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Candidate Managment Procedures for Indian Ocean skipjack tuna

Prepared for the Indian Ocean Tuna Commission

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Executive Summary

This document provides background information to inform the Commission's decision on the adoption of a skipjack tuna Management Procedure (MP), as outlined in the Commission workplan. Two MP types are presented. Both have very similar performance and are likely to meet the Commission's objectives with a high probability. Each MP-type was tuned to meet managment objectives for skipjack with a 50%, 60% or 70% probability between 2034 and 2038. Tuning was conducted assuming either a symmetric or asymmetric limit to the allowable TAC change. This yielded a total of twelve candidate MPs. Simulation testing indicated that the tuning criteria will determine the overall stock status and average Total Allowable Catch (TAC). The MP-type determined the stability of the TAC over time, with the more stable MP-type also having a lower maximum possible catch. For the asymmetric TAC change limit, a smaller reduction in the TAC was allowed, but this led to more frequent changes over time.

Possible decisions to be made by the Commission include:

1. Selection of the level of performance that the Commission wishes to achieve in the future: 50%, 60%, or 70% probability of meeting management objectives between 2034 and 2038.
2. Selection of one of the two MP-types, indicating whether priority should be given to catch stability or the maximum possible catch;
3. Selection of a 10% or 15% limit to the reduction of the TAC.

Selection of the performance level (1) and desired stability (2) will have a greater impact on the overall outcome than selection of the change limit (3), and will help to identify which of the twelve candidate MPs should be preferred.

Adoption of an MP for skipjack will help improve the standard for skipjack tuna fishery management for the Indan Ocean and globally.

Introduction

In 2016, the IOTC adopted Resolution 16/02 (IOTC, 2016), which described a harvest control rule (HCR) to be used for setting a recommended total allowable catch (TAC) for skipjack tuna (SKJ), based on outputs from the stock assessment. This stock assessment is conducted in the same year that the HCR is implemented, typically using catch data up to and including the previous year. Each associated catch recommendation is valid for the subsequent 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 (SC, 2017). A second implementation of the HCR was conducted in 2020 (SC, 2020), based on an updated stock assessment by Fu (2020). The outputs were used to calculate a recommended catch limit for 2021–2023 of 514 thousand tonnes (IOTC, 2021). The stock assessment was repeated in 2023 (Fu, 2023), yielding a recommended catch limit for 2024–2026 of 629 thousand tonnes (SC, 2023). The realised catch from the fishery consistently exceeds the recommended limit by 15% – 30% each year (Table 1).

Table 1: Recommended catch from current HCR and realised catches used by Fu (2023) in tonnes. *Note that the 2023 catch is predicted by the stock assessment based on current exploitation rates and is not an empirical value.

Year	Recommended catch	Realised catch	Overcatch
2018	470,029	606,134	29%
2019	470,029	590,388	26%
2020	470,029	547,258	16%
2021	513,572	655,115	28%
2022	513,572	648,697	26%
2023	513,572	*596,511	*16%
2024	628,606	–	–
2025	628,606	–	–
2026	628,606	–	–

As part of CMM 16/02 and 21/03 the IOTC has committed to a program of development and refinement of the HCR, and to subject it to simulation-based evaluation. An HCR that has the data inputs specified and which has been simulation tested is referred to as a Management Procedure (MP). The cyclical process of simulation testing, review and selection of MPs is known as Management Procedure Evaluation, or Management Strategy Evaluation (MSE), with the latter terminology preferred by the IOTC. This work has been on-going since 2019, with candidate MPs being repeatedly tested and reviewed by the WPM and TCMP.

This document describes twelve candidate MPs for SKJ and summarises the results from simulation testing of their performance. The intention is to provide sufficient information to facilitate the decision-making processes of the Commission in relation to the adoption of a SKJ MP in the IOTC.

MSE summary

The purpose of MSE is to evaluate candidate MPs against a range of possible conditions of the population and fishery dynamics. It aims to find the best performing MP that meets the management objectives of the Commission and is robust to a range of uncertainties.

Operating Models

The operating models (OMs) are the set of simulation models designed to include the plausible range of fishery dynamics and which are used to simulation test the MPs. The SKJ OMs replicate the set of stock assessment models developed be Fu (2023). This set of models is considered to represent our best understanding of the resource dynamics and how it will respond to harvesting in the future. The "reference set" of models includes 36 alternative models. These operating models were used to simulation test the performance of candidate MPs over an 18 year projection period (2023 to 2040 inclusive). The recommended catch from 2023 to 2026 was fixed based on outputs from the current HCR (Table 1), with candidate MPs being implemented to recommend the catch from 2027 onwards, at three year intervals. Simulated catch rate data was provided as an input to the MP with a two-year total lag between availability of the data and setting of a TAC (i.e., a one year data lag and one-year implementation lag).

Management Objectives

The overall objective of the Commission is the conservation and optimum utilisation of tuna stocks in the IOTC area of competence. Specific management objectives outlined in Resolution 15/10 for key target species (IOTC, 2015), including SKJ, are to maintain the biomass at or above biomass levels required to produce MSY (B_{MSY}) and maintain the exploitation rate at or below the associated level (E_{MSY}). Because of difficulties in estimating MSY for SKJ, management targets have been conventionaly set (following Resolutions 16/02 and 21/03) at the biomass and exploitation associated with a 40% depletion below the unexploited equilibrium population size (i.e., $B_{40\%}$ and $E_{40\%}$ respectively; IOTC, 2015, 2016).

Candidate Management Procedures

The managment target is defined as the exploitation rate being less than $E_{40\%}$ (no overfishing) and biomass being greater than $B_{40\%}$ (not overfished). Three objectives consistent with this management target determined the minimum performance required of the MP. To be considered, the MP must meet one of the following:

- A 50% probability of meeting managment objectives between 2034-2038.
- A 60% probability of meeting managment objectives between 2034-2038.
- A 70% probability of meeting managment objectives between 2034-2038.

The target "quadrant" was defined by the managment objectives above. A process of "tuning" was used to select MPs that matched the listed 50%, 60% and 70% probabilities of being in this target quadrant. In common with other IOTC stocks, if an MP matched one of these criteria then it was selected as a "candidate" MP for further consideration.

All candidate MPs presented use a step-linear HCR to set a TAC based on standardised catch rate indices from the Maldivian PL and European PSLS fisheries. These two catch rate indices are combined to create an index of population status (depletion). The relationship between stock status, as measured by this index, and the TAC is shown in Figure 1. The MPs are described in more detail in Appendix A.

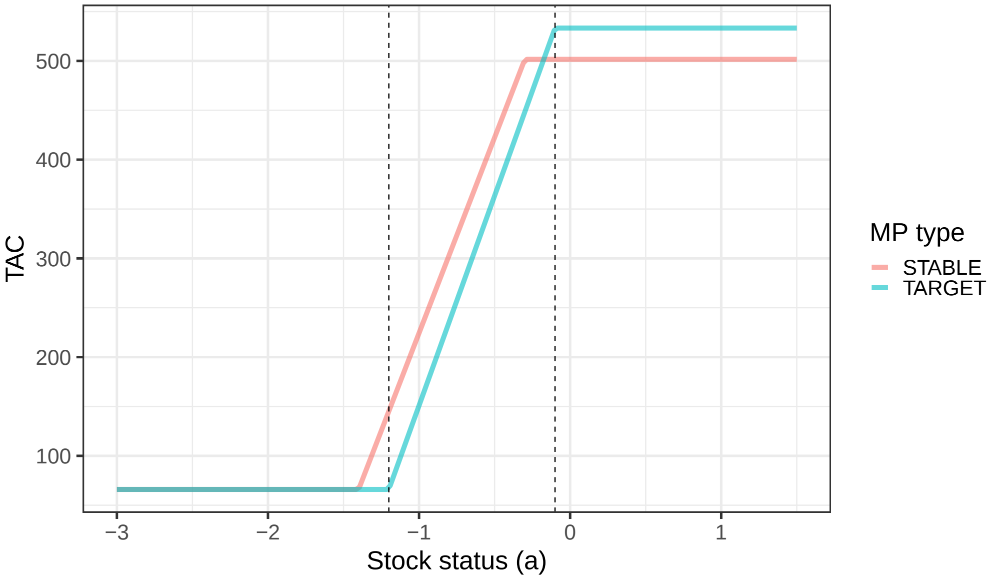

Figure 1: Harvest control rule for candidate MPs. The HCR outputs a recommended TAC based on a stock status indicator (*a*). The indicator is calculated from standardised catch rate indices from the Maldivian PL and European PSLS fisheries (Appendix A). Vertical dashed lines indicate the value of *a* at depletion levels of $B_{10\%}$ and $B_{40\%}$. Two MP-types are shown. The TARGET MP-type uses values of *a* at $B_{10\%}$ and $B_{40\%}$ to define the shape of the control rule. The STABLE MP-type is designed to create a more stable TAC time series. The STABLE MP-type has a lower maximum catch compared to the TARGET MP-type, when tuned to the same tuning criteria (Table A1).

Two MP-types were considered (Figure 1). For each of the tuning criteria, both MP-types were tuned by changing the value of the maximum possible catch. The inflection points for each MP-type were fixed during tuning. This was repeated assuming a symmetric (SYM: 15% up, 15% down) change limit for the TAC, or an asymmetric (ASY: 15% up, 10% down) change limit.

All MPs:

- assume a 3-year management cycle and calculate a total allowable catch (TAC) for the entire IOTC management area;
- assume a minimum artisanal catch that is not subject to TAC restrictions;
- assume a 2-year total lag between the availability of catch rate data and implementation of a TAC.

Results

Tuning of the MPs yielded the twelve candidate MPs listed in Table 2. A full set of diagnostis is provided in Appendix B. Overall MP properties:

- Overall stock status and average catch are primarily determined by tuning to 50%, 60% or 70% criteria, not by the MP-type or TAC change limit;
- The STABLE MP-type is more stable without any noticable reduction in the average TAC;
- The TARGET MP-type has a higher possible TAC (Figure 1 and Table A1);

- The ASY TAC change limit led to more frequent TAC changes but can improve overall stability for the less stable TARGET MP-type.

Overall, the TAC change limit had the smallest effect on outcome. Stock status and catch stability were primarily determined by the tuning criteria and MP-type.

Table 2: Summary diagnostic outputs for selection of index-based MPs (see Table A1 for the list of MP definitions). MP's were STABLE or TARGET (see Figure 1), imposed symmetric (SYM) or asymmetric (ASY) change limits on the TAC, and were tuned to the 50%, 60% or 70% tuning criteria. Darker shading indicates better performance.

MP	Total Catch	Lower TAC Quantile	Number of TAC changes	Average TAC change	Pr. SSB above target	Pr. SSB above MSY
MP-STABLE-ASY-50%	530.46	517.14	3	4.18	0.38	0.92
MP-STABLE-ASY-60%	521.3	512.86	3	4.08	0.43	0.92
MP-STABLE-ASY-70%	512.05	507.41	3	4.91	0.48	0.93
MP-STABLE-SYM-50%	529.63	518.24	3	3.24	0.41	0.94
MP-STABLE-SYM-60%	523.29	513.93	2	3.43	0.46	0.94
MP-STABLE-SYM-70%	513.78	506.28	2	4.02	0.54	0.96
MP-TARGET-ASY-50%	529.12	515.03	5	8.16	0.38	0.93
MP-TARGET-ASY-60%	520.27	509.66	5	7.92	0.43	0.94
MP-TARGET-ASY-70%	511.81	504.91	5	7.67	0.49	0.94
MP-TARGET-SYM-50%	519.22	505.62	5	9.41	0.41	0.95
MP-TARGET-SYM-60%	511.55	499.73	5	9.38	0.51	0.96
MP-TARGET-SYM-70%	503.87	492.17	4	8.53	0.54	0.96

Simulation results listed in Table 2 and Appendix B indicate that the tuning criteria can be ranked according to the desired stock status and TAC. The 50% tuning yields the highest stock depletion (lowest stock biomass) with the highest catch. The 70% criteria yields the lowest depletion (highest stock biomass) with the lowest catch. The STABLE MP-type generates a more stable TAC over time, which can lead to a higher average catch, but has a lower maximum possible catch compared to the TARGET MP-type (Figure 1 and Table A1). The asymmetric change limit imposed a lower change limit on TAC reductions and this led to a small increase in the frequency of TAC changes over time. For the less stable TARGET MP-type, the ASY change limit led to a more stable TAC timeseries. However, for the STABLE MP-type, the ASY change limit appeared to reduce TAC stability, because more frequent TAC changes were required. These observations are summarised in Table 3, which lists their qualitative performance.

Table 3: Qualitative performance criteria and recommendations for MP design. (* The ASY limit is preferred for the TARGET MP-type).

Criteria	MP-type	TAC change limit	Tuning objective (50%, 60%, 70% prob. of being in the target quadrant)
Maximum possible catch	TARGET	–	50%
Maximum average catch	STABLE	–	50%
Catch stability	STABLE	SYM*	70%
Stock status	–	–	70%

Actions for the Commission

Possible decisions for the Commission include:

1. Selection of the management objective that the MP will be tuned to: a 50%, 60% or 70%, probability of meeting the management target. This will determine the stock status and overall catch;
2. Selection of either the TARGET or STABLE MP-type. This will determine whether stabilty of the TAC over time should be given preference over the maximum allowable catch;
3. Selection of a 10% or 15% limit to the reduction of the TAC. This will have a small impact on TAC stability, with a more restrictive change limit likely leading to more frequent TAC changes.

Selection from these alternate options will identify which of the twelve candidate MPs should be preferred.

Acknowledgements

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Appendix A: Candidate Management Procedures

Description of Management Procedures

The proposed candidate MPs contain a Harvest Control Rule (HCR) that converts an index of depletion (a_y) into a Total Allowable Catch (TAC). The shape of the HCR is defined by the maximum possible catch ($\mathrm{C}_{\mathrm{max}}$), the minium possible catch ($\mathrm{C}_{\mathrm{min}}$), and the safety a_{X} and threshold a_{T} parameters. The HCR can be written in mathematical form as:

$$\mathrm{C}^{\mathrm{TAC}} = \begin{cases} \mathrm{C}_{\mathrm{max}} & \text{for} \quad \mathrm{a}_y \geq \mathrm{a}_{\mathrm{T}} \\ (\mathrm{C}_{\mathrm{max}} - \mathrm{C}_{\mathrm{min}}) \times \frac{\mathrm{a}_y - \mathrm{a}_{\mathrm{X}}}{\mathrm{a}_{\mathrm{T}} - \mathrm{a}_{\mathrm{X}}} + \mathrm{C}_{\mathrm{min}} & \text{for} \quad \mathrm{a}_{\mathrm{X}} < \mathrm{a}_y < \mathrm{a}_{\mathrm{T}} \\ \mathrm{C}_{\mathrm{min}} & \text{for} \quad \mathrm{a}_y \leq \mathrm{a}_{\mathrm{X}} \end{cases} \tag{1}$$

For values $\mathrm{a}_y \leq \mathrm{a}_{\mathrm{X}}$, the recommended catch is equal to $\mathrm{C}_{\mathrm{min}}$. The value of $\mathrm{C}_{\mathrm{min}}$ is set at an assumed artisinal catch of 66 thousand tonnes. As a_y increases, the recommended catch also increases, until for values of $\mathrm{a}_y \geq \mathrm{a}_{\mathrm{T}}$ the recommended catch is equal to $\mathrm{C}_{\mathrm{max}}$, which is the maximum possible TAC (Figure A1). In addition, a maximum possible TAC change is included as part of the MP definition, with notation $\Delta^{\mathrm{TAC}}_{limit}$.

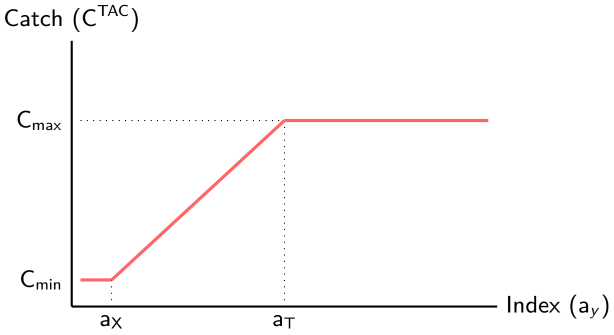


Figure A1: Schematic representation of the empirical Harvest Control Rule (Equation 1) that was proposed as part of a data-based MP (Edwards, 2021b,a). Parameters $\mathrm{C}_{\mathrm{min}}$, a_{X}, a_{T} were fixed. Each MP was tuned by adjusting $\mathrm{C}_{\mathrm{max}}$ to match the tuning criteria.

The tuning process involved changing $\mathrm{C}_{\mathrm{max}}$ to meet the tuning criteria, whilst keeping a_{X}, a_{T} and $\mathrm{C}_{\mathrm{min}}$ fixed. Tuning parameters a_{X} and a_{T} for the TARGET MPs correspond to a depletion of approximately 10% and 40% respectively. For the STABLE MPs, a_{X} and a_{T} correspond to depletions of approximately 8% and 32% respectively. Tuning yielded the twelve candidate MPs in Table 2 with parameters values listed in Table A1.

Table A1: Tuning parameters for MPs tuned to the 50%, 60% and 70% tuning criteria.

MP	C_{min}	C_{max}	a_X	a_T	Δ^{TAC}_{limit}
MP-STABLE-ASY-50%	66.02	528.13	-1.40	-0.30	0.10%, 0.15%
MP-STABLE-ASY-60%	66.02	512.29	-1.40	-0.30	0.10%, 0.15%
MP-STABLE-ASY-70%	66.02	488.52	-1.40	-0.30	0.10%, 0.15%
MP-STABLE-SYM-50%	66.02	533.41	-1.40	-0.30	0.15%, 0.15%
MP-STABLE-SYM-60%	66.02	522.85	-1.40	-0.30	0.15%, 0.15%
MP-STABLE-SYM-70%	66.02	507.01	-1.40	-0.30	0.15%, 0.15%
MP-TARGET-ASY-50%	66.02	562.46	-1.20	-0.10	0.10%, 0.15%
MP-TARGET-ASY-60%	66.02	533.41	-1.20	-0.10	0.10%, 0.15%
MP-TARGET-ASY-70%	66.02	504.37	-1.20	-0.10	0.10%, 0.15%
MP-TARGET-SYM-50%	66.02	551.90	-1.20	-0.10	0.15%, 0.15%
MP-TARGET-SYM-60%	66.02	533.41	-1.20	-0.10	0.15%, 0.15%
MP-TARGET-SYM-70%	66.02	512.29	-1.20	-0.10	0.15%, 0.15%

Data inputs

The proposed MPs are based on standardised CPUE indices from the Maldivian PL (Medley et al., 2020b,a, 2023) and European PSLS fleets (Guery et al., 2020, Guery, 2020, Kaplan et al., 2023). These indices are both used routinely in Indian Ocean SKJ assessments (Fu, 2017, 2020, 2023).

The log-transformed PL and PSLS indices, offset by the mean and averaged across all four seasons within the year, show similar trends over time when plotted for overlapping years (1995 to 2021 inclusive; Figure A2). On this basis, the index in Equation 2, with notation a_y, has been proposed as in input value for the MP (Edwards, 2021b), with the reference value (a^{REF}) calculated from the 1995 to 2021 period.

Figure A2: Time series of the log-trasformed PL (blue) and PSLS (orange) indices between 1995 and 2021 (Fu, 2023), offset by their respective mean values. The grey line illustrates the arithmetic mean of the two log-trasformed indices (Equation 2).

$$\mathrm{a}^{\mathrm{REF}} = \frac{1}{2 \cdot n_s \cdot n_y} \cdot \left\{ \sum_{y=1995}^{2021} \sum_s \log\left(\mathrm{CPUE}_{y,s}^{\mathrm{PSLS}}\right) + \sum_{y=1995}^{2021} \sum_s \log\left(\mathrm{CPUE}_{y,s}^{\mathrm{PL}}\right) \right\} \tag{2a}$$

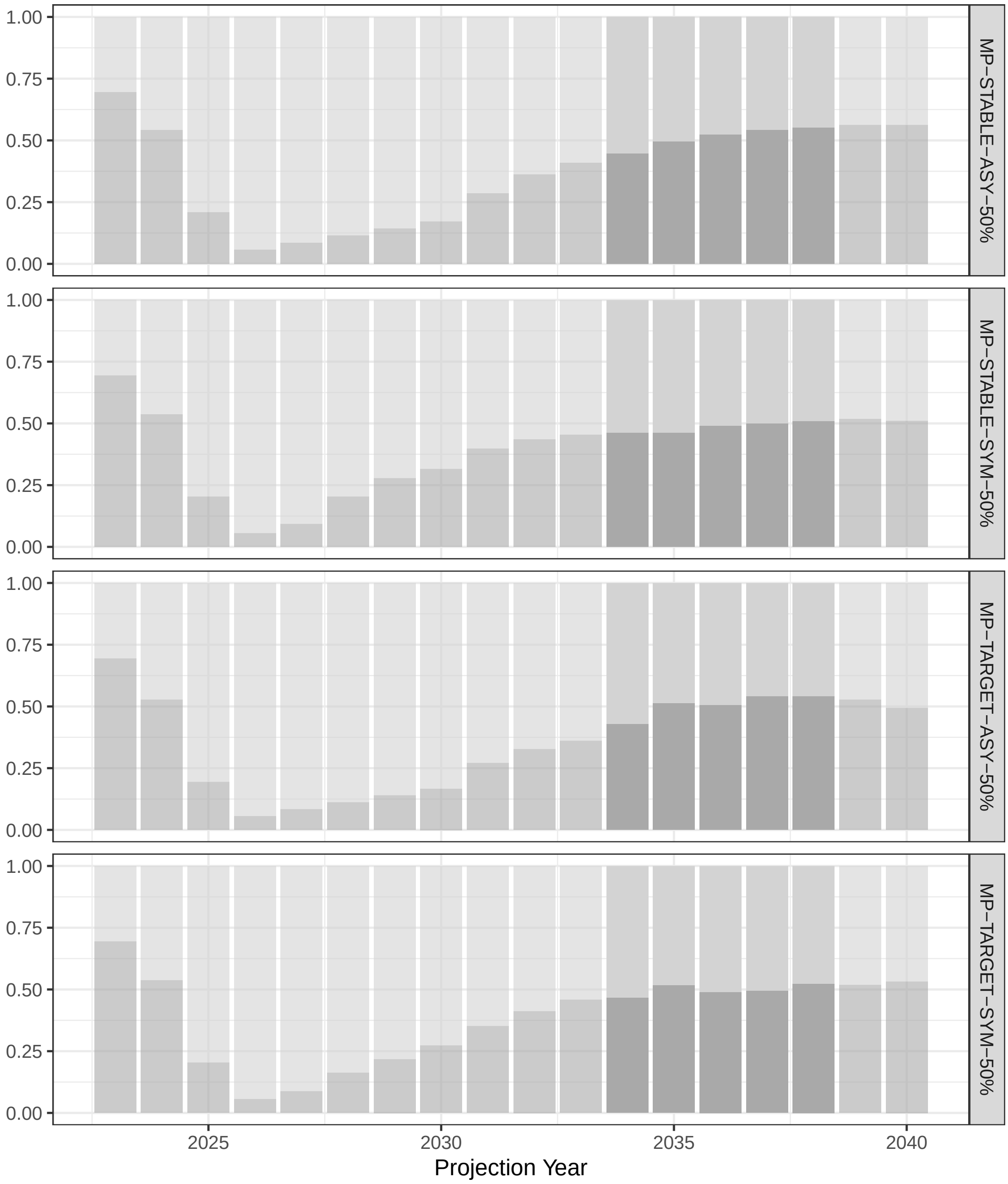
$$\mathrm{a}_y = \frac{1}{2 \cdot n_s} \cdot \left\{ \sum_s \log\left(\mathrm{CPUE}_{y-3,s}^{\mathrm{PSLS}}\right) + \sum_s \log\left(\mathrm{CPUE}_{y-3,s}^{\mathrm{PL}}\right) \right\} - \mathrm{a}^{\mathrm{REF}} \tag{2b}$$

Exceptional Circumstances

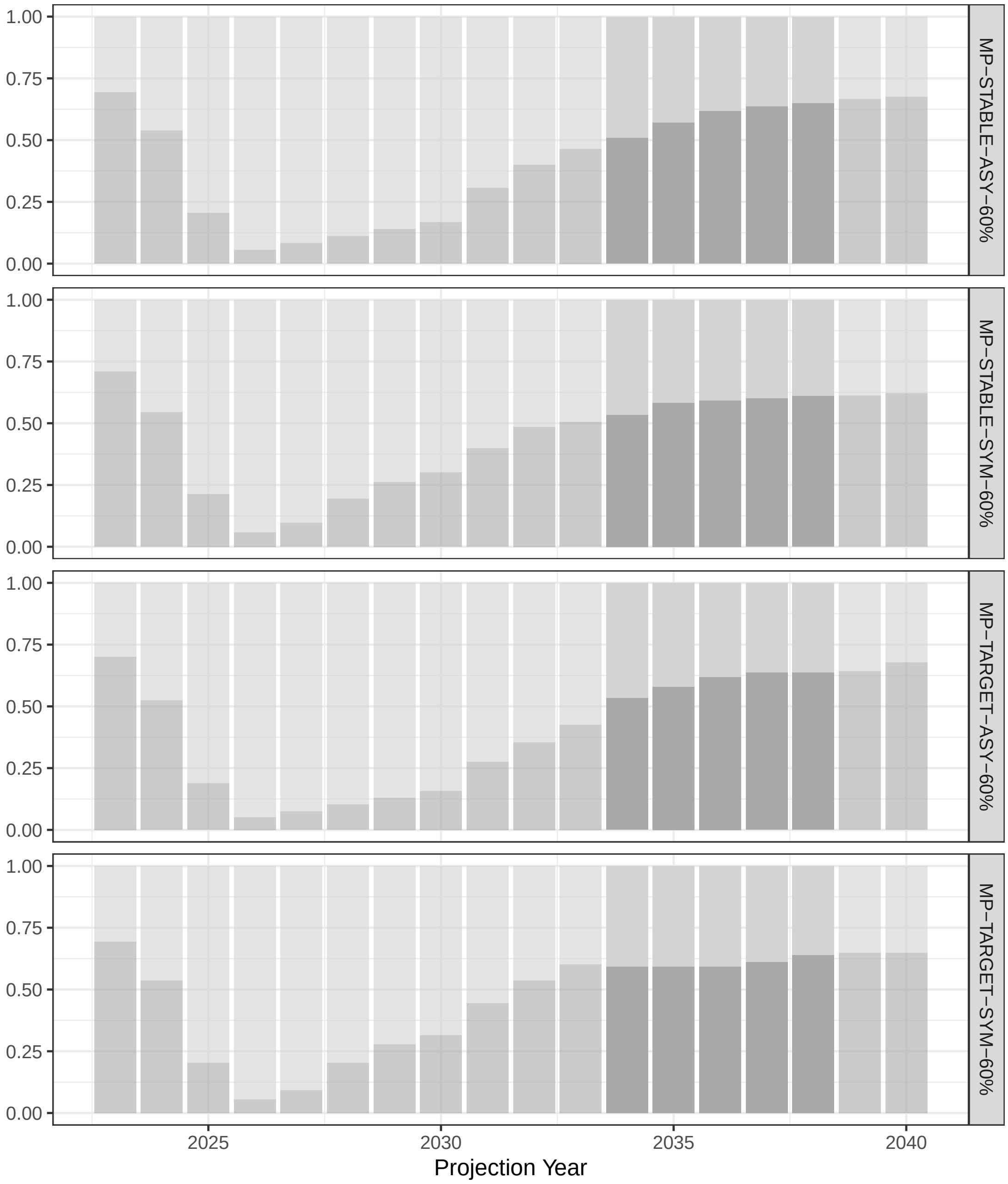
The process for evaluating exceptional circumstances adopted by the IOTC SC is described in Appendix 6a of the 2021 IOTC SC report (SC, 2021).

Appendix B: Simulation testing results

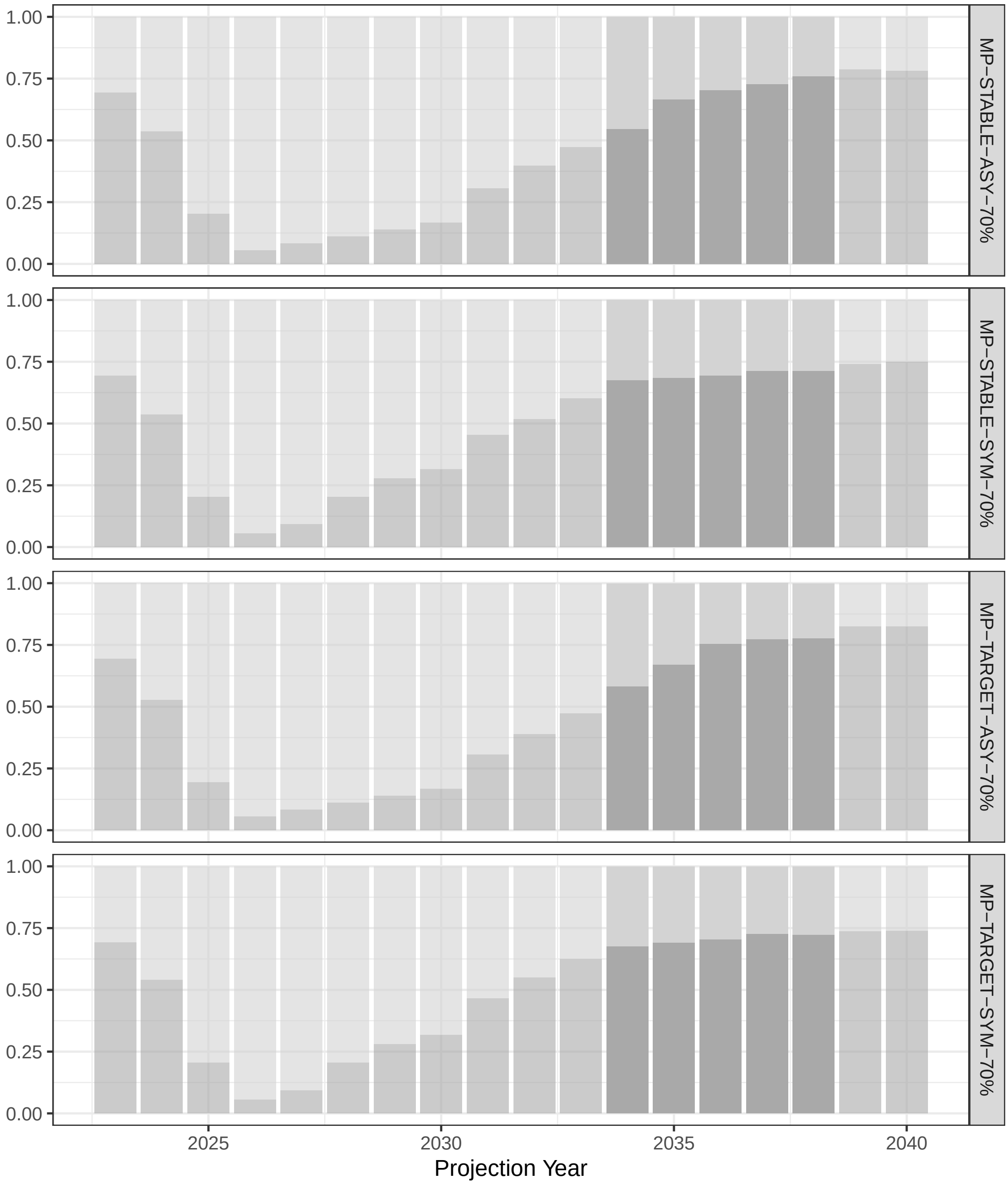
Reference case



(a) MP's tuned to 50% probability of being in the target quadrant.

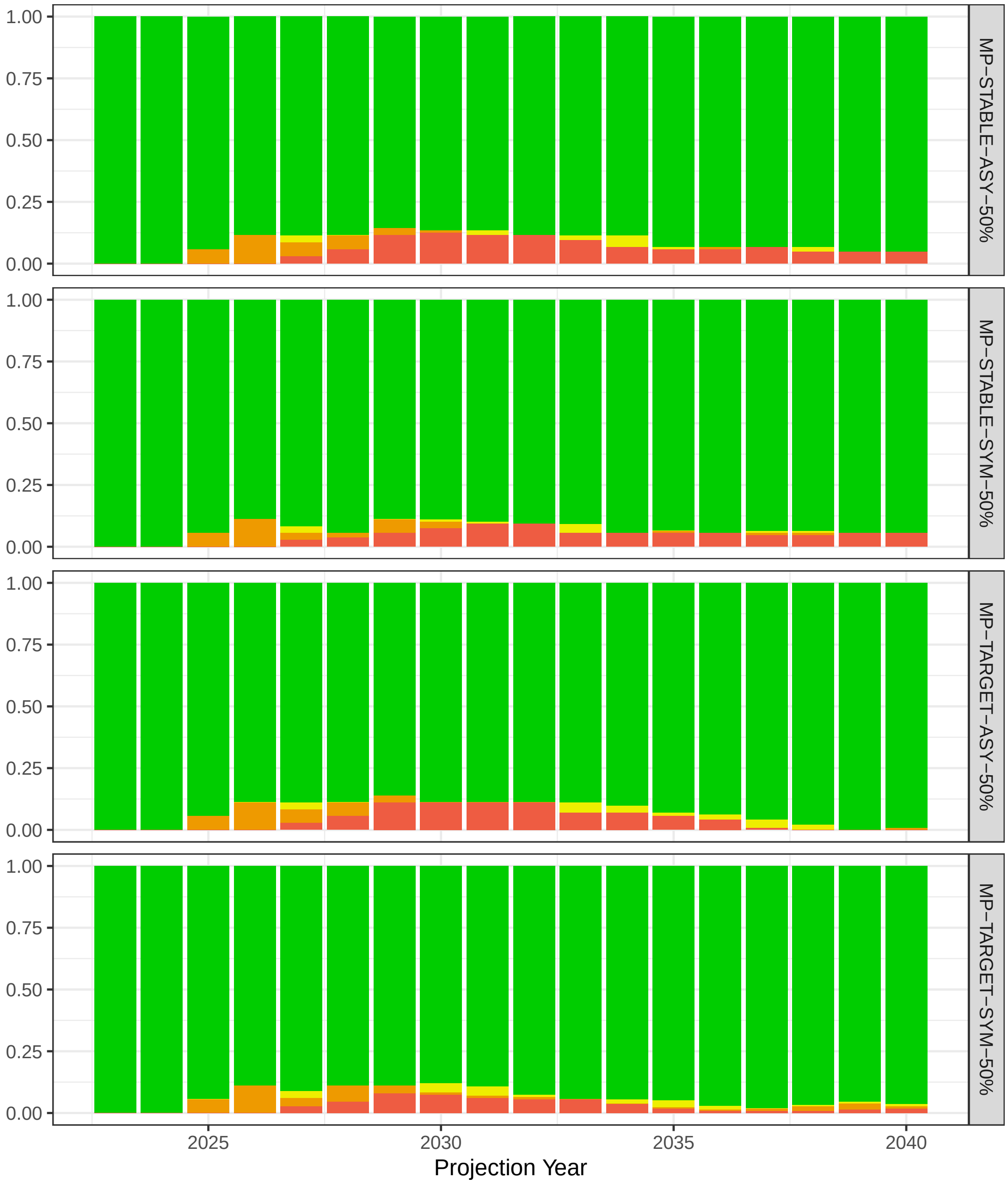


(b) MP's tuned to 60% probability of being in the target quadrant.

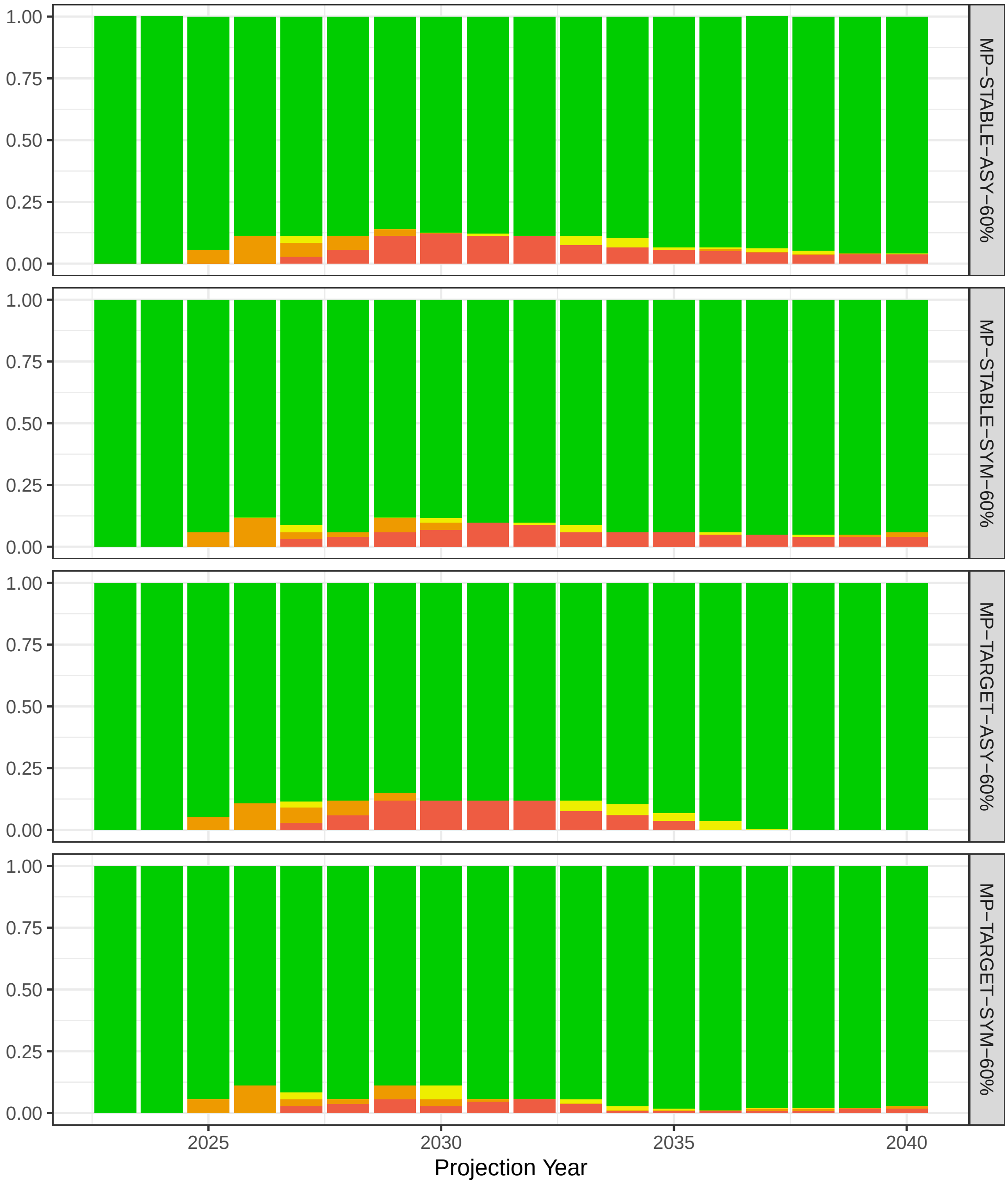


(c) MP's tuned to 70% probability of being in the target quadrant.

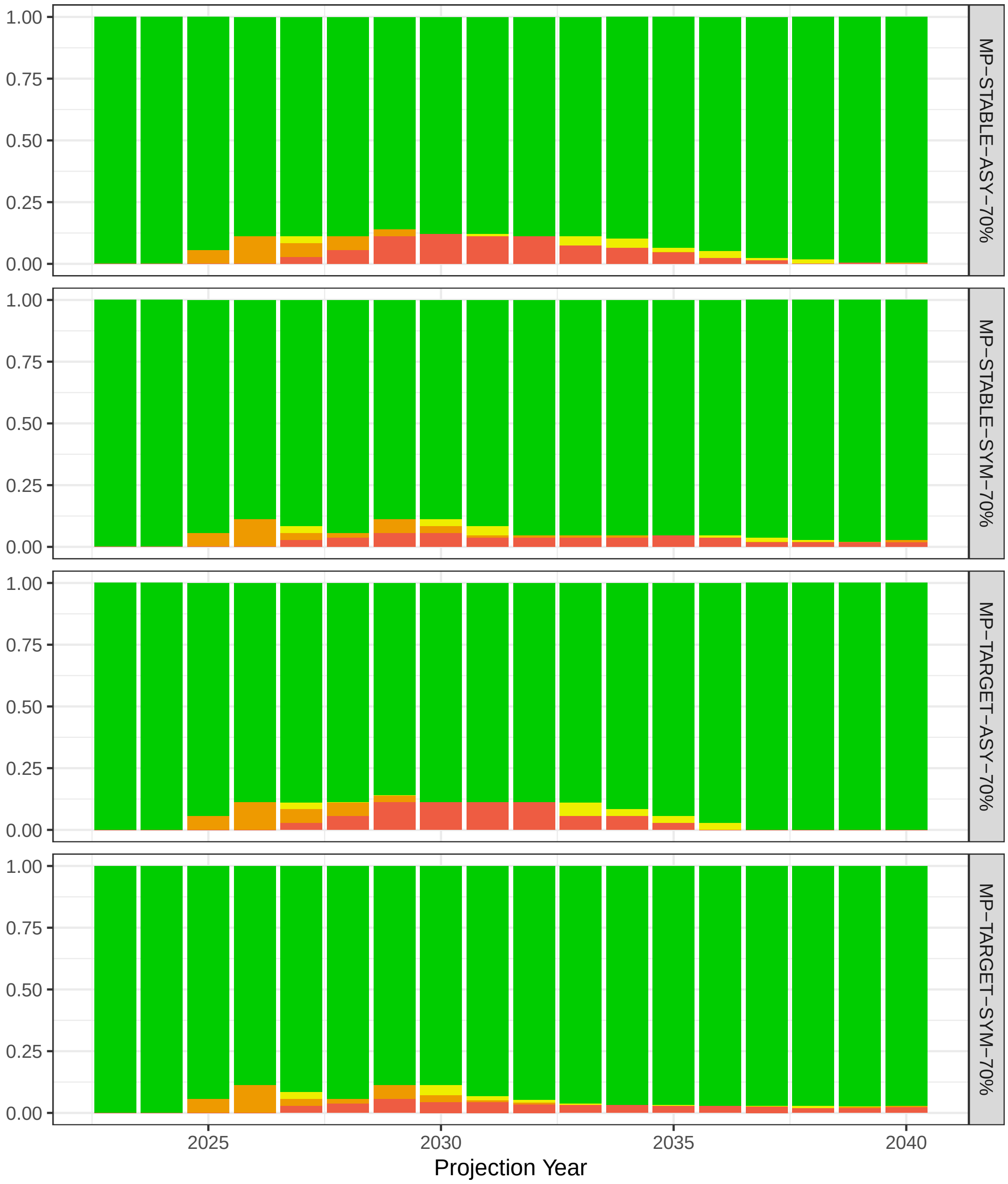
Figure A3: Simulated probabilities of being in the target quadrant over time, per MP (Table A1). Between 2023 and 2026 the TAC was fixed at known values (Table 1), after which the TAC was set by the MP. Each MP was tuned using the target quadrant probabilities between 2034 and 2038 inclusive.



(a) MP's tuned to 50% probability of being in the target quadrant.



(b) MP's tuned to 60% probability of being in the target quadrant.



(c) MP's tuned to 70% probability of being in the target quadrant.

Figure A4: Simulated probabilities of being in each Kobe quadrant over time, per MP (Table A1). Between 2023 and 2026 the TAC was fixed at known values (Table 1), after which the TAC was set by the MP.

Table A2: Diagnostic outputs for MP evaluations over 14 year projection period (2027 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 five TAC implementation years (2027, 2030, 2033, 2036 and 2039 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)		
$C_y^{\mathrm{TAC}} \neq C_{y-1}^{\mathrm{TAC}}$	n. TAC changes	Count
$\lvert C_y^{\mathrm{TAC}}/C_{y-1}^{\mathrm{TAC}} - 1\rvert$	TAC change	Mean % change
Pr. $\lvert C_y^{\mathrm{TAC}}/C_{y-1}^{\mathrm{TAC}} - 1\rvert > 10\%$	TAC change $> 10\%$	Probability
Pr. $\lvert C_y^{\mathrm{TAC}}/C_{y-1}^{\mathrm{TAC}} - 1\rvert > 5\%$	TAC change $> 5\%$	Probability
Pr. $C_y^{\mathrm{TAC}}/C_{y-1}^{\mathrm{TAC}} - 1$ at limit	TAC change at limit	Probability
Catch rate		
$\mathrm{CPUE}_{[PL]}$	CPUE for PL fleet	Geometric mean
$\mathrm{CPUE}_{[PSLS]}$	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. $> B_{40\%}$	$B_y > B_{40\%}$	Probability
Pr. $> B_{\mathrm{MSY}}$	$B_y > B_{\mathrm{MSY}}$	Probability
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	$B_y < B_{\mathrm{MSY}}$ and $E_y > E_{\mathrm{MSY}}$	Probability
Pr. Kobe Green	$B_y > B_{\mathrm{MSY}}$ and $E_y < E_{\mathrm{MSY}}$	Probability
Majuro Quadrants		
Pr. Majuro Red	$B_y < B_{20\%}$	Probability
Pr. Majuro White	$B_y > B_{20\%}$ and $E_y < E_{40\%}$	Probability

Table A3: Diagnostic outputs for evaluation of index-based MPs with a target tuning probability of 50% (see Table A1 for the list of MP definitions and Table A2 for a description of each diagnostic).

Performance Statistic	Units	MP-STABLE-ASY-50%	MP-STABLE-SYM-50%	MP-TARGET-ASY-50%	MP-TARGET-SYM-50%
C_y^{TAC}	10^3 tonnes	530.46 (517.14 - 532.74)	529.63 (518.24 - 529.63)	529.12 (515.03 - 543.68)	519.22 (505.62 - 535.50)
C_{lq}^{TAC}	10^3 tonnes	517.14	518.24	515.03	505.62
C_{2027}^{TAC}	10^3 tonnes	565.74 (565.74 - 565.74)	534.31 (534.31 - 534.31)	565.74 (565.74 - 565.74)	543.69 (534.31 - 554.54)
C	10^3 tonnes	532.98 (517.47 - 536.60)	532.66 (514.22 - 534.24)	530.90 (507.56 - 549.76)	527.25 (505.42 - 548.62)
$C_{[PL]}$	10^3 tonnes	107.51 (103.33 - 112.51)	107.19 (103.20 - 112.20)	108.04 (102.66 - 112.01)	107.58 (102.03 - 112.21)
$C_{[PSLS]}$	10^3 tonnes	140.46 (129.89 - 149.62)	140.11 (130.86 - 148.40)	139.89 (128.40 - 150.61)	138.37 (128.85 - 149.55)
$C_{[PSFS]}$	10^3 tonnes	25.95 (24.83 - 26.62)	25.89 (24.87 - 26.56)	26.05 (24.62 - 26.76)	25.78 (24.38 - 26.92)
$C_y/C_{40\%}$	Proportion	1.00 (0.89 - 1.09)	1.00 (0.89 - 1.09)	1.00 (0.91 - 1.08)	1.00 (0.90 - 1.08)
C_y/C_{MSY}	Proportion	0.91 (0.78 - 1.01)	0.91 (0.78 - 1.01)	0.91 (0.80 - 0.99)	0.91 (0.79 - 1.00)
$C_y^{TAC} \neq C_{y-1}^{TAC}$	Count	3.00 (2.00 - 5.00)	3.00 (2.00 - 5.00)	5.00 (4.00 - 5.00)	5.00 (4.00 - 5.00)
$\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert$	Percent	4.18 (3.33 - 8.17)	3.24 (3.03 - 7.42)	8.16 (5.65 - 10.25)	9.41 (5.31 - 12.16)
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 10\%$	Prob.	0.24	0.24	0.37	0.50
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 5\%$	Prob.	0.51	0.32	0.74	0.71
Pr. $C_y^{TAC}/C_{y-1}^{TAC} - 1$ at upp. limit	Prob.	0.00 (0.00 - 0.00)	0.00 (0.00 - 0.00)	0.00 (0.00 - 0.20)	0.00 (0.00 - 0.20)
Pr. $C_y^{TAC}/C_{y-1}^{TAC} - 1$ at low. limit	Prob.	0.00 (0.00 - 0.00)	0.20 (0.20 - 0.20)	0.00 (0.00 - 0.00)	0.20 (0.00 - 0.20)
$CPUE_{[PL]}$	Rate	0.07 (0.06 - 0.08)	0.07 (0.06 - 0.08)	0.07 (0.06 - 0.08)	0.07 (0.06 - 0.08)
$CPUE_{[PSLS]}$	Rate	16.86 (14.50 - 19.24)	17.07 (15.07 - 19.46)	16.82 (15.08 - 18.96)	17.06 (15.21 - 19.22)
E_y	Rate	0.58 (0.48 - 0.79)	0.57 (0.48 - 0.79)	0.59 (0.50 - 0.74)	0.57 (0.48 - 0.72)
$E_y/E_{40\%}$	Proportion	1.05 (0.78 - 1.57)	1.02 (0.77 - 1.52)	1.06 (0.82 - 1.46)	1.04 (0.80 - 1.44)
E_y/E_{MSY}	Proportion	0.62 (0.37 - 0.95)	0.62 (0.37 - 0.92)	0.61 (0.39 - 0.88)	0.60 (0.38 - 0.87)
B_y	10^3 tonnes	829.42 (601.40 - 987.68)	842.83 (616.80 - 1000.87)	814.87 (642.88 - 970.91)	841.36 (662.06 - 989.25)
B_y/B_0	Proportion	0.37 (0.27 - 0.46)	0.38 (0.28 - 0.46)	0.37 (0.29 - 0.45)	0.38 (0.29 - 0.46)
B_y/B_{MSY}	Proportion	1.54 (1.02 - 2.37)	1.58 (1.10 - 2.39)	1.58 (1.06 - 2.32)	1.60 (1.15 - 2.36)
Pr. $> B_{40\%}$	Prob.	0.38	0.41	0.38	0.41
Pr. $> B_{MSY}$	Prob.	0.92	0.94	0.93	0.95
Pr. $> B_{20\%}$	Prob.	1.00	1.00	1.00	1.00
Pr. $> B_{10\%}$	Prob.	1.00	1.00	1.00	1.00
Pr. Target Quadrant	Prob.	0.38	0.40	0.36	0.39
Pr. Kobe Red	Prob.	0.07	0.06	0.06	0.04
Pr. Kobe Green	Prob.	0.90	0.92	0.92	0.93
Pr. Majuro Red	Prob.	0.00	0.00	0.00	0.00
Pr. Majuro White	Prob.	0.91	0.93	0.93	0.95

Table A4: Diagnostic outputs for evaluation of index-based MPs with a target tuning probability of 60% (see Table A1 for the list of MP definitions and Table A2 for a description of each diagnostic).

Performance Statistic	Units	MP-STABLE-ASY-60%	MP-STABLE-SYM-60%	MP-TARGET-ASY-60%	MP-TARGET-SYM-60%
C_y^{TAC}	10^3 tonnes	521.30 (512.86 - 526.41)	523.29 (513.93 - 523.29)	520.27 (509.66 - 532.70)	511.55 (499.73 - 524.86)
C_{lq}^{TAC}	10^3 tonnes	512.86	513.93	509.66	499.73
C_{2027}^{TAC}	10^3 tonnes	565.74 (565.74 - 565.74)	534.31 (534.31 - 534.31)	565.74 (565.74 - 565.74)	534.31 (534.31 - 534.31)
C	10^3 tonnes	521.16 (509.80 - 527.42)	524.67 (510.57 - 525.94)	519.24 (499.63 - 534.82)	516.99 (500.35 - 533.23)
$C_{[PL]}$	10^3 tonnes	105.37 (102.23 - 110.15)	105.65 (102.48 - 110.78)	105.57 (100.90 - 109.28)	105.37 (101.33 - 109.17)
$C_{[PSLS]}$	10^3 tonnes	137.54 (128.36 - 146.63)	138.15 (129.29 - 145.91)	136.36 (126.59 - 146.44)	135.77 (126.64 - 145.50)
$C_{[PSFS]}$	10^3 tonnes	25.43 (24.59 - 26.08)	25.51 (24.63 - 26.22)	25.43 (24.15 - 26.10)	25.35 (24.20 - 26.11)
$C_y/C_{40\%}$	Proportion	0.99 (0.88 - 1.08)	0.99 (0.88 - 1.09)	0.98 (0.89 - 1.07)	0.97 (0.88 - 1.07)
C_y/C_{MSY}	Proportion	0.90 (0.77 - 0.99)	0.90 (0.80 - 1.00)	0.89 (0.78 - 0.98)	0.88 (0.77 - 0.98)
$C_y^{TAC} \neq C_{y-1}^{TAC}$	Count	3.00 (2.00 - 5.00)	2.00 (2.00 - 4.00)	5.00 (4.00 - 5.00)	5.00 (4.00 - 5.00)
$\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert$	Percent	4.08 (3.70 - 8.13)	3.43 (3.43 - 7.88)	7.92 (5.16 - 9.59)	9.38 (4.71 - 11.29)
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 10\%$	Prob.	0.24	0.24	0.37	0.46
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 5\%$	Prob.	0.49	0.32	0.73	0.64
Pr. $C_y^{TAC}/C_{y-1}^{TAC} - 1$ at upp. limit	Prob.	0.00 (0.00 - 0.00)	0.00 (0.00 - 0.00)	0.00 (0.00 - 0.00)	0.00 (0.00 - 0.06)
Pr. $C_y^{TAC}/C_{y-1}^{TAC} - 1$ at low. limit	Prob.	0.00 (0.00 - 0.00)	0.20 (0.20 - 0.20)	0.00 (0.00 - 0.00)	0.20 (0.20 - 0.20)
$CPUE_{[PL]}$	Rate	0.07 (0.06 - 0.08)	0.07 (0.06 - 0.08)	0.07 (0.06 - 0.08)	0.07 (0.06 - 0.08)
$CPUE_{[PSLS]}$	Rate	17.24 (14.87 - 19.58)	17.38 (15.31 - 19.78)	17.27 (15.36 - 19.38)	17.45 (15.61 - 19.72)
E_y	Rate	0.56 (0.46 - 0.75)	0.55 (0.46 - 0.74)	0.57 (0.47 - 0.71)	0.54 (0.46 - 0.69)
$E_y/E_{40\%}$	Proportion	1.01 (0.76 - 1.48)	1.00 (0.78 - 1.44)	1.02 (0.78 - 1.41)	1.00 (0.77 - 1.34)
E_y/E_{MSY}	Proportion	0.60 (0.36 - 0.93)	0.60 (0.38 - 0.89)	0.59 (0.38 - 0.89)	0.57 (0.36 - 0.81)
B_y	10^3 tonnes	843.50 (628.35 - 1010.17)	850.50 (651.40 - 1016.94)	835.47 (665.11 - 998.74)	873.25 (692.89 - 1015.49)
B_y/B_0	Proportion	0.38 (0.28 - 0.47)	0.39 (0.29 - 0.47)	0.38 (0.29 - 0.46)	0.40 (0.31 - 0.47)
B_y/B_{MSY}	Proportion	1.59 (1.02 - 2.41)	1.59 (1.11 - 2.26)	1.61 (1.05 - 2.36)	1.66 (1.23 - 2.41)
Pr. $> B_{40\%}$	Prob.	0.43	0.46	0.43	0.51
Pr. $> B_{MSY}$	Prob.	0.92	0.94	0.94	0.96
Pr. $> B_{20\%}$	Prob.	1.00	1.00	1.00	1.00
Pr. $> B_{10\%}$	Prob.	1.00	1.00	1.00	1.00
Pr. Target Quadrant	Prob.	0.43	0.46	0.42	0.49
Pr. Kobe Red	Prob.	0.07	0.05	0.05	0.03
Pr. Kobe Green	Prob.	0.91	0.93	0.92	0.95
Pr. Majuro Red	Prob.	0.00	0.00	0.00	0.00
Pr. Majuro White	Prob.	0.92	0.93	0.94	0.96

Table A5: Diagnostic outputs for evaluation of index-based MPs with a target tuning probability of 70% (see Table A1 for the list of MP definitions and Table A2 for a description of each diagnostic).

Performance Statistic	Units	MP-STABLE-ASY-70%	MP-STABLE-SYM-70%	MP-TARGET-ASY-70%	MP-TARGET-SYM-70%
C_y^{TAC}	10^3 tonnes	512.05 (507.41 - 514.16)	513.78 (506.28 - 513.78)	511.81 (504.91 - 520.50)	503.87 (492.17 - 513.98)
C_{lq}^{TAC}	10^3 tonnes	507.41	506.28	504.91	492.17
C_{2027}^{TAC}	10^3 tonnes	565.74 (565.74 - 565.74)	534.31 (534.31 - 534.31)	565.74 (565.74 - 565.74)	534.31 (534.31 - 534.31)
C	10^3 tonnes	508.17 (501.59 - 511.30)	512.39 (502.65 - 513.52)	507.88 (490.70 - 518.83)	512.47 (497.80 - 520.71)
$C_{[PL]}$	10^3 tonnes	102.56 (100.49 - 107.37)	103.34 (100.97 - 108.09)	102.99 (98.42 - 106.92)	103.52 (100.14 - 107.94)
$C_{[PSLS]}$	10^3 tonnes	134.38 (125.53 - 143.15)	135.20 (126.46 - 143.42)	133.39 (124.55 - 143.27)	135.13 (126.28 - 143.16)
$C_{[PSFS]}$	10^3 tonnes	24.75 (24.13 - 25.42)	24.91 (24.18 - 25.59)	24.76 (23.73 - 25.44)	24.94 (24.00 - 25.61)
$C_y/C_{40\%}$	Proportion	0.96 (0.85 - 1.06)	0.97 (0.86 - 1.07)	0.96 (0.86 - 1.05)	0.96 (0.86 - 1.06)
C_y/C_{MSY}	Proportion	0.87 (0.75 - 0.97)	0.88 (0.75 - 0.98)	0.87 (0.75 - 0.95)	0.88 (0.76 - 0.98)
$C_y^{TAC} \neq C_{y-1}^{TAC}$	Count	3.00 (3.00 - 5.00)	2.00 (2.00 - 4.00)	5.00 (3.00 - 5.00)	4.00 (3.00 - 5.00)
$\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert$	Percent	4.91 (4.71 - 7.44)	4.02 (4.02 - 7.38)	7.67 (4.54 - 10.22)	8.53 (4.67 - 10.96)
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 10\%$	Prob.	0.24	0.25	0.38	0.46
Pr. $\lvert C_y^{TAC}/C_{y-1}^{TAC} - 1\rvert > 5\%$	Prob.	0.50	0.46	0.70	0.63
Pr. $C_y^{TAC}/C_{y-1}^{TAC} - 1$ at upp. limit	Prob.	0.00 (0.00 - 0.00)	0.00 (0.00 - 0.00)	0.00 (0.00 - 0.00)	0.00 (0.00 - 0.00)
Pr. $C_y^{TAC}/C_{y-1}^{TAC} - 1$ at low. limit	Prob.	0.00 (0.00 - 0.00)	0.20 (0.20 - 0.20)	0.00 (0.00 - 0.00)	0.20 (0.20 - 0.20)
$CPUE_{[PL]}$	Rate	0.07 (0.06 - 0.08)	0.07 (0.06 - 0.08)	0.07 (0.06 - 0.08)	0.07 (0.06 - 0.08)
$CPUE_{[PSLS]}$	Rate	17.69 (15.47 - 20.09)	17.73 (15.94 - 20.17)	17.73 (15.74 - 19.93)	17.88 (15.89 - 20.10)
E_y	Rate	0.53 (0.44 - 0.70)	0.52 (0.44 - 0.69)	0.54 (0.45 - 0.69)	0.52 (0.44 - 0.67)
$E_y/E_{40\%}$	Proportion	0.97 (0.72 - 1.41)	0.95 (0.72 - 1.35)	0.98 (0.74 - 1.34)	0.95 (0.73 - 1.34)
E_y/E_{MSY}	Proportion	0.56 (0.34 - 0.90)	0.56 (0.34 - 0.83)	0.56 (0.34 - 0.87)	0.55 (0.35 - 0.83)
B_y	10^3 tonnes	861.77 (662.04 - 1037.19)	883.53 (690.16 - 1045.74)	867.65 (689.95 - 1026.69)	884.25 (696.07 - 1043.21)
B_y/B_0	Proportion	0.39 (0.29 - 0.48)	0.40 (0.31 - 0.48)	0.40 (0.30 - 0.48)	0.40 (0.31 - 0.48)
B_y/B_{MSY}	Proportion	1.64 (1.04 - 2.47)	1.67 (1.15 - 2.48)	1.67 (1.06 - 2.48)	1.68 (1.20 - 2.47)
Pr. $> B_{40\%}$	Prob.	0.48	0.54	0.49	0.54
Pr. $> B_{MSY}$	Prob.	0.93	0.96	0.94	0.96
Pr. $> B_{20\%}$	Prob.	1.00	1.00	1.00	1.00
Pr. $> B_{10\%}$	Prob.	1.00	1.00	1.00	1.00
Pr. Target Quadrant	Prob.	0.47	0.53	0.49	0.54
Pr. Kobe Red	Prob.	0.05	0.03	0.05	0.03
Pr. Kobe Green	Prob.	0.92	0.94	0.93	0.95
Pr. Majuro Red	Prob.	0.00	0.00	0.00	0.00
Pr. Majuro White	Prob.	0.94	0.95	0.94	0.96

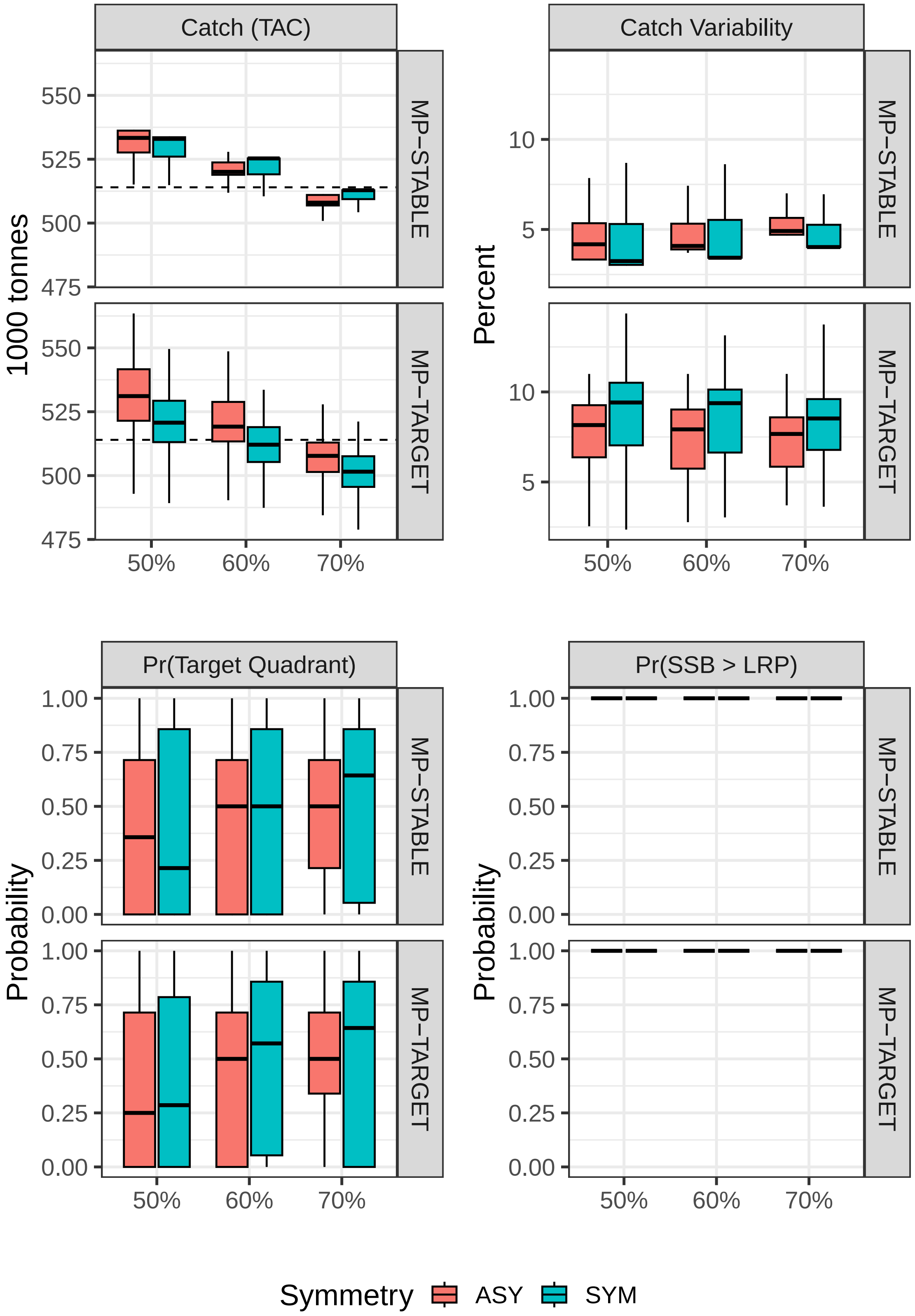
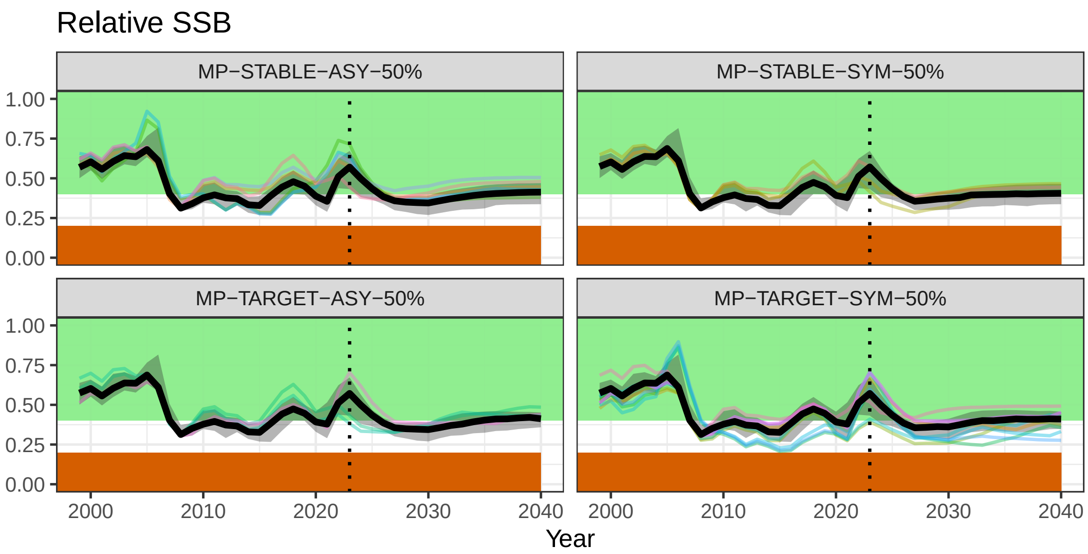
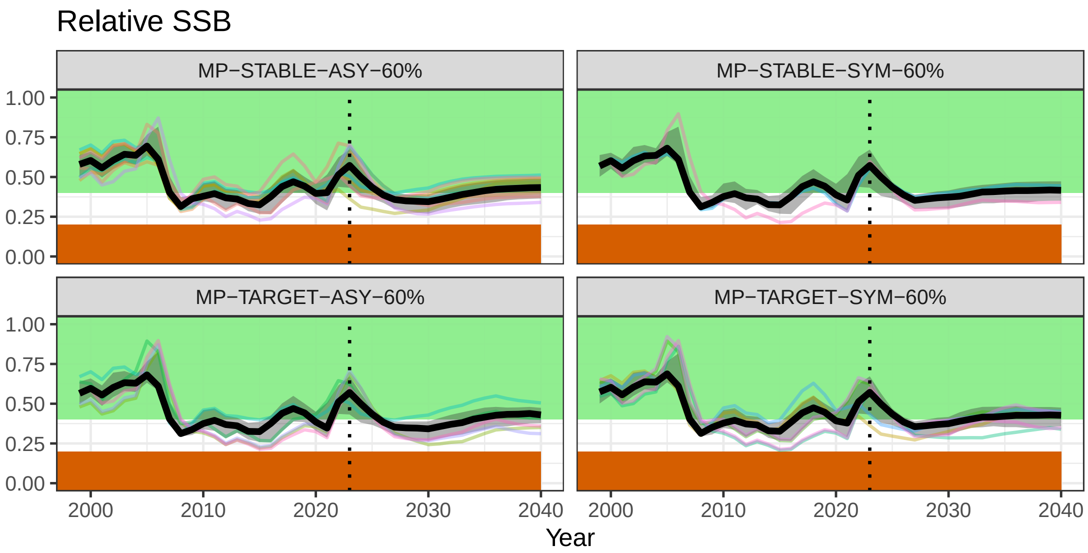


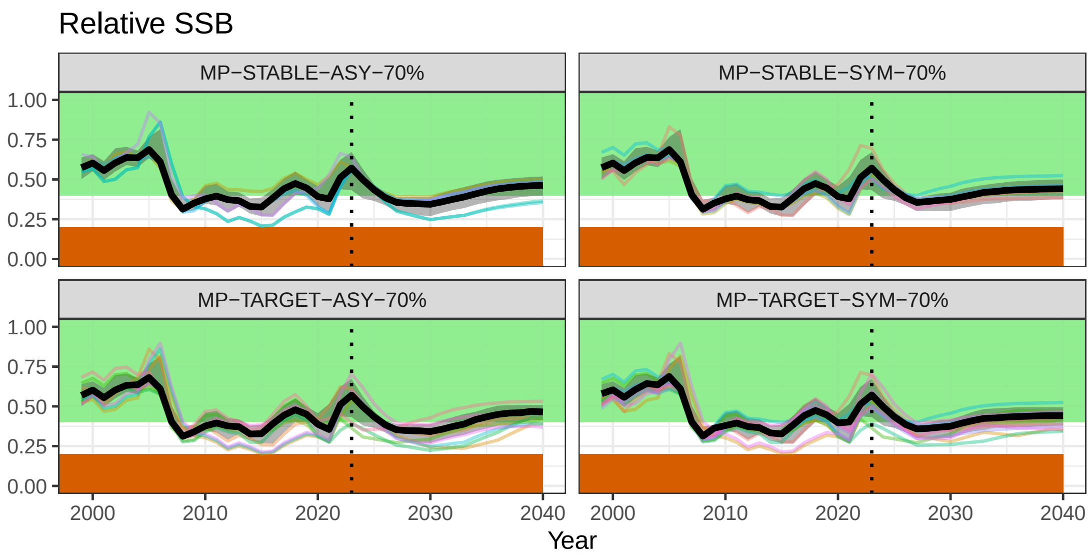
Figure A5: Summary diagnostics calculated over the projection period for MP's listed in Table A1. Boxplots show the median and distribution of values across OMs, projection years and stochastic iterations.



(a) MP's tuned to 50% probability of being in the target quadrant.

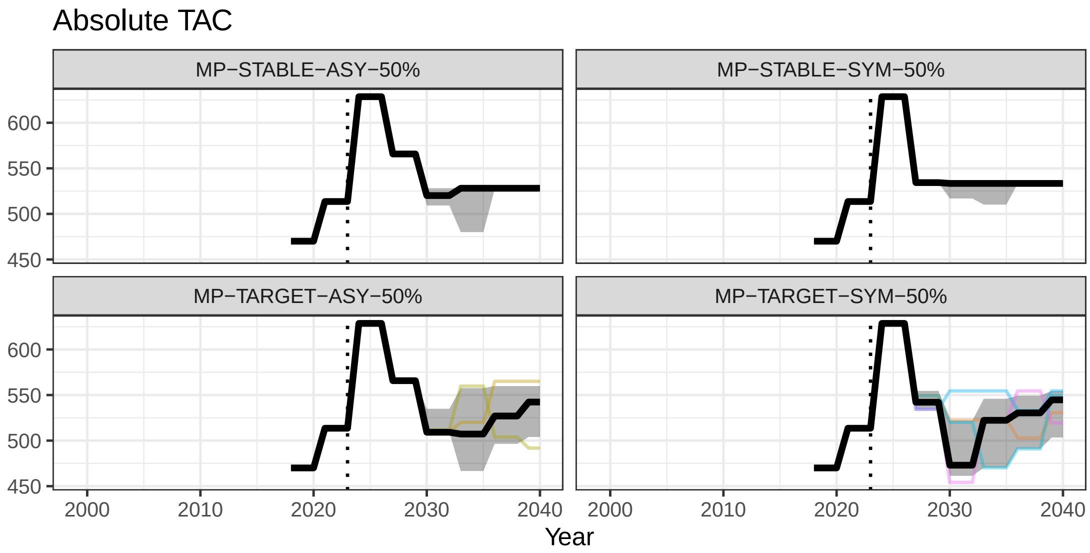


(b) MP's tuned to 60% probability of being in the target quadrant.

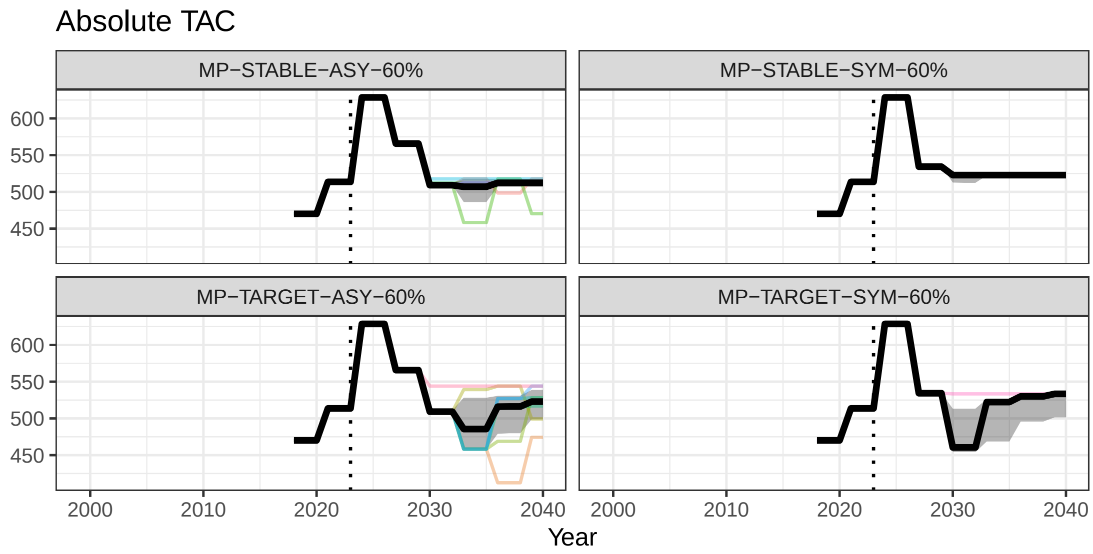


(c) MP's tuned to 70% probability of being in the target quadrant.

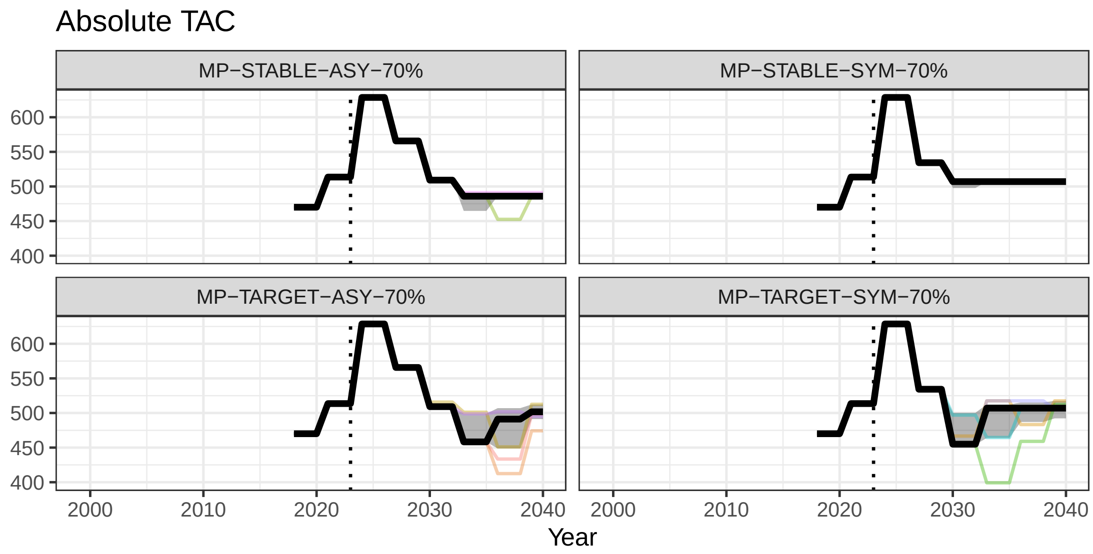
Figure A6: Simulated values of relative SSB (B_y/B_0) over time. Operating model projections are from 2023 onwards (vertical dashed line). The median value across OMs and stochastic iterations is shown as a black line with a sample of individual runs. The distribution of OM runs around the median is shaded grey. Values above the TRP and below the LRP are shaded in green and red respectively.



(a) MP's tuned to 50% probability of being in the target quadrant.

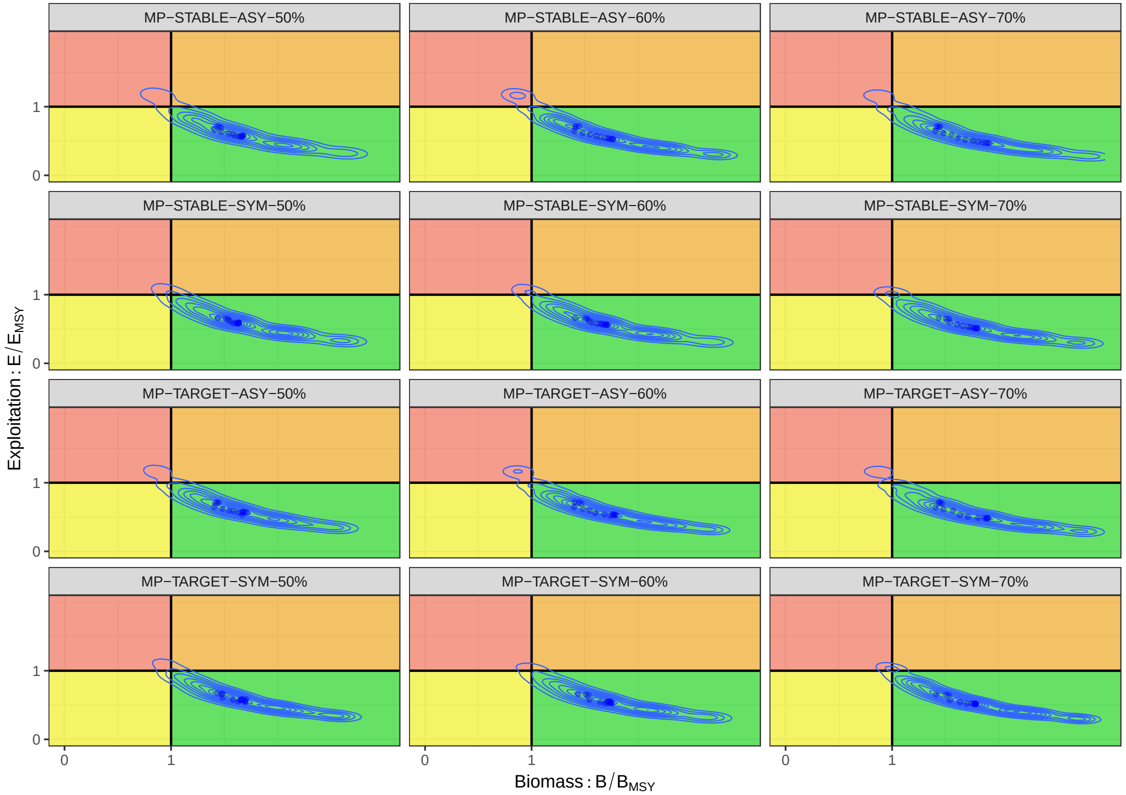


(b) MP's tuned to 60% probability of being in the target quadrant.

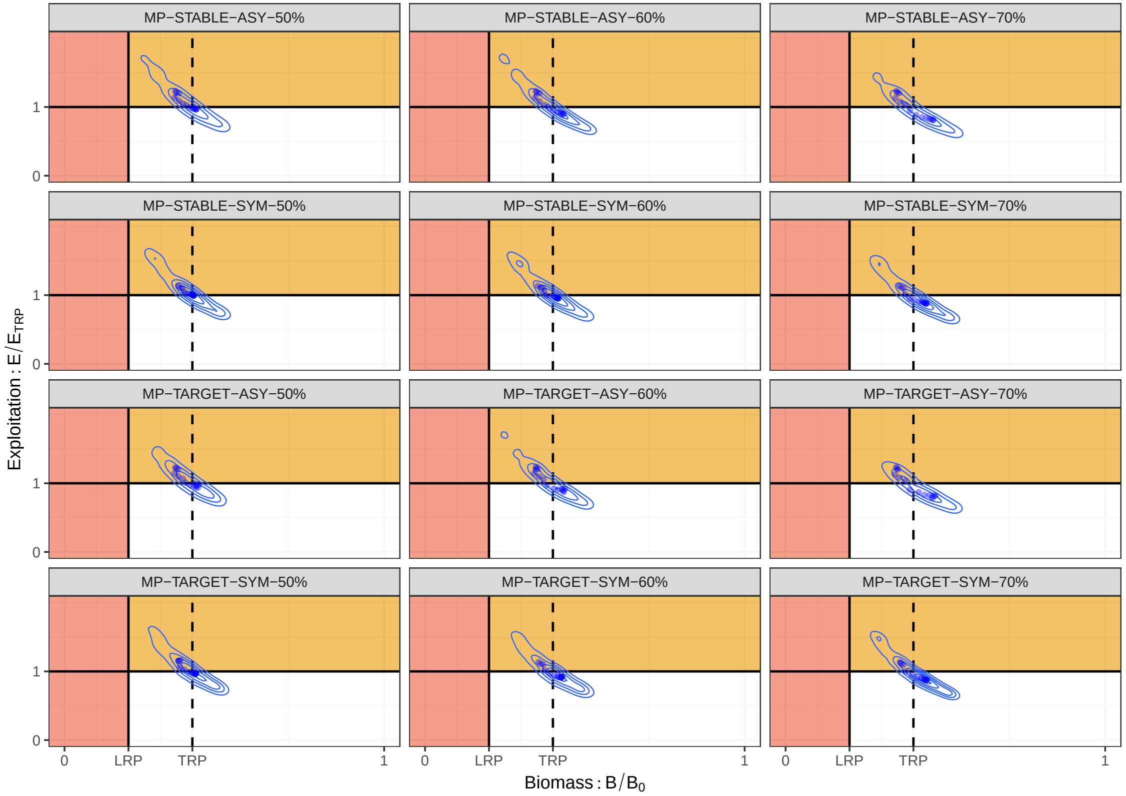


(c) MP's tuned to 70% probability of being in the target quadrant.

Figure A7: Simulated values of the TAC in 1000 tonnes over time. Operating model projections are from 2023 onwards (vertical dashed line). TAC values for 2018 to 2026 are fixed at those listed in Table 1. The MP is used to set the TAC from 2027 at three year intervals. The median value across OMs and stochastic iterations is shown as a black line with a sample of individual runs. The distribution of OM runs around the median is shaded grey.



(a) Kobe phase plots



(b) Majuro phase plots

Figure A8: Kobe phase plots (top panel) and Majuro phase plots (bottom panel) for tuned MPs listed in Table A1. Contours show a two-dimensional histogram of stock status across all years for which the MP was used to set catches (i.e. 2027 to 2040), 36 operating model runs and three stochastic iterations for each run. Blue points show the median values per year for each MP. 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 B_{MSY} and E_{MSY}, whereas the Majuro plot uses Target and Limit Reference Points (TRP and LRP) equal to $B_{40\%}$ and $B_{20\%}$ respectively.

Robustness testing