Presentation of an empirical MP for Indian Ocean skipjack tuna

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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 (WPM; Edwards, 2020, IOTC, 2020a) and the Technical Committee on Management Procedures (TCMP; Edwards, 2021b, IOTC, 2021c), in which a suitable simulation framework was proposed, evaluations of an empirical MP were presented to the WPM (Edwards, 2021a), and the MSE Task Force (Edwards, 2022). The current work presents a summary of that work and proposes a set of empirical MPs for consideration by the TCMP.

1 Introduction

Empirical Management Procedures were proposed for Indian Ocean SKJ by Edwards (2021b), based on CPUE indices from the PL and PSLS fleets, which are both used routinely in assessments of the stock status (Fu, 2017, 2020). Performance of the MPs was simulated forward in time by Edwards (2021a,b, 2022) using a Stock Synthesis III Operating Model to generate the dynamics (see Edwards, 2020, for a justification of this approach). Structural uncertainty, including alternative spatial representations, was obtained from the grid of runs used in constructing the stock assessment by Fu (2020).

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 IOTC (2021c), tuning criteria that matched a 50%, 60% and 70% probability were adopted. Performance diagnostics were presented in accordance with recommendations by IOTC (2021a). Robustness tests were constructed based on feedback from the Working Party on Methods (IOTC, 2021b). These examined the influence of unaccounted for implementation error (over-catch of the TAC) and an unexpected drop in recruitment on performance of the MPs.

Reference points and Management Objectives: 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 $E_{20\%}$. The objectives of management are to "maintain the skipjack tuna stock biomass at, or above, the target reference point while avoiding the limit reference point" (IOTC, 2015).

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 ($B_{20\%}$)

2 Empirical MP

Empirical MPs are based on descriptive models of the raw data. An MP 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). We give a brief overview of the decision algorithm and data inputs here, with a more complete description provided by Edwards (2021a,b). A glossary of terms is given in Table 1.

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. Previous work has shown this stock status indicator to have a strong, linear and positive relationship to stock depletion (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 $y+3$.

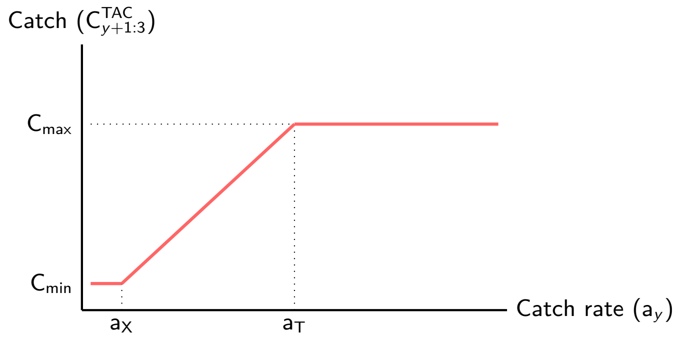

Figure 1: Schematic representation of the empirical Harvest Control Rule (Equation 2) being proposed as part of the MP.

2.3 HCR tuning parameters

Current management of Indian Ocean Skipjack is informed by an HCR that uses the biomass depletion as an input. Tuning parameters specified in Res. 16/02 are the threshold value (T): the spawning biomass depletion below which catch is decreased from it's maximum value; and the safety limit (X): the level below which the non-subsistence fishery is closed. These are set to $B_T = B_{40\%}$ and $B_X = B_{10\%}$ on the assumption that values for $B_{40\%}$ and $B_{10\%}$ are available when the HCR is executed.

The current empirical HCR being proposed replaces B_T and B_X with equivalent values of a_T and a_X. To inform selection of the a_X and a_T tuning parameters, the relationship between depletion (B_{y+1}/B_0) and a_y was estimated by Edwards (2021b). Based on this previous work, $a_X = -5.00$ and $a_T = -1.70$ were selected as appropriate tuning parameters for the HCR.

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 (specified in Section 3.5). The minimum catch was fixed at $C_{min} = 0.10 \times C_{40\%}$. The precise values for C_{max} and C_{min} tested as part of the tuning process are listed in Table A2.

Table 2: Median and 80% quantile status estimates across twenty-four model runs (Table A1), 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 Simulation evaluation framework

The evaluation framework was based on a set of SS III operating models (Methot Jr. & 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).

3.1 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, and twelve two area runs, described in IOTC (2020b) and listed in Table A1. Models were re-fitted for validation purposes, giving the results summarised in Table 2.

3.2 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, with implementation of the MP every third year, starting in 2023 (to set the recommended catch for 2024 to 2026 inclusive).

3.3 Dimensions

A total of nine MPs were tested (Table A2). For each MP, the 24 operating model variations were projected (Table A1), with ten stochastic iterations for each. Each simulation projected the stock forward twenty-one years from 2020 to 2040 inclusive.

3.4 Diagnostics

Performance of each MP was evaluated primarily against stated management objectives for the stock: to maintain the stock biomass at or above the TRP of $B_{40\%}$; to avoid the LRP of $B_{20\%}$. A comprehensive list of diagnostics with which to compare MPs was obtained from Bentley & Adam (2016) and described in Table 3. These include an expression of stock status using the Kobe strategy matrix. Following recommendations from IOTC (2021c) and IOTC (2021a), stock status was also reported using the Majuro quadrants. In addition, further diagnostic statistics were created to measure stability of the TAC being recommended the MP (see Edwards, 2022).

3.5 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. Kobe Green (Table 3) when averaged across projection years 11 to 15 (2030 to 2034 inclusive). Three tuning criteria were used, similar to the IOTC bigeye tuna stock:

50%: Pr. Kobe Green = 0.5

60%: Pr. Kobe Green = 0.6

70%: Pr. Kobe Green = 0.7

If an MP matched one of these tuning criteria to within 1% then it was selected for further consideration.

3.6 Robustness tests

Following recommendations from the Working Party on Methods (IOTC, 2021b), we investigated robustness of the MP to implementation error: catches higher than the recommended TAC; and recruitment decline: a short-term drop in productivity of the fishery. In each case robustness tests were conducted by introducing a constant multiplier to either the stochastic catch implementation error or the recruitment deviations, generated as described by Edwards (2021a).

3.6.1 Implementation error

In 2017, implementation of the HCR led to a recommendation for 2018–2020 of 470,029 tonnes. The actual catch in 2018 was approximately 607 thousand tonnes: 29% above the recommended catch limit; and in 2019 the catch was 547 thousand tonnes: 16% greater. Based on these observations, the following implementation error values were assessed:

R01: 20% positive catch error from 2021 to 2040;

R02: 30% positive catch error from 2021 to 2040;

R03: 40% positive catch error from 2021 to 2040;

3.6.2 Recruitment decline

As suggested by IOTC (2021b), a decline in recruitment of approximately 55% for eight consecutive quarters was considered a reasonable starting point for evaluations of response of the MPs to recruitment decline. Based on this recommendation, the following recruitment declines were included:

R01: 50% decline from 2021 to 2023;

R02: 50% decline from 2022 to 2024;

R03: 50% decline from 2023 to 2025;

These will simulate scenarios in which the recruitment has dropped three, two or one years before implementation of the MP.

4 Results

4.1 Tuning and selection of MPs

MPs were selected 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 4. As expected, MPs that meet the 50% tuning criteria have a higher C_{max} compared to MPs that meet the 60% ad 70% tuning criteria.

Table 4: Tuning parameters for MPs that matched the 70%, 60% and 50% tuning criteria. Values for C_{min} and C_{max} are given in units of thousand tonnes.

MP	C_{min}	C_{max}	a_X	a_T	Pr. Kobe Green	Tuning criteria
MP2	53.21	492.17	-5.00	-1.70	0.70	70%
MP4	53.21	518.77	-5.00	-1.70	0.59	60%
MP6	53.21	545.38	-5.00	-1.70	0.51	50%

Timeseries of the Kobe quadrant probabilities for each MP are given in Figure 2. To illustrate the overall performance of each MP, phase plots for each MP are given in Figure 3. The simulations suggest that MPs that pass the 50% tuning criteria will keep the stock close to the TRP, but with a higher risk that the LRP will be crossed. For MP2, tuned to the 70% criteria, there is a higher probability that the stock will stay above both the LRP and TRP.

Figure 4 shows the catch rate index dynamics over time for the one and two area models. Conversion of these projected index values into a recommended catch is illustrated in Figure 5. From the distribution of system states around the control rule, we can see that the less conservative 50% rule has a higher variability in the recommended catch, despite similar median index values over the projection period. The system variability for each MP is further illustrated by the biomass, catch and exploitation rate dynamics in Figures 6, 7, 8 and 9. Numeric diagnostics are given in Table A3. It can be seen from Figures 7 and 8 that MP6 has a higher variability when compared to more conservative MP2 and MP4. More frequent changes in the TAC recommendation allow MP6 to yield a higher average catch at the expense of a lower B_y (Figure 10 and Table A3).

With reference to Figure 7, which shows clear differences between the MPs, catch stability diagnostics in Table A3 indicate that $|C^{TAC}_{y+1}/C^{TAC}_{y} - 1|$ and Max. $|C^{TAC}_{y+1}/C^{TAC}_{y} - 1|$ are the most suitable for comparing stability of the TAC implementation process. The maximum change observed for MP2 has an upper limit close to 30%, whereas the maximum change for MP6 has an upper limit of around 120%. We note also that the probability of the TAC change exceeding 15% or 30% is small and suggests that inclusion of these TAC change limits will have limited affect on MP performance within the context of the simulations being conducted (although they become relevant to more extreme scenarios conducted as part of the robustness testing).

In summary, the least conservative MP6 (Kobe 50%) has a higher catch, at the expense of less stability in the catches, lower depletion and lower catch rates (Figure 10). The trade-offs between catch and other performance criteria are shown in Figure 11. As expected, the most conservative MP2 (Kobe 70%) has the lowest catch, but highest catch stability, stock biomass and catch rate values.

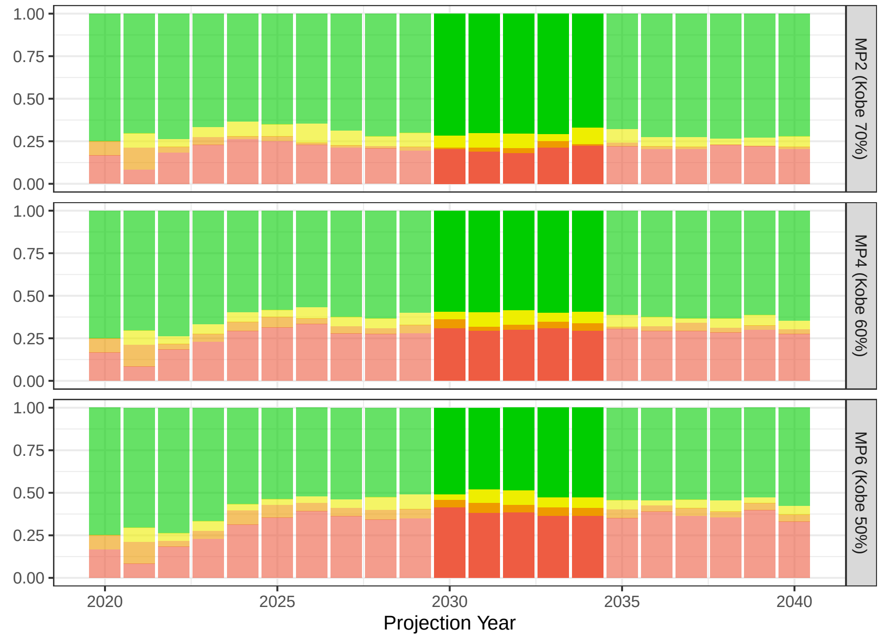

Figure 2: Kobe time series for MPs listed in Table 4. Average quadrant probabilities for each year, across all model runs and iterations for that MP, are shown. Probabilities between 2030 and 2034 inclusive were used to select MPs using the tuning criteria.

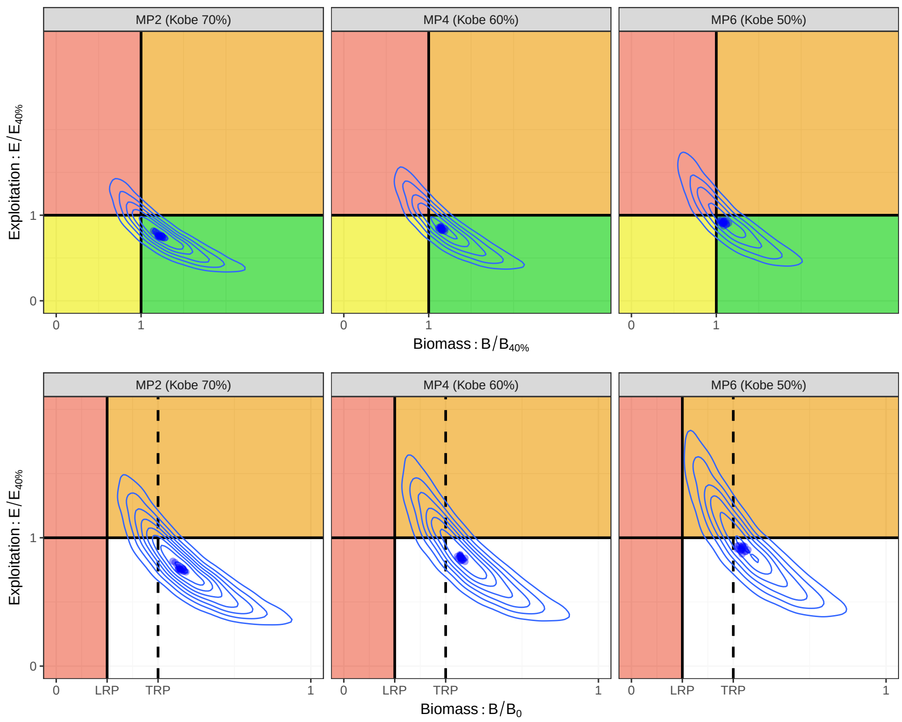

Figure 3: Kobe phase plots (top panel) and Majuro phase plots (bottom panel) for MPs listed in Table 4. Contours show a two-dimensional histogram of stock status across all years for which the MP was used to set catches (i.e. 2024 to 2040), twenty-four model runs and ten stochastic iterations for each run. Blue points show the median values per year and MP for each tuning criteria.

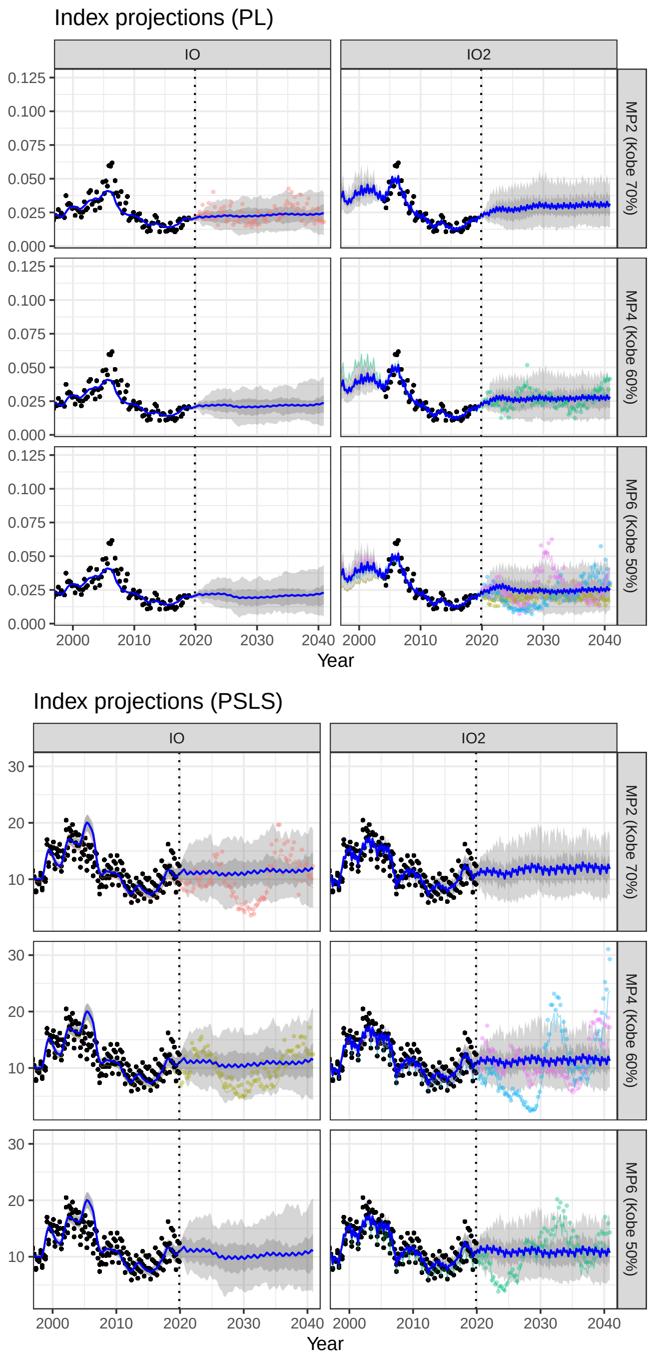

Figure 4: Index projections for IO and IO2 model runs (see Table A1). Black points represent empirical data. Fitted values in blue with 50% and 90% quantiles in grey. A sample of stochastic iterations is shown for the projection period.

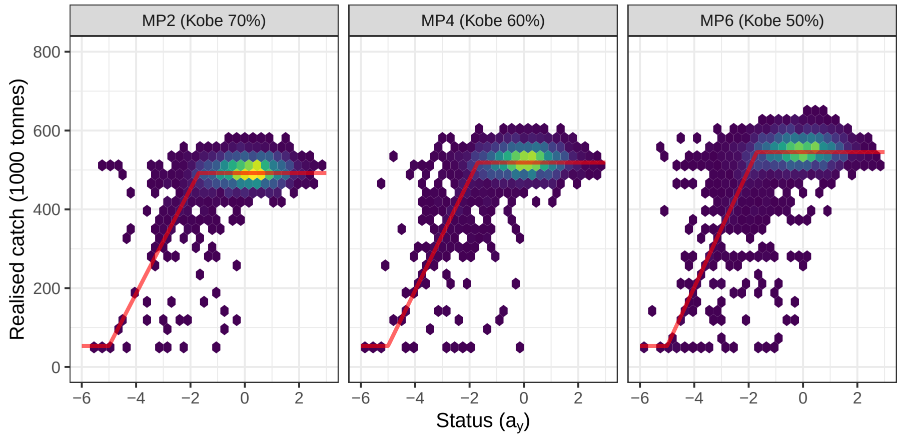

Figure 5: Two dimensional histogram of projection years (2024 to 2040) for each MP, showing the distribution of runs and iterations by stock status (measured by a_y) and realised catch. Lighter colors indicate a higher density of iterations. The HCR is shown (thick red line). The C_{max} values for each HCR are approximately 492, 519 and 545 thousand tonnes respectively for MP2, MP4 and MP6 (Table 4).

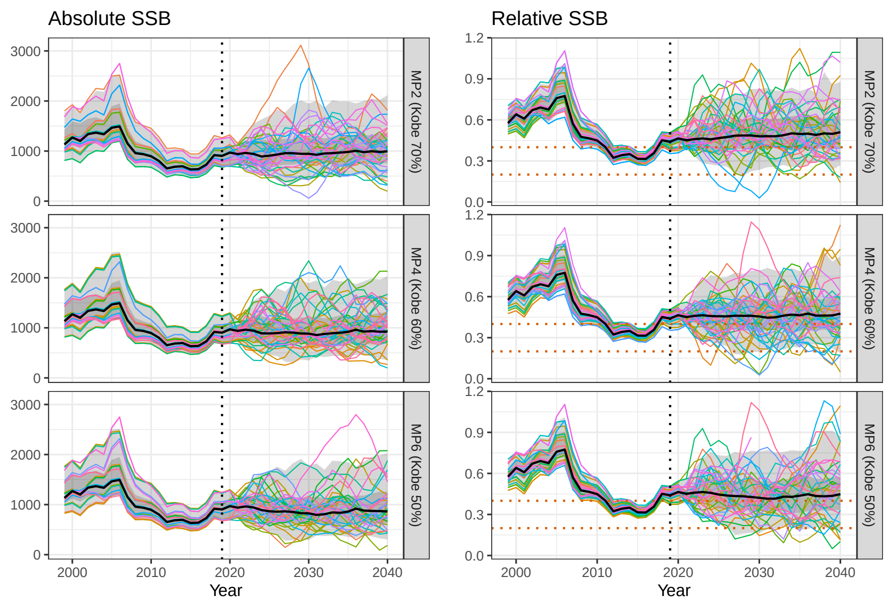

Figure 6: Spawning stock biomass dynamics following projection under each MP (Table 4). A sample of stochastic iterations is shown with 90% and 50% quantiles shaded in grey. Relative values are given according to B_0 for each run. Depletion reference points of 20% and 40% are shown as horizontal dashed lines.

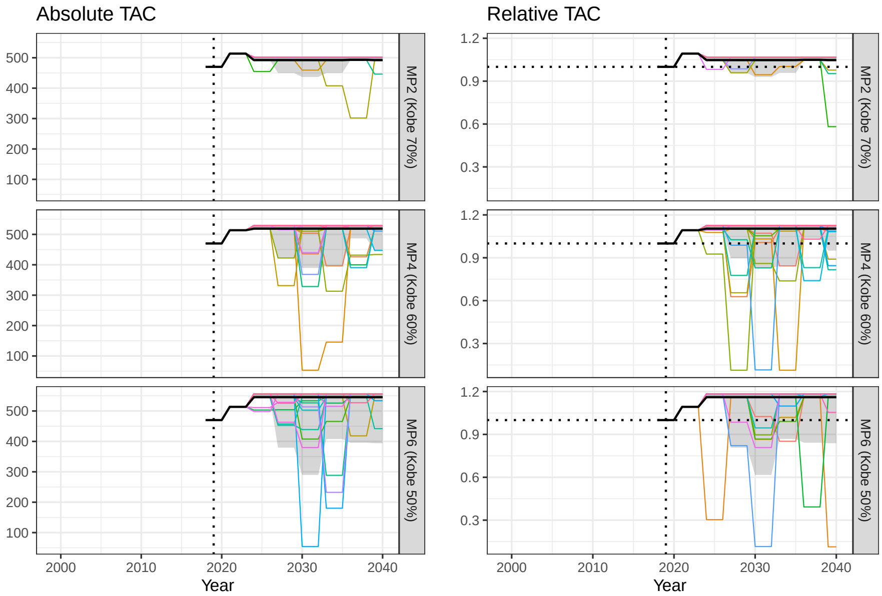

Figure 7: Total Allowable Catch dynamics following projection under each MP (Table 4). The TAC is assumed to be 513,572 tonnes for 2021–2023 (IOTC, 2020c). The first year of MP implementation is 2024. A sample of stochastic iterations is shown with 90% and 50% quantiles shaded in grey. Relative values are given using the 2018–2020 TAC of 470,029 tonnes as a reference.

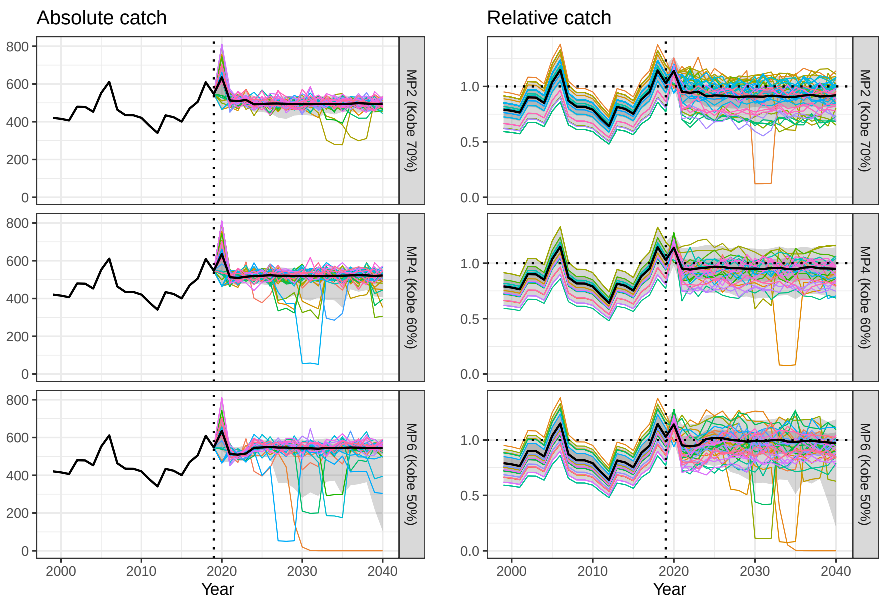

Figure 8: Realised catch dynamics following projection under each MP (Table 4). A sample of stochastic iterations is shown with 90% and 50% quantiles shaded in grey. Relative values are given according to $C_{40\%}$ for each run.

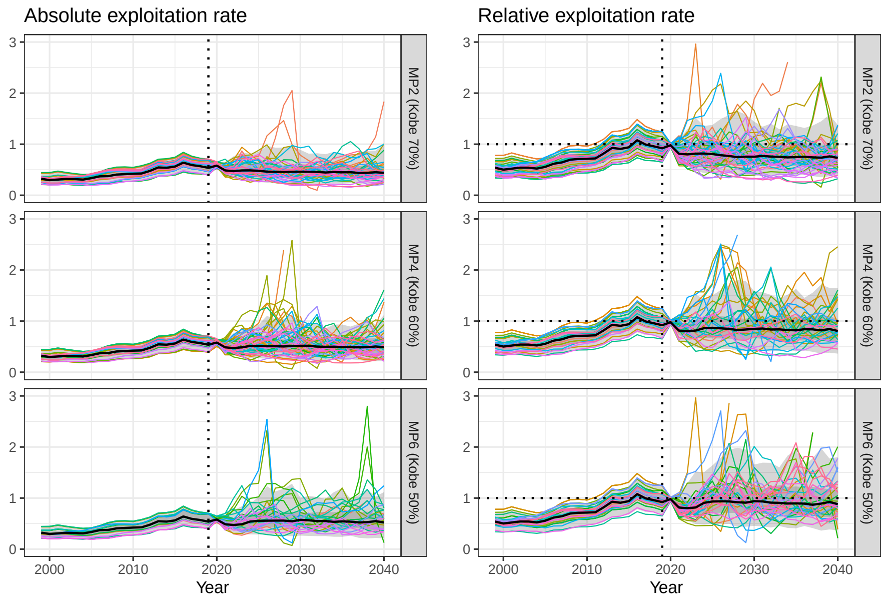

Figure 9: Exploitation rate dynamics following projection under each MP (Table 4). A sample of stochastic iterations is shown with 90% and 50% quantiles shaded in grey. Relative values are given according to $E_{40\%}$ for each run.

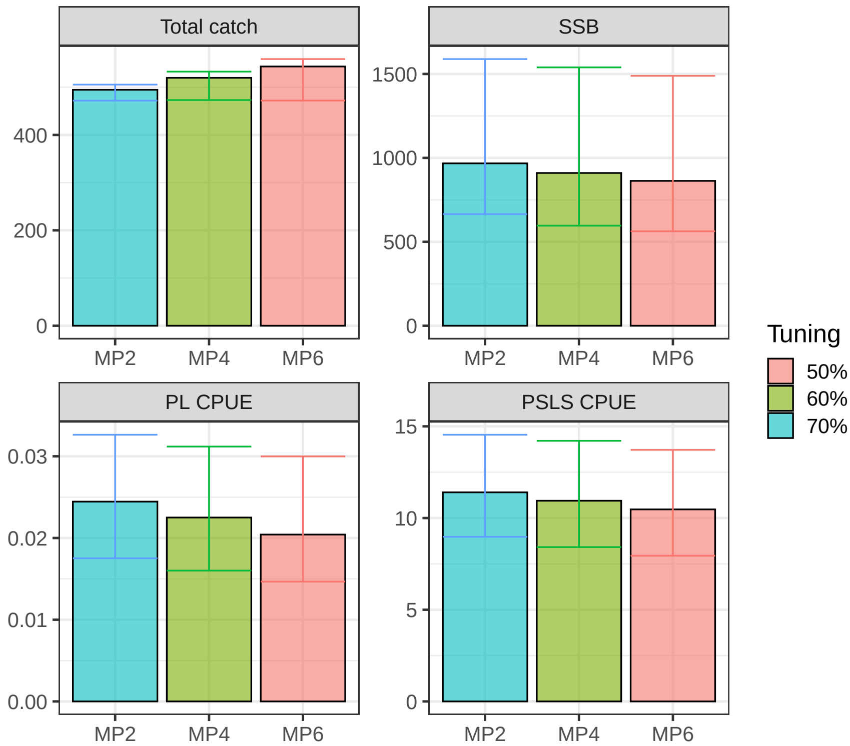

Figure 10: Summary diagnostic outputs (described in Table 3) for MPs listed in Table 4. The median and 90% quantile values are shown across all simulated values between 2024 and 2040.

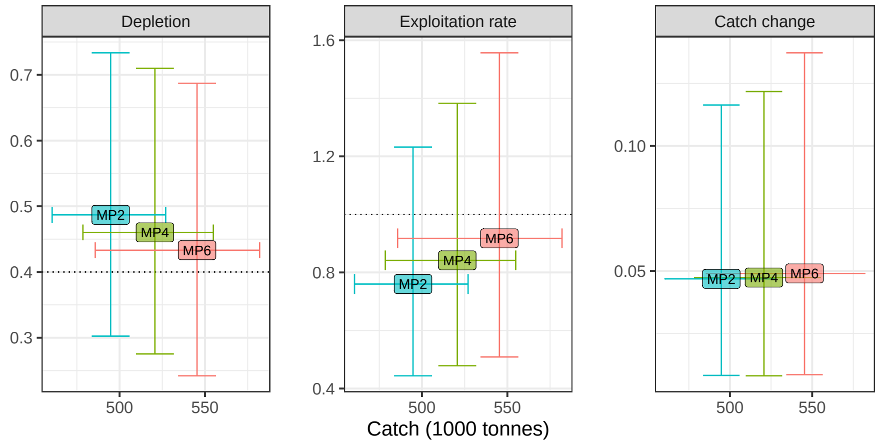

Figure 11: Tradeoff plots showing the total catch against: depletion relative to B_0; exploitation rate relative to $E_{40\%}$; and the TAC change (see Table 3). MPs are listed in Table 4. The median and 90% quantile values are shown across all simulated values between 2024 and 2040.

4.2 Robustness

The three MPs, corresponding to the three tuning criteria, were further subjected to robustness testing to evaluate their performance under extreme circumstances and to attempt to define those circumstances under which the MPs may no longer be suitable for management. Perturbation of each MP by the robustness tests is shown in Tables 5 and 6, measured using the same diagnostic that was used for tuning.

Table 5: Probability of being in the Kobe Green quadrant 2030–2034 folling MP robustness evaluation (Implementation).

MP (Tuning)	Robustness Test	Pr. Kobe Green
MP2 (Kobe 70%)	R01	0.51
MP2 (Kobe 70%)	R02	0.44
MP2 (Kobe 70%)	R03	0.38
MP4 (Kobe 60%)	R01	0.45
MP4 (Kobe 60%)	R02	0.41
MP4 (Kobe 60%)	R03	0.35
MP6 (Kobe 50%)	R01	0.40
MP6 (Kobe 50%)	R02	0.42
MP6 (Kobe 50%)	R03	0.36

Table 6: Probability of being in the Kobe Green quadrant 2030–2034 folling MP robustness evaluation (Recruitment).

MP (Tuning)	Robustness Test	Pr. Kobe Green
MP2 (Kobe 70%)	R01	0.70
MP2 (Kobe 70%)	R02	0.64
MP2 (Kobe 70%)	R03	0.65
MP4 (Kobe 60%)	R01	0.62
MP4 (Kobe 60%)	R02	0.56
MP4 (Kobe 60%)	R03	0.53
MP6 (Kobe 50%)	R01	0.54
MP6 (Kobe 50%)	R02	0.48
MP6 (Kobe 50%)	R03	0.47

4.2.1 Implementation error

It can be seen in Table 5 how implementation errors will lower the probability of the stock being in the Kobe Green quadrant between 2030–2034. Only MP2, which is the most conservative MP, is able to maintain the stock within the Kobe Green quadrant for those years with a probability of greater than 50%. And only under the weakest of the robustness tests (R01).

A more detailed picture of stock status under implementation error can be found in Tables A4, A5 and A6. Stock status dynamics are given in Figures 12 to 15, and also Figure 16.

From comparisons with Table A3, we can see that a positive implementation error yields a higher average catch. However the TAC is lower. The higher the implementation error, the lower the TAC. For MP2 for example, the average TAC recommendation in Table A3 is 492 thousand tonnes. As the implementation error increases from 20% (R01) to 40% (R03), the average TAC drops from 478 to 435 thousand tonnes (Table A4). This is a reflection of the status of the stock, with higher implementation error being associated with lower spawning stock biomass values. Under positive implementation error, stability of the stock over time

(Figure 12) is ultimately maintained by a reduction in the realised catches (Figure 14), which is particularly pronounced for MP6. This maintains the exploitation rate at a reasonable level (Figure 15).

However, despite being responsive, ability of the MPs to maintain the stock in the Kobe Green quadrant appears to be poor. MP2 for example has a simulated Pr. Kobe Green diagnostic of 0.34 – 0.46 depending on the degree of implementation error. For MP6 it is 0.30 – 0.35. This indicates that the more conservative MPs are more robust to implementation error in maintaining the stock closer to its management objectives.

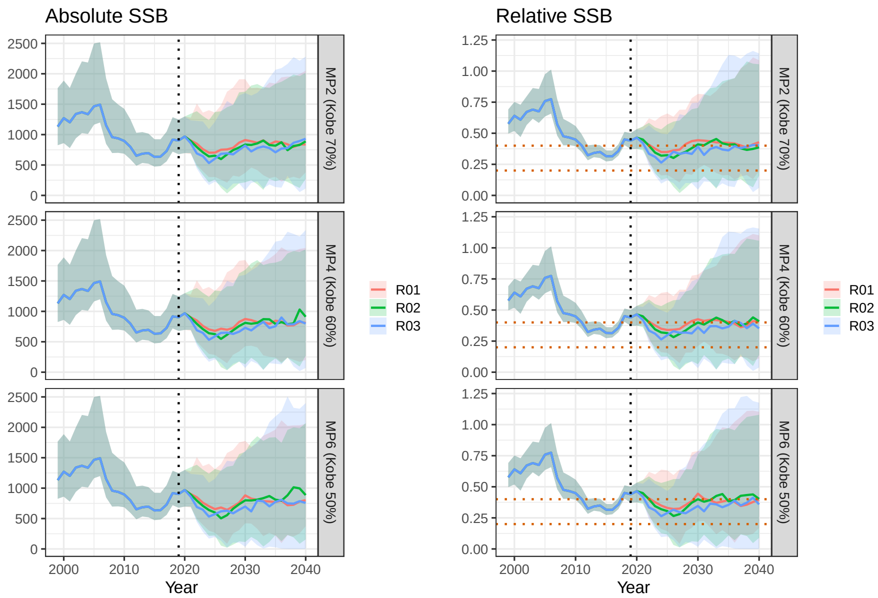

Figure 12: Spawning stock biomass dynamics following projection under each MP and Robustness test (Implementation error). The median and 90% for each robustness test are shown. Relative values are given according to B_0 for each run. The TRP and LRP are shown as horizontal dashed lines.

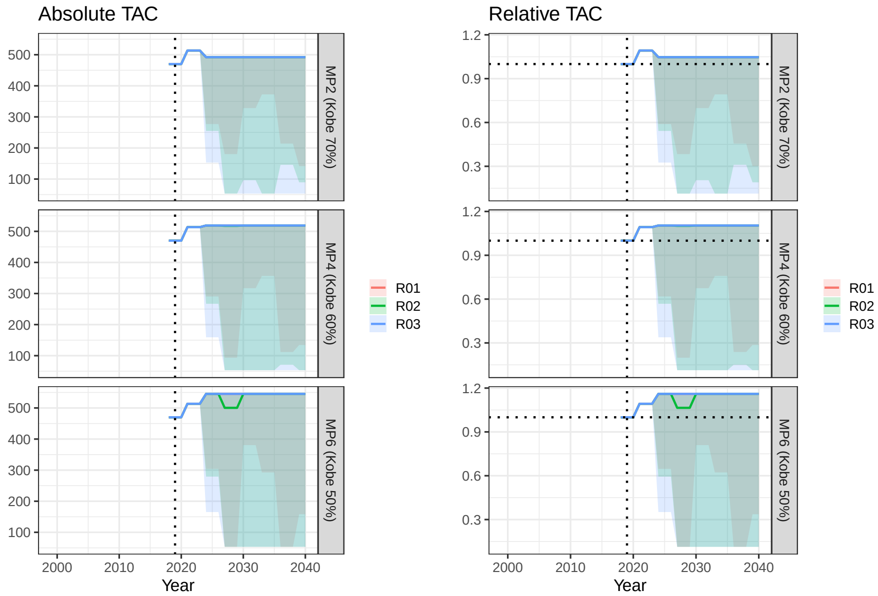

Figure 13: Total Allowable Catch dynamics following projection under each MP and Robustness test (Implementation error). The TAC is assumed to be 513,572 tonnes for 2021–2023 (IOTC, 2020c). The first year of MP implementation is 2024. The median and 90% for each robustness test are shown. Relative values are given using the 2018–2020 TAC of 470,029 tonnes as a reference.

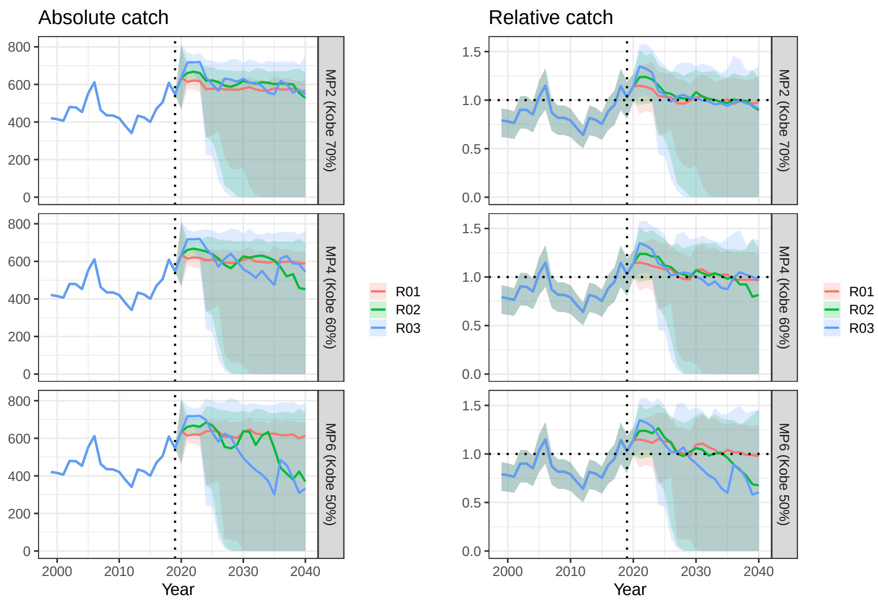

Figure 14: Catch dynamics following projection under each MP and Robustness test (Implementation error). The median and 90% for each robustness test are shown. Relative values are given according to $C_{40\%}$ for each run.

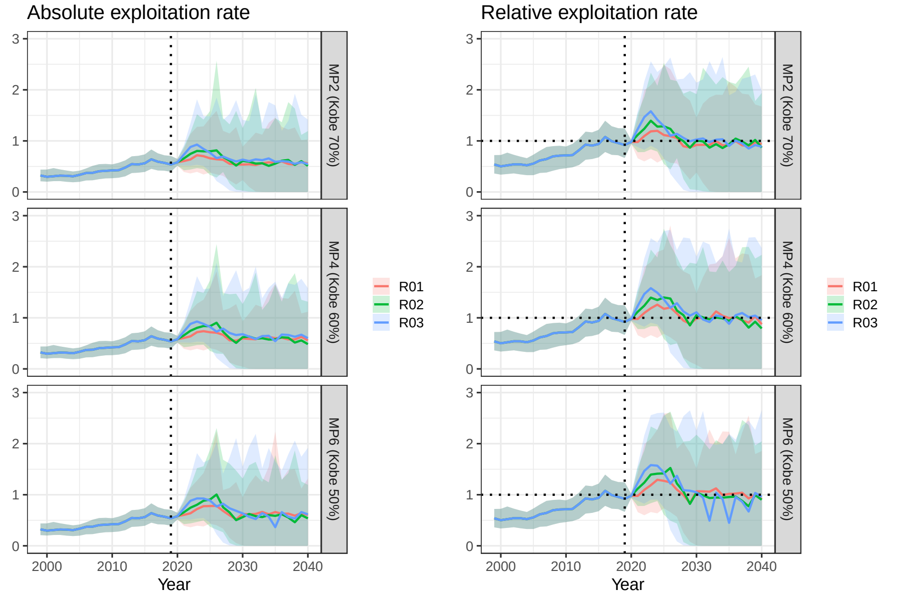

Figure 15: Exploitation rate dynamics following projection under each MP and Robustness test (Implementation error). The median and 90% for each robustness test are shown. Relative values are given according to $E_{40\%}$ for each run.

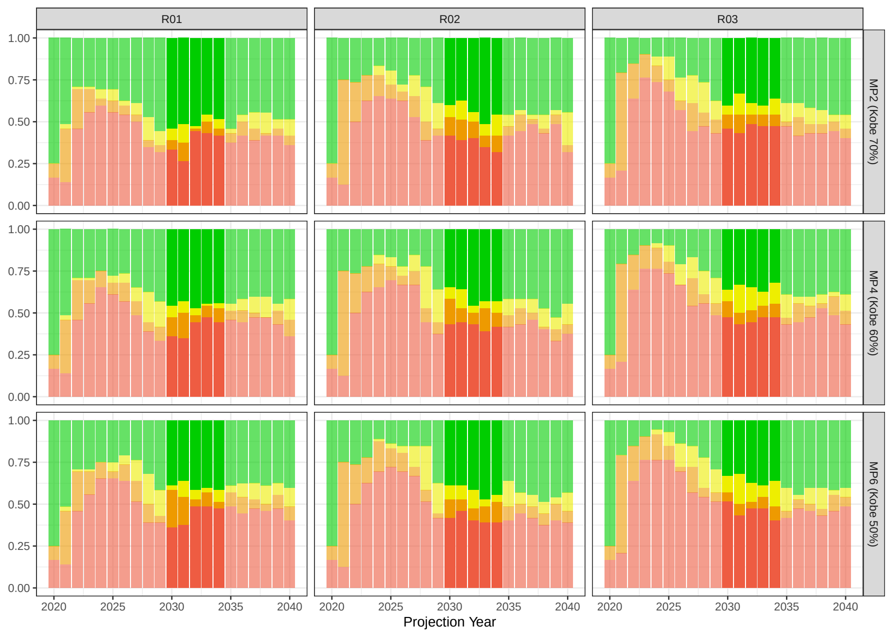

Figure 16: Kobe time series for MPs under each Robustness test (Implementation error). Average quadrant probabilities for each year, across all runs and iterations are shown.

4.2.2 Recruitment decline

Compared to their robustness to implementation error, the MPs appear to perform more favorably in instances of short term recruitment decline, with MP2 and MP4 both able to maintain Pr. Kobe Green (2030–2034) at or above 50% (Table 6). For purposes of visualizing the decline, Figure 17 shows the recruitment dynamics over time for each robustness test. Figures 18 to 22 give the resultant system dynamics and Tables A7 to A9 report the summary diagnostics.

Following a three year 50% drop in recruitment, all MPs respond to the associated drop in B_y (Figure 18) by drastically cutting the recommended TAC (Figure 19). However this is insufficient to prevent an increase in the exploitation rate (Figure 21). The reasons for this are two-fold. For some of the tests, it appears that the recommended TAC is cut to a value that equals the minimum TAC of $C_{min} = 53$ thousand tonnes. However for R01 (and for R02 under MP2) this is not the case. Rather the lag in implementing the MP has contributed to an increase in the exploitation rate because the TAC is maintained despite a drop in B_y. For R02 and R03, a recruitment drop in 2022 or later does not immediately affect the TAC for 2024 – 2026. The TAC is maintained for that period, as B_y declines, and only changed appropriately in 2027 – 2029.

Reassuringly, despite extreme changes in the TAC (Figure 19), the MPs are responsive and capably of bringing the stock back to its prior status (Figure 22). Although changes in the TAC are extreme, their magnitude is only a consequence of hypothetical recruitment scenarios, rather than being justified by data from the fishery. Nevertheless, we can state the trivial observation that a 50% drop in the recruitment is likely to lead to an unacceptable change in the TAC recommendation, regardless of the timing of that drop (Tables A7 to A9). Further work will be required to ascertain what recruitment drop could be accommodated within acceptable limits of a TAC change.

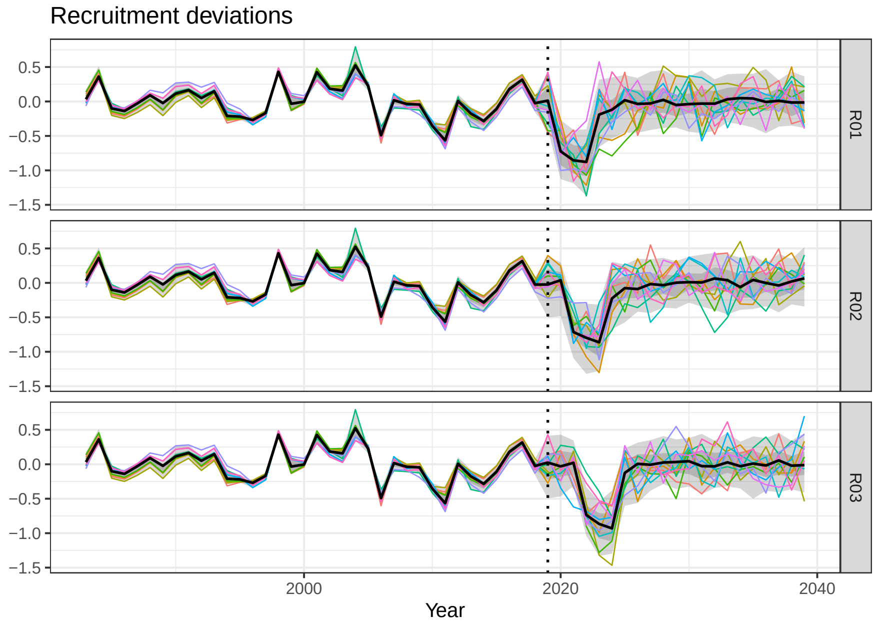

Figure 17: Recruitment deviations for recruitment robustness trials

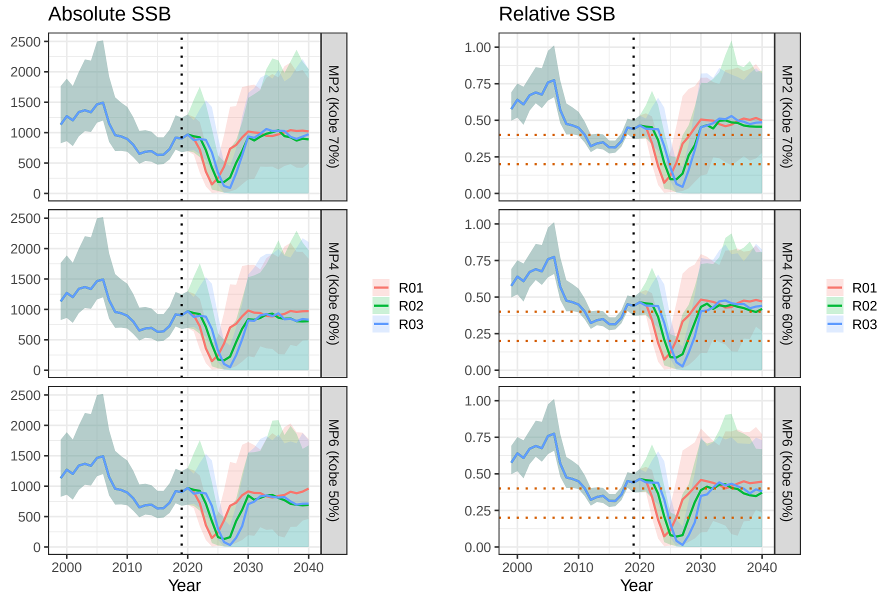

Figure 18: Spawning stock biomass dynamics following projection under each MP (Table 4). The median and 90% for each robustness test are shown. Relative values are given according to B_0 for each run. The TRP and LRP are shown as horizontal dashed lines.

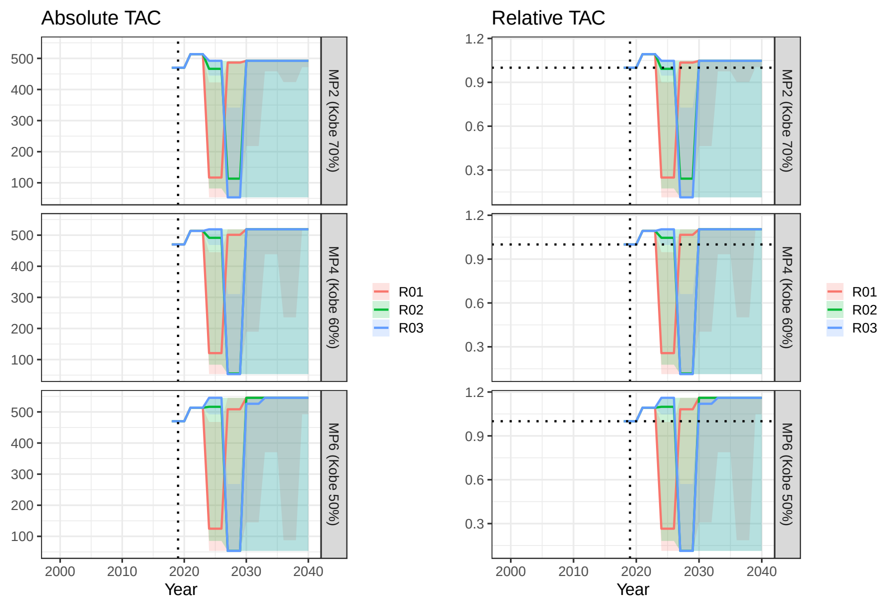

Figure 19: Total Allowable Catch dynamics following projection under each MP (Table 4). The TAC is assumed to be 513,572 tonnes for 2021–2023 (IOTC, 2020c). The first year of MP implementation is 2024. The median and 90% for each robustness test are shown. Relative values are given using the 2018–2020 TAC of 470,029 tonnes as a reference.

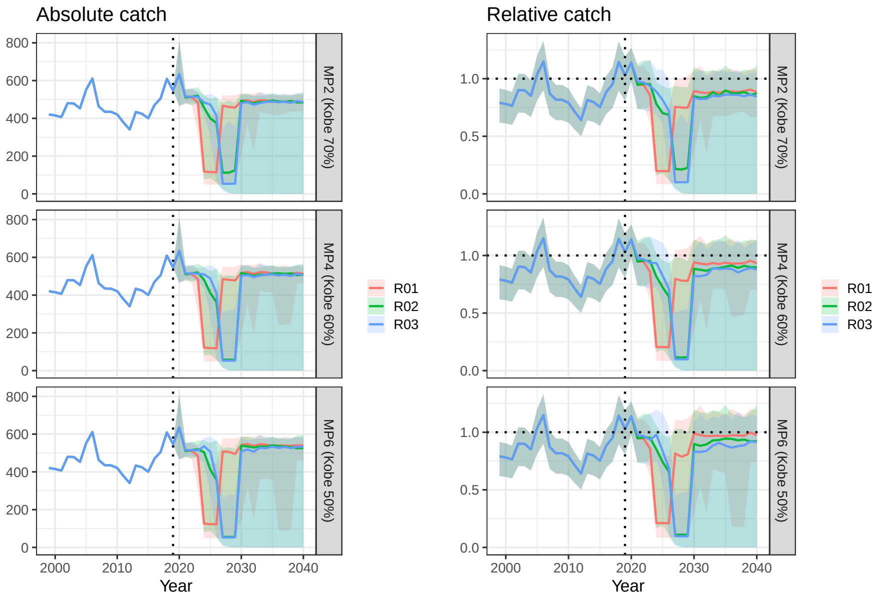

Figure 20: Catch dynamics following projection under each MP (Table 4). The median and 90% for each robustness test are shown. Relative values are given according to $C_{40\%}$ for each run.

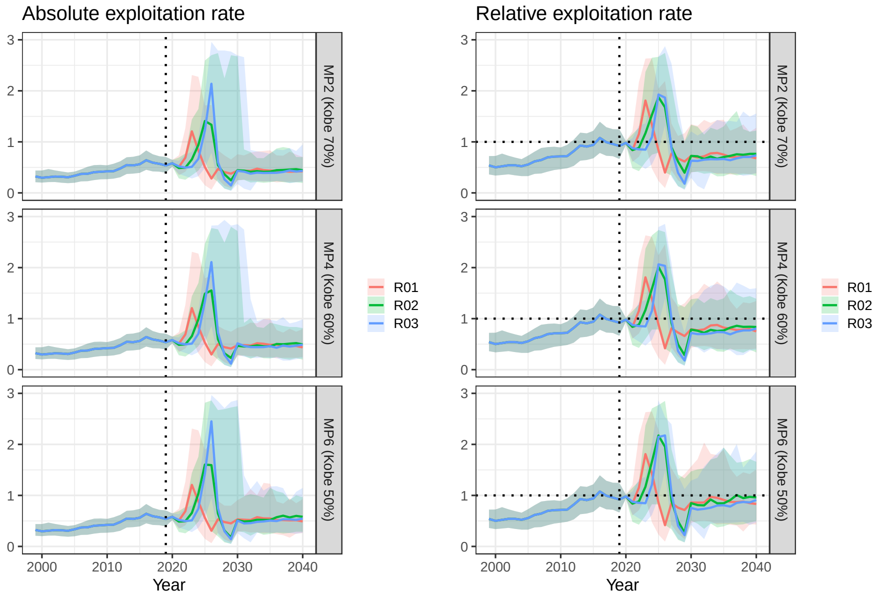

Figure 21: Exploitation rate dynamics following projection under each MP (Table 4).The median and 90% for each robustness test are shown. Relative values are given according to $E_{40\%}$ for each run.

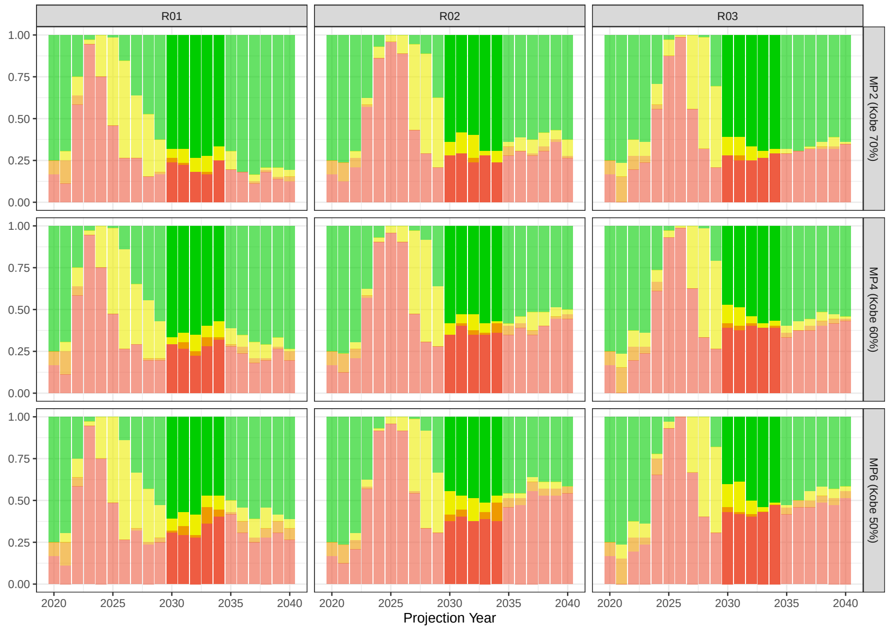

Figure 22: Kobe time series for MPs listed in Table 4. Average quadrant probabilities for each year, across all runs and iterations are shown.

5 Summary

Three MPs have been presented that match the 50%, 60% and 70% tuning criteria, and which exhibit familiar trade-offs between catch, catch stability and stock biomass. Diagnostics concerning the catch stability indicate that 30% or 15% limits to the TAC change could be accommodated without much apparent consequence for performance of the MP (noting that a 30% limit is already included in current management; Section A).

We note that performance evaluation and potential adoption of these MPs is 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. Work is needed to ensure consistency in how these data are to be generated going forward, including a schedule that is aligned to the years in which the MP is to be implemented.

The MPs were subjected to simple robustness tests to diagnose their performance under varying levels of implementation error and stock productivity. These are not only necessary for confidence in the MP, but also help to provide limits beyond which an MP may become inadequate for stock management.

Implementation error: Results indicate that performance of the MPs in maintaining the stock status is undermined when catches exceed the recommended TAC, and that this will lead to a reduction in the catch over time. The larger the implementation error, the greater the decline in MP performance. The susceptiblity of each MP is dependent on how aggressive the MP is. The average TAC for the most conservative MP (MP2 Kobe 70%) drops by 12% (from 492 to 435 thousand tonnes) as the implementation error increases (and the realised catch increases; Table A4). For MP6 however (Kobe 50%), the average TAC is predicted to drop by 17% at the highest level of implementation error (from 545 to 454 thousand tonnes), and the realised catch is predicted to drop by 14% (Table A6). This would suggest that in the absence of further information on the implementation error, the more conservative of the MPs is likely to be more robust to possible over-catch of the TAC.

Recruitment decline: The MPs are responsive to recruitment-driven changes in the stock biomass, and able to recover the stock from extreme but short-term declines in productivity. This provides confidence that the MPs are behaving appropriately.

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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).

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A Current management

Based on the work of Bentley and Adam (Adam & Bentley, 2013, Bentley & 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 2021–2023 inclusive (IOTC, 2020c).

Using the terminology of Bentley & 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:

$$\mathrm{I}_y = \begin{cases} 1 & \text{for } \mathrm{B}_y \geq \mathrm{B}_{40\%} \\ \frac{\mathrm{B}_y - \mathrm{B}_{10\%}}{\mathrm{B}_{40\%} - \mathrm{B}_{10\%}} & \text{for } \mathrm{B}_{10\%} < \mathrm{B}_y < \mathrm{B}_{40\%} \\ 0 & \text{for } \mathrm{B}_y \leq \mathrm{B}_{10\%} \end{cases} \tag{2a}$$

Closure of the fishery at $\mathrm{B}_y \leq \mathrm{B}_{10\%}$ refers to the non-subsistence fishery only.

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

$$\mathrm{E}_y = \mathrm{I}_y \times \mathrm{E}_{40\%} \tag{2b}$$

The exploitation rate is defined as the catch over the vulnerable (selected) component of the biomass (Section 2.1.3, Bentley & 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:

$$\mathrm{C}^{\mathrm{TAC}}_{y+1:3} = \mathrm{I}_y \times \mathrm{E}_{40\%} \times \mathrm{B}_y \tag{2c}$$

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 $\mathrm{B}_y \leq \mathrm{B}_{10\%}$, in which case $\mathrm{C}^{\mathrm{TAC}}_{y+1:3}$ will always be zero.

Input values for the control rule ($\mathrm{B}_{40\%}$, $\mathrm{B}_{10\%}$, and $\mathrm{E}_{40\%}$) 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. Since derivation of these input values is not explicitly defined, the current means for generating a recommended catch is not classified as a Management Procedure (Punt et al., 2016).

B Model runs and tuning parameters

Table A1: List of 24 SS III assessment runs used as operating models, reproduced from Table 2 of IOTC (2020b).

Label	Area	Steepnes (h)	Catchability trend	Tag likelihood weighting (λ)
io_h70_q0_tlambda01	1	0.7	1.0000	0.1
io_h70_q0_tlambda1	1	0.7	1.0000	1.0
io_h70_q1_tlambda01	1	0.7	1.0125	0.1
io_h70_q1_tlambda1	1	0.7	1.0125	1.0
io_h80_q0_tlambda01	1	0.8	1.0000	0.1
io_h80_q0_tlambda1	1	0.8	1.0000	1.0
io_h80_q1_tlambda01	1	0.8	1.0125	0.1
io_h80_q1_tlambda1	1	0.8	1.0125	1.0
io_h90_q0_tlambda01	1	0.9	1.0000	0.1
io_h90_q0_tlambda1	1	0.9	1.0000	1.0
io_h90_q1_tlambda01	1	0.9	1.0125	0.1
io_h90_q1_tlambda1	1	0.9	1.0125	1.0
io2_h70_q0_tlambda01	2	0.7	1.0000	0.1
io2_h70_q0_tlambda1	2	0.7	1.0000	1.0
io2_h70_q1_tlambda01	2	0.7	1.0125	0.1
io2_h70_q1_tlambda1	2	0.7	1.0125	1.0
io2_h80_q0_tlambda01	2	0.8	1.0000	0.1
io2_h80_q0_tlambda1	2	0.8	1.0000	1.0
io2_h80_q1_tlambda01	2	0.8	1.0125	0.1
io2_h80_q1_tlambda1	2	0.8	1.0125	1.0
io2_h90_q0_tlambda01	2	0.9	1.0000	0.1
io2_h90_q0_tlambda1	2	0.9	1.0000	1.0
io2_h90_q1_tlambda01	2	0.9	1.0125	0.1
io2_h90_q1_tlambda1	2	0.9	1.0125	1.0

Table A2: MP tuning parameters testing using simulation. Values for C_{min} and C_{max} are given in units of thousand tonnes.

MP	C_{min}	C_{max}	a_X	a_T
MP1	53.21	478.87	-5.00	-1.70
MP2	53.21	492.17	-5.00	-1.70
MP3	53.21	505.47	-5.00	-1.70
MP4	53.21	518.77	-5.00	-1.70
MP5	53.21	532.08	-5.00	-1.70
MP6	53.21	545.38	-5.00	-1.70
MP7	53.21	558.68	-5.00	-1.70
MP8	53.21	571.98	-5.00	-1.70
MP9	53.21	585.28	-5.00	-1.70

C Diagnostic outputs

Table A3: Diagnostic outputs for evaluation of index-based MPs (see Table 4 for the list of MP definitions and Table 3 for a description of each diagnostic). The best performing MP for each summary statistic is shaded.

Diagnostic	Units	MP2 (Kobe 70%)	MP4 (Kobe 60%)	MP6 (Kobe 50%)
$C^{TAC}_{y+1:3}$	10^3 tonnes	492.17 (468.12 - 502.02)	518.77 (481.36 - 529.16)	545.38 (482.68 - 556.3)
C	10^3 tonnes	494.63 (471.84 - 505.44)	519.76 (473.11 - 532.69)	543.44 (471.93 - 559.04)
$C_{[PL]}$	10^3 tonnes	80.73 (76.35 - 85.35)	84.27 (77.61 - 89.73)	87.63 (73.24 - 93.52)
$C_{[PSLS]}$	10^3 tonnes	186.88 (175.58 - 192.37)	196.24 (178.68 - 202.77)	204.43 (180.77 - 212.99)
$C_{[PSFS]}$	10^3 tonnes	27.8 (25.65 - 28.84)	29.12 (26.36 - 30.38)	30.37 (27.07 - 31.91)
$C_y/C_{40\%}$	Proportion	0.91 (0.73 - 1.02)	0.94 (0.76 - 1.06)	0.96 (0.77 - 1.08)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	1 (1 - 3)	1 (1 - 4)	1 (1 - 4)
$\|C^{TAC}_{y+1}/C^{TAC}_y - 1\|$	Percent	0 (0 - 11)	1 (0 - 16)	1 (1 - 34)
Max. $\|C^{TAC}_{y+1}/C^{TAC}_y - 1\|$	Percent	4 (2 - 32)	3 (1 - 60)	8 (6 - 121)
Pr. $\|C^{TAC}_{y+1}/C^{TAC}_y - 1\| > 30\%$	Prob.	0.03	0.05	0.08
Pr. $\|C^{TAC}_{y+1}/C^{TAC}_y - 1\| > 15\%$	Prob.	0.05	0.09	0.11
$CPUE_{[PL]}$	Rate	0.02 (0.02 - 0.03)	0.02 (0.02 - 0.03)	0.02 (0.01 - 0.03)
$CPUE_{[PSLS]}$	Rate	11.14 (8.81 - 13.64)	10.6 (8.31 - 13.41)	10.25 (7.81 - 12.98)
E_y	Rate	0.46 (0.29 - 0.64)	0.51 (0.3 - 0.7)	0.55 (0.32 - 0.77)
$E_y/E_{40\%}$	Proportion	0.79 (0.49 - 1.09)	0.85 (0.53 - 1.21)	0.93 (0.56 - 1.3)
B_y	10^3 tonnes	967.41 (664.95 - 1588.69)	910.06 (596.26 - 1539.14)	862.96 (562.92 - 1488.81)
B_y/B_0	Proportion	0.48 (0.35 - 0.65)	0.44 (0.32 - 0.62)	0.42 (0.29 - 0.6)
B_{MIN}/B_0	Proportion	0.31 (0.17 - 0.47)	0.28 (0.14 - 0.45)	0.26 (0.11 - 0.42)
Pr. $> B_{20\%}$	Prob.	0.98	0.96	0.94
Pr. $> B_{10\%}$	Prob.	1	0.99	0.99
Pr. Kobe Red	Prob.	0.21	0.3	0.36
Pr. Kobe Green	Prob.	0.7	0.61	0.53
Pr. Majuro Red	Prob.	0 (0 - 0.12)	0 (0 - 0.18)	0 (0 - 0.18)
Pr. Majuro White	Prob.	0.82 (0.35 - 1)	0.71 (0.24 - 1)	0.59 (0.18 - 1)

Table A4: Diagnostic outputs for robustness to implemetation error for MP2 (Kobe 70%) (see Table 4 for the list of MP definitions and Table 3 for a description of each diagnostic).

Diagnostic	Units	R01	R02	R03
$C^{TAC}_{y+1:3}$	10^3 tonnes	478.69 (393.45 - 492.17)	458.13 (364.65 - 492.17)	435.51 (311.8 - 492.17)
C	10^3 tonnes	555.05 (338.43 - 592.88)	540 (194.08 - 638.75)	515.19 (141.27 - 678.44)
$C_{[PL]}$	10^3 tonnes	88.86 (37.89 - 96.91)	81.78 (18.18 - 103.4)	70.37 (11.78 - 109.66)
$C_{[PSLS]}$	10^3 tonnes	213.44 (142.98 - 227.54)	218.97 (81.29 - 248.99)	216.76 (60.21 - 260.74)
$C_{[PSFS]}$	10^3 tonnes	31.39 (24.56 - 34.05)	33.27 (14.87 - 37.29)	34.52 (12.12 - 39.75)
$C_y/C_{40\%}$	Proportion	0.92 (0.25 - 1.07)	0.88 (0.01 - 1.09)	0.77 (0 - 1.05)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	3 (1 - 5)	3 (1 - 5)	4 (1 - 6)
$\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	5 (1 - 57)	15 (1 - 153)	24 (1 - 183)
Max. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	13 (4 - 187)	47 (4 - 825)	78 (4 - 825)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 30\%$	Prob.	0.16	0.22	0.32
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 15\%$	Prob.	0.22	0.3	0.42
$CPUE_{[PL]}$	Rate	0.02 (0.01 - 0.03)	0.02 (0.01 - 0.03)	0.01 (0.01 - 0.04)
$CPUE_{[PSLS]}$	Rate	9.24 (7.12 - 12.55)	9.02 (5.66 - 12.22)	8.11 (5.26 - 13.91)
E_y	Rate	0.57 (0.1 - 0.85)	0.61 (0.01 - 0.91)	0.63 (0 - 0.95)
$E_y/E_{40\%}$	Proportion	0.99 (0.19 - 1.38)	1.02 (0.01 - 1.46)	1.06 (0 - 1.5)
B_y	10^3 tonnes	844.48 (494 - 1436.75)	815.54 (448.29 - 1300.49)	763.3 (417.13 - 1468.64)
B_y/B_0	Proportion	0.38 (0.23 - 0.61)	0.36 (0.2 - 0.53)	0.34 (0.17 - 0.62)
B_{MIN}/B_0	Proportion	0.21 (0.09 - 0.38)	0.16 (0.03 - 0.28)	0.14 (0.04 - 0.31)
Pr. $> B_{20\%}$	Prob.	0.9	0.83	0.79
Pr. $> B_{10\%}$	Prob.	0.98	0.94	0.94
Pr. Kobe Red	Prob.	0.42	0.45	0.49
Pr. Kobe Green	Prob.	0.46	0.38	0.34
Pr. Majuro Red	Prob.	0 (0 - 0.29)	0.12 (0 - 0.41)	0.18 (0 - 0.53)
Pr. Majuro White	Prob.	0.5 (0.12 - 0.94)	0.41 (0.06 - 0.82)	0.29 (0.06 - 0.82)

Table A5: Diagnostic outputs for robustness to implemetation error for MP4 (Kobe 60%) (see Table 4 for the list of MP definitions and Table 3 for a description of each diagnostic).

Diagnostic	Units	R01	R02	R03
$C^{TAC}_{y+1:3}$	10^3 tonnes	495.33 (387.56 - 518.77)	462.63 (359.92 - 518.77)	440.57 (315.81 - 518.77)
C	10^3 tonnes	558.53 (280.04 - 624.16)	533.53 (159.79 - 659.41)	516.98 (130.28 - 684.78)
$C_{[PL]}$	10^3 tonnes	88.94 (30.78 - 101.17)	75.63 (15.74 - 107.45)	65.87 (10.61 - 112.05)
$C_{[PSLS]}$	10^3 tonnes	219.5 (120.42 - 242.09)	213.46 (73.66 - 260.68)	210.05 (47.32 - 270.68)
$C_{[PSFS]}$	10^3 tonnes	32.68 (22.19 - 36.24)	33.99 (13.02 - 39.52)	35.1 (8.86 - 41.71)
$C_y/C_{40\%}$	Proportion	0.92 (0.07 - 1.08)	0.79 (0 - 1.09)	0.75 (0 - 1.04)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	3 (1 - 5)	3 (1 - 6)	4 (1 - 6)
$\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	8 (0 - 118)	17 (0 - 161)	30 (0 - 186)
Max. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	27 (1 - 400)	63 (1 - 875)	86 (1 - 875)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 30\%$	Prob.	0.21	0.25	0.36
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 15\%$	Prob.	0.27	0.32	0.45
$CPUE_{[PL]}$	Rate	0.02 (0.01 - 0.03)	0.02 (0.01 - 0.03)	0.01 (0.01 - 0.04)
$CPUE_{[PSLS]}$	Rate	8.99 (5.94 - 12.69)	8.69 (5.45 - 12.36)	7.53 (5.1 - 14.03)
E_y	Rate	0.62 (0.02 - 0.87)	0.56 (0 - 0.99)	0.68 (0 - 0.98)
$E_y/E_{40\%}$	Proportion	1.09 (0.04 - 1.5)	0.98 (0.01 - 1.51)	1.14 (0 - 1.55)
B_y	10^3 tonnes	814.37 (480.01 - 1442.45)	800.47 (413.32 - 1270.52)	735.5 (386.05 - 1478.83)
B_y/B_0	Proportion	0.36 (0.22 - 0.61)	0.36 (0.19 - 0.54)	0.32 (0.17 - 0.63)
B_{MIN}/B_0	Proportion	0.19 (0.07 - 0.35)	0.15 (0.02 - 0.27)	0.12 (0.02 - 0.29)
Pr. $> B_{20\%}$	Prob.	0.87	0.81	0.75
Pr. $> B_{10\%}$	Prob.	0.97	0.93	0.91
Pr. Kobe Red	Prob.	0.46	0.47	0.52
Pr. Kobe Green	Prob.	0.4	0.35	0.3
Pr. Majuro Red	Prob.	0.06 (0 - 0.41)	0.12 (0 - 0.47)	0.18 (0 - 0.58)
Pr. Majuro White	Prob.	0.41 (0.12 - 0.94)	0.41 (0.06 - 0.76)	0.29 (0.06 - 0.82)

Table A6: Diagnostic outputs for robustness to implemetation error for MP6 (Kobe 50%) (see Table 4 for the list of MP definitions and Table 3 for a description of each diagnostic).

Diagnostic	Units	R01	R02	R03
$C^{TAC}_{y+1:3}$	10^3 tonnes	517.77 (379.4 - 545.38)	482.67 (367.81 - 545.38)	454.86 (287.97 - 545.38)
C	10^3 tonnes	551.92 (244.57 - 652.79)	513.81 (151.16 - 678.47)	465.07 (115.85 - 693.66)
$C_{[PL]}$	10^3 tonnes	83.92 (26.32 - 105.65)	65.32 (14.39 - 110.69)	52.59 (9.52 - 111.96)
$C_{[PSLS]}$	10^3 tonnes	224.81 (104.51 - 255.06)	205.31 (60.27 - 272.56)	194.95 (41.37 - 283.59)
$C_{[PSFS]}$	10^3 tonnes	33.52 (21.76 - 38.41)	34.75 (9.97 - 40.89)	35.06 (8.43 - 43.97)
$C_y/C_{40\%}$	Proportion	0.92 (0.04 - 1.09)	0.72 (0 - 1.09)	0.66 (0 - 1.06)
C^{TAC}_{y+1} not equal to C^{TAC}_{y}	Count	3 (1 - 5)	3 (1 - 6)	4 (1 - 6)
$\lvert C^{TAC}_{y+1}/C^{TAC}_{y} - 1\rvert$	Percent	11 (1 - 192)	23 (1 - 176)	36 (1 - 211)
Max. $\lvert C^{TAC}_{y+1}/C^{TAC}_{y} - 1\rvert$	Percent	30 (6 - 925)	80 (6 - 925)	110 (6 - 925)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_{y} - 1\rvert > 30\%$	Prob.	0.24	0.27	0.39
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_{y} - 1\rvert > 15\%$	Prob.	0.29	0.36	0.45
$CPUE_{[PL]}$	Rate	0.02 (0.01 - 0.03)	0.02 (0.01 - 0.03)	0.01 (0.01 - 0.04)
$CPUE_{[PSLS]}$	Rate	8.53 (5.66 - 13.42)	8.4 (4.67 - 12.32)	7.27 (4.11 - 14.2)
E_y	Rate	0.64 (0.01 - 0.88)	0.56 (0 - 1.03)	0.71 (0 - 1.11)
$E_y/E_{40\%}$	Proportion	1.08 (0.02 - 1.46)	0.96 (0 - 1.64)	1.18 (0 - 1.7)
B_y	10^3 tonnes	758.85 (458.33 - 1435.88)	799.84 (399.49 - 1292.63)	745.79 (321.82 - 1437.71)
B_y/B_0	Proportion	0.34 (0.22 - 0.61)	0.35 (0.17 - 0.56)	0.3 (0.12 - 0.65)
B_{MIN}/B_0	Proportion	0.17 (0.03 - 0.33)	0.14 (0.02 - 0.28)	0.11 (0.01 - 0.29)
Pr. $> B_{20\%}$	Prob.	0.86	0.8	0.73
Pr. $> B_{10\%}$	Prob.	0.96	0.92	0.88
Pr. Kobe Red	Prob.	0.48	0.48	0.52
Pr. Kobe Green	Prob.	0.35	0.34	0.3
Pr. Majuro Red	Prob.	0.12 (0 - 0.35)	0.12 (0 - 0.47)	0.24 (0 - 0.64)
Pr. Majuro White	Prob.	0.32 (0.06 - 0.82)	0.41 (0.01 - 0.76)	0.24 (0 - 0.82)

Table A7: Diagnostic outputs for robustness to recruitment deviations for MP2 (Kobe 70%) (see Table 4 for the list of MP definitions and Table 3 for a description of each diagnostic).

Diagnostic	Units	R01	R02	R03
$C^{TAC}_{y+1:3}$	10^3 tonnes	414.71 (339.52 - 453.22)	414.71 (130.67 - 468.93)	414.71 (130.67 - 454.28)
C	10^3 tonnes	417.21 (347.73 - 456.53)	414.56 (64.49 - 472.62)	407.49 (69.26 - 457.53)
$C_{[PL]}$	10^3 tonnes	66.68 (37.53 - 76.12)	65.56 (9.91 - 76.51)	63.01 (10.15 - 77.67)
$C_{[PSLS]}$	10^3 tonnes	160.69 (117.73 - 184.22)	167.88 (22.93 - 196.63)	161.55 (24.96 - 209.44)
$C_{[PSFS]}$	10^3 tonnes	25.01 (21.71 - 28.54)	25.26 (5.4 - 32.18)	25.15 (5.19 - 39.02)
$C_y/C_{40\%}$	Proportion	0.64 (0.49 - 0.81)	0.63 (0 - 0.86)	0.6 (0 - 0.81)
C^{TAC}_{y+1} not equal to C^{TAC}_{y}	Count	2 (2 - 4)	3 (2 - 4)	3 (2 - 4)
$\lvert C^{TAC}_{y+1}/C^{TAC}_{y} - 1\rvert$	Percent	73 (15 - 152)	41 (10 - 155)	153 (16 - 154)
Max. $\lvert C^{TAC}_{y+1}/C^{TAC}_{y} - 1\rvert$	Percent	301 (56 - 825)	173 (31 - 825)	825 (77 - 825)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_{y} - 1\rvert > 30\%$	Prob.	0.34	0.31	0.29
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_{y} - 1\rvert > 15\%$	Prob.	0.39	0.36	0.31
$CPUE_{[PL]}$	Rate	0.02 (0.01 - 0.03)	0.02 (0 - 0.02)	0.02 (0 - 0.02)
$CPUE_{[PSLS]}$	Rate	8.47 (4.96 - 10.68)	8.03 (0 - 10.32)	8.21 (0 - 9.89)
E_y	Rate	0.43 (0.31 - 0.61)	0.49 (0.34 - 2.79)	0.48 (0.31 - 4.54)
$E_y/E_{40\%}$	Proportion	0.73 (0.51 - 1.1)	0.85 (0.56 - 5.06)	0.79 (0.52 - 7.44)
B_y	10^3 tonnes	872.53 (538.75 - 1377.64)	754.1 (39.59 - 1214.4)	775.96 (47.91 - 1296.09)
B_y/B_0	Proportion	0.38 (0.22 - 0.49)	0.33 (0 - 0.47)	0.33 (0 - 0.47)
B_{MIN}/B_0	Proportion	0.07 (0.01 - 0.13)	0.07 (0 - 0.18)	0.04 (0 - 0.15)
Pr. $> B_{20\%}$	Prob.	0.81	0.7	0.69
Pr. $> B_{10\%}$	Prob.	0.89	0.79	0.77
Pr. Kobe Red	Prob.	0.24	0.4	0.4
Pr. Kobe Green	Prob.	0.58	0.44	0.46
Pr. Majuro Red	Prob.	0.12 (0.06 - 0.35)	0.24 (0.06 - 0.94)	0.18 (0.12 - 0.94)
Pr. Majuro White	Prob.	0.76 (0.24 - 0.88)	0.65 (0 - 0.82)	0.68 (0 - 0.82)

Table A8: Diagnostic outputs for robustness to recruitment deviations for MP4 (Kobe 60%) (see Table 4 for the list of MP definitions and Table 3 for a description of each diagnostic).

Diagnostic	Units	R01	R02	R03
$C^{TAC}_{y+1:3}$	10^3 tonnes	436.61 (356.18 - 476.66)	433.93 (133.1 - 484.92)	436.61 (135.37 - 467.48)
C	10^3 tonnes	438.77 (360.25 - 476.88)	429.6 (60.92 - 492.57)	425.12 (67.79 - 476.13)
$C_{[PL]}$	10^3 tonnes	70.01 (36.34 - 78.76)	63.01 (8.84 - 80.5)	57.27 (10.32 - 79.7)
$C_{[PSLS]}$	10^3 tonnes	169.62 (123.94 - 191.83)	171.42 (21.61 - 216.77)	167.22 (23.94 - 212.59)
$C_{[PSFS]}$	10^3 tonnes	26.21 (22.42 - 30.01)	26.83 (5.01 - 34.26)	26.47 (4.84 - 46.33)
$C_y/C_{40\%}$	Proportion	0.66 (0.5 - 0.85)	0.63 (0 - 0.88)	0.6 (0 - 0.82)
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	83 (15 - 161)	55 (13 - 162)	150 (15 - 162)
Max. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	329 (53 - 875)	249 (41 - 875)	801 (90 - 875)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 30\%$	Prob.	0.36	0.32	0.31
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 15\%$	Prob.	0.41	0.36	0.33
$CPUE_{[PL]}$	Rate	0.02 (0.01 - 0.02)	0.02 (0 - 0.02)	0.01 (0 - 0.02)
$CPUE_{[PSLS]}$	Rate	8.11 (4.73 - 10.47)	7.3 (0 - 9.74)	7.36 (0 - 9.43)
E_y	Rate	0.46 (0.33 - 0.65)	0.54 (0.35 - 3.86)	0.55 (0.33 - 4.73)
$E_y/E_{40\%}$	Proportion	0.8 (0.56 - 1.1)	0.91 (0.59 - 6.59)	0.9 (0.53 - 7.81)
B_y	10^3 tonnes	813.02 (508.47 - 1332.85)	715.72 (34.75 - 1183.7)	690.97 (55.05 - 1295.59)
B_y/B_0	Proportion	0.35 (0.2 - 0.47)	0.29 (0 - 0.45)	0.28 (0 - 0.46)
B_{MIN}/B_0	Proportion	0.07 (0.01 - 0.13)	0.05 (0 - 0.16)	0.02 (0 - 0.14)
Pr. $> B_{20\%}$	Prob.	0.8	0.65	0.62
Pr. $> B_{10\%}$	Prob.	0.88	0.75	0.72
Pr. Kobe Red	Prob.	0.29	0.47	0.47
Pr. Kobe Green	Prob.	0.51	0.38	0.38
Pr. Majuro Red	Prob.	0.12 (0.06 - 0.41)	0.24 (0.12 - 0.94)	0.24 (0.12 - 0.94)
Pr. Majuro White	Prob.	0.76 (0.24 - 0.88)	0.5 (0 - 0.82)	0.53 (0 - 0.82)

Table A9: Diagnostic outputs for robustness to recruitment deviations for MP6 (Kobe 50%) (see Table 4 for the list of MP definitions and Table 3 for a description of each diagnostic).

Diagnostic	Units	R01	R02	R03
$C^{TAC}_{y+1:3}$	10^3 tonnes	458.52 (354.49 - 499.61)	439.35 (135.46 - 507.47)	446.71 (140.06 - 481.01)
C	10^3 tonnes	455.75 (362.3 - 497.19)	440.82 (56.51 - 509.95)	432.36 (61.05 - 472.58)
$C_{[PL]}$	10^3 tonnes	72.08 (31.42 - 82.72)	62.17 (7.83 - 82.98)	43.17 (8.72 - 80.4)
$C_{[PSLS]}$	10^3 tonnes	176.73 (130.14 - 200.29)	175.65 (20.46 - 229.45)	161.09 (21.79 - 219.17)
$C_{[PSFS]}$	10^3 tonnes	27.26 (23.03 - 30.92)	28.16 (4.54 - 43.4)	28.64 (4.48 - 51.59)
$C_y/C_{40\%}$	Proportion	0.68 (0.49 - 0.88)	0.64 (0 - 0.9)	0.59 (0 - 0.76)
C^{TAC}_{y+1} not equal to C^{TAC}_y	Count	3 (2 - 5)	3 (2 - 4.9)	3 (2 - 4)
$\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	92 (15 - 172)	77 (16 - 171)	145 (16 - 170)
Max. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert$	Percent	337 (53 - 925)	307 (54 - 925)	765 (90 - 925)
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 30\%$	Prob.	0.37	0.33	0.31
Pr. $\lvert C^{TAC}_{y+1}/C^{TAC}_y - 1\rvert > 15\%$	Prob.	0.42	0.38	0.33
$CPUE_{[PL]}$	Rate	0.02 (0.01 - 0.02)	0.01 (0 - 0.02)	0.01 (0 - 0.02)
$CPUE_{[PSLS]}$	Rate	7.66 (4.49 - 10.25)	6.45 (0 - 9.35)	6.25 (0 - 8.93)
E_y	Rate	0.49 (0.36 - 0.71)	0.61 (0.4 - 5.04)	0.59 (0.37 - 4.83)
$E_y/E_{40\%}$	Proportion	0.86 (0.6 - 1.17)	1.04 (0.64 - 8.24)	1.04 (0.63 - 8.05)
B_y	10^3 tonnes	762.19 (470.12 - 1285.08)	657.01 (33.32 - 1112.42)	605.02 (40.1 - 1191.7)
B_y/B_0	Proportion	0.34 (0.18 - 0.45)	0.26 (0 - 0.43)	0.24 (0 - 0.43)
B_{MIN}/B_0	Proportion	0.07 (0.01 - 0.13)	0.04 (0 - 0.15)	0.01 (0 - 0.12)
Pr. $> B_{20\%}$	Prob.	0.79	0.62	0.58
Pr. $> B_{10\%}$	Prob.	0.88	0.72	0.67
Pr. Kobe Red	Prob.	0.34	0.53	0.52
Pr. Kobe Green	Prob.	0.44	0.32	0.32
Pr. Majuro Red	Prob.	0.18 (0.06 - 0.41)	0.26 (0.12 - 0.94)	0.29 (0.12 - 0.94)
Pr. Majuro White	Prob.	0.59 (0.18 - 0.88)	0.41 (0 - 0.76)	0.35 (0 - 0.82)