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Indian Ocean Skipjack Tuna Stock Assessment 1950-2009 (Stock Synthesis)

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1. Summary

A stock assessment of the Indian Ocean skipjack tuna (*Katsuwonas pelamis*, SKJ) population 1950-2009 is presented. The analysis represents the first attempt to integrate the available data for this fishery into a unified framework (using *Stock Synthesis* software). Considerable effort was spent examining the uncertainties associated with various assumptions, and parameters that are known to be difficult to estimate (e.g. stock recruit steepness and natural mortality).

Core assumptions in all models included:

- Spatially-aggregated, age-structured population, iterated on a quarterly time-step 1950-2009. A sensitivity analysis was undertaken in which it was assumed that the western Indian Ocean might represent an isolated population.
- Four fisheries (catch in mass extracted without error):
  - PL – Maldivian Pole and Line (baitboat) fleet
  - PSLS - FAD/log associated Purse Seine (PS) sets from the EU/Seychelles fleets
  - PSFS – Free School (unassociated) Purse Seine sets from the EU/Seychelles fleets
  - Other - includes PS from other nations and all other fleets (primarily gillnet fleets from Sri Lanka, Iran, Pakistan and Indonesia).
- Relative abundance indices:
  - Pole and Line fishery standardized CPUE (2004-2009)
  - Nominal CPUE from the French component of the PSFS fishery was tested.
- Beverton-Holt stock-recruit dynamics, with fixed steepness and spawning biomass proportional to the total mass of mature fish. Models were compared with deterministic and stochastic recruitment (annual deviates 1993-2008 with estimated variance, and quarterly deviates from 2004-8).
- Two von Bertalanffy length-at-age relationships were compared:
  - L_{inf} = 70cm, k=0.37, L(age 0) fixed at 20cm.
  - L_{inf} = 83cm, k=0.22, L(age 0) fixed at 20cm.
- Maturity was invariant over time with 50% mature at length 38 cm (~1.75 y).
- Non-parametric (cubic spline) length-based selectivity was estimated for each fleet independently (with sufficient flexibility to describe logistic, dome-shaped or polymodal functions).
- Two approaches were used for including the tagging data:
  - RTTP-IO data only (~78 000 releases) with recoveries only for the EU/Seychelles PS fleets (including fixed estimates for the reporting rates derived from tag seeding experiments).
  - RTTP-IO plus small-scale tagging programmes (~100 000 combined releases). Maldivian Pole and Line tag recoveries were also included in this case (with stationary reporting rate estimated as a free parameter).
- Objective function terms included:
  - likelihoods for:
    - PL CPUE (and nominal PSFS CPUE in some cases)

- Catch-at-Length from all fleets (with assumed sample sizes generally much lower than observed),
- tag recoveries from the EU/Seychelles fleets (and Maldives PL fleet in some cases),
  - Priors on all estimated parameters.

A systematic exploration of the interactions among different sets of assumptions was undertaken. The final stock status estimates represent a synthesis from a grid of 180 models (balanced factorial design of the 5 assumption options):

- 2 tagging programme release/recovery options
- 2 growth curve options
- 3 Tag recovery negative binomial overdispersion options (τ = 2, 20, 70)
- 3 M options:
  - estimated (age-specific)
  - fixed at estimates from the preliminary Brownie analysis
  - fixed values from recent ICCAT assessment
- 5 stock recruit steepness options (h = 0.55 - 0.95)

In most cases, the models estimated a highly productive stock, with high natural mortality, and moderate depletion. The models often suggested that a sizeable proportion of the spawning stock is essentially invulnerable to the fishery. In some cases, the sustainable yield is estimated to increase with increasing effort, such that it may not be possible to seriously overfish the stock (i.e. very large increases in effort would be required to make small gains in catch and would result in uneconomical catch rates). The robustness of this conclusion needs further consideration.

The Maximum Posterior Density (MPD, best fit) estimates from these models indicates a broad range of uncertainty, including a few scenarios in which $SB_{2009} < SB_{MSY}$ and $C_{2009} > MSY$ (a proxy for F/F_{MSY} due to numerical problems in the estimation of F_{MSY}). The more pessimistic interpretations were generally associated with lower M values, and lower stock-recruit steepness. A somewhat subjective (but transparent) scheme was devised by the authors to weight the relative plausibility of the 180 models. The weighting scheme was subsequently revised by the broader WPTT (only 90 models are represented in the final synthesis), and yielded the following reference point estimates (median, 5th-95 percentiles of the weighted distribution of MPD estimates):

- SB_{2009}/SB_{MSY} = 2.56 (1.09 – 5.83)
- C_{2009}/MSY = 0.81 (0.54 - 1.16) (F_{2009}/F_{MSY} could not be estimated reliably)
- MSY = 564 (395 - 843) thousand t (C_{2009} = 456 thousand t)

The weighting scheme was also applied to deterministic constant catch projections (catches at 60%, 80%, 100%, 120% and 140% of 2009 levels) and presented in the form of a Kobe-2 Strategy Matrix (for the projected stock status in years 2012 and 2019).

The equivalent model fitting and weighting procedure was repeated for the western Indian Ocean under the assumption that it may represent a reasonably discrete sub-population. These latter results were not examined in detail, but it is notable that they tended to be more optimistic than the aggregate Indian Ocean results:

- SB_{2009}/SB_{MSY} = 3.17 (1.79 – 9.17)
- C_{2009}/MSY = 0.56 (0.33 – 0.92)
- MSY = 531 (323 – 900) thousand t (C_{2009} = 298 thousand t).

A number of recommendations for future assessments are discussed.

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Introduction

The Indian Ocean skipjack tuna (*Katsuwona pelamis*, SKJ) fishery is one of the largest tuna fisheries in the world, with total catches of 400-600 thousand t over the past decade (Figure 1). Some bioeconomic modelling of the fish population and fishery was undertaken a few years ago (Mohamed 2007), but there has never been an integrated model-based stock assessment presented to the Indian Ocean Tuna Commission (IOTC). To date, management advice has relied on data-based indicators, and mortality estimates from analyses of the recent RTTP-IO tagging data (Edwards et al. 2010). Several factors provide the impetus for a full model-based assessment at this time:

- The RTTP-IO tag recovery data (and reporting rate estimates) allow the direct estimation of natural and fishing mortality.
- The RTTP-IO tag growth increment data have enabled the direct estimation of a SKJ length-at-age relationship for the Indian Ocean.
- Vessel-specific catch rates for the Maldivian pole and line fishery have been recorded since 2004, which allow the estimation of a (short) relative abundance index.
- Stable or declining catches since ~2006 might be interpreted as an indication that the SKJ fishery is near full exploitation.
- The Maldives is seeking Marine Stewardship Council (MSC) certification for the domestic SKJ fishery, and this requires a broader assessment of all fisheries affecting this population.

The other tropical tuna RFMOs have conducted model-based assessments for SKJ (Maunder and Harley 2003, ICCAT 2009, Hoyle et al. 2011). However, this is recognized as a difficult species to assess (e.g. because the population dynamics are very rapid, spawning may be continuous, the selectivity is generally uninformative about year-class strength, and relative abundance indices derived from pole and line and purse seine fisheries are generally considered to be less reliable than those derived from longline fisheries). These problems have led the IATTC to move away from model-based assessments to provide advice on the basis of data-based indicators (Maunder 2009). It is possible that the IOTC may choose to go in a similar direction, however, with the success of the RTTP-IO, an attempt at integrative modelling is certainly warranted.

A key feature of this work is the illustration that the stock status inferences are sensitive to several poorly-quantified model assumptions. The assessment presents the implications of many alternative assumptions, and their interactions. The stock status advice represents a synthesis of models, which are combined with a plausibility weighting scheme (initially proposed by the authors and subsequently revised and agreed by the broader WPTT).

Fishery History

The Indian Ocean SKJ catch history is shown in Figure 1. Catches increased steadily from the 1980s to a peak in 2006, and catches in 2007-9 have been steady at 73-76% of the peak. Figure 3 illustrates the spatial distribution of the catches (the locations are not very accurate for most of the coastal fleets).

The Maldives has sustained a pole and line (PL, bait boat) SKJ fishery for many centuries, with catches increasing dramatically due to mechanization and deployment of larger vessels starting in the 1970s, and installation of anchored FADs in the 1980s. The Maldives has experienced substantial catch declines since the peak in 2006, for reasons that are not entirely clear. Adam (2010) suggests that this may reflect declining SKJ abundance, limitations to bait availability or changing economic incentives (e.g. high fuel prices).

There has been a rapid increase in SKJ catches with the introduction of the purse seine fleets in the 1980s (e.g. Pianet et al. 2011). The European/Seychelles PS catch has fluctuated considerably since around 2000 without a clear trend. Piracy in the prime fishing areas near Somalia has affected the way the fleet operates, but it is not clear how much effect this has had on recent catches. There has been a steep decline in the nominal purse seine FAD-set catch rates since 2002, however, this decline is not seen in the free school sets from the same fleet, and the interannual catch rate variability is very high (Figure 15, Dorizo et al. 2008).

A substantial portion of the total catch is taken by a mix of artisanal and semi-industrial gears, with minor catches dating back before the pre-industrial period. For the assessment, these fleets have been pooled together, in the heterogeneous *Other* fleet. The bulk of the recent catch in this fishery is from the gillnet fisheries of Sri Lanka, Indonesia, Iran and Pakistan. These fleets were mostly operating in coastal waters historically, but long distance trips to international waters have been noted in recent years (spatial data is largely unavailable for these fleets). The aggregate catches of these fleets has been increasing steadily (with a possible minor decrease in the most recent 2-3 years).

Methods

Assessment Philosophy

This assessment is guided by a number of general principles:

- Model sensitivity – Fisheries assessment models tend to be over-parameterized (more unknowns than informative data) such that it is inevitable that somewhat arbitrary constraining assumptions are required to produce tractable estimators (e.g. Schnute and Richards 2001). Unfortunately, results are often sensitive to these arbitrary assumptions, and the implications of these sensitivities (and their interactions) should be formally admitted within the assessment advice, rather than attempting to identify a uniquely preferable model.

- Model complexity – For most modelling problems, there is an optimal level complexity that provides the best results, depending on the objectives (e.g. Walters 1986). However, it is often not easy to identify the optimal complexity for a given problem. This is often described as a bias-variance trade-off. Very simple models (e.g. deterministic production models) may appear to provide very precise estimates, but are structurally limited and may not be able to describe relevant dynamics in sufficient detail, resulting in serious estimation biases. In contrast, very complicated, highly disaggregated models have the potential to describe a range of biologically realistic features. But the data are usually insufficient to estimate the necessary biological characteristics, resulting in a high estimation variance (though this may not be evident in the variance estimates for any individual model, because of strong constraining assumptions). e.g. Without adequate tag releases and recoveries (and reporting rate estimates) outside of the core purse seine area, it is difficult to provide useful estimates of movement into and out of this region.

- A small amount of good data can be more informative than a whole lot of bad data. e.g. Rather than treating each fleet independently, we have focussed on 3 core fleets with the best size composition sampling, tag reporting rate estimates from seeding experiments, etc. The other fleets have been pooled into one poorly sampled aggregate. The aggregate selectivity for this latter fleet might not be well estimated, but the size samples are given very low weight in the objective function. This should ensure that the stationary selectivity assumption for these fleets are not very influential in the parameter estimation (an alternative approach might be to estimate variable selectivity over time). Further analysis of the available data would be required to understand the best options for further partitioning these fleets.

- When different data sources conflict, there is a good chance that the best answer is not the average of the two. At least one of the datasets may be fundamentally wrong, or misleading in the context of the model, and discarding different series in turn may lead to a more appropriate coverage of the uncertainty in the system. (e.g. Schnute and Hilborn 1993)

- The myth of objectivity – while modern fisheries models draw on a sound theoretical framework of statistical inference, we rarely have the sort of sample sizes or understanding of stochastic processes to meet the formal statistical requirements. Likelihoods provide a useful tool, but are not usually rigorously applied in fisheries models. Inevitably subjective decisions are required in the modelling process, and these should be clearly stated. The weighting table for assessment assumptions in the final assessment synthesis is the most obvious example in this case. All assessments include subjective weightings, the difference here is that more non-zero values are included.

- In fisheries assessments, there is generally an expectation that more data and analyses will lead to a reduction in uncertainty. Paradoxically however, this often is not the case (e.g. for reasons mentioned above). The perception of uncertainty often increases in relation to the amount of time spent examining a problem. Comprehensive efforts to honestly admit various sources of uncertainty often leads to the conclusion that it cannot be appreciably reduced, and that effort should be spent evaluating management options that are robust to this uncertainty to the extent possible (e.g. using methods such as Management Strategy Evaluation, MSE).

Software

The model was implemented with the 32 bit MS Windows version of Stock Synthesis V3.22a (SS3). Technical details are (mostly) described in Methot (2000, 2009). This is a powerful and flexible stock assessment package with efficient function minimization, implemented with AD Model Builder (http://admb-project.org/). For the models explored here, function minimization generally required ~6 minutes on a 3.0 GHz PC (not including inverse Hessian calculations).

Data and Model Assumptions

For continuity of the arguments, related data and model assumptions are described together. The SS3 template control file is appended (attachment 2) to resolve incomplete or ambiguous descriptions of the models.

Spatial Structure

The population dynamics are spatially aggregated. There remains an open question of the appropriate spatial structure to use for this tuna population (and most others). Qualitatively, the tagging data suggest that SKJ migrate quickly (*e.g*. Figure 4, Figure 5). Unfortunately, the limited distribution of tag releases, and small number of returns (and absence of tag reporting rate estimates) outside of the European/Seychelles purse seine fleets (mainly operating in the western equatorial Indian Ocean) makes it difficult to quantify large-scale movements at this time. It is notable that basin-scale movements into the eastern Indian Ocean were observed from the EU/Seychelles fleet (Figure 4), even though very little fishing occurred in this area. Potential concerns for the spatial structure include:

- The Maldives PL CPUE index is derived from the relatively small area of the Maldives EEZ. Even if this series is a reliable indicator of abundance for the Maldives region, it may only be indicative of the broader population to the extent that relative density of the distribution remains stable among years (a common assumption in CPUE standardization, but the spatial extrapolation is particularly large in this case).

- Worm and Tittensor (2011) suggests that there may have been a range contraction in the Indian Ocean SKJ population (contraction from the southern periphery toward the core area). If this is correct, it would be consistent with a hyperstable abundance index, as the CPUE signal in this assessment is derived only from the Maldives region. However, there are reasons for doubting the analysis. As noted by the authors, their conclusion was largely driven by longline data, and longline fisheries catch very few SKJ. There are also known changes in targeting and data reporting standards over time. Figure 14 shows the reported SKJ catch, effort and nominal CPUE over time for the LL fleets. The erratic patterns strongly suggest that reported longline CPUE is not indicative of SKJ abundance in general, and may not be very informative about presence/absence either.

- Recent genetic analyses (Dammannagado et al. 2011) have suggested that there might be two (or more) SKJ populations in the Indian Ocean. If this is correct, an aggregated assessment may not be appropriate. But we currently do not have enough information to know what the appropriate structure should be.

To partially admit the concerns about multiple sub-populations with limited spatial mixing, we included a sensitivity analysis, in which it is assumed that there are discreet populations west and east of 80°E, which is roughly consistent with Dammannagado et al. (2011). This was accomplished by removing the catches and samples from the eastern IO, and running the model for the western IO alone. This is only an approximation for the western sub-population, because: i) the small amount of EU/SEZ operations in the eastern IO (including tag recoveries) were assumed to be part of the western population, and ii) all of the Sri Lankan fleet was assumed to operate in the east (it is known that Sri Lankan vessels operate in the west as well, but the Secretariat has limited information describing the spatial distribution). An equivalent model could not be fit for the eastern IO because there are no abundance indices, and minimal tag releases or recoveries in that region. Model options are defined:

- io – whole Indian Ocean
- we – western Indian Ocean only

Temporal units

Data were disaggregated by quarter (quarter 1 = Jan-Mar), and the model was iterated on quarterly time-steps, to represent the rapid dynamics of this population, over the period 1952-2009 (plus 10 years of projections).

Age Structure

The SKJ population was represented with an annual/four season configuration. SS3 can resolve many population features on a seasonal basis (e.g. recruitment, fishery removals, M_{age}). However, the tags can only be assigned to annual age classes (discussed below). The alternative of defining quarterly time periods as years is worth future consideration.

The age structure in 1950 was assumed to be in unfished equilibrium (ignoring the small artisanal catches that were taken historically).

Sex Structure

The model was sex-aggregated (and reported spawning biomass is the summed mass of all mature fish).

Fishery definitions

Four fleets were defined on the basis of gear type and area of operation (Figure 1):

1. PL – Maldivian Pole and Line fleet.
2. PSLS - FAD/log associated Purse Seine (PS) sets from the EU/Seychelles fleets.
3. PSFS - unassociated PS sets from the EU/Seychelles fleets.
4. Other - includes all other fleets, primarily gillnet fleets from Sri Lanka, Iran, Indonesia and Pakistan, but also non-EU/Seychelles PS fleets, and small coastal fleets (including non-PL fisheries from the Maldives), and a trivial catch from longliners.

The *Other* fleet is a heterogeneous mix of fisheries. However, further partitioning this fleet is not expected to make much difference to the analysis because the size composition data are poor for most of these fleets. None of these fleets are considered to be informative with respect to catch rates or tag recoveries, and we would not expect that the relative year-class strength information derived from the stationary selectivity assumption to be reliable.

Total catch

The total catches were calculated by the Secretariat (Herrera et al., 2011). This is a complicated process that requires a number of approximations and substitutions for fleets with poor data (including those discussed below under size composition data). The catch time series for the 4 fleets is shown in Figure 1. Data from important fleets was not available for 2010 in time to be included in the assessment.

The model uses the standard difference form of the Baranov catch equations to describe the populations dynamics. Catch in mass was used in the model for all fleets, and was assumed to be known essentially without error and extracted precisely to within the numerical tolerance in the iterative solving of the (SS3 'hybrid') catch equations.

CPUE as a relative abundance index and catchability assumptions

Kolody and Adam (2011) describe the standardized Maldives PL CPUE series adopted as the relative abundance index for the period 2004-9. There are a number of concerns about using this CPUE series in this assessment:

- The time series is very short. While it does cover the peak fishery and recent years, it is not informative about relative abundance in the period during the industrialization of the fishery, beginning in the 1980s.
- The Maldives PL CPUE index is derived from the relatively small area of the Maldives EEZ, and may not be a good index for the broader population.
- The nature of the relationship between pole and line CPUE and abundance is unclear, particularly since most of the effort is thought to be targeted on anchored FADs in recent years. There is no known trend in the use of FADs during this period, but in general, FAD fishing might be expected to cause a hyper-stable relationship between CPUE and abundance.
- There were a number of irregularities in the PL data analysis that could not be resolved. In particular, the large number of positive effort, zero catch observations could not be explained. This probably reflects a combination of effort misreporting (vessels that falsely reported fishing to avoid a license fee), and gear misreporting (many pole and line vessels also operate as handliners which target reef fishes or large yellowfin tuna).

Originally, two CPUE series with somewhat different trends were adopted to represent the most important uncertainties from the Maldives CPUE analysis, however, the trends were not sufficiently different to justify parallel analyses.

Standardization of CPUE indices derived from PS fisheries is problematic, but we expect that such indices would be at least as good as those derived for the PL fishery, because those fleets operate over a broader area, and encompass a broader time period. In some of the initial models, the nominal free school PS series from the French fleet was included (Chassot et al. 2011) in combination with the PL series.

The standardized PL and nominal French PSFS CPUE series are compared in Figure 13. Both series indicate a strong peak around 2005-6. The PSFS series suggests a stronger decline since that time, but the proportion of free school sets has also declined dramatically in recent years. There are three very strong cycles in the PSFS series which may suggest high recruitment variability. These peaks are generally evident in the nominal PSFS CPUE observed with all of the main PS fleets combined, but are not obvious in the nominal PSLS CPUE (Figure 15).

Options examined in the exploration of uncertainty:

- U0 = preferred PL CPUE series only (zero catch observations were treated as indicative of targeting other species)

- U1 = preferred PL CPUE series and PSFS series
- U2 = sensitivity PL CPUE series only (zero catch observations treated as SKJ targeting)

Quarterly indices were used for the PL CPUE, with an assumed CV of 10% (lognormal observation errors). Only annual series were available for the PSFS CPUE, and these were (arbitrarily) assigned to quarter 2 only (also assumed CV of 10%). We do not actually believe that the CV of 10% is realistic for either of these fisheries. However, in general, we would not have much confidence in stock status inferences from models that fail to fit the core features of the relative abundance series.

Size Composition Data

The catch-at-length data were compiled by the secretariat (Herrera et al., 2011). This process involves a number of approximations and substitutions because some fleets have very poor data, and some fleets do not report data at the appropriate resolution.

Catch-at-length distributions aggregated over time, and time series of mean length are shown by fleet in Figure 16. There is no obvious pattern to indicate strong seasonal recruitment. The bimodal distribution in the PL fishery suggests a heterogeneous mix of two life history stages. Brief exploration did not reveal any obvious spatial/seasonal explanation for the two modes, but this is worth further investigation. The recent decline in mean size in the *Other* fleet probably reflects the erratic sampling from this fleet. In the future it might be worth further partitioning these fleets to reflect likely differences in selectivity to the extent possible (but this is expected to be a low priority for the assessment overall).

Catch-at-length sample sizes are often very large, however, in these sorts of models, it is generally a bad idea to allow the size composition data to be weighted too highly. The size composition data influence these models in two main ways: i) ensuring that the correct age distribution is removed from the population by the fishery, and ii) providing information about relative year class strength through the stationary selectivity assumption. The second point in particular can lead to misleading inferences for a number of reasons, including: selectivity (gear selectivity combined with spatial distributions and environmental variability) is often not stationary, samples are often not really representative of the catch, and growth/mortality assumptions may not be appropriate.

In this assessment, all length composition samples were down-weighted to a considerable degree, and a range of options were explored to test if the model was sensitive to these assumptions. The *Other* fleet was further downweighted, because it represents a heterogeous mix of fisheries, many of which are poorly and/or inconsistently sampled. Different input sample size assumption options were examined in the model grids:

- CL1: $N_{PL,PS\ input} = \min(N_{obs}/10, 1000)$; $N_{Other,input} = \min(N_{obs}/10, 100)$
- CL5: $N_{PL,PS\ input} = \min(N_{obs}/10, 500)$; $N_{Other,input} = \min(N_{obs}/10, 50)$
- CL2: $N_{PL,PS\ input} = \min(N_{obs}/10, 200)$; $N_{Other,input} = \min(N_{obs}/10, 20)$
- CL04: $N_{PL,PS\ input} = \min(N_{obs}/10, 40)$; $N_{Other,input} = \min(N_{obs}/10, 4)$

The catch-at-size distributions are aggregated in 22 bins of length 3 cm (≤20 to >80 cm). The multinomial likelihood was used in the model, with an additional 1% added to each length bin (predicted and observed) to make the term more robust to outliers.

Selectivity

A non-parametric, pseudo-length-based function was estimated independently for the selectivity of the 4 fleets. Selectivity parameters were estimated for a series of length-class nodes, with cubic spline interpolation between nodes (the default specification was adopted in which the node spacing and initial parameter values were calculated within SS3). The length-based concept is applied in the calculation of the predicted catch-at-length distribution. However, the length-based selectivity is converted to an age-based selectivity for purposes of removing the appropriate portion of the population in the catch (i.e. cumulative effects of length-based selectivity on the length-at-age distribution are not described in the model). The function is flexible enough to represent dome-shaped, monotonically increasing (e.g. logistic), and polymodal functions (and was motivated by the clear bimodal distribution of the PL fleet). Seven nodes were estimated for the PL fleet, and 5 nodes for the PSLS, PSFS and Other fleets.

Given the high resolution information on selectivity that may be available through the tagging studies, the possibility of estimating temporal variability in selectivity was explored for the informative fleets (1-3). Selectivity options were defined:

- ss: stationary selectivity for all fleets
- sa: annual selectivity deviates for the PSLS and PSFS fleets 2004-9

As noted in the results below, it may be worth considering partitioning some fleets by quarter to represent seasonally-varying selectivity, but there was not pursued.

Size-at-Age

Two relationships for mean length-at-age were examined (Figure 6), representing updates of previous analyses, but using the most recent tagging data. The two curves followed the standard von Bertalanffy growth function, with Length(a=0) fixed at 20cm. If the absolute age is wrong because of error in the Length(a=0) assumption, this would manifest itself primarily as an incorrect lag between the timing of spawning and recruitment. Since the stock recruitment relationship is highly uncertain, and the lag error is likely to be short for this species, this is expected to have a negligible impact on the assessment (furthermore, in the current configuration, SS3 only calculates spawning biomass once annually, even with quarterly recruitment). The two growth curve options were:

- L70 – L_{inf} = 70cm, k = 0.37 (A. Anganuzzi and J. Million, IOTC Secretariat, pers. comm., update of Hillary et al. 2008)
- L83 – L_{inf} = 83cm, k = 0.22 (Eveson 2011, update of Eveson and Million 2008)

The L70 curve was estimated with unconstrained L_{inf}. In recognition of the mode of large SKJ observed in the (poorly sampled) longline fishery (Figure 7), the L83 curve was fit with fixed L_{inf} = 83 cm. For comparison, we note the L_{inf} values for the Atlantic 95-97 cm (ICCAT 2009) and Western Pacific 80cm (Hoyle et al. 2011).

The mass-length relationship is adopted from Secretariat (2005): $mass = 5.32\text{E-}6\ Length^{3.35}$.

Maturity

Maturity estimates from Grande et al. (2010) were adopted: invariant over time, with 50% maturity at length 38 cm. This is very similar to the 40 cm value reported in the WCPFC assessment (Hoyle et al. 2011), and the knife-edge age 2.0 y assumption adopted for the Atlantic (ICCAT 2009).

Stock Recruitment

A Beverton-Holt stock recruit relationship was assumed (the SS3 'flat-top' version in which R_t does not increase beyond R_0 if SB_t happens to exceed SB_0). It was assumed that spawning biomass is equal to the mass of the mature population. In recognition of the difficulty in estimating steepness (*h*), different fixed values were examined in the model grids:

- h55: h = 0.55
- h65: h = 0.65
- h75: h = 0.75
- h85: h = 0.85
- h95: h = 0.95

Only the h=0.75 option was assumed for the initial sensitivity testing. However, all values were included in the stock status grid, and differentially weighted by plausibility in the final stock status synthesis.

Deviations from the stock-recruitment relationship were assumed to follow a lognormal distribution, and a range of options were explored:

- r0 = deterministic recruitment
- rqs = annual deviates from 1983-2008 (estimated $\sigma_{R,\ annual}$), with some flexibility in quarterly deviates from 2004-2008 ($\sigma_{R,season}$ = 0.1)

The period 2004-2008 was given extra recruitment flexibility because of the informative tag data during this period. The lognormal bias correction ($-0.5\sigma^2$) for the mean of the stock recruit relationship was applied during the period 1983-2008.

Tags

Tag Release and Recovery Data

Hallier and Million (2009) provide an overview of the RTTP-IO tagging project (~78000 SKJ releases). In 2011, additional tagging data (~22000 SKJ releases) from several small-scale projects were merged with the RTTP-IO database. The largest number of small-scale SKJ releases were in the Maldives (Jauharee and Adam 2009), but SKJ were also released near Lakshadweep, Mayotte, Sumatra, offshore eastern Indian Ocean, and the Andaman Islands. Table 1 describes key features of the two tagging data sets explored in the assessment. Figure 4 and Figure 5 provide graphical summaries of tag releases, recoveries, time at liberty and net displacements.

We have more confidence in the RTTP-IO data than the small-scale tagging programs, because the RTTP-IO has a much larger number of tags, released by more experienced taggers under more consistent conditions, and a database that has been gradually developed over time by the IOTC

Secretariat. In contrast, the small-scale tagging programs were only recently merged with the RTTP-IO database (such that there may be undiscovered errors), we have no tag shedding estimates for these fleets (very few fish were double-tagged, and no analysis has been conducted to date), and tag-induced mortality may be higher for some small-scale programmes (e.g. particularly for the smallest fish, and purse seine releases in the eastern Indian Ocean). However, there are possible benefits to the inclusion of the small-scale tagging programmes due to i) substantially more tags, ii) longer release time series, and iii) inclusion of a broader range of fish sizes/ages. Additional insight into spatial dynamics may also be possible, but not in the context of the current spatially-aggregated assessment.

The two different approaches for using the tag data were compared, with model grid definitions:

- rttp – RTTP-IO releases, PSLS and PSFS recoveries
- rtss – RTTP-IO and small-scale releases, PL, PSLS and PSFS recoveries

We have the most confidence in the tag recovery data from the PSLS and PSFS fleets, because of the reporting rate estimates derived from the tag seeding experiments (e.g. Hillary et al. 2008; updated by A. Anganuzzi, IOTC Secretariat, pers. comm.). Quarterly point estimates of the reporting rates were included as shown in Table 2.

We do not have reporting rate estimates from the PL fleet. However, as appreciable numbers were returned, it is thought that recoveries from this fleet might still be informative. In model runs that included the PL recoveries, a stationary reporting rate for the PL fleet was estimated (with a very diffuse prior).

In general we have a poorer understanding of the operations of the *Other* fleets, and there are no reporting rate estimates. These recoveries were excluded from the analyses, and reporting rates set to 0 (the PL fleet received a similar treatment, when the RTTP data alone were used).

Several irregularities in the tagging data were addressed in the following ad hoc ways:

- A small number of SKJ releases were omitted from the analysis because of:
    - no recorded release length,
    - no recovery fleet,
    - no release or recovery date (or recovery precedes release)
- A small number of releases recaptured by the tagging vessels were ignored.
- The EU PS tag recoveries of unknown set-type were assigned a set-type according to the total proportion of known FS and LS set types in the PSFS and PSLS fisheries (by quarter).
- The coastal fleets on the east coast of Africa, *i.e.* in Kenya and Zanzibar, have presumably intercepted some tags near the primary release location, before they were fully mixed with the broader population. This represents an unknown, but probably small number of tags.

Tag Recovery pre-processing for Stock Synthesis

The model tracks multiple homogenous tag groups over time, where a tag group consists of all individuals of a particular age class released in a particular year/quarter. For the 2-3 fleets which were considered informative, each tag recovery observation for a particular tag release group and recovery period was calculated:

$$R_{LS}^{Total} = \frac{1}{r^{sea}} \quad (R_{LS}^{sea} + \hat{P}_{LS}^{sea} R_{unk}^{sea}) + \frac{1}{\hat{P}_{outside}} \left(\frac{1}{r^{SEZ}} \quad (R_{LS}^{SEZ} + \hat{P}_{LS}^{SEZ} R_{unk}^{SEZ}) \right)$$

$$R_{FS}^{Total} = \frac{1}{r^{sea}} (R_{FS}^{sea} + (1 - \hat{P}_{LS}^{sea}) R_{unk}^{sea}) + \frac{1}{\hat{P}_{outside}} \left(\frac{1}{r^{SEZ}} \quad (R_{FS}^{SEZ} + (1 - \hat{P}_{LS}^{SEZ}) R_{unk}^{SEZ}) \right)$$

$$R_{PL}^{Total} = R_{PL}^{MLD}$$

where:

subscripts indicate fishery/landing types (LS = EU/Seychelles PS log set, FS = EU/Seychelles PS free school set, unk=unknown set-type, PL = Maldivian Pole and Line, outside = EU/Seychelles catch landed outside of the Seychelles),

superscripts indicate recovery locations (sea = aboard fishing vessel, SEZ = port of Seychelles, MLD = Maldives).

For readability, scripts denoting tag release group and recovery time period are omitted:

R^{Total} = number of 'observed' recaptures for a particular fishery (and tag group and time period), as input to the model.

r = the reporting rate. Note that for PS tags removed at sea, r was assumed to be 1.0. Reporting rates from the Seychelles are listed in Table 2. Within the model, PS reporting rates were set to 1.0, while PL reporting rates were estimated as a free parameter (and ignored in the pre-processing).

$\hat{P}_{LS}$ is the proportion of PS tags recovered from unknown set-type which are actually of set-type LS, estimated as the proportion of tags of known set-type LS recoveries at sea of all known set-type recoveries at sea (by quarter).

$\hat{P}_{outside}$ is the scaling factor to account for the EU PS recaptures not landed in the Seychelles, estimated by the mean of the proportion of EU PS catch landed in the Seychelles relative to the total EU PS catch (by quarter).

These calculations provide a point estimate for the total number of tag recoveries that should have been made in the PS fisheries, such that the reporting rates can be set to 100% in the model. In part, this represents a work-around solution because *Stock Synthesis* cannot represent temporal variability in reporting rates. This ignores potential variance implications, but given that the reporting rates were generally very high for the PSFS and PSLS fleets, this is probably not important. The alternative work-around solution of defining a different fleet for each recovery time period could be employed, but this extra complication does not seem justified in this case.

Tag Mixing
In the population model, tagged fish are assumed to have identical dynamics to the general population. We expect that a reasonable period of mixing is required before this assumption would be valid. Figure 5 suggests that maximum tag displacements within the core PS area reach a plateau within a few weeks of release. If this displacement was entirely due to random movement, it might suggest that 1 full quarter would be sufficient to achieve full mixing. However, the figure does not account for the distribution of fishing effort (i.e. if all the gear is deployed a long way from the release site, all recoveries will suggest rapid movement, but they might not represent the movement of the general population). Also, directed seasonal migration can cause large displacements, without necessarily resulting in uniform mixing. Sensitivity to the mixing assumption was examined with mixing periods of 2 and 4 quarters (as shown in Figure 5, there are so few tag recoveries with a time of liberty exceeding 4 quarters that longer mixing periods probably do not contain much useful information):

- t2 = 2 quarter mixing period
- t4 = 4 quarter mixing period

Tag Age Assignment
The length of release of each tag is recorded in the database, but the model dynamics require tags to be assigned ages. The age of each individual tag was estimated from the mean growth curve, and a unique tag group was defined for each age/year/quarter release strata. The age estimation occurs external to the model (in a process similar to 'cohort-slicing' that is sometimes used to infer catch-at-age from catch-at-length data). Note that this annual resolution of tag age assignments might introduce substantial aggregation errors for this species (i.e. tags of age 1.0 and 1.75 are assigned identical biological characteristics, but in reality may be very different). It might be desirable to assign tags to quarterly age classes, however, this was not done in the first instance because:

- Quarterly age assignments lead to a very large number of tag release events.
- Given the large degree of variability in length-at-age, the quarterly age assignments are not very accurate (particularly for larger/older fish).
- SS3 automatically truncates fractional tag age assignments to the nearest annual age class. This could be circumvented by reconfiguring the model with quarters defined as years.

Tag-induced Mortality and Shedding
Following Gaertner and Hallier (2009), we assumed that the chronic tag shedding was very low (0.015 y^{-1}). The initial tag shedding was (mistakenly) omitted, but represents a trivial number of tags (i.e. initial retention estimated as 0.987).

Tag recovery likelihood
The negative binomial distribution allows for overdispersion relative to the ideal, independent movement, fully-mixed, tag recovery distribution (*e.g.* which might be expected to conform to the Poisson distribution). However, note that increasing the overdispersion to a very large number is not the same as down-weighting the tag recovery likelihood term. Three options were explored for the overdispersion parameter τ (applied equally across all tag groups):

- od02 : τ = 2 (close to ideal Poisson tag recovery assumptions)
- od20 : τ = 20

- od70 : τ = 70

Note that the ADMB log_negbinomial_density function is parameterized in terms of $\tau = \sigma^2/\mu$; $\tau>1$, and this is equivalent to the R function dnbinom(x, size, mu) where $\sigma^2 = \mu + \mu^2/size$, pr = size/(size+μ).

Natural Mortality

Given the reliance of this assessment on the tagging data, and the general success of the RTTP-IO, we considered the estimation of M to be worth attempting. M_{age} was described by a series of annual nodes (with linear interpolation for quarterly ages between nodes). Parameters consisted of a normal prior (SD=1) with mode 0.8 for the first age, and deviations from the preceding age for subsequent ages (prior log(dev) mean = 0, SD=1). For the RTTP data, nodes were estimated for ages 1-4, with younger and older ages fixed equal to age 1 or 4. When the small-scale data were included, age 0 was also estimated (i.e. due to the presence of substantial numbers of smaller fish).

Models with the M_a estimates from the independent Brownie tag analysis (Eveson 2011, preliminary values from the L_{inf} = 83cm option) and recent ICCAT assessments (ICCAT 2009) were also included, with the following grid definitions:

- MeA1 – M estimated ages 1-4+ (flat prior)
- MeAs – M estimated ages 0-4+ (flat prior)
- MAt – M equal to the ICCAT value (0.8 all ages)
- MB – preliminary Brownie estimate for the L_{inf} = 83 cm model.

Reference case SS3 M_a estimates are compared with the fixed values in Figure 11 and the distribution of estimates from the stock status grid are shown in Figure 42.

Model Specifications

The assessment is described in several stages, with combinations of assumption options summarized in Table 4 (abbreviations in Table 3):

1) Reference models (ref1-ref4) were selected to demonstrate typical dynamics, diagnostics and contrasting features. These models should not be considered preferential.

2) Explore sensitivity to the size composition assumptions (grid A1, balanced design of 8 models). Models were specified that deviated with respect to 3 options:
    - 2 input catch-at-length sample sizes
    - 2 growth curves
    - 2 selectivity options

3) Explore sensitivity to the tagging assumptions (gridA2, balanced design of 24 models), including:
    - 2 growth curves
    - 2 tagging programme options: i.e. inclusion/exclusion of small-scale tagging programmes and Maldives PL tag recaptures
    - 3 negative binomial overdispersion parameters
    - 2 tag mixing periods

4) Explore sensitivity to the CPUE series and recruitment variability (gridA3, balanced design of 8 models). The intent was to see if the estimation of recruitment variability makes a big difference relative to stationary production dynamics (e.g. in relation to the question of whether or not we can confidently estimate recruitment deviates with the available data), and to demonstrate how much influence the nominal PSFS CPUE series is likely to have if included.

5) Stock Status estimates (Grid A4, balanced design of 180 models) including seemingly important, plausible options from 1-4 above, plus a range of stock recruit steepness and M options. The final stock status estimates are derived from a synthesis of the 180 models from gridA4. Key summary diagnostics are considered, and a somewhat subjective (but hopefully transparent) weighting scheme is adopted. The stock status summary consists of the weighted estimates of B_{2009}/B_{MSY}, C_{2009}/MSY (as a proxy for F_{2009}/F_{MSY}), presented in a Kobe phase plot, and 3 and 10 year constant catch projections presented in a Kobe 2 Strategy Matrix decision table (See *Uncertainty Quantification* and *Projections* below).

6) A subset of models were refit for the spatial sensitivity trial which includes only the western Indian Ocean.

In general, models were compared on the basis of:

- CPUE RSME (Root Mean Squared Error) – describes the fit to the CPUE series. Ideally, this value should be very similar to the assumed SD of the CPUE observation errors. In all of the models discussed here, the CPUE RMSE of the Maldivian PL fleet was very similar (and the quality of fit was good but not as good as the input CV of 10%). Inclusion of the nominal PSFS CPUE series had very little effect on the fit to the PL CPUE or size composition data.
- Output ESS (Effective Sample Size) – describes the fit to the size composition data for each fleet (average of annual observations). ESS indicates how well the predicted size composition data fits the observations (irrespective of the assumed sample size). An ESS of 200 means that on average, the fit is as good as would be expected for a true random sample of 200. The ESS does not explicitly distinguish between random noise and systematic lack of fit (and it is the latter quality that we are usually most interested in). However, when used as a relative index to compare models fit to the same data set, lower ESS is usually associated with a higher systematic lack of fit.
- Recruitment trend – this measure describes the systematic lack of fit that arises when the recruitment deviates are estimated for this specific situation (the RMSE and auto-correlation would be of more general interest in most applications). The intent is to identify suspicious trends in recruitment that are not supported by either the tagging or CPUE data.
- Tag recovery sums of squares – sum of the squared deviations between predicted and observed tag recoveries as a rough index of the tag fit that is not dependent on the overdisperion assumption. This was not reported because it is not an appropriate metric for comparing models with different growth curves or based on different tag release programmes.
- Likelihood terms –The likelihoods are useful for qualitative discussions of which options appear to be more compatible, etc., but literal interpretation of likelihoods in these models

will generally lead to some counter-intuitive results, and over-optimistic perceptions of precision (e.g. see below). The overall objective function values (likelihoods and priors) are presented for some subsets of results that are comparable in principle (i.e. use the same data in a consistent fashion), to discuss the evidence for steepness and natural mortality options.

MSY Calculations

MSY, B_{MSY}, F_{MSY} and equilibrium yield estimates are calculated on the basis of the F_{age} distribution estimated for 2009. The argument might be made that an average over several recent years may be more appropriate in general. However, this may not be true if there are strong trends in the catch distribution among fleets (which seems to be occurring in Indian Ocean tuna fisheries currently).

Seemingly due to the unusual dynamics of this fishery (see Results and Discussion), the SS3 F_{MSY} calculations usually failed, either due to a blatant numerical problem, or a more subtle inability to find the correct value (these calculations are independent of the overall function minimization). As a consequence, *MSY* and B_{MSY} values were extracted from the peak of the equilibrium yield curve. Instead of F_t/F_{MSY}, we report the proxy C_t/MSY. This proxy is potentially misleading because: i) it may incorrectly suggest F/F_{MSY} is exceeded if biomass is high (in the early part of the fishery or following large recruitment), ii) it may incorrectly suggest that $F<F_{MSY}$ when the stock is highly depleted, and iii) due to flat yield curves, it is possible that $C \approx$ MSY even though $F<<F_{MSY}$.

Uncertainty Quantification

The stock assessment process often appears to involve a haphazard search for one or a very few model specifications which appear to be plausibly consistent with the data, and a priori expectations. Most commonly, some statistical description of uncertainty are provided for the quantities of interest under the assumption that a particular model is 'correct' (*e.g.* likelihood profiles or Bayesian posteriors). However, in this case, there are some fundamental problems with interpreting the likelihoods literally: *i)* the data are not the same for all models (*i.e.* changing the input sample size between two models invalidates a direct comparison of the likelihoods, and the use of AIC, BIC etc.), *ii)* these are complicated highly parameterized models with many assumptions that are poorly justified, usually with evidence of systematic failures in the model fit, such that a literal interpretation of the likelihood is not justified, and *iii)* it is known from simulation studies, that some important parameters cannot be estimated reliably with the type of data and observational contrast that are typically available (*e.g.* steepness, M).

The approach used here focuses on the model selection uncertainty, which is usually much greater than the statistical uncertainty conditional on any individual model. We only consider the Maximum Posterior Density (MPD) estimates, and stock status descriptors are derived from a weighted combination of the MPD estimates. This is similar to the approach used by the CCSBT (originally in the context of stock assessment, and subsequently in the development of operating models for Management Strategy Evaluation), and introduced to the WPTT in 2010 for BET (Kolody et al. 2010).

A comparison of the two approaches might be considered by an analogy of observing a large street mural at night. The first case is analogous to observing the part that happens to fall under the streetlamp. The second case is like walking around with a little flashlight. The view is never as impressive in the second case, but one is less likely to miss something important. If time permitted, it would have been preferable to consider the two sources of uncertainty together.

Projections

Projections were conducted from the MPD estimates of all models at catch (in mass) of 60%, 80%, 100%, 120% and 140% of 2009 levels (assuming relative F_{age} from 2009). The projections used deterministic recruitment from the stock recruitment relationship (starting in 2009). This approach ignores two important sources of uncertainty: statistical uncertainty in the parameter estimates, and recruitment variability. However, as in the previous section, the approach does incorporate the model selection uncertainty, which may exceed both of these sources of uncertainty. Three and Ten year projection results are summarized in a management decision table (Kobe 2 Strategy Matrix). As with the current stock status reporting, C_t/MSY is reported as a proxy for F_t/F_{MSY}.

5. Results and Discussion

General Comments on model performance

Other than the F_{MSY} calculation problems, the SS3 software seemed to perform well in the context of this assessment. Only a subset of models was examined in full detail, while automated checks were applied to identify:

- Large maximum gradients at the final solution. These values generally suggested that the solution was near the minimum (1E-2 – 1E-6), but there were some obvious minimization failures (notably when temporal variability in selectivity was estimated).
- Parameters on bounds – there were frequently two problems. $M_{a=0,1}$ was always questionably low for the RTTP data, near the lower bound of 0.075 in some cases. A parameter defining the terminal gradient in one of the cubic spline selectivity functions was sometimes flagged. This did not seem to impair the fit to the size composition data (and may reflect a reporting bug in this new SS3 feature as the reported parameter estimate usually seemed to be within the reported bounds).
- Outlier behaviour with respect to fitting the catch-at-length and CPUE data was summarized with the RMSE and ESS indices.

As a general test of the function minimizer performance, one of the more complicated models (i.e. with M estimated: io_h75_MeAs_L83_U0_rqs_t2_od20_ss_rtss_CL04) was refit 50 times, using the same phased parameter estimation sequence, but different permutations of initial values for:

- virgin recruitment (5 values spanning 3 orders of magnitude)
- M (5 values, 0.4, 0.6, 0.8, 1.2, 1.6, initially constant with age)
- selectivity (2 options, SS3 cubic spline default settings, or flat selectivity for all fleets)

There were 3 general outcomes from this convergence test. The batch files for all models with the highest initial virgin recruitment value aborted abnormally, providing no results (the remaining 40 minimizations ran normally). The models with the flat initial selectivity option all converged near the same, unrealistic parameter space (i.e. extremely high biomass, with clearly poor fits to the data).

The remaining 20 models all converged to essentially the same plausible parameters. It is notable that the maximum final gradients for these 20 minimizations spanned a substantial range (0.02 – 0.0003), but the stock status reference points were equal to 3 significant figures.

The optimistic interpretation of these results suggests that: i) the SS3 function minimizer consistently converges to the same minimum from a broad range of 'reasonable' initial values, ii) minimization failures tend to be extreme and easy to identify if they do occur, and iii) solutions with marginal convergence criteria (e.g. maximum gradients ~ 0.02) were very similar to the minimizations that were more clearly successful. However, it is unclear how general these results are. The SS3 automated option for specifying the node structure and initial values for the cubic spline selectivity appears to function well, but may be worth further investigation.

Reference Case Models

Four representative models (ref1-ref4) are defined in Table 4 and used to illustrate general features typical of most other models examined here:

- There was always a reasonable fit to the PL CPUE series (Figure 17, Figure 18). The PSFS CPUE fit was reasonable when it was included in the likelihood, though the model did not describe the extremes of the peaks and troughs in this series. Removing the PSFS CPUE series from the model had little effect on the PL CPUE fit, as the two series are consistent in the period of overlap.
- The models always provided an excellent fit to the aggregate size composition data (Figure 19). However, the fit to individual years was much less impressive. The fit to the quarterly aggregated size composition data suggests that there is not a strong seasonal signal in the selectivity (Figure 20). Seasonal selectivity would probably improve the CL fit for the PSFS fleet, but the seasonal lack of fit is trivial compared to the lack of fit in individual years.
- There was generally a reasonable fit to the gross features of the tag recovery data. Figure 21, Figure 22 and Figure 23 show the predicted and observed tag recoveries for example models ref1 (with the RTTP data only) and ref2 (with the small-scale data included). These two datasets seem to be providing different signals about M that warrant further investigation (e.g. Figure 11). The estimated $M_{a=0,1}$ is undoubtedly low for ref1, and this was a general feature of the MeA1 (rttp) options. In contrast, using the combined RTTP and small-scale tagging data, MeAs (rtss) options, generally provided M(a) estimates that were consistent with (but higher than) the pattern of the preliminary Brownie estimates, and similar in magnitude to the assumed M in the ICCAT assessment (e.g. ref2, Figure 11). This is discussed further below and in Figure 42.
- The selectivity consistently suggested that the youngest ages (including the 38cm maturity threshold) are only weakly vulnerable to the fisheries (Figure 26). There is estimated to be a dome-shaped selectivity for the larger fish as well. The dome shape could be an artefact of the low resolution M estimates for older ages, combined with the small number of observations of large fish, and uncertain growth curves.
- There was no obvious deviation from a Beverton-Holt stock recruit function (Figure 24, Figure 25). Annual recruit deviates suggest high variability (ref1 sigma = 0.53) is required to match the size composition and CPUE data. Continuous spawning might be expected to cause important seasonal variability in recruitment for this species. This was evident with the lower overdispersion (od02, not shown), but this also often led to the model estimating

one or two dominant recruitment seasons, with trivial recruitment in the other seasons. However, we have little confidence in the recruitment estimates prior to 2004 (when the tagging programmes and PL CPUE data begin).

- It is notable that the models estimate a steep population decline in the period ~1980-1990 (Figure 27). No CPUE data were fit during that period, so the signal is driven largely by the catch-at-size data and catch removal history. The steep decline (and subsequent increase) in spawning biomass represents the combined result of the fishery and the estimated recruitment pattern. This trend is doubtful, and not evident in the nominal PSFS or PSLS CPUE series (e.g. Figure 15).
- The combination of high M, young maturity and weak selectivity of young fish suggest that it could be very difficult to seriously overfish this population (i.e. a protected biomass of young spawners might ensure that the population is sustainable even with inconceivably large increases in effort). Figure 28 shows the equilibrium yield curves for ref1 and ref4. Both models suggest that there is a protected part of the spawning population that will not be touched even with >> 10-fold increases in effort. Ref4 is the most extreme example, suggesting that catches will always continue to increase with greater effort (above a certain level of effort, further catch increases would become insignificant and CPUE would decline steeply). The fit of ref4 to the CPUE series, size composition data, and tag data is (visually) comparable to the other ref models (not shown). The main difference is the higher steepness assumption (which we cannot estimate reliably), and the natural mortality estimate. Steepness 0.95 is very high, but if any species is capable of that sort of recruitment compensation, it is probably skipjack. The ref4 M estimate is high (~2.7 for age 1 fish, ~1.0 for other ages), which ensures the reserve of young spawners. Overall, the ref4 M estimate for combined ages 0-1 is less than the preferred estimates coming out of the most recent WCPO assessments (Hoyle et al 2011). So qualitatively, the dynamics of ref4 may be plausible.

Testing Size Composition Assumptions

The 8 models defined in GridA1 (Table 4) suggested:

- The models with temporal variability in selectivity often ran into convergence problems (unacceptably high maximum gradients) and were not thoroughly pursued.
- The mean output effective sample size (ESS) from all fleets was always less than 200 (Figure 29), and this was also true for higher input sample sizes (e.g. CL1, CL5, not shown).
- The MSY and depletion estimates corresponding to these options are shown in Figure 30, and it is noted that the CL2 options are more optimistic.
- In recognition of the convergence failures, and likely over-weighting of the size data with the CL2 (or greater) option, only the stationary selectivity options (sa) and CL04 option were carried forward. Both growth curves were carried forward.

Testing Tagging Assumptions

The 24 models defined in Grid A2 (Table 4) suggested:

- Model convergence was reasonable in all cases
- None of the options made a substantial difference to the fit to the CPUE or size composition data (Figure 31, Figure 32).
- Inclusion of the small-scale tuna tagging programmes (and estimating M(0)), resulted in more productive stock status estimates in general, as did the lower tag overdispersion assumptions (Figure 33).
- The 4 quarter mixing period suggested a marginally more productive stock than a 2 quarter mixing period, however, given the small number of releases at liberty for greater than a year, we are reluctant to pursue the 4 quarter mixing option.
- At this time, we have more confidence in the RTTP data than the small-scale tagging data, however the apparent sensitivity to the inclusion of the small-scale data suggests that further investigation is warranted.

Testing CPUE and Recruitment Assumptions

The 8 models defined in Grid A3 (Table 4) suggested:

- The model convergence was better (lower maximum gradients) with more constraints (i.e. deterministic recruitment and/or when the PSFS CPUE series was included).
- None of the assumptions made an appreciable difference to the fit to the PL CPUE (not shown) and CL data (Figure 34).
- MSY and depletion estimates were more optimistic with deterministic recruitment (Figure 35).
- It is unclear whether it would be better to impose additional structure on the model by using more tightly constrained recruitment, analogous to a production model, or including a long PSFS CPUE series that we do not believe. At this time, we have opted for the more pessimistic options rather than imposing optimistic structure to fill the data gap during the industrialization of the fishery.

Stock Status Grid

The 180 models in GridA4 (Table 4) were defined after consideration of the exploratory analyses above, and in recognition that MSY-related reference points are usually sensitive to steepness and mortality assumptions. Results indicate:

- Convergence was adequate for all configurations (no obvious failures on the basis of the maximum gradient, but some cases are probably marginal).
- The predicted model fits to the CPUE (not shown) and size composition data were very consistent across the model options (Figure 36)
- The stock status and productivity estimates show appreciable sensitivity to all of the grid A4 options except the growth curve (MSY - Figure 37, SB_{2009}/SB_{MSY} - Figure 38, C_{2009}/MSY Figure 39 and SB_{2009}/SB_0 - Figure 40).
- Figure 41 shows the estimated juvenile spawning reserve associated with the different options. i.e. As shown in the example equilibrium yield curves (Figure 28), it appears that all of the models with steepness > 0.85 have some invulnerable spawning biomass (as long as F remains below the very high constraint that Stock Synthesis software uses to calculate the yield curve).

- Among subsets of the grid A4 models that are comparable in principle (Figure 43), the likelihood clearly has the lowest preference for the M values estimated from the independent Brownie analysis (option MB). This is a concern given that the most informative data about M in the assessment (the tagging data) are essentially the same as that used independently in the Brownie analysis. For any fixed M assumption, the likelihood consistently recognizes higher steepness as providing a better fit. However, the steepness likelihood values are much closer in magnitude than the M values, and the considerable auto-correlation in the recruitment deviation time series was ignored (i.e. this would further reduce the difference in likelihood among steepness values).

Comparison of M estimates with the independent Brownie tagging analysis

The distribution of M_a estimated within the SS3 assessment are compared with the preliminary Brownie estimates (L83 growth curve option, Eveson 2011) in Figure 42. The SS3 estimates are generally higher than the Brownie estimates, but with a very similar relative pattern for ages 2-4+. The MeA1 estimates (from the rttp tagging programme option) for ages 0-1 are very low and unrealistic. In contrast, for the MeAs estimates (including RTTP and small-scale releases), the $M_{a=0,1}$ estimates are much higher, and more consistent with expectations.

The comparison between the Brownie and SS3 M estimates is a useful exercise. The two approaches are essentially using the tagging information in the same way, and we would hope the results would be very similar. The main differences in the two approaches include:

i. The SS3 estimates are influenced by all of the other data and assumptions in the assessment model. Given that we generally do not consider CPUE and catch-at-size data to be sufficiently informative to estimate M, these data might provide more of a hindrance to the M estimates than an assistance. Furthermore, the Brownie estimates are not constrained by stationary selectivity assumptions.
ii. The temporal resolution in the two models was not exactly the same. The preliminary Brownie model assigned all tags to integer ages and was iterated on an annual time step. The SS3 model assigned all tags to integer ages each quarter, and was iterated on a quarterly time-step. Also, the SS3 M estimates actually differ within annual age classes (i.e. linear interpolation between annual nodes as shown in Figure 11).
iii. The preliminary Brownie estimates assigned release ages to fish older than age 4, while the SS3 approach assumed a homogeneous age 4+ group. Note that the preliminary Brownie-Petersen estimates were similar to the Brownie estimates, but also require cohort-slicing to age the catch data (and for these reasons were not considered in this assessment).
iv. The Brownie model assumed that tagged fish were fully mixed with the general population in the time-step after release. This assumes very rapid mixing in some cases (i.e. fish released in Dec and recaptured in Jan), and ignores some data when the fish would have actually been mixing for almost a year (i.e. fish released in Jan and reconvered in Dec). In contrast, the SS3 model assumed two quarters to achieve full mixing (i.e. minimum of 3 months plus one day mixing, and all observations of 6+ months mixing included).

Overall, we are not aware of any reason to expect the Brownie estimates to be biased low, but exploration of a finer time-scale and longer mixing period are encouraged for the Brownie analysis.

In the originally proposed weighting scheme for the final stock status synthesis, the MeA1 (rttp) option was given equal weight to the MeAs (rtss) options. After examining the distribution of M estimates during the WPTT, it was decided that the MeA1-rttp options would be removed from the final weighting scheme (but the MeAs-rtss option was retained). This did not have a large effect on the overall results. We note that the M estimates from the WCPFC (Hoyle *et al*. 2011) are higher than any of the values considered here, and would make the assessment even more optimistic if adopted.

Following the WPTT, brief additional analyses into the source of the low $M_{a=0,1}$ for the MeA1 option was undertaken, including:

- extreme downweighting of some or all of the catch-at-length data and CPUE series.
- allowing selectivity to change on an annual time-step during the RTTP (quarterly was not tested)
- changing the cubic spline length-based selectivity to a flexible age-based selectivity.

None of these options removed the fundamental problem of low $M_{a=0,1}$. It appears that the low $M_{a=0,1}$ estimates are supported in the model by the RTTP tagging data, and the source of the divergence from the Brownie model remains unresolved. Since there are 5 or fewer age 0 tag releases (depending on the growth curve), the M information must be associated with the age 1 releases.

Model Weighting for the Stock Status Synthesis

The range of models represented in Grid A4 recognizes a considerable amount of uncertainty in the stock status. Obviously some of the models are closer to reality than others, but are we able to objectively choose among them (and have other important dimensions been left out?) As in a classical Bayesian analysis, there are two basic ways to assign credibility to different options:

1) Prior weighting – experience from other fisheries systems has obviously helped to formulate the alternative models in the first place. Can the different scenarios be weighted to reflect the prior beliefs of the analysts or broader WPTT? There is obviously an element of subjectivity in this process. But this is true in any model formulation and selection. At least in this case the weightings are transparent and open to criticism.

2) Likelihoods – what do the data tell us about the plausibility of the different models? To weight the parameter estimates by the likelihood, we are assuming the data were generated according to well-defined probabilistic processes and that the model is correct. That is what we are doing within each model for some parameters (*i.e.* virgin recruitment, selectivity, catchability). However, we tend to be sceptical about the capacity of the model to estimate many key parameters (*e.g.* steepness, M, Figure 43). Often the data appear to be very unlikely within the constraints of the model and this will pull a parameter estimate toward a very precise value (or bound), while common sense might suggest that, qualitatively, the fit to the important data sources does not seem all that different with alternative parameter values. There is a further problem with the likelihood weighting in this case, in that it is not meaningful to compare all of these models (*i.e.* rttp and rtss model options use different data).

We developed the current stock status estimates on the basis of a subjective weighting scheme (Table 5), after consideration of the following points:

- A single option was adopted for the following assumptions leading up to the stock status grid, for reasons described above i.e.:
  - ss - constant selectivity (non-stationary assumption led to convergence problems as implemented)
  - t2 - Two quarter mixing period – this is probably not long enough to insure full mixing throughout the Indian Ocean, but may be reasonable for the core PS area. Longer periods seriously erode the information content in this key data.
  - CL04 – higher effective sample size options generally did not result in a substantial improvement in fit to the size compostion data, and given the questionable assumption of stationary selectivity, overfitting these data probably represents a risk of misleading inferences.
  - U0 – only the Maldives CPUE series was used. This was reasonably consistent with the PSFS nominal series over the period of overlap. However, if we are prepared to believe that the nominal PS CPUE series is reliable, we could probably extend it all the way back to the early 1980s, not bother with the modelling, and conclude that the stock shows no signs of depletion.
  - rqs – given the variability in the size composition data, and the oscillations in the CPUE data, there clearly seems to be substantial recruitment variability, such that a deterministic recruitment model seems difficult to justify (though constraining recruitment prior to ~2004 might have provided a sensible alternative option).
- We maintained the two growth curve options with equal weighting.
- Stock recruitment steepness is generally difficult to estimate, especially if there is poor contrast in stock size. There may also be environmental factors driving long-term trends in recruitment productivity. ISSF (2011) summarizes steepness estimates from other tuna fisheries. Recognizing that there is a self-reinforcing circularity in adopting values from other oceans, we note that the high values reported seem to be consistent with what we would expect for species with SKJ life history. We would tend to give higher weight to the steepness values around 0.8, but not rule out the possibility of lower or higher values (and note that the likelihood values tend to support the highest steepness). The WPTT preferred to emphasize slightly higher steepness values than the original proposal:
  - h55 = 0
  - h65 = 0 (original proposal by the authors = 0.1)
  - h75 = 0.3
  - h85 = 0.4
  - h95 = 0.3 (original proposal by the authors = 0.2)
- Tag overdispersion parameter. We would tend to have more confidence in the information content of the tagging data than the other data, and accordingly downweight the high over-dispersion parameter (we recognize a potential problem here in that overdisprersion is not really analogous to down-weighting the likelihood, and this issue merits further consideration). However, the lowest overdispersion option is also downweighted, because the tag recoveries always showed some erratic patterns that suggested tags were not uniformly mixed in the SKJ population:

  - od02 =0.2
  - od20 =0.6
  - od70 =0.2
- The different M options were all weighted equally in the initial scheme proposed by the authors. When the full distribution of M estimates was examined in the WPTT, it was agreed that the MeA1 (rttp) option were unrealistic (Figure 42) and would be given zero weight in the final synthesis (other M options, including MeAs received the originally proposed weighting).
- We weighted the RTTP tagging programme releases more highly than the combined RTTP-small scale programmes (and PL tag recoveries), because we are more familiar with the RTTP programmes and data at this time:
  - rttp = 0.75
  - rtss = 0.25

It was initially unclear whether the WPTT would engage in the process of model weighting, and whether concensus could be achieved. Only a few individuals contributed to the discussion, but there were no major disagreements expressed, and a sensible outcome was achieved. This process may be a useful mechanism to open up the assessment to participants with less technical modelling experience.

The current stock status estimates from the final weighting scheme (Table 5) are presented in Table 6, with time series plots and a Kobe phase plot shown in Figure 44 and Figure 45. The Kobe 2 Strategy Matrix is provided in Table 7. Key assessment outputs are tabulated in Attachment 1.

Western Indian Ocean sensitivity analysis

The stock status grid was refit for the western Indian Ocean only (e.g. catches from Figure 2), as a rough indication of what the stock status may be if the western Indian Ocean represented a discrete sub-population, from which we note:

- There were a few models that resulted in marginal convergence (maximum gradients >0.01), and would have warranted further consideration if time permitted.
- Overall the estimated dynamic were similar to, and the stock status more optimistic than, the results for the aggregate Indian Ocean. Reference points are summarized in Table 6, Kobe 2 Strategy matrix in Table 8, and summary time series plots in Figure 46 and Figure 47).
- In general this result seems plausible, but the results were not all intuitively consistent with the aggregate Indian Ocean results. e.g. Median MSY for the Western Indian Ocean is only ~10% less than median MSY for the aggregate Indian Ocean, and the upper 95th percentile for MSY is estimated to be greater for the western IO than the aggregate IO.

6. Conclusions

1. This analysis represents a first attempt to integrate the most important fisheries and life history data into a single Indian Ocean SKJ assessment. There are serious concerns about important sources of data. Most notably:
   - It is unclear whether either the PL or PSFS CPUE series are proportional to abundance. It would be desirable to have a relative abundance index that spans the period of industrialization beginning in the 1980s.
   - The quality of the catch data and size sampling from some important fleets is uncertain. This is particularly true for the *Other* fleet, which accounts for a large and increasing proportion of the catch in recent years.

2. The assessment results tend to suggest that the SKJ population has high natural mortality, limited selectivity of the youngest spawners, and high recruitment compensation with declining spawning biomass. As a consequence, there may be a reserve of young spawners that are largely invulnerable to the fishery. If this is true, even large increases in effort might not have much effect on the recruitment output and sustainable yield of the population. This possibility is encouraging from the perspective of the resilience of the stock, but it is not yet conclusive. And it should be emphasized that large increases in effort would still be expected to cause a serious decline in catch rates.

3. While we do not have a lot of confidence in the estimated population abundance trends, the evidence that is available (and the SKJ life history strategy) suggest that large fluctuations in abundance should be expected due to high recruitment variability. It is likely that 2005-2006 were exceptional years, and declining catches and catch rates since then are probably partially attributable to the fisheries, and partially attributable to a return to more typical levels of recruitment.

4. The aggregate Indian Ocean population appears to be moderately depleted, with a low probability that MSY reference points are currently being exceeded:
   - B_{2009}/B_0 = 0.51 (0.31 - 0.70)
   - B_{2009}/B_{MSY} = 2.07 (1.04 – 5.13)
   - C_{2009}/MSY = 0.89 (0.60 - 1.15)
   - Kobe plot is provided in Figure 44, reference point summary in Table 6, and Kobe 2 Strategy Matrix in Table 7.

5. If there is a discrete western Indian Ocean sub-population, the preliminary sensititivity analysis suggests that the population is in even better shape than the aggregate Indian Ocean population:
   - B_{2009}/B_0 = 0.59 (0.41 – 0.85)
   - B/B_{MSY} = 2.74 (1.43 – 7.14)
   - C_{2008}/MSY = 0.63 (0.37 – 0.92)
   - Kobe plot is provided in Figure 45, reference point summary in Table 6, and Kobe 2 Strategy Matrix in Table 8.

6. Suggested priorities for improving the assessment:
    - Further analysis of the tagging data:
        - Use a higher temporal resolution (e.g. quarterly) to represent the population and fishery dynamics.
        - Further investigate M,F,N and mixing period estimators using external tagging analyses.
        - The general assumption of very low tag-induced mortality might need to be revisited.
    - Explore the standardization of PS CPUE series dating back to 1983. The WPTT 2011 noted that the EU PS fisheries had species composition samping problems prior to 1991, but this should have only affected BET and YFT, not SKJ.
    - Improvements to the Maldivian PL CPUE series might also be possible:
        - The WPTT suggested that it may be possible to develop a series based on the pre-mechanization period. However, since mechanization began in 1974, and observations from individual vessel data are not available until 2004, this may not be very helpful.
        - The large number of months with positive PL effort and zero SKJ catch requires further investigation.
    - In the absence of reliable abundance indices spanning the industrialization of the fishery, it may not be possible to do much more than modelling speculative scenarios that bound 'worst case' and 'best case' interpretations of how abundance changed during the development of the fishery. e.g. This could involve imposing effort creep scenarios on the CPUE series, or constraining recruitment dynamics prior to 2004.
    - Further explore the assumptions that suggest a young spawning biomass reserve is likely for this population. e.g. Could there be a sampling bias for precocious spawners such that the average age at maturity is under-estimated?
    - Increase the fishery disaggregation of the *Other* fisheries where the data are sufficient.
    - The WPTT raised concern that the growth curves might not be capturing the rapid initial growth rate for this species (e.g. Kayama et al. 2009). Further efforts to reconcile the proposed initial growth rate and the mode of large fish observed in the longliners should be undertaken.
    - Resolve the issue of the stock structure as suggested by the recent genetic analysis.

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We are grateful for the contributions of various parties toward the compilation of data and preparatory analyses. *Stock Synthesis* software and supporting graphical routines produced by Rick Methot, Ian Taylor (and colleagues) were very useful and much appreciated. Thanks to Paige Eveson for contributing to the update and discussion of growth curves and tag analyses. Thanks to Alejandro Anganuzzi for contributing to the update and discussion of growth curves and reporting rate estimates. Thanks to participants of the WPTT for numerous useful suggestions, particularly Shiham Adam and colleagues at the Maldives MRC.

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Table 1. Summary of the two sets of tagging data options used in the SKJ assessment.

model Grid option	rttp	Comments	rtss	Comments
Release Programme	RTTP-IO		RTTP-IO + small-scale	Small-scale releases in the vicinity of Maldives, Sumatra, Lakshadweep, Mayotte, Seychelles and offshore areas
Release Period	2005-7		2002-9	
Recovery Fleets	EU/Sey PS	Reporting rates from tag seeding	EU/Sey PS Maldives PL	PS reporting rates from tag seeding; PL Reporting Rates estimated
Recovery Period	2005-9		2004-9	
Total number of releases	78333		100620	
Number of releases in analysis	77893	Small number of releases omitted for reasons described in text	100088	Small number of releases omitted for reasons described in text
***Number of release groups**	L83: 40 L70: 45	Yr/Qtr/Age strata	L83: 79 L70: 83	Yr/Qtr/Age strata
Total number of recoveries included in the analysis	10248	Only includes EU/Seychelles PS recoveries (Small number of recoveries omitted for reasons described in text)	12765	Only includes EU/Seychelles PS and Maldives PL recoveries (Small number of recoveries omitted for reasons described in text)

* Number of release groups depends on the length-at-age assumption.

Table 2. Raw tag seeding data for the EU/Seychelles PS vessels unloading in the Seychelles, and the reporting rate (point estimates) adopted in the assessment (Alejandro Anganuzzi, IOTC, pers. comm.).

Year	Quarter	SKJ Tags Seeded	SKJ Seeds Recovered	Reporting Rate in the assessment
2004	1	1	-	0.485
2004	2	1	-	0.595
2004	3	11	5	0.488
2004	4	2	1	0.664
2005	1	36	23	0.595
2005	2	21	19	0.696
2005	3	72	37	0.597
2005	4	47	25	0.754
2006	1	-	-	0.918
2006	2	36	36	0.946
2006	3	69	60	0.918
2006	4	204	191	0.959
2007	1	99	91	0.972
2007	2	77	73	0.982
2007	3	188	173	0.972
2007	4	151	139	0.986
2008	1	30	30	0.945
2008	2	22	16	0.964
2008	3	78	74	0.946
2008	4	52	45	0.973
2009	1	29	25	0.970
2009	2	-	-	0.980
2009	3	-	-	0.970
2009	4	-	-	0.985

Table 3. Model option abbreviation definitions.

Assumption	Option Abbreviation
Tag Data	rttp – only RTTP releases, only EU/PS recoveries rtss – RTTP and small-scale releases, EU/PS and Maldives recoveries
Tag Mixing Periods	t2 – 2 quarters t4 – 4 quarters
Tag Recovery Overdispersion	od02 – negative binomial overdispersion parameter $\tau = 2$ od20 – $\tau = 20$ od70 – $\tau = 70$
Growth	L70 – L_{inf} = 70cm, k = 0.37 L83 – L_{inf} = 83cm, k = 0.22
Selectivity	ss – stationary sa – annual deviations estimated 2004-2008
Recruitment Deviations	rqs – annual recruitment deviates estimated 1983-2008 (and quarterly 2004-8) r0 – deterministic recruitment
Stock-Recruit Steepness	h55 – steepness = 0.55. h65 h75 h85 h95
Natural Mortality	MeA1/MeAs – M estimated: ages 1-4 for MeA1(rttp) and ages 0-4 for MeAs(rtss) MB – M fixed from the preliminary estimates from Eveson 2011 (Brownie, Linf=83 cm) MAt – M fixed from the ICCAT values (0.8)
CPUE Series	U0 – only Maldives CPUE 2004-2009 included U1 – Maldives and nominal PSFS CPUE 1991-2009 included
Catch-at-Length	CL04 – input sample size = min(N/10, 40) for PL, PSFS and PSLS CL2 – input sample size = min(N/10, 200) for PL, PSFS and PSLS
Spatial Option	io – whole Indian Ocean (default unless stated otherwise) we – only western Indian Ocean

Table 4. Model assumption combinations used in selected models and grids (where a grid represents the list of models with a balanced design of all possible permutations of the indicted options)

Model Option	Model or Grid (number of models)							
	ref1 (1)	ref2 (1)	ref3 (1)	ref4 (1)	A1 (8)	A2 (24)	A3 (8)	A4 (180)
Tag Data	rttp	rtss	rttp	rtss	rttp	rttp rtss	rttp	rttp rtss
Tag Mixing Periods	t2	t2	t2	t2	t2	t2 t4	t2	t2
Tag Recovery Overdispersion	od20	od20	od20	od02	od20	od02 od20 od70	od20	od02 od20 od70
Growth	L83	L83	L83	L83	L70 L83	L70 L83	L70 L83	L70 L83
Selectivity	ss	ss	ss	ss	ss sa	ss	ss	ss
Recruitment Deviations	rqs	rqs	rqs	rqs	rqs	rqs	rqs r0	rqs
Stock-Recruit Steepness	h75	h75	h75	h95	h75	h75	h75	h55 h65 h75 h85 h95
Natural Mortality	MeA1	MeAs	MeA1	MeAs	MeA1	MeA1/s	MeA1	MeA1/s MB MAt
CPUE Series	U1	U1	U0	U0	U1	U1	U1 U0	U0
Catch-at-Length weighting	CL04	CL04	CL04	CL04	CL2 CL04	CL04	CL04	CL04

Table 5. Weighting scheme for the 180 models represented in the final stock status synthesis (grid A4) and used in the Kobe-2 Strategy Matrix (Table 7).

	Option Weighting **Weightings adopted by the WPTT are shown in bold** *Original author proposals are shown in italics (if different)*			
Tag Data*	**rttp = 0.75**	**rtss = 0.25**		
Tag Mixing Periods	**t2 = 1.0**			
Tag Recovery Overdispersion	**od02 = 0.2**	**od20 = 0.6**	**od70 = 0.2**	
Growth	**L70 = 0.5**	**L83 = 0.5**		
Selectivity	**ss = 1.0**			
Recruitment Deviations	**rqs = 1.0**			
Stock-Recruit Steepness	**h55 = h65 = 0** h55=0, *h65=0.1*	**h75 = 0.3**	**h85 = 0.4**	**h95 = 0.3** *h95=0.2*
Natural Mortality*	**MeA1 = 0** *MeA1 = 0.33*	**MeAs = 0.33**	**MB = 0.33**	**MAt = 0.33**
CPUE Series	**U0 = 1.0**			
Catch-at-Length weighting	**CL04 = 1.0**			

*note that mortality option MeA1 is only relevant with rttp, and MeAs is only relevant with rtss (otherwise all permutations of options are represented in the stock status grid)

Table 6. Stock status summary table, based on the weighted combination of MPD models as defined in Table 5. Stock status values represent the median and 5th-95th percentiles.

Management Quantity	io - Aggregate Indian Ocean	we – Western IO only
2009 catch estimate (1000 t)	456	298
Mean 2005-2009 catch (1000 t)	492	379
MSY (1000 t)	564 (395 - 843)	531 (323 – 900)
Current Data Period	1950-2009	1950-2009
C(2009)/MSY (proxy for F(Current)/F(MSY))	0.81 (0.54 – 1.16)	0.56 (0.33 – 0.92)
SB(Current)/SB(MSY)	2.56 (1.09 – 5.83)	3.17 (1.79 – 9.17)
SB(Current)/SB(0)	0.53 (0.29 – 0.70)	0.63 (0.42 - 0.99)

Table 7. Aggregate Indian Ocean Kobe-2 Strategy Matrix indicating the estimated stock status implications of different constant catch strategies, with the assumptions described in grid A4 (Table 4), and the weighting options agreed by the WPTT (Table 5).

Stock status Reference Point	Projection Time frame	Indian Ocean Percentage of weighted scenarios that violate the Reference Point				
		C(2009) -40%	C(2009) -20%	C(2009) 456 000 t	C(2009)+20%	C(2009)+40%
P(SSB_t<SSB_{MSY})	In 3 years	<1	5	5	10	18
	In 10 years	<1	5	19	31	56
P(C_t>MSY) proxy for P(F_t>F_{MSY})	In 3 years	<1	<1	31	45	72
	In 10 years (any year)	<1	<1	31	45	72

Table 8. Western Indian Ocean Kobe-2 Strategy Matrix indicating the estimated stock status implications of different constant catch strategies, with the assumptions described in grid A4 (Table 4), and the weighting options agreed by the WPTT (Table 5).

Stock status Reference Point	Projection Time frame	Western Indian Ocean Percentage of weighted scenarios that violate the Reference Point				
		C(2009) -40%	C(2009) -20%	C(2009) 298 000 t	C(2009)+20%	C(2009)+40%
P(SSB_t<SSB_{MSY})	In 3 years	<1	1	1	3	6
	In 10 years	<1	<1	3	11	25
P(C_t>MSY) proxy for P(F_t>F_{MSY})	In 3 years	<1	<1	2	11	30
	In 10 years (any year)	<1	<1	2	11	30

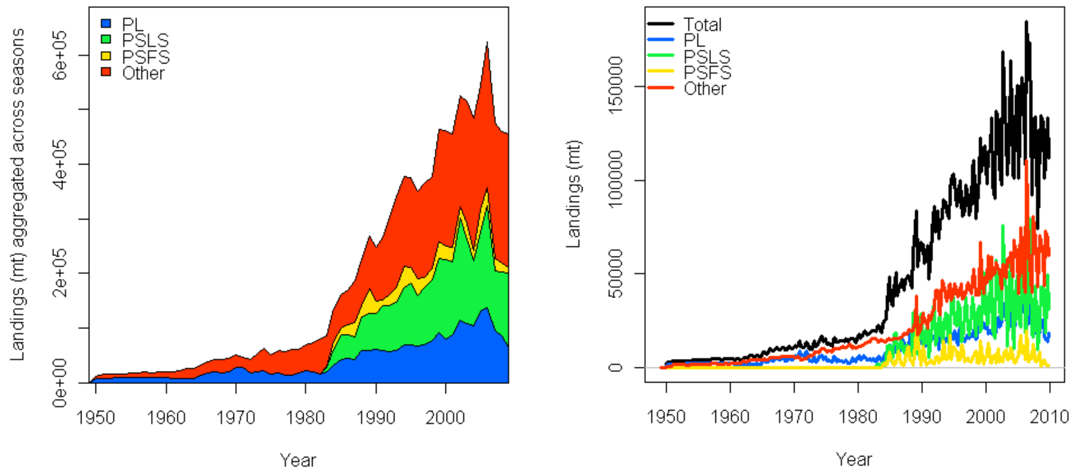


Figure 1. Aggregate Indian Ocean SKJ catch in mass over time disaggregated by the fleets defined for the assessment. Left panel - stacked annual catches; right panel – quarterly time series.

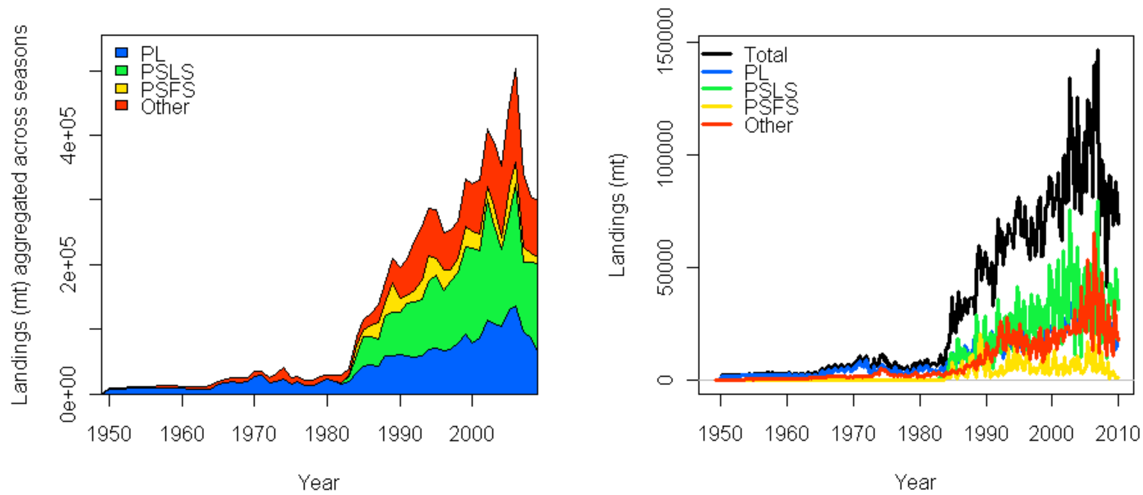


Figure 2. Western Indian Ocean SKJ catch in mass over time disaggregated by the fleets defined for the assessment. Left panel - stacked annual catches; right panel – quarterly time series.

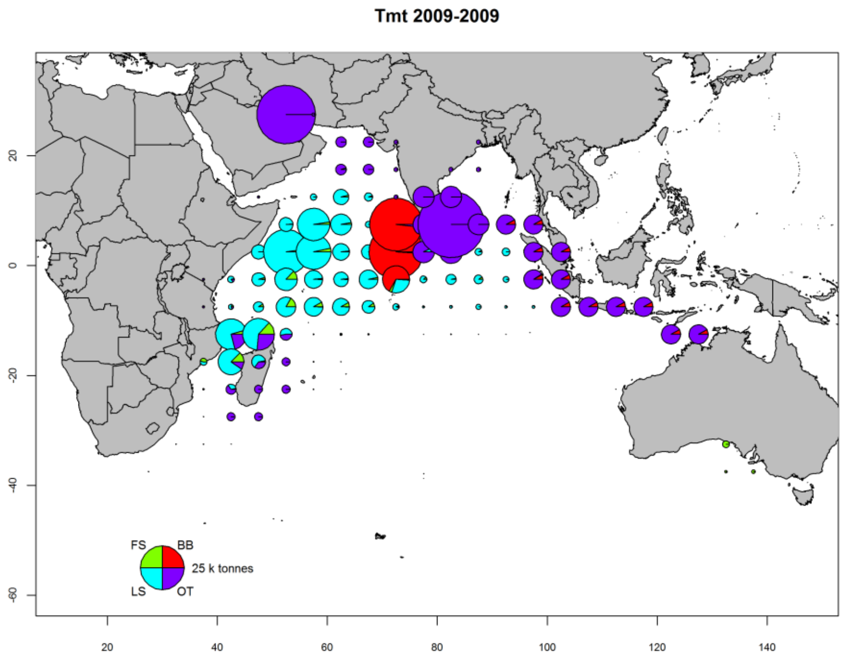


Figure 3. Indian Ocean SKJ catch distribution in 2009. Note that the spatial distribution is not accurate for most of the *other* (OT) fleets.

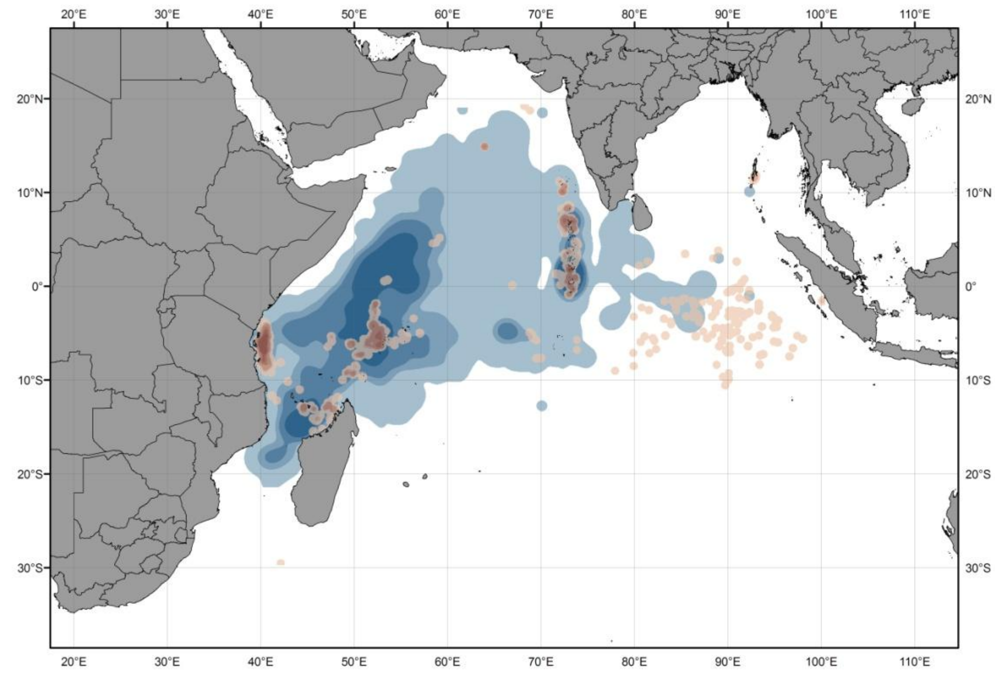


Figure 4. Summary of SKJ tag releases (red) and recoveries (blue) from the RTTP-IO and small-scale programmes 2003-2010.

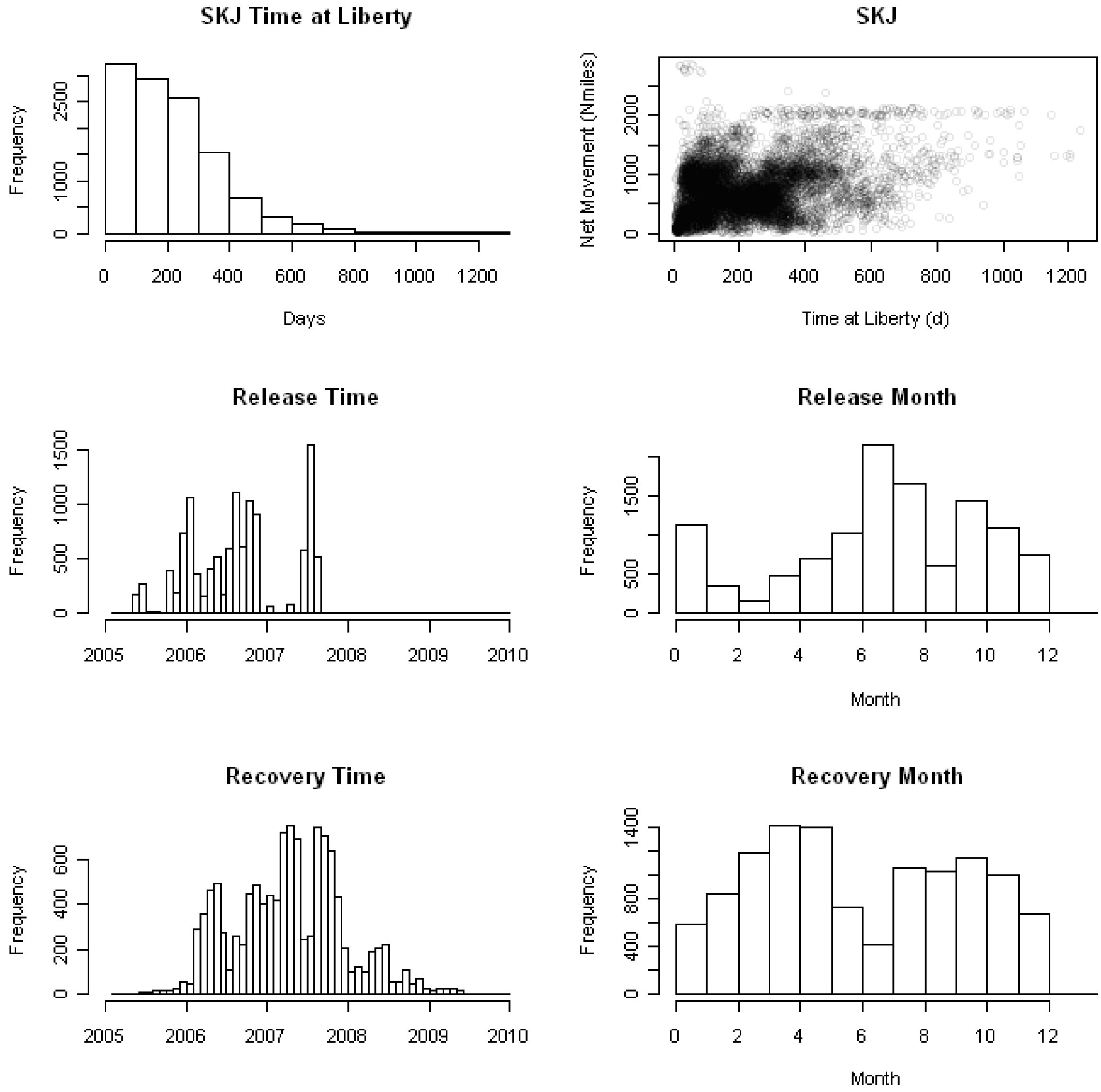


Figure 5. Summary of RTTP-IO SKJ tag release and recovery information 2005-2009.

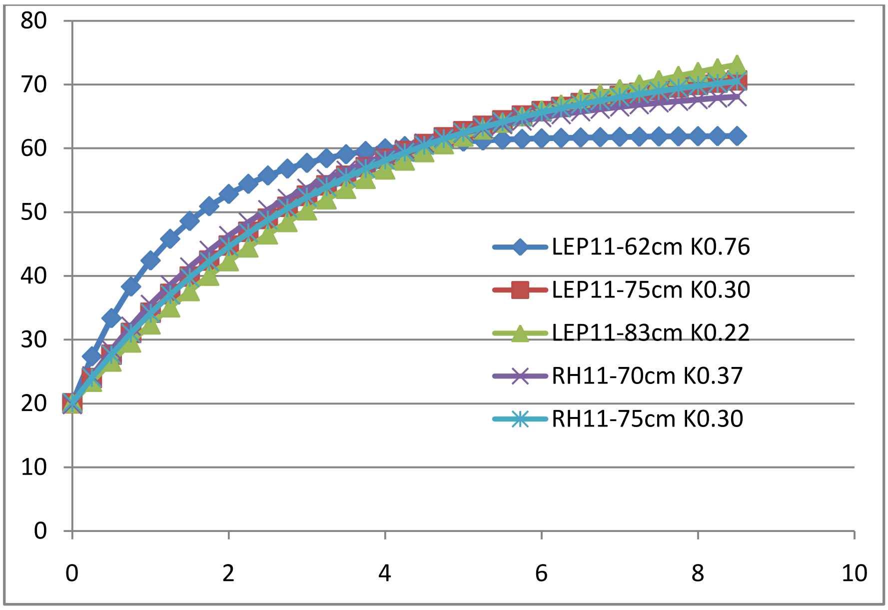


Figure 6. SKJ mean length-at-age relationships. The two used in the analysis were L70 = RH11-70cm K0.37 and L83 = LEP11-83cm K0.22.

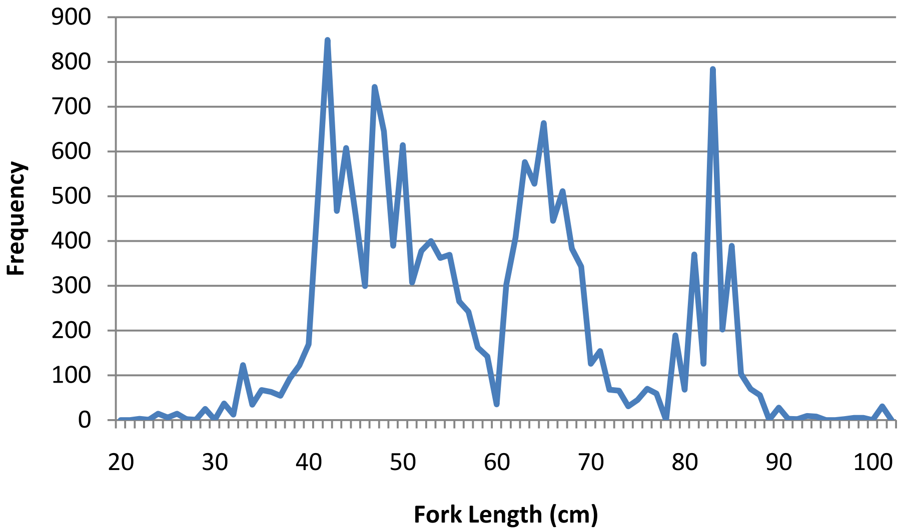


Figure 7. Indian Ocean longline SKJ catch-at-length samples (aggregated across time and fleets).

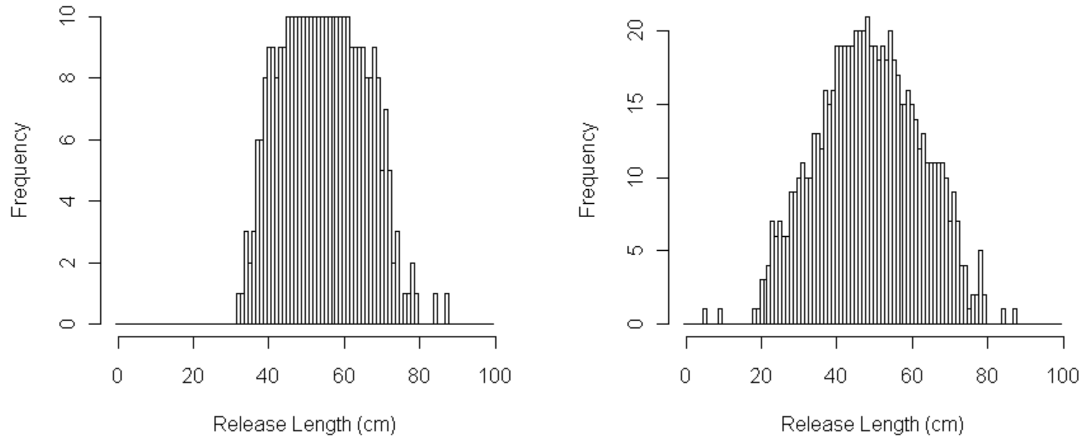


Figure 8. Distribution of tag release length-classes from the RTTP-IO (left) and combined RTTP-IO and small-scale tagging programmes (right). (Note that this is not the number of actual tags released)

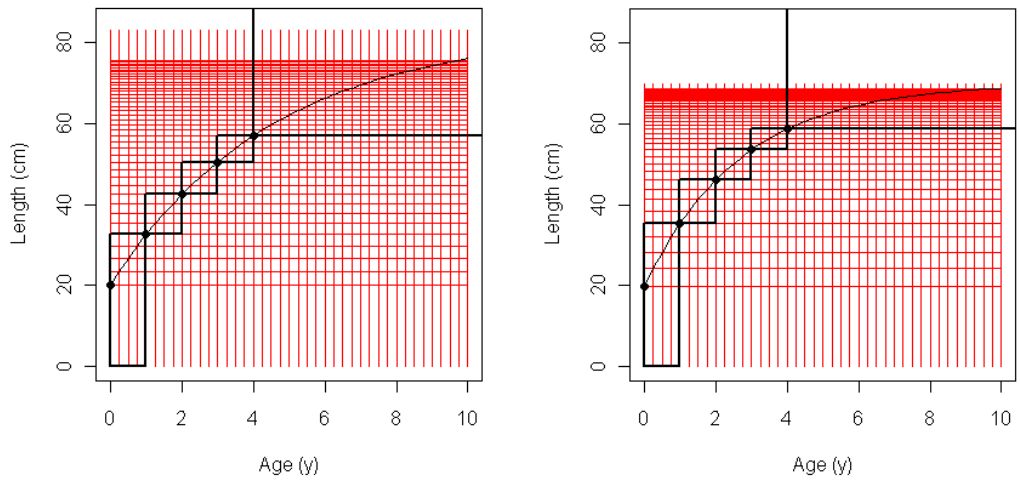


Figure 9. Relationships used for the assignment of tag lengths to ages for the two growth curves: L83 left, and L70 right. The tag release age is defined by the black circle preceding the black box that encompasses the tag release length.

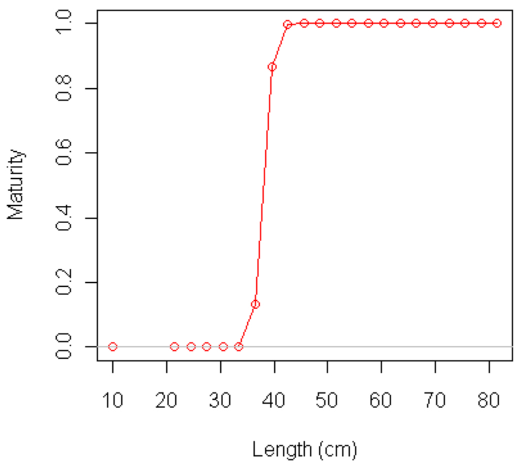


Figure 10. Assumed SKJ maturity-at-length (proportion).

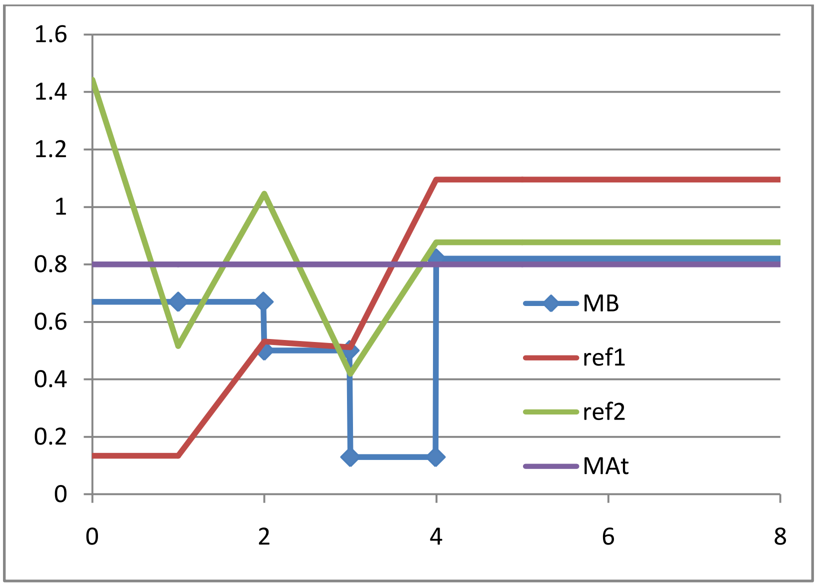


Figure 11. SKJ natural mortality, comparing values from recent ICCAT assessment (MAt), with the preliminary Brownie estimates (MB), and assessment point estimates from two models: ref1 (including RTTP tags only) and ref2 (including RTTP and small-scale tags).

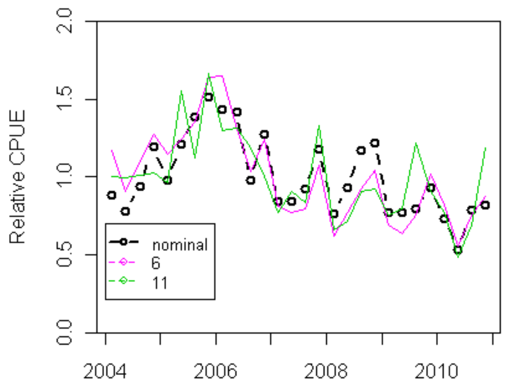


Figure 12. Standardized CPUE from the Maldivian Pole and Line fleet (PL). Series 11 = model option 'U0', 'U1', series 6 = 'U2'

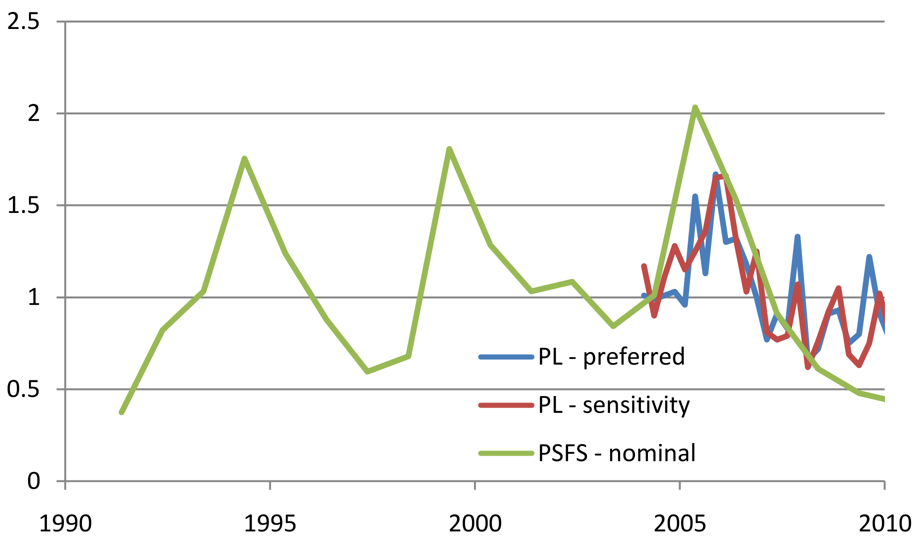


Figure 13. Comparison of the standardized PL CPUE series (numbers) with the nominal French PSFS CPUE series (mass). All series rescaled to a mean of unity over the period 2004-2010.

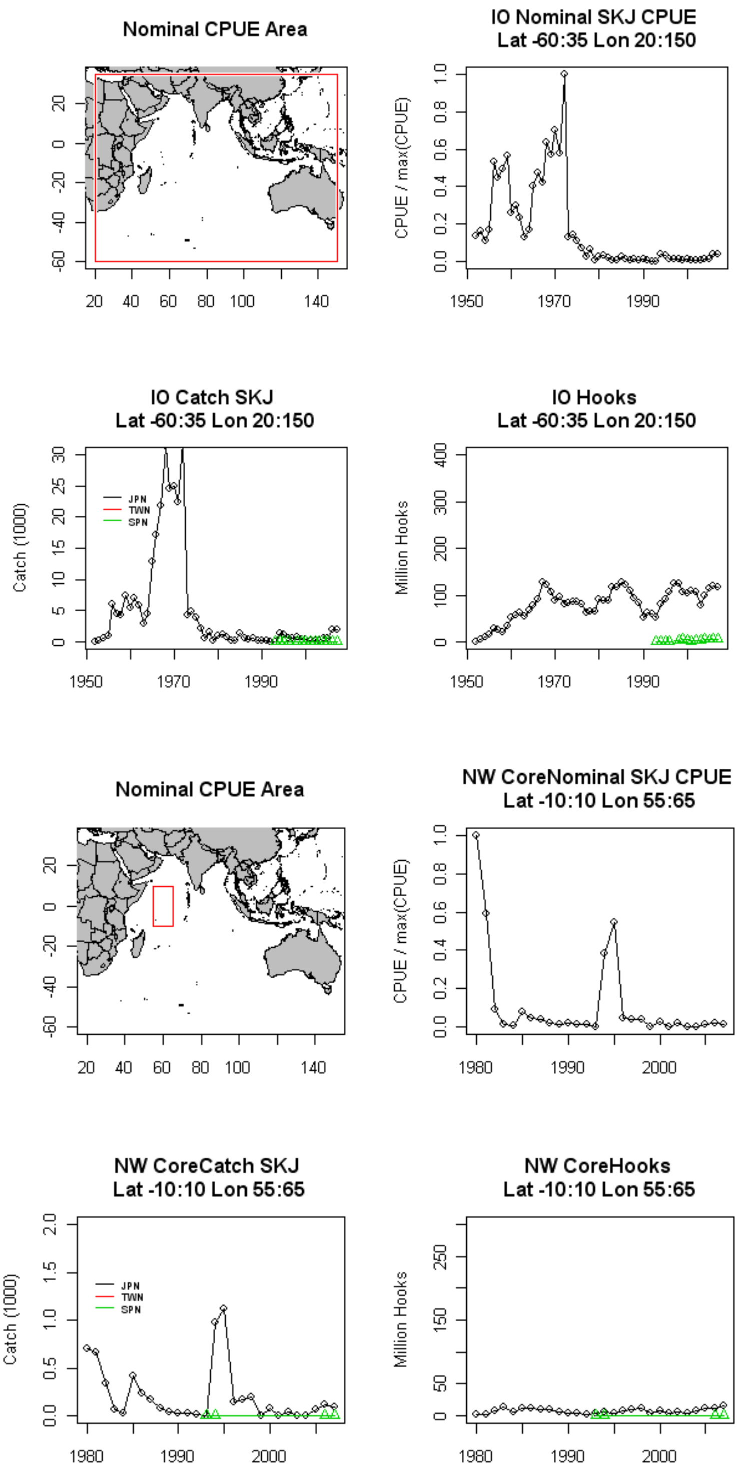


Figure 14. Summary of SKJ catch, effort and nominal (effort-weighted) CPUE from the main Indian Ocean longline fleets as reported to the IOTC. Top 4 panels cover the whole IOTC convention area; bottom 4 panels are restricted to a core SKJ area, as defined in the maps.

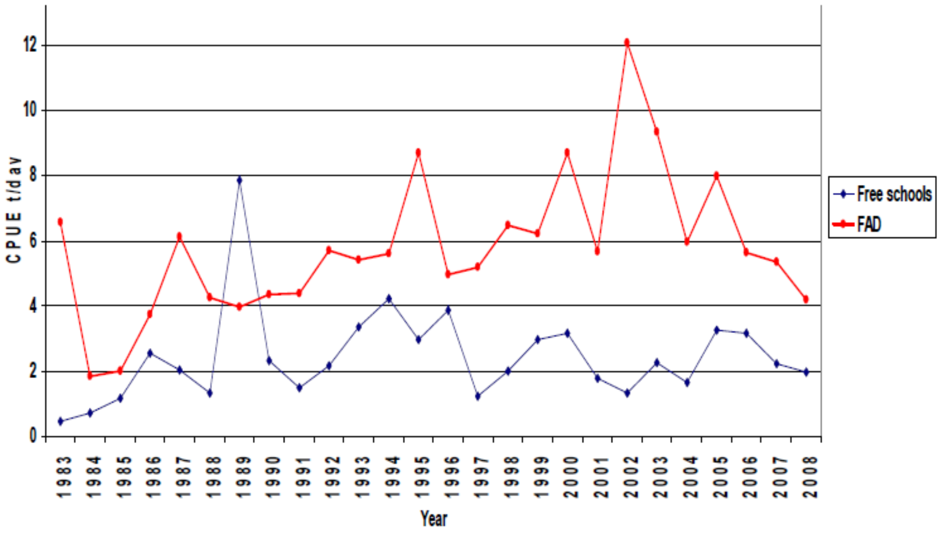


Figure 15. Nominal SKJ CPUE for EU/Seychelles purse seine fleets (Jan-Jul), by set-type (from Dorizo et al. 2008).

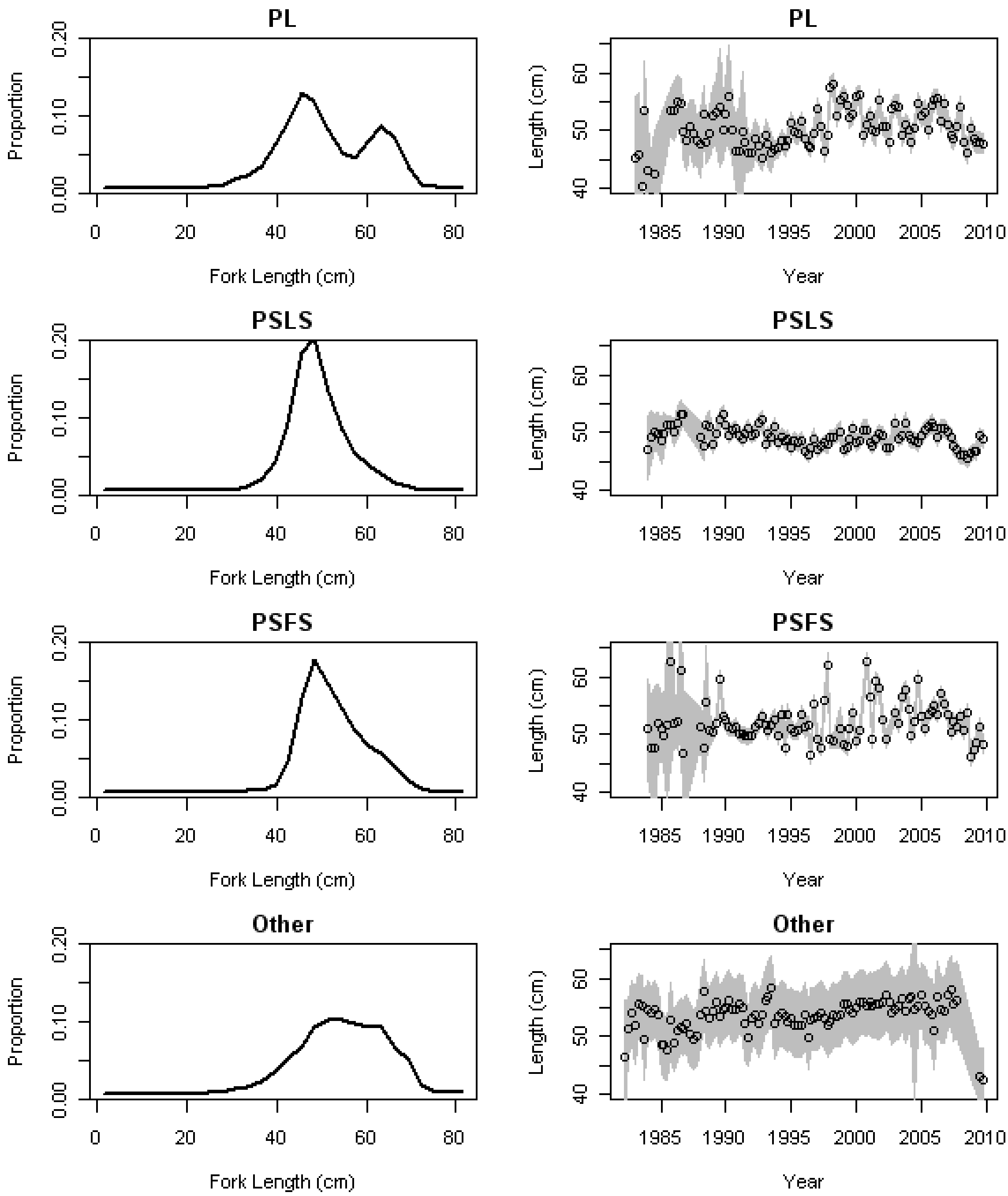


Figure 16. Size composition summary by fleet. The left column represents the sum over time with all years weighted equally, right column represents the quarterly time series of mean length (with 95% CI for an assumed sample size of min(N/10, 1000) for PL, PSLS and PSFS fleets, min(N/10, 100) for Other.

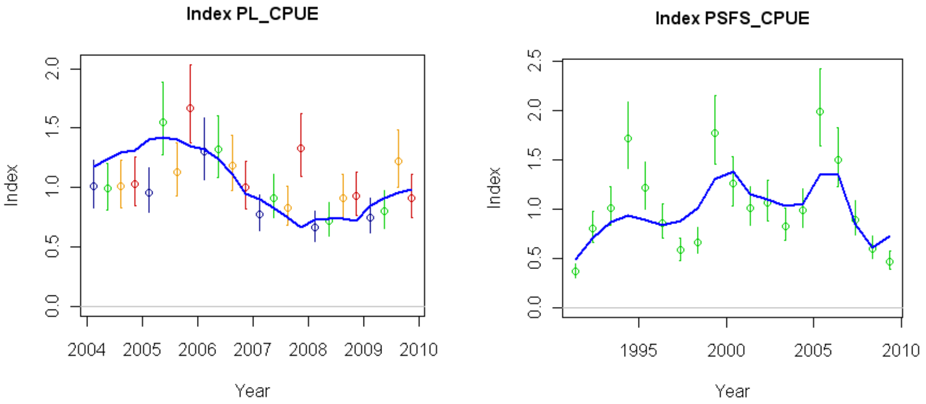


Figure 17. Predicted (line) and observed (points) CPUE for the model ref1. Error bars indicate the 95 % CI for a 10% CV. (Models and grids are defined in Table 4)

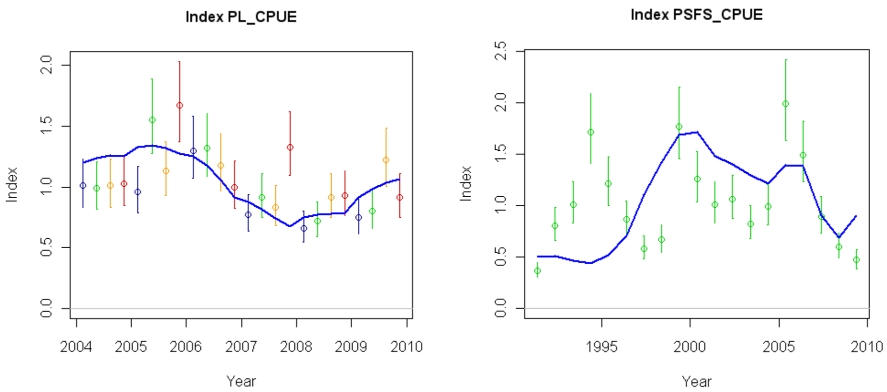


Figure 18. Predicted (line) and observed (points) CPUE for the model ref3 (PSFS CPUE not included in the likelihood). Error bars indicate the 95 % CI for a 10% CV. (Models and grids are defined in Table 4)

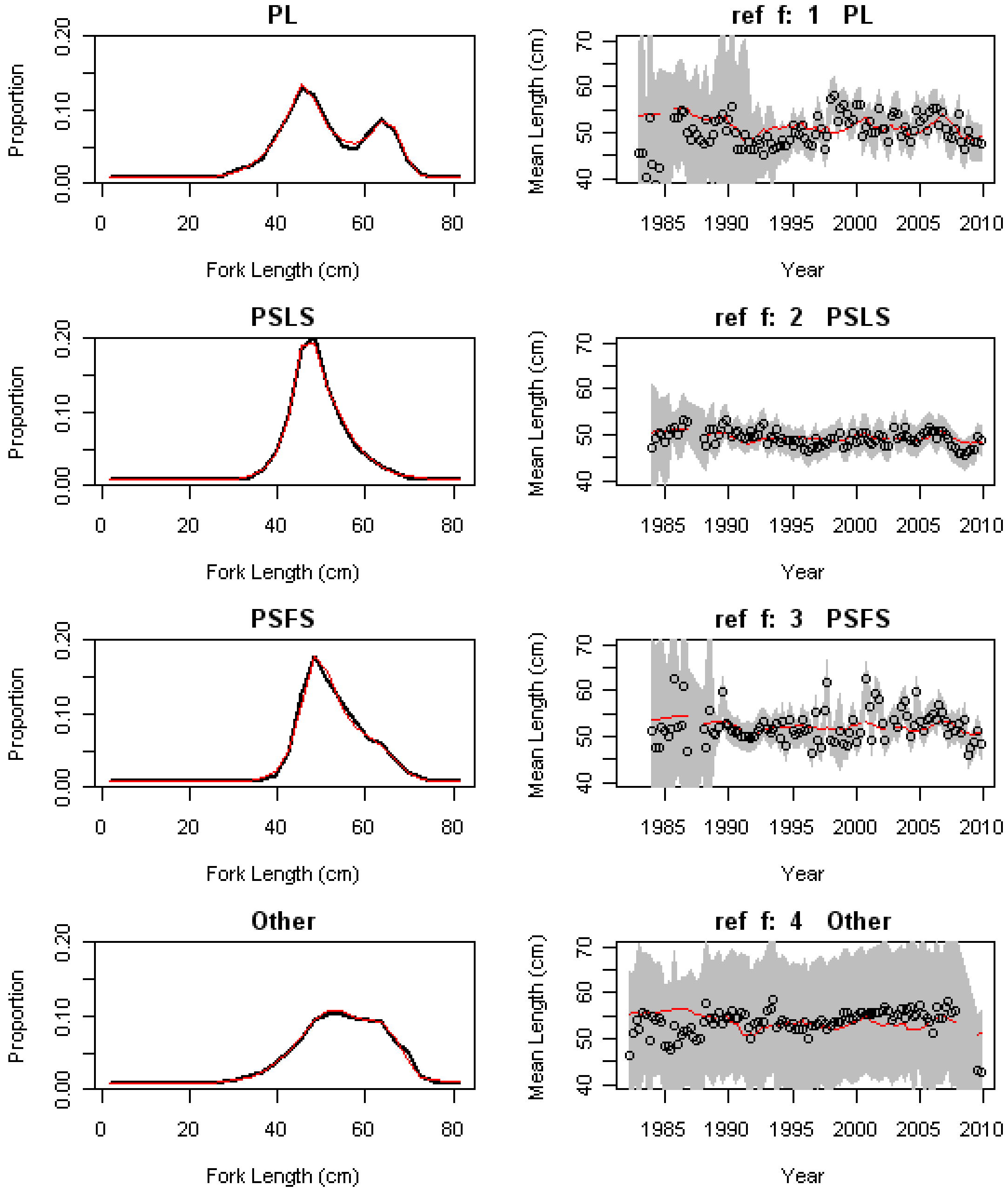


Figure 19. Predicted (red) and observed (black) catch size composition for the reference model ref1 (left column is the aggregated distribution over time, right column is the time series of mean catch). (Models and grids are defined in Table 4)

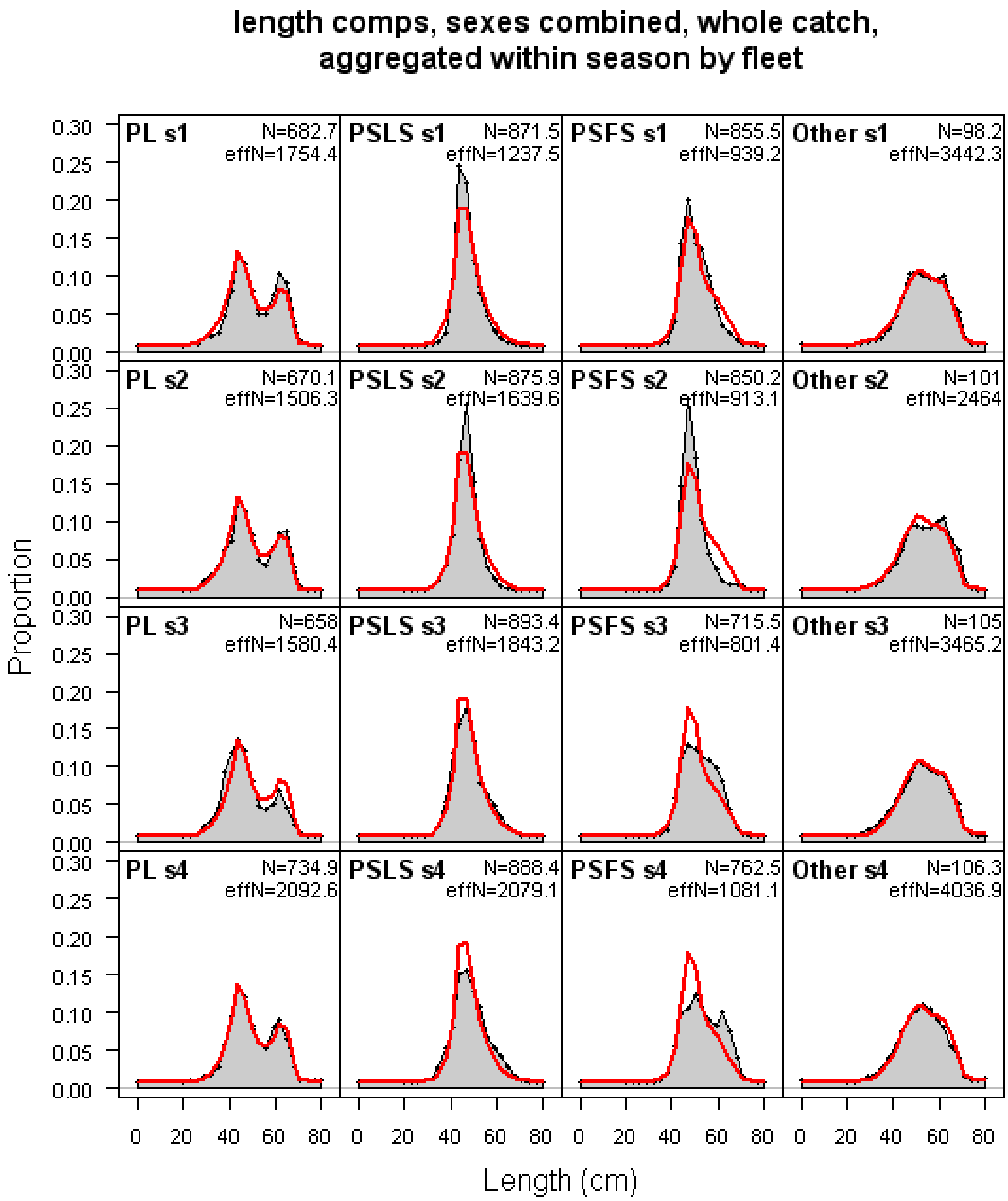


Figure 20. Predicted (red) and observed (black) catch size composition for the reference model ref1, disaggregated by season. (Models and grids are defined in Table 4)

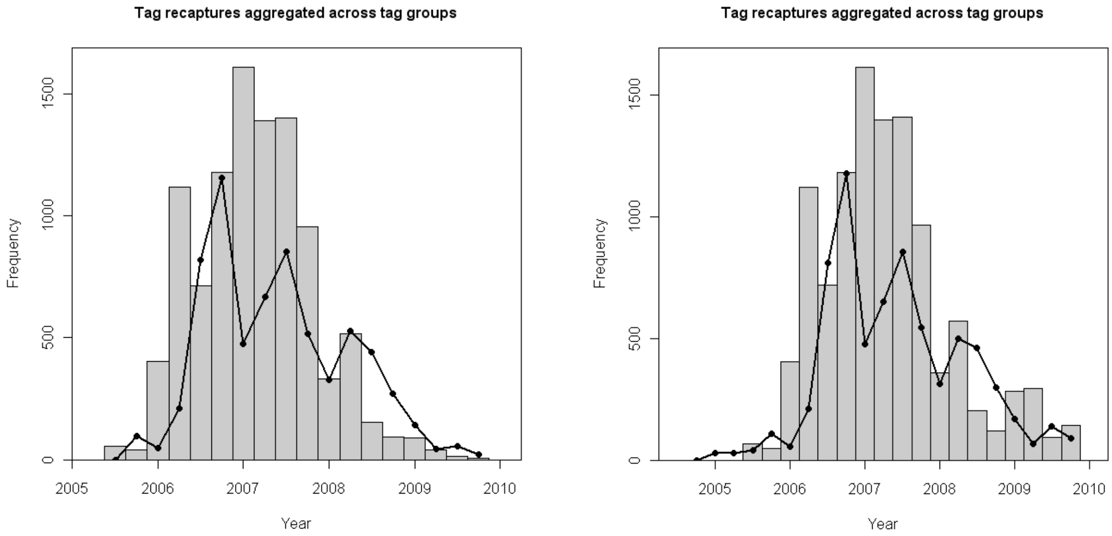


Figure 21. Predicted and observed tag recaptures aggregated across all tag groups for ref1 (left, rttp option) and ref2 (right, rtss option). Note that this figure includes observed recaptures during the mixing period, which are not predicted by the model. (Models and grids are defined in Table 4)

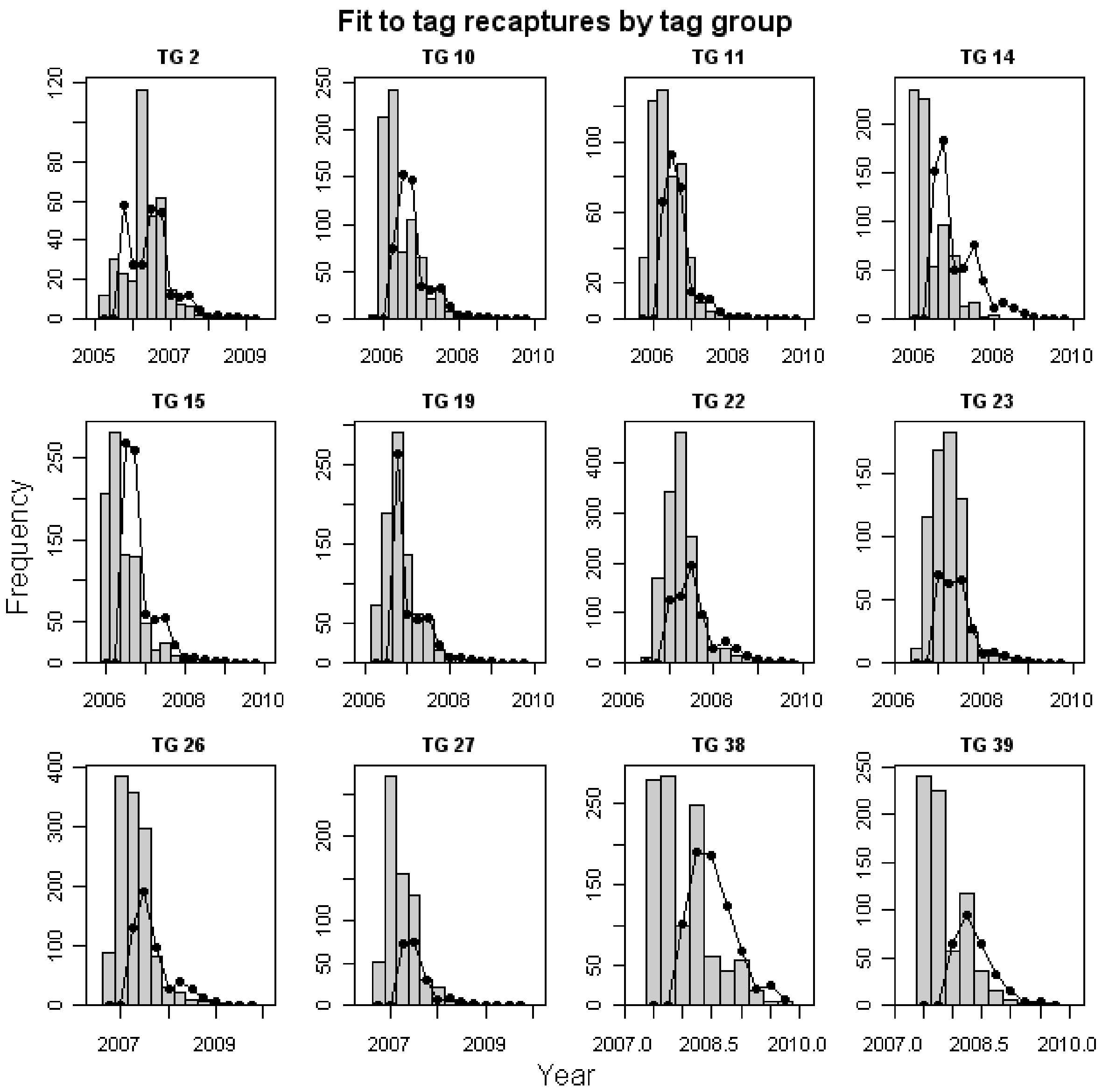


Figure 22. Predicted (lines) and observed (bars) tag recaptures for the 12 largest tag groups for model ref1. Note that the first two observed bars in each plot are part of the incomplete mixing period, and are not predicted by the model. (Models and grids are defined in Table 4)

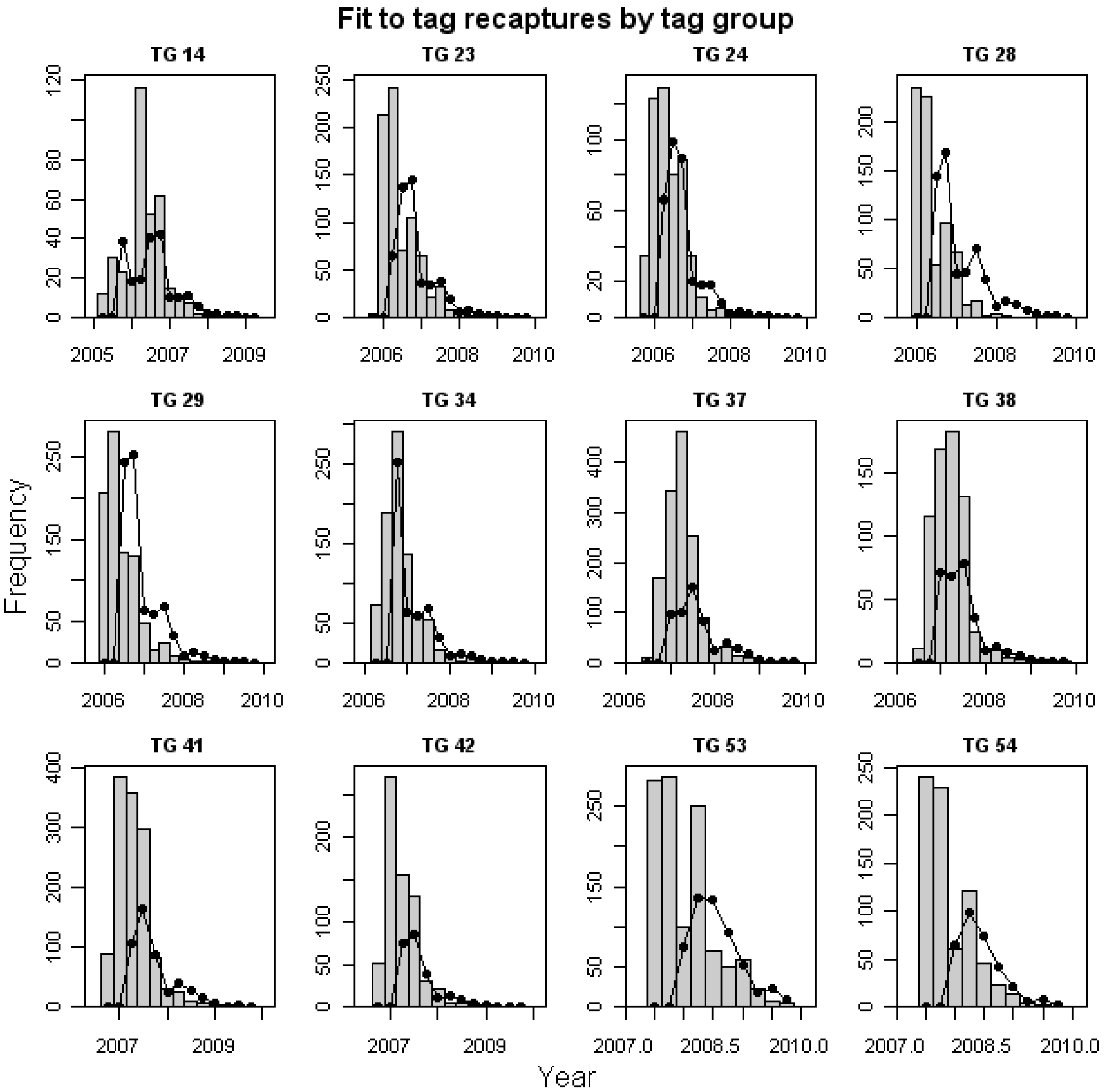


Figure 23. Predicted (lines) and observed (bars) tag recaptures for the 12 largest tag groups for model ref2. Note that the first two observed bars in each plot are part of the incomplete mixing period, and are not predicted by the model. (Models and grids are defined in Table 4)

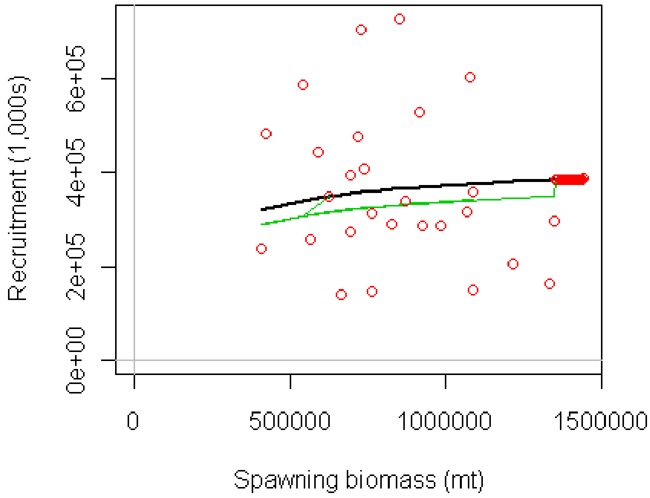


Figure 24. Stock recruitment relationship and annual deviates for ref1. (Models and grids are defined in Table 4)

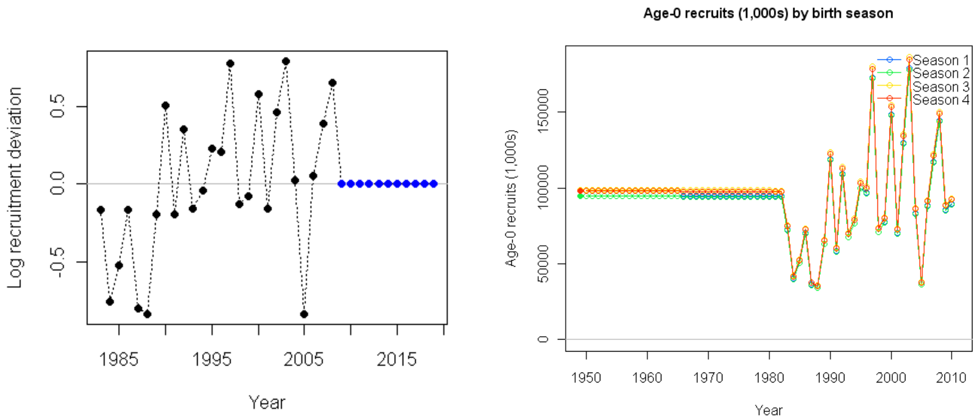


Figure 25. Time series of estimated annual recruitment deviations (left panel), and recruitment by season (right panel) for ref1. (Models and grids are defined in Table 4)

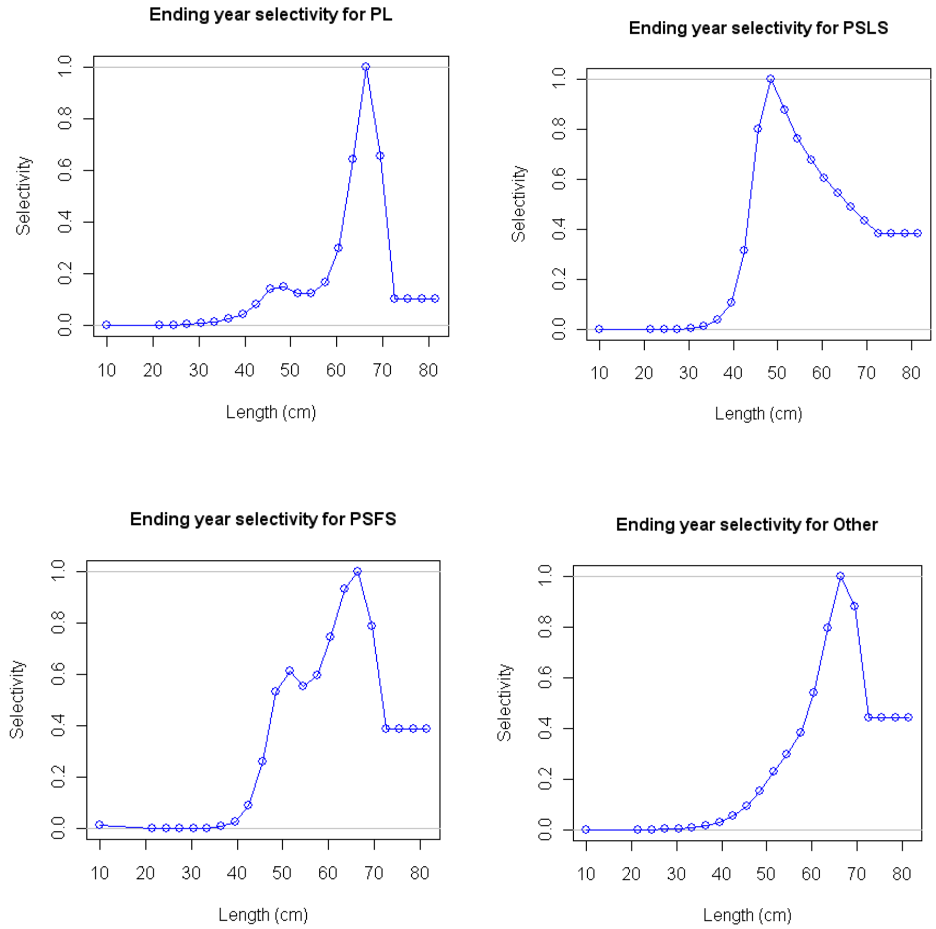


Figure 26. Selectivity estimated for the reference case model ref1. (Models and grids are defined in Table 4)

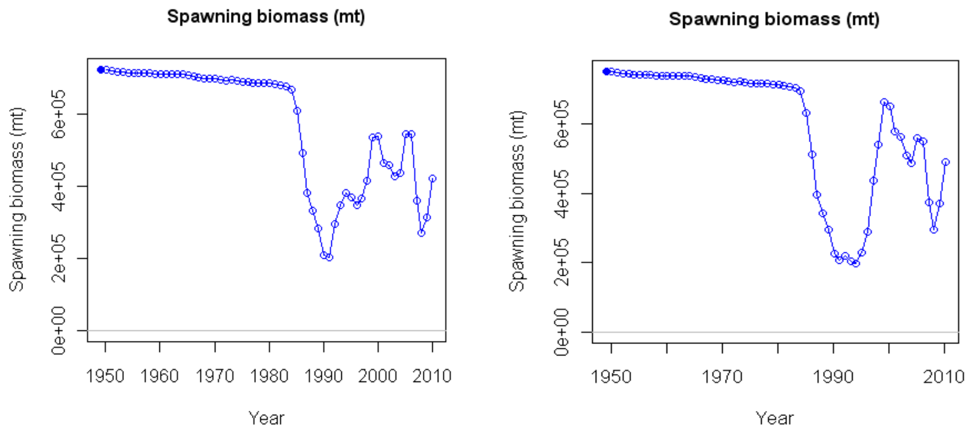
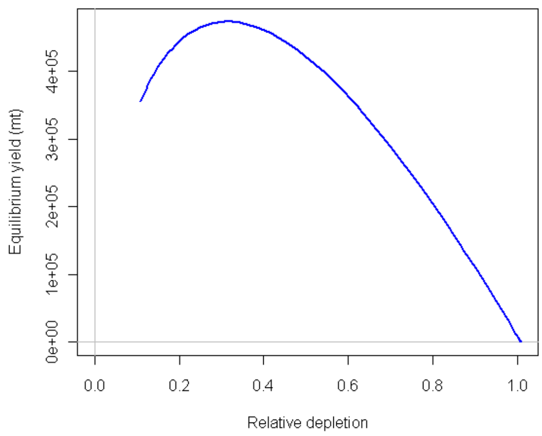


Figure 27. Estimated spawning biomass for ref1 (left, includes the PSFS CPUE series), and ref3 (right, excludes the PSFS CPUE series). (Models and grids are defined in Table 4)



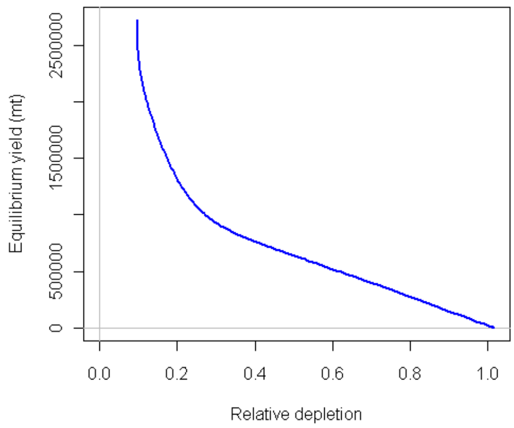


Figure 28. Equilibrium yield curves for example models ref1 and ref4 (defined in Table 4).

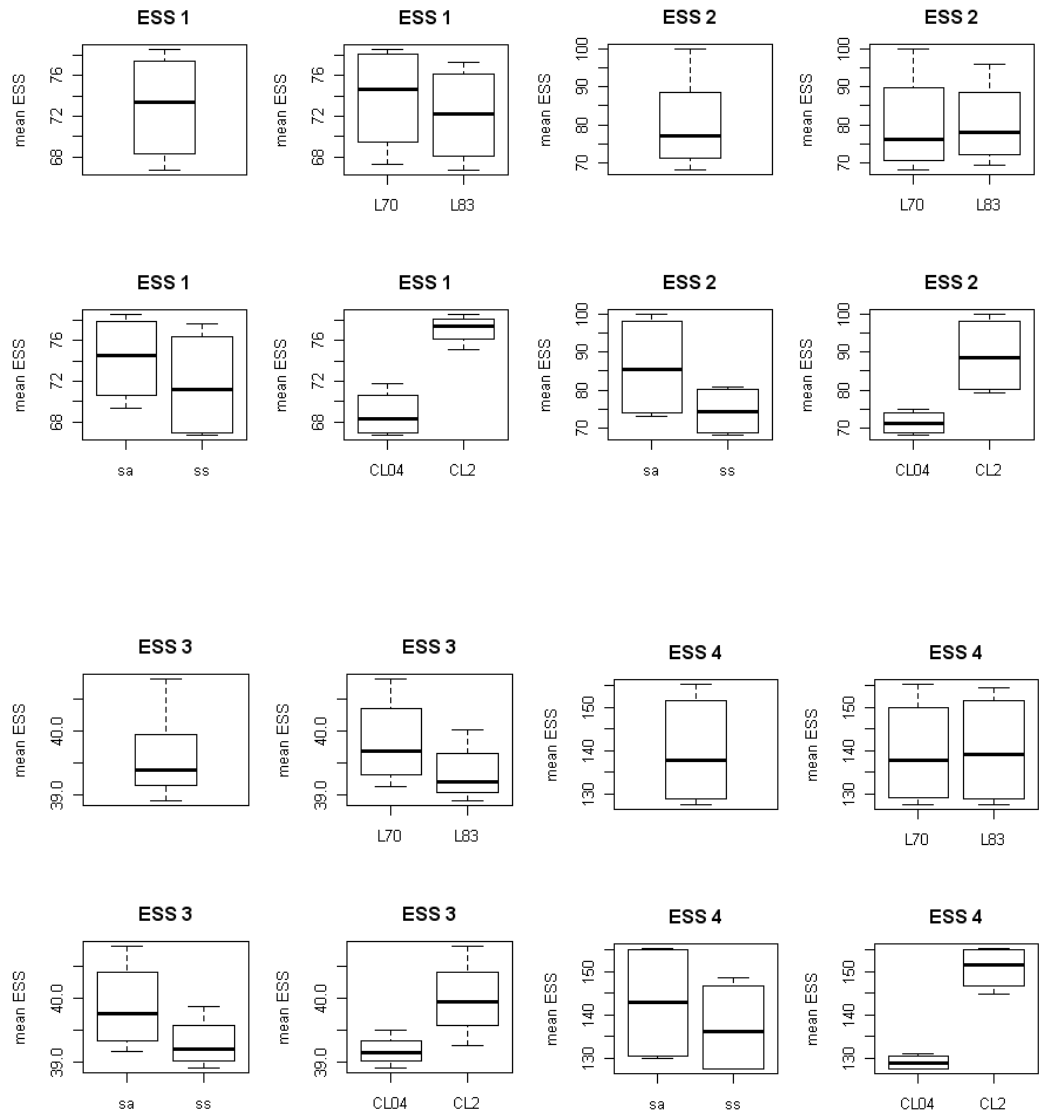


Figure 29. Summary of gridA1 models (Table 4) quality of fit to the size composition data, partitioned by fleet (1-4) and the assumption options listed in Table 3.

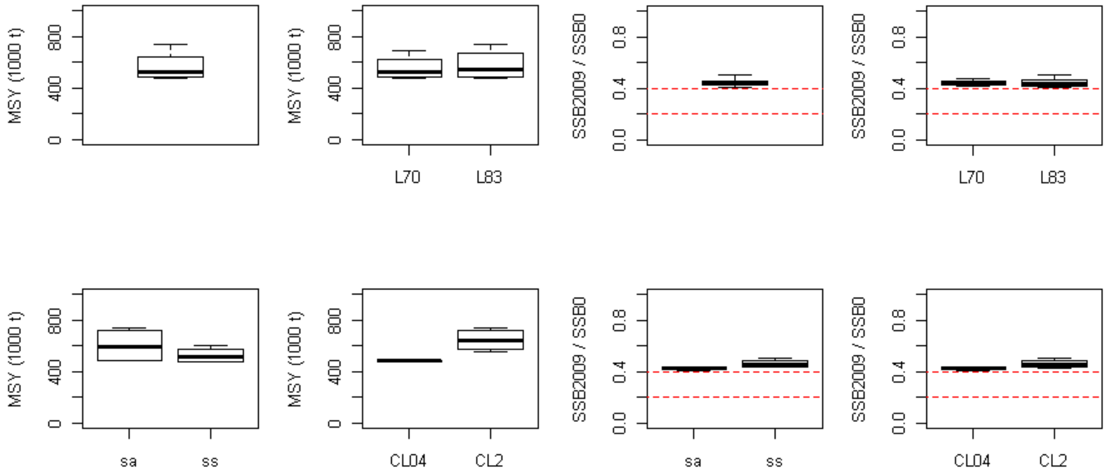
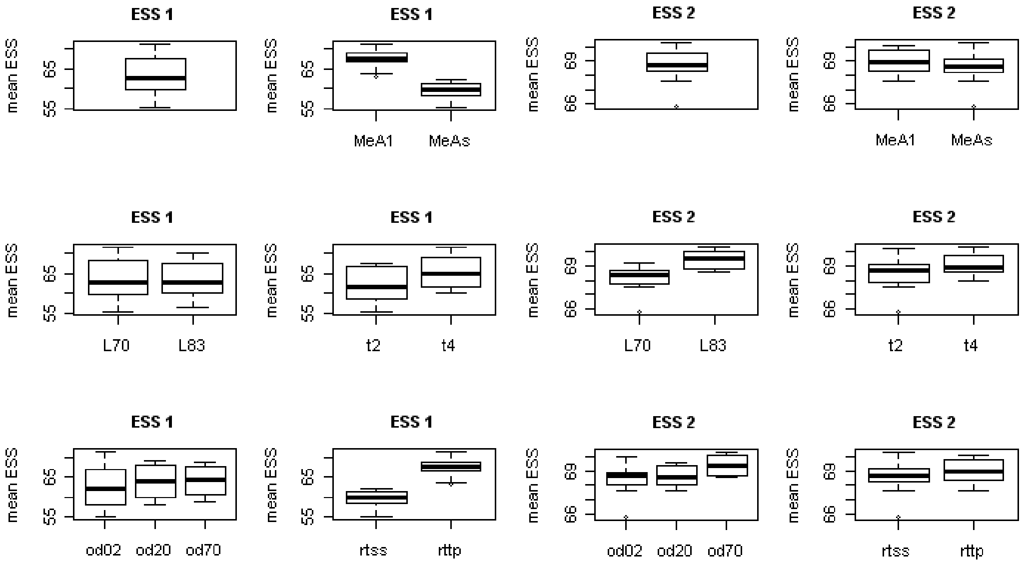


Figure 30. Summary of gridA1 models (Table 4) MSY and depletion MPD estimates, partitioned by the assumption options listed in Table 3.



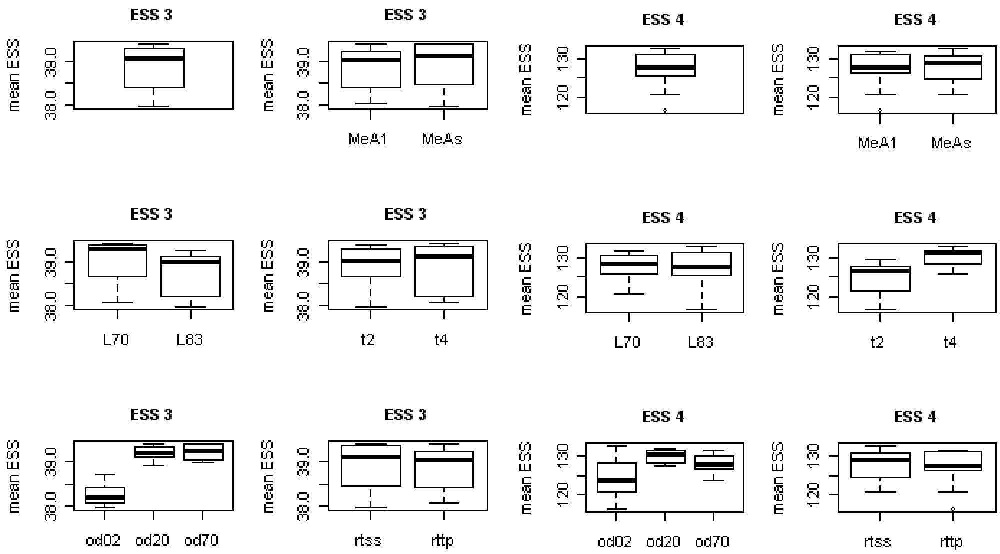


Figure 31. Summary of the quality of fit to the size composition data for the 24 models from gridA2 (Table 4), partitioned by fleet (1-4) and the different assumption options defined in Table 3.

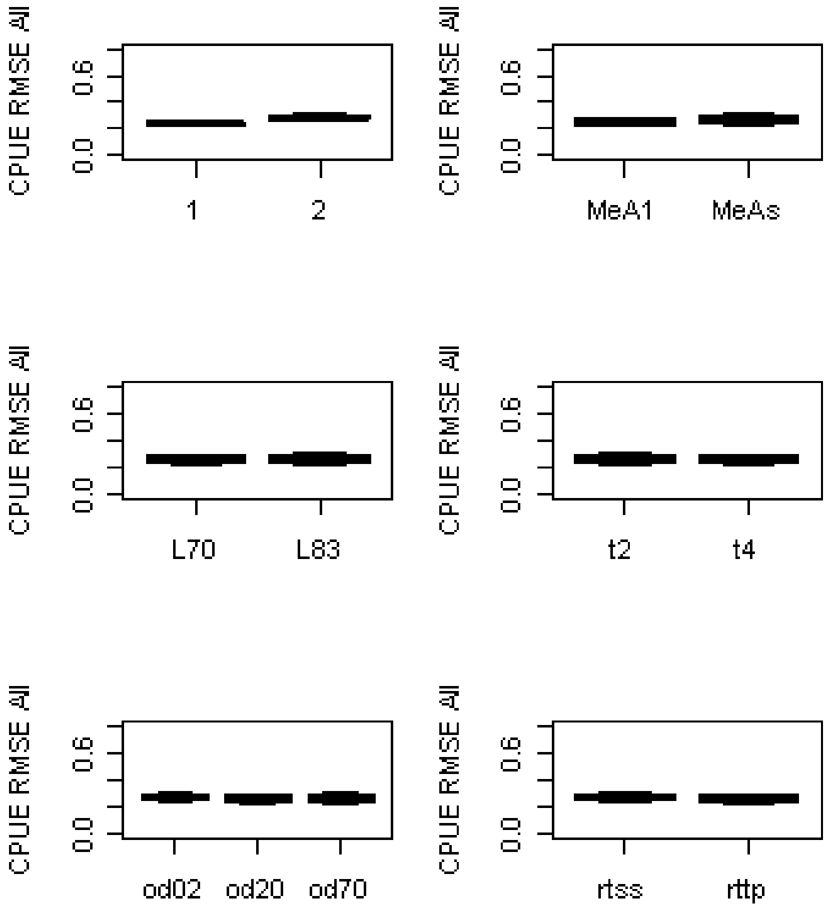


Figure 32. Summary of model fits to the CPUE data for the 24 models from gridA2 (Table 4), partitioned by fleet (1=PL, 2=PSFS) in top left panel; aggregated across fleets in the other panels, partitioned by the other assumption options defined in Table 3.

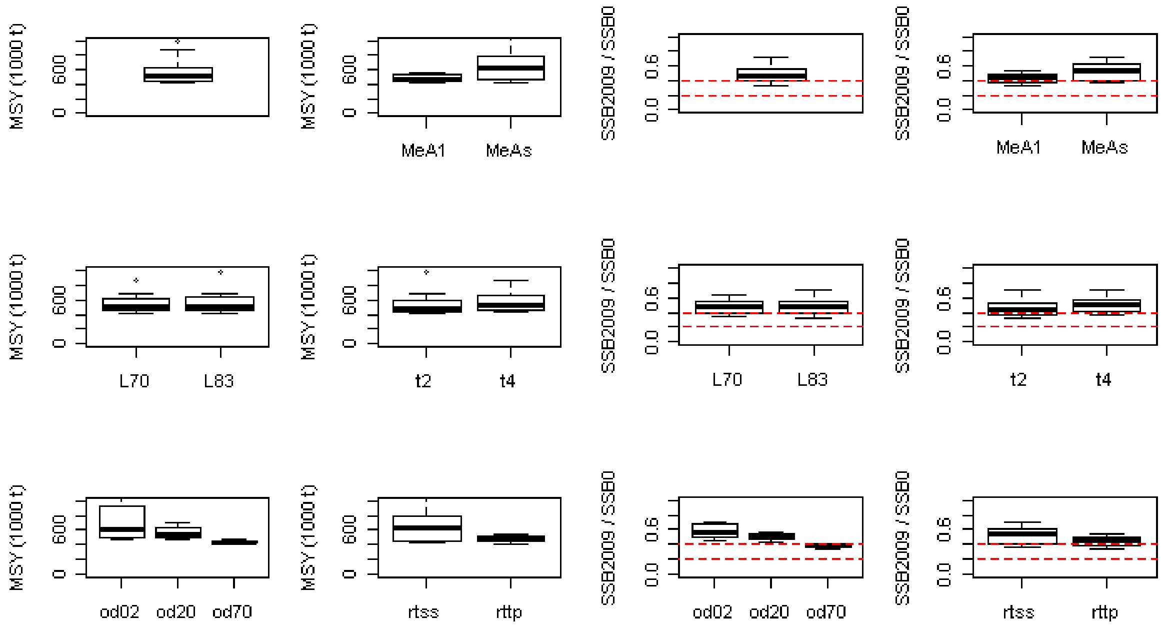


Figure 33. MSY and SB_{2009}/SB_0 MPD estimates for the 24 models from gridA2 (Table 4), partitioned by the different assumption options defined in Table 3.

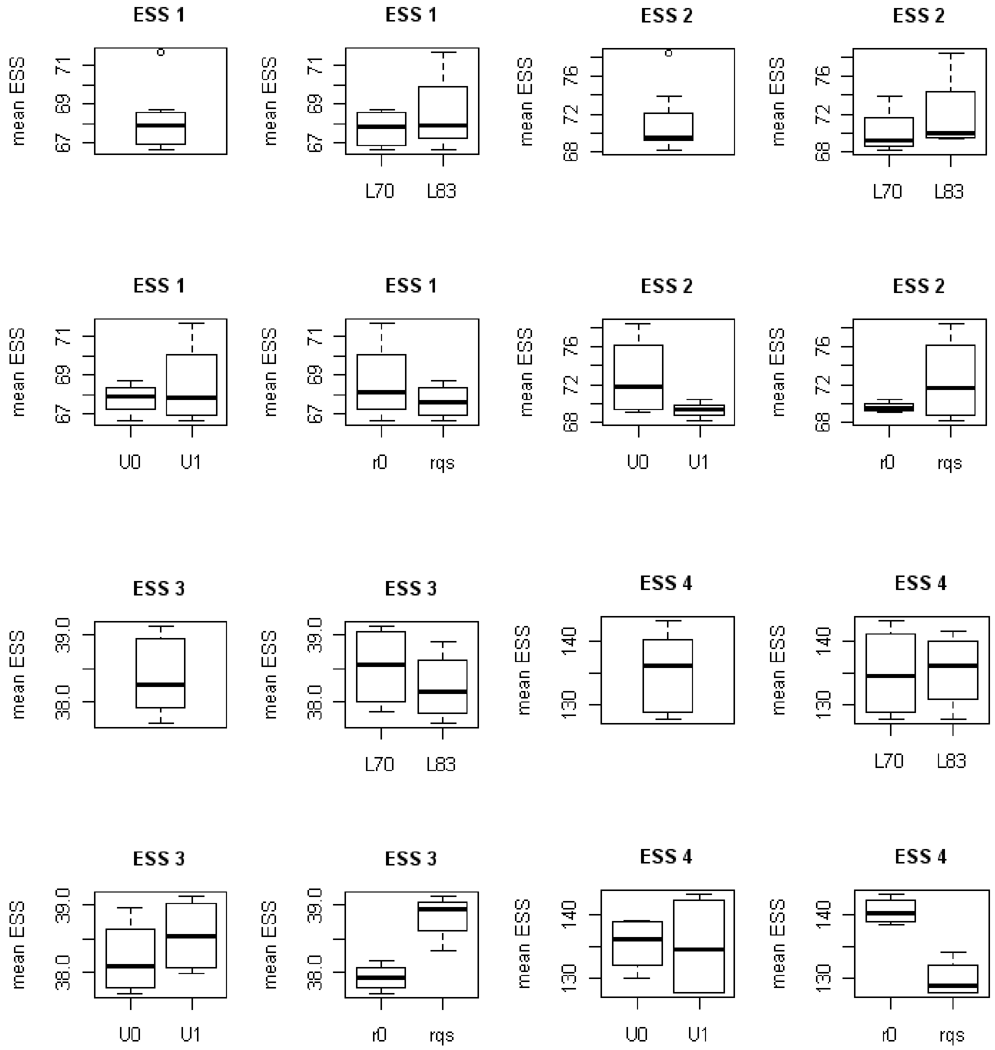


Figure 34. Summary of the quality of fit to the size composition data for the 8 models from gridA3 (Table 4), partitioned by fleet (1-4) and the different assumption options defined in Table 3.

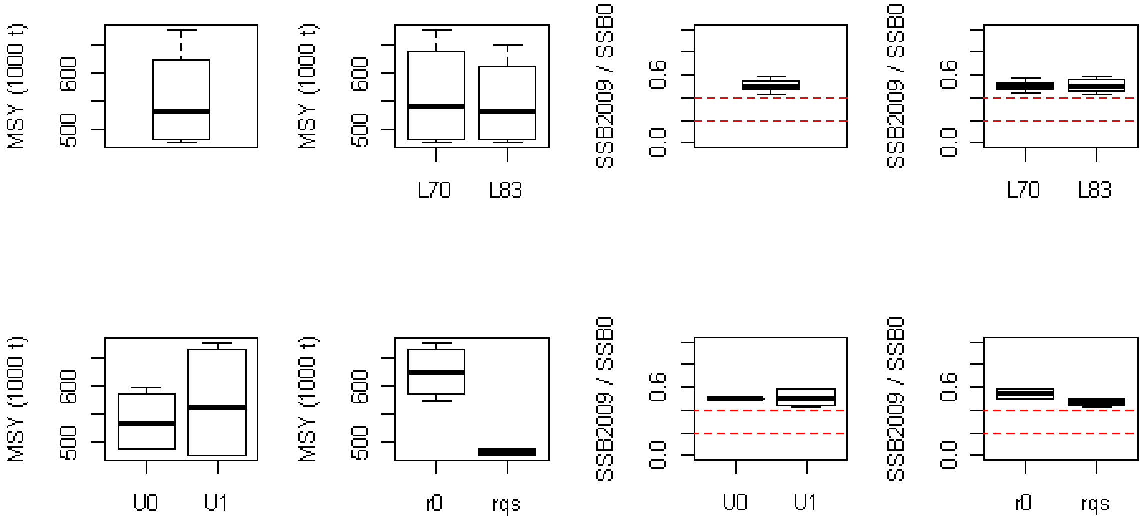


Figure 35. MSY and SB_{2009}/SB_0 MPD estimates for the 8 models from gridA3 (Table 4), partitioned by the different assumption options defined in Table 3.

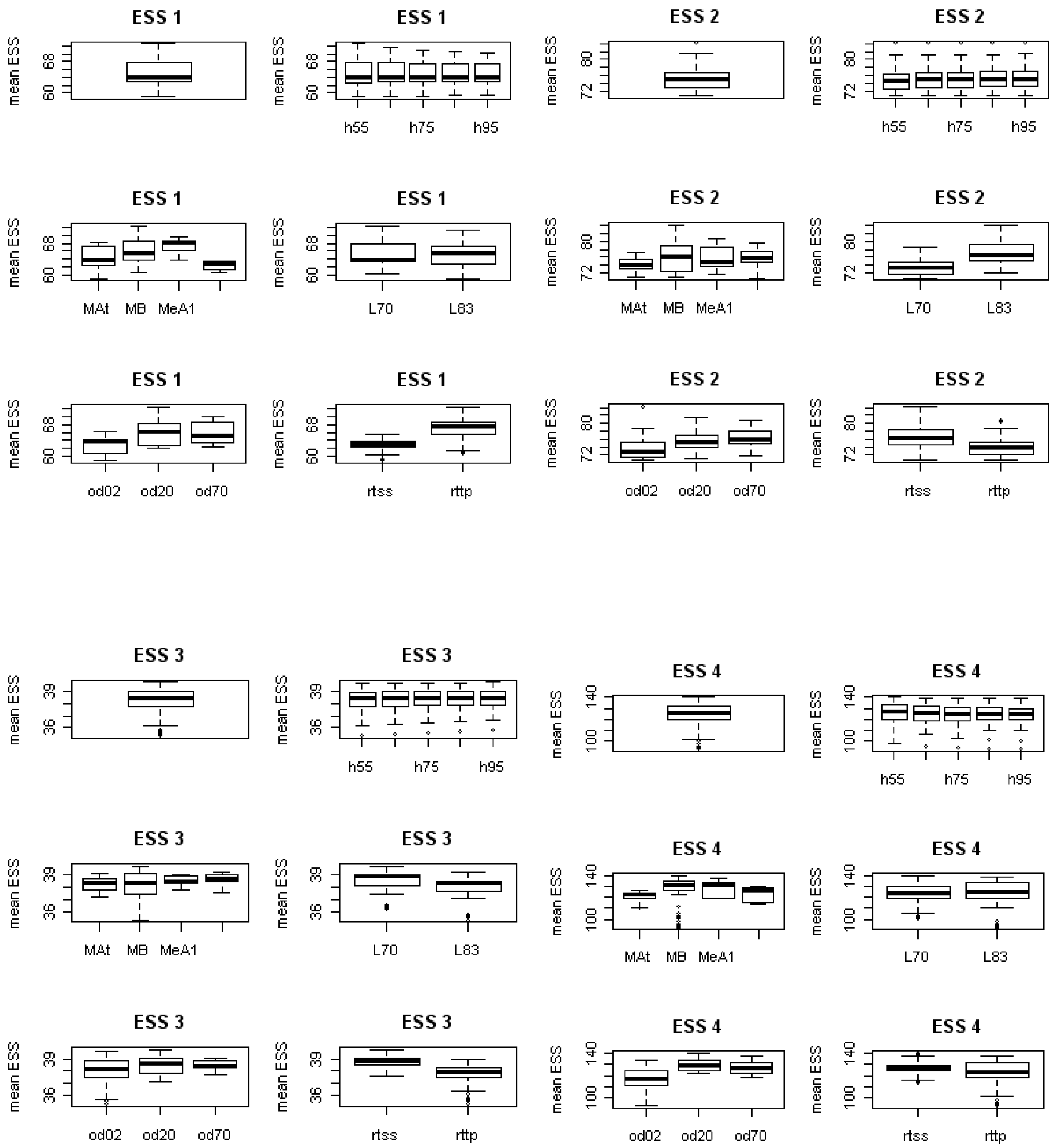


Figure 36. Summary of model fits to the size composition data for the 180 models from gridA4 (Table 4), partitioned by fleet (1-4) and the different assumption options defined in Table 3.

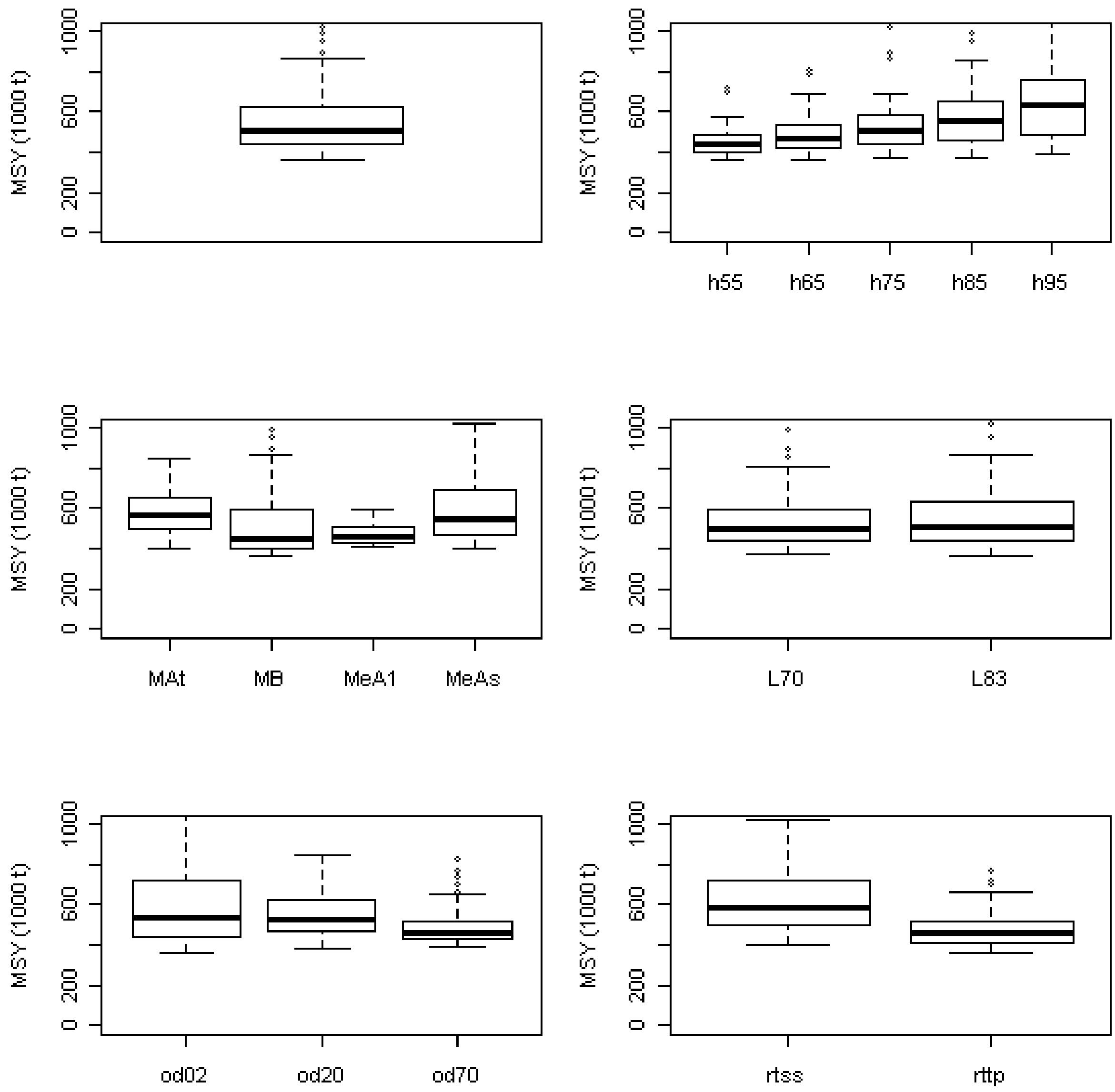


Figure 37. MSY MPD estimates for the 180 models from the stock status grid A4 (Table 4), partitioned by the different assumption options defined in Table 3.

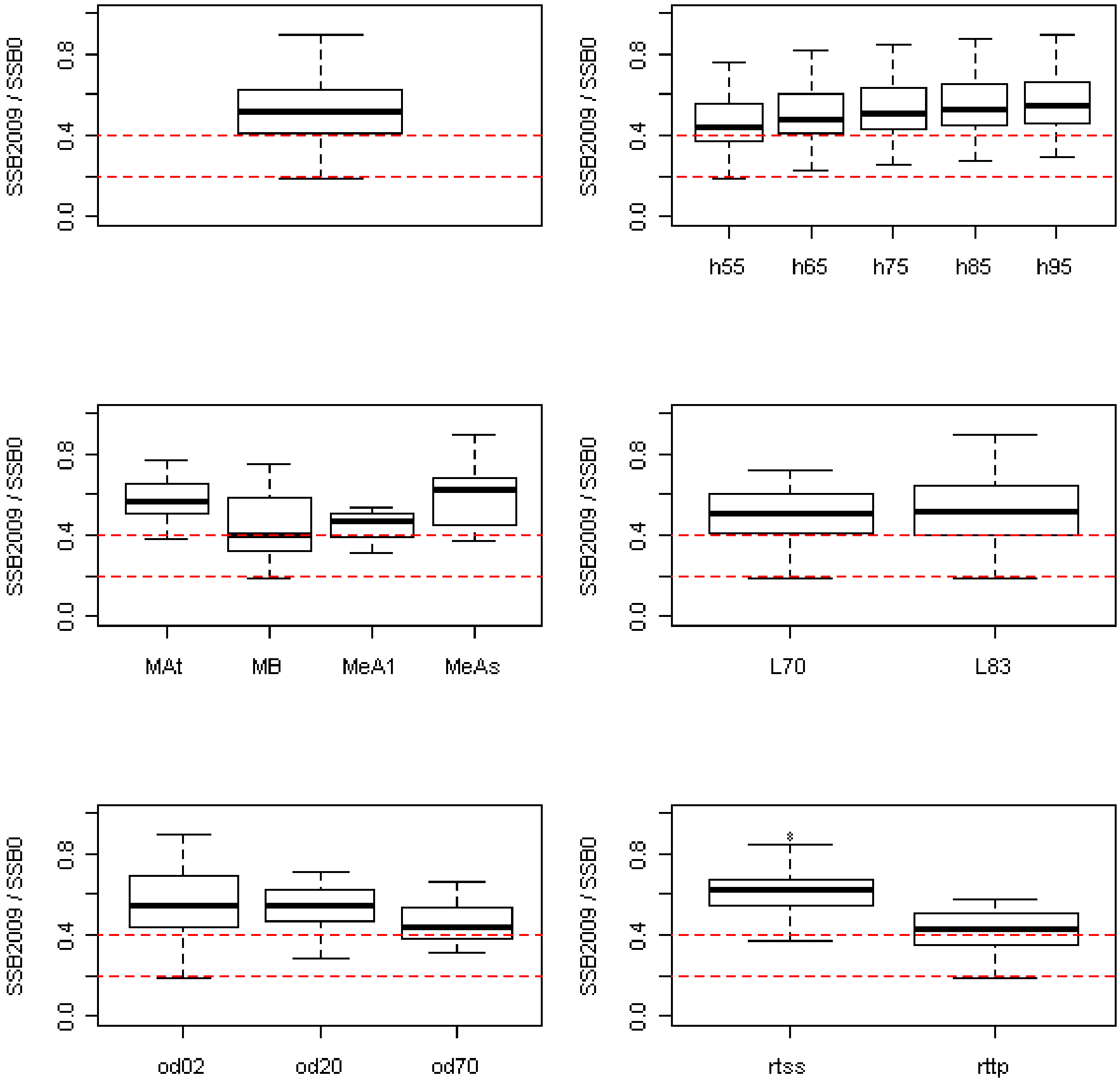


Figure 38. Depletion MPD estimates for the 180 models from the stock status grid A4 (Table 4), partitioned by the different assumption options defined in Table 3.

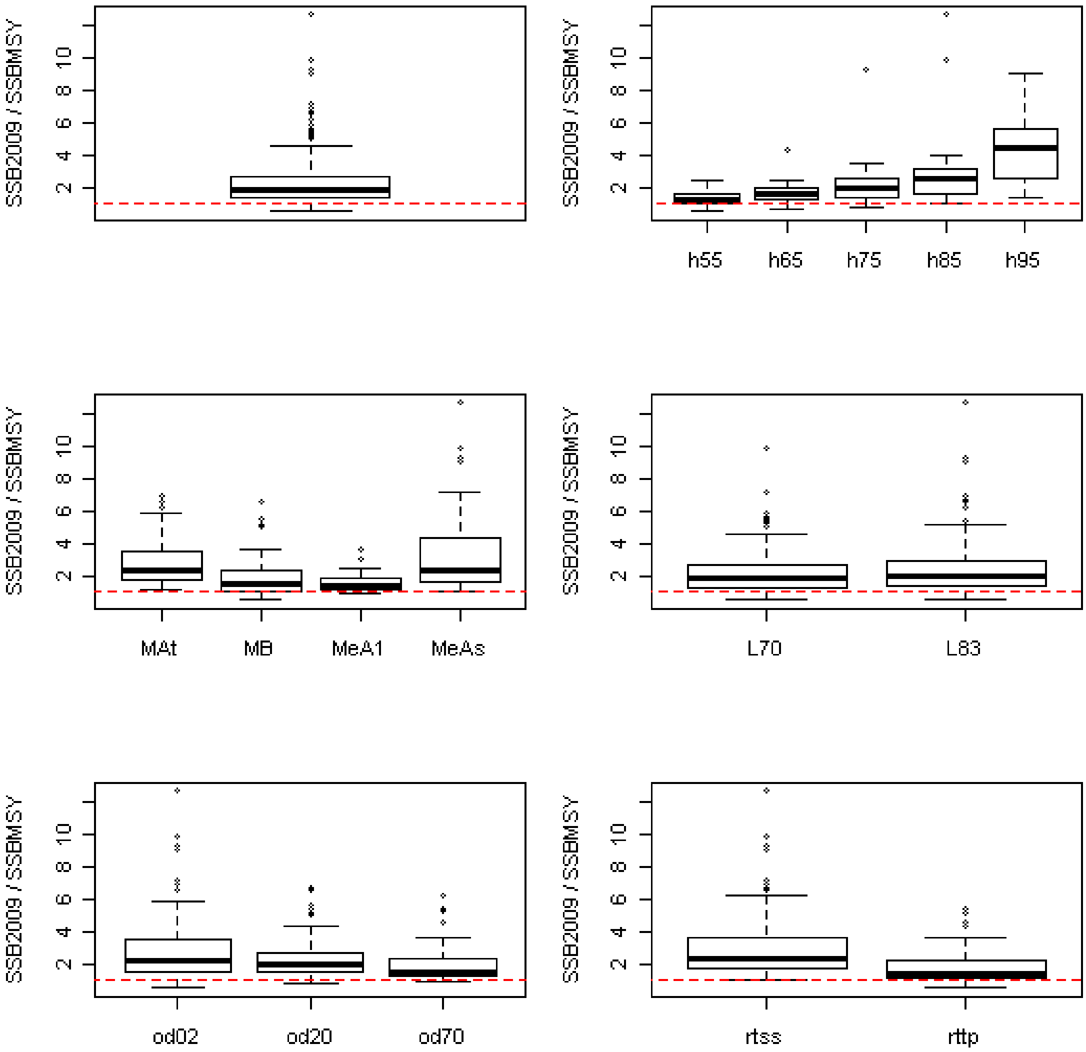


Figure 39. ***SB_{2009}/SB_{MSY}* MPD estimates for the 180 models from gridA4 (Table 4), partitioned by the different assumption options defined in Table 3**

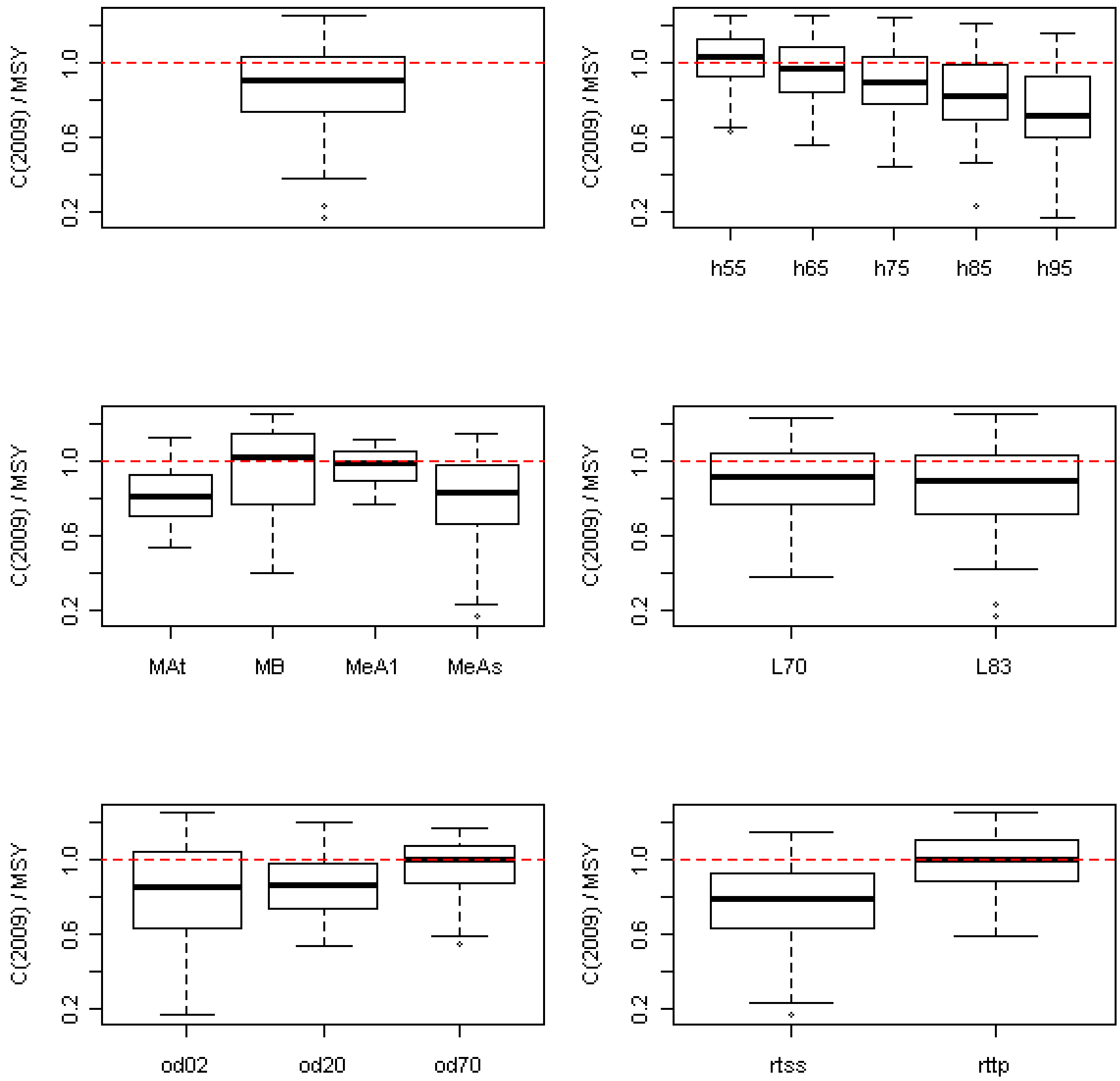


Figure 40. C_{2009}/MSY MPD estimates for the 180 models from the stock status grid A4 (Table 4), partitioned by the different assumption options defined in Table 3.

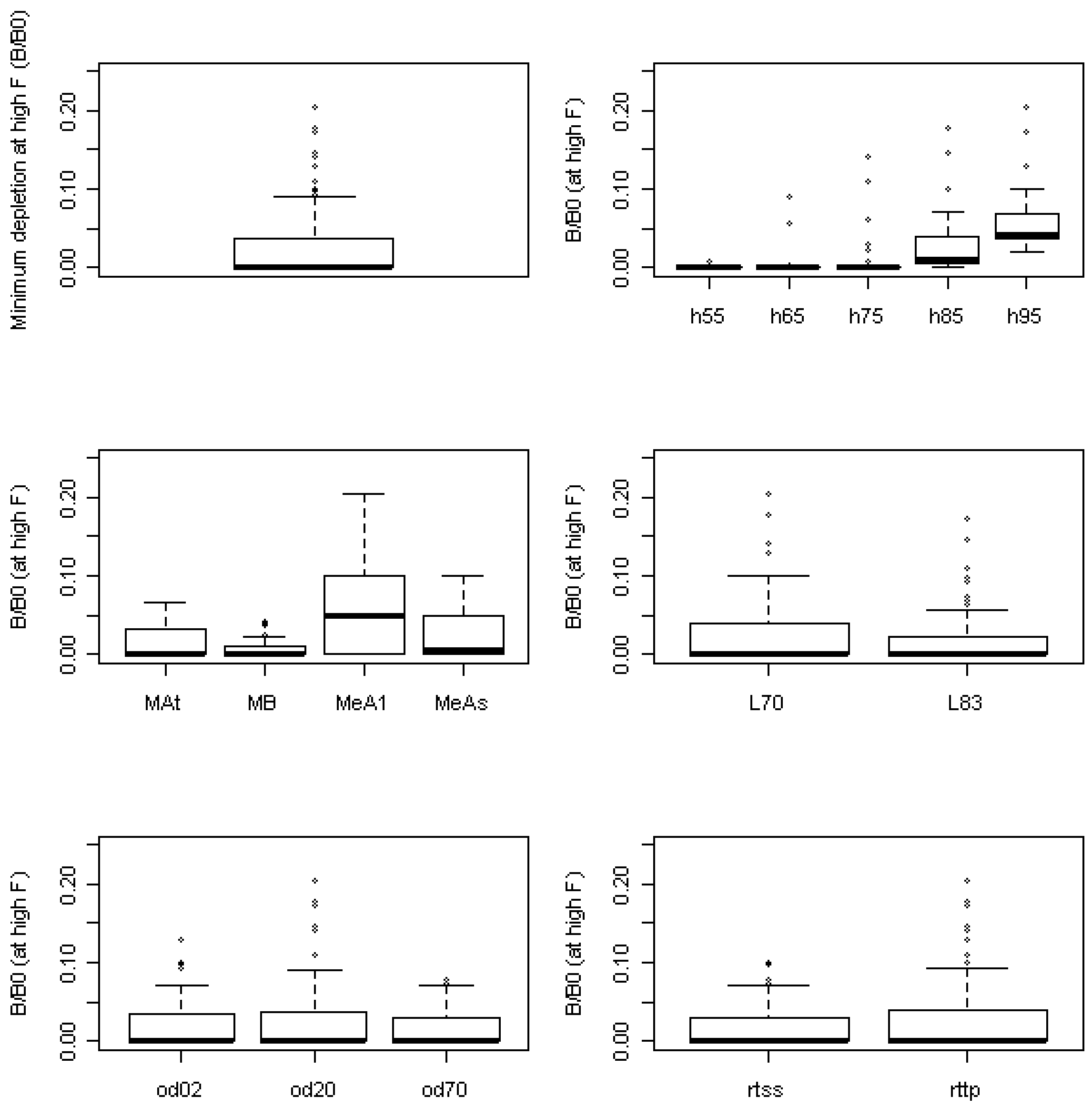


Figure 41. Estimates of *SB/SB$_0$* when the fishery is subject to extremely (unrealistically) high fishing mortality, indicating the estimated spawning biomass reserve for the 180 models from the stock status grid A4 (Table 4), partitioned by the different assumptions defined in Table 3.

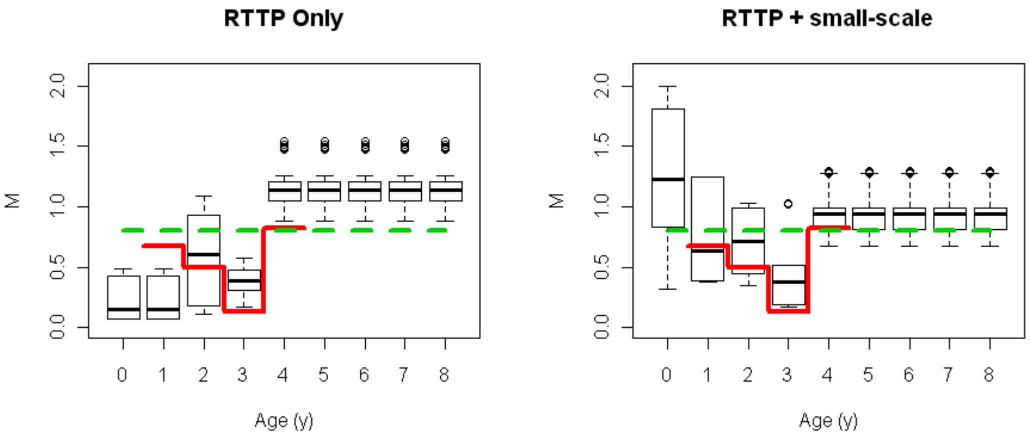


Figure 42. Comparison of natural mortality estimates from the assessment (grid A4, 30 estimates in each boxplot), with those from the independent Brownie estimates (L_{inf} = 83 cm option, red line) and the assumed value in recent ICCAT assessments (green broken line). The left panel includes models with only the RTTP releases (and PS recoveries), the right panel includes the RTTP and small-scale releases (with PS and PL recoveries).

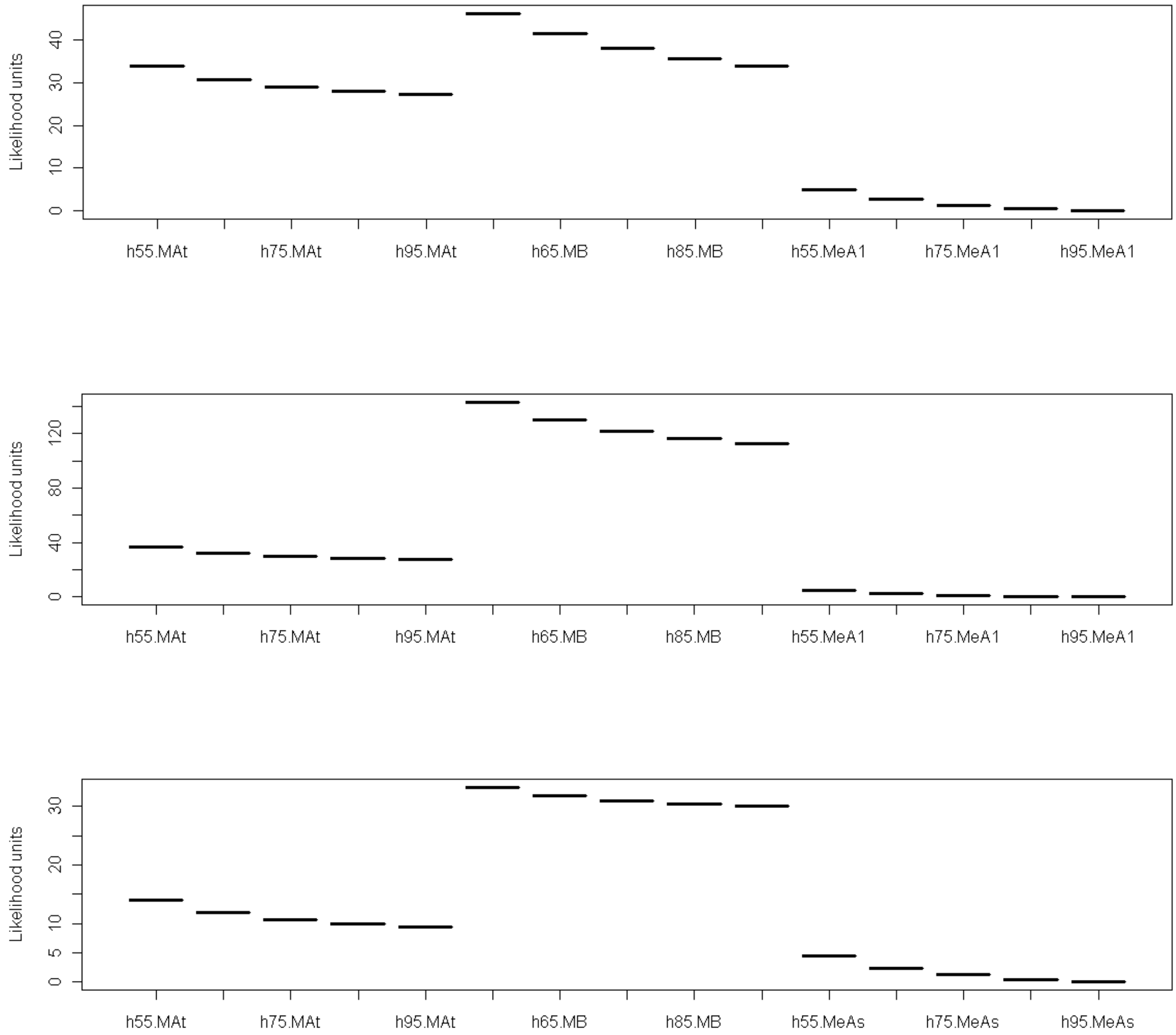


Figure 43. Comparison of (relative) likelihood values for steepness and M values from a subset of gridA4 (Table 4) models that are comparable in principle (within each panel). Top panel: rttp, od20, L83; Middle panel: rttp, od02, L70; Bottom Panel: rtss, od20, L83.

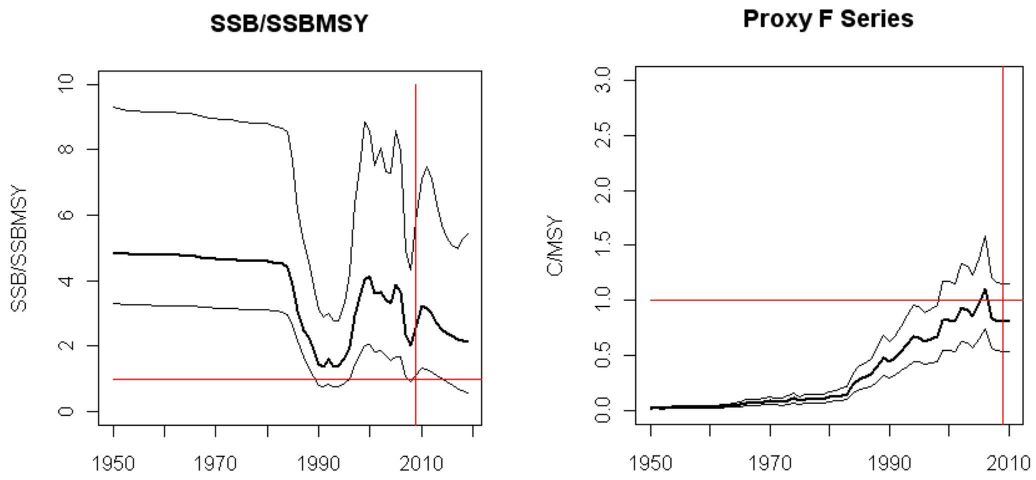


Figure 44. Aggregate Indian Ocean time series of MSY-based reference point estimates from the weighted stock status grid (A4) of models, including 10 years of catch projections at 2009 levels. Thick black lines represent the median value from the weighted distribution (Table 5) of MPD estimates aggregate of 180 models. Thin black lines represent the 5th and 95th percentiles.

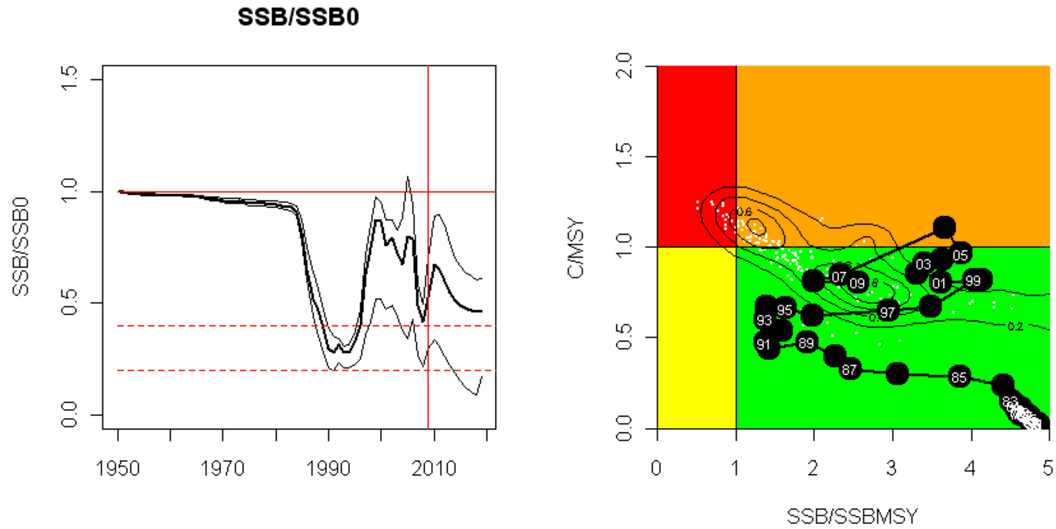


Figure 45. Aggregate Indian Ocean: Left panel – depletion estimates (5th, 50th, 95th percentiles) from the 180 models of the weighted (Table 5) stock status grid (A4), including 10 years of catch projections at 2009 levels. Right panel - Kobe plot for the stock status grid A4. Black circles represent the time series of annual median values from the weighted stock status grid. Contours represent a smoothed probability density function (relative to maximum 1) for the weighted model results from 2009. White points indicate individual MPD estimates. Note that *C_t/MSY* is used as a proxy for *F_t/F_{MSY}* (reasons for this and caveats for interpretation are provided in the main text).

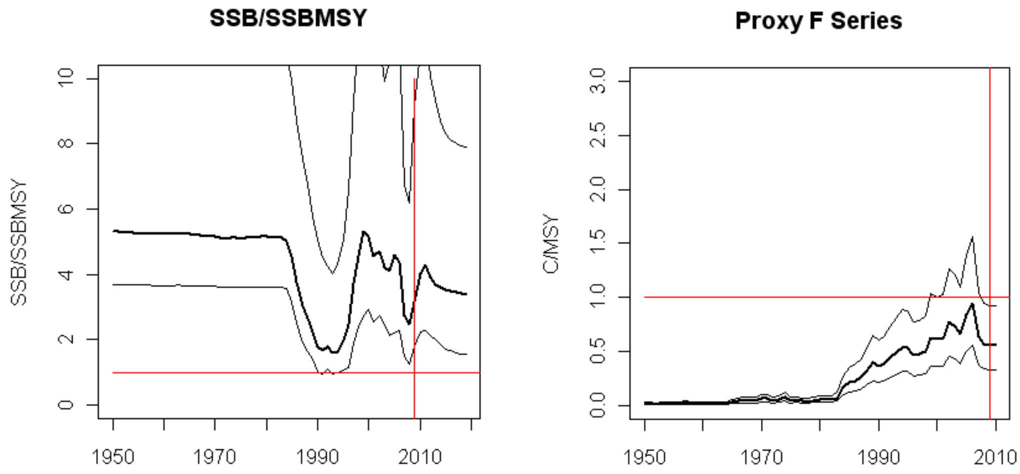


Figure 46. Western Indian Ocean time series of MSY-based reference point estimates from the weighted stock status grid (A4) of models, including 10 years of catch projections at 2009 levels. Thick black lines represent the median value from the weighted distribution (Table 5) of MPD estimates aggregate of 180 models. Thin black lines represent the 5th and 95th percentiles.

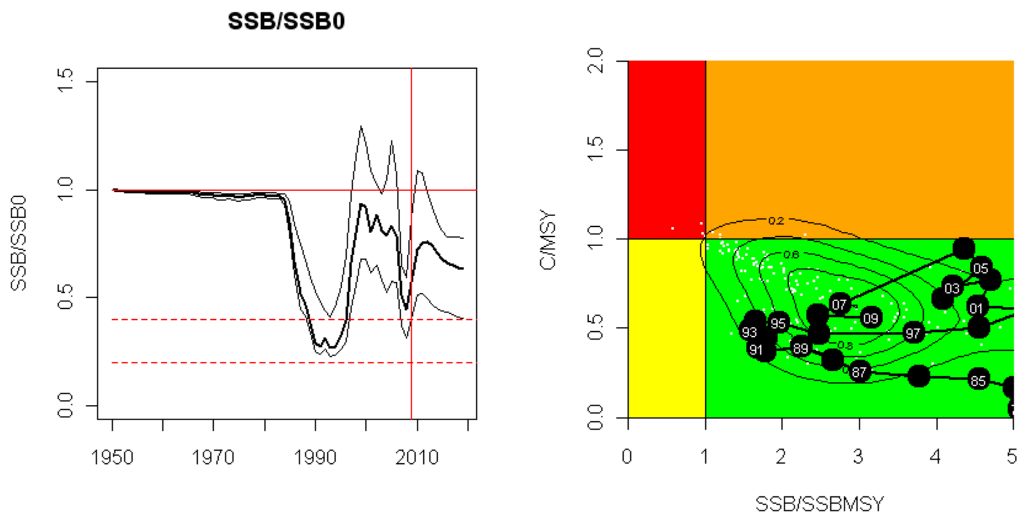


Figure 47. Western Indian Ocean: Left panel – depletion estimates (5th, 50th, 95th percentiles) from the 180 models of the weighted (Table 5) stock status grid (A4), including 10 years of catch projections at 2009 levels. Right panel - Kobe plot for the stock status grid (A4). Black circles represent the time series of annual median values from the weighted stock status grid. Contours represent a smoothed probability density function (relative to maximum 1) for the weighted model results from 2009. White points indicate individual MPD estimates. Note that C_t/MSY is used as a proxy for F_t/F_{MSY} (reasons for this and caveats for interpretation are provided in the main text).

Attachment 1. Summary of key assessment outputs.

Time series of stock assessment outputs are often requested for external analyses (e.g. meta-analyses or systematic reviews). Several time series from the aggregate Indian Ocean SKJ assessment are provided below, representing the final weighted distribution of model results from the stock status grid (A4). We would advise caution in using these time series for a number of reasons, including (but not limited to):

- None of the time series is based on a single internally consistent model. Each quantile could be drawn from a different model between consecutive time-steps. This could suggest a very erratic time series (particularly for absolute values), e.g. a jump from a low M model one year to a high M model the next year might suggest a very large shift in biomass that is not observed within any individual model.
- Time series are dubious prior to 2004 because of the absence of informative relative abundance series in the assessment. As discussed in the main text, there was always a dubious decline and increase in biomass between 1983 and 2004 that was estimated in the absence of a relative abundance index, and is not consistent with nominal PS CPUE series.
- Recruitment series have additional concerns:
    - No recruit deviates were estimated prior to 1983, and only the 2003-2008 period included quarterly deviates.
    - All models included fixed steepness, so this assumption had to have some influence in determining the recruitment time series.

Spawning Biomass (t) Mean and percentiles from the weighted distribution of models					Total Biomass (t) Mean and percentiles from the weighted distribution of models			
time	mean	5th	50th	95th	mean	5th	50th	95th
1950	1.71E+06	1264440	1599550	2780550	2.08E+06	1562130	1958000	3210470
1951	1.70E+06	1257410	1592420	2771780	2.07E+06	1555030	1950550	3201620
1952	1.70E+06	1251440	1586280	2763110	2.07E+06	1548940	1943890	3192900
1953	1.69E+06	1248290	1583080	2757820	2.06E+06	1545670	1940100	3187510
1954	1.69E+06	1246000	1580870	2754210	2.06E+06	1543290	1937310	3183800
1955	1.69E+06	1244170	1579130	2751470	2.06E+06	1541410	1935100	3180950
1956	1.69E+06	1242910	1577960	2749550	2.06E+06	1540110	1933560	3178890
1957	1.68E+06	1241780	1576900	2747870	2.05E+06	1538950	1932200	3177060
1958	1.68E+06	1239970	1575120	2745380	2.05E+06	1537110	1930150	3174440
1959	1.68E+06	1239430	1574640	2744400	2.05E+06	1536540	1929430	3173360
1960	1.68E+06	1238980	1574240	2743680	2.05E+06	1536060	1928840	3172560
1961	1.68E+06	1238820	1574090	2743320	2.05E+06	1535900	1928590	3172140
1962	1.68E+06	1238690	1573950	2743040	2.05E+06	1535770	1928400	3171810
1963	1.68E+06	1236830	1571990	2740560	2.05E+06	1533890	1926400	3169260
1964	1.67E+06	1233990	1568980	2736530	2.05E+06	1531000	1923280	3165160
1965	1.67E+06	1231860	1566750	2733200	2.04E+06	1528820	1920840	3161760
1966	1.67E+06	1226830	1561680	2726410	2.04E+06	1523710	1915330	3154870
1967	1.66E+06	1220160	1554910	2717110	2.03E+06	1516900	1907940	3145440
1968	1.65E+06	1214710	1549430	2708950	2.02E+06	1511300	1901700	3137110
1969	1.65E+06	1211560	1546320	2703800	2.02E+06	1508040	1897900	3131780
1970	1.64E+06	1208340	1543220	2699070	2.01E+06	1504730	1894130	3126840
1971	1.64E+06	1202240	1537310	2691320	2.01E+06	1498490	1887400	3118810
1972	1.64E+06	1200470	1535820	2688400	2.01E+06	1496620	1885130	3115710
1973	1.64E+06	1202520	1537950	2689970	2.01E+06	1498680	1886960	3117160
1974	1.63E+06	1197790	1533070	2684010	2.00E+06	1493420	1881890	3110930
1975	1.62E+06	1189210	1524140	2672230	1.99E+06	1482200	1872550	3098910
1976	1.62E+06	1192000	1526910	2673970	1.99E+06	1484270	1874980	3100530
1977	1.62E+06	1187890	1522590	2668650	1.99E+06	1479240	1870510	3094970
1978	1.62E+06	1187040	1521320	2666980	1.99E+06	1477690	1869380	3093200
1979	1.62E+06	1184350	1517950	2663120	1.99E+06	1474000	1866390	3089120
1980	1.61E+06	1182840	1515950	2660800	1.98E+06	1471950	1864620	3086640
1981	1.61E+06	1176220	1508000	2652420	1.98E+06	1464130	1857610	3078040
1982	1.60E+06	1170020	1499760	2643540	1.97E+06	1456020	1850940	3068990
1983	1.59E+06	1163130	1490530	2633390	1.95E+06	1437830	1833160	3053280
1984	1.56E+06	1132910	1464030	2603740	1.85E+06	1338160	1739190	2960630
1985	1.40E+06	978632	1296090	2427060	1.60E+06	1135670	1477650	2656900
1986	1.15E+06	758345	1033320	2093110	1.34E+06	897870	1215040	2328980
1987	9.27E+05	591414	813792	1770210	1.18E+06	774527	1049890	2068970
1988	8.21E+05	528724	720800	1541660	1.01E+06	640832	902186	1739400
1989	6.80E+05	408581	601556	1290010	8.34E+05	507430	751525	1469030
1990	5.30E+05	303607	454066	1068280	7.31E+05	440775	669135	1327470
1991	4.95E+05	286904	429983	963569	7.42E+05	467732	691991	1212290
1992	5.20E+05	338815	464570	888355	7.08E+05	467235	670453	1081250
1993	4.67E+05	304624	419489	798632	7.06E+05	478761	654804	1100120
1994	4.72E+05	297991	429230	823954	7.93E+05	516387	728169	1231630
1995	5.54E+05	333997	509098	993613	8.85E+05	538491	806141	1423800
1996	6.71E+05	355951	624050	1234080	1.19E+06	655449	1076530	1896420
1997	1.00E+06	519814	936694	1794340	1.47E+06	759828	1338230	2375970
1998	1.20E+06	606217	1119810	2162330	1.73E+06	906258	1581040	2842600
1999	1.41E+06	737403	1315050	2564900	1.87E+06	1007070	1747020	3071780
2000	1.39E+06	748793	1269890	2544720	1.75E+06	953967	1662210	2985290
2001	1.25E+06	665906	1101480	2400610	1.75E+06	975872	1638180	3094230
2002	1.28E+06	704714	1156430	2392570	1.71E+06	951765	1610340	2917860
2003	1.18E+06	633225	1039540	2280890	1.62E+06	838613	1501470	2999330
2004	1.16E+06	527845	983937	2479470	1.74E+06	757276	1575730	3192930
2005	1.31E+06	471284	1177870	2576630	1.76E+06	875949	1715120	2927330
2006	1.24E+06	617761	1125280	2290420	1.44E+06	776063	1416990	2482390
2007	8.01E+05	372082	725600	1662340	1.11E+06	574508	1052620	2129080
2008	6.75E+05	298407	610765	1417380	1.19E+06	623696	1058300	2230780
2009	8.78E+05	403286	774525	1739600	1.41E+06	687180	1215630	2504870
2010	1.10E+06	454175	991640	2211710	1.50E+06	683047	1383450	2771750

SB(t)/SBMSY					C(t)/MSY			
Mean and percentiles from the weighted distribution of models					Mean and percentiles from the weighted distribution of models			
time	mean	5^{th}	50^{th}	95^{th}	mean	5^{th}	50^{th}	95^{th}
1950	5.45E+00	3.31297	4.869237	9.297482	0.021624	0.013761	0.020578	0.029405
1951	5.42E+00	3.295304	4.843607	9.255827	0.027915	0.017765	0.026565	0.03796
1952	5.40E+00	3.278485	4.821725	9.218825	0.027309	0.017379	0.025988	0.037137
1953	5.39E+00	3.268713	4.810374	9.198946	0.028793	0.018323	0.0274	0.039154
1954	5.38E+00	3.262679	4.802449	9.185271	0.030399	0.019345	0.028929	0.041338
1955	5.37E+00	3.257967	4.796274	9.174814	0.030995	0.019725	0.029496	0.042149
1956	5.37E+00	3.254577	4.792169	9.167862	0.032326	0.020572	0.030762	0.043958
1957	5.36E+00	3.25156	4.788421	9.161657	0.035915	0.022856	0.034178	0.048839
1958	5.35E+00	3.247109	4.782138	9.151315	0.034398	0.02189	0.032734	0.046776
1959	5.35E+00	3.245395	4.780389	9.148327	0.034866	0.022188	0.033179	0.047412
1960	5.35E+00	3.244092	4.778961	9.145972	0.034871	0.022192	0.033185	0.04742
1961	5.35E+00	3.243458	4.778533	9.14511	0.035009	0.022279	0.033316	0.047607
1962	5.35E+00	3.242993	4.778212	9.144305	0.040637	0.025861	0.038671	0.05526
1963	5.34E+00	3.238653	4.771501	9.132929	0.046337	0.029488	0.044096	0.063012
1964	5.33E+00	3.231706	4.761113	9.115118	0.047992	0.030541	0.045671	0.065262
1965	5.32E+00	3.226137	4.753403	9.101558	0.059943	0.038146	0.057043	0.081513
1966	5.30E+00	3.214255	4.735233	9.071509	0.07185	0.045724	0.068375	0.097705
1967	5.28E+00	3.198051	4.711067	9.031233	0.077053	0.049035	0.073326	0.10478
1968	5.26E+00	3.18399	4.69147	8.998253	0.077174	0.049112	0.073441	0.104945
1969	5.24E+00	3.175273	4.680511	8.979235	0.081507	0.05187	0.077564	0.110837
1970	5.23E+00	3.167022	4.66941	8.960677	0.092621	0.058942	0.088141	0.12595
1971	5.21E+00	3.152979	4.647885	8.922345	0.087284	0.055546	0.083062	0.118692
1972	5.20E+00	3.147671	4.642031	8.910934	0.080085	0.050965	0.076211	0.108903
1973	5.21E+00	3.150707	4.650027	8.924677	0.097641	0.062137	0.092918	0.132777
1974	5.19E+00	3.140017	4.633321	8.895111	0.116639	0.074227	0.110997	0.158611
1975	5.16E+00	3.11938	4.602158	8.838247	0.092846	0.059086	0.088355	0.126257
1976	5.17E+00	3.123236	4.612582	8.855395	0.110855	0.070546	0.105493	0.150746
1977	5.15E+00	3.113868	4.59816	8.82961	0.105695	0.067262	0.100582	0.143729
1978	5.15E+00	3.111186	4.595447	8.824315	0.112558	0.07163	0.107114	0.153062
1979	5.14E+00	3.104462	4.585952	8.807231	0.112461	0.071568	0.107021	0.15293
1980	5.13E+00	3.100402	4.580848	8.797774	0.129391	0.082342	0.123132	0.175952
1981	5.11E+00	3.08539	4.557502	8.755537	0.137219	0.087324	0.130582	0.186597
1982	5.09E+00	3.070025	4.535942	8.715442	0.147237	0.093699	0.140116	0.20022
1983	5.06E+00	3.052648	4.511954	8.671124	0.160675	0.102251	0.152903	0.218494
1984	4.96E+00	2.97312	4.405044	8.533252	0.250513	0.159422	0.238396	0.34066
1985	4.44E+00	2.627256	3.86589	7.688116	0.301573	0.191916	0.286986	0.410093
1986	3.59E+00	2.159496	3.067146	6.160434	0.317992	0.202365	0.302611	0.432421
1987	2.89E+00	1.658943	2.467027	5.173795	0.345858	0.220098	0.329129	0.470315
1988	2.59E+00	1.326693	2.262474	4.596943	0.419054	0.266679	0.398785	0.56985
1989	2.15E+00	1.05971	1.904628	3.825263	0.500986	0.318819	0.476753	0.681264
1990	1.65E+00	0.815796	1.428449	3.124308	0.462367	0.294243	0.440002	0.628749
1991	1.56E+00	0.768642	1.383976	2.877692	0.498036	0.316942	0.473946	0.677253
1992	1.68E+00	0.85273	1.594157	3.015965	0.565557	0.359911	0.538201	0.769072
1993	1.50E+00	0.761768	1.374163	2.757188	0.636157	0.40484	0.605386	0.865077
1994	1.52E+00	0.765839	1.391743	2.786119	0.702948	0.447344	0.668947	0.955902
1995	1.78E+00	0.874969	1.638993	3.348432	0.697885	0.444122	0.664128	0.949017
1996	2.16E+00	0.982709	1.972038	4.222311	0.654632	0.416597	0.622967	0.8902
1997	3.25E+00	1.440706	2.94369	6.359657	0.682358	0.434241	0.649353	0.927904
1998	3.87E+00	1.714553	3.481827	7.439774	0.704839	0.448548	0.670747	0.958475
1999	4.54E+00	2.023297	4.043901	8.842433	0.863325	0.549405	0.821566	1.173991
2000	4.49E+00	2.041158	4.137197	8.575896	0.860818	0.54781	0.819181	1.170582
2001	4.00E+00	1.842261	3.617286	7.536867	0.850215	0.541063	0.809091	1.156163
2002	4.12E+00	1.879253	3.629112	8.070904	0.980469	0.623954	0.933044	1.333289
2003	3.78E+00	1.717938	3.403478	7.314846	0.961081	0.611616	0.914594	1.306924
2004	3.68E+00	1.570327	3.305129	7.301734	0.901362	0.573612	0.857764	1.225716
2005	4.29E+00	1.680352	3.878676	8.587352	1.013201	0.644784	0.964193	1.377799
2006	4.08E+00	1.659686	3.665076	7.973985	1.16478	0.741246	1.10844	1.583924
2007	2.58E+00	1.080161	2.33822	4.895386	0.889244	0.5659	0.846231	1.209237
2008	2.18E+00	0.911695	1.998088	4.340738	0.856193	0.544867	0.814779	1.164293
2009	2.88E+00	1.090835	2.558251	5.825396	0.849654	0.540706	0.808557	1.155401

Recruitment (1000)

Mean and percentiles from the weighted distribution of models

time	mean	5th	50th	95th
1950	266976.03	143448	241148	447790
1950.25	255332.35	133283	224421	422198
1950.5	275151.85	145120	243956	472184
1950.75	331046.85	167979	303165	534618
1951	266918.01	143438	241138	447777
1951.25	255277.04	133273	224375	422050
1951.5	275092.12	145110	243939	472020
1951.75	330974.54	167967	303086	534587
1952	266865.58	143428	241127	447764
1952.25	255226.9	133264	224334	421923
1952.5	275038.05	145100	243925	471877
1952.75	330909.65	167956	303009	534560
1953	266836.53	143423	241121	447756
1953.25	255199.08	133259	224313	421858
1953.5	275008.02	145094	243918	471804
1953.75	330874.17	167949	302961	534546
1954	266816.16	143419	241117	447750
1954.25	255179.6	133256	224298	421828
1954.5	274987.01	145090	243913	471755
1954.75	330849.35	167945	302928	534538
1955	266800.02	143416	241114	447746
1955.25	255164.23	133253	224286	421808
1955.5	274970.51	145088	243909	471715
1955.75	330829.74	167942	302902	534531
1956	266789.04	143415	241112	447743
1956.25	255153.59	133251	224279	421794
1956.5	274958.99	145086	243906	471687
1956.75	330815.99	167940	302884	534527
1957	266779.09	143413	241110	447741
1957.25	255143.99	133250	224272	421781
1957.5	274948.59	145084	243904	471662
1957.75	330803.79	167938	302868	534523
1958	266763.17	143410	241107	447737
1958.25	255128.88	133247	224260	421761
1958.5	274932.33	145081	243900	471619
1958.75	330784.32	167935	302844	534515
1959	266757.99	143409	241106	447736
1959.25	255124.1	133247	224256	421755
1959.5	274927.14	145081	243899	471608
1959.75	330778.29	167934	302834	534514
1960	266754	143409	241105	447735
1960.25	255120.12	133246	224254	421750
1960.5	274922.89	145080	243898	471599
1960.75	330773.26	167933	302827	534512
1961	266752.3	143408	241105	447734
1961.25	255118.45	133246	224253	421748
1961.5	274921.07	145080	243898	471595
1961.75	330771.29	167933	302824	534512
1962	266750.82	143408	241105	447734
1962.25	255117.09	133246	224252	421746
1962.5	274919.65	145080	243898	471591
1962.75	330769.5	167933	302820	534512
1963	266734.49	143405	241102	447730
1963.25	255101.46	133243	224238	421724
1963.5	274902.8	145077	243894	471544
1963.75	330749.11	167929	302797	534503
1964	266708.92	143401	241097	447724
1964.25	255076.94	133239	224218	421689
1964.5	274876.4	145072	243887	471472
1964.75	330717.33	167924	302760	534489
1965	266689.05	143397	241093	447719
1965.25	255058.05	133235	224202	421662
1965.5	274855.94	145068	243881	471419
1965.75	330692.84	167920	302729	534479
1966	266644.7	143389	241085	447708
1966.25	255015.83	133228	224168	421603
1966.5	274810.44	145060	243869	471299
1966.75	330638.03	167910	302666	534456
1967	266584.92	143378	241073	447694
1967.25	254958.49	133218	224121	421522
1967.5	274748.76	145049	243853	471136
1967.75	330563.86	167897	302580	534426
1968	266534.42	143369	241063	447568
1968.25	254910.28	133209	224083	421456
1968.5	274696.77	145040	243840	471005
1968.75	330501.85	167886	302503	534401
1969	266504.43	143363	241057	447491
1969.25	254881.56	133204	224062	421418
1969.5	274665.77	145034	243833	470930
1969.75	330465.23	167880	302454	534388
1970	266474.83	143358	241052	447414
1970.25	254853.28	133199	224040	421380
1970.5	274635.31	145029	243825	470855
1970.75	330429.01	167874	302409	534375
1971	266421.1	143349	241042	447275
1971.25	254801.92	133190	223998	421310
1971.5	274579.91	145019	243811	470710
1971.75	330362.21	167863	302334	534349
1972	266404.43	143346	241039	447235
1972.25	254785.89	133187	223988	421291
1972.5	274562.71	145016	243807	470674
1972.75	330342.17	167859	302305	534343
1973	266420.35	143348	241041	447276
1973.25	254801.22	133190	224003	421315
1973.5	274579.12	145019	243813	470725
1973.75	330362.75	167862	302319	534355
1974	266377.66	143341	241034	447161
1974.25	254760.34	133183	223954	421257
1974.5	274535.11	145012	243801	470603
1974.75	330309.38	167854	302260	534332
1975	266296.97	143327	241019	446947
1975.25	254683.31	133170	223826	421147
1975.5	274452.06	144997	243779	470378
1975.75	330209.22	167837	302147	534289
1976	266318.14	143330	241021	447003
1976.25	254703.48	133173	223867	421177
1976.5	274473.86	145000	243787	470448
1976.75	330236.48	167841	302163	534304
1977	266280.57	143323	241015	446903
1977.25	254667.64	133167	223806	421127
1977.5	274435.1	144994	243777	470344
1977.75	330189.82	167833	302110	534285
1978	266271.28	143322	241013	446876
1978.25	254658.63	133165	223792	421115
1978.5	274425.39	144992	243775	470320
1978.75	330178.38	167831	302093	534281
1979	266245.14	143317	241008	446805
1979.25	254633.72	133161	223752	421079
1979.5	274398.61	144988	243769	470247

1979.75	330145.94	167826	302054	534268
1980	266230.56	143315	241005	446767
1980.25	254619.77	133159	223729	421061
1980.5	274383.52	144985	243765	470210
1980.75	330128.2	167823	302031	534262
1981	266170.36	143304	240995	446610
1981.25	254562.17	133149	223631	420981
1981.5	274321.46	144974	243748	470044
1981.75	330053.35	167810	301948	534230
1982	266111.16	143293	240983	446457
1982.25	254505.68	133138	223539	420902
1982.5	274260.62	144963	243733	469886
1982.75	329980.38	167797	301861	534201
1983	198509.48	69570.4	185098	366674
1983.25	189653.7	72222	168177	338747
1983.5	204387.95	77533.6	184842	378887
1983.75	250486.73	102558	231294	453373
1984	117730.07	52585.5	117435	204726
1984.25	112238.71	54589.9	110435	189117
1984.5	120960.5	58593.3	121364	211505
1984.75	147367.83	75565.8	153336	254958
1985	132579.18	63179.2	109393	239039
1985.25	127238.75	58720.5	102006	233200
1985.5	136962.23	63943.5	108725	256274
1985.75	163743.48	74106.9	137993	256775
1986	208426.44	97155.6	180710	370063
1986.25	199357.75	90269.2	164201	342603
1986.5	214674.04	98287.9	180460	383164
1986.75	261544.88	113819	228701	461031
1987	115975.81	65459	113950	194565
1987.25	110626.52	67590	107533	179731
1987.5	119166.51	72501	114327	201010
1987.75	145335.86	81521.8	145867	242363
1988	103261.37	61335.2	91952.9	162321
1988.25	98735.34	56985.2	84422.6	152259
1988.5	106325.39	62050	91801.1	167699
1988.75	128493.93	71859.8	116237	202567
1989	156571.21	85632.9	140099	272039
1989.25	150251.74	79544.3	139184	265407
1989.5	161913.33	86630.7	145087	291718
1989.75	191973.98	101645	165852	295061
1990	201757.42	130833	199462	345692
1990.25	192379.49	125978	183708	319426
1990.5	207235.69	138412	194100	357152
1990.75	249675.63	140557	254403	427858
1991	111958.18	68675.8	104975	168747
1991.25	107050.33	64049.8	95275.5	164623
1991.5	115356.97	70811.4	104781	180927
1991.75	139820	81612.3	133443	205093
1992	188311.14	113700	161464	300591
1992.25	180465.04	105633	156486	293268
1992.5	194383.87	115024	165036	322276
1992.75	230298.19	133743	196125	339829
1993	261136.04	166031	227413	411793
1993.25	249862.95	154222	207753	393234
1993.5	269349.46	167967	227099	432155
1993.75	324655.07	194843	288909	512818
1994	215111.69	116547	182706	365436
1994.25	206268.59	108249	177933	356523
1994.5	222449.96	117906	185280	391913
1994.75	264619.8	136916	233286	396662
1995	464062.2	247048	413623	746459
1995.25	444050.44	229661	376226	721858
1995.5	478242.64	249923	413052	792668
1995.75	559953.97	287503	518667	907704
1996	296145.95	137000	292960	514268
1996.25	282627.99	142221	267437	476554
1996.5	304663.96	152717	292477	533139
1996.75	376668.02	191141	370378	644260
1997	429090.91	205987	355885	758947
1997.25	411371.59	191279	337682	740435
1997.5	443848.95	208388	359680	814043
1997.75	536921.27	247034	440147	819861
1998	324216.47	157913	338015	646371
1998.25	308130.89	156882	329373	597314
1998.5	331992.53	163443	366479	667708
1998.75	405546.29	159201	406326	797538
1999	222008.03	115846	194500	368901
1999.25	212827.08	107597	182269	359908
1999.5	229236.45	117196	193914	395614
1999.75	276584.74	136143	240002	412521
2000	435808.49	221864	368084	774460
2000.25	417098.3	206072	334254	756194
2000.5	449981.09	224450	367575	830638
2000.75	545701.42	260878	469702	843083
2001	272656.22	133134	280006	553903
2001.25	259341.55	135934	269043	511893
2001.5	279650.35	146049	293210	572286
2001.75	338263.18	161288	309314	685583
2002	321633.59	146779	255746	658691
2002.25	309349.15	136367	240421	642635
2002.5	333189.56	148490	255309	706518
2002.75	389267.69	173401	317623	717081
2003	492181.98	134589	393987	999584
2003.25	468934.31	139709	357853	971926
2003.5	506702.31	150041	395375	1068100
2003.75	640496.69	169742	498239	1269380
2004	298121.39	125253	252754	408717
2004.25	283786.99	124144	246617	384869
2004.5	305774.4	131979	271056	414207
2004.75	394157.7	130631	352942	744689
2005	77754.69	32234.2	67412.7	114815
2005.25	73855.31	31414.6	63995	110366
2005.5	79672	34723.9	67372.6	120217
2005.75	92328.67	35796.3	79971.4	141873
2006	224418.62	52579.2	202558	376109
2006.25	214968.07	50079.4	194001	372758
2006.5	233589.45	50127.8	204409	396562
2006.75	406761.26	154575	278004	777349
2007	378872.98	83883.3	295419	807533
2007.25	364212.28	79862.2	292020	787841
2007.5	395356.06	79947.1	304134	866947
2007.75	651607.27	247005	459416	1186450
2008	397589.38	182098	364136	755092
2008.25	379458.78	173468	330771	706200
2008.5	410602.62	173670	363805	781788
2008.75	501716.25	266411	469047	952728
2009	255643.81	139919	229499	430174
2009.25	244457.28	130237	208550	412867
2009.5	263456.96	141622	229182	453725
2009.75	317468.73	162883	288500	531128
2010	259966.77	141131	236699	440685
2010.25	248591.16	131129	215093	418740

2010.5	267926.63	142775	236372	462714
2010.75	322630.16	165265	293775	533373
2011	259963.34	141098	235568	441545
2011.25	248597.97	131099	214065	419074
2011.5	267939.64	142742	235242	461795
2011.75	322462.38	165227	296099	533127
2012	258422.48	139306	232714	438114
2012.25	247125.53	130814	211472	417198
2012.5	266358.47	142432	232393	458485
2012.75	320457.89	164868	292720	532210
2013	256466.2	135472	230379	432637
2013.25	245243.08	130368	209350	414187
2013.5	264337.24	141947	230061	455176
2013.75	318032.17	163716	289095	531016
2014	254702.62	130821	228599	428310
2014.25	243538.14	128211	207732	411740
2014.5	262512.15	139419	228283	452486
2014.75	315857.5	160349	286776	530133
2015	253109.16	124617	227181	426661
2015.25	241987.99	125426	206444	410064
2015.5	260862.91	136390	226868	450645
2015.75	313857.38	156865	285959	529560
2016	251366.88	115693	226039	425589
2016.25	240278.17	120102	205406	408894
2016.5	259061.22	128918	225727	449359
2016.75	311595.44	142537	285578	529186
2017	249402.25	101497	225837	424822
2017.25	238331.19	105365	205089	408057
2017.5	257011.08	113099	225419	448440
2017.75	309104.64	128403	285460	528941
2018	248739.64	122531	225775	424274
2018.25	237672.9	114053	205033	407463
2018.5	256234.92	121475	225357	447787
2018.75	308960.05	142642	285382	528780
2019	249257.02	116260	225733	423975
2019.25	238226.12	108216	204996	407040
2019.5	256735.86	117676	225316	447322
2019.75	310189.89	135342	285318	528482

Attachment 2. Template for the SS3 Control.SS file.

Different model options are flagged with '*# xxx*' followed by the option identifier from Table 5 (*e.g.* '# xxx h75' corresponds to steepness 0.75). Individual model specifications are generated by removing the flags corresponding to the desired options.

```
1 #_N_Growth_Patterns
1 #_N_Morphs_Within_GrowthPattern
# 1 #_Morph_between/within_stdev_ratio (no read if N_morphs=1)
# 1 #vector_Morphdist_(-1_in_first_val_gives_normal_approx)
# 1 #   number of recruitment designs
4 #  number of recruitment designs
0 # recruitment interaction requested
#GP seas pop
 1 1 1
 1 2 1
 1 3 1
 1 4 1
# 1 2 1
# 1 3 1
# 1 4 1
# 0 # N_movement_definitions goes here if pop > 1
# 1.0 # first age that moves (real age at begin of season, not integer)
# 1 1 1 2 4 10 # example move definition for seas=1, morph=1, source=1 dest=2, age1=4, age2=10
2 #_Nblock_Designs
5 5 # N_Blocks_per design
1960 1988 1989 1993 1994 1998 1999 2003 2004 2009
1960 1976 1977 1984 1985 1992 1993 2000 2001 2009
0.5 #_fracfemale
1 #_natM_type:_0=1Parm; 1=N_breakpoints;_2=Lorenzen;_3=agespecific;_4=agespec_withseasinterpolate
#5 #_N_breakpoints
#.75  1.25  1.75 2.25 3.75  # age(real) at M breakpoints

# xxx MAt 5 #_N_breakpoints
# xxx MAt 0 1 2 3 4 # age(real) at M breakpoints
# xxx MeA1 4 #_N_breakpoints
# xxx MeA1 1 2 3 4 # age(real) at M breakpoints
# xxx MeAs 5 #_N_breakpoints
# xxx MeAs 0 1 2 3 4 # age(real) at M breakpoints
# xxx MB 6 #_N_breakpoints
# xxx MB 1.99 2 2.99 3 3.99 4 # age(real) at M breakpoints

1 # GrowthModel: 1=vonBert with L1&L2; 2=Richards with L1&L2; 3=not implemented; 4=not implemented

0 #_Growth_Age_for_L1 #mid-season used for calculations
999 #_Growth_Age_for_L2 (999 to use as Linf)
0.1 #_SD_add_to_LAA (set to 0.1 for SS2 V1.x compatibility)
#Should see if alternate t0 0 is better to admit growth effects of younger ages inflating CV
0 #_CV_Growth_Pattern:  0 CV=f(LAA); 1 CV=F(A); 2 SD=F(LAA); 3 SD=F(A)
1 #_maturity_option:  1=length logistic; 2=age logistic; 3=read age-maturity matrix by growth_pattern
#_placeholder for empirical age-maturity by growth pattern
1 #_First_Mature_Age
1 #_fecundity option:(1)eggs=Wt*(a+b*Wt);(2)eggs=a*L^b;(3)eggs=a*Wt^b
0 ### Hermaphroditism season ###
3 #_parameter_offset_approach (1=none, 2= M, G, CV_G as offset from female-GP1, 3=like SS2 V1.x)
1 #_env/block/dev_adjust_method (1=standard; 2=with logistic trans to keep within base parm bounds)
#_growth_parms
#_LO HI INIT PRIOR PR_type SD PHASE env-var use_dev dev_minyr dev_maxyr dev_stddev Block Block_Fxn

# WCPFC fixed
# xxx MPa 0.075 4 2.5 2.5  0 1 -5 0 0 0 0 0 0.5 0 0 # NatM_p_1_Fem_GP:1_
# xxx MPa -3 3 -0.36 -0.36 0 1 -7 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MPa -3 3 -0.55 -0.55 0 1 -7 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MPa -3 3  0.4   0.4  0 1 -6 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MPa -3 3  0.28  0.28 0 1 -6 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_

# ICCAT flat M
# xxx MAt 0.075 2 0.8 0.8 0 1 -5 0 0 0 0 0 0.5 0 0 # NatM_p_1_Fem_GP:1_
# xxx MAt -3 3 -0.0 -0.0  0 1 -7 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MAt -3 3 -0.0 -0.0  0 1 -7 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MAt -3 3 -0.  -0.   0 1 -6 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MAt -3 3 -0.  -0.   0 1 -6 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_


# ICCAT flat M initial
# RTTP only
# xxx MeA1 0.075 2 0.8  0.8  0 1 5 0 0 0 0 0 0.5 0 0 # NatM_p_1_Fem_GP:1_
# xxx MeA1 -5    3 -0. -0.   0 1 7 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MeA1 -5    3 -0. -0.   0 1 7 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MeA1 -5    3 -0. -0.   0 1 6 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# small-scale
# xxx MeAs 0.075 2 0.8  0.8  0 1 5 0 0 0 0 0 0.5 0 0 # NatM_p_1_Fem_GP:1_
# xxx MeAs -5    3 -0. -0.   0 1 7 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MeAs -5    3 -0. -0.   0 1 7 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
```

```
# xxx MeAs -5    3 -0. -0.   0 1 6 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MeAs -5    3 -0. -0.   0 1 6 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_


# Brownie (but not BP) L83 alt fixed
# Linf=83, Brownie: a(1:4)=   0.68      0.50      0.13      0.82
# xxx MB  0.075 2 0.68  0.68  0 1 -5 0 0 0 0 0 0.5 0 0 # NatM_p_1_Fem_GP:1_
# xxx MB  -5    3 -0.2926 -0.2926   0 1 -7 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MB  -5    3 -0. -0.   0 1 -7 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MB  -5    3 -1.347 -1.347   0 1 -6 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MB  -5    3 -0. -0.   0 1 -6 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_
# xxx MB  -5    3 1.8417 1.8417   0 1 -6 0 0 0 0 0 0.5 0 0 # NatM_p_2_Fem_GP:1_

  -30 30   20  20 0 100 -5 0 0 0 0 0 0.5 0 0 # L_at_Amin_Fem_GP_1
# xxx L83  50 100  83   83 0 100 -5 0 0 0 0 0 0.5 0 0 # L_at_Amax_Fem_GP_1
# xxx L83  -3 3  0.22 0.22 0 100 -1 0 0 0 0 0 0.5 0 0 # VonBert_K_Fem_GP_1
# xxx L70  50 100  70.2   70.2 0 100 -5 0 0 0 0 0 0.5 0 0 # L_at_Amax_Fem_GP_1
# xxx L70  -3 3  0.373 0.373 0 100 -1 0 0 0 0 0 0.5 0 0 # VonBert_K_Fem_GP_1

# start with CV20%, decrease to 10% at older ages
   0.01 60 0.2 0.2 0 100 -5 0 0 0 0 0 0.5 0 0 # CV_young_Fem_GP_1_ #try alternates to account for growth
   -3 3 -0.69 -0.69 0 100 -5 0 0 0 0 0 0.5 0 0  # CV_old_Fem_GP_1_ #try alternates to account for growth

 -3 3 5.32e-006 5.32e-006 0 100 -1 0 0 0 0 0 0.5 0 0 # Wtlen1_Fem
 2 4 3.34958 3.34958 0 100 -1 0 0 0 0 0 0.5 0 0 # Wtlen2_Fem

 1 150 38 38 0 100 -1 0 0 0 0 0 0.5 0 0 # Mat50_Fem
## xxx MAtm58 1 150 58 58 0 100 -1 0 0 0 0 0 0.5 0 0 # Mat50_Fem
## xxx MAtm38 1 150 38 38 0 100 -1 0 0 0 0 0 0.5 0 0 # Mat50_Fem
## xxx MeA1m58 1 150 58 58 0 100 -1 0 0 0 0 0 0.5 0 0 # Mat50_Fem
## xxx MeA1m38 1 150 38 38 0 100 -1 0 0 0 0 0 0.5 0 0 # Mat50_Fem
## xxx MeA.1m58 1 150 58 58 0 100 -1 0 0 0 0 0 0.5 0 0 # Mat50_Fem
## xxx MeA.1m38 1 150 38 38 0 100 -1 0 0 0 0 0 0.5 0 0 # Mat50_Fem
## xxx MBm58 1 150 58 58 0 100 -1 0 0 0 0 0 0.5 0 0 # Mat50_Fem
## xxx MBm38 1 150 38 38 0 100 -1 0 0 0 0 0 0.5 0 0 # Mat50_Fem


# xxx check maturity slope sensible...
 -8 1 -1.25 -1.25 0 100 -1 0 0 0 0 0 0.5 0 0 # Mat_slope_Fem
 0 2 1 1 0 100 -1 0 0 0 0 0 0.5 0 0 # Eggs1_Fem
 -1 1 0 0 0 100 -1 0 0 0 0 0 0.5 0 0 # Eggs2_Fem
 -4 4 0 0 -1 99 -3 0 0 0 0 0 0.5 0 0 # RecrDist_GP_1_
 -4 4 0 0 -1 99 -3 0 0 0 0 0 0.5 0 0 # RecrDist_Area_1_
 -4 4 0 0 -1 99 -3 0 0 0 0 0 0.5 0 0 # RecrDist_Seas_1_
 -4 4 0 0 0 0.1 5 0 1 1983 2008 0.3 0 0 # RecrDist_Seas_2_
 -4 4 0 0 0 0.1 5 0 1 1983 2008 0.3 0 0 # RecrDist_Seas_3_
 -4 4 0 0 0 0.1 5 0 1 1983 2008 0.3 0 0 # RecrDist_Seas_4_
 1 1 1 1 -1 99 -3 0 0 0 0 0 0.5 0 0 # CohortGrowDev
# 0  #custom_MG-env_setup (0/1)
# -2 2 0 0 -1 99 -2 #_placeholder for no MG-environ parameters
# 0  #custom_MG-block_setup (0/1)
# -2 2 0 0 -1 99 -2 #_placeholder for no MG-block parameters
#_seasonal_effects_on_biology_parms
 0 0 0 0 0 0 0 0 0 0 #_femwtlen1,femwtlen2,mat1,mat2,fec1,fec2,Malewtlen1,malewtlen2,L1,K
# -2 2 0 0 -1 99 -2 #_placeholder for no seasonal MG parameters
# -2 2 0 0 -1 99 -2 #_placeholder for no MG dev parameters
5 # placeholder for #_MGparm_Dev_Phase
#_Spawner-Recruitment
6 #_SR_function: 1=null; 2=Ricker; 3=std_B-H; 4=SCAA; 5=Hockey; 6=B-H_flattop; 7=Survival_3Parm
#_LO HI INIT PRIOR PR_type SD PHASE
 0 35 20 20 0 10 1 # SR_R0 ##
# xxx h55 0.201 0.99 0.55 0.55 0 10 -2 # SR_steepness
# xxx h65 0.201 0.99 0.65 0.65 0 10 -2 # SR_steepness
# xxx h75 0.201 0.99 0.75 0.75 0 10 -2 # SR_steepness
# xxx h85 0.201 0.99 0.85 0.85 0 10 -2 # SR_steepness
# xxx h95 0.201 0.99 0.95 0.95 0 10 -2 # SR_steepness
  0 10 0.6 0.6 0 10 6 # SR_sigmaR
 -5 5 0 0 0 1 -3 # SR_envlink
 -5 5 0 0 0 1 -4 # SR_R1_offset ## changed from -4 (fixed) to 1 (estimated) ##
 0 0.5 0 0 -1 99 -2 # SR_autocorr
0 #_SR_env_link
0 #_SR_env_target_0=none;1=devs;_2=R0;_3=steepness
# xxx r0   0 #do_recdev:  0=none; 1=devvector; 2=simple deviations
# xxx rqs  1 #do_recdev:  0=none; 1=devvector; 2=simple deviations
1983 # first year of main recr_devs; early devs can preceed this era
2008 # last year of main recr_devs; forecast devs start in following year
4 #_recdev phase
1 #0 # (0/1) to read 11 advanced options
0 #_recdev_early_start (0=none; neg value makes relative to recdev_start)
-4 #_recdev_early_phase
-10 #_forecast_recruitment phase (incl. late recr) (0 value resets to maxphase+1)
1 #_lambda for prior_fore_recr occurring before endyr+1
960 #_last_early_yr_nobias_adj_in_MPD
1983 #_first_yr_fullbias_adj_in_MPD
2008 #_last_yr_fullbias_adj_in_MPD
2009 #_first_recent_yr_nobias_adj_in_MPD
1 #_max_bias_adj_in_MPD
0 # period of cycle in recruitment
```

```
-15 #min rec_dev
15 #max rec_dev
0 #_read_recdevs
#_end of advanced SR options
#Fishing Mortality info
0.15 # F ballpark for tuning early phases
2000 # F ballpark year(neg value to disable)
3 # F_Method:  1=Pope; 2=instan. F; 3=hybrid (hybrid is recommended)
7 # max F or harvest rate, depends on F_Method ## We can changed from 0.99 to 4 if F_method is hyblid(3) ##
# no additional F input needed for Fmethod 1
# read overall start F value; overall phase; N detailed inputs to read for Fmethod 2
5 # read N iterations for tuning for Fmethod 3 (recommend 3 to 7)
# Fleet Year Seas F_value se phase (for detailed setup of F_Method=2)
#_initial_F_parms
#_LO HI INIT PRIOR PR_type SD PHASE ## changed the following maximum values from 0.9 to 3.99 ##

 0 3.99 0.0 0.0   0 100  -1 # InitF_1_LL (longline)
 0 3.99 0.0 0.0   0 100  -1 # InitF_2_PSFS
 0 3.99 0.0 0.0   0 100  -1 # InitF_3_PSLS
 0 3.99 0.0 0.0   0 100  -1 # InitF_4_Other

#_Q_setup
 # A=do power, B=env-var, C=extra SD, D=devtype(<0=mirror, 0/1=none, 2=cons, 3=rand, 4=randwalk); E=0=num/1=bio, F=err_type
 #_A  B  C  D  E  F ## change the following values of error-type from 0 to 30 for the future ##
 0 0 0 0
 0 0 0 0
 0 0 0 0
 0 0 0 0
 0 0 0 0
 0 0 0 0
 # 0 #_0=read one parm for each fleet with random q; 1=read a parm for each year of index
#_Q_parms(if_any)
# # Double normal size selectivity option
# # Start Size Sel Block
# #_size_selex_types
# #_Pattern Discard Male Special
# 24 0 0 0 # 1
# 24 0 0 0 # 2
# 24 0 0 0 # 3
# 24 0 0 0 # 4
# 5  0 0 1 # 1

#_size_selex_types
#_Pattern Discard Male Special
# piecewise size selex
# 6 0 0 9 # 1
# 6 0 0 7 # 2
# 6 0 0 7 # 3
# 6 0 0 7 # 4
# 5 0 0 1 # 5

# cubic spline size selex
 27 0 0 7 # 1
 27 0 0 5 # 2
 27 0 0 5 # 3
 27 0 0 5 # 4
 5 0 0 1 # CPUE mirror 1
 5 0 0 3 # CPUE mirror 3
#_age_selex_types = none
10 0 0 0 # f1
10 0 0 0 # f2
10 0 0 0 # f3
10 0 0 0 # f4
10 0 0 0 # cpue1
10 0 0 0 # cpue FSLS
#_LO HI INIT PRIOR PR_type SD PHASE env-var use_dev dev_minyr dev_maxyr dev_stddev Block Block_Fxn
## 1. LL (longline)
#
# fishery 1 #max age 15
# LO HI INIT PRIOR PR_type SD PHASE
#len bounds
#_LO HI INIT PRIOR PR_type SD PHASE env-var use_dev dev_minyr dev_maxyr dev_stddev Block Block_Fxn
 0 0 0 0 -1 0 -99 0 0 0 0 0.5 0 0 # SizeSpline_Code_PL_1
 -0.001 1 0.247221 0 1 0.001 3 0 0 0 0 0.5 0 0 # SizeSpline_GradLo_PL_1
 -1 0.001 -0.658209 0 1 0.001 3 0 0 0 0 0.5 0 0 # SizeSpline_GradHi_PL_1
 1 1 22.6447 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_1_PL_1
 1 1 37.5977 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_2_PL_1
 1 1 42.0377 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_3_PL_1
 1 1 45.702 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_4_PL_1
 1 1 51.7386 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_5_PL_1
 1 1 59.9904 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_6_PL_1
 1 1 71.3145 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_7_PL_1
 -9 7 -4.42509 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_1_PL_1
 -9 7 -2.2233 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_2_PL_1
 -9 7 -1.56912 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_3_PL_1
 -9 7 -1 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_4_PL_1
 -9 7 -1.26099 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_5_PL_1
 -9 7 -0.55179 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_6_PL_1
```

```
-9 7 -0.579285 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_7_PL_1
0 0 0 0 -1 0 -99 0 0 0 0 0.5 0 0 # SizeSpline_Code_PSLS_2
-0.001 1 0.622317 0 1 0.001 3 0 0 0 0 0.5 0 0 # SizeSpline_GradLo_PSLS_2
-1 0.001 -0.110388 0 1 0.001 3 0 0 0 0 0.5 0 0 # SizeSpline_GradHi_PSLS_2
1 1 23.125 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_1_PSLS_2
1 1 41.9035 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_2_PSLS_2
1 1 45.6322 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_3_PSLS_2
1 1 50.2975 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_4_PSLS_2
1 1 70.9228 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_5_PSLS_2
-9 7 -8.9974 0 1 0.001 -2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_1_PSLS_2
-9 7 -2.05844 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_2_PSLS_2
-9 7 -1 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_3_PSLS_2
-9 7 -0.954789 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_4_PSLS_2
-9 7 -2.24451 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_5_PSLS_2
0 0 0 0 -1 0 -99 0 0 0 0 0.5 0 0 # SizeSpline_Code_PSFS_3
-0.001 1 0.0149309 0 1 0.001 3 0 0 0 0 0.5 0 0 # SizeSpline_GradLo_PSFS_3
-1 0.001 -0.245826 0 1 0.001 3 0 0 0 0 0.5 0 0 # SizeSpline_GradHi_PSFS_3
1 1 23.1313 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_1_PSFS_3
1 1 44.1442 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_2_PSFS_3
1 1 48.4634 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_3_PSFS_3
1 1 54.7779 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_4_PSFS_3
1 1 71.2972 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_5_PSFS_3
-9 7 -8.99994 0 1 0.001 -2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_1_PSFS_3
-9 7 -2.04755 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_2_PSFS_3
-9 7 -1 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_3_PSFS_3
-9 7 -1.02858 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_4_PSFS_3
-9 7 -1.20735 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_5_PSFS_3
0 0 0 0 -1 0 -99 0 0 0 0 0.5 0 0 # SizeSpline_Code_Other_4
-0.001 1 0.0655165 0 1 0.001 3 0 0 0 0 0.5 0 0 # SizeSpline_GradLo_Other_4
-1 0.001 -0.202624 0 1 0.001 3 0 0 0 0 0.5 0 0 # SizeSpline_GradHi_Other_4
1 1 22.5552 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_1_Other_4
1 1 44.2844 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_2_Other_4
1 1 51.4468 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_3_Other_4
1 1 58.8149 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_4_Other_4
1 1 72.4351 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Knot_5_Other_4
-9 7 -4.41096 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_1_Other_4
-9 7 -1.92167 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_2_Other_4
-9 7 -1 0 -1 0 -99 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_3_Other_4
-9 7 -0.364211 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_4_Other_4
-9 7 0.286711 0 1 0.001 2 0 1 2004 2008 0.05 0 0 # SizeSpline_Val_5_Other_4
1 1 1 1 1 99 -3 0 0 0 0 0.5 0 0 # SizeSel_5P_1_PL_CPUE
22 22 22 22 1 99 -3 0 0 0 0 0.5 0 0 # SizeSel_5P_2_PL_CPUE
3 3 3 3 3 99 -3 0 0 0 0 0.5 0 0 # SizeSel_5P_1_PSFS_CPUE
22 22 22 22 1 99 -3 0 0 0 0 0.5 0 0 # SizeSel_5P_2_PSFS_CPUE

# xxx sa 4 # selparm_Dev_Phase
# xxx sa 1 # selparm_adjust_method 1=direct, 2=logistic transform

# xxx ss -4 # selparm_Dev_Phase
# xxx ss 1 # selparm_adjust_method 1=direct, 2=logistic transform



1 # TG_custom:  0=no read; 1=read
#tag loss parameter - for each tag grp
# -10 10 9 9 1 0.001 -4 0 0 0 0 0 0 0 # TG_loss_init_1_
# chronic tag loss - for each tag group
# -10 10 9 9 1 0.001 -4 0 0 0 0 0 0 0 # TG_loss_chronic_1_
# Overdispersion  for the negative binomial for each tag group
# 1 10 200 200 1 0.001 -4 0 0 0 0 0 0 0 # TG_overdispersion_1_
#tag loss parameter - for each tag grp
# -10 10 9 9 1 0.001 -4 0 0 0 0 0 0 0 # TG_loss_init_1_
#set to negligible value

*****************    Repeated release group parameters are omitted below here ****************************

# xxx rttp # xxx L83 -15 10 -10 -10 1 0.001 -4 0 0 0 0 0 0 0 # TG_loss_init_1_ by release group what is the parameter definition; what is 1,2,3 ?!
# xxx rtss # xxx L83 -15 10 -10 -10 1 0.001 -4 0 0 0 0 0 0 0 # TG_loss_init_1_ by release group what is the parameter definition; what is 1,2,3 ?!
# xxx rttp # xxx L70 -15 10 -10 -10 1 0.001 -4 0 0 0 0 0 0 0 # TG_loss_init_1_ by release group what is the parameter definition; what is 1,2,3 ?!
# xxx rtss # xxx L70 -15 10 -10 -10 1 0.001 -4 0 0 0 0 0 0 0 # TG_loss_init_1_ by release group what is the parameter definition; what is 1,2,3 ?!

# chronic tag loss - for each tag group
# xxx rttp # xxx L83  -15 10 -4.185 -4.185 1 0.001 -4 0 0 0 0 0 0 0  # chronic tag loss
# xxx rtss # xxx L83  -15 10 -4.185 -4.185 1 0.001 -4 0 0 0 0 0 0 0  # chronic tag loss
# xxx rttp # xxx L70  -15 10 -4.185 -4.185 1 0.001 -4 0 0 0 0 0 0 0  # chronic tag loss
# xxx rtss # xxx L70  -15 10 -4.185 -4.185 1 0.001 -4 0 0 0 0 0 0 0  # chronic tag loss

# Overdispersion  for the negative binomial for each tag group
# xxx rttp # xxx L83 # xxx od02 1 150   2 2 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion
# xxx rtss # xxx L83 # xxx od02 1 150   2 2 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion
# xxx rttp # xxx L70 # xxx od02 1 150   2 2 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion
# xxx rtss # xxx L70 # xxx od02 1 150   2 2 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion

# Overdispersion  for the negative binomial for each tag group
# xxx rttp # xxx L83 # xxx od20 1 150   20 20 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion
# xxx rtss # xxx L83 # xxx od20 1 150   20 20 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion
# xxx rttp # xxx L70 # xxx od20 1 150   20 20 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion
```

xxx rtss # xxx L70 # xxx od20 1 150   20 20 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion

Overdispersion for the negative binomial for each tag group
xxx rttp # xxx L83 # xxx od70 1 150   70 70 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion
xxx rtss # xxx L83 # xxx od70 1 150   70 70 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion
xxx rttp # xxx L70 # xxx od70 1 150   70 70 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion
xxx rtss # xxx L70 # xxx od70 1 150   70 70 1 0.001 -4 0 0 0 0 0 0 0 # tag overdispersion

*****************   Repeated release group parameters are omitted above here ****************************

#PS recoveries already inflated by RR (PSLS and PSFS), estimate PL, force zero for others
#_LO HI INIT PRIOR PR_type SD PHASE env-var use_dev dev_minyr dev_maxyr dev_stddev Block Block_Fxn
-20 20 0 0 1 99 1 0 0 0 0 0 0 0 # TG_report_fleet:_1_
-20 20 10 10 1 0.2 -4 0 0 0 0 0 0 0 # TG_report_fleet:_2_
-20 20 10 10 1 0.2 -4 0 0 0 0 0 0 0 # TG_report_fleet:_2_
-20 20 -10. -10. 1 2. -4 0 0 0 0 0 0 0 # TG_report_fleet:_1_
LO HI INIT PRIOR PR_type SD PHASE
Exponential decay rate in reporting rate for each fleet (default=0, negative value to get decay)
-4 0 0 0 0 2 -4 0 0 0 0 0 0 0 # TG_rpt_decay_fleet:_1_
-4 0 0 0 0 2 -4 0 0 0 0 0 0 0 # TG_rpt_decay_fleet:_2_
-4 0 0 0 0 2 -4 0 0 0 0 0 0 0 # TG_rpt_decay_fleet:_1_
-4 0 0 0 0 2 -4 0 0 0 0 0 0 0 # TG_rpt_decay_fleet:_2_
1 #_Variance_adjustments_to_input_values
#_1 2 3
0 0 0 0 0 0 #_add_to_survey_CV
0 0 0 0 0 0 #_add_to_discard_CV
0 0 0 0 0 0 #_add_to_bodywt_CV
xxx CL1   1.0 1.0 1.0 1.0 1 1 #_mult_by_lencomp_N
xxx CL5   0.5 0.5 0.5 0.5 1 1 #_mult_by_lencomp_N
xxx CL2   0.2 0.2 0.2 0.2 1 1 #_mult_by_lencomp_N
xxx CL04   0.04 0.04 0.04 0.04 1 1 #_mult_by_lencomp_N
1 1 1 1 1 1 #_mult_by_agecomp_N
1 1 1 1 1 1 #_mult_by_size-at-age_N
30 #_DF_for_discard_like
30 #_DF_for_meanbodywt_like
4 #_maxlambdaphase
1 #_sd_offset
10 # number of changes to make to default Lambdas (default value is 1.0)
Like_comp codes: 1=survey; 2=disc; 3=mnwt; 4=length; 5=age; 6=SizeFreq; 7=sizeage; 8=catch;
9=init_equ_catch; 10=recrdev; 11=parm_prior; 12=parm_dev; 13=CrashPen; 14=Morphcomp; 15=Tag-comp; 16=Tag-negbin
#like_comp fleet/survey phase value sizefreq_method

#CPUE
#keep or drop PSFS coupled with PL series
xxx U0 1 6 1 0. 1
xxx U1 1 6 1 1. 1

#size
4 1 1 1. 1
4 2 1 1. 1
4 3 1 1. 1
4 4 1 1. 1
tags...not clear on assignment definitions
15 tag-comp does not seem to do anything?
#
15 2 2 1. 1
15 3 2 1. 1
#seems to do something
16 1 2 1. 1
16 2 2 1. 1
16 3 2 1. 1
lambdas (for info only; columns are phases)
0 #_CPUE/survey:_1
0 #_CPUE/survey:_2
1 #_CPUE/survey:_3
1 #_lencomp:_1
1 #_lencomp:_2
0 #_lencomp:_3
1 #_init_equ_catch
1 #_recruitments
1 #_parameter-priors
0 #_parameter-dev-vectors
100 #_crashPenLambda
0 # (0/1) read specs for extra stddev reporting
0 1 -1 5 1 5 1 -1 5 # placeholder for selex type, len/age, year, N selex bins, Growth pattern, N growth ages, NatAge_area(-1 for all), NatAge_yr, N Natages
-1 1 1 1 1 # placeholder for vector of selex bins to be reported
-1 1 1 1 1 # placeholder for vector of growth ages to be reported
-1 1 1 1 1 # placeholder for vector of NatAges ages to be reported
999