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Presentation of empirical MPs for Indian Ocean skipjack tuna accounting for implementation error

Prepared for the Indian Ocean Tuna Commission

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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). The current work is in response to feedback from the TCMP (IOTC, 2022). 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%.

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). 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. These criteria meant that the simulations yielded three candidate MPs for consideration.

A positive implementation error of between 20% and 40% was assumed during robustness testing of the candidate MPs. Results from this testing were presented to the TCMP in 2022 (Edwards, 2022b). These showed an expected deterioration in performance of the MP at higher levels of implementation error. If a positive implementation error is suspected, the simulations suggested that a more conservative MPs should be preferred.

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, 2022). The current work attempts to fulfill this request.

Following Edwards (2022a), realised catches from the fishery in 2018 and 2019 were 29% and 16% higher than the recommended TAC. Based on these observations, 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. Positive implementation error was consistently applied over the period from 2021 (the first year of projected catches) to 2040. Only a very small amount of stochasticity was applied to the catches, to allow overall patterns to be more easily discerned.

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.

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:

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

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 $y+3$.

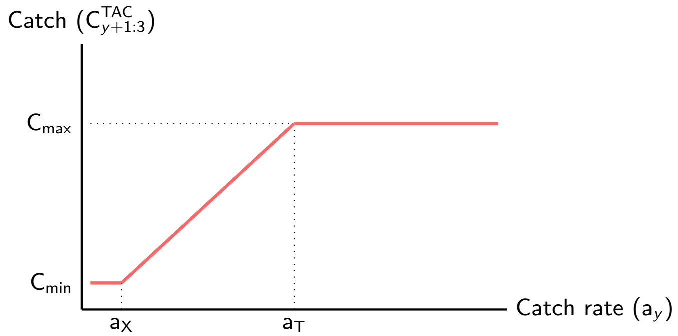


Figure 1: Schematic representation of the empirical Harvest Control Rule (Equation 1) being proposed as part of the MP.

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, the value for C_{max} was varied from 185 to 560 thousand tonnes in increments of 5 thousand tonnes. 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

3 Results

Each MP was simulated forward in time from 2021 to 2040 and selected as a candidate for further consideration if it matched the 50%, 60% or 70% tuning criteria. This was repeated assuming positive implementation error values of:

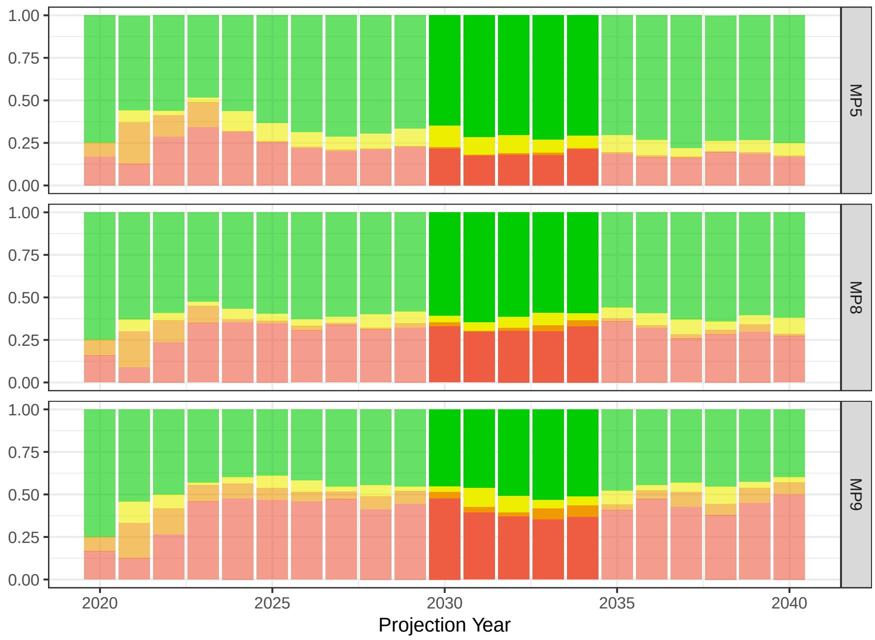
- **R01:** 10%;
- **R02:** 20%;
- **R03:** 30%;
- **R04:** 40%.

For each implementation error, the three tuned candidate MPs are listed in Table 4. Some of the MPs are selected more than once, depending on the combination of tuning criteria and implementation error assumed. Their dynamics used for the tuning are illustrated in Figures 2a to 2d. It can be seen that at higher levels of implementation error, the stock spends more time in the Kobe red quadrant during the early period of the projection, but that each MP returns the stock to the appropriate probability of being in the Kobe green quadrant.

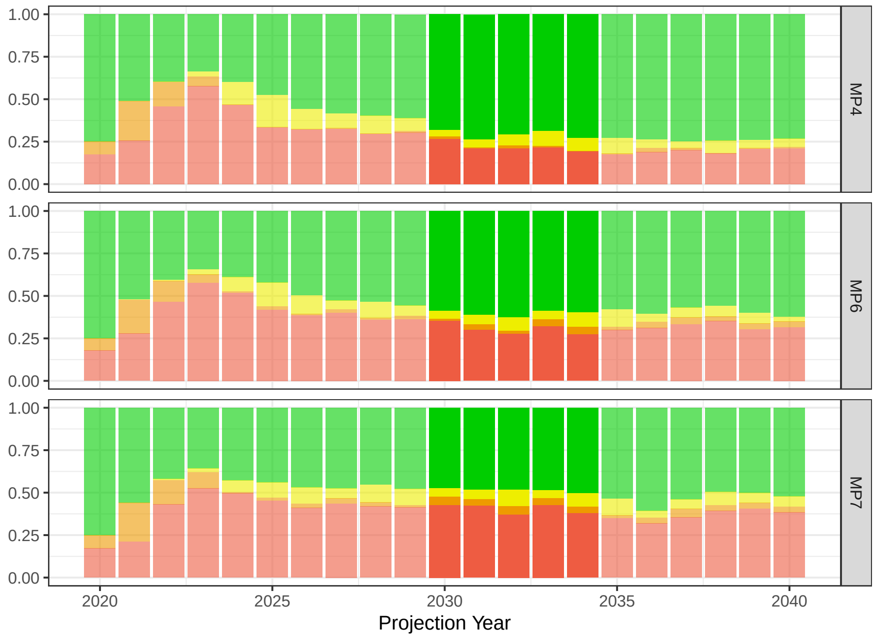
System dynamics under each of the candidate MPs, at each of the assumed levels of implementation error, are shown in Figures 3 to 6. Despite high levels of implementation error, the tuned MPs are able to prevent overexploitation of the stock (Figures 3 and 4). At higher implementation error, the TAC is set at a correspondingly lower level (Figure 5), leading to a similar realised catch (Figure 6), and similar stock dynamics. This is further emphasised in the summary diagnostics shown in Figure 7, with more detailed results listed in Tables 5 to 8. Results are similar, regardless of the implementation error assumed, with the only difference being that the TAC is set at a much more conservative value if the implementation error is assumed to be higher.

Table 4: MP tuning parameters

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

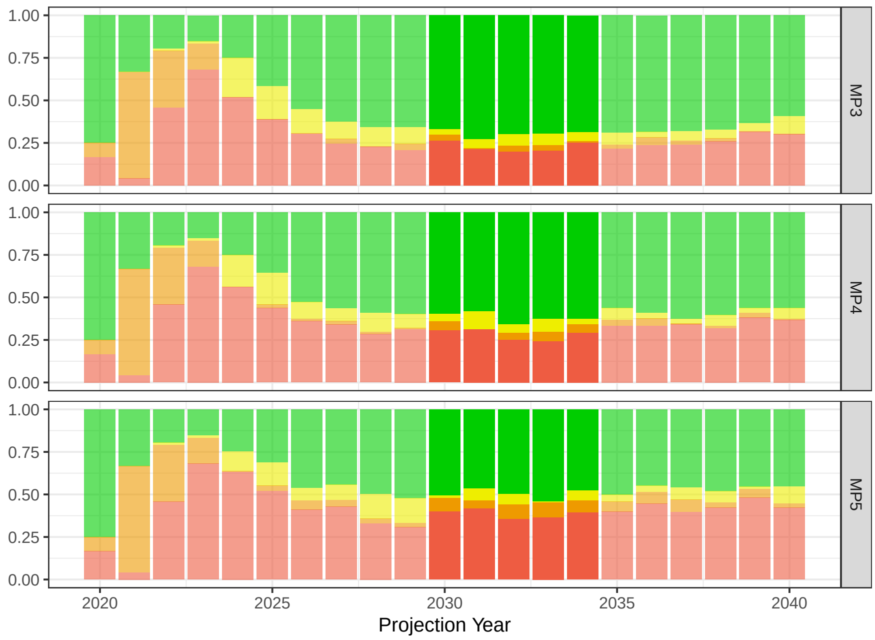


(a) Kobe time series for MPs, assuming an implementation error of 10% (R01).

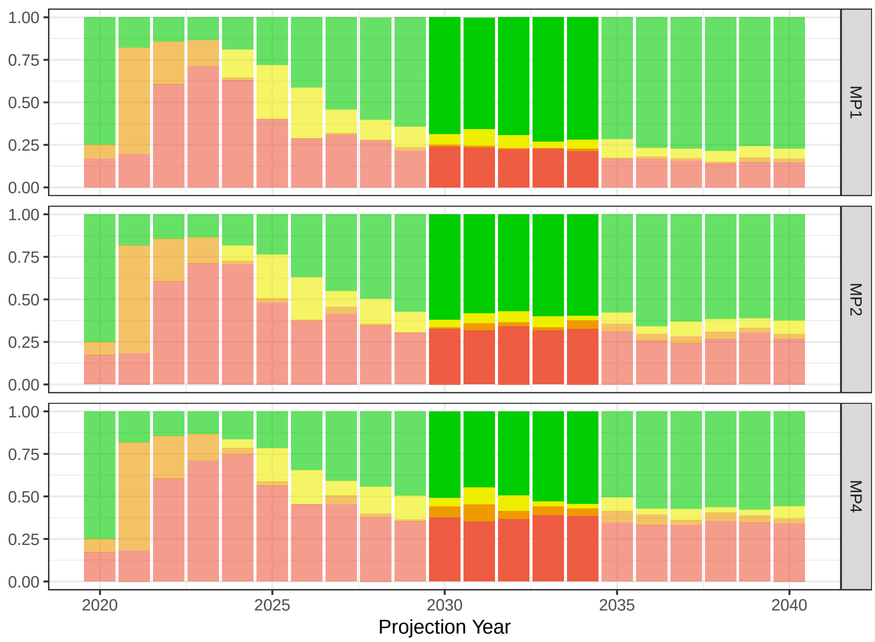


(b) Kobe time series for MPs, assuming an implementation error of 20% (R02).

Figure 2: Kobe time series for MPs listed in Table 4. 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 select MPs using the tuning criteria.



(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. 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 select MPs using the tuning criteria.

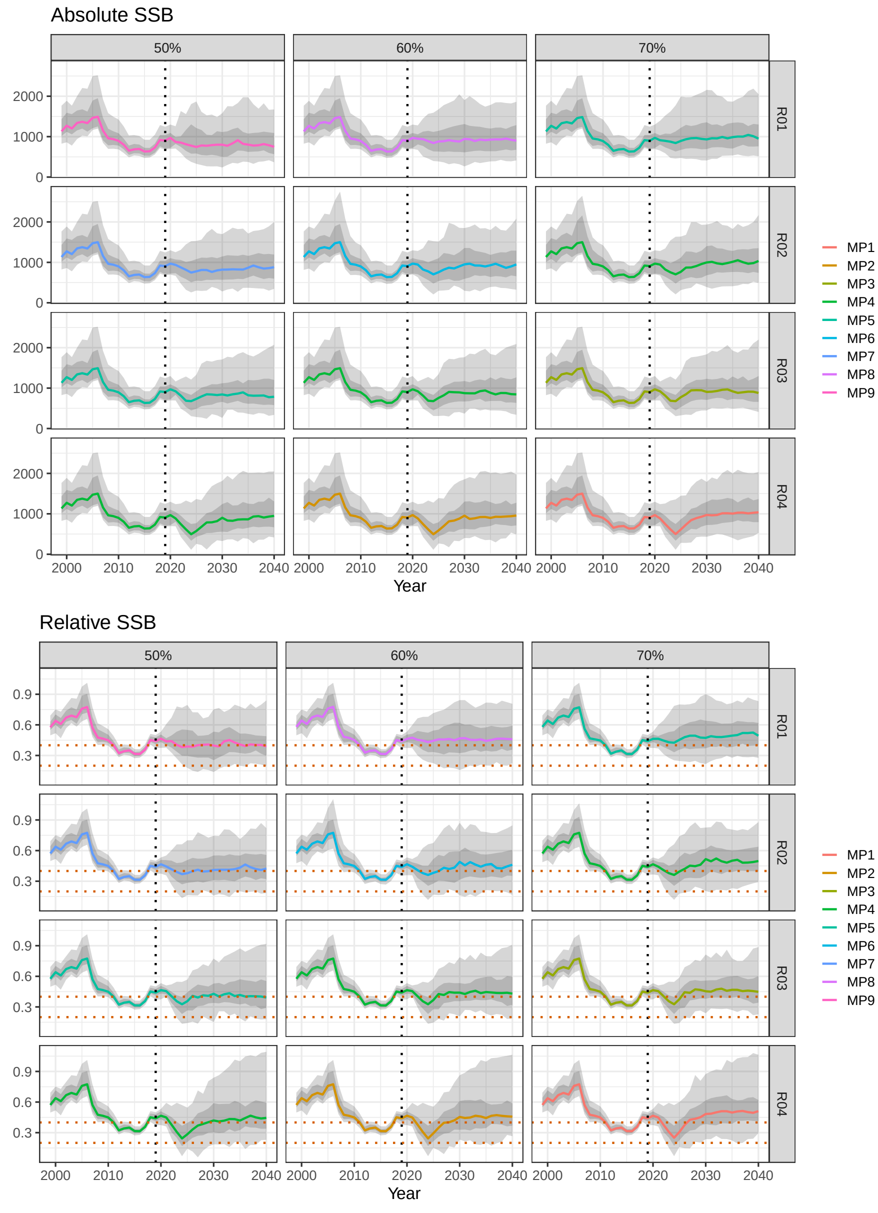


Figure 3: Spawning stock biomass dynamics following projection under each MP (Table 4), with 90% and 50% quantiles shaded in grey. Projections are shown for each tuning criteria (50%, 60% and 70%), and each implementation error (R01 to R04). Relative values are given according to B_0 for each run. Depletion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

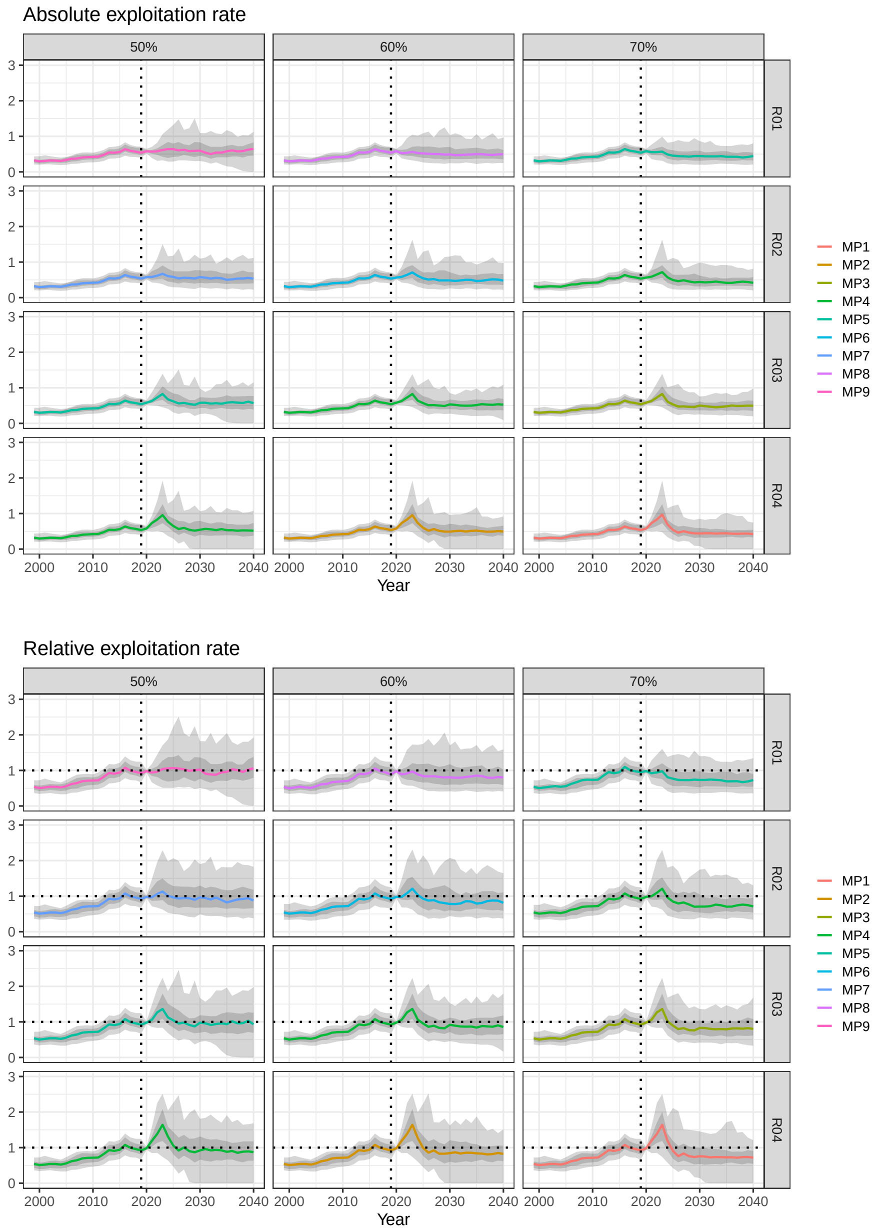
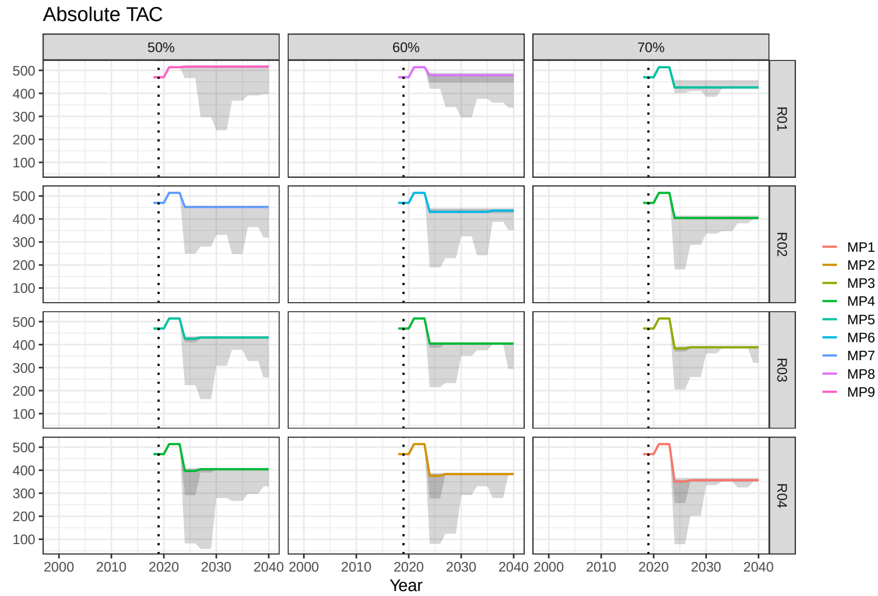


Figure 4: Exploitation rate dynamics following projection under each MP (Table 4), with 90% and 50% quantiles shaded in grey. Relative values are given according to $E_{40\%}$ for each run. Projections are shown for each tuning criteria (50%, 60% and 70%), and each implementation error (R01 to R04).



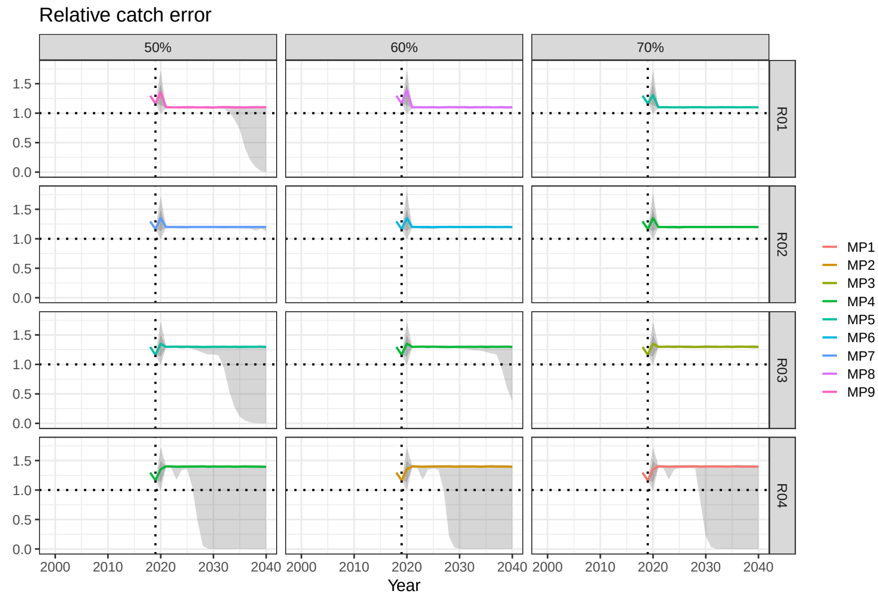


Figure 5: Total Allowable Catch dynamics following projection under each MP (Table 4), with 90% and 50% quantiles shaded in grey. The TAC is assumed to be 470,029 tonnes for 2018 – 2020, and 513,572 tonnes for 2021–2023. The first year of MP implementation is 2024. Catch implementation error is shown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

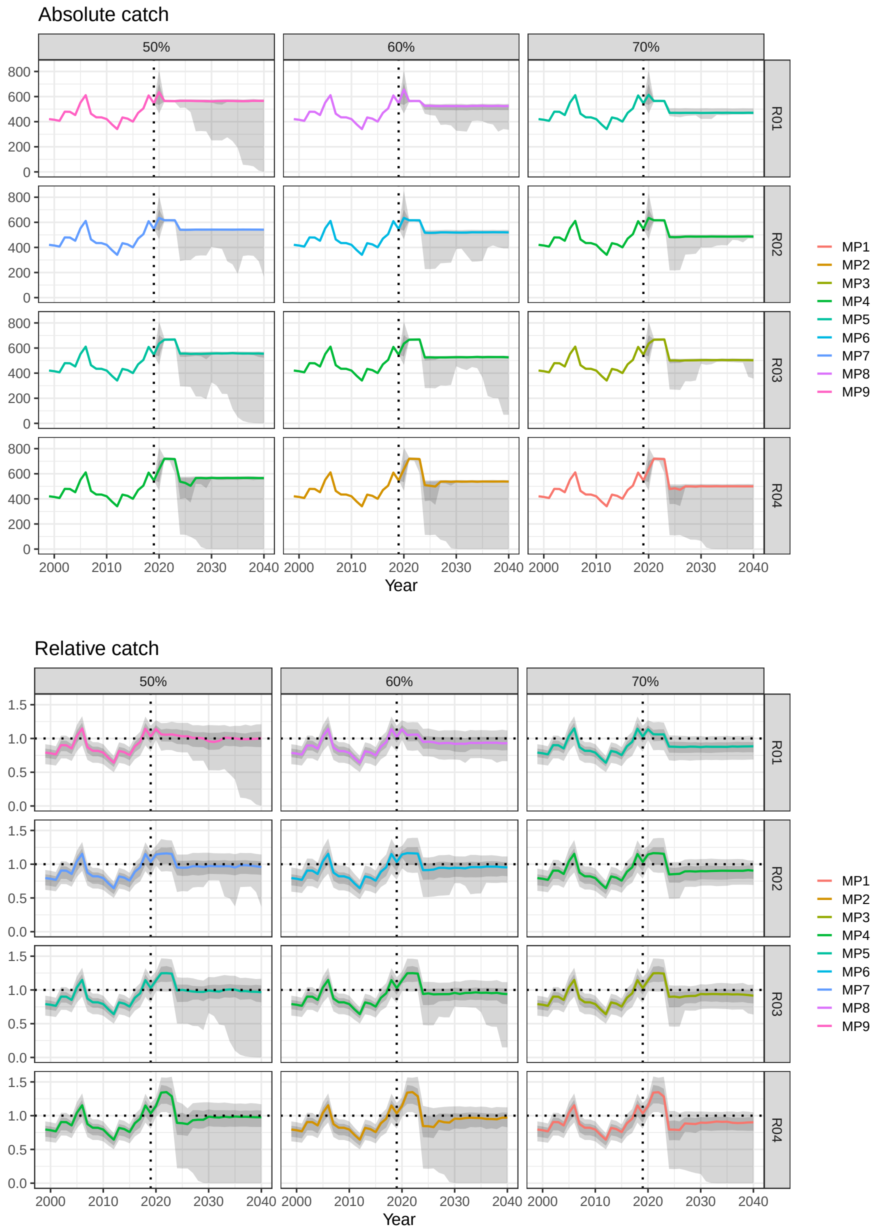
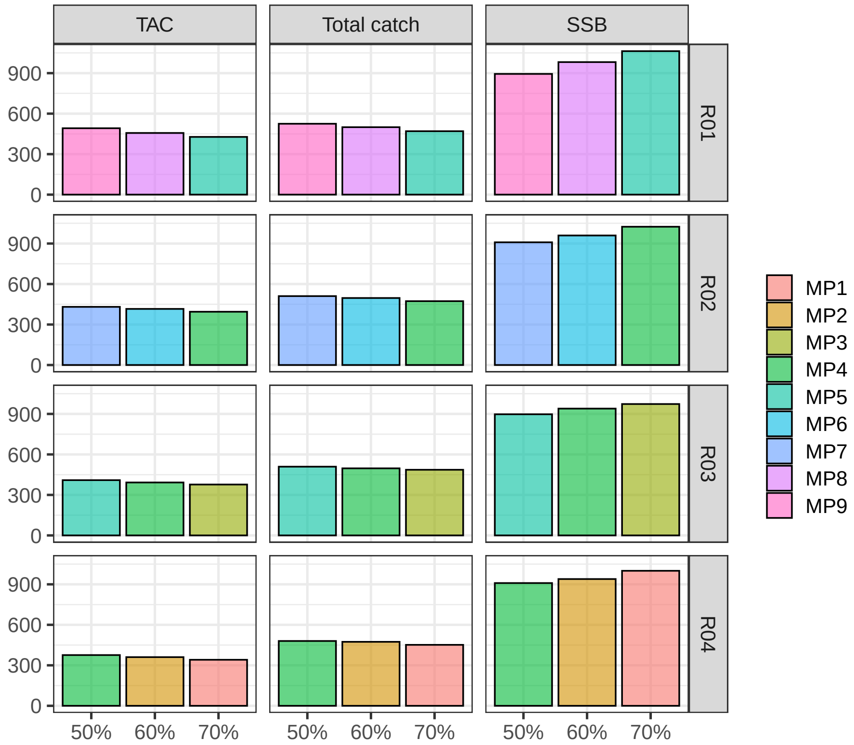


Figure 6: Realised catch dynamics following projection under each MP (Table 4), with 90% and 50% quantiles shaded in grey. Relative values are given according to $C_{40\%}$ for each run. Projections are shown for each tuning criteria (50%, 60% and 70%), and each implementation error (R01 to R04).



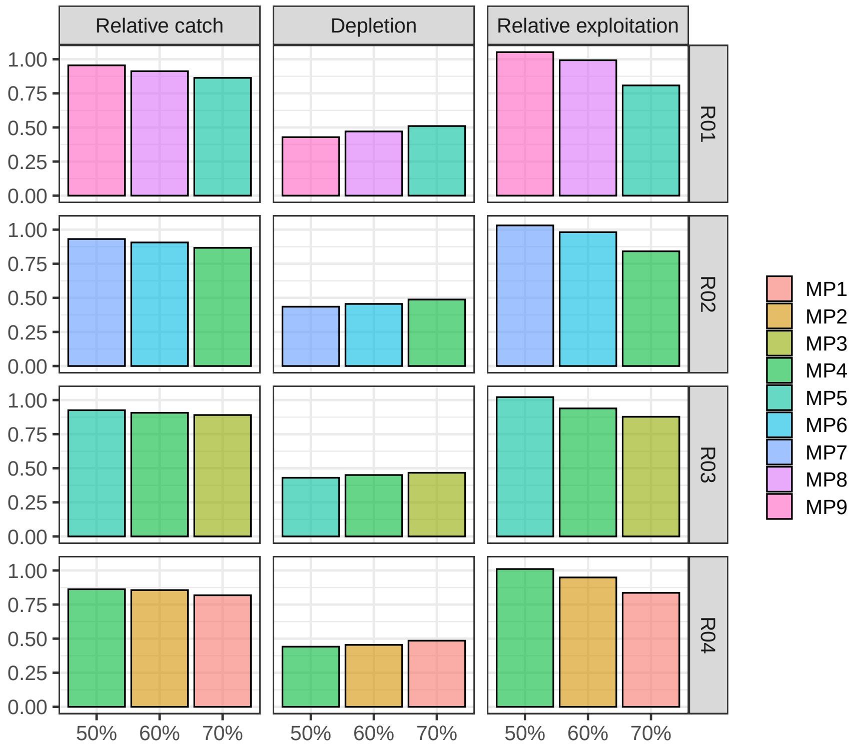


Figure 7: Summary diagnostic outputs (described in Table 3) for MPs listed in Table 4. Values are shown for each tuning criteria (50%, 60% and 70%), and each implementation error (R01 to R04). Precise values are listed in Tables 5 to 8.

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	425.66 (413.69 - 457.58)	466.59 (424.19 - 484.19)	505.52 (450.56 - 521.43)
C	10^3 tonnes	468.33 (454.84 - 503.11)	511.43 (459.05 - 533.52)	548.42 (455.84 - 572.18)
$C_{[PL]}$	10^3 tonnes	76.91 (73.98 - 81.98)	84.04 (73.77 - 88.92)	89.48 (71.24 - 94.37)
$C_{[PSLS]}$	10^3 tonnes	177.65 (164.9 - 189.79)	190.59 (171.21 - 204.8)	207.92 (172.75 - 219.23)
$C_{[PSFS]}$	10^3 tonnes	26.47 (24.1 - 28.35)	28.41 (25.42 - 30.78)	30.67 (26.09 - 32.99)
$C_y/C_{40\%}$	Proportion	0.88 (0.71 - 0.99)	0.91 (0.75 - 1.04)	0.97 (0.78 - 1.07)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	1 (0 - 3)	1 (0 - 4)	3 (1 - 5)
$\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	2.85 (1.82 - 9.9)	2.16 (0.95 - 21.07)	4.05 (0.08 - 35.93)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 30\%$	Prob.	0.03	0.08	0.12
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 15\%$	Prob.	0.18	0.13	0.19
$CPUE_{[PL]}$	Rate	0.02 (0.02 - 0.03)	0.02 (0.01 - 0.03)	0.02 (0.01 - 0.03)
$CPUE_{[PSLS]}$	Rate	11.15 (8.88 - 13.19)	10.5 (8.12 - 12.67)	9.74 (7.55 - 12.55)
E_y	Rate	0.45 (0.26 - 0.64)	0.52 (0.32 - 0.75)	0.58 (0.34 - 0.85)
$E_y/E_{40\%}$	Proportion	0.74 (0.47 - 1.08)	0.87 (0.54 - 1.27)	0.97 (0.58 - 1.38)
B_y	10^3 tonnes	953.91 (655.96 - 1711.82)	898.85 (570.75 - 1520.76)	821.84 (499.44 - 1350.43)
B_y/B_0	Proportion	0.48 (0.35 - 0.66)	0.44 (0.29 - 0.62)	0.39 (0.27 - 0.58)
Pr. $> B_{20\%}$	Prob.	0.98	0.94	0.93
Pr. $> B_{10\%}$	Prob.	1	0.99	0.99
Pr. Kobe Red	Prob.	0.21	0.32	0.43
Pr. Kobe Green	Prob.	0.69	0.6	0.45
Pr. Majuro Red	Prob.	0 (0 - 0.06)	0 (0 - 0.18)	0 (0 - 0.21)
Pr. Majuro White	Prob.	0.88 (0.35 - 1)	0.71 (0.18 - 1)	0.5 (0 - 0.94)

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	399.06 (361.84 - 415.02)	425.66 (366.97 - 445.53)	450.37 (382.42 - 452.26)
C	10^3 tonnes	480.2 (433.05 - 496.96)	511.75 (438.4 - 533)	537.92 (443.43 - 543.51)
$C_{[PL]}$	10^3 tonnes	78.6 (68.34 - 82.28)	83.75 (66.39 - 87.73)	86.88 (71.22 - 90.15)
$C_{[PSLS]}$	10^3 tonnes	181.8 (165.61 - 190.58)	194.63 (167.62 - 204.87)	201.1 (171.47 - 210.62)
$C_{[PSFS]}$	10^3 tonnes	27.07 (24.4 - 28.59)	28.91 (25.09 - 30.66)	29.81 (25.89 - 31.67)
$C_y/C_{40\%}$	Proportion	0.87 (0.72 - 0.98)	0.9 (0.75 - 1.04)	0.93 (0.76 - 1.05)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	1 (0 - 3)	1 (0 - 4)	1 (0 - 4)
$\|C^{TAC}_{y+1}/C^{TAC}_y - 1\|$	Percent	3.72 (3.2 - 33.73)	2.85 (2.33 - 48.08)	2.71 (1.99 - 48.13)
Pr. $\|C^{TAC}_{y+1}/C^{TAC}_y - 1\| > 30\%$	Prob.	0.09	0.12	0.12
Pr. $\|C^{TAC}_{y+1}/C^{TAC}_y - 1\| > 15\%$	Prob.	0.26	0.25	0.18
$CPUE_{[PL]}$	Rate	0.02 (0.02 - 0.03)	0.02 (0.01 - 0.03)	0.02 (0.01 - 0.03)
$CPUE_{[PSLS]}$	Rate	10.58 (8.09 - 13.32)	10.05 (7.37 - 12.95)	9.84 (7.11 - 12.37)
E_y	0.46 (0.29 - 0.71)	0.51 (0.32 - 0.77)	0.56 (0.34 - 0.8)	
$E_y/E_{40\%}$	Proportion	0.76 (0.5 - 1.21)	0.84 (0.54 - 1.35)	0.92 (0.58 - 1.38)
B_y	10^3 tonnes	936.75 (545.17 - 1545.08)	885.36 (498.73 - 1470.66)	844.81 (511.58 - 1412.35)
B_y/B_0	Proportion	0.46 (0.29 - 0.65)	0.43 (0.26 - 0.63)	0.4 (0.25 - 0.58)
Pr. $> B_{20\%}$	Prob.	0.96	0.93	0.93
Pr. $> B_{10\%}$	Prob.	1	0.99	0.99
Pr. Kobe Red	Prob.	0.26	0.35	0.4
Pr. Kobe Green	Prob.	0.66	0.55	0.49
Pr. Majuro Red	Prob.	0 (0 - 0.18)	0 (0 - 0.24)	0 (0 - 0.29)
Pr. Majuro White	Prob.	0.88 (0.24 - 1)	0.71 (0.06 - 1)	0.56 (0.12 - 1)

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	383.09 (355.51 - 393.74)	404.38 (369.82 - 409.7)	423.37 (378.37 - 436.3)
C	10^3 tonnes	497.98 (457.07 - 511.44)	519.57 (455.99 - 532.51)	543.44 (394.73 - 564.34)
$C_{[PL]}$	10^3 tonnes	81.46 (74.64 - 85.35)	84.81 (73.28 - 88.46)	88.08 (63.4 - 93.07)
$C_{[PSLS]}$	10^3 tonnes	187.36 (171.17 - 195.69)	195.39 (172.36 - 204.39)	204.82 (153.36 - 215.67)
$C_{[PSFS]}$	10^3 tonnes	27.91 (25.28 - 29.32)	28.96 (25.94 - 30.77)	30.52 (25.59 - 32.39)
$C_y/C_{40\%}$	Proportion	0.91 (0.73 - 1.01)	0.93 (0.72 - 1.04)	0.96 (0.71 - 1.07)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	1 (1 - 3)	2 (1 - 4)	2 (1 - 4.5)
$\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	4.23 (3.89 - 21.85)	3.98 (3.37 - 24.73)	5.49 (2.51 - 30.06)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 30\%$	Prob.	0.09	0.1	0.13
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 15\%$	Prob.	0.24	0.27	0.3
$CPUE_{[PL]}$	Rate	0.02 (0.02 - 0.03)	0.02 (0.01 - 0.03)	0.02 (0.01 - 0.03)
$CPUE_{[PSLS]}$	Rate	10.56 (8.42 - 12.46)	10.29 (8 - 12.25)	9.81 (7.37 - 12.04)
E_y	Rate	0.49 (0.3 - 0.73)	0.52 (0.31 - 0.78)	0.57 (0.31 - 0.82)
$E_y/E_{40\%}$	Proportion	0.81 (0.52 - 1.21)	0.89 (0.53 - 1.29)	0.96 (0.56 - 1.39)
B_y	10^3 tonnes	904.92 (569.95 - 1486.77)	875.6 (545.87 - 1427.28)	829.64 (498.69 - 1371.33)
B_y/B_0	Proportion	0.46 (0.32 - 0.6)	0.44 (0.29 - 0.59)	0.41 (0.27 - 0.58)
Pr. $> B_{20\%}$	Prob.	0.97	0.95	0.93
Pr. $> B_{10\%}$	Prob.	0.99	0.99	0.99
Pr. Kobe Red	Prob.	0.27	0.34	0.42
Pr. Kobe Green	Prob.	0.62	0.56	0.45
Pr. Majuro Red	Prob.	0 (0 - 0.12)	0 (0 - 0.18)	0 (0 - 0.24)
Pr. Majuro White	Prob.	0.88 (0.18 - 1)	0.71 (0.12 - 1)	0.47 (0.12 - 0.94)

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	350.06 (308.19 - 364.41)	370.36 (324.38 - 388.41)	385.61 (341.44 - 409.7)
C	10^3 tonnes	483.69 (407.75 - 508.24)	512.64 (410.3 - 542.88)	525.44 (286.28 - 571.46)
$C_{[PL]}$	10^3 tonnes	78.53 (33.55 - 83.11)	83.11 (27.24 - 88.81)	85.1 (26.47 - 92.8)
$C_{[PSLS]}$	10^3 tonnes	185.97 (161.24 - 197.02)	198.72 (160.16 - 209.45)	205.53 (103.31 - 222.29)
$C_{[PSFS]}$	10^3 tonnes	27.64 (24.48 - 29.38)	29.28 (24.93 - 31.44)	30.55 (18.79 - 33.28)
$C_y/C_{40\%}$	Proportion	0.83 (0.65 - 0.97)	0.86 (0.67 - 1.02)	0.87 (0.04 - 1.04)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	2 (1 - 4)	2 (0 - 4)	2 (0 - 5)
$\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	9.39 (4.93 - 56.06)	11.61 (4.06 - 107.41)	13.17 (3.37 - 124.94)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 30\%$	Prob.	0.22	0.21	0.21
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 15\%$	Prob.	0.3	0.33	0.37
$CPUE_{[PL]}$	Rate	0.02 (0.01 - 0.03)	0.02 (0.01 - 0.03)	0.02 (0.01 - 0.03)
$CPUE_{[PSLS]}$	Rate	10.25 (7.57 - 12.94)	9.7 (7.02 - 12.48)	9.36 (6.5 - 12.15)
E_y	Rate	0.45 (0.28 - 0.73)	0.51 (0.31 - 0.77)	0.53 (0.02 - 0.8)
$E_y/E_{40\%}$	Proportion	0.76 (0.48 - 1.16)	0.87 (0.53 - 1.3)	0.92 (0.04 - 1.33)
B_y	10^3 tonnes	938.4 (550.76 - 1473.23)	865.25 (518.77 - 1426.81)	851.79 (519.37 - 1413.98)
B_y/B_0	Proportion	0.45 (0.29 - 0.59)	0.41 (0.26 - 0.61)	0.4 (0.24 - 0.6)
Pr. $> B_{20\%}$	Prob.	0.94	0.92	0.9
Pr. $> B_{10\%}$	Prob.	0.99	0.98	0.97
Pr. Kobe Red	Prob.	0.25	0.35	0.4
Pr. Kobe Green	Prob.	0.63	0.53	0.47
Pr. Majuro Red	Prob.	0 (0 - 0.24)	0.06 (0 - 0.25)	0.06 (0 - 0.29)
Pr. Majuro White	Prob.	0.82 (0.29 - 1)	0.68 (0.12 - 1)	0.53 (0.12 - 0.94)

4 Summary

Simulations were performed assuming a positive implementation error of between 10% and 40%, and indicate that the MP can be tuned to accommodate this error if it is approximately known. The tuned MPs yield similar performance statistics, with the exception that the recommended TAC (determined by the C_{max} tuning parameter) is lower at higher levels of implementation error (Figure 8). Contrary to the previous simulation exercise (Edwards, 2022b), in which robustness to implementation error was tested after tuning, tuning has now been performed with the implementation error included.

This simulation exercise allows MPs to be selected based on both their tuning to the 50%, 60% and 70% tuning criteria, and also the implementation error applied during the tuning process. For example, the most conservative MP would be MP1-R04 (Table 4), which is able to maintain the stock in the Kobe green quadrant with a probability of 70% when the implementation error is 40% (R04). The least conservative MP would be MP9-R01, which is tuned to the 50% criteria when implementation error is at 10% (R01). It is also possible to select MPs based on their performance across a range of implementation errors. For example, simulations of MP4 suggest that it may maintain the stock within the Kobe green quadrant 70% of the the time when implementation error is 20% (R02), and 50% of the time when implementation error is at 40% (R04; Table 4). These considerations should be helpful when choosing an MP for potential adoption.

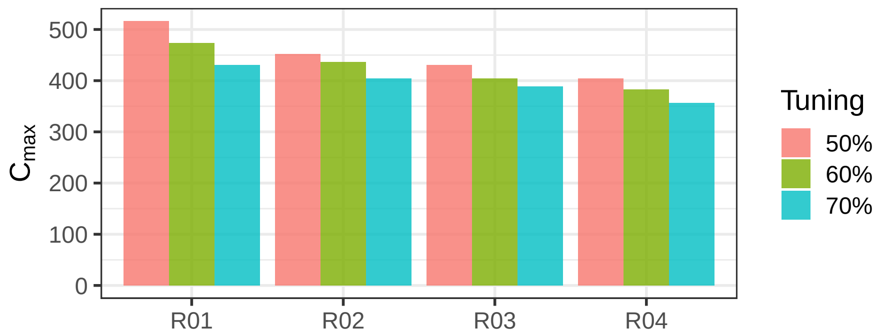


Figure 8: Summary of MP tuning at different levels of implementation error.

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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)*

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)*

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