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Final Report for GEF/ABNJ/FAO-CSIRO Project:

Scientific and Technical Support for Indian Ocean Yellowfin and Bigeye Tuna Management Procedure Development: Phase 2

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Dale Kolody (Dale.Kolody@csiro.au), Paavo Jumppanen

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1 Contents

2 Executive Summary

This report summarizes scientific and technical developments undertaken in support of the Indian Ocean Tuna Commission (IOTC) Management Strategy Evaluation (MSE) process for yellowfin and bigeye tunas from Sep2017 – Sep2019, as defined under the IOTC/FAO-CSIRO Letter of Agreement (FAO Budget Code TF.FIDFD.TF5G110014024, including 12 month extension). This project was conducted with the oversight of the IOTC Working Party on Methods (WPM), IOTC Working Party on Tropical Tunas (WPTT), the IOTC MSE Task Force (an informal sub-group of the WPM and de facto project steering committee), with feedback from the IOTC Technical Committee on Management Procedures (TCMP). The following points summarize key deliverables from the project:

1. Continued iterative development of bigeye and yellowfin tuna Operating Models. This includes the processes of representing uncertainty, conditioning models (fitting to data), evaluating model plausibility, and updating the MSE projection software to add new structural features in line with feedback from the IOTC working groups, and to improve computational efficiency (e.g. with C++ sub-routines and multi-threaded code).
2. Development and evaluation of candidate Management Procedures, to achieve the management objectives articulated by the TCMP, notably in the form of MP tuning objectives.
3. Presentation of results to the IOTC technical working groups, and participation in the deliberations related to improving stock assessment models and the representation of uncertainty, particularly as related to defining Operating Models. This includes an element of capacity building in the TCMP, to help improve understanding among managers of how the MP development and selection process works, and to solicit appropriate feedback.
4. Project outputs include a publicly accessible software archive (https://github.com/pjumppanen/niMSE-IO-BET-YFT/), a series of IOTC working and information papers, updated user manual and technical specification document for the software, quick reference "current state of the Operating Model" documents, and this final report, all of which will be archived in the git repository (along with the earlier documentation).

Progress toward the above objectives is summarized in the annotated bibliography of 15 IOTC working and information papers.

Additionally, there is a critique on the status of the MP development provided, highlighting ongoing concerns both in the software and methods employed by the authors, and the broader IOTC MP process. The current phase of the project has been completed, however the ongoing need for yellowfin and bigeye MSE scientific and technical support will continue, until either Management Procedures are successfully adopted, or the Commission abandons the effort. At the time of writing, funding has been secured to ensure that the final working papers produced under the current FAO-CSIRO Letter of Agreement can be presented to the WPTT and WPM in 2019, and funding for another ~12 month cycle of scientific and technical support has been identified.

3 Acronyms and definitions used in this document

ABT	Atlantic Bluefin Tuna.
BET	Bigeye tuna.
CCSBT	Commission for the Conservation of Southern Bluefin Tuna.
CPUE	Catch per Unit Effort; usually assumed to be standardized into a relative abundance index for fish vulnerable to a particular fishery.
HCR	Harvest Control Rule – the numerical algorithm for recommending a management action (e.g. providing a TAC given a biomass estimate). In this document, the term is generally not intended to encompass data collection and analysis or fitting a stock assessment model, as these are considered to be separate components of a complete MP.
ICCAT	International Commission for the Conservation of Atlantic Tuna
IOTC	Indian Ocean Tuna Commission.
IWC	International Whaling Commission.
OM	Operating Model – this usually refers to the combination of the generic projection software and suite of model specifications used to simulation test the performance of candidate MPs. We often refer to the OM projection software and OM parameterization separately.
MP	Management Procedure – the simulation-tested combination of pre-agreed data collection methods, supporting analysis, and Harvest Control Rule. The term is often used interchangeably with MSE, however the *sensu stricto* MP definition (as used in the IWC and CCSBT) explicitly requires a very high level of pre-specification (i.e. of the data requirements and supporting analyses), to preclude the inherent risk of assessment groups failing to reach consensus during the application of an HCR. MSE is a broader term that does not necessarily imply the same degree of pre-specification.
MSE	Management Strategy Evaluation – the process (or final product) of simulation testing a fishery management strategy (see MP).
MSY	Maximum Sustainable Yield.
TAC	Total Allowable Catch – the catch quota set by an MP (it could be fishery-specific or the aggregate across fisheries, depending on context).
WPM	IOTC Working Party on Methods.
WPTT	IOTC Working Party on Tropical Tunas
YFT	Yellowfin tuna.

4 Introduction

This project report is structured to identify the various objectives and achievements under the ABNJ/FAO-CSIRO Letter of Agreement (FAO Budget Code TF.FIDFD.TF5G110014024, including 12 month extension), and orient the reader to the appropriate references to follow up on details. There is no synthesis of working papers into a single narrative that re-iterates all of the technical documents and committee deliberations over the past three years. The background below is largely extracted from the phase 1 final report (Kolody and Jumpannen 2016). Section 5 itemizes specific objectives and achievements, while section 6 identifies key challenges that remain with the overall development of the IOTC bigeye and yellowfin MSE.

4.1 Background

In pursuing the objectives of achieving conservation and optimum utilization of tuna stocks, the Indian Ocean Tuna Commission (IOTC) committed to pursuing Management Strategy Evaluation (MSE) for the key target species of swordfish and albacore, skipjack, bigeye and yellowfin tunas (IOTC 2011).

MSE is a process in which a fishery system, including the fish population, fishery, and management decisions, are simulated over a medium to long term time horizon, and performance of the management system is evaluated with respect to explicit management objectives (e.g. see Punt et al. 2014 and references therein). A computer simulator (Operating Model, OM) is intended to describe the main uncertainties in the system, including the current state of the fish population and stochastic future events. The Management Procedure (MP) is the algorithm that recommends a unique management action given the data, and is applied at pre-determined intervals. The MP should use feedback control, to change the management action in response to new information about the changing state of the fishery. Simulation-tested MPs offer many advantages over the traditional cycle of stock assessment and ad hoc decision making, including: i) MPs should be robust to the main uncertainties in the system (i.e. provide reasonable management performance regardless of the true underlying dynamics), ii) MPs are evaluated against multiple explicit management objectives, and iii) pre-agreement on data collection, analytical methods and harvest control rules pre-empts disagreements about management actions arising from a failure to reach a consensus assessment.

In this project, we have aimed to evaluate MPs using the *sensu stricto* definition, in which the MP explicitly includes the specification of the data collection and analytical methods to be used, in conjunction with a Harvest Control Rule (HCR), e.g. as used in the southern bluefin tuna fishery (e.g. Hillary et al. 2016). In some other applications, the MP does not include the internal specification of data collection and analysis. For example, IOTC Resolution 16/02 prescribes an HCR that assumes a sensible skipjack stock assessment will always be available. In the skipjack case, the simulation testing involved simulating stock status outputs with a known degree of accuracy and precision. Given that the former approach requires assumptions about simulated assessment data observation errors, the distinction between the two approaches may appear subtle. But assessment model inferences are often biased in ways that are difficult to anticipate, particularly when there are substantial structural errors in the model. Simulating the assessment process is probably the best way to reliably represent these potential biases. However, there is a more important operational distinction between the two approaches that is critical when assessment bodies are unable to reach a consensus view of the stock status (and indeed adoption of the MP approach was motivated by this problem in some international fisheries organizations). The *sensu stricto* MP approach explicitly pre-empts the problem of conflicting assessments, because the MP data and analyses are agreed in advance (and simulation tested to ensure that performance is robust to alternative plausible assessment interpretations). The stock assessments for the IOTC fisheries have undergone substantial changes in recent years, and it would not be surprising if they continue to evolve in the foreseeable future, such that consensus is not inevitable. The *sensu stricto* approach may have the further advantage that resources required for the traditional stock assessment process should not be required every time that the MP is evaluated. If the internal MP "assessment" is a straightforward mechanical calculation, this potentially frees up assessment resources for other strategic research needs.

The MSE process can be partitioned into a series of steps (represented schematically in Figure 1):

1. Identification of management objectives and quantifiable performance measures
2. Development of a range of Operating Models (OMs) to represent the uncertainty in the fishery
3. Development of candidate Management Procedures (MPs)
4. Simulation testing of candidate MPs using the OMs
5. Selection of a preferred MP based of the simulated performance with respect to the management objectives (performance measures)
6. Implementation of the MP

The process is rarely a linear sequence, as individual steps tend to be iteratively revisited as information is exchanged among participants, and decision makers come to understand the possible performance trade-offs. It is useful to think about MSE within the broader context of fishery management as shown in Figure 2. Following adoption of an MP, it should not be expected that the MP will continue to manage the fishery in perpetuity, on "auto-pilot" (i.e. the “meta-rules” in Figure 2 exercise a higher level control on the MP). The MP should include periodic performance reviews, to ensure that the MP is meeting the management objectives, and that the management objectives remain appropriate. It would be optimistic to expect that MPs will always perform well, and there should be regular scientific oversight of the fishery to check whether the system has moved into a space that was not encompassed by the original simulation process. It is probably not possible to anticipate all of the "exceptional circumstances" which could arise, but possible problems include: i) new observations may indicate that the OM understated the uncertainty of the system (e.g. unrecognized biological uncertainties become evident), ii) the fisheries data may cease to be as informative as expected (e.g. longline CPUE may no longer be available on the spatial and temporal scales used historically), iii) management actions may not be as effective as expected (e.g. due to IUU fishing), or 4) new data may become available that improve assessment and management. If exceptional circumstances arise, they should be examined to see if they affect the management recommendation, and the MP should be temporarily suspended until the issues can be resolved, or a new MP evaluated and implemented.

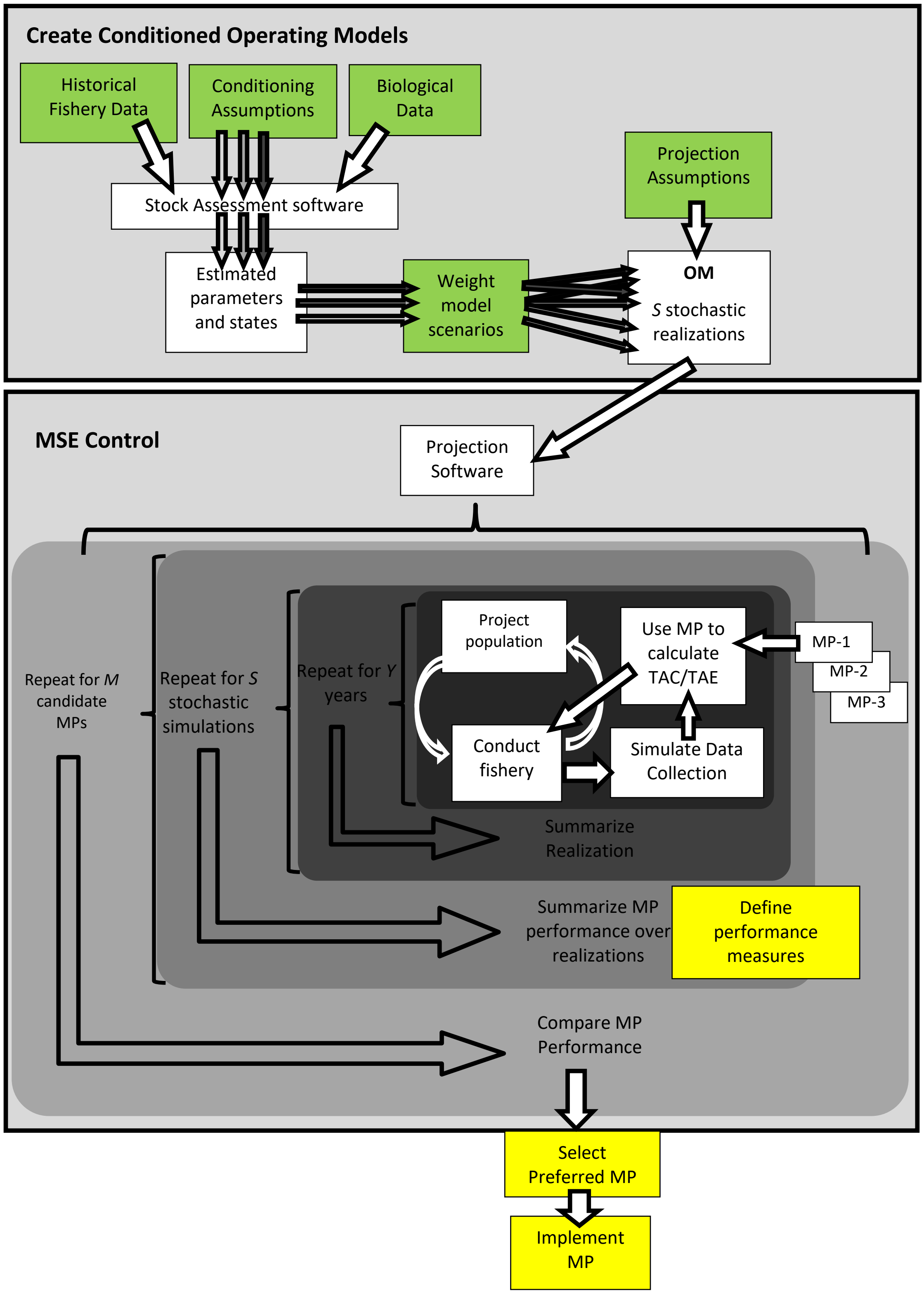

Figure 1. Schematic flowchart of the MSE process, emphasizing the technical elements as implemented in this project. Key points for integrating broader scientific input are highlighted in green, while other stakeholder and manager (Commission) inputs are highlighted in yellow.

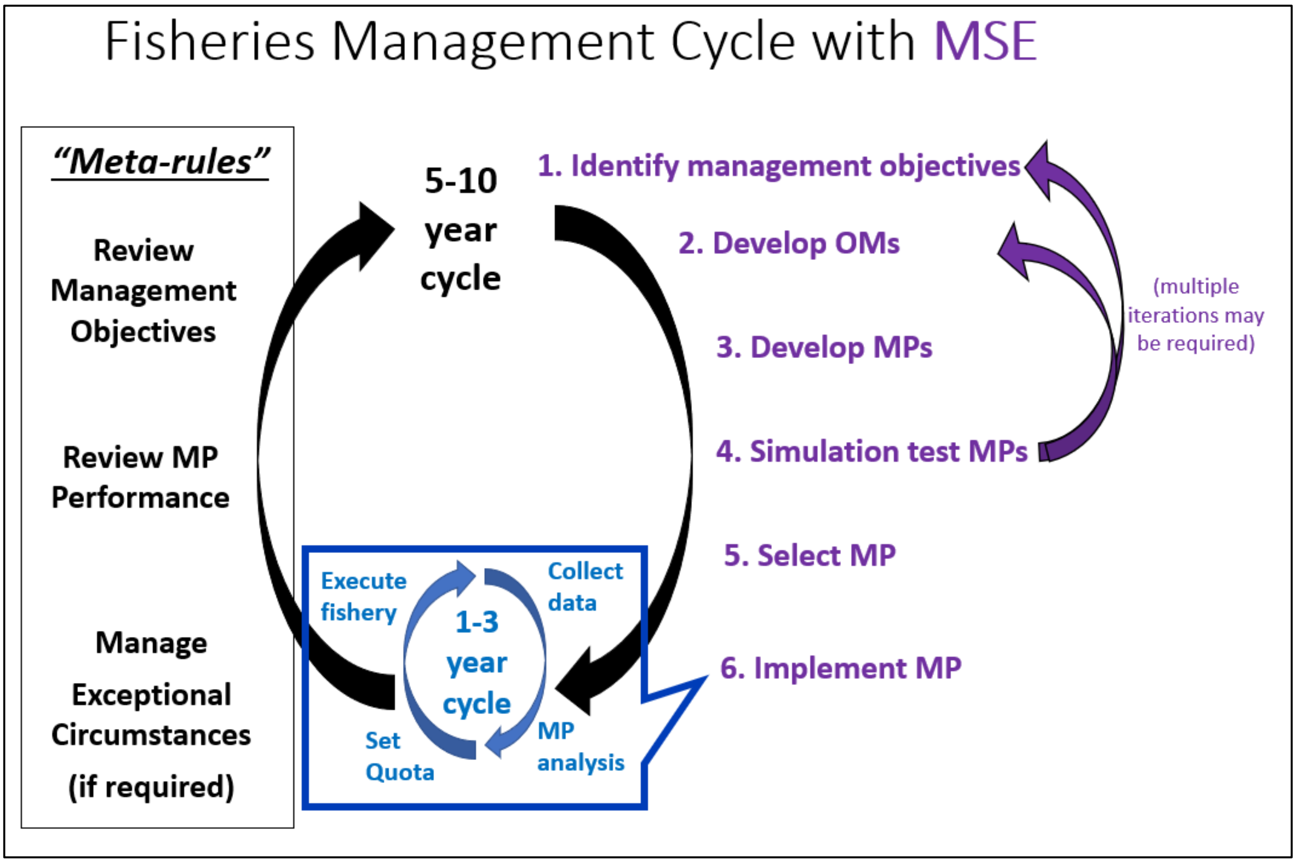

Figure 2. Schematic of a fisheries management cycle in which the MSE process (numbered 1-6) is one part of a larger cycle.

5 IOTC Yellowfin & Bigeye Tuna MSE Phase 2 Objectives and Achievements

The ABNJ/FAO-CSIRO Letter of Agreement identified a number of objectives pertaining to the development of the bigeye and yellowfin Management Procedures. The overarching objectives include:

- Ongoing development of the MP evaluation software.
- Updating of Operating Models in collaboration with the relevant experts at the IOTC WPTT and WPM, and in parallel with the stock assessment processes.
- Evaluation of candidate Management Procedures
- Presentation of results to the IOTC technical working parties (and other scientific bodies as appropriate) for feedback.

In addition to the IOTC-related outputs below, the project funded participation in two CSIRO Management Strategy Evaluation - Community of Practice workshops, which were used to compare a diverse array of MSE applications, work toward a common understanding of terms, and identify best practice methods.

5.1 Project reports

Progress is summarized in the series of documents listed below, organized by meeting (publicly available from https://github.com/pjumppanen/niMSE-IO-BET-YFT/, and archived to the IOTC website in most cases). Documents are cited in reverse chronological order below (results from more recent documents supersede older documents).

Sep 2019 – Final Report (this document)

- Three working papers have been prepared and will be presented to the WPTT and WPM 2019 that describe the latest OM developments, and the implications of the revised MP tuning objectives from the TCMP (2019).
    - IOTC–2019–WPM10–08 – *Update on IOTC Bigeye Tuna MSE Operating Model Development October 2019*
    - IOTC–2019–WPM10-09 - *Update on IOTC Yellowfin Tuna MSE Operating Model Development October 2019*
        - This includes a contribution toward the international yellowfin stock assessment review process, in recognition that the assessment and OM issues are closely-linked.
    - IOTC–2019–WPM10–11 – *IOTC Bigeye and Yellowfin Tuna Management Procedure (MP) Evaluation Update Oct 2019*
- Concise reference documents summarizing key features of the most recent reference set OM for each species are appended to the first two working papers. The history of working party and developer decisions that led to the most recent versions of the OMs are not systematically documented, and the interested reader may have to read through the history of working papers and meeting reports (even then it may not always be clear why working groups made particular decisions).

Jun 2019 – TCMP

- Two working papers were submitted to the TCMP 2019 describing progress and soliciting feedback:
    - IOTC-2019-TCMP03-10 – *IOTC Bigeye Tuna Management Procedure Evaluation Update June 2019*
    - IOTC-2019-TCMP03-11 – *IOTC Yellowfin Tuna Management Procedure Evaluation Update June 2019*

- TCMP (2019) and the Commission (IOTC 2019) provided additional feedback and requests, some of which were addressed in the WPTT/WPM 2019 working papers (above), and some require further interpretation from the technical working parties.

Mar 2019 – IOTC MSE Task Force Meeting (WPM 2019)

- Two working papers were presented to this informal technical meeting (submitted to the IOTC archive as information papers for the 2019 WPM):
    - IOTC–2019–WPM10–info02 – *Update on IOTC Bigeye Tuna MSE Operating Model Development October 2018*
    - IOTC–2019–WPM10– info03 – *Update on IOTC Bigeye Tuna MSE Operating Model Development October 2018*
- The yellowfin OM was completely reconditioned from the 2018 stock assessment. This was not the original plan, but was undertaken in recognition of substantive changes to the assessment tagging assumptions, historical catch revisions, and the international review collaboration proposed for 2019.
- Fractional factorial design was found to be effective for bigeye tuna for representing the uncertainty of a large grid of OM model assumptions, while greatly reducing the number of models fitted (at the expense of confounding at least some interactions).
- A more rigorous approach to OM model fitting was adopted, in which minimization was repeated from multiple jittered starting points (there is no guarantee that this will identify the global minimum objective function, but this should greatly reduce the impact of minimization failures and sensitivity to initial conditions).

Nov 2018 – WPTT/WPM

- Three working papers were presented:
    - IOTC–2018–WPM09–09 – *Update on IOTC Bigeye Tuna MSE Operating Model Development October 2018*
    - IOTC–2018–WPM09–10 - *Update on IOTC Yellowfin Tuna MSE Operating Model Development October 2018*
    - IOTC–2018–WPM09–11 – *IOTC Bigeye and Yellowfin Tuna Management Procedure (MP) Evaluation Update Oct 2018*
- The WPTT and WPM made a series of recommendations for the next iteration of reference set and robustness set OMs.

Jun 2018 – TCMP

- Two working papers were submitted to the TCMP 2018 describing progress and soliciting feedback:

- IOTC-2018-TCMP03-info-10 – *IOTC Bigeye Tuna Management Procedure Evaluation Update June 2018*
  - IOTC-2019-TCMP03-info-11 – *IOTC Yellowfin Tuna Management Procedure Evaluation Update June 2018*
- The TCMP revised tuning objectives for bigeye based on the probability of remaining in the green Kobe zone in the period 2030-2034.
- The TCMP revised tuning objectives for yellowfin to median Spawning Biomass rebuilding to the target level by 2029, 2034 and 2039.

Mar 2018 – IOTC MSE Task Force Meeting

- Two working papers were prepared, which were subsequently submitted to the IOTC archive as WPM information papers:
  - IOTC–2018–WPTT20–INFO1 – *Update on IOTC Bigeye Tuna Management Procedure Evaluation March 2018*
  - IOTC–2018–WPTT20–INFO2 – *Update on IOTC Yellowfin Tuna Management Procedure Evaluation March 2018*
- The proposed yellowfin Operating Model was problematic in that the data were not very effective for discriminating among very different perceptions of stock status (if the tags were excluded). A new approach was proposed in which the OM was sampled from a large grid of models, on the basis of estimated depletion and productivity (MSY), with a central tendency consistent with the assessment, but arbitrarily inflated variance. This was judged to be a practical solution for an undesirable situation. However, it was found to be unnecessary following the OM update in relation to the new WPTT (2018) stock assessment.

Nov 2017 – WPTT/WPM.

- One working paper was presented:
  - IOTC–2017–WPTT19–49 – *Update on IOTC Yellowfin Tuna Management Procedure Evaluation Oct 2017*
- This paper represented a substantial revision to the yellowfin Operating Model following the MP development hiatus between Jun 2016 and Sep 2017. The WPTT and WPM made a series of recommendations for the next iteration of reference set and robustness set OMs.

5.2 MSE Software developments

All of the source code, compiled executables, and scripts required to reproduce the results described in this report are publicly available for unrestricted use from Github (https://github.com/pjumppanen/MSE-IO-BET-YFT). Stock Synthesis model fitting results are not publicly archived, because of the file size (but could be circulated if necessary). The core MSE software developed in phase 1 of the project has incrementally evolved. OM conditioning has been modified in two key ways:

- Individual assessment model conditioning runs are now automatically refit from jittered initial conditions to reduce the effect of sensitivity to initial parameter values observed in the assessments. This does not guarantee that global minima are identified, but it should reduce the impact of outliers. We were able to demonstrate that MP evaluation performance from an OM ensemble did not appear to be substantially impacted by the minimization sensitivity.
- Fractional factorial design is now routinely used to define an OM ensemble that appears to encapsulate most of the uncertainty associated with a large number of assumption levels, without having to evaluate all of the higher order assumption interactions. When coupled with the repeated minimization above, conditioning remains the most computationally-demanding component of the MSE process, and can take still take several days with access to ~50 CPUs on a cluster. Our tests indicated that 50-150 carefully-selected models provided similar MP evaluation performance to much larger grids (e.g. of several hundred models), though we would not necessarily expect this to be the case in the extreme tails of the performance indicators distributions.

The OM projection software remains functionally almost the same as the phase 1 product, with most of the new extensions related to utilities for manipulating results. There was however a major efficiency improvement on the backend of the system realized through parallelization of the projection sub-routines and improved memory usage. Currently, a simple MP can be tuned (~14 MP evaluations) with a 500 realization OM in less than an hour on a standard laptop PC. The projection software still supports parallel R and C++ projection dynamics. The overhead of maintaining both is a burden, but has proven worthwhile from the perspective of minimizing bugs.

Considerable effort was taken to improve the model-based MPs. Without some numerical tricks, simple production models can have serious problems reliably fitting the dynamics of the age-structured OMs.

6 Critique of the IOTC yellowfin and bigeye MP development process

Following the format of the final report from phase 1, the following is a compilation of concerns identified by the authors, related to both the MSE scientific and technical development, and issues with the process that may impede the eventual adoption of MPs. These comments are not intended to undermine the MSE process, but rather flag challenges that might benefit from further consideration from the broader scientific community, including reviewers, or the next generation of developers that might carry this work forward in the future. A number of the concerns from the phase 1 final report are repeated, with commentary indicating progress or changes of perspectives realized in phase 2.

6.1 Operating Model Projections

1) The R-based and C++ based projection sub-routines use different implementations for the catch equations, and a decision will ultimately have to be made to select one or the other for MP evaluation. The two implementations provided very similar MP evaluation results except when fishing mortality rates are very high in the yellowfin spatial model. Ideally this would not be an issue if reasonably conservative MPs were being tested. However, the yellowfin population is estimated to be substantially depleted now (especially the North-East) and the choice of sub-routine may have some influence on MP selection. It can be argued that the C++ code is more consistent with the SS conditioning model, and therefore should be selected on that basis. However, we would question whether either approach is very realistic when fishing mortality rates are so high that quotas cannot be met, catch rates are uneconomical, and incentives exist for fleets to stop fishing, move among areas and/or switch species targeting.
    - *We no longer consider the implementation issue in point 1 to be important, except that it identifies an issue in the OM conditioning. The current perception is that there are internal consistency problems in most or all yellowfin Stock Synthesis models (including the 2018 assessment). Retrospective analyses suggest that recent abundance estimates are too low to sustain recent catches. The catch likelihood in Stock Synthesis is frequently larger than expected, which suggests that the observed catch cannot be easily extracted, and some element of the model is probably implausible. The yellowfin assessment is to be subject to further review through a joint effort at the IOTC WPTT in 2019, with potential implications for the OM.*
2) The [2016] projection software is slower than desired, but should be adequate for the purpose. Options exist for improving the speed. More of the MSE code could be implemented in C++ (including the simulated observation processes and any computationally demanding MP calculations), or the R code could be parallelized more effectively. Implementing the R-based catch equation approximation in C++ would be an option for dramatically improving speed. However, speed is probably not an urgent problem unless/until substantially more complicated OMs or MPs are required (e.g. multi-stock, multi-species or MPs based on fitting complicated assessment models).
    - *In phase 2, the code has been made much more efficient in terms of memory usage, improved use of efficient R array functions, and the C++ and R implementations are parallelized to the point that an individual MP (500 realizations of 25 year projections) can be accurately tuned (~14 repeated MP evaluations) in less than an hour (using 8 or less CPUs) on a standard laptop PC.*

3) The OM (and MPs) assume that an aggregate relative abundance index will be available for the stock, derived from a combination of CPUE series with exactly one from each area. If CPUE observations cease to be available from some regions, or additional series are added, this will require code changes. Additionally, the simulated error characteristics for the index are applied to the aggregate index at this time (i.e. to simplify considerations about how independent the error structure is by season and area). The MPs are provided with a small number of imputed CPUE observations from recent years.
    - *The structural limits of the code remain, but have not represented a problem so far. Further analyses were undertaken to ensure that CPUE error characteristics were consistent with the OM in terms of annualized deviations and lag(1) autocorrelation. However, it has been observed that the current range of CPUE series uncertainty can lead to discontinuities between the single CPUE series that the MP must use, and the population dynamics that were fit with a different CPUE series. This issue merits further investigation.*
4) Independent reviews for the Indian Ocean skipjack and albacore MSEs suggested that alternative stock-recruit functions (e.g. Ricker) should be considered. We are not aware of evidence from bigeye or yellowfin tuna population to suggest that recruitment initially increased with declining *SB* (as predicted by a Ricker function), or that there is a mechanism that would lead one to expect a Ricker function (e.g. high rates of cannibalism, redd superimposition), so we have not considered this to be a priority. The Ricker function has been retained from the original ABT code, but has not been used in OM conditioning or tested in the projections.
    - *The possibility of a Ricker function was also raised for yellowfin and bigeye in 2018. Some conditioning tests were undertaken with a Ricker SR function in 2019. The estimated Ricker functions were qualitatively not much different from a Beverton-Holt function (i.e. minimal dome-shape), such that we would not expect that this recruitment uncertainty would introduce any fundamentally new and insightful challenges to the MPs (at least no more than would be achieved by manipulating steepness, which is already represented with multiple fixed values to represent uncertainty).*
5) Stationarity assumptions - there is a long list of stationary assumptions in most stock assessment models, that are required to produce tractable estimators. Non-stationarity in *M*, growth and recruitment processes could have important implications for production dynamics. Non-stationarity in recruitment distribution and/or movement dynamics might introduce the need to reconsider fleet distribution dynamics.
    - *Flexibility to add non-stationarity in several OM parameters was added, but the developers have asked the Working Parties for explicit, justified scenarios to examine, instead of having the developers embark upon open-ended speculation that may not be plausible and may not fulfil the WP request.*
6) We have included options for projecting non-stationary fishing selectivity (using parameterizations linked to long period sine wave oscillations). This is intended to introduce temporally-structured noise to the size composition distributions to prevent these data from being unrealistically informative for the MP (but will affect CPUE as well).

However, the parameterization was arbitrarily conceived from qualitative arguments and it would not even make sense to attempt to estimate the parameters.

- *For consistency with other species, and the dot point in 5 above, we have removed the non-stationarity selectivity from reference set OMs.*

7) MSY-based reference points depend on fishing selectivity and biology and are not stationary if the biology changes or selectivity changes (including a change in the relative fishing mortality among fisheries with stationary individual selectivity, as would be observed with fishery-specific quotas allocated with constant relative catches). In this case, the reported reference points are fixed, based on the "recent" effective effort distributions (i.e. estimated fishing mortality). We would suggest that the approach of using "proxy" reference points based on depletion would be preferable for bigeye and yellowfin (as adopted for skipjack).
    - *The OM code has been modified to allow MSY reference point calculations based on relative catch allocations (assuming stationary selectivity). However, TCMP (2019) created a committee to revisit the issue of IOTC reference points, and we would encourage the adoption of other depletion-based reference points to avoid this complication.*
8) There is some evidence to suggest that Indian Ocean yellowfin and bigeye population connectivity might be more complicated than the homogenous mixing assumed in most assessments to date. With this in mind, the projection code partially supports the option of multiple stocks with independent biology, but the implementation has not been tested, and stock-specific population diagnostics are not reported at this time.
    - *This issue remains unchanged.*
9) Ignoring the multi-species technical interactions in tropical tuna fisheries may limit the utility of MP evaluations (or at least increases the importance of management implementation errors). The projection code partially maintains the ABT feature of multiple independent populations within a species (though it remains untested), and it should be reasonably straightforward to extend this feature to a multi-species context. However it is not a trivial modification, and conditioning would require the data for the different species to be supplied with compatible fishery definitions. Representing the joint uncertainty of multiple species could presumably be easily achieved by independently sampling the species-specific OMs.
    - *This issue remains unchanged, though may be revisited in relation to the ongoing Indian Ocean stock structure project (Davies et al. 2018).*
10) Tag dynamics have not been included in the projection model. It may prove desirable in the future to simulate the collection and analysis of conventional or genetics-based mark-recapture methods to evaluate MPs based on fisheries-independent monitoring. Ideally this would be achieved by simulating tagging programmes within the MSE framework, and developing MPs that used simple tag-based indicators (as opposed to full statistical tag-based estimators that might be too computationally demanding to simulation test).
    - *This issue remains unchanged, except that we now think the more appropriate (and economically feasible) Operating Model feature would be to include Close-Kin Mark Recapture experiments for fisheries independent monitoring.*

6.2 Operating Model Conditioning

1) We opted to weight all model specifications within the demonstration OMs equally at this time. Our rationale was based on the observation that none of the models showed egregious problems (in terms of fitting to the data or radical outlier behaviour), and the expectation that heavy-tailed OMs are probably going to require a more robust MP than centrally-weighted OMs. We would expect that other IOTC scientists have relevant insight about specific SS model formulations to add, remove or differentially weight in the OMs.
    - *The most recent versions of the OMs use equal weighting of the models retained in the grid. However, there is more attention given to the filtering of models for plausibility (particularly the catch likelihood that seems to flag implausible dynamics). Thus all retained models are weighted equally, while the rejected models might be considered as receiving a weight of 0. We are also using fractional factorial design to set up the grid. Together, these processes tend to result in an irregular number of models, such that the OMs are now sampled randomly with replacement to achieve the desired number of realizations (500 has become the standard for reporting to the TCMP).*
2) Ignoring parameter estimation uncertainty (for those parameters not included in the OM grid) might provide an understatement of some key uncertainties. We have attempted to avoid understatement of uncertainty by using the grid-based approach, and adding a number of projection options, including user-defined parameters for some process and observation errors, (CV and auto-correlation), non-stationary selectivity, and error on the initial numbers-at-age. However, we recognize that this approach is subjective and other IOTC scientists may have good arguments for alternative assumptions.
    - *This issue remains unchanged, though the IOTC scientific community has had several opportunities to express alternative views.*
3) The IWC and CCSBT MP processes found value in distinguishing between "reference" and "robustness" OMs (e.g. Punt et al 2014). The reference OMs were intended to provide a general description of the fishery with a reasonable description of uncertainty evident from the historical data. In contrast, robustness OMs comprised a series of OMs that were considered to have a low probability, but potentially very negative consequences (e.g. sustained recruitment failure, large IUU catches). We did not define any robustness scenarios for bigeye or yellowfin, but these may be worth considering.
    - *In recent iterations, the technical working groups have proposed many robustness scenarios for both bigeye and yellowfin. These have been addressed in different ways: i) some uncertainty dimensions have been tested and either rejected as implausible or elevated to the reference set OM, ii) several standard robustness tests are now presented alongside the reference set MP evaluation results, iii) some of the robustness set requests have been referred back to the technical working groups for further clarification and prioritization.*

4) Depending on how the Commission decides to manage the tropical tuna populations, it may be necessary to reconsider the fishery definitions used in the assessment and MSE. The MSE results currently do not provide nation-specific results (though the IOTC secretariat would have the information required to decompose the fisheries post-hoc if required). At this time bigeye, yellowfin and skipjack fisheries are defined differently, which may confuse communication and management decisions in the short-term, and makes multi-species MSE difficult to implement in the longer term.
    - *This issue remains unchanged.*

6.3 Most recent Bigeye reference set OM

The bigeye reference set assessment is now 3 years old, with an update scheduled for 2019. The reference set OM will need to be compared with the new assessment to ensure that reasonable consistency is maintained. Many of the concerns about data quality and spatial assumptions that affect yellowfin are also of concern for bigeye, though bigeye is not subject to as much scrutiny as yellowfin, presumably because of the optimistic stock status.

6.4 Most recent Yellowfin Operating Model

The most recent yellowfin OM is very pessimistic, with some dubious numerical characteristics. This is also observed in the most recent (Fu et al. 2018 assessment), and is part of the motivation for the international collaborative review process initiated in 2019. We have a number of concerns about the assessment that cannot be easily resolved, but will not attempt to summarize those concerns here. We recognize that pragmatic decisions will need to be made as a result of the review, and the OM will need to take on board the relevant findings of this process. It is not clear how far the yellowfin review process will get in 2019, since the formal assessment is not scheduled until 2020. The review is revisiting some very fundamental assumptions that could drastically alter the perceived stock status. Depending on what the review concludes, this could leave the yellowfin MSE in an awkward state for the 2020 TCMP. i.e. It may be necessary to either i) present results from an OM that is no longer considered appropriate, or ii) present results from a new OM that is a work in progress, potentially subject to dramatic change again in 2020.

6.5 Candidate Management Procedures

1) There have been many MPs described in the literature in recent years, and some may provide better performance than those considered here. Time invested in improving MPs would probably be best spent after the performance objectives have been more narrowly defined (e.g. tuning objectives agreed). If the data requirements and performance of the various MPs are essentially equivalent, it might simplify the communication process within the Commission if fewer MPs were used among species.
    - *The TCMP has been successful in defining reasonable tuning objectives, and TCMP (2019) decided that two were adequate for each of bigeye and yellowfin. This has allowed a targeted improvement of yellowfin MPs. At the 2019 TCMP, the tuned*

candidate MPs had a tendency to overshoot the rebuilding objectives on average (with corresponding loss of economic opportunity). Further exploration has resulted in customized MPs that approach the target and stabilize near the target (on average).

2) The candidate MPs described [in phase 1 final report] Table 5 did not attempt to use information from the size composition data. Provided that selectivity (and associated assumptions of growth and *M*) remain stable, size data may provide useful information about incoming recruitment or spawning biomass. This was the intent of the size composition data in the Prince et al. (2011) empirical MP, however, the species-specific evaluations of that MP in Kolody et al. (2010) failed to demonstrate that the size composition data improved performance relative to the purely CPUE-based MPs.
    - *Some simple attempts to use size composition were examined in phase 2 but were not obviously successful. If these approaches are to be pursued, this will require further consideration of how to realistically simulate catch-at-length sampling errors (e.g. there are thought to be substantial and poorly understood errors in the longline data, and ignoring these issues could provide unrealistically informative data to the candidate MPs).*
3) From the demonstration case yellowfin and bigeye results described here, it appears that the situation for the two species is very different, and it may not be sensible to aim for the same generic management objectives. To bring the two species to a similar stock status (and comparable risk level) in the medium term would appear to require some combination of i) aggressive catch reductions and rebuilding for yellowfin, and ii) an increased exploitation rate on bigeye. The rate of yellowfin rebuilding should be carefully considered as a management objective, while increasing bigeye exploitation rates may not be in the interest of industry, depending on the economics of declining catch rates (and possibly market responses to increased supply).
    - *The 2019 TCMP was able to identify tuning objectives that differ by species and appear to provide sensible MP performance. In the case of yellowfin, the TCMP also accepted that a two phase approach may be required, in which an MP is first adopted to achieve rebuilding, then subject to review and re-implemented. Thus, the TCMP seems to have implicitly accepted that the specific MPs will need to be different (at least in terms of control parameters, and perhaps structural form as well).*
4) The MPs examined to date all prescribe quota changes relative to the previous quota. This may not be appropriate if there are large implementation errors. For example, in the case of bigeye, there may be no incentive for industry to catch the elevated quotas that would be required to bring SB down to SB_{target}. The MP algorithm may respond by recommending higher quotas and eventually the quotas and catches could become decoupled from one another. Of course, the same is true if catches greatly exceed quotas. Some facility for relatively minor carry-over of under-catches and over-catches from one year to the next would be worth considering, and provided that the over- and under- catches are small, there would probably be no need to explicitly evaluate this within the MP.

- *Modest implementation errors have been defined in the robustness tests (reported and unreported over-catch bias, and increased variance). These suggest that a 10% over-catch bias or 10% CV should not have a substantial impact on MP performance.*

5) Model-based MPs, such as the observation error Pella-Tomlinson models presented here, may have additional practical problems that are not a concern for the empirical MPs. Fitting an age-structured assessment model every time step can be prohibitively time-consuming in a simulation context, and may not be easy to automate. If the model does not always converge reliably to a global minimum, this may affect MP performance and the MP selection process. These were genuine problems in the CCSBT process, partly related to the fact that production models were difficult to fit to historical SBT dynamics. The Pella-Tomlinson models generally appeared to provide reasonable performance in this study (though the fit to the simulated bigeye and yellowfin data was often poor). It is important to avoid the awkward situation of creating an MP that offers the best performance subject to flawed model fitting.
    - *This issue remains relevant. While we have greatly improved the model-based MP parameter estimation reliability, there remain situations in which it is questionable. This may not matter, i.e. if the CPUE has collapsed, we don't need a perfect production model to prescribe appropriate action. However, it is conceivable that a simple age-structured model would be able to fit complicated age-structured dynamics better than a surplus production model.*

6.6 The broader IOTC MSE process

1) MP communication within the TCMP – Despite the ongoing efforts at capacity building (at the TCMP, in the technical working groups, and other initiatives, e.g. ABNJ sponsored workshops), it seems clear that the majority of TCMP participants are not yet comfortable with their understanding of Management Procedures, or how the process of selecting and adopting an MP will work. This is evident from the formal discussion within the TCMP, and the informal (confidential) surveys undertaken at the end of TCMP03-2019. However, many participants expressed the view that they are learning at the TCMP, and there are several individuals, among multiple delegations, that appear to have a workable understanding of MPs. A reasonable outcome for the IOTC might be achieved if there is a small critical mass of sufficiently informed individuals spread among the CPCs, that have the respect and trust of other like-minded CPCs (e.g. in terms of representing the general interests of coastal state or distant-water fishing nations). A draft yellowfin MP resolution (IOTC-2019-S23-PropP) was submitted to the 2019 Commission (it was intended primarily for educational purposes and withdrawn for future development and resubmission). This has reportedly helped the commissioners to understand how MP adoption will work, and the implications that MP adoption will potentially have for fisheries management.
2) CPC engagement in the IOTC MP evaluation process. The MP development process appears to be gaining support and understanding within the IOTC technical working groups, and we would expect this engagement to increase further if the yellowfin MP resolution is taken seriously. However there still seems to be a disconnect in which many scientists might not

realize that most of the issues that affect the stock assessment also affect the OM conditioning, and hence will influence management performance if an MP is adopted. It would probably be worth trying to increase engagement further. One path would be to encourage the more quantitatively-inclined scientists to develop and evaluate their own MPs in a friendly competitive process.

3) Catch allocations – MP performance will depend to some degree on the catch allocations among fisheries, which are not yet resolved. To date, all of the simulations assume that catch proportions will be allocated in line with recent historical catches. The 2019 Commission (IOTC 2019) expressed interest in seeing MP evaluation results from alternative quota allocations, but the request was not clearly defined. It should not be the role of the scientists to speculate about political decisions.
4) Scientific and Technical Support Funding for MP development – given the magnitude and value of the IOTC fisheries, it is disappointing that there is no long-term funding commitment to see the MSE process through to fruition. Without such a commitment, it may be difficult to ensure continuity of consultants and maintain the momentum to sustain the process. An additional 12 months of funding (to at least Dec 2020) has been identified to continue the yellowfin and bigeye MSE scientific and technical support. However, this will probably not be sufficient to see MPs for both species through to adoption, e.g. yellowfin appears to be the highest priority to date (with a draft resolution in development), but the assessment that underpins the Operating Model may undergo a major revision in 2020-21, following the assessment review.

7 Concluding Remarks

The phase 2 project has successfully achieved the objectives set out in the FAO-CSIRO Letter of Agreement, and this appears to have helped the IOTC to move toward the goal of adopting Management Procedures for bigeye and yellowfin tunas. It seems likely that many IOTC working party participants originally viewed MSE as a discrete research project undertaken by 1 or 2 individuals, largely in isolation, over a short time period, to report back as to whether status quo stock assessment processes and default Harvest Control Rules are likely to provide acceptable management outcomes. There now appears to be a genuine recognition of the advantages to be achieved through a full MP evaluation and adoption process. At the scientific level, this is shown through the proposals for alternative modelling assumptions. There is currently a substantial international review of the yellowfin stock assessment underway. The instigation of the review was probably not strongly influenced by the MP process, but the pessimistic MP results and draft yellowfin MP resolution presumably continue to reinforce the need for rigour in the IOTC scientific process. At the management level, TCMP participants (at least a core group and hopefully a critical mass) appear to have embraced the concept of MP tuning to quantify explicit medium-term management objectives. We note that the CCSBT MP development process was originally targeted to take 2-3 years, but ultimately took around 10 years. Given the far greater complexity of the IOTC fisheries, and the limited scientific capacity among the members, it is perhaps not surprising that the IOTC yellowfin and bigeye MP processes are also taking longer than originally expected.

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CONTACT US

t 1300 363 400
+61 3 9545 2176
e csiroenquiries@csiro.au
w www.csiro.au

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CSIRO Oceans & Atmosphere
Dale Kolody
t +61 3 6232 5
e dale.kolody@csiro.au