# Evaluations of an empirical MP for Indian Ocean skipjack tuna

*Prepared for the Indian Ocean Tuna Commission*

*October 7, 2021*

Report prepared by:
Charles T T Edwards

For any information regarding this report please
contact the author at:

CESCAPE Consultancy Services
32 Waihoanga Road
Otaki 5582
New Zealand

Email: cescapecs@gmail.com
Telephone: +64-21-575879

## CESCAPE Client Report

| | |
|---|---|
| Client project code: | MTF/INT/661/MUL (TFAA970097099) |
| Project name: | Fisheries Management Strategy Evaluation |
| Project end date: | June 30, 2022 |
| Date of report: | October 7, 2021 |
| Prepared for: | IOTC Working Party on Methods, October 2021 |

# Contents

## Project Background and Objectives

The primary objective of this work is to develop a Management Procedure (MP) for Indian Ocean Skipjack tuna (SKJ), which includes specification of the data inputs, harvest control rule (HCR) and management outputs, and that has been fully tested using an appropriate simulation framework.

Following the presentation of developmental work to the Working Party on Methods (Edwards, 2020a,b, IOTC, 2020a), the MSE Task Force (IOTC, 2021b) and the Technical Committee on Management Procedures (Edwards, 2021, IOTC, 2021c), in which a suitable simulation evaluation framework was proposed, the current work presents further development of an empirical MP with which to recommend a total catch for the fishery.

# 1 Introduction

An empirical MP is based on descriptive rather than process based models. The MPs of this type was proposed by Edwards (2021), being based on CPUE indices from the PL and PSLS fleets, which are both used routinely in assessments of the stock (Fu, 2017, 2020). The MPs were tested using an Operating Model that uses Stock Synthesis III to generate the dynamics (Edwards, 2020b). Structural uncertainty was obtained from the grid of assessment runs used by Fu (2020). This work is further developed in the current report, implementing recommendations from IOTC (2021c). These include updates to the terminology and means by which the results are presented, as well as tuning of the MPs in a manner that allows them to be compared.

## 1.1 Current management

Based on the work of Bentley and Adam (Adam and Bentley, 2013, Bentley and Adam, 2014a,b, 2015, 2016) Resolution 16/02 (IOTC, 2016) was adopted in 2016 as a means of setting catch quotas for SKJ. It specified a Harvest Control Rule (HCR) that was implemented in 2017 to provide a recommended catch limit of 470,029 tonnes for the period 2018–2020 inclusive, and more recently in 2020 to recommend a preliminary catch limit of 513,572 tonnes for 2019–2023 (IOTC, 2020c).

Using the terminology of Bentley and Adam (2016) and IOTC (2016), the HCR outputs an intensity multiplier ($I_y$) as a function of the spawning stock biomass ($B_y$), where $y$ is the most recent year of available data, using a step-linear relationship:

$$I_y = \begin{cases} 1 & \text{for } B_y \geq B_{40\%} \\ \frac{B_y - B_{10\%}}{B_{40\%} - B_{10\%}} & \text{for } B_{10\%} < B_y < B_{40\%} \\ 0 & \text{for } B_y \leq B_{10\%} \end{cases} \tag{1a}$$

Closure of the fishery at $B_y \leq B_{10\%}$ refers to the non-subsistence fishery only.

Multiplication of the intensity by a target exploitation rate gives the realised exploitation rate:

$$E_y = I_y \times E_{40\%} \tag{1b}$$

The exploitation rate is defined as the catch over the vulnerable (selected) component of the biomass (Section 2.1.3, Bentley and Adam, 2016). However in the control rule itself the exploitation rate is implicitly re-defined as a proportion of the spawning stock biomass. Thus the recommended catch is set using the following relationship:

$$C_{y+1:3} = I_y \times E_{40\%} \times B_y \tag{1c}$$

The following additional meta-rules were also endorsed:

- The recommended catch limit should not exceed 900,000 tonnes;
- The change in recommended catch from the previous year should not exceed 30% unless $B_y \leq B_{10\%}$, in which case $C_{y+1:3}$ will always be zero.

Input values for the control rule ($B_{40\%}$, $B_{10\%}$, and $E_{40\%}$) are obtained as medians across estimated values from the grid of SS III assessment runs in the year in which the control rule is applied. In 2017, there were 36 alternative assessment model runs in the final grid (Fu, 2017, IOTC, 2017). Following implementation of the control rule, the catch in 2018 was approximately 607 thousand tonnes: 29% above the recommended catch limit; and in 2019 the catch was 547 thousand tonnes. Despite these high catches, the stock assessment in 2020, consisting of 24 grids (Fu, 2020, IOTC, 2020b), yielded a positive stock status.

## 1.2 Terminology

In the context of Res. 16/02 the HCR inputs are $B_y$, $B_0$ (from which we obtain $B_{40\%}$ and $B_{10\%}$), and $E_{40\%}$ (the equilibrium exploitation rate associated with $B_{40\%}$). These are referred to as "inputs" because they are estimated during implementation. Specifically, Res. 16/02 requires that $B_y$, $B_{40\%}$, $B_{10\%}$, and $E_{40\%}$ are taken as median values across the most recent stock assessment grid. However, it could also be that values for $B_{40\%}$, $B_{10\%}$ and $E_{40\%}$ used in Equation 1 are fixed based on prior evaluations of the control rule. In this case they would be referred to as "tuning parameters," because they have been used to adjust performance of the HCR so as to meet the desired evaluation criteria. The distinction between HCR inputs and tuning parameters is an important consideration when designing a HCR for evaluation. During evaluation of an MP we are required to simulate the HCR inputs forward in time. Simulations of, for example $B_y$, is typically considered feasible, but simulations of derived quantities such as $E_{40\%}$ are not.

A second and equally important distinction is between the tuning parameters required to implement an HCR and the performance metrics used to evaluate performance during simulation. Metrics are often reported relative to a reference point. If, for example, we report the ratio $B_y/B_{40\%}$, then this would be a common performance metric relating to proximity of the stock to its target reference point. This use of $B_{40\%}$ as a reference point for performance evaluation is conceptually different from use of $B_{40\%}$ as a tuning parameter.

### 1.2.1 Reference points

Reference points for SKJ are depletion based (IOTC, 2016), because of known difficulties in estimation of MSY (Res. 15/10, IOTC, 2015). The target reference point (TRP) is $B_{40\%}$, which is the spawning stock biomass at 40% of $B_0$. The associated exploitation rate is $E_{40\%}$. The limit reference point (LRP) is $B_{20\%}$, with associated exploitation rate of $E_{20\%}$.

### 1.2.2 Tuning parameters

Tuning parameters specified in Res. 16/02 are the threshold value (T): the spawning biomass level below which fishing intensity is decreased; and the safety limit (X): the level below which the non-subsistence fishery is closed. These are set to $B_T = B_{40\%}$ and $B_X = B_{10\%}$.

## 1.3 Empirical MP

Empirical MPs are based on descriptive models of the raw data, rather than the process based models applied in model-based MPs. Their main advantages are that they are simple to understand, apply and ultimately communicate (Rademeyer et al., 2007). They are also more amenable to comprehensive evaluation and notwithstanding their simplicity have been shown

**Table 1:** Terms used for description of the MP and performance evaluation. The subscript $y$ refers to the year.

| Notation | Description |
|---|---|
| **Output** | |
| $C_{y+1:3}$ | Total recommended catch for years $y+1$ to $y+3$ |
| **Tuning parameters** | |
| $C_{TARGET}$ | Target catch |
| $I_{min}, I_{max}$ | Min. and Max. fishing intensity multipliers |
| $a_X, a_T$ | Safety level and threshold values for $a_y$ |
| **Input** | |
| $a_y$ | Mean of the log-normalised PL and PSLS abundance indices per year |
| **Reference points** | |
| TRP | Target Reference point ($B_{40\%}$) |
| LRP | Limit Reference point ($B_{20\%}$) |

to perform well in both simulation tests (Geromont and Butterworth, 2015a,b) and long-term observational studies (Breen et al., 2016).

A management procedure has three primary components, namely the data inputs, the decision algorithm (including the harvest control rule but also meta-rules) and management outputs (Punt et al., 2016). These are dealt with in reverse order here. A glossary of terms used for description of the MPs is provided in Table 1.

### 1.3.1 Management output

Because the SKJ fishery is catch controlled, the MP must output a catch. Since the stock biomass is unknown, a fishing mortality output could not be converted into a catch for management purposes.

### 1.3.2 Harvest control rule

Calculation of a recommended catch from the data inputs occurs via a harvest control rule. In the current context, the HCR calculates a fishing intensity multiplier $I_y$ that represents a proportion of a known catch value ($C^*$). With analogy to Equation 1c, the recommended catch is then:

$$C_{y+1:3} = I_y \times C^*$$

If a stock is in reasonable condition then choice of $C^*$ can be informed by recent catches and an MP can be constructed to maintain the catch and catch rates at or above their current levels via small adjustments in $I_y$. The recent assessments for SKJ suggest that the stock is healthy, with current catches close to the estimated target catch at $B_{40\%}$ (Fu, 2017, 2020). Although there is concern that these catches may not be sustainable should environmental conditions change (IOTC, 2020b), they nevertheless provide an indicative starting point for management.

We consider here an empirical MP that depends on indices of abundance to provide a status relative to a preferred index value (location; e.g. Hoshino et al., 2020). The MPs use an abundance index $a_y$ relative to a threshold value $a_T$, which is perceived as a desirable catch rate for the stock:

$$I_y = \frac{a_y}{a_T}$$

If $a_y > a_T$ then the catch is increased, if $a_y < a_T$ then the catch is reduced. Rules of this type would usually include a lower safety limit $a_X$ below which extreme management measures are taken (e.g. closure of the fishery):

$$I_y = \begin{cases} \frac{a_y - a_X}{a_T - a_X} & \text{for} \quad a_y \geq a_X \\ I_{min} & \text{for} a_y < a_X \end{cases}$$

If a desirable target catch is reasonably well known, then a plateau at $I_y = I_{max}$ can be included for $a_y > a_T$ to maintain the catch close that value, with $a_T$ chosen to be low enough to ensure stability in $I_y$ and high enough to ensure that it is sensitive to reductions in the stock abundance. This is the same functional form as Equation 1a.

For the HCR we assume that the target catch $C_{TARGET}$, is known from the assessment of Fu (2020). The catch is then:

$$C_{y+1:3} = I_y \times C_{TARGET} \tag{2a}$$

The fishing intensity is adjusted using:

$$I_y = \begin{cases} I_{max} & \text{for} \quad a_y \geq a_T \\ \frac{a_y - a_X}{a_T - a_X} & \text{for} \quad a_X < a_y < a_T \\ I_{min} & \text{for} \quad a_y \leq a_X \end{cases} \tag{2b}$$

For values of $a_X < a_y < a_T$, the fishing intensity increases linearly to $I_y = I_{max}$ at $a_y = a_T$, so that $C_{y+1:3} = I_{max} \times C_{TARGET}$. The recommended catch is constant for values of $a_y > a_T$. For $a_y < a_X$ the fishing intensity is fixed at $I_{min}$.

For the HCR to be fully specified, the tuning parameters need to be defined, in this case values for $a_T$, $a_X$, $I_{min}$ and $I_{max}$.

### 1.3.3 Data inputs

The stock status indicator $a_y$ was calculated from the log-normalised PL and PSLS abundance indices. These show similar trends over time, and we calculate $a_y$ as the mean of the two log-normalised indices across all four seasons within the year. A catch weighted mean of the two indices, as suggested in Section 54 of IOTC (2021c), did not noticeably change the result.

To inform selection of the $a_X$ and $a_T$ tuning parameters, the relationship between depletion ($B_y/B_0$) and $a_{y-1}$ was estimated by Edwards (2021). Using outputs from the stock assessment grid, the value of $a_{y-1}$ associated with different depletion levels was obtained. These were used to derive equivalent tuning parameter values (Table 2). Previous work has shown that constructing an HCR using these tuning parameters can yield a similar performance to an

HCR constructed using the equivalent depletion-based tuning parameters and inputs (Edwards, 2021).

**Table 2:** Estimated values for $a_X$ and $a_T$ at different depletion levels (Edwards, 2021).

| Depletion | Equivalent tuning parameter |
|---|---|
| $B/B_0 = 0.5$ | $a_T = -0.7$ |
| $B/B_0 = 0.4$ | $a_T = -1.2$ |
| $B/B_0 = 0.3$ | $a_T = -1.7$ |
| $B/B_0 = 0.2$ | $a_X = -2.2$ |
| $B/B_0 = 0.1$ | $a_X = -3.0$ |
| $B/B_0 = 0.0$ | $a_X = -5.0$ |

Given $a_X$ and $a_T$ in Table 2, values of $I_{min}$, $I_{max}$ and $C_{TARGET}$ are also needed. The safety level was set at $I_{min} = 0.1$, and $C_{TARGET}$ tonnes was set at 521.64 thousand tonnes, equal to the median target catch ($C_{40\%}$) estimated across the grid of current assessment runs (Fu, 2020, listed in Table 3). The full list of HCR parameterisations is given in Table A2.

# 2 Simulation framework

The evaluation framework was based on a set of SS III operating models (Methot Jr. and Wetzel, 2013, version 3.30.16.02), called from within **R** (R Core Team, 2021) and making use of the `r4ss` **R**-package (Taylor et al., 2021). Justification for this approach was provided by Edwards (2020b). Reference code developed for implementation of the current project is stored in `https://github.com/cttedwards/skj`.

## 2.1 Operating models

Operating models were based on the SKJ stock assessment of Fu (2020), covering the period 1950 to 2019 inclusive. The assessment included a grid of twelve single area SS III runs described in IOTC (2020b). Labels per run are listed in Table A1. The two-area model was not considered. Models were re-fitted for validation purposes, giving the results summarised in Table 3.

**Recruitment deviations:** An auto-regressive (AR1) time series model was fitted to the log-recruitment residuals estimated by SS III for the period 1983 to 2018. Recruitment for 2019 was estimated by the model as a free parameter. Recruitment deviations from 2020 onwards were generated using a auto-regressive random walk that was additive on the log-scale.

**Implementation of the catch:** The catch in 2020 was set by SS III as equal to the estimated target fishing mortality per run ($C_{40\%}$). The TAC from 2021 to 2023 was fixed at 513,572 tonnes based on recommendation from IOTC (2020c). Thereafter the MP was used to set the catch. Annual, multiplicative catch deviations (implementation errors) were generated from a Gamma distribution with a mean of 1 and standard deviation of 0.05 (Section 51, IOTC, 2021c).

**Table 3:** Median and 80% CI reference point estimates across model runs using SS3.30. Catch and biomass values are given in units of 1000 tonnes. Values for 2020 are estimated assuming a one-year projection from 2019 with exploitation equal to $E_{40\%}$.

| Quantity | Median | 80% quantiles |
|---|---|---|
| $B_0$ | 1960.235 | (1667.205 - 2545.134) |
| $B_{40\%}$ | 784.093 | (666.881 - 1018.052) |
| $B_{2020}$ | 912.73 | (706.534 - 1296.445) |
| $C_{40\%}$ | 521.638 | (461.215 - 671.073) |
| $C_{2020}$ | 601.763 | (479.161 - 801.305) |
| $E_{40\%}$ | 0.594 | (0.536 - 0.644) |
| $E_{2020}$ | 0.573 | (0.52 - 0.641) |
| $B_{2020}/B_0$ | 0.474 | (0.391 - 0.531) |
| $B_{2020}/B_{40\%}$ | 1.185 | (0.977 - 1.328) |
| $C_{2020}/C_{40\%}$ | 1.16 | (1.01 - 1.268) |
| $E_{2020}/E_{40\%}$ | 0.975 | (0.942 - 1.011) |

**Observation:** The last year of CPUE data was 2019. Future observations were generated from the exploitable biomass values predicted by SS III and the estimated catchabilities. Multiplicative observation errors were estimated from the log-residuals of the SS III model fits and applied to simulated index values using random numbers generated from a log-normal distribution. For runs assuming a constant catchability the observation errors had a mean of one. For runs with an increasing catchability (Table A1), the PSLS observation errors were assumed to have a mean that increased by 1.25% per year (Fu, 2020, IOTC, 2020b).

## 2.2 Dimensions

A total of 42 MPs were tested (Table A2). For each MP, the twelve operating model variations were projected (Table A1), with twenty stochastic iterations for each. To ensure comparability of the simulation results across MPs being applied to a particular operating model run, stochastic deviations and error values were generated for each iteration and the same values per iteration applied across all the MPs being tested. Each simulation projected the stock forward twenty-one years from 2020 to 2040 inclusive, with implementation of the MP every third year, starting in 2023 (to set the recommended catch for 2024 to 2026).

## 2.3 Diagnostics

Performance of each MP was evaluated primarily against stated management objectives for the stock (IOTC, 2015): to maintain the stock biomass at or above the TRP of $B_{40\%}$ (equivalent to $B_{MSY}$); to avoid the LRP of $B_{20\%}$. Each of these reference points has associated exploitation rates of $E_{40\%}$ and $E_{20\%}$ respectively. A list of diagnostics with which to compare MPs was obtained from Bentley and Adam (2016) and are described in Table 4. These include an expression of stock status using the Kobe strategy matrix. In addition, following Section 24 of IOTC (2021c) and IOTC (2021a), stock status was also reported using the Majuro quadrants.

**Table 4:** Diagnostic outputs for MP evaluations. Each performance statistic is generated by first calculating the summary statistic per run and iteration across projection years, and then reporting the median and 80% quantiles across those values – unless the statistic is a probability, in which case it is calculated as a proportion across all projection years, runs and iterations simultaneously.

| Performance Statistic | Description | Summary statistic |
|---|---|---|
| **Catch** | | |
| C | Total catch | Mean |
| $C_{[PL]}$ | Catch for PL fleet | Mean |
| $C_{[PSLS]}$ | Catch for PSLS fleet | Mean |
| $C_{[PSFS]}$ | Catch for PSFS fleet | Mean |
| $C_y/C_{40\%}$ | Relative catch | Geometric mean |
| **Catch stability** | | |
| Pr. $C_y = 0$ | Closure | Probability |
| Pr. $> C_{y-1}$ | Catch increase | Probability |
| Pr. $< C_{y-1}$ | Catch decrease | Probability |
| $\lvert C_{y+1}/C_y - 1\rvert$ | Catch change | Geometric mean |
| **Catch rate** | | |
| $CPUE_{[PL]}$ | CPUE for PL fleet | Geometric mean |
| $CPUE_{[PSLS]}$ | CPUE for PSLS fleet | Geometric mean |
| **Exploitation rate** | | |
| $E_y$ | Exploitation rate | Geometric mean |
| $E_y/E_{40\%}$ | Relative exploitation rate | Geometric mean |
| **Stock biomass** | | |
| $B_y$ | Stock biomass | Mean |
| $B_y/B_0$ | Depletion | Geometric mean |
| $B_{MIN}/B_0$ | Min. depletion | Minimum |
| Pr. $> B_{20\%}$ | $B_y > B_{20\%}$ | Probability |
| Pr. $> B_{10\%}$ | $B_y > B_{10\%}$ | Probability |
| **Kobe Quadrants** | | |
| Pr. Red | $B_y < B_{40\%}$ and $E_y > E_{40\%}$ | Probability |
| Pr. Green | $B_y > B_{40\%}$ and $E_y < E_{40\%}$ | Probability |
| **Majuro Quadrants** | | |
| Pr. Red | $B_y < B_{20\%}$ | Probability |
| Pr. White | $B_y > B_{20\%}$ and $E_y < E_{40\%}$ | Probability |

## 2.4 Tuning

MPs were tuned using the Kobe strategy matrix quadrants, so that all MPs matched to the same "tuning criteria" have equivalent values for Pr. Green (Table 4) when averaged across projection years 11 to 15 (2030 to 2034 inclusive). Three tuning criteria were used (Section 77, IOTC, 2021c), similar to other IOTC stocks:

**50%**: Pr. Green = 0.5

**60%**: Pr. Green = 0.6

**70%**: Pr. Green = 0.7

If an MP matched one of these tuning criteria with a relative error tolerance of 5% then it was selected for further comparisons with other MPs that matched the same tuning criteria.

# 3 Results

MPs were selected and grouped according to whether they met the 50%, 60% or 70% tuning criteria. The full list of MPs that were evaluated is given in Table A2, and those that were tuned successfully to the different criteria are given in Table 5. MPs that meet the 50% tuning criteria have a higher $I_{max}$ compared to MPs that meet the 60% ad 70% tuning criteria. However these more aggressive MPs cannot tolerate the higher values of $a_X$ and $a_T$ included in the evaluation. This is likely due to the higher catch variability associated with higher values of $a_X$ and $a_T$, since the MP will become more sensitive to changes in the $a_y$ input.

**Table 5:** Tuning parameters for MPs that pass the 50%, 60% and 70% tuning criteria. A full list of MPs evaluated is given in Table A2.

| MP | $I_{min}$ | $I_{max}$ | $a_X$ | $a_T$ | $C_{TARGET}$ | Pr. Green | Tuning |
|---|---|---|---|---|---|---|---|
| MP4 | 0.10 | 0.93 | -5.00 | -1.70 | 521.64 | 0.73 | 70% |
| MP5 | 0.10 | 0.94 | -5.00 | -1.70 | 521.64 | 0.72 | 70% |
| MP6 | 0.10 | 0.95 | -5.00 | -1.70 | 521.64 | 0.68 | 70% |
| MP7 | 0.10 | 0.96 | -5.00 | -1.70 | 521.64 | 0.67 | 70% |
| MP10 | 0.10 | 0.99 | -5.00 | -1.70 | 521.64 | 0.62 | 60% |
| MP11 | 0.10 | 1.00 | -5.00 | -1.70 | 521.64 | 0.59 | 60% |
| MP12 | 0.10 | 1.01 | -5.00 | -1.70 | 521.64 | 0.57 | 60% |
| MP13 | 0.10 | 1.02 | -5.00 | -1.70 | 521.64 | 0.58 | 60% |
| MP16 | 0.10 | 1.05 | -5.00 | -1.70 | 521.64 | 0.52 | 50% |
| MP17 | 0.10 | 1.06 | -5.00 | -1.70 | 521.64 | 0.50 | 50% |
| MP18 | 0.10 | 1.07 | -5.00 | -1.70 | 521.64 | 0.50 | 50% |
| MP19 | 0.10 | 1.08 | -5.00 | -1.70 | 521.64 | 0.49 | 50% |
| MP25 | 0.10 | 0.93 | -3.00 | -1.20 | 521.64 | 0.73 | 70% |
| MP26 | 0.10 | 0.94 | -3.00 | -1.20 | 521.64 | 0.72 | 70% |
| MP27 | 0.10 | 0.95 | -3.00 | -1.20 | 521.64 | 0.70 | 70% |
| MP28 | 0.10 | 0.96 | -3.00 | -1.20 | 521.64 | 0.68 | 70% |
| MP32 | 0.10 | 1.00 | -3.00 | -1.20 | 521.64 | 0.61 | 60% |
| MP33 | 0.10 | 1.01 | -3.00 | -1.20 | 521.64 | 0.60 | 60% |
| MP34 | 0.10 | 1.02 | -3.00 | -1.20 | 521.64 | 0.59 | 60% |
| MP35 | 0.10 | 1.03 | -3.00 | -1.20 | 521.64 | 0.57 | 60% |

A illustrative timeseries of the Kobe quadrant probabilities for each group of MPs is given in Figure 1. Phase plots for each group of MPs are given in Figure 2. These illustrate the overall performance of each MP group. The simulations suggest that MPs that pass the 50% tuning criteria will keep the stock close to the TRP, but with a risk that the LRP will be crossed. For MPs that pass the 70% criteria, there is a higher probability that the stock will stay above both the LRP and TRP.

Summary diagnostics are given in Figure 3 (and listed in Table A3), in each case showing the tuning groups. MPs that pass the 50% criteria tend to have a higher catch, but lower depletion and lower catch rates. The trade-offs between catch and other performance criteria are shown in Figure 4. As expected, higher catches are associated with a lower depletion and a higher exploitation rate.

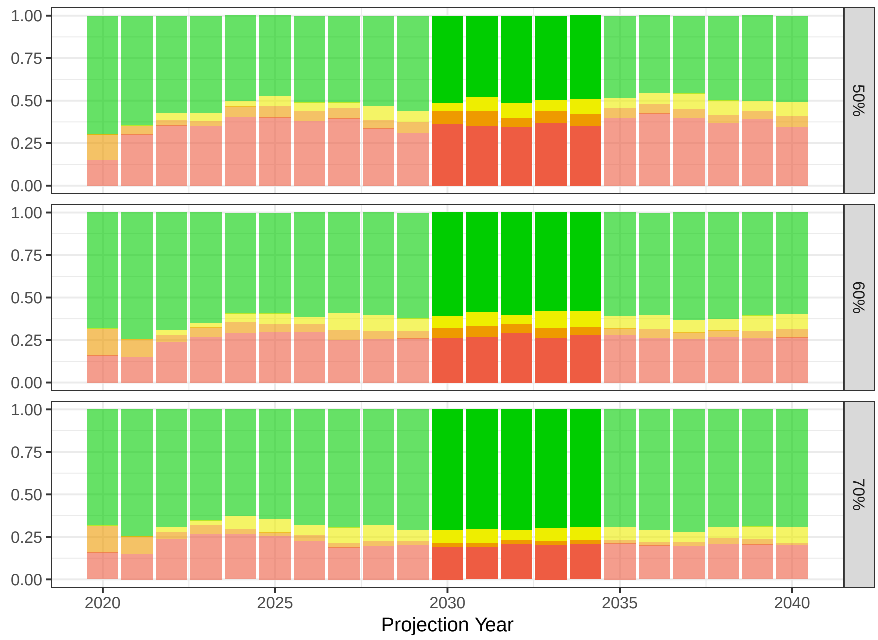


**Figure 1:** Kobe time series for MPs listed in Table 5. Average quadrant probabilities for each year, across all MPs within the tuning criteria, are shown. Probabilities between 2030 and 2034 were used to select MPs using the tuning criteria.

The biomass, catch and exploitation rate dynamics are illustrated in Figures 5, 6 and 7. These are particularly useful for illustrating the system variability for each MP. It can be seen for instance, that MPs tuned to the 50% criteria (MPs 16 to 19), typically have a higher system variability when compared to MPs with otherwise similar tuning parameters (MPs 4 to 13). Within tuning criteria groups, it can also be seen that lower values for $a_X$ and $a_T$ lead to more stability in the catch and exploitation rates.

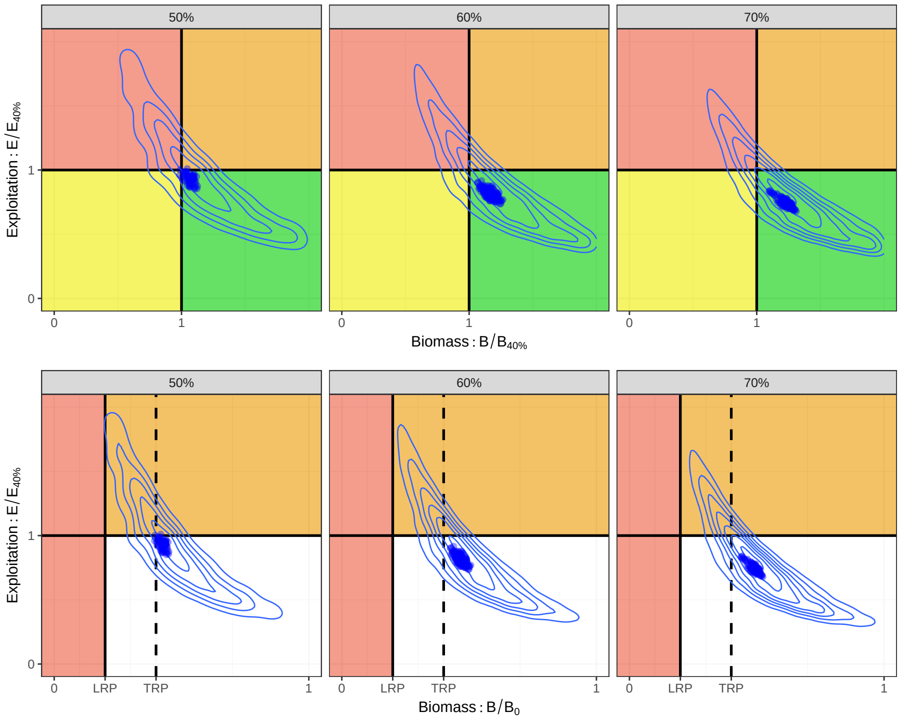


**Figure 2:** Kobe phase plots (top panel) and Majuro phase plots (bottom panel). Contours show a two-dimensional histogram of stock status across all years for which the MP was used to set catches (i.e. 2024 to 2040), twelve model runs, iterations, and MPs grouped by tuning criteria. Blue points show the median values per year and MP for each tuning criteria.

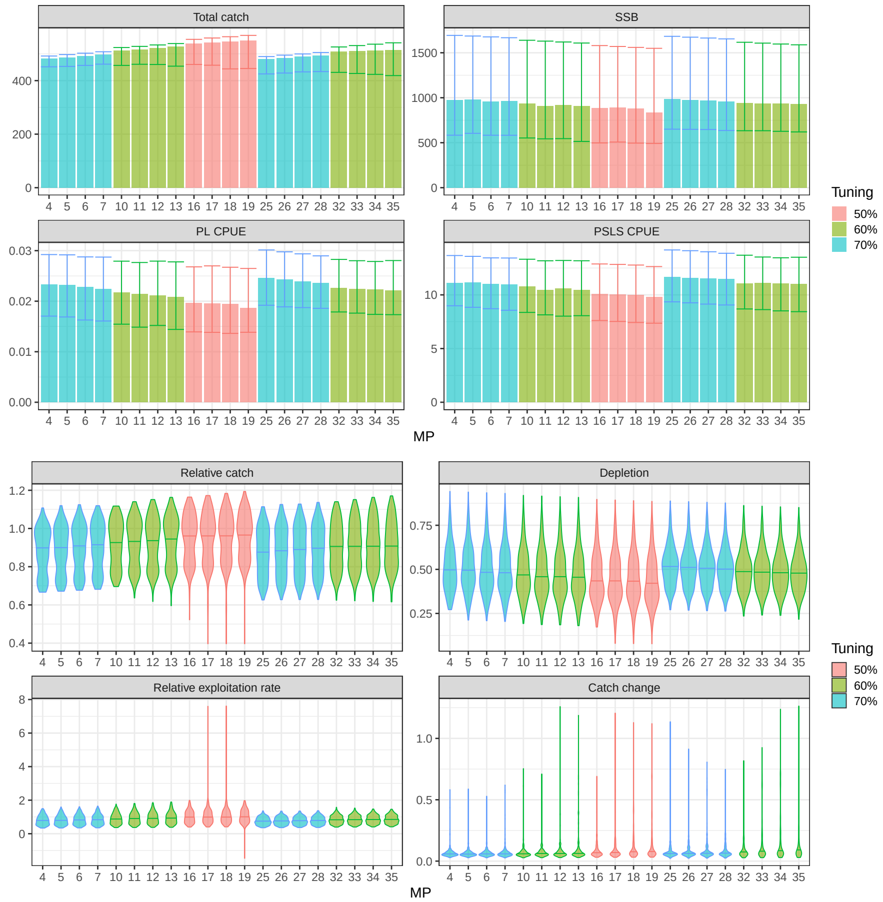


**Figure 3:** Diagnostic outputs (Table 4) for MPs listed in Table 5.

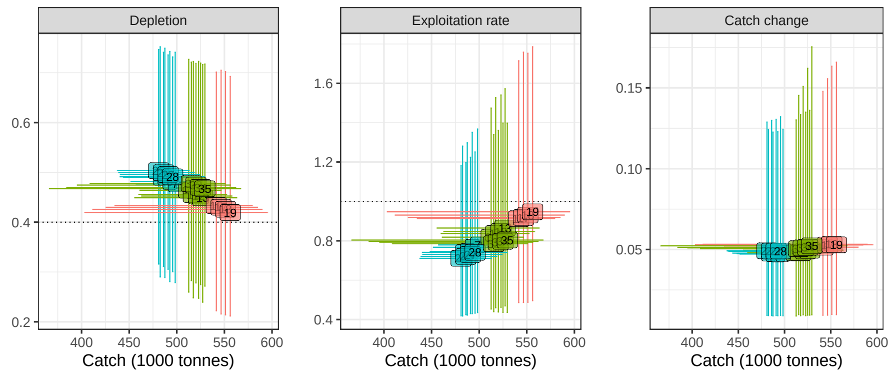


**Figure 4:** Tradeoff plots showing the total catch against: depletion relative to $B_0$; exploitation rate relative to $E_{40\%}$; and the catch change (see Table 4). MPs are listed in Table 5.

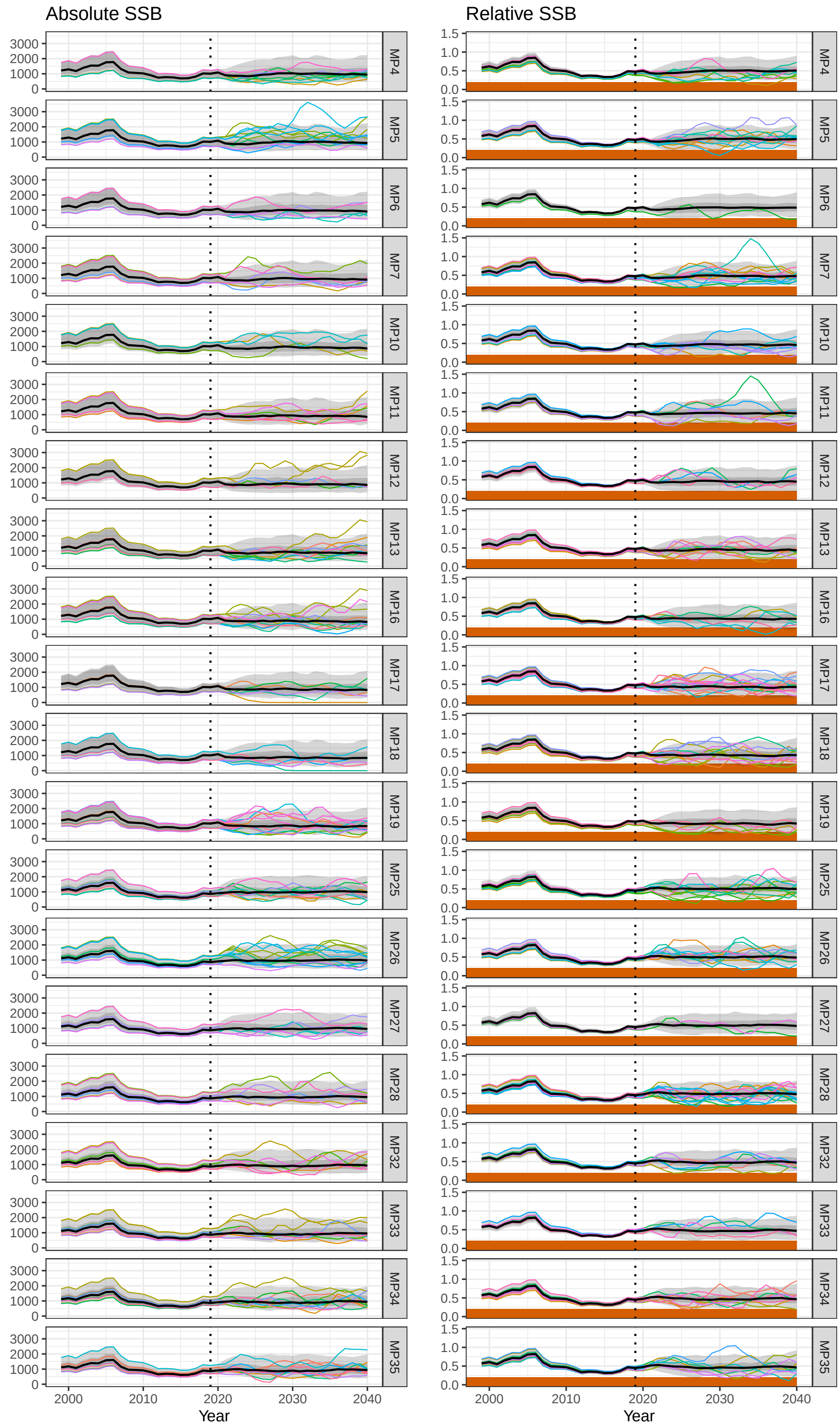


**Figure 5:** Spawning stock biomass dynamics following projection under each MP (Table 5). A sample of stochastic iterations is shown with 90% and 50% quantiles shaded in grey. Relative values are given according to $B_0$ for each run. Depletion values of 0-20% (i.e. below the LRP) in shaded red.

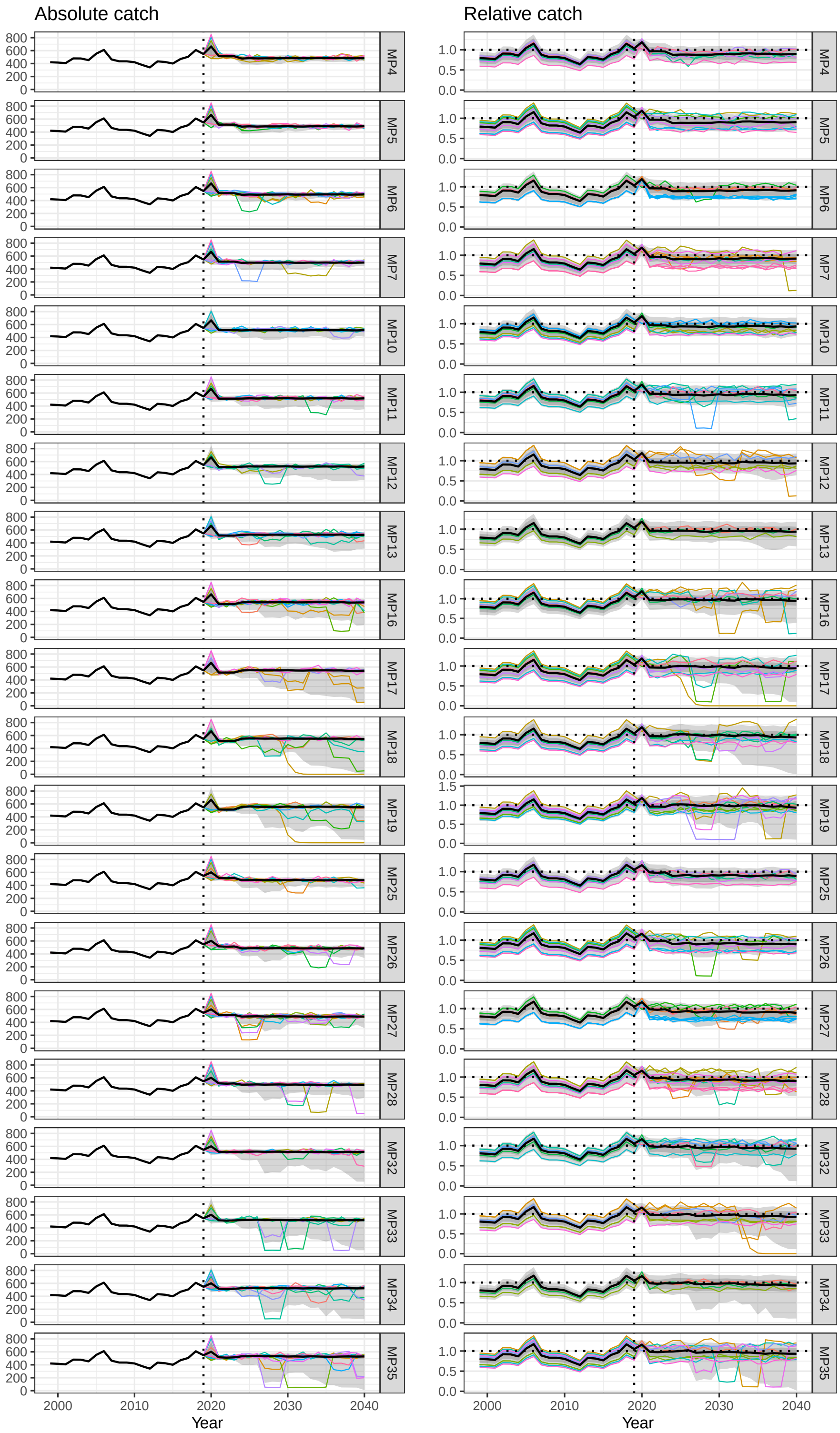


**Figure 6:** Catch dynamics following projection under each MP (Table 5). A sample of stochastic iterations is shown with 90% and 50% quantiles shaded in grey. Relative values are given according to $C_{40\%}$ for each run.

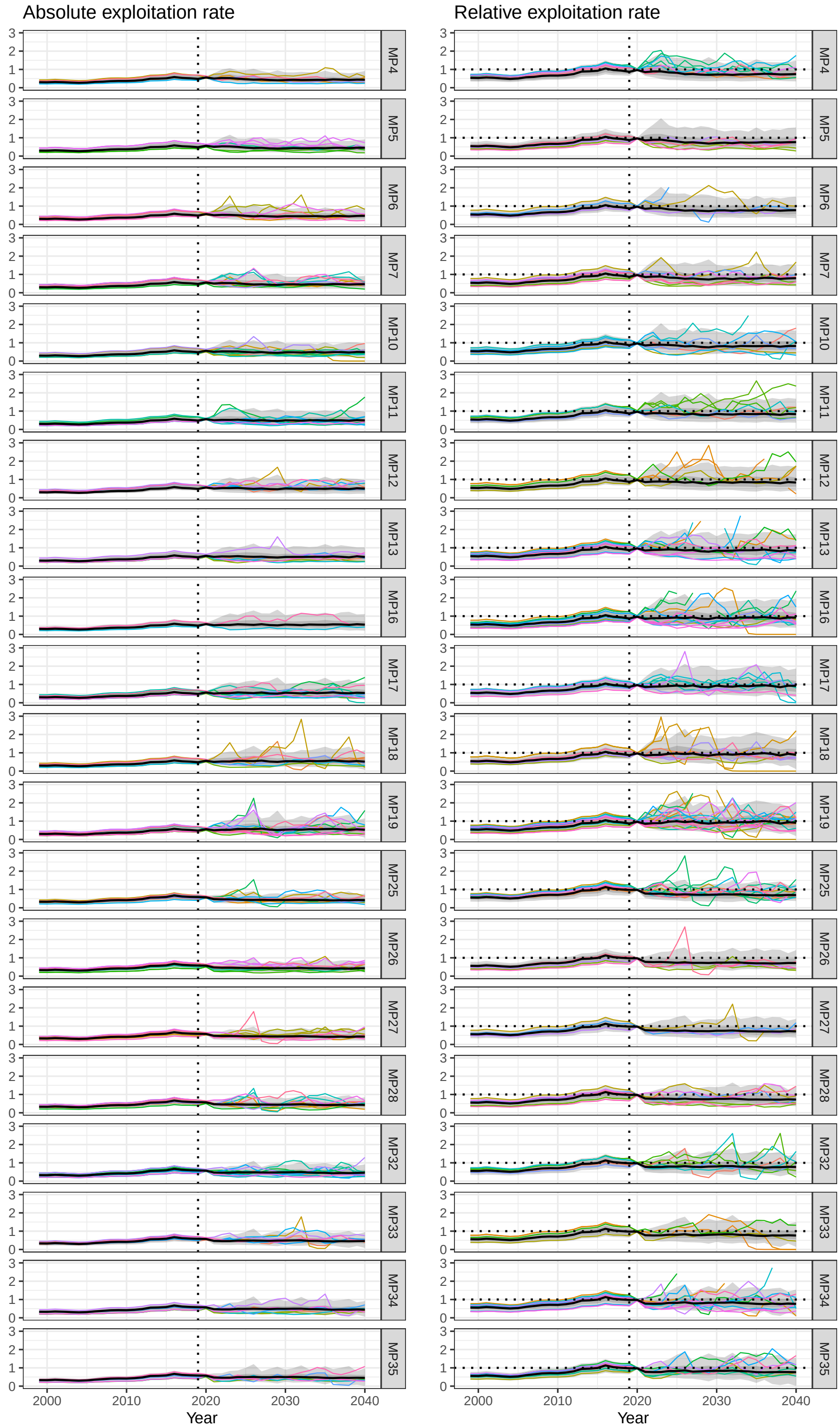


**Figure 7:** Exploitation rate dynamics following projection under each MP (Table 5). A sample of stochastic iterations is shown with 90% and 50% quantiles shaded in grey. Relative values are given according to $E_{40\%}$ for each run. Both absolute and relative exploitation rates are given an upper bound of $E_y = 3$

## 4 Summary and further work

Out of 42 MPs simulation tested, this work has presented summary statistics and performance diagnostics for those that passed the 50% (4 MPs), 60% (8 MPs) and 70% (8 MPs) tuning criteria. These performance metrics are all dependent on consistent future calculation of the PL (Medley et al., 2020a,b) and PSLS (Guery, 2020, Guery et al., 2020) CPUE indices currently available.

Before an MP is selected as the most likely to lead to a desirable management outcome, further simulation testing will be required, particularly concerning alternate future recruitment assumptions and implementation error. Feedback from the Working Party on Methods is required concerning the current suite of MPs, how their performance is measured and the desirable tuning criteria for the stock.

## 5 Acknowledgements

I am grateful to Dan Fu (IOTC) for providing the SS III files and to Alistair Dunn (Ocean Environmental) for providing computer support.

This project was funded by the IOTC under project code MTF/INT/661/MUL (TFAA970097099).

## 6 References

Adam, S., Bentley, N., 2013. Progress and arrangements for Management Strategy Evaluation work of Indian Ocean Skipjack Tuna. Research Report (IOTC-2013-WPTT15-42) .

Bentley, N., Adam, S., 2014a. Management procedure evaluation for the Indian Ocean skipjack tuna fishery: model description and conditioning. Research Report (IOTC-2014-WPM05-08) .

Bentley, N., Adam, S., 2014b. Management Strategy Evaluation for Indian ocean skipjack tuna: first steps. Research Report (IOTC-2014-WPTT16-39) .

Bentley, N., Adam, S., 2015. An operating model for the Indian Ocean skipjack tuna fishery. Research Report (IOTC-2015-WPTT17-35) .

Bentley, N., Adam, S., 2016. Management strategy evaluation for the Indian Ocean skipjack tuna Fishery. Research Report (IOTC-2016-WPM07-15 Rev 1) .

Breen, P.A., Bentley, N., Haist, V., Starr, P.J., Sykes, D.R., 2016. Management Procedures for New Zealand Rock Lobster Stocks. Management Science in Fisheries (Chapter 6) .

Edwards, C.T.T., 2020a. Applications of a Bayesian biomass dynamic model to Indian Ocean Skipjack Tuna. Research Report (IOTC–2020–WPM11–09) .

Edwards, C.T.T., 2020b. Developments toward an MSE framework for Indian Ocean skipjack tuna using Stock Synthesis III. Research Report (IOTC–2020–WPM11–10) .

Edwards, C.T.T., 2021. Initial developments of an empirical MP for Indian Ocean Skipjack Tuna. Research Report (IOTC–2021–TCMP04–07) .

Fu, D., 2017. Indian Ocean Skipjack Tuna stock assessment 1950–2016 (Stock Synthesis). Research Report (IOTC–2017–WPTT19–47 Rev 1) .

Fu, D., 2020. Preliminary Indian Ocean Skipjack Stock Assessment (Stock Synthesis). Research Report (IOTC–2020–WPTT22(AS)–10) .

Geromont, H.F., Butterworth, D.S., 2015a. Complex assessments or simple management procedures for efficient fisheries management: a comparative study. ICES Journal of Marine Science 72, 262–274.

Geromont, H.F., Butterworth, D.S., 2015b. Generic management procedures for data-poor fisheries: forecasting with few data. ICES Journal of Marine Science 72, 251–261.

Guery, L., 2020. Standardized purse seine CPUE of skipjack in the Indian Ocean for the European fleet. Research Report (IOTC–2020–WPTT22(AS)–INF04) .

Guery, L., Aragno, V., Kaplan, D., M., G., Baez, J., Abascal, F., J., U., Marsac, F., Merino, G., Gaertner, D., 2020. Skipjack CPUE series standardization by fishing mode for the European purse seiners operating in the Indian Ocean. Research Report (IOTC–2020–WPTT22(DP)–12) .

Hoshino, E., Hillary, R., Davies, C., Satria, F., Sadiyah, L., Ernawati, T., Proctor, C., 2020. Development of pilot empirical harvest strategies for tropical tuna in Indonesian archipelagic waters: Case studies of skipjack and yellowfin tuna. Fisheries Research 227, 105539.

IOTC, 2015. IOTC Conservation and Management Measures, Resolution 15/10, On Target and Limit Reference Points and a Decision Framework. IOTC–2015–CMM–R[E] .

IOTC, 2016. IOTC Conservation and Management Measures, Resolution 16/02, On Harvest Control Rules for Skipjack in the IOTC Area of Competence. IOTC–2016–CMM–R[E] .

IOTC, 2017. Report of the 19th Session of the IOTC Working Party on Tropical Tunas. Seychelles, 17– 22 October 2017. IOTC–2017–WPTT19–R[E] .

IOTC, 2020a. Report of the 11th Session of the IOTC Working Party on Methods. Virtual Meeting, 14 - 15 October 2020. IOTC–2020–WPM11–R[E] Rev1 .

IOTC, 2020b. Report of the 22nd Session of the IOTC Working Party on Tropical Tunas, Stock Assessment Meeting. Virtual Meeting, 19 - 23 October 2020. IOTC–2020–WPTT22(AS)–R[E] Rev1 .

IOTC, 2020c. Report of the 23rd Session of the IOTC Scientific Committee. IOTC–2020–SC23–R[E] .

IOTC, 2021a. Defining stock status against conservation and management reference points: a global review for informing the process of status determination for key IOTC stocks; Ad-Hoc Reference Point Working Group. IOTC-2021-TCMP04-12 Rev1 .

IOTC, 2021b. Report of the 12th Session of the IOTC Working Party on Methods (Management Strategy Evaluation Task Force). Virtual Meeting, 1-5 March 2021. IOTC–2021–WPM12(MSE)–R[E] .

IOTC, 2021c. Report of the 4th IOTC Technical Committee on Management Procedures. Virtual Meeting, 4 - 5 June 2021. IOTC–2021–TCMP04–R[E] .

Medley, P., Ahusan, M., Adam, S., 2020a. Addendum to IOTC-2020-WPTT22(DP)-11. Research Report (IOTC–2020–WPTT22(AS)–INF05) .

Medley, P., Ahusan, M., Adam, S., 2020b. Bayesian Skipjack and Yellowfin Tuna CPUE Standardisation Model for Maldives Pole and Line 1970-2019. Research Report (IOTC-2020-WPTT22(DP)-11) .

Methot Jr., R., Wetzel, C., 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fisheries Research 142, 86–99.

Punt, A.E., Butterworth, D.S., de Moor, C.L., De Oliveira, J.A.A., Haddon, M., 2016. Management strategy evaluation: best practices. Fish and Fisheries 17, 303–334.

R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. URL: `https://www.R-project.org/`. version 4.0.5.

Rademeyer, R.A., Plaganyi, E.E., Butterworth, D.S., 2007. Tips and tricks in designing management procedures. ICES Journal of Marine Science 64, 618–625.

Taylor, I.G., Doering, K.L., Johnson, K.F., Wetzel, C.R., Stewart, I.J., 2021. Beyond visualizing catch-at-age models: Lessons learned from the r4ss package about software to support stock assessments. Fisheries Research 239, 105924. URL: https://doi.org/10.1016/j.fishres.2021.105924.

# A Appendix

**Table A1:** List of twelve single area SS III assessment runs used as operating models, reproduced from Table 2 of IOTC (2020b)

| Label | Steepnes ($h$) | Catchability trend | Tag likelihood weighting ($\lambda$) |
|---|---|---|---|
| io_h70_q0_tlambda01 | 0.7 | 1.0000 | 0.1 |
| io_h70_q0_tlambda1 | 0.7 | 1.0000 | 1.0 |
| io_h70_q1_tlambda01 | 0.7 | 1.0125 | 0.1 |
| io_h70_q1_tlambda1 | 0.7 | 1.0125 | 1.0 |
| io_h80_q0_tlambda01 | 0.8 | 1.0000 | 0.1 |
| io_h80_q0_tlambda1 | 0.8 | 1.0000 | 1.0 |
| io_h80_q1_tlambda01 | 0.8 | 1.0125 | 0.1 |
| io_h80_q1_tlambda1 | 0.8 | 1.0125 | 1.0 |
| io_h90_q0_tlambda01 | 0.9 | 1.0000 | 0.1 |
| io_h90_q0_tlambda1 | 0.9 | 1.0000 | 1.0 |
| io_h90_q1_tlambda01 | 0.9 | 1.0125 | 0.1 |
| io_h90_q1_tlambda1 | 0.9 | 1.0125 | 1.0 |

**Table A2:** Tuning parameters for all MPs evaluated

| MP | $I_{min}$ | $I_{max}$ | $a_X$ | $a_T$ | $C_{TARGET}$ |
|---|---|---|---|---|---|
| MP1 | 0.10 | 0.90 | -5.00 | -1.70 | 521.64 |
| MP2 | 0.10 | 0.91 | -5.00 | -1.70 | 521.64 |
| MP3 | 0.10 | 0.92 | -5.00 | -1.70 | 521.64 |
| MP4 | 0.10 | 0.93 | -5.00 | -1.70 | 521.64 |
| MP5 | 0.10 | 0.94 | -5.00 | -1.70 | 521.64 |
| MP6 | 0.10 | 0.95 | -5.00 | -1.70 | 521.64 |
| MP7 | 0.10 | 0.96 | -5.00 | -1.70 | 521.64 |
| MP8 | 0.10 | 0.97 | -5.00 | -1.70 | 521.64 |
| MP9 | 0.10 | 0.98 | -5.00 | -1.70 | 521.64 |
| MP10 | 0.10 | 0.99 | -5.00 | -1.70 | 521.64 |
| MP11 | 0.10 | 1.00 | -5.00 | -1.70 | 521.64 |
| MP12 | 0.10 | 1.01 | -5.00 | -1.70 | 521.64 |
| MP13 | 0.10 | 1.02 | -5.00 | -1.70 | 521.64 |
| MP14 | 0.10 | 1.03 | -5.00 | -1.70 | 521.64 |
| MP15 | 0.10 | 1.04 | -5.00 | -1.70 | 521.64 |
| MP16 | 0.10 | 1.05 | -5.00 | -1.70 | 521.64 |
| MP17 | 0.10 | 1.06 | -5.00 | -1.70 | 521.64 |
| MP18 | 0.10 | 1.07 | -5.00 | -1.70 | 521.64 |
| MP19 | 0.10 | 1.08 | -5.00 | -1.70 | 521.64 |
| MP20 | 0.10 | 1.09 | -5.00 | -1.70 | 521.64 |
| MP21 | 0.10 | 1.10 | -5.00 | -1.70 | 521.64 |
| MP22 | 0.10 | 0.90 | -3.00 | -1.20 | 521.64 |
| MP23 | 0.10 | 0.91 | -3.00 | -1.20 | 521.64 |
| MP24 | 0.10 | 0.92 | -3.00 | -1.20 | 521.64 |
| MP25 | 0.10 | 0.93 | -3.00 | -1.20 | 521.64 |
| MP26 | 0.10 | 0.94 | -3.00 | -1.20 | 521.64 |
| MP27 | 0.10 | 0.95 | -3.00 | -1.20 | 521.64 |
| MP28 | 0.10 | 0.96 | -3.00 | -1.20 | 521.64 |
| MP29 | 0.10 | 0.97 | -3.00 | -1.20 | 521.64 |
| MP30 | 0.10 | 0.98 | -3.00 | -1.20 | 521.64 |
| MP31 | 0.10 | 0.99 | -3.00 | -1.20 | 521.64 |
| MP32 | 0.10 | 1.00 | -3.00 | -1.20 | 521.64 |
| MP33 | 0.10 | 1.01 | -3.00 | -1.20 | 521.64 |
| MP34 | 0.10 | 1.02 | -3.00 | -1.20 | 521.64 |
| MP35 | 0.10 | 1.03 | -3.00 | -1.20 | 521.64 |
| MP36 | 0.10 | 1.04 | -3.00 | -1.20 | 521.64 |
| MP37 | 0.10 | 1.05 | -3.00 | -1.20 | 521.64 |
| MP38 | 0.10 | 1.06 | -3.00 | -1.20 | 521.64 |
| MP39 | 0.10 | 1.07 | -3.00 | -1.20 | 521.64 |
| MP40 | 0.10 | 1.08 | -3.00 | -1.20 | 521.64 |
| MP41 | 0.10 | 1.09 | -3.00 | -1.20 | 521.64 |
| MP42 | 0.10 | 1.10 | -3.00 | -1.20 | 521.64 |

**Table A3:** Diagnostic outputs for evaluation of MPs (see Table 5 for the list of MP definitions and Table 4 for a description of each diagnostic).

| Performance Statistic | MP4 | MP5 | MP6 | MP7 | MP10 | MP11 | MP12 | MP13 | MP16 | MP17 | MP18 | MP19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Catch** | | | | | | | | | | | | |
| C | 482.04 | 487.22 | 491.87 | 497.55 | 511.64 | 516.30 | 521.75 | 526.52 | 538.98 | 543.14 | 546.19 | 550.40 |
| $C_{[PL]}$ | 77.70 | 78.58 | 79.36 | 80.23 | 82.50 | 83.11 | 84.02 | 84.76 | 86.84 | 87.61 | 88.35 | 88.99 |
| $C_{[PSLS]}$ | 185.04 | 186.94 | 188.79 | 190.89 | 196.45 | 197.98 | 200.14 | 201.98 | 206.75 | 208.53 | 210.24 | 210.99 |
| $C_{[PSFS]}$ | 27.89 | 28.19 | 28.46 | 28.76 | 29.57 | 29.82 | 30.17 | 30.41 | 31.12 | 31.40 | 31.60 | 31.81 |
| $C_y/C_{40\%}$ | 0.88 | 0.88 | 0.89 | 0.89 | 0.92 | 0.92 | 0.92 | 0.93 | 0.94 | 0.94 | 0.94 | 0.94 |
| **Catch stability** | | | | | | | | | | | | |
| Pr. $C_y = 0$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pr. $> C_{y-1}$ | 0.49 | 0.49 | 0.50 | 0.50 | 0.50 | 0.50 | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | 0.52 |
| Pr. $< C_{y-1}$ | 0.51 | 0.51 | 0.50 | 0.50 | 0.50 | 0.50 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.48 |
| $\lvert C_{y+1}/C_y - 1\rvert$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.07 | 0.07 | 0.07 | 0.07 |
| **Catch rate** | | | | | | | | | | | | |
| $CPUE_{[PL]}$ | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| $CPUE_{[PSLS]}$ | 11.05 | 11.01 | 10.83 | 10.75 | 10.50 | 10.38 | 10.35 | 10.24 | 9.96 | 9.92 | 9.86 | 9.70 |
| **Exploitation rate** | | | | | | | | | | | | |
| $E_y$ | 0.45 | 0.45 | 0.47 | 0.47 | 0.48 | 0.50 | 0.50 | 0.51 | 0.55 | 0.54 | 0.54 | 0.55 |
| $E_y/E_{40\%}$ | 0.77 | 0.77 | 0.80 | 0.80 | 0.83 | 0.86 | 0.85 | 0.89 | 0.95 | 0.94 | 0.94 | 0.97 |
| **Stock biomass** | | | | | | | | | | | | |
| $B_y$ | 976.69 | 981.43 | 960.13 | 963.49 | 937.41 | 908.01 | 921.04 | 909.98 | 883.81 | 891.61 | 880.73 | 835.99 |
| $B_y/B_0$ | 0.48 | 0.48 | 0.47 | 0.46 | 0.45 | 0.44 | 0.43 | 0.43 | 0.41 | 0.41 | 0.41 | 0.40 |
| $B_{MIN}/B_0$ | 0.31 | 0.31 | 0.31 | 0.30 | 0.29 | 0.28 | 0.28 | 0.27 | 0.24 | 0.25 | 0.25 | 0.23 |
| Pr. $> B_{20\%}$ | 0.97 | 0.97 | 0.97 | 0.97 | 0.95 | 0.95 | 0.94 | 0.94 | 0.92 | 0.91 | 0.92 | 0.91 |
| Pr. $> B_{10\%}$ | 1.00 | 1.00 | 1.00 | 0.99 | 0.99 | 0.99 | 0.99 | 0.98 | 0.98 | 0.98 | 0.98 | 0.97 |
| **Kobe Quadrants** | | | | | | | | | | | | |
| Pr. Red | 0.23 | 0.22 | 0.24 | 0.25 | 0.28 | 0.30 | 0.31 | 0.33 | 0.36 | 0.37 | 0.37 | 0.38 |
| Pr. Green | 0.69 | 0.69 | 0.66 | 0.65 | 0.61 | 0.59 | 0.58 | 0.57 | 0.52 | 0.51 | 0.49 | 0.48 |
| **Majuro Quadrants** | | | | | | | | | | | | |
| Pr. Red | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pr. White | 0.88 | 0.88 | 0.82 | 0.82 | 0.76 | 0.71 | 0.71 | 0.65 | 0.59 | 0.53 | 0.53 | 0.47 |

**Table A3:** (*Continued*) Diagnostic outputs for evaluation of MPs (see Table 5 for the list of MP definitions and Table 4 for a description of each diagnostic).

| Performance Statistic | MP25 | MP26 | MP27 | MP28 | MP32 | MP33 | MP34 | MP35 |
|---|---|---|---|---|---|---|---|---|
| **Catch** | | | | | | | | |
| C | 480.01 | 484.67 | 489.33 | 493.91 | 507.89 | 509.95 | 513.10 | 515.09 |
| $C_{[PL]}$ | 77.35 | 78.10 | 78.81 | 79.47 | 81.82 | 82.50 | 82.80 | 83.06 |
| $C_{[PSLS]}$ | 184.17 | 185.84 | 187.47 | 189.27 | 194.27 | 195.45 | 196.46 | 197.26 |
| $C_{[PSFS]}$ | 27.54 | 27.81 | 28.08 | 28.24 | 29.16 | 29.34 | 29.57 | 29.65 |
| $C_y/C_{40\%}$ | 0.86 | 0.87 | 0.88 | 0.88 | 0.87 | 0.87 | 0.87 | 0.86 |
| **Catch stability** | | | | | | | | |
| Pr. $C_y = 0$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pr. $> C_{y-1}$ | 0.48 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.49 | 0.50 |
| Pr. $< C_{y-1}$ | 0.52 | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | 0.51 | 0.50 |
| $\|C_{y+1}/C_y - 1\|$ | 0.06 | 0.06 | 0.06 | 0.06 | 0.07 | 0.07 | 0.08 | 0.08 |
| **Catch rate** | | | | | | | | |
| $CPUE_{[PL]}$ | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| $CPUE_{[PSLS]}$ | 11.60 | 11.52 | 11.43 | 11.35 | 11.11 | 11.04 | 11.01 | 10.95 |
| **Exploitation rate** | | | | | | | | |
| $E_y$ | 0.42 | 0.43 | 0.44 | 0.45 | 0.46 | 0.46 | 0.46 | 0.46 |
| $E_y/E_{40\%}$ | 0.71 | 0.72 | 0.73 | 0.74 | 0.78 | 0.78 | 0.78 | 0.78 |
| **Stock biomass** | | | | | | | | |
| $B_y$ | 985.70 | 974.84 | 967.23 | 958.87 | 943.75 | 937.60 | 934.79 | 928.09 |
| $B_y/B_0$ | 0.51 | 0.50 | 0.49 | 0.49 | 0.47 | 0.46 | 0.46 | 0.46 |
| $B_{MIN}/B_0$ | 0.33 | 0.32 | 0.32 | 0.31 | 0.29 | 0.28 | 0.28 | 0.27 |
| Pr. $> B_{20\%}$ | 0.99 | 0.99 | 0.99 | 0.98 | 0.97 | 0.97 | 0.97 | 0.97 |
| Pr. $> B_{10\%}$ | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.99 | 1.00 |
| **Kobe Quadrants** | | | | | | | | |
| Pr. Red | 0.17 | 0.18 | 0.19 | 0.20 | 0.23 | 0.23 | 0.24 | 0.25 |
| Pr. Green | 0.73 | 0.72 | 0.70 | 0.69 | 0.64 | 0.63 | 0.62 | 0.60 |
| **Majuro Quadrants** | | | | | | | | |
| Pr. Red | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Pr. White | 0.88 | 0.88 | 0.88 | 0.88 | 0.79 | 0.76 | 0.76 | 0.71 |