Update on the development of MSE analysis of candidate Management Procedures for Indian Ocean albacore

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*Iago Mosqueira**

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*European Commission, DG Joint Research Centre (JRC), Directorate D - Sustainable Resources, Unit D.02 Water and Marine Resources, Via E. Fermi 2749, 21027 Ispra VA, Italy. iago.mosqueira@ec.europa.eu

1 Summary

This document presents the latest iteration in the development of the operating model (OM) for Indian Ocean albacore tuna. The operating model is developed around the Stock Synthesis (SS3) stock assessment, conducted by WPTmT in 2016, and considers a number of sources of uncertainty, as identified by WPTmT and WPM, in the estimation of population trajectories and dynamics. The complete grid of structural uncertainty covers seven model elements, as follows:

- Natural mortality (M), 5 values.
- Variance in stock-recruitment residuals (sigmaR), 2 values.
- Steepness in the Beverton & Holt stock-recruitment relationship, 3 values.
- Coefficient of variation for the fit to CPUE data (cpuecv), 4 values.
- Effective sampling size of the length composition data (ess), 3 values.
- Yearly increase in the catchability coefficient of the CPUE series (llq), 2 values.
- Functional form of the CPUE selectivity curve (llsel), 2 values.

This creates an initial set with a total of 1,440 SS3 model runs. The results of those runs are then checked for convergence and a total of 1,095 runs are kept for further processing.

The OM has then been extended to the start of 2018 from the last year of data employed in the model configuration, 2014. The population model has been projected by aplying the nominal catches of the 2015-2017 period, as reported to IOTC in September 2018. A large number of model runs estrimated population abundnaces in 2014 that could not explain the catches observed in the 2015-2017 period, or did so only through extremely large increases in effort (tenfold or larger). Those runs were thus considered unfeasible, and excluded from the reference case OM. This leads to a model containing 414 equally weighted population and fishery trajectories.

This reference set has been used to find the Management Procedure (MP) parameter sets able to lead to the performance values requested by TCMP (IOTC 2018). For albacore tuna the four tuning objectives are:

- TA1: Average Spawning biomass (SB) over the period 2019-2038 exceeds SB MSY in exactly 50% of the simulations.
- TA2: The stock status is in the Kobe green quadrant over the period 2019-2038 exactly 50% of the time (averaged over all simulations).
- TA3: The stock status is in the Kobe green quadrant over the period 2019-2038 exactly 60% of the time (averaged over all simulations).
- TA4: The stock status is in the Kobe green quadrant over the period 2019-2038 exactly 70% of the time (averaged over all simulations).

Two candidate MPs are being tested so far: a model-free MP that calculates the Total Allowable Catch (TAC) based on on trends and levels of a single CPUE series, and a model-based one that estimates stock status based on a Pella-Tomlinson biomass dynamics model fit and suggests a TAC according to target and limit levels for biomass depletion.

The tuned MPs are able to obtain the requested performance values, but in some cases at the cost of bringing the stock to dangerously low levels. The combined effect of a population that is on average at a higher level of abundance that management requests, and the computation of performance indicators for tuning for the whole period of projection, leads to this behaviour. The effect of different performance computation periods and of alternative probability levels has been investigated, and alternative tuning periods could be considered.

2 Introduction

A simulation model of the albacore tuna (*Thunnus alalunga*) fishery and population in the Indian Ocean has been developed to evaluate the comparative performance of alternative Management Procedures (MP) for this stock under the management of the Indian Ocean Tuna Commission (IOTC). The Operating Model (OM) has been constructed around the current best knowledge of the history and dynamics of the stock, as represented by the stock assessment model reviewed and accepted by the Working Party on Temperate Tuna (WPTmT) of IOTC, and then used by its Scientific Committee (SC) as the basis for providing management advice.

The OM presented here has been constructed using as base case the last stock assessment exercise, carried out in 2016 (IOTC 2016) using the Stock Synthesis 3 modelling platform (SS3, Methot and Wetzel (2013)). Structural uncertainty in this model has been incorporated into the OM condition process by means of a grid of alternative formulations for various submodels and model parameters that were not being estimated from data.

An initial set of simulation runs for two possible management procedures have been conducted: exploration runs, tentative evaluation runs (for two MPs) and some robustness tests. The runs shown here are presented as proofs of concept and for discussion of the approach taken, including the choice of scenarios. They are expected to be rerun based on feedback and discussion for the SC.

2.1 Background

The initial deliberations of the strategy to follow for the development of the albacore MSE platform by the WPM (IOTC 2014a; IOTC 2015) agreed on using the stock assessment carried out and reviewed by WPTmT, based on SS3 (Methot and Wetzel 2013), as a basis for the population and fishery model to use when building an OM for this stock. Uncertainties concerning structural elements of the model formulation were considered to be the primary factor of concern. Both estimation and observation uncertainty were also relevant but were deemed to be of secondary importance.

The decision was thus made to construct a grid of model runs built around feasible, or at least not too extreme, values for a number of assumptions and fixed parameters in the population model. The impact of some of these elements in the model have already been explored in some detail by the researchers carrying out past stock assessments (Hoyle, Sharma, and Herrera 2014; Langley and Hoyle 2016).

The structure of the uncertainty grid used to build the current operating model has remained stable from previous iterations (Mosqueira and Sharma 2014). It is built around the population dynamics and assumptions in the Stock Synthesis 3 stock assessment framework (Methot and Wetzel 2013) and uses as starting point the stock assessment presented and reviewed at the Sixth Session of the Working Party on Temperate Tunas (Langley and Hoyle 2016).

According to the results of the last stock assessment, shown in Figure 1 the biomass of albacore tuna has been slowly declining as catches increased over the 1950-2000 period, having probably fallen below the B_{MSY} target at some point in the past. The stock then recovered, as a result of a decrease in catches after 2001, and is now considered to be around the target level of $B = B_{MSY}$

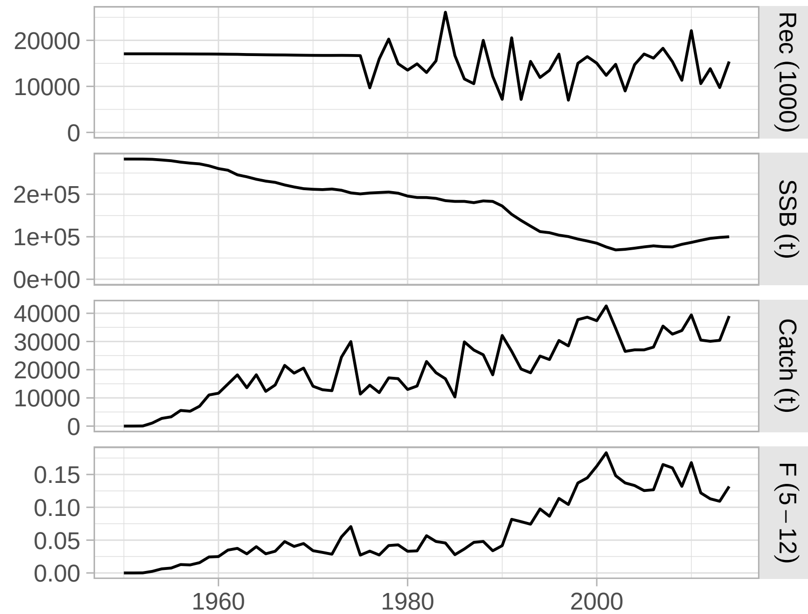

Figure 1: Yearly time series of recruitment, SSB, catch and fishing mortality estimated by the WPTmT SS3 stock assessment for Indian Ocean albacore in 2016.

3 Structure and assumptions

The stock assessment model reviewed and accepted by the Working Party on Temperate Tunas (IOTC 2014b), is implemented in SS3 version 3.24z, which has been also employed for running the OM grid.

3.1 Areas and seasons

The current model partitions the Indian Ocean into four regions, divided latitudinally along the 25°S parallel and longitudinally along the 75°E meridian (Figure 2).

3.2 Fisheries

The model includes a total of 11 fisheries, including in this case an aggregaqted Longline fishery for each of the four regions. For a detailed explanation of the data and fleets included in each of these fisheries, please refer to Langley and Hoyle (2016).

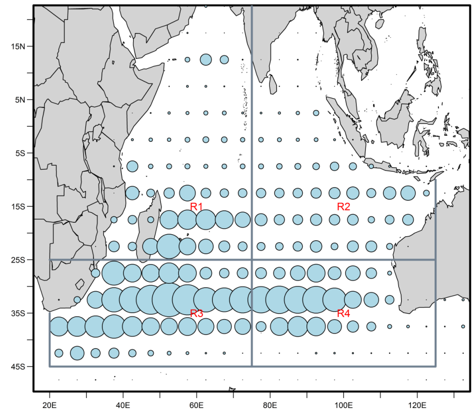

Figure 2: Spatial stratification of the Indian Ocean albacore data and stock assessment model (areas R-1 to R4). Aggregated catches (in numbers of fish) for the Japanese and Taiwanese LL fleets, for the 1950-2014 period, are shown. From (Langley and Hoyle 2016)

Table 1: Definition of fisheries used in the albacore operating model, after Langley and Hoyle (2016).

Fishery	Code	Flag	Gear	Area
1	LL1	All	Longline	1 (NW)
2	LL2	All	Longline	2 (NE)
3	LL3	All	Longline	3 (SW)
4	LL4	All	Longline	4 (SE)
5	DN3	CN-TW	Drift net	3 (SW)
6	DN4	CN-TW	Drift net	4 (SE)
7	PS1	All	Purse seine	1 (NW)
8	Other1	All	Other gears	1 (NW)
9	Other2	All	Other gears	2 (NE)
10	Other3	All	Other gears	3 (SW)
11	Other4	All	Other gears	4 (SE)

3.3 CPUE Indices

A new set of standardized CPUE indices has been derived using generalized linear models (GLM) operational from longline catch and effort data provided by Japan, Korea and Taiwan, China. (Hoyle et al. 2016). The operating model conditioning used the same series as the final runs of the stock assessment (Langley and Hoyle 2016), a combined industrial longline series, on each of the four areas, and restricted to the 1979-2014 period (Figure 3).

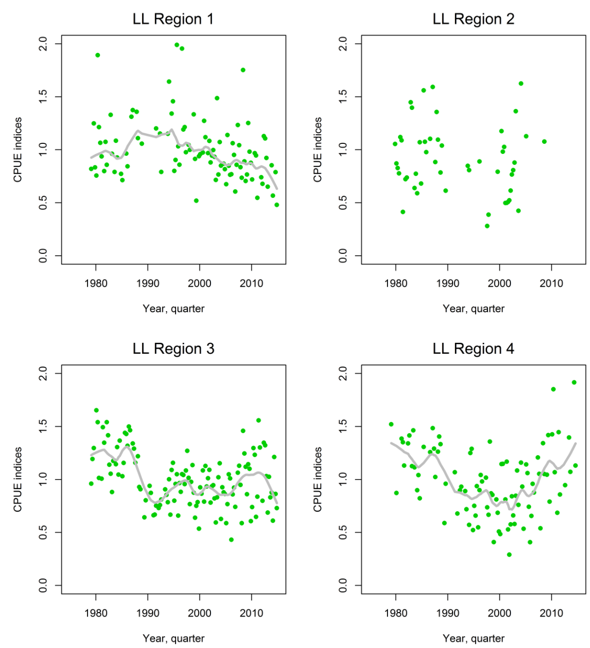

Figure 3: Quarterly standardised CPUE series for the industrial longline fleets from 1979-2014. From Langley and Hoyle (2016).

Of these four areas, area 3 is considered to represent the core of the distribution of the stock. The management procedures tested make use of a single CPUE, taken to be that corresponding to area 3.

4 Uncertainty grid

Fisheries data is in general less informative that would be ideal when it comes to estimating a large number of model parameters, which are often correlated. In the case of the Indian Ocean albacore stock, a number of reasons are limiting our ability to obtain reliable model fits. Problems exists with the data completeness and quality (Secretariat 2016), not limited to but including total catch statistics, length distribution in catches, and biological information.

We also depend on our ability to produce sensible indices of changes in abundance in the stock based only on Catch-per-unit-effort data from commercial fleets, where issues of targeting, operating and others are all known to influence the relationship between stock abundance and CPUE [@], despite recent work on standardization of the longline CPUE series for this stock (Hoyle et al. 2016).

The seven factors currently considered in the structural uncertainty grid for the albacore OM are the following.

4.1 Natural mortality vector (*M*)

A common unknown in most stock assessment models, the base case considered in the stock assessment session was supplemented with alternative values of higher and lower M for either all ages, or different for juveniles (ages 0 to 4) and adults (age 5 or older), for a total of five possibilities,

- Constant M at 0.2 for all ages.
- Constant M at 0.3 for all ages.
- Constant M at 0.4 for all ages.
- M=0.4 at age 0, decreasing to 0.3 at age 5 and older.
- M=0.4 at age 0, decreasing to 0.2 at age 5 and older.

4.2 Variance of the recruitment deviates (*sigmaR*)

Two values were considered for the true variability of recruitment in the population (*sigmaR*), 0.4 and 0.6, as set by variable `SR_sigmaR` in the 3 control file.

4.3 Steepness of the stock-recruits relationship (*steepness*)

Three values for the steepness (h) of the stock-recruitment relationship are being used: 0.7, 0.8, and 0.9. The Beverton and Holt stock-recruit model implemented in SS3 (Methot and Taylor 2011) is as follows,

$$R_y = \frac{4hR_0B_y}{B_0(1-h) + B_y(5h-1)} \tag{1}$$

where R_y is the estimated recruitment for year y, h is steepness, R_0 is the virgin recruitment, B_y is the biomass in year y, and B_0 is virgin biomass, the spawning biomass before fishing started.

4.4 Coefficient of variation of the CPUE series (*cpuecv*)

Four values for the coefficient of variation in the CPUE series were included: 0.2, 0.3, 0.4 and 0.5.

4.5 Effective Sampling Size of each length data point (*ess*)

Three values were used for the relative weight of length sampling data in the total likelihood, through changes in the effective sampling size parameter, of 20, 50 and 100. This alters the relative weighting of length samples and CPUE series in informing the model about stock dynamics and the effects of fishing at length.

4.6 Catchability trends in the CPUE Longline fleet (*LLq*)

Two scenarios were considered for the effective catchability of the CPUE fleet. On the first one it was assumed that the fleet had not improved its ability to fish for albacore over time, or that any increase had been captured by the CPUE standardization process. An alternative scenario considered a 2.5% increase in catchability by correcting the CPUE index to reflect this.

4.7 Form of the selectivity curve for the CPUE fleet (*LLsel*)

Two possible functional forms for the selectivity of the CPUE LL fleet were considered: a logistic function (Log), where selectivity stays at the maximum level, or double normal (DoNorm), where selectivity drops at some point in the age range.

5 Model fits

The model fits for the full OM grid cover a wide range of estimates of productivity and past dynamics, but do not lead to extremely high values of virgin biomass as was the case on the first iteration of the albacore OM, based on the 2014 stock assessment. A plot of the distribution of estimates of spawning virgin biomass obtained in this grid (Figure 4) shows that many model runs estimate a much lower starting point for the stock that what the base case stock assessment returns.

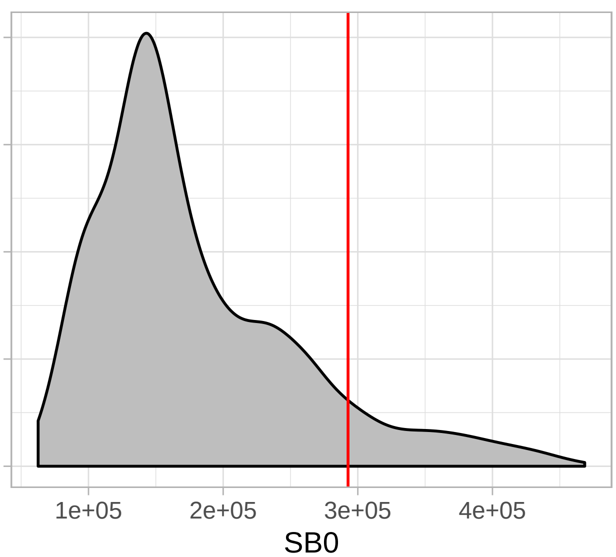

Figure 4: Distribution of the 1,440 estimates of virgin spawning biomass (SB0) obtained from the full OM grid. The red line shows the estimate returned by the base case WPTmT stock assessment run.

It should be noted that the current OM grid does not include the WPTmT base case stock assessment run. This run was carried out using the reported sample sizes in the length composition data, while the OM grid has three fixed values, `ess=c(20,50,100)`. The values in the original dataset are never greater than 10. A comparison of the value of B_0 returned by the stock assessment with those in the grid that are closer to it for the main factors (ess and llsel), can be found in Figure 5

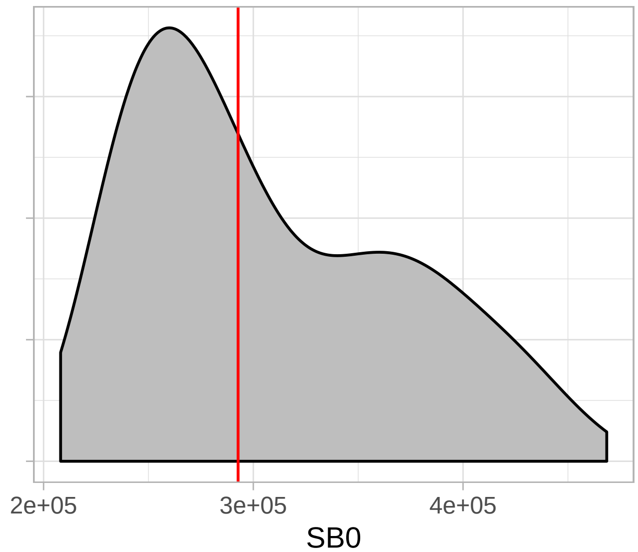

Figure 5: Distribution of the 240 estimates of virgin biomass (SB0) obtained from the OM grid where ESS=20 and double normal LL selectivity. The red line shows the estimate returned by the base case WPTmT stock assessment run.

5.1 Estimates of B_0 by factor level

Some of the factors in the OM grid have clearly a stronger influence on the estimates of virgin stock size returned by each model run. Two and even three-level interactions must also be considered. A first visual inspection of the distribution of estimates of B_0 by factor (Figures **??** and **??**) shows the effect of, first, ess and llsel, and second, of M and cpuecv. The first pair of factors have a large influence on the estimates, both in isolation and when combined. A number of model runs appear to start from fairly low biomasses. Only those sharing the selectivity model with the stock assessment run, and with values of ess closest to those used there (top left panel) contain the stock assessment value on the center of the distribution.

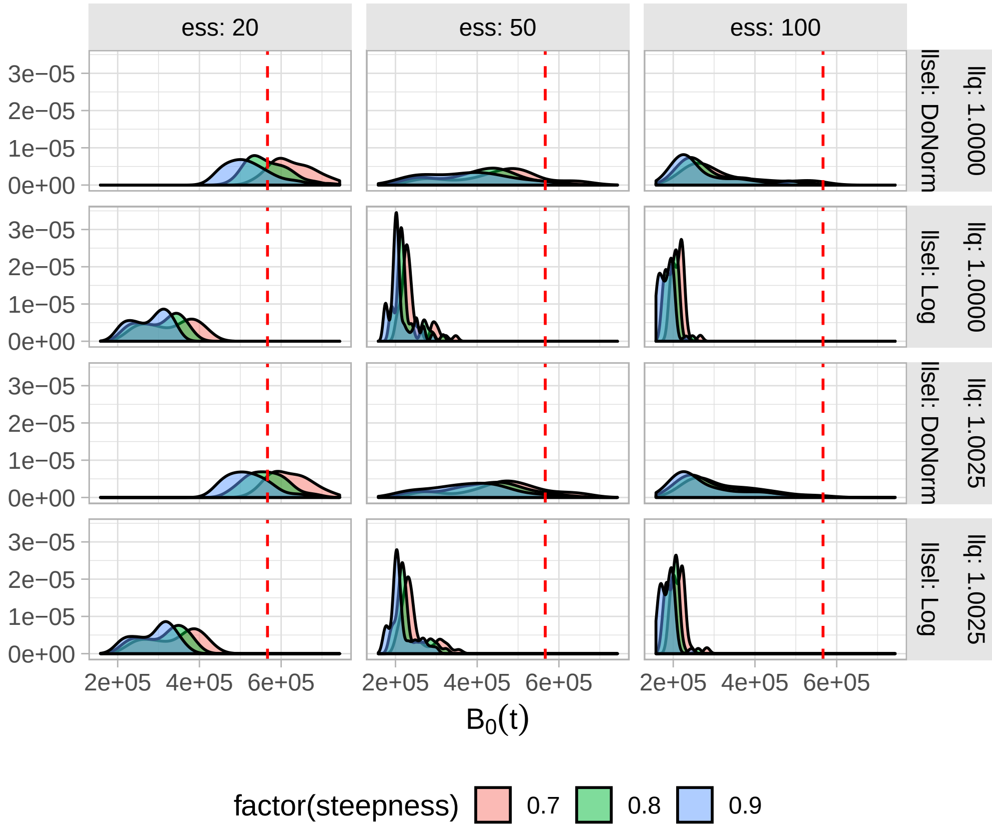

Figure 6: Distribution of the estimates of virgin stock biomass returned by the converged model runs, separated by factor levels for: steepness, llq, llsel and ess. The red line show the value obtained by the base case stock assessment.

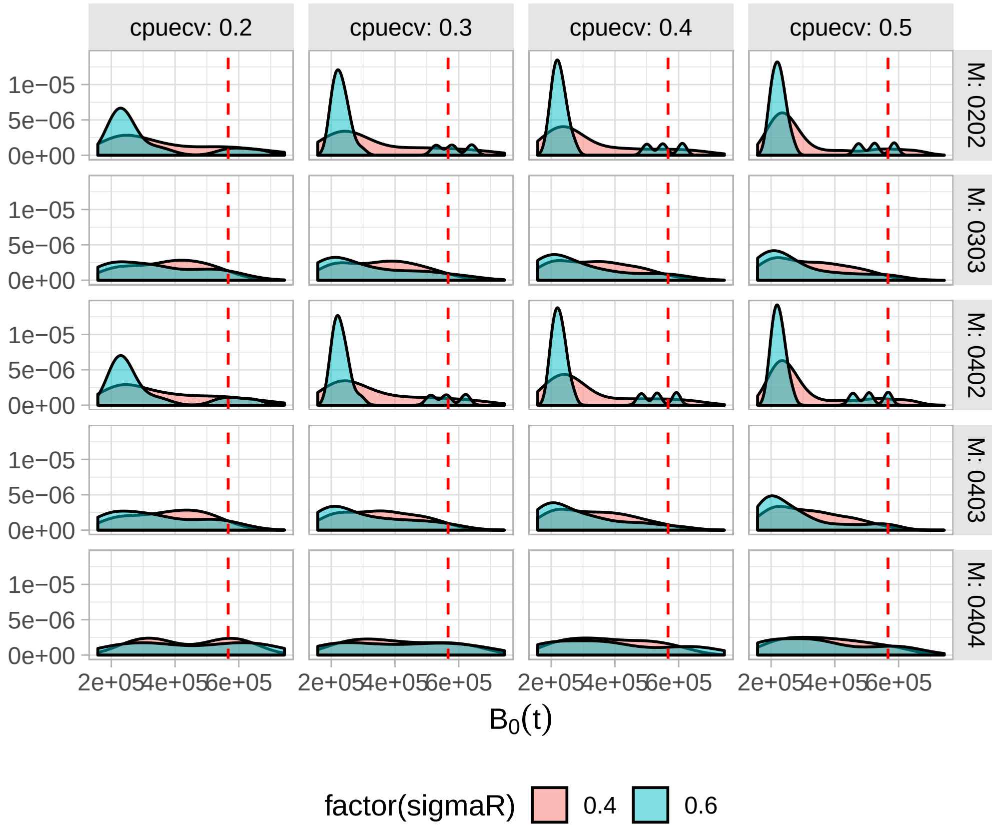

Figure 7: Distribution of the estimates of virgin stock biomass returned by the converged model runs, separated by factor levels for: sigmaR, M and cpuecv. The red line show the value obtained by the base case stock assessment.

These differences can also be observed on plots of the 2014 depletion level (Figures 8 and 9). Runs assuming a logarithmic selectivity curve, and more so with increasing values for ess, return estimates of stock status as low as 2% of virgin biomass.

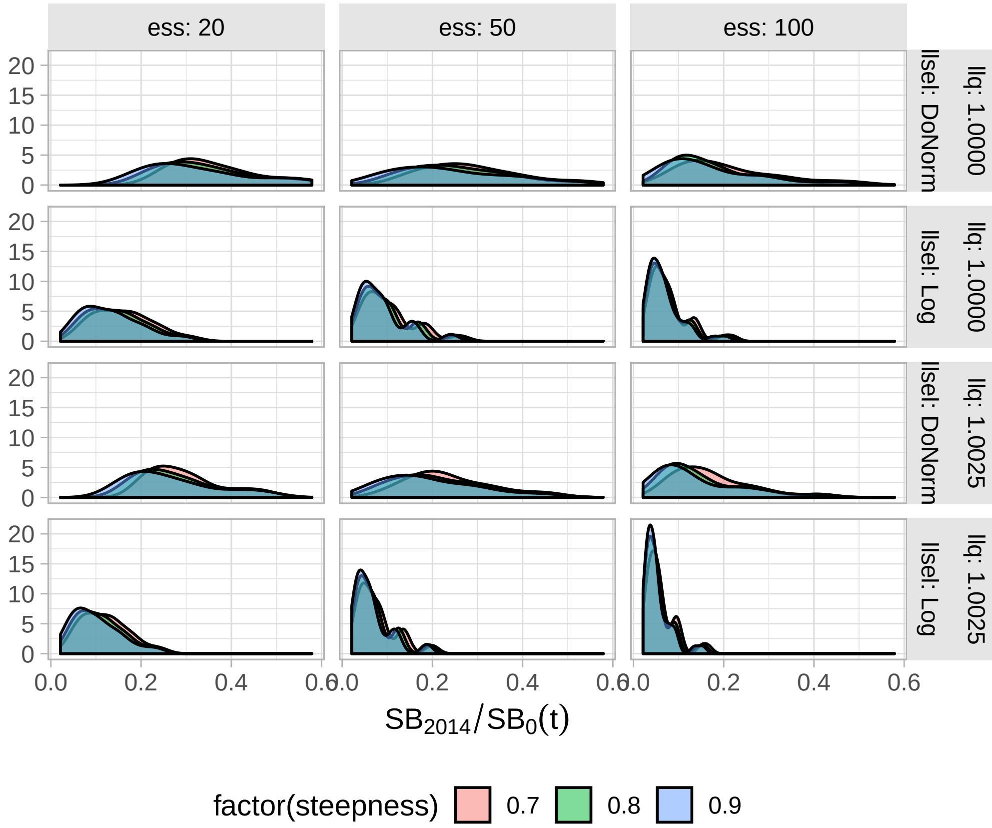

Figure 8: Distribution of the ratio of current SSB to virgin SSB returned by the converged model runs, separated by factor levels for: steepness, llq, llsel and ess.

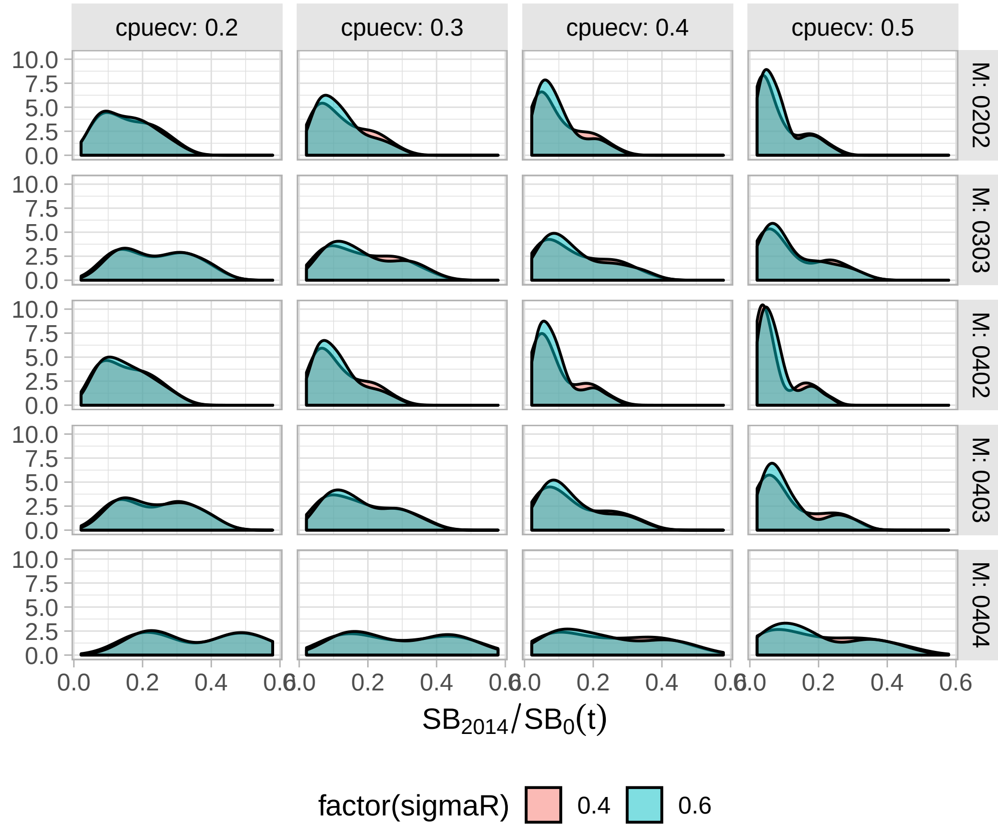

Figure 9: Distribution of the ratio of current SSB to virgin SSB returned by the converged model runs, separated by factor levels for: sigmaR, M and cpuecv.

5.2 Model convergence diagnostics

Model convergence is generally evaluated first using two basic indicators: the maximum gradient of the parameters at the solution, *Final convergence*, and whether a variance-covariance matrix can be calculated by inverting the model Hessian. For the later, a total of 1,432 out of the 1,440 model runs in the grid returned a positive-definite Hessian, and onmly those model runs were kept for subsequent diagnostics.

A threshold convergence level of 0.001 has been used in the past for the albacore OM runs. The effect of the choice of convergence level on the distribution of values for virgin spawning biomass can be observed in Figure 10. The strictest of the four levels considered (0.0001), has the largest effect in the number of runs retained and in the distribution of biomass estimates. A total of 479 models would be accepted if a level of 0.0001 was used, while for the other three, the same 1,096 models would be retained. The same value used in the past, 0.001 has been used this time, which leaves 337 runs out of the OM set.

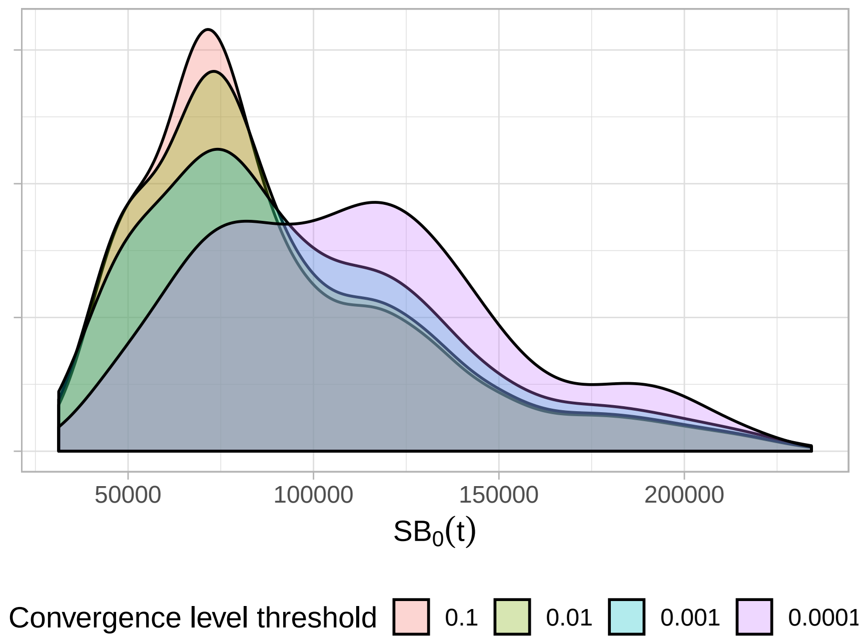

Figure 10: Distribution of estimates of virgin spawning biomass (SB_0) depending on the threshod used to ascertain model convergence.

5.3 Differences on time series

After selecting model runs according to convergence levels, the effect of individuals factors and levels on the estimates obtained can also be investigated by looking at the differences in the time series of SSB. Apart from similar patterns to those observed on the distribution of values for virgin biomass, the decrease in the number of runs has reduced the uncertainty for those factor levels where most unconverged runs concentrated.

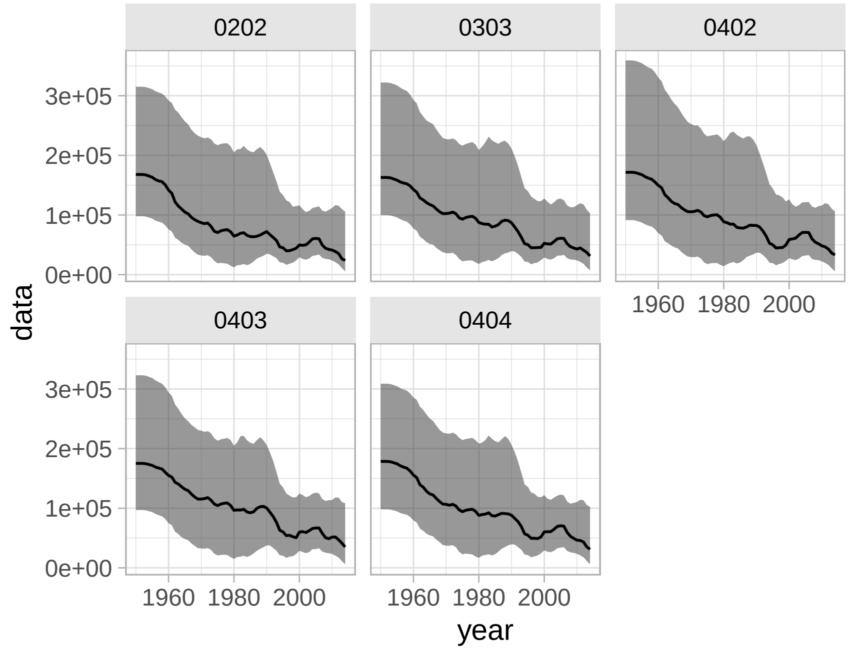

Figure 11: Time series of spawning biomass (SB) for different levels of natural mortality (M) .

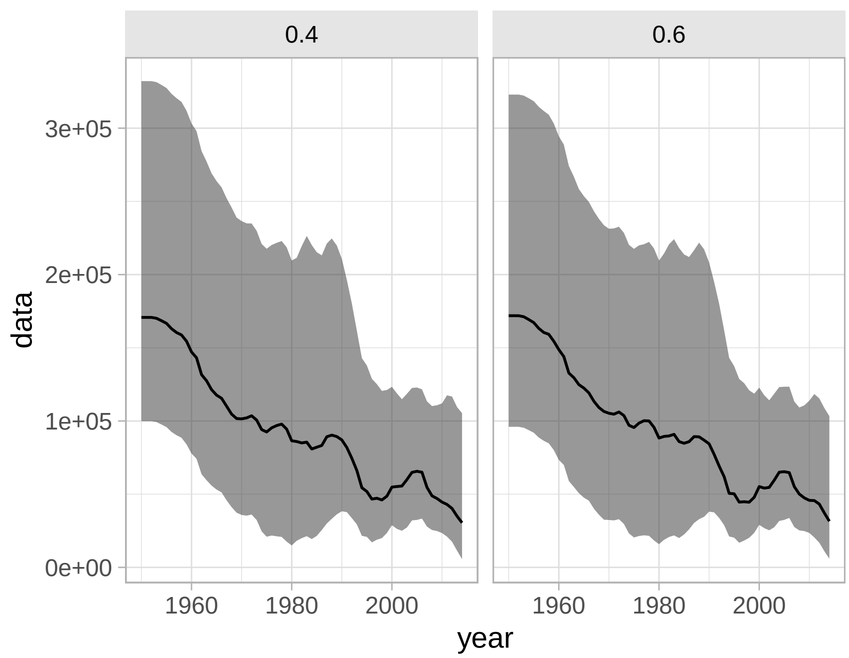

Figure 12: Time series of spawning biomass (SB) for different levels of recruitment variance (sigmaR) .

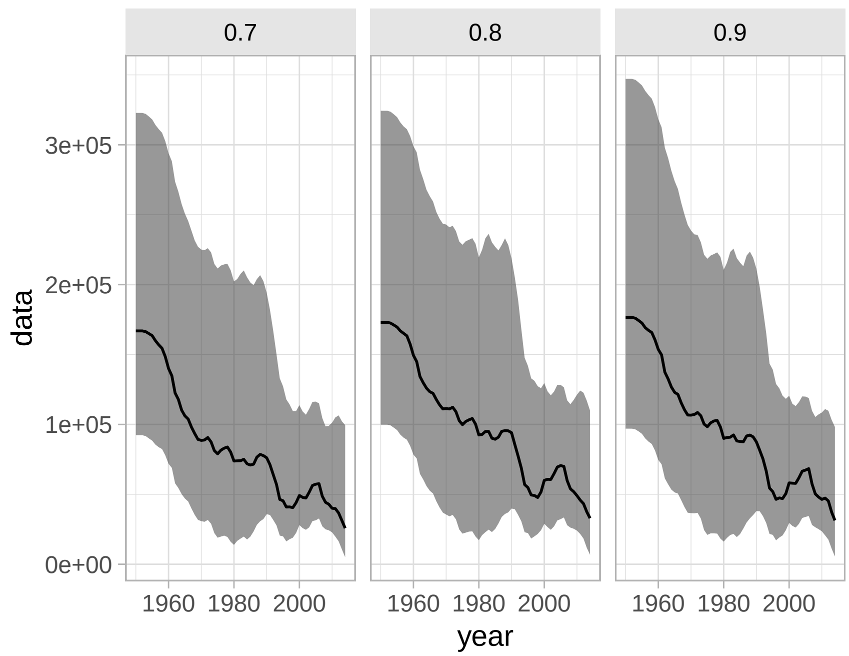

Figure 13: Time series of spawning biomass (SB) for different levels of SRR steepness .

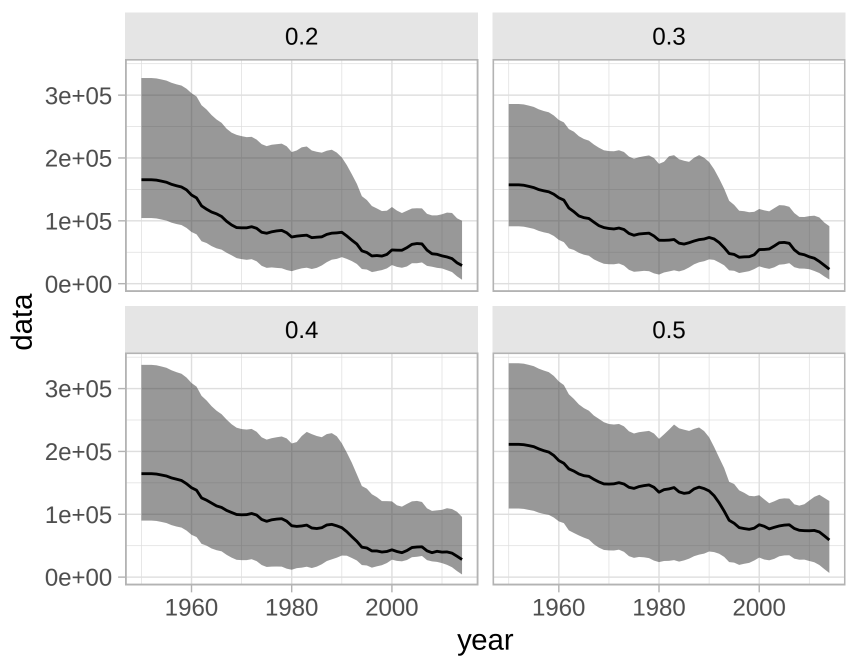

Figure 14: Time series of spawning biomass (SB) for different levels of CV in the CPUE residuals (cpuecv) .

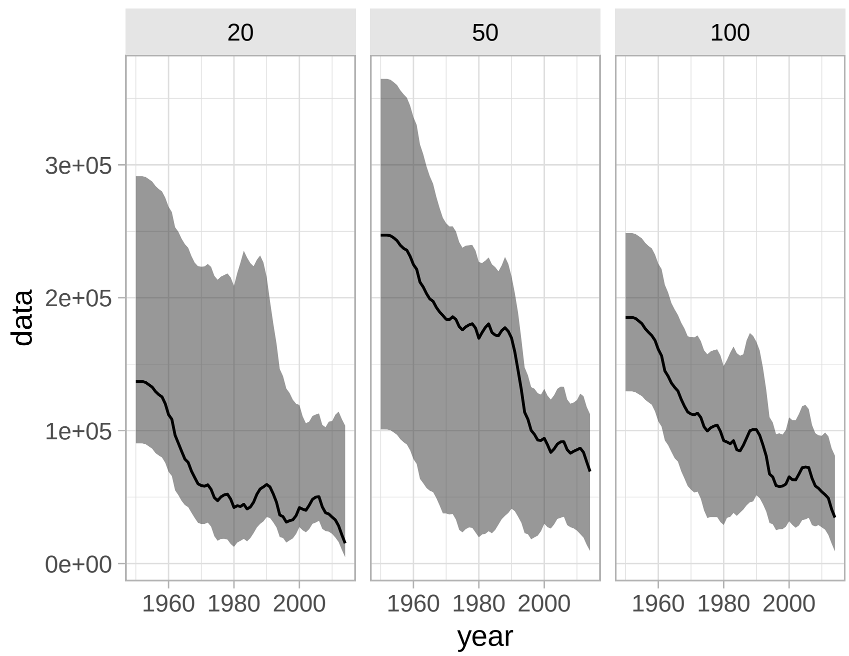

Figure 15: Time series of spawning biomass (SB) for different levels of effective sampling size (ess) .

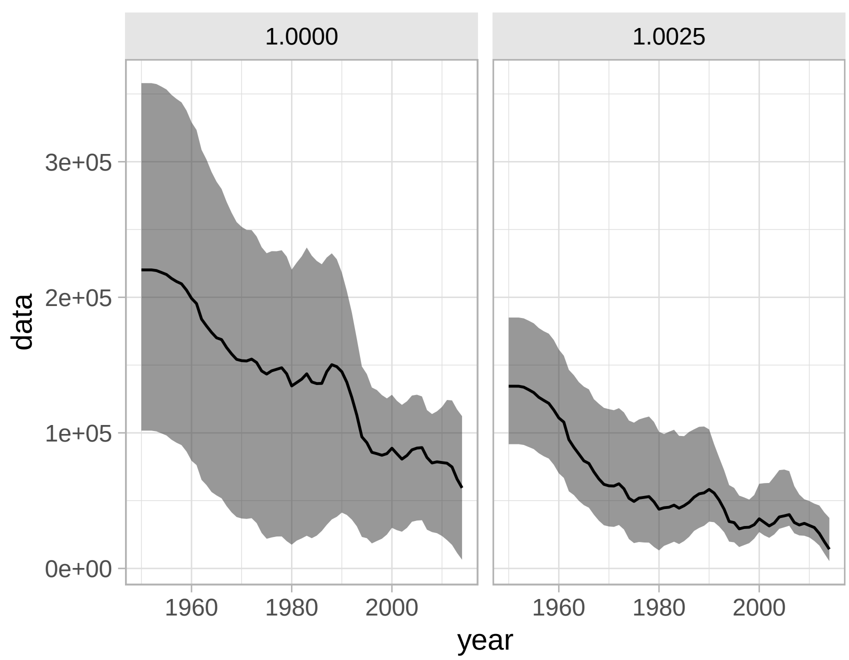

Figure 16: Time series of spawning biomass (SB) for different levels of increase in CPUE LL catchability (llq) .

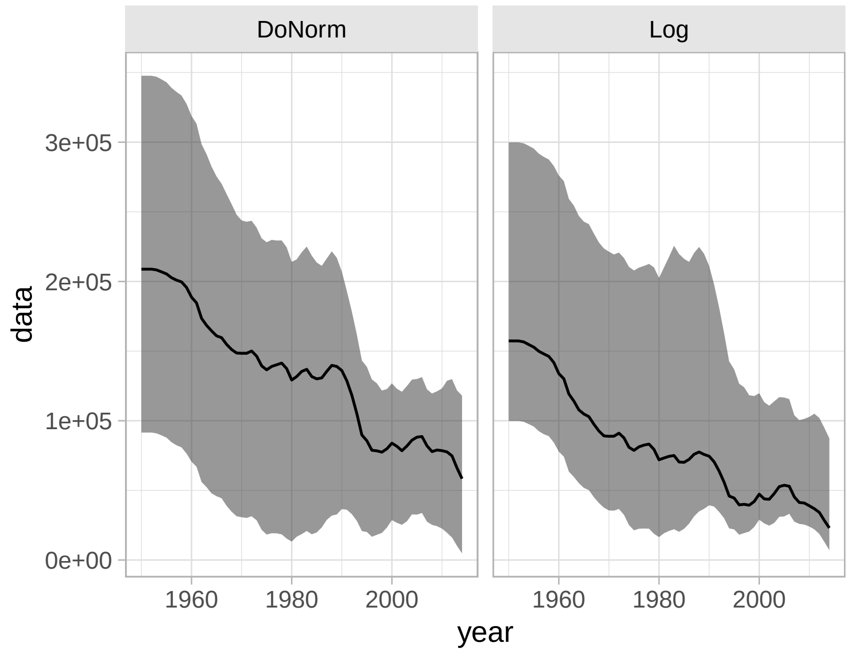

Figure 17: Time series of spawning biomass (SB) for different levels of functional form of CPUE selectivity (llsel) .

5.4 Updating of OM to 2017

The current stock assessment of albacore (IOTC 2014c) provides estimates of stock abundance and mortality up to 2014, given the current two year lag in data availability for this stock. The input data necessary to update to the SS3 model to the current year, standardized CPUE series and catch-at-length by fleet, is not available. The model was updated to 2018 by projecting forward the population for the 2015-2017 period with the nominal catches currently reported to IOTC for those years: 35371, 35307, and 38337 t respectively. The projection has been carried out assuming no changes in selectivity, and with recruitment as estiamted from the application of the SR models for each run, plus lognormal noise.

A large proportion of models runs, 62%, could not explain the observed catches for the 2015-2017 period, or could do so only by assuming a large increase in effort, tenfold or higher. A majority of these runs originated from the part of grid where ess values were higher (50 or 100), and that assumed a logistic selectivity curve. All runs with populations unable to support the 2015-2017 nominal catches were excluded from the grid. The grid of runs used to construct the OM reference set thus includes 414 runs.

6 Base case Operating Model

The uncertainty in population trajectories contained in the base case OM for albacore extends around the current stock assessment, although the median trajectory of SSB in the OM over the last few years is more pesimistic (Figure 18).

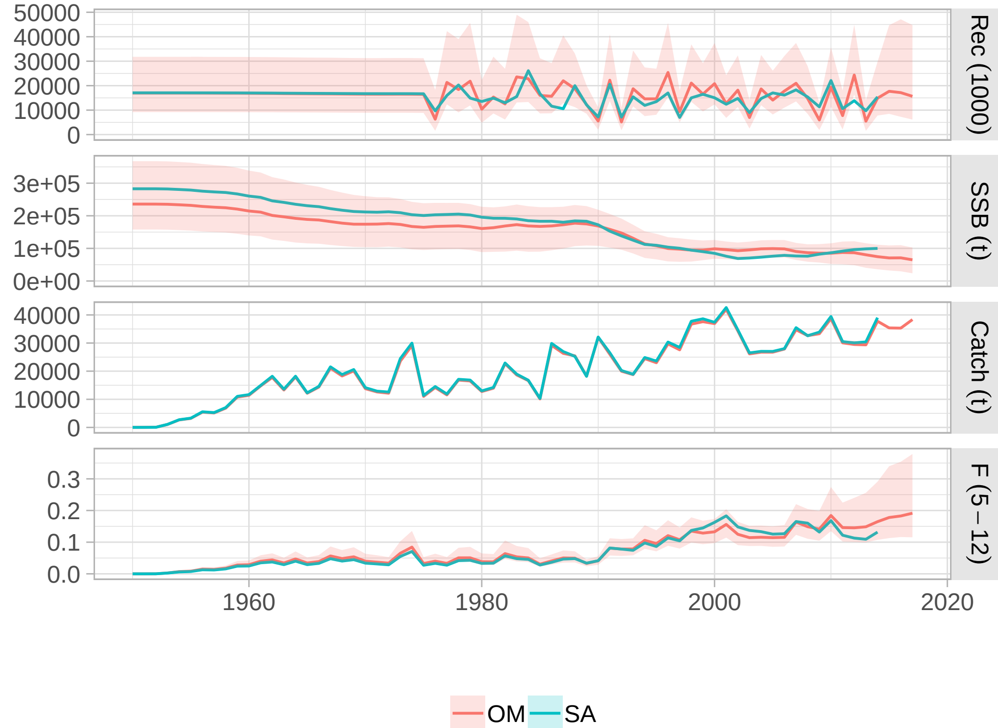

Figure 18: Time series of recruitment, SSB, catch and fishing mortality in the base case OM and for the WPTmT base case SA.

The same spread of uncertainty can be observed on a plot of the time series of relative SB and F values (Figure 19).

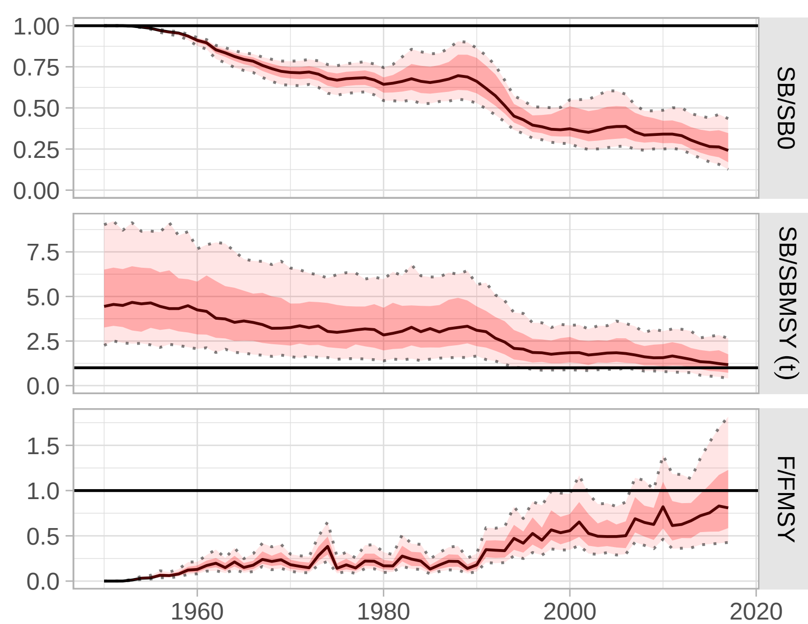

Figure 19: Time series of spawning biomass (SB) and fishing mortality (F) relative to virgin spawning biomass (SB0), spawning biomass at MSY (SBMSY), and fihsing mortality at MSY (FMSY), for the base case albacore operating model.

A more detailed look at the spread of uncertainty around the estimates of SSB shows values concentrated in the central quantiles but also that the extremes of the distribution cover a large range of alternative initial conditions. Current estimates of stock status do not discount the possibility of the stock being in low biomass levels.

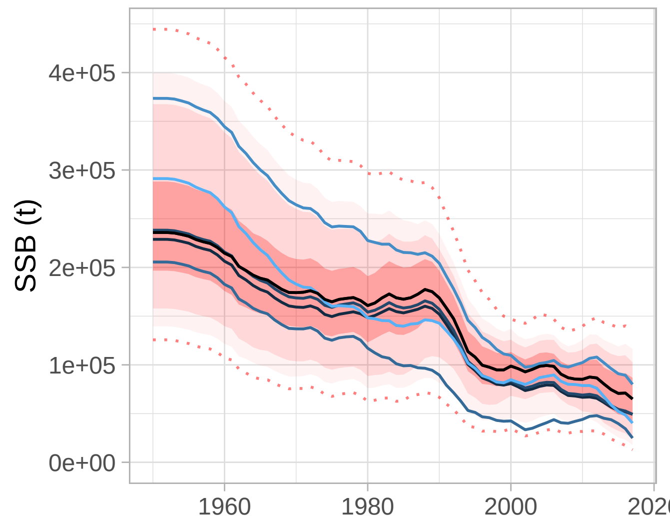

Figure 20: Time series of the estimates of SSB for the model runs included in base case OM. The probability contours depict the 0.99, 0.95, 0.90 and 0.75 quantiles, the black line the median value, while coloured lines show a random choice of five individual iterations.

7 Tuning of proposed management procedures

The last session of the IOTC Technical Committee on Management Procedures (IOTC 2018), put forward a set of four management objectives against which MPs should be tuned for:

- TA1: `Pr(mean(SB(2019:2038))>=SB(MSY)) = 0.5`. Average Spawning biomass (SB) over the period 2019-2038 exceeds SB MSY in exactly 50% of the simulations).
- TA2: `Pr(Kobe green zone 2019:2038) = 0.5`. The stock status is in the Kobe green quadrant over the period 2019-2038 exactly 50% of the time (averaged over all simulations).
- TA3: `Pr(Kobe green zone 2019:2038) = 0.6`. The stock status is in the Kobe green quadrant over the period 2019-2038 exactly 60% of the time (averaged over all simulations).
- TA4: `Pr(Kobe green zone 2019:2038) = 0.7`. The stock status is in the Kobe green quadrant over the period 2019-2038 exactly 70% of the time (averaged over all simulations).

7.1 Management Procedures tested

Two types of management procedures have been applied to the base case OM, one based on an stock assessment model, and another that is driven by changes in the CPUE series.

7.1.1 Pella-Tomlison stock assessment

The family of management procedures implemented through this function use the results of a biomass dynamics stock assessment to inform the harvest control rule on stock status. A decision is then made on changes to the total allowable catch levels from those set on the previous year of application of the procedure.

Two sources of information are generated to feed the assessment model: total catch in the fishery and an index of abundance. This is being obtained from an observation, with lag, of the biomass available to the CPUE fleet, with different levels of observation error, bias and hyperstability. A Pella-Tomlison biomass dynamics model is then fit to the data. The estimates of both depletion level, as the ratio of the spawning biomass in the last year of data to that in the first year, and of the F-at-MSY reference point, are then passed on to the harvest control rule.

The harvest control rule in Figure 21 returns a suggested value for catch in the next management year based on the depletion level, but can also limit changes in the TAC from previous values, both when increasing and decreasing. The decision is then applied to the stock and fishery, with a given lag, and with or without error.

The MP performance can be thus explored for a number of parameters:

- *Dlimit*, the depletion level at which the fishery is closed, shown at 0.10 in Figure 21.
- *Dtarget*, The target depletion level, shown at 0.40
- *lambda*, multiplier for *Dtarget*, defaults to 1.
- *dlatc*, lower limit to changes in TAC, e.g. 10%
- *dhtac*, upper limit to chnages in TAC, e,g, 10%
- *dlag*, lag in data collection, number of years between last year of data and current.
- *mlag*, lag in management, number of years current and implementation of advice.

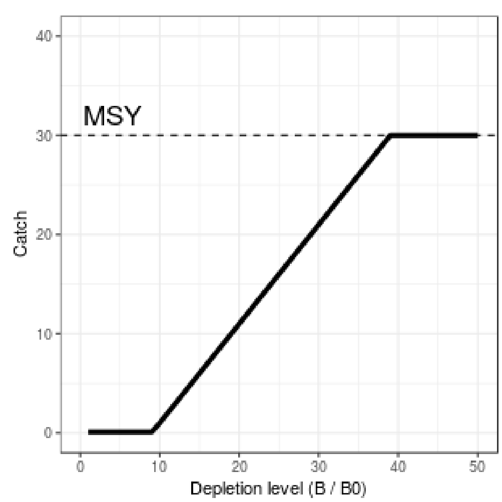

Figure 21: Diagram of the Harvest Control Rule implemented in the biomass-dynamics based MP .

7.1.2 CPUE trend-based indicator

A different set of MPs is implemented by this function. The ony source of information for the harvest control rule is, in this case, the index of abundance provided by the generated CPUE series. As before, the observation refers to chmnages in abundance of the part of the stock available to the choosen fleet. Only a single CPUE series can be used. The same processes related to error, bias and hyperstability covered above are of application in this case.

The harvest control rule takes the form $T_t = T_{t-1} * (1 + \lambda * b)$ where T is the TAC for the previous time step, λ is a response multiplier, and b is the slope of a linear model fit to the last *ny* years of data (Figure 22).

The parameters controlling the behaviour of this MP are thus:

- *lambda*, the response multiplier controlling how fast or slow is the rule to respond to changes in CPUE trend.
- *ny*, number of years from last to use to fit the linear trend
- *dlatc*, lower limit to changes in TAC, e.g. 10%
- *dhtac*, upper limit to chnages in TAC, e,g, 10%
- *dlag*, lag in data collection, number of years between last year of data and current.
- *mlag*, lag in management, number of years current and implementation of advice.

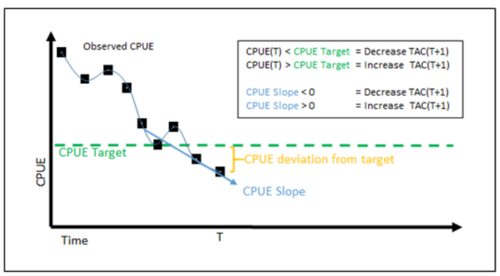

Figure 22: Diagram of the Harvest Control Rule implemented by the CPUE-based MP.

7.2 Performance Statistics

All performance indicators in the set adopted by the SC (IOTC 2016) are computed for every MP run. The performance statistics, and types of management objectives behind them, for the evaluation of management procedures are as follows:

- Status
  - **S1**: Mean spawner biomass relative to unfished, *SB/SB[0]*
  - **S2**: Minimum spawner biomass relative to unfished, *min(SB/SB[0]*
  - **S3**: Mean spawnwer biomass relative to SBMSY, *SB/SB[MSY]*
  - **S4**: Mean fishing mortality relative to target, *F/F[target]*

- **S5**: Mean fishing mortality relative to FMSY, *F/F[MSY]*
- **S6**: Probability of being in Kobe green quadrant, *P(Green)*
- **S7**: Probability of being in Kobe red quadrant, *P(Red)*
- **S8**: Probability of SB greater/equal than SBMSY, *P(SB >= SB[MSY])*

- Fishing mortality
  - **F1**: Probability of spawner biomass being above 20 SB[0], *P(SB > 0.20 %%* SB[0])*
  - **F2**: Probability of spawner biomass being above SBlim, *P(SB > SB[lim])*

- Yield
  - **Y1**: Mean catch over years (1000 t), *hat(C), 1000 t*
  - **Y3**: Mean proportion of MSY, *C/MSY*

- Abundance
  - **T1**: Mean absolute proportional change in catch, *var(C)*

- Stability
  - **T2**: Catch variability, *CV(C)*
  - **T3**: Variance in fishing mortality, *var(F)*
  - **T4**: Probability of fishery shutdown, *P(catch < 0.1 %%* MSY)*

7.3 Tuned MPs

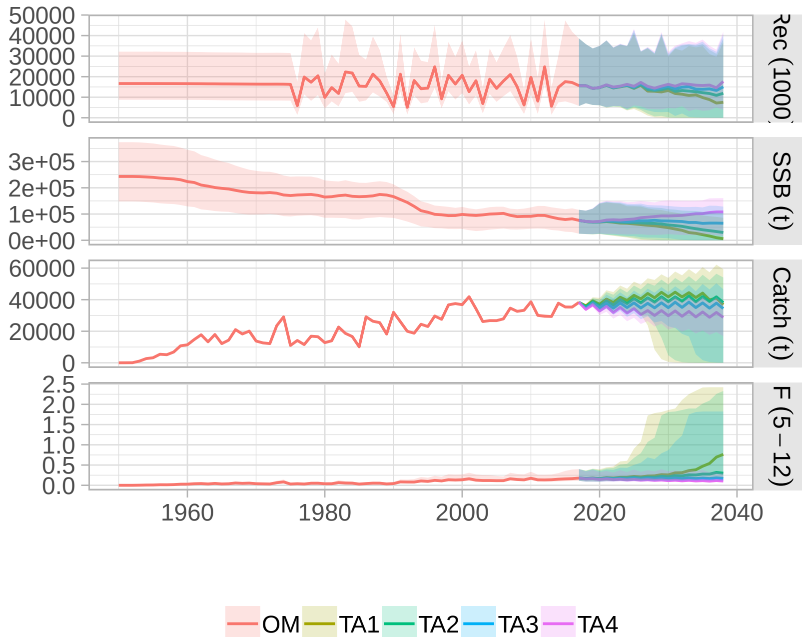

Figure 23: Trajectories of recruitment, SSB, catch and F for the CPUE-based manasgement procedures obtained by tuning for the four management objectives.

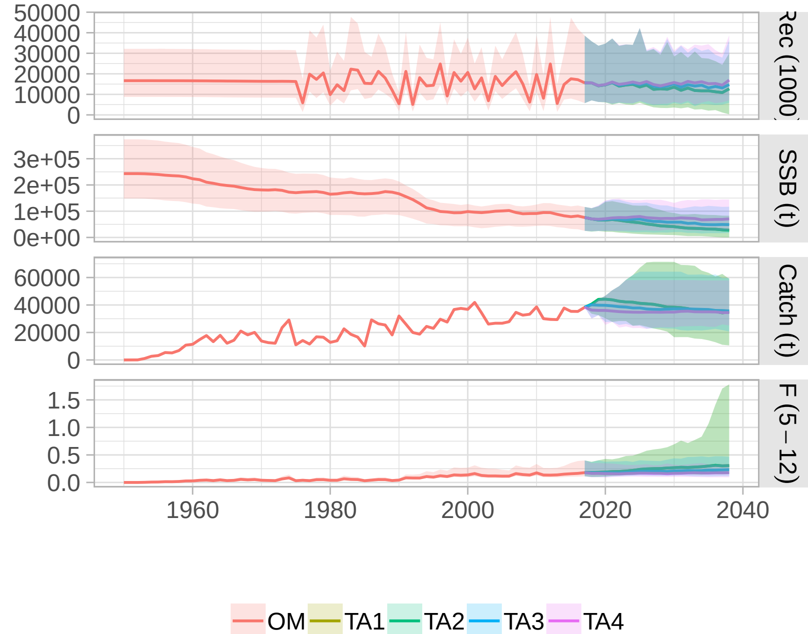

Figure 24: Trajectories of recruitment, SSB, catch and F for the biomass dynamics-based manasgement procedures obtained by tuning for the four management objectives.

7.4 Effect of performance computation period

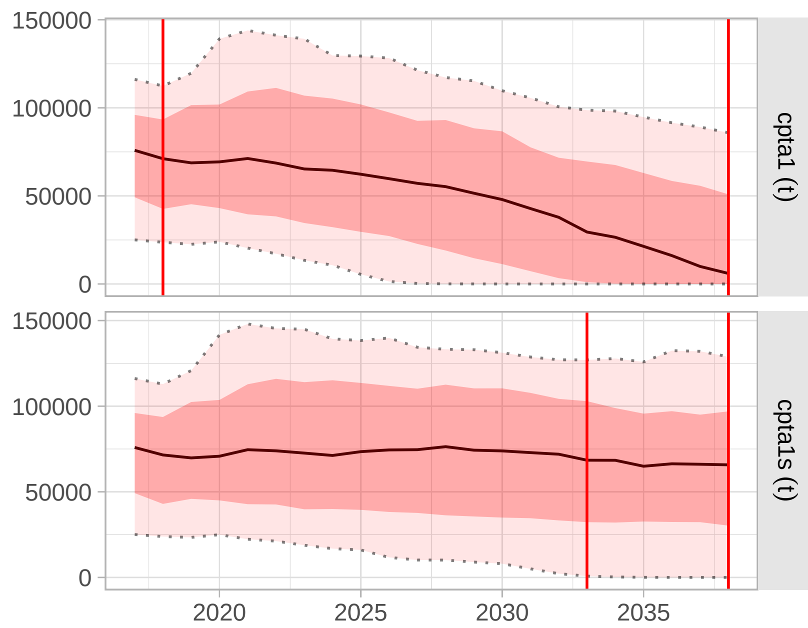

Figure 25: Trajectories of SSB for the projection period (2018-2038) when tuning the CPUE-based procedure to the TA1 objective. The top panel shows the result of computing the procedure's performance for the full projection period, while the bottom one show the effect of tuning for the final five years (2033-2038) only.

8 Constant projections

For comparison purposes, a reference set of constant catch or fishing mortality projections have also been carried out (Figure 26).

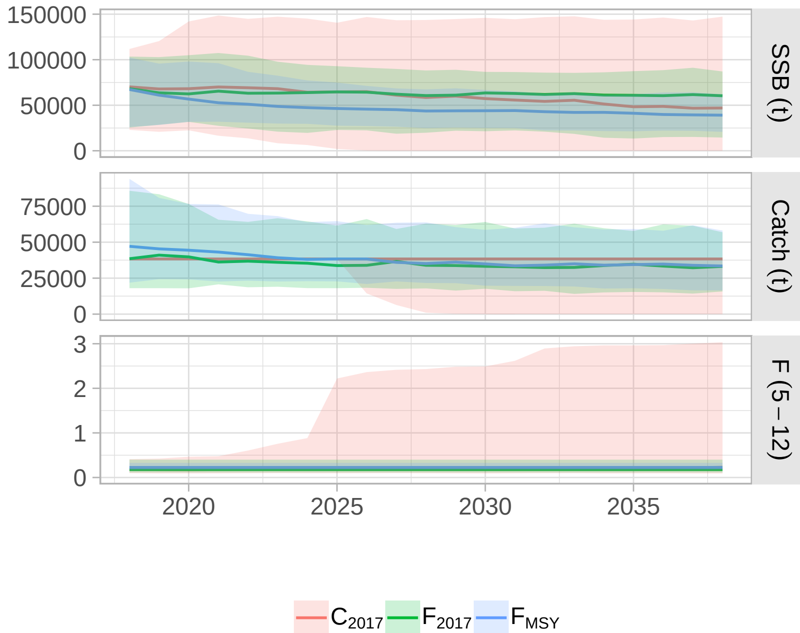

Figure 26: Projections under constant catch and fishing mortality scenarios.

9 Management Procedures performance

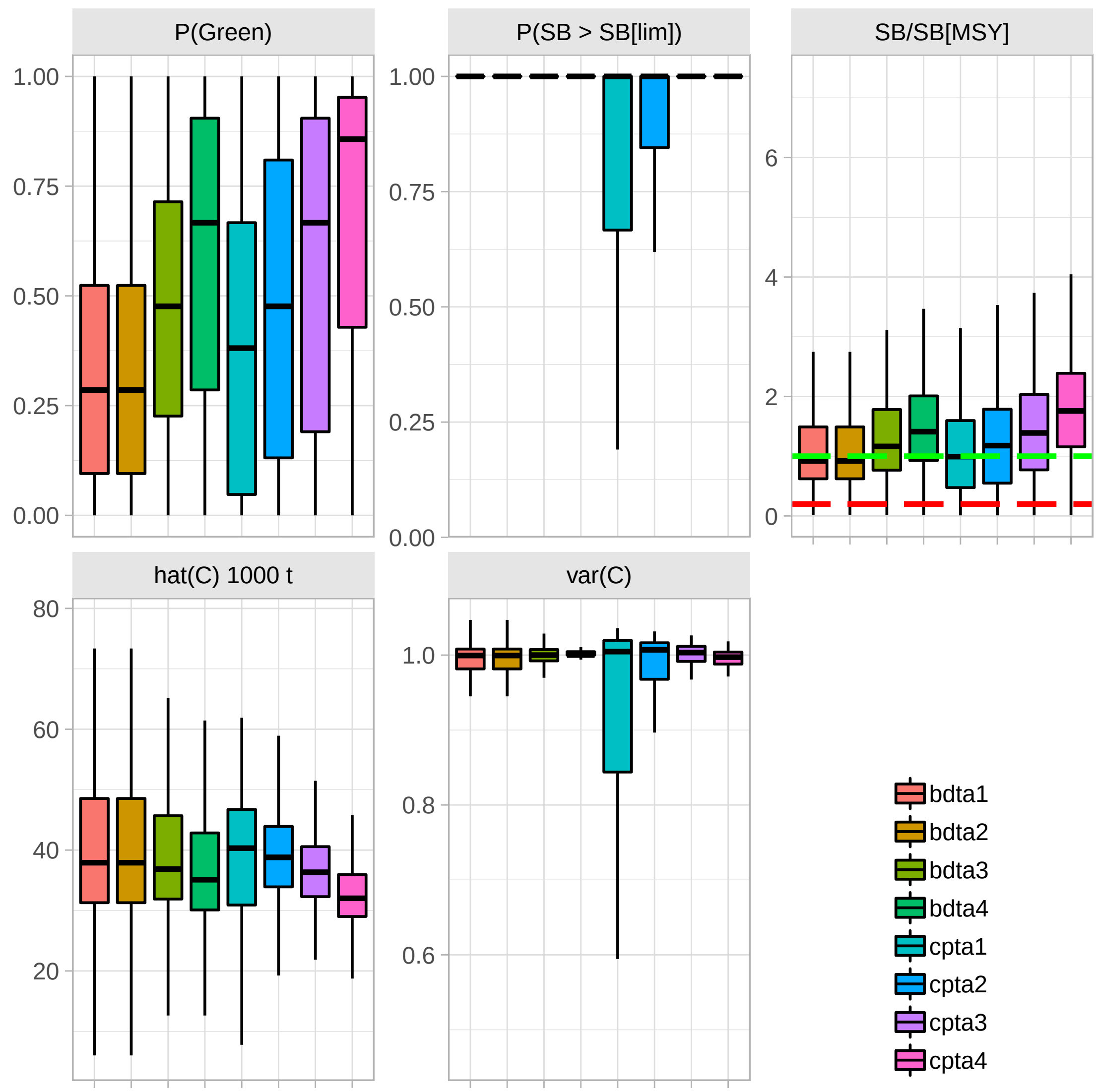

Figure 27: Boxplot comparing the performance of the eight candidate management procedures, from two families (BD and CP), tuned for the four management objectives (TA1-TA4), and along five performance indicators averaged over the 2019-2038 period. Horizontal line is the median, while boxes represent the 25^{th}-75^{th} percentiles, and thin lines the 10^{th}-90^{th} percentiles. Red and green horizontal lines represent the interim limit and target reference points for the mean SB/SB MSY performance measure.

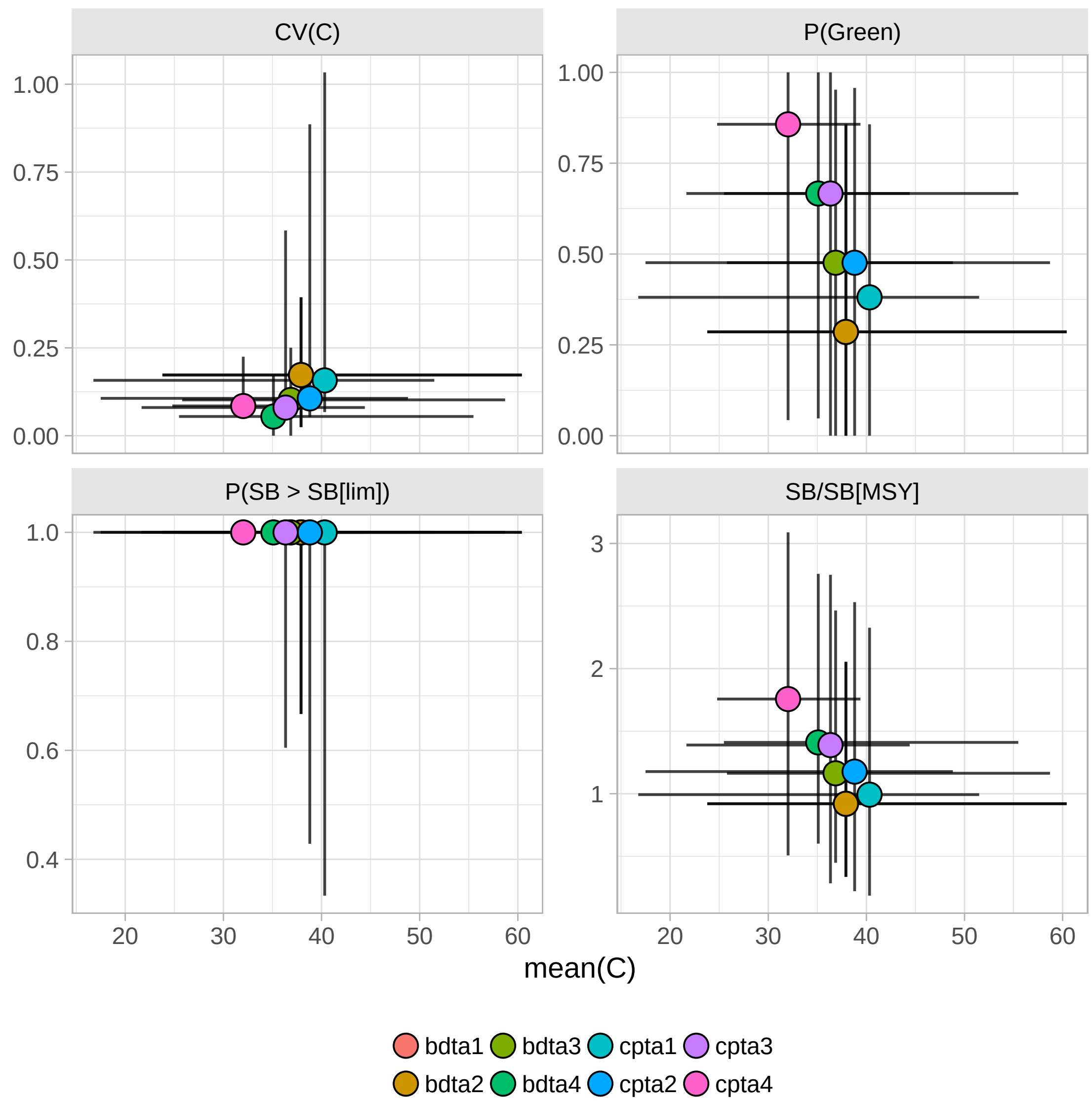

Figure 28: Trade-off plots comparing the performance of the eight candidate management procedures, from two families (BD and CP), tuned for the four management objectives (TA1-TA4), and for mean catch against four performance indicators, all averaged over the 2019-2038 period. The circle shows the median value, while lines represent the 10^{th}-90^{th} percentiles. Red and green horizontal lines represent the interim limit and target reference points for the mean SB/SB MSY performance measure.

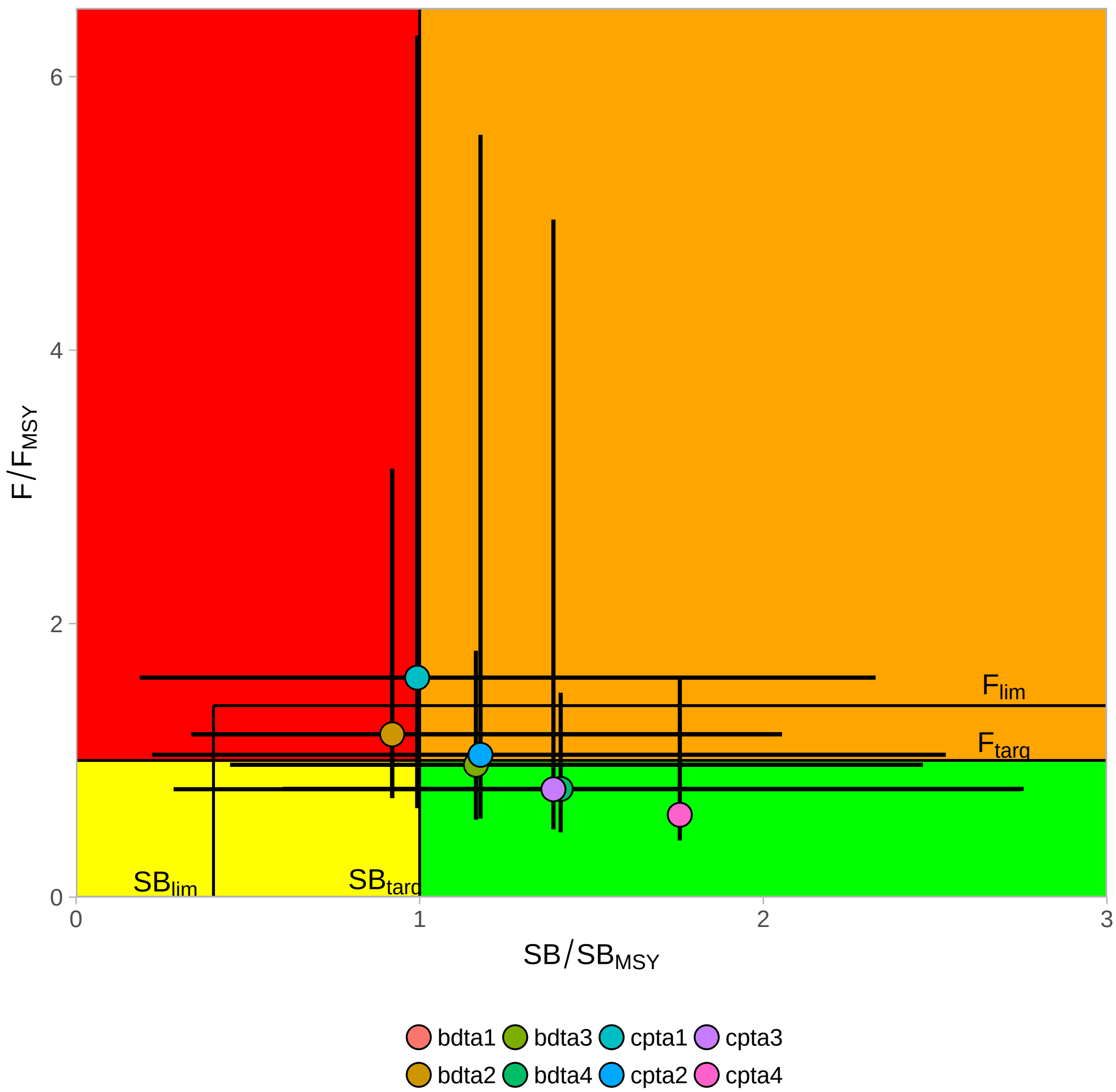

Figure 29: Kobe plot comparing the performance of the eight candidate management procedures, from two families (BD and CP), and tuned for the four management objectives (TA1-TA4), averaged over the 2019-2038 period. The circle shows the median value, while lines represent the 10^{th}-90^{th} percentiles. Black lines show the limit reference points along the two dimensions

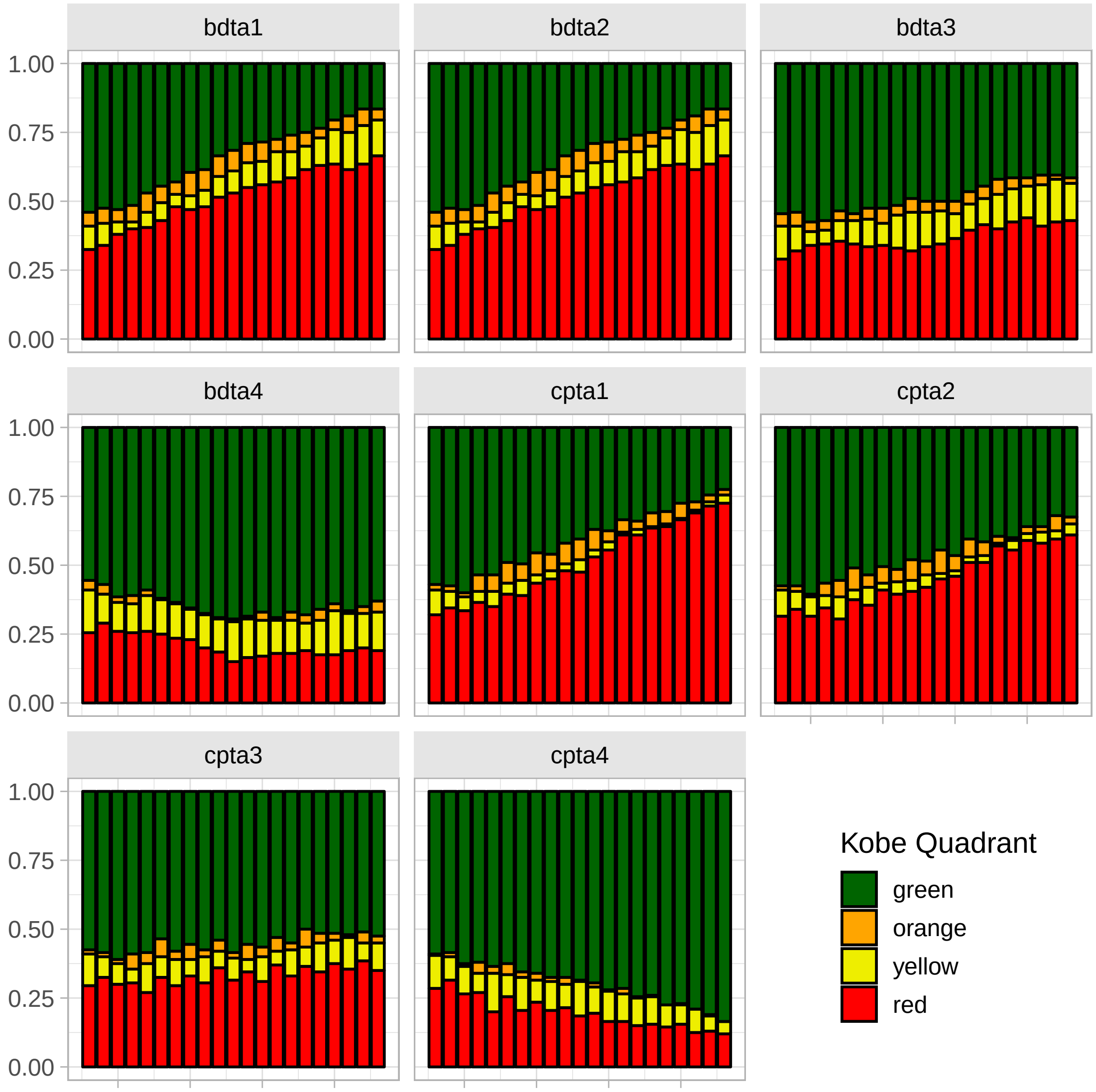

Figure 30: Proportion over time of simulations in each of the Kobe quadrants over time for each of the candidate MPs from two families (BD and CP), and tuned for the four management objectives (TA1-TA4).

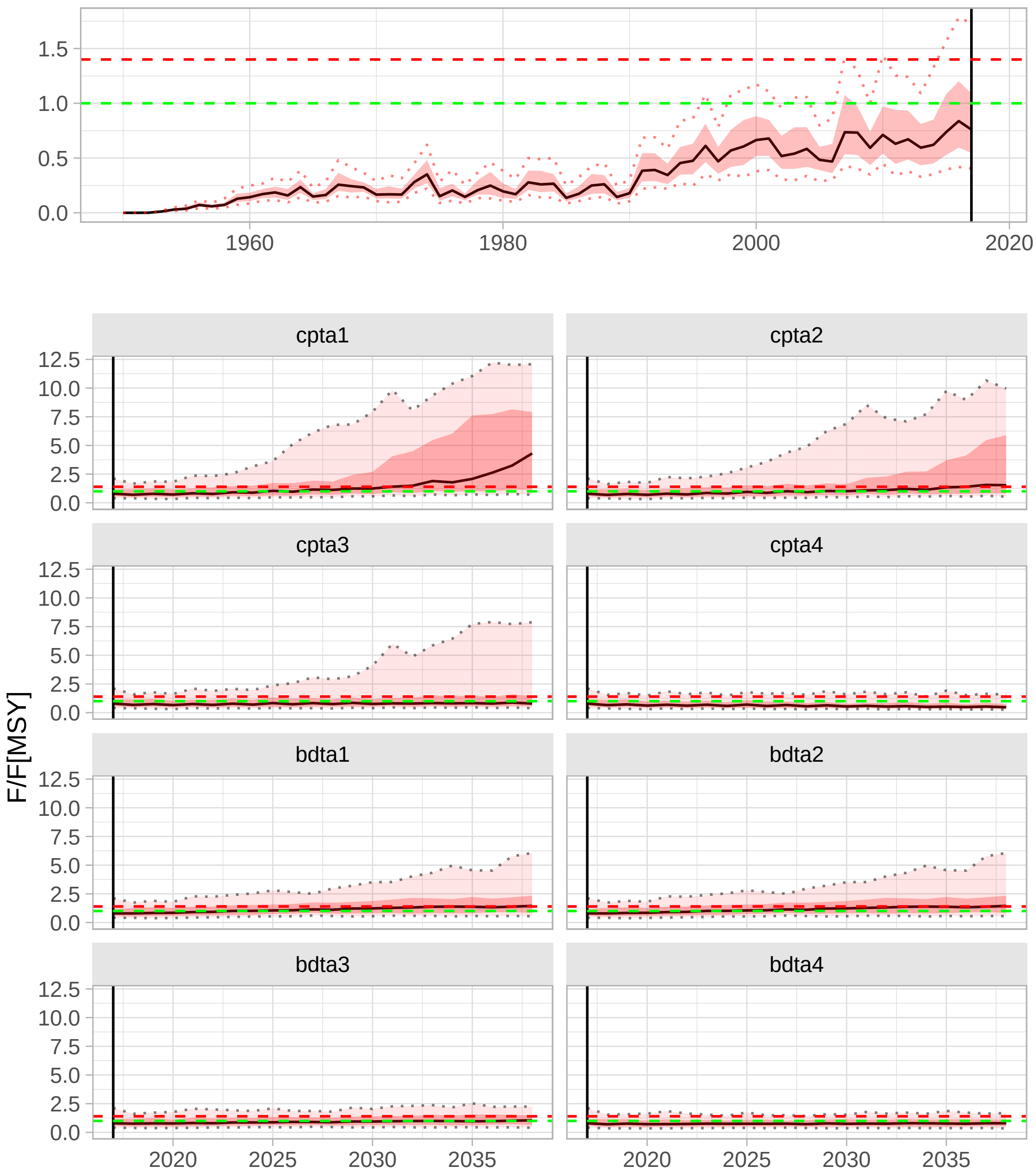

Figure 31: Time series of fishing mortality over that at MSY (F/F_{MSY}). Top panel shows the trajectory for the OM, while the lower panels show them for each of the eight candidate management procedures, from two families (BD and CP), and tuned for the four management objectives (TA1-TA4). The black circle shows the median value, while shaded areas represent the 25^{th}-75^{th} percentiles and the 10^{th}-90^{th} percentiles. Red and green horizontal lines represent the interim limit and target reference points for F/F_{MSY}.

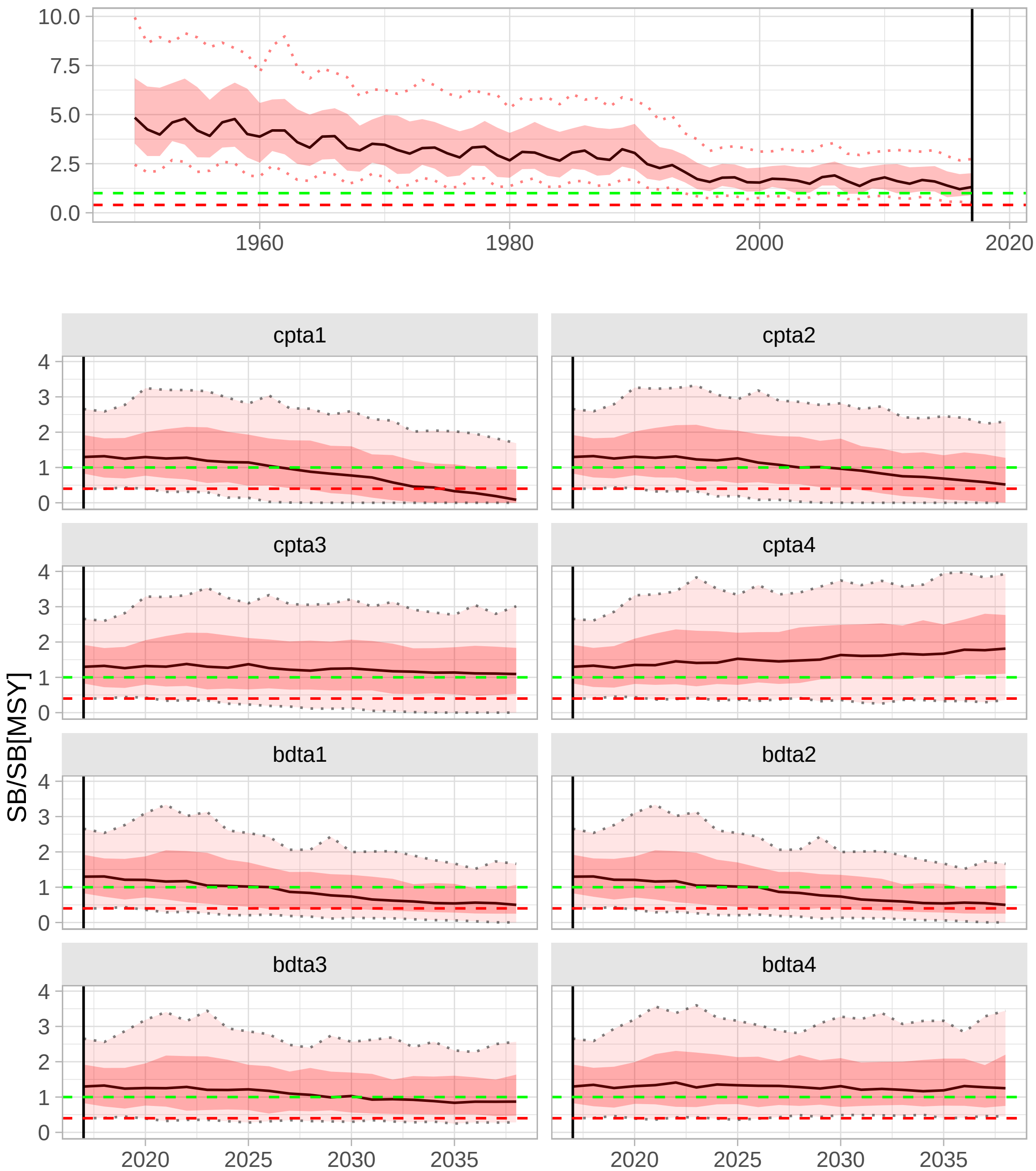

Figure 32: Time series of spawning biomass over that at MSY (SB/SB_{MSY}). Top panel shows the trajectory for the OM, while the lower panels show them for each of the eight candidate management procedures, from two families (BD and CP), and tuned for the four management objectives (TA1-TA4). The black circle shows the median value, while shaded areas represent the 25^{th}-75^{th} percentiles and the 10^{th}-90^{th} percentiles. Red and green horizontal lines represent the interim limit and target reference points for SB/SB_{MSY}.

Table 2: Performance of the eight candidate MPs with respect to key performance measures, averaged over the period 2019-2038.

mp	$P(SB > SB_{lim})$	$CV(C)$	$P(Green)$	$\hat{C}1000t$	SB/SB_{MSY}
bdta1	1.00 (0.67-1.0)	0.23	0.35	37.91 (23.78-60.4)	1.1
bdta2	1.00 (0.67-1.0)	0.23	0.35	37.91 (23.78-60.4)	1.1
bdta3	1.00 (1.00-1.0)	0.14	0.47	36.86 (25.79-58.7)	1.4
bdta4	1.00 (1.00-1.0)	0.097	0.59	35.10 (25.48-55.5)	1.6
cpta1	1.00 (0.33-1.0)	0.36	0.4	40.32 (16.75-51.5)	1.2
cpta2	1.00 (0.43-1.0)	0.27	0.47	38.80 (17.50-48.8)	1.3
cpta3	1.00 (0.60-1.0)	0.21	0.56	36.34 (21.66-44.4)	1.5
cpta4	1.00 (1.00-1.0)	0.17	0.68	32.02 (24.79-39.4)	1.8

Table 3: Performance indicators for the eight candidate MPs over the first 5 years, 2019-2023.

	5 year average		bdta1	bdta2	bdta3	bdta4	cpta1	cpta2	cpta3	cpta4
1	Mean spawner biomass relative to unfished	SB/SB_0	0.29	0.29	0.30	0.31	0.30	0.31	0.31	0.32
2	Minimum spawner biomass relative to unfished	$min(SB/SB_0$	0.21	0.21	0.22	0.23	0.22	0.23	0.23	0.24
3	Mean spawnwer biomass relative to SBMSY	SB/SB_{MSY}	1.51	1.51	1.58	1.65	1.58	1.61	1.65	1.70
4	Mean fishing mortality relative to target	F/F_{target}	1.17	1.17	1.03	0.92	1.20	1.13	1.05	0.94
5	Mean fishing mortality relative to FMSY	F/F_{MSY}	1.17	1.17	1.03	0.92	1.20	1.13	1.05	0.94
6	Probability of being in Kobe green quadrant	$P(Green)$	0.53	0.53	0.57	0.60	0.56	0.58	0.59	0.62
7	Probability of being in Kobe red quadrant	$P(Red)$	0.38	0.38	0.33	0.28	0.34	0.32	0.30	0.26
8	Probability of SB greater/equal than SBMSY	$P(SB >= SB_{MSY})$	0.61	0.61	0.64	0.67	0.65	0.65	0.67	0.69
9	Probability of spawner biomass being above 20 SB[0]	$P(SB > 0.20 \cdot SB_0)$	0.60	0.60	0.62	0.64	0.62	0.63	0.64	0.67
10	Probability of spawner biomass being above SBlim	$P(SB > SB_{lim})$	0.98	0.98	0.99	0.99	0.97	0.98	0.98	0.99
11	Mean proportion of MSY	C/MSY	1.28	1.28	1.21	1.13	1.21	1.17	1.13	1.06
12	Mean absolute proportional change in catch	$var(C)$	1.01	1.01	1.00	1.00	1.01	1.01	1.00	0.99
13	Catch variability	$CV(C)$	0.07	0.07	0.06	0.06	0.07	0.07	0.07	0.07
14	Variance in fishing mortality	$var(F)$	0.01	0.01	0.00	0.00	0.02	0.02	0.02	0.01
15	Probability of fishery shutdown	$P(C < 0.1 \cdot MSY)$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 4: Performance indicators for the eight candidate MPs over the first 10 years, 2019-2028.

	10 year average		bdta1	bdta2	bdta3	bdta4	cpta1	cpta2	cpta3	cpta4
1	Mean spawner biomass relative to unfished	SB/SB_0	0.26	0.26	0.29	0.31	0.28	0.29	0.31	0.33
2	Minimum spawner biomass relative to unfished	$min(SB/SB_0$	0.16	0.16	0.19	0.20	0.18	0.19	0.20	0.22
3	Mean spawnwer biomass relative to SBMSY	SB/SB_{MSY}	1.35	1.35	1.49	1.63	1.45	1.52	1.61	1.73
4	Mean fishing mortality relative to target	F/F_{target}	1.37	1.37	1.12	0.96	1.61	1.45	1.26	1.01
5	Mean fishing mortality relative to FMSY	F/F_{MSY}	1.37	1.37	1.12	0.96	1.61	1.45	1.26	1.01
6	Probability of being in Kobe green quadrant	$P(Green)$	0.45	0.45	0.53	0.60	0.51	0.55	0.59	0.64
7	Probability of being in Kobe red quadrant	$P(Red)$	0.42	0.42	0.34	0.27	0.38	0.35	0.30	0.24
8	Probability of SB greater/equal than SBMSY	$P(SB >= SB_{MSY})$	0.55	0.55	0.61	0.70	0.61	0.63	0.67	0.71
9	Probability of spawner biomass being above 20 SB[0]	$P(SB > 0.20 \cdot SB_0)$	0.52	0.52	0.58	0.65	0.58	0.60	0.63	0.68
10	Probability of spawner biomass being above SBlim	$P(SB > SB_{lim})$	0.97	0.97	0.98	0.98	0.93	0.94	0.95	0.97
11	Mean proportion of MSY	C/MSY	1.30	1.30	1.22	1.14	1.21	1.17	1.11	1.02
12	Mean absolute proportional change in catch	$var(C)$	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.97
13	Catch variability	$CV(C)$	0.13	0.13	0.10	0.08	0.14	0.12	0.11	0.11
14	Variance in fishing mortality	$var(F)$	0.03	0.03	0.02	0.01	0.08	0.06	0.05	0.02
15	Probability of fishery shutdown	$P(C < 0.1 \cdot MSY)$	0.01	0.01	0.00	0.00	0.02	0.02	0.01	0.01

Table 5: Performance indicators for the eight candidate MPs over the full 20 years, 2019-2038.

	20 year average		bdta1	bdta2	bdta3	bdta4	cpta1	cpta2	cpta3	cpta4
1	Mean spawner biomass relative to unfished	SB/SB_0	0.21	0.21	0.26	0.31	0.22	0.25	0.29	0.35
2	Minimum spawner biomass relative to unfished	$min(SB/SB_0$	0.09	0.09	0.14	0.17	0.09	0.12	0.16	0.19
3	Mean spawnwer biomass relative to SBMSY	SB/SB_{MSY}	1.12	1.12	1.38	1.63	1.14	1.29	1.51	1.83
4	Mean fishing mortality relative to target	F/F_{target}	1.77	1.77	1.29	1.04	2.78	2.18	1.66	1.15
5	Mean fishing mortality relative to FMSY	F/F_{MSY}	1.77	1.77	1.29	1.04	2.78	2.18	1.66	1.15
6	Probability of being in Kobe green quadrant	$P(Green)$	0.34	0.34	0.47	0.59	0.39	0.46	0.57	0.69
7	Probability of being in Kobe red quadrant	$P(Red)$	0.51	0.51	0.38	0.28	0.52	0.44	0.32	0.20
8	Probability of SB greater/equal than SBMSY	$P(SB >= SB_{MSY})$	0.47	0.47	0.57	0.69	0.48	0.57	0.65	0.79
9	Probability of spawner biomass being above 20 SB[0]	$P(SB > 0.20 \cdot SB_0)$	0.41	0.41	0.53	0.64	0.45	0.51	0.61	0.72
10	Probability of spawner biomass being above SBlim	$P(SB > SB_{lim})$	0.92	0.92	0.97	0.98	0.81	0.86	0.91	0.95
11	Mean proportion of MSY	C/MSY	1.23	1.23	1.21	1.15	1.16	1.14	1.07	0.97
12	Mean absolute proportional change in catch	$var(C)$	0.96	0.96	0.98	0.99	0.90	0.93	0.95	0.96
13	Catch variability	$CV(C)$	0.23	0.23	0.14	0.09	0.37	0.28	0.22	0.17
14	Variance in fishing mortality	$var(F)$	0.07	0.07	0.03	0.02	0.25	0.16	0.09	0.05
15	Probability of fishery shutdown	$P(C < 0.1 \cdot MSY)$	0.04	0.04	0.02	0.01	0.11	0.08	0.06	0.03

10 Software platform

The work presented here has been carried out using two main tools: the SS3 stock assessment platform (Methot and Wetzel 2013) for OM conditioning, and the FLR libraries (Kell et al. (2007), http://flr-project.org) for data input of OM model runs, assemblage of the base case OM, implementation and evaluation of the MPs, computational workload, and model output and summaries.

The grid of model runs was constructed by altering for each factor combination the SS3 input files. Manipulation of these files was facilitated by the use of the `r4ss` R package. The `setgrid` function in the `ioalbmse` package is responsible for carrying out the alterations for each element in grid as necessary. A generic R package, `ss3om`, has also been developed to load the results of the SS3 runs into FLR.

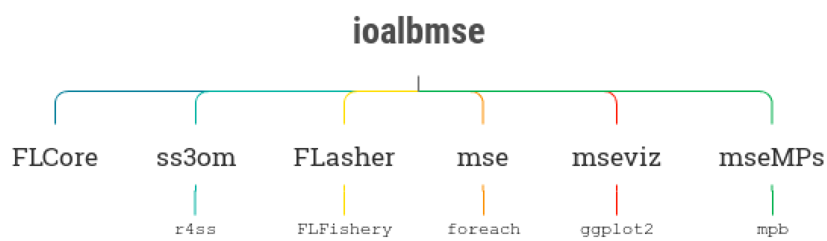

Figure 33: Main R/FLR packages involved in the implementation of the analyses presented.

10.1 Accesing code and results

The source code employed in this work is being kept in an open version control server, namely http://github.com/iotcwpm/ALB, where current and previous versions of the code can be inspected and downloaded. Results of the operating model conditioning and of the MSE runs are also stored in the same repository.

11 Discussion

This document presents very briefly most of the work that has been carried out so far to prepare and test a simulation platform for the evaluation of management procedures for Indian Ocean albacore. A base case operating model is now available for this stock, with the ability to be easily applied to the construction of other operating models based on the same computational platform: a combination of SS3 (Methot and Wetzel 2013) and FLR (Kell et al. 2007).

Some extra work is required, as discussed below, to obtain a definite set of MP evaluations. Given the limited manpower available for this work, priorities will need to be identified. some of the development work carried out could be use for other IOTC stocks, specially if an OM is to be developed based on an stock assessment carried out using the SS3 platform.

11.1 Next steps

The work for Indian Ocean albacore is still not complete, and a number of necessary steps have been identified. First, a set of tuning runs in which the full biomass dynamics model is fit needs to be finalized. Code is currently being updated to avoid the relatively large number of not convergence in the model fits. Second, the tuning runs need to be carried out wiht a 3 year lag in stock status. The runs presented assume a yearly time step due to some computational glitch which has now been resolved.

Also, robustness tests should be carried out on the tuned MPs, including, but for not limited to the following:

- Recruitment failure (50% of expected recruits) for the first 2-3 years of MP application.
- TAC implementation error of 10% a year, reported or not.
- Increase in LL CPUE catchability of 2% per year over the simulation period.

Finally, runs are being prepared for an alternative model-based MP which applies a relatively simple statistical catch-at-age model with a single CPUE series. This has been considered given the problems of convergence of the biomass dynamics model.

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