Initial robustness trial of empirical MPs for Indian Ocean skipjack tuna

Prepared for the Indian Ocean Tuna Commission

March 17, 2023

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, 2023
Date of report:	March 17, 2023
Prepared for:	IOTC 14th Working Party on Methods, March 2023

Contents

Project Background and Objectives

The 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.

A simulation framework has been proposed to the Working Party on Methods (WPM; Edwards, 2020, IOTC, 2020a) and the Technical Committee on Management Procedures (TCMP; Edwards, 2021b, IOTC, 2021c), and evaluations of an empirical MP were delivered to the WPM (Edwards, 2021a), and the MSE Task Force (Edwards, 2022a). At the TCMP in 2022, a preliminary set of MPs was presented (Edwards, 2022b) and received feedback from the TCMP (IOTC, 2022b). In particular:

> 67. The TCMP NOTED that previously, a request had been made to the developer to remove positive bias in catches and therefore implementation error had been removed from the OM tuning. The TCMP AGREED that it is best practice to include implementation error and this option should once again be explored in the tuning. In addition, the tuning should continue to use the three options for being in the green zone of 50%, 60% and 70%.

In response, candidate MPs were tuned to the 50%, 60% and 70% turning criteria under the assumption of constant, positive implementation error values of 10%, 20%, 30% and 40%. These results were presented by Edwards (2022c) to the WPM (IOTC, 2022a). The current work is a first step towards testing robustness of these candidate MPs to recruitment failure, and ability of the MPs to recover the fishery.

1 Introduction

Empirical Management Procedures for Indian Ocean SKJ, based on CPUE indices from the PL and PSLS fleets, have been evaluated by simulation and presented to the WPM and TCMP (Edwards, 2021a,b, 2022a,b,c). Management Procedures were tuned using the Kobe Green quadrant as a measure of stock status. Specifically, MPs were selected using the simulated probability of the stock being in the Kobe Green quadrant between 2030 to 2034 inclusive. Based on recommendations from the IOTC (2021c), tuning criteria that matched a 50%, 60% and 70% probability were adopted.

At the TCMP in 2022 it was agreed that the MPs should include implementation error during the tuning: i.e., MPs should be tuned to the 50%, 60% and 70% levels with a degree of implementation error assumed (IOTC, 2022b). Based on this request, a set of candidate MPs was presented to the WPM by Edwards (2022c). In this work, MPs were tuned assuming an implementation error of between 10% and 40%. Given a known TAC of 513,572 tonnes for the period 2021 to 2023 (IOTC, 2021c), the MP was assumed by the simulation to set catches from 2024 onwards with a positive implementation error consistently applied over the period from 2021 (the first year of projected catches) to 2040.

The current work presents an initial set of robustness trials of the candidate MPs presented by Edwards (2022c). In particular, it tests robustness of each MP to recruitment failure. The recruitment failure scenario was chosen as the most extreme from those initially presented by Edwards (2022b). This involved a 50% drop in recruitment between the years 2023 to 2025; i.e., immediately before and after the first year in which the candidate MP is used to set the TAC (2024). The magnitude of the recruitment failure was recommended by IOTC (2021b).

Each candidate MP, tuned to each of the three tuning criteria, and assuming each of the four implementation error scenarios (a total of twelve combinations) was simulation tested assuming recruitment failure. Performance diagnostics were presented in accordance with the recommendations of IOTC (2021a). These are described in detail by Edwards (2022a), along with set up of the operating model and simulation framework. For ease of reference, the empirical MP being simulated is described again here, along with tuning parameters selected by Edwards (2022c).

2 Empirical MPs

2.1 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 (Edwards, 2021b).

2.2 Harvest control rule

As part of the MP, calculation of a recommended catch from the data inputs occurs via a harvest control rule (HCR). In the current context, the recommended catch, $C^{TAC}_{y+1:3}$ is adjusted using values of a_y as input:

$$C^{TAC}_{y+1:3} = \begin{cases} C_{max} & \text{for} \quad a_y \geq a_T \\ (C_{max} - C_{min}) \times \frac{a_y - a_X}{a_T - a_X} + C_{min} & \text{for} \quad a_X < a_y < a_T \\ C_{min} & \text{for} \quad a_y \leq a_X \end{cases} \tag{1}$$

For values $a_y \leq a_X$, the recommended catch is equal to C_{min}. As a_y increases, the recommended catch also increases, until for values of $a_y \geq a_T$ the recommended catch is equal to C_{max}. A schematic of the relationship between a_y and $C^{TAC}_{y+1:3}$ is given in Figure 1. When applying the MP, there is a lag of one year between calculation of the input data in year y and setting of the catch for years $y+1$ to $y+3$.

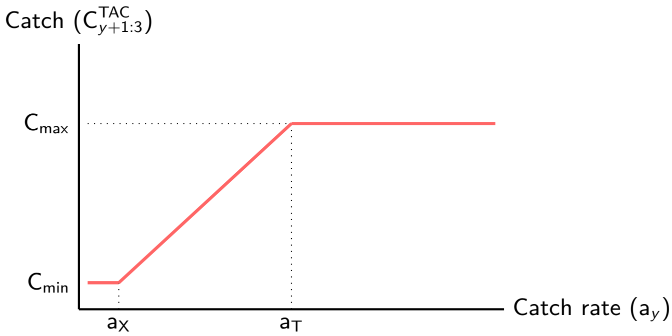


Figure 1: Schematic representation of the empirical Harvest Control Rule (Equation 1) being proposed as part of the MP.

2.3 HCR tuning parameters

Information on the history of exploitation for the stock, condensed into the most recent stock assessment, was used to select an appropriate level for the maximum catch C_{max}. From the assessment of Fu (2020), we can infer that deterministic $C_{40\%} \approx 532,075$ tonnes (Table 2). Proposed values for the maximum catch C_{max} were informed by our knowledge of $C_{40\%}$, with simulation then used to select a value likely to yield the desired management outcome. Specifically during tuning, the value for C_{max} was varied from 185 to 560 thousand tonnes in increments of 5 thousand tonnes (Edwards, 2022c). The minimum catch was fixed at $C_{min} = 0.10 \times C_{40\%} \approx 53,208$ tonnes. Based on previous work by Edwards (2021b), $a_X = -5.00$ and $a_T = -1.70$ were selected as appropriate tuning parameters for the HCR.

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

Notation	Description
Output	
$C^{TAC}_{y+1:3}$	Total recommended catch for years $y+1$ to $y+3$
Tuning parameters	
C_{min}, C_{max}	Min. and Max. catch outputs
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	
$C_{40\%}$	Catch associated with $B_{40\%}$
TRP	Target Reference point ($B_{40\%}$)
LRP	Limit Reference point ($B_{20\%}$)

Table 2: Median and 80% quantile status estimates across twenty-four model runs (Edwards, 2022b), estimated using SS3.30. Catch and biomass values are given in units of 1000 tonnes. This table is equivalent to the stock assessment results given in Table 3 of IOTC (2020b). Values for 2020 are estimated assuming a one-year projection from 2019 with exploitation equal to $E_{40\%}$.

Quantity	Median (80% quantiles)
B_0	1984.605 (1744.839 - 2486.458)
$B_{40\%}$	793.842 (697.935 - 994.582)
B_{2020}	969.478 (706.899 - 1280.479)
$C_{40\%}$	532.075 (474.135 - 663.049)
C_{2020}	635.185 (483.536 - 790.993)
$E_{40\%}$	0.597 (0.541 - 0.65)
E_{2020}	0.58 (0.532 - 0.643)
B_{2020}/B_0	0.464 (0.389 - 0.518)
$B_{2020}/B_{40\%}$	1.161 (0.972 - 1.295)
$C_{2020}/C_{40\%}$	1.14 (1.003 - 1.246)
$E_{2020}/E_{40\%}$	0.98 (0.947 - 1.011)

Table 3: Diagnostic outputs for MP evaluations over 17 year projection period (2024 to 2040). 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. For catch stability statistics, only six TAC implementation years (from 2024 inclusive) were used.

Performance Statistic	Description	Summary statistic
Catch		
$C^{TAC}_{y+1:3}$	Total Allowable Catch	Mean
C	Total realised 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 (TAC years)		
C^{TAC}_{y+1} not equal to C^{TAC}_y	n. TAC changes	Count
$\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	TAC change	Mean % change
Max. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Max. TAC change	Max. % change
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 30\%$	TAC change $> 30\%$	Probability
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 15\%$	TAC change $> 15\%$	Probability
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. Kobe Red	$B_y < B_{40\%}$ and $E_y > E_{40\%}$	Probability
Pr. Kobe Green	$B_y > B_{40\%}$ and $E_y < E_{40\%}$	Probability
Majuro Quadrants		
Pr. Majuro Red	$B_y < B_{20\%}$	Probability
Pr. Majuro White	$B_y > B_{20\%}$ and $E_y < E_{40\%}$	Probability

2.4 MP tuning

MPs were tuned using the Kobe strategy matrix quadrants, so that all candidate MPs matched the 50%, 60% or 70% tuning criteria values for Pr. Kobe Green (Table 3) when averaged across projection years 11 to 15 (2030 to 2034 inclusive). This was repeated assuming positive implementation error values of:

- **R01:** 10%;
- **R02:** 20%;
- **R03:** 30%;
- **R04:** 40%.

For each implementation error, the three tuned candidate MPs are listed in Table 4. Some of the MPs were selected more than once, depending on the combination of tuning criteria and implementation error assumed. System dynamics under each of the candidate MPs, at each of the assumed levels of implementation error, are detailed by Edwards (2022c).

Table 4: MP tuning parameters and probability of being in the Kobe Green quadrant between 2030 and 2034. Probabilities are shown from the tuning described by Edwards (2022c) and for the robustness testing in the current report.

MP (tuning)	Imp. error	C_{min}	C_{max}	a_X	a_T	Pr. Kobe Green	
						Tuning	Robustness test
MP9 (Kobe 50%)	R01	53.21	516.11	-5.00	-1.70	0.49	0.43
MP8 (Kobe 60%)	R01	53.21	473.55	-5.00	-1.70	0.61	0.51
MP5 (Kobe 70%)	R01	53.21	430.98	-5.00	-1.70	0.70	0.61
MP7 (Kobe 50%)	R02	53.21	452.26	-5.00	-1.70	0.49	0.50
MP6 (Kobe 60%)	R02	53.21	436.30	-5.00	-1.70	0.60	0.57
MP4 (Kobe 70%)	R02	53.21	404.38	-5.00	-1.70	0.71	0.67
MP5 (Kobe 50%)	R03	53.21	430.98	-5.00	-1.70	0.49	0.40
MP4 (Kobe 60%)	R03	53.21	404.38	-5.00	-1.70	0.62	0.48
MP3 (Kobe 70%)	R03	53.21	388.41	-5.00	-1.70	0.70	0.54
MP4 (Kobe 50%)	R04	53.21	404.38	-5.00	-1.70	0.50	0.36
MP2 (Kobe 60%)	R04	53.21	383.09	-5.00	-1.70	0.59	0.43
MP1 (Kobe 70%)	R04	53.21	356.49	-5.00	-1.70	0.70	0.46

3 Results

Following tuning and the presentation of candidate MPs by Edwards (2022c), each MP was re-evaluated assuming recruitment failure (a drop in recruitment by 50%) between 2023 and 2025. Simulated Kobe quadrant probabilities over time are shown in Figures 2a to 2d. Recruitment failure leads to a sharp increase in the probability of the fishery being in the Kobe Red quadrant, and a drop in the probability of being in the Kobe Green quadrant during the tuning period (Table 4).

The timing of recruitment failure is such that it is assumed to occur immediately following the period 2021 to 2023, when the TAC is fixed at 513 thousand tonnes. The MP is used to set the TAC for 2024 to 2026, using the CPUE indices from the previous year. The MP does not therefore anticipate the recruitment failure, overestimates the TAC, and the stock is overfished (Figures 2, 3 and 4). Immediately following, for the period 2027 to 2029, the TAC is reduced to the minimum allowed of 53 thousand tonnes (Figure 5). As a consequence of this three year cut in the TAC, the stock recovers rapidly, and the TAC set by the MP for 2030 onwards is relatively high and stable.

Summary diagnostics for each MP under the assumed recruitment failure are shown in Figures 7 and Tables 5 to 8. These can be compared to the same Tables presented by Edwards (2022c). As a result of the recruitment failure, the SSB is lower. The TAC and Total catch are also lower, but result in a higher rate of exploitation. These patterns are to be expected from how the robustness test has been designed.

(a) Kobe time series for MPs, assuming an implementation error of 10% (R01).

(b) Kobe time series for MPs, assuming an implementation error of 20% (R02).

Figure 2: Kobe time series for MPs listed in Table 4, with assumed recruitment failure between 2023 and 2025. Average quadrant probabilities for each year, across all model runs and iterations for that MP, are shown. Probabilities between 2030 and 2034 inclusive were used to calculate the probabilities listed in the Table 4.

(c) Kobe time series for MPs, assuming an implementation error of 30% (R03).

(d) Kobe time series for MPs, assuming an implementation error of 40% (R04).

Figure 2: Kobe time series for MPs listed in Table 4, with assumed recruitment failure between 2023 and 2025. Average quadrant probabilities for each year, across all model runs and iterations for that MP, are shown. Probabilities between 2030 and 2034 inclusive were used to calculate the probabilities listed in the Table 4.

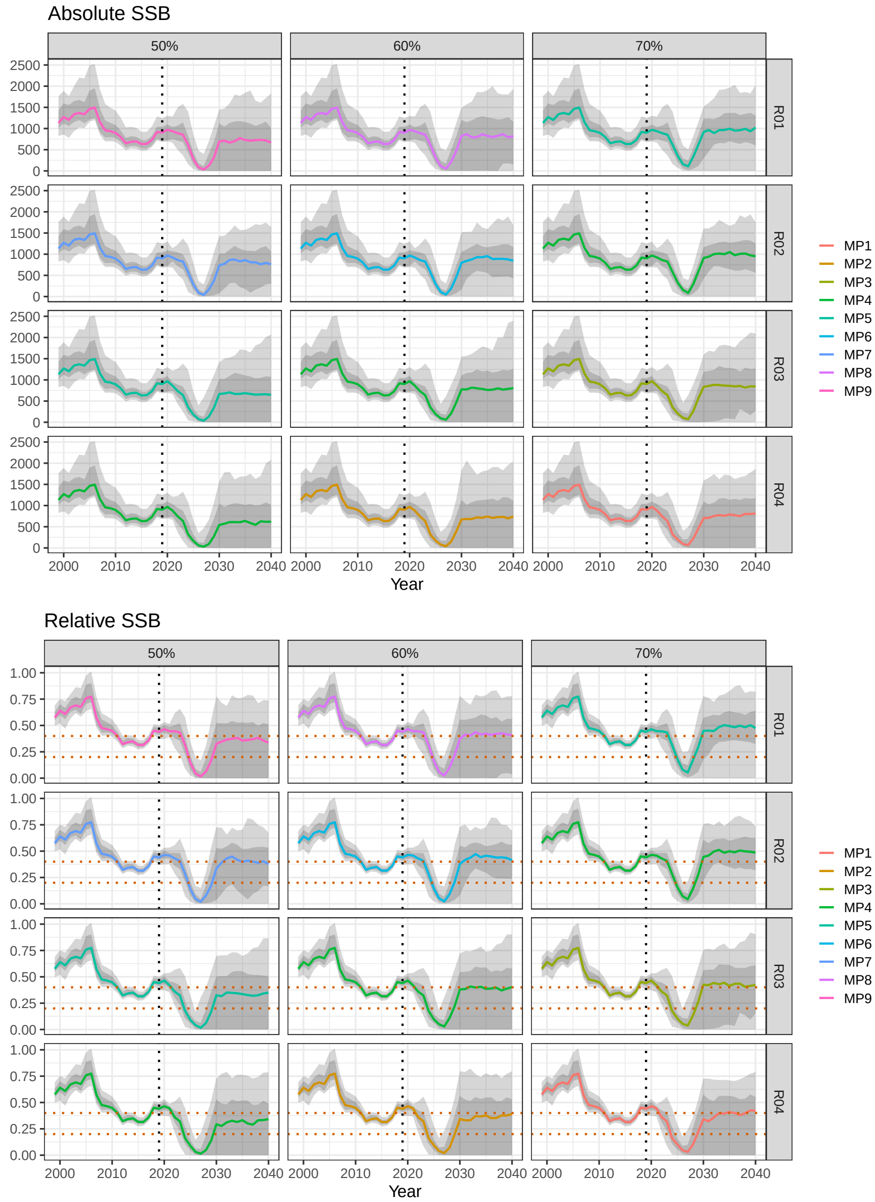


Figure 3: Spawning stock biomass dynamics following projection under each MP (Table 4), assuming recruitment failure between 2023 and 2025, with 90% and 50% quantiles shaded in grey. Projections are shown for each tuning criteria (50%, 60% and 70%), and each implementation error (R01 to R04). Relative values are given according to B_0 for each run. Depletion reference points of 20% and 40% are shown as horizontal dashed lines.

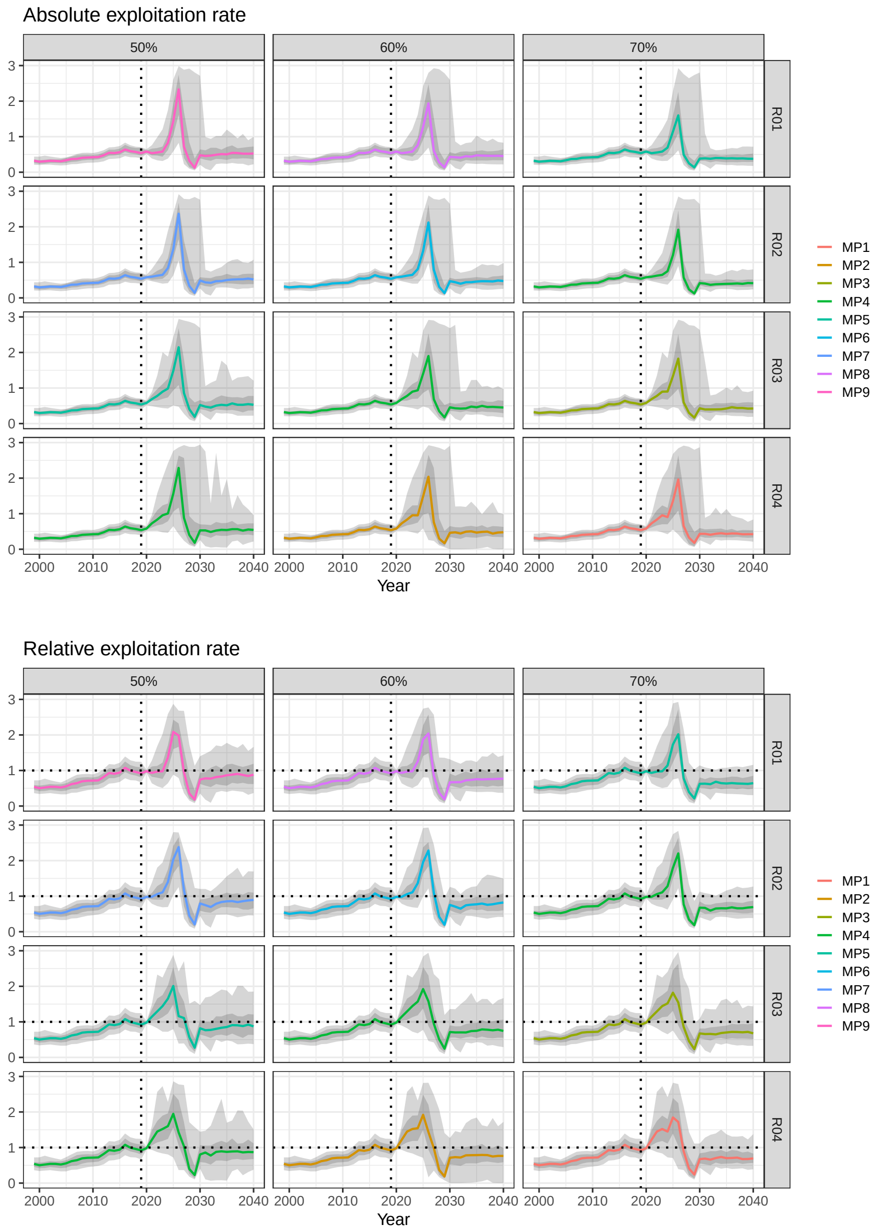
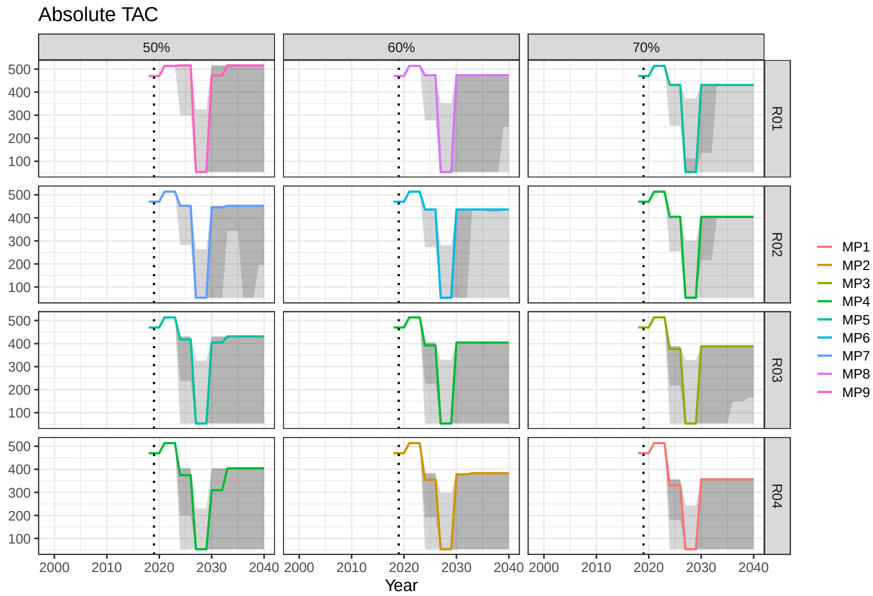


Figure 4: Exploitation rate dynamics following projection under each MP (Table 4), assuming recruitment failure between 2023 and 2025, with 90% and 50% quantiles shaded in grey. Relative values are given according to $E_{40\%}$ for each run. Projections are shown for each tuning criteria (50%, 60% and 70%), and each implementation error (R01 to R04).



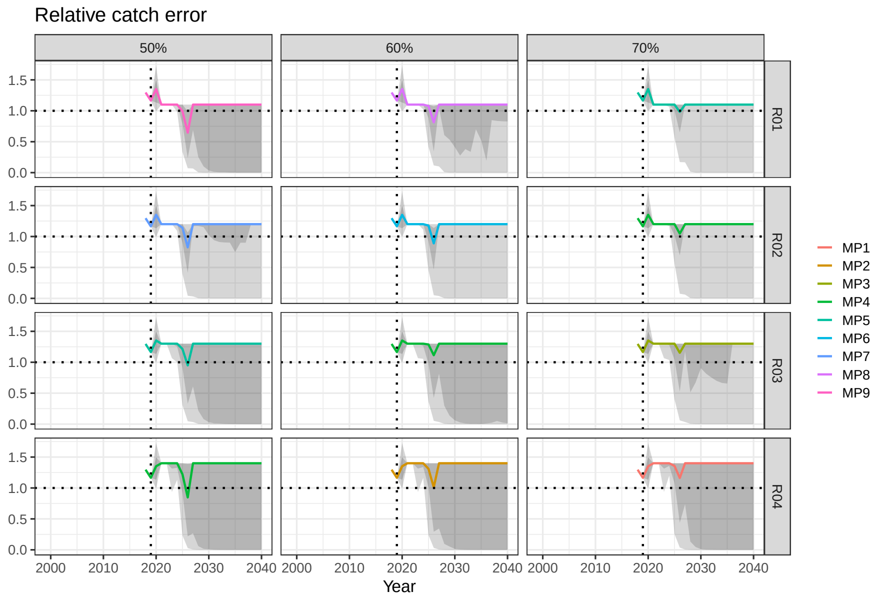
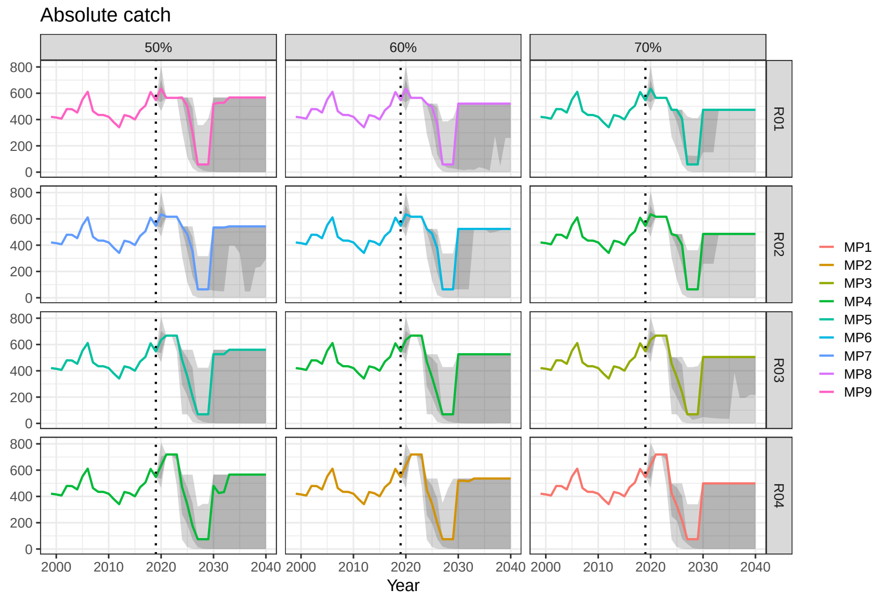


Figure 5: Total Allowable Catch dynamics following projection under each MP (Table 4), assuming recruitment failure between 2023 and 2025, with 90% and 50% quantiles shaded in grey. The TAC is assumed to be 470,029 tonnes for 2018 – 2020, and 513,572 tonnes for 2021–2023. The first year of MP implementation is 2024. Catch implementation error is shown relative to the TAC. Projections are shown for each tuning criteria (50%, 60% and 70%), and each implementation error (R01 to R04).



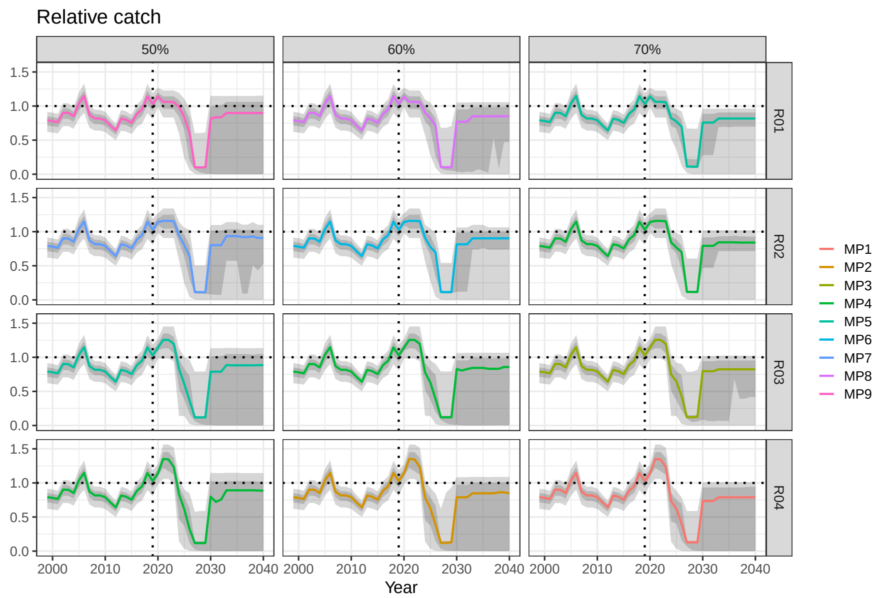


Figure 6: Realised catch dynamics following projection under each MP (Table 4), assuming recruitment failure between 2023 and 2025, with 90% and 50% quantiles shaded in grey. Relative values are given according to $C_{40\%}$ for each run. Projections are shown for each tuning criteria (50%, 60% and 70%), and each implementation error (R01 to R04).

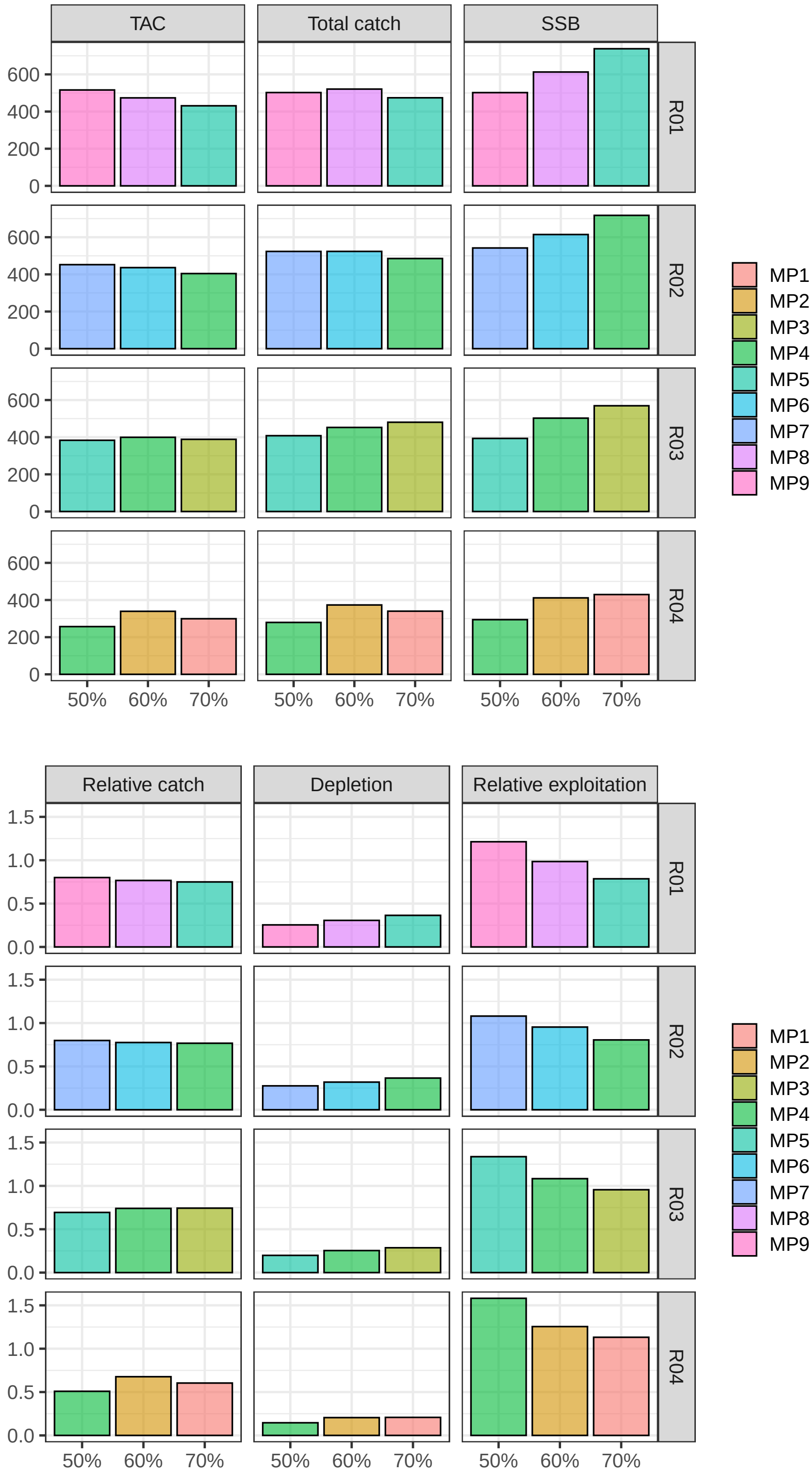


Figure 7: Summary diagnostic outputs (described in Table 3) for MPs listed in Table 4, assuming recruitment failure between 2023 and 2025. Values are shown for each tuning criteria (50%, 60% and 70%), and each implementation error (R01 to R04). Precise values are listed in Tables 5 to 8.

Table 5: Diagnostic outputs for evaluation of index-based MPs assuming a positive implementation error of 10% (R01; see Table 4 for the list of MP definitions and Table 3 for a description of each diagnostic).

Performance Statistic	Units	MP5 (Kobe 70%)	MP8 (Kobe 60%)	MP9 (Kobe 50%)
$C^{TAC}_{y+1:3}$	10^3 tonnes	364.31 (119.87 - 395.65)	391.99 (127.11 - 418.2)	397.85 (134.82 - 438.51)
C	10^3 tonnes	394.34 (54.49 - 439.91)	421.79 (46.61 - 462)	434.02 (49.24 - 491.95)
$C_{[PL]}$	10^3 tonnes	57.89 (8.27 - 73.1)	41.32 (5.87 - 78.98)	31.03 (7.12 - 88.34)
$C_{[PSLS]}$	10^3 tonnes	154.47 (19.37 - 186.88)	165.9 (18 - 223.27)	161.01 (17.49 - 240.41)
$C_{[PSFS]}$	10^3 tonnes	24.05 (3.85 - 30.18)	26.64 (3.75 - 37.93)	29.79 (3.81 - 48.25)
$C_y/C_{40\%}$	Proportion	0.59 (0 - 0.74)	0.58 (0 - 0.73)	0.58 (0 - 0.75)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	3 (2 - 4)	3 (2 - 4)	3 (2 - 5)
$\|C^{TAC}_{y+1}/C^{TAC}_y - 1\|$	Percent	98.11 (17.29 - 135.62)	114.34 (16.09 - 147.76)	147.96 (15.03 - 164.68)
Pr. $\|C^{TAC}_{y+1}/C^{TAC}_y - 1\| > 30\%$	Prob.	0.31	0.31	0.31
Pr. $\|C^{TAC}_{y+1}/C^{TAC}_y - 1\| > 15\%$	Prob.	0.46	0.33	0.34
$CPUE_{[PL]}$	Rate	0.02 (0 - 0.02)	0.01 (0 - 0.02)	0.01 (0 - 0.02)
$CPUE_{[PSLS]}$	Rate	7.71 (0 - 10.76)	6.77 (0 - 9.84)	5.85 (0 - 9.24)
E_y	Rate	0.44 (0.3 - 4.84)	0.54 (0.33 - 4.97)	0.61 (0.38 - 5.1)
$E_y/E_{40\%}$	Proportion	0.74 (0.51 - 8.07)	0.86 (0.56 - 8.67)	1.02 (0.64 - 8.98)
B_y	10^3 tonnes	806.18 (30.21 - 1300.49)	702.16 (24.69 - 1198.47)	630.96 (24.78 - 1185.51)
B_y/B_0	Proportion	0.34 (0 - 0.49)	0.27 (0 - 0.45)	0.23 (0 - 0.42)
Pr. $> B_{20\%}$	Prob.	0.66	0.59	0.55
Pr. $> B_{10\%}$	Prob.	0.74	0.67	0.63
Pr. Kobe Red	Prob.	0.38	0.49	0.56
Pr. Kobe Green	Prob.	0.46	0.37	0.3
Pr. Majuro Red	Prob.	0.21 (0.06 - 1)	0.24 (0.12 - 1)	0.29 (0.12 - 1)
Pr. Majuro White	Prob.	0.71 (0 - 0.88)	0.53 (0 - 0.77)	0.35 (0 - 0.76)

Table 6: Diagnostic outputs for evaluation of index-based MPs assuming a positive implementation error of 20% (R02; see Table 4 for the list of MP definitions and Table 3 for a description of each diagnostic).

Performance Statistic	Units	MP4 (Kobe 70%)	MP6 (Kobe 60%)	MP7 (Kobe 50%)
$C^{TAC}_{y+1:3}$	10^3 tonnes	342.41 (113.05 - 363.97)	364.87 (116.86 - 377.99)	369.66 (114.69 - 382.4)
C	10^3 tonnes	402.45 (54.08 - 436.46)	425.04 (49.93 - 454.22)	430.39 (50.72 - 459.71)
$C_{[PL]}$	10^3 tonnes	55.33 (7.48 - 74.01)	46.93 (7.39 - 81.43)	35 (7.12 - 82.72)
$C_{[PSLS]}$	10^3 tonnes	158.38 (18.31 - 207.26)	165.06 (17.51 - 220.38)	158.58 (17.08 - 233.84)
$C_{[PSFS]}$	10^3 tonnes	24.52 (3.71 - 35.12)	27.03 (3.81 - 44.71)	29.2 (3.91 - 56.81)
$C_y/C_{40\%}$	Proportion	0.58 (0 - 0.76)	0.58 (0 - 0.74)	0.58 (0 - 0.73)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	3 (2 - 4)	3 (2 - 4)	3 (2 - 4.1)
$\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	115.11 (18.02 - 128.02)	123.61 (17.14 - 137.26)	139.73 (16.7 - 143.36)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 30\%$	Prob.	0.33	0.33	0.32
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 15\%$	Prob.	0.48	0.49	0.36
$CPUE_{[PL]}$	Rate	0.02 (0 - 0.02)	0.01 (0 - 0.02)	0.01 (0 - 0.02)
$CPUE_{[PSLS]}$	Rate	7.47 (0 - 10.19)	6.69 (0 - 9.4)	6.12 (0 - 9.01)
E_y	Rate	0.47 (0.33 - 4.93)	0.55 (0.38 - 5.07)	0.59 (0.41 - 5.16)
$E_y/E_{40\%}$	Proportion	0.79 (0.55 - 8.63)	0.91 (0.63 - 8.8)	1.02 (0.68 - 8.88)
B_y	10^3 tonnes	775.2 (29.32 - 1120.27)	687.23 (30.36 - 1083.12)	648.98 (27.11 - 1029.69)
B_y/B_0	Proportion	0.32 (0 - 0.43)	0.27 (0 - 0.41)	0.24 (0 - 0.38)
Pr. $> B_{20\%}$	Prob.	0.66	0.61	0.57
Pr. $> B_{10\%}$	Prob.	0.74	0.69	0.65
Pr. Kobe Red	Prob.	0.39	0.47	0.53
Pr. Kobe Green	Prob.	0.46	0.39	0.33
Pr. Majuro Red	Prob.	0.24 (0.12 - 1)	0.24 (0.12 - 1)	0.29 (0.12 - 1)
Pr. Majuro White	Prob.	0.65 (0 - 0.82)	0.53 (0 - 0.76)	0.47 (0 - 0.71)

Table 7: Diagnostic outputs for evaluation of index-based MPs assuming a positive implementation error of 30% (R03; see Table 4 for the list of MP definitions and Table 3 for a description of each diagnostic).

Performance Statistic	Units	MP3 (Kobe 70%)	MP4 (Kobe 60%)	MP5 (Kobe 50%)
$C^{TAC}_{y+1:3}$	10^3 tonnes	308.82 (100.68 - 339.24)	315.99 (102.12 - 349.12)	316.81 (104.04 - 364.31)
C	10^3 tonnes	401.55 (44.8 - 448.07)	413.16 (38.6 - 468.69)	411.54 (43.52 - 474.16)
$C_{[PL]}$	10^3 tonnes	46.98 (4.89 - 76.38)	44.68 (4.85 - 78.78)	33.72 (5.52 - 81.9)
$C_{[PSLS]}$	10^3 tonnes	152.12 (15.32 - 210.05)	155.64 (13.61 - 217.73)	146.9 (14.82 - 227.45)
$C_{[PSFS]}$	10^3 tonnes	24.89 (3.3 - 37.51)	25.76 (3.22 - 40.71)	26.91 (3.24 - 43.08)
$C_y/C_{40\%}$	Proportion	0.56 (0 - 0.73)	0.56 (0 - 0.74)	0.54 (0 - 0.75)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	3 (2 - 4)	3 (2 - 4)	3 (2 - 5)
$\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	93.39 (18.45 - 126.38)	106.7 (18.02 - 131.33)	104.79 (17.29 - 141.16)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 30\%$	Prob.	0.36	0.36	0.37
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 15\%$	Prob.	0.47	0.48	0.49
$CPUE_{[PL]}$	Rate	0.01 (0 - 0.02)	0.01 (0 - 0.02)	0.01 (0 - 0.02)
$CPUE_{[PSLS]}$	Rate	6.5 (0 - 9.6)	5.88 (0 - 9.14)	5.3 (0 - 8.74)
E_y	Rate	0.52 (0.32 - 4.95)	0.56 (0.34 - 5.17)	0.7 (0.41 - 5.16)
$E_y/E_{40\%}$	Proportion	0.88 (0.56 - 8.41)	0.93 (0.58 - 8.91)	1.13 (0.68 - 8.83)
B_y	10^3 tonnes	693.97 (19.63 - 1292.63)	655.2 (19.13 - 1302.01)	528.95 (21.79 - 1157.19)
B_y/B_0	Proportion	0.27 (0 - 0.44)	0.23 (0 - 0.42)	0.21 (0 - 0.38)
Pr. $> B_{20\%}$	Prob.	0.57	0.54	0.5
Pr. $> B_{10\%}$	Prob.	0.66	0.63	0.59
Pr. Kobe Red	Prob.	0.47	0.53	0.59
Pr. Kobe Green	Prob.	0.38	0.34	0.28
Pr. Majuro Red	Prob.	0.29 (0.17 - 1)	0.29 (0.17 - 1)	0.35 (0.18 - 1)
Pr. Majuro White	Prob.	0.59 (0 - 0.77)	0.47 (0 - 0.76)	0.32 (0 - 0.76)

Table 8: Diagnostic outputs for evaluation of index-based MPs assuming a positive implementation error of 40% (R04; see Table 4 for the list of MP definitions and Table 3 for a description of each diagnostic).

Performance Statistic	Units	MP1 (Kobe 70%)	MP2 (Kobe 60%)	MP4 (Kobe 50%)
$C^{TAC}_{y+1:3}$	10^3 tonnes	265.61 (83.01 - 306.01)	279.3 (95.25 - 324.88)	280.43 (87.34 - 342.41)
C	10^3 tonnes	371.66 (38.38 - 436.04)	394.97 (37.79 - 476.61)	388.92 (36.24 - 479.37)
$C_{[PL]}$	10^3 tonnes	31.86 (4.88 - 73.55)	31.04 (4.21 - 83.91)	24.52 (3.84 - 82.25)
$C_{[PSLS]}$	10^3 tonnes	138.07 (12.98 - 214)	140.26 (12.87 - 237.46)	138.64 (12.15 - 240.64)
$C_{[PSFS]}$	10^3 tonnes	23.85 (2.95 - 34.32)	26.36 (2.96 - 45.56)	27.59 (2.85 - 57.59)
$C_y/C_{40\%}$	Proportion	0.53 (0 - 0.67)	0.55 (0 - 0.72)	0.54 (0 - 0.71)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	3 (2 - 4)	3 (2 - 4)	3 (2 - 4)
$\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	73.73 (19.28 - 116.33)	91.14 (18.59 - 125.12)	88.41 (18.02 - 131.69)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 30\%$	Prob.	0.43	0.36	0.35
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 15\%$	Prob.	0.44	0.45	0.46
$CPUE_{[PL]}$	Rate	0.01 (0 - 0.02)	0.01 (0 - 0.02)	0.01 (0 - 0.02)
$CPUE_{[PSLS]}$	Rate	6.16 (0 - 9.05)	5.74 (0 - 8.73)	4.9 (0 - 8.2)
E_y	Rate	0.56 (0.35 - 5.5)	0.63 (0.35 - 5.36)	0.74 (0.4 - 5.29)
$E_y/E_{40\%}$	Proportion	0.9 (0.57 - 9.39)	1.02 (0.59 - 9.42)	1.25 (0.67 - 9.48)
B_y	10^3 tonnes	659.51 (14.43 - 1090.05)	610.75 (15.91 - 1252.15)	532.56 (13.29 - 1015.97)
B_y/B_0	Proportion	0.23 (0 - 0.42)	0.22 (0 - 0.4)	0.18 (0 - 0.37)
Pr. $> B_{20\%}$	Prob.	0.51	0.51	0.45
Pr. $> B_{10\%}$	Prob.	0.59	0.59	0.54
Pr. Kobe Red	Prob.	0.54	0.57	0.64
Pr. Kobe Green	Prob.	0.34	0.31	0.25
Pr. Majuro Red	Prob.	0.29 (0.17 - 1)	0.35 (0.12 - 1)	0.41 (0.18 - 1)
Pr. Majuro White	Prob.	0.47 (0 - 0.82)	0.41 (0 - 0.82)	0.21 (0 - 0.71)

4 Summary

In the current work, robustness testing has been used to stress-test the system and evaluate the ability of pre-selected MPs to recover the stock following a period of over-exploitation and SSB collapse. The MPs evaluated had been previously presented by Edwards (2022c). Each of the twelve MPs had been tuned to the 50%, 60% and 70% tuning criteria under assumed positive implementation errors of 10%, 20%, 30% and 40%.

Simulation outputs demonstrate that the MP is able to recover the stock rapidly, but only with implausible cuts in the TAC. For more realistic evaluation, limits to the TAC change are required (e.g., a maximum change in the TAC of 15%). However, this will also require more "realistic" robustness scenarios to be a worthwhile exercise. Arbitrary levels of stock collapse, with limits on how the MP can respond, will lead to reductions in MP performance that are difficult to interpret. The current work is therefore best viewed as indicative of the intrinsic design properties of each MP, which appear to be sound, but only a preliminary demonstration of how robustness testing can be performed. For a more definitive evaluation of performance, further work will be required towards a more precise definition of the robustness scenarios, and with limits on how much the TAC can be changed at any given MP implementation.

5 Acknowledgements

I am grateful to Dan Fu (IOTC) for providing the SS III files, to Alistair Dunn (Ocean Environmental) for providing computer support and to the support of other colleagues working on MSE for IOTC (Iago Mosqueira, Richard Hillary, Ann Preece and Ashley Williams).

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

6 References

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

Edwards, C.T.T. (2021a). Evaluation of empirical control rules for Indian Ocean Skipjack. *Research Report (IOTC–2021–WPM12–10)*

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

Edwards, C.T.T. (2022a). Further evaluations of an empirical MP for Indian Ocean Skipjack Tuna. *Research Report (IOTC–2022–WPM13(MSE)–07)*

Edwards, C.T.T. (2022b). Presentation of an empirical MP for Indian Ocean skipjack tuna. *Research Report (IOTC–2022–TCMP05–09)*

Edwards, C.T.T. (2022c). Presentation of empirical MPs for Indian Ocean skipjack tuna accounting for implementation error. *Research Report (IOTC–2022–WPM13–09)*

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

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 (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. Online, 18 - 20 October 2021. *IOTC–2021–WPM12–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]*

IOTC (2022a). Report of the 13th Session of the IOTC Working Party on Methods. Online, 19 - 21 October 2022. *IOTC–2022–WPM13–R[E]*

IOTC (2022b). Report of the 5th IOTC Technical Committee on Management Procedures. Seychelles, 13 - 14 May 2022. *IOTC–2022–TCMP05–R[E]*