# Preliminary stock assessment of yellowfin tuna in the Indian Ocean using MULTIFAN-CL.

Adam Langley, John Hampton, Miguel Herrera and Julien Million

**DRAFT 16 October 2008**

## 1 Introduction

This paper presents the current 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, previous stock assessments of yellowfin tuna have been conducted using 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 2008).

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 ( $F_{current}/\tilde{F}_{MSY}$ ). Likelihood profiles of these ratios are used to describe their uncertainty.

## 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. The new information on the spatial distribution of tagged fish compared with the spatial extent of the purse seine fishery is presented in Figure 1.

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. 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 other 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.

There is little information on yellowfin movement patterns in the Indian Ocean, and what information there is comes 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, distant-water longliners and purse seiners that operate widely in equatorial and tropical waters. Purse seiners 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 to about 350,000 mt due mainly 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 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.

In recent years (2005–2007), purse seine has been the dominant fishing method, harvesting 37% of the yellowfin tuna catch (by weight), with the longline, gillnet, and handline fisheries comprising 27%, 18% and 10% of the total catch, respectively. A smaller component of the catch was taken by the regionally important baitboat (4.1%) and troll (3.5%) 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 (52%; region 2, see Figure 1) and, to a lesser extent, the Arabian Sea (24%), and the eastern equatorial region (19%, region 5). 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 accounts for a small proportion of the total yellowfin catch (4%) taken exclusively by longline (Figure 2).

## 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.

## 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–130°E. Within this overall area, a five-region spatial stratification was adopted for the assessment (Figure 1). The rationale for this stratification was to separate the tropical area, where both surface and longline fisheries occur year-round, from the higher latitudes, where the longline fisheries occur more seasonally. The spatial stratification is also designed to minimise the spatial heterogeneity in the magnitude and trend in longline CPUE and the size composition of the longline catch.

## 3.2 Temporal stratification

The time period covered by the assessment is 1960–2007. Within this period, data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec). While catch data are available prior to 1960, this represents the first year for which standardised longline CPUE indices were available.

## 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). Sixteen fisheries have been defined for this analysis on the basis of region, gear type, and, in the case of purse seine, set type (Table 1).

A single 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 data were apportioned into two separate 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). Most (>90%) of the purse-seine catch occurs within the eastern equatorial region (region 2) with the remainder of the catch taken close to the region (along the borders with regions 1, 3, and 5). For simplicity, the purse-seine catches and effort from outside region 2 were reassigned to the region 2 purse-seine fisheries.

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 region 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).

Two troll fisheries were defined, representing separate fisheries in regions 2 (Maldives) and 5. Minor troll catches are also taken in region 1 and the catch and effort from this component of the fishery was reassigned to the fishery within region 2.

A handline fishery was defined within region 1, principally representing catches by the Yemenese fleet.

For regions 1, 2, 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. All catches were expressed in numbers of fish (Figure 3).

No effort data were available for the handline (HD 1), other (OT 1, 2, and 5) and the troll (TR 5) fisheries – instead a proxy effort series was constructed that was directly proportional to the catch. 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 is 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) (Okamoto san, 29/9/2008) (Figure 6). 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 0.18, 1.00, 0.28, 0.17, and 0.75, 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.

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 (11–13 cm to 199–200 cm). Each length-frequency 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 and observer programmes since the mid-1980s. The samples are comprised of very large numbers of individual fish measurements.

<u>Longline</u>: Historical data were collected by port sampling of Japanese longliners unloading in Japan and from sampling aboard Japanese 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 relationship. Length frequency data from the Taiwanese longline fleet are also available from 1980–2006.

<u>Baitboat</u>: Size data are available from the fishery from 1983 to 2006. No sampling data are available from the earlier period of the fishery (1952–2006).

<u>Troll</u>: No size data are available from the TR 2 fishery. The troll fishery in region 5 was sampled during two periods: 1985–1990 and 1994–98.

<u>Handline</u>: Limited sampling of the handline fishery was conducted over the last decade.

<u>Other:</u> No length samples are available from the “Other” fisheries in regions 1 and 2 (OT 1 & 2) and only a small number of samples are available from the OT 5 fishery.

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. The tag releases occurred almost exclusively 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 2008 for further details). All tag releases were included in the data set, with the exception of those fish tagged in the last two quarters of 2007 (the mixing phase of the last tag group). Tags recovered in 2008, the year following the termination of the model period, were excluded from the tag recovery data set.

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 45,822 releases were classified into 12 tag release groups in this way. In total, 6,536 tag recoveries 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 region 1.

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.

Because the tag returns by purse seiners were not accompanied by information concerning the set type, tag-return data were aggregated across set types for the purse seine fisheries in region 2. The population dynamics model was in turn configured to predict equivalent estimated tag recaptures by these grouped fisheries.

## 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 25 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 data were available for yellowfin tuna from the Indian Ocean.

The population is “monitored” in the model at quarterly time steps, extending through a time window of 1952–2007. The main population dynamics processes are as follows:

#### 4.1.1 Recruitment

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

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

Spatially-aggregated recruitment was assumed to have a weak relationship with the spawning biomass via a Beverton and Holt stock-recruitment relationship (SRR). The SRR was incorporated mainly so that yield analysis and stock projections 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 it is generally necessary to constrain the parameterisation in order to have stable model behaviour. We incorporated a beta-distributed prior on the “steepness” ($S$) of the SRR, with $S$ defined as the ratio of the equilibrium recruitment produced by 20% of the equilibrium unexploited spawning biomass to that produced by the equilibrium unexploited spawning biomass (Francis 1992; Maunder and Watters 2001). The beta-distribution of the prior has a lower bound at 0.2, a mode = 0.85, and standard deviation = 0.16 (Figure 8).

#### 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 early years of the fishery when exploitation rates were very low.

Previous studies have revealed that the growth of yellowfin tuna less than about 80 cm deviate from the standard von Bertalanffy growth pattern. Growth was modelled to allow the mean lengths of the first eight quarterly age-classes to be independent parameters, with the remaining mean lengths following a von Bertalanffy growth curve. These deviations attract a small penalty to avoid over-fitting the size data.

#### 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. Note however that 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 $2 \times 6 \times 4 = 48$ movement parameters. The seasonal pattern of movement persists from year to year with no allowance for longer-term variation in movement. The movement coefficients are invariant with respect to age.

#### 4.1.5 Natural mortality

Natural mortality (*M*) was held fixed at pre-determined age-specific levels as applied in the Pacific Ocean (western and central; eastern) yellowfin tuna stock assessments. *M*-at-age was determined externally of the MULTIFAN-CL model using estimates of *M* by length category from tagging data, sex-ratio data and the assumed maturity-at-age schedule. Essentially, this method reflects the hypothesis that the higher proportion of males in sex-ratio samples with increasing length is due to the higher natural mortality of females after they reach maturity. The externally-estimated *M*-at-age is shown in 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 five longline fisheries, a common age-based selectivity function was modelled using a logistic curve. For the other fisheries, selectivity was modelled using a cubic spline interpolation to estimate age-specific selectivity. This is a form of smoothing, but the number of parameters for each fishery is the number of cubic spline "nodes" that are deemed to be sufficient to characterise selectivity over the age range. We chose five nodes, which seems to be sufficient to allow for reasonably complex selectivity patterns. For 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" fisheries in regions 1 and 2, 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 fishery in region 2. The selectivity of the "Other" fisheries was assumed to be equivalent among the three regions, while a common selectivity was assumed for the two troll fisheries.

#### 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. For the fisheries without estimates of effort (GI 1, OT 1, 2, & 5, and TR5), effort was assumed to be proportional to catch, while the variance of the priors was high (approximating a CV of about 0.7), thus allowing catchability changes to compensate for the miss-specification of the effort series. 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 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 second 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 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. A similar likelihood function was used for the weight-frequency data.

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- and weight-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. The effective sample size was also investigated using an iterative reweighting procedure, following following McAllister and Ianelli (1997).

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 $\alpha$ and $\beta$. 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 ($\tilde{SB}_{MSY}$) 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 2003–2006. We do not include 2007 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 (1960–2007). 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

A range of separate model options were investigated, as described in Table 4. The analyses included:

i. The *initial model* described in the preceding sections.

ii. A model with steepness of the SRR fixed at 0.85 (*fix-steepness*).

iii. Iterative reweighting of the length frequency samples, following McAllister and Ianelli (1997), for the principal fisheries (longline, purse-seine, and baitboat) (*size-reweighting*). The revised sample size by fishery is presented in Table 5. The iterative reweighting resulted in a significant increase in the effective sample sizes for the purse-seine school set (PS FS 2) and most of the longline fisheries (excluding LL 3).

iv. A model with growth parameters fixed to replicate the mean length-at-age estimates from the analysis of yellowfin tag growth increment data (P. Everson, 18/9/2008) (*fix-growth*).

v. Running the model without the tag release/recovery data (*no-tag*).

vi. Running the model for the region 2 subarea of the IO only (*region2*).

From the range of options the *size-reweighting* model was selected as the base-case analysis on the basis that a parsimonious approach was used to determine the weighting of the length frequency data in the total likelihood and the assumed value of steepness was more reasonable than that estimated by the model (0.40). The *size-reweighting* model also satisfied a range of other criteria relating to the fit to the various data sets included in the model (see below).

# 6 Results

The results from the base-case (*size-reweighting*) and the range of sensitivities are presented below. In the interests of brevity, some categories of results are presented for the base-case analysis 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 the five IO analyses is given in Table 6. Due to differences in the length frequency data set (*size-reweighting*) and prior structure the total likelihood values are not strictly comparable. However, the values do provide some insights into the various model options. The alternative growth model (*fix-growth*) has a substantially poorer fit to the three components of the likelihood (catch, length and tag), while the model without tag data (*no-tag*) has an improved better fit to the catch and length data compared to other model (*Initial model* and *fix-steepness*).

## 6.2 Fit diagnostics (base-case)

We can assess the fit of the model to the four 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 almost all 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). The exception is the poor fit to the size data from the “OT 5” fishery for which a very limited number of samples (3) are available.
- For most fisheries, the size composition of individual length samples is consistent with the temporal trend in the size composition of the fishery-specific exploitable component of the population (Figure 12). A number of fisheries have considerable variability in the size frequency data (for example PS FS 2, LL 1 and LL 3) which is more likely to be reflective of sampling error. As previously noted, the model does not adequately fit the length frequency data from the “OT 5” fishery. Further, the model does not reflect the strong decline in the length of fish sampled from the gillnet fishery in region 1 (GI 1); such a trend was not evident in the length data collected from the other fisheries in the same region, most notably the longline fishery (LL 1).

- 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, LL2, and OT1) indicating the assumption of a constant reporting rate, albeit very low (less than 20%), may be reasonable for these fisheries. Conversely, the fit to tag recoveries from the composite artisanal fisheries in region 2 (OT2) is poor as the model substantially under-estimates the number of tag recoveries in the main recovery period (2006 onwards) (Figure 15). In part, this reflects the fact that the size selectivity for this fishery is unknown.
- The model predicts tag attrition reasonably well (Figure 14). Most of the tag recoveries are from fish at liberty for up to about 18 months reflecting the relatively high fishery-specific mortality by the purse-seine fleet and the associated high tag reporting rate for the fleet. The decline in tag recoveries for extended periods at liberty is reflective of 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 most of the principal longline fisheries, there is no strong trend evident in the effort deviations, except for the early period of the model (prior to 1965) when the decline in longline CPUE for the LL 2 and LL 5 fisheries was substantially higher than predicted by the model (positive effort deviates) (Figure 16). For region 1, the Japanese longline CPUE index is not considered a reliable index of stock abundance – the indices are variable among quarters, have a relatively high standard error, and no estimates of standardised effort are available for a significant proportion of the model time steps. Consequently, effort deviates for this fishery are substantially higher than for the other longline fisheries and there are strong temporal trends in the effort deviates for the fishery (positive during the 1980s) as the model attempts to fit the fishery catch data via interpolation of the missing effort data.

## 6.3 Model parameter estimates (base-case unless otherwise stated)

### 6.3.1 Growth

The estimated growth curve is shown in Figure 17. The non-von Bertalanffy growth of juvenile yellowfin tuna is evident, with slow growth for young age classes and near-linear growth in the 70–120 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 increases steadily with increasing age (Figure 17).

The growth estimated from the MFCL model is substantially different from the growth estimated from tag length increment data (P. Everson, 18/9/2008) and used in the *fix-growth* analysis (Figure 17). Growth rates are depressed for the first 12 quarters before increasing rapidly until approaching a maximum length slightly smaller than estimated by the MFCL model.

### 6.3.2 Movement

Two representations of the movement estimates are shown in Figure 18 and Figure 19. The estimated movement coefficients for adjacent model regions are shown in Figure 18. Coefficients for some region boundaries are close to zero, while overall, most movement rates are low. The highest movement rates occur between region 2 and region 3, peaking at a 33% northward movement in the second quarter.

The distribution of regional biomass by source region derived from a simulation using the movement coefficients is presented in Figure 19. 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 about 30% of region 4 biomass is sourced from recruitment in region 5. Regional fidelity is highest in region 1 with limited transfer of biomass from this region and almost all biomass sourced from recruitment within the region, while region 5 receives virtually no fish from outside the region (Figure 19).

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”.

#### 6.3.3 Selectivity

The common selectivity of the five longline fisheries, parameterised using a logistic function, is constrained to be 1.0 for the oldest age classes and attains full selectivity at age 10 quarters (Figure 20). The associated purse-seine and baitboat fisheries have high selectivity for juvenile fish (age classes 2–3 and 3–4, respectively), while the free-school purse-seine fishery selects substantially older fish. The high selectivity of the oldest age classes by the baitboat fishery is consistent with the capture of relatively small numbers of large fish by the fishery.

Limited or no size data were available from a number of fisheries, specifically the artisanal fisheries (OT 1, 2 & 5) and the troll fishery in region 2 (TR 2). 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.

#### 6.3.4 Catchability

Catchability in the longline fisheries was assumed to be constant over time (Figure 21), with the exception of seasonal variation (not shown in figure).Time-series changes in catchability are evident for several fisheries; there is evidence of a general increase in catchability for the purse seine fisheries, particularly the associated sets fishery (PS LS 2). For many of the non industrial scale fisheries, no reliable effort data were available and effort data were fabricated assuming a constant catch rate. For these fisheries (GI 1, OT 1, OT 2, OT 5 & TR 5), the trends in catchability are meaningless, rather they provide a mechanism for the model to fit the catch data 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.

#### 6.3.5 Tag-reporting rates

Tag reporting rates for the purse-seine fisheries (combined for the estimation of tag recoveries) were fixed in the analysis (Figure 22). 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 20%), with the exception of the artisanal fisheries in regions 1 and 2 (OT 1 & 2).

### 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 23. 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 very high during the early model period and generally declines during 1960–75. Recruitment tends to fluctuate about this lower level throughout 1975–2003 and, subsequently declines from 2003–07. The most recent recruitments are estimated to be the lowest of the entire model period.

There are sharp initial declines in recruitment in regions 2 and 5, which are the model’s response to the rapid declines in CPUE in these regions. The recent sharp decline in overall IO recruitment is due primarily to the decline in estimated recruitment in region 2. This appears to be principally driven by the decline in the longline CPUE index and recent trends in the size composition of the longline catch from the region.

For the entire IO, recruitment estimates for early period of the model (1960–1970) are considerably more uncertain than the subsequent period (Figure 23).

A comparison of IO recruitment estimates for the different analyses is provided in Figure 24. Most of the analyses yield comparable trends in recruitment, with the exception of the alternative growth sensitivity (*fix-*

*growth*). The slower initial growth results in an inflation of the overall recruitment level while maintaining a comparable temporal trend in recruitment (Figure 24).

#### 6.4.2 Biomass

The estimated biomass trajectory for each region and for the entire IO is shown in Figure 25 and Figure 26 for the base-case analysis. Adult and total biomass is estimated to have declined throughout the model period with the steepest declines occurring during the 1960s and 1970s. This trend is largely driven by the decline in biomass within regions 2 and 5 — historically these regions accounted for the most of the IO biomass. In the early 2000s, there was a sharp increase in biomass within region 1; however, biomass trends for this region are highly uncertain due to the uncertainty associated with the region-specific CPUE indices.

There are very narrow confidence intervals around the time-series of estimated biomass for each region (Figure 25). These confidence intervals do not accurately reflect the true level of uncertainty as they are predicated on the high precision of estimated recruitment time-series and the assumption that natural mortality at age is known without error.

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 27) shows generally good correspondence between the model estimates and the data. As noted previously, there is a discrepancy between the two series in the early period from regions 2 and 5, while the fit to the CPUE indices for region 1 is generally poor throughout the series.

The comparison of total biomass trends for the different analyses is shown in Figure 28. Most of the analyses yield very similar trends in total biomass, with the alternative growth scenario (*fix-growth*) being the exception. For this analysis, total biomass is inflated in accordance with the higher overall level of recruitment (see Figure 24).

The trend in total biomass for the model restricted to the spatial domain of region 2 (*region2*) was comparable to the region 2 component of the biomass from the entire IO analysis (Figure 29).

#### 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 30). For the most recent years (2006–2007), the period for which tag data are available, the model that excludes the tag data (*no-tag*) yields slightly lower estimates of overall fishing mortality for adult yellowfin compared to the base-case analysis (including tags). The difference is much more pronounced when comparing the fishing mortality rates solely from region 2, the region encompassing most of the tag release/recovery data (Figure 31), with age specific exploitation rates at least twice the level for the principal age classes when the tagging data set is included.

Fishing mortality rates are estimated to be lowest for the model with the alternative growth parameterisation (*fix-growth*), largely reflecting the higher recruitment levels and differences in the age-specific selectivity (Figure 30).

Recent fishing mortality rates, for the period used in the computation of references points (2003–2006), were highest in regions 1 and 2, particularly for the younger age classes (3–10) and the oldest age classes in region 2 (Figure 32). By comparison, exploitation rates were low in the other regions.

#### 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 33. Impacts are significant in regions 1 and 2, while the strong decline in biomass in region 5 is not attributed to the effect of fishing. The fishery impact in region 2 accounts for most of the reduction in total IO biomass that is attributable to fishing.

The biomass ratios are plotted in Figure 34. These figures indicate strong fishery depletion (60% reduction) of yellowfin tuna in regions 1 and 2, while low-moderate impacts are attributable to fishing in the other regions. For the entire IO, recent levels of fishing have resulted in about a 50% reduction in total biomass.

6.4.5 Yield analysis

Symbols used in the following discussion are defined Table 7. The yield analysis conducted in this assessment incorporates the SRR (Figure 36) into the equilibrium biomass and yield computations. The preliminary analysis estimated a very low value of steepness (0.40), indicating a strong relationship between adult biomass and recruitment. The low value of steepness is influenced by the strong decline in adult biomass and recruitment, particularly in the first 15 years of the model period and in the most recent years (Figure 36). The estimated value of steepness is considered to be implausibly low for a tuna species and, consequently, was fixed at a higher value (0.85) for alternative model runs, including the base-case.

Equilibrium yield and biomass (spawning and total) are computed as a function of multiples of the 2003–2006 average fishing mortality-at-age (Figure 37). For the base-case model (*reweight size*), a maximum yield (*MSY*) of 494,400 mt per annum is achieved at *fmult* = 1.70; i.e. at 170% of the current level of age-specific fishing mortality. This represents a ratio of $F_{current}/\tilde{F}_{MSY}$ equal to 0.59 (approximately 1/1.70); current exploitation rates are lower than the exploitation rates to produce the *MSY*. The equilibrium biomass at *MSY* is estimated at 1,203,000 mt, approximately 40% of the equilibrium unexploited biomass (Table 8). Equilibrium yield at the current level of fishing mortality ($\tilde{Y}_{F_{current}}$ = 446,400 mt) is consistent with recent levels of total catch from the fishery, averaging about 464,000 mt in 2003–2006.

As noted above, the *MSY*-based management quantities are highly sensitive to the assumptions regarding steepness. In contrast to the base-case, the model with the estimated low value of steepness (*initial model*), yielded a substantially lower estimate of *MSY* (261,520 mt) at levels of fishing mortality considerably lower than current (2003–2006) levels; the *fmult* is 0.56 corresponding to a ratio of $F_{current}/\tilde{F}_{MSY}$ equal to 1.79 (Table 8).

For the base-case analysis, 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 (1960–2007). 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 38 and Figure 39). For the base-case model, exploitation rates were low from 1960 to 1980, although total and adult biomass declined rapidly relative to $\tilde{B}_{MSY}$ and $\tilde{SB}_{MSY}$, respectively. During the late 1980s and early 1990s, the relative biomass levels ($B_t/\tilde{B}_{MSY}$ and $SB_t/\tilde{SB}_{MSY}$) declined while $F_t/\tilde{F}_{MSY}$ steadily increased. Fishing mortality rates and biomass levels remained relatively stable during the late 1990s before increasing again in the 2000s resulting in a decline in the relative biomass levels ($B_t/\tilde{B}_{MSY}$ and $SB_t/\tilde{SB}_{MSY}$). Recent fishing mortality rates have remained considerably below the $F_{MSY}$ level, although recent (2006) levels of total biomass have approached the $\tilde{B}_{MSY}$ level due to the low estimates of recent recruitment (Figure 38). Recent adult biomass remained considerably above the $\tilde{SB}_{MSY}$ level (Figure 39).

Equilibrium yield and total biomass as functions of multiples of the 2003–2006 average fishing mortality-at-age are shown in Figure 40 for the various entire IO analyses. The three runs with fixed (0.85) steepness, including the model without tag data, all yield comparable results (i.e. $F_{current}/\tilde{F}_{MSY}$ of 0.54–0.61). Fishing mortality rates for the model excluding tag data (*no-tag*) are higher in the most recent years (2006–2007) but these years do not significantly influence the fishing mortality-at-age schedule used to compute the MSY reference points (2003–2006).

The scenario with the alternative growth (*fix-growth*) is considerably more optimistic ($F_{current}/\tilde{F}_{MSY}$ = 0.29) due to the significantly different biological characteristics and population dynamics; growth rates are substantially lower for younger age classes while M- and maturity-at-age are equivalent to the other scenarios resulting in higher levels of recruitment and lower exploitation rates.

For the range of scenarios, the equilibrium total and adult biomass at *MSY* are estimated to be 39–51% and 26–41% of the equilibrium unexploited total and adult biomass, respectively (Table 8).

For the model encompassing region 2 only, the current levels of fishing mortality exceed the $F_{MSY}$ level ($F_{current}/\tilde{F}_{MSY}$ = 1.43) for the analysis with steepness estimated (0.60) (Table 8) and are below the $F_{MSY}$

level ( $F_{current}/\tilde{F}_{MSY}$ = 0.87) when steepness is fixed at the higher value (0.85). The slightly more pessimistic stock status of region 2 compared to the entire IO ( $F_{current}/\tilde{F}_{MSY}$ of 0.87 and 0.59, respectively) reflects the higher levels of fishing mortality in the core area of the fishery. Nevertheless, at the sub-regional level, current (2003–2006) levels of adult and total biomass are estimated to be above the respective *MSY*-based reference points (Table 8).

# 7 Discussion and conclusions

This is the first application of MULTIFAN-CL to the assessment of the Indian Ocean yellowfin tuna stock. The assessment is considerably more complex than previous assessments as it is configured to reflect the spatial dynamics of stock and the principal region-specific fisheries. The assessment also represents 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).

In general, the model diagnostics reveal that the model provides a good fit to the main data sets included in the assessment. Nevertheless, the assessment identified a range of issues 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. Improvement of tag recovery estimates from the purse-seine fishery. Currently, good estimates of tag reporting rates are available for purse-seine caught fish landed in the Seychelles. However, limited information is available for the component of the purse-seine catch landed in other ports.

ii. 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.

iii. No information is currently available regarding tag reporting rates from other fisheries. Some of these fisheries have returned a substantial number of tags and estimates of reporting rates for these fisheries would increase the utility of the total tag release/recovery data set.

iv. The current assessment model includes five sub-regions. Region-specific, standardised CPUE indices are available for the Japanese longline fleet; however, limited catch and effort data are available from region 1 and the index for this region is considerably less reliable than for the other regions. The Japanese longline index for region 1 was retained for consistency among regions, thereby, enabling key parameters (selectivity and catchability) to be shared between the principal longline fisheries in each region. Nonetheless, the application of an alternative index of stock abundance, such as derived from the Taiwanese longline catch and effort data, should be investigated for this region in future.

v. 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.

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

vi. The current assessment applies values of natural mortality and maturity at age that are currently used in the WCPO assessment of yellowfin. However, for all oceans, there is sparse information available concerning these key biological parameters.

vii. The assessment assumes a constant catchability of yellowfin by the longline fisheries, as indexed by the Japanese standardized CPUE index. 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. More detailed information regarding gear technology and fishing strategy is necessary to investigate changes in longline catchability over the model period.

viii. The assessment also assumes that the selectivity of a fishery has remained constant throughout the model period. There is no strong evidence to suggest that this assumption is invalid, although it may be possible that changes in targeting behaviour, for example the increased targeting of bigeye tuna by the longline fleet, may have resulted in a change in the size selectivity of key fisheries.

ix. 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. In the case of the current assessment, the estimated value of steepness is considered to be implausibly low. Instead, in the absence of direct observations or sufficient data spanning a wide range of stock size, it may be more appropriate to adopt a default value of steepness, derived via meta analysis. Additionally, consideration should be given to 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. The latter analysis was beyond the scope of the current assessment and should be conducted as part of a thorough examination of the model uncertainty, particularly with respect to key management measures (reference points).

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

1. Exploitation rates and fishery impacts vary between regions, with highest impacts occurring in the western equatorial region (region 2), where the purse-seine fishery is concentrated, and in region 1 (Arabian Sea). Fishery impacts in the other regions are relatively low.
2. For a number of regions, most notably regions 2 and 5, historical declines in longline CPUE are explained by a decline in recruitment, particularly early in the model period. This is a frequent observation in tuna age structured population models, particularly when the model is reliant solely on CPUE and size data from the longline fishery, either at the regional level or throughout the model domain. The large initial declines in CPUE suggest that trends in CPUE may not be proportional to vulnerable biomass during the developmental phase of the fishery. The estimation of a declining trend in recruitment over the longer term, as evident in region 5, indicates that the model attains a better fit to the various data via recruitment processes rather than through an increase in fishing mortality. The influence of the structural assumptions of the model, such as penalties on recruitment deviations, should be investigated via simulation modeling.
3. The current assessment indicates a strong decline in yellowfin recruitment in recent years, principally within region 2. As a consequence, total biomass has declined and recent (2006–2007) exploitation rates are at historically high levels, approximately 20% higher than the “current” (2003–2006 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 strongly influenced by the SRR. The base-case analysis has assumed a value for steepness that the authors consider reasonable for yellowfin tuna; however, there needs to be a more formal analysis and consideration of the appropriate value for steepness or the range of values that should be considered. The conclusions of the current assessment, with respect to the *MSY*-based reference points, hinge on value of steepness used. The very low value of steepness, estimated from the model, results in a ratio of $F_{current}/\tilde{F}_{MSY} > 1$ (i.e. overfishing is occurring), whereas, assuming a higher (more plausible) value of steepness results in a ratio of $F_{current}/\tilde{F}_{MSY} < 1$ (i.e. overfishing not occurring).
5. For all model scenarios investigated, current adult and total biomass remained above the respective *MSY*-based reference points ( $\tilde{B}_{MSY}$ and $S\tilde{B}_{MSY}$ ); i.e. the fishery is not in an over-fished state. This also pertains to the most heavily fished sub-region of the model (region 2). Nonetheless, given the recent decline in recruitment and the corresponding decline in total biomass and increasing fishing mortality rates, the status of the stock should be carefully monitored over the next few years.
6. The tagging data were relatively informative in the stock assessment model, particularly for region 2, the area that accounted for most of the tag releases and recoveries. The inclusion of the tag data set resulted in a significant increase in the estimates of recent (2006–2007) levels of fishing mortality in

region 2 and is likely to have increased the precision of recent estimates of recruitment and exploitable biomass in the region. Subsequent tag recoveries, from 2008 and beyond, will be available for inclusion in future assessments.

## 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 Chris O'Brien provided guidance and support and comments on a draft version of the report. Additional comments and input were provided via the WTTP mailing list, most notably from Alain Fonteneau and Richard Hillary. Simon Hoyle fixed a crucial bug in the MFCL code.

## 9 References

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.

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.

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.

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 2008. 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].

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.

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 | 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 | All | Longline | 2 |
| 8. PS LS 2 | All | Purse seine, log/FAD sets | 2 |
| 9. OT 2 | All | Other | 2 |
| 10. TR 2 | All | Troll | 2 |
| 11. LL 3 | All | Longline | 3 |
| 12. LL 4 | All | Longline | 4 |
| 13. GI 5 | All | Gillnet | 5 |
| 14. LL 5 | All | Longline | 5 |
| 15. OT 5 | All | Other | 5 |
| 16. TR 5 | All | Troll | 5 |

**Table 2. Tag releases and 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 | 4 |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 2 | 1 | 69 | 0 | 0 |
| 3 | 0 | 3 | 0 | 0 |

| **2006** | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 |
| 2 | 34 | 2543 | 0 | 0 |
| 3 | 0 | 2 | 0 | 0 |

| **2007** | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1 | 38 | 21 | 0 | 0 |
| 2 | 13 | 3744 | 2 | 1 |
| 3 | 0 | 1 | 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) | No. | 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 | 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 | 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 | 2 | - | - | 0 | 100 |
| Tag reporting | Common tag reporting rate for the two 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 | 15 | 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 | 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 (beta prior for steepness with mode at 0.85 and SD of 0.16, lower bound 0.2) .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) | 1 | - | - | -20 | 20 |
| | | Spatially aggregated recruitment deviations (ln) | 192 | SRR | 0.7 | -20 | 20 |
| | | Average spatial distribution of recruitment | 4 | - | - | 0 | 1 |
| | | Time series deviations from average spatial distribution (ln) | 760 | 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 1952–56 and movement rates. | Initial recruitment scaling (ln) | 1 | - | - | -8 | 8 |
| Age and growth | 28 quarterly age-classes, with the last representing a plus group. Juvenile age-classes 1-8 have independent mean lengths constrained by | Mean length age class 1 | 1 | - | - | 20 | 40 |
| | | Mean length age class 28 | 1 | - | - | 140 | 200 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | a small penalty for deviation from the von Bertalanffy growth curve; adult age-class mean lengths constrained by VB curve. SD of length-at-age are log-linearly related to the mean length-at-age. Mean weights ($W_j$) computed internally by estimating the distribution of weight-at-age from the distribution of length-at-age and applying the weight-length relationship $W = aL^b$ (a= 1.585e-05, b= 3.045, source Nishida & Shono 2007). | von Bertalanffy *K* | 1 | - | - | 0 | 0.3 |
| | | Independent mean lengths | 7 | 0 | 2.2 | | |
| | | Length-at-age SD | 1 | - | - | 3 | 8 |
| | | Dependency on mean length (ln) | 1 | - | - | -1.00 | 1.00 |
| Selectivity | Constant over time. Coefficients for the last 4 age-classes are constrained to be equal. Longline fisheries LL 1–5 share selectivity parameters. For all fisheries, selectivity parameterised with 5-node cubic spline, except longline selectivities with logistic function (non decreasing with age). | Selectivity coefficients (5 cubic spline nodes or 2 logistic parameters per fishery) | 57 | - | - | 0 | 1 |
| Catchability | Constant over years and among regions for longline fisheries (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, OT2, OT5, TR5). | Average catchability coefficients (ln) | 12 | - | - | -15 | 1 |
| | | Seasonality amplitude (ln) | 16 | 0 | 2.2 | - | - |
| | | Seasonality phase | 16 | - | - | - | - |
| | | Catchability deviations biennial (ln) | 122 | 0 | 0.7 | -0.8 | 0.8 |
| | | Catchability deviations annual (ln) | 219 | 0 | 0.1 | -0.8 | 0.8 |
| Fishing effort | Variability of effort deviations constrained by a prior distribution with (on the log scale) mean 0 and SD 0.1 for LL 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) | 944 | 0 | 0.16 | -6 | 6 |
| | | Effort deviations other (ln) | 1899 | 0 | 0.22 | -6 | 6 |
| Natural mortality | Age-dependent but constant over time and among regions. All parameters are specified (see Figure 9). | Average natural mortality (ln) | 0 | - | - | - | - |
| | | Age-specific deviations (ln) | 0 | - | - | - | - |
| Movement | Age-independent and variant by quarter but constant among years. No age-dependent variation. | Movement coefficients | 48 | 0 | 0.32 | 0 | 3 |
| | | Age-dependent component (ln) | 0 | 0 | 0.32 | -4 | 4 |
| Maturity | Age-dependent and specified – age-class 0-6: 0; 7: 0.25; 8: 0.5; 9: 0.75; 10-28: 1.0 | None | na | na | na | 0 | 1 |

**Table 4. Summary of the range of model options investigated.**

| Scenario | Description | Rationale |
|---|---|---|
| | | |
| **Initial model** | • JP LL CPUE index in each region with shared, time invariant catchability and selectivity among regions.<br>• Temporal variation in catchability for all other fisheries.<br>• Fixed reporting rate for PS fishery.<br>• SRR steepness estimated.<br>• Length freq. sample size = n/20, with a maximum of 50,<br>• M-at-age fixed (values equivalent to PO). | |
| **Fix-steepness** | • Fix steepness of SRR at 0.85.<br>• Other assumptions equivalent to *initial model*. | *Initial model* estimated an unrealisticly low value for steepness of the SRR (h=0.40). Alternative value of 0.85 considered a reasonable alternative. |
| **Size-reweighting (proposed <u>base case</u>)** | • Fix steepness of SRR at 0.85.<br>• Iterative reweighting of the length frequency sample data for the key fisheries (LL, PS, BB). Single fishery-specific weighting.<br>• Other assumptions equivalent to *initial model*. | Iterative reweighting a more parsimonious method of determining the appropriate fishery-specific weighting for the length frequency data. |
| **Fix-growth** | • Mean length at age fixed at values estimated independently from the tag data set (P. Everson, 18/9/2008).<br>• Fix steepness of SRR at 0.85.<br>• Other assumptions equivalent to *initial model*. | Considered a plausible alternative growth pattern. |
| **No-tag** | • Model run with tag data excluded.<br>• Fix steepness of SRR at 0.85.<br>• Other assumptions equivalent to *initial model*. | Assess influence of the tag data set on the stock assessment model. |
| **Region2** | • Conduct model for only the region 2 sub area.<br>• Other assumptions equivalent to *initial model*.<br>• Steepness estimated (0.598). | Region 2 is the core area of the fishery. Assess the sensitivity of the IO model results for region 2 by removing influence of data from beyond that region, essentially assumptions relating to movement and sharing catchability/selectivity of LL among regions. |

**Table 5. Effective sample size of the length frequency data by fishery for the initial model (n/20) and the final sample size determined by iterative reweighting. The highlighted fisheries are the fisheries for which iterative reweighting was undertaken.**

| Fishery | Sample size | |
|---|---|---|
| | Initial | Final |
| 1. GI 1 | 50 | 50 |
| 2. HD 1 | 50 | 50 |
| 3. LL 1 | 50 | 72 |
| 4. OT 1 | 50 | 50 |
| 5. BB 2 | 50 | 52 |
| 6. PS FS 2 | 50 | 94 |
| 7. LL 2 | 50 | 128 |
| 8. PS LS 2 | 50 | 60 |
| 9. OT 2 | 50 | 50 |
| 10. TR 2 | 50 | 50 |
| 11. LL 3 | 50 | 60 |
| 12. LL 4 | 50 | 111 |
| 13. GI 5 | 50 | 50 |
| 14. LL 5 | 50 | 209 |
| 15. OT 5 | 50 | 50 |
| 16. TR 5 | 50 | 50 |

**Table 6.** Details of objective function components for the stock assessment models.

| Objective function component | Initial model | Fix steepness | Reweight size | Fix growth | No tag |
|---|---|---|---|---|---|
| Total catch log-likelihood | 235.6 | 235.8 | 257.3 | 277.2 | 214.0 |
| Length frequency log-likelihood | -323852.0 | -323849.4 | -369952.6 | -323047.7 | -324041.5 |
| Tag log-likelihood | 2409.4 | 2410.6 | 2455.0 | 2973.9 | - |
| Penalties | 4763.1 | 4761.8 | 5258.9 | 6546.3 | 4608.7 |
| Total function value | -316443.9 | -316441.2 | -361981.4 | -313250.3 | -319218.8 |
| | | | | | |
| Number of parameters | 4519 | 4517 | 4517 | 4505 | 4518 |

**Table 7.** Description of symbols used in the yield analysis.

| Symbol | Description |
|---|---|
| $F_{current}$ | Average fishing mortality-at-age for 2003–2006 |
| $F_{MSY}$ | 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 (2003–2006) total biomass |
| $SB_{current}$ | Average current (2003–2006) adult biomass |
| $B_{1995}$ | Average total biomass in 1995 |
| $SB_{1995}$ | Average adult biomass in 1995 |
| $B_{current,F=0}$ | Average current (2003–2006) total biomass in the absence of fishing. |

**Table 8.** Estimates of management quantities for the stock assessment models. 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 | Initial model | Fix steepness | Reweight size | Fix growth | No tag | Region 2 |
|---|---|---|---|---|---|---|---|
| $\tilde{Y}_{F_{current}}$ | mt per year | 160,040 | 458,400 | 446,400 | 444,400 | 494,000 | 125,120 |
| $\tilde{Y}_{F_{MSY}}$ (or $MSY$) | mt per year | 261,520 | 500,000 | 494,400 | 625,600 | 563,200 | 136,440 |
| $\tilde{B}_0$ | mt | 3,412,000 | 3,005,000 | 3,051,000 | 4,480,000 | 3,446,000 | 1,096,000 |
| $\tilde{B}_{F_{current}}$ | mt | 587,900 | 1,651,000 | 1,697,000 | 3,403,000 | 2,018,000 | 338,600 |
| $\tilde{B}_{MSY}$ | mt | 1,603,000 | 1,204,000 | 1,203,000 | 2,286,000 | 1,386,000 | 490,300 |
| $\tilde{SB}_0$ | mt | 2,275,000 | 2,005,000 | 2,068,000 | 3,091,000 | 2,249,000 | 712,800 |
| $\tilde{SB}_{F_{current}}$ | mt | 308,000 | 860,200 | 917,100 | 2,052,000 | 1,049,000 | 158,900 |
| $\tilde{SB}_{MSY}$ | mt | 935,600 | 531,300 | 547,100 | 1,034,000 | 587,700 | 252,700 |
| $B_{current}$ | mt | 1,746,169 | 1,703,746 | 1,834,039 | 3,068,102 | 2,057,741 | 774,386 |
| $SB_{current}$ | mt | 1,023,037 | 992,931 | 1,128,198 | 2,202,508 | 1,176,193 | 430,006 |
| $B_{current,F=0}$ | mt | 2,873,332 | 2,830,666 | 2,968,063 | 3,982,441 | 3,215,174 | 1,435,347 |
| $B_{current}/\tilde{B}_0$ | | 0.51 | 0.57 | 0.60 | 0.68 | 0.60 | 0.71 |
| $B_{current}/\tilde{B}_{F_{current}}$ | | 2.97 | 1.03 | 1.08 | 0.90 | 1.02 | 2.29 |
| $B_{current}/\tilde{B}_{MSY}$ | | 1.09 | 1.42 | 1.52 | 1.34 | 1.48 | 1.58 |
| $B_{current}/B_{current,F=0}$ | | 0.61 | 0.60 | 0.62 | 0.77 | 0.64 | 0.54 |
| $SB_{current}/\tilde{SB}_0$ | | 0.45 | 0.50 | 0.55 | 0.71 | 0.52 | 0.60 |
| $SB_{current}/\tilde{SB}_{F_{current}}$ | | 3.32 | 1.15 | 1.23 | 1.07 | 1.12 | 2.71 |
| $SB_{current}/\tilde{SB}_{MSY}$ | | 1.09 | 1.87 | 2.06 | 2.13 | 2.00 | 1.70 |
| $\tilde{B}_{F_{current}}/\tilde{B}_0$ | | 0.17 | 0.55 | 0.56 | 0.76 | 0.59 | 0.31 |
| $\tilde{SB}_{F_{current}}/\tilde{SB}_0$ | | 0.14 | 0.43 | 0.44 | 0.66 | 0.47 | 0.22 |
| $\tilde{B}_{MSY}/\tilde{B}_0$ | | 0.47 | 0.40 | 0.39 | 0.51 | 0.40 | 0.45 |
| $\tilde{SB}_{MSY}/\tilde{SB}_0$ | | 0.41 | 0.26 | 0.26 | 0.33 | 0.26 | 0.35 |
| $F_{current}/\tilde{F}_{MSY}$ | | 1.79 | 0.61 | 0.59 | 0.29 | 0.54 | 1.43 |
| $\tilde{B}_{F_{current}}/\tilde{B}_{MSY}$ | | 0.37 | 1.37 | 1.41 | 1.49 | 1.46 | 0.69 |
| $\tilde{SB}_{F_{current}}/\tilde{SB}_{MSY}$ | | 0.33 | 1.62 | 1.68 | 1.98 | 1.78 | 0.63 |
| $\tilde{Y}_{F_{current}}/MSY$ | | 0.61 | 0.92 | 0.90 | 0.71 | 0.88 | 0.92 |
| $B_{current}/B_{1995}$ | | 0.96 | 0.97 | 0.98 | 0.81 | 1.06 | 1.07 |
| $SB_{current}/SB_{1995}$ | | 0.98 | 0.99 | 1.02 | 0.91 | 1.09 | 1.21 |

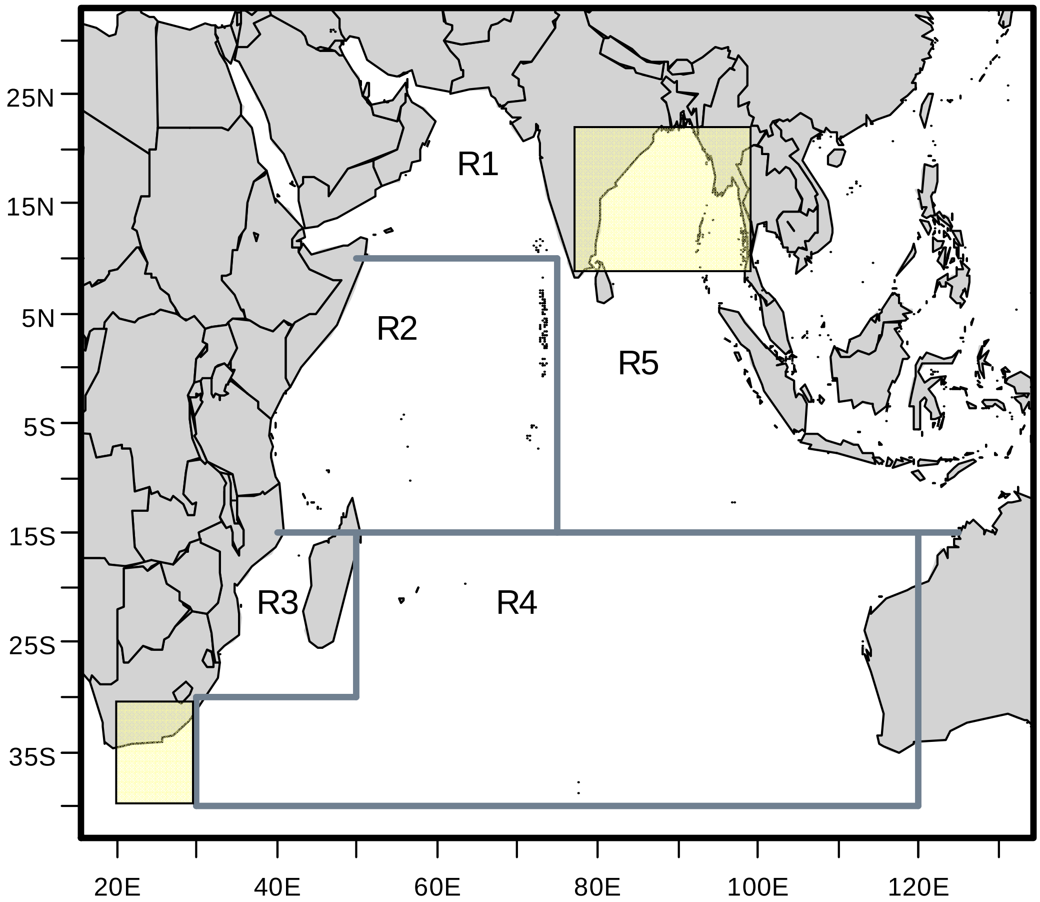



**Figure 1. S**patial stratification of the Indian Ocean for the MFCL assessment model. Note that catches from the highlighted areas have been allocated to neighbouring areas R5 and R4.

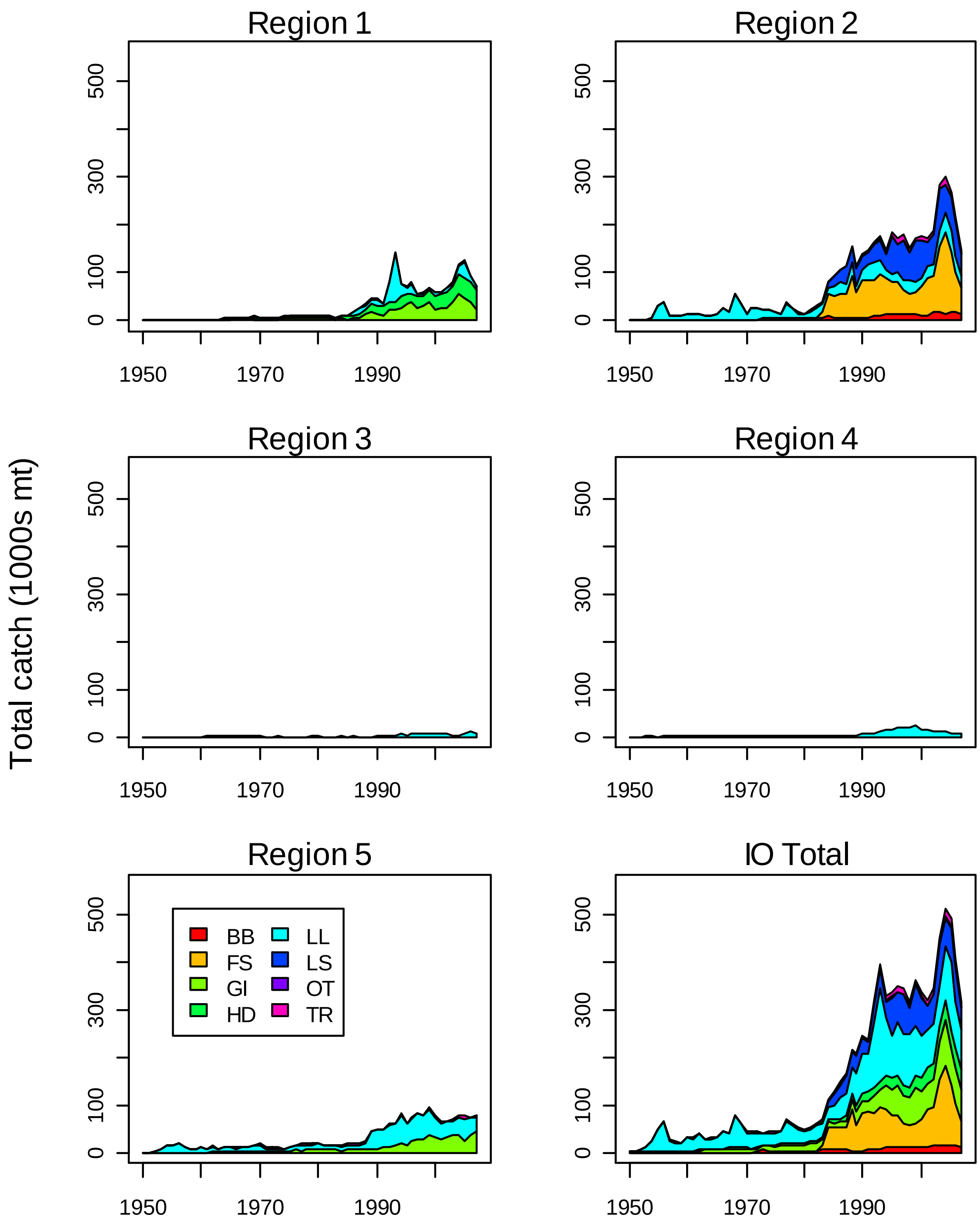



**Figure 2.** Total annual catch (1000s mt) of yellowfin tuna by fishing method and MFCL region from 1950 to 2007 (BB, baitboat; FS, purse-seine, free schools; GI, gillnet; HD, handline; LL, longline; LS, purse-seine, log sets; OT, other; TR, troll).

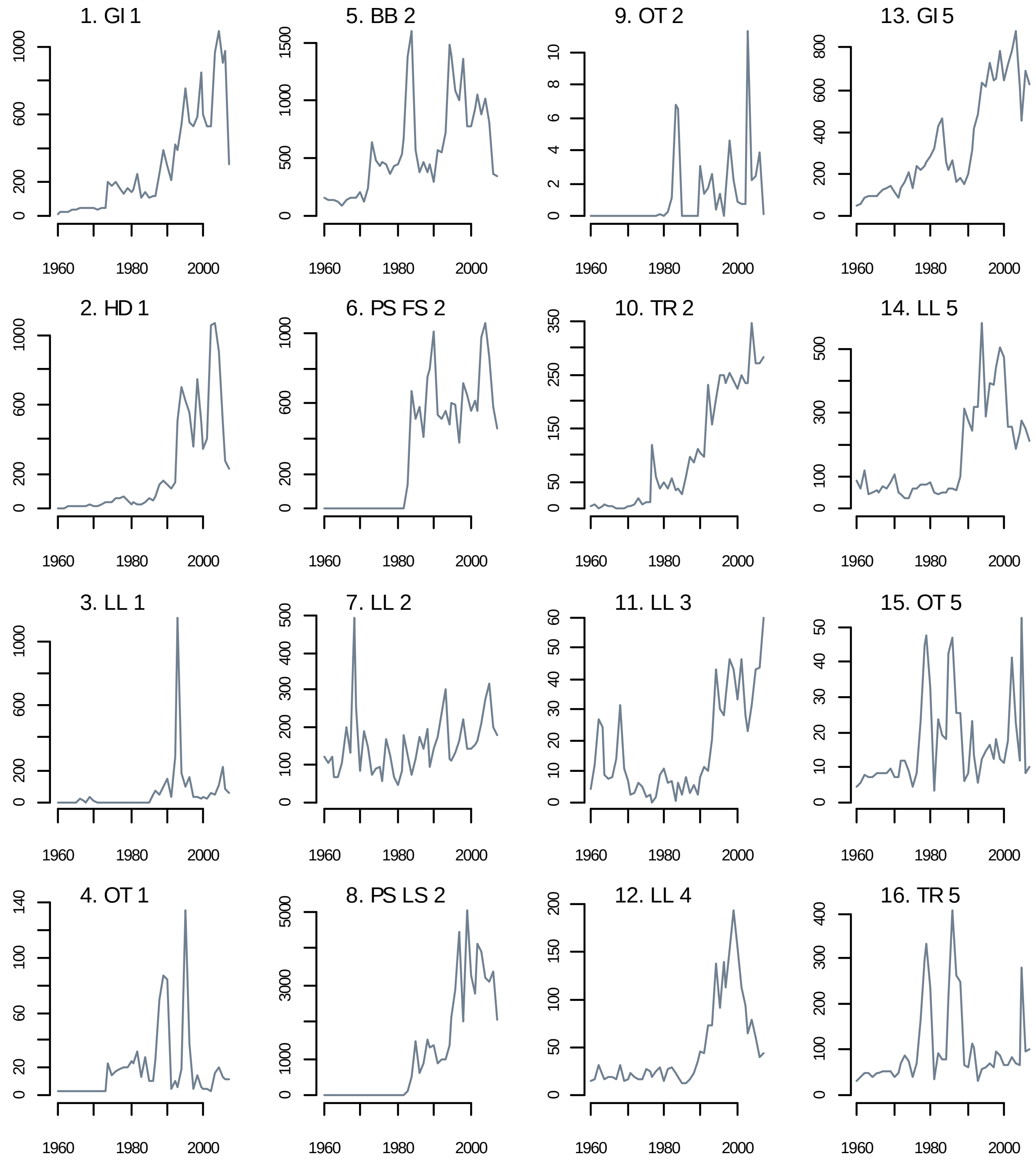



**Figure 3.** Quarterly catches, by fishery. Catches are in number (thousands) of fish. Note the y-axis differs among plots.

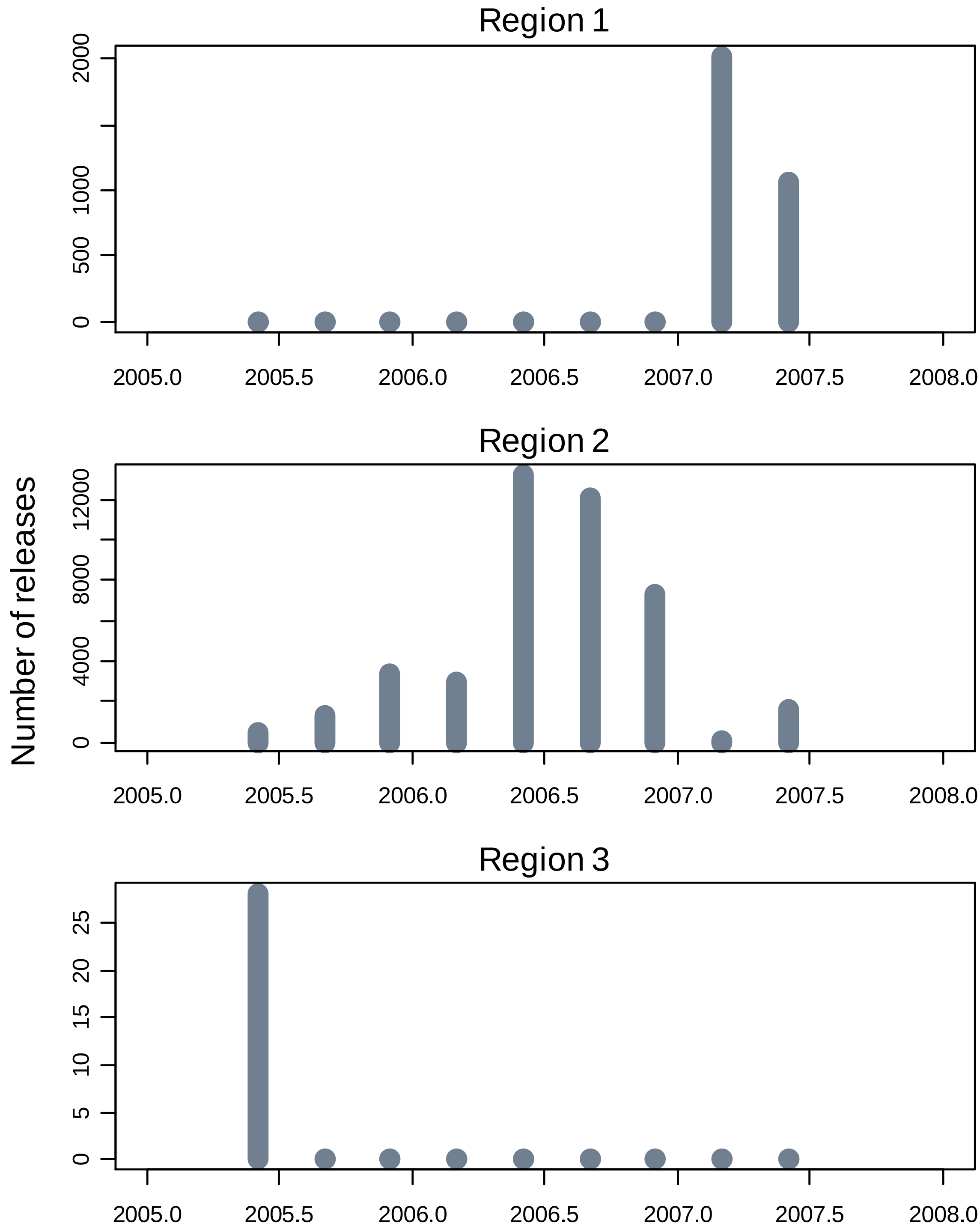



**Figure 4. Number of tag releases by region and quarter included in the MFCL data set. No tag releases occurred in regions 4 and 5.**

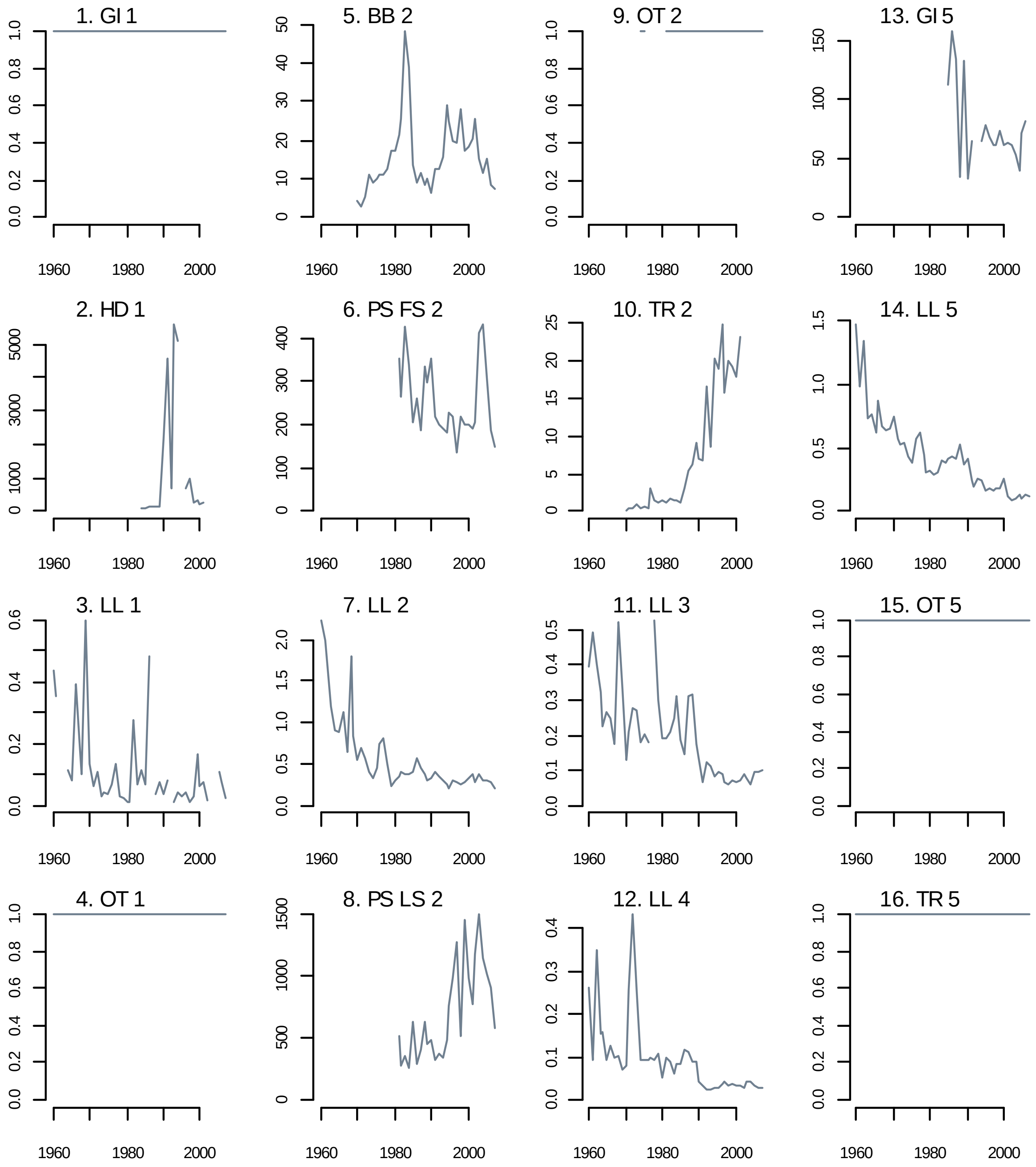



**Figure 5. Quarterly c**atch-per-unit-effort (CPUE) by fishery. Units are catch (number) per GLM-standardised effort (fisheries LL 1–5), catch (number) per day fished/searched (PS fisheries) and catch (number) per trip. Note that CPUE for "Other" and troll fisheries is arbitrary and not based on data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

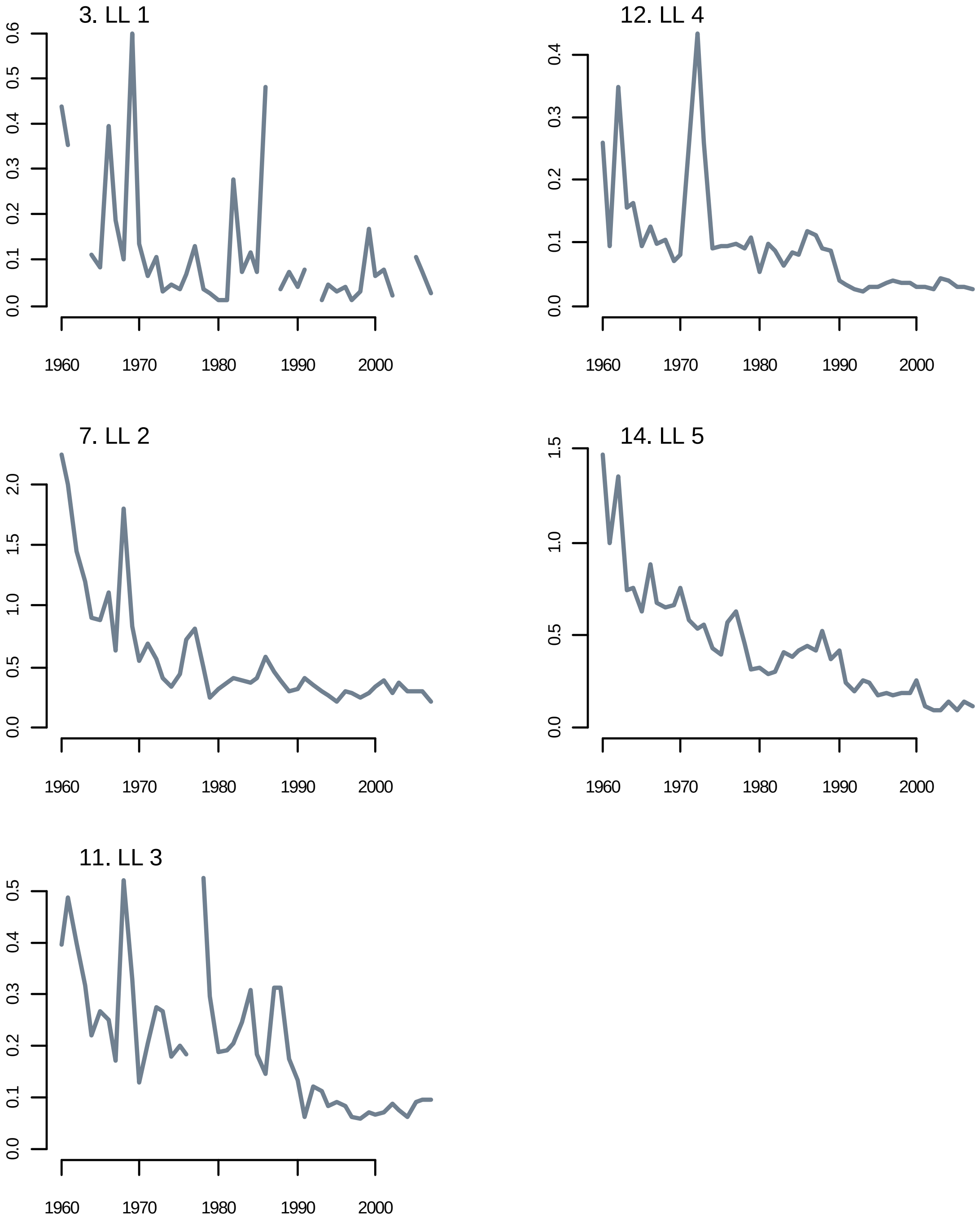



**Figure 6. Annualised** GLM standardised catch-per-unit-effort (CPUE) for the principal longline fisheries (LL ALL 1–5) scaled by the respective region scalars.

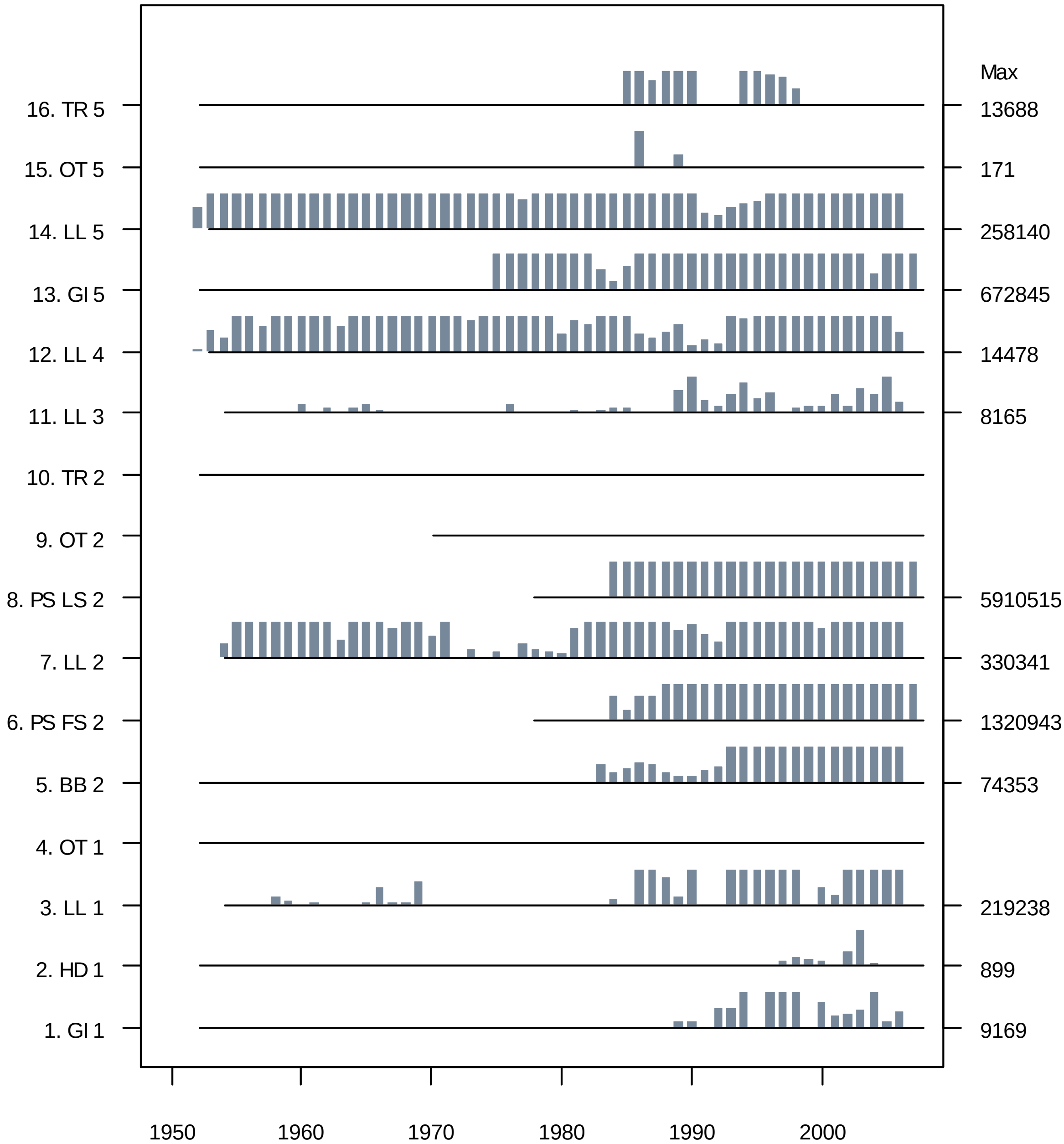



**Figure 7.** Number of fish length measurements by year for each fishery. The height of the bar is proportional to the maximum sample size, up to a maximum of 4000 fish per annum. The maximum annual number of fish measured in each fishery is given on the right-hand side. The extent of the horizontal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

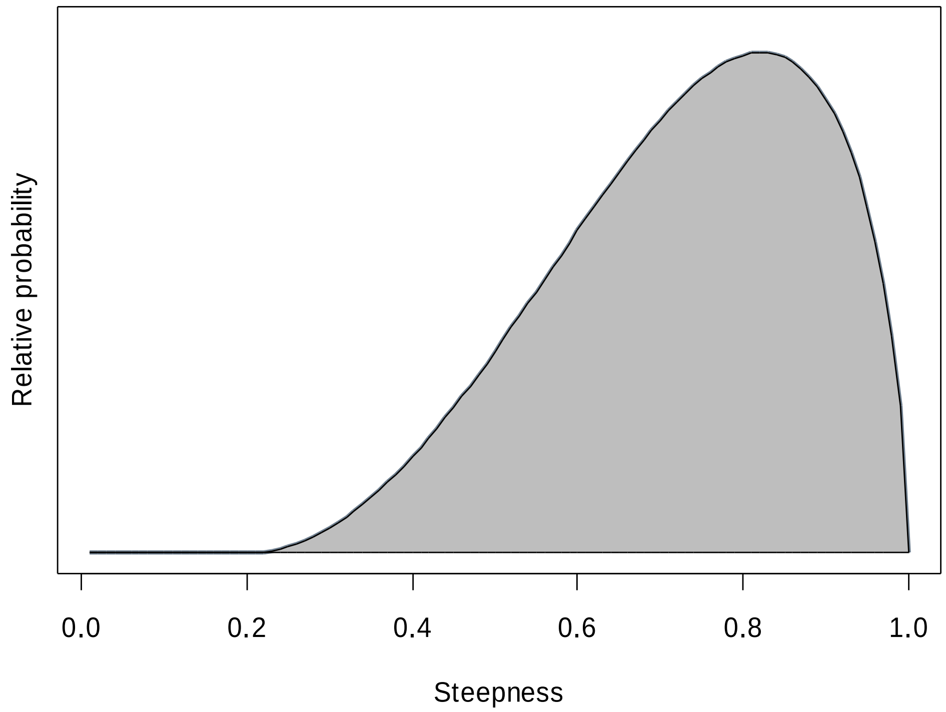



**Figure 8.** Prior for the steepness parameter of the relationship between spawning biomass and recruitment (SSR) (mode = 0.85, standard deviation = 0.16).

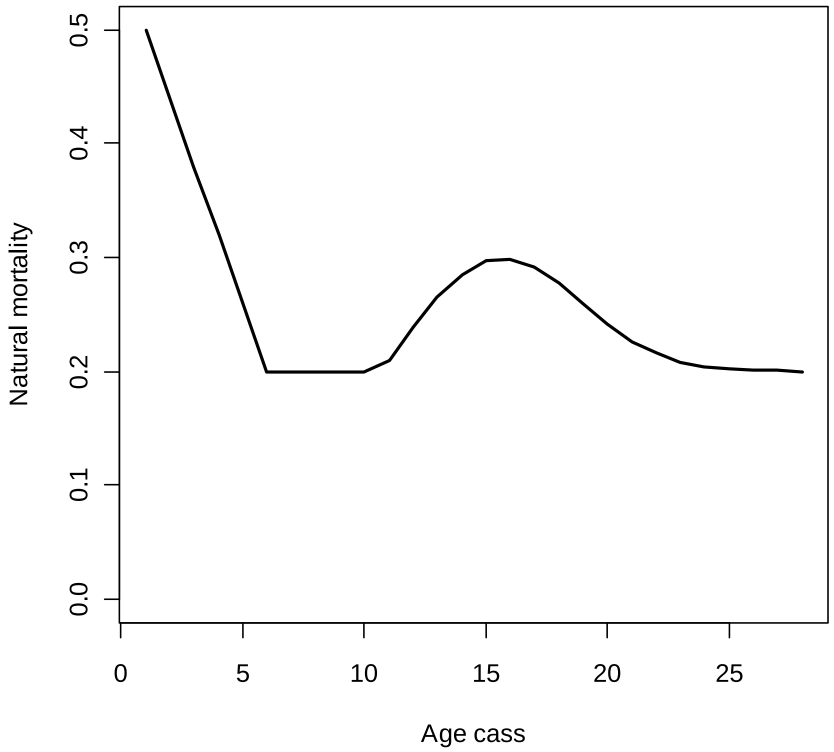



**Figure 9.** Age-specific natural mortality assumed for the assessment.

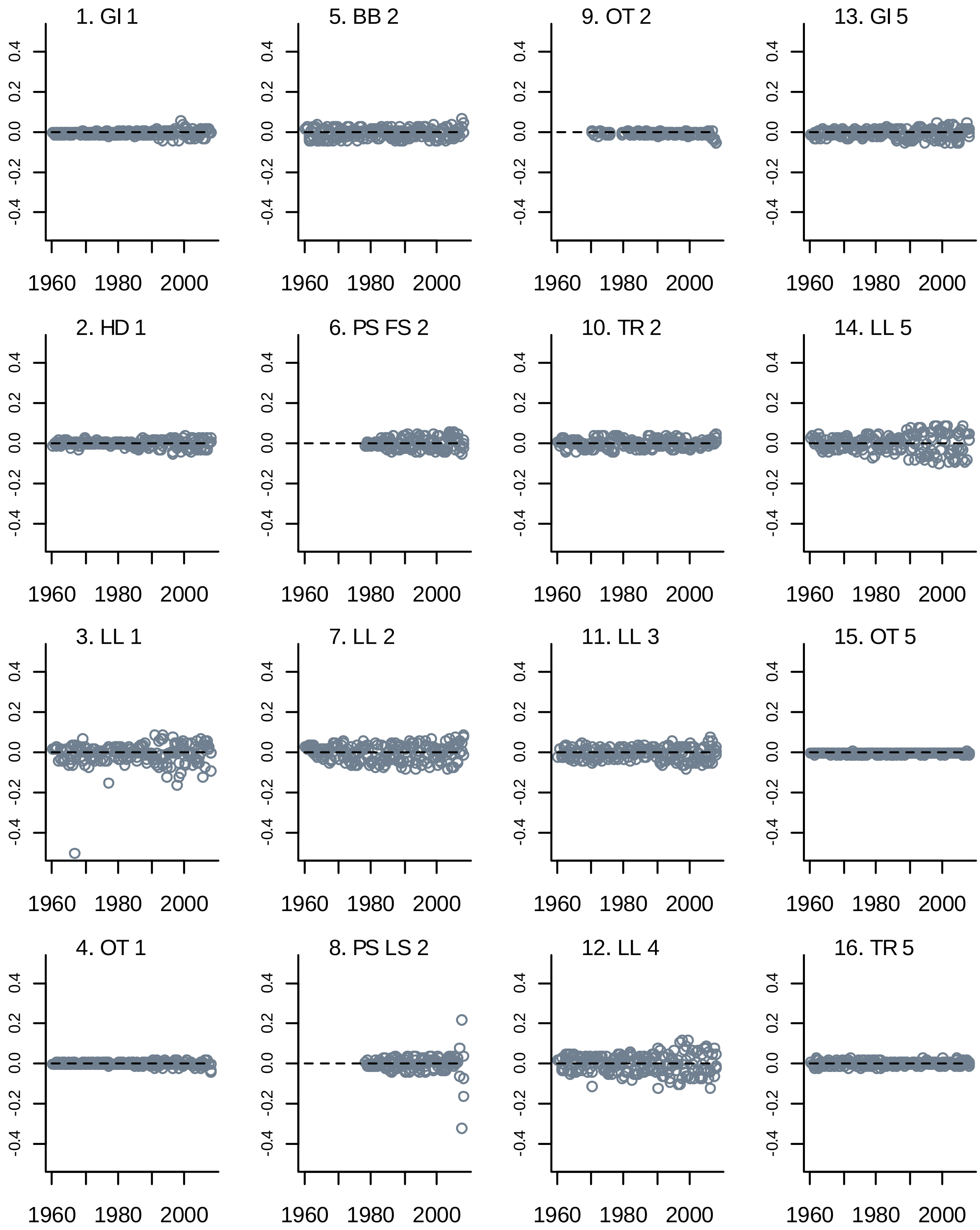



**Figure 10.** Residuals of ln (total catch) for each fishery.

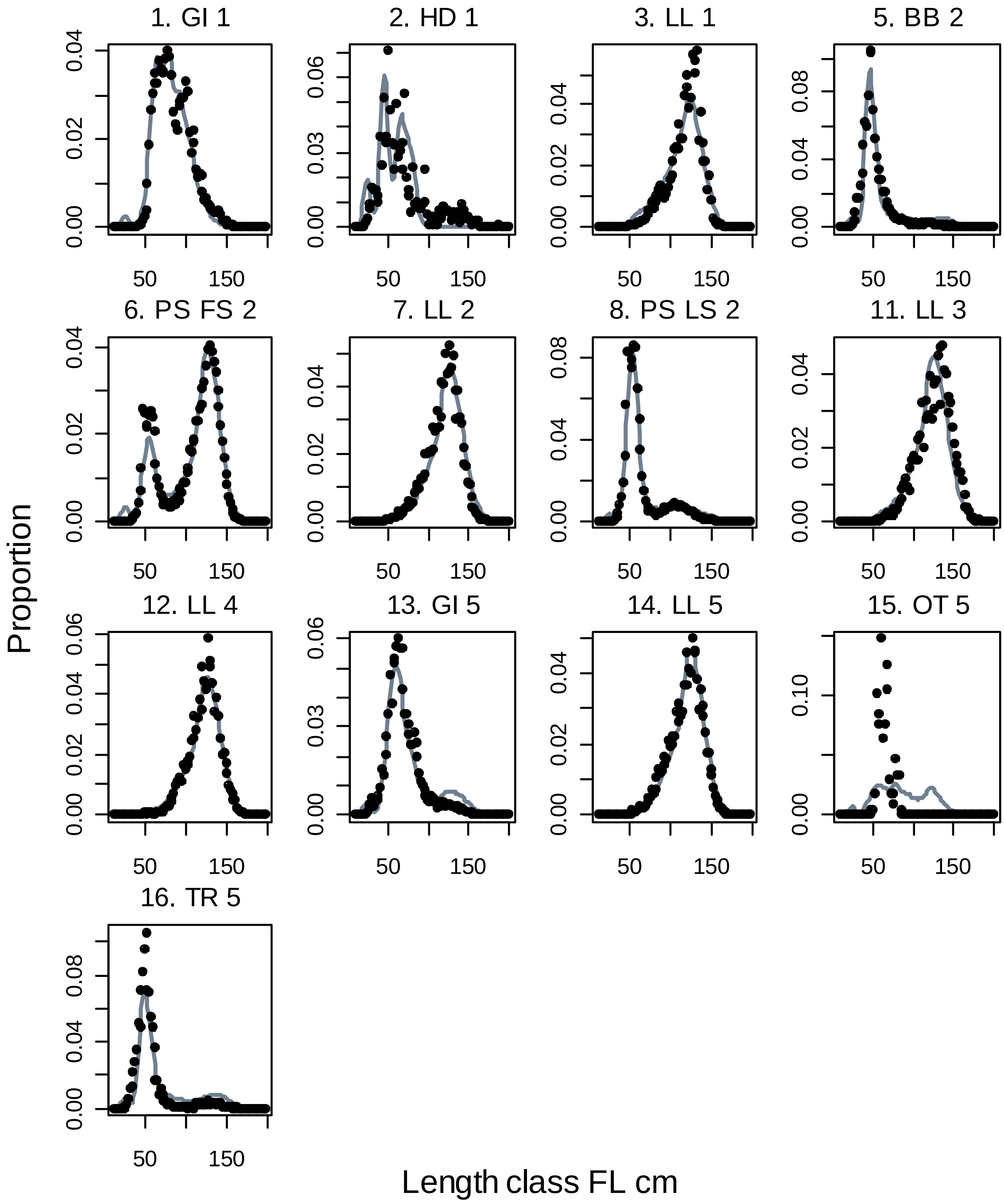



**Figure 11.** Observed (points) and predicted (line) length frequencies (in cm) for each fishery aggregated over time.

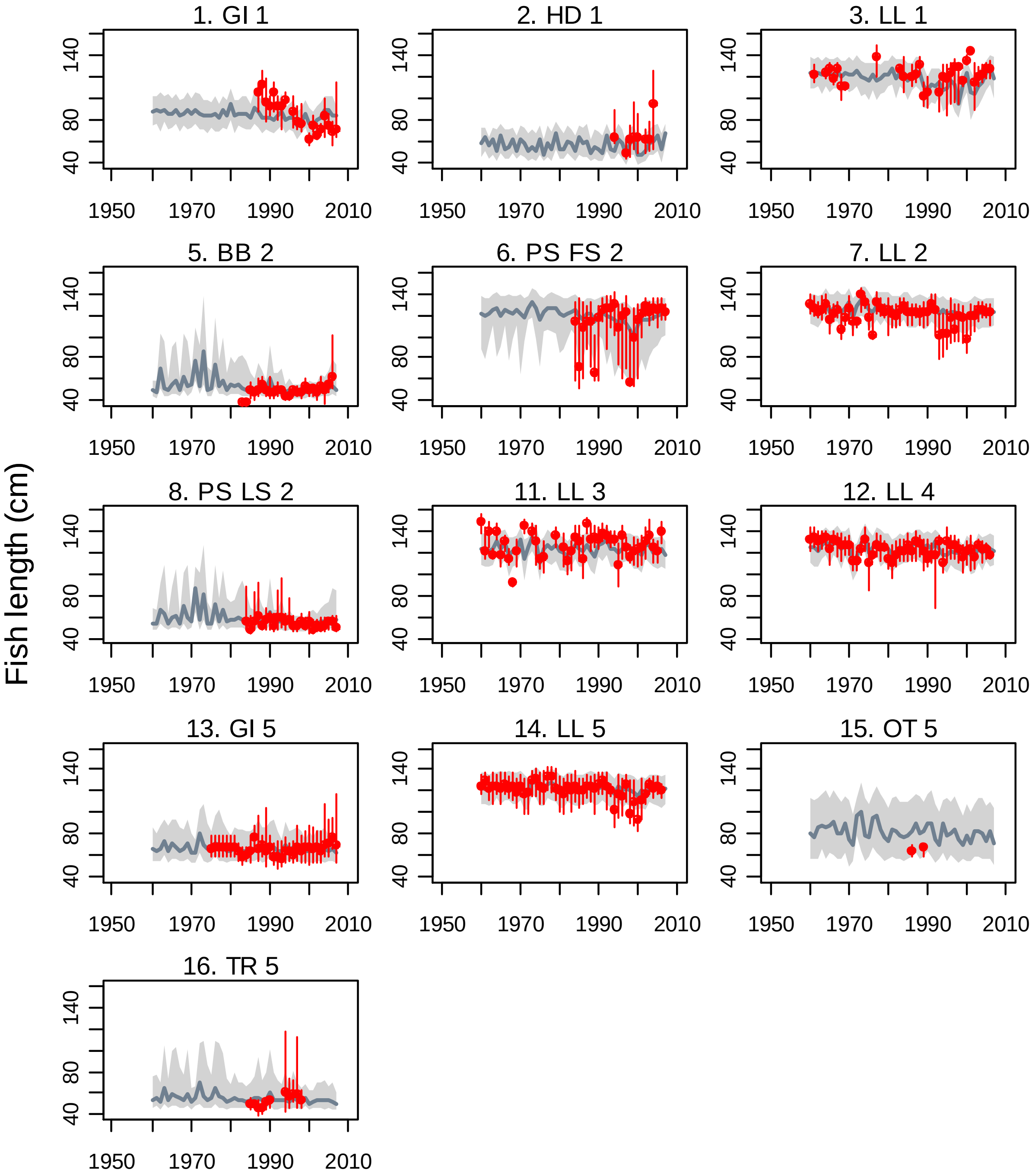



**Figure 12.** A comparison of the observed (red points) and predicted (grey line) median fish length (FL, cm) of yellowfin tuna by fishery for the main fisheries with length data. The confidence intervals represent the values encompassed by the 25% and 75% quantiles. Sampling data are aggregated by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

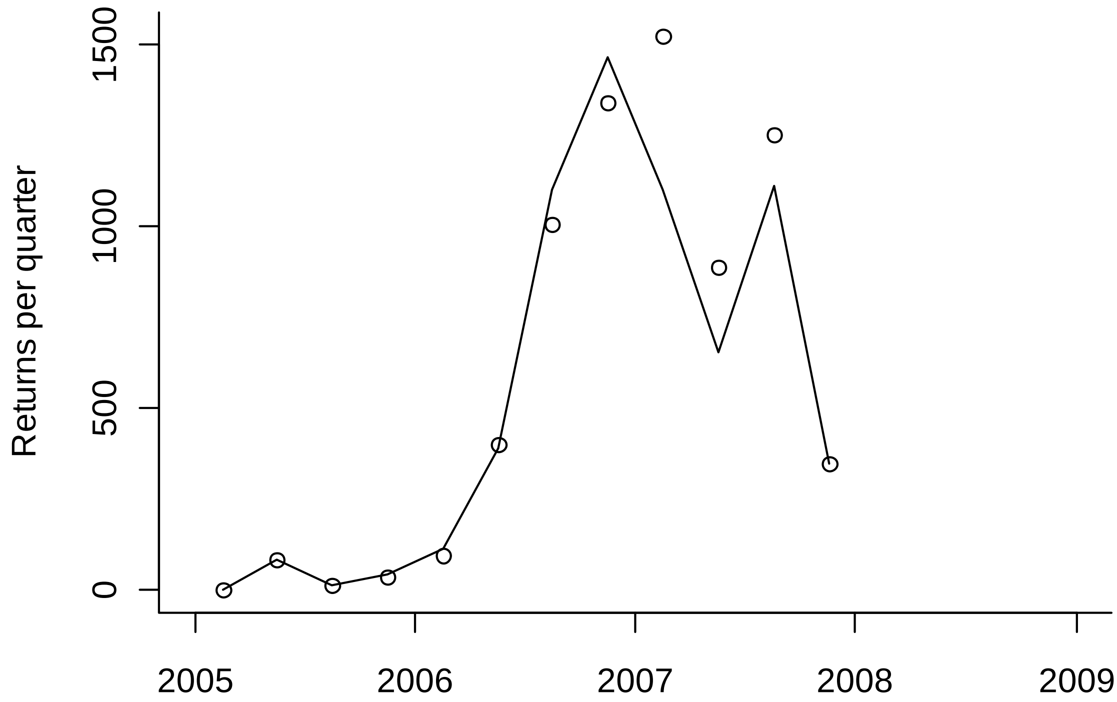



**Figure 13.** Number of observed (points) and predicted (line) tag returns by recapture period (quarter). Observed tag returns have been corrected for the purse-seine reporting rate (see text for details).

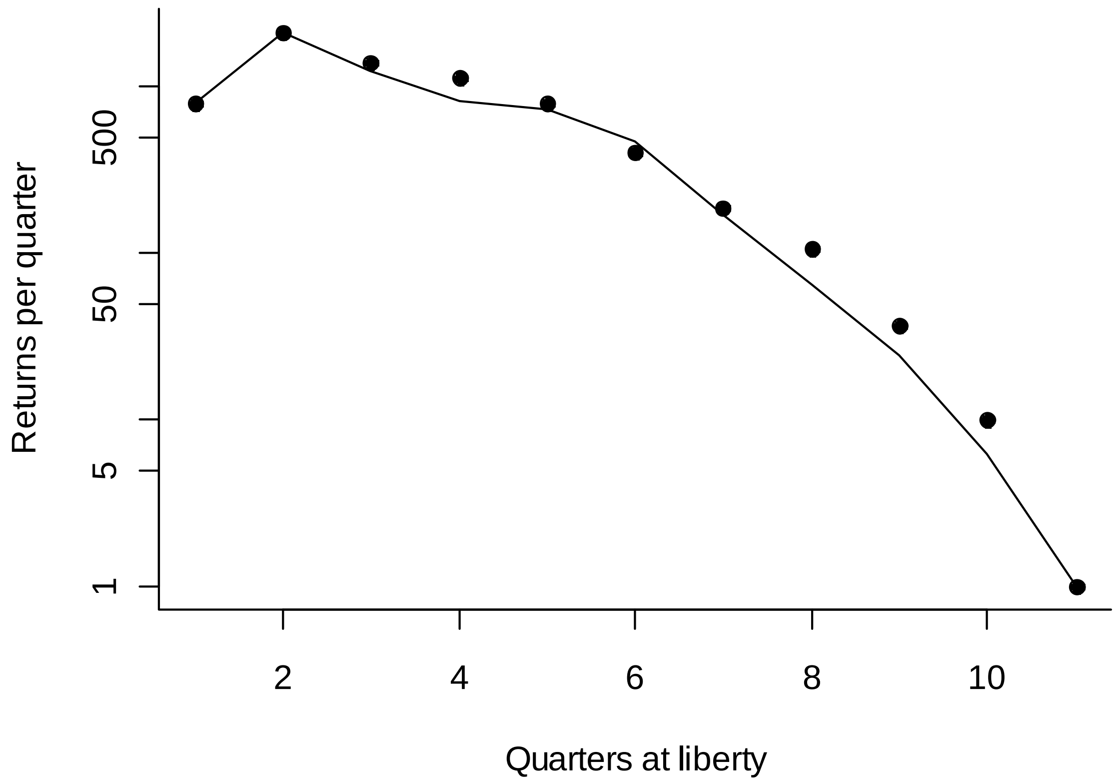



**Figure 14**. Number of observed (points) and predicted (line) tag returns by periods at liberty (quarters). Observed tag returns have been corrected for the purse-seine reporting rate (see text for details).

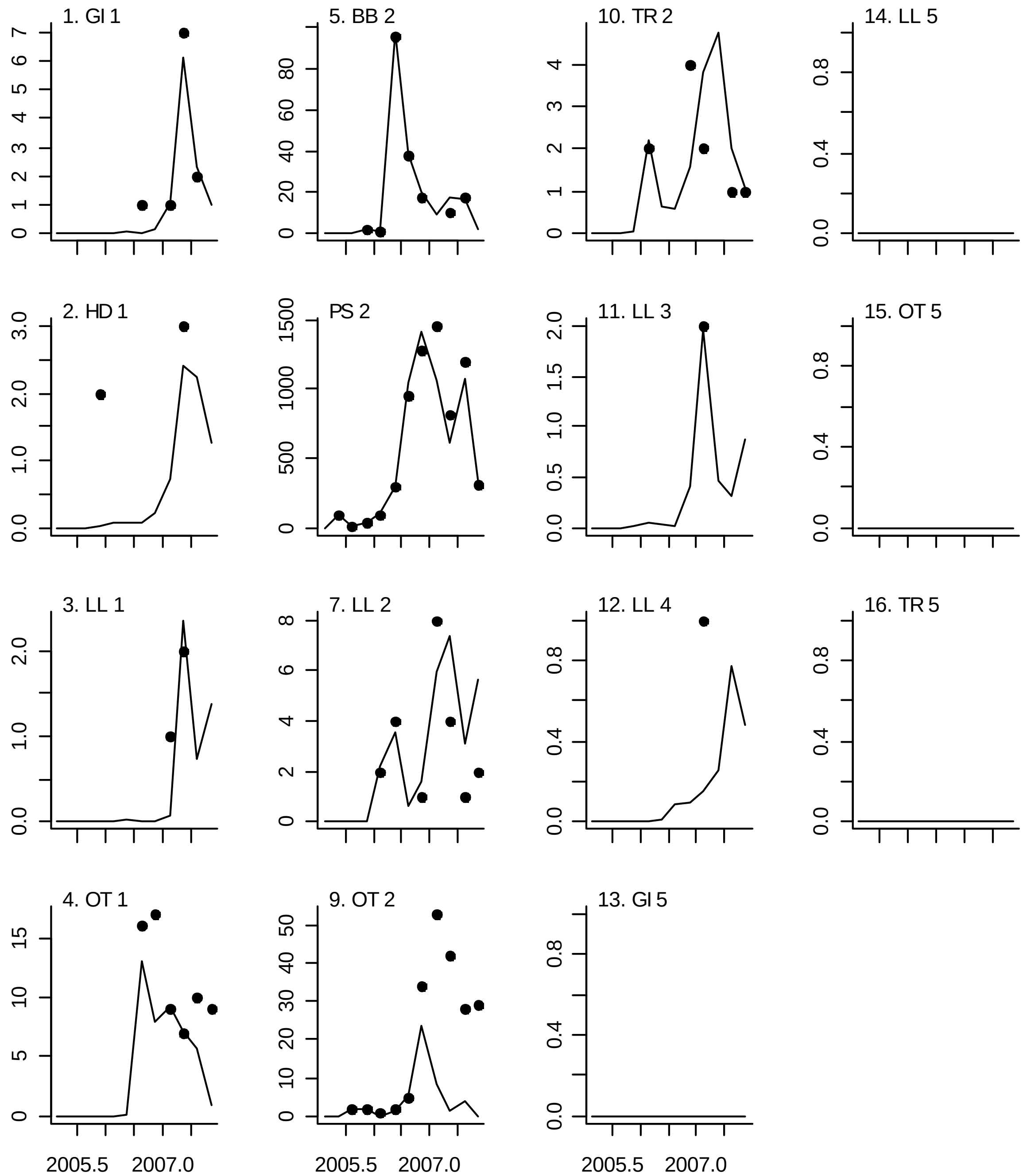



**Figure 15.** Number of observed (points) and predicted (line) tag returns by recapture period (quarter) for the various fisheries (or groups of fisheries) defined in the model. Observed tag returns have been corrected for the purse-seine reporting rate (see text for details).

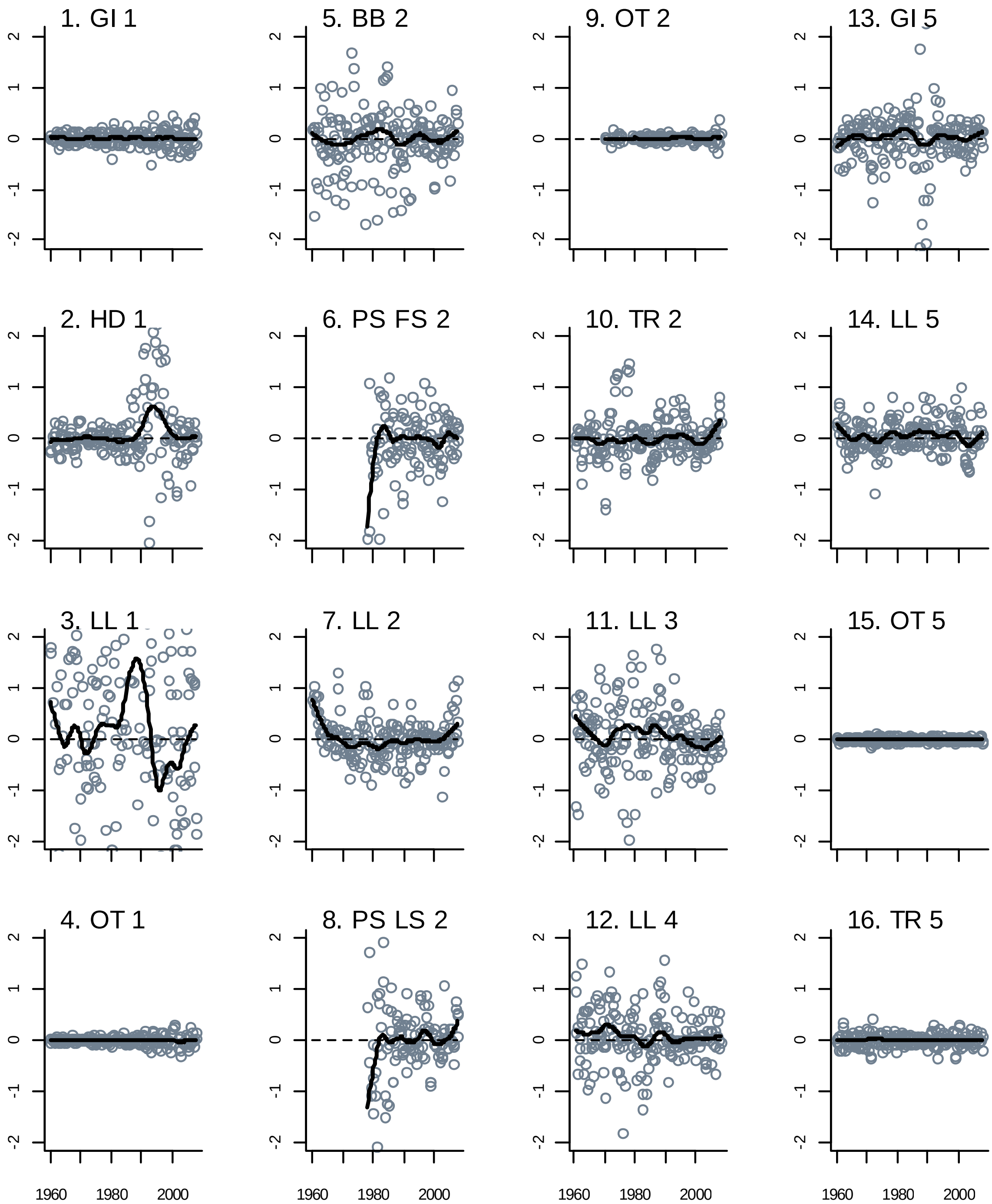



**Figure 16.** Effort deviations by time period for each fishery. The solid line represents a lowess fit to the data.

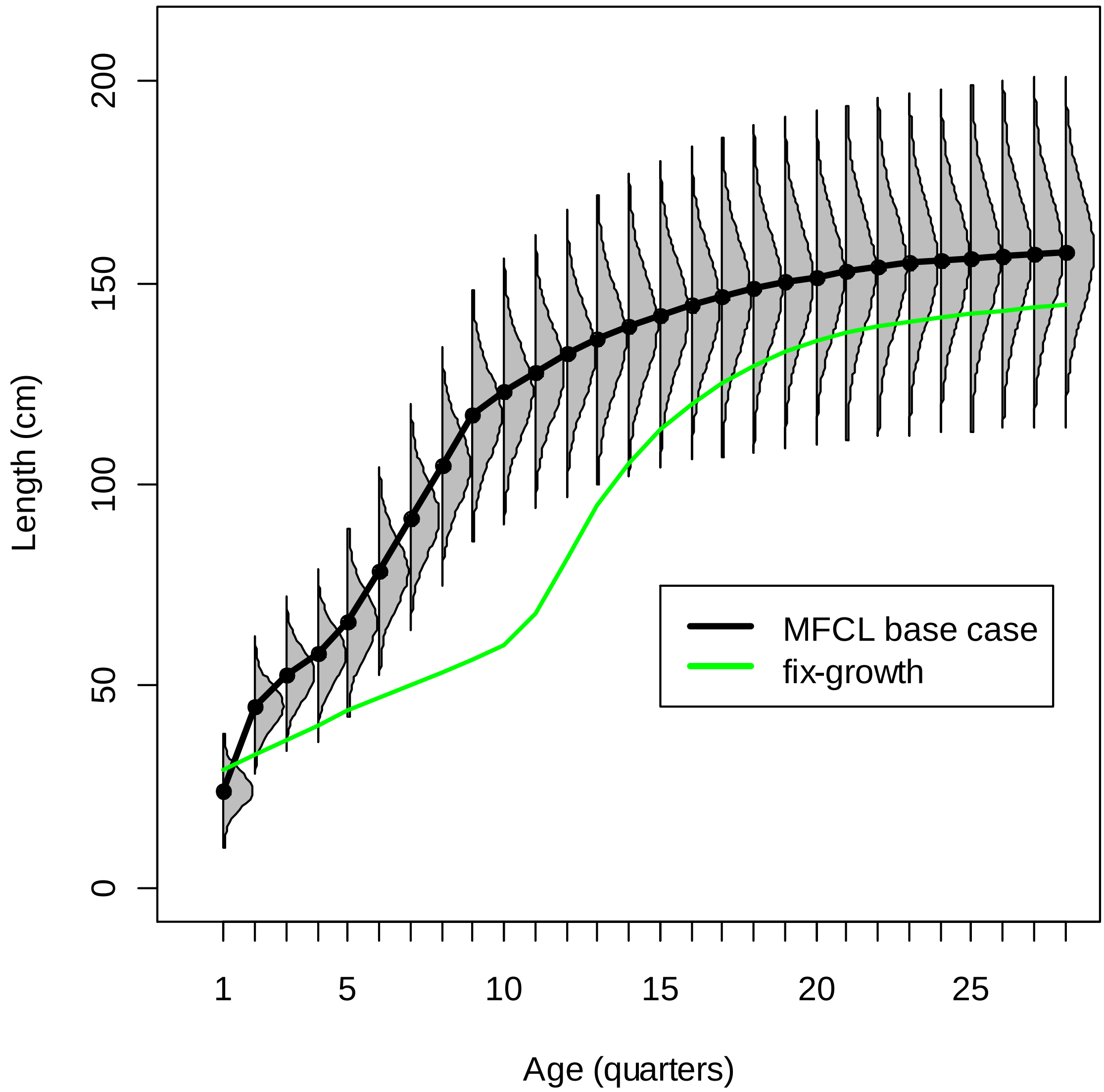



**Figure 17.** Estimated growth of yellowfin derived from the base-case assessment model. The black line represents the estimated mean length (FL, cm) at age and the grey area represents the estimated distribution of length at age. The estimated mean length at age from the tag analysis (P. Everson 18/9/2008) is also presented.

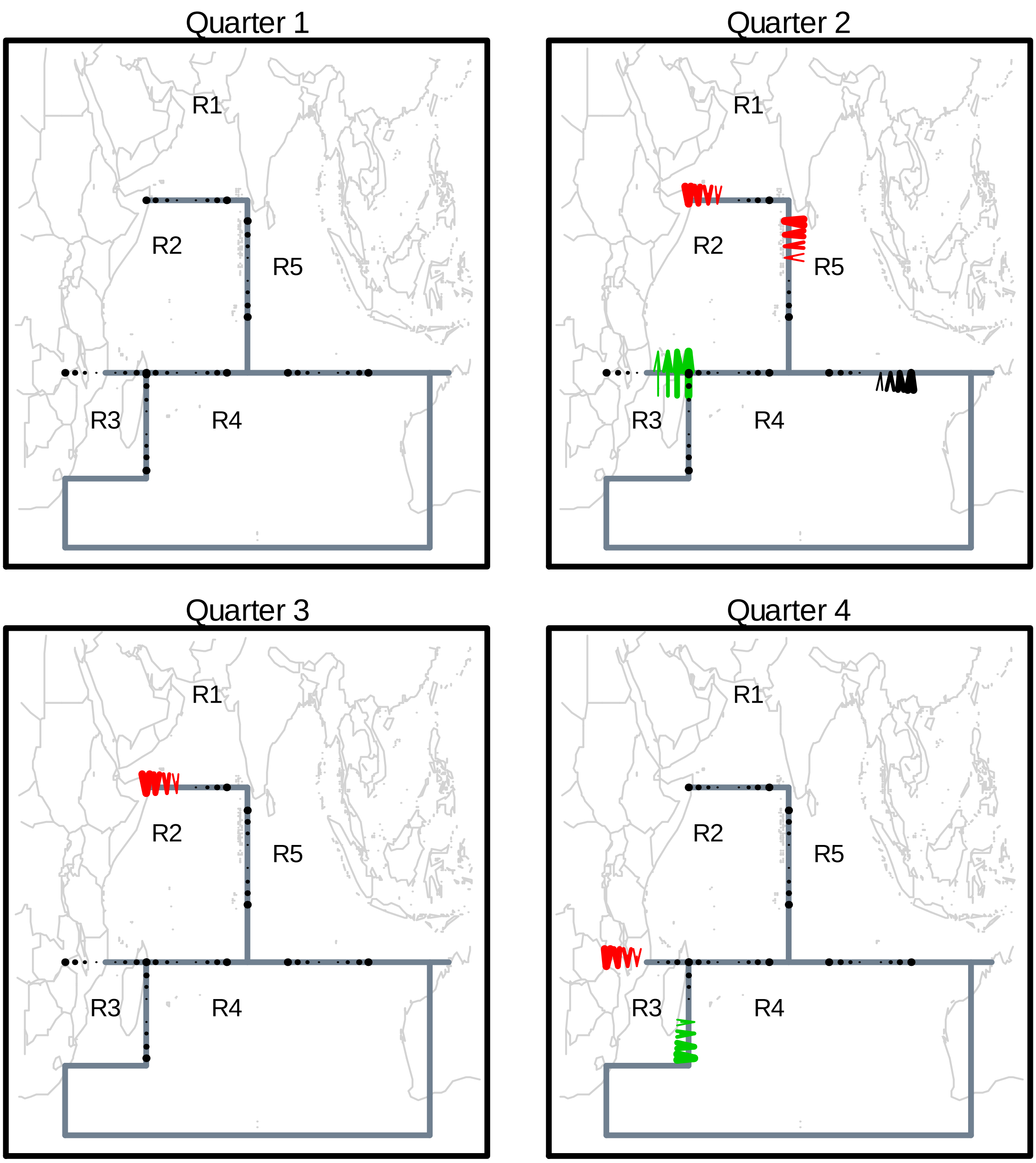



**Figure 18.** Estimated quarterly movement coefficients at age (1, 7, 15, 25 quarters) from the base-case model. The movement coefficient is proportional to the length of the arrow and increased weight of the arrow represents increasing age. The maximum movement (quarter 2, region 3 to region 2) represents movement of 33% of the fish at the start of the quarter. Movement rates are colour coded: black, 0.5–5%; red 5–10%; green >10%.

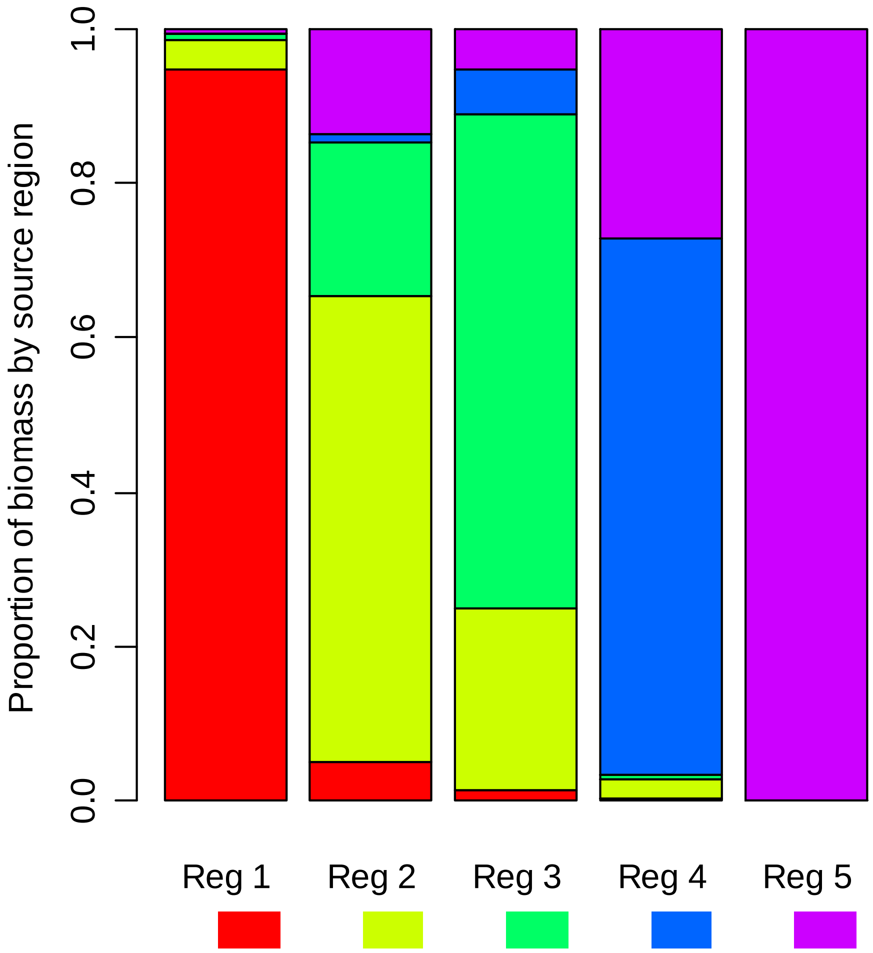



**Figure 19.** Proportional distribution of total biomass (by weight) in each region (Reg 1–5) apportioned by the source region of the fish. The colour of the home region is presented below the corresponding label on the x-axis. The biomass distributions are calculated based on the long-term average distribution of recruitment among regions, estimated movement parameters, and natural mortality. Fishing mortality is not taken into account.

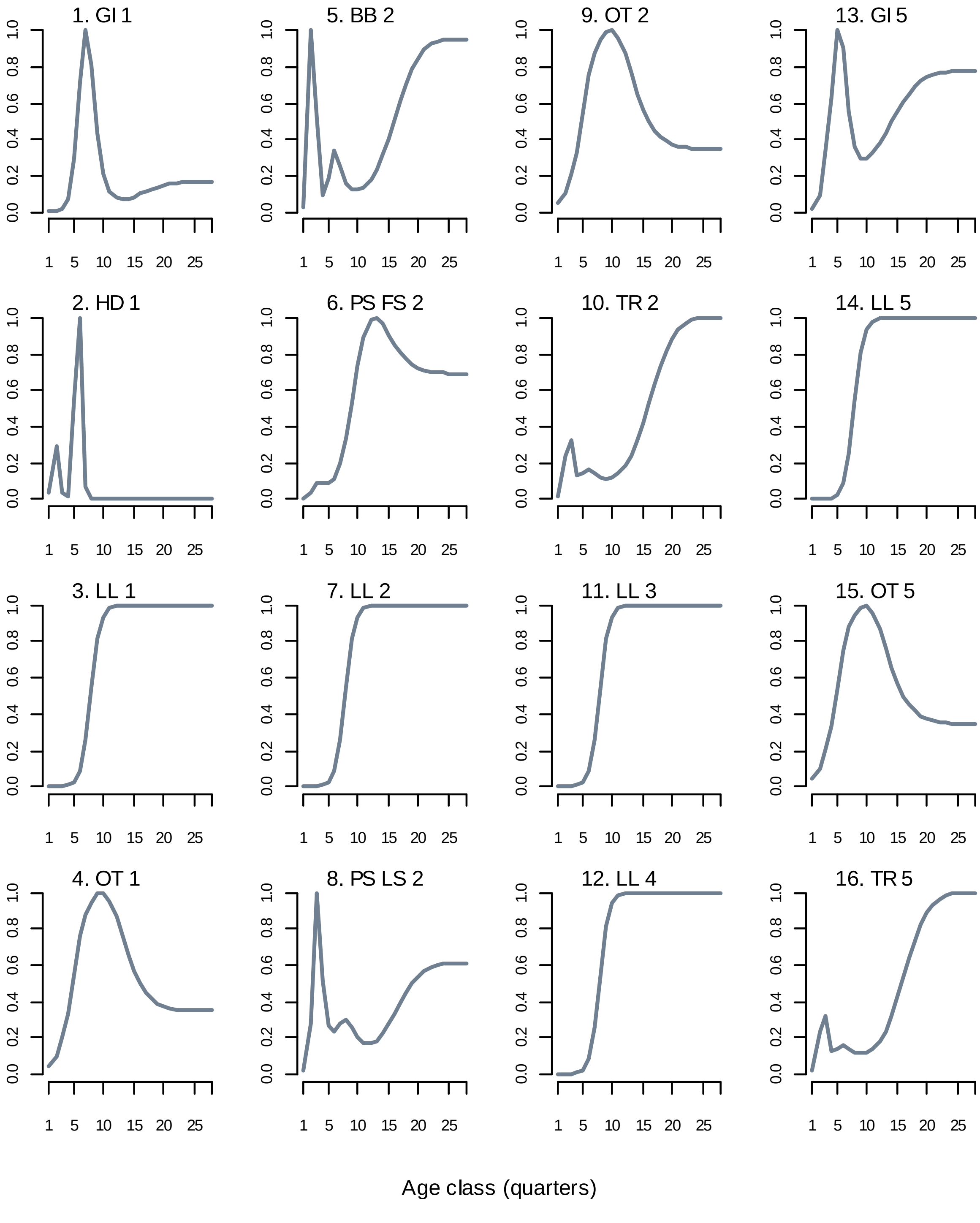



**Figure 20.** Selectivity coefficients, by fishery.

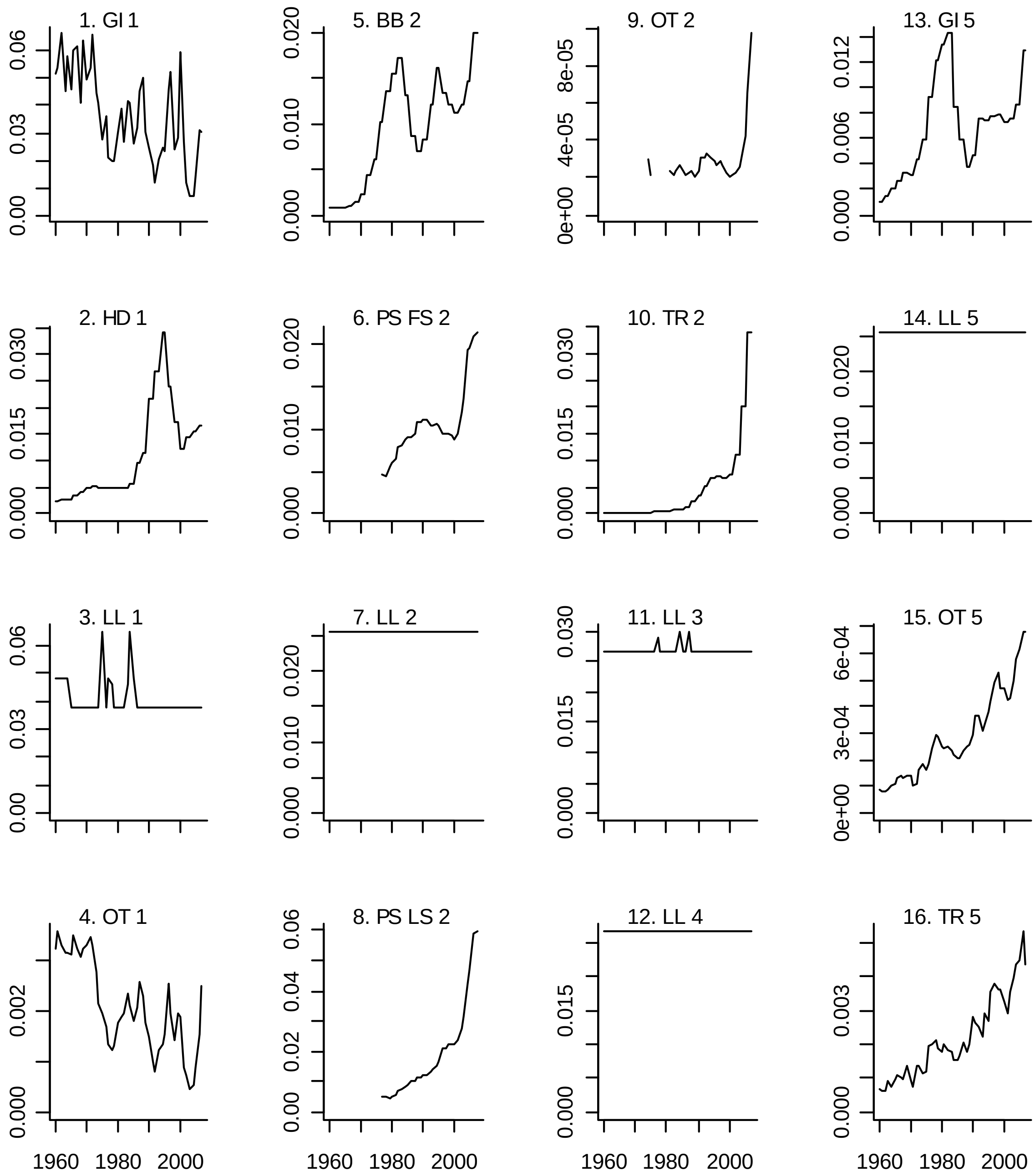



**Figure 21.** Average annual catchability time series, by fishery.

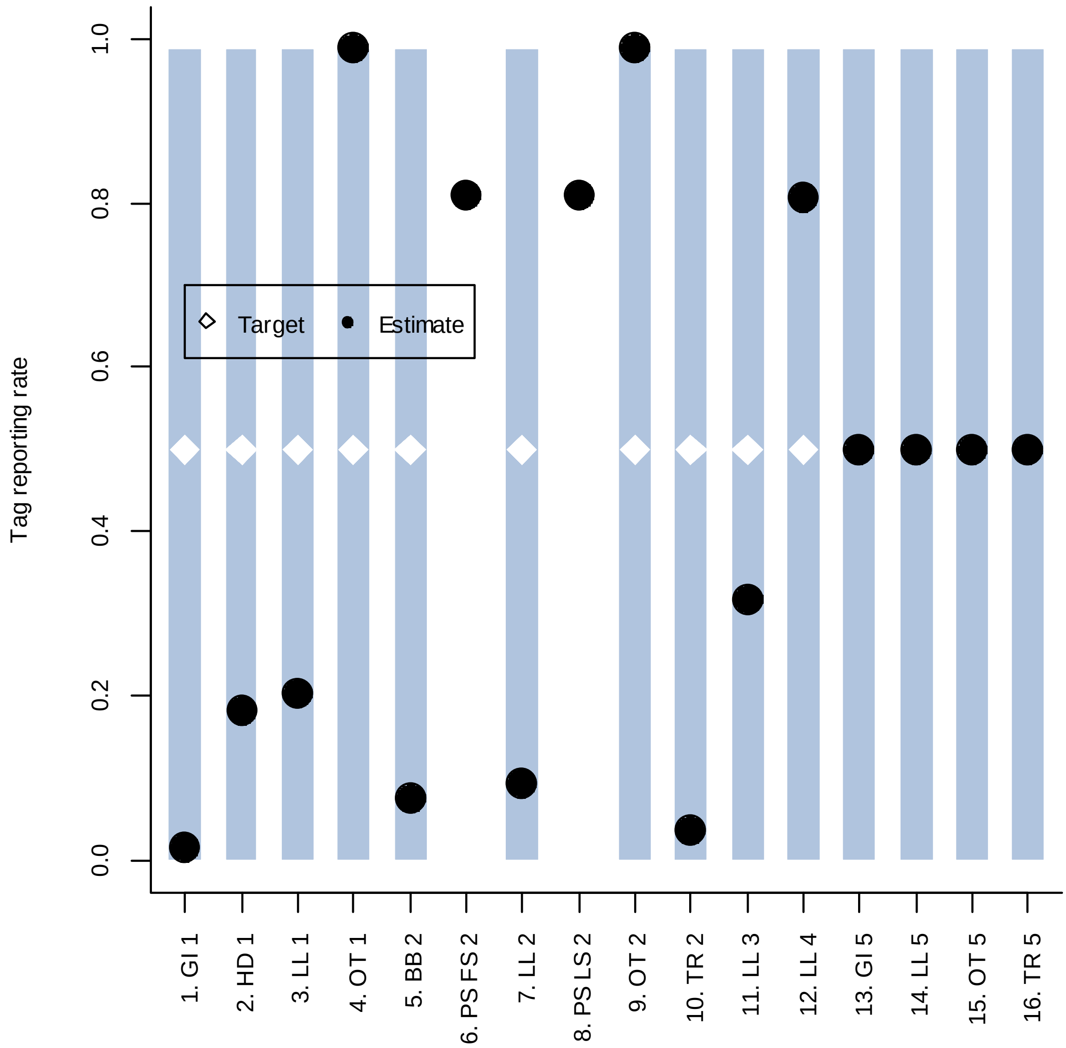



**Figure 22.** Estimated tag-reporting rates by fishery (black circles). The white diamonds indicate the modes of the priors for each reporting rate and the grey bars indicate a range of ±1 SD. The reporting rates for the purse-seine fishery were fixed.

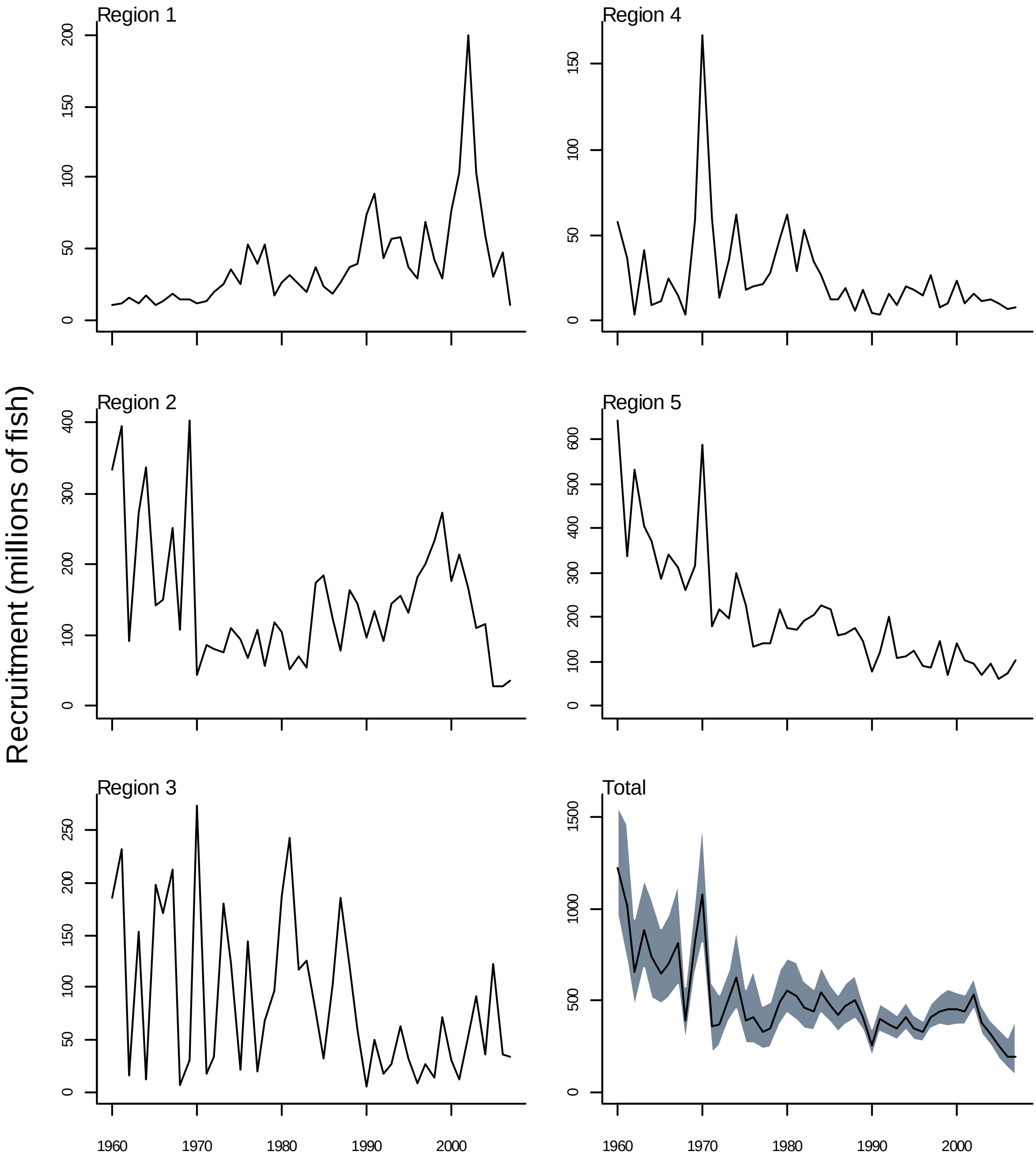



**Figure 23.** Estimated annual recruitment (millions of fish) by region and for the IO. The shaded area for the IO indicates the approximate 95% confidence intervals.

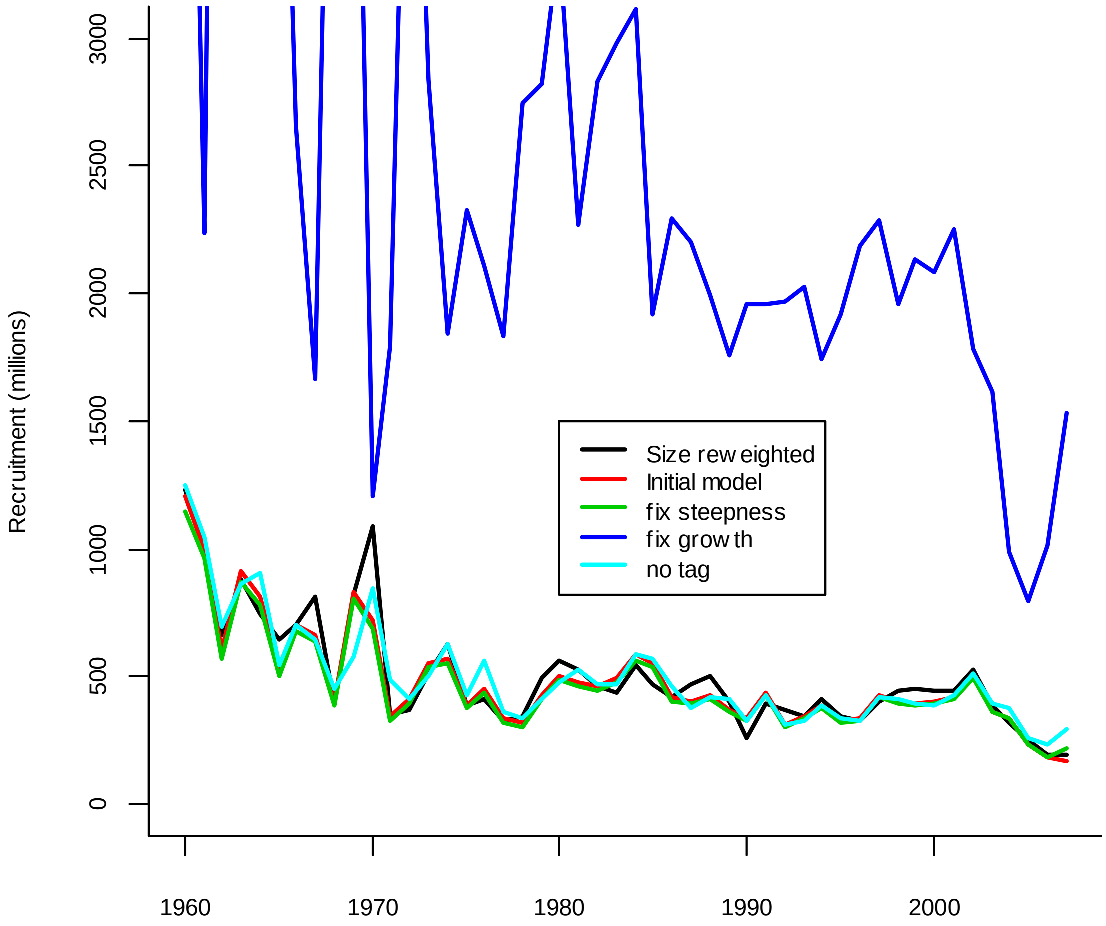



**Figure 24.** Estimated annual recruitment (millions of fish) for the IO obtained from the different model options.

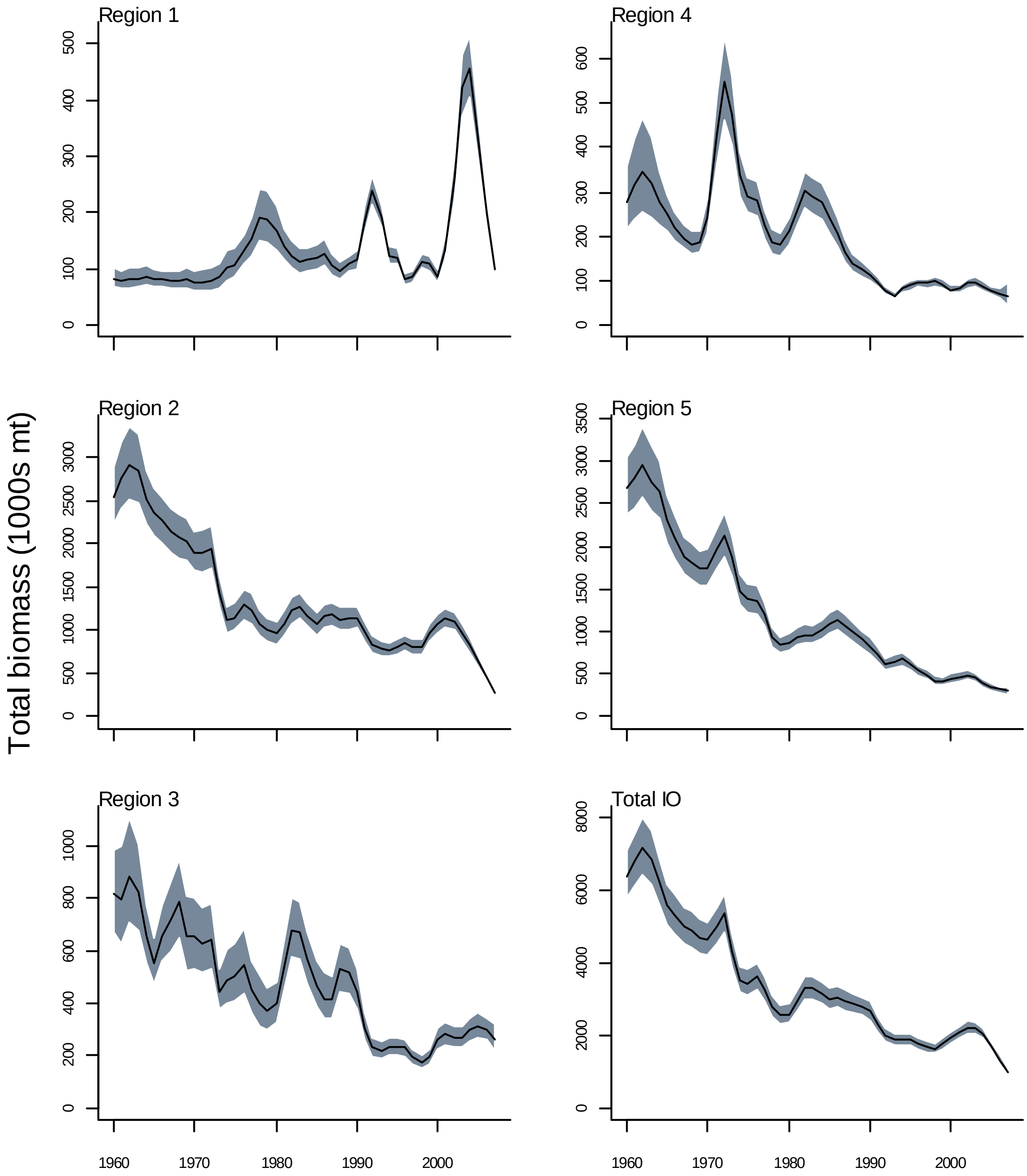



**Figure 25.** Estimated annual average total biomass (thousand mt) by region and for the IO for the base-case analysis. The shaded areas indicate the approximate 95% confidence intervals.

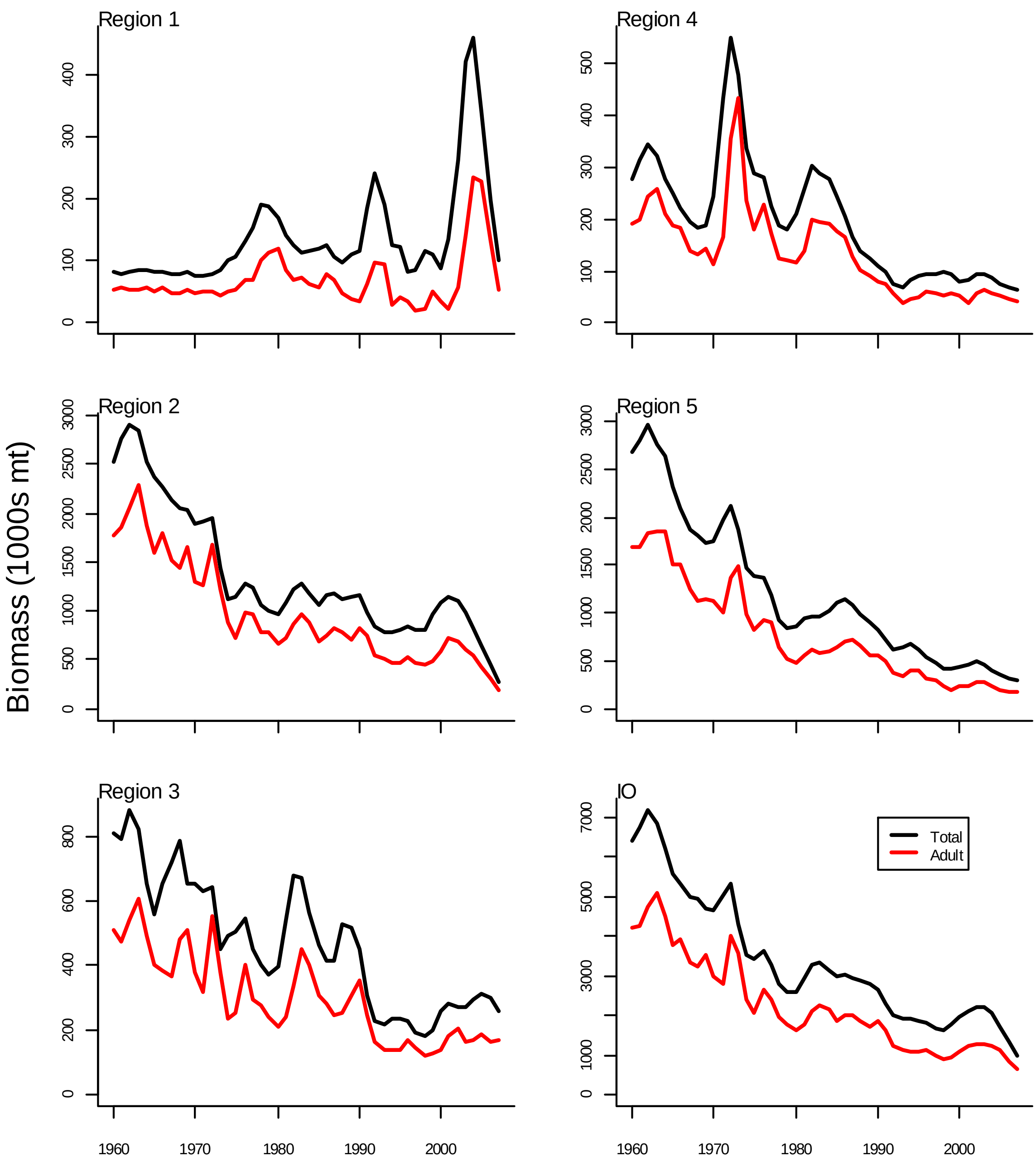



**Figure 26.** Temporal trend in total and adult biomass (1000s mt) by region and for the entire IO from the base-case assessment.

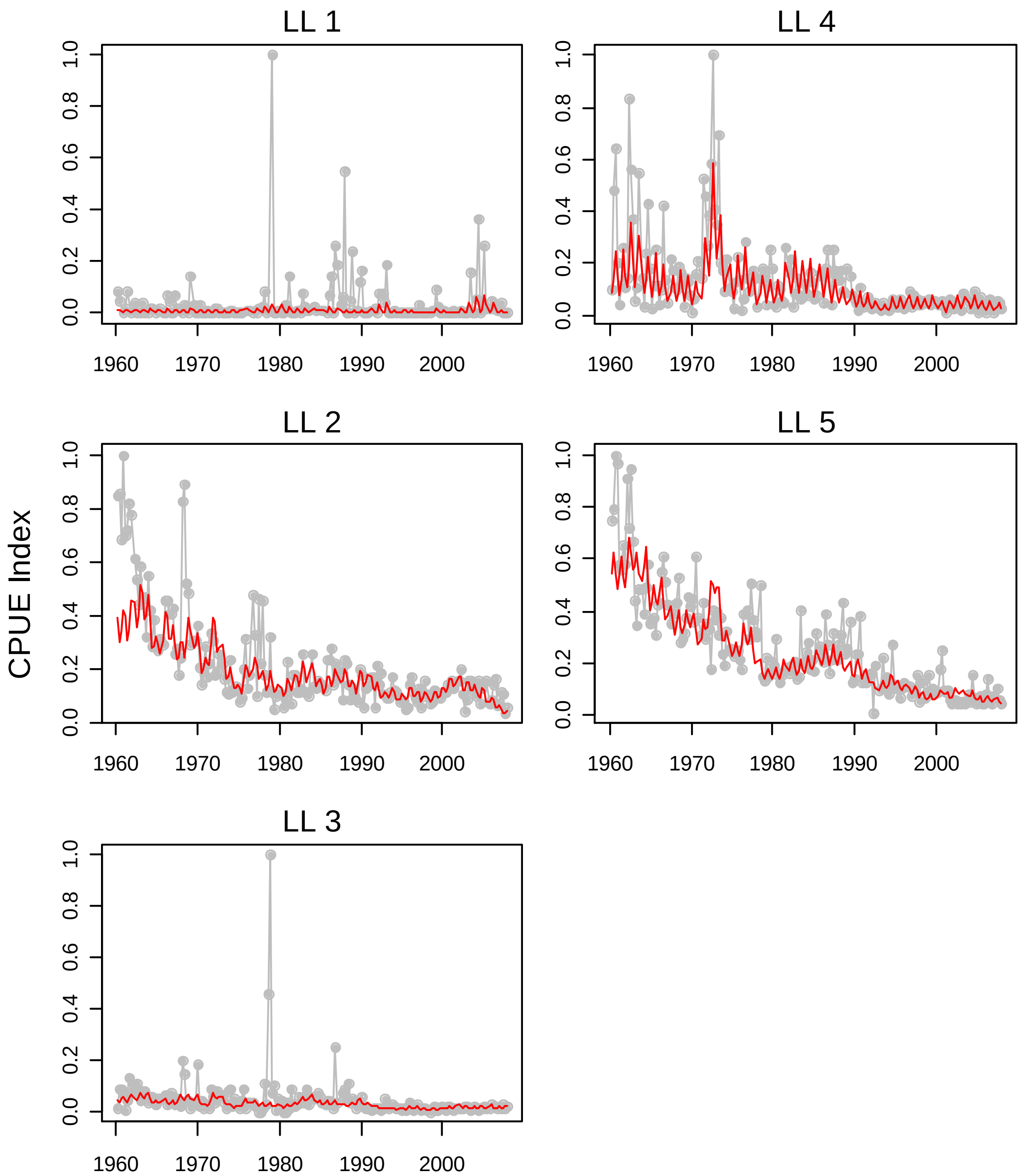



**Figure 27.** A comparison of longline exploitable biomass by quarter and region (red line) and the quarterly standardised CPUE indices (grey line and points) for the fisheries. For comparison, both series are scaled to the average of the series.

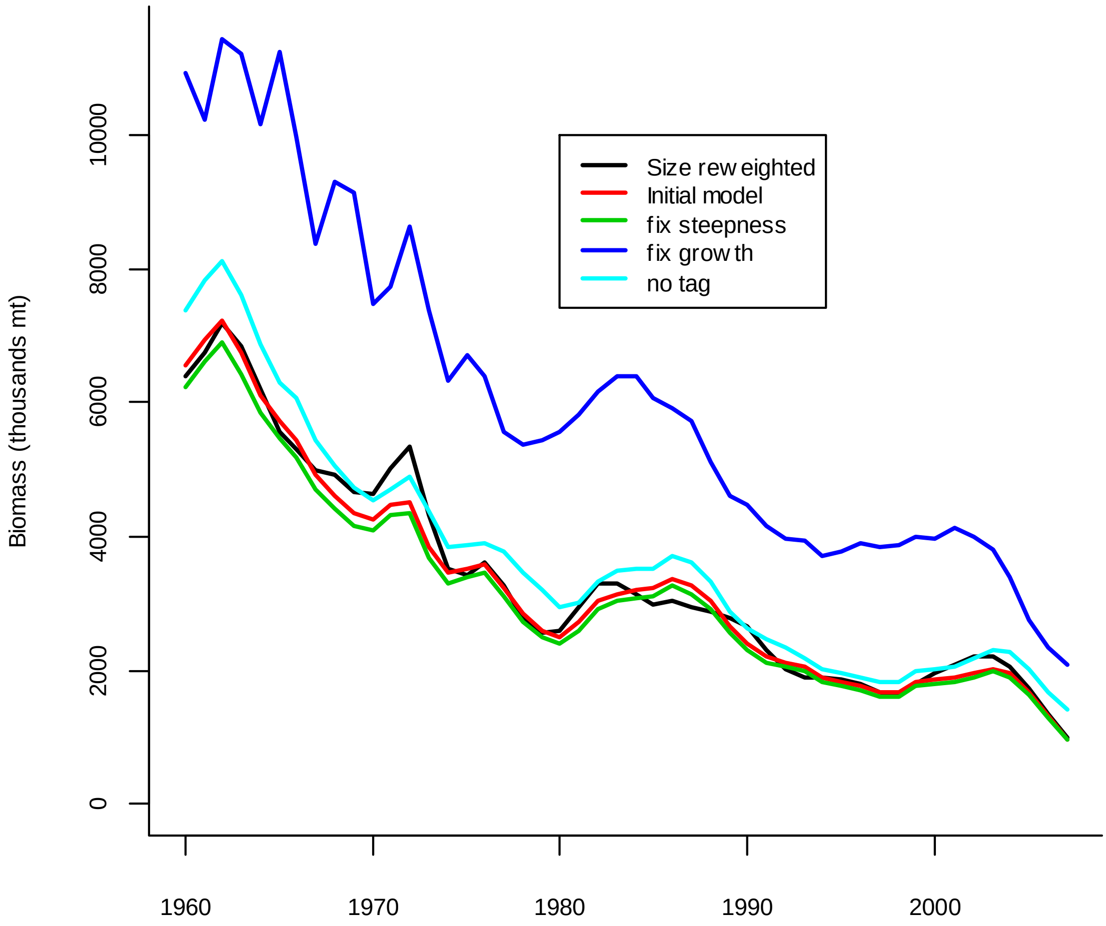



**Figure 28.** Estimated annual average total biomass (thousands mt) for the IO obtained from a range of different model options.

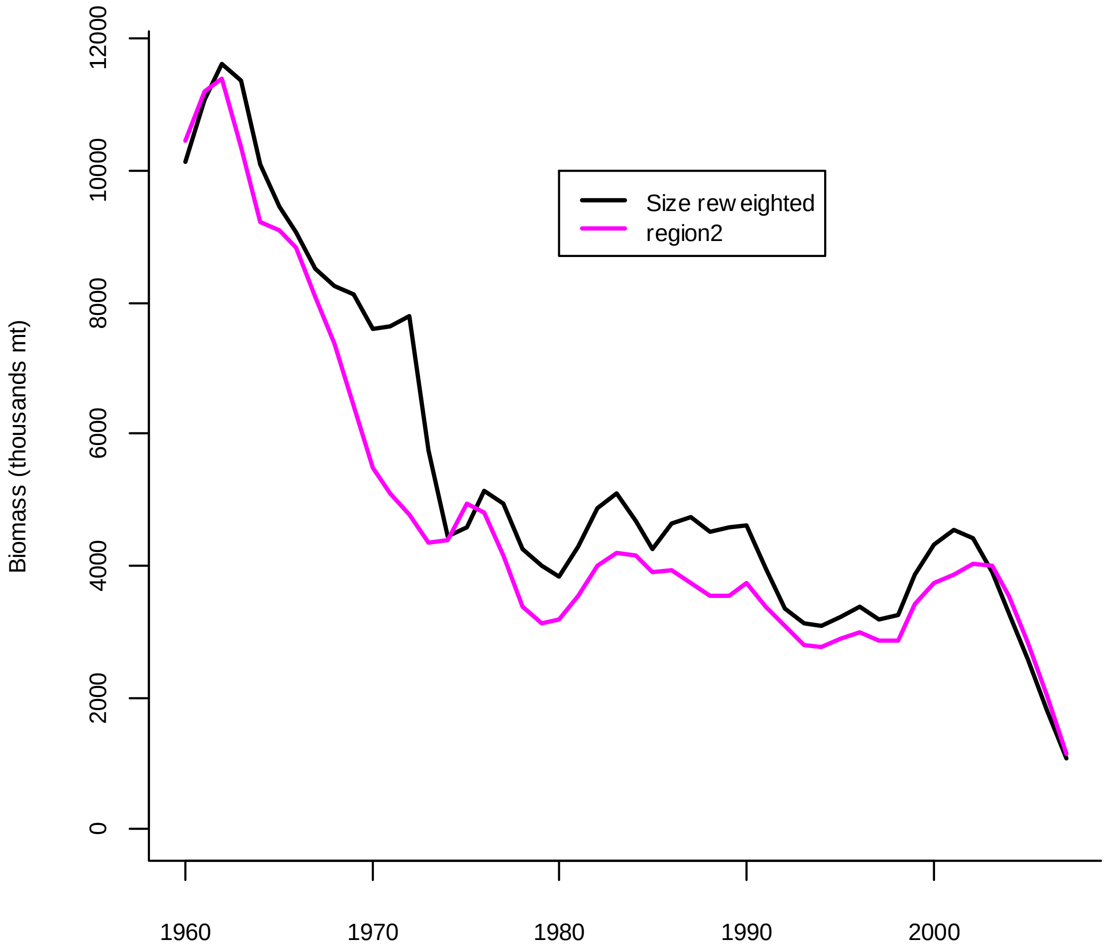



**Figure 29.** Annual total biomass for MFCL region 2 from the IO base-case model and for the single region model sensitivity (region2).

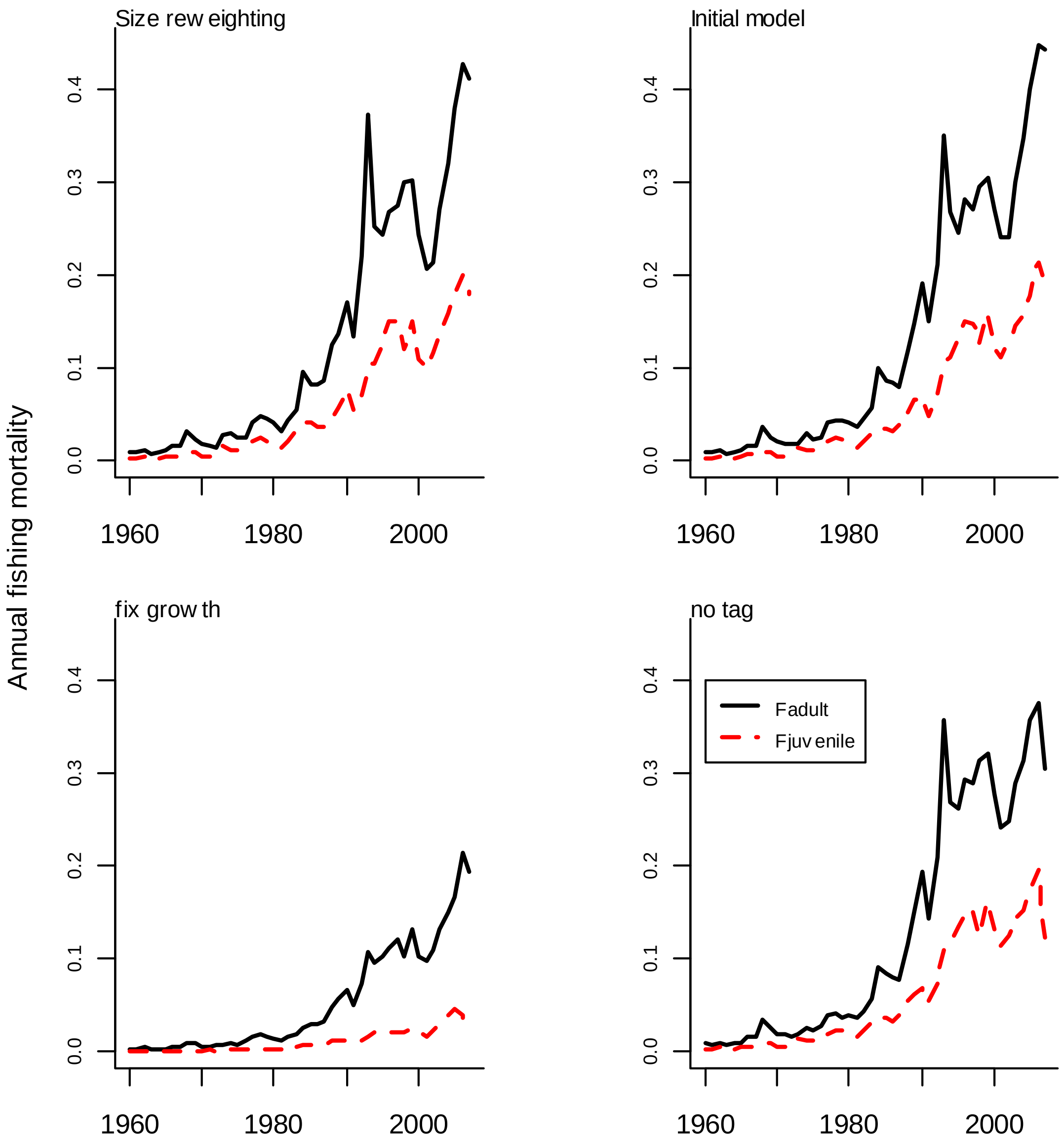



**Figure 30.** Estimated annual average juvenile and adult fishing mortality for the IO obtained from the separate model options.

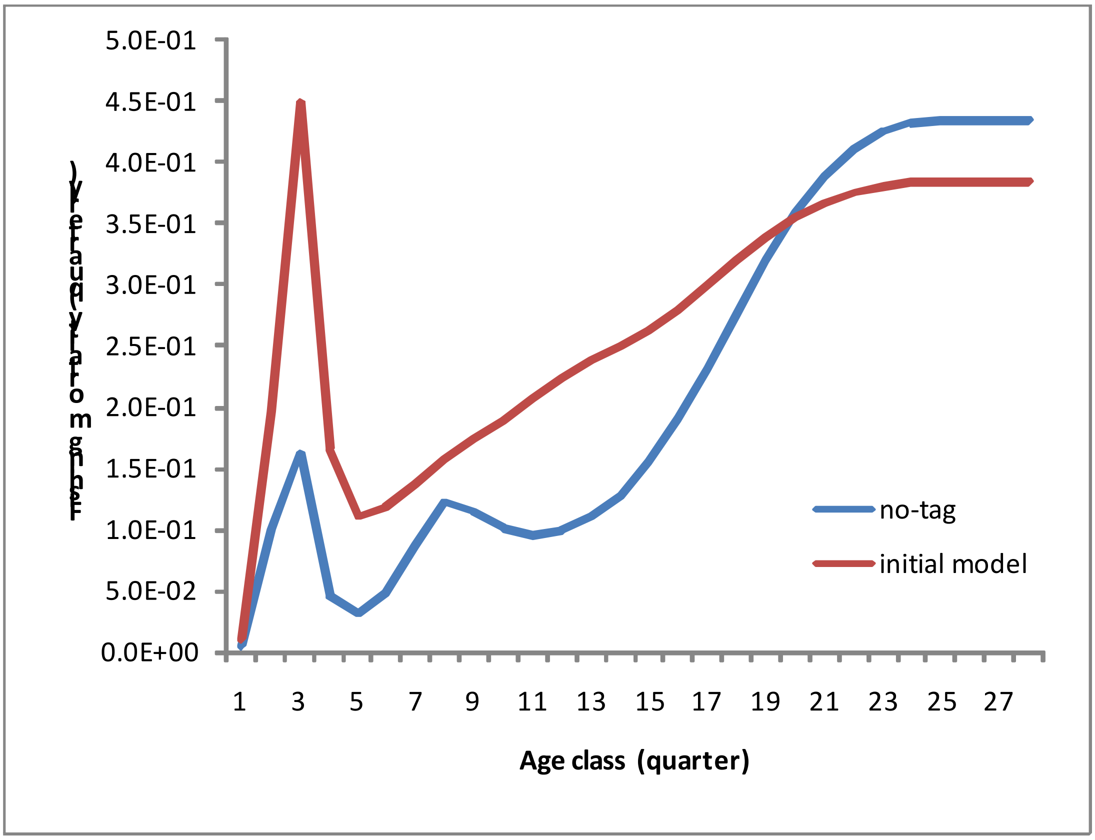



**Figure 31.** Comparison of the average (quarterly) fishing mortality by age class for region 2 for the 2006-2007 period for the comparative MFCL models including (*initial model*) and excluding (*no-tag*) the tag data set.

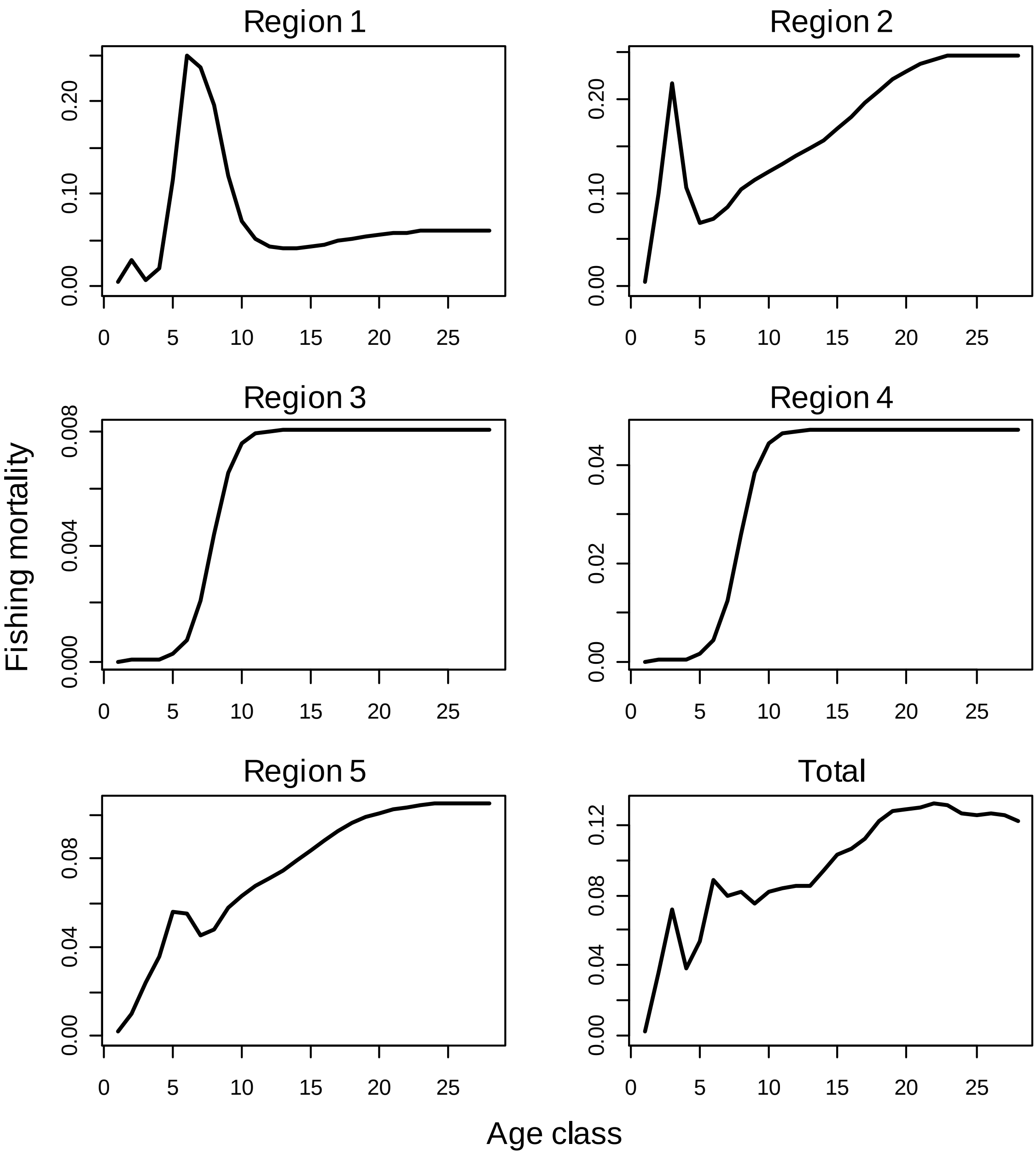



**Figure 32.** Fishing mortality (quarterly, average) by age class and region for the period used to determine the total F-at-age included in the calculation of MSY based reference points (2003–06). Note that the y-axis varies between plots.

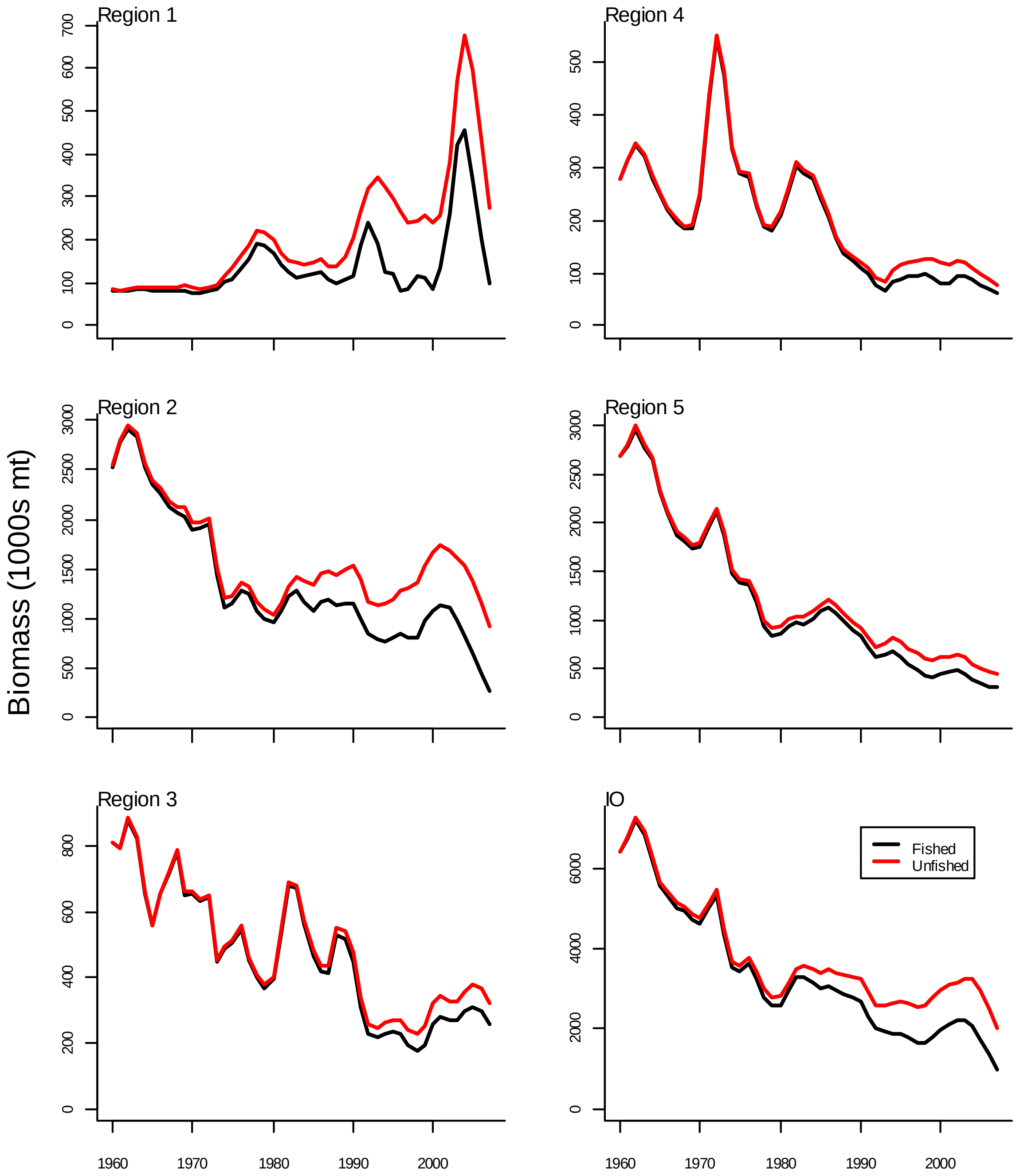



**Figure 33.** Comparison of the estimated total biomass trajectories (lower heavy lines) with biomass trajectories that would have occurred in the absence of fishing (upper thin lines) for the base-case model for each region and for the IO.

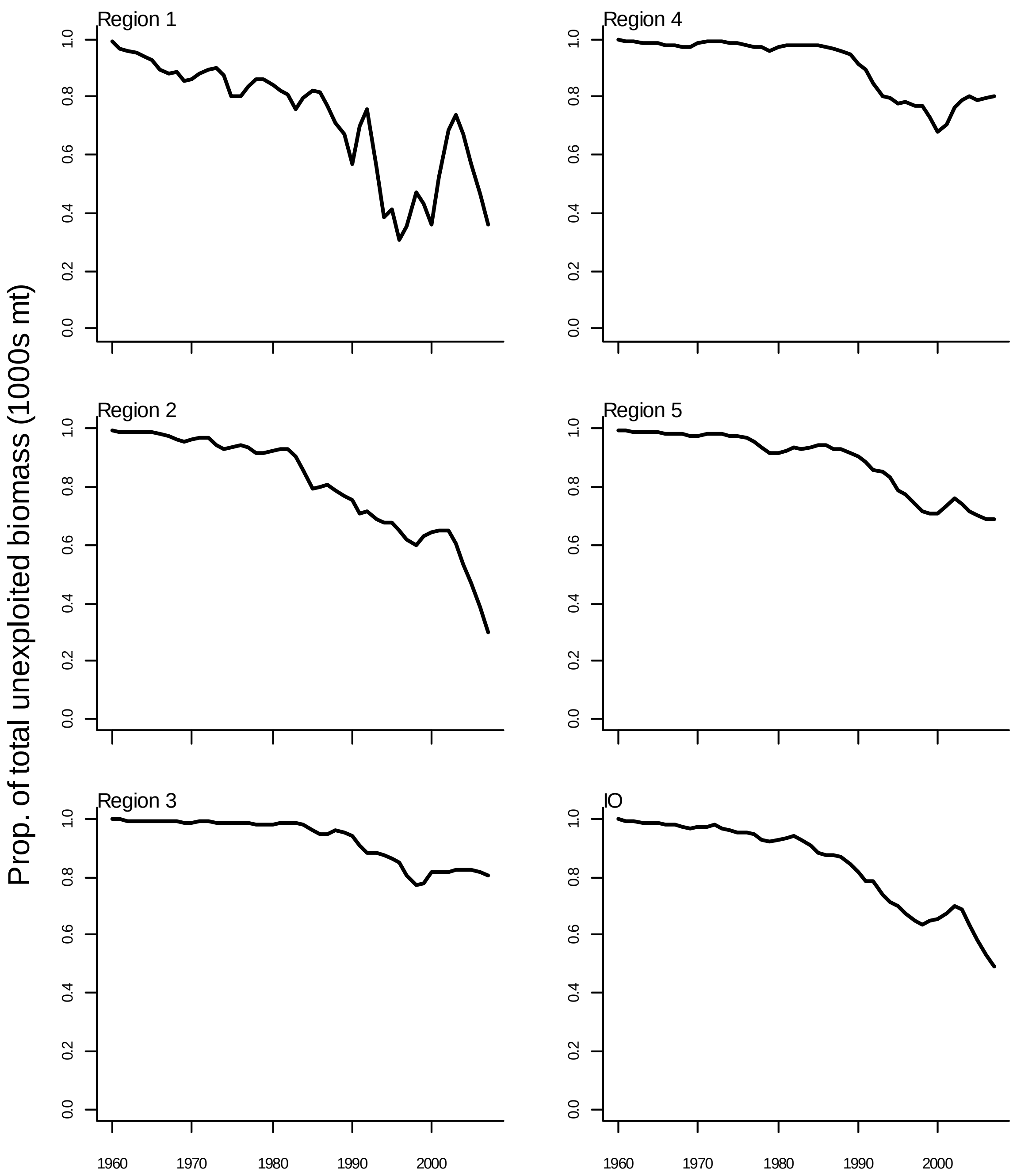



**Figure 34.** Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for each region and the IO.

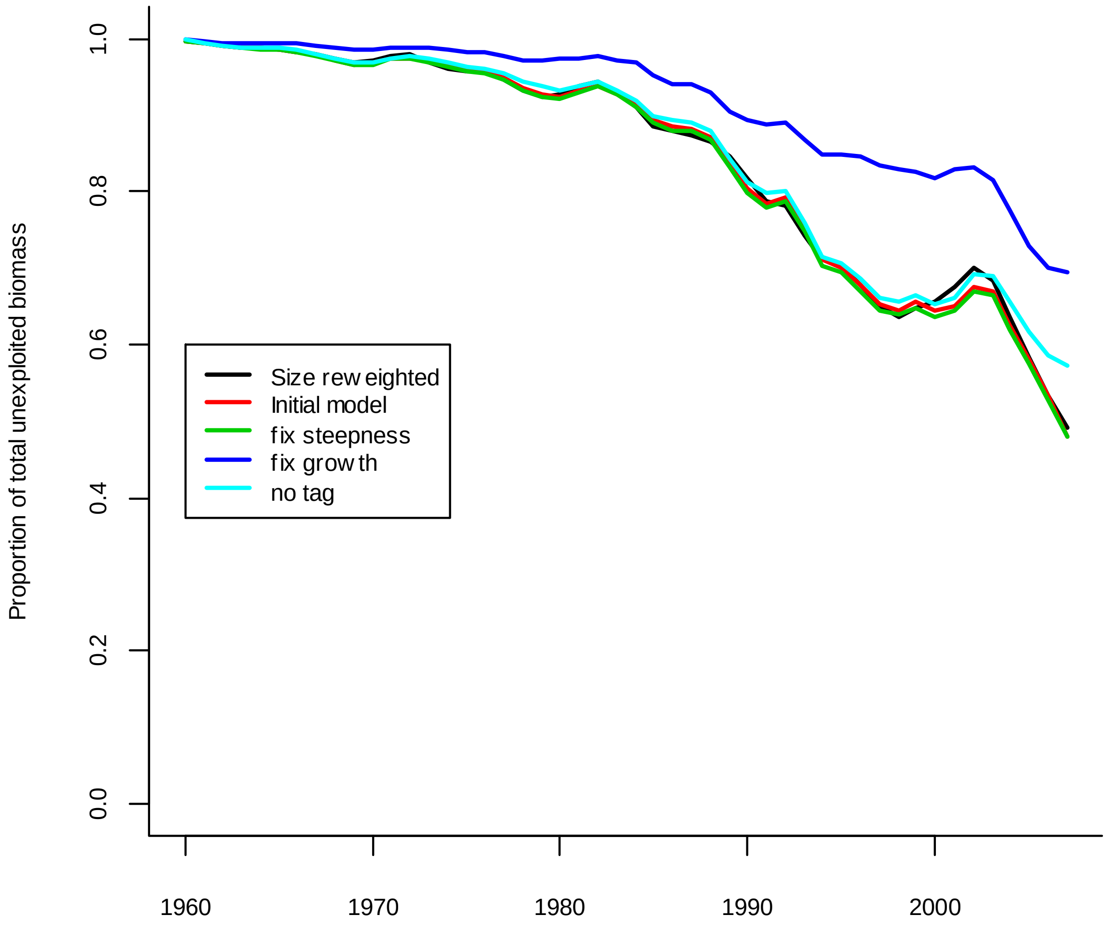



**Figure 35.** Ratios of exploited to unexploited total biomass ($B_t/B_{0,t}$) for the IO obtained from the separate analyses.

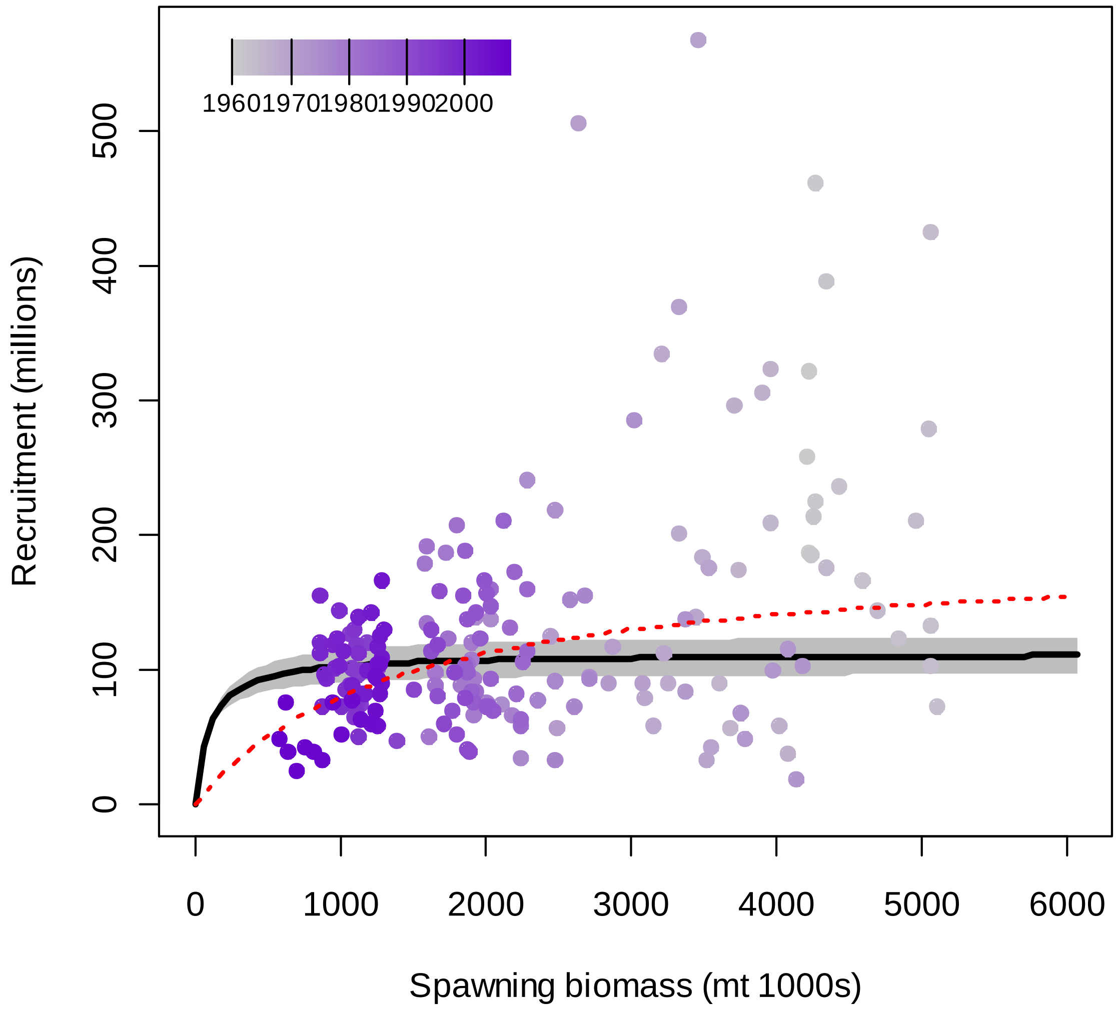



**Figure 36.** Relationship between equilibrium recruitment and equilibrium spawning biomass for the base-case (*reweight size*) with steepness of the SRR is fixed at 0.85 (black line). The grey area indicates the 95% confidence region. The points represent the estimated recruitment-spawning biomass and the colour of the points denotes the time period from which the estimate was obtained (see legend). The red line represents the SRR for the model with steepness estimated (*initial model*).

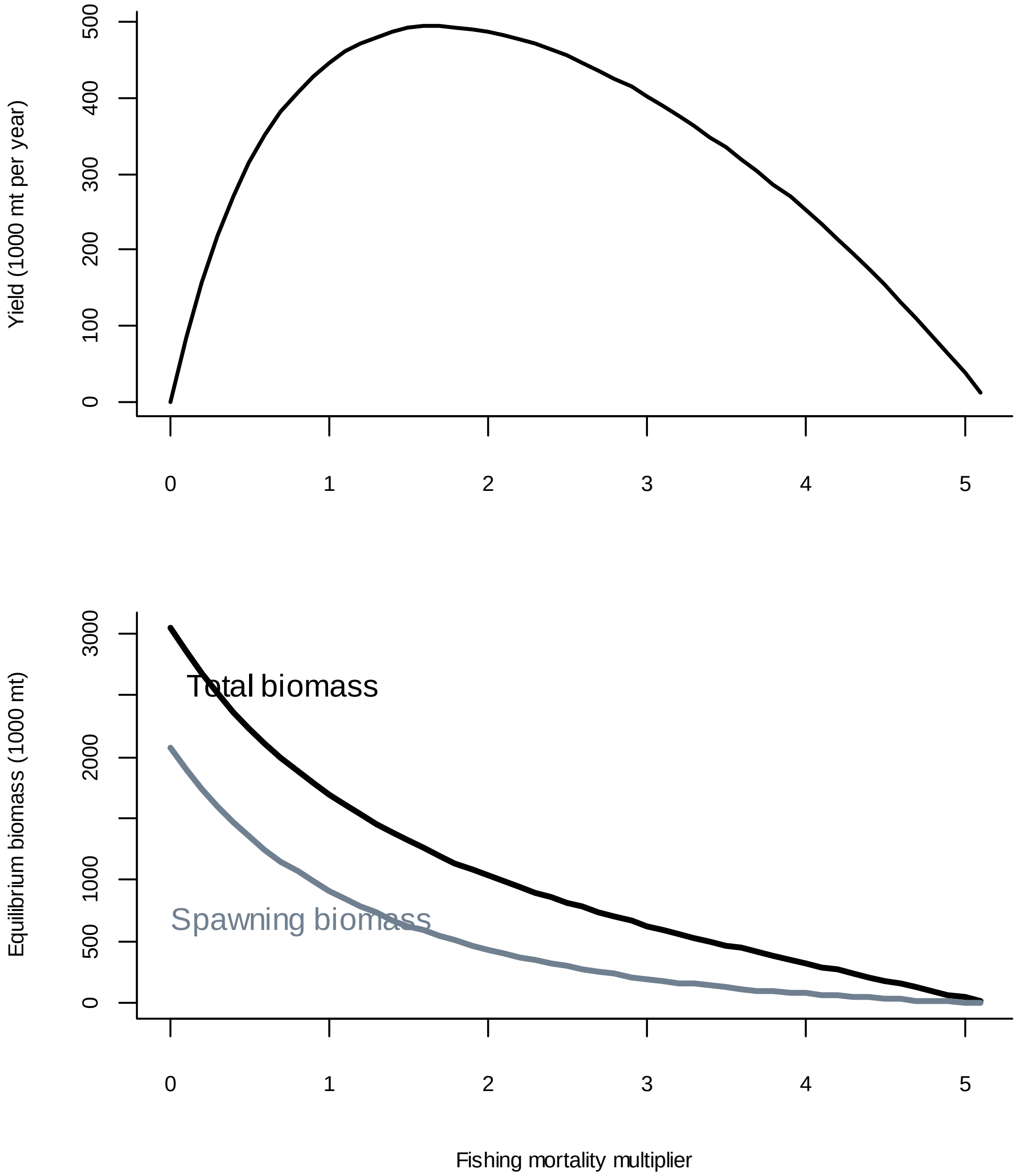



**Figure 37.** Yield, equilibrium biomass and equilibrium spawning biomass as a function of fishing mortality multiplier for the base case analysis.

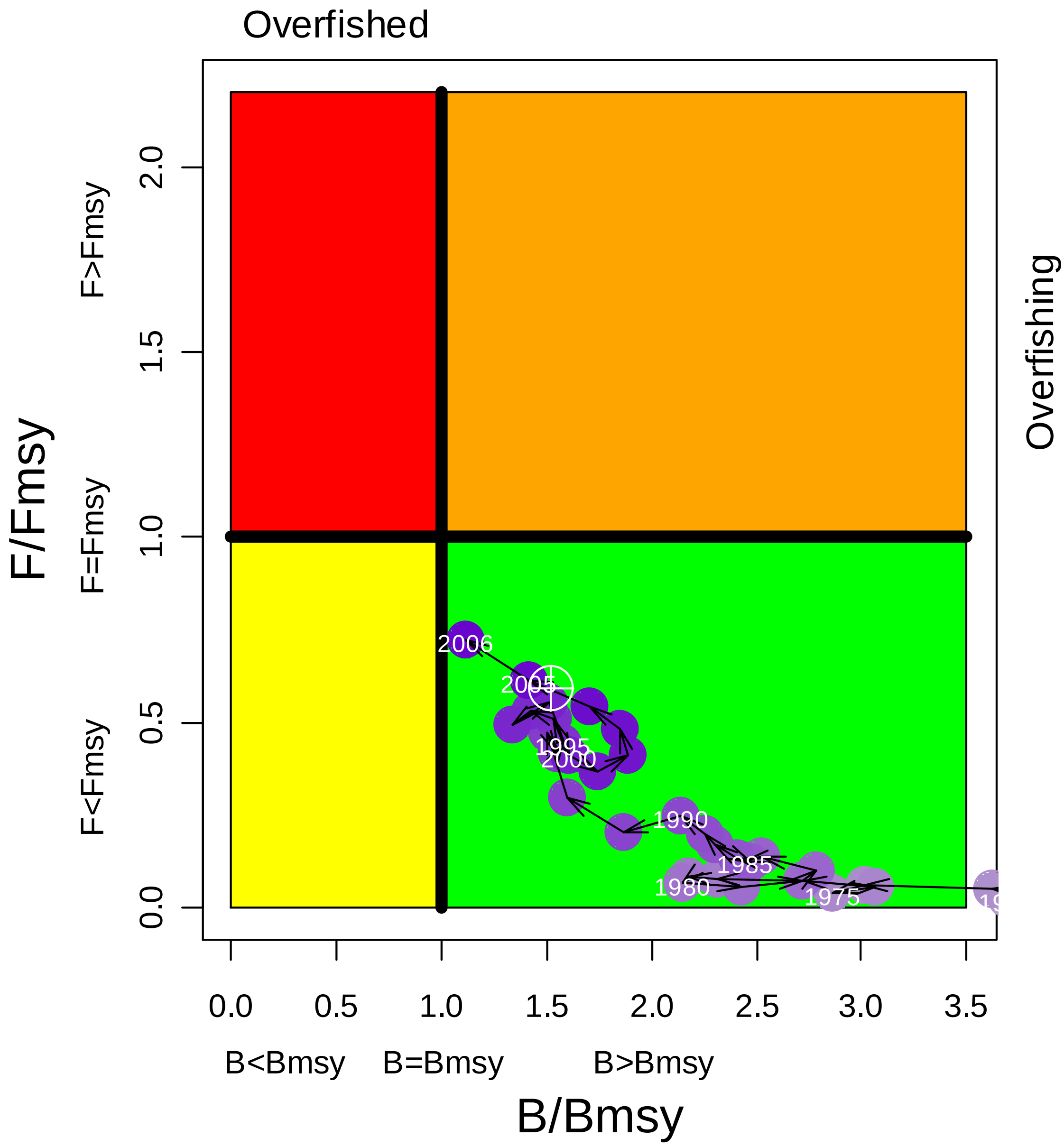



**Figure 38.** Temporal trend in annual stock status, relative to $B_{MSY}$ (x-axis) and $F_{MSY}$ (y-axis) reference points, for the model period, except the last year (1960–2006). The colour of the points is graduated from mauve (1960) to dark purple (2006) and the points are labelled at 5-year intervals. The white cross represents the reference points computed for the “current” period (2003–2006).

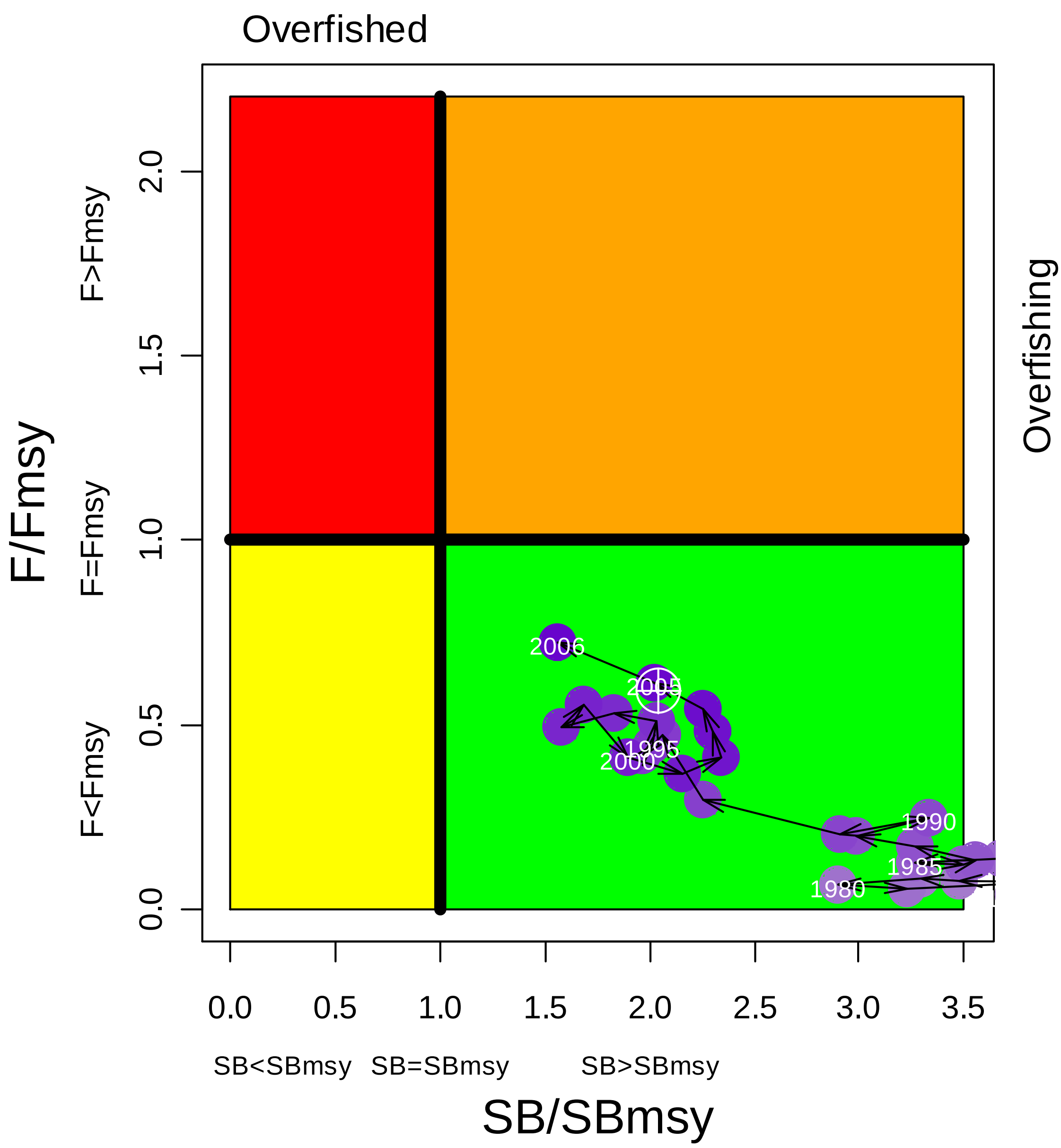



**Figure 39. Temporal trend in annual stock status, relative to $SB_{MSY}$ (x-axis) and $F_{MSY}$ (y-axis) reference points, for the model period, except the last year (1960–2006). The colour of the points is graduated from mauve (1960) to dark purple (2006) and the points are labelled at 5-year intervals. The white cross represents the reference points computed for the "current" period (2003–2006).**

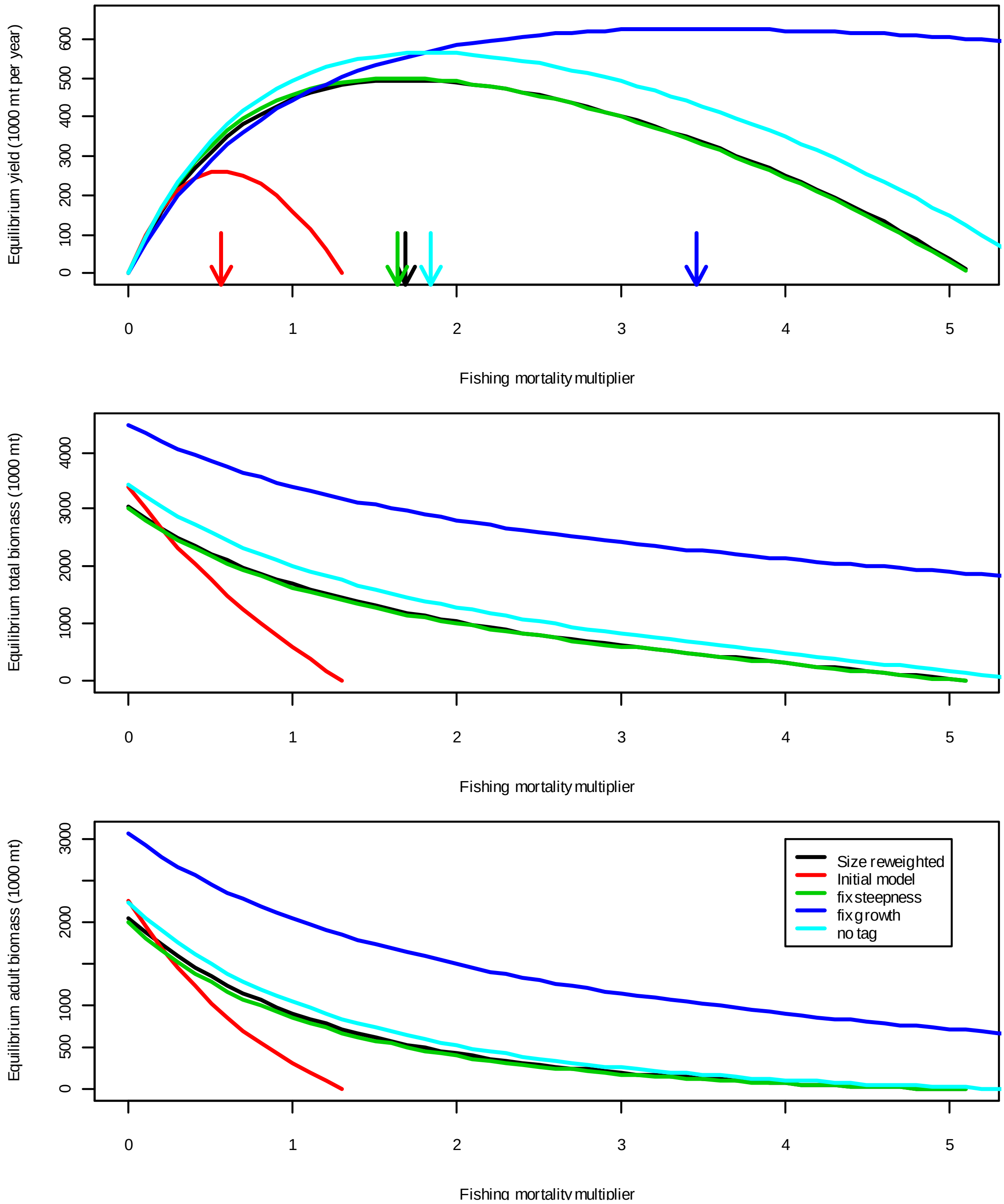


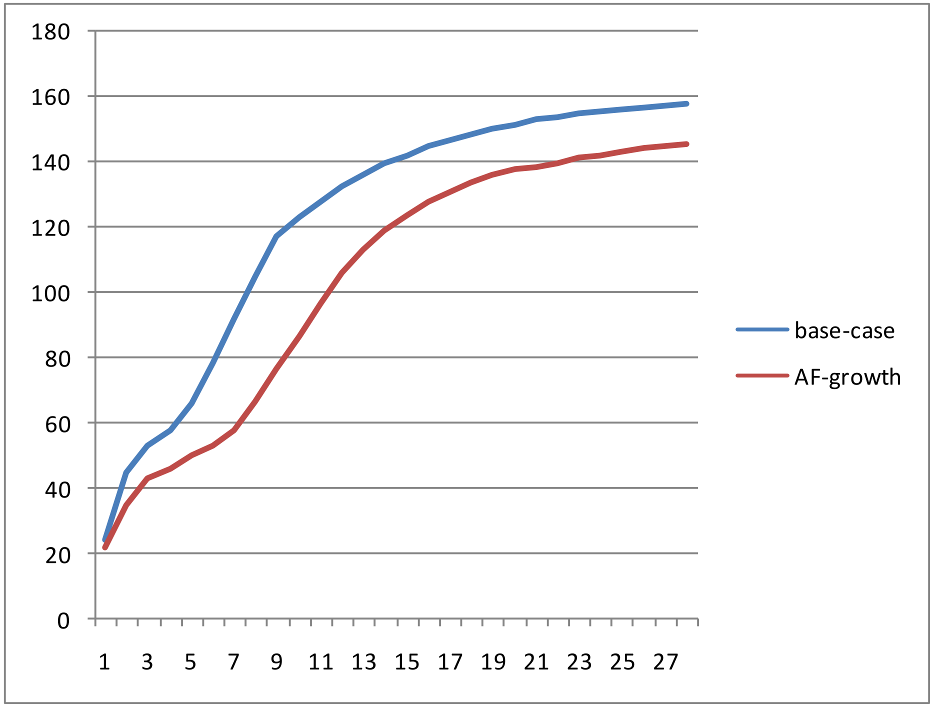

**Figure 40.** Yield (top), equilibrium biomass (middle) and equilibrium spawning biomass (bottom) as a function of fishing mortality multiplier obtained from the separate model options. In the upper panel, the arrows indicate the value of the fishing mortality multiplier at maximum yield.

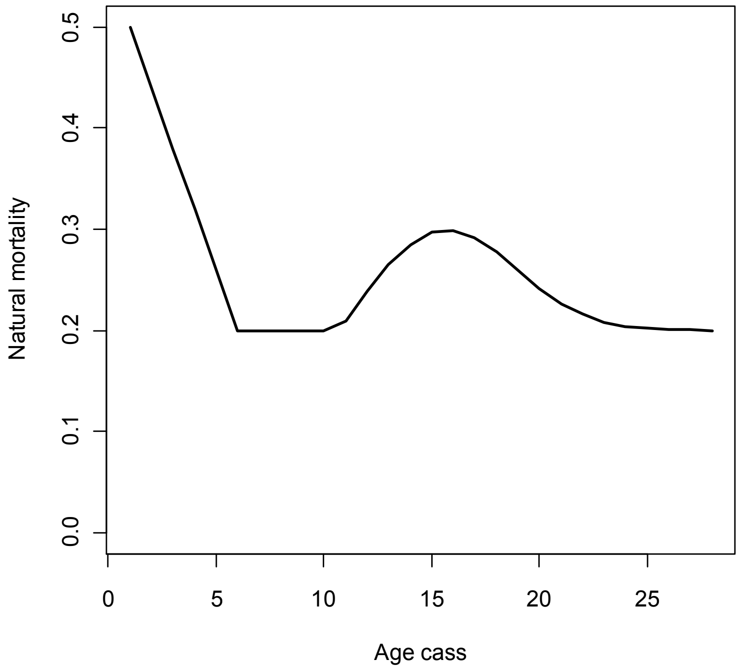
# Changes from previous model runs

- TW CPUE index (1968-2007) incorporated for Region 1 (single composite index).
- Separate longline fisheries pre/post 1972.
- Selectivity LL pre/post 1972 equivalent.
- Temporal deviations in catchability for LL pre 1972.
- LL selectivity cubic spline parameterisation. Freedom to estimate declining right-hand limb.
- Change tag mixing from 6 mo to 3 mo.
- Steepness estimated.

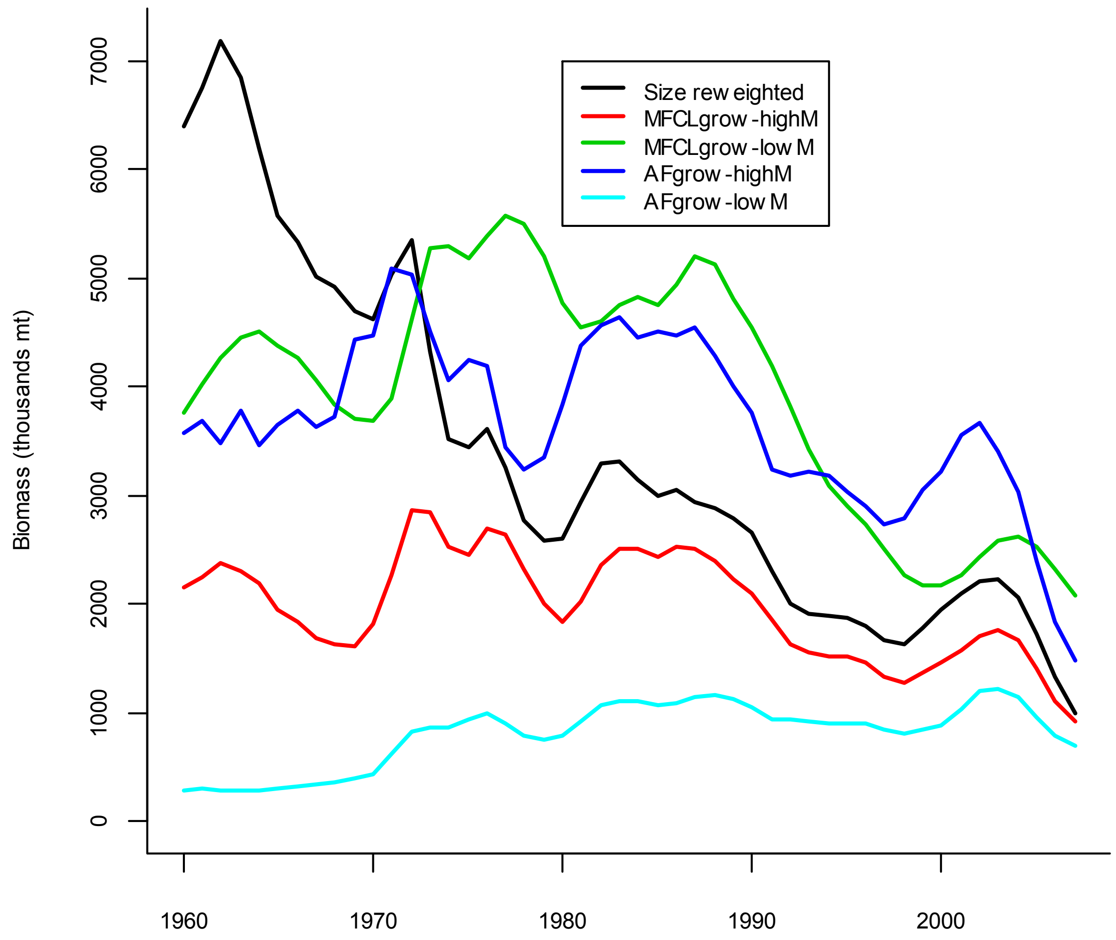
# Scenarios

| Scenario | Growth | Natural mortality |
|---|---|---|
| | | |
| MFCLgrow-highM | MFCL estimated. | WCPO M-at-age |
| MFCLgrow-lowM | MFCL estimated. | 0.4 * WCPO M-at-age |
| AFgrow-highM | Fonteneau, MFCL sd fixed | WCPO M-at-age |
| AFgrow-lowM | Fonteneau, MFCL sd fixed | 0.4 * WCPO M-at-age |

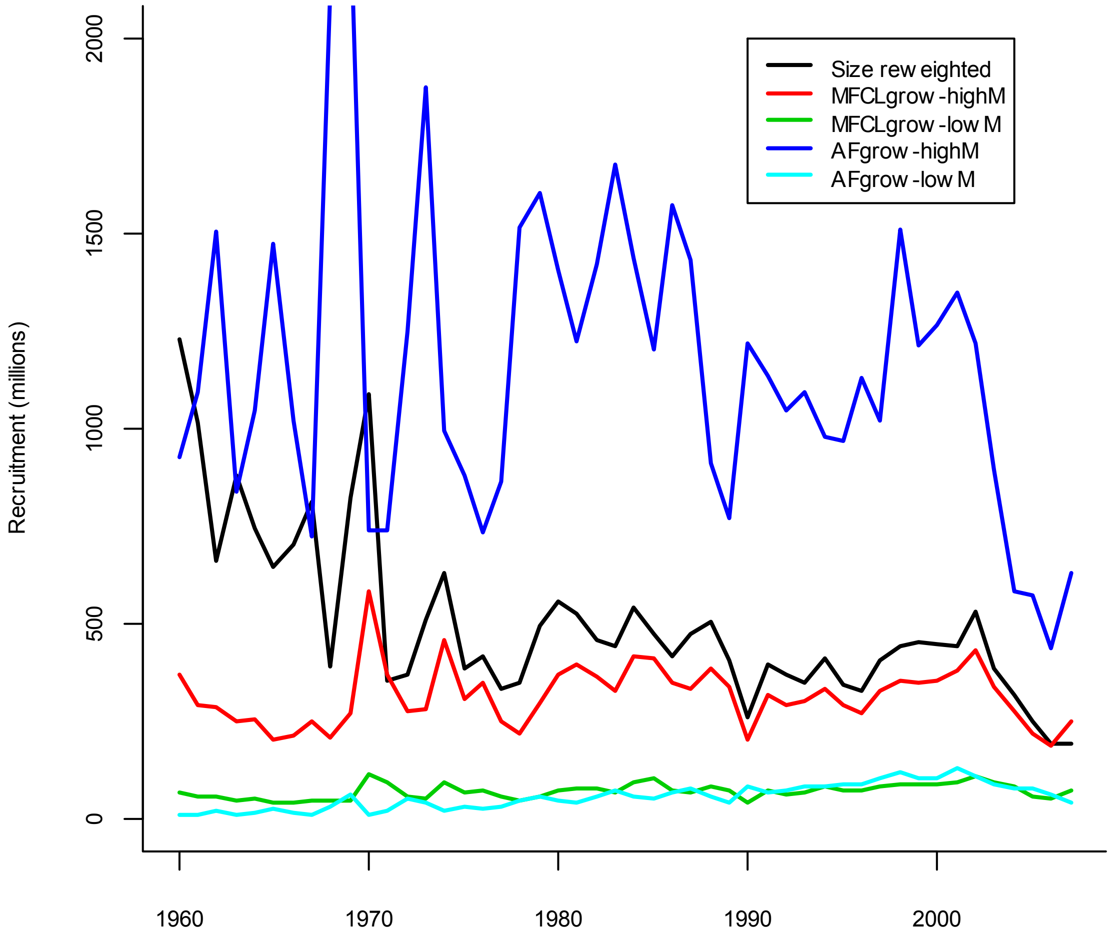


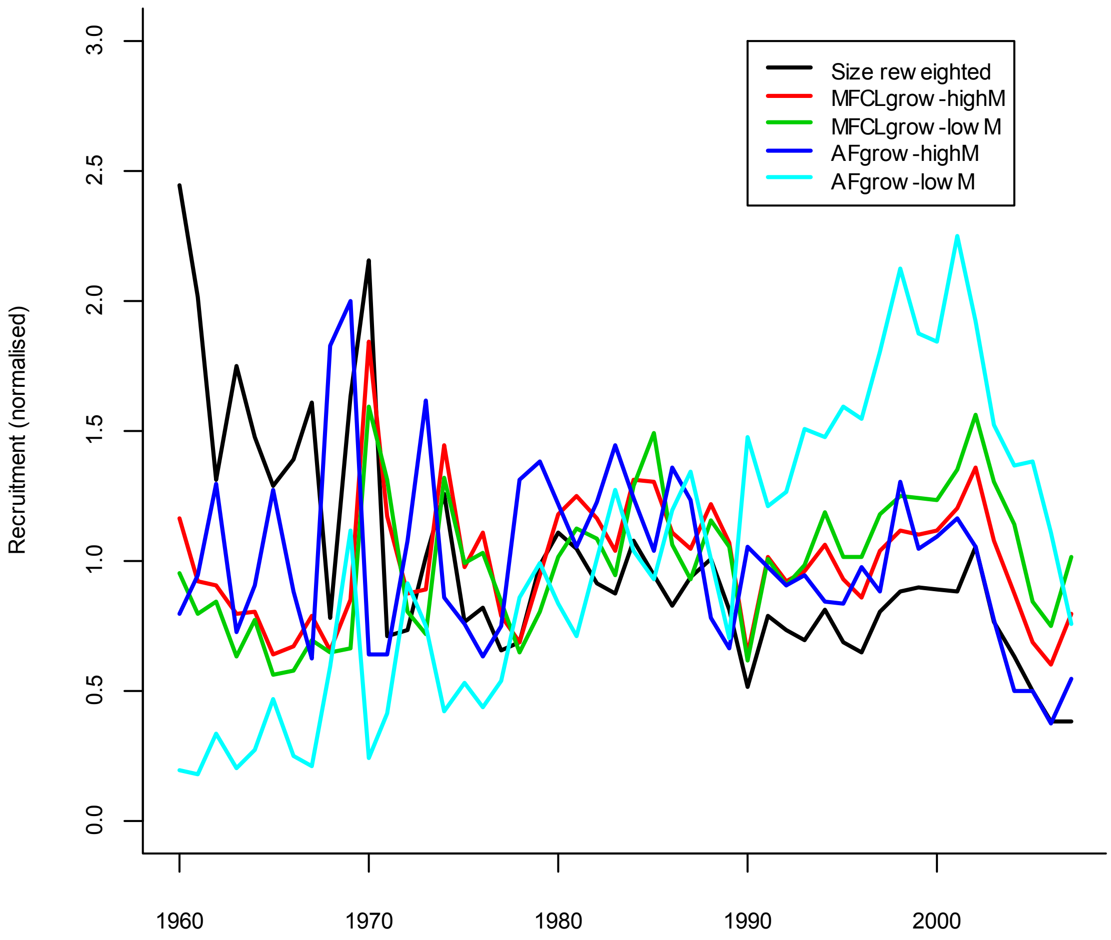
# Biomass (total)

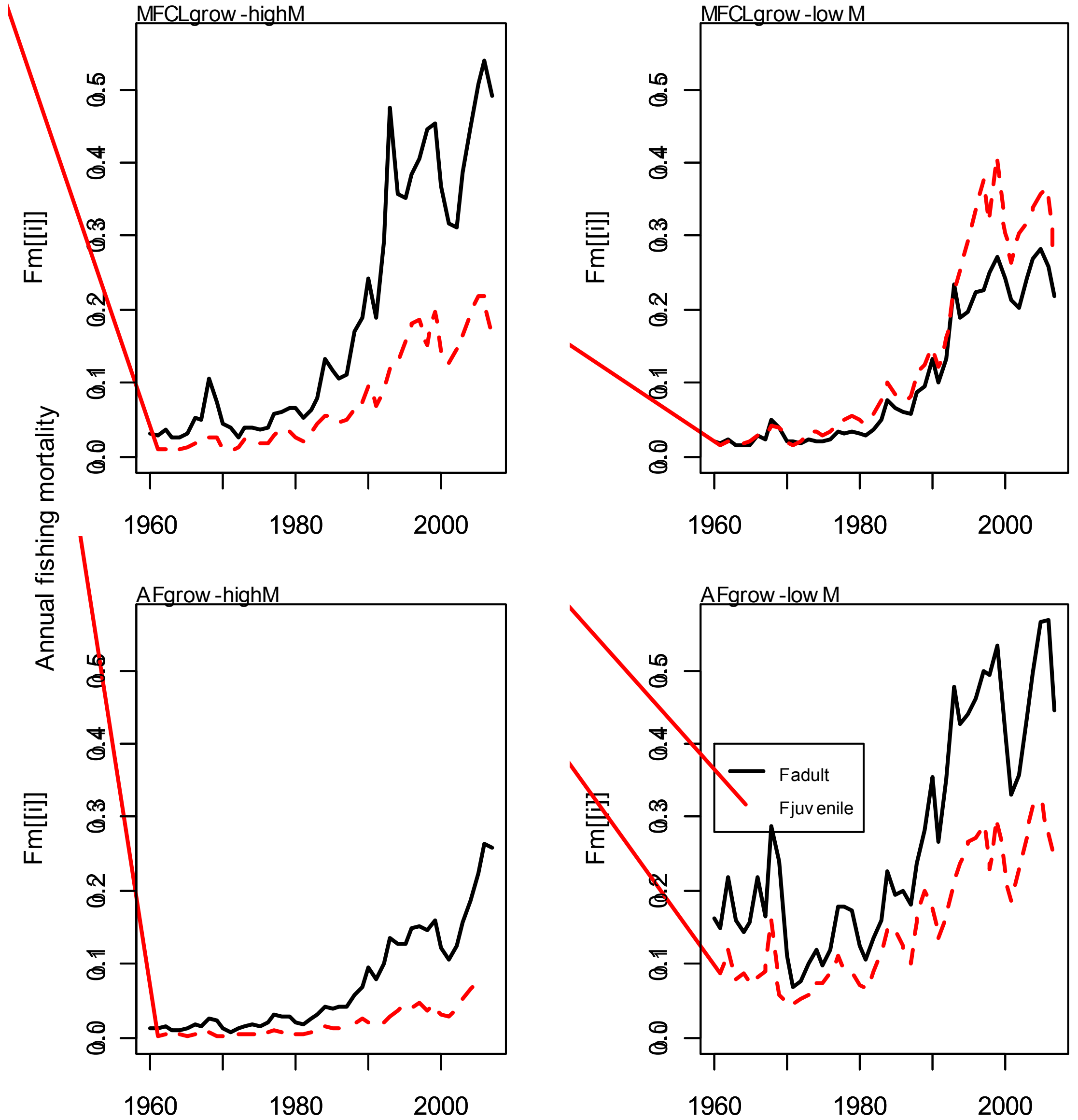


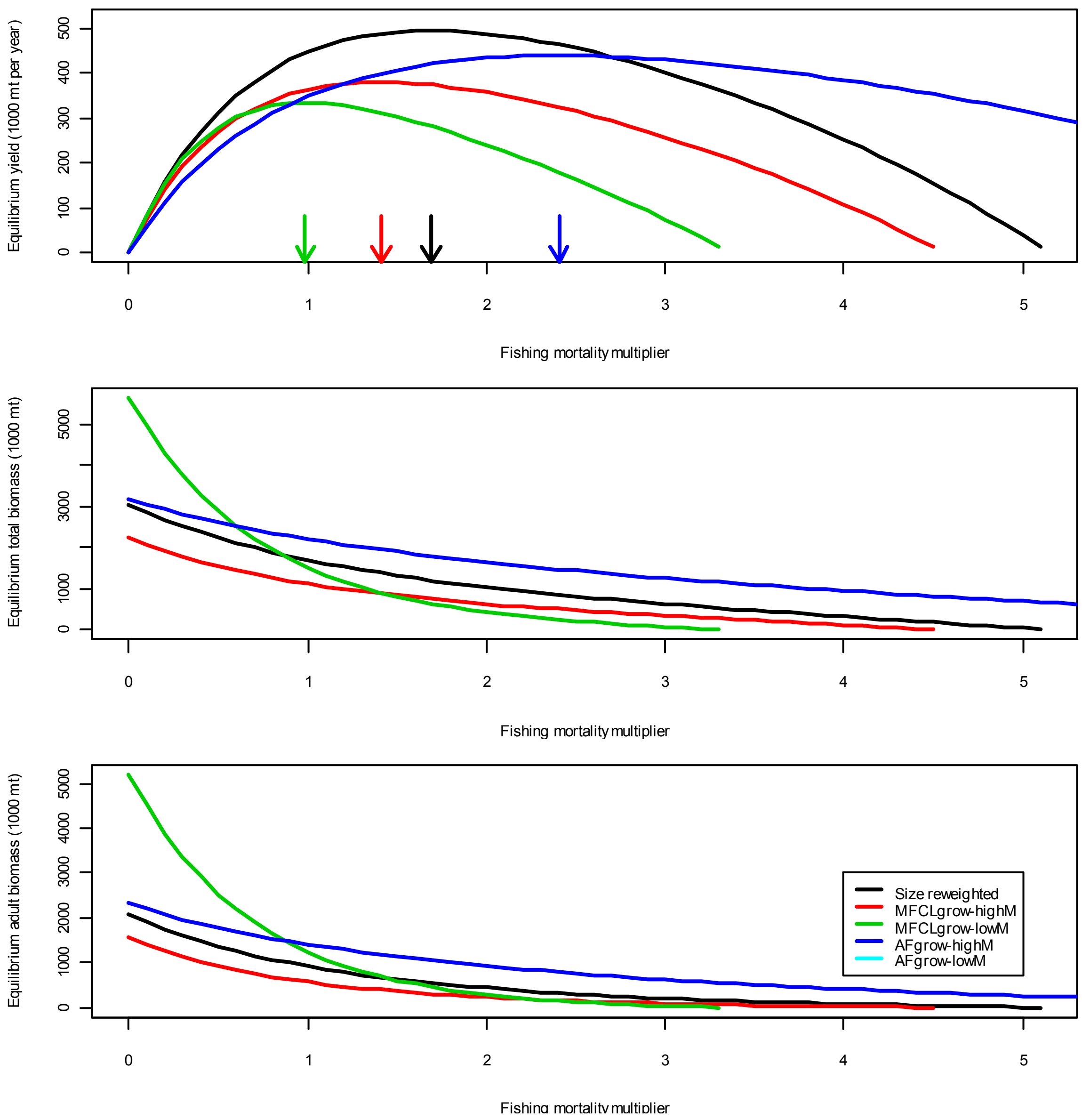
# Recruitment



# Recruitment




MFCLgrow -highM
MFCLgrow -low M
AFgrow -highM
AFgrow -low M
Annual fishing mortality
Fm[[i]]
0.0
0.1
0.2
0.3
0.4
0.5
1960
1980
2000
Fadult
Fjuvenile

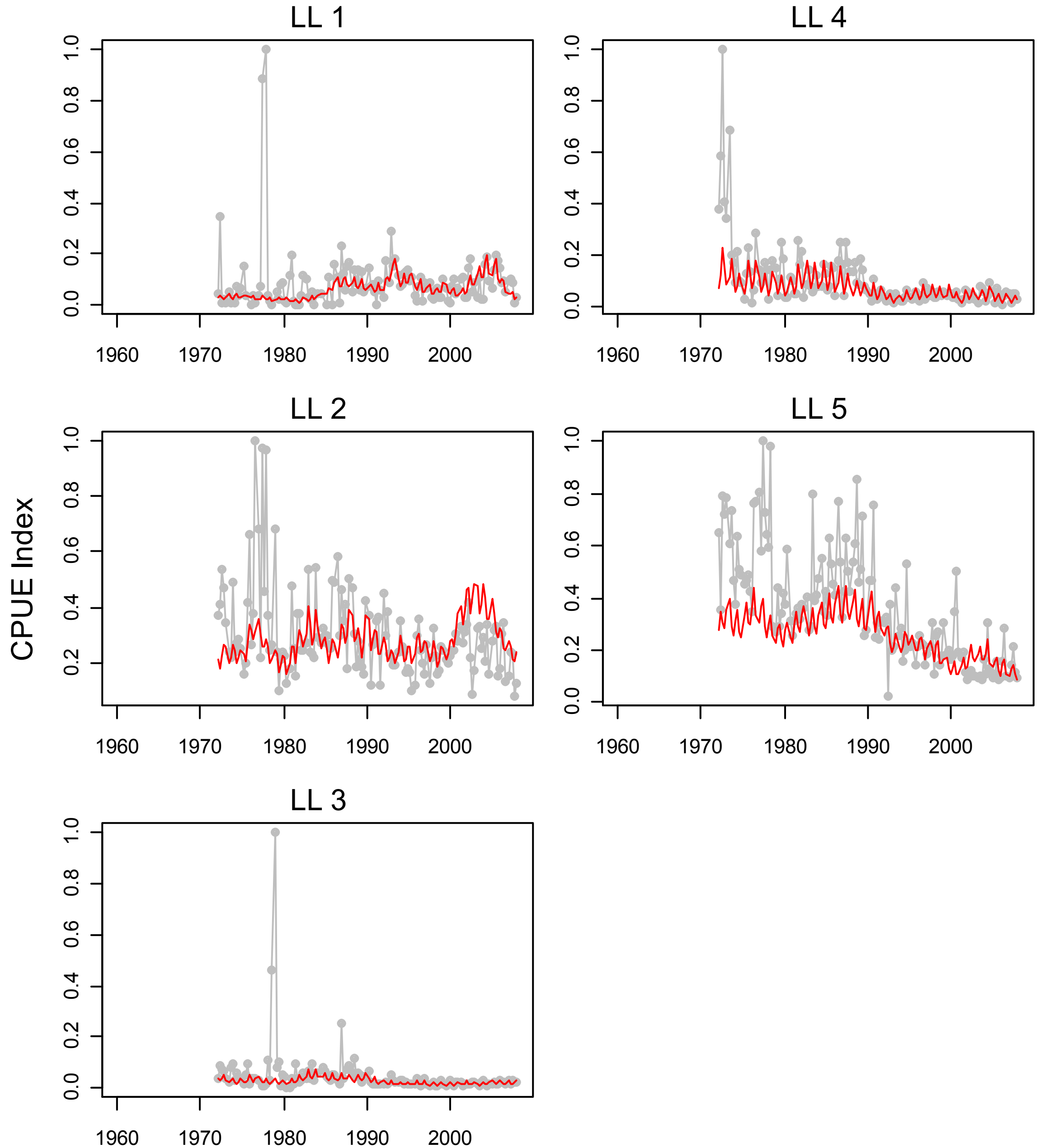

Equilibrium yield (1000 mt per year)
Fishing mortality multiplier
Equilibrium total biomass (1000 mt)
Fishing mortality multiplier
Equilibrium adult biomass (1000 mt)
Fishing mortality multiplier
Size reweighted
MFCLgrow-highM
MFCLgrow-lowM
AFgrow-highM
AFgrow-lowM

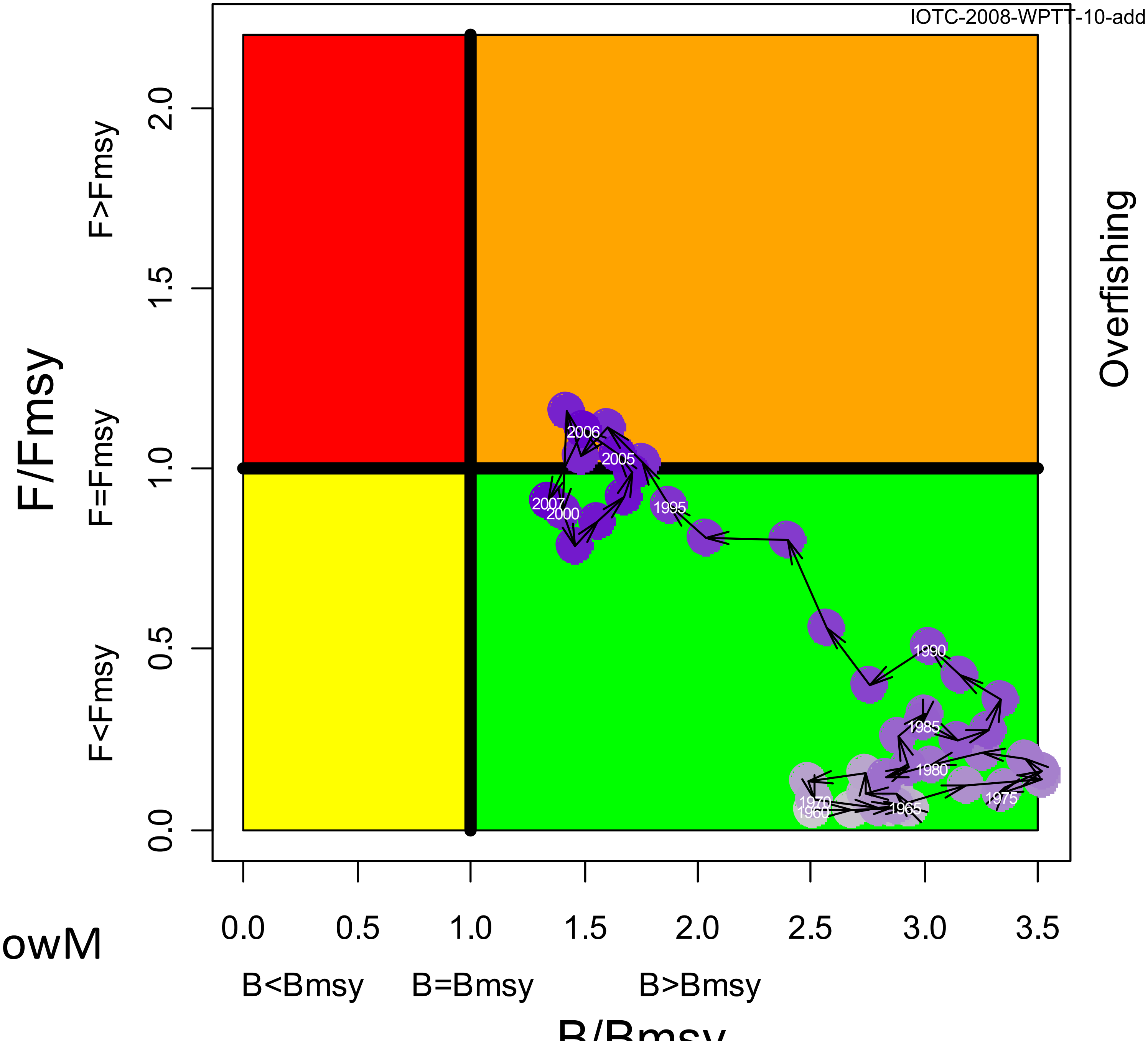
| | MFCLgrow-highM | MFCLgrow-lowM | AFgrow-highM | AFgrow-lowM |
|---|---|---|---|---|
| | | | | |
| Total -LL | -363148.9 | -363612.6 | -360180.8 | -359770.2 |
| LF LL | -370482.8 | -370746.9 | -368635.7 | -368448.7 |
| Tag LL | 2835.9 | 2728.45 | 3497.4 | 3507.9 |
| | | | | |
| MSY (mt) | 379,440 | 333,200 | 438,800 | |
| steepness | 0.88 | 0.95 | 0.73 | |
| Fmult | 1.41 | 0.99 | 2.40 | |
| | | | | |
| | | | | |

AFgrow-lowM not estimating credible parameters for the SRR.

AFgrow-lowM

Poor fit to CPUE series.






MFCLgrow-lowM

27 October 2008

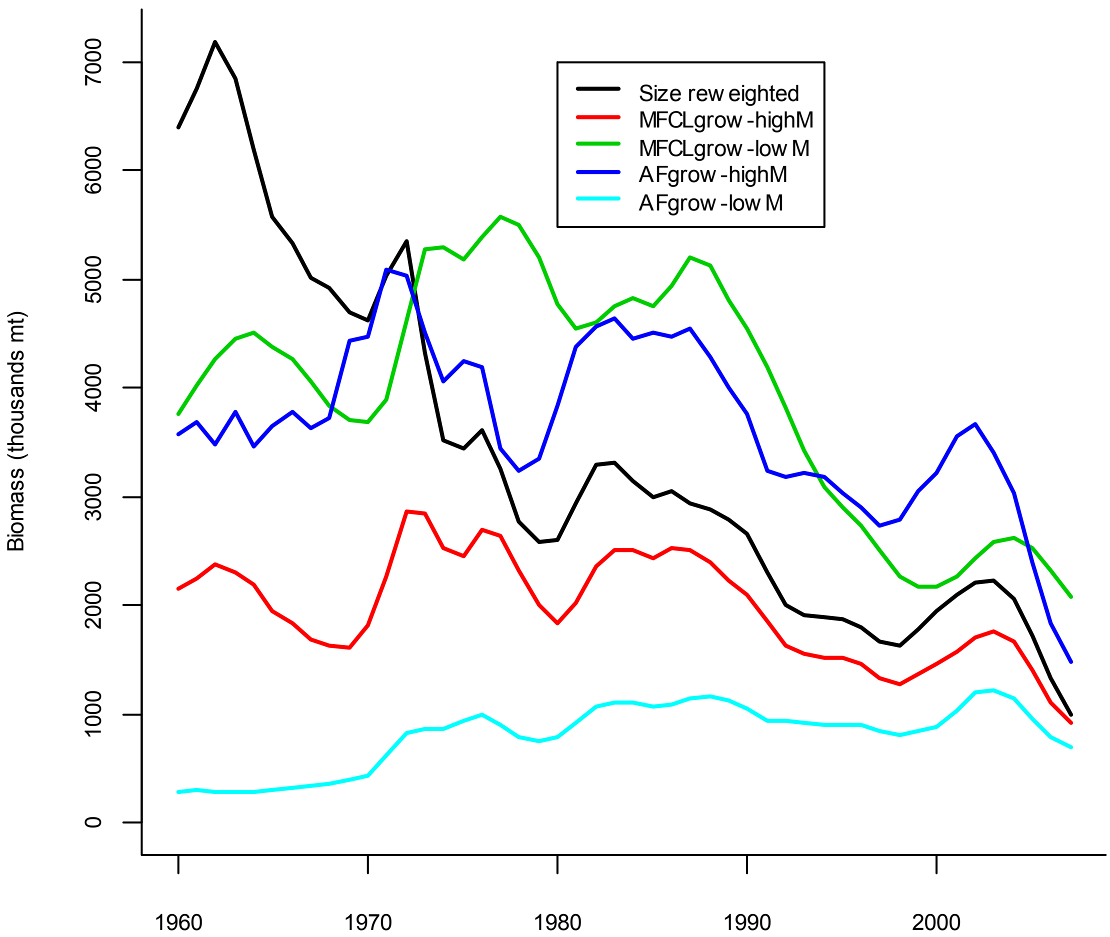
Changes from previous model runs

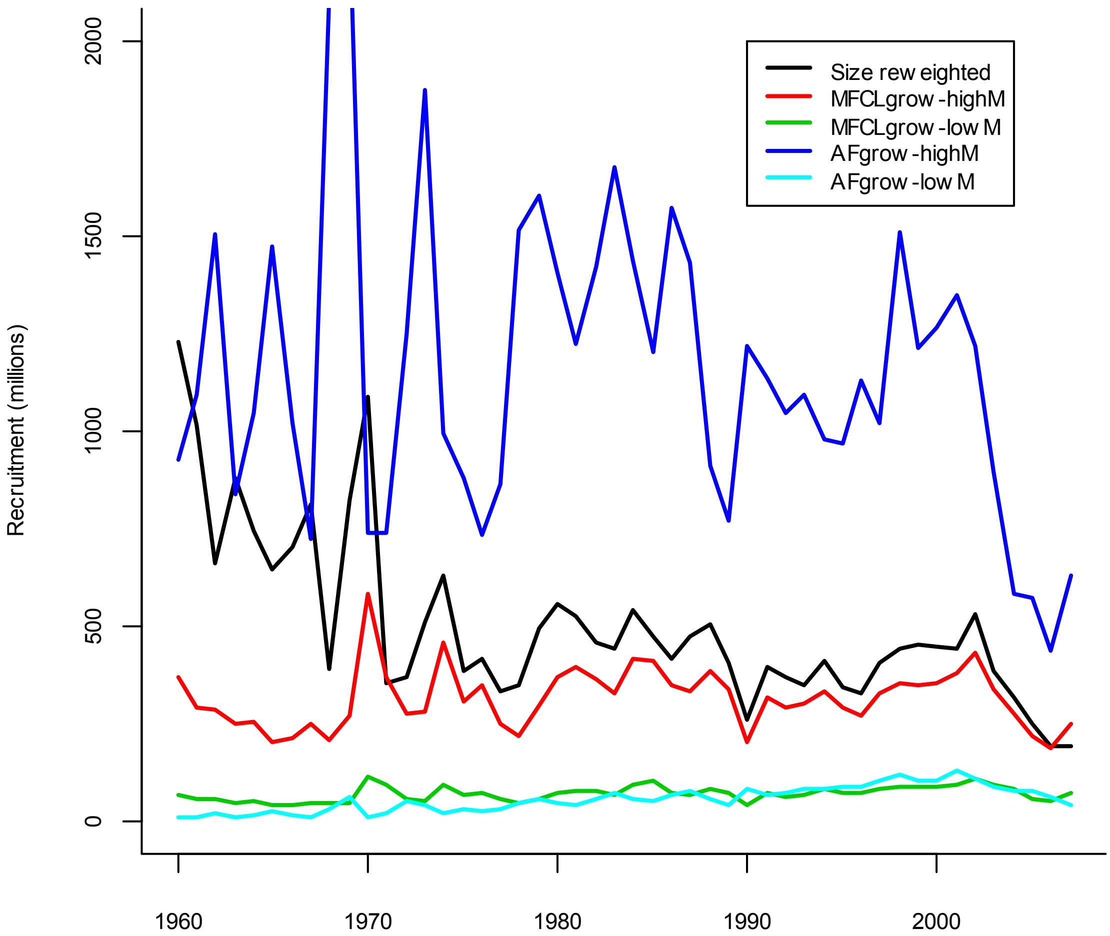
- TW CPUE index (1968-2007) incorporated for Region 1 (single composite index).
- Separate longline fisheries pre/post 1972.
- Selectivity LL pre/post 1972 equivalent.
- Temporal deviations in catchability for LL pre 1972.
- LL selectivity cubic spline parameterisation. Freedom to estimate declining right-hand limb.
- Change tag mixing from 6 mo to 3 mo.
- Steepness estimated.

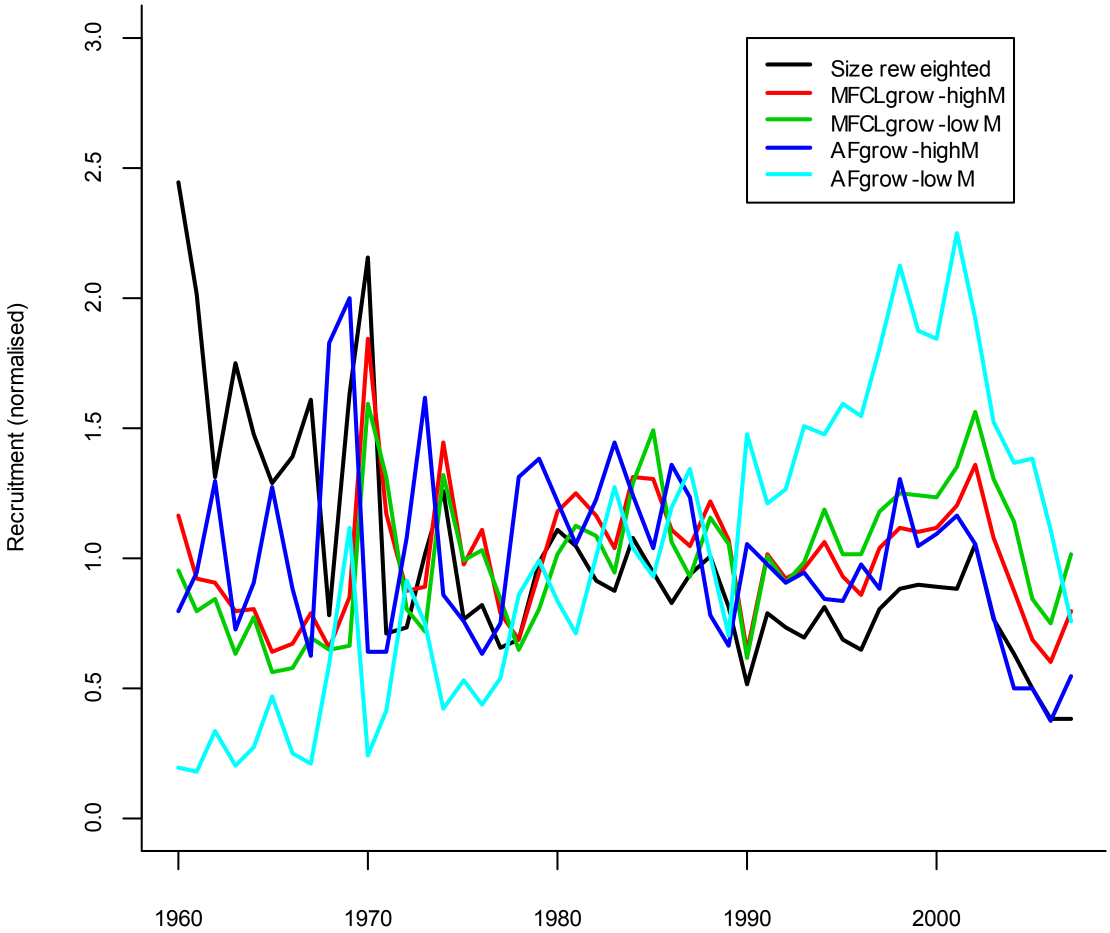
Scenarios considered:

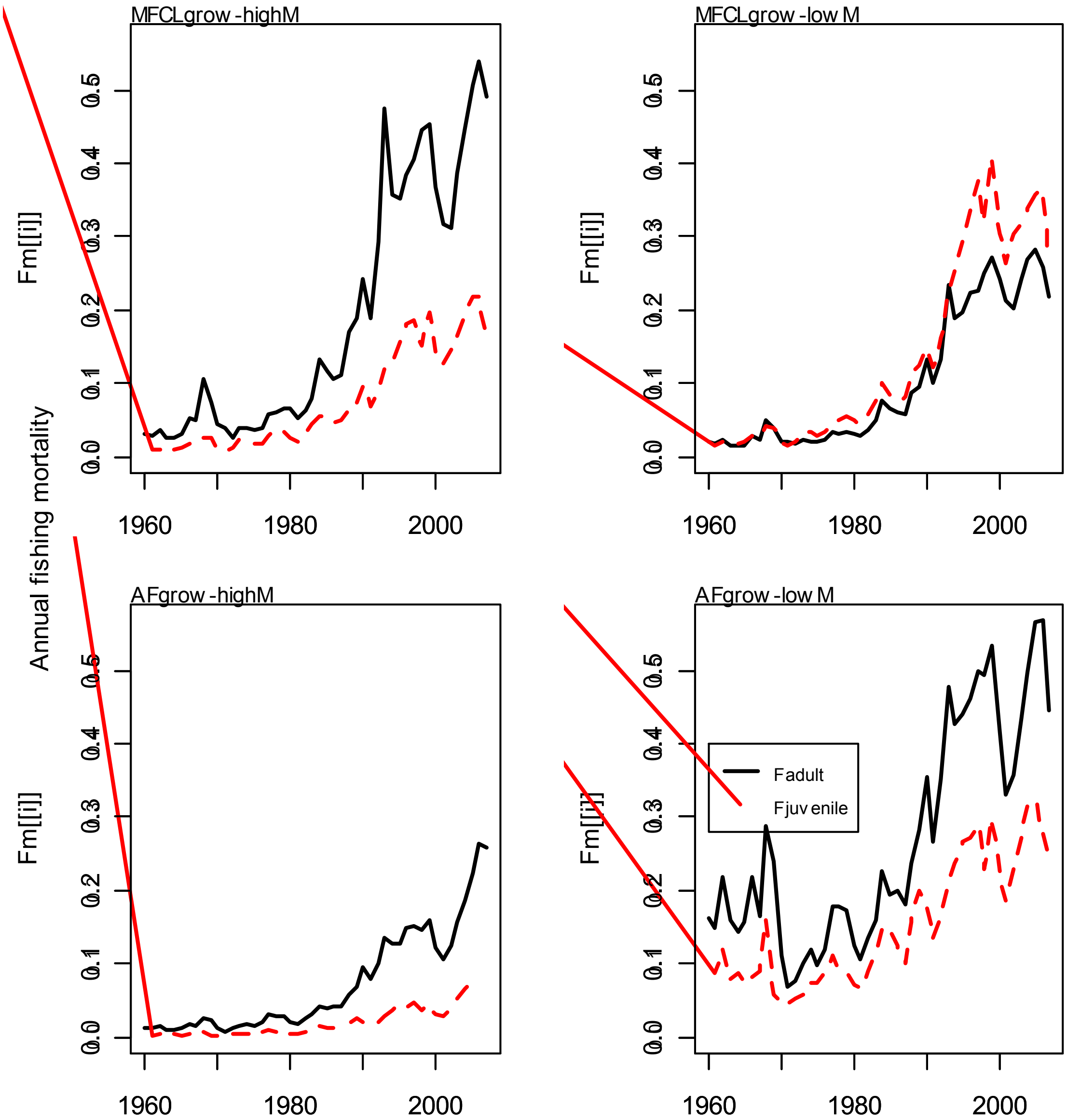
| Scenario | Growth | Natural mortality |
|---|---|---|
| | | |
| MFCLgrow-highM | MFCL estimated. | WCPO M-at-age |
| MFCLgrow-lowM | MFCL estimated. | 0.4 * WCPO M-at-age |
| AFgrow-highM | Fonteneau, MFCL sd fixed | WCPO M-at-age |
| AFgrow-lowM | Fonteneau, MFCL sd fixed | 0.4 * WCPO M-at-age |

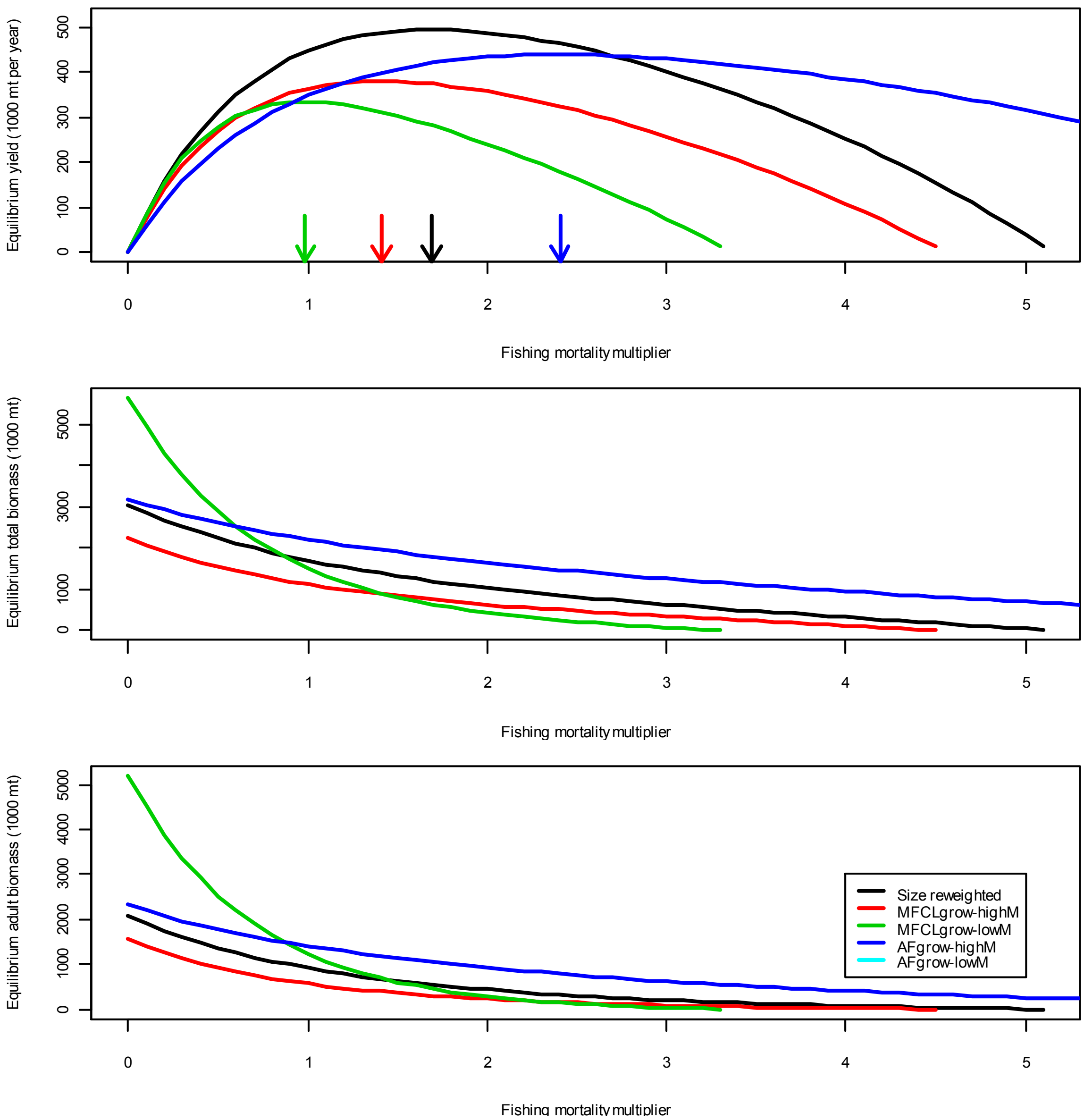
| | MFCLgrow-highM | MFCLgrow-lowM | AFgrow-highM | AFgrow-lowM |
|---|---|---|---|---|
| | | | | |
| Total -LL | -363148.9 | -363612.6 | -360180.8 | -359770.2 |
| LF LL | -370482.8 | -370746.9 | -368635.7 | -368448.7 |
| Tag LL | 2835.9 | 2728.45 | 3497.4 | 3507.9 |
| | | | | |
| MSY (mt) | 379,440 | 333,200 | 438,800 | |
| steepness | 0.88 | 0.95 | 0.73 | |
| Fmult | 1.41 | 0.99 | 2.40 | |
| | | | | |
| | | | | |

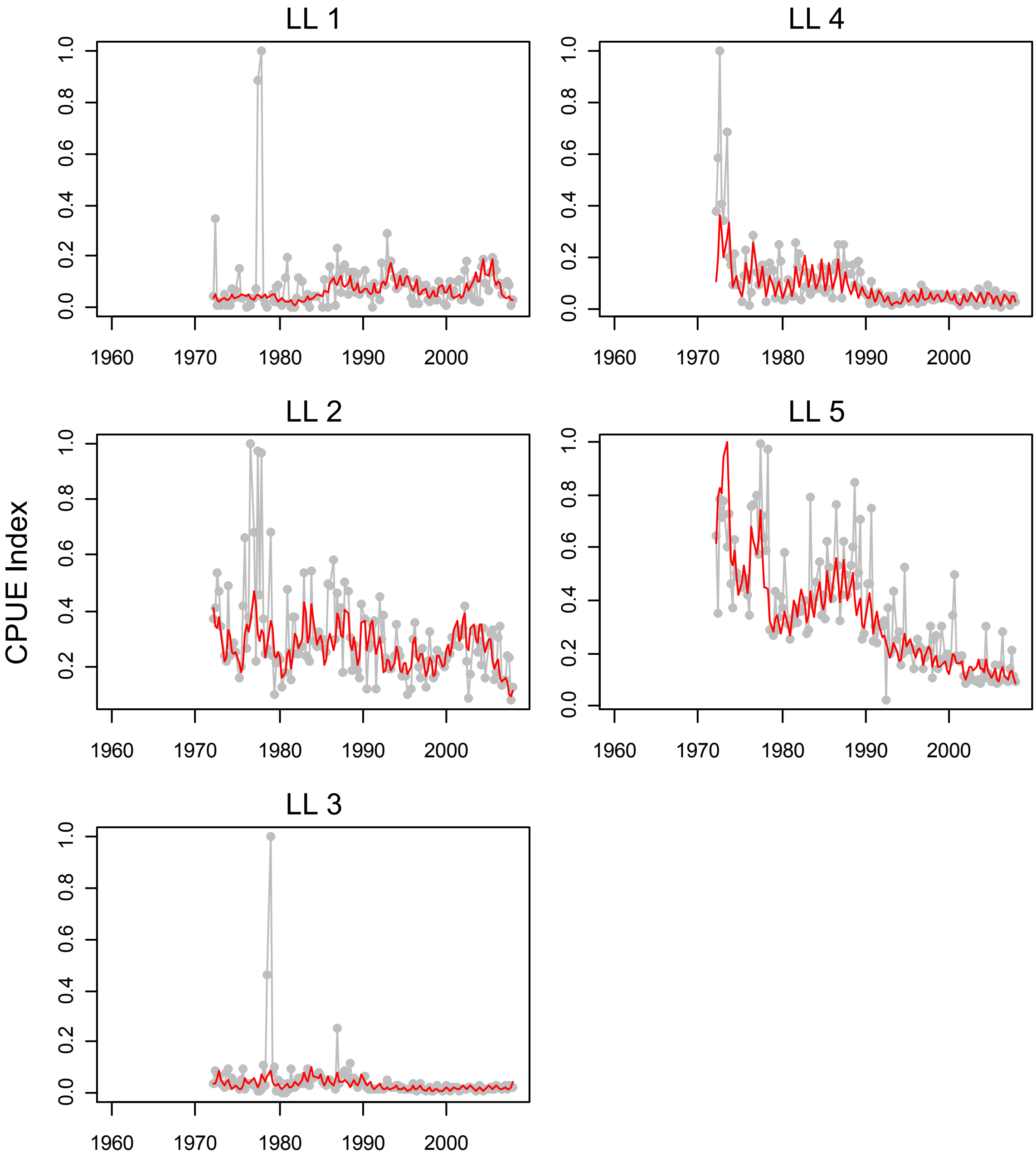

Biomass (thousands mt)
0
1000
2000
3000
4000
5000
6000
7000
1960
1970
1980
1990
2000
Size rew eighted
MFCLgrow -highM
MFCLgrow -low M
AFgrow -highM
AFgrow -low M


Size rew eighted
MFCLgrow -highM
MFCLgrow -low M
AFgrow -highM
AFgrow -low M
Recruitment (millions)
0
500
1000
1500
2000
1960
1970
1980
1990
2000

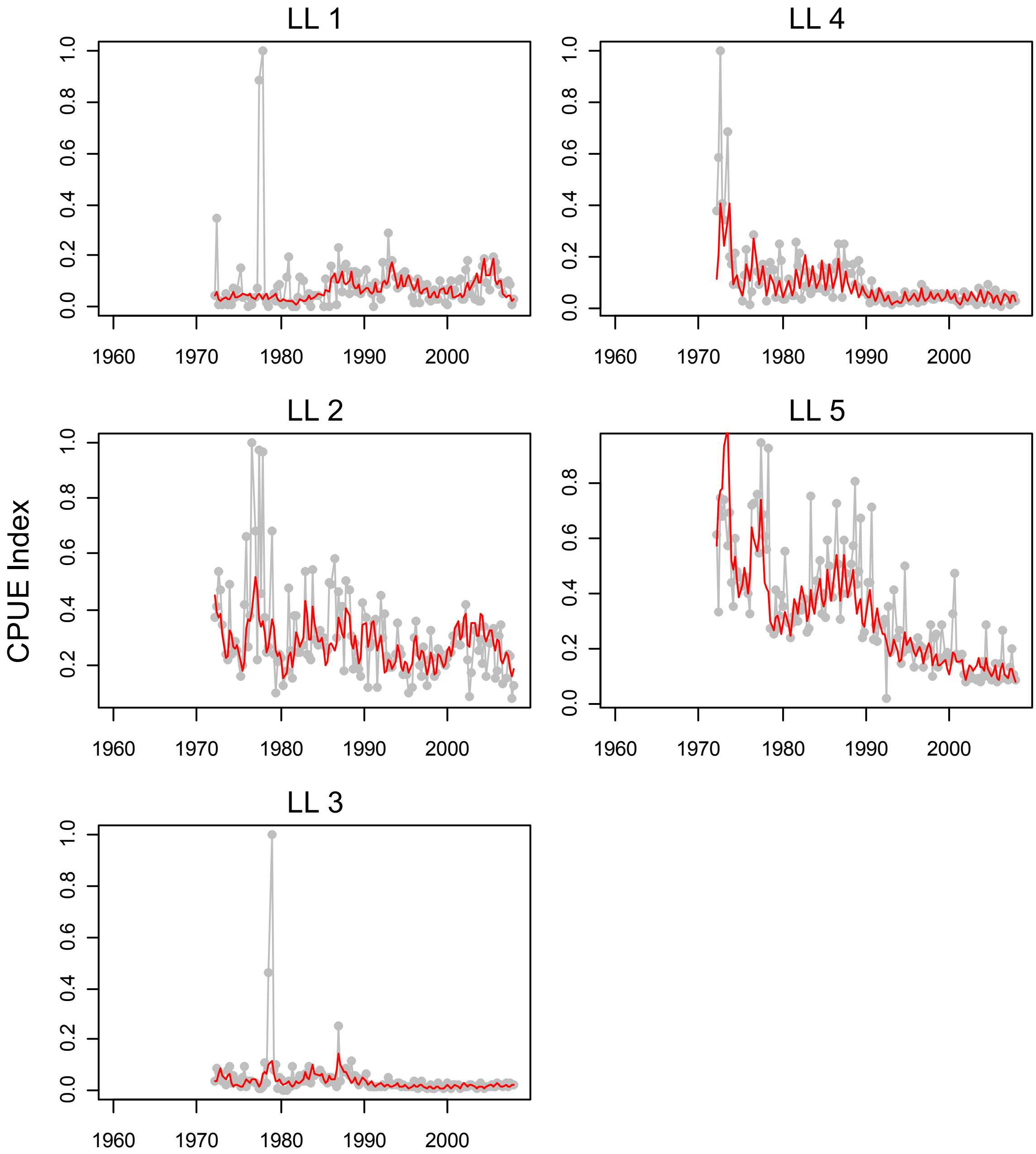

Size rew eighted
MFCLgrow -highM
MFCLgrow -low M
AFgrow -highM
AFgrow -low M
Recruitment (normalised)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
1960
1970
1980
1990
2000


MFCLgrow -highM
MFCLgrow -low M
AFgrow -highM
AFgrow -low M
Annual fishing mortality
Fm[[i]]
0.0
0.1
0.2
0.3
0.4
0.5
1960
1980
2000
Fadult
Fjuvenile

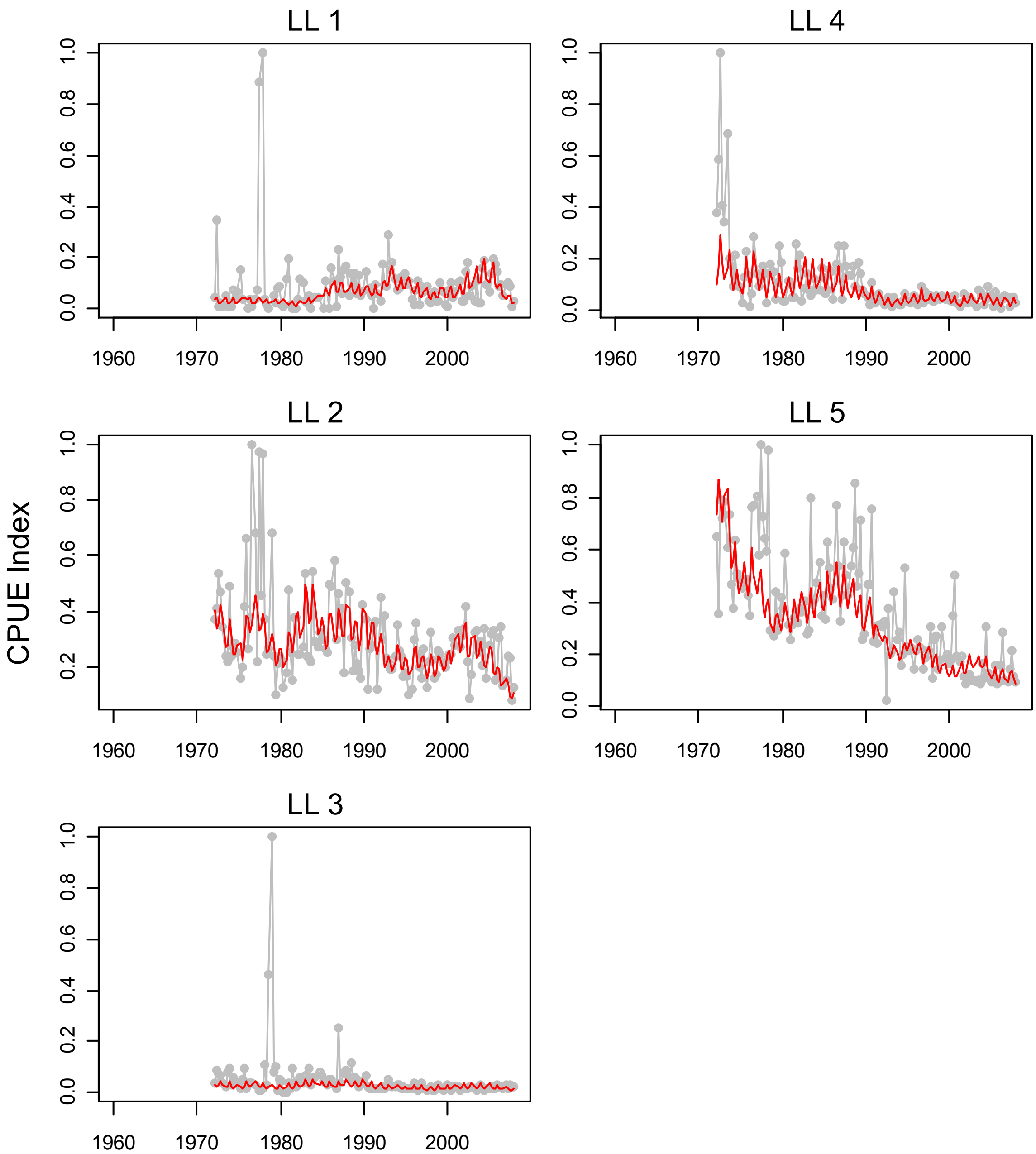

Equilibrium yield (1000 mt per year)
0
100
200
300
400
500
0
1
2
3
4
5
Fishing mortality multiplier
Equilibrium total biomass (1000 mt)
0
1000
3000
5000
0
1
2
3
4
5
Fishing mortality multiplier
Equilibrium adult biomass (1000 mt)
0
1000
2000
3000
4000
5000
0
1
2
3
4
5
Fishing mortality multiplier
Size reweighted
MFCLgrow-highM
MFCLgrow-lowM
AFgrow-highM
AFgrow-lowM



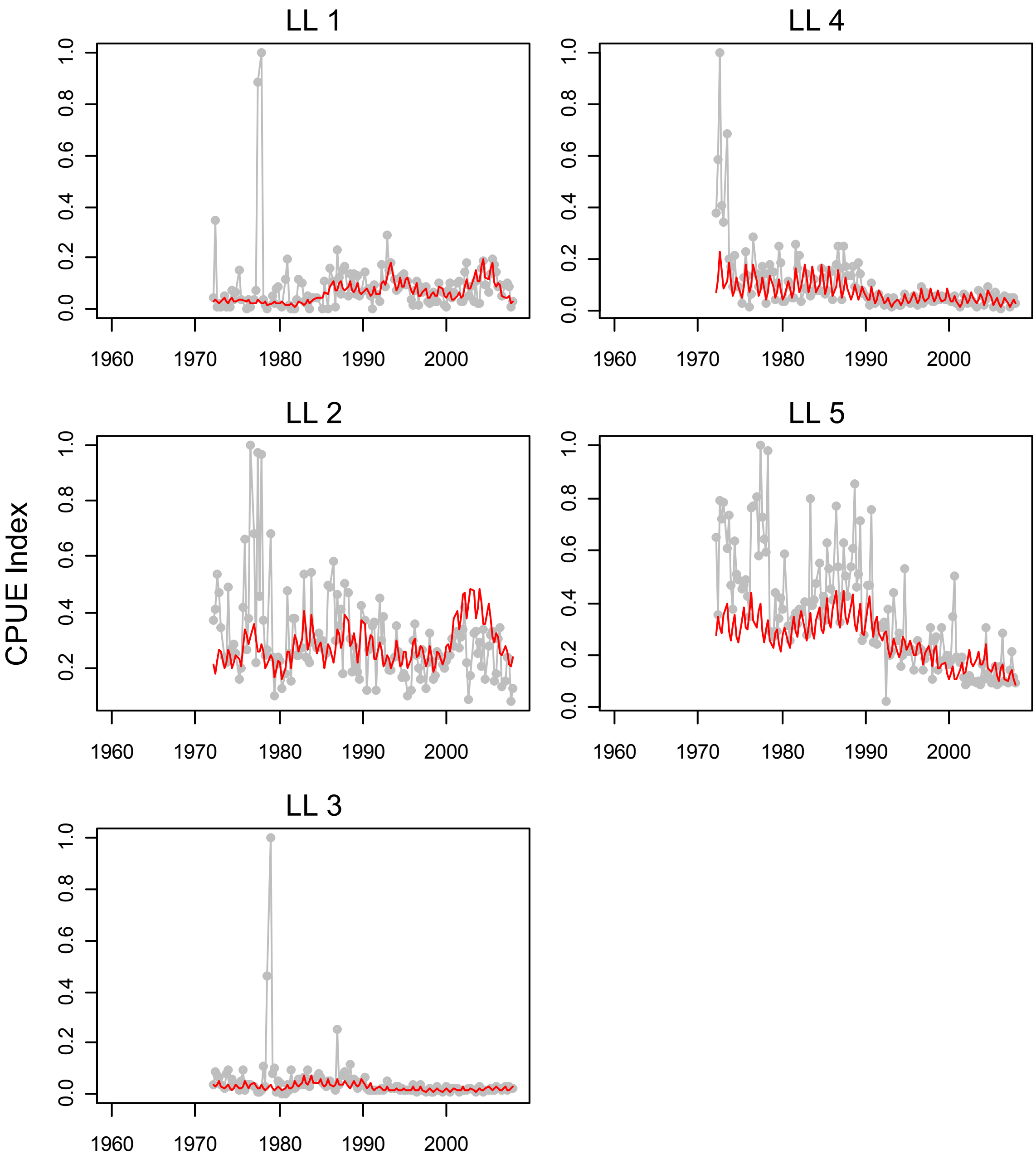

MFCL growth, high M



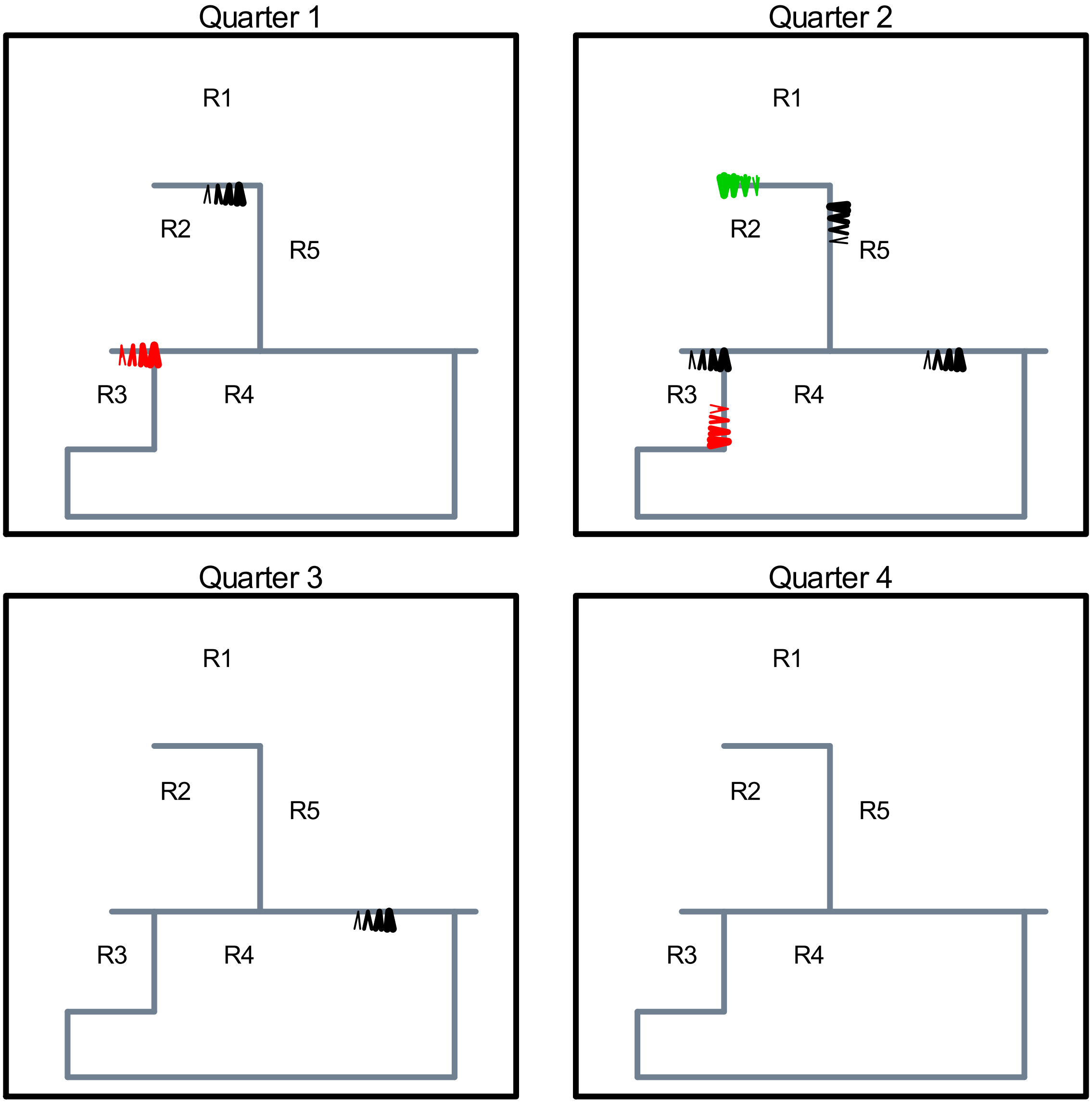

MFCL growth, low M



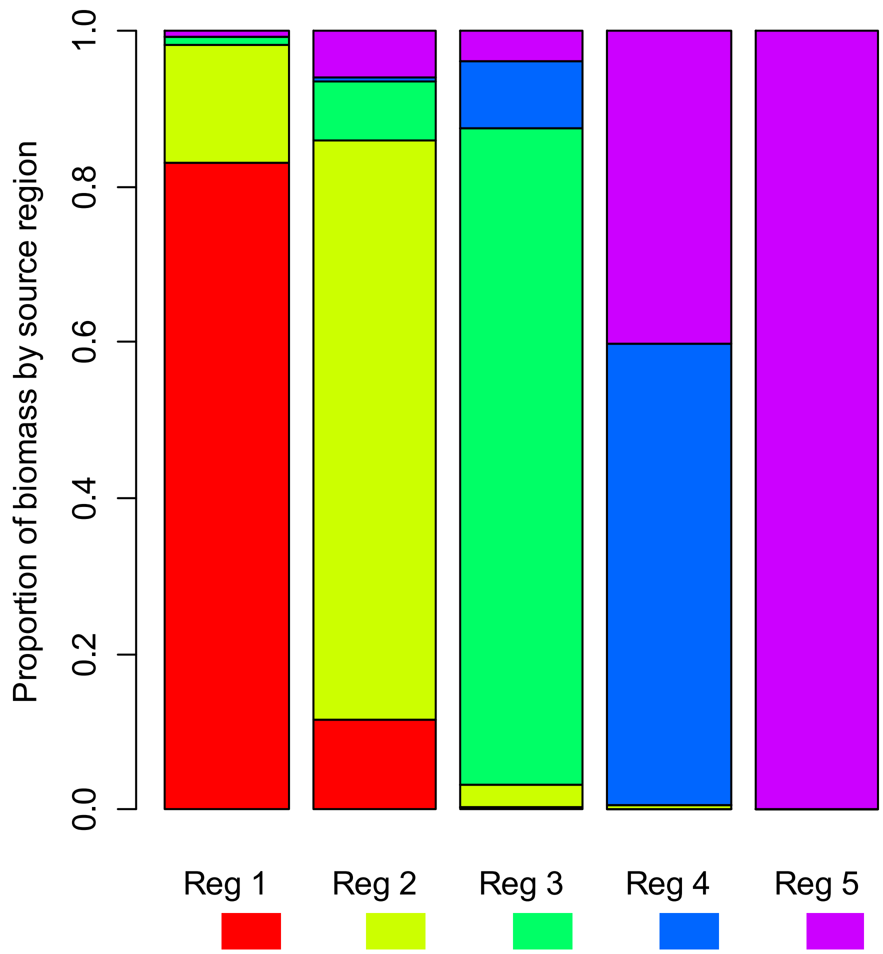

AF Growth, high M




AF growth, low M




Movement, MFCLgrow-lowM


Proportion of biomass by source region
0.0
0.2
0.4
0.6
0.8
1.0
Reg 1
Reg 2
Reg 3
Reg 4
Reg 5

28 October 2008

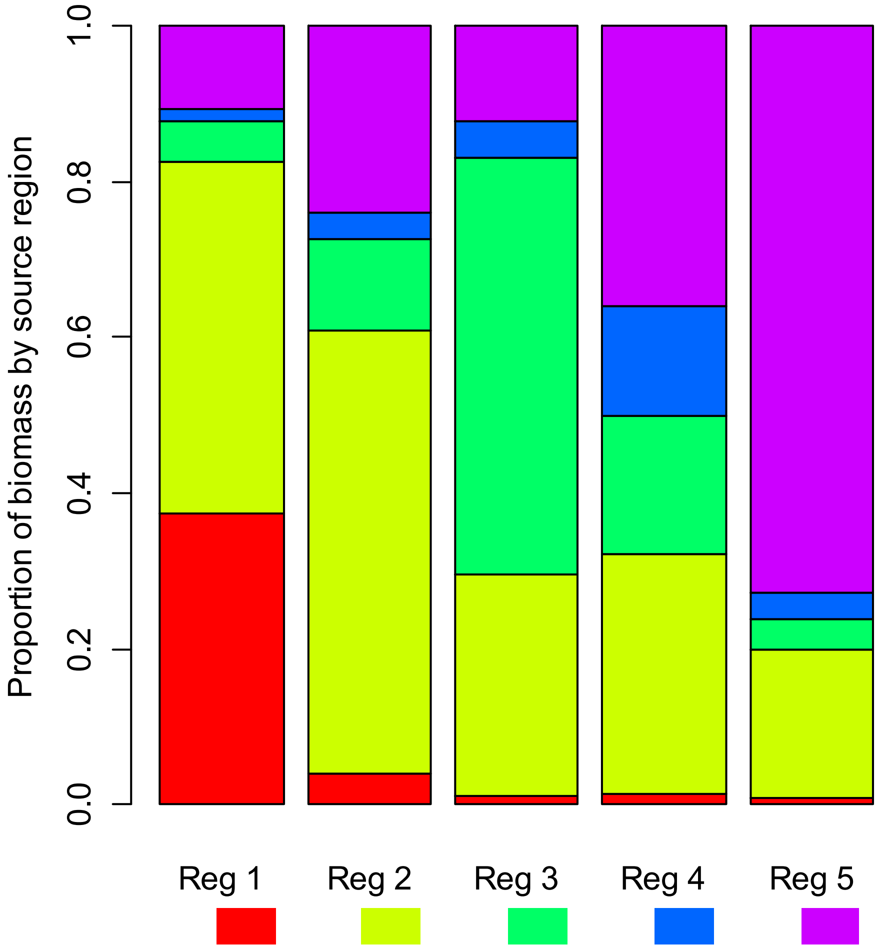
The MFCLgrow-lowM model was used to explore the sensitivity of the MSY based reference points to assumptions regarding the steepness of the stock recruitment relationship. Three levels of steepness were considered: 0.60, 0.70, and 0.80.

| | MFCLgrow-lowM | Steepness 0.80 | Steepness 0.70 | Steepness 0.60 |
|---|---|---|---|---|
| | | | | |
| Total -LL | -363612.6 | -363611.4 | -363609.6 | -363607.0 |
| LF LL | -370746.9 | | | |
| Tag LL | 2728.45 | | | |
| | | | | |
| MSY (mt) | 333,200 | 299,720 | 276,440 | 251,280 |
| steepness | 0.95 | 0.80 | 0.70 | 0.60 |
| Fmult | 0.99 | 0.78 | 0.67 | 0.57 |
| F/Fmsy | 1.01 | 1.28 | 1.49 | 1.75 |
| | | | | |

In addition, the sensitivity to the movement assumptions was also examined. A movement scenario that transferred approximately 2.5% of the fish in a region across each boundary (at each quarter, all age classes) was run to simulate a relatively well mixed stock (high-move). All other assumptions were equivalent to the MFCLgrow-lowM model run.

Conversely, a further run was undertaken with negligible movement between regions in all quarters (no-move).

| | MFCLgrow-lowM | High-move | No-move | Age-move |
|---|---|---|---|---|
| | | | | |
| Total -LL | -363612.6 | -360976.9 | -361206.4 | |
| LF LL | -370746.9 | -369975.1 | -369678.5 | |
| Tag LL | 2728.45 | 2717.6 | 3016.0 | |
| | | | | |
| MSY (mt) | 333,200 | 502,400 | 488,000 | |
| steepness | 0.95 | 0.71 | 0.59 | |
| Fmult | 0.99 | 1.37 | 1.23 | |
| F/Fmsy | 1.01 | 0.73 | 0.81 | |
| B/Bmsy | 1.63 | 1.75 | 1.72 | |




High-move movement dynamics.

27 October 2008

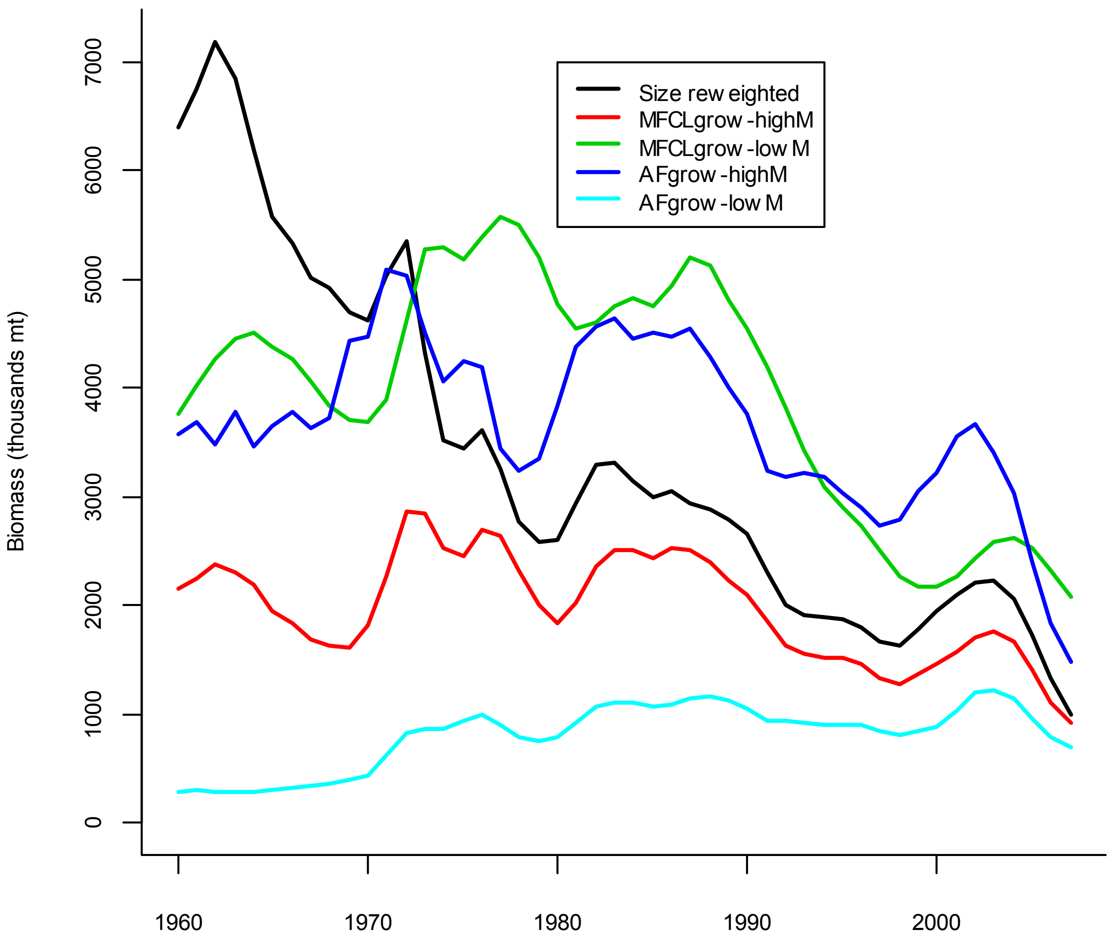
Changes from previous model runs

- TW CPUE index (1968-2007) incorporated for Region 1 (single composite index).
- Separate longline fisheries pre/post 1972.
- Selectivity LL pre/post 1972 equivalent.
- Temporal deviations in catchability for LL pre 1972.
- LL selectivity cubic spline parameterisation. Freedom to estimate declining right-hand limb.
- Change tag mixing from 6 mo to 3 mo.
- Steepness estimated.

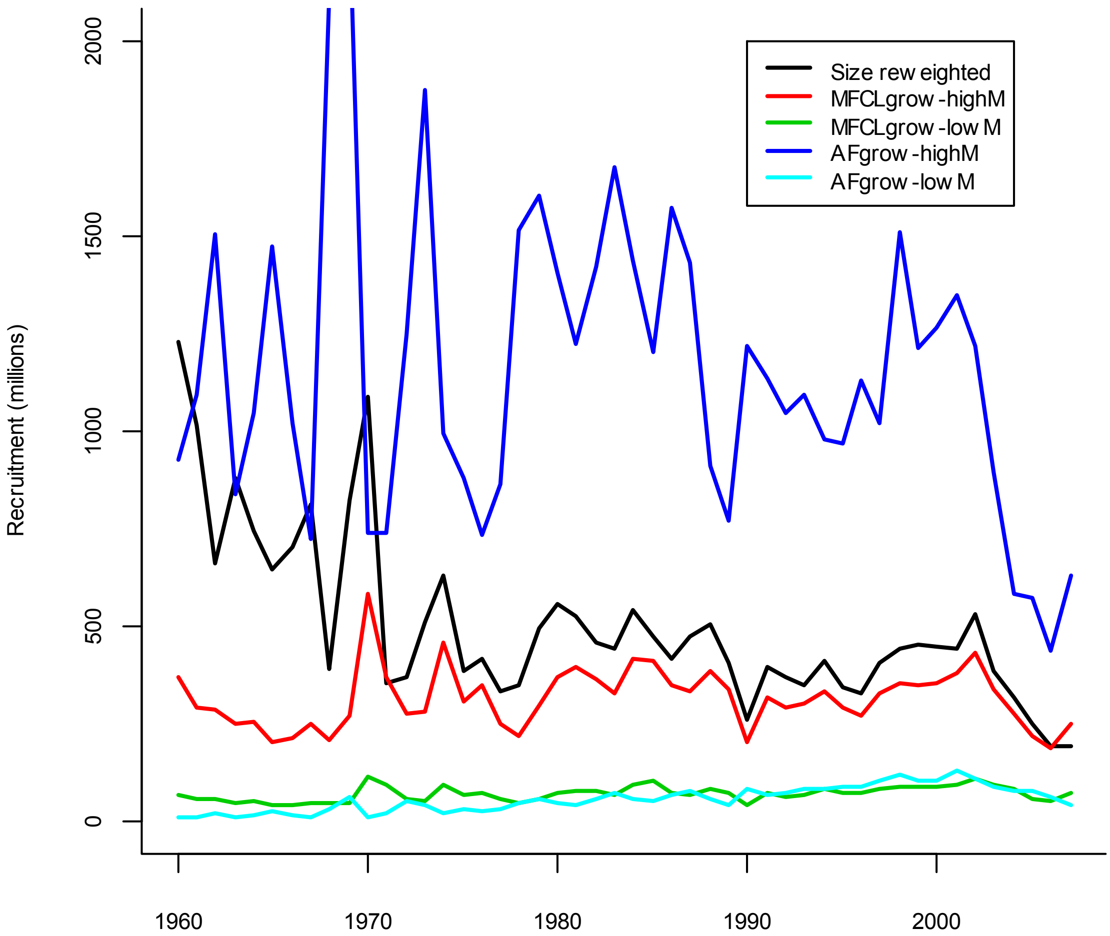
Scenarios considered:

| Scenario | Growth | Natural mortality |
|---|---|---|
| | | |
| MFCLgrow-highM | MFCL estimated. | WCPO M-at-age |
| MFCLgrow-lowM | MFCL estimated. | 0.4 * WCPO M-at-age |
| AFgrow-highM | Fonteneau, MFCL sd fixed | WCPO M-at-age |
| AFgrow-lowM | Fonteneau, MFCL sd fixed | 0.4 * WCPO M-at-age |

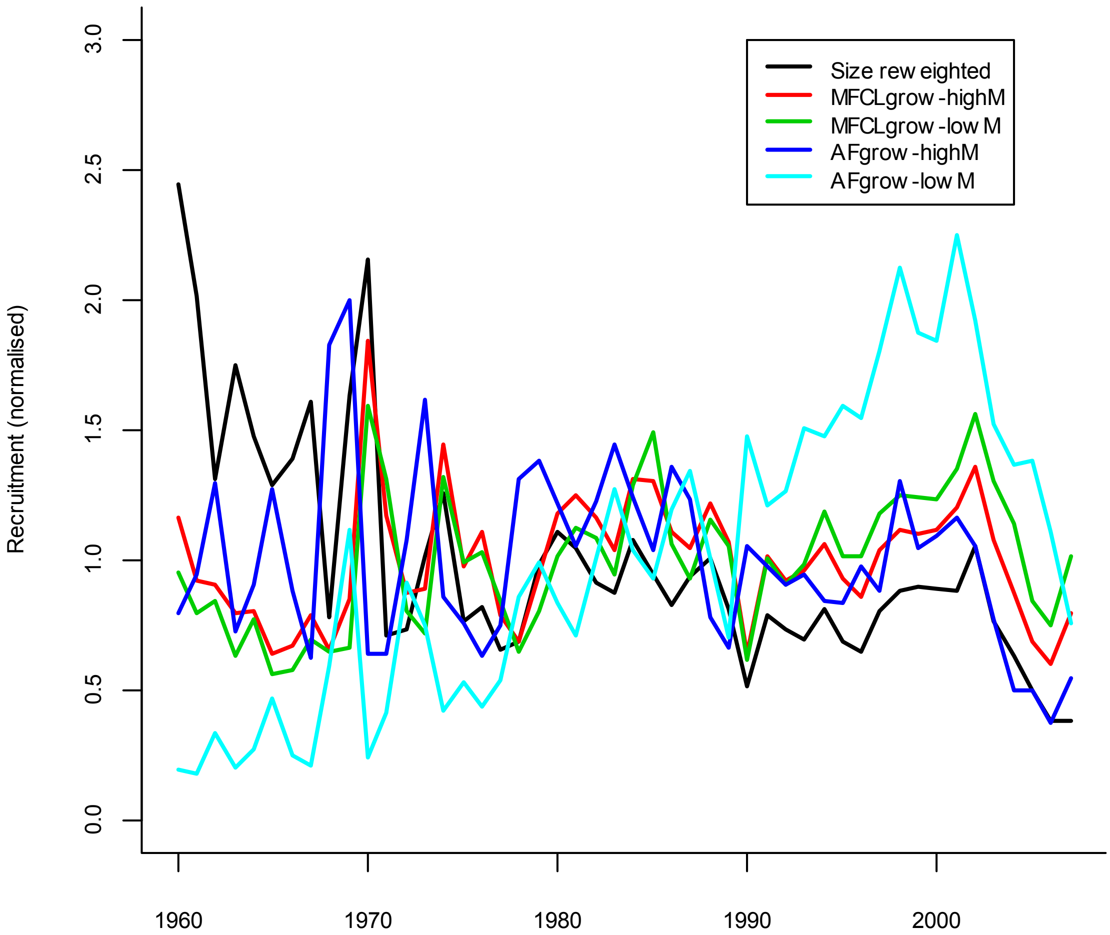
| | MFCLgrow-highM | MFCLgrow-lowM | AFgrow-highM | AFgrow-lowM |
|---|---|---|---|---|
| | | | | |
| Total -LL | -363148.9 | -363612.6 | -360180.8 | -359770.2 |
| LF LL | -370482.8 | -370746.9 | -368635.7 | -368448.7 |
| Tag LL | 2835.9 | 2728.45 | 3497.4 | 3507.9 |
| | | | | |
| MSY (mt) | 379,440 | 333,200 | 438,800 | |
| steepness | 0.88 | 0.95 | 0.73 | |
| Fmult | 1.41 | 0.99 | 2.40 | |
| | | | | |
| | | | | |



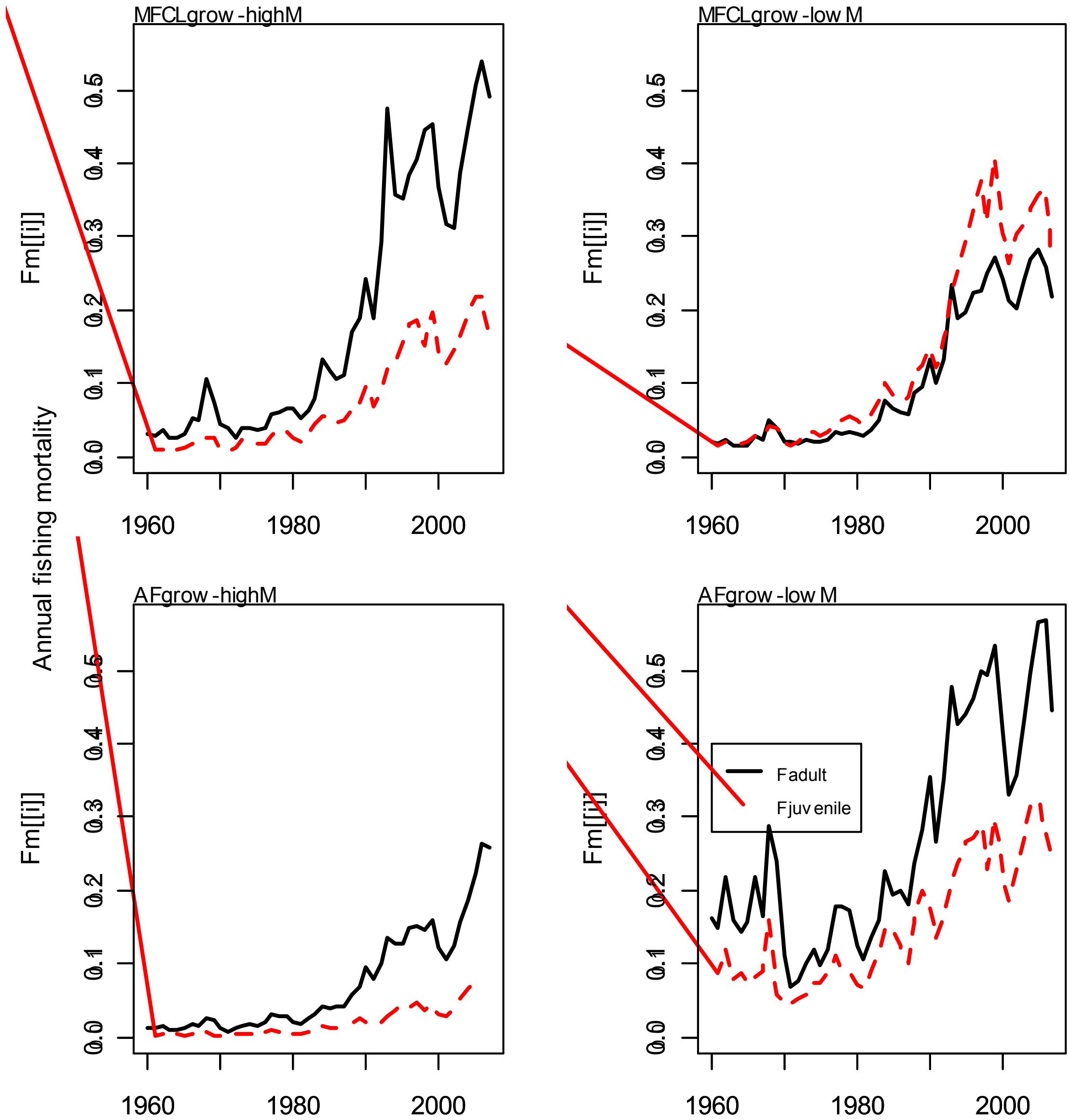
Size rew eighted
MFCLgrow -highM
MFCLgrow -low M
AFgrow -highM
AFgrow -low M
Biomass (thousands mt)
0
1000
2000
3000
4000
5000
6000
7000
1960
1970
1980
1990
2000

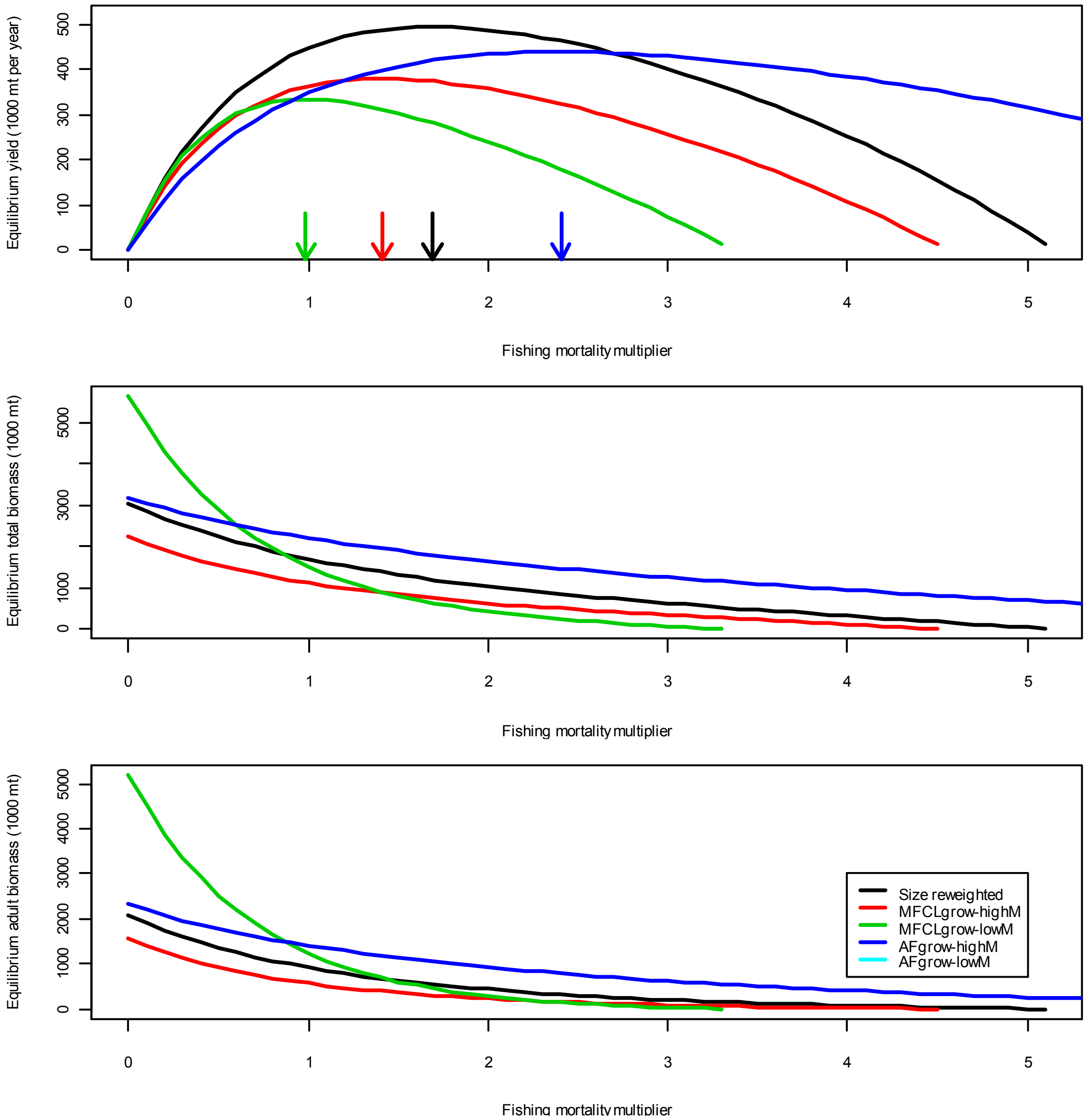


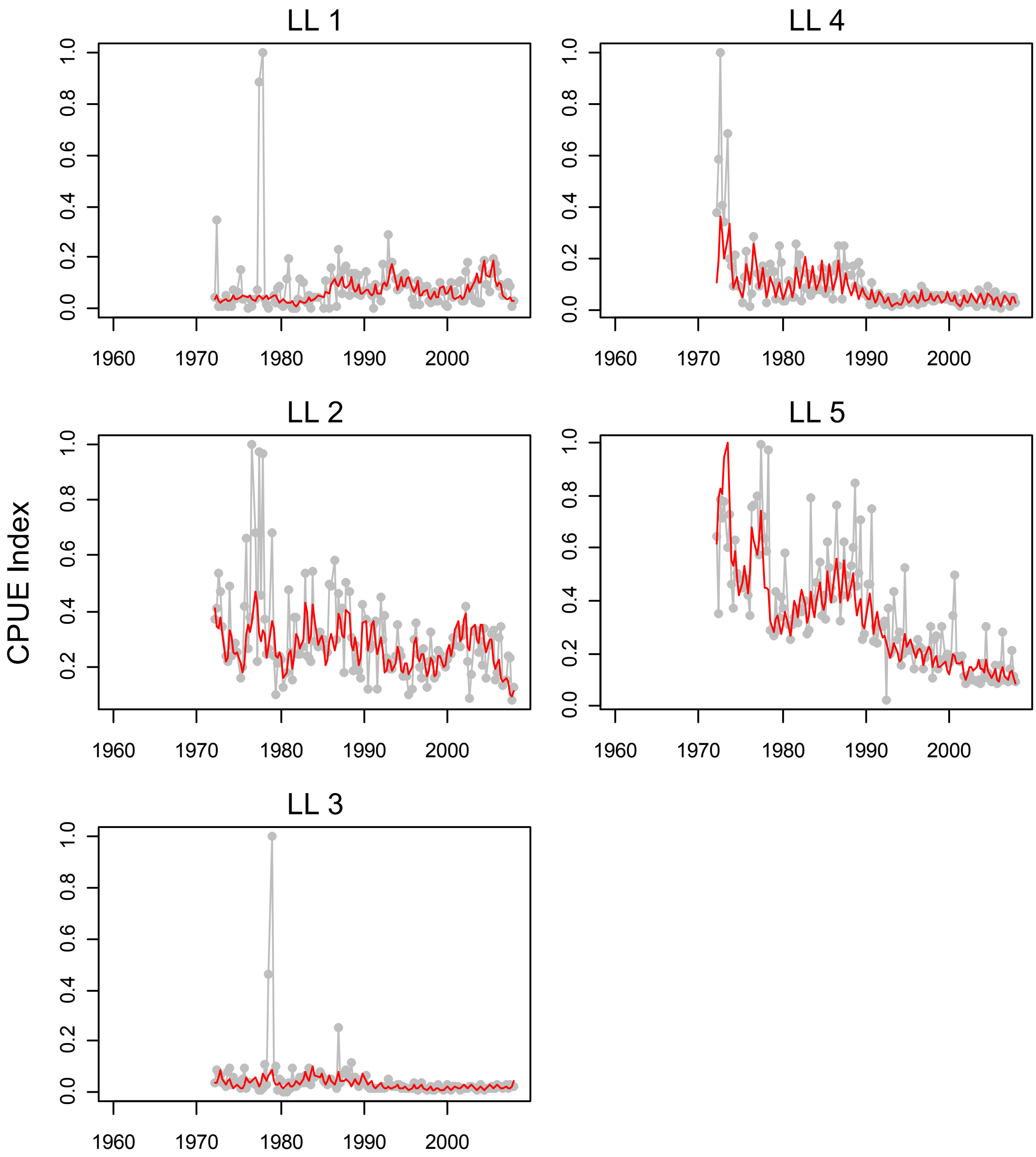
Recruitment (millions)
0
500
1000
1500
2000
1960
1970
1980
1990
2000
Size rew eighted
MFCLgrow -highM
MFCLgrow -low M
AFgrow -highM
AFgrow -low M



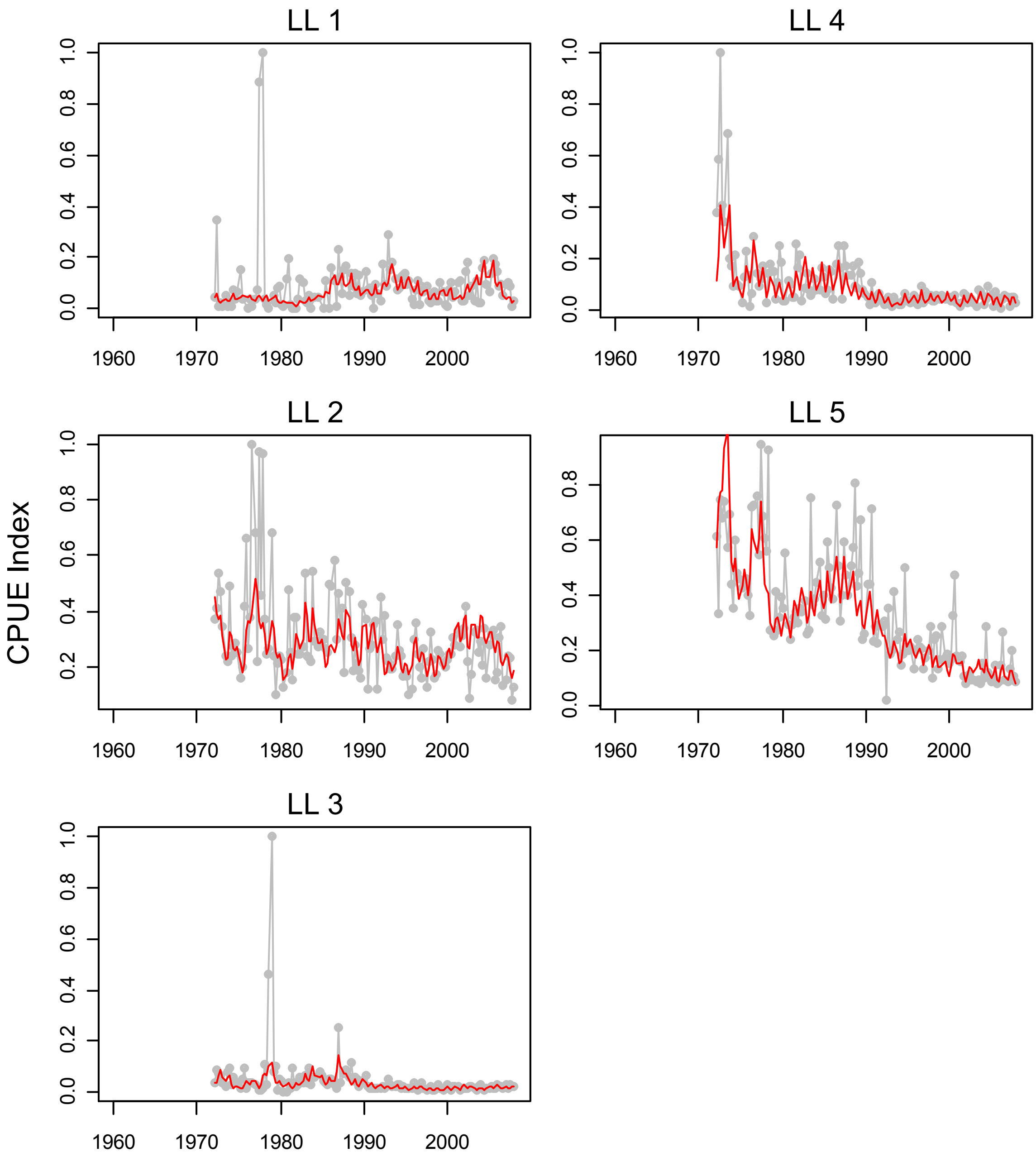
Size rew eighted
MFCLgrow -highM
MFCLgrow -low M
AFgrow -highM
AFgrow -low M
Recruitment (normalised)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
1960
1970
1980
1990
2000


MFCLgrow - highM
MFCLgrow - low M
AFgrow - highM
AFgrow - low M
Annual fishing mortality
Fm[[i]]
Fadult
Fjuvenile
0.0
0.1
0.2
0.3
0.4
0.5
1960
1980
2000

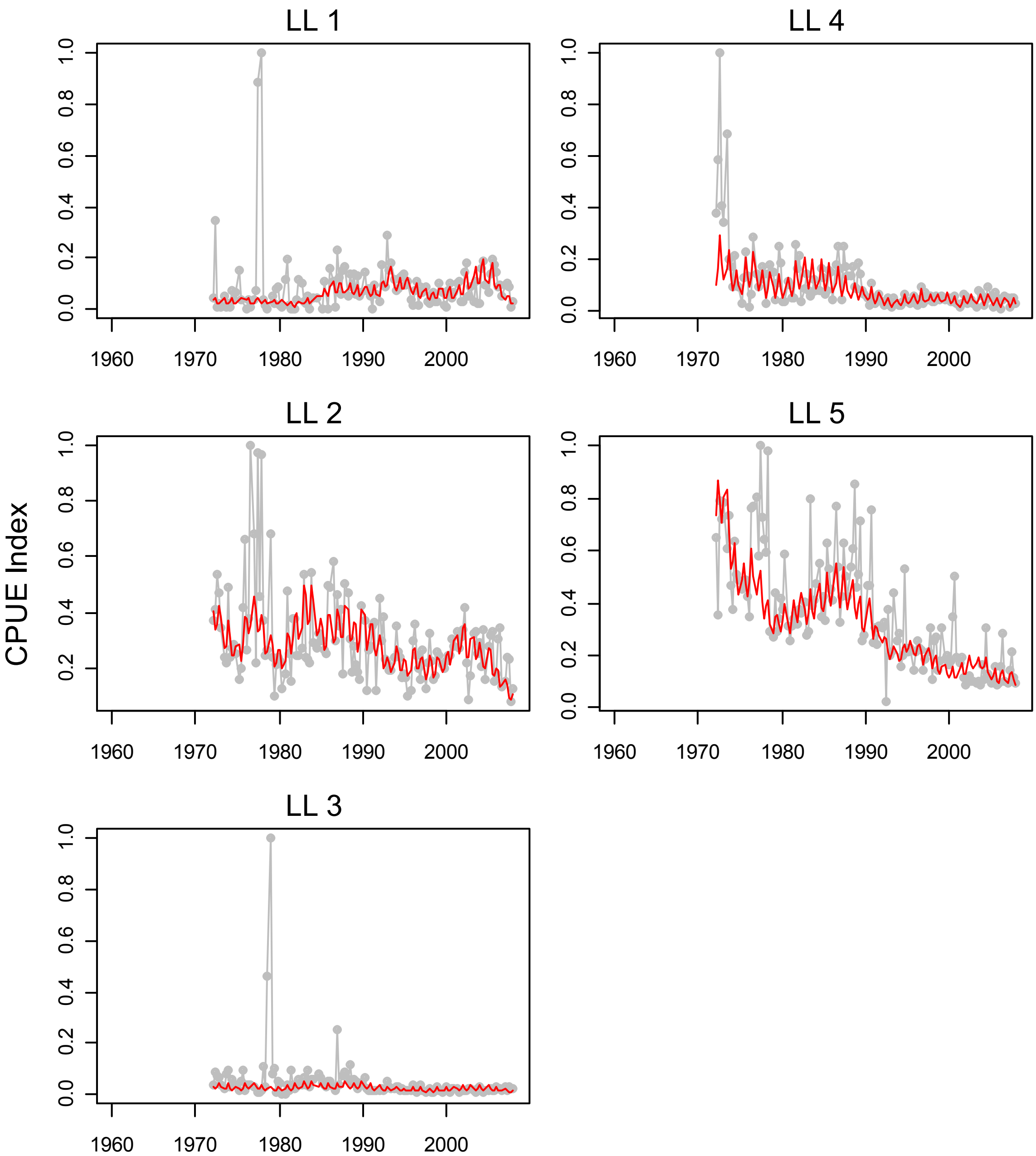

Equilibrium yield (1000 mt per year)
Fishing mortality multiplier
Equilibrium total biomass (1000 mt)
Fishing mortality multiplier
Equilibrium adult biomass (1000 mt)
Size reweighted
MFCLgrow-highM
MFCLgrow-lowM
AFgrow-highM
AFgrow-lowM
Fishing mortality multiplier



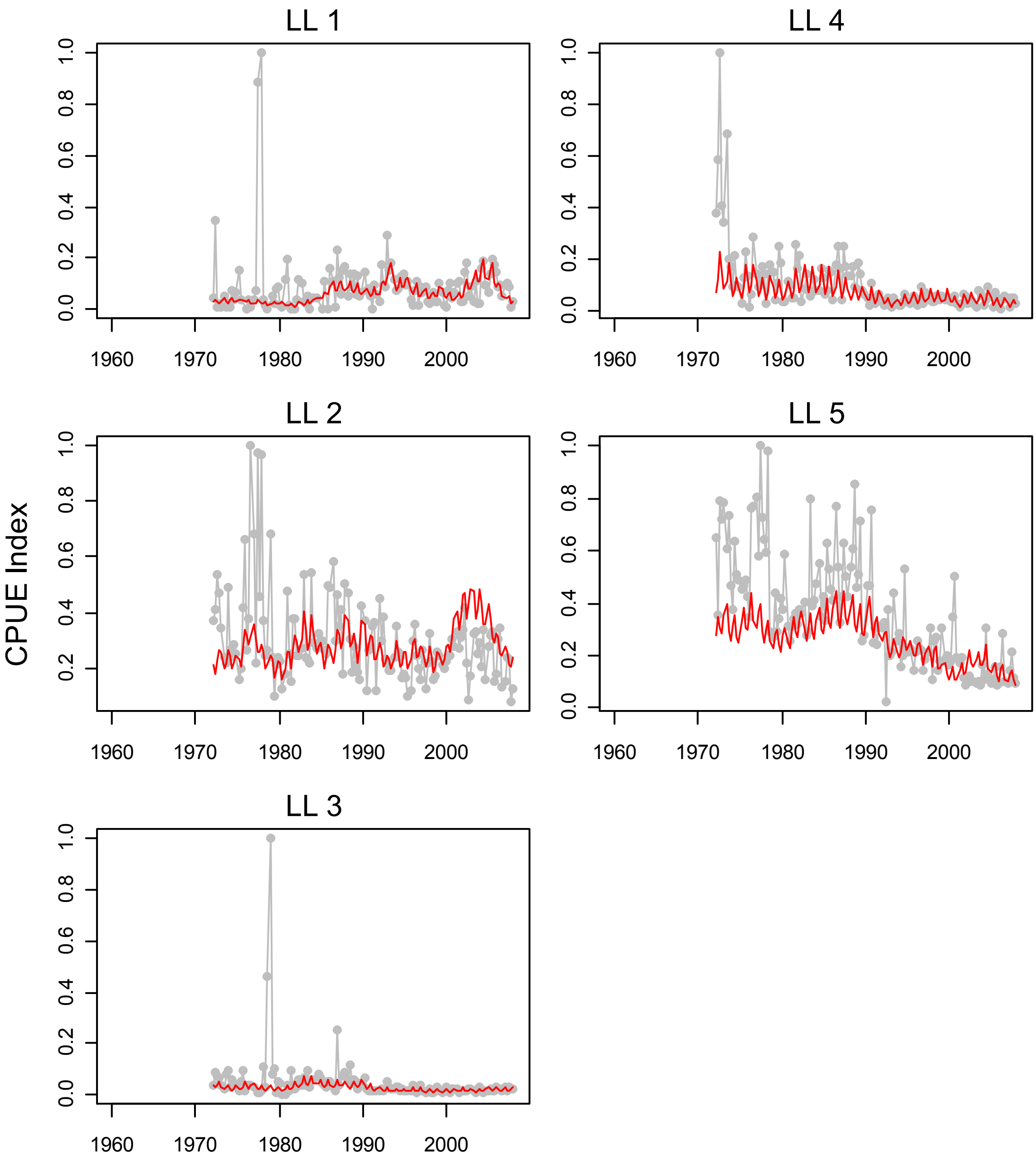

MFCL growth, high M



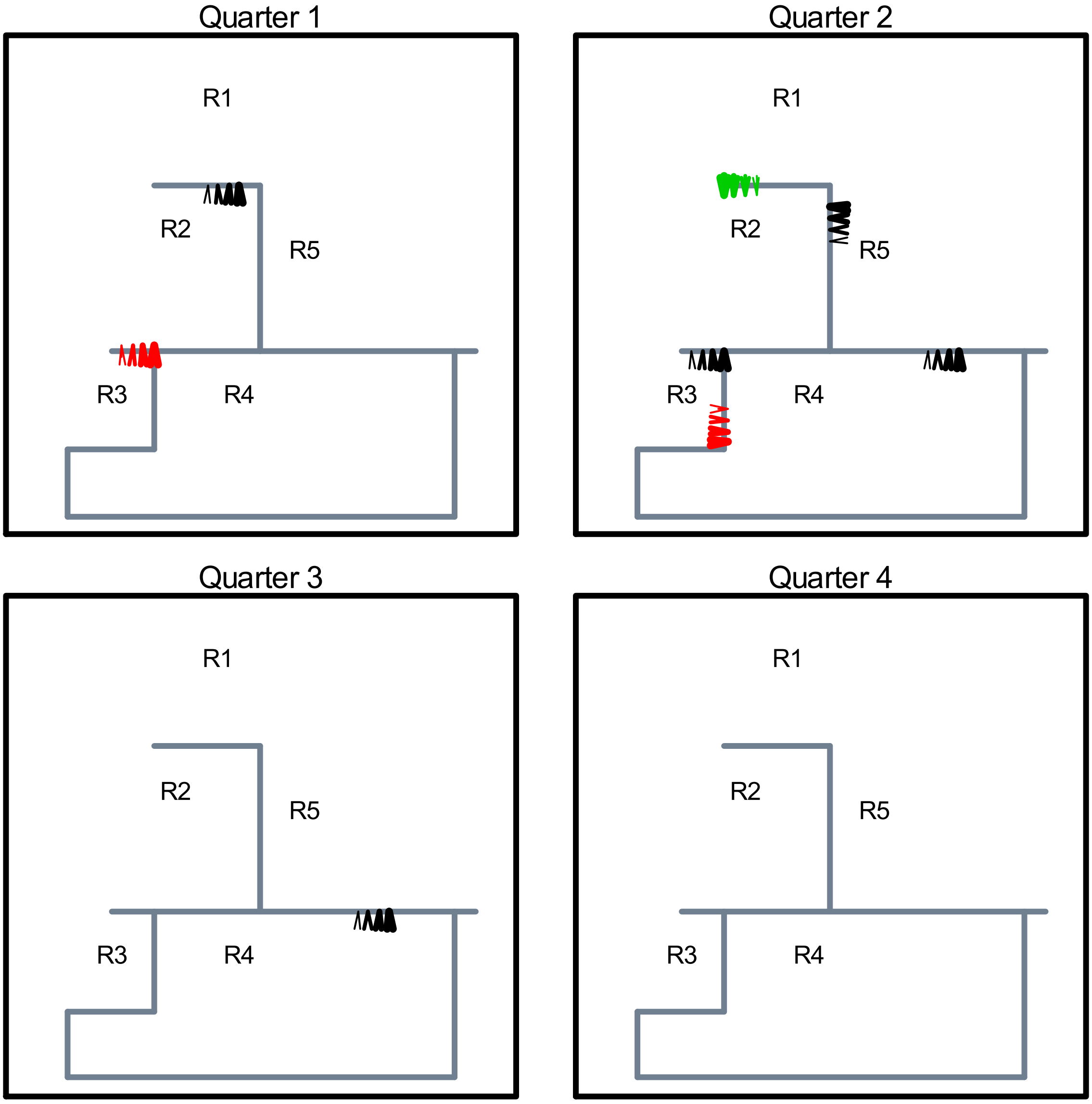

MFCL growth, low M



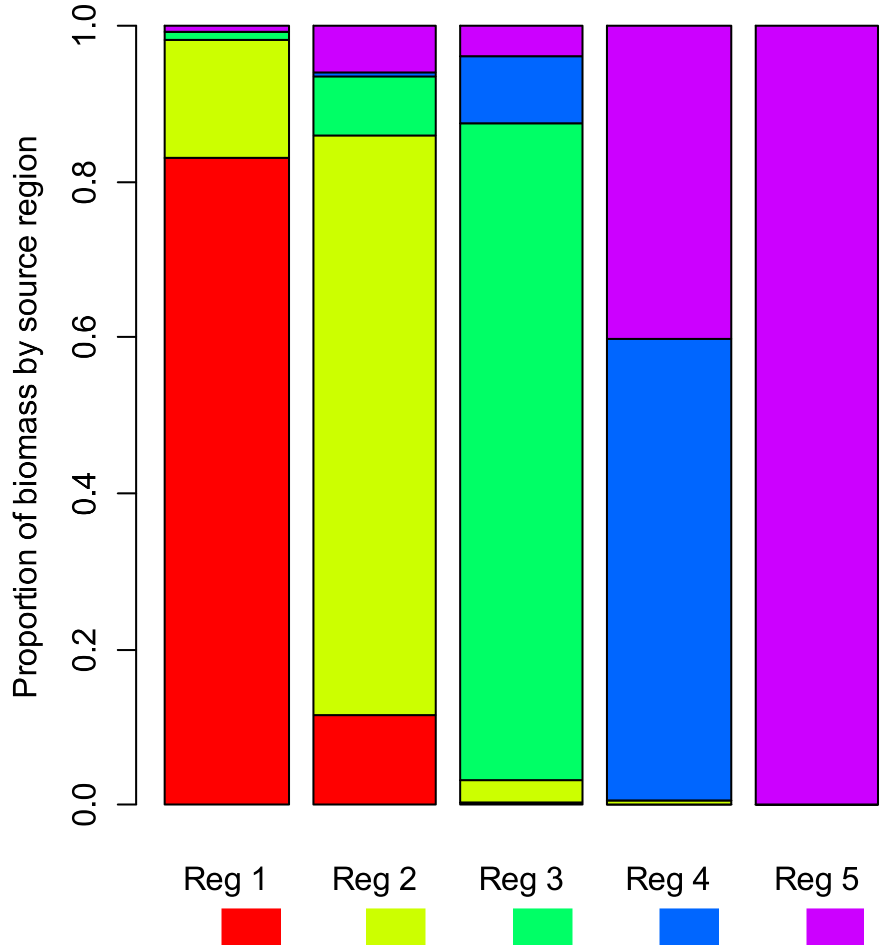

AF Growth, high M




AF growth, low M




Movement, MFCLgrow-lowM


Proportion of biomass by source region
0.0
0.2
0.4
0.6
0.8
1.0
Reg 1
Reg 2
Reg 3
Reg 4
Reg 5

28 October 2008

The MFCLgrow-lowM model was used to explore the sensitivity of the MSY based reference points to assumptions regarding the steepness of the stock recruitment relationship. Three levels of steepness were considered: 0.60, 0.70, and 0.80.

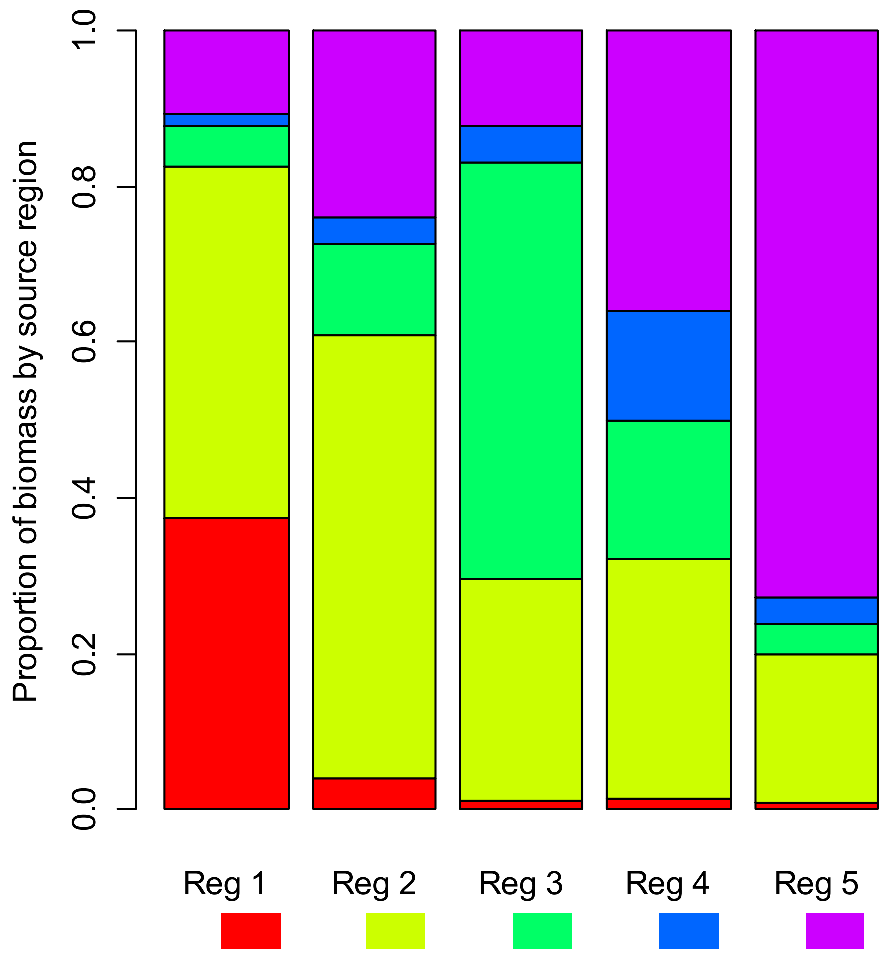
| | MFCLgrow-lowM | Steepness 0.80 | Steepness 0.70 | Steepness 0.60 |
|---|---|---|---|---|
| | | | | |
| Total -LL | -363612.6 | -363611.4 | -363609.6 | -363607.0 |
| LF LL | -370746.9 | | | |
| Tag LL | 2728.45 | | | |
| | | | | |
| MSY (mt) | 333,200 | 299,720 | 276,440 | 251,280 |
| steepness | 0.95 | 0.80 | 0.70 | 0.60 |
| Fmult | 0.99 | 0.78 | 0.67 | 0.57 |
| F/Fmsy | 1.01 | 1.28 | 1.49 | 1.75 |
| B/Bmsy | 1.63 | 1.38 | 1.25 | 1.13 |
| SB/SBmsy | 1.67 | 1.37 | 1.22 | 1.09 |
| B2007/Bmsy | 1.34 | 1.13 | 1.03 | 0.93 |
| SB2007/SBmsy | 1.44 | 1.18 | 1.05 | 0.94 |

Note: current conditions are derived for the 2003-2006 average.

In addition, the sensitivity to the movement assumptions was also examined. A movement scenario that transferred approximately 2.5% of the fish in a region across each boundary (at each quarter, all age classes) was run to simulate a relatively well mixed stock (high-move). All other assumptions were equivalent to the MFCLgrow-lowM model run.

Conversely, a further run was undertaken with negligible movement between regions in all quarters (no-move).

| | MFCLgrow-lowM | High-move | No-move | Age-move |
|---|---|---|---|---|
| | | | | |
| Total -LL | -363612.6 | -360976.9 | -361206.4 | |
| LF LL | -370746.9 | -369975.1 | -369678.5 | |
| Tag LL | 2728.45 | 2717.6 | 3016.0 | |
| | | | | |
| MSY (mt) | 333,200 | 502,400 | 488,000 | |
| steepness | 0.95 | 0.71 | 0.59 | |
| Fmult | 0.99 | 1.37 | 1.23 | |
| F/Fmsy | 1.01 | 0.73 | 0.81 | |
| B/Bmsy | 1.63 | 1.75 | 1.72 | |




High-move movement dynamics.