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ASSESSMENT OF CANDIDATE MANAGEMENT PROCEDURES AND HARVEST CONTROL RULES FOR THE WESTERN ATLANTIC SKIPJACK TUNA

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SUMMARY

This document outlines the proposed updates to the western Atlantic skipjack tuna management strategy evaluation (MSE) process, including revisions to the operating models and candidate management procedures (CMPs). The operating models now incorporate a combined relative abundance index, calculated using inverse-variance weighted averages across the distinct indices available. Both index-based and model-based CMPs include a tuning parameter designed to optimize performance. Additionally, an asymmetrical decision rule has been implemented for both classes of CMPs to enhance management adaptability.

RÉSUMÉ

Le présent document présente les actualisations proposées à apporter au processus d'évaluation de la stratégie de gestion (MSE) pour le listao de l'Atlantique Ouest, y compris les révisions des modèles opérationnels et des procédures de gestion potentielles. Les modèles opérationnels incluent désormais un indice d'abondance relative combiné, calculé en utilisant des moyennes pondérées par l'inverse de leur variance parmi les différents indices disponibles. Les CMP basées sur un indice et les CMP basées sur un modèle incluent un paramètre de calibrage destiné à optimiser leur performance. En outre, une règle de décision asymétrique a été appliquée pour les deux types de CMP afin de renforcer l'adaptabilité de gestion.

RESUMEN

En este documento se describen las actualizaciones propuestas para el proceso de evaluación de la estrategia de ordenación (MSE) del listado del Atlántico occidental, incluidas las revisiones de los modelos operativos y los procedimientos de ordenación candidatos (CMP). Los modelos operativos incorporan ahora un índice combinado de abundancia relativa, calculado con medias ponderadas de varianza inversa de los distintos índices disponibles. Tanto los CMP basados en índices como los basados en modelos incluyen un parámetro de ajuste diseñado para optimizar el rendimiento. Además, se ha implementado una regla de decisión asimétrica para ambas clases de CMP con el fin de mejorar la adaptabilidad de la ordenación.

KEYWORDS

Management procedures; stock assessment; performance metrics; closed-loop simulation; harvest strategy

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1. Introduction

The development of the Management Strategy Evaluation (MSE) framework for Western Atlantic skipjack (W-SKJ) began in 2020, driven by the need for improved science-based management strategies for tropical tuna species in the Atlantic. This initiative was spearheaded by the Tropical Tunas Species Group (TT-SG) of the Standing Committee on Research and Statistics (SCRS) (Huynh *et al*., 2020; Mourato *et al*., 2022a; Mourato *et al*., 2022b; Sant'Ana *et al*., 2023).

The initial steps in the development of the W-SKJ MSE involved building a conceptual framework for evaluating different management strategies. In 2022, ICCAT formally adopted conceptual management objectives for W-SKJ through Resolution 22-02, which laid the foundation for the operationalization of the MSE framework (ICCAT Res. 22-02, 2022). These objectives were designed to ensure the long-term sustainability of the W-SKJ stock while balancing the needs of the fisheries that depend on it.

One of the key components of the MSE framework is the development of Operating Models (OMs), which simulate the biological and fisheries dynamics of the W-SKJ stock under various scenarios of uncertainty. The W-SKJ MSE OMs were initially developed based on the results of the most recent stock assessment (see Cardoso *et al*., 2022), which consolidated nine scenarios to represent a wide range of possible outcomes (Mourato *et al*., 2022b; Sant'Ana *et al*., 2023). Over the course of 2023 and 2024, significant updates were made to these OMs, including the incorporation of a combined relative abundance index weighted by the inverse of the variance of the four indices used in the last stock evaluation (Sant'Ana & Mourato, 2024).

In addition to reconditioning the OMs, the MSE technical team worked on tuning the Candidate Management Procedures (CMPs). These procedures include both abundance index-based and model-based approaches, with a key innovation being the introduction of a tuning parameter. This parameter allows for the optimization of fishing yields while adhering to specified stock limits. The team also developed an empirical rule to regulate changes in Total Allowable Catch (TAC) over time, enabling symmetrical or asymmetrical adjustments depending on stock trends (Sant'Ana & Mourato, 2024).

In May 2023, the Panel 1 intersessional meeting marked a critical milestone, as ICCAT began the process of operationalizing the management objectives. By consulting with key stakeholders and receiving input from the Tropical Tunas MSE Sub-Group, the technical team refined the CMPs to better align with the new OMs. The goal is to identify CMPs that are resilient to the uncertainties inherent in stock assessments and that can sustainably manage the fishery over the long term.

Looking ahead, the SCRS is expected to provide a final set of CMPs to the Commission in late 2024. This will be the culmination of several years of work, incorporating the latest scientific knowledge and stock assessment data, and will represent a significant step toward implementing a fully operational MSE framework for the W-SKJ fishery. The adoption of these CMPs will provide a pathway for sustainable management that balances conservation objectives with the economic realities of the fishery, ensuring the long-term viability of both the stock and the communities dependent on it.

The purpose of this document is to present the updates, including the reconditioning of OMs, the tuning of CMPs, and a comprehensive evaluation of the performance metrics for the tuned CMPs, taking into account the newly available OMs.

2. Material and Methods

2.1 Reconditioning the operating models

In the 2022 ICCAT stock assessment for Atlantic skipjack, the management advice was derived using the Stock Synthesis model (Cardoso *et al*., 2022). This assessment outlined several scenarios, including an uncertainty grid that accounted for variations in growth patterns and steepness, resulting in a total of nine models. For the current analysis, we utilized the 27 OMs (Operating Models) from the previous study (Mourato *et al*., 2022b and Sant'Ana *et al*., 2023; see **Table 1** for details), expanding on this by adding nine OMs (1-9) with perfect TAC (Total Allowable Catch) implementation, nine OMs (10-18) with a 10% overage error in TAC implementation, and nine OMs (19-27) with a 20% overage error. Additionally, other components were incorporated into the conditioning of the OMs through the SS2OM R function (see openMSE vignettes at https://openmse.com/features-importing-ss3/2-om/). This included the manual input of observed data used in the assessment, such as catch, abundance indices, and size data into the relevant data slots. A comparison between the outputs from Stock Synthesis assessment models and openMSE approach for OMs conditioning are shown in **Figures 1**, **2**, **3** and **4**.

2.2 Performance metrics

In line with the recommendations of the MSE Tropical Tunas Technical Sub-group and the adopted conceptual management objectives focused on safety, stock status, yield, and stability criteria (Res. 22-02), this analysis incorporated 20 performance metrics (PMs) (see **Table 2** for details).

2.3 Development of the candidate management procedures

We utilized a subset of CMPs from the previous analysis (see Mourato *et al*., 2022b, and Sant'Ana *et al*., 2023 for details), which were based on both index-based and assessment model-based harvest control rules (HCRs), as follows:

- FMSYref: A reference method which the TAC is calculated assuming perfect knowledge of F_{MSY}, derived directly from the operating model with a target fishing at 100% of F_{MSY}.
- FMSYref75: A reference method which the TAC is calculated assuming perfect knowledge of F_{MSY}, derived directly from the operating model with a target fishing at 75% of F_{MSY}.
- FMSY110: A reference method which the TAC is calculated assuming perfect knowledge of F_{MSY}, derived directly from the operating model with a target fishing at 110% of F_{MSY}.
- IR_01 – The TAC is adjusted using the ratio between the average index from the most recent two years (numerator) and the average index from the three preceding years (denominator) in the time series. Additionally, the TAC is adjusted asymmetrically, with up to a 20% increase if the stock trend is rising, or up to a 25% decrease if the stock trend is declining, as indicated by this ratio.
- IR_02 – The TAC is adjusted using the ratio between the average index from the most recent two years (numerator) and the average index from the three preceding years (denominator) in the time series. Additionally, the TAC is adjusted symmetrically, with up to a 20% increase or decrease, based on the stock trend (as indicated by this ratio).
- IR_03 – The TAC is adjusted using the ratio between the average index from the most recent two years (numerator) and the average index from the three preceding years (denominator) in the time series, without correction or additional adjustment for the TAC based on the stock trend, as indicated to the IR_01 and IR_02.
- CE_01 – A constant exploitation rate aiming to keep the exploitation rate constant over time by considering the recent historical level. Additionally, the TAC is adjusted asymmetrically, with up to a 20% increase if the exploitation rate trend is rising, or up to a 25% decrease if the exploitation rate trend is declining.
- CE_02 - A constant exploitation rate aiming to keep the exploitation rate constant over time by considering the recent historical level. Additionally, the TAC is adjusted symmetrically, with up to a 20% increase or decrease, based on the exploitation rate trend.
- CE_03 - A constant exploitation rate aiming to keep the exploitation rate constant over time by considering the recent historical level, without correction or additional adjustment for the TAC based on the exploitation rate trend, as indicated to the CE_01 and CE_02.

For the model-based CMPs, following the guidance from the MSE Tropical Tunas Technical Sub-group, the Target Biomass (B_{target}) was set at SB_{MSY}, with the Limit Biomass (B_{lim}) defined as 40% of SB_{MSY}. **Figure 5** illustrates the Harvest Control Rules (HCRs) used in the MSE simulations. In the green area, stock levels are equal to or above B_{target}, where fishing mortality is set at either 100% or 80% of the relative fishing mortality at MSY. When stock size falls between B_{lim} and B_{target}, fishing mortality decreases proportionally with stock depletion or spawning biomass relative to MSY. However, if stock levels drop below B_{lim} (indicating stock collapse), fishing mortality is reduced to 10% of the relative MSY level. Based on this HCR, the following model-based CMPs were implemented in the MSE simulations:

- SP_01 - A surplus production model with an 100-40 control rule based on spawning biomass at MSY level with associated maximum F at 80% and minimum F at 10% of F_{MSY} with fixed TAC for the 2021 and 2022, based on the task 1 data.
- SP_02 - A state-space surplus production model with an 100-40 control rule based on spawning biomass at MSY level with associated maximum F at 80% and minimum F at 10% of F_{MSY} with fixed TAC for the 2021 and 2022, based on the task 1 data.
- SP_03 - A surplus production model with an 100-40 control rule based on spawning biomass at MSY level with associated maximum F at 100% and minimum F at 10% of F_{MSY} with fixed TAC for the 2021 and 2022, based on the task 1 data.

– SP_04 - A state-space surplus production model with an 100-40 control rule based on spawning biomass at MSY level with associated maximum F at 100% and minimum F at 10% of F_{MSY} with fixed TAC for the 2021 and 2022, based on the task 1 data.

For CMPs based on surplus production models, the parameterization allowed the model to determine the optimal B_{MSY}/K ratio. The stock was assumed to be in an unfished state for initial depletion, i.e., close to 1. The initial intrinsic growth rate parameter (r) was set using a lognormal distribution with a mean of 0.416 and a standard deviation of 0.148, consistent with the most recent assessment (Sant'Ana *et al*., 2022). Additionally, for state-space models, the process and observation errors were freely estimated by the model (see the SAMtool package for details). It is important to note that for CMPs utilizing abundance indices as input (e.g., IRs or SPs), a combined index was used, based on the inverse variance weighed average, as shown in **Figure 6**. Finally, we explored a tuning parameter as a relative multiplier that could, for instance, adjust the current fishing mortality rate to bring it closer to or farther from the reference level (F_{MSY}) for model-based MPs, or adjust the exploitation rate for empirical index-based management procedures. **Figure 7** illustrates how this process was carried out, optimizing to determine the best tuning parameters.

2.4 MSE settings

The projection period for this closed-loop MSE simulation was 30 years, with 300 replicates. The management period and CMPs implementation were set at 3-year intervals. Selectivity was based on the F-at-age in the terminal year of the historical period (e.g., 2020). A coefficient of variation of 0.4 and autocorrelation derived from the operating model conditioning were used to define the model's error structure. The stock-recruitment relationship followed the Beverton-Holt model, with the *SigmaR* parameter set to 0.4 across all OMs. Parameters governing the probability of individuals remaining in each stock ("*prob_staying*," "*Size_area_1*," and "*Frac_area_1*") were set at 0.5, approximating a single-area model while allowing some degree of exchange (migration) between western and eastern stocks. Observation model parameters were configured according to the "*Precise_unbiased*" model available in the OpenMSE R package.

2.5 Robustness tests

Robustness tests were conducted by considering two sets of OMs (**Table 1**) that account for possible scenarios involving a lack of catch control, such as unreported catches or illegal fishing. These tests included:

– Nine OMs (10-18) assuming a 10% overage error in TAC implementations.
– Nine OMs (19-27) assuming a 20% overage error in TAC implementations.

3. Results and Discussion

All MSE simulations converged successfully, with sufficient iterations to stabilize each selected CMP within the model. **Table 3** presents the median statistics of PMs across the adopted conceptual management objectives, which are based on safety, status, yield, and stability criteria, including for the reference set of OMs (OMs 1-9). Violin plots display the statistics and value distributions for each PM across these management objectives (**Figures 8-18**).

Figure 8 illustrates the statistics for the assessment model-based CMPs in relation to status (PGKs), where all CMPs achieved probabilities above 70% (or very close) across all time windows for the projection period (**Table 3**). For CMPs based on F_{MSY}, only "FMSYref75" satisfied the criteria established for the PGKs PMs (**Figure 9; Table 3**). The index-based CMPs also resulted in probabilities exceeding the 70% threshold for the status management objectives, except for PGK_{long}, where the probability was 69% for the IRs CMPs (**Figure 9; Table 3**). Similarly, for the constant exploitation rate CMPs ("CE_01", "CE_02", and "CE_03"), the established criteria were met, though PGK_{long} fell short at 69%, similar to the index-based CMPs (**Figure 10; Table 3**).

For the safety management objective, which requires that the probability of the stock falling below B_{LIM} (0.4 * B_{MSY}) should not exceed 10% at any point during the 30-year projection period, all CMPs met this criterion, with a few exceptions observed for the $nLRP_{long}$ in the index-based and surplus production model CMPs. However, the probabilities in these cases were still very close to the threshold value (**Figures 11-13; Table 3**). Regarding the maximization of yield (AvC PMs), simulations indicated that all CMPs resulted in catches around 20,000 t, with a slight decrease in AvC_{long} compared to the early part of the projection period. This decline was more pronounced in the surplus production model CMPs (**Figures 14-16; Table 3**). For the stability criterion, which mandates that changes in TAC between management periods should not exceed 20%, only the state-space surplus production models ("SP_02" and "SP_04") and the constant exploitation rate CMPs did not meet this requirement, as they exhibited TAC variations greater than 20% (**Figure 17; Table 3**).

Projections of fishing mortality and biomass, both relative to MSY levels, as well as TAC projections, were generated using the nine-reference case OMs for all CMPs and are presented in **Figure 18**. For the constant exploitation rate CMPs ("CE_01", "CE_02", and "CE_03"), the biomass trajectories show a slight upward trend during the early projection period (first 12 years), remaining above the B_{MSY} level. This is followed by a stable trend that continues until the end of the projection time series. Similar patterns were observed for the index-based CMPs ("IR_01", "IR_02", and "IR_03") (**Figure 18**). For the assessment model-based CMPs ("SP_01", "SP_02", "SP_03", and "SP_04"), the biomass trajectories remain stable during the early projection period (first 12 years), staying above the BMSY level. This is followed by a slight upward trend that persists until the end of the projection period, with the state-space surplus production models ("SP_02" and "SP_04") showing a more pronounced increase (**Figure 18**).

The fishing mortality trajectories remained relatively stable throughout the projection period for all CMPs, with the exception of the state-space surplus production models ("SP_02" and "SP_04"), which exhibited a declining trend (**Figure 18**). This decline can be partially attributed to the fishing mortality ramp in the HCRs, which adjusts based on stock size. With regard to the projected TAC levels, the index-based CMPs ("IR_01", "IR_02", and "IR_03") and the constant exploitation rate CMPs ("CE_01", "CE_02", and "CE_03") displayed a very stable trend throughout the projection period. In contrast, the assessment model-based CMPs ("SP_01", "SP_02", "SP_03", and "SP_04") showed a declining trend, with the state-space surplus production models ("SP_02" and "SP_04") exhibiting a more pronounced decline (**Figure 18**).

The proportion of years in each Kobe quadrant is shown in **Figure 19**. Most CMPs resulted in a higher proportion of time spent in the green quadrant, indicating favorable stock status. Notably, the state-space surplus production model CMPs ("SP_02" and "SP_04") produced more optimistic outcomes, with a large portion of the simulations falling within the green quadrant, indicating better stock status over projection period (**Figure 19**).

The results of the robustness tests indicated that assuming an overage error in TAC implementations led to generally worse performance metrics related to stock status, safety, and stability, with the OMs reflecting a 20% error showing even worse outcomes compared to those with a 10% overage in TACs (**Figures 20. 21 and 22**).

4. Acknowledgements

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Table 1. Operating model scenarios for the management strategy evaluation of the western Atlantic Skipjack stock.

Operating model	*Growth vector*	*Steepness*	*SigmaR*	*Scenario*
OM 1	25th	0.6	0.4	Perfect TAC implementation
OM 2	50th			
OM 3	75th			
OM 4	25th	0.7		
OM 5	50th			
OM 6	75th			
OM 7	25th	0.8		
OM 8	50th			
OM 9	75th			
OM 10	25th	0.6		10% overage TAC error implementation
OM 11	50th			
OM 12	75th			
OM 13	25th	0.7		
OM 14	50th			
OM 15	75th			
OM 16	25th	0.8		
OM 17	50th			
OM 18	75th			
OM 19	25th	0.6		20% overage TAC error implementation
OM 20	50th			
OM 21	75th			
OM 22	25th	0.7		
OM 23	50th			
OM 24	75th			
OM 25	25th	0.8		
OM 26	50th			
OM 27	75th			

Table 2. List of performance metrics considered in the close-loop MSE simulation for the management strategy evaluation of the western Atlantic Skipjack stock.

Management Objectives (Res. 22-02)	*Proposed Corresponding Performance Metric Statistics*
Status The stock should have a 70% or greater probability of occurring in the green quadrant of the Kobe matrix using a 30-year projection period as determined by the SCRS.	PGK_{short}: Probability of being in the Kobe green quadrant (i.e., $SSB \geq SSB_{MSY}$ and $F<F_{MSY}$) in year 1-3. PGK_{medium}: Probability of being in the Kobe green quadrant (i.e., $SSB \geq SSB_{MSY}$ and $F<F_{MSY}$) in year 4-10 PGK_{long}: Probability of being in the Kobe green quadrant (i.e., $SSB \geq SSB_{MSY}$ and $F<F_{MSY}$) over years 11-30 *PGK*: Probability of being in the Kobe green quadrant (i.e., $SSB \geq SSB_{MSY}$ and $F<F_{MSY}$) over years 1-30 *POF*: Probability of $F>F_{MSY}$ over years 1-30 *PNOF*: Probability of $F<F_{MSY}$ over years 1-30
Safety There should be no greater than 10% probability of the stock falling below B_{LIM} ($0.4*B_{MSY}$) at any point during the 30-year projection period.	LRP_{short}: Probability of breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 1-3 LRP_{medium}: Probability of breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 4-10 LRP_{long}: Probability of breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 11-30 *LRP*: Probability of breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 1-30 $nLRP_{short}$: Probability of not breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 1-3 $nLRP_{medium}$: Probability of not breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 4-10 $nLRP_{long}$: Probability of not breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 11-30 *nLRP*: Probability of not breaching the limit reference point (i.e., $SSB<0.4*SSB_{MSY}$) over years 1-30
Yield Maximize overall catch levels in the short (1-3 years), medium (4-10 years) and long (11-30 years) terms.	AvC_{short} – Median catches (t) over years 1-3 AvC_{medium} – Median catches (t) over years 4-10 AvC_{long} – Median catches (t) over years 11-30
Stability Any changes in TAC between management periods should be 20 20% or less.	$VarC_{medium}$ – Variation in TAC (%) between management cycles over year 4-10 $VarC_{long}$ – Variation in TAC (%) between management cycles over years 11-30 Var_{all} – Variation in TAC (%) between management cycles over years 1-30

Table 3. Performance metrics for each MP showing the averaged statistics across the reference set of OMs with perfect TAC implementation (OMs 1-9).

MP	AvC_short	AvC_med	AvC_long	PGK_short	PGK_med	PGK_long	PGK	PNOF	nLRP_short	nLRP_med	nLRP_long	nLRP	VarCmedium	VarClong	VarC
IR_01	20581	21096	20065	0.71	0.72	0.69	0.70	0.77	1.00	0.96	0.88	0.91	0.01	0.00	0.00
IR_02	20581	21096	20065	0.71	0.72	0.69	0.70	0.77	1.00	0.96	0.88	0.91	0.01	0.00	0.00
IR_03	20581	21106	20061	0.71	0.72	0.69	0.70	0.77	1.00	0.96	0.88	0.91	0.01	0.00	0.00
CE_01	20677	20609	20324	0.71	0.72	0.69	0.70	0.80	1.00	0.96	0.92	0.94	0.22	0.31	0.25
CE_02	20677	20712	20641	0.71	0.72	0.67	0.69	0.79	1.00	0.96	0.91	0.93	0.21	0.29	0.23
CE_03	20677	21571	20189	0.71	0.68	0.64	0.66	0.77	1.00	0.95	0.90	0.92	0.34	0.53	0.37
SP_01	21616	22142	19716	0.70	0.68	0.71	0.70	0.78	1.00	0.94	0.89	0.92	0.04	0.02	0.02
SP_02	21395	17649	15658	0.68	0.75	0.87	0.82	0.90	1.00	0.96	0.96	0.97	0.31	0.26	0.28
SP_03	21616	22142	19716	0.70	0.68	0.71	0.70	0.78	1.00	0.94	0.89	0.92	0.04	0.02	0.02
SP_04	21395	17695	15771	0.68	0.75	0.86	0.82	0.89	1.00	0.96	0.96	0.97	0.31	0.26	0.28

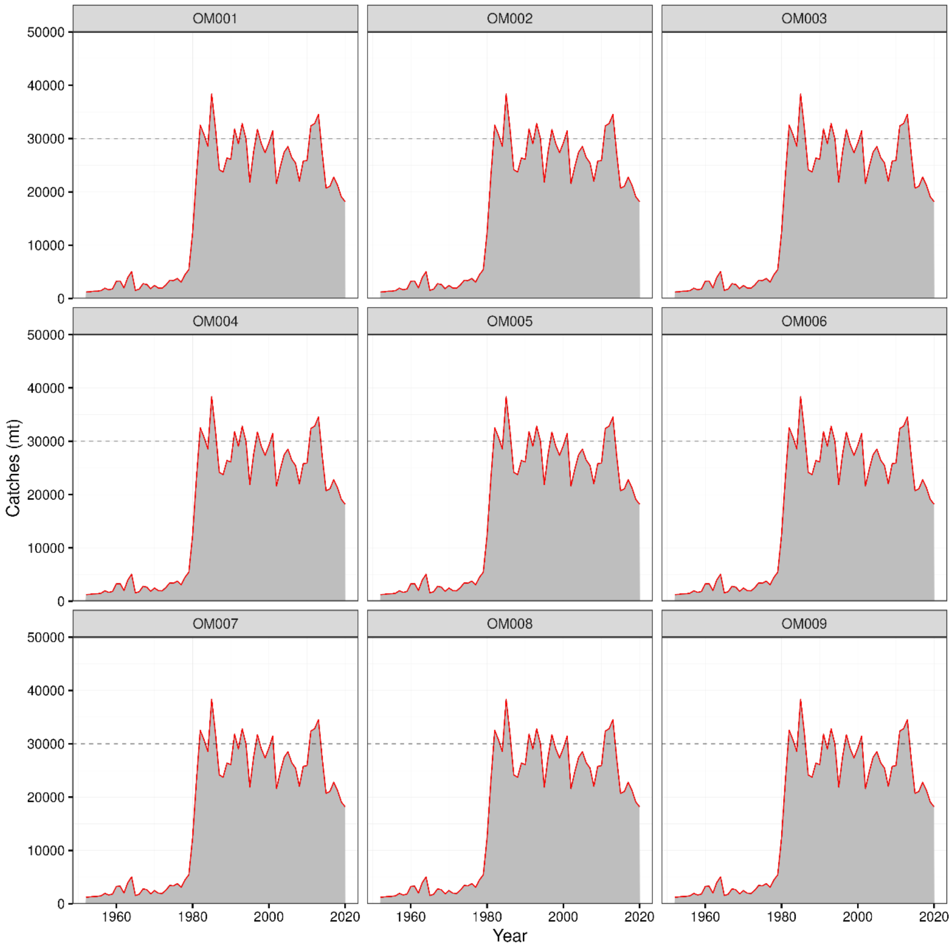

Figure 1. Catch time series comparison in the operating model conditioning scenarios for the management strategy evaluation of the western Atlantic Skipjack stock.

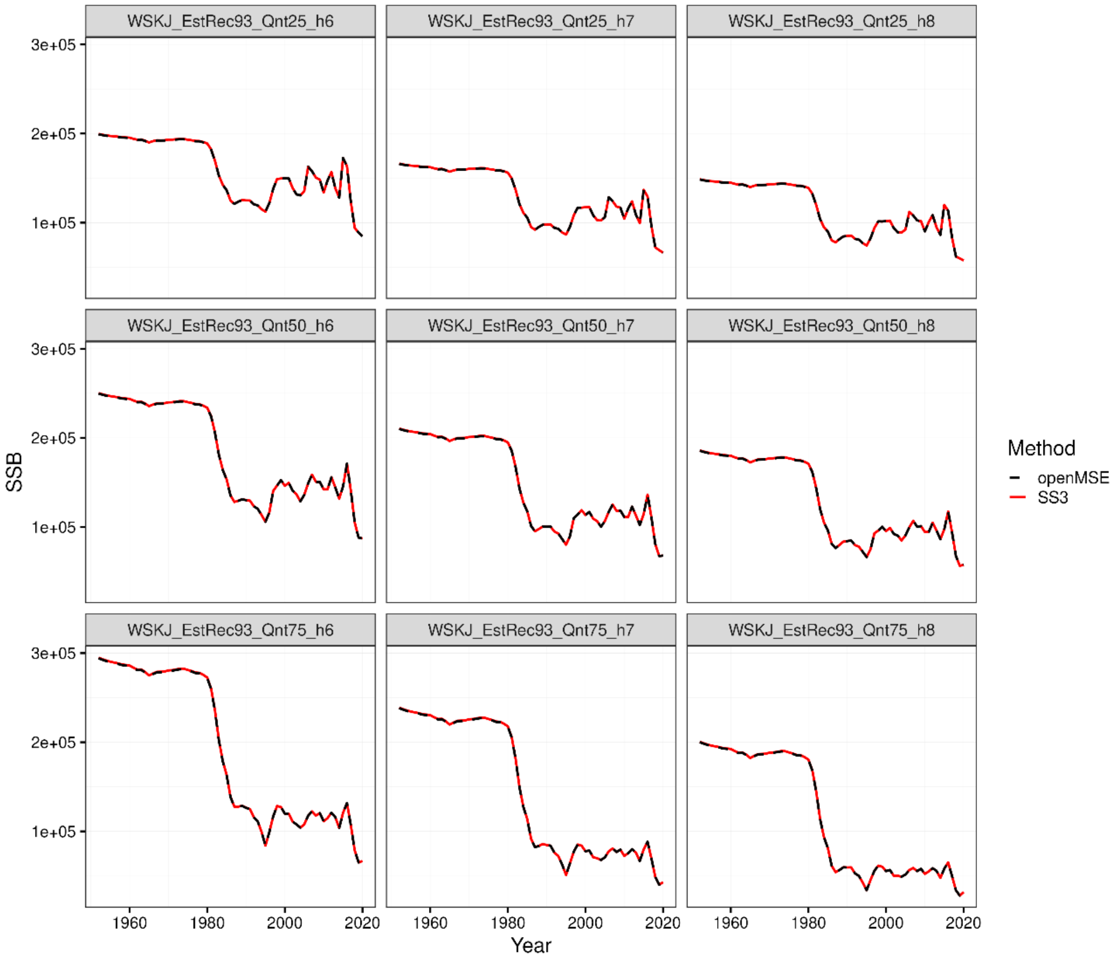

Figure 2. Spawning biomass time series comparison in the operating model conditioning scenarios for the management strategy evaluation of the western Atlantic Skipjack stock.

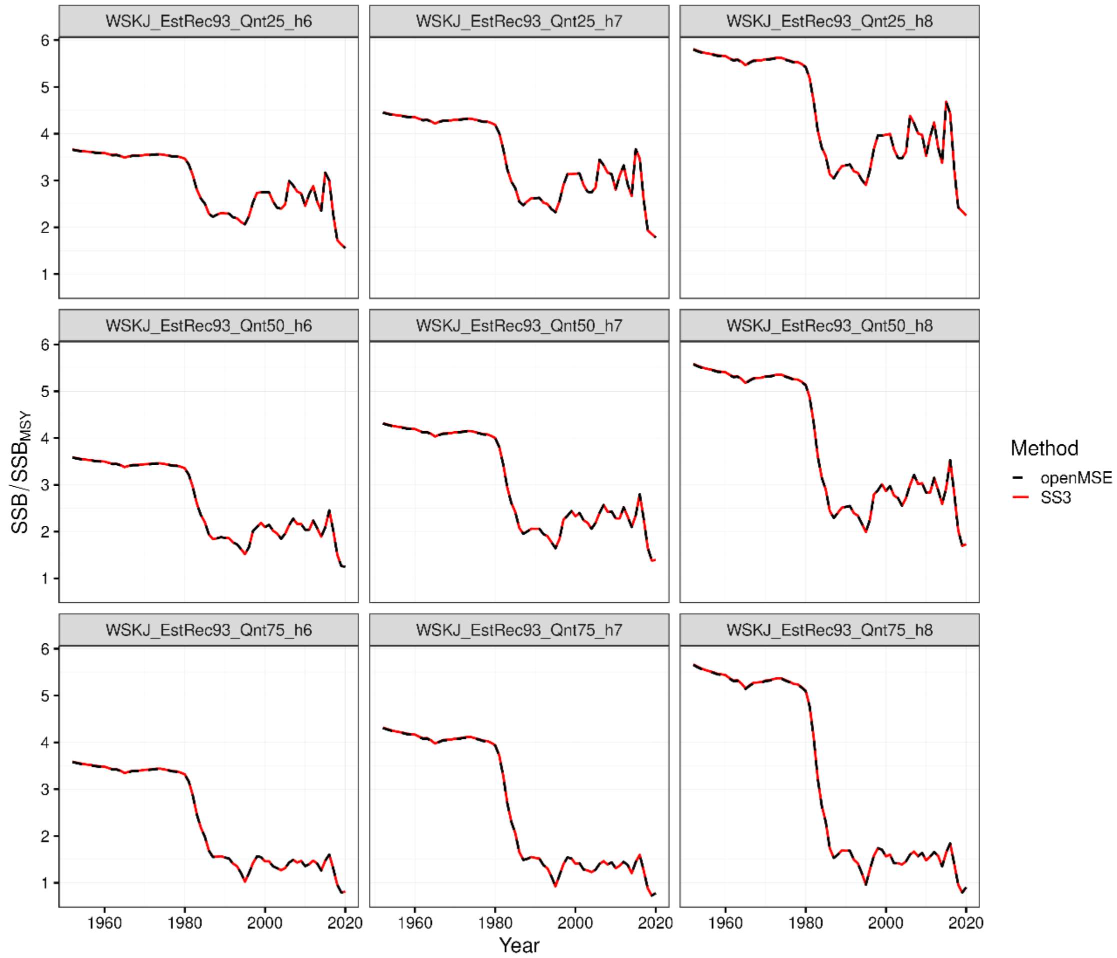

Figure 3. Spawning biomass relative to the MSY time series comparison in the operating model conditioning scenarios for the management strategy evaluation of the western Atlantic Skipjack stock.

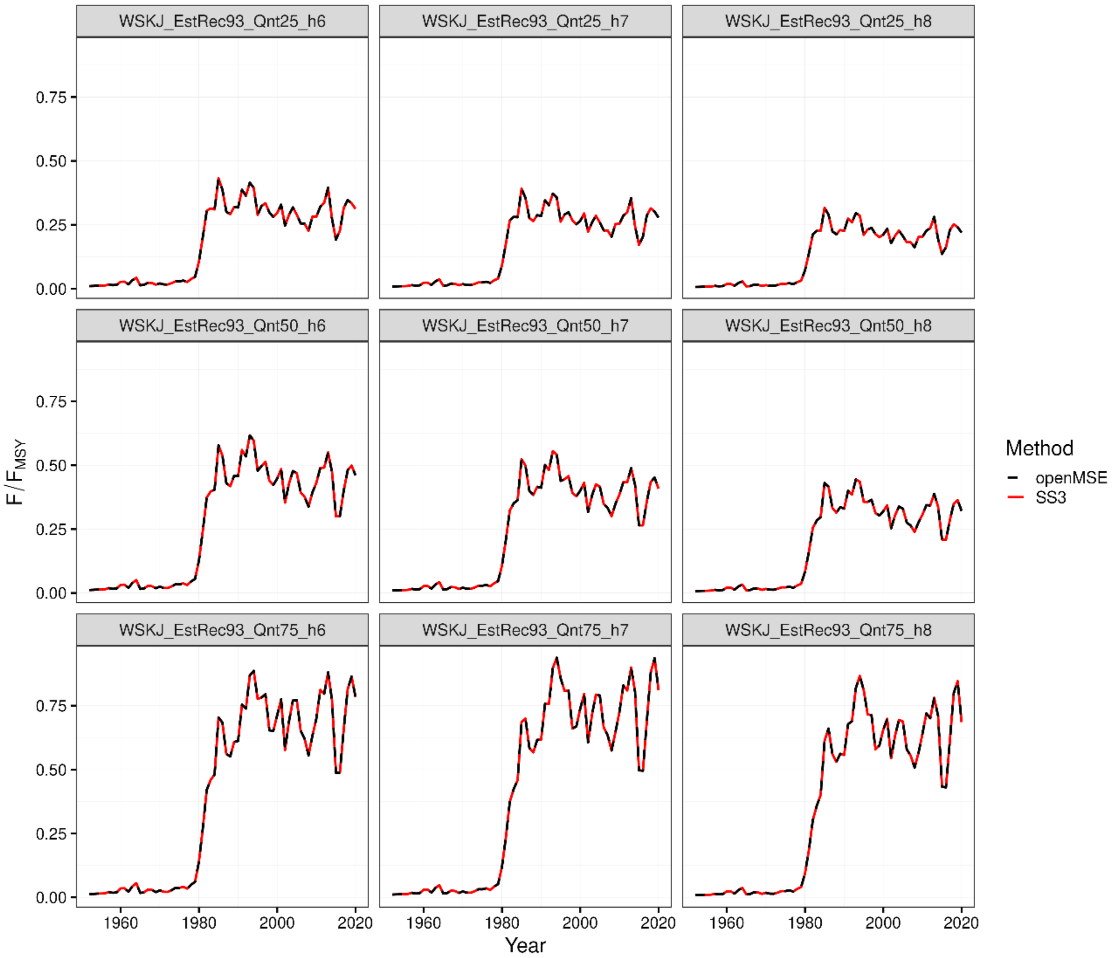

Figure 4. Fishing mortality relative to the MSY time series comparison in the operating model conditioning scenarios for the management strategy evaluation of the western Atlantic Skipjack stock.

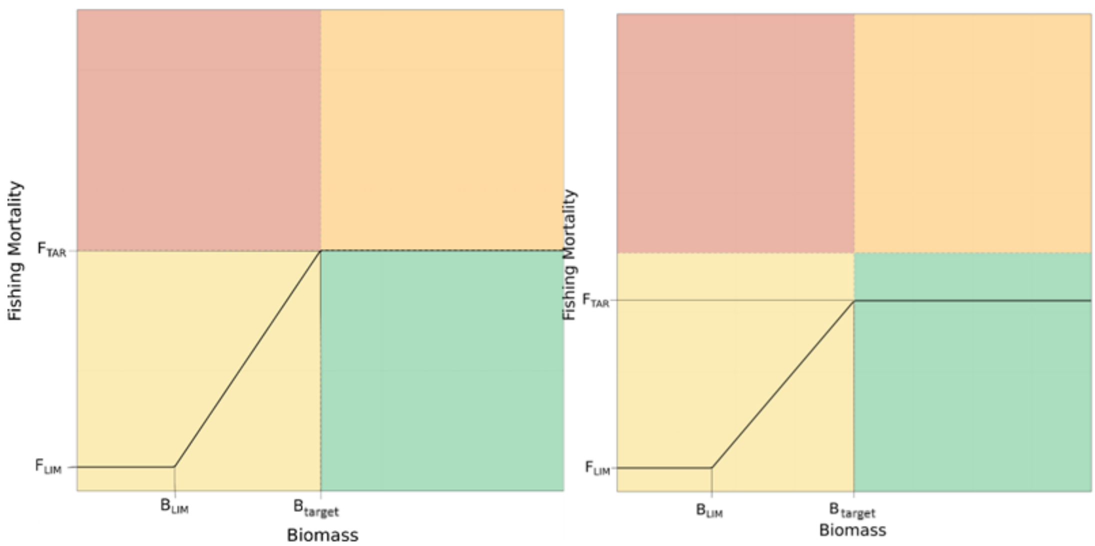

Figure 5. Harvest control rule (HCR) that will be applied in the MSE simulations for the assessment model-based CMPs.

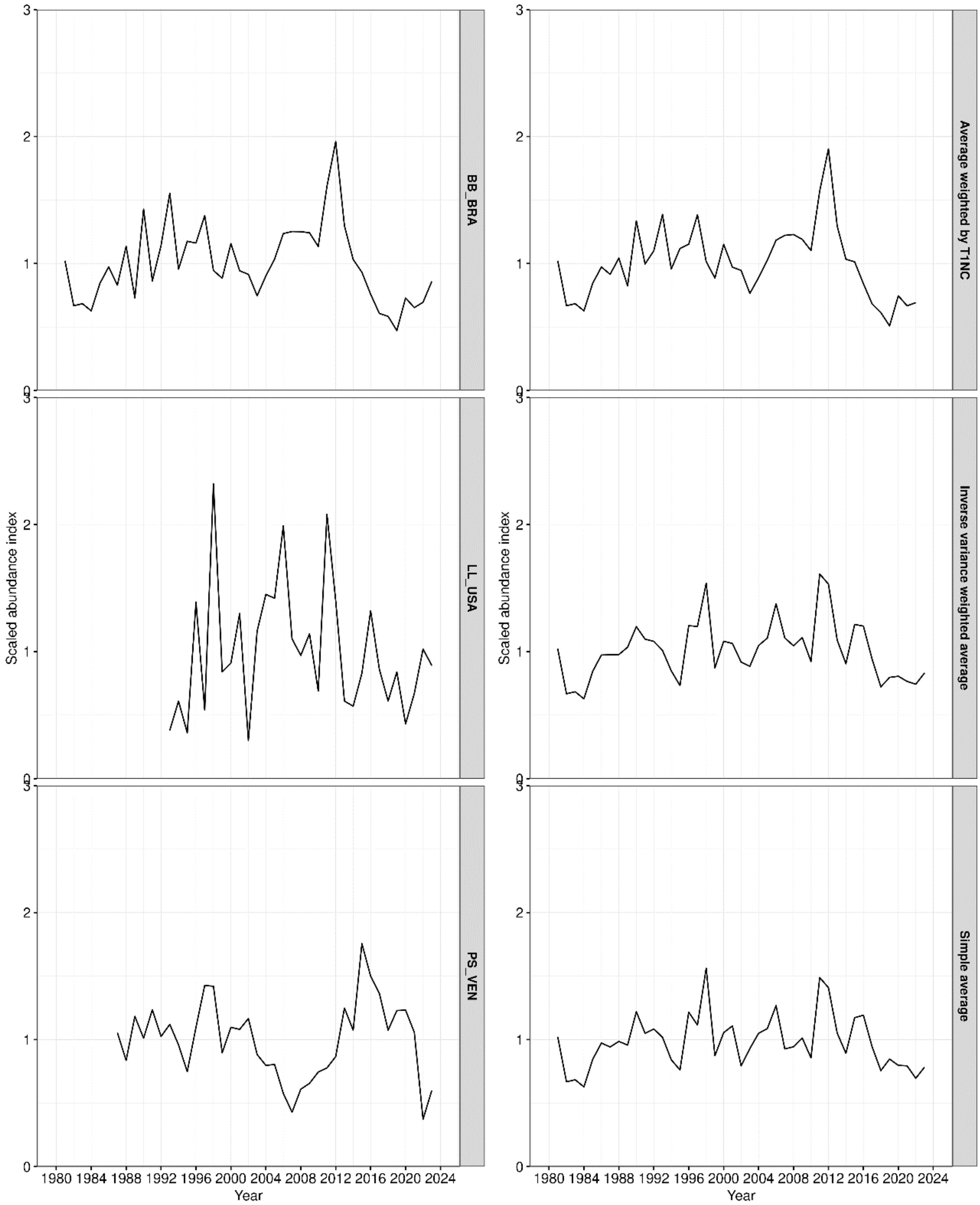

Figure 6. Combined CPUE approach for the management strategy evaluation of the western Atlantic Skipjack stock.

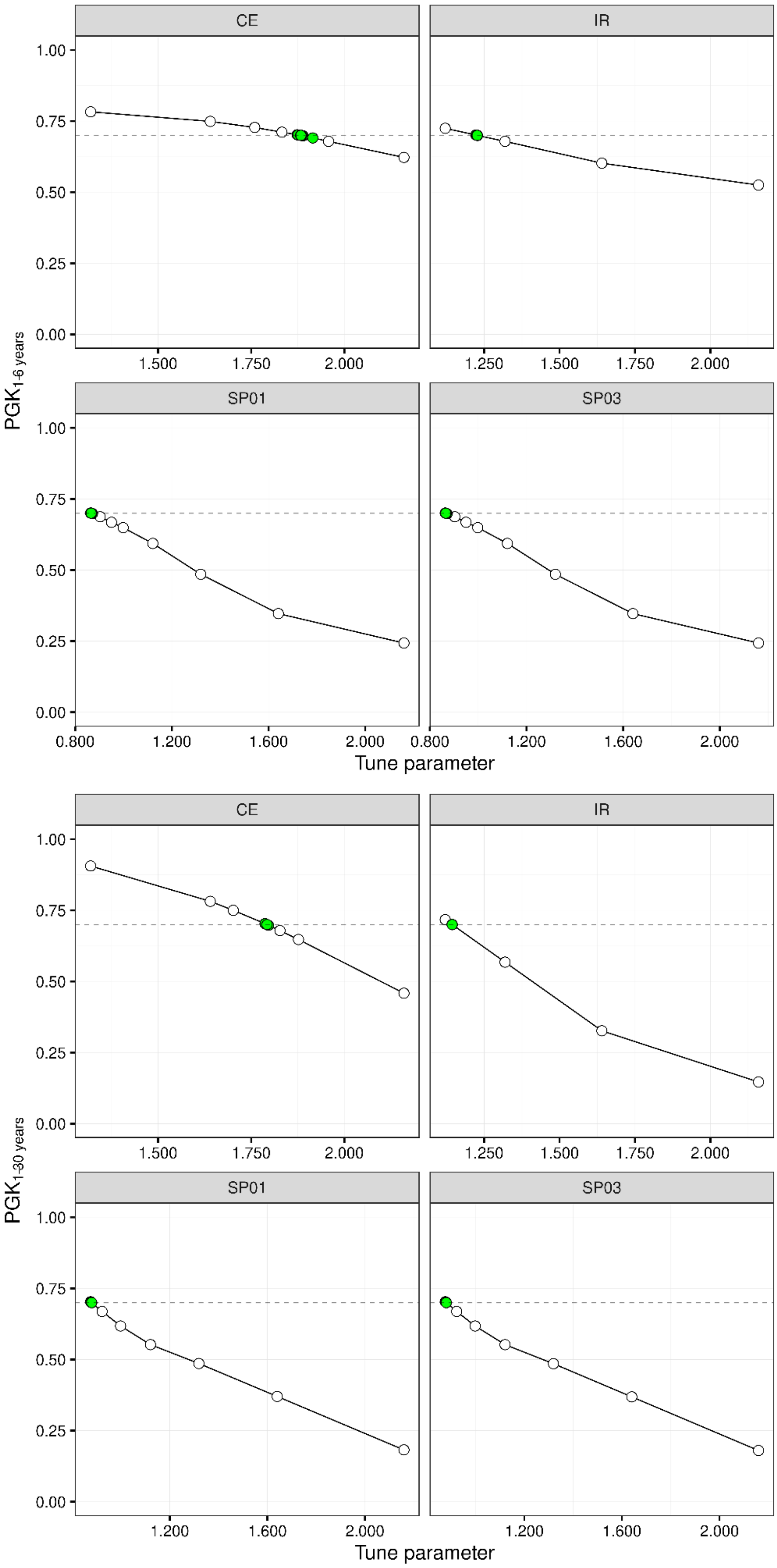

Figure 7. Tuning parameter profile for the management strategy evaluation of the western Atlantic Skipjack stock.

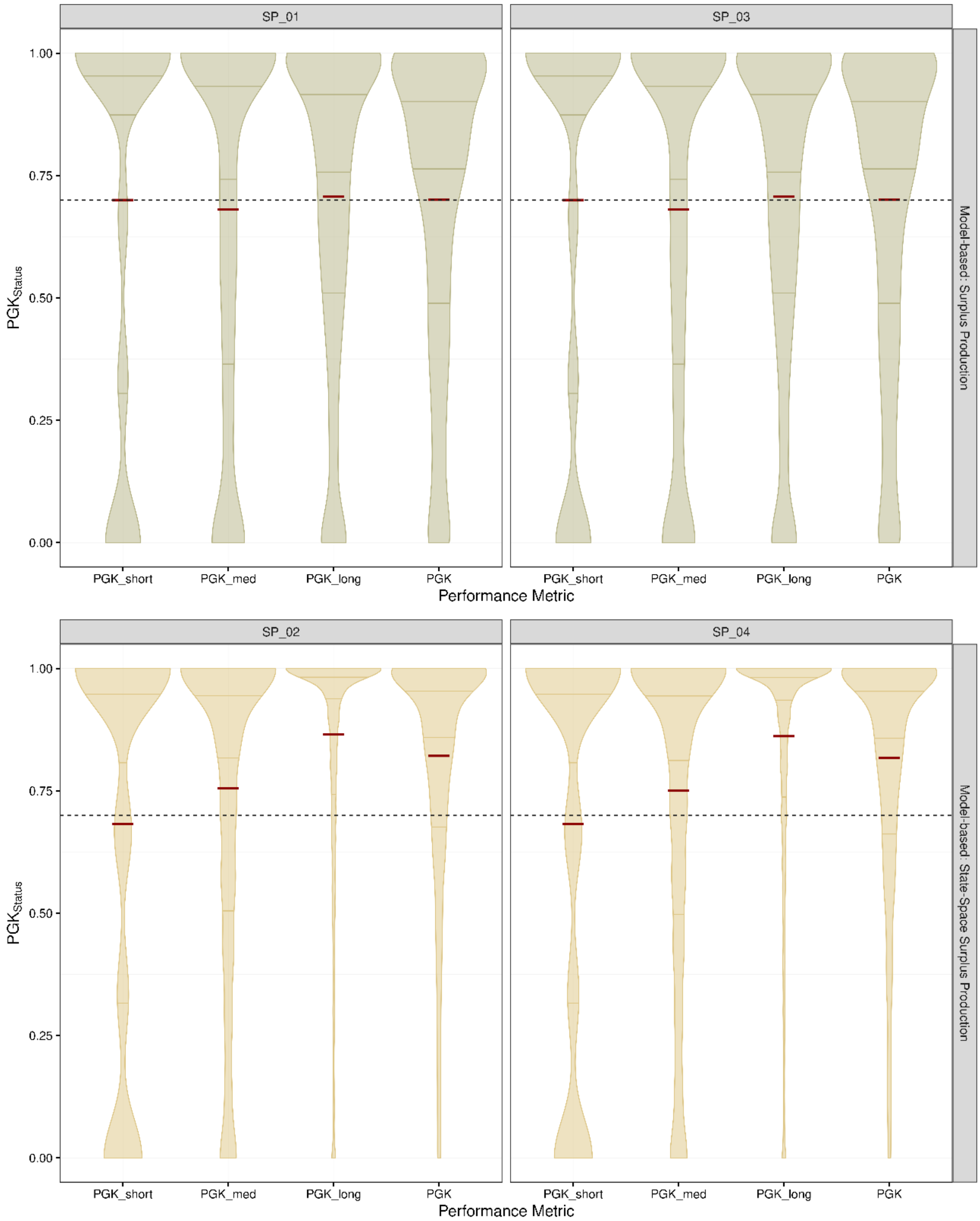

Figure 8. Performance metric violin plot for the probability of being in the green quadrant of the Kobe diagram for the different tune parameters implemented for the CMPs.

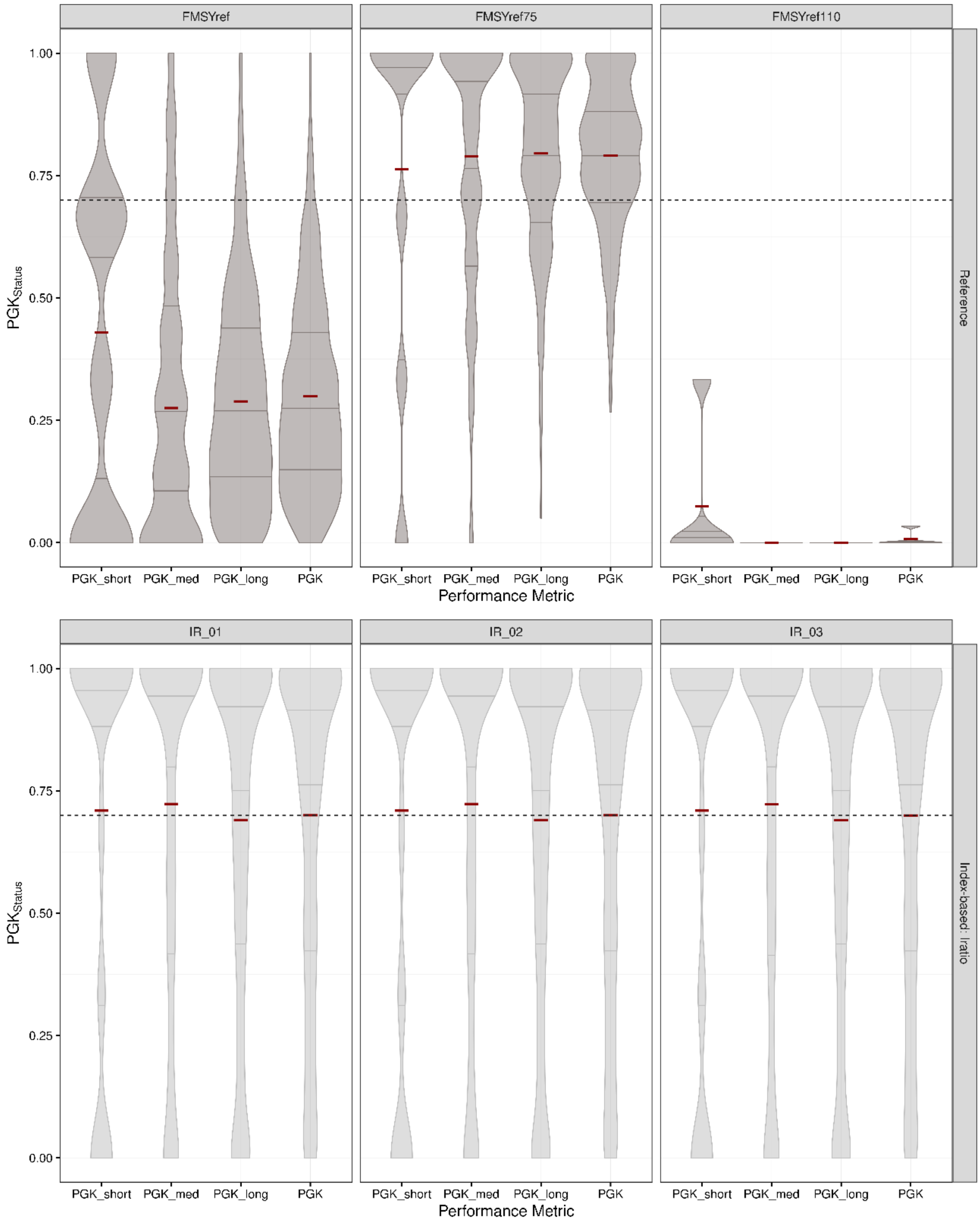

Figure 9. Performance metric violin plot for the probability of being in the green quadrant of the Kobe diagram for the different tune parameters implemented for the CMPs.

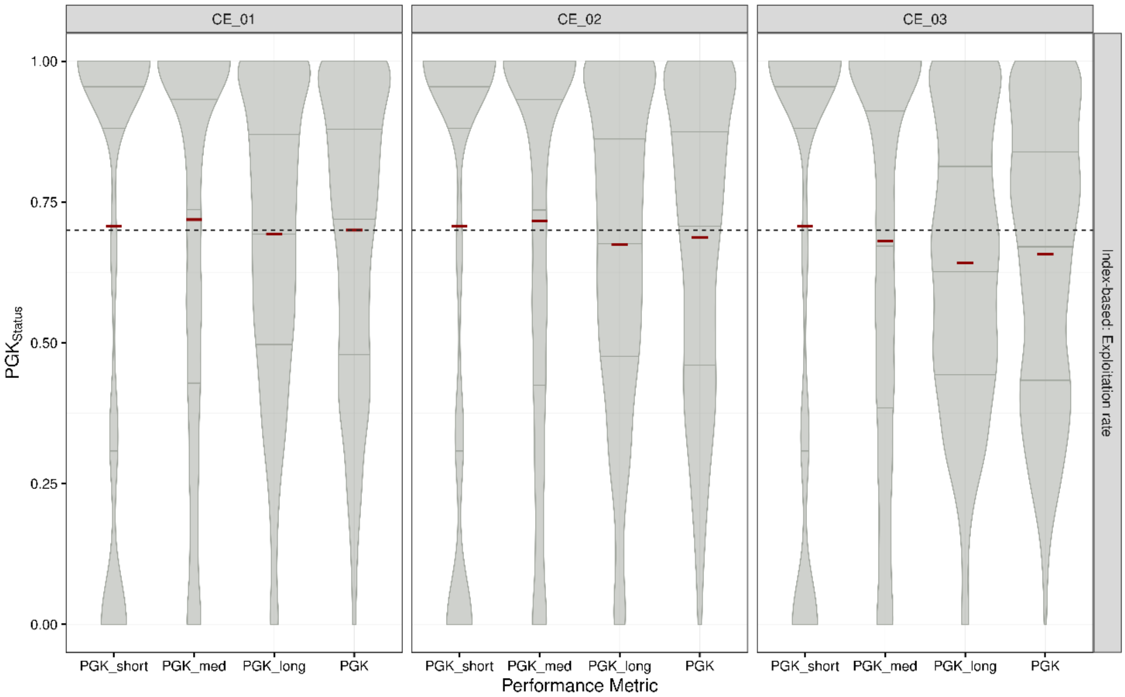

Figure 10. Safety Performance metric violin plot for each CMP for the management strategy evaluation of the western Atlantic Skipjack stock.

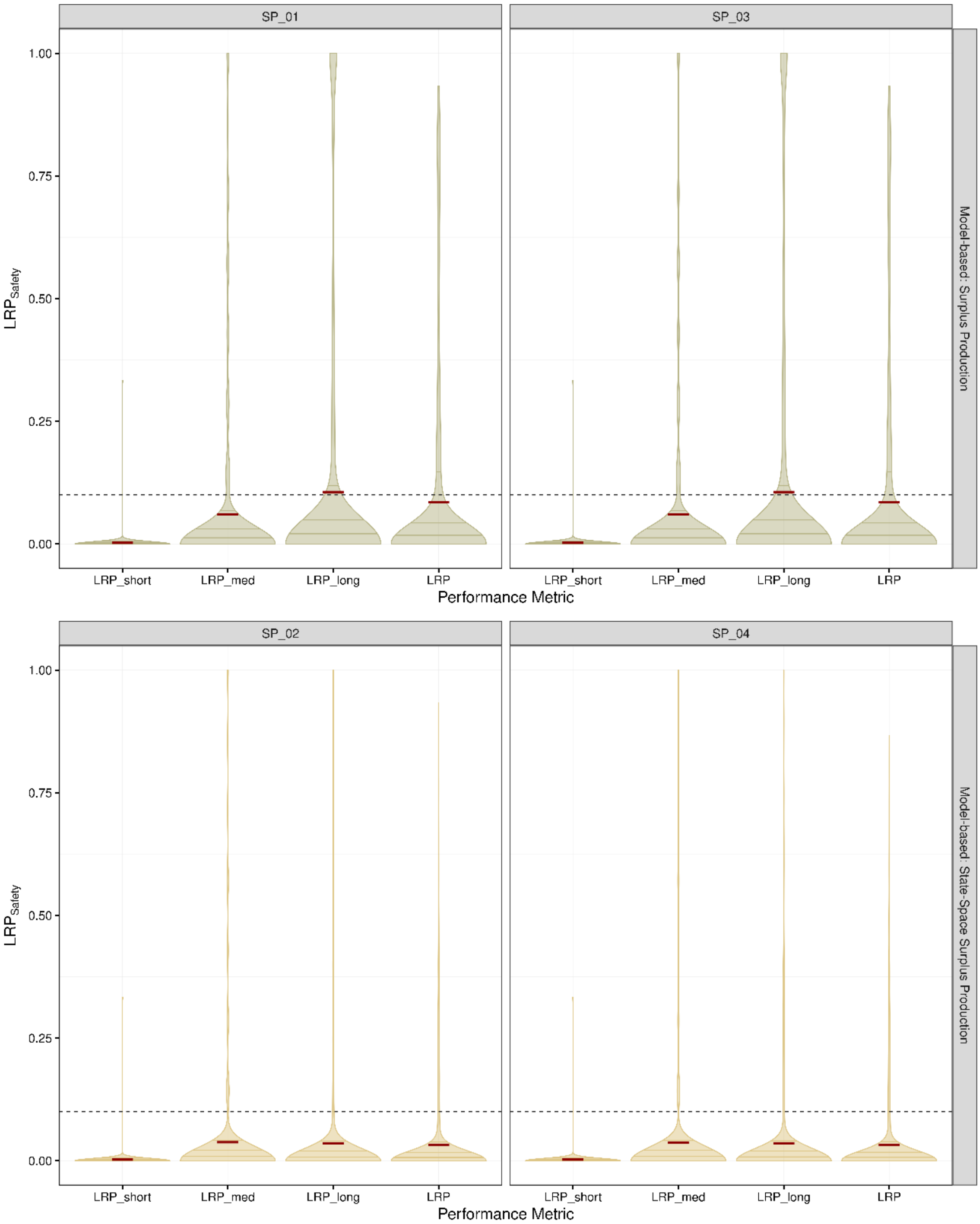

Figure 11. Safety Performance metric violin plot for each CMP for the management strategy evaluation of the western Atlantic Skipjack stock.

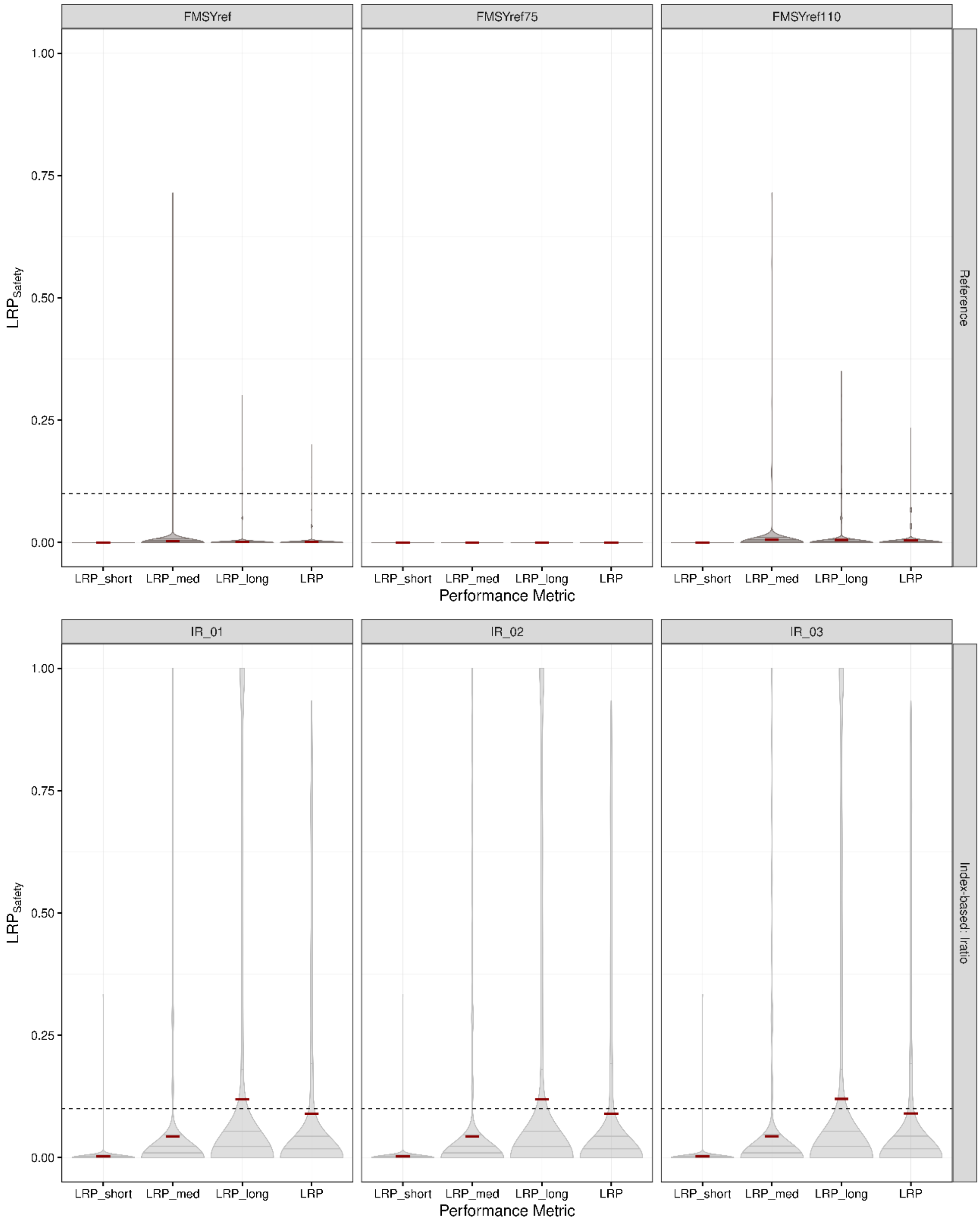

Figure 12. Safety Performance metric violin plot for each CMP for the management strategy evaluation of the western Atlantic Skipjack stock.

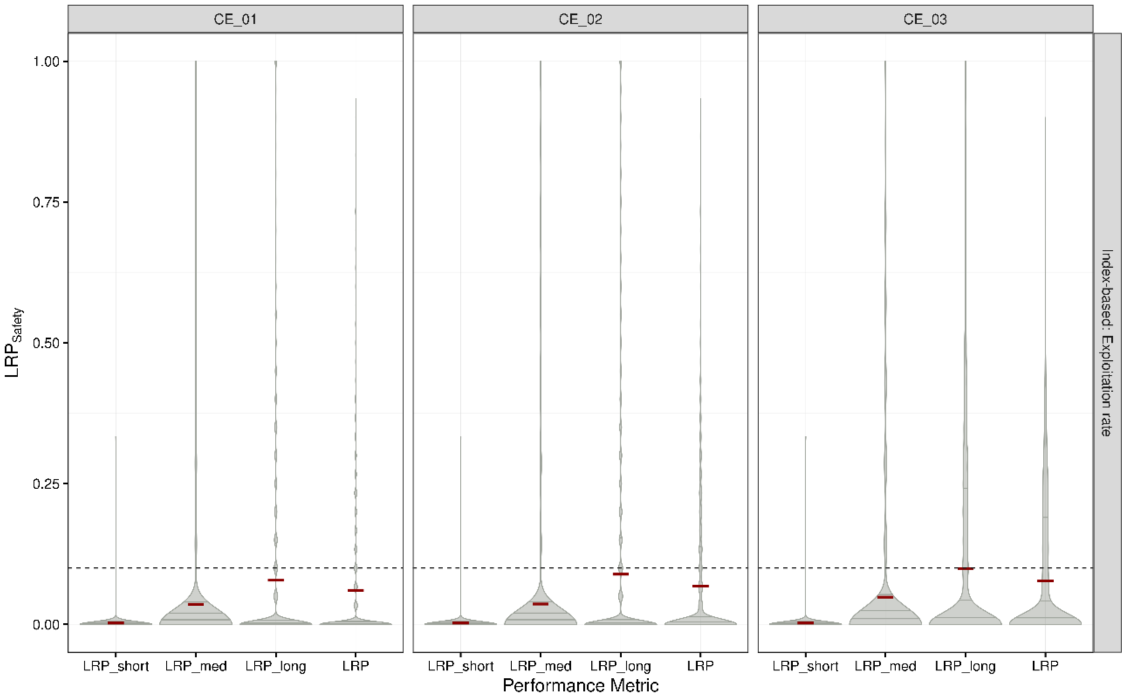

Figure 13. Safety Performance metric violin plot for each CMP for the management strategy evaluation of the western Atlantic Skipjack stock.

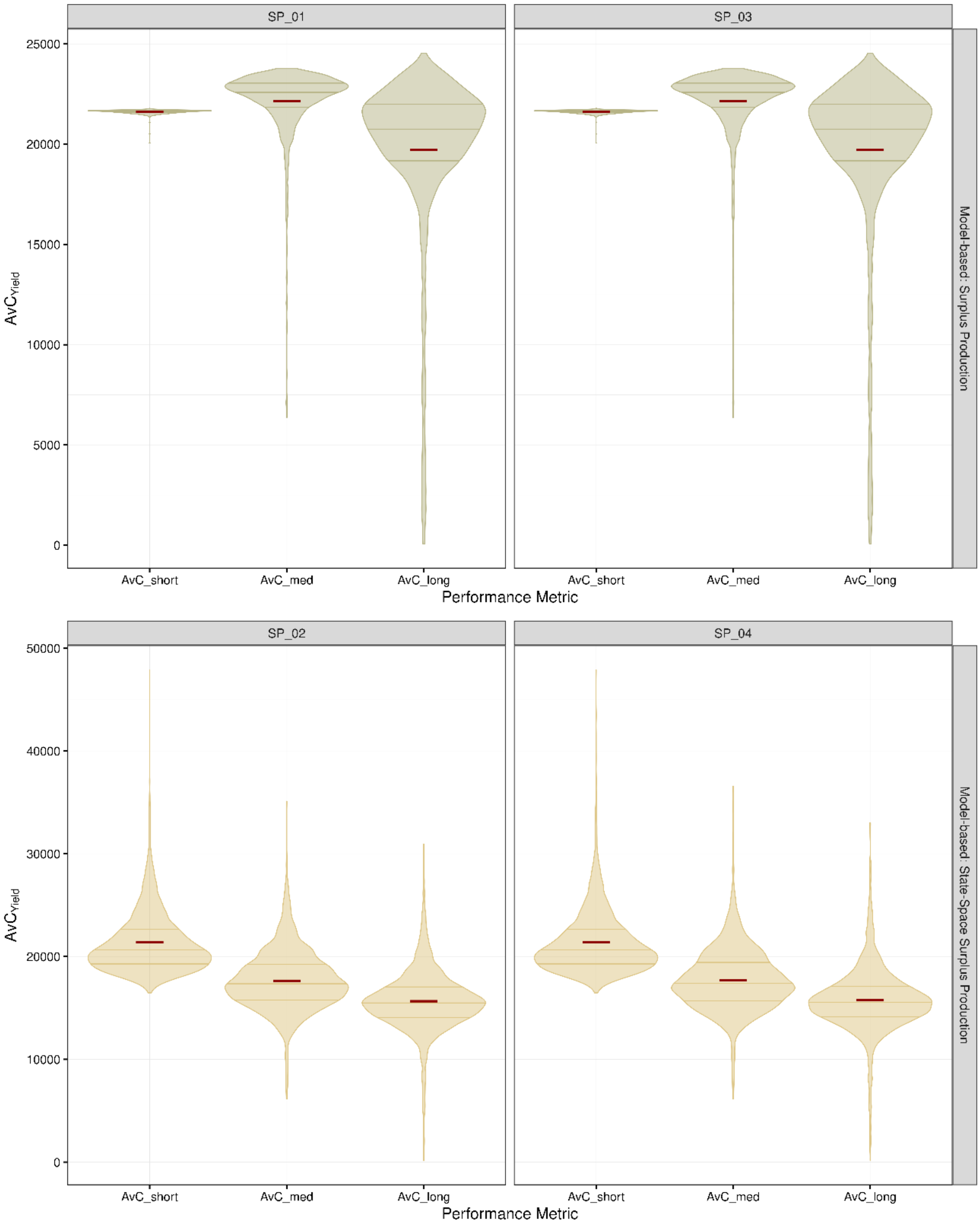

Figure 14. Yield Performance metric violin plot for each CMP for the management strategy evaluation of the western Atlantic Skipjack stock.

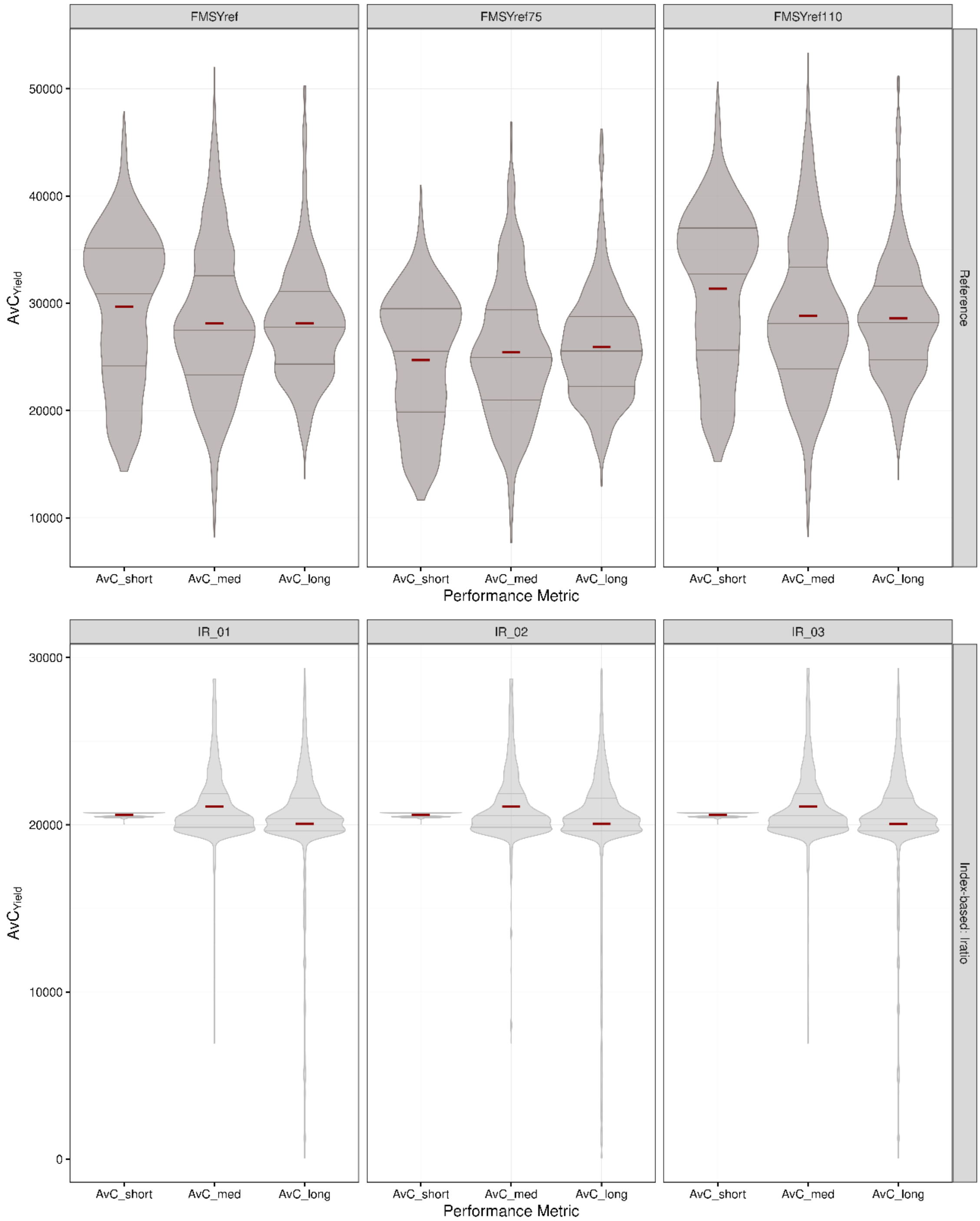

Figure 15. Yield Performance metric violin plot for each CMP for the management strategy evaluation of the western Atlantic Skipjack stock.

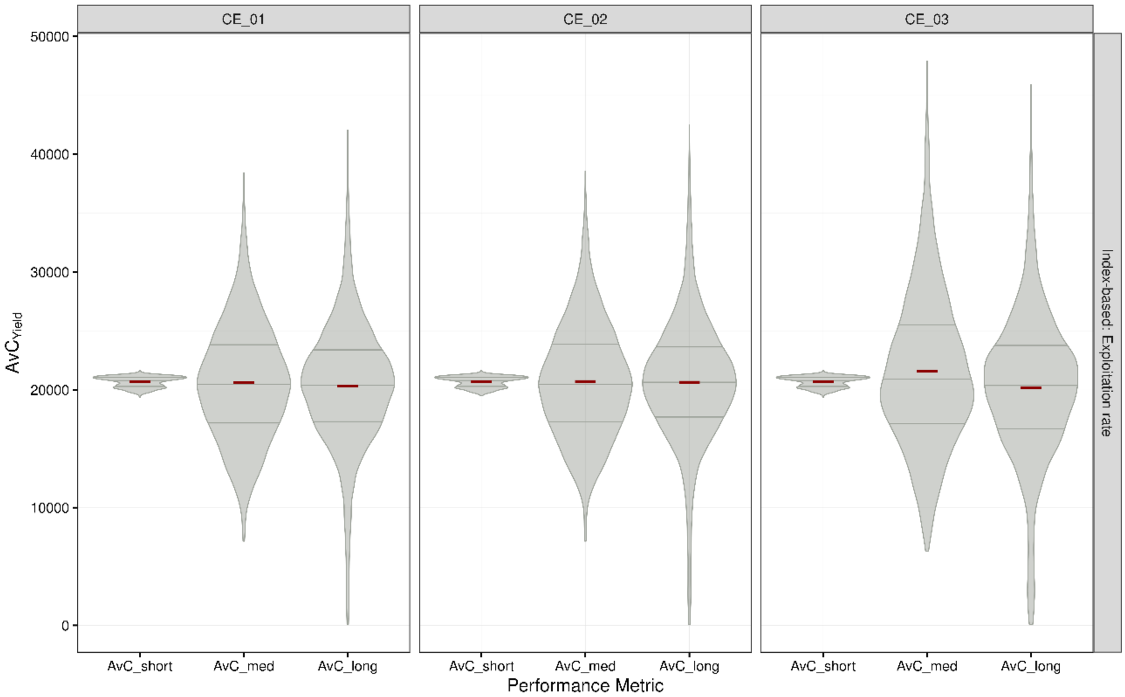

Figure 16. Yield Performance metric violin plot for each CMP for the management strategy evaluation of the western Atlantic Skipjack stock.

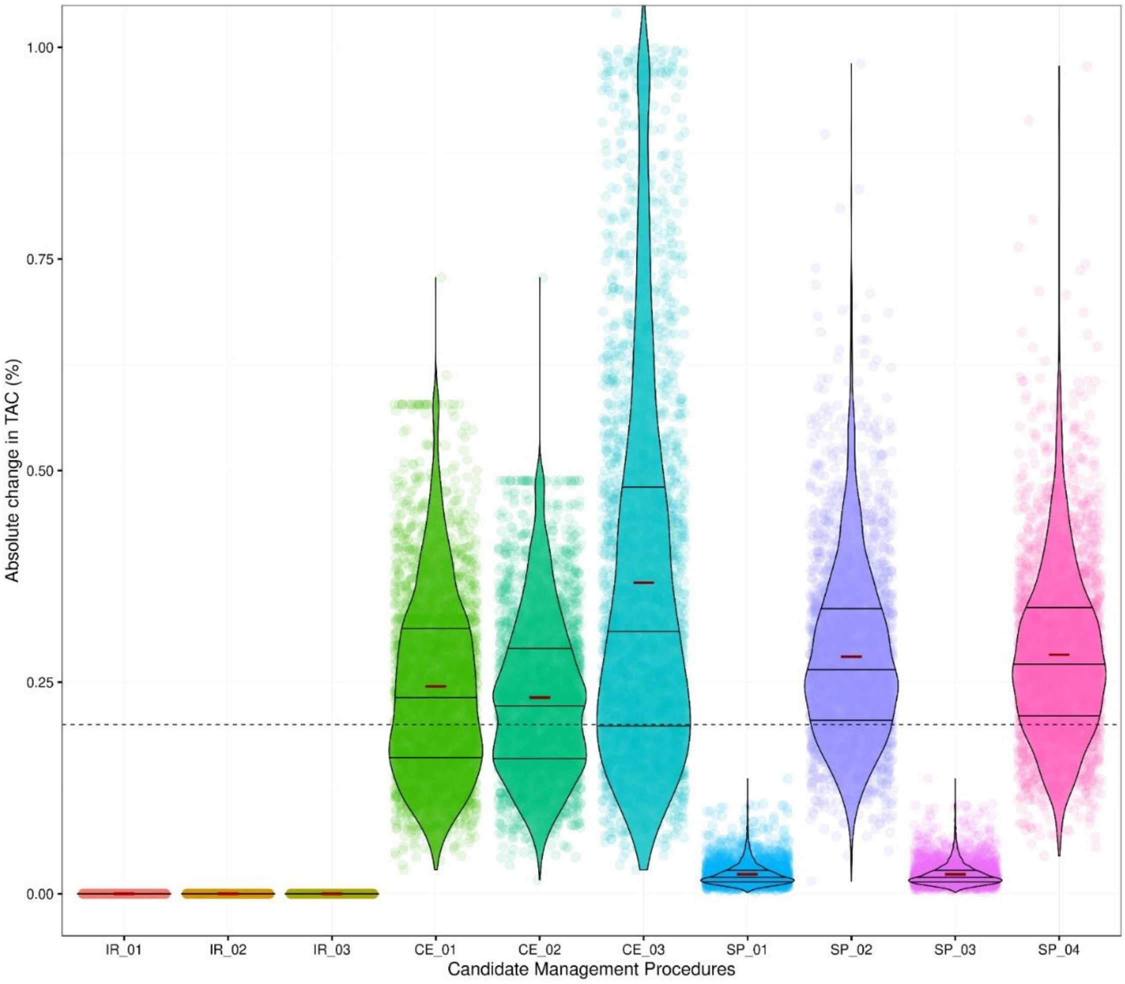

Figure 17. Stability Performance metric violin plot for each CMP for the management strategy evaluation of the western Atlantic Skipjack stock.

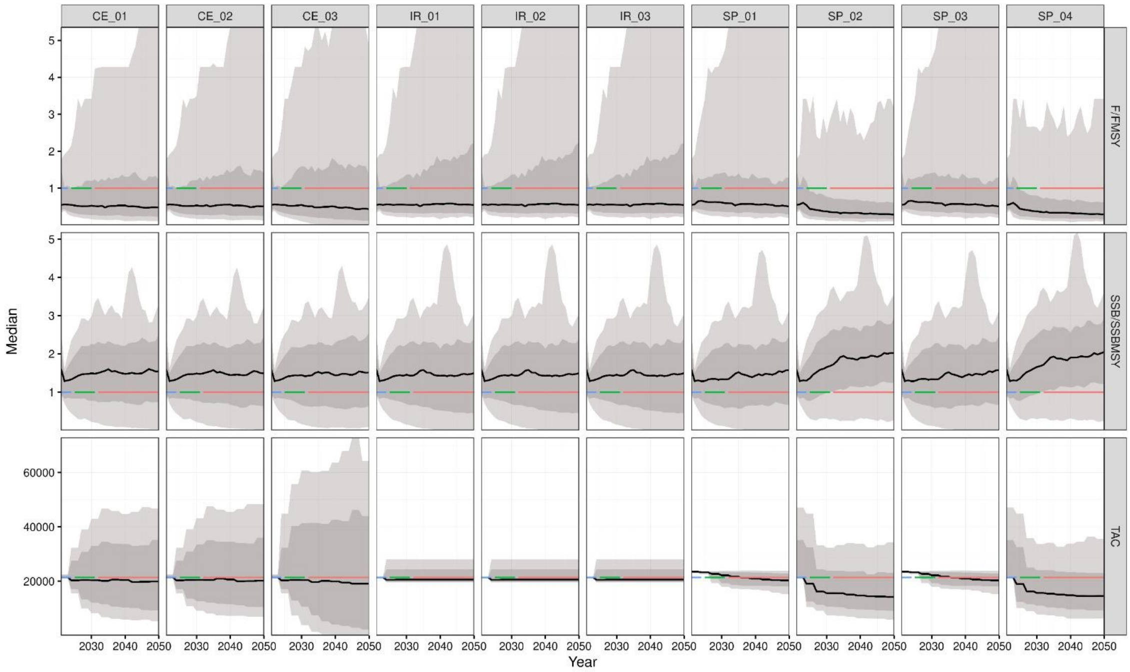

Figure 18. Projections of fishing mortality (upper panels) and biomass (middle panels), both relative to maximum sustainable yield (MSY) levels, along with Total Allowable Catch (TAC) (lower panels) projections, were calculated based on the nine reference case operating models for all CMPs. The horizontal lines are color-coded to represent different projection periods: short-term (1-3 years), medium-term (4-10 years), and long-term (11-30 years).

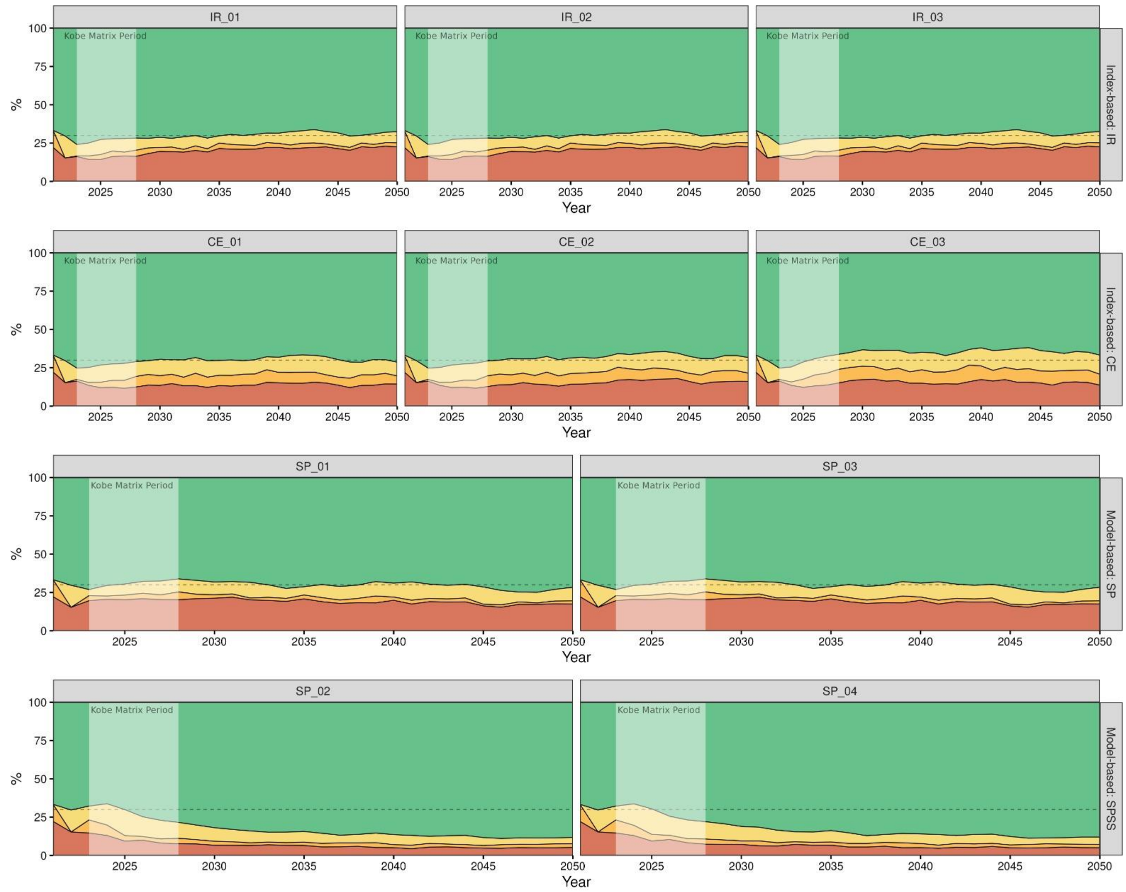

Figure 19. Probability of being in each of the Kobe plot through years.

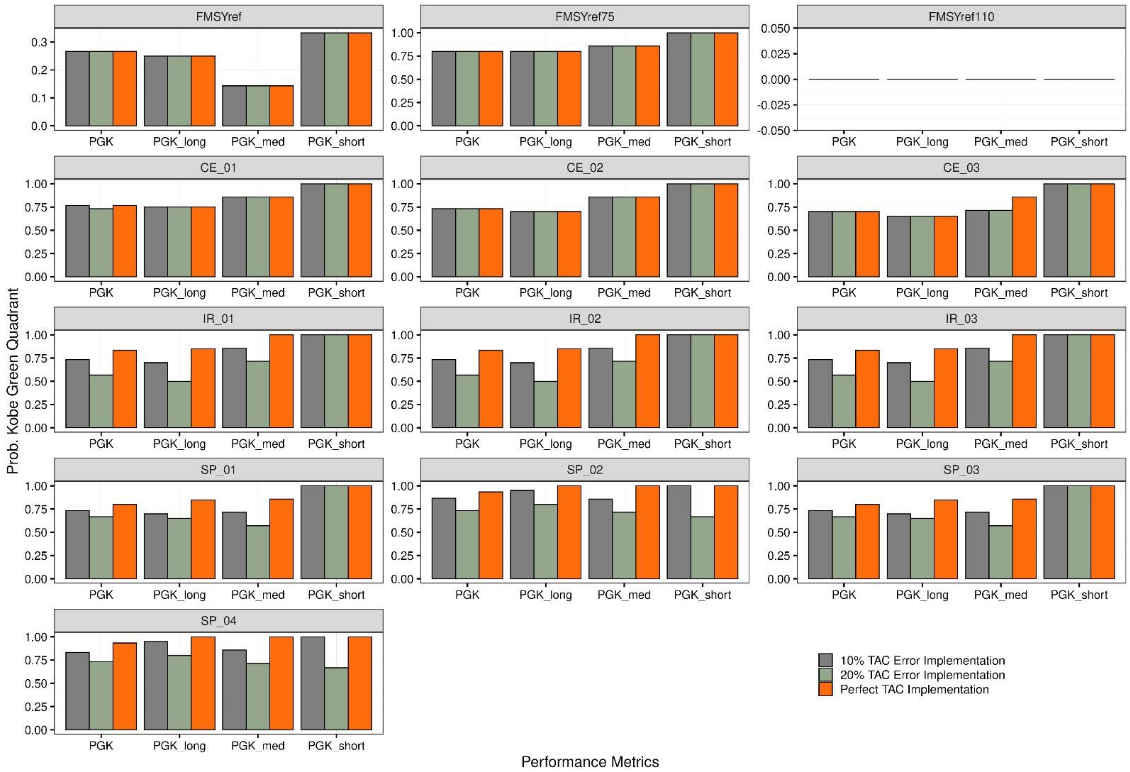

Figure 20. Status Performance metrics comparison between reference case OMs and robustness tests Oms.

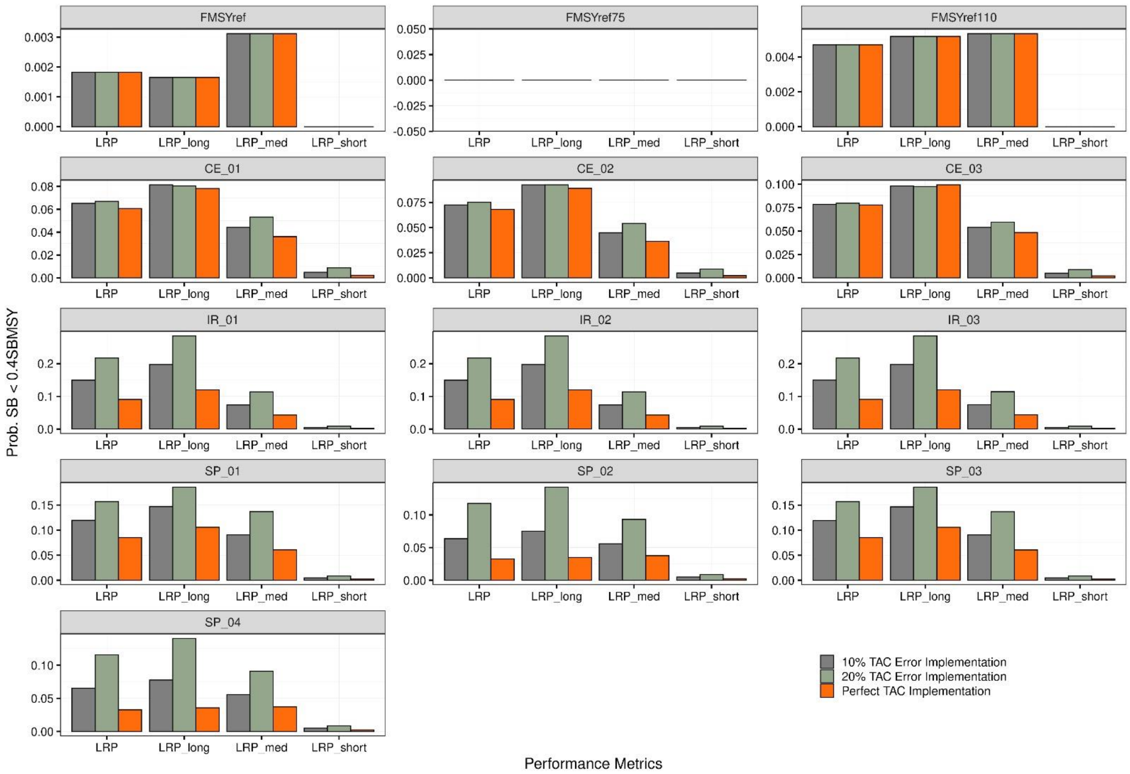

Figure 21. Safety Performance metrics comparison between reference case OMs and robustness tests Oms.

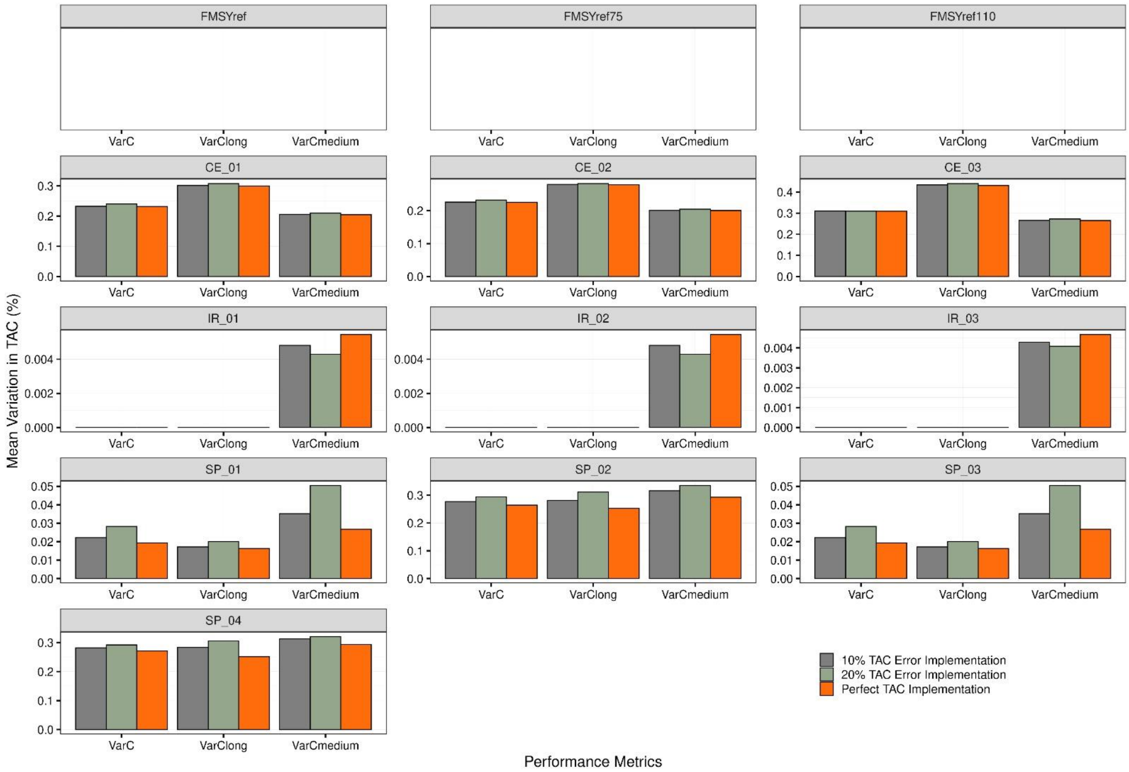

Figure 22. Stability Performance metrics comparison between reference case OMs and robustness tests Oms.