Management Strategy Evaluation for the Indian Ocean Tuna Albacore Stock

Iago Mosqueira[*]

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Abstract

This document presents the development of the technical platform and intial results for Management Strategy Evaluation for Indian Ocean albacore tuna. The work includes the development of a reference case Operating Model for the stock, an open source computational platform for the evaluation of alternative Management Procedures, an initial set of simulations for three MPs, and the presentation and output for inspection and analysis of the results. The Operating Model is based around the Stock Synthesis stock assessment conducted by WPTmT and incorporates the main sources of uncertainty identified in the estimation of population trajectories and dynamics according to the data available at IOTC.

Contents

1 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 models reviewed 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.

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

The OM presented here has been constructed using as base case the previous stock assessment exercise, carried out in 2014 (IOTC 2014) using the Stock Synthesis 3 software platform (SS3, (Methot and Wetzel 2013). Work is in progress to update the OM to be based on the most recent stock assessment exercise (IOTC 2016). Problems have also been identified with some of the settings of the model runs when conditioning the OM that will require rerunning the conditioning procedure once those are resolved.

An initial set of simulation runs for two possible management procedures have been conducted: exploration runs, tentative evaluation runs (for one MP) and some robustness runs. Code if also available to run a full grid tuning of any of the MPs. 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 WPM.

2 Operating Model

The basic structure of the operating model is equivalent to that presented previously (Mosqueira and Sharma 2014, Mosqueira and Scoot (2015)). 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 Fifth Session of the Working Party on Temperate Tunas (Hoyle, Sharma, and Herrera 2014), with one major difference. The separation of the Taiwanese longline (TWN LL) fleet into two periods of operation, early and late, was not considered in the base OM model. The temporal changes in selectivity that the WPTmT runs attempted to capture were not deemed important enough to justify the extra complexity in OM structure.

This iteration of the OM has taken into consideration the recommendations made by WPTmT (IOTC 2014, Table 12) with regards to the scenarios for different model parameters, as well as the feedback from the last session of WPM (IOTC 2015b), including the report from the two invited experts. This has had as the main consequence an increase in the size of the model grid to a total of 1,440 model runs.

2.1 Structure and assumptions

The model applies a quarterly (three month) time step, and runs over a single region (Figure). Spawning takes place in the fourth quarter, and fish are recruited into the population at the start of the following calendar year, that is they turn into age 1 fish after only three months. The model uses 15 age classes (ages 0 to 14), but age 0 is subsequently dropped from the results and recruitment is assumed to be represented by the abundance of age 1 fish.

The model incorporates catch at length data for a total of seven fleets, as follows

- Japanese longline fleet operating in the North region (`F1_JPN_LL_N`)
- Taiwanese longline fleet operating in the North region (`F2_TWN_LL_N`)
- Purse seine fleet (`F3_PS_N`)
- Other fisheries (`F4_Other_N`)
- Japanese longline fleet operating in the Southern region (`F5_JPN_LL_S`)
- Taiwanese longline fleet operating in the Southern region (`F6_TWN_LL_S`)
- Driftnets (`F7_Drift`)

The separation of longline fleets in Northern and Southern regions (Figure 2) attempts to capture the differences in selectivity due to different main target species for those fleets: tropical tuna in the Northern region and albacore (but also Southern bluefin) in the South.

2.2 Uncertainty grid

A factorial grid covering seven possible sources of uncertainty in the determination of stock dynamica and status was applied.

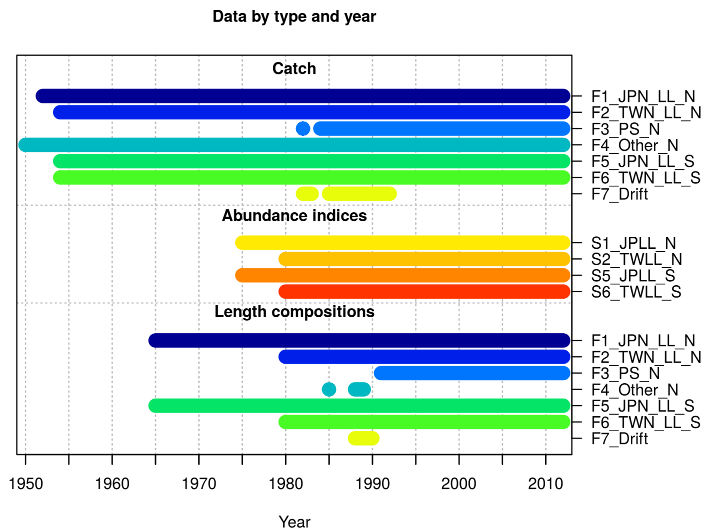

Figure 1: Data coverage by year for each fleet and source: catch, abundance indices and length composition.

2.2.1 Natural Mortality vector (*M*)

A common unknown in most stock assessment models, the base case considered in the stock assessment session, $M =$ (IOTC 2014) was supplemented with alternative values of higher and lower M for either all ages, or different for juveniles (ages 1 to 4, M0) and adults (age 5 or older, M1), for a total of five possibilities:

1. `0202`: Constant M at 0.2 for all ages.
2. `0303`: Constant M at 0.3 for all ages.
3. `0404`: Constant M at 0.4 for all ages.
4. `0403`: M=0.4 at age 0, decreasing to 0.3 at age 5 and older.
5. `0402`: M=0.4 at age 0, decreasing to 0.2 at age 5 and older.

The third option above, $M = 0.4$ for all ages, led to non-convergent model runs in all cases and was subsequently dropped.

2.2.2 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. Set by variable *SR_sigmaR* in the `ss3.ctl` file.

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

Three values for the steepness (h) of the stock-recruitment relationship were considered: 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.

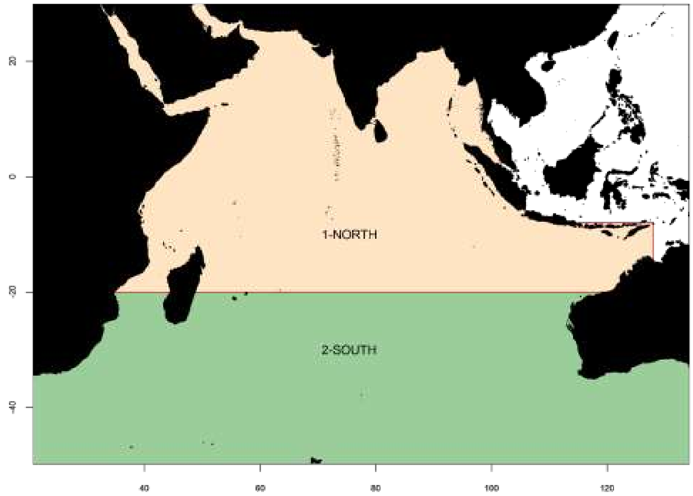

Figure 2: Regions used in the albacore SS3 OM for separating the fleets activity.

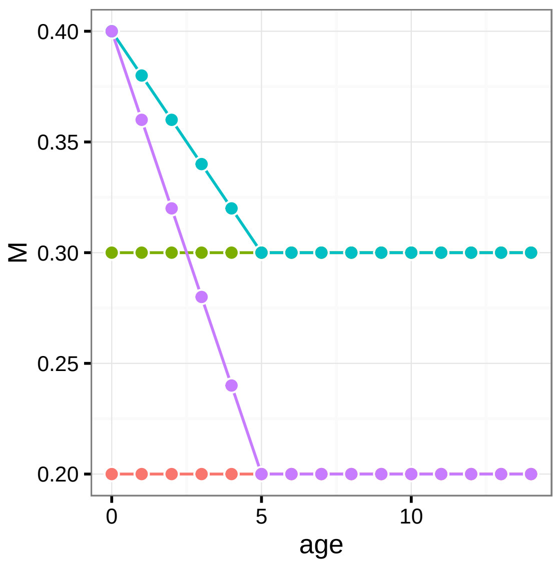

Figure 3: Natural mortality at age vectors used in the OM grid.

There is little or no information in stock assessment data sets to estimate steepness (Pepin), so most tuna stock assessment choose to set it at a fixed value. (Simon 2012) showed that steepness in tuna stocks is likely to be at the high end of the range while (Szuwalski et al. 2014) showed that SSB is more likely to be driven by recruitment than recruitment by SSB.

2.2.4 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.

2.2.5 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.

2.2.6 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.

2.2.7 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.

2.3 Conditioning

The grid of models setup according to the options specified above was run using Stock Synthesis 3 (SS3) for Linux, version 3.24u.

2.4 Diagnostics

The aggregated population model obtained from the complete grid of model runs included a high proportion of unrealistic estimates. The virgin recruitment (`LN(R0)`) estimate obtained in some of the runs was at the higher limit specified in the model control ($ln(R_0) < 15$). This gives indication of a mismatch between the information content of the data and a particular set of fixed parameters, or of conflicts between the various data sources. Figure shows the distribution (in log scale) of the estimates of unfished biomass.

Runs where the final estimate of virgin recruitment was at it maximum, a total of 32, were identified and then excluded from the operating model set.

For the remaining 688 runs, the relationship between the various parameters in the grid and the values of unfished biomass (B_0) was investigated through a linear model of the form

$$B_0 \sim M + \sigma_R + h + c_v + S_{len} + q_{LL} + s_{LL} \tag{2}$$

where B_0 is the estimated unfished biomass, and all other variable are as above. This simple model, with no interactions, indicated that three of the parameters were responsible for the majority of the variation in B_0 estimates: natural mortality (`M` in Table 1), weight assigned to the length data (`ess`) and the functional form of the selectivity for the CPUE fleet (`llsel`).

Figure 5 shows the estimated values of virgin biomass (B_0) across the various scenarios for those three variables.

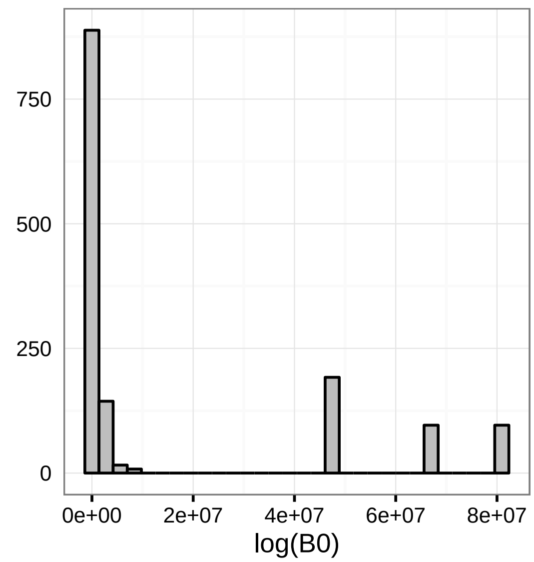

Figure 4: Distribution of estimates of unfished biomass, in log scale, from the full grids of model runs.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
M	4	2.70e+17	6.75e+16	193.22	0.0000
sigmaR	1	1.32e+13	1.32e+13	0.04	0.8460
steepness	1	4.03e+11	4.03e+11	0.00	0.9729
cpuecv	1	2.35e-13	2.35e-13	0.00	1.0000
ess	1	7.78e+16	7.78e+16	222.56	0.0000
llq	1	2.95e+12	2.95e+12	0.01	0.9269
llsel	1	2.41e+17	2.41e+17	689.21	0.0000
Residuals	1429	5.00e+17	3.50e+14		

Table 1: Results of the linear model.

2.5 Model selection based on carrying capacity K

The feasibility of the model runs was assessed according on available estimates of the available habitat A for Indian Ocean albacore and the limit this must impose of K, the carrying capacity. Data on estimates of K for albacore stocks across all oceans were obtained from the relevant RFMO-approved stock assessments (IATTC 2014, (**???**)), while estimates of suitable habitat by ocean for albacore were obtained from the authors of (Arrizabalaga et al. 2015) (Table 2)

	Habitat size (sq. km)	K (t)
Indian Ocean	6073	474828
Mediterranean	244	
North Atlantic	3752	357600
North Pacific	7547	398200
South Atlantic	3779	350000
South Pacific	7426	307830

Table 2: Estimates of habitat size and carrying capacity for most albacore stocks.

A linear model of the form $K \sim 0 + h$, where h is the potential habitat size, and 0 indicates a zero intercept, was fitted using the `lm` function in the R statistical language (R Core Team 2015), and the estimates of the coefficient and its standard error (Table 3) were used to generate an upper plausible limit for K and, by assuming equilibrium conditions prior to the start of industrial fishing, for B_0. This was conservatively computed as the upper 99.9% confidence

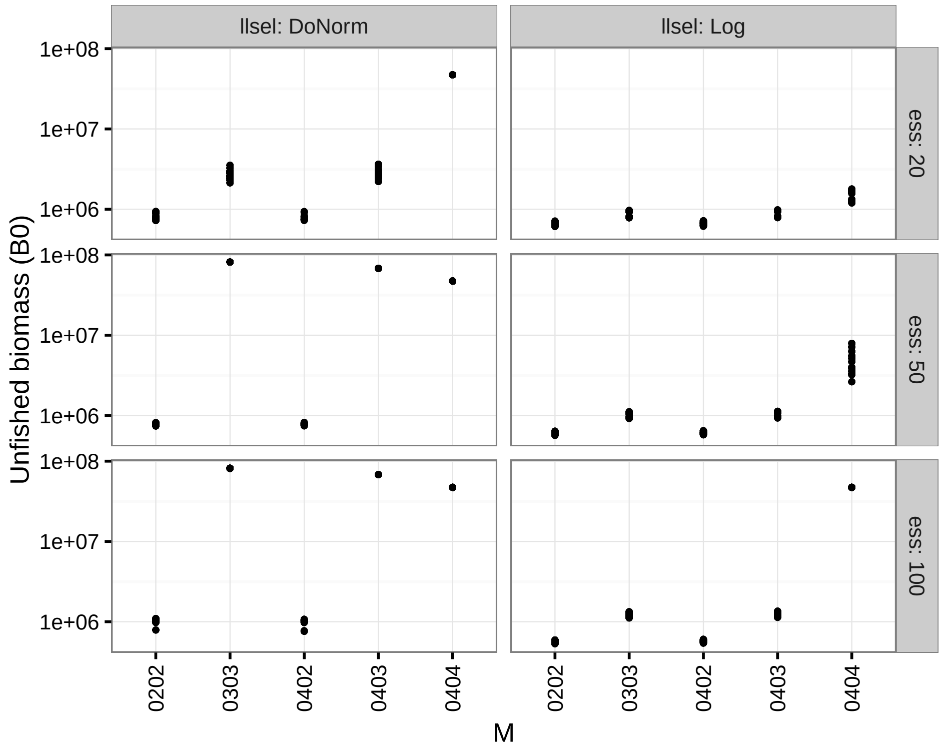

Figure 5: Values of estimated unfished biomass for each scenario of natural mortality (M), selectivity curve (llsel) and weight of length samples (ess).

interval around the estimate of the slope coefficient, by using the calculated ratio for the Indian Ocean of $6,073\, t/m^2$.

	Estimate	Std. Error	t value	Pr(>|t|)
habitat	61.1200	9.6948	6.30	0.0032

Table 3: Linear model estimate of the relationship between estimates of K, carrying capacity, and habitat size across stocks and oceans.

The upper limit obtained, $B_0 = 878127$, was then used to select model runs deemed plausible. This brought down the total number of runs included in the operating model to 616. The model is presented in Figures 6, 7 and 8.

2.6 Comparison of 2014 and 2016 stock assessments

The most recent meeting of WPTmT (IOTC 2016) conducted an updated stock assessment on the albacore stock. The latest iteration of the SS3 model (Langley and Hoyle 2016), has introduced a series of changes in the structure of the model, most notable the separation in two sexes, new definition of fisheries, and adoption of a single value of natural mortality across all ages. This has made the code used previously to operate on the SS3 input files, and for loading the results of the model runs, unable to work on the 2016 model files. The second issue, loading of outputs, has already been solved, but work remains to be done on the first.

An important difference on the input data used between both years has been the CPUE series for the longline fleets. a more detailed analysis of the operational data for the Japanese, Taiwanese and Korean fleets catching albacore has led to what is probably an improved index of abundance for the stock.

A comparison of the base case results for both assessments (Figure 9), shows that the newer model run estimates a lower initial biomass, thus leading to a better outlook for the stock.

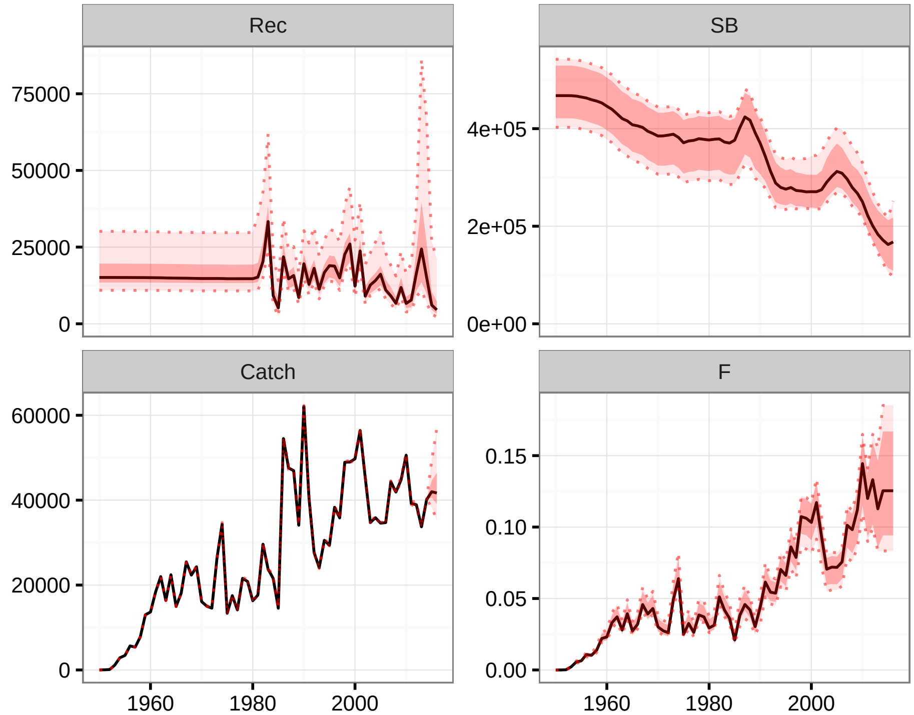

Figure 6: Time series of the conditioned OM estimates of recruitment (age 1), SB, Catch and mean fishing mortality across the fully selected ages(F). Black lines represent the median value, while bands show the 50 and 90 percent probability intervals.

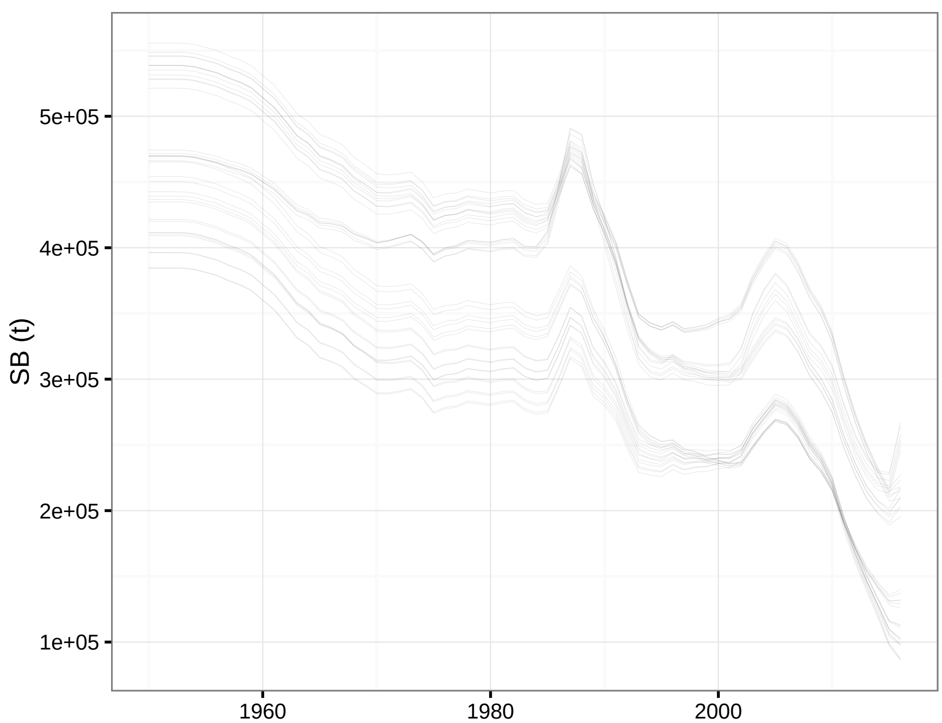

Figure 7: Trajectories of spawning biomass (SB) obtained from the model runs in the OM contidioning grid.

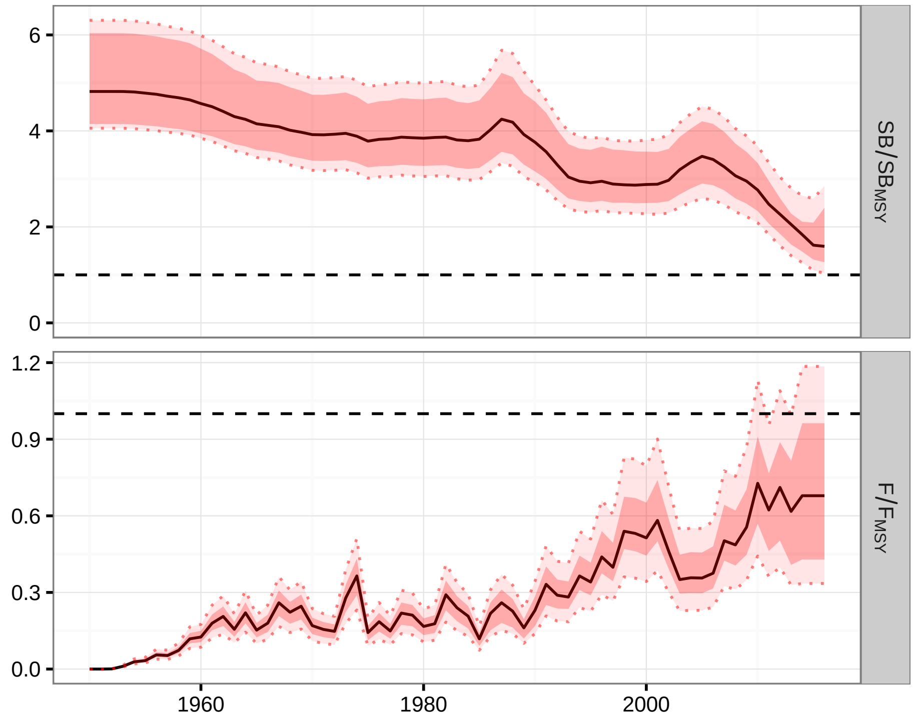

Figure 8: Time series of SSB and fishing mortality ratios over the MSY values.

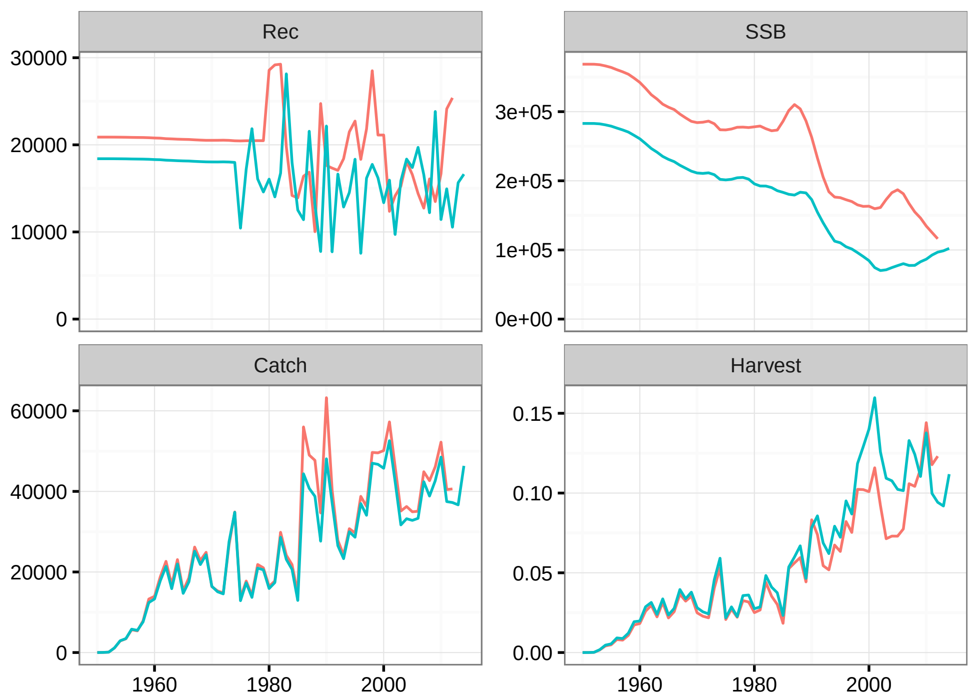

Figure 9: Population trajectories estimated by the base case runs of SS3 in 2014 (in red) and 2016 (in blue).

How this results impact the existing OM is to be considered. The population trajectory estimated by the 2016 stock assessment falls outside of the 95% probability intervals of the operating model (Figure 10), indicating that an update of the OM is needed to incorporate the latest scientific consensus on the stock. However, simulation testing of management procedures should be based on operating models that reflect the dynamics and future responses of the stock to management, variability and error, rather than a precise estimate of current status, i.e. an MP tested on an OM based on the previous stock assessment should be still valid when applied to the population and indicators provided by the newer model, unless they both lead to very diverging views on the dynamics of the stock.

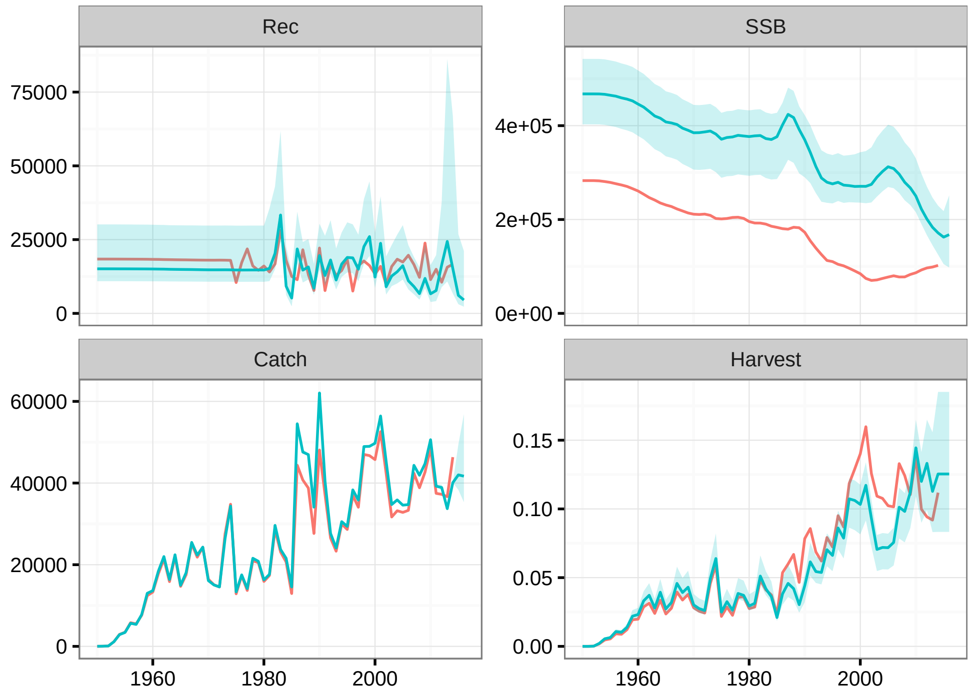

Figure 10: Population trajectories estimated by the base case run of SS3 in 2016 (red) and the OM grid (blue).

3 Management procedures

3.1 IRate

This is a model-free procedure, driven by trends in the CPUE series compared with reference values set from a period in the past (Bentley and Adam 2015). A number of parameters determine its behaviour and speed of response to trends in CPUE:

- Reference years, years used when computing reference values
- Responsiveness, the degree of smoothing in the biomass index
- HR multiplier, the target harvest rate relative to levels over the reference years
- Biomass threshold, levels of biomass index, relative to historic, below which harvest is reduced
- Biomass limit, biomass index level, relative to historic, at which the fishery is closed
- Maximum TAC, total maximum value in catch allowed
- Lags in data collection, between years of application and last year of CPUE data, and management implementation, between proposed TAC and actual implementation to the fishery.
- Frequency of application, how often is the MP applied, in years.

3.1.1 Perturbation tests

A simple *perturbation test* was conducted for each MP under analysis. Starting from an stock under MSY equilibrium, a one-year shock in fishing mortality was imposed on it, and the MP is then applied for a number of years, as follows:

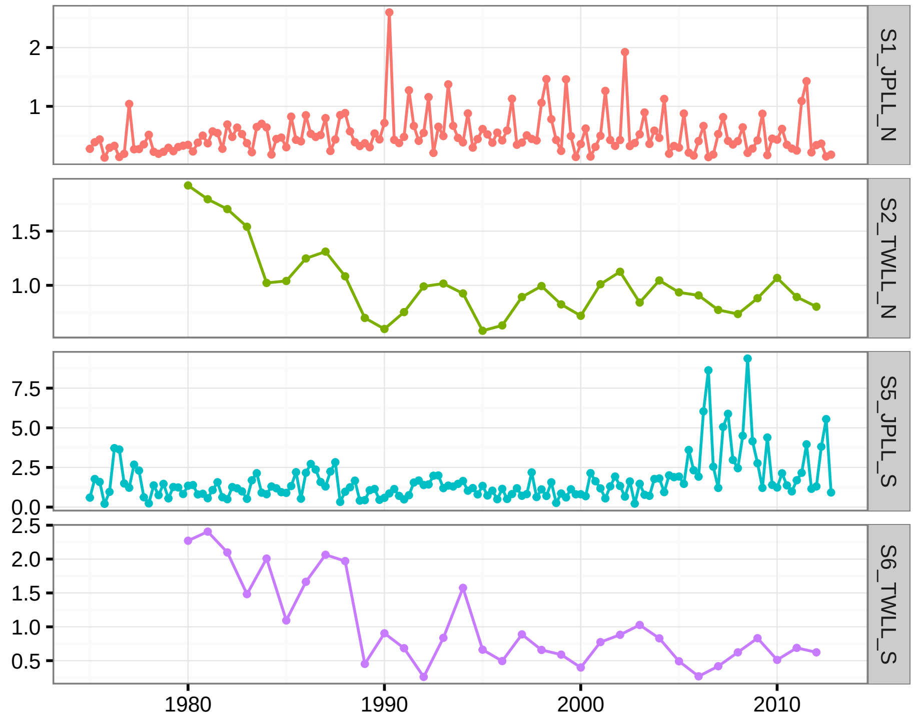

Figure 11: Indices of abundances in biomass used in the 2014 stock assessment. Series S1 and S2 (top two panels) corresponded to nthe Japanese and Taiwanese longline fleets operating in the Northern area, while S5 and S6 correspond to the same fleets in the Southern area.

1. Project stock, under current biological parameters and selectivity, from the last year of the OM and for 50 years with $F = F_{MSY}$.
2. Impose for one year a shock in fishing mortality, $F = 4 \cdot F_{MSY}$.
3. Start applying the MP one year after the shock, and for another 30 years.

In these runs the MP was applied under very favourable conditions: no error in observation, nor in implementation, and stock-recruit residuals introduced only during the MP application period. Also, and for the *IRate* MP, the year of the F shock was excluded from the period used to set the historical CPUE level. The assumption here was that such an increase in fishing mortality, probably due to an increase in effective and/or nominal effort, would not go unnoticed and the data point would be left out in the application of the MP to avoid an undue bias in the reference levels.

Other arguments in the MP were set as follows to average values:

- `responsiveness=0.5`
- `hr_multiplier=1.1`
- `biomass_threshold=0.5`
- `biomass_limit=0.2`
- `maxTAC=600000`
- `DLAG=1`, `MLAG=1` and `SFREQ=2`
- `errcpue=~0`, `effcpue=~0`

The length of time taken for the MP to recover the stock to its desired levels was recorded as a way of measuring the ability of the MP to bring the fishery back to its desired levels following such an event.

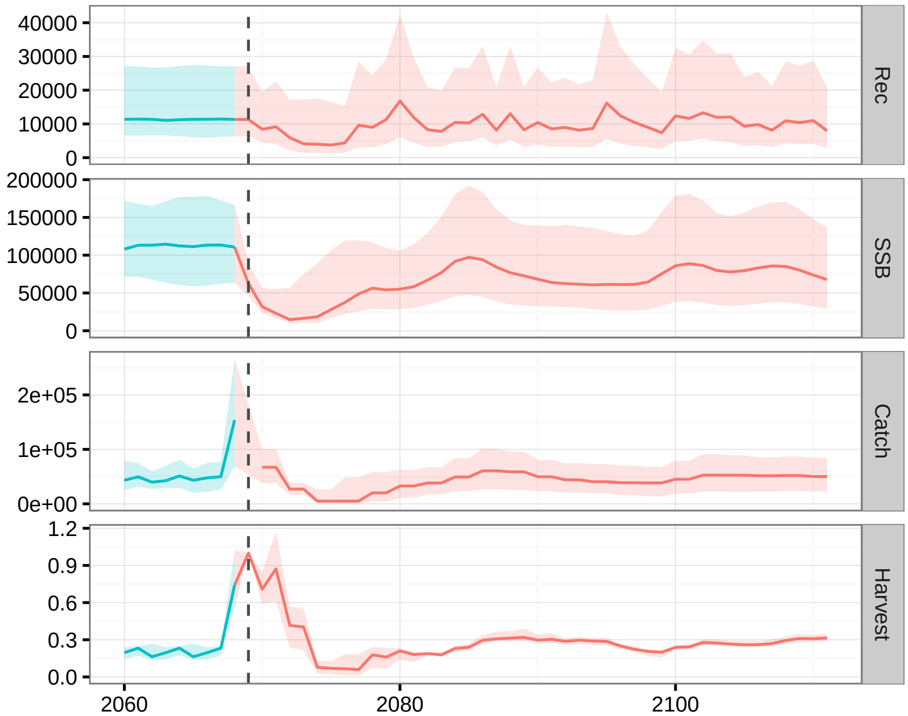

Figure 12: Perturbation test for the IRate MP. The first vertical line represents the start of the period where the stock is exploited at F_{MSY} levels. The second one indicates the start of the period of application of the MP.

3.2 BRule

This is a generic management procedure that conducts a biomass-based stock assessment and compares the estimates of stock status with those set as reference points. These are the main arguments to the MP:

- Biomass threshold
- Biomass limit
- Fishing mortality target
- Spawning biomass at MSY estimate
- Lags in data collection, between years of application and last year of CPUE data, and management implementation, between proposed TAC and actual implementation to the fishery.
- Implementation error

3.2.1 Perturbation tests

A similar perturbation test was also conducted for this MP, following the protocol outlined above (Section 3.1.1). In this case, the values chosen for the MP arguments were:

- `bthreshold = 1`
- `blim = 0.4 * SBMSY`
- `ftarget = FMSY`
- `DLAG=1, MLAG=1, SFREQ=1`
- `errcpue=~0, effcpue=~0, errimp=~0`

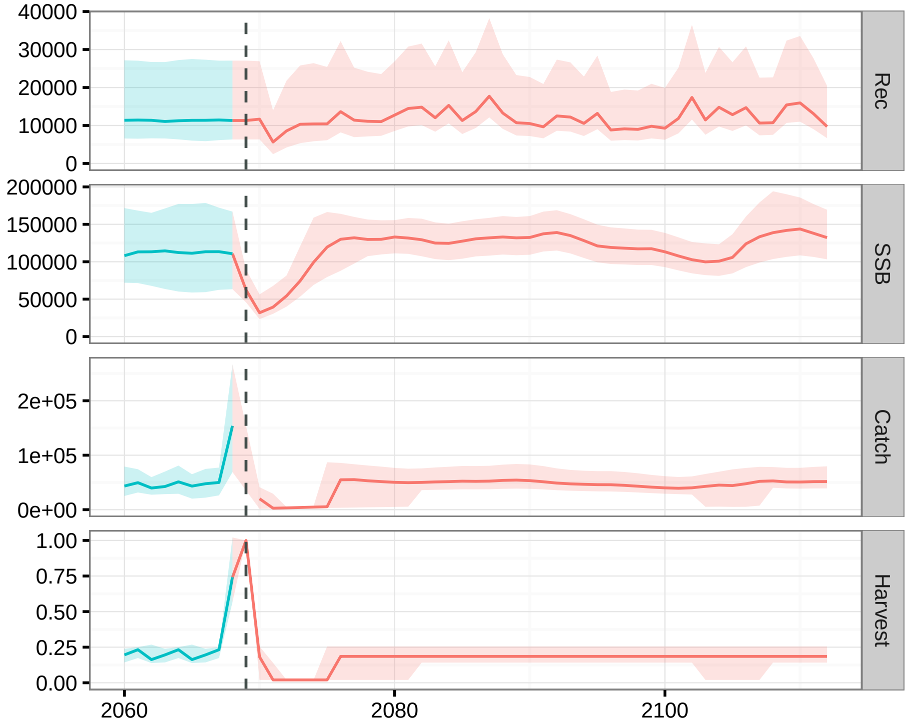

Figure 13: Perturbation test for the BRule MP. The first vertical line represents the start of the period where the stock is exploited at F_{MSY} levels. The second one indicates the start of the period of application of the MP.

4 Management objectives

4.1 Performance measures

The table of performance measures adopted by the IOTC Scientific Committee, at its 2015 Session (IOTC 2015a), has been implemented as a list of formulas to be applied to the results of MP simulation runs. Table **??** presents the adopted indicators with the formulas used for computation, the code employed for selection in the plot methods, and the name used internally. Please note the formulas, in the R sense of an object of the `formula` class, make use of methods defined in the `FLCore` library (i.e. `yearMeans`).

Table 4: Performance indicators adopted by IOTC as implemented in the `ioalbmse` code

Name	Code	formula
mean(SB/SB_0)	S1	`~yearMeans(SB/SB0)`
min(SB/SB_0)	S2	`~apply(SB/SB0, c(1, 3:6), min)`
mean(SB/SB_MSY)	S3	`~yearMeans(SB/SBMSY)`
mean(F/F_target)	S4	`~yearMeans(F/Ftarget)`
mean(F/F_MSY)	S5	`~yearMeans(F/FMSY)`
P(Green)	S6	`~yearSums((SB > SBMSY) + (F < FMSY))/length(SB)`
P(Red)	S7	`~yearSums((SB < SBMSY) + (F > FMSY))/length(SB)`
P(SB > 0.20 SB0)	F1	`~yearSums(SB > 0.2 * SB0)/length(SB)`
P(B > Blim)	F2	`~yearSums(SB > SBlim)/length(SB)`
mean(C)	Y1	`~yearMeans(C)`
mean(C/MSY)	Y3	`~yearMeans(C/MSY)`
mean(CR)	A1	`~yearMeans(SB/SB0)`

Name	Code	formula
mean(C_t / C_t-1)	T1	`~yearMeans(C[, -1]/C[, -dims(C)$year])`
var(C)	T2	`~yearVars(C)`
var(F)	T3	`~yearVars(F)`
P(C < 0.1 MSY)	T4	`~yearSums(C < 0.1 * MSY)/length(C)`

5 Software implementation

Development of this work has been carried out using an open source code repository and collaboration platform, hosted at http://github.com/iotcwpm/ALB.

Operating model conditioning runs have been contacted using Stock Synthesis version 3.24U[1], running on a Linux 64-bit platform.

The `ioalbmse` package is based on the tools available in the FLR project (http://flr-project.org), that provides a collection of R packages for the development, application and testing of simulation models of fisheries systems (Kell et al. 2007). The whole set of packages used, except those directly available from the Comprehensive R Archive Netowkr (CRAN), are available at http://github.com/iotcwpm/R.

5.1 Software Versions

The following versions of R and R packages have been used for the model runs presented in this document:

- R version 3.3.1 (2016-06-21)
- FLCore: 2.6.0.20161024
- FLash: 2.5.99
- FLBRP: 2.5.20150204
- FLife: 1.1
- mse: 0.0.1.9003
- ggplotFL: 2.5.20161007
- ggplot2: 2.1.0
- ggstance: 0.2.9000
- data.table: 1.9.7

6 Results

Runs of the two management procedures presented before were conducted. First, some initial exploration runs covering a limited range of values for the input arguments in each MP. These attempt tp provide a first indication of the effect of those arguments in the capacity of each MP to manage the stock. Second, some initial robustness runs tested the effect of different levels of error in observation, estimation and implementation on the performance scores of each MP.

A third set would constitute the evaluation runs for each MP, that would then be used for a formal comparison of the performance of all MPs along a number of priority trade-offs. It is intended to carry out these runs based on the feedback from IOTC WPM on the results of the previous two sets. It would also incorporate any other MP the WPM would like to propose.

The management procedures should also be tuned to a set of management objectives, rank in order of preference. This would entail running the evaluation procedure for each MP for a large and fairly fine grid of input arguments and over different error scenarios. This is to be carried out once a set of objectives exist that are considered to be clear enough in their definition, levels of risk and time frame.

6.1 Initial exploration runs

A limited grid of MP argument values was used to explore the behaviour of both MPs when applied to the current OM.

[1] SS-V3.24U-fast;_08/29/2014;*Stock_Synthesis_by_Richard_Methot*(NOAA)_using_ADMB_11.2_Linux64

6.1.1 IRate

A total of 32 runs were carried out with the following values for various arguments:

- responsiveness=c(0.3, 0.9)
- hr_multiplier=c(0.4, 0.8)
- biomass_threshold=c(0.2, 0.4)
- biomass_limit=c(0.4, 0.6)
- maxTAC=c(3e5, 4e5)

while timing parameters were kept at single values, SFREQ=2, MLAG=2 and DLAG=2. Error levels were set as errcpue=~rnorm(mean=0, sd=cpue * 0.20) and effcpue=~0. Years for COUE reference levels were 1980 to 2010.

Figure 14 shows the time series of spawning biomass for a selection of six IRate MP runs. Similar results are shown for catch (Figure 15) and SB/SB_{MSY} (Figure 16).

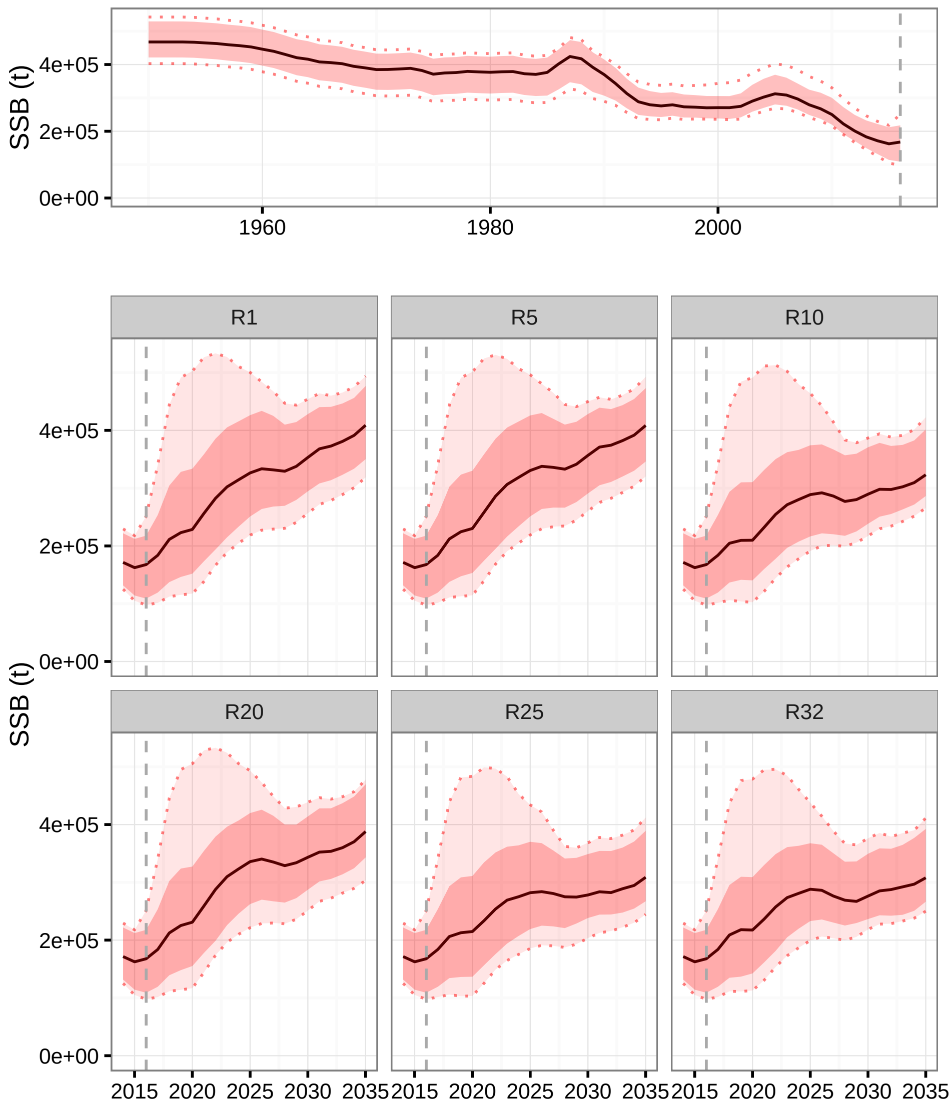

Figure 14: Trajectories of spawning biomass in the operating model (top panel) and from six runs of the IRate MP.

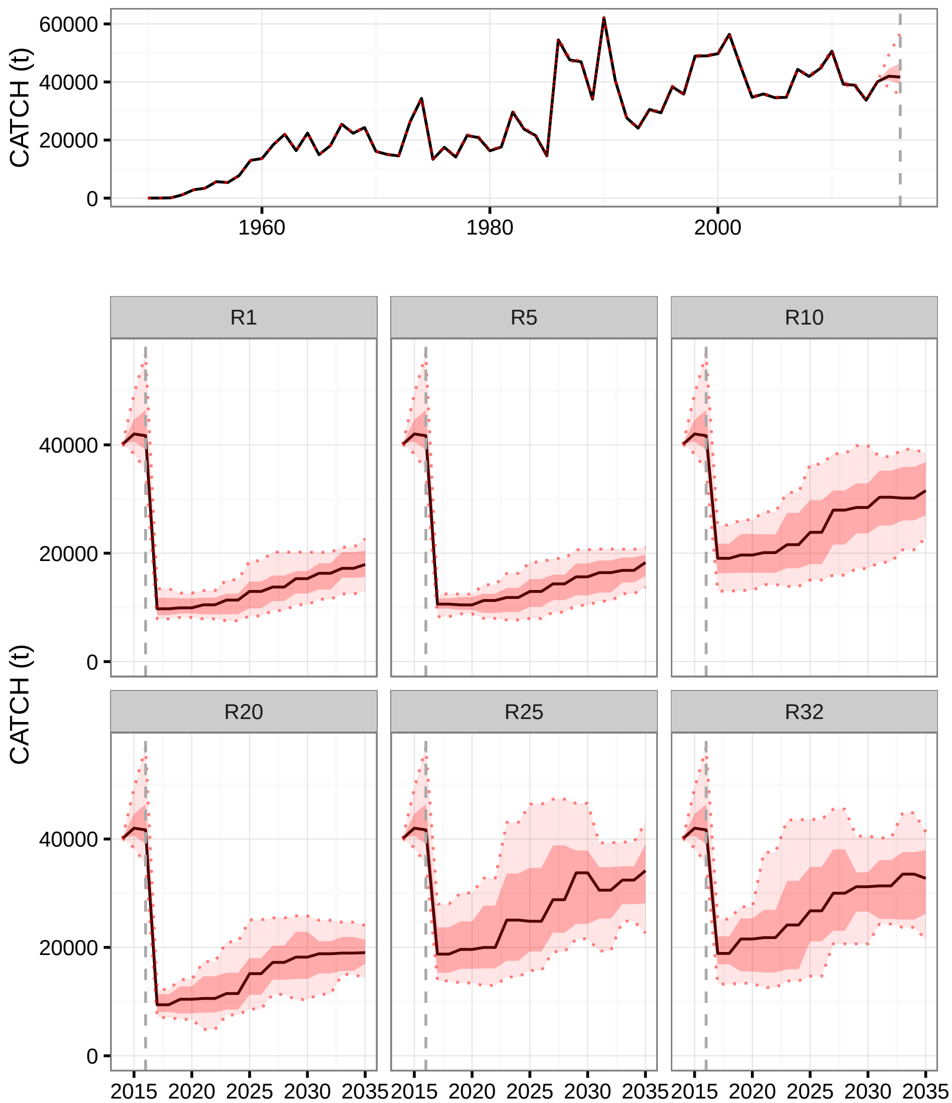

Figure 15: Trajectories of catch in the operating model (top panel) and from six runs of the IRate MP.

The results of the MP runs included in this exploratory set can be used to explore the trade-offs across different management objectives, but plotting the values across two selected performance indicators, in this case the mean spawner biomass relative to unfished in 2035 and the mean catch over the years of projection.

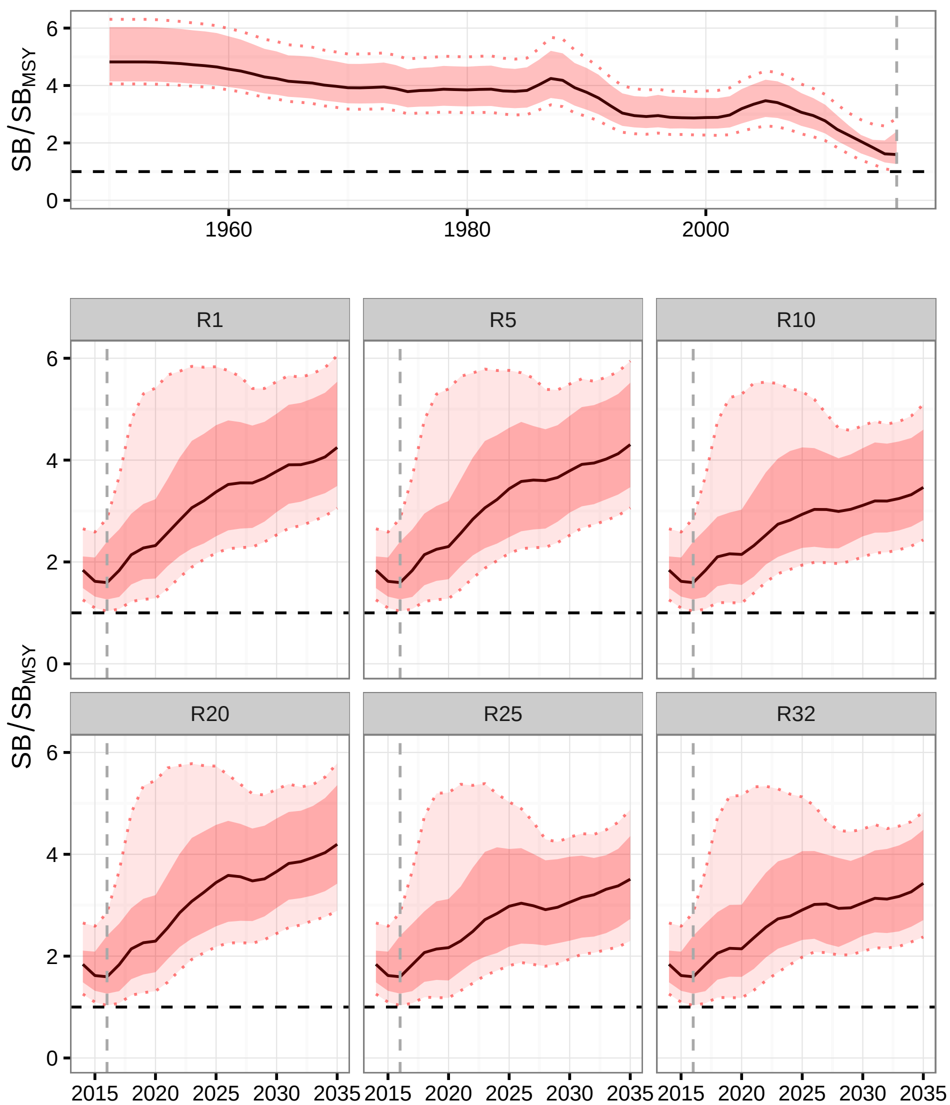

Figure 16: Trajectories of spawning biomass over the biomass at MSY in the operating model (top panel) and from six runs of the IRate MP.

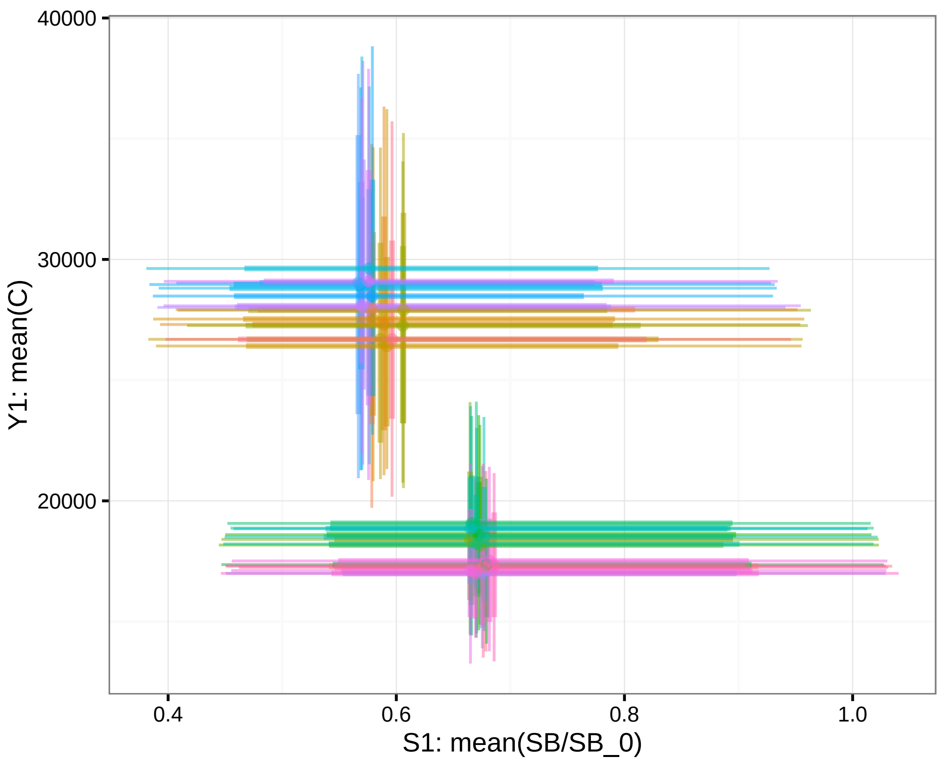

Figure 17: Trade-off plot for a set of runs of the IRate MP, and for two performance indicators: S1 (Mean spawner biomass relative to unfished), and T1 (Mean catch over years) in 2035

6.1.2 BRule

For the BRule MP, the exploratory runs included the following values for various input arguments:

- bthreshold=seq(0.8, 1.2, length=3)
- blim=seq(0.3, 0.6, length=2)
- SFREQ=seq(1, 3)
- DLAG=seq(1, 2)

while ftarget=refpts['FMSY'], bmsy=refpts['SBMSY'], MLAG=2, and errors were set at a zero level.

Figure 18 shows the time series of spawning biomass for a selection of six IRate MP runs. Similar results are shown for catch (Figure 19) and SB/SB_{MSY} (Figure 20).

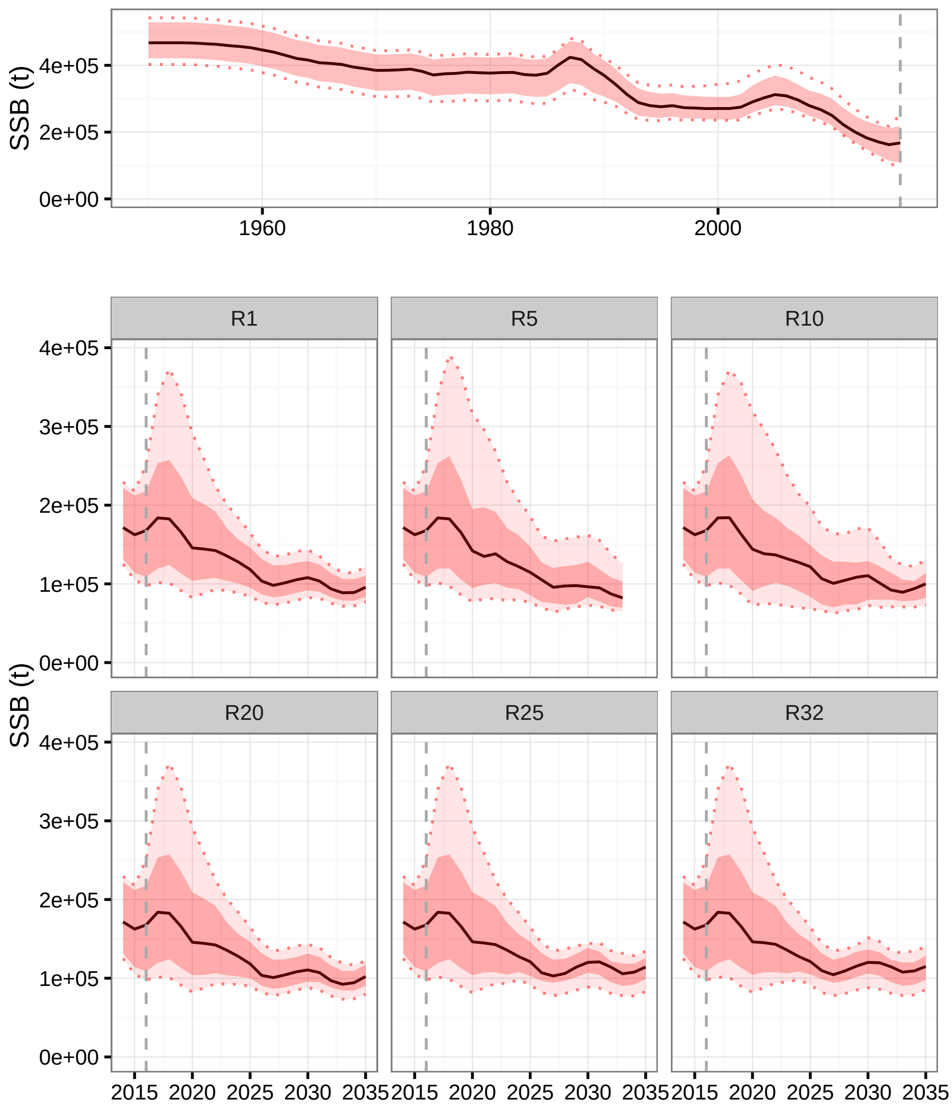

Figure 18: Trajectories of spawning biomass in the operating model (top panel) and from six runs of the BRule MP.

As before, the results of the MP runs included in this exploratory set can be used to explore the trade-offs across different management objectives, but plotting the values across two selected performance indicators, in this case the mean spawner biomass relative to unfished in 2035 and the mean catch over the years of projection.

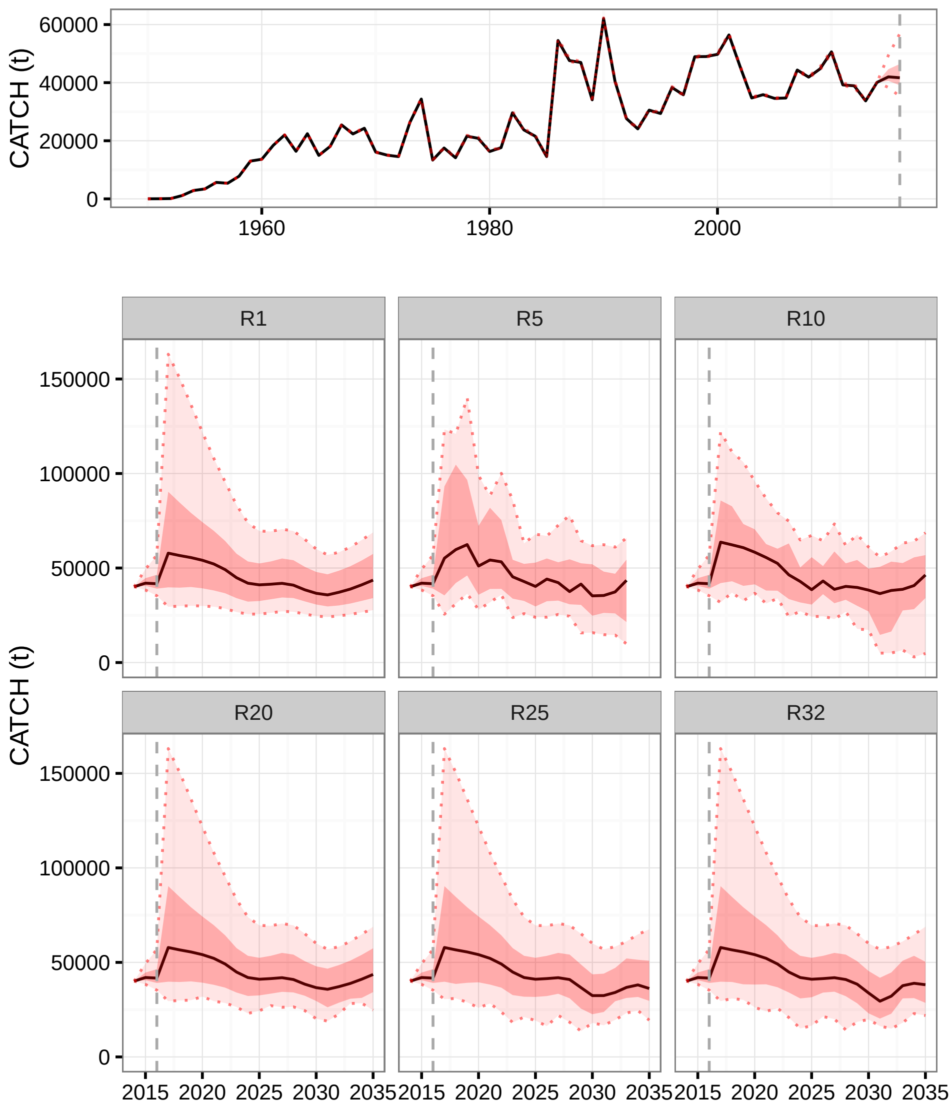

Figure 19: Trajectories of catch in the operating model (top panel) and from six runs of the BRule MP.

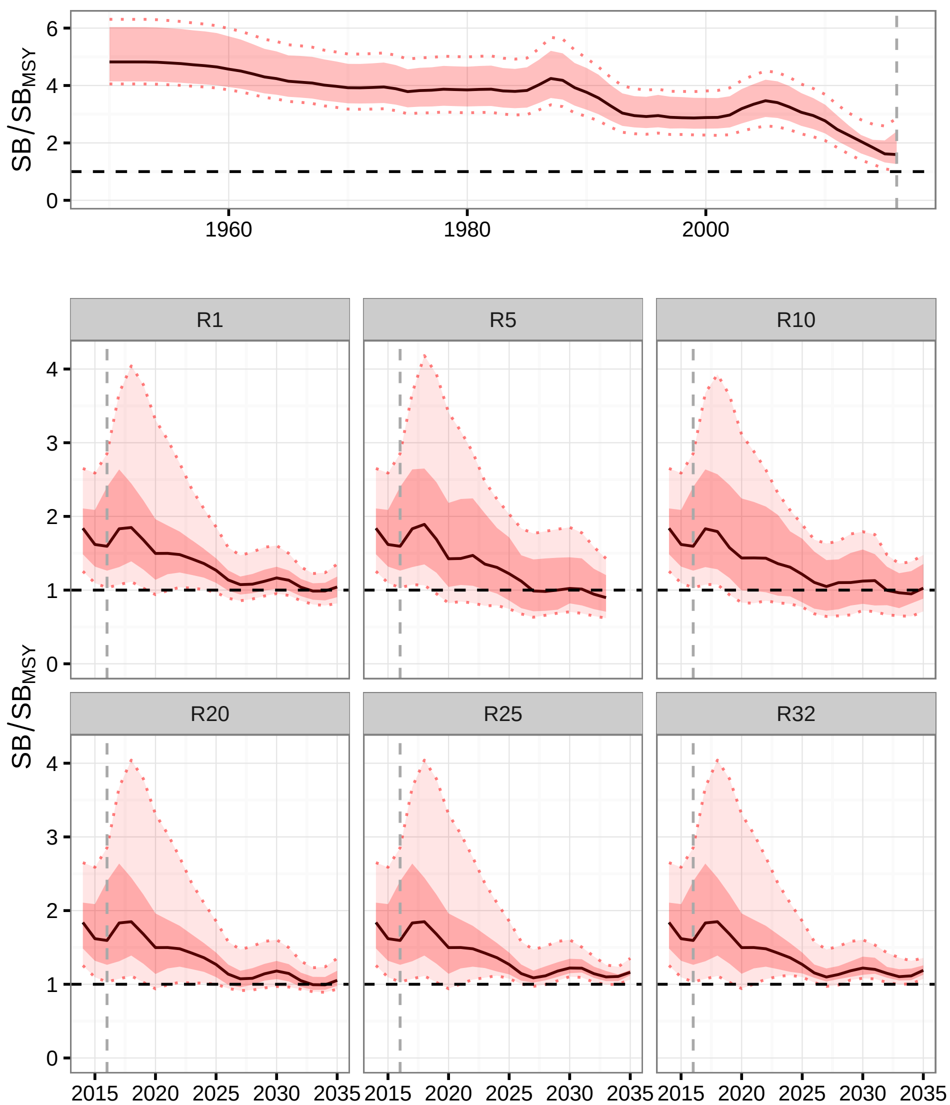

Figure 20: Trajectories of spawning biomass over the biomass at MSY in the operating model (top panel) and from six runs of the BRule MP.

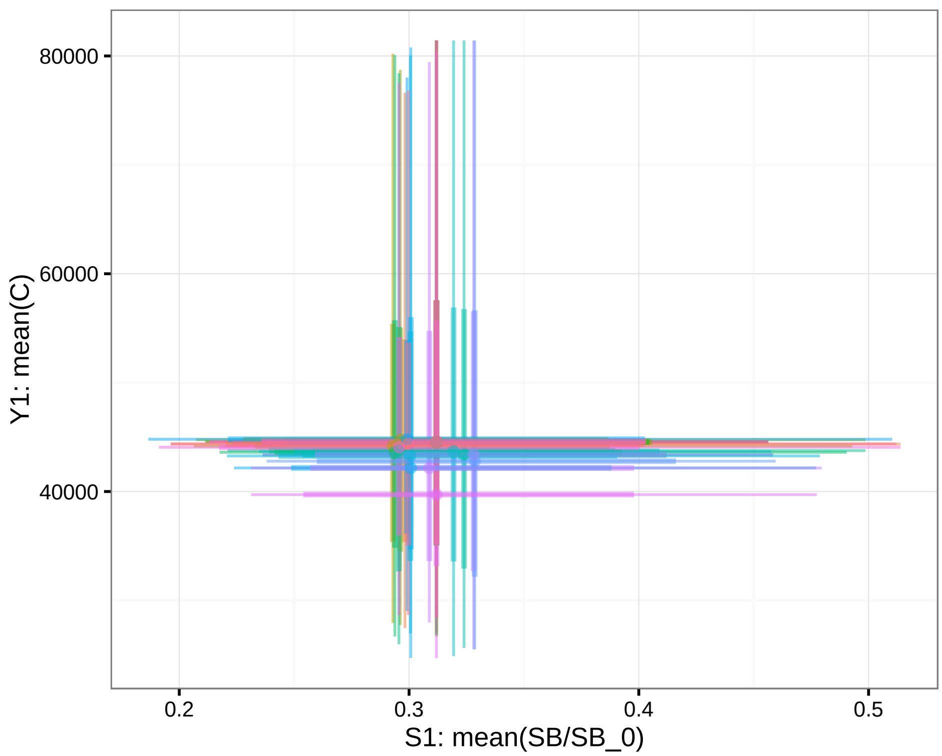

Figure 21: Trade-off plot for a set of runs of the BRule MP, and for two performance indicators: S1 (Mean spawner biomass relative to unfished), and T1 (Mean catch over years) in 2035

A combined trade-off plot for both MPs (Figure), appers to show a marlked difference in thwe approach that the two types of procedure are taking when applied to this stock in terms of conservation vs. exploitation. At this point this could be the results of errors in implementation rather than a natural feature of the MPs and should be further explored. The comparison should obnviosuly be extended to other trade-offs to better identify what factors might be behind this differences.

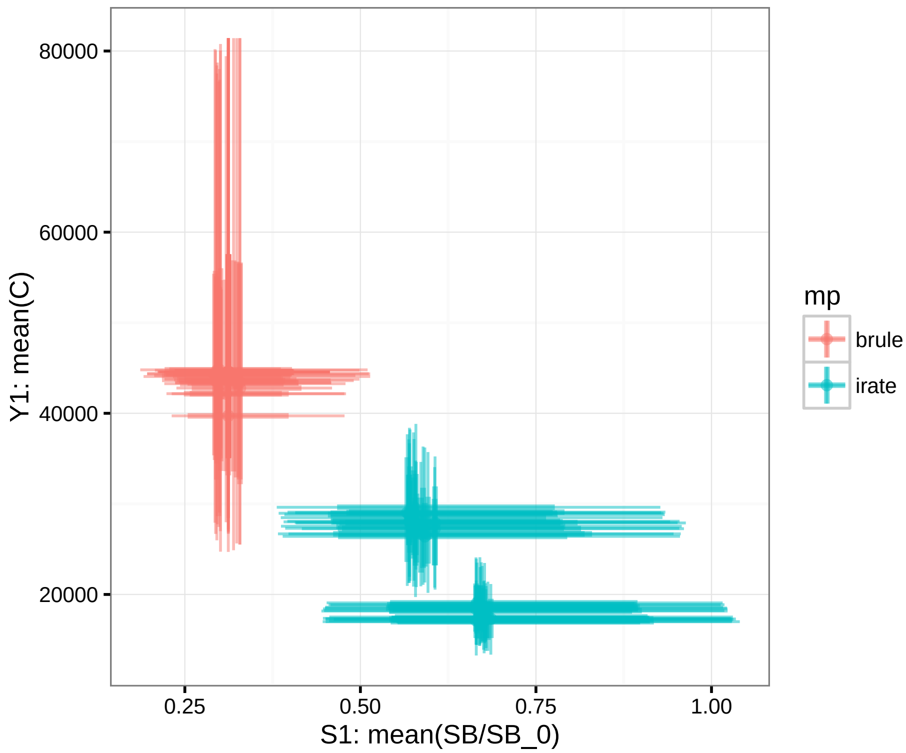

Figure 22: Trade-off plot for the exploratory runs for both MPs (IRate and BRule), and for two performance indicators: S1 (Mean spawner biomass relative to unfished), and T1 (Mean catch over years) in 2035

6.2 Robustness runs

An example set of some robustness runs can be found in Figure 23, for the BRule MP and different levels of error in the stock assessment estimate of vulnerable biomass. These are normaly-distributed errors with various CV levels.

7 Discussion

The work presented here is very much in progress, has been severely limited by the availability of time, and as such present a taste of the possible application to this stock that IOTC could use to generate more final advice. The code developed for this study has been made as flexible and extendable as possible, and should be able to accommodate the necessary improvements and changes WPM might suggest.

The operating model currently being used is still based on the previous stock assessment conducted by IOTC WPTmT in 2014. The comparison of the populations trajectories for the stock as determined by both the previous (IOTC 2014) and the most recent stock assessment (IOTC 2016), indicate that relatively minor changes in model parameters can have a large effect in the estimated population trajectories and productivity estimates.

Alternative management procedures should also be tested. CPUE-based MPs appear to be attractive for this stock given recent advances in the standardization of the longline CPUE series. A fuller understanding of the factors behind

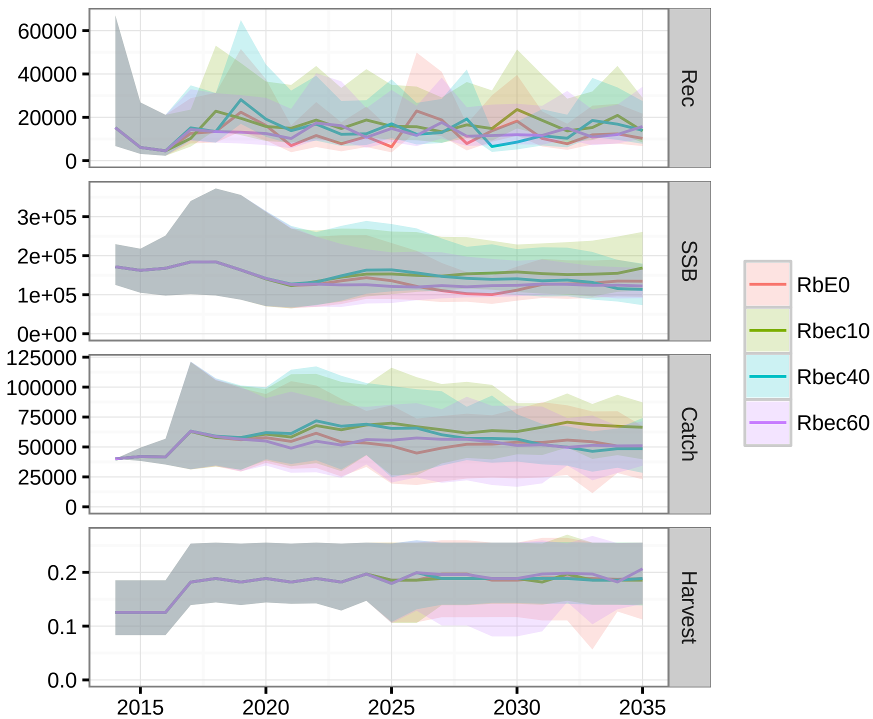

Figure 23: Robustness runs for the BRule MP with different levels of error (CV) in the estimation of vulnerable biomass, from 0.10 (Rbec10) to 0.60 (Rbec60).

different levels of error and bias in those series should lead to a more detailed exploration of their effect on the various MPs, but also on possible mechanisms to create series and HCRs that are more robust to those uncertainties.

Tuning of management procedures, to determine the set of MP and HCR arguments that lead to a better performance, can only be finalized once a clear set of ranked or weighted objectives has been agreed. The datasets already generated of values at different time steps for all performance indicators in Table **??** and across all proposed MPs could be quickly put to use once that decision is made.

A complete documentation of the code and implementation of every element in the simulations is being conducted, and a higher priority needs to be given to this important component of the work. Unfortunately, the existing limitations on time have so far relegated it.

8 Acknowledgements

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References

Arrizabalaga, Haritz, Florence Dufour, Laurence Kell, Gorka Merino, Leire Ibaibarriaga, Guillem Chust, Xabier Irigoien, et al. 2015. "Global Habitat Preferences of Commercially Valuable Tuna." *Deep Sea Research Part II: Topical Studies in Oceanography* 113: 102–12. doi:http://dx.doi.org/10.1016/j.dsr2.2014.07.001.

Bentley, Nokome, and M. Shiham Adam. 2015. "Management Strategy Evaluation for the Indian Ocean Skipjack Tuna." *IOTC WPM06, Montpellier, France, 23–27 November 2015* IOTC–2015–WPM06-09. http://iotc.org/sites/default/files/documents/2015/10/IOTC-2015-WPM06-09_-_SKJ_OM.pdf.

Hoyle, Simon D, Rishi Sharma, and Miguel Herrera. 2014. "Stock Assessment of Albacore Tuna in the Indian Ocean for 2014 Using Stock Synthesis." *IOTC WPTmT* WPTmT05–24_Rev1.

IATTC. 2014. "Summary of the Fishery and Assessments of the Major Stocks of Tuna Exploited in the Eastern Pacific Ocean." *Inter-American Tropical Tuna Commission. 89th Meeting. Guayaquil, Ecuador. 29 June-3 July 2015* DOCUMENT IATTC-89-04a. http://iotc.org/sites/default/files/documents/2014/12/IOTC-2014-WPM05-06-ALB-OM.pdf.

IOTC. 2014. "Report of the Fifth Session of the IOTC Working Party on Temperate Tunas." *IOTC WPTmT05, Busan (KR) 28-31 July 2014.* IOTC–2014–WPTmT05–R[E].

———. 2015a. "Report of the Eighteenth Session of the IOTC Scientific Committee." *IOTC SC18, Bali, Indonesia, 23–27 November 2015* IOTC–2015–SC18–R[E].

———. 2015b. "Report of the Sixth Session of the IOTC Working Party on Methods." *IOTC WPM06, Montpellier, France, 23–27 November 2015* IOTC–2015–WPM06–R[E].

———. 2016. "Report of the Sixth Session of the IOTC Working Party on Temperate Tunas." *IOTC WPTmT06, Shangai (CN), 18-21 July 2016.* IOTC–2016–WPTmT06–R[E].

Kell, L. T., I. Mosqueira, P. Grosjean, J-M. Fromentin, D. Garcia, R. Hillary, E. Jardim, et al. 2007. "FLR: An Open-Source Framework for the Evaluation and Development of Management Strategies." *ICES Journal of Marine Science: Journal Du Conseil* 64 (4): 640–46. doi:10.1093/icesjms/fsm012.

Langley, Adam, and Simon D Hoyle. 2016. "Stock Assessment of Albacore Tuna in the Indian Ocean Using Stock Synthesis." *IOTC WPTmT* IOTC-2016-WPTmT06–25.

Methot, Richard D, and Ian G Taylor. 2011. "Adjusting for Bias Due to Variability of Estimated Recruitments in Fishery Assessment Models." *Canadian Journal of Fisheries and Aquatic Sciences* 68 (10): 1744–60. doi:10.1139/f2011-092.

Methot, Richard D, and Chantell R Wetzel. 2013. "Stock Synthesis: A Biological and Statistical Framework for Fish Stock Assessment and Fishery Management." *Fisheries Research* 142. Elsevier: 86–99.

Mosqueira, I., and F. Scoot. 2015. "Operating Model for Indian Ocean Albacore Tuna." *IOTC WPM* IOTC-2014-WPM06-08. http://www.iotc.org/sites/default/files/documents/2015/10/IOTC-2015-WPM06-08_-_ALB_MSE.pdf.

Mosqueira, I., and R. Sharma. 2014. "Base Operating Model for Indian Ocean Albacore Tuna, Scenarios Included and Model Conditioning." *IOTC WPM* IOTC-2014-WPM05-06. http://iotc.org/sites/default/files/documents/2014/12/IOTC-2014-WPM05-06-ALB-OM.pdf.

Pepin, Pierre"Reconsidering the Impossible — Linking Environmental Drivers to Growth, Mortality, and Recruitment of Fish." *Canadian Journal of Fisheries and Aquatic Sciences* 0 (0): 1–11. doi:10.1139/cjfas-2015-0091.

R Core Team. 2015. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Simon, Jean-Marc AND Bonhommeau, Maximilien AND Fromentin. 2012. "Effects of Stochasticity in Early Life History on Steepness and Population Growth Rate Estimates: An Illustration on Atlantic Bluefin Tuna." *PLoS ONE* 7 (10). Public Library of Science: e48583. doi:10.1371/journal.pone.0048583.

Szuwalski, Cody S, Katyana A Vert-Pre, André E Punt, Trevor A Branch, and Ray Hilborn. 2014. "Examining Common Assumptions About Recruitment: A Meta-Analysis of Recruitment Dynamics for Worldwide Marine Fisheries." *Fish and Fisheries*, n/a–/a. doi:10.1111/faf.12083.