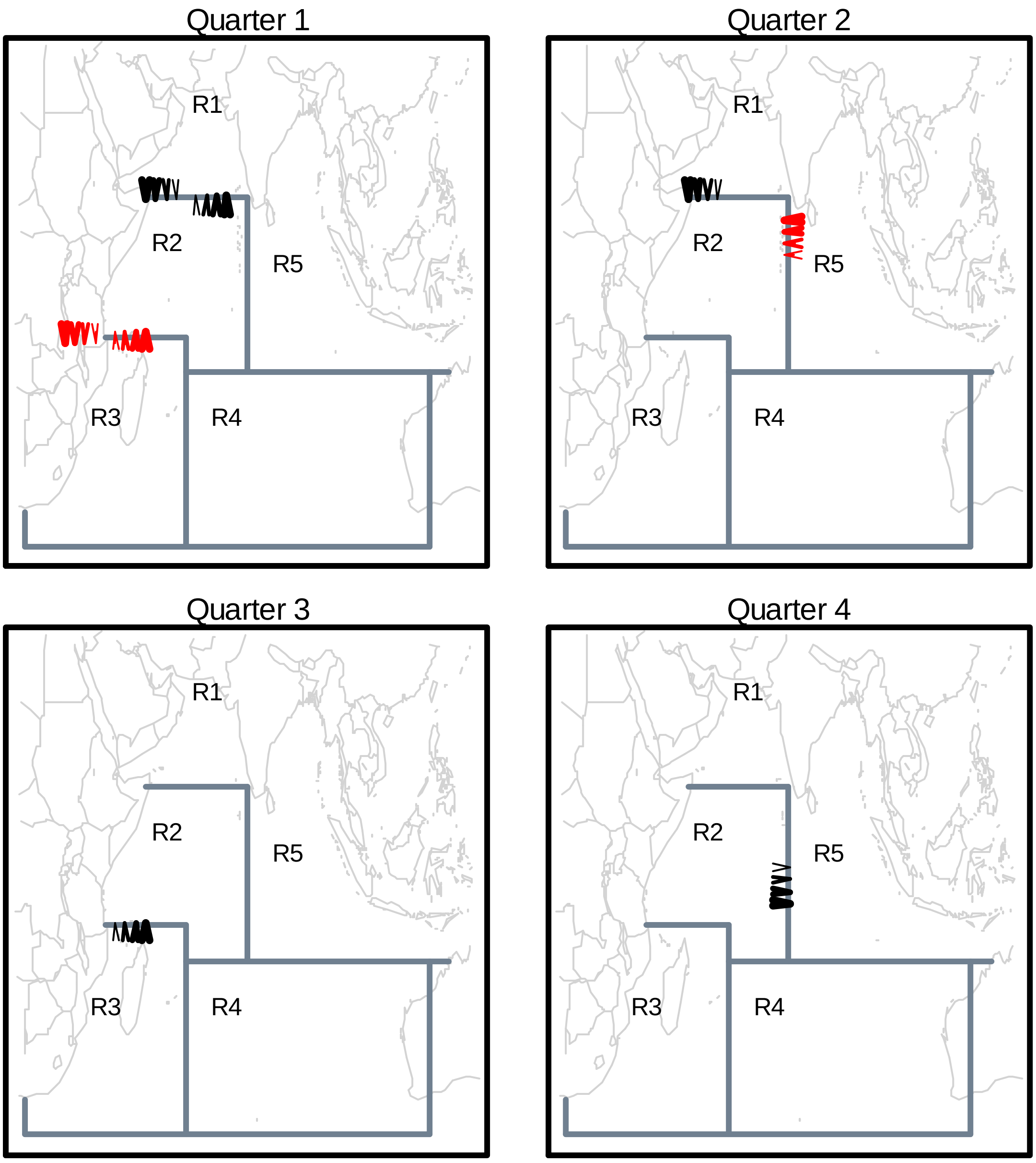

Figure 17. Estimated quarterly movement coefficients at age (1, 7, 15, 25 quarters) from the base-case model. The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age. The maximum movement (quarter 1, region 3 to region 2) represents movement of 8.7% of the fish at the start of the quarter. Movement rates are colour coded: black, 0.5–5%; red 5–10%; green >10%.

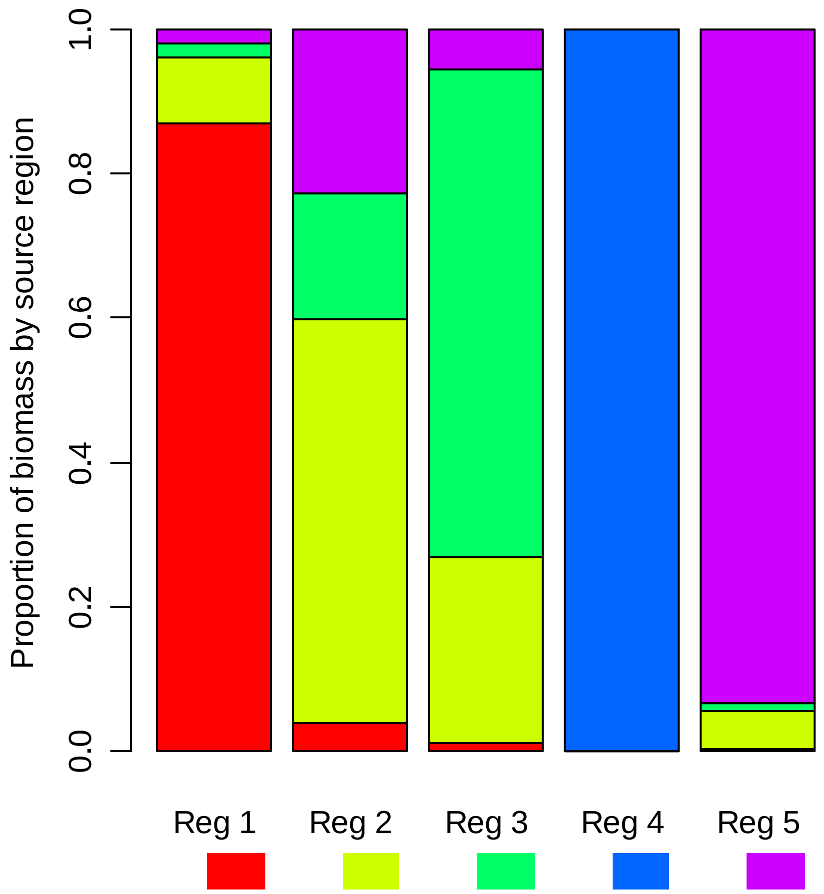

Figure 18. Proportional distribution of total biomass (by weight) in each region (Reg 1–5) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment among regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

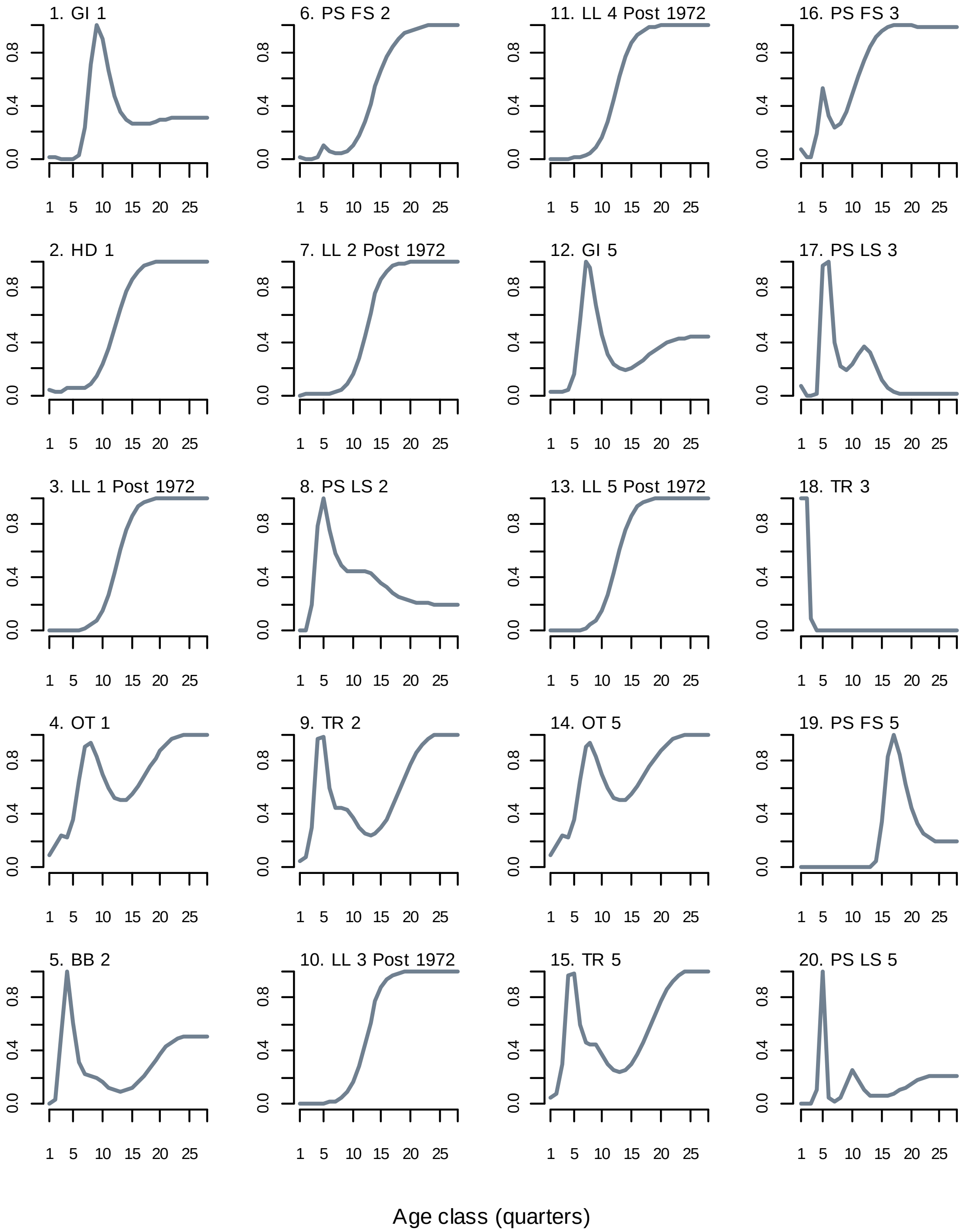

Figure 19. Selectivity coefficients, by fishery.

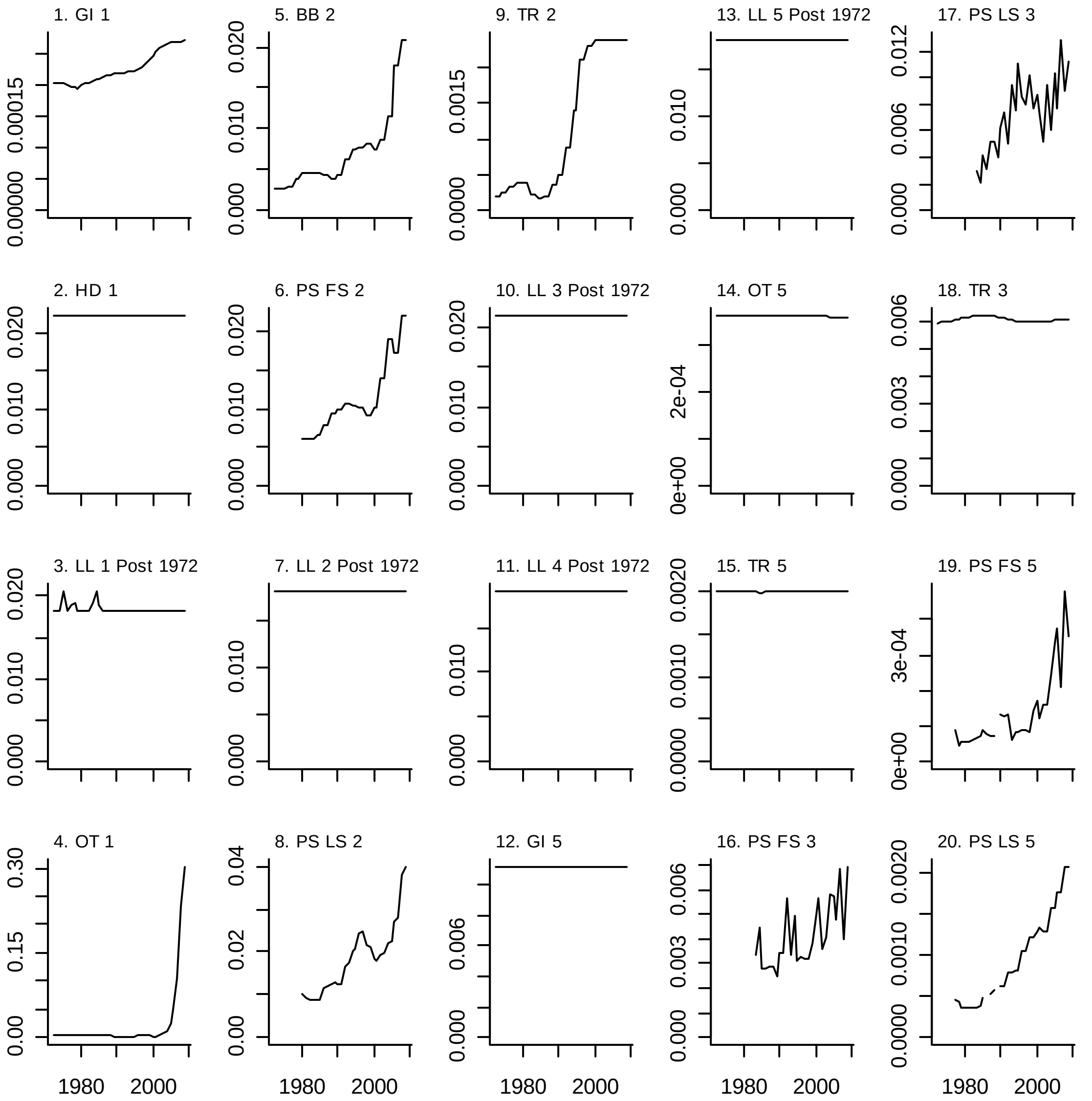

Figure 20. Average annual catchability time series, by fishery.

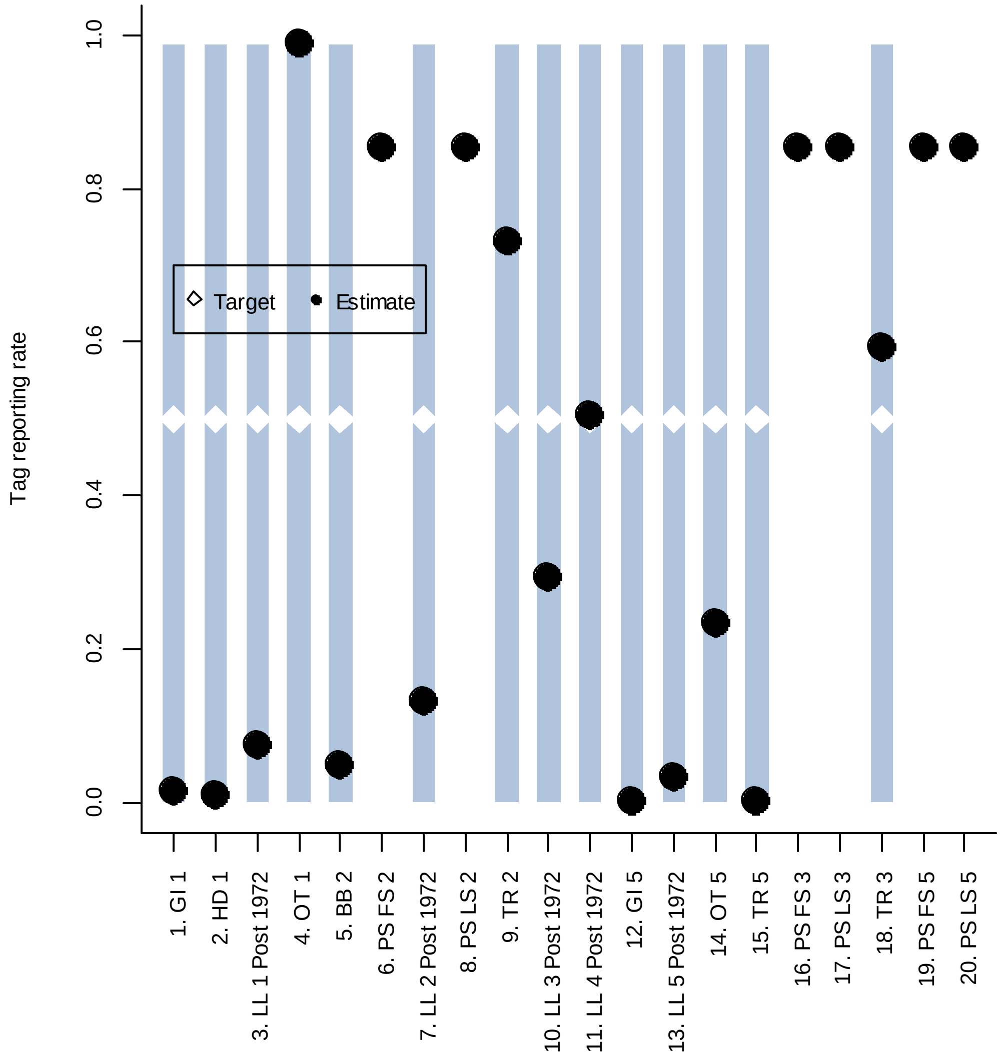

Figure 21. Estimated tag-reporting rates by fishery (black circles). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars indicate a range of ±1 SD. The reporting rates for the purse-seine fishery were fixed.

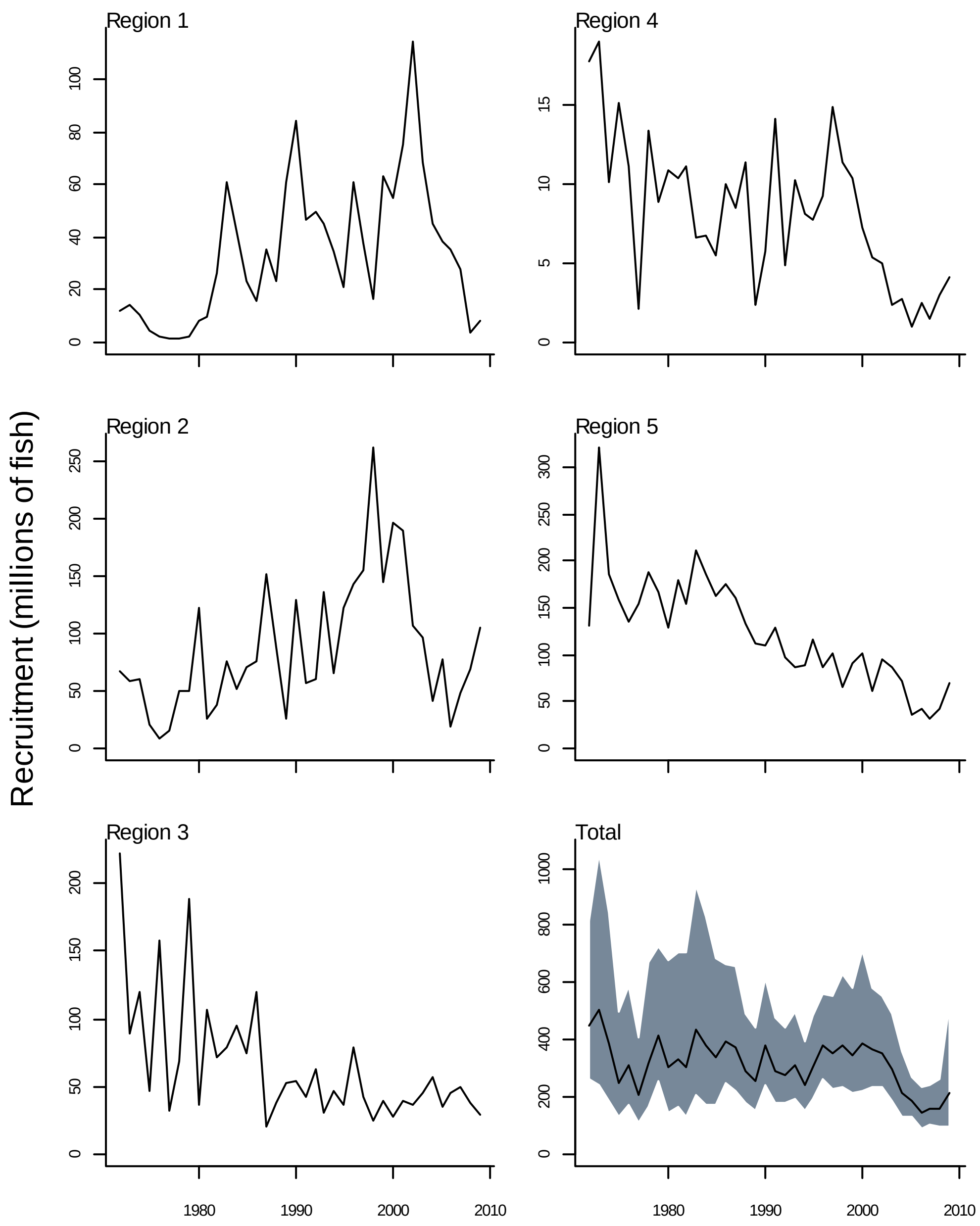

Figure 22. Estimated annual recruitment (millions of fish) by region and for the IO. The shaded area for the IO indicates the approximate 95% confidence intervals.

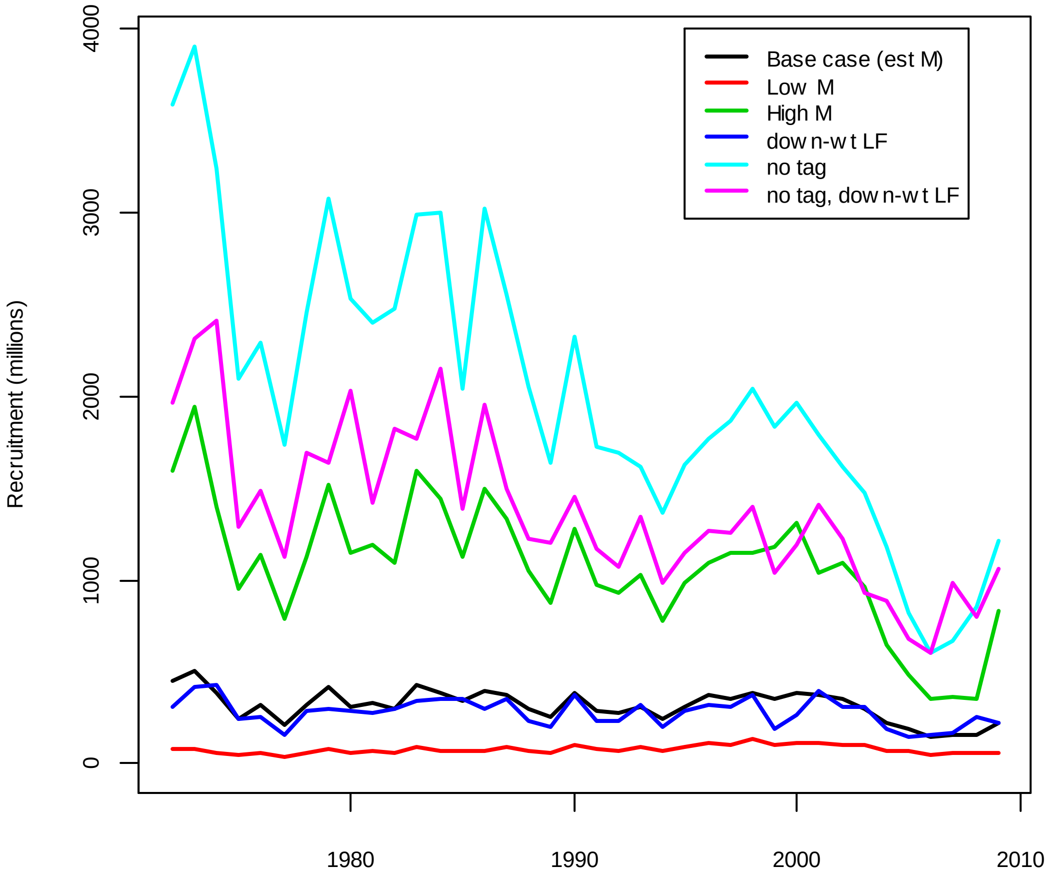

Figure 23a. Estimated annual recruitment (millions of fish) for the IO obtained from the different model options.

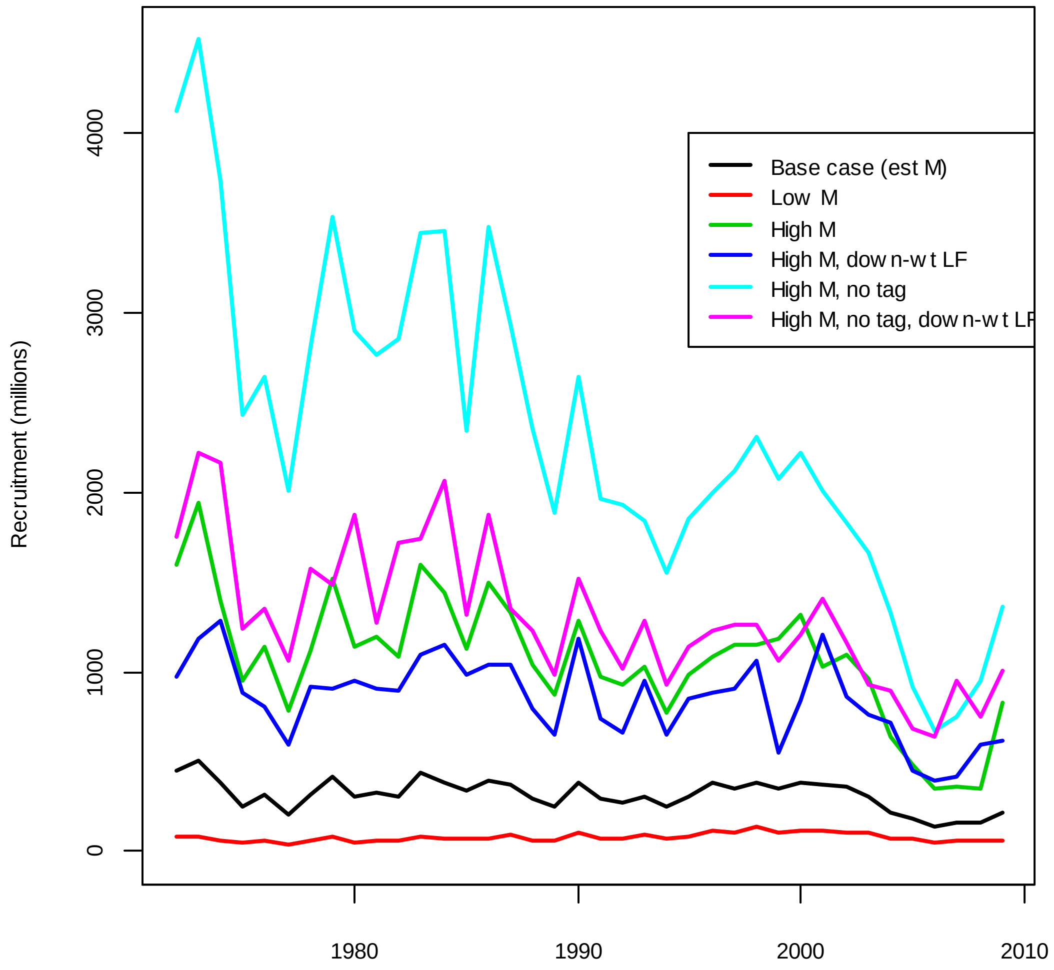

Figure 23b. Estimated annual recruitment (millions of fish) for the IO obtained from the different model options.

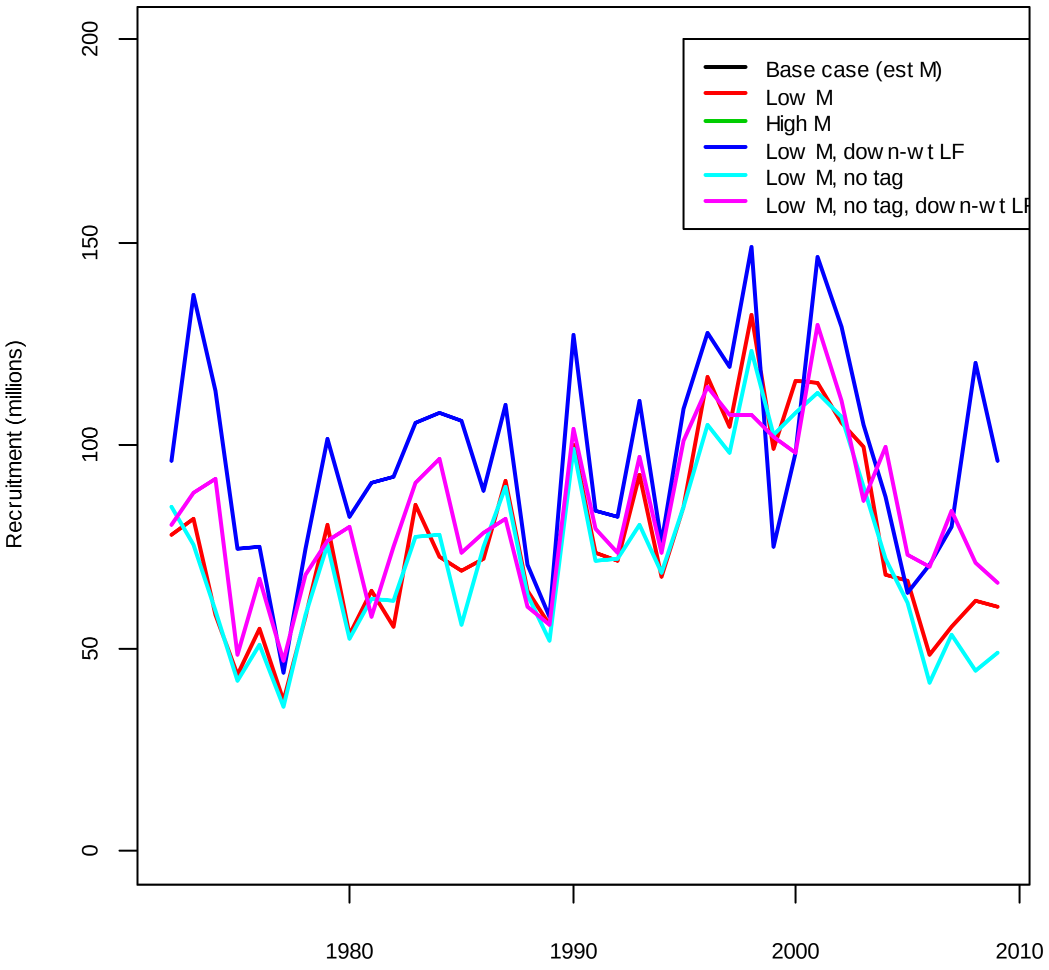

Figure 23c. Estimated annual recruitment (millions of fish) for the IO obtained from the different model options.

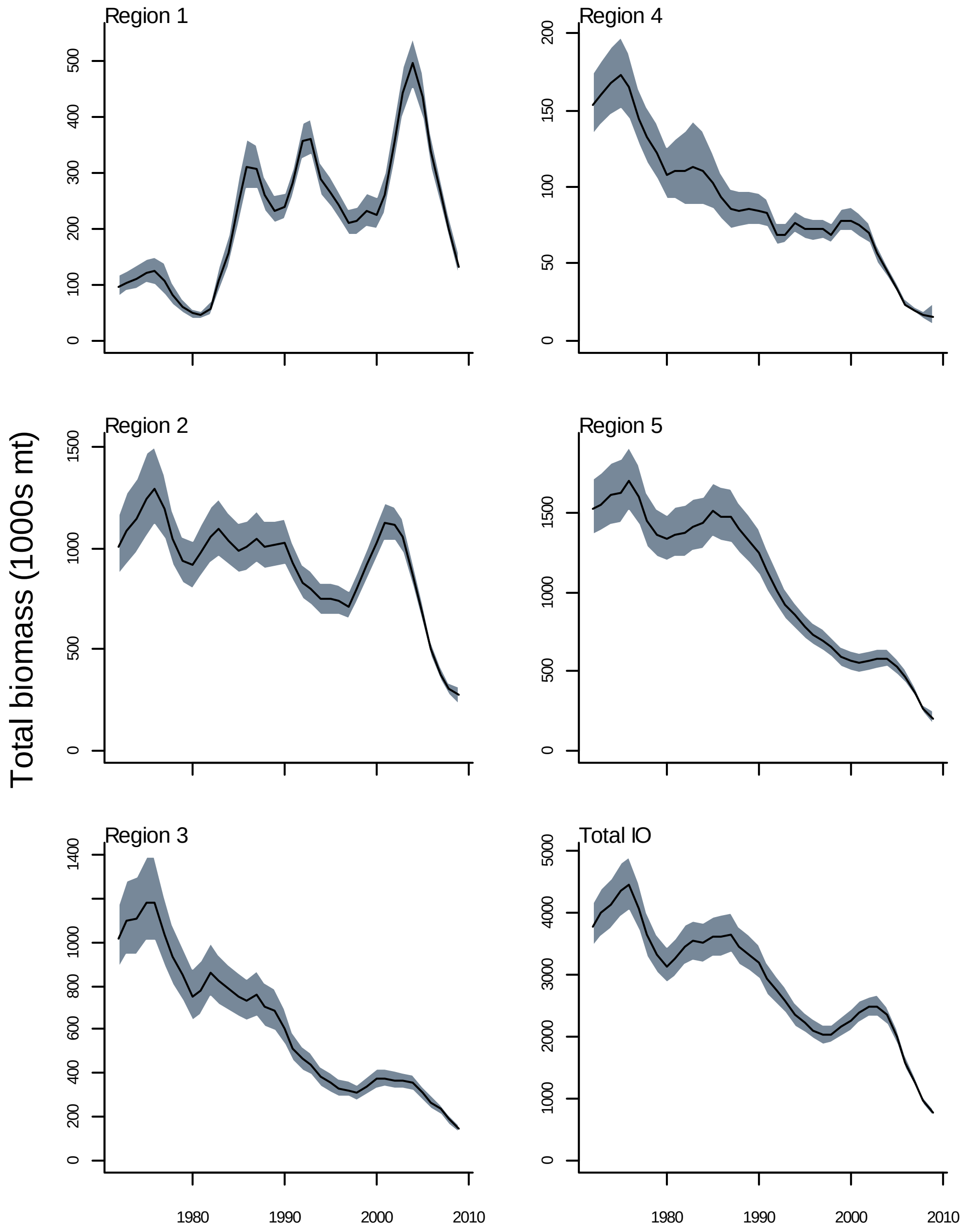

Figure 24. Estimated annual average total biomass (thousand mt) by region and for the IO for the base-case analysis. The shaded areas indicate the approximate 95% confidence intervals.

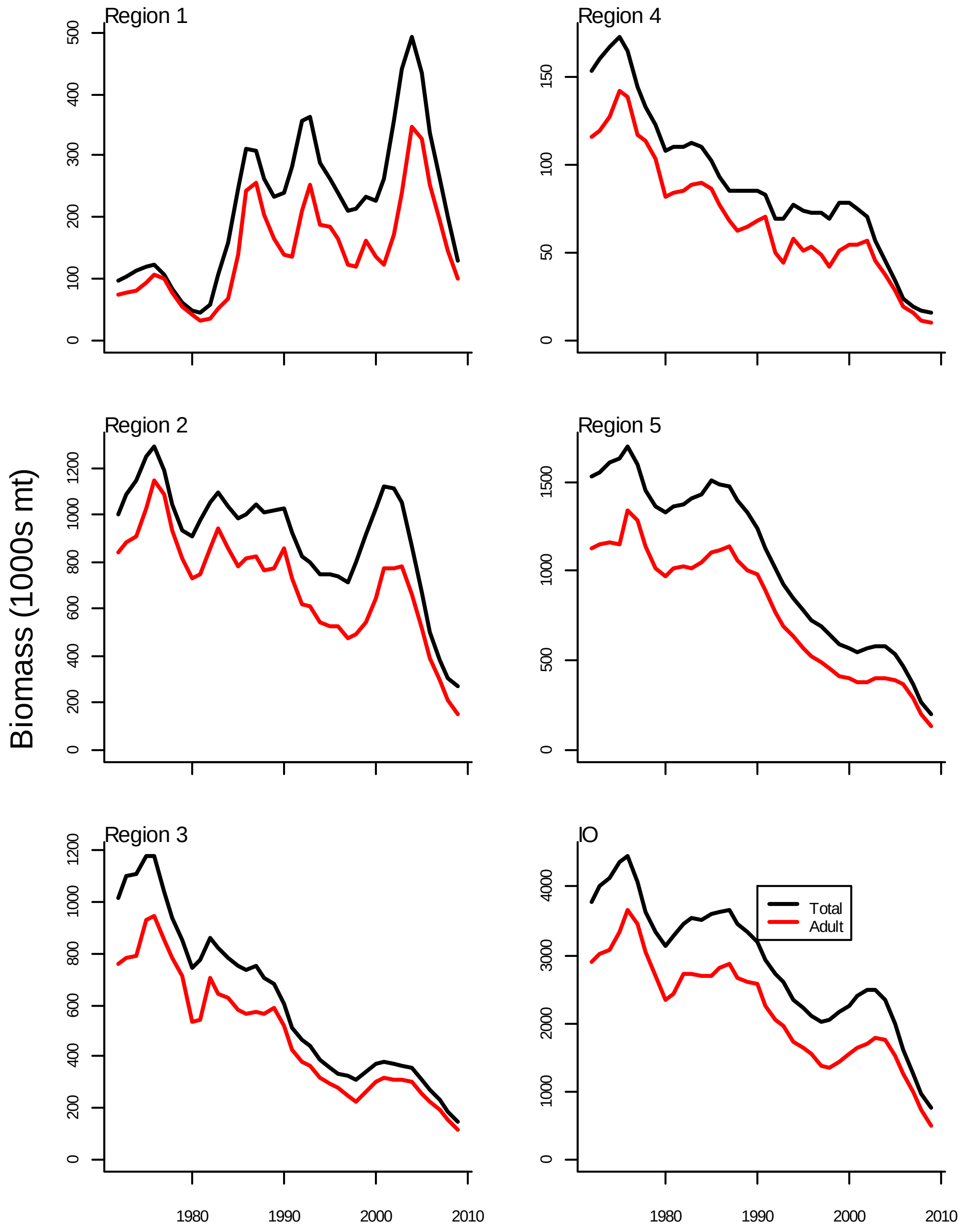

Figure 25. Temporal trend in total and adult biomass (1000s mt) by region and for the entire IO from the base-case assessment.

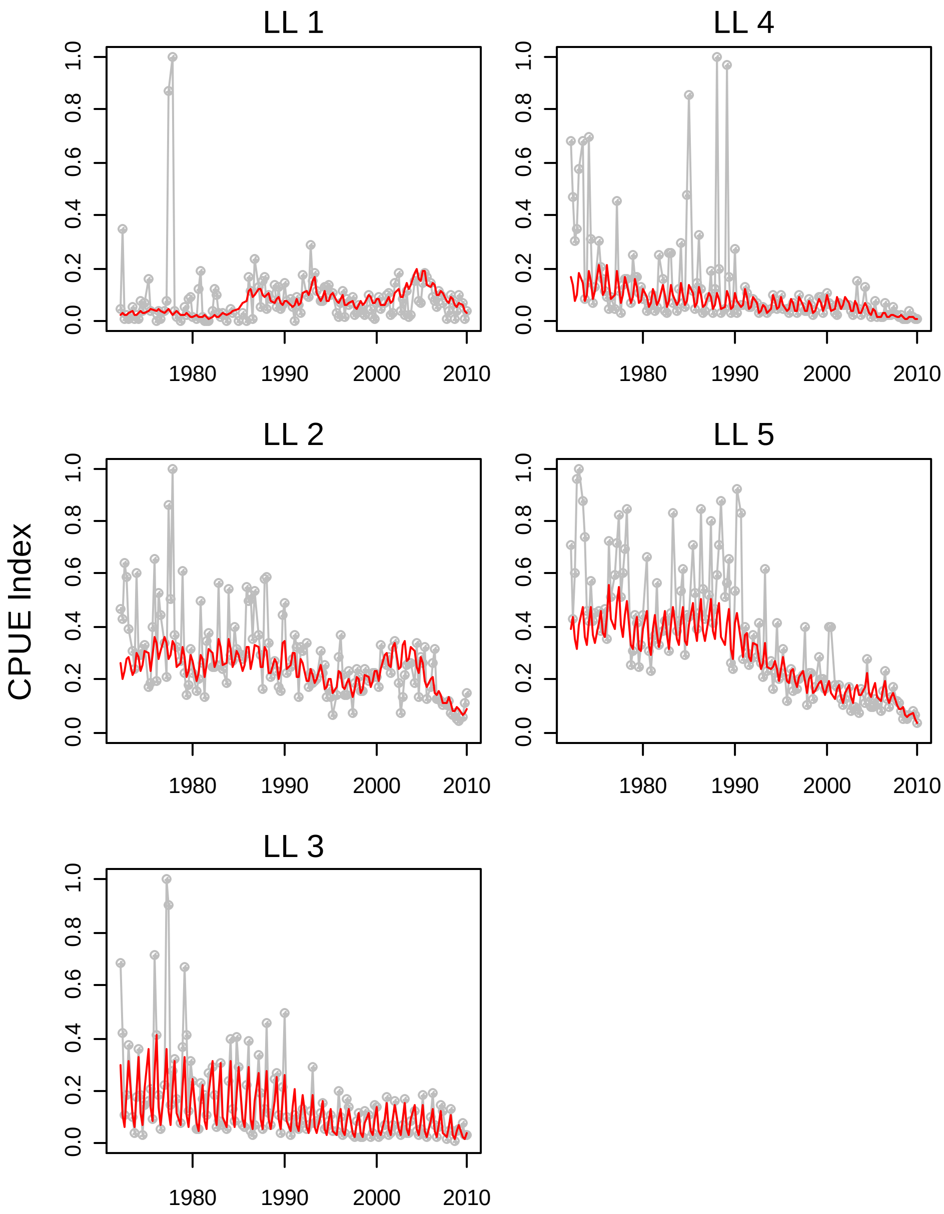

Figure 26. A comparison of longline exploitable biomass by quarter and region (red line) and the quarterly standardised CPUE indices (grey line and points) for the fisheries. For comparison, both series are scaled to the average of the series.

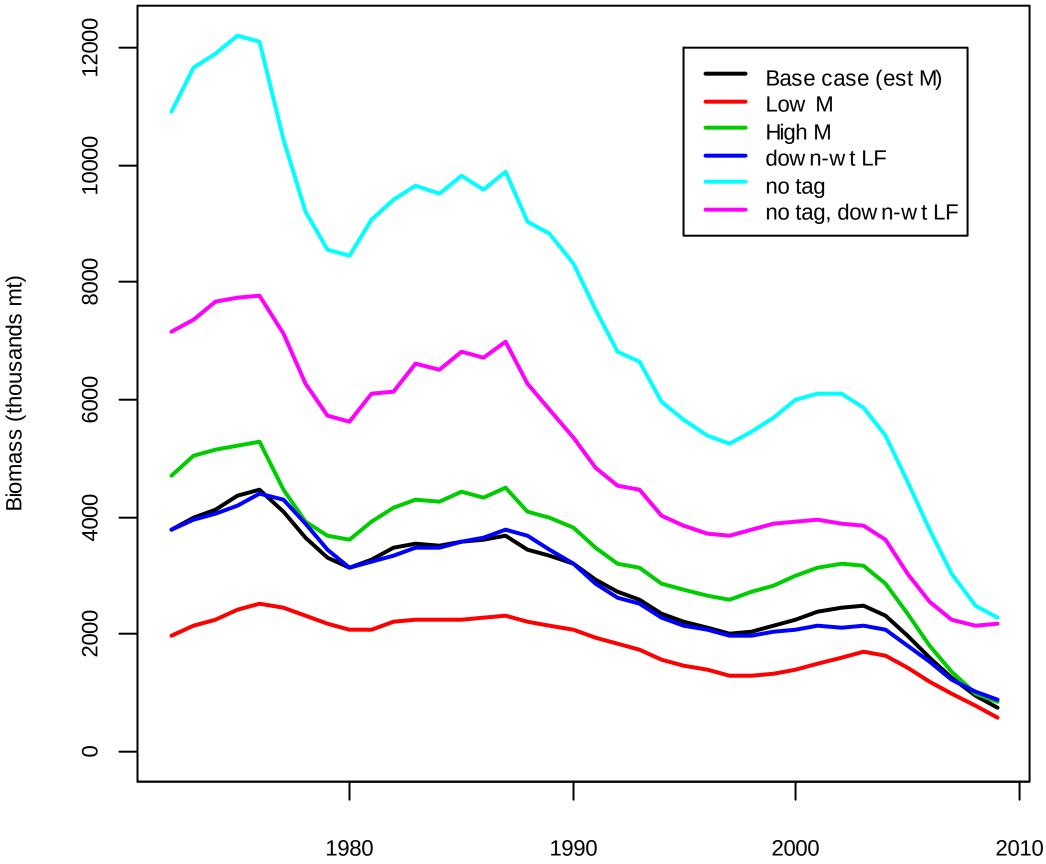

Figure 27a. Estimated annual average total biomass (thousands mt) for the IO obtained from a range of different model options.

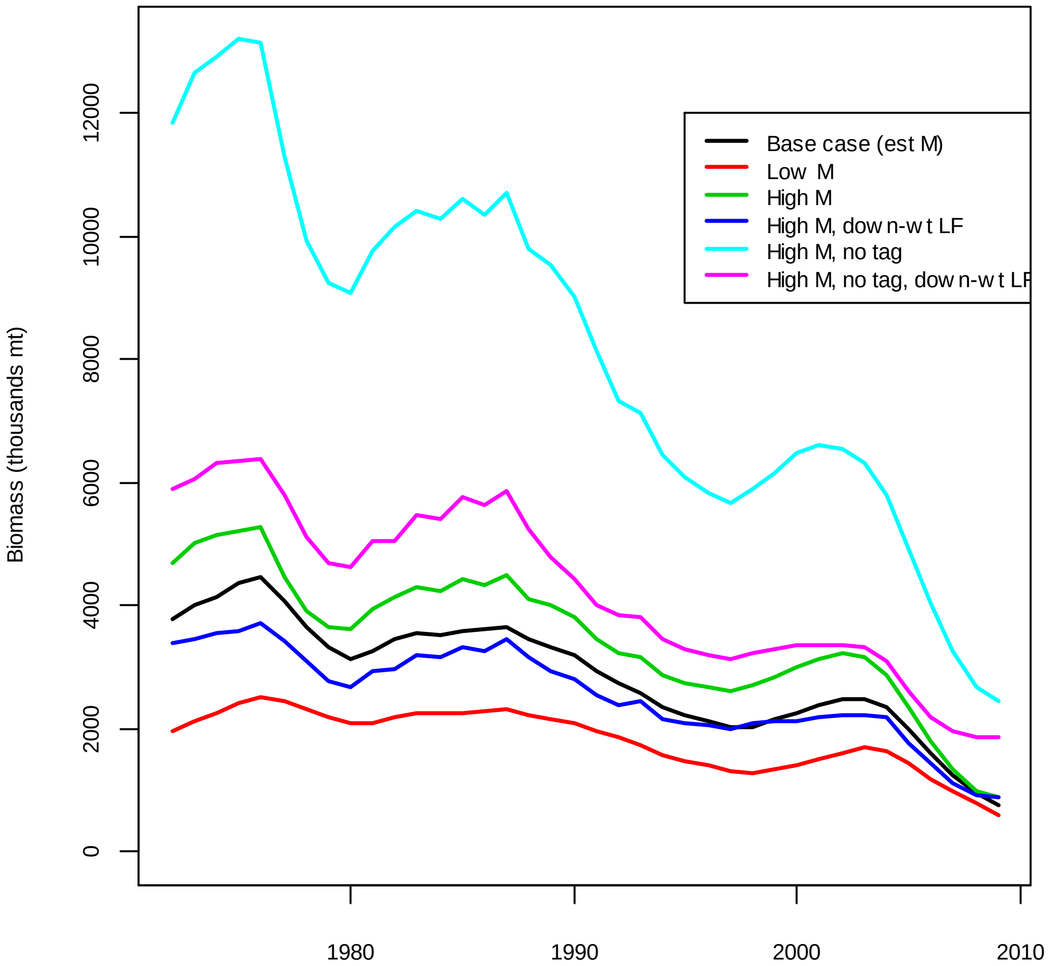

Figure 27b. Estimated annual average total biomass (thousands mt) for the IO obtained from a range of different model options.

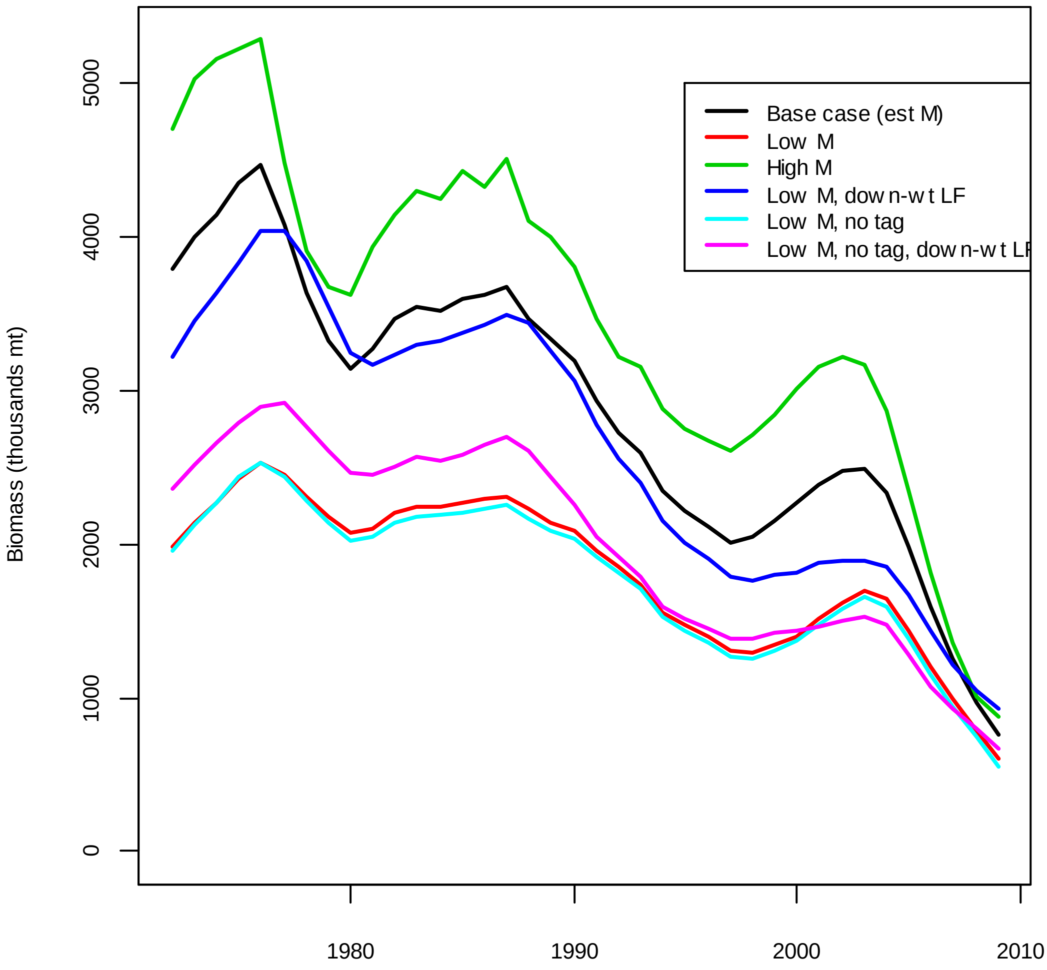

Figure 27c. Estimated annual average total biomass (thousands mt) for the IO obtained from a range of different model options.

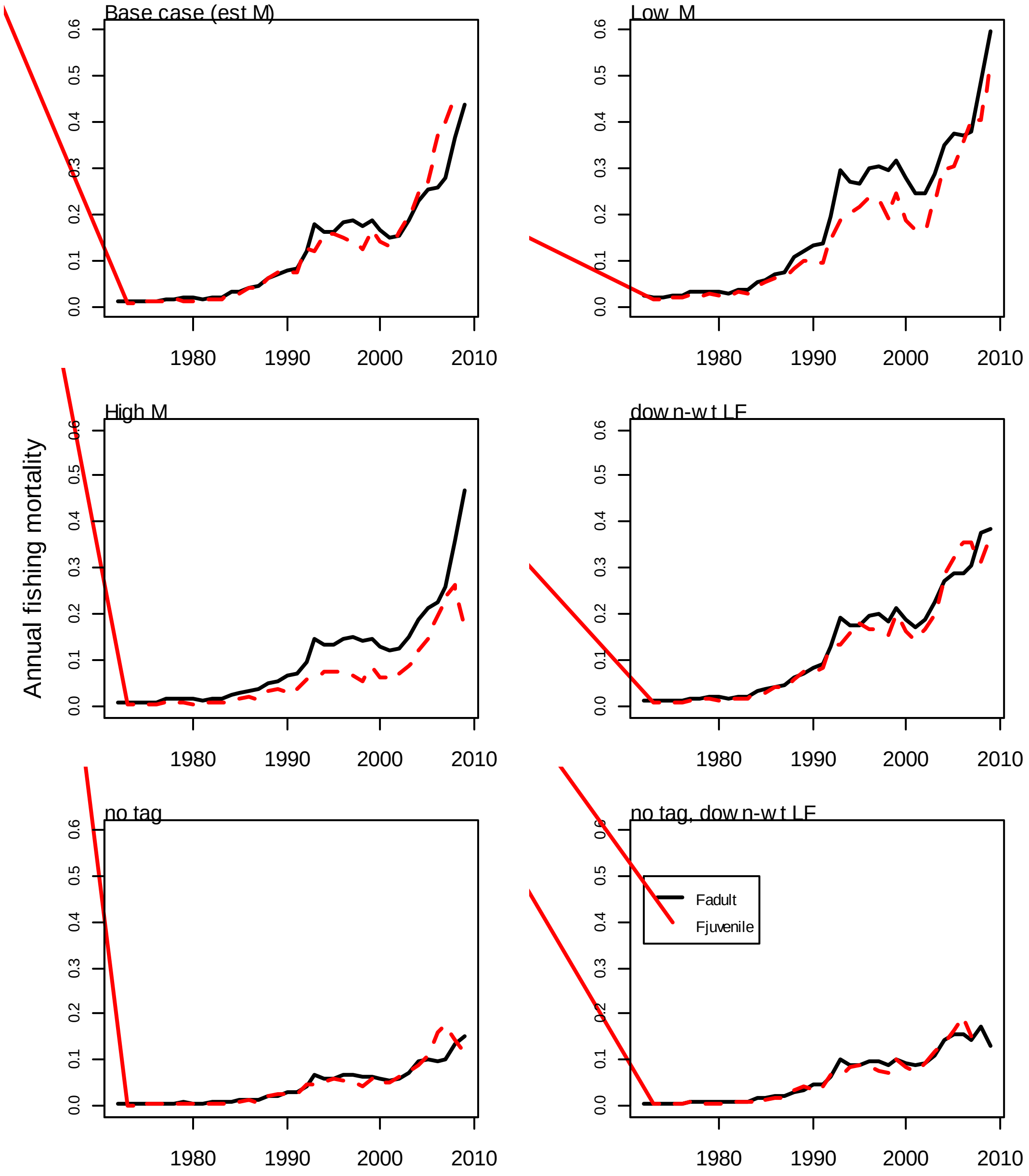

Figure 28. Estimated annual average juvenile and adult fishing mortality for the IO obtained from the separate model options. The *no tag*, *down-wt LF* and *no tag*, *down-wt LF* options are based on the model that estimates average natural mortality (*est M*).

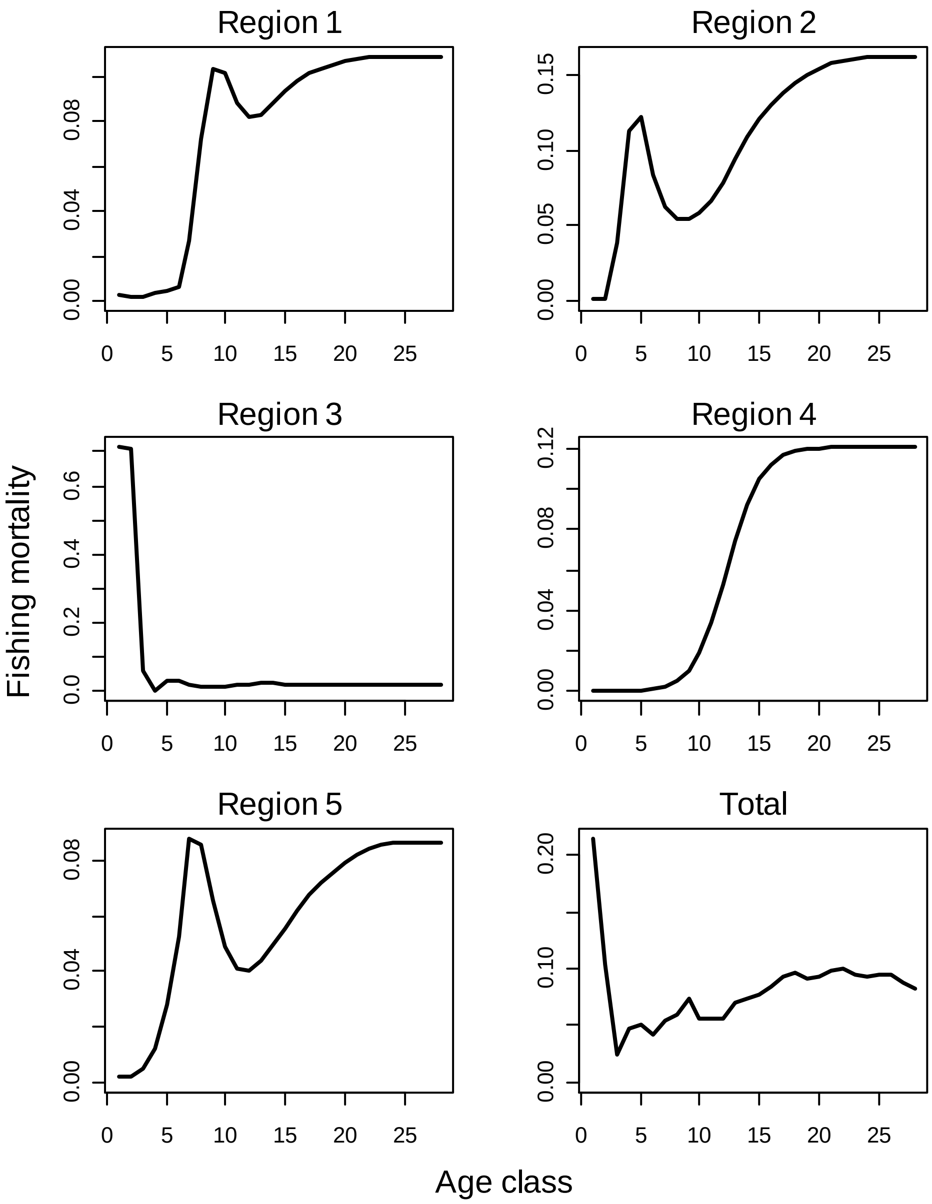

Figure 29. Fishing mortality (quarterly, average) by age class and region for the period used to determine the total F-at-age included in the calculation of MSY based reference points (2005–08). Note that the y-axis varies between plots.

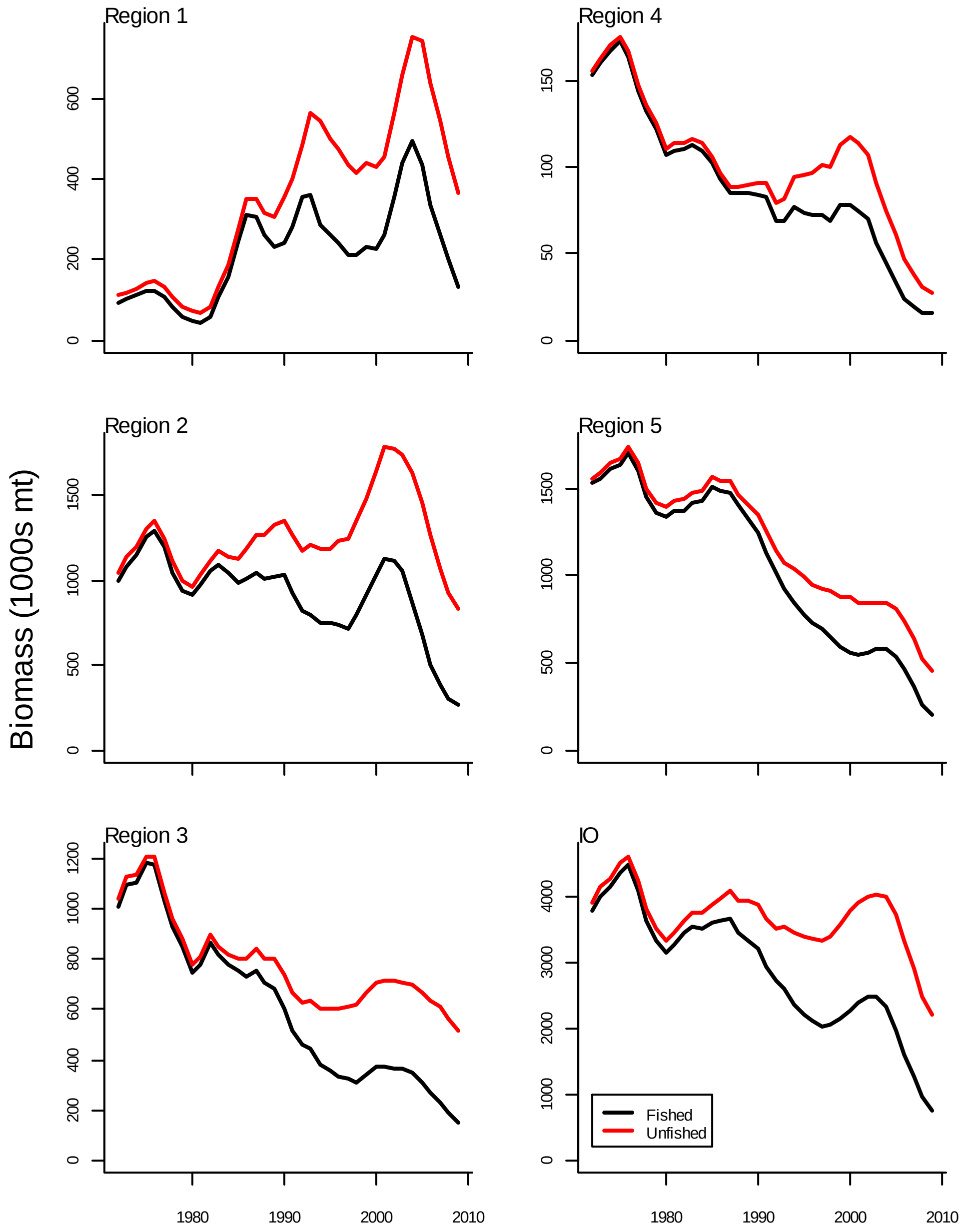

Figure 30. Comparison of the estimated total biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper thin lines) for the base-case model for each region and for the IO.

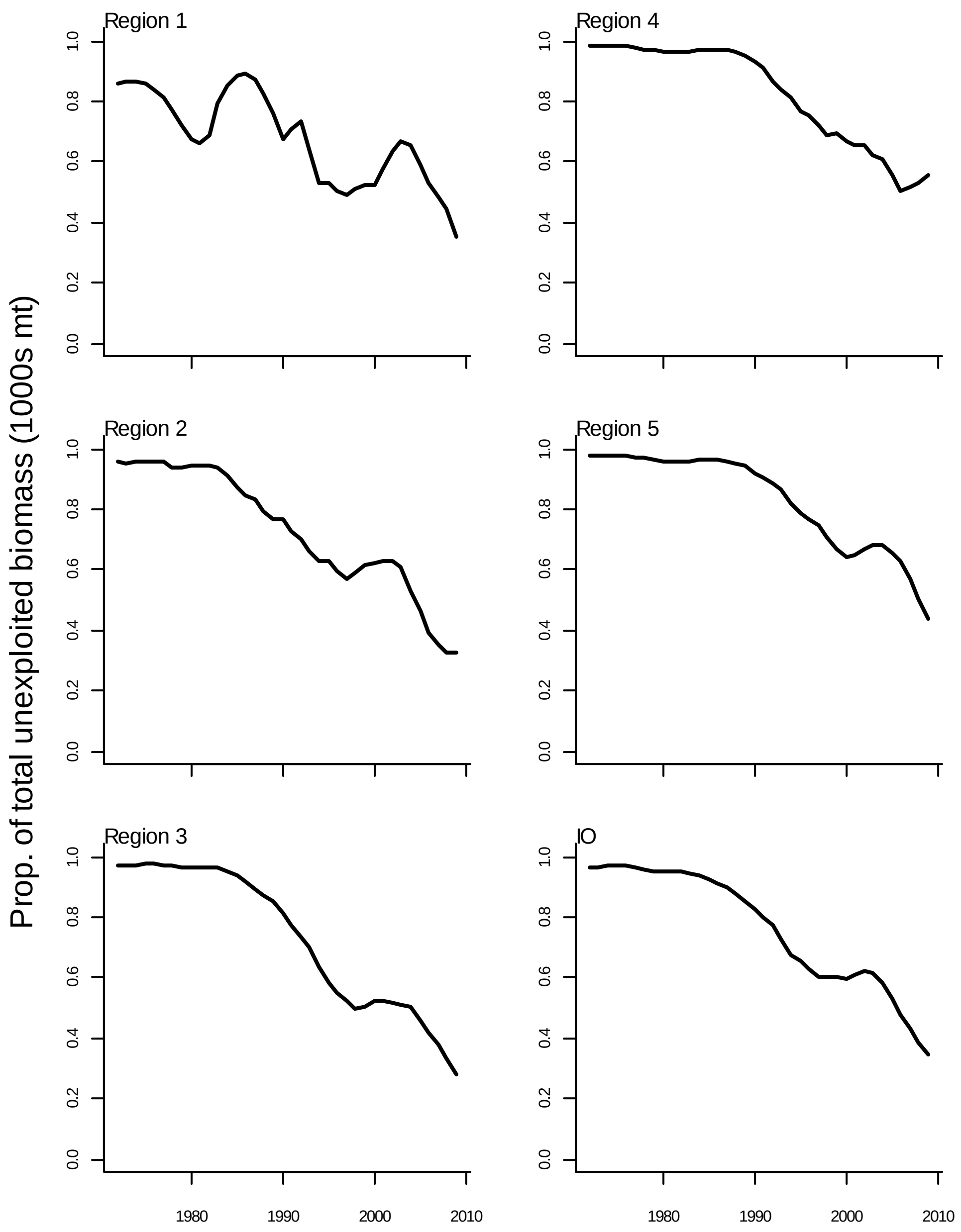

Figure 31. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the IO.

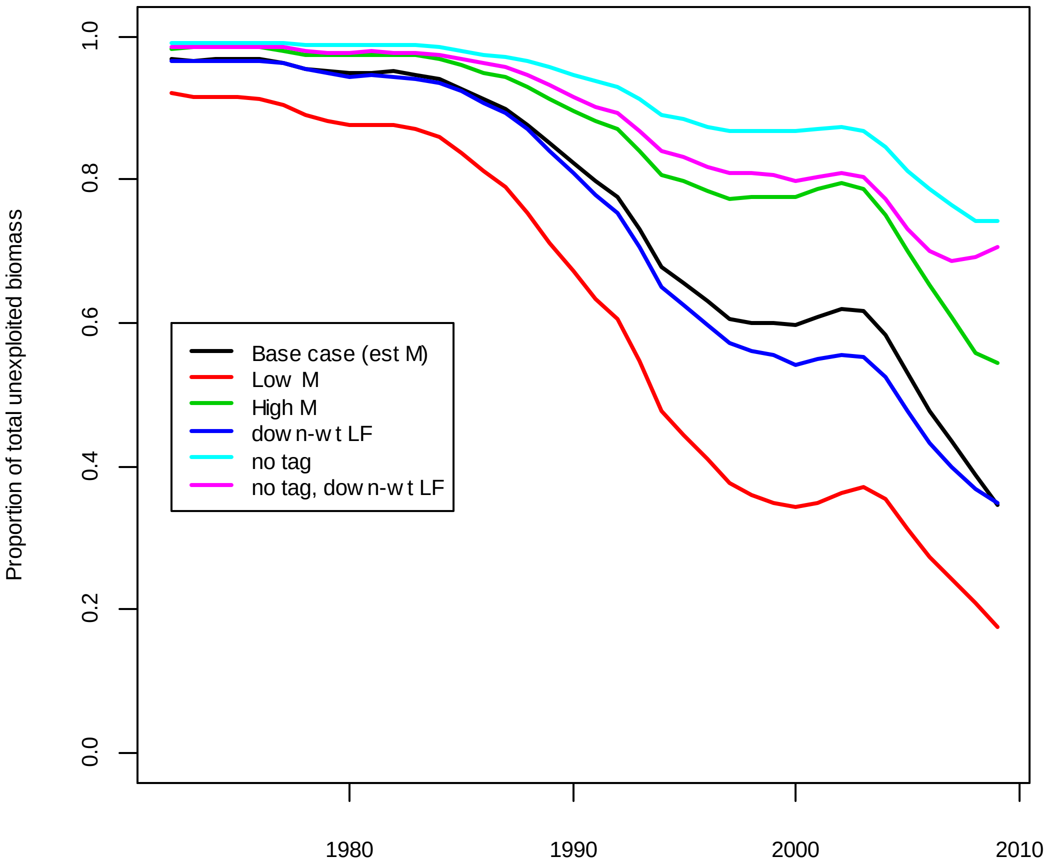

Figure 32. Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for the IO obtained from the separate analyses.

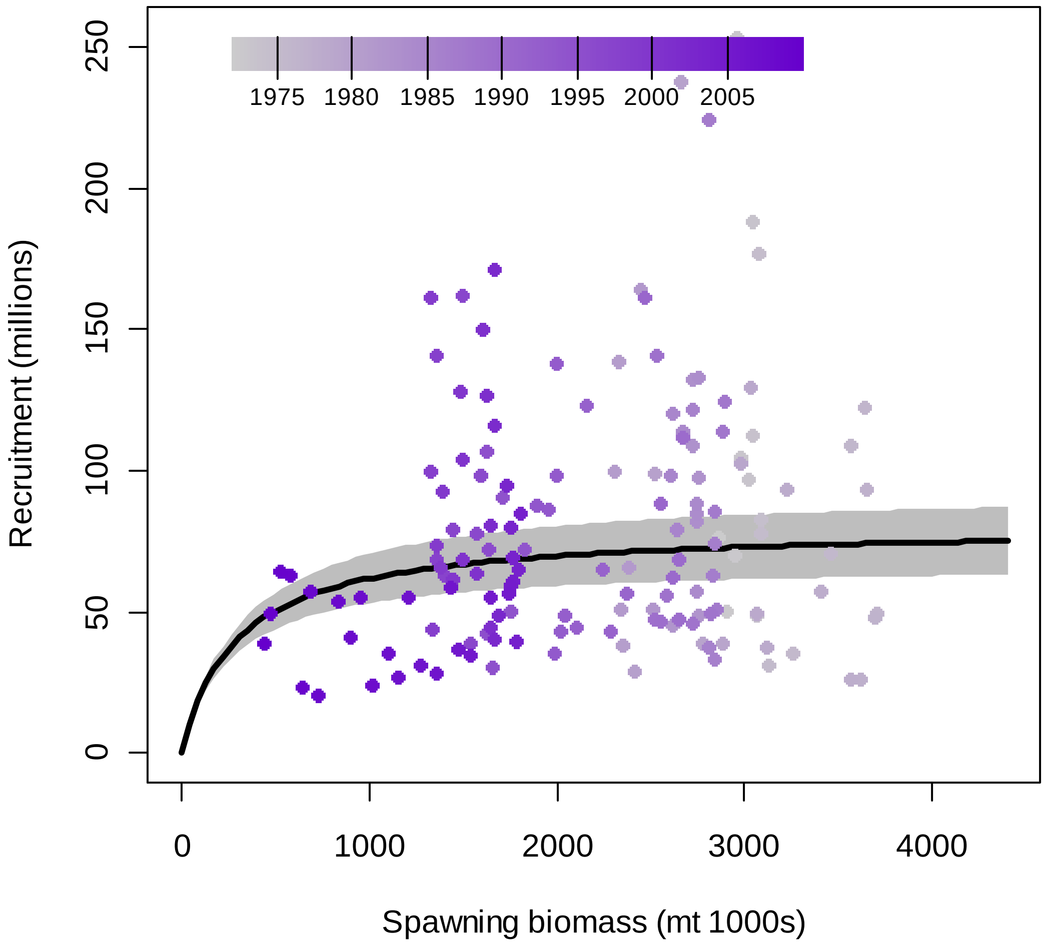

Figure 33. Relationship between equilibrium recruitment and equilibrium spawning biomass for the base-case with steepness of the SRR is fixed at 0.70 (black line). The grey area indicates the 95% confidence region. The points represent the estimated recruitment-spawning biomass and the colour of the points denotes the time period from which the estimate was obtained (see legend).

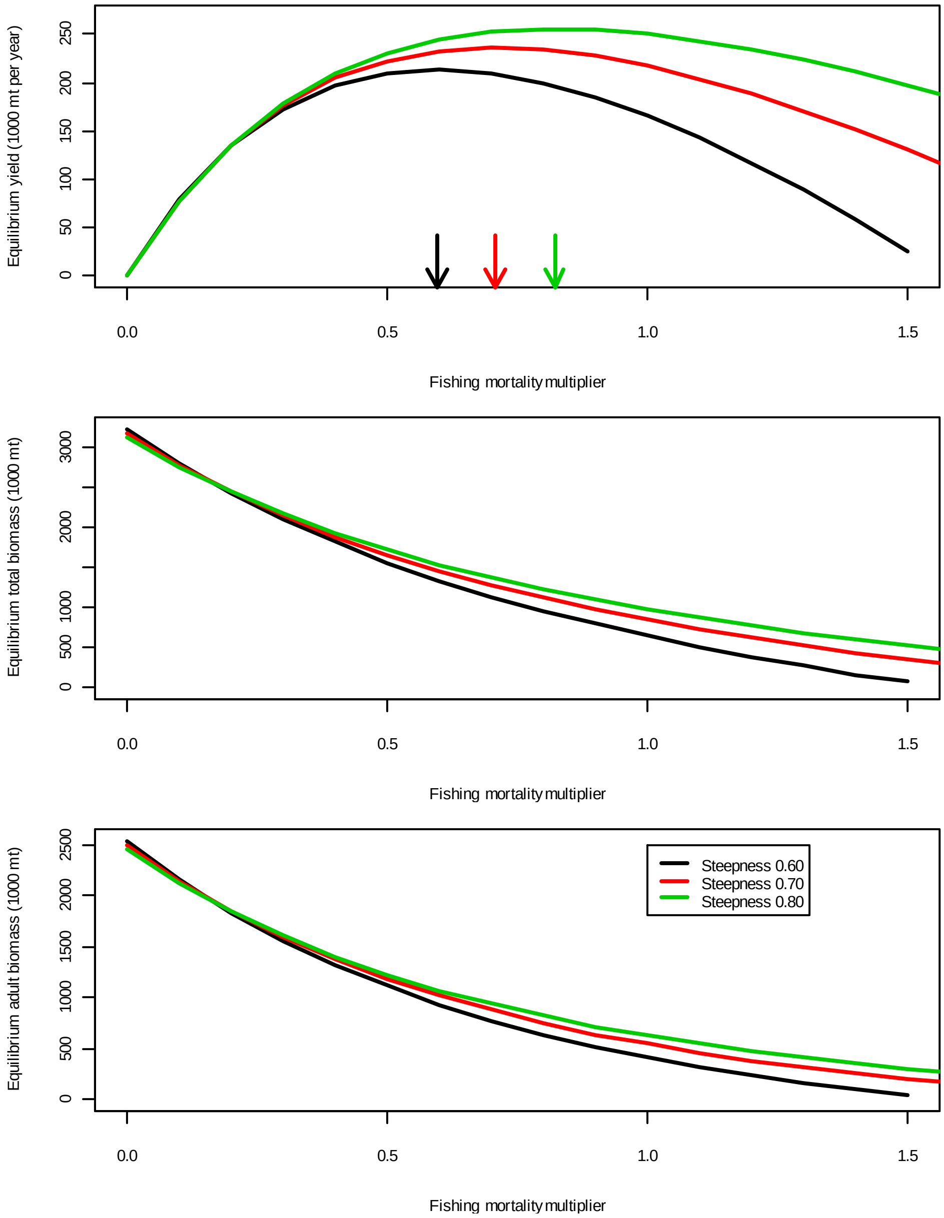

Figure 34. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier obtained from the *base case* model with three different values for steepness. In the upper panel, the arrows indicate the value of the fishing mortality multiplier at maximum yield.

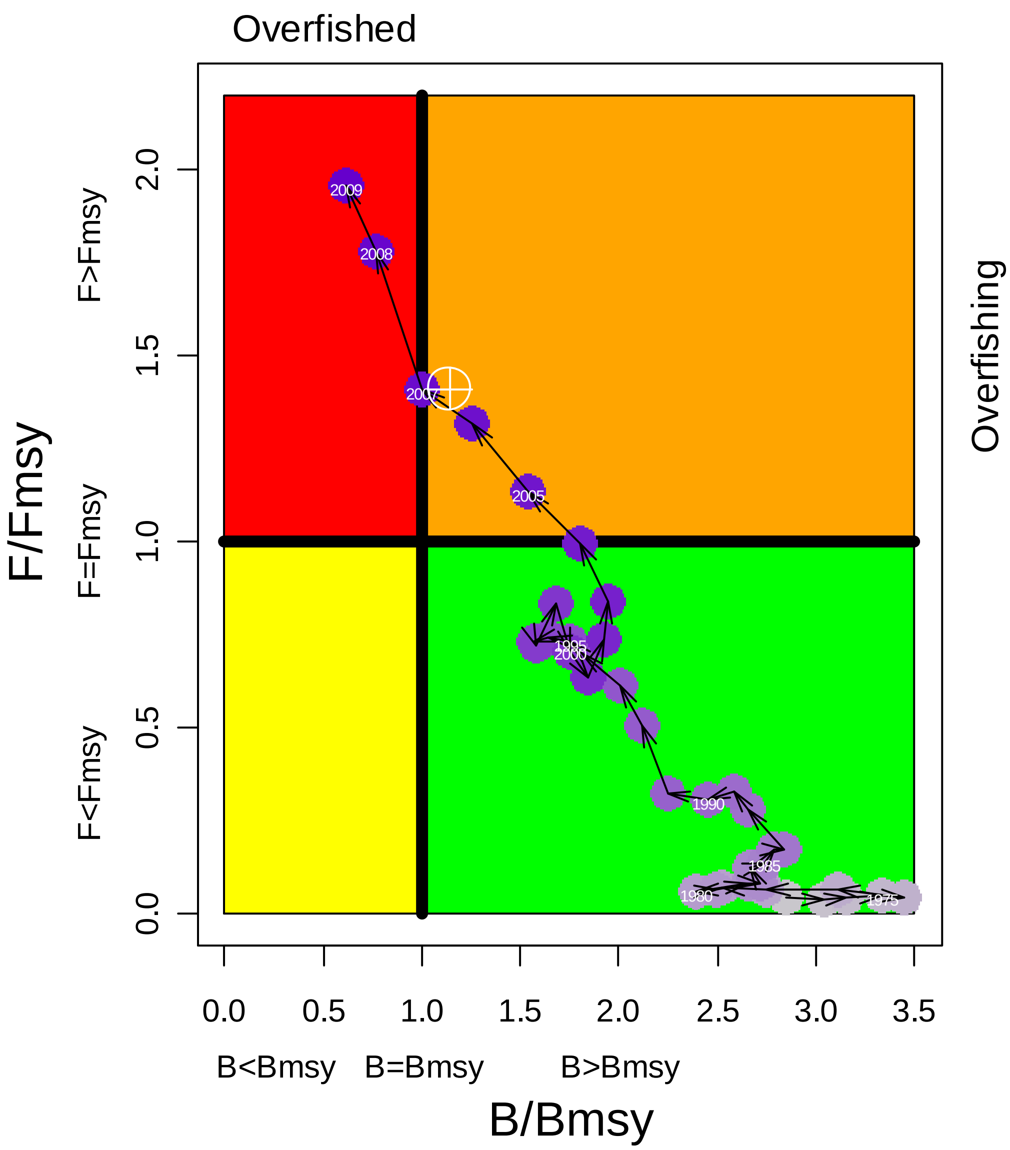

Figure 35. Temporal trend in annual stock status, relative to B_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period for the *base case* model with steepness fixed at 0.70. The colour of the points is graduated from mauve (1972) to dark purple (2009) and the points are labelled at 5-year intervals. The white cross represents the reference points computed for the “current” period (2005–2008).

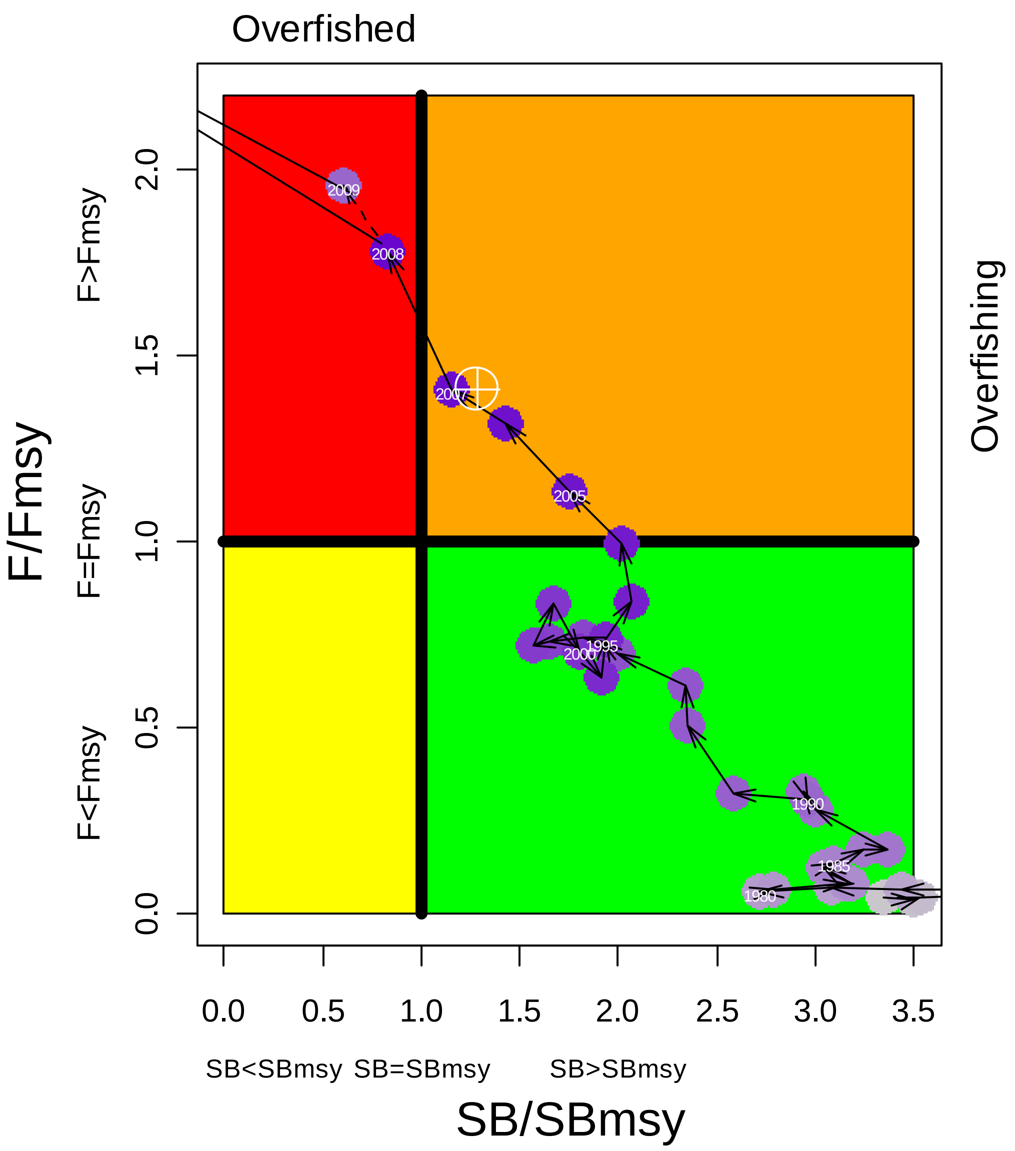

Figure 36. Temporal trend in annual stock status, relative to SB_{MSY} (x-axis) and F_{MSY} (y-axis) reference points, for the model period for the *base case* model with steepness fixed at 0.70. The colour of the points is graduated from mauve (1972) to dark purple (2009) and the points are labelled at 5-year intervals. The white cross represents the reference points computed for the "current" period (2005–2008).

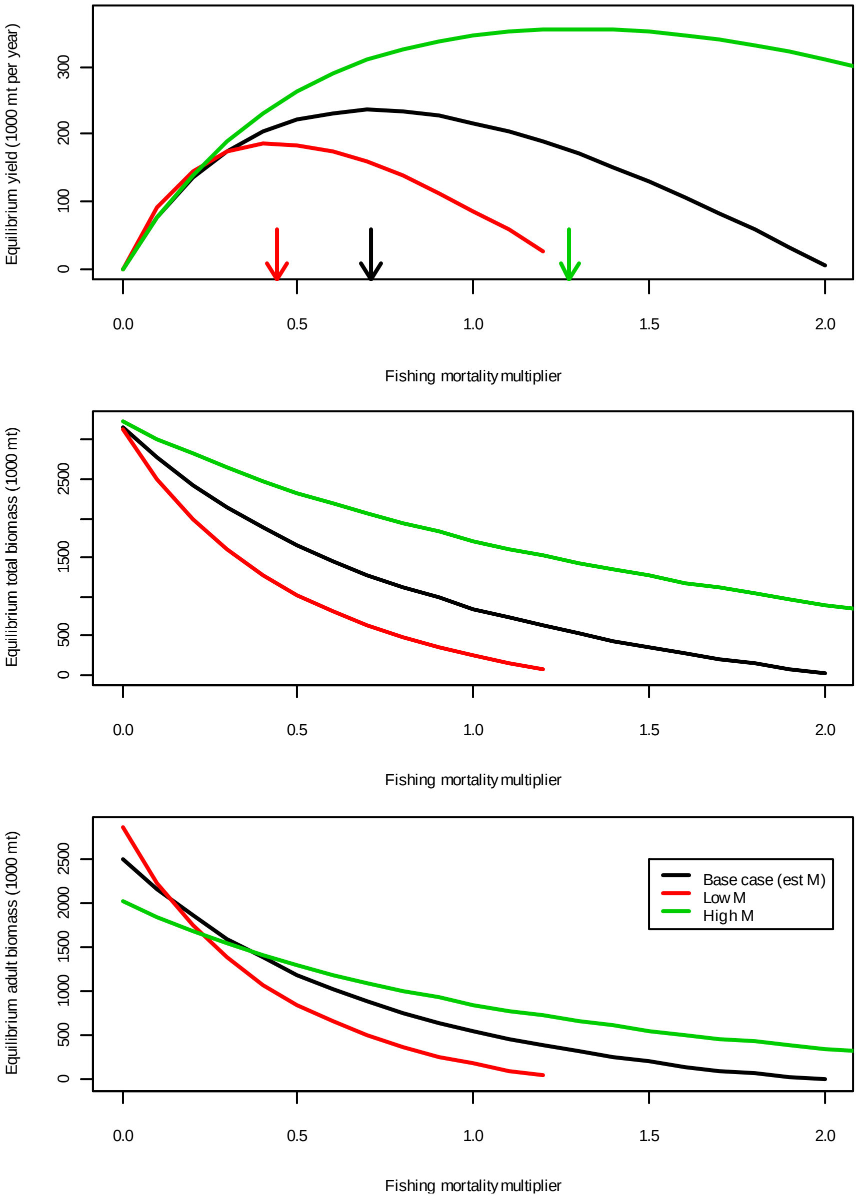

Figure 37. Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier obtained from the model options with different overall levels of natural mortality (steepness = 0.7). In the upper panel, the arrows indicate the value of the fishing mortality multiplier at maximum yield.