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Update on IOTC Yellowfin Tuna Management Strategy Evaluation Operating Model development Oct 2018

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Contents

1 Summary

This paper summarizes progress on the development of Operating Models (OMs) for IOTC yellowfin (YFT) tuna. MP evaluation updates for yellowfin and bigeye tunas are described in Kolody and Jumppanen (2018a). This paper builds on the work presented and reviewed at the IOTC informal MSE Working Group in March 2018 (Kolody and Jumppanen 2018d,e).

The latest version of the MSE software is publicly available from github, with a recently updated technical description and user manual (https://github.com/pjumppanen/niMSE-IO-BET-YFT/).The BET and YFT MSE projection software has undergone several changes in the past year, with a substantial rewrite to improve memory usage and parallel processing, which greatly improves MP evaluation speed. Most of these changes to the computational engine are not visible to the end user.

The proposed new reference case OM is derived from the 2016 assessment, starting from a balanced grid of 864 Stock Synthesis specifications, including all combinations of the following options:

- 3 X Beverton-Holt stock recruit relationship steepness
- 3 X Natural mortality vectors
- 2 X tag likelihood weighting
- 2 X CPUE standardization method
- 2 X CPUE catchability trend
- 2 X CPUE observation error assumptions
- 2 X catch-at-length sample size assumptions
- 3 X recruitment variance assumptions (σ_R)

Since the WPM informal MSE working group in March 2018, additional work was undertaken to improve the process for inspecting the plausibility of models within the grid. Following filtering of models for numerical convergence, and rerunning some models with relaxed parameter bounds, there were still a substantial number of models retained in the grid which exhibit very different inferences from the assessment which most would consider implausible. The majority of the problems are associated with estimated recruitment deviation trends that are suggestive of non-stationary production dynamics. The quality of the model fits to the CPUE and size composition data were not associated with the perceptions of plausible production dynamics in an obvious way. Models which excluded (highly down-weighted) the tags were generally more optimistic, and problematic in terms of estimating long-term declining recruitment trends. While tags generally constrain the model to a plausible parameter space, there are reasons to doubt the tag inferences (notably the slow rates of tag mixing that invalidate tag estimator assumptions). At the WPM informal MSE group meeting in March 2018, a new approach for the OM was proposed and debated. It involved i) expanding the grid of models with additional uncertainty dimensions (above), and ii) sampling the expanded grid (with replacement) to create an OM that has central tendencies for SB/SB(MSY) and MSY that are consistent with the assessment, but with CVs that are inflated by an arbitrary factor (to be determined by the broader IOTC MSE community). Results presented here assume a factor of 3 inflation of the variance relative to the inverse Hessian estimates from the reference case assessment model (CV ~ 13% for both quantities), and zero correlation. The sampling was conducted with equal representation of options within 2 dimensions - inclusion/exclusion of tags, and CPUE catchability trends of 0 and 1% per annum. While the approach was endorsed in principle by the WPM informal MSE group, we recognize that this is a potentially controversial approach that requires broader debate.

The proposed reference case OM (OMref18.1) is the subset of 685 models, each assigned a weighting factor from the stochastic sub-sampling approach. For the MP evaluations presented in the companion paper, this grid was sampled with replacement to attain 250 realizations. Key projection assumptions are unchanged from previous iterations:

- Initial population states (with added error) and most parameters defined by the SS specifications
- stationary selectivity for all fleets
- CPUE CV = 0.3 (quarterly, autocorrelation = 0.5)
- quarterly recruitment CV = 0.6 (quarterly, auto-correlation = 0.5)
- first TAC implemented in 2019; bridging catches 2016:2018 = 413Kt (2016 level)
- catch implementation error CV = 0

Further considerations on CPUE observation error and recruitment variability for projections are discussed. Two robustness scenario OMs are proposed (with MP evaluation results presented in the companion paper).

2 Introduction

The Indian Ocean Tuna Commission has committed to a path of using Management Strategy Evaluation (MSE) to meet its obligations for adopting the precautionary approach. IOTC Resolution 12/01 *"On the implementation of the precautionary approach"* identifies the need for fishery reference points and harvest strategies that will help to maintain the stock status at a level that is consistent with the reference points. Resolution 13/10 "*On interim target and limit reference points and a decision framework*" identified interim reference points and elaborated on the need to formulate management measures relative to the reference points, using MSE to evaluate harvest strategies in recognition of the various sources of uncertainty in the system. Resolution 15/10 supersedes 13/10 with a renewed mandate for the Scientific Committee to evaluate the performance of harvest control rules with respect to the species-specific interim target and limit reference points, no later than 10 years following the adoption of the reference points, for consideration of the Commission and their eventual adoption. A species-specific workplan was re-affirmed at the 2017 Commission Meeting, outlining the steps required to adopt simulation-tested Management Procedures for the highest priority species (IOTC 2017). Recognizing the iterative nature of the MSE process, the workplan identifies 2019 as the earliest possible date for MP adoption.

This paper describes i) the assumptions used for conditioning the proposed new reference case OM, ii) the process used to evaluate and reject or retain the models within the OM ensemble and the proposed sampling procedure to create the final ensemble, iii) general characteristics of the final ensemble, iv) additional considerations for projection assumptions, and v) some robustness scenario OMs (which were used to test MPs in Kolody and Jumppanen 2018a). Considerations for the next iteration of the MSE process are presented for feedback from the IOTC WPM and WPTT.

This paper assumes familiarity with fairly technical subject matter. More detailed explanations can be found in Kolody and Jumppanen (2016), Jumppanen and Kolody (2018) and various progress reports produced since the last YFT MSE update to the WPTT and WPM (Kolody and Jumppanen 2018a,b,c,d,e,f).

3 Yellowfin Reference Case OM Conditioning

3.1 Relationship between the stock assessment and Operating Models

The intention has always been to maintain a close relationship between the stock assessment modelling and the conditioning of OMs. The two processes are analogous in several respects, i.e. similar population dynamics models are fit to the same data, subject to the same concerns about model formulation and assumption violations, etc. It would be difficult to justify the two initiatives evolving in different directions from the same scientific process. Accordingly, the yellowfin assessment of Langley (2016) provides the core of the OM conditioning process. Key features of the assessment and OM include:

- Parameter estimation with Stock Synthesis 3.24z software
- 4 regions (Figure 1)
- Quarterly dynamics, including recruitment and movement (implemented with calendar quarters as SS-model-years)
- 25 fisheries (21 with some temporal variation handled as independent fisheries)
- Parameter estimation objective function includes
    - Total catch
    - Standardized longline CPUE (one series per region)
    - Size composition data
    - Tags (down-weighted to be essentially excluded in some OM scenarios)
    - Recruitment penalties on deviations from stock recruit relationship and mean spatial distribution
- Estimated parameters:
    - Fishery selectivity (various functional forms, parameters shared among some fleets)
    - Longline catchability (in aggregate - regional scaling factors are used to scale relative density to relative abundance among regions)
    - Virgin recruitment
    - Recruitment deviations from the Beverton-Holt stock-recruit relationship, recruitment spatial partitioning among tropical regions (1 and 4) and deviations from the mean spatial distribution.
    - Juvenile and adult movement rates
    - Initial fishing mortality

One structural difference between the yellowfin assessment and the OM models relates to seasonality in movement. The assessment linked migration rates to environmental indices. This would add an additional complication for the OM, because it would require projections of environmental indices (or the net effect of environmental indices). It also remains unclear whether these indices were really helpful for the assessment in disentangling seasonal movement from catchability. The assessment inferences were not substantively changed when this extra complexity was removed. If this approach is explored in the future, we would recommend testing whether inter-annual variability associated with real environmental indices has any explanatory power over and above fixed seasonal effects.

Relative to the traditional stock assessment, OM conditioning has an increased emphasis on uncertainty quantification and projections required to develop robust feedback-based MPs through the MSE process. The reference set OM is an ensemble of assessment models that includes several alternative plausible assumptions. The approach to uncertainty quantification adopted here is similar to that used in the CCSBT, in which the emphasis is on model structural uncertainty (including parameters about which the data are expected to be uninformative), and stochastic recruitment uncertainty (and observation error) in the projections. The Maximum Posterior Density Estimates (best point estimates) for the individual models are collated, with the expectation that the uncertainty among point estimates will generally be greater than the parameter estimation uncertainty conditional on any individual model. Once an adequate OM has been defined, it should not need to be updated with the frequency expected for the traditional stock assessment process. Unless new evidence emerges to indicate that the uncertainty encompassed by the OM no longer captures reality, we would hope that an MP would remain valid for something on the order of 5-10 years (i.e. until the next thorough MP review scheduled as part of the adoption process).

Robustness OMs are generally considered less likely than the reference set, but they are defined to represent plausible, troublesome situations, that may help identify pathological MP behaviour in particular circumstances, and assist in choosing among MPs that are otherwise equivalent. An MP cannot be expected to be robust to every imaginable outcome (attempting to do so would likely result in an extremely conservative MP and considerable lost economic opportunity). Carl Walters famously uses the term "vampires in the basement" to describe serious and unanticipated events which undermine ecological models. Because these types of events are unavoidable, a normal part of the MP approach involves regular oversight (e.g. simple analyses to determine if "exceptional circumstances" have arisen which render the MP inappropriate, at least temporarily), and a scheduled review period, at which point a detailed evaluation should determine if the MP testing remains valid, and whether there have been other changes in circumstance, e.g. changing Commission objectives, new assessment tools, etc.

For the purposes of this paper, we refer to a number of individual models, OM ensembles, and option abbreviations as defined in Table 1 and Table 2.

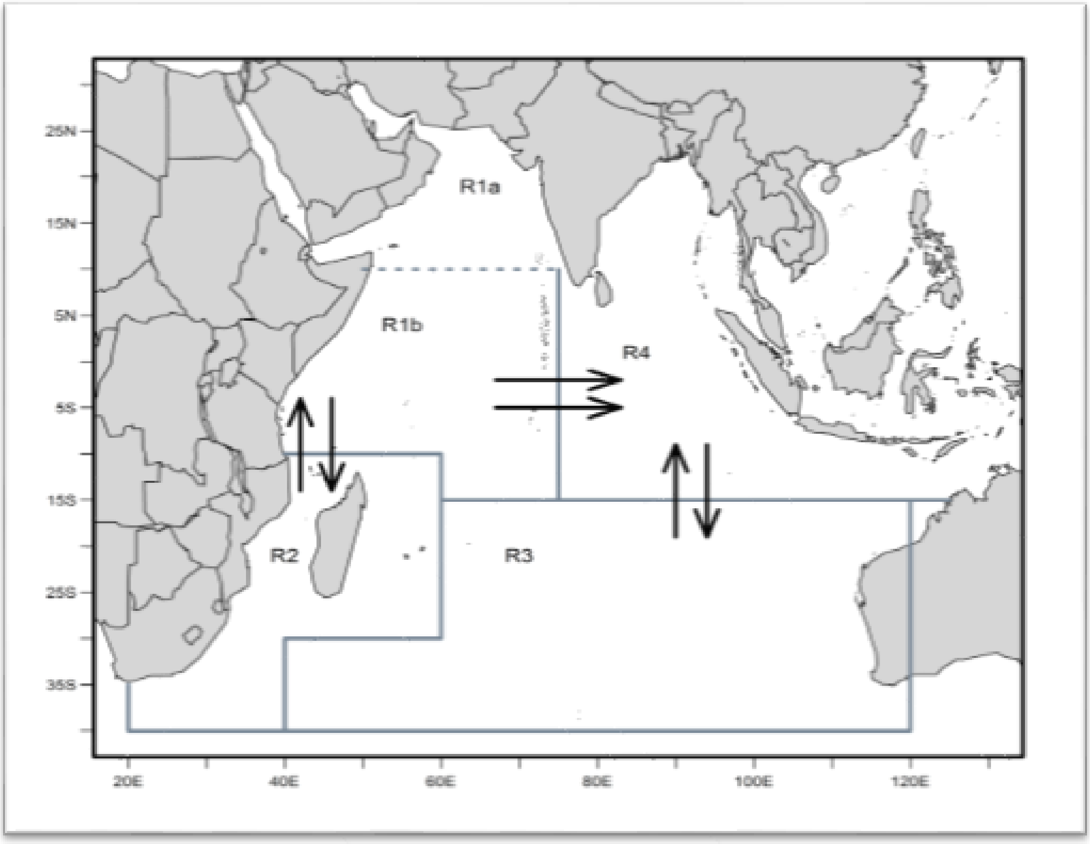


Figure 1. Spatial structure for yellowfin tuna assessment and all OMs discussed in this report (figure from Langley 2015).

Table 1. Yellowfin reference case and robustness case Model and OM ensemble definitions (current and historical).

Model Name	Definition (assumption abbreviations are defined in Table 2)
OMrefY1	Reference case OM as proposed by the WPM and WPTT in 2016, reviewed in WPM and WPTT 2017. Consists of an ensemble of 216 models, each differing from the stock assessment in 1-6 assumptions. This unweighted OM included many implausible models (commonly related to recruitment time series trends) h70, h80, h90 M10, M08, M06 t00, t01, t10 q0, q1 iH, iC x3, x8
OMgridY17.2	Unweighted combination 693 models from an ad hoc mix of grids with and without tags (models with poor convergence removed).
OMrefY17.2	Reference case OM, proposed by the authors for feedback at the 2018 IOTC informal MSE meeting (Kolody and Jumppanen 2018e). It consisted of ~300 SS specifications, sampled from 2 unbalanced OM grids (with and without tags). Sampling of the two grids was conducted to achieve a balanced combination of the following options (representation of the other grid options is generally not proportional to the original grid assumptions): t10, t0001 q0, q1
OMgridY18.1	The reference case grid. It builds on the approach of OMref17.2, but includes a more balanced initial grid of 864 models, with one round of relaxing bounds constraints; 684 models were retained after removing convergence failures and second iteration bounds problems h70, h80, h90 M10, M08, M06 t0001, t10 q0, q1 iH, iC, i10H, i10C ESS5, CLRW

	*note that the tag mixing options x3 and x8 were intended to be included in this grid (with option t10), but x8 was inadvertently excluded.
OMrefY18.1	The reference case proposed in the current paper. OMgrid18.1 was randomly sampled to attain reasonable consistency with the central tendency of the assessment (as discussed in the text). Sampling was achieved with a balanced combination of tag weighting (t10, t0001) and catchability (q0, q1) options, but no constraints on the other grid assumption options.
OMrobY18.1.recShock	Robustness scenario OM with 8 consecutive quarters of poor recruitment (55% of expected values, similar to estimates for YFT in the early 2000s). (conditioning unchanged from OMrefY18.1)
OMrobY18.1.impErrCV10	Robustness scenario OM in which each fishery has a 40% catch implementation error CV (independent by year and fishery). This corresponds to an annual aggregate CV >10%. (conditioning unchanged from OMrefY18.1)
OMrobY18.1.under	Robustness scenario OM in which TACs are ignored for 10 years (fishing mortality constant at current levels) before the TAC is taken without error (conditioning unchanged from OMrefY18.1)
OMrobY18.1.over	Robustness scenario OM with consistent 10% overcatch for all fleets (catch is accurately reported) (conditioning unchanged from OMrefY18.1)
OMrobY18.1.qTrend3	Robustness scenario OM with longline CPUE catchability trend of 3% per year in projections (conditioning unchanged from OMrefY18.1)

Table 2. Model assumption option abbreviations (as used in the text and figures). Bold indicates the assessment base case assumption. Some abbreviations may relate to explorations that have not yet been examined, or are not reported in the current document.

Abbreviation	Definition
	Stock-recruit function (*h* = steepness)
h70	Beverton-Holt, *h* = 0.7
h80	**Beverton-Holt, *h* = 0.8**
h90	Beverton-Holt, *h* = 0.9
Rh70	Ricker, *h* = 0.7
Rh80	Ricker, *h* = 0.8
Rh90	Ricker, *h* = 0.9
	Recruitment deviation penalty
sr4	σ_R = 0.4
sr6	**σ_R = 0.6**
sr8	σ_R = 0.8
	Future recruit failure
r55	3 years of poor recruitment (2019-21 proposed by the authors); deviation of -0.55 (consistent with SA-base estimates in the early 2000s), applied on top of the usual random deviate)
	Natural mortality multiplier relative to SA-base
M10	**1.0**
M08	0.8
M06	0.6
	Tag recapture data weighting (tag composition and negative binomial)
t00	λ = 0
t0001	λ = 0.001
t001	λ = 0.01
t01	λ = 0.1
t10	**λ = 1.0**
t15	λ = 1.5
	Assumed longline CPUE catchability trend (compounded)
q0	**0% per annum**
q1	1% per annum
q3	3% per annum
q5	5% per annum
	Tropical CPUE standardization method (error assumption for all series)
iH	**Hooks Between Floats (σ_{CPUE} = 0.3)**
i10H	Hooks Between Floats (σ_{CPUE} = 0.1)
iC	Cluster analysis (σ_{CPUE} = 0.3)
i10C	Cluster analysis (σ_{CPUE} = 0.1)
	Tag mixing period
x3	**3 quarters**

x8	8 quarters
	Longline selectivity
SS	**Stationary, logistic, shared among areas**
S4	LL selectivity independent among areas
NS	Temporal variability estimated in 10 year blocks
ST	Logistic selectivity trend estimated over time
Sdev	15 years of selectivity deviations estimated (most recent years)
Sspl	Cubic spline function (to admit possibility of dome-shape)
	Size composition input Effective Sample Sizes (ESS)
ESS2	ESS = 2, all fisheries
ESS5	**ESS = 5, all fisheries**
CLRW	ESS = One iteration of re-weighting; the output ESS from the reference case assessment analogue (fishery-specific, mean over time), capped at 100.

4 MSE software developments

The latest version of the MSE software is publicly available from github, with a recently updated technical description and user manual (https://github.com/pjumppanen/niMSE-IO-BET-YFT/).The BET and YFT MSE projection software has undergone several changes in the past year, with a substantial rewrite to improve memory usage and parallel processing, which greatly improves MP evaluation speed. Most of these changes to the computational engine are not visible to the end user. Modifications that are relevant for the user include:

- Software for producing TCMP standard graphics and tables has been updated.
- There is improved functionality for MP tuning, and simplified organization of access to parameters of tuned MPs.
- The C++ projection algorithm now accepts an argument that sets the maximum fishing mortality for a fishery. This option was added to explore and evaluate how sensitive MP evaluation and selection decisions are to this numerical assumption, and compare differences between R and C++ implementations. Constraints to the maximum F were only expected to be required in rare circumstances, however the YFT simulations suggest that these situations might be common for some fisheries (e.g. longline), but not necessarily others (e.g. purse seine FAD sets). This is discussed further below.
- An optional argument to impose a time series of recruitment multipliers has been added to facilitate recruitment failure robustness scenarios.
- An optional argument to impose a time series of catch/effort multipliers has been added to facilitate robustness scenarios with time series structure in implementation error. The approach was originally intended to address the BET situation, in which it appears that the stock could sustain higher catches than are currently being realized. Thus it seems likely that the TAC may be systematically under-caught, and the MP should be robust to a sudden change in fishing incentives if historical catches and TACs become disconnected in the MP recommendations.

5 OMgridY18.1 and OMrefY18.1: Proposal for the conditioned YFT reference set OM

5.1 A proposed approach and specification for the YFT reference OM

The path for proposing a new YFT reference set OM involved a circuitous exploration of many model assumptions and their interactions, in a number of grids, some of which are defined in Table 1 and Table 2. Additional details are provided in Kolody and Jumppanen (2018e). The approach proposed here builds on the proposal and recommendations of the IOTC MWP informal MSE meeting in March 2018. Specific items that required more attention at that time included:

- Make a properly balanced grid ensemble. OMgridY18.1 (Table 1) supersedes the ad hoc combination of grids that were merged in March 2018 (OMgridY17.2).
- Improve the process for evaluating model plausibility. This was attempted with a more systematic approach to evaluating convergence criteria and identifying parameters on bounds (along with the usual qualitative inspection of quality of fit to data indicators). This did not resolve the fundamental problem that the YFT data appear to be consistent with stock status inferences that are generally considered to be implausible. Furthermore, conducting the inverse Hessian calculations proved to be very time-consuming, as some specifications took more than 24 hours to finish. Running the grid on a cluster with 50 cores made the calculations possible, but further developments should consider cleverness rather than brute force. Some unexplained errors were introduced in a few cases, possibly due to network interruptions, but these are not expected to change the general character of the proposed OM. For future iterations, it appears that the gradient criteria is closely related to and usually more stringent than the Hessian criterion, such that the latter might not be required if computational time is an issue.

High level characteristics of OMgrid18.1 are shown in Figure 2. The unweighted grid OMgrid18.1 suffers from the same plausibility concerns as earlier unweighted grids. The recent efforts to deal with parameters on bounds and convergence criteria did not resolve the fundamental problem. The unweighted grid supports a very large range of MSY estimates and this is associated with a strong negative recruitment deviation trend (Figure 3). Figure 4 illustrates the relationship among various stock status indicators, quality of fit to data indicators, and model assumptions. From the diagnostics examined, there is no obvious inconsistency between the models and CPUE and CL observations that would identify the implausible models. Inclusion of the tags does constrain the models considerably, however, given the concerns about tag mixing, we are reluctant to put complete faith in the tags in the current model structure.

Accordingly, we propose OMref18.1, which consists of OMgrid18.1 subject to:

- Rejecting models that fail the plausibility criteria including i) Hessian matrix not positive definite (rare, and possibly related to occasional network failures when running the grid) and ii) maximum gradient of the objective function with respect to the parameters > 0.01 (the arbitrary standard adopted for ALB and BET).

- Stochastic sampling (with replacement) of OMgrid18.1 to attain a mean distribution of SB(current)/SB(MSY) and MSY point estimates that are consistent with the assessment, but with CVs that are inflated by an arbitrary factor (to be debated by the broader IOTC scientific community). Results presented here assume a factor of 3 inflation of the variance relative to the inverse Hessian estimates from the reference case assessment model (CV ~ 13% for both quantities), and zero correlation. The sampling was conducted with equal representation of options within 2 dimensions - inclusion/exclusion of tags, and CPUE catchability trends of 0 and 1% per annum.

The high level characteristics (Figure 5) and recruitment trends (Figure 6) of OMref18.1 are (not surprisingly) much more consistent with the assessment than the unweighted grid, and the appropriateness of the grid sampling variance needs to be considered. The median MSY is in line with the assessment (Figure 7), while median depletion is slightly more optimistic (Figure 8, Figure 9). From Figure 5, it is evident that steepness sampling was relatively evenly represented across all levels (in aggregate, not necessarily with respect to the tag, LL catchability or other dimensions in the grid, since there could be complicated interactions). The sampling also resulted in reasonably even representation of the CPUE and size composition weighting options. The intermediate M assumption was clearly preferred, as were the lower recruitment variability options. It is perhaps noteworthy that the intermediate M assumption was not included in the 2016 assessment (the high value was the preferred assumption, while the low value was supported by the tags and considered to be a lower plausible bound by the assessment analyst and WPTT). Other characteristics of OMgrid18.1 and OMref18.1 are compared in Figure 7 - Figure 14.

The tag weighting option T01 (tag likelihood down-weighting by a factor of 0.1, which was included in the assessment exploration and used in the previous OM iteration), was intentionally omitted to reduce the number of dimensions in OMgridY18.1. The 8 quarter tag mixing period option (x8) was inadvertently omitted. As a consequence of the reduced tag assumptions, the tag options are more polarized, i.e. we either have a lot of confidence in the tags, or no confidence. Given that the distribution of OMrefY18.1 inferences and diagnostics (e.g. Figure 7 - Figure 14) are not strongly bimodal as a result (except for the tag likelihood), it is not obvious that additional intermediate tag options would add any new and interesting uncertainty to the grid.

The Catch-at-Length weighting option CLRW is new in this OM iteration, and is worth further consideration. The option is essentially assigning an assumed effective sample size for the size composition data equal to the value estimated from the quality of fit observed from fitting the assessment (up to a maximum of 100). This value is often much higher than the value input to the assessment (uniformly 5), and there is a risk that over-weighting the CL data (with the assumption of stationary selectivity) erodes the fit to the CPUE data (which is generally considered to be more informative in an assessment). This certainly happens to some degree. The intent was not to assert that we believe the CLRW assumption (nor that iterative re-weighting is necessarily a good approach in general). Rather it was intended to introduce more variability in the relative weighting of the different data sources. Given that the relative quality of fit to the size data is fairly robust among all the model options considered (Figure 13), we would not expect this approach to have an unreasonable impact on the models.

The grid-sampling approach is successful for providing OM results that seem plausible, however it is not ideal, and we repeat the pros and cons from Kolody and Jumppanen (2018e) here. We recognize that it may seem like a subjective and somewhat backward process for deriving the reference case OM. We would normally hope that the data provide useful inferences about stock status and productivity, not that we would be selecting models on the basis of our preconceived notions about stock status and productivity. But the data do not appear to be as informative as we would hope. It is perhaps more intellectually honest to explicitly admit that we are using these perceptions as a guide to plausibility in this case, rather than invoking convoluted lines of reasoning that are attempting to achieve the same outcome via an indirect route. Our approach has some resemblance to the approaches suggested by Martell et al (2008), in which they propose re-framing the stock assessment question, so that management quantities of interest (including MSY) are defined as leading variables in the assessment models, with priors.

We note the following points for OMrefY18.1:

- Relative to OMrefY1 (the original 2016 OM proposal), the expanded model options in OMgridY18.1 add additional diversity and smooth out the OM stock status distributions. Notably, the ensemble identifies plausible models that do not depend on the tagging data, and hence may introduce more variability to challenge the MPs. These models were all reasonably consistent with the CPUE and size composition data.
- The bivariate OM sampling approach is a transparent admission that we are relying on the central tendencies of MSY and B/BMSY from the stock assessment process as explicit criteria for defining the OM. This seems to imply that one (or a couple) assessment models (despite some recognized shortcomings) provides more assessment insight than the hundreds of models explored for the OM. However, we would express the situation differently - both the assessment and the OM exploration indicated that the data are not as informative as we would hope, and were largely consistent with a large range of inferences. The OM did not provide obvious evidence for rejecting the point estimates of the assessment (and uncertainty in the assessment is always admitted to be problematic to quantify). By adopting key assessment inferences as an anchor, the proposed OM recognizes the collective "wisdom of the crowd", the IOTC WPTT community (for better or worse), including their deliberations and subjective perceptions (e.g. that the yellowfin population is probably near full exploitation, and recent catches were probably near MSY). We consider it likely that these sorts of considerations often influence complicated assessment model results, whether or not they are explicitly articulated.
- Explicitly sampling with respect to SSB/SSBMSY maintains a level of consistency with the assessment reference points, and tuning objectives defined for MP performance evaluation and eventual selection.
- MSY-based sampling addresses one of the most obvious sources of model implausibility in the OM grids (unrealistic MSY and the related issue of production dynamics that are not consistent with standard assumptions of tuna recruitment compensation, and/or stationarity in the stock recruit relationship).
- OMrefY18.1 admits far more uncertainty than the assessment, both in terms of the magnitude of the stock status variance, and the structural diversity introduced through

alternative assumptions. By defining the uncertainty relative to the assessment it provides a convenient framework for communication and reproducibility. e.g. If the WPTT/WPM agrees that a certain CV is appropriate, it can be reproduced despite other changes in the OM grid that might be requested in parallel, and which could skew the central tendency in unexpected ways. It remains a topic for broader discussion as to whether we have "enough" (or too much) uncertainty within OMrefY18.1, but this can be easily adjusted using the current approach. By coincidence, the OMrefY18.1 CVs were very similar to the reported 2016 BET assessment CVs (which were derived from a small grid of models).

- The sampling approach allows a limited number of dimensions of the grid to be sampled in pre-specified proportions. However, this is not perfect, and can only be achieved with a relatively small subset of dimensions (because of the potentially incompatible interactions among some assumptions). We proposed that inclusion/exclusion of tags and CPUE catchability trends are the most important priorities for equal weighting.

Figure 15 shows the dynamics of OMref18.1 with constant catch projections (fishing moratorium and recent current catches of 413Kt). The OM predicts that the stock would recover to unfished levels by 2030 if the fishery stopped with higher variance than observed historically. Constant current catch projections suggest that almost half of the scenarios will exceed the biomass limit reference point by 2040 and more than half of scenarios would fail to remove the current quota starting in the early 2020s. With current catch projections, the assessment K2MSM reported P(SB2018 < SBMSY) = 88% and P(B2025 < BMSY) = 100%, while the OMref18.1 indicates 50% <P(SB2018 < SBMSY) < 75% for both dates. This suggests that the OM is consistent with what one would expect if the OM has higher variability (as intended). Projections for both the assessment and the OM run into numerical limits in this case, due to the very high exploitation rates required to sustain these catches.

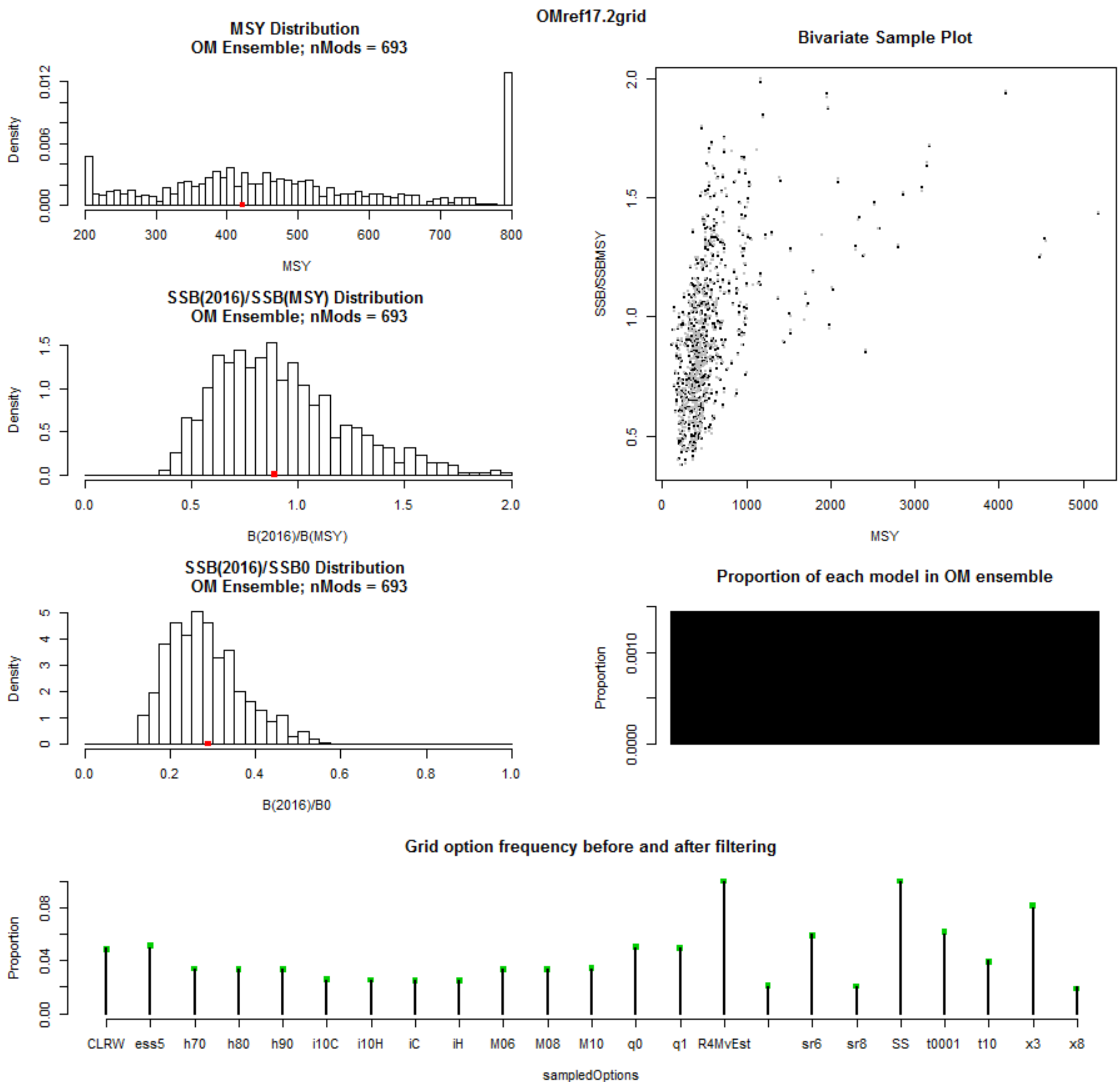


Figure 2. Characteristics of OMgrid18.1 (after filtering for convergence and parameters on bounds problems), the 685 model, uniformly weighted ensemble from which OMrefY18.1 is sampled. Red points indicate the point estimates from the 2016 assessment. The middle right panel indicates the relative frequency of the models sampled (i.e. uniform sampling in this case). The bottom panel indicates the relative proportion of the individual assumptions in the ensemble (green points) relative to the original grid (black lines), i.e. identical in this case. MSY values < 200 Kt and > 800Kt are aggregated at the bounds of the histogram.

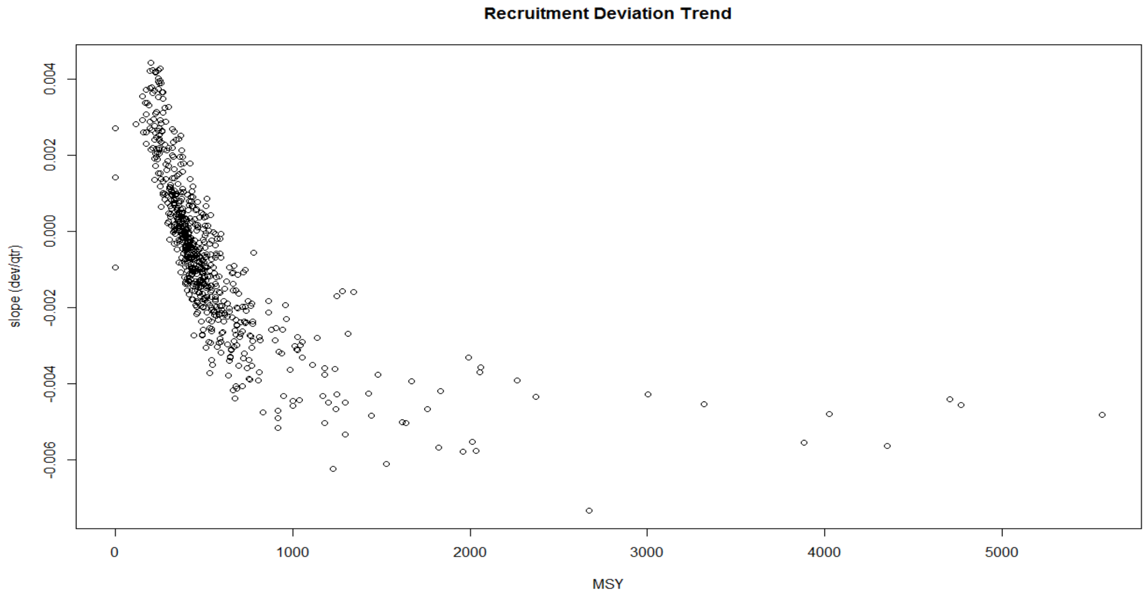


Figure 3. OMgridY18.1 relationship between MSY and the recruitment deviation trend.

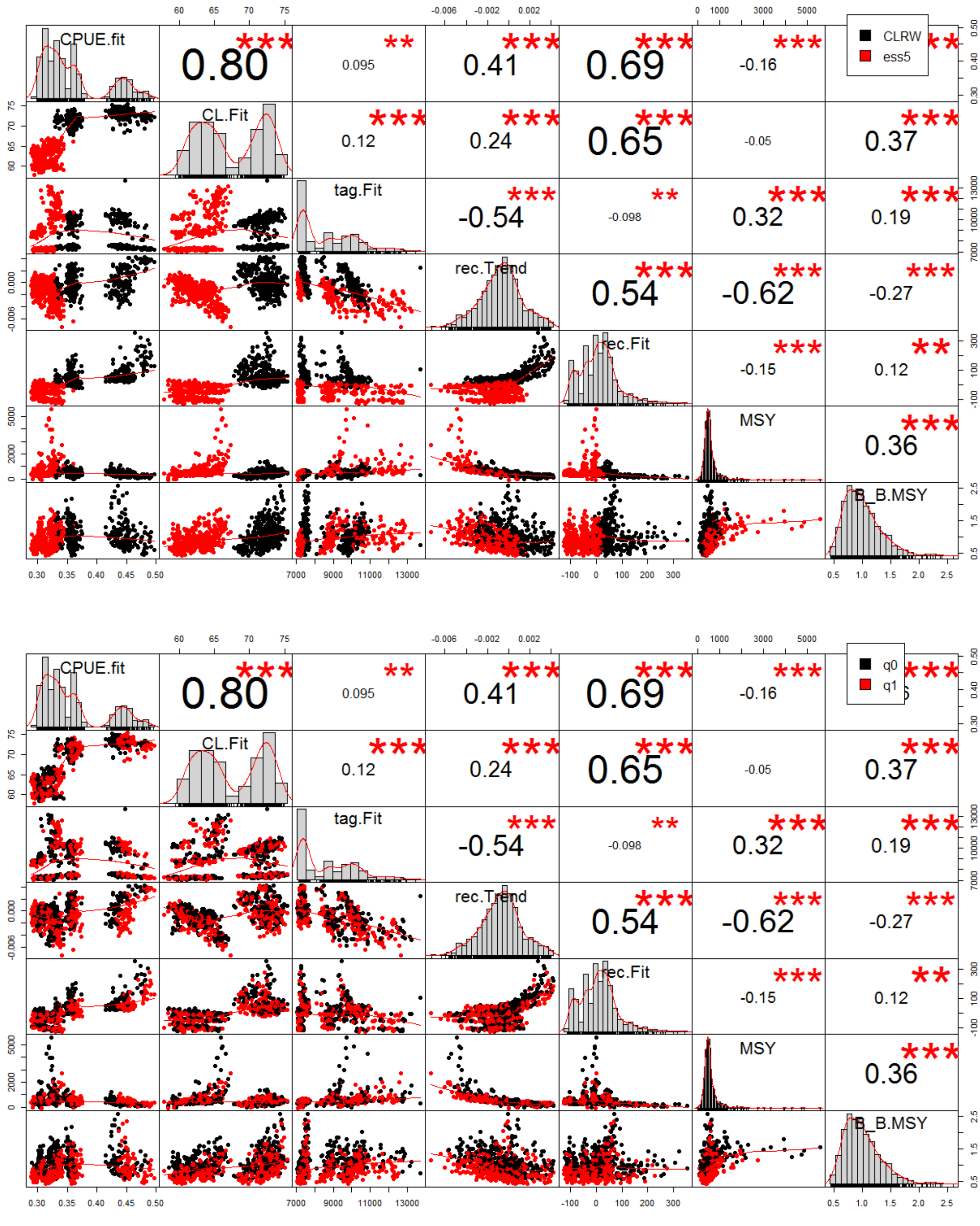


Figure 4a. OMgridY18.1 correlations among various stock status and quality of fit indicators. Points are partitioned by colour according to the different assumption options indicated in the legend.

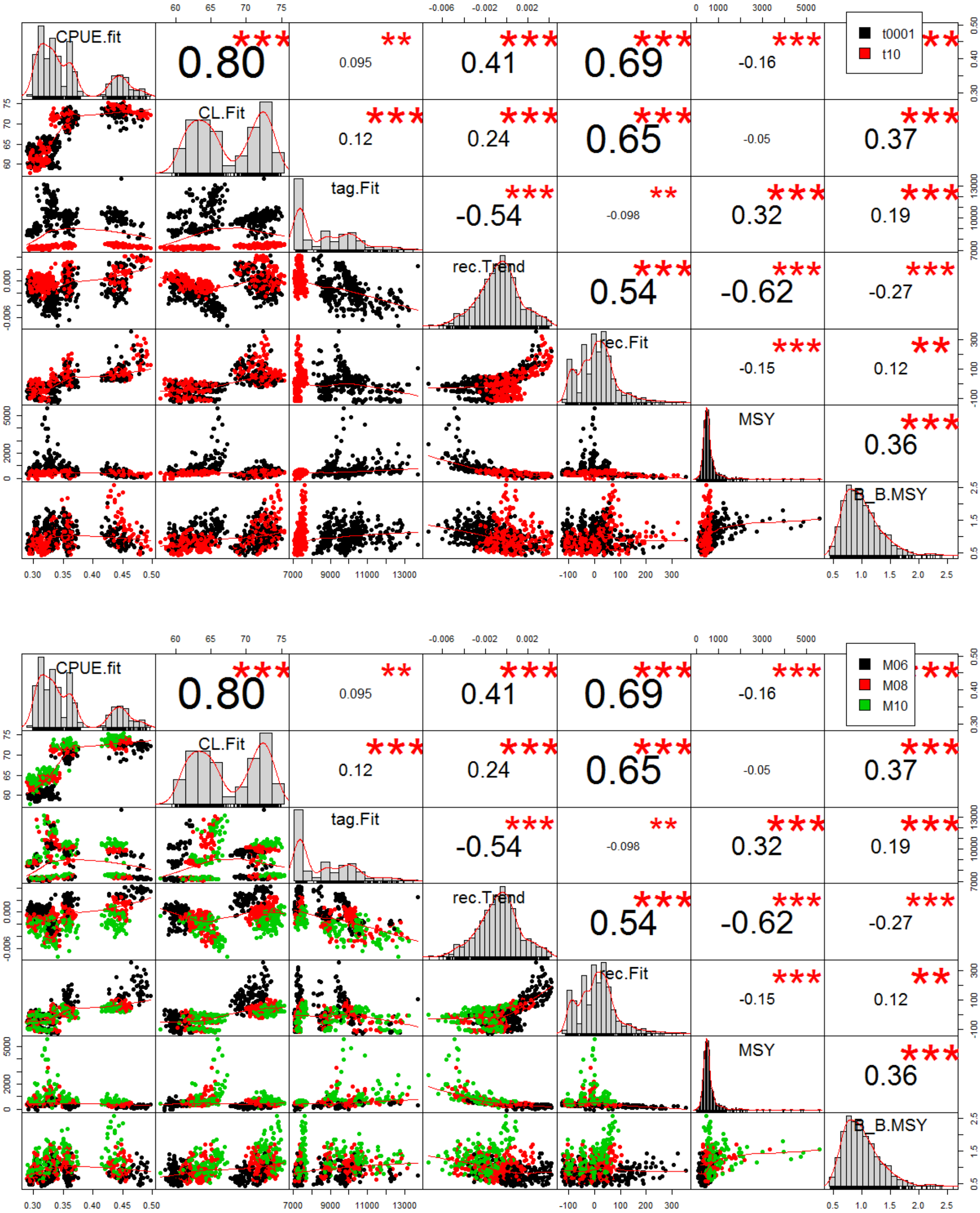
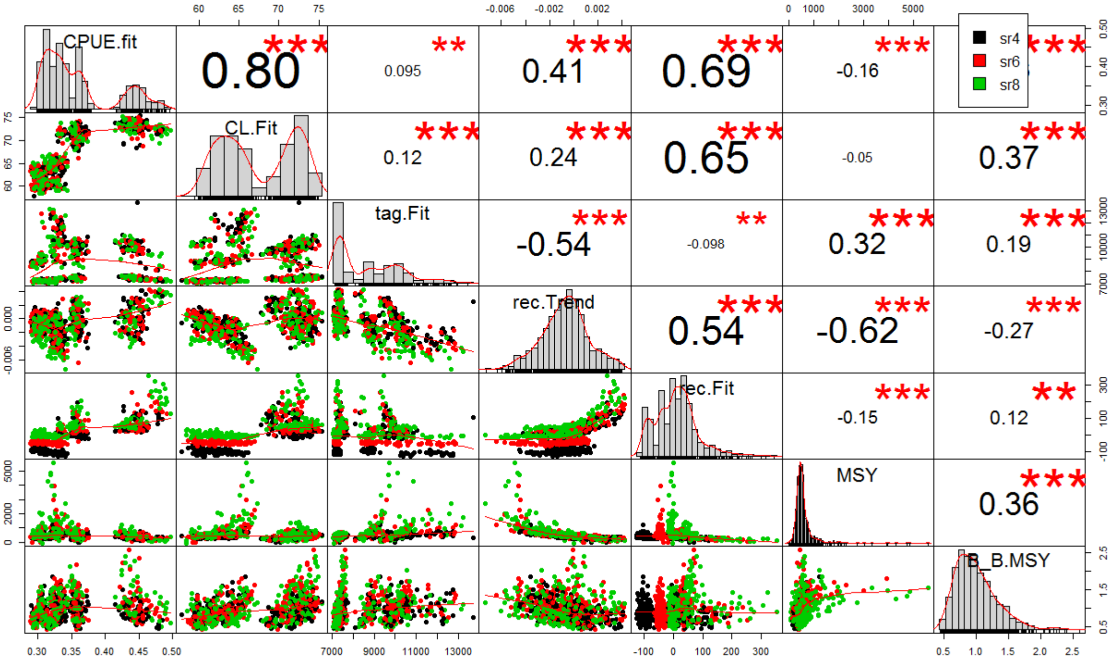


Figure 4b. OMgridY18.1 correlations among various stock status and quality of fit indicators. Points are partitioned by colour according to the different assumption options indicated in the legend.



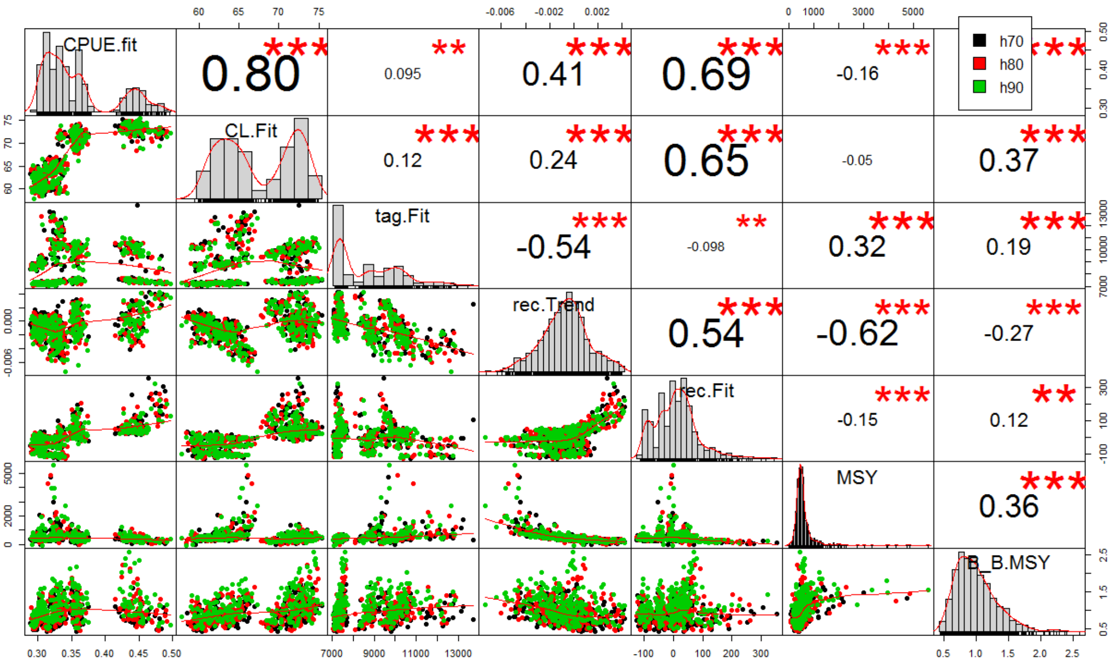


Figure 4c. OMgridY18.1 correlations among various stock status and quality of fit indicators. Points are partitioned by colour according to the different assumption options indicated in the legend.

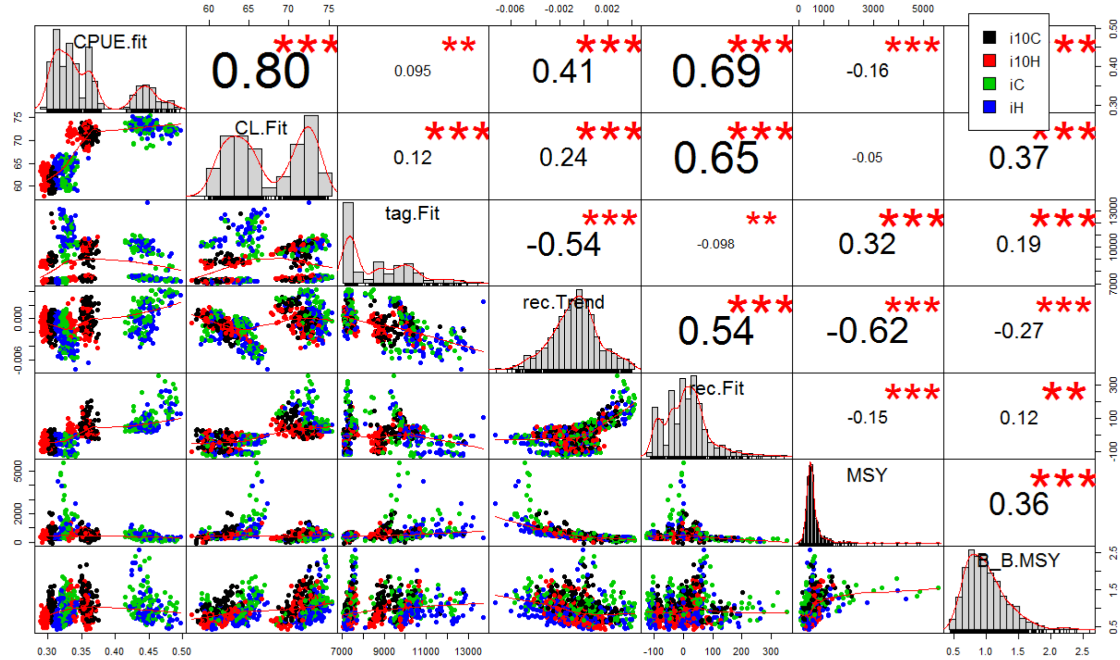


Figure 4d. OMgridY18.1 correlations among various stock status and quality of fit indicators. Points are partitioned by colour according to the different assumption options indicated in the legend.

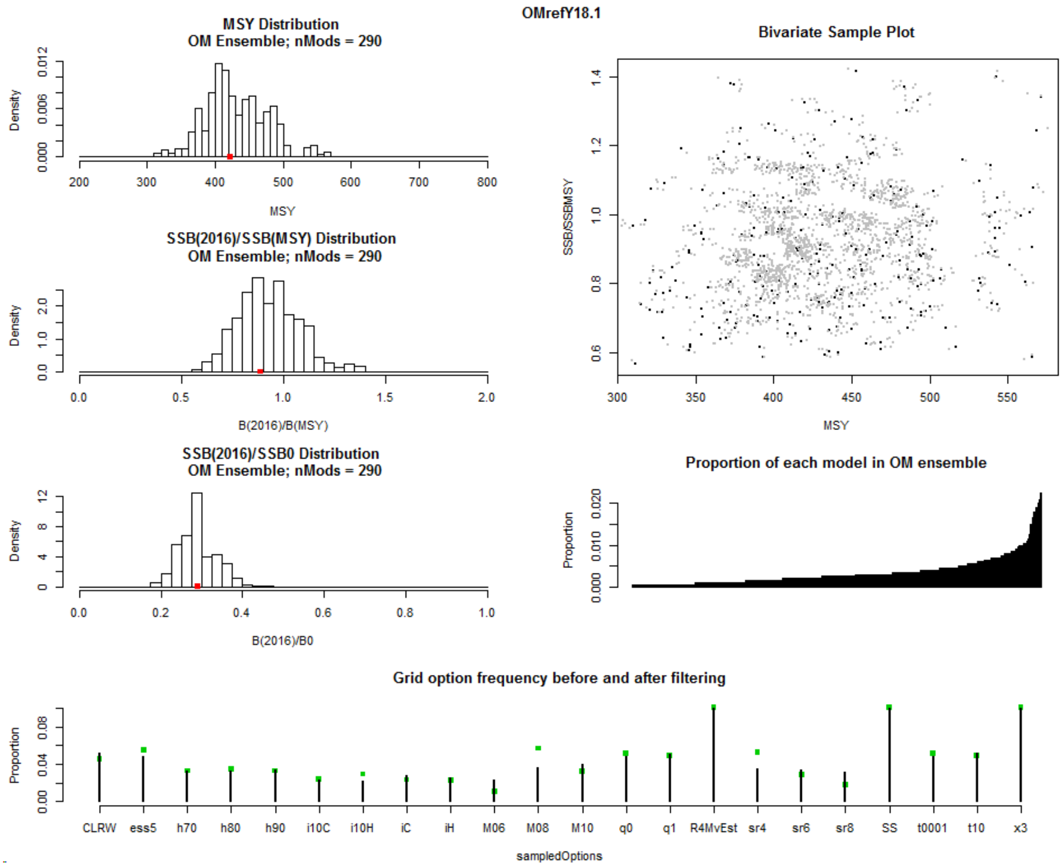


Figure 5. Characteristics of OMrefY18.1, the proposed reference set OM using the bivariate sampling. Red points indicate the point estimates from the 2016 assessment. The top right panel indicates the relationship between MSY and SSBY/SSBMSY (grey points are jitters to emphasize repeat sampling frequency). The middle right panel indicates the relative frequency of the models sampled. The bottom panel indicates the relative proportion of the individual assumptions in the ensemble (green points) relative to the original grid OMgrid18.1 (black lines).

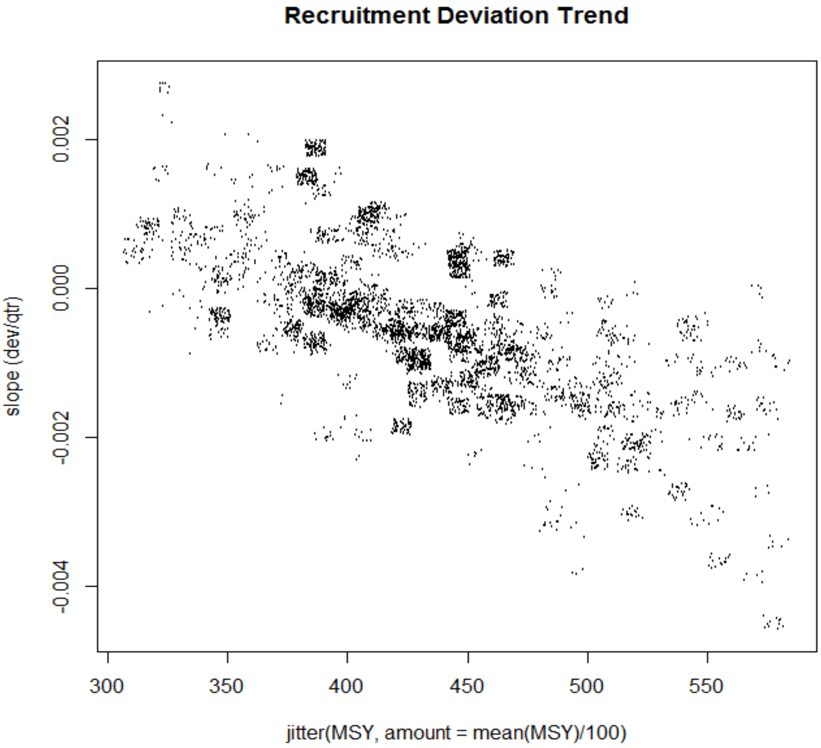
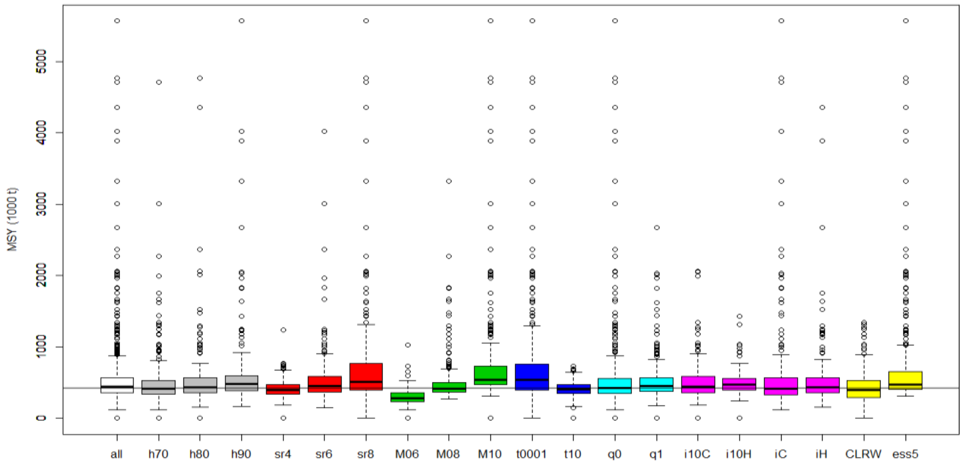


Figure 6. OMrefY18.1 relationship between MSY and the recruitment deviation trend (jittered to indicate repeat sampling).



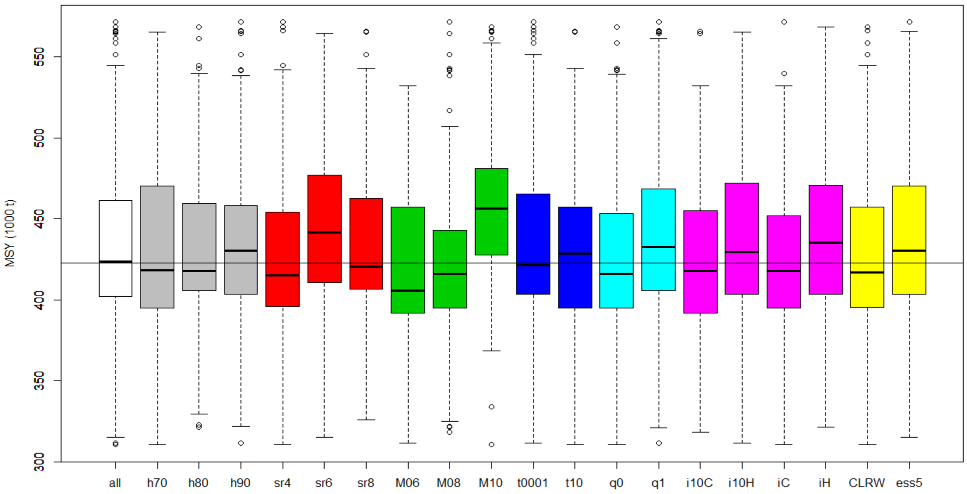
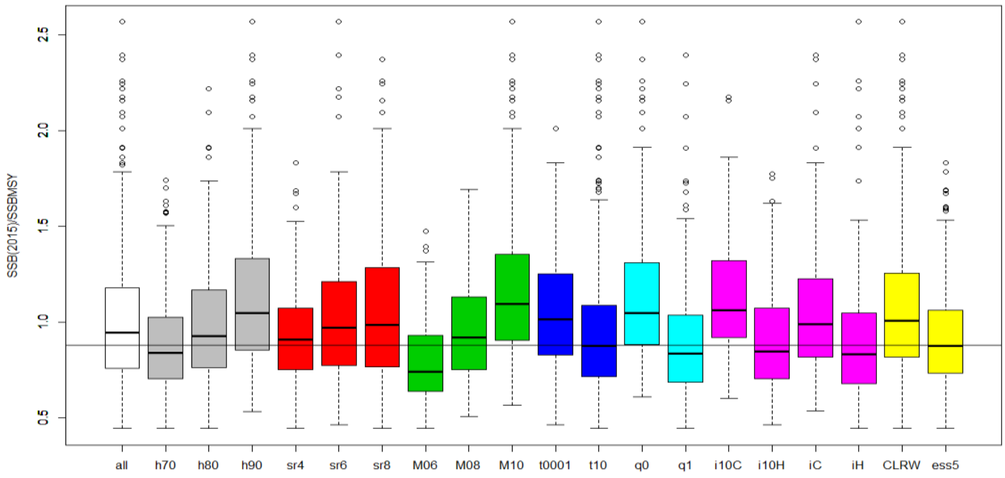


Figure 7. OMgridY18.1 (top) and OMrefY18.1 (bottom) MSY estimates, partitioned by assumptions (all models are encompassed within an individual colour set). The reference line is the 2016 assessment estimate.



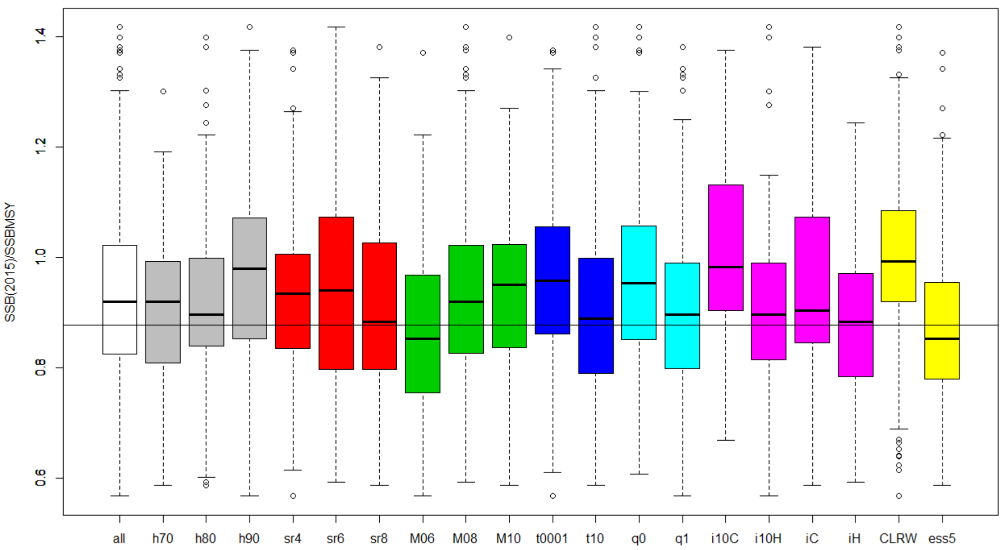


Figure 8. OMgridY18.1 (top) and OMrefY18.1 (bottom) SB(2015)/SB(MSY) estimates, partitioned by assumptions (all models are encompassed within an individual colour set). (note Y-axis scales differ)

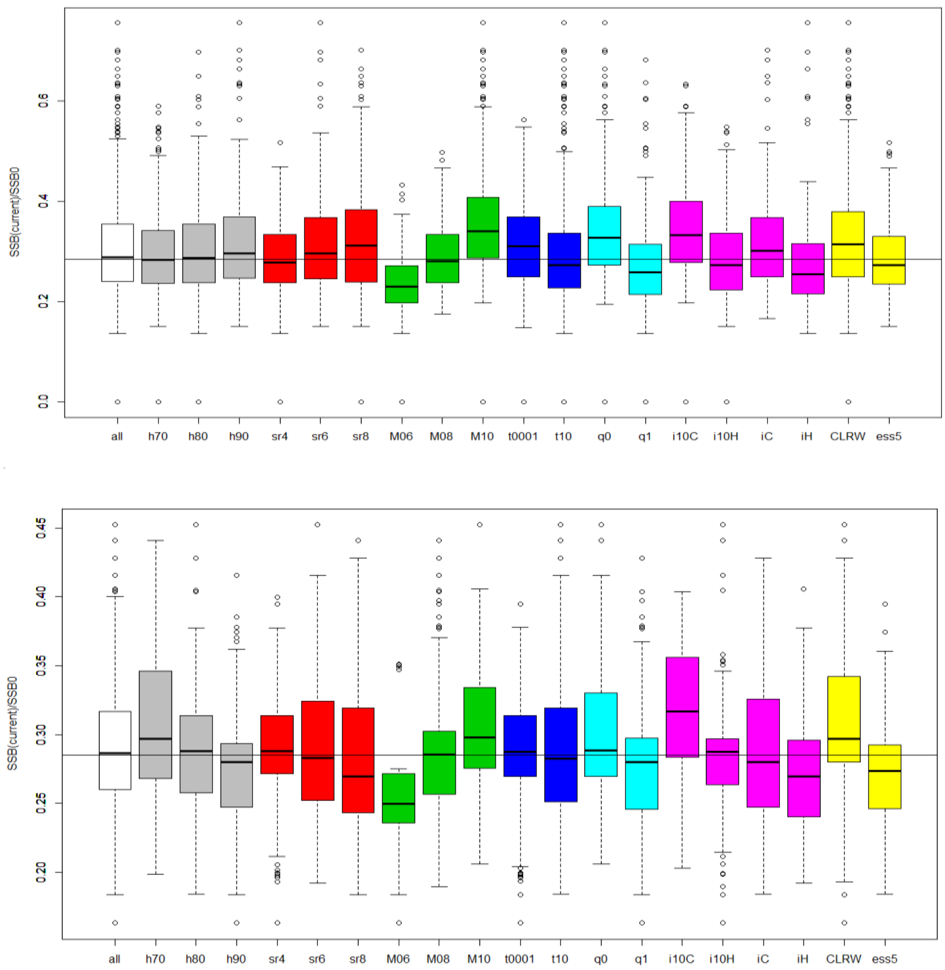


Figure 9. OMgridY18.1 (top) and OMrefY18.1 (bottom) SB(2015)/SB(0) estimates, partitioned by assumptions (all models are encompassed within an individual colour set).

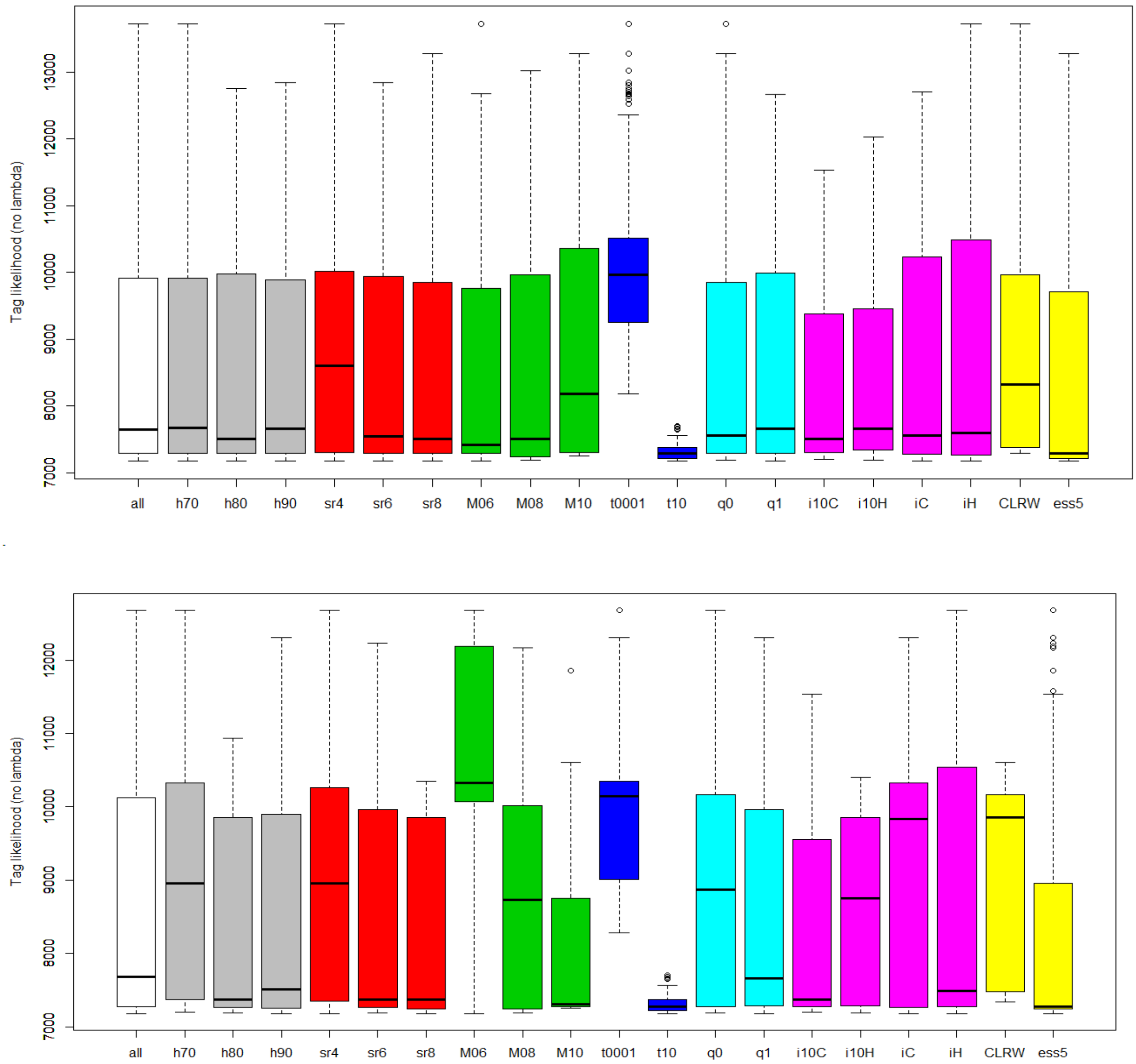


Figure 10. OMgridY18.1 (top) and OMrefY18.1 (bottom) quality of fit to the tags (bottom panel, likelihoods before λ weighting). Note that many of these summary statistics are not directly comparable because there are different data in the models, i.e. HBF- or cluster-based CPUE, and the short/long tag mixing periods.

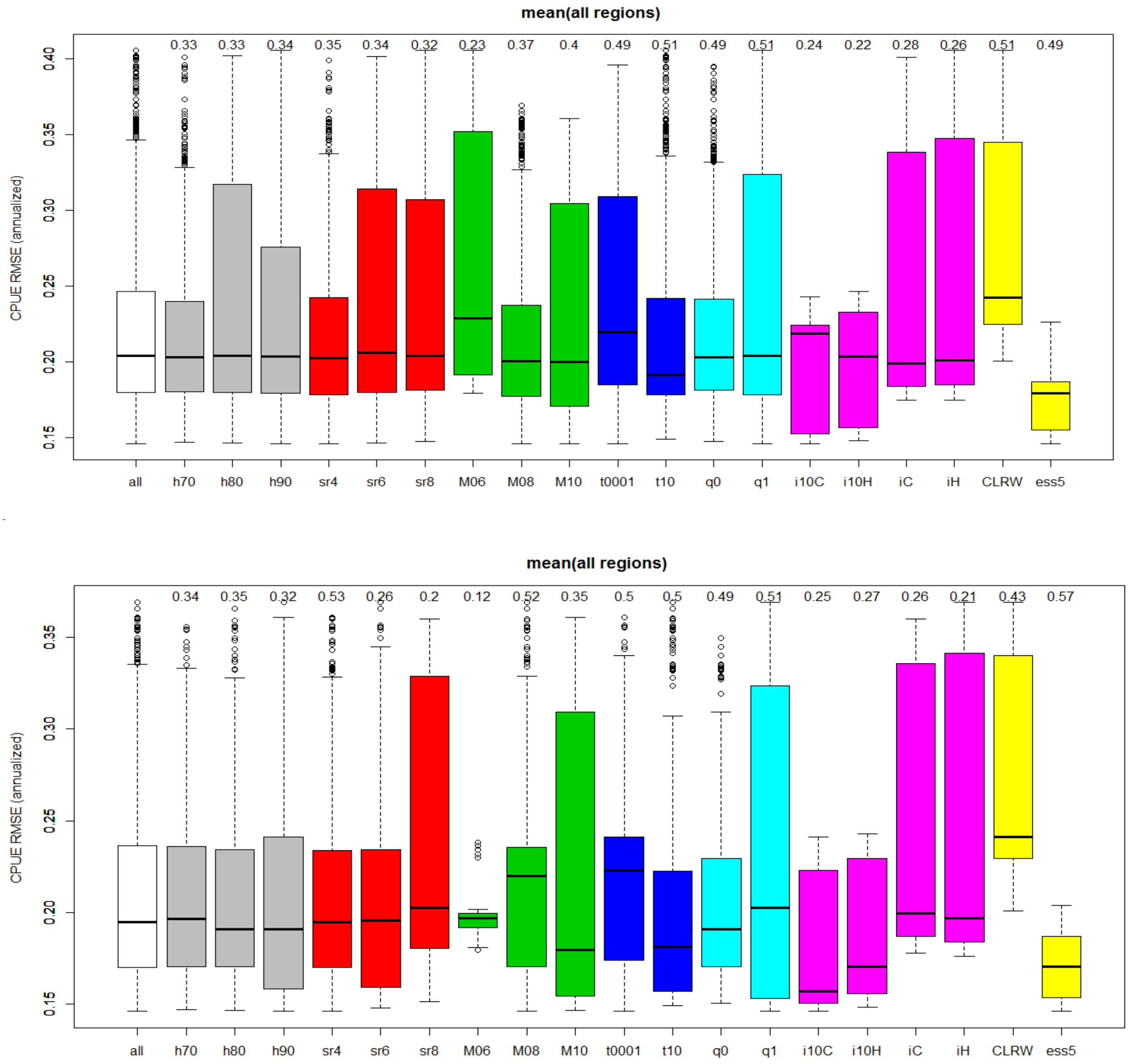


Figure 11. OMgridY18.1 (top) and OMrefY18.1 (bottom) quality of fit to the CPUE (annualized RMSE, mean among regions).

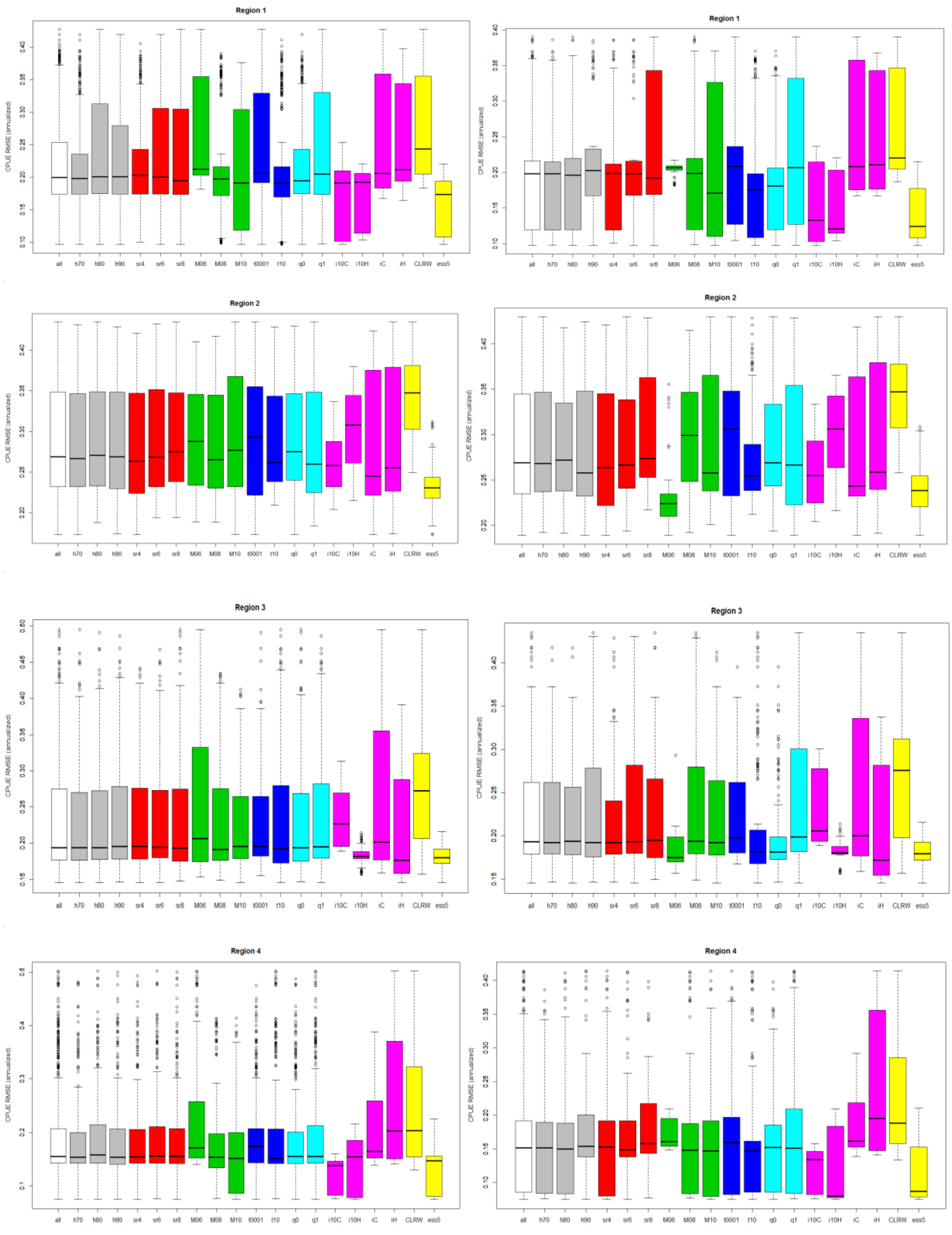


Figure 12. OMgridY18.1 (left) and OMrefY18.1 (right) fit to the CPUE (annualized RMSE) by region (top to bottom), partitioned by model assumption. Note that two fundamentally different CPUE series are used in the tropical regions.

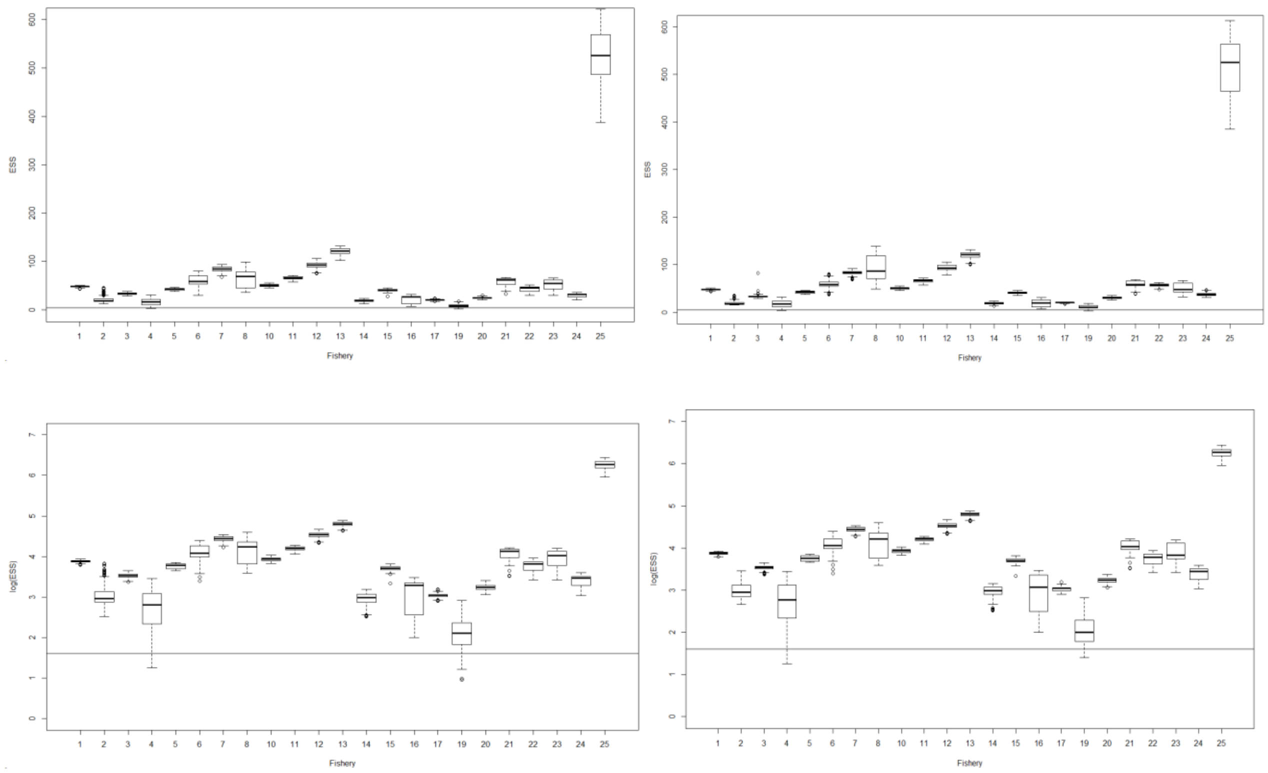


Figure 13. OMgridY18.1 (left) and OMrefY18.1 (right) quality of fit to the Catch-at-Length data (post-fit effective sample size, log-scale in bottom panels), partitioned by fishery, but pooled over all model assumptions. The reference line (5) is the assumption in the assessment.

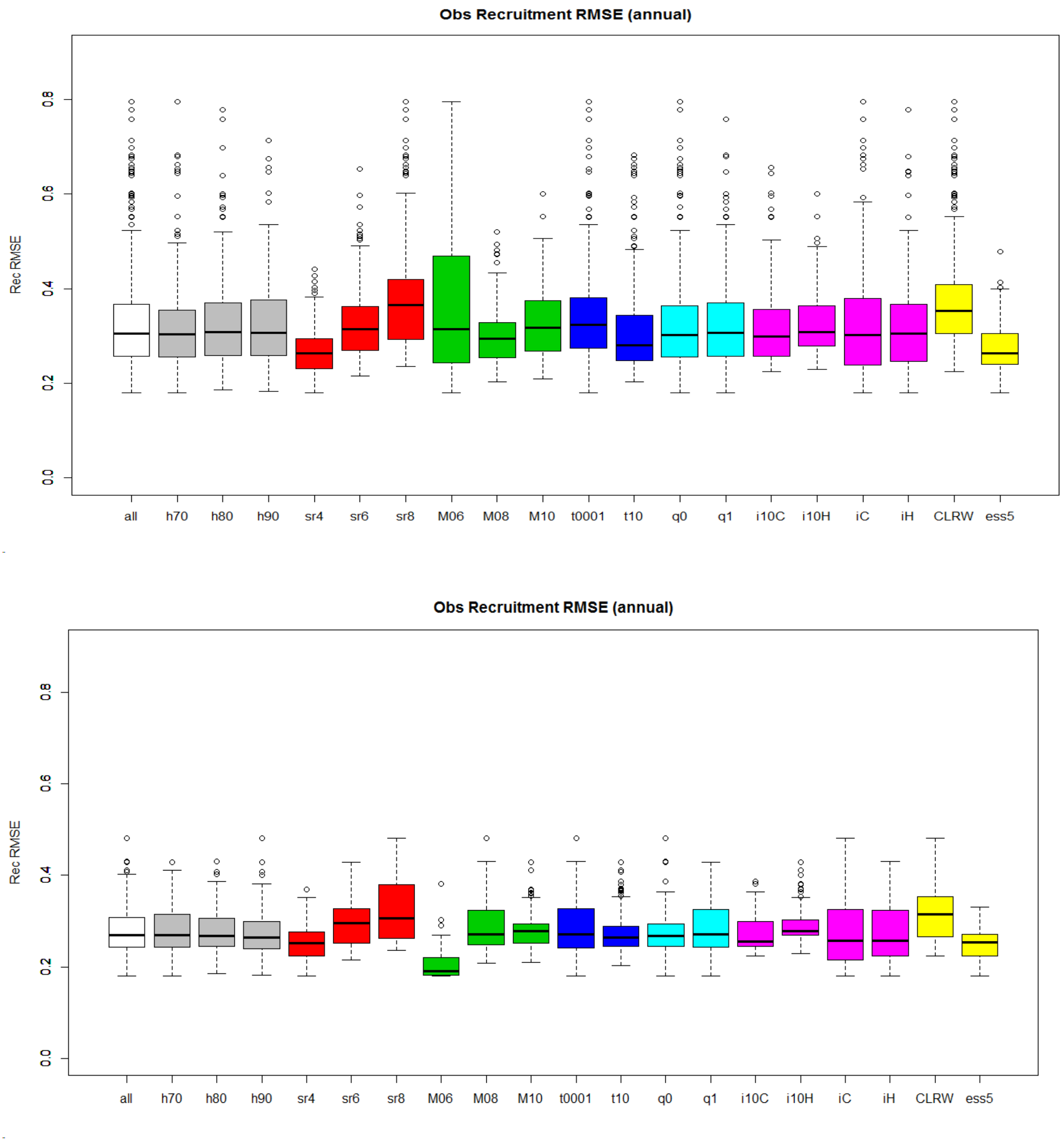


Figure 14. OMgridY18.1 (top) and OMrefY18.1 (bottom) post-fit (annualized and spatially-aggregated) recruitment variability, partitioned by model assumptions.

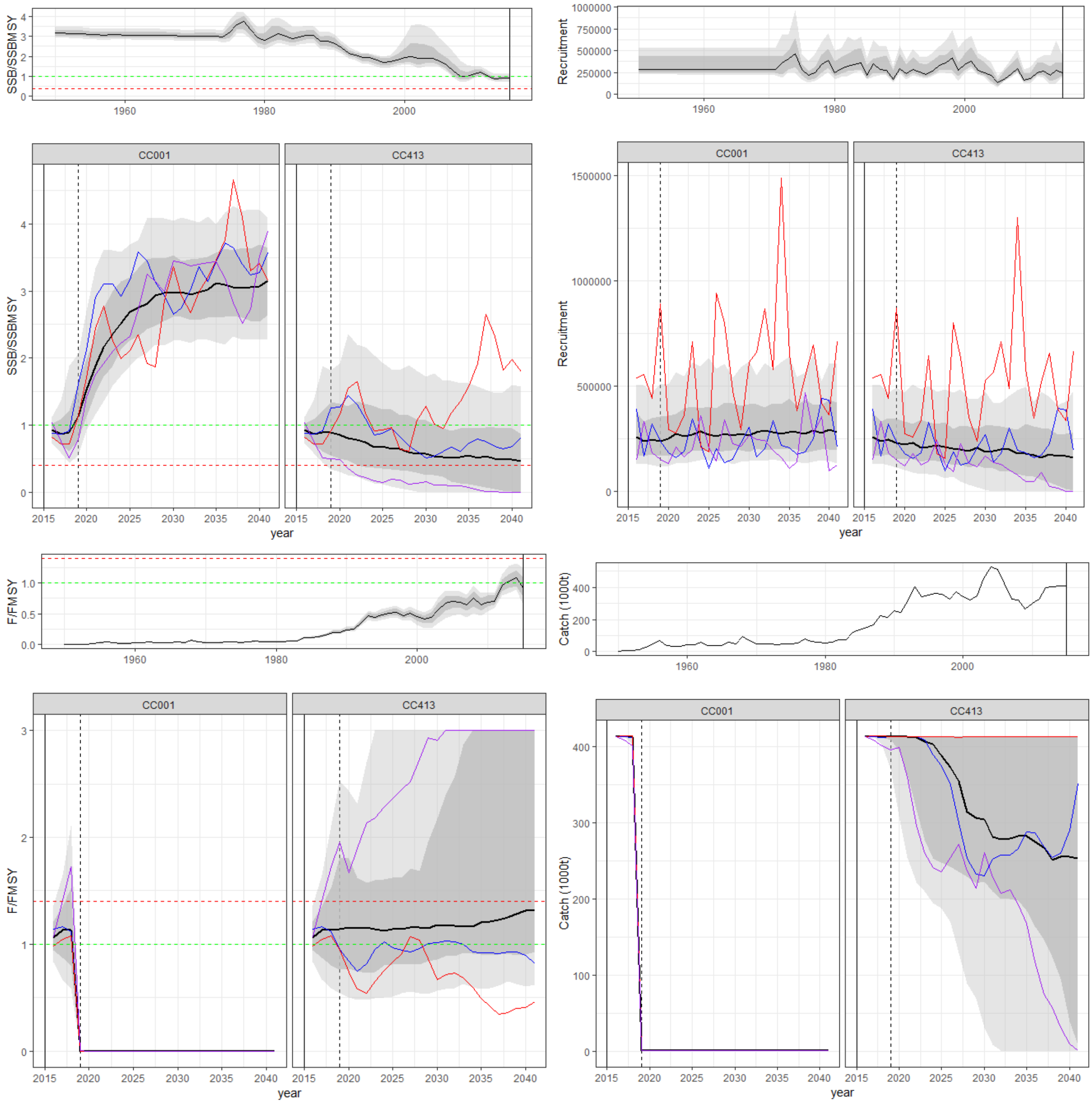


Figure 15. OMrefY18.1 constant catch projections (fishing moratorium and recent current catch 413 Kt).

5.1 Numerical considerations of high fishing mortality

Figure 16 shows that there is not much difference among MP evaluation results for 3 different high F assumptions, for the most aggressive YFT rebuilding tuning objective (note that there is not much difference among the new YFT tuning objectives as discussed in Kolody and Jumppanen (2018a)):

- ".cpp" - the default C++ sub-routine - assumes that Baranov F fishing mortality over 20 is possible, essentially driving any vulnerable component of the population to zero.
- ".C80" - the maximum F for the most highly selected age group of each fishery is constrained to 1.61 (again using the C++ sub-routine). This would be an 80% depletion (in an individual time-step) if a single fishery was operating (the depletion may be much higher given that there are multiple fisheries).
- ".R" - the high F constraint for the Pope's approximation in the original R sub-routine is more complicated (described in the user manual) and deviates systematically from the Baranov solution as F increases.

It is notable that the C80 option is very similar to the R option, and this provides further confidence in the consistency and interchangeability in the two approaches. There is an additional difference in the two implementations in that the R sub-routine attempts to extract exactly one quarter of the annual quota independently in each quarter. Failure to extract the partial quota in the first quarter is not compensated for by extracting more in subsequent quarters. In contrast, the C++ sub-routine solves for the total quota removal across four seasons simultaneously. The C++ option is preferable in the sense that a shortfall in one quarter can be made up by a surplus in other quarters from new growth and recruitment. However neither option is likely a realistic reflection of how the fisheries would react to extreme depletion (when vessels would likely move, change targeting or quit).

At this time, we are using the default C++ sub-routine for all MSE projections. In addition to being theoretically more attractive, it is also faster by a factor of around 2 (the overall MSE framework speed is still constrained by higher level R code and the interface with C++).

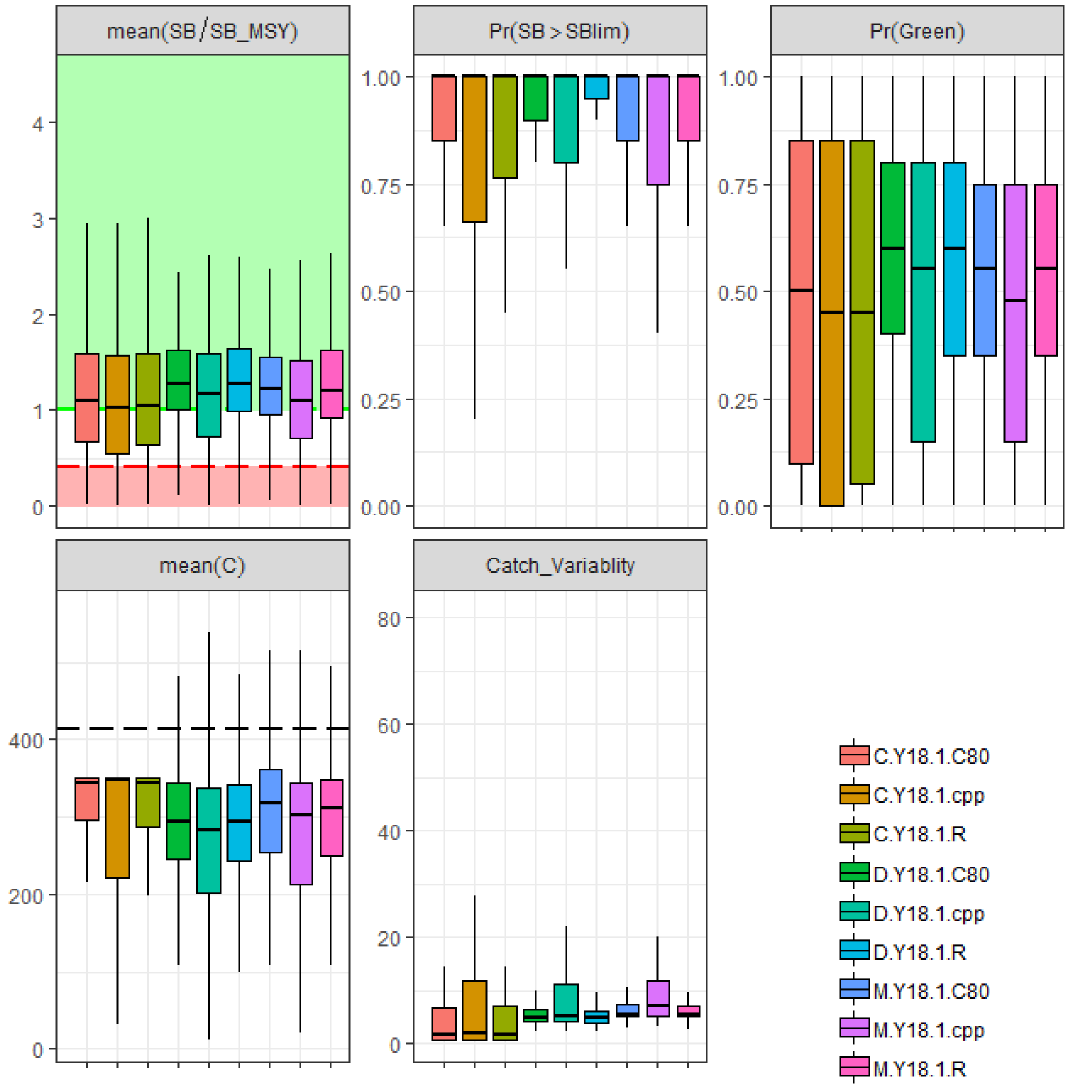


Figure 16. Comparison of 3 MPs for the most aggressive tuning criteria defined by the TCMP in 2018 (Y18.1 - see Kolody and Jumppanen 2018a for details), each assuming 3 different approaches for the numerical constraints on the high F scenarios.

5.2 Revisiting the YFT OM recruitment variance assumptions

The BET and YFT OMs were initially parameterised with independent quarterly recruitment (σ_R = 0.6, auto-correlation ρ = 0.5). The σ_R value was selected to be consistent with the assessment assumptions, while ρ was arbitrarily chosen to be "big enough to matter, but not overwhelming".

Concerns with the initial assumptions include:

- Variability among the conditioned OMs was not examined, and sensitivity to the σ_R assumption in the assessment was not tested. However, σ_R has now been added to the YFT grid. It has an effect on the conditioning, and important interactions with other assumptions (Figure 7 - Figure 14).

- If the projection time series are summed over 4 season years, the OM projection assumptions corresponds to an annual σ_R = 0.42 and ρ = 0.22, which was not directly compared with the assessment inferences.
- The interaction among quarterly stochastic error, annual stochastic error and deterministic seasonal effects was never explicitly examined. i.e. The current assessment structure assumes, σ_R = 0.6, with independent quarterly deviations, but if most of this variability is due to a consistent seasonal pattern, this represents a much simpler management problem than interannual variability.

To check the appropriateness of the adopted values in more detail, we calculated the quarterly and annual recruitment CV from the output recruitment deviations from the reference case YFT assessment, with and without a simple linear model estimating fixed seasonal effects, and the corresponding auto-correlation (Table 3). The quarterly and annual recruitment deviation series are shown in Figure 1. It appears that:

- While seasonal effects are highly significant, but most of the variability is attributed to stochastic noise, i.e. seasonality can effectively be ignored.
- When aggregated at an annual level, the quarterly recruitment assumptions in the OM projections to date result in a higher CV and lower auto-correlation than the assessment outputs. (Through simulation trial and error, rather than clever mathematics), we find that annual σ_R = 0.23, ρ = 0.38 is achieved (approximately) with quarterly σ_R = 0.29 and ρ = 0.67.

The annual σ_R from the assessment (σ_R = 0.23) is considerably lower than the current OM projection assumption and at the lower end of the ISSF (2011) meta-analysis of 14 tuna populations (the annual σ_R = 0.42 assumed in the OM projections is around the 79th percentile of the ISSF analysis). Figure 18 shows the difference in simulated time series using the OM assumption and values inferred from the assessment. The lower CV options were associated with the more plausible models (Figure 5). Given the desire for robustness in the MSE process, the higher assumed variance in the OM might be appropriate, but we seek feedback from the WPM and WPTT on whether the OM projection recruitment variability assumptions should be reduced in future iterations. These assumptions could be scenario-specific, but presumably there would still need to be a minimum lower bound defined.

Table 3. Comparison of quarterly and annual recruitment characteristics from the 2016 assessment (assuming quarterly deviations are independent), from the 2016 assessment with estimated seasonal effects, and from the OM projection assumptions.

Rec Dev series	Summary period	SD	auto-correlation
Assessment	quarter	0.451	0.243
Fixed Seasonal Effects	quarter	0.367	0.351
Original OM projection assumption	quarter	0.6	0.5
Assessment	annual	0.234	0.379
Fixed Seasonal Effects	annual	0.234	0.340
Original OM projection assumption	annual	0.43	0.21

Figure 17. Comparison of quarterly and annual recruitment deviations without seasonal effects (black) and with seasonal effects (red).

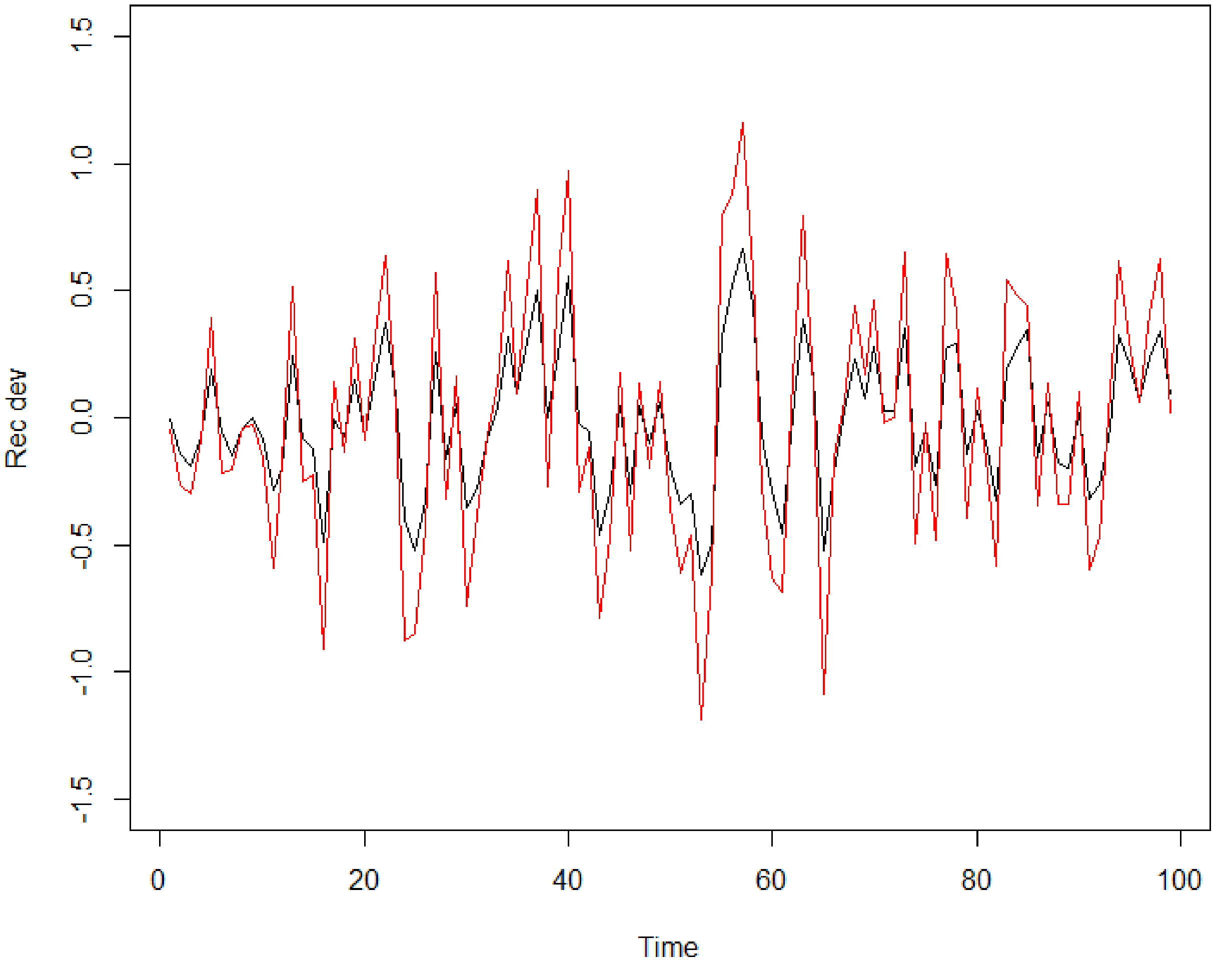


Figure 18. Simulated 100 year annual recruitment deviation time series, comparing the yellowfin 2016 assessment variance and auto-correlation characteristics (black) with the current OM projection assumptions (red).

6 Yellowfin Robustness OMs

We explored two robustness tests for YFT:

- OMrobY18.1.recShock - Given that YFT is estimated to have had a period of poor recruitment in the early 2000s, how would MP performance be affected if there were 8 consecutive quarters of poor recruitment (55% of expected values)? (Figure 19)

- *OMrobY18.1.qTrend3* - What happens if the longline CPUE catchability trend is 3% per year going forward (but remains as in the reference scenario for conditioning)?

The consequences for MP performance are presented in the companion paper Kolody and Jumppanen (2018a). These OMs are easy to define and test because they involve using the reference case OM with changes to the projection specifications only. Other robustness tests that require modification to the code and/or reconditioning of a whole grid should be carefully prioritized.

We provide some discussion points for future consideration of YFT robustness scenarios below.

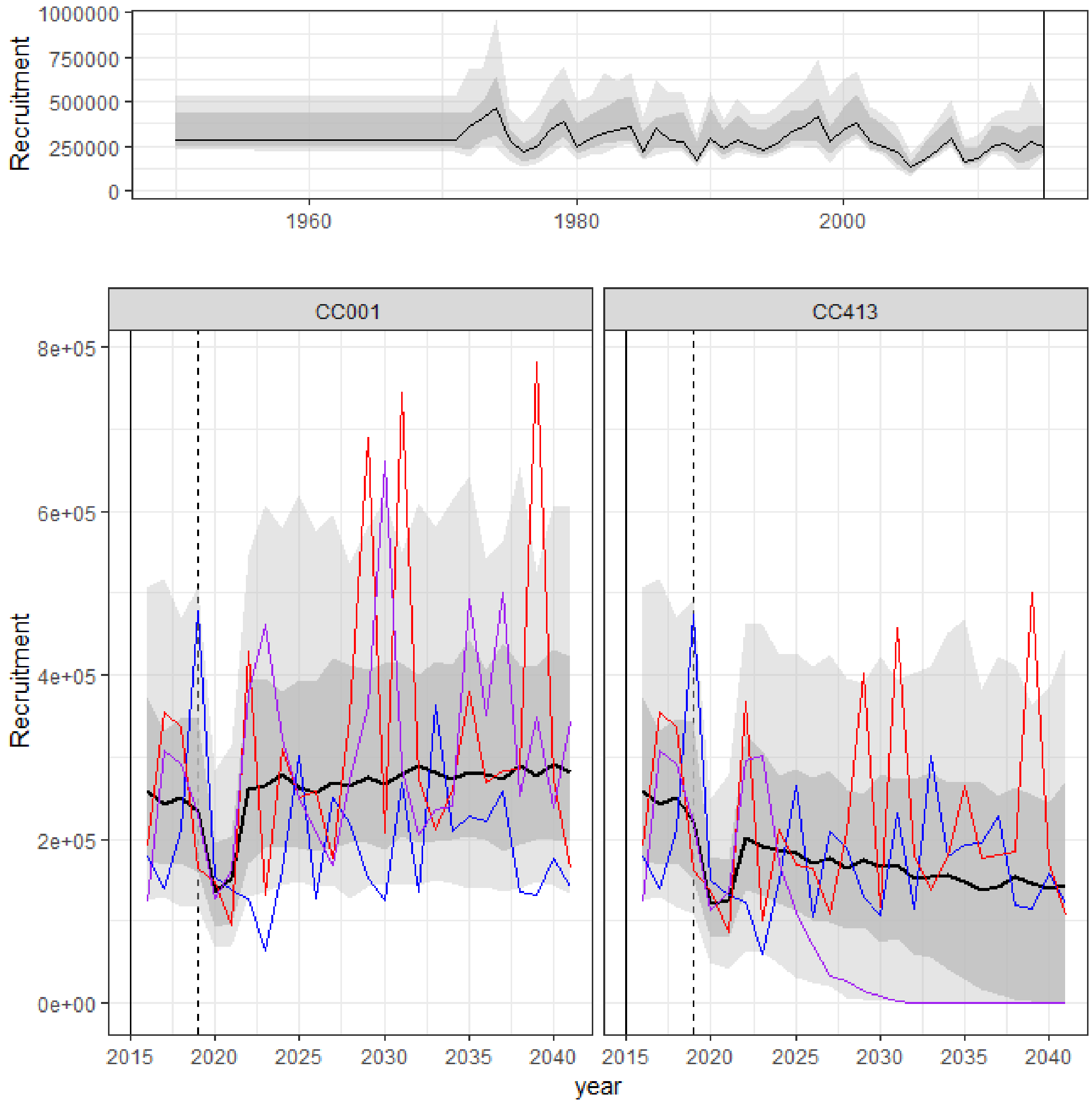


Figure 19. Yellowfin recruitment time series for the robustness scenario OMrobY18.1.recShock and two constant catch projections.

7 Summary of YFT MSE Progress toward the requests from the IOTC Working Parties

Below is a compiled list of MSE development requests identified from the last IOTC WPTT, WPM and TCMP, noting progress toward the requests:

WPM (2017) provided the following guidance for the next iteration (***bold** comments indicate progress):

> *51. The WPM AGREED on the general specification of the reference case OM, but RECOGNISED the need for further work to identify and eliminate implausible models (notably the very high MSY scenarios). The "habitat approach" (Arrizabalaga et al) was proposed as one option.*
>
> *** We have not yet come up with plausibility criteria that constrain the unweighted YFT OM grids to a plausible parameter space. Attempts to address the issue included: i) revisiting the numerical convergence criteria, ii) screening for models with parameters on bounds and/or relaxing bounds, iii) screening models on the basis of recruitment deviation trends and/or high recruitment variances. None of these solutions were very satisfactory, so we have tentatively proposed the grid sampling approach in which the OM conforms to the central tendency of the assessment, but the variance can be arbitrarily adjusted. At this time, we remain concerned that the basic structure of the model is over-parameterized for the available data (this problem is not unique to IOTC YFT).**
>
> *52. The WPM NOTED there were similar issues with some extremely high MSY values estimated in the skipjack assessment. This was also influenced by the tagging data and was overcome by excluding some of the data from the small-scale tagging programmes. The yellowfin tuna assessment only included the RTTP tagging data, however, if enough data exist for the species from the small-scale tagging programmes then this might also be investigated.*
>
> *** Adding the small-scale tagging data to the RTTP data is potentially a non-trivial task, involving considerable data processing (e.g. tag age assignments and differential tag recovery proportion estimates based on tag seeding experiments, fleet behaviour and landing ports) and hampered by the loss of tagging staff from the IOTC secretariat. The authors have been advised that the secretariat is investigating options for re-analyzing the tagging data, in which case this point may be revisited in a future iteration.**

53. The WPM DISCUSSED the use of alternative catch history scenarios for a robustness OM, however, no specific proposals were made.

***This will not be addressed unless/until specific proposals are made.**

WPTT (2017) provided the following guidance for the next iteration of the yellowfin MSE:

*233. The WPTT **AGREED** on the general specification of the reference case OM as defined by the WPTT and WPM in 2016. Noting that it was difficult to specify explicit new scenarios outside of the context of a recent assessment, the following scenarios were suggested for further consideration in the OM robustness tests (with potential inclusion in the OM reference set, subject to review by WPM):*

- *Ricker stock recruitment curve.*

  *** This option is built into the MSE software, but not yet tested. We speculate that it is a low priority for a stock that is currently near full exploitation and expected to be managed for reasonably stable biomass, i.e. because stock size variability should not have much impact on future recruitment variability if it is stable. Its also notable that none of the 5 tRFMO tuna assessments consider a Ricker stock recruit relationship.**

- *Recruitment shock (sustained poor recruitment consistent with the worst outcomes in the historical record).*

  ***This has been implemented and defined as a robustness scenario, with results presented in Kolody and Jumppanen (2018a).**

- *Alternative options for growth (among those considered plausible in recent YFT growth analyses).*

  * **Reconditioning would require a re-analysis of the tagging data, and will be deferred unless/until the secretariat progresses this. Temporal variability in biology for future projections has been added to the simulator, but not parameterized or tested. see response to 234 below**

- *Alternative selectivity (e.g. dome-shaped vs: asymptotic, and region-specific).*

  ***see response to 234 below**

- *Alternative catchability increase scenarios (e.g. 3 or 5%).*

  ***The 3% scenario was defined as a robustness scenario, with results presented in Kolody and Jumppanen (2018a). The catchability trend applies only to the projections, while conditioning from OMrefY18.1.**

- *Explore options for temporal variability in biological parameters (e.g. natural mortality, growth, recruitment and migration) in relation to climate change. It was noted that these sorts of effects might not be important over the time-scale which an MP might be expected to operate without a thorough review (e.g., 5-10 years), and if they are important, they might undermine a lot of the stationary dynamics assumptions that underpin the modern fisheries assessment and management paradigm.*

  ***Temporal variability in biology for future projections has been added to the simulator, but this has not been parameterized or tested. This was not interpreted as a priority for the reasons defined in the dot point. see response to 234 below**

*234. The WPTT **SUGGESTED** using a partially confounded design to increase the number of dimensions that could be included in the reference OM.*

* **At this time, we have not entertained sensitivity tests that require reconditioning, because we are still struggling to identify a satisfactory approach to constrain the sensitivities that are already defined within the sizable reference case OM grid. Partially confounded design represents an interesting approach for examining more sensitivity options with a limited number of model runs. This may prove useful since we are approaching the computational limits of what can be added in a balanced grid. However, until we figure out how to define what an acceptable level of uncertainty is, recognition that the model is very sensitive to even more options will probably not help forward progress.**

TCMP (2018) provided new tuning objectives for presentation to TCMP03 in 2019. Tuned MP results for the new objectives are presented in Kolody and Jumppanen (2018a)

8 Discussion

We continue to welcome feedback on any aspect of the OM formulation, software or MSE workplan. It should be recognized that a number of subjective decisions need to be made is an MSE process. Ideally, MSE in an RFMO context should be undertaken with the active engagement of many parties, including at the technical level, to represent the broad scientific experience within the working parties. We continue to encourage other member scientists to download the source code, and scrutinize OM assumptions, performance characteristics and MP formulations, and present alternative views where appropriate (please contact the authors ahead of time, to ensure that the latest version of the code is available from github).

We highlight the following priority points for feedback/endorsement for the phase 2 YFT MSE to move forward in the next iteration:

YFT reference case OM

- The "grid-sampling" proposed for the YFT reference case OM OMref18.1 is a new and potentially controversial approach that requires broader discussion and feedback from the IOTC WPM and WPTT.

- The sensitivity to model assumptions arises because the assessment problem is over-parameterized for the type and amount of data that are available (this is certainly not unique to Indian Ocean yellowfin). This is our best attempt at a pragmatic solution to move the MSE forward, with some arguments provided in the text for justification.

- This problem should be considered in the context of the 2018 YFT assessment deliberations. If there are fundamentally new insights into how to structure the assessment model, the approach might be adopted for the OM. However, we would be hesitant to restructure the OM without compelling evidence that the assessment is actually better, and not simply different.

- Are there any alternative recommendations for dealing with potentially influential parameter bounds and priors?

- Are there any dimensions in the reference case conditioning grid that should be added or removed?

- Are there additional model diagnostics that should be examined, presented and/or applied for defining plausibility of the grid? Seasonal and spatial issues have not been considered in much detail to date.

- Should there be further refinement of the projection assumptions,

    - e.g. CPUE and recruitment variability could be linked directly to individual assessment specification outputs. If this is deemed necessary, it would be prudent to retain minimum levels, to ensure that the OM scenarios are not unrealistically easy to manage.

YFT robustness tests:

We note that the term robustness test is often used in two ways i) "likely" uncertainty options that are worth testing to see if they affect MP performance, in which case they should be added to the reference case, and ii) "less likely" but plausible and troubling scenarios which are used to test MPs independent of the reference set OM. Robustness tests of the first sort might best be covered under the dot points in the reference case above.

However, given that we are already facing the situation of too much uncertainty in the reference case grid, it is not clear how robustness tests should be approached if they require reconditioning. To be computationally pragmatic, testing could first be conducted within a subset of the grid. Perhaps a dimension could be removed to make room for a different one. If this new grid is also subject to sampling like the reference case (as seems necessary), we would expect stock status characteristics to be similar in both. This does not necessarily mean that MP performance will be similar, but it likely downplays the potential impact of a robustness test. Additional robustness scenarios that require modifications to the conditioning and/or projection code, should be considered and specified carefully. i.e. Do they represent genuine concerns coming from the stock assessment process? Can they be meaningfully quantified? Do they need to be tested as a full dimension within the reference case grid, or can they be defined by a representative subset of dimensions?

Given that the approach to grid sampling has not yet been endorsed, and the concerns above, we considered it premature to attempt to evaluate any robustness scenarios that require re-conditioning. In addition to the recruitment shock and catchability trend scenarios defined here, the BET MP evaluation included three different implementation error robustness tests, which can easily be applied to YFT.

In the interest of clear communication, its worth considering which robustness tests should be presented to the TCMP. Unless the tests identify a specific plausible concern, or they offer additional information that will be useful in helping to select among MPs, it may not be worth presenting them.

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