Candidate empirical MPs for Indian Ocean skipjack tuna

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Project 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. The MPs being developed are empirical, being based on abundance indices typically used in the stock assessment. Simulation testing has demonstrated that when appropriately tuned, such MPs can perform well. The current report presents the latest iteration of this work, with a number of updates since TCMP 2022. Three tuned MPs are presented, along with robustness testing of the potential implications of positive implementation error. Results demonstrate that a conservative MP is more likely to achieve management goals given the possibility of catches exceeding recommendations made by the MP.

1 Introduction

In 2016, the IOTC adopted Resolution 16/02 (IOTC, 2016). This described a harvest control rule (HCR) to be used for setting a recommended catch for skipjack (SKJ), based on outputs from the stock assessment. Each catch recommendation would be valid for a three year period. Using outputs from the 2017 assessment (Fu, 2017), the HCR was first implemented at the end of that year to give a recommended catch limit for 2018–2020 of 470 thousand tonnes (IOTC, 2017a, SC, 2017). A second implementation of the HCR was conducted in 2020 (SC, 2020), based on an updated stock assessment by Fu (2020), and used to calculate a recommended catch limit for 2021–2023 of 513 thousand tonnes (IOTC, 2021b).

Resolution 16/02 also requested a further review and possible modification of the HCR to be conducted no later than 2021. In 2018, the IOTC Working Party on Methods (WPM) noted that Resolution 16/02 does not describe a fully specified Management Procedure (MP), since the underlying data required and assessment methodology are not defined (IOTC, 2018). Hence the WPM suggested that the review required under Resolution 16/02 be conducted with the aim of determining a fully specified MP for SKJ. This was noted by the SC in 2018 (SC, 2018) and provides motivation for the current work, which has been on-going since early 2019.

1.1 Current management

Based on the work of Bentley and Adam (Adam & Bentley, 2013, Bentley & Adam, 2014b,a, 2015, 2016), Resolution 16/02 describes a Harvest Control Rule (HCR) that can be use to set a recommended catch for the fishery. Using their terminology, the HCR outputs an intensity multiplier (I_y) as a function of the spawning stock biomass (B_y), using a step-linear relationship:

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

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

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

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

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

The following additional meta-rules were also endorsed:

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

Input values for the control rule ($B_{40\%}$, $B_{10\%}$, and $E_{40\%}$) are obtained as medians across estimated values from the grid of SS III assessment runs in the year in which the control rule is applied. Using the 2017 assessment (Fu, 2017, IOTC, 2017b), the HCR was implemented to provide a recommended catch limit of 470,029 tonnes for the period 2018–2020 inclusive. Following implementation of the control rule, realised catches have been consistently higher than the recommended catch limit. Nevertheless, the stock assessment in 2020 yielded a positive stock status estimate (Fu, 2020, IOTC, 2020), which was used to recommend an increased catch limit of 513,572 tonnes for 2019–2023.

1.2 Development of a new Management Procedure

Under Resolution 16/02 the recommended catch is based primarily on an estimate of the stock status (B_y) and reference points ($B_{40\%}$, $B_{20\%}$, and $E_{40\%}$), which provide both the parameters needed to define the control rule and the stock status inputs required to implement it. Although the product of substantial development work, the stock status estimator is not fully specified and it cannot therefore be formally tested through simulation. Although the stock assessment process may yield our best understanding of the resource status, continuous refinement and development of the assessment model and data inputs mean that by it's nature it cannot be simulated. A more parsimonious and better defined stock status estimator is needed for an MP. To explore such a possibility, a biomass dynamic model was applied to catch and abundance data from the 2017 SKJ assessment, and shown to provide reasonable estimates of the depletion (Edwards, 2020). However, since that initial work, the abundance indices have been updated (Medley et al., 2020b,a, Guery et al., 2020, Guery, 2020). Work presented to the WPM Management Strategy Evaluation Task Force (MSETF) in 2021 demonstrated that, given the updated indices, this type of model is no longer able to extract information on the biomass depletion (IOTC, 2021c). For this reason, an empirical MP was suggested as an alternative.

An empirical MP is based on descriptive rather than process based models. Initial work towards development of this approach was presented to the TCMP by Edwards (2021b). The MP was based on CPUE indices from the PL and PSLS fleets, which are both used routinely in assessments of the stock (Fu, 2017, 2020). There is a positive and log-linear relationship between these indices and the stock biomass depletion being estimated by the stock assessment. Edwards (2021b) showed that the CPUE indices can therefore be used as informative inputs to an empirical MP, generating catches similar to those calculated assuming perfect knowledge of the resource. It was recommended by the TCMP that these empirical MPs be tuned using the Kobe Green quadrant as a measure of stock status. Specifically, MPs were to be selected using the simulated probability of the stock being in the Kobe Green quadrant when averaged across projection years 11 to 15 (2030 to 2034 inclusive). Based on recommendations by the TCMP (IOTC, 2021e), tuning criteria that matched a 50%, 60% and 70% probability of being in the Kobe Green quadrant were adopted. If an MP matched one of these tuning criteria then it was selected for further consideration.

Edwards (2021a) presented tuned empirical MPs to the WPM (IOTC, 2021d), and based on feedback subsequently presented robustness testing results to the WPM MSETF (Edwards, 2022a). The robustness testing considered implementation error (i.e. catches higher than the recommendation) and the potential consequences of recruitment failure. Based on this work, a preliminary set of candidate MPs was presented to the TCMP in 2022, and received feedback (Edwards, 2022b, IOTC, 2022b). In particular the TCMP requested to include implementation

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

Notation	Description
Output	
C_y^{TAC}	Total recommended catch for three years y to $y + 2$
Tuning parameters	
C_{min}, C_{max}	Min. and Max. catch outputs
a_X, a_T	Safety level and threshold values for a_y
Input	
$a_{y=L}$	Mean of the log-normalised PL and PSLS abundance indices for year L
Reference points	
$C_{40\%}$	Catch associated with $B_{40\%}$
TRP	Target Reference point ($B_{40\%}$)
LRP	Limit Reference point ($B_{20\%}$)

error as part of the tuning process. In response to this request, 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 to the following WPM (Edwards, 2022c, IOTC, 2022a) and then subjected to further robustness testing for presentation to the WPM MSETF Edwards2023a. This meeting provided technical feedback on the work, that has been used to further develop the simulation testing framework. These suggestions included: 1) tuning of the MP assuming no-implementation error; 2) revision of the terminology used to define the tuning criteria; 3) inclusion of MSY-based diagnostics; 4) inclusion of a 15% limit on the change in recommendation catch; and 4) including a data 2–3 year lag in the implementation cycle.

The current report provides an overview of the state of MP development and presents candidate MPs that are based on updated simulations, and with reference to previous recommendations.

2 Candidate MPs

A set of three candidate MPs are proposed in the current work, each associated with one of the 50%, 60% or 70% tuning criteria. These MPs utilise the same data inputs, and have a common structural form for the HCR, but differ in the precise values by which the HCR is defined. We give a brief overview of the decision algorithm and data inputs here, with a more complete description provided by Edwards (2021b,a). A glossary of terms is given in Table 1.

2.1 Data inputs

The stock status indicator a_L was calculated from the log-normalised PL and PSLS abundance indices. These show similar trends over time, and we calculate a_L 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 for year y (C_y^{TAC}) is adjusted using values of a_L as input:

$$C_y^{TAC} = \begin{cases} C_{max} & \text{for} \quad a_L \geq a_T \\ (C_{max} - C_{min}) \times \frac{a_L - a_X}{a_T - a_X} + C_{min} & \text{for} \quad a_X < a_L < a_T \\ C_{min} & \text{for} \quad a_L \leq a_X \end{cases} \quad (2)$$

where a_L refers to the stock status indicator in lagged year $y = L$. The lagged year is the most recent year for which input data are available. It is assumed that the most recent data available are up to 2 years prior to year y. For values $a_L \leq a_X$, the recommended catch is equal to C_{min}. As a_L increases, the recommended catch also increases, until for values of $a_L \geq a_T$ the recommended catch is equal to C_{max}. A schematic of the relationship between a_L and C_y^{TAC} is given in Figure 1.

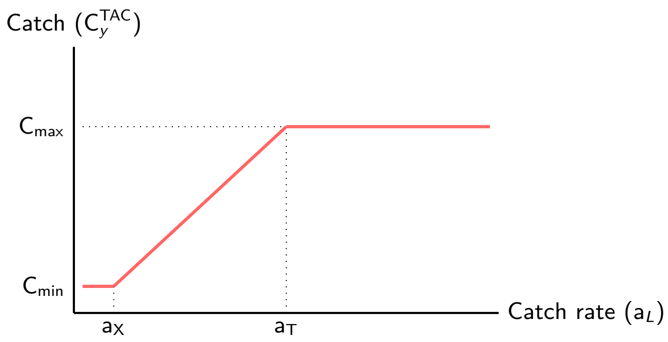

Figure 1: Schematic representation of the empirical Harvest Control Rule (Equation 1) being proposed as part of the MP.

2.3 HCR tuning parameters

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_L 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 3.6). 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 3. The MP tuning parameters also now include a symmetric limit to the amount that the recommended catch can change during any given implementation. This has been set at 15% for all MPs.

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 (2020). 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_{MSY}	477.103 (323.100 - 595.333)
B_{2020}	969.478 (706.899 - 1280.479)
$C_{40\%}$	532.075 (474.135 - 663.049)
C_{MSY}	605.834 (509.798 - 745.603)
C_{2020}	635.185 (483.536 - 790.993)
$E_{40\%}$	0.597 (0.541 - 0.650)
E_{MSY}	1.066 (0.795 - 1.501)
E_{2020}	0.580 (0.532 - 0.643)
B_{2020}/B_0	0.464 (0.389 - 0.518)
$B_{2020}/B_{40\%}$	1.161 (0.972 - 1.295)
B_{2020}/B_{MSY}	2.074 (1.516 - 2.72)
$C_{2020}/C_{40\%}$	1.140 (1.003 - 1.246)
C_{2020}/C_{MSY}	1.037 (0.900 - 1.116)
$E_{2020}/E_{40\%}$	0.980 (0.947 - 1.011)
E_{2020}/E_{MSY}	0.544 (0.418 - 0.681)

Table 3: MP parameters tested during tuning. Retained MPs are labelled, with their associated tuning criteria.

MP	C_{min}	C_{max}	a_X	a_T	% change limit
	53.21	425.66	-5.00	-1.70	15
	53.21	430.98	-5.00	-1.70	15
	53.21	436.30	-5.00	-1.70	15
	53.21	441.62	-5.00	-1.70	15
	53.21	446.94	-5.00	-1.70	15
	53.21	452.26	-5.00	-1.70	15
	53.21	457.58	-5.00	-1.70	15
	53.21	462.91	-5.00	-1.70	15
	53.21	468.23	-5.00	-1.70	15
	53.21	473.55	-5.00	-1.70	15
	53.21	478.87	-5.00	-1.70	15
MP1-70%	53.21	484.19	-5.00	-1.70	15
	53.21	489.51	-5.00	-1.70	15
	53.21	494.83	-5.00	-1.70	15
	53.21	500.15	-5.00	-1.70	15
	53.21	505.47	-5.00	-1.70	15
	53.21	510.79	-5.00	-1.70	15
	53.21	516.11	-5.00	-1.70	15
	53.21	521.43	-5.00	-1.70	15
	53.21	526.75	-5.00	-1.70	15
MP2-60%	53.21	532.08	-5.00	-1.70	15
	53.21	537.40	-5.00	-1.70	15
	53.21	542.72	-5.00	-1.70	15
	53.21	548.04	-5.00	-1.70	15
	53.21	553.36	-5.00	-1.70	15
	53.21	558.68	-5.00	-1.70	15
MP3-50%	53.21	564.00	-5.00	-1.70	15
	53.21	569.32	-5.00	-1.70	15
	53.21	574.64	-5.00	-1.70	15
	53.21	579.96	-5.00	-1.70	15
	53.21	585.28	-5.00	-1.70	15
	53.21	590.60	-5.00	-1.70	15
	53.21	595.92	-5.00	-1.70	15
	53.21	601.24	-5.00	-1.70	15
	53.21	606.57	-5.00	-1.70	15
	53.21	611.89	-5.00	-1.70	15

Table 4: 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, and were calculated relative to the previous TAC.

Performance Statistic	Description	Summary statistic
Catch		
C_y^{TAC}	Total Allowable Catch (three years)	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
$C_y/C_{40\%}$	Catch rel. to target	Geometric mean
C_y/C_{MSY}	Catch rel. to MSY	Geometric mean
Catch stability (TAC years only)		
$C_y^{TAC} \neq C_{y-1}^{TAC}$	n. TAC changes	Count
$\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert$	TAC change	Mean % change
Max. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert$	Max. TAC change	Max. % change
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 10\%$	TAC change $> 10\%$	Probability
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 5\%$	TAC change $> 5\%$	Probability
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert = 15\%$	TAC change at limit	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
$E_y/E_{40\%}$	Exploitation rel. to target	Geometric mean
E_y/E_{MSY}	Exploitation rel. to MSY	Geometric mean
Stock biomass		
B_y	Stock biomass	Mean
B_y/B_0	Depletion rel. to B_0	Geometric mean
B_y/B_{MSY}	Depletion rel. to B_{MSY}	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
Target Quadrant		
Pr. Target Quadrant	$B_y > B_{40\%}$ and $E_y < E_{40\%}$	Probability
Kobe Quadrants		
Pr. Kobe Red	$B_y < B_{MSY}$ and $E_y > E_{MSY}$	Probability
Pr. Kobe Green	$B_y > B_{MSY}$ and $E_y < E_{MSY}$	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 (2020). Models were re-fitted for validation purposes, giving the results summarised in Table 2.

3.2 Implementation of the catch

The TAC for 2020 was set at 470,029 tonnes (SC, 2017), with a realised catch of 547, 289 tonnes, based on known catches from the fishery. The TAC from 2021 to 2023 was fixed at 513,572 tonnes (SC, 2020), with realised catches of 650,331 tonnes per year for that period. Thereafter the MP was used to set the catch, with implementation of the MP every third year and with 2-year data lag (i.e., the first implementation set a recommended catch for 2024 to 2026 inclusive, based on data assumed to be available up to and including 2022).

3.3 Dimensions

A total of 36 MPs were tested (Table 3). For each MP, the 24 operating model variations were projected, with ten stochastic iterations for each. Each simulation projected the stock forward twenty-one years from 2020 to 2040 inclusive.

3.4 Reference points

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

3.5 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 $B_{40\%}$; and to avoid the LRP of $B_{20\%}$ (IOTC, 2015). A comprehensive list of diagnostics with which to compare MPs was obtained from Bentley & Adam (2016) and described in Table 4. These include an expression of stock status using the Kobe strategy matrix. Following recommendations from IOTC (2021e) and IOTC (2021a), stock status was also reported using the Majuro quadrants. The Kobe and Majuro matrices differ in the reference points used to diagnose stock status. The Kobe matrix is defined using MSY-based reference points. Due to the difficulty in estimating these reference points, the TRP and LRP have been used in previous work for presentation of the Kobe diagnostics (i.e. Kobe strategy matrices have been drawn using the $B_{40\%}$ and $E_{40\%}$ reference points, rather than B_{MSY} and E_{MSY}). In the current work, Kobe matrices are drawn using B_{MSY} and E_{MSY}. Estimated values for B_{MSY} and E_{MSY} listed in Table 2 and also used to construct additional diagnostic outputs (Table 4). Presentations of the Majuro plots (using the LRP and TRP) are unchanged.

3.6 Tuning

MPs were tuned using the probability that $B_y > B_{40\%}$ and $E_y < E_{40\%}$ when averaged across projection years 11 to 15 (2030 to 2034 inclusive). This is referred to as the "Target quadrant," in a departure from previous terminology, so as to distinguish it from the Kobe quadrants that are defined using B_{MSY} and E_{MSY} (Table 4). Three tuning criteria were used, corresponding to the probability of being in the Target quadrant of 50%, 60% and 70%. If an MP matched one of these tuning criteria to within 1% then it was selected for further consideration.

3.7 Robustness tests

Following initial recommendations from the WPM (IOTC, 2021d), robustness to implementation error has been investigated in each subsequent iteration of MP development. This involves simulation of the consequences that follow from the realised catches being higher than the recommended catch. A similar exercise was repeated in the current investigation. In each case robustness tests were conducted by introducing a constant multiplier to the recommended catch output by the MP, from 2024 onwards (the first year of MP implementation). Four implementation error values were tested, corresponding to a positive overcatch of 10%, 20%, 30% and 40% (Edwards, 2022c, 2023). These are referred to as robustness trials R01 to R04 respectively.

4 Results and Conclusions

4.1 Tuned MPs

The MPs listed in Table 3 were simulated forward in time, and the three that matched the different tuning criteria were retained. These are referred to as: MP1-70%; MP2-60% and MP3-50%; depending on the value assumed for C_{max} and the tuning criteria. The tuning process is expressed visually in Figure 2, which shows the average probability of being the in the target quadrant over time.

Diagnostic outputs for each tuned MP are listed in Table 5 and illustrated in Figure 3. These show that the more aggressive MP-50% yields a higher expected catch at the expense of a lower stock biomass. The different degree of fishing pressure placed on the stock by each of the MPs is further illustrated in the Kobe and Majuro phase plots (Figure 4).

4.2 Robustness testing

Given the different levels of exploitation exerted by each of the control rules, we would expect them to perform differently under different levels of assumed implementation error. Simulation testing of MP1-70%, MP2-60% and MP3-50%; assuming implementation errors of 10% to 40%, provides the results illustrated in Figures 5 and 6.

At low levels of implementation error (R01: 10%), the trade off between catch and stock biomass is retained. However as the implementation error increases this trade-off breaks down. For an implementation error of R04: 40%, the more aggressive MP3-50% yields both a lower stock biomass and a lower catch. The MP is unable to to compensate adequately for such a high implementation error and the stock is depleted. At higher levels of depletion the TAC is reduced by the MP, and the realised catch therefore also declines. This result demonstrates that if positive implementation error is high a more aggressive MP may not necessarily lead to higher catches. It also provides insight into the likelihood that the tuned MPs will management objectives. For example, if implementation error is as high as 40%, MP-70% still has a 55% predicted probability of keeping the stock within the Kobe Green quadrant (Table 6). But for MP-50%, that probability drops to 30%. Therefore, for reasons of both stock status and catch, the more conservative MP1-70% would be preferred in instances where the implementation error is high. Choosing an appropriate MP may therefore depend on the implementation error assumed.

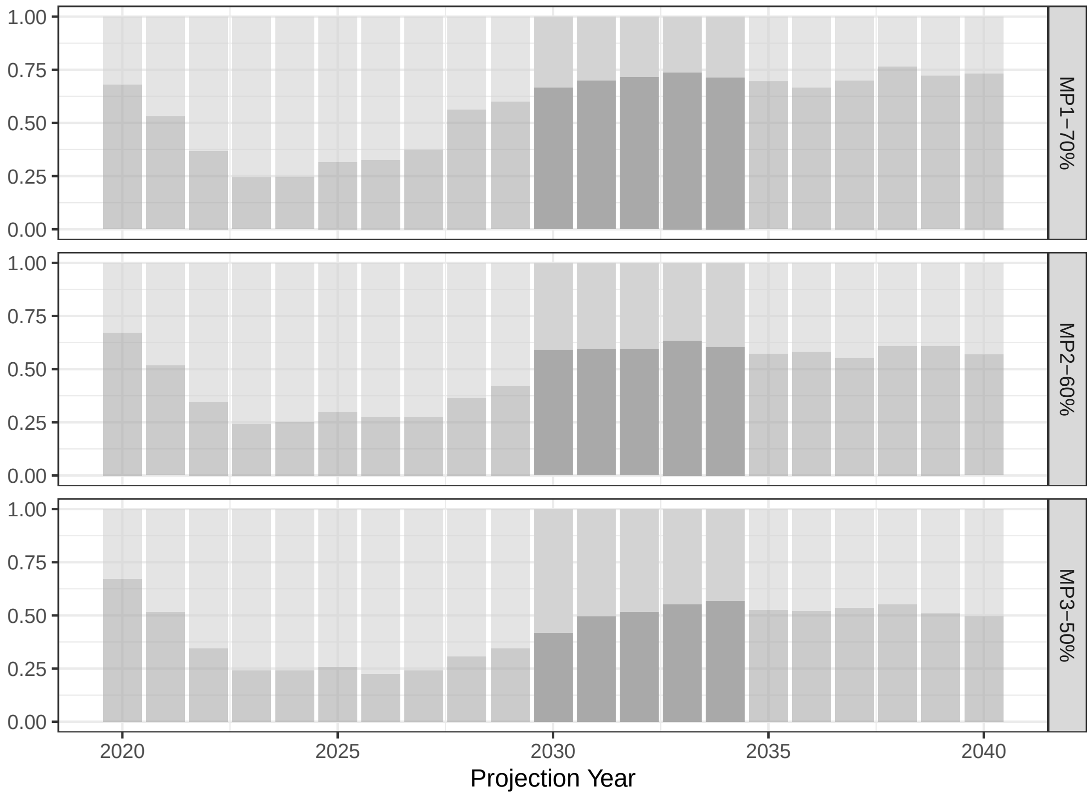

Figure 2: Time series for tuned MPs listed in Table 3. Average target quadrant probabilities (defined in Table 4) for each year, across all model runs and iterations for that MP, are shown. Probabilities between 2030 and 2034 inclusive were used to select MPs using the tuning criteria

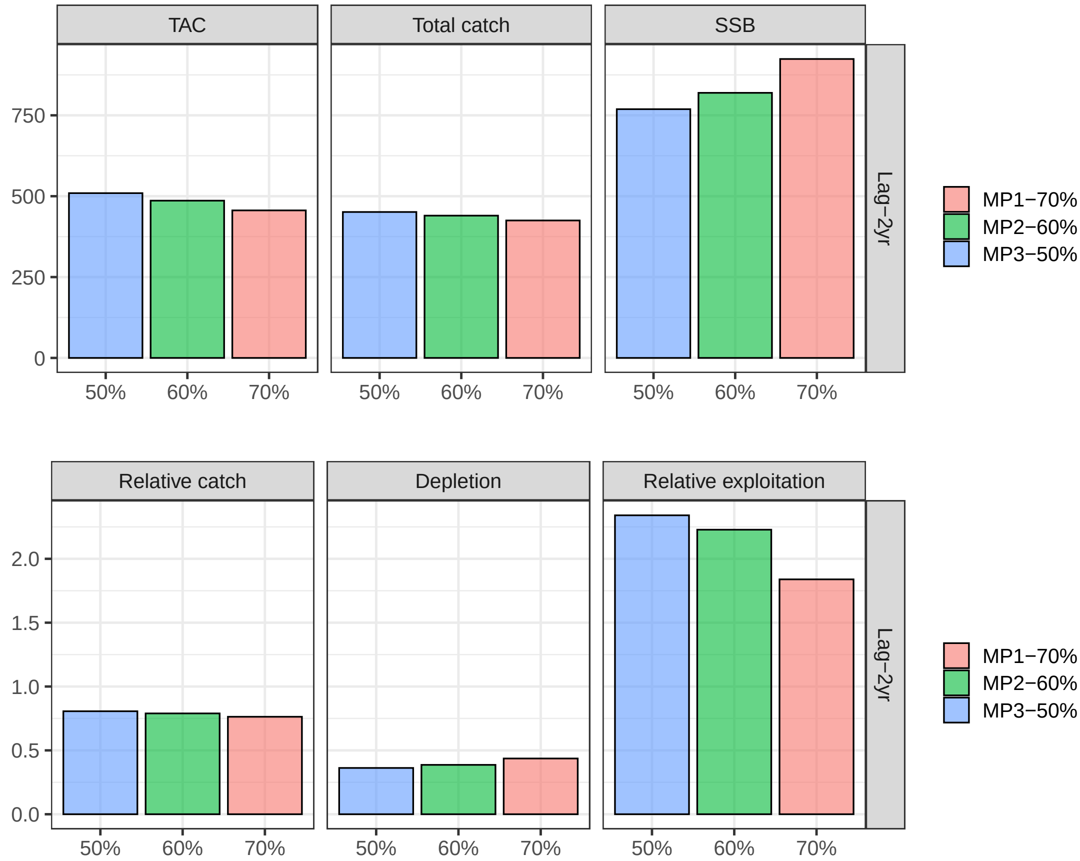

Figure 3: Summary diagnostic outputs for tuned MPs listed in Table 3. Mean values are shown across all simulated values between 2024 and 2040. The spawning stock biomass (SSB) is the sum across age 1+ individuals. The total catch is calculated using length-based selectivity ogives, and includes some younger fish.

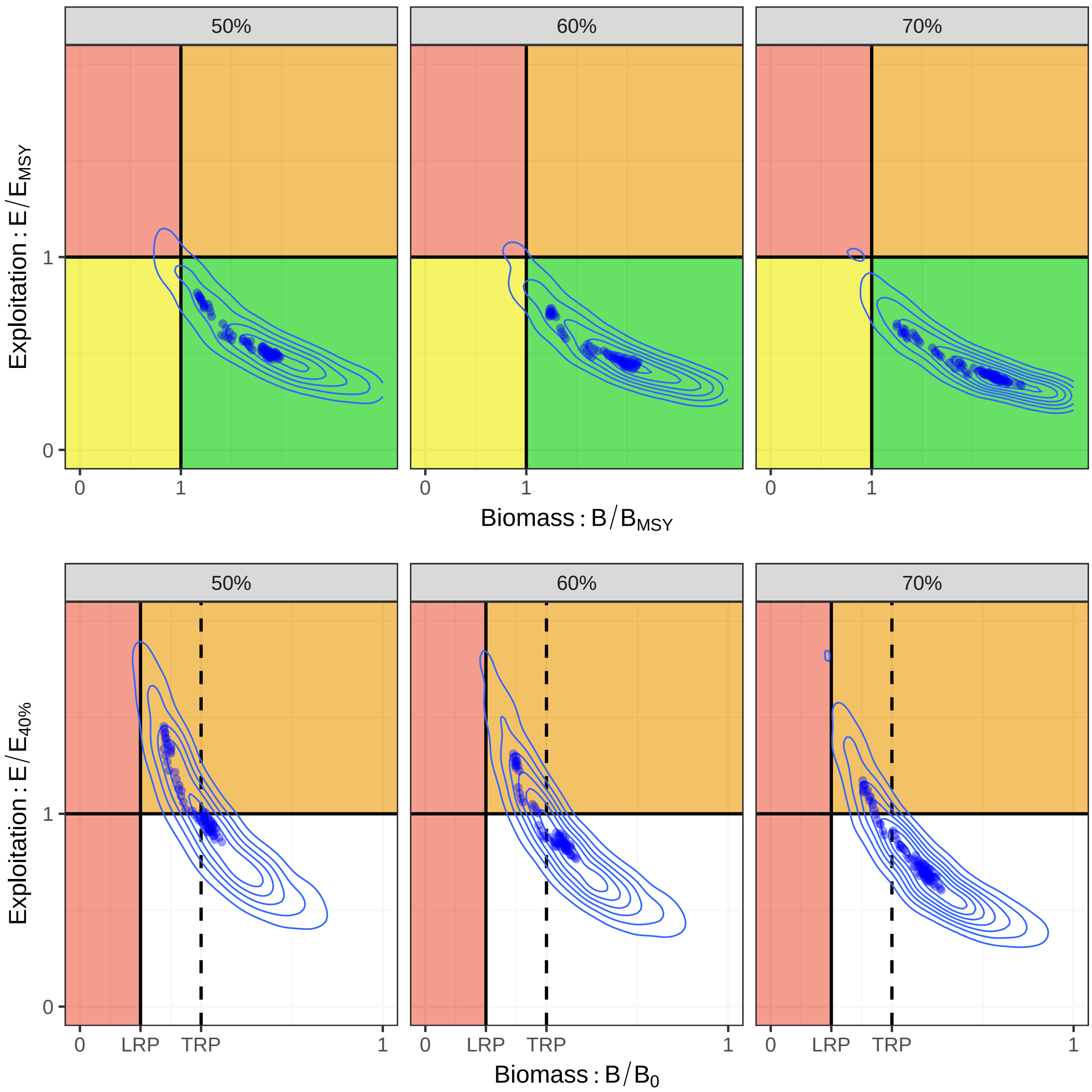

Figure 4: Kobe phase plots (top panel) and Majuro phase plots (bottom panel) for tuned MPs listed in Table 3. Contours show a two-dimensional histogram of stock status across all years for which the MP was used to set catches (i.e. 2024 to 2040), twenty-four model runs and ten stochastic iterations for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

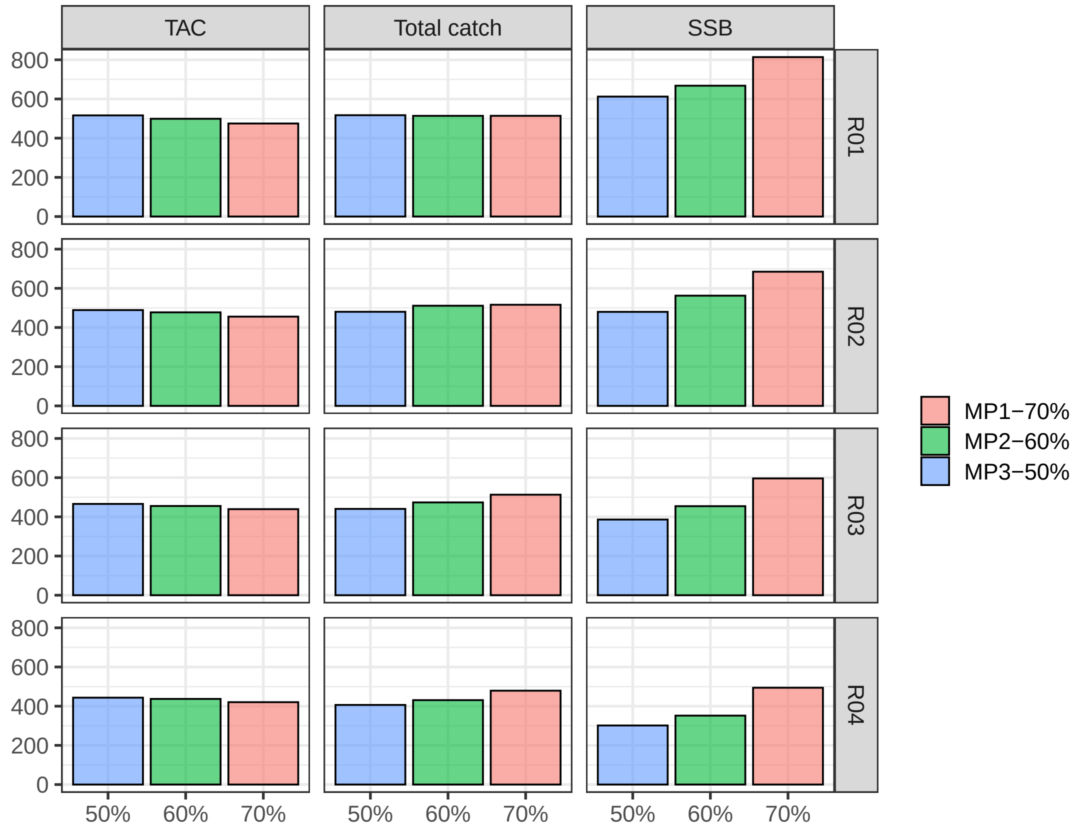

Figure 5: Summary outputs for robustness trials: R01 (10% positive implementation error) to R04 (40% positive implementation error). Mean values are shown across all simulated values between 2024 and 2040. The spawning stock biomass (SSB) is the sum across age 1+ individuals. The total catch is calculated using length-based selectivity ogives, and includes some younger fish.

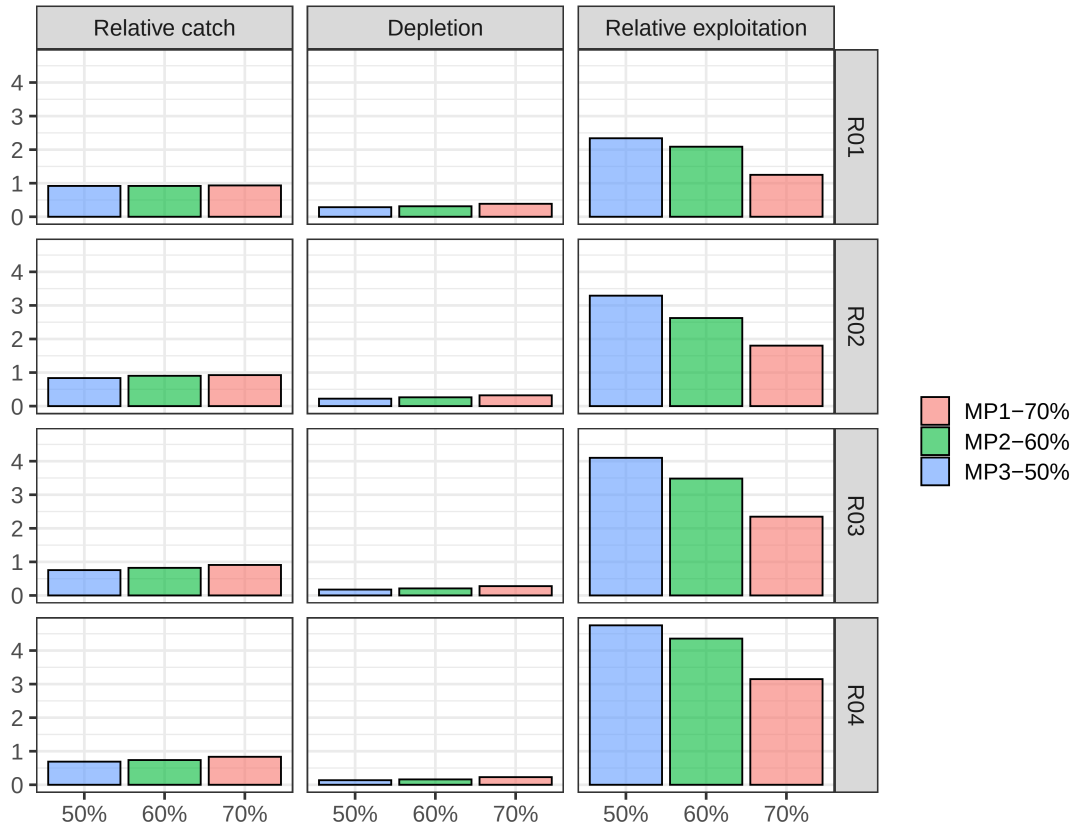

Figure 6: Summary outputs for robustness trials: R01 (10% positive implementation error) to R04 (40% positive implementation error). Mean values are shown across all simulated values between 2024 and 2040.

Table 5: Diagnostic outputs for evaluation of index-based MPs with an assumed lag of 2 years (see Table 3 for the list of MP definitions and Table 4 for a description of each diagnostic).

Performance Statistic	Units	MP1-70%	MP2-60%	MP3-50%
C_y^{TAC}	10^3 tonnes	474.51 (319.62 - 489.51)	520.60 (334.06 - 532.18)	546.70 (353.68 - 564.00)
C	10^3 tonnes	474.51 (93.24 - 489.51)	517.75 (65.99 - 536.86)	541.67 (61.73 - 564.00)
$C_{[PL]}$	10^3 tonnes	77.44 (9.66 - 80.85)	83.73 (6.33 - 87.86)	87.44 (6.13 - 92.86)
$C_{[PSLS]}$	10^3 tonnes	180.84 (48.75 - 188.97)	196.40 (23.57 - 205.12)	207.40 (21.73 - 216.75)
$C_{[PSFS]}$	10^3 tonnes	26.88 (8.93 - 28.42)	28.99 (4.66 - 30.78)	30.65 (4.41 - 32.58)
$C_y/C_{40\%}$	Proportion	0.83 (0.00 - 0.95)	0.88 (0.00 - 1.01)	0.91 (0.00 - 1.06)
C_y/C_{MSY}	Proportion	0.76 (0.00 - 0.88)	0.79 (0.00 - 0.95)	0.83 (0.00 - 0.98)
$C_y^{TAC} \neq C_{y-1}^{TAC}$	Count	1.00 (0.00 - 6.00)	1.00 (0.00 - 6.00)	2.00 (0.00 - 6.00)
$\|C_y^{TAC}/C_{y-1}^{TAC} - 1\|$	Percent	1.30 (0.78 - 14.46)	3.63 (0.43 - 13.85)	6.54 (1.46 - 13.85)
Pr. $\|C_y^{TAC}/C_{y-1}^{TAC} - 1\| > 10\%$	Prob.	0.26	0.31	0.38
Pr. $\|C_y^{TAC}/C_{y-1}^{TAC} - 1\| > 5\%$	Prob.	0.36	0.36	0.50
Pr. $\|C_y^{TAC}/C_{y-1}^{TAC} - 1\| = 15\%$	Prob.	0.23	0.28	0.30
$CPUE_{[PL]}$	Rate	0.02 (0.00 - 0.03)	0.02 (0.00 - 0.03)	0.02 (0.00 - 0.03)
$CPUE_{[PSLS]}$	Rate	10.46 (0.00 - 13.32)	9.71 (0.00 - 12.79)	9.12 (0.00 - 12.37)
E_y	Rate	0.48 (0.28 - 3.91)	0.57 (0.32 - 4.94)	0.63 (0.32 - 5.06)
$E_y/E_{40\%}$	Proportion	0.78 (0.51 - 6.45)	0.91 (0.54 - 9.01)	1.00 (0.57 - 9.24)
E_y/E_{MSY}	Proportion	0.43 (0.27 - 3.94)	0.51 (0.31 - 5.33)	0.54 (0.34 - 5.34)
B_y	10^3 tonnes	907.92 (24.69 - 1562.27)	822.00 (22.73 - 1474.63)	772.40 (20.70 - 1388.06)
B_y/B_0	Proportion	0.44 (0.00 - 0.63)	0.40 (0.00 - 0.60)	0.37 (0.00 - 0.57)
B_y/B_{MSY}	Proportion	1.96 (0.00 - 3.02)	1.79 (0.00 - 2.85)	1.66 (0.00 - 2.71)
Pr. $> B_{20\%}$	Prob.	0.84	0.78	0.76
Pr. $> B_{10\%}$	Prob.	0.88	0.84	0.83
Pr. Target Quadrant	Prob.	0.60	0.49	0.43
Pr. Kobe Red	Prob.	0.17	0.22	0.25
Pr. Kobe Green	Prob.	0.80	0.75	0.71
Pr. Majuro Red	Prob.	0.16	0.22	0.24
Pr. Majuro White	Prob.	0.82	0.76	0.72

Table 6: Diagnostic outputs for robustness trials of MP1-70% (see Table 3 for the list of MP definitions and Table 4 for a description of each diagnostic).

Performance Statistic	Units	R01	R02	R03	R04
C_y^{TAC}	10^3 tonnes	484.19 (443.28 - 484.19)	484.19 (343.05 - 484.19)	467.14 (342.16 - 484.19)	430.68 (342.16 - 484.19)
C	10^3 tonnes	532.61 (487.61 - 532.61)	581.03 (212.77 - 581.03)	606.07 (138.96 - 629.44)	601.31 (120.31 - 677.86)
$C_{[PL]}$	10^3 tonnes	86.45 (79.88 - 90.03)	93.65 (33.19 - 96.28)	97.77 (19.29 - 103.13)	88.33 (16.72 - 109.25)
$C_{[PSLS]}$	10^3 tonnes	200.04 (182.87 - 206.96)	217.60 (78.82 - 225.77)	229.78 (50.26 - 244.59)	235.47 (42.27 - 263.40)
$C_{[PSFS]}$	10^3 tonnes	30.00 (26.53 - 31.18)	32.13 (13.07 - 33.96)	33.79 (9.07 - 36.64)	34.45 (8.32 - 39.28)
$C_y/C_{40\%}$	Proportion	0.98 (0.78 - 1.06)	1.00 (0.01 - 1.11)	1.03 (0.00 - 1.13)	1.00 (0.00 - 1.13)
C_y/C_{MSY}	Proportion	0.87 (0.71 - 0.97)	0.87 (0.01 - 1.01)	0.93 (0.00 - 1.01)	0.91 (0.00 - 1.00)
$C_y^{TAC} \neq C_{y-1}^{TAC}$	Count	1.00 (1.00 - 5.00)	1.00 (1.00 - 6.00)	5.00 (1.00 - 6.00)	5.00 (1.00 - 6.00)
$\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert$	Percent	0.95 (0.95 - 9.36)	0.95 (0.95 - 13.45)	6.15 (0.95 - 13.45)	10.95 (0.95 - 13.45)
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 10\%$	Prob.	0.10	0.21	0.35	0.47
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 5\%$	Prob.	0.30	0.41	0.57	0.67
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert = 15\%$	Prob.	0.08	0.19	0.29	0.44
$CPUE_{[PL]}$	Rate	0.02 (0.01 - 0.02)	0.01 (0.00 - 0.02)	0.01 (0.00 - 0.02)	0.01 (0.00 - 0.02)
$CPUE_{[PSLS]}$	Rate	10.04 (7.02 - 10.99)	8.84 (0.11 - 9.99)	7.98 (0.01 - 9.27)	6.60 (0.00 - 8.79)
E_y	Rate	0.58 (0.34 - 0.93)	0.71 (0.40 - 1.15)	0.84 (0.47 - 4.10)	0.97 (0.55 - 4.59)
$E_y/E_{40\%}$	Proportion	1.03 (0.59 - 1.67)	1.30 (0.69 - 2.00)	1.45 (0.79 - 6.76)	1.59 (0.94 - 7.57)
E_y/E_{MSY}	Proportion	0.52 (0.32 - 1.15)	0.65 (0.37 - 1.40)	0.78 (0.41 - 3.84)	0.82 (0.50 - 4.27)
B_y	10^3 tonnes	805.43 (459.85 - 1396.97)	633.78 (103.60 - 1281.57)	562.81 (56.32 - 1178.67)	495.67 (43.49 - 1068.86)
B_y/B_0	Proportion	0.39 (0.23 - 0.55)	0.31 (0.00 - 0.51)	0.28 (0.00 - 0.47)	0.25 (0.00 - 0.42)
B_y/B_{MSY}	Proportion	1.82 (0.82 - 2.56)	1.52 (0.01 - 2.29)	1.24 (0.00 - 2.06)	1.13 (0.00 - 1.87)
Pr. $> B_{20\%}$	Prob.	0.92	0.82	0.76	0.63
Pr. $> B_{10\%}$	Prob.	0.97	0.90	0.84	0.73
Pr. Target Quadrant	Prob.	0.47	0.32	0.22	0.14
Pr. Kobe Red	Prob.	0.15	0.22	0.27	0.39
Pr. Kobe Green	Prob.	0.83	0.74	0.68	0.55
Pr. Majuro Red	Prob.	0.08	0.18	0.24	0.37
Pr. Majuro White	Prob.	0.84	0.75	0.69	0.55

Table 7: Diagnostic outputs for robustness trials of MP2-60% (see Table 3 for the list of MP definitions and Table 4 for a description of each diagnostic).

Performance Statistic	Units	R01	R02	R03	R04
C_y^{TAC}	10^3 tonnes	532.08 (376.00 - 532.08)	504.99 (376.00 - 532.08)	467.88 (376.00 - 532.08)	425.78 (376.00 - 531.58)
C	10^3 tonnes	585.28 (200.34 - 585.28)	605.99 (134.84 - 638.49)	600.66 (116.24 - 691.70)	410.41 (104.50 - 744.21)
$C_{[PL]}$	10^3 tonnes	93.82 (30.94 - 96.99)	96.36 (19.17 - 104.61)	82.72 (16.13 - 111.48)	48.36 (14.93 - 119.18)
$C_{[PSLS]}$	10^3 tonnes	219.19 (73.22 - 227.43)	231.78 (48.53 - 248.10)	237.31 (41.16 - 268.78)	174.68 (35.90 - 289.83)
$C_{[PSFS]}$	10^3 tonnes	32.37 (12.98 - 34.21)	34.01 (9.05 - 37.17)	35.03 (8.08 - 40.08)	31.98 (8.02 - 43.36)
$C_y/C_{40\%}$	Proportion	1.01 (0.00 - 1.11)	1.03 (0.00 - 1.12)	1.02 (0.00 - 1.14)	0.44 (0.00 - 1.15)
C_y/C_{MSY}	Proportion	0.88 (0.00 - 1.01)	0.93 (0.00 - 1.00)	0.92 (0.00 - 1.02)	0.41 (0.00 - 1.01)
$C_y^{TAC} \neq C_{y-1}^{TAC}$	Count	1.00 (1.00 - 6.00)	5.00 (1.00 - 6.00)	6.00 (1.00 - 6.00)	6.00 (1.20 - 6.00)
$\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert$	Percent	0.60 (0.60 - 13.10)	6.80 (0.60 - 13.10)	10.60 (0.60 - 13.10)	11.33 (0.75 - 13.10)
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 10\%$	Prob.	0.24	0.39	0.50	0.58
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 5\%$	Prob.	0.26	0.41	0.52	0.62
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert = 15\%$	Prob.	0.19	0.34	0.46	0.56
$CPUE_{[PL]}$	Rate	0.01 (0.00 - 0.02)	0.01 (0.00 - 0.02)	0.01 (0.00 - 0.02)	0.00 (0.00 - 0.01)
$CPUE_{[PSLS]}$	Rate	8.74 (0.00 - 9.90)	7.58 (0.00 - 9.20)	6.17 (0.00 - 8.42)	0.91 (0.00 - 7.62)
E_y	Rate	0.79 (0.41 - 3.42)	0.95 (0.49 - 4.32)	1.10 (0.58 - 4.65)	2.19 (0.72 - 4.85)
$E_y/E_{40\%}$	Proportion	1.38 (0.70 - 5.64)	1.54 (0.83 - 7.15)	1.73 (1.00 - 7.66)	3.68 (1.21 - 7.99)
E_y/E_{MSY}	Proportion	0.67 (0.38 - 3.18)	0.80 (0.45 - 4.03)	0.90 (0.54 - 4.32)	2.08 (0.66 - 4.50)
B_y	10^3 tonnes	622.69 (73.90 - 1272.74)	533.25 (50.68 - 1158.77)	444.87 (41.51 - 1035.74)	228.41 (36.42 - 897.27)
B_y/B_0	Proportion	0.31 (0.00 - 0.51)	0.28 (0.00 - 0.46)	0.24 (0.00 - 0.41)	0.05 (0.00 - 0.35)
B_y/B_{MSY}	Proportion	1.51 (0.00 - 2.26)	1.27 (0.00 - 2.03)	1.09 (0.00 - 1.81)	0.18 (0.00 - 1.56)
Pr. $> B_{20\%}$	Prob.	0.81	0.72	0.59	0.45
Pr. $> B_{10\%}$	Prob.	0.87	0.81	0.70	0.57
Pr. Target Quadrant	Prob.	0.29	0.18	0.08	0.02
Pr. Kobe Red	Prob.	0.24	0.31	0.44	0.57
Pr. Kobe Green	Prob.	0.73	0.65	0.51	0.37
Pr. Majuro Red	Prob.	0.19	0.28	0.41	0.55
Pr. Majuro White	Prob.	0.74	0.65	0.52	0.37

Table 8: Diagnostic outputs for robustness trials of MP3-50% (see Table 3 for the list of MP definitions and Table 4 for a description of each diagnostic).

Performance Statistic	Units	R01	R02	R03	R04
C_y^{TAC}	10^3 tonnes	551.87 (398.56 - 564.00)	502.22 (398.56 - 564.00)	451.33 (398.56 - 564.00)	400.79 (398.56 - 549.03)
C	10^3 tonnes	606.46 (146.30 - 620.40)	600.51 (120.62 - 676.80)	463.94 (106.61 - 733.20)	343.50 (98.82 - 768.58)
$C_{[PL]}$	10^3 tonnes	98.84 (19.59 - 101.74)	89.87 (16.79 - 109.08)	51.73 (15.15 - 117.46)	36.27 (13.66 - 123.26)
$C_{[PSLS]}$	10^3 tonnes	228.52 (52.60 - 241.07)	235.38 (42.34 - 262.99)	191.11 (36.86 - 284.90)	119.12 (33.06 - 294.79)
$C_{[PSFS]}$	10^3 tonnes	33.76 (9.63 - 36.11)	34.48 (8.34 - 39.22)	34.08 (8.15 - 41.59)	30.18 (7.29 - 46.03)
$C_y/C_{40\%}$	Proportion	1.01 (0.00 - 1.14)	1.00 (0.00 - 1.13)	0.64 (0.00 - 1.16)	0.16 (0.00 - 1.14)
C_y/C_{MSY}	Proportion	0.92 (0.00 - 1.01)	0.92 (0.00 - 1.00)	0.58 (0.00 - 1.01)	0.15 (0.00 - 1.02)
$C_y^{TAC} \neq C_{y-1}^{TAC}$	Count	5.00 (1.00 - 6.00)	5.00 (1.00 - 6.00)	6.00 (1.00 - 6.00)	6.00 (4.00 - 6.00)
$\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert$	Percent	5.12 (1.64 - 14.14)	11.64 (1.64 - 14.14)	12.52 (1.64 - 14.14)	14.14 (4.68 - 14.14)
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 10\%$	Prob.	0.31	0.47	0.57	0.65
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 5\%$	Prob.	0.55	0.67	0.77	0.87
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert = 15\%$	Prob.	0.27	0.44	0.55	0.64
$CPUE_{[PL]}$	Rate	0.01 (0.00 - 0.02)	0.01 (0.00 - 0.02)	0.00 (0.00 - 0.01)	0.00 (0.00 - 0.01)
$CPUE_{[PSLS]}$	Rate	8.06 (0.00 - 9.35)	6.63 (0.00 - 8.80)	4.18 (0.00 - 7.86)	0.55 (0.00 - 7.19)
E_y	Rate	0.82 (0.45 - 4.18)	0.99 (0.55 - 4.59)	1.43 (0.68 - 4.81)	2.27 (0.84 - 4.95)
$E_y/E_{40\%}$	Proportion	1.43 (0.77 - 6.88)	1.59 (0.95 - 7.56)	2.20 (1.15 - 7.92)	4.00 (1.43 - 8.16)
E_y/E_{MSY}	Proportion	0.76 (0.40 - 3.88)	0.88 (0.51 - 4.26)	1.13 (0.63 - 4.47)	2.46 (0.73 - 4.60)
B_y	10^3 tonnes	553.11 (53.41 - 1198.34)	480.75 (43.65 - 1071.37)	353.20 (37.22 - 929.65)	185.38 (33.65 - 786.57)
B_y/B_0	Proportion	0.29 (0.00 - 0.48)	0.25 (0.00 - 0.42)	0.18 (0.00 - 0.37)	0.02 (0.00 - 0.31)
B_y/B_{MSY}	Proportion	1.31 (0.00 - 2.10)	1.13 (0.00 - 1.87)	0.70 (0.00 - 1.62)	0.07 (0.00 - 1.44)
Pr. $> B_{20\%}$	Prob.	0.77	0.62	0.49	0.37
Pr. $> B_{10\%}$	Prob.	0.86	0.72	0.61	0.50
Pr. Target Quadrant	Prob.	0.23	0.13	0.03	0.02
Pr. Kobe Red	Prob.	0.26	0.42	0.53	0.64
Pr. Kobe Green	Prob.	0.69	0.54	0.40	0.30
Pr. Majuro Red	Prob.	0.23	0.38	0.51	0.63
Pr. Majuro White	Prob.	0.70	0.54	0.40	0.30

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