JOINT IATTC AND WCPFC-NC WORKING GROUP ON THE MANAGEMENT OF PACIFIC BLUEFIN TUNA INTERSESSIONAL MEETING
SECOND SESSION (JWGI-02)

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Anticipated duration: 2 hours

PACIFIC BLUEFIN TUNA MANAGEMENT STRATEGY EVALUATION
(Executive Summary)

IATTC-NC-JWGI02-2025/WP-01

Pacific Bluefin Tuna Working Group
ISC[1]

[1] International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean

1 Executive Summary

History and Goal of PBF Management Strategy Evaluation

Pacific bluefin tuna (PBF) is a highly migratory species whose range covers the entire North Pacific and which sustains economically important fisheries in Chinese Taipei, Japan, Korea, Mexico and the United States. Due to its broad range, the stock is managed internationally by two Regional Fisheries Management Organizations (RFMOs), the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter American Tropical Tuna Commission (IATTC). Fishing records date back to the 1800s and the stock has experienced high fishing pressure, with spawning stock biomass (SSB) falling to 2% of unfished SSB (2%$SSB_{F=0}$) in 2009 and 2010. Following the decline of the stock, management measures were put in place by the RFMOs to rebuild the stock to a first rebuilding target of 6.3%$SSB_{F=0}$, and then a second rebuilding target of 20%$SSB_{F=0}$. The management measures were successful, with SSB surpassing the 2nd rebuilding target in 2021.

Now that the stock has rebuilt to the second rebuilding target of 20%$SSB_{F=0}$, the RFMOs tasked the ISC PBF working group (WG) to develop a management strategy evaluation (MSE) to inform development of a long-term management procedure (MP) for PBF. MSE is a process that evaluates the tradeoffs and performance of candidate management procedures under a range of uncertainties using computer simulations. Testing of management procedures in an MSE allows for the ruling out of those management procedures that do not perform adequately in a computer simulation as we would not expect them to perform well in the real world. It also enables managers to identify specific management objectives and quantitative metrics with which to evaluate performance and lays bare the tradeoffs between them. The RFMOs finalized the harvest candidate harvest control rules (HCRs) to be tested and agreed on the management objectives and performance metrics with which to evaluate their performance in 2023 and requested the ISC PBF WG to finalize the MSE in 2025. In February 2025, after being presented with a set of preliminary results by the ISC, the RFMOs further reduced the HCRs to be tested in the MSE to a final set. This PBF MSE examined performance of 16 candidate management procedures for PBF put forward by the RFMOs relative to the set of management objectives and performance metrics agreed-upon by the RFMOs given uncertainty using a closed loop computer simulation that recreates the real-world management process, from data collection, assessment of stock status, and management procedure implementation (Fig. E1).

In the MSE, the management process is described by the management procedure. A management procedure establishes management actions (here the setting of a total allowable catch, TAC) with the aim of achieving the stated management objectives. It specifies (1) what harvest control rule (HCR) will be applied, (2) how stock status estimates will be calculated (here via a stock assessment), and (3) how data will be monitored. The management procedures in this MSE only differ in terms of the HCR and associated control points used. As in the real world, estimates of the condition of the PBF stock relative to reference points are calculated via a simulated stock assessment, the estimation model (EM). For this MSE, the estimation model is an age-structured production model with estimated recruitment deviates (ASPM-R+). The + indicates that size frequency data from the Chinese Taipei and Japanese longline fleets were included and their selectivities estimated . It is a simplified version of the 2024 PBF stock assessment model. The virtual stock is monitored by collecting data on catch and size composition as in the real world. Data on catch, size composition, and the index of abundance are generated with some observation error from operating models (OMs), which are mathematical representations of the possible true dynamics of the stock and fisheries. Those observations are then fed into the simulated stock assessment (i.e., the EM, Fig. ES1). As in the real world, the results from the simulated assessment are then used to inform management of the PBF fisheries, based on the candidate HCR being tested (Fig. ES1). The resulting management action (i.e. TAC) then impacts the simulated fleets and PBF stock (Fig. ES1). At the end of the 23-year long simulation, output from the operating models is used to compute performance metrics to assess performance relative to the set of management objectives of each of the candidate HCRs.

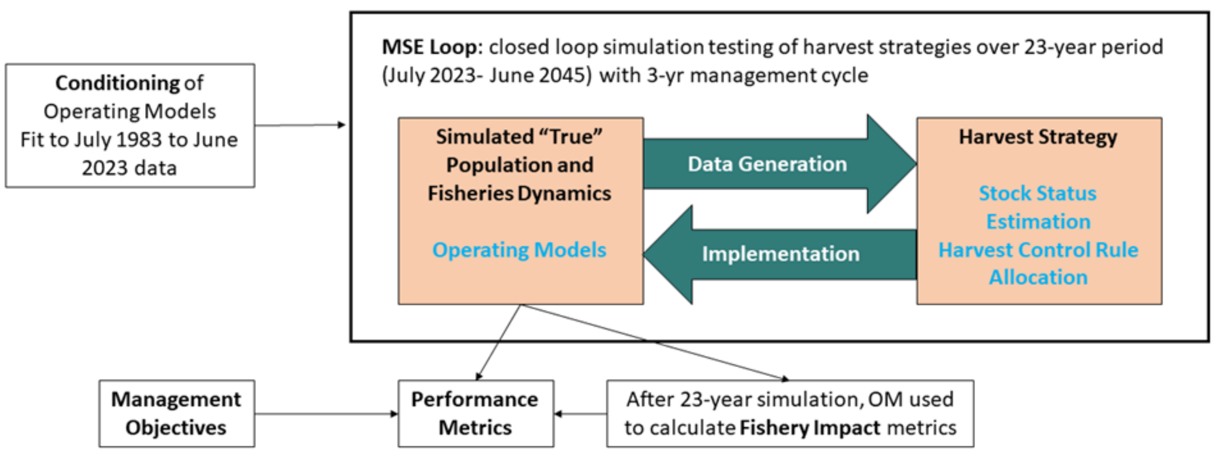

Figure ES1. Overview of the PBF MSE closed-loop simulation framework showing the MSE feedback loop where data is sampled with error from the operating models and fed into the management procedure, which includes a simulated assessment, which determines stock status and informs the harvest control rule (HCR). The HCR then determines a management action (i.e. TAC) which then affects the dynamics of the "true" population in the operating model.

Management Objectives and Performance Indicators

The management objectives and associated performance indicators for this MSE were agreed upon by the RFMOs following two PBF MSE workshops and additional discussions at two WCPFC NC and IATTC PBF Joint Working Group (JWG) meetings. They are outlined in

Table ES1. Performance indicators were used to quantitatively evaluate the performance of the HCRs tested relative to the management objectives.

Table ES1. List of management objectives and performance indicators put forward by the JWG and used in the PBF management strategy evaluation. SSB refers to spawning stock biomass, LRP to limit reference point, and F to fishing mortality, measured as 1-SPR where SPR is the spawning potential ratio, the ratio of the cumulative spawning biomass that an average recruit is expected to produce over its lifetime when the stock is fished at the current fishing level to the cumulative spawning biomass that could be produced by an average recruit over its lifetime if the stock was unfished. F_{TARGET} is the target reference point based on fishing mortality.

Category	Operational Management Objective	Performance Indicator
Safety	There should be a less than a 20%* probability of the stock falling below the LRP	Probability that SSB< LRP in any given year of the evaluation period
Status	To maintain fishing mortality at or below F_{TARGET} with at least 50% probability	Probability that $F \leq F_{TARGET}$ in any given year of the evaluation period Probability that SSB is below the equivalent biomass depletion levels associated with the candidates for F_{TARGET}
Stability	To limit changes in overall catch limits between management periods to no more than 25%, unless the ISC has assessed that the stock is below the LRP	Percent change upwards in catches between management periods excluding periods when SSB<LRP Percent change downwards in catches between

		management periods excluding periods when SSB<LRP
Yield	Maintain an equitable balance in proportional fishery impact between the WCPO and EPO	Median fishery impact (in %) on SSB in the terminal year of the evaluation period by fishery and by WCPO fisheries and EPO fisheries
	To maximize yield over the medium (5-10 years) and long (10-30 years) terms, as well as average annual yield from the fishery.	Expected annual yield over years 5-10 of the evaluation period, by fishery. Expected annual yield over years 10-30 of the evaluation period, by fishery. Expected annual yield in any given year of the evaluation period, by fishery.
	To increase average annual catch in all fisheries across WCPO and EPO	

*The acceptable levels of risk may vary depending on the LRP selected, but should be no greater than 20%.

Harvest Control Rules

The HCRs and reference points considered in this MSE (Table ES2) were put forward by the JWG. HCRs specify a management action given spawning stock biomass estimates in relation to biomass-based control points. More specifically, the HCRs identify, given stock status, a desired fishing mortality (F) on the stock, calculated as 1-SPR, where SPR is the spawning potential ratio, the ratio of the cumulative spawning biomass that an average recruit is expected to produce over its lifetime when the stock is fished at the current fishing level to the cumulative spawning biomass that could be produced by an average recruit over its lifetime if the stock was unfished (Fig. ES2).

Within the MSE simulation, a TAC is then set using the desired F and the current biomass from the estimation model (i.e. the EM), which is a simplified assessment model using an age-structured production model with estimated recruitment deviates (ASPM-R+). The TAC is then kept constant for three years until the next assessment. In addition, the first expected TAC to be applied in 2026 is also calculated based on the EM, but outside of the MSE simulation loop. To do so, the EM was updated with catches and an updated index of abundance for fishing year 2023 (i.e., up to June 2024), the latest year for which data is available. The potential TACs are listed in Table ES4.

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Table ES2. List of harvest control rules (HCRs) tested in the PBF MSE. The target reference point (F_{TARGET}) is an indicator of fishing mortality based on SPR. SPR is the spawning potential ratio, the ratio of the cumulative spawning biomass that an average recruit is expected to produce over its lifetime when the stock is fished at the current fishing level to the cumulative spawning biomass that could be produced by an average recruit over its lifetime if the stock was unfished. An F_{TARGET} of FSPR40% is associated with a fishing mortality that would leave 40% of the SSB per recruit as compared to the unfished state. An F_{TARGET} of FSPR20% implies a higher fishing mortality (i.e., 1-SPR of 0.8) and would result in a SSB per recruit of 20% of the unfished SPR. The threshold (ThRP) and limit reference points (LRP) are SSB-based and refer to the specified percentage of equilibrium unfished SSB ($SSB_{F=0}$). The minimum F (F_{min}) refers to the fraction of the F_{TARGET} that the fishing intensity is set to when SSB is below the limit reference point, except for HCRs 4 and 12 which specify a specific fishing mortality. Note that for HCRs 5 and 13 when the ThRP is breached the HCR switches from constant fishing mortality at the F_{TARGET} to a constant TAC set at the catch limits defined in CMM2021-02 (WCPFC 2021) and C-21-05 (IATTC 2021). While HCRs 5, 6, 7, 13, 14, and 15 do not use LRPs as control points, an LRP of median SSB 1952-2014 (6.3% $SSB_{F=0}$) has been specified by the JWG to compute performance metrics. HCRs 9 to 16 are identical to HCRs 1 to 8 except for the allocation of fishing pressure between the Western Central Pacific Ocean (WCPO) fleet segment and the Eastern Pacific Ocean (EPO) fleet segment. HCRs 1 to 8 were tuned to reach a fishery impact ratio between the WCPO and EPO of 80% to 20% (80:20), while HCRs 9 to 16 were tuned to reach a WCPO:EPO fishery impact ratio of 70:30.

HCR number	**F_{TARGET}**	**Control Point 1 (ThRP)**	**Control Point 2 (LRP)**	**Number of Control Points**	**F_{min}**	**WCPO:EPO Impact Ratio**
1	FSPR30%	20%$SSB_{F=0}$	15%$SSB_{F=0}$	2	10% F_{TARGET}	80:20

2	FSPR30%	25%$SSB_{F=0}$	15%$SSB_{F=0}$	2	10% F_{TARGET}	80:20
3	FSPR40%	25%$SSB_{F=0}$	20%$SSB_{F=0}$	2	10% F_{TARGET}	80:20
4	FSPR30%	20%$SSB_{F=0}$	10%$SSB_{F=0}$	2	FSPR70%	80:20
5	FSPR25%	20%$SSB_{F=0}$	NA	1	NA	80:20
6	FSPR20%	20%$SSB_{F=0}$	NA	1	NA	80:20
7	FSPR25%	15%$SSB_{F=0}$	NA	1	NA	80:20
8	FSPR30%	20%$SSB_{F=0}$	7.7%$SSB_{F=0}$	2	5% F_{TARGET}	80:20
9	FSPR30%	20%$SSB_{F=0}$	15%$SSB_{F=0}$	2	10% F_{TARGET}	70:30
10	FSPR30%	25%$SSB_{F=0}$	15%$SSB_{F=0}$	2	10% F_{TARGET}	70:30
11	FSPR40%	25%$SSB_{F=0}$	20%$SSB_{F=0}$	2	10% F_{TARGET}	70:30
12	FSPR30%	20%$SSB_{F=0}$	10%$SSB_{F=0}$	2	FSPR70%	70:30
13	FSPR25%	20%$SSB_{F=0}$	NA	1	NA	70:30
14	FSPR20%	20%$SSB_{F=0}$	NA	1	NA	70:30
15	FSPR25%	15%$SSB_{F=0}$	NA	1	NA	70:30
16	FSPR30%	20%$SSB_{F=0}$	7.7%$SSB_{F=0}$	2	5% F_{TARGET}	70:30

These HCRs define the management action to be taken (i.e. F) given the estimated ratios of SSB to biomass-based control points from the simulated stock assessment. Some HCRs have two control points, with the first being labeled the threshold reference point (ThRP) and the second being labeled the limit reference point (LRP). Having two control points generally helps avoid reaching low biomass levels, where severe management action is taken, and rebuild the stock back to a target state faster. All the HCRs considered in this MSE, have a target state based on fishing mortality (F_{TARGET}). This is the target reference point (TRP) and the state that management wants to achieve. Figure ES2 outlines, for each HCR, what the allowed F is based on the status of estimated SSB relative to $SSB_{F=0}$. For all HCRs, if SSB is above the first control point, F is managed to be at the F_{TARGET} (Fig. ES2). If SSB falls below the first control point, for all HCRs but 5 and 13 the allowed fishing intensity is reduced in proportion to the estimated relative SSB down to a minimum level at the second control point for HCRs with two control points or down to 0 for those with one control point, to allow biomass to increase back to the target (Fig. ES2). For HCRs 5 and 13, a constant catch management, which was similar to the one applied in 2015-2022, is applied if the SSB breaches its first control point. Historically, the stock has been under intense fishing pressure and fishing mortality as estimated by the latest stock assessment has never been at a 40%SPR or lower level, even when the stricter management measures were in place (Fig. ES2).

It is important to note that the LRPs and TRPs in HCRs here are used as both control points of management actions, and as measuring sticks to evaluate performance. However, control points can take different values from the LRPs and TRPs. LRPs and TRPs, in principle, can also simply play the role of reference points to evaluate the performance of HCRs. In these cases, the level of the LRPs and TRPs would only be used as measuring sticks without affecting the management actions under the HCRs.

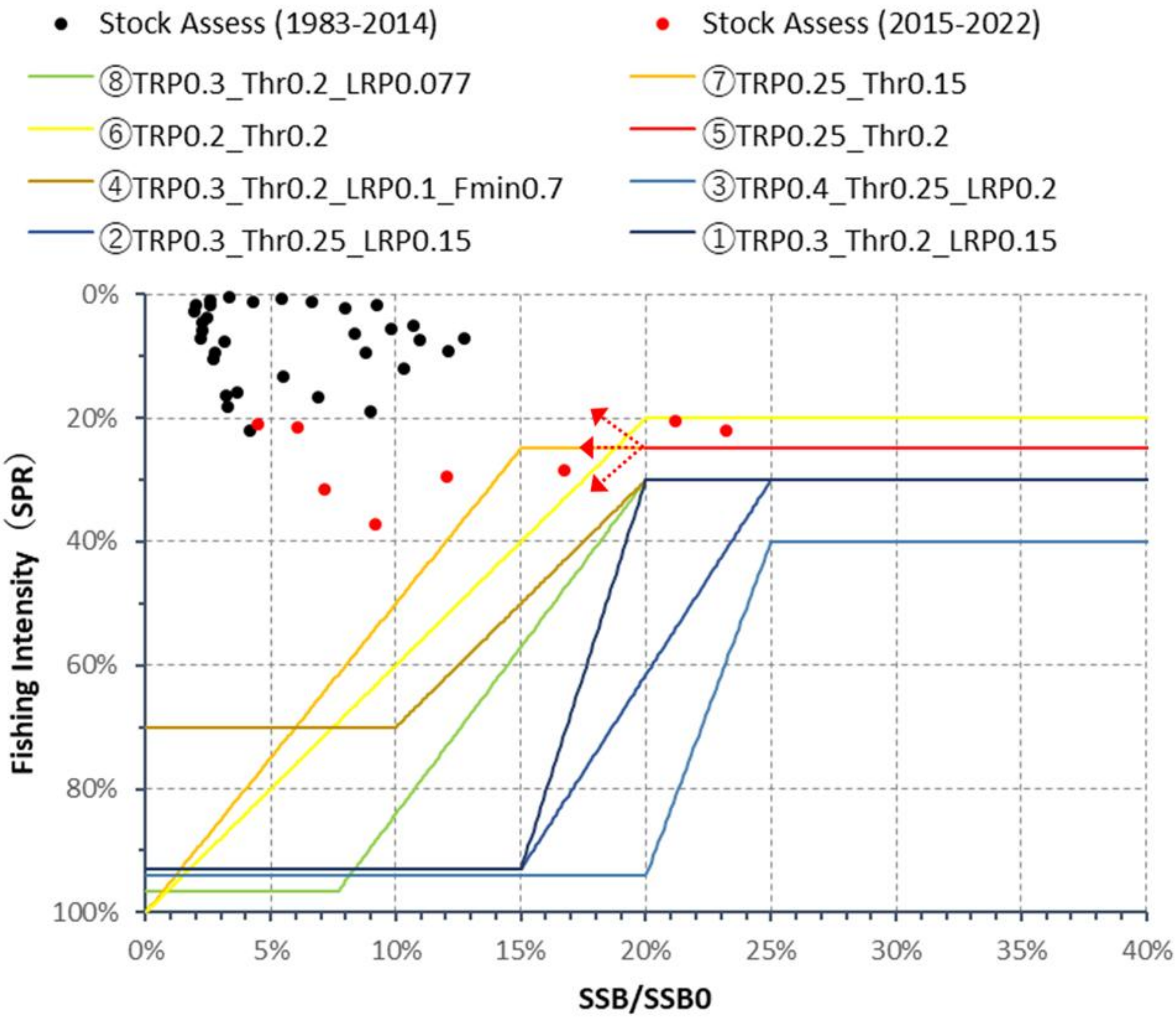

Figure ES2. Candidate HCR evaluated in the PBF MSE. Fishing intensity is an indicator of fishing mortality based on SPR. SPR is the spawning potential ratio that would result from the current year's pattern and intensity of fishing mortality relative to the unfished stock. SSB/SSB0 is SSB relative to the equilibrium unfished SSB ($SSB_{F=0}$). The points are annual estimates of SPR and relative SSB from the latest PBF stock assessment (ISC 2024). Red dots represent the years when stricter catch limits were in place to rebuild the stock. For HCR 5 (red line), a constant catch management, which was similar with the one applied in 2015-2022, is applied if the SSB breaches a control point set at 20%$SSB_{F=0}$. Resulting illustrative fishing intensities for a constant catch are shown as dashed arrows. Note HCRs 9 to 16 are not represented as they are identical in shape to HCRs 1 to 8.

Uncertainties considered

MSE recreates the real-world management process to ensure management procedures will work even given errors in the observations, assessment, and implementation. The PBF MSE framework therefore adds realistic error to the data going into the simulated stock assessment (i.e., the EM). As would happen in the real world, the MSE framework also runs the EM every three years and estimates stock status given this data to ensure that estimation error is considered. The MSE also simulates a realistic lag between the availability of data going into the assessment and the implementation of management action. For instance, the first EM in the MSE has data up to fishing year 2023, i.e., up to June 2024, to set a TAC starting in calendar year 2026. TAC is provided in three categories of fleets; WPO large fish, WPO small fish and EPO, based on the recent (2015-2022) selectivity. Since the fleets may catch more than assigned by the TAC due to discards, the MSE also implements an implementation error by adding 1.2% higher catch than set by the HCR to EPO recreational fleets, 5% to the WCPO fleets except for the Japanese troll for penning fleet, which is set at 100% to account for potentially high discards.

In addition to uncertainty related to the management process, the MSE also considers uncertainty stemming from our limited understanding of the true population or fisheries dynamics. This was done by developing 20 different OMs, or 20 different equally plausible "true" versions of the system. In developing the potential OMs, the ISC PBF WG discussed the most influential sources of uncertainty for the PBF stock and identified uncertainty related to the natural mortality, growth, and steepness parameter as the most influential. The PBF WG then identified plausible ranges for these parameters and developed population dynamics models with those many different parameter combinations. Models that passed a series of quantitative diagnostics tests to ensure they were plausible and could reasonably reconstruct past patterns in PBF observations were selected as a reference set and given equal weight. Models that demonstrated unsatisfactory diagnostics were discarded. The OM reference set spans a wide range of stock status (ADD FIGURE). All results and performance metrics are calculated across this entire reference set.

In addition to the reference set, the PBF WG also identified three robustness tests. These are less likely than the reference set and so should not be given the same weight, but are still considered plausible. They are a way to test HCR behavior under extreme conditions detrimental to stock productivity. These robustness tests were: 1) a doubling of discards; 2) an effort creep for the Chinese Taipei long-line fleet on which the main index of abundance is based; and 3) about a 40% 10-year long drop in recruitment, starting from 2052. Robustness OMs were constructed by modifying OM1, which has the same setting as the 2024 base-case assessment model. Results for the robustness set are presented separately. Finally, as PBF recruitment can vary greatly between years due to unknown environmental factors, even when SSB remains comparable, the MSE also considered process uncertainty in recruitment. This was done by, for each OM, sampling recruitment deviations from a normal distribution with σ_R=0.6 and mean 0 in log space.

For each HCR/OM combination, 100 iterations with different random trajectories in recruitment were run. Less than 1% of all the simulated assessments had estimation issues and produced unrealistically low estimated SSB (less than 1 fish) that were not seen in the OM and were not caused by the HCRs. These unrealistically low estimated SSBs appeared to be caused by unrealistic estimation error due to non-convergence. While this only happened for EMs in some assessment years, iterations, and OMs, to ensure the HCRs were exposed to the same recruitment trends, we discarded the iterations associated with this estimation issue for all OMs and HCRs, leaving a total of 78 iterations per OM/HCR combination with which to compute performance metrics. Removing these iterations was considered reasonable given that it did not greatly affect the performance metrics (see details in main text).

Table ES3. List of the 20 operating models (OMs) in the reference set representing different productivity scenarios and their parameter specifications. The models were considered equally plausible and given equal weight in the calculation of performance metrics. M_{2+} refers to natural mortality for age 2 and older fish, L_2 refers to the length at age 3, and h refers to steepness. OM 1 has the same parameter specifications as the current base case stock assessment for Pacific bluefin tuna.

OM #	**M_{2+}**	**L_2**	**h**
1	0.25	118.57	0.999
2	0.25	118	0.91
3	0.193	118.57	0.97
4	0.193	118	0.999
5	0.193	118	0.99
6	0.193	118.57	0.99
7	0.193	119	0.99
9	0.25	118	0.999
10	0.25	119	0.999
11	0.25	118	0.99

12	0.25	118.57	0.99
13	0.25	119	0.99
14	0.25	118	0.97
15	0.25	119	0.97
16	0.25	118	0.95
17	0.25	118.57	0.95
18	0.25	119	0.95
19	0.25	118	0.93
20	0.25	118.57	0.93
21	0.25	119	0.93

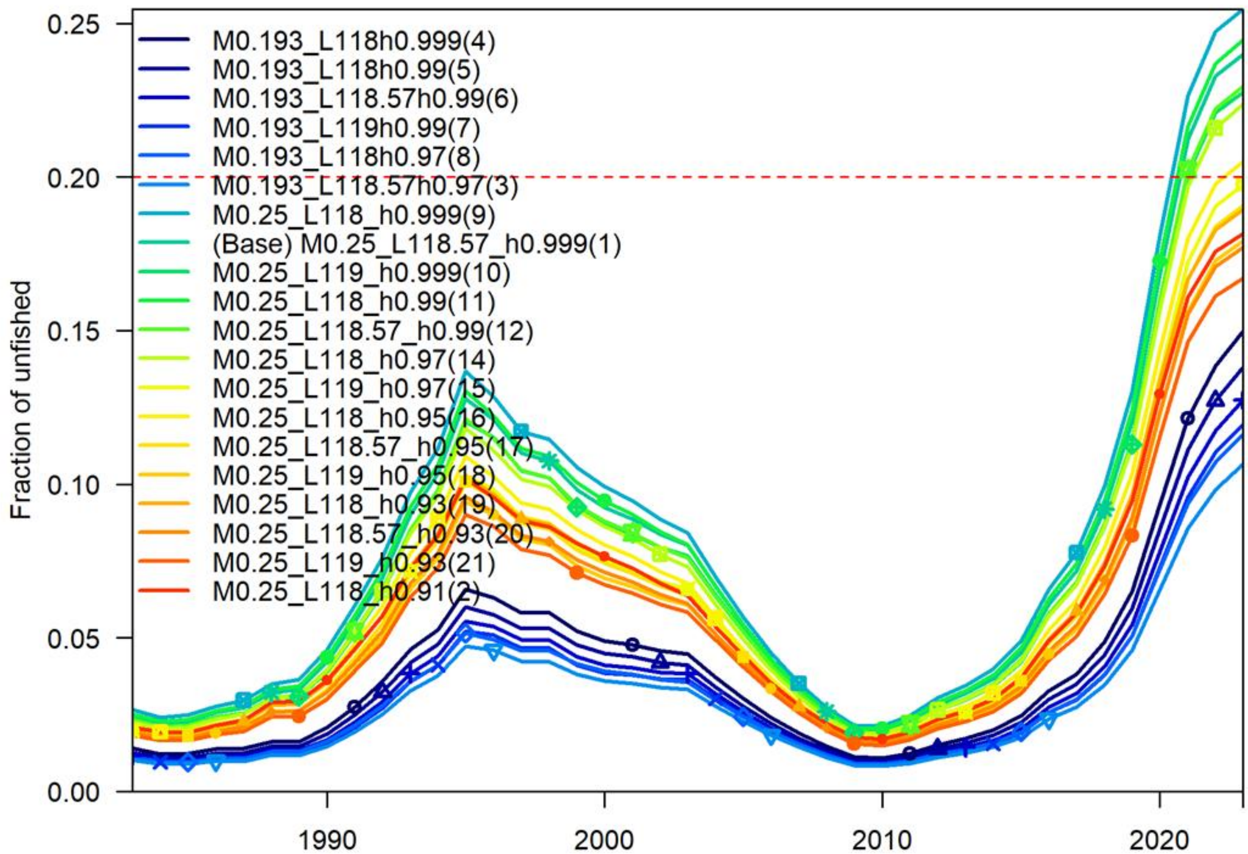

Figure ES2.

Results

The results of the MSE analysis can be summarized in eight main points:

1. *All HCRs were able to maintain a low probability (<20%) of the stock breaching their respective LRP and the IATTC's interim reference point for tropical tunas of 7.7%SSB$_{F=0}$. In addition, all HCRs except for HCRs 6 and 14 were also able to maintain a low probability (<20%) of breaching the second rebuilding target of 20%SSB$_{F=0}$. Under all HCRs, median SSB increased from initial conditions to levels above their respective target (Fig. ES2).*

Even when considering the range of uncertainties in stock productivity, recruitment variability, observation, estimation, and implementation, all HCRs met the safety objective and had a less than 20% probability of SSB being below their respective LRP and a less than 10% probability of breaching the IATTC's interim reference point for tropical tunas (Figs. ES3 and ES4, Table ES4). Furthermore, all HCRs except 6 and 14, had a probability less than 20% of SSB being below the second rebuilding target of 20%SSB$_{F=0}$ (Fig. ES5, Table ES4). Also, under all HCRs, median SSB increased from initial conditions to levels above their respective target (Fig. ES2).

The PBF WG has no specific recommendation for an LRP with which to test safety performance, especially given that the PBF stock has recovered from a very low level of SSB (2% of $SSB_{F=0}$).

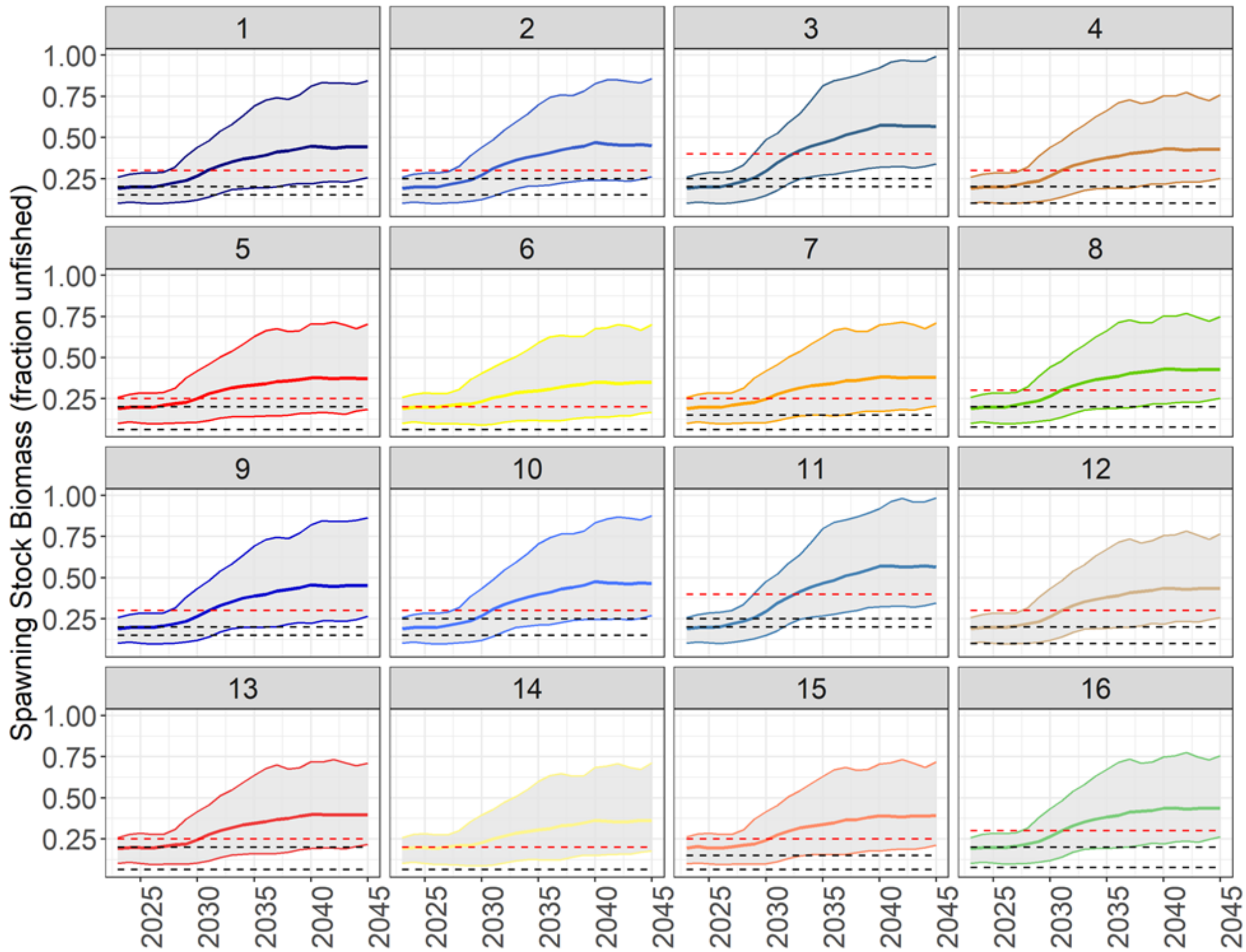

Figure ES2. Trends in median relative spawning stock biomass (SSB/unfished SSB, thick solid color lines) from the operating model under all iterations and reference scenarios by harvest control rule (HCR). The grey shading represents trends in the 5th to 95th quantiles range. The lowest black dotted line represents the lowest control point for each HCR and the highest line the highest . The dashed red line represents the SSB associated with the respective F_{TARGET}. Note that HCRs 5, 6, 7, 13, 14, and 15 do not have a second control point, so the LRP that was specified by the JWG to assess performance was indicated by the lowest dashed line.

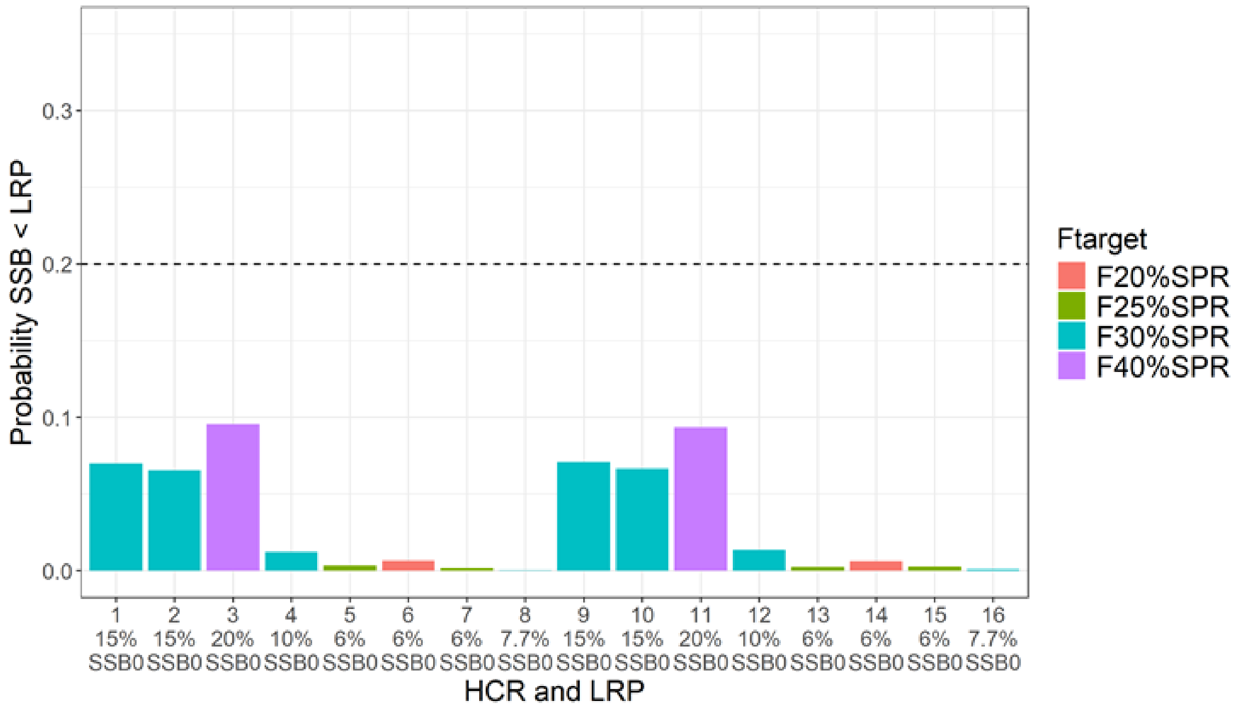

Figure ES3. Probability, for each harvest control rule (HCR), of spawning stock biomass (SSB) being below the limit reference point (LRP) specified by each HCR across all reference scenarios, iterations, and simulation years. The x axis shows both the HCR number and the LRP relative biomass level associated with each HCR.

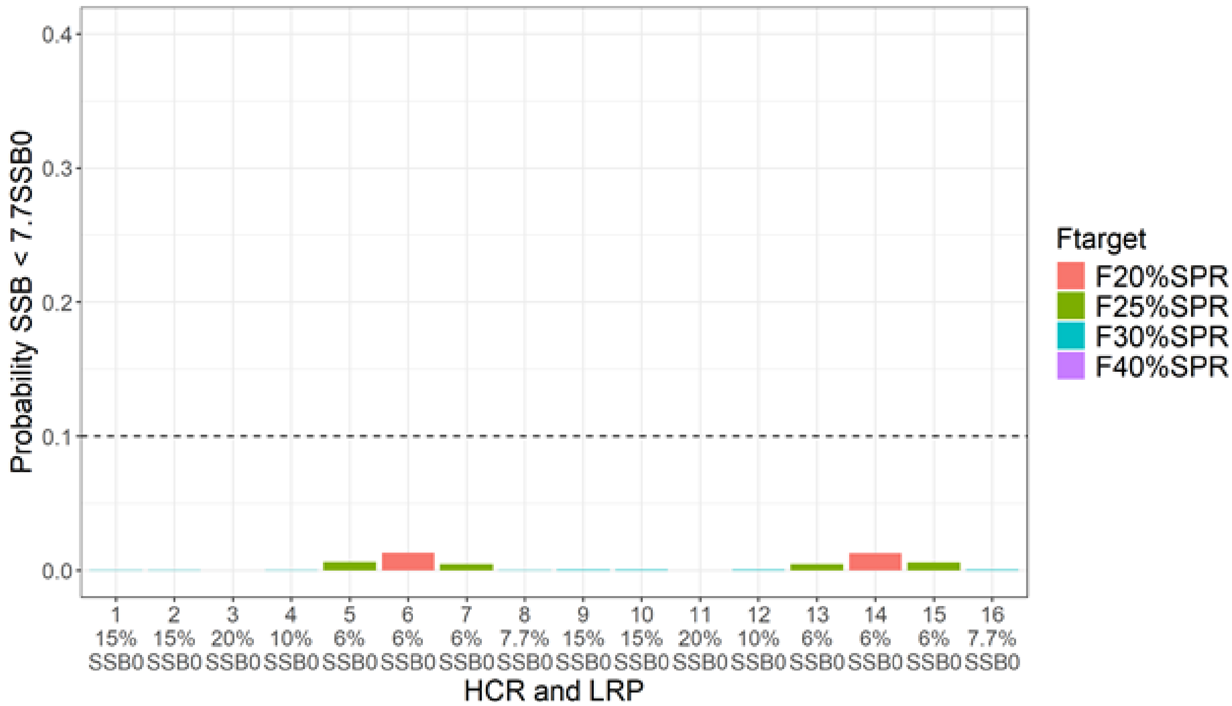

Figure ES4. Probability, for each harvest control rule (HCR), of spawning stock biomass (SSB) being less than 7.7%$SSB_{F=0}$ across all reference scenarios, iterations, and simulation years. The x axis shows both the HCR number and the LRP relative biomass level associated with each HCR. The horizontal dotted line represents a 10% probability.

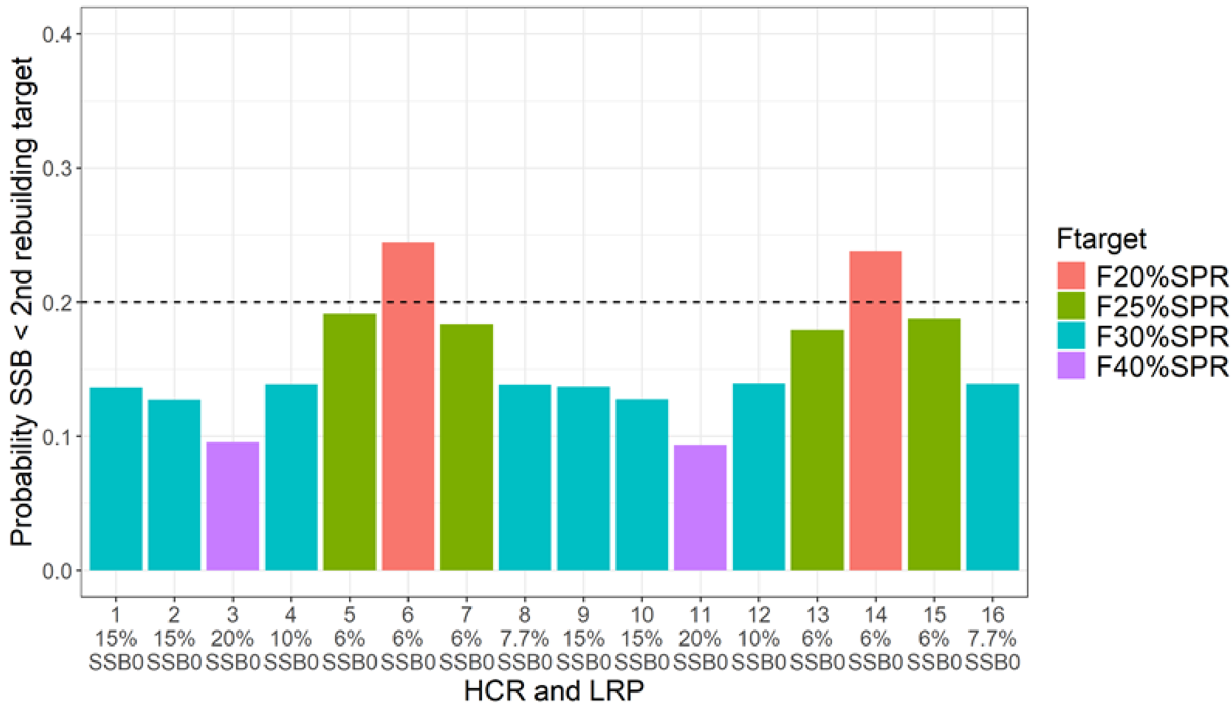

Figure ES5. Probability, for each harvest control rule (HCR), of spawning stock biomass (SSB) being less than 20%$SSB_{F=0}$ across all reference scenarios, iterations, and simulation years. The x axis shows both the HCR number and the LRP relative biomass level associated with each HCR. The horizontal dotted line represents a 20% probability.

2. *There was a tradeoff between the safety metrics (e.g., probability of being at or above the second rebuilding target of 20%$SSB_{F=0}$) and yield metrics (e.g., median annual catch in mt). Those HCRs that had the highest probability of SSB being at or above the second rebuilding target had the lowest yield metrics and vice-versa.*

Due to their higher F_{TARGET}, HCRs 3 and 11 maintained a higher SSB and had the highest probability of SSB being at and above the second rebuilding target of 20%$SSB_{F=0}$, but this came at the cost of lower yields (Fig. ES6), with these HCRs having the lowest total catch, as well as the lowest fleet segment specific (i.e., WCPO large, WCPO small, and EPO) TACs (Figs. ES7, ES8, ES9, and ES10, Table ES4). HCRs with the same F_{TARGET} performs similarly for safety and yield metrics.

Given tradeoffs between the different performance indicators, the choice of a preferred HCR is dependent on the priorities of the respective managers and stakeholders regarding the different management objectives and their level of risk aversion.

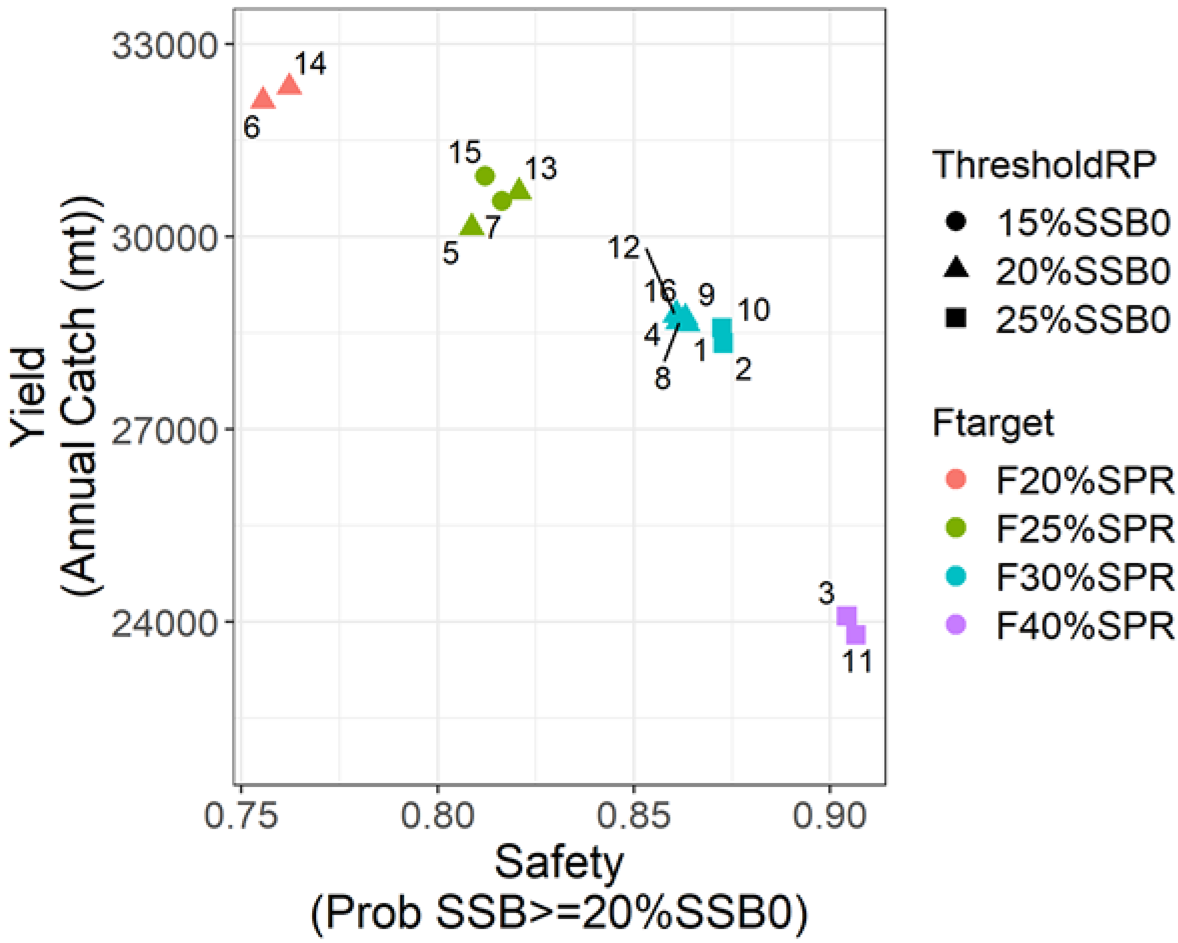

Figure ES6. Median annual total catch versus the probability of spawning stock biomass (SSB) being at or above the second rebuilding target of 20%$SSB_{F=0}$. Note that to ensure that for both measures a higher value is better, here we reversed the second performance metric shown in Fig. ES5 to be the probability of SSB≥20%$SSB_{F=0}$ instead of the probability of SSB<20%$SSB_{F=0}$. Each HCR is labeled and represented by a symbol colored according to their F_{TARGET}. The ThresholdRP is the first control point for each HCR and stands for threshold reference point.

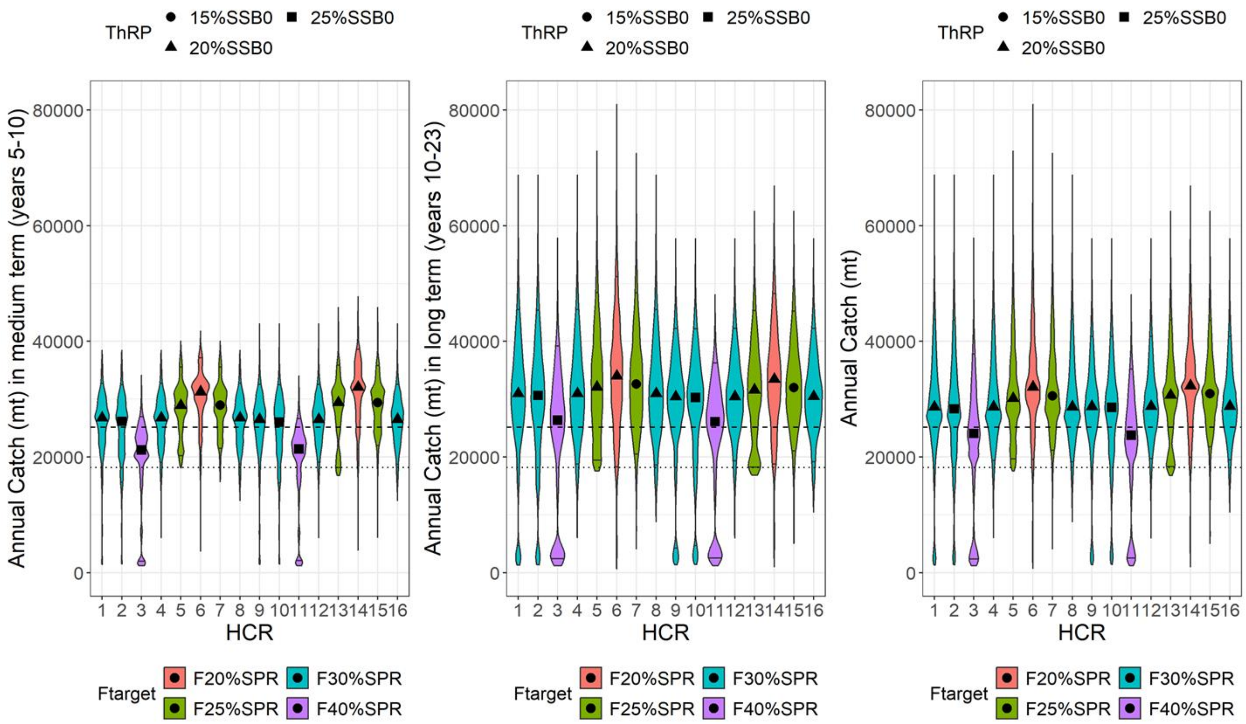

Figure ES7. Violin plots showing the probability density of total annual catch (including discards and the EPO recreational fleet) for each harvest control rule (HCR) across all iterations, reference scenarios, and simulation years in the medium term (first panel), long term (second panel), and all years (third panel). The medium term shows the annual catch distribution over years 5 to 10 of the simulation, the long term over years 10 to 23 of the simulation. The marker inside each violin plot is the median medium term, long term, or annual catch and horizontal solid lines within each violin represent the 5th to 95th quantile range. The ThRP is the first control point for each HCR and stands for Threshold reference point. Colors represent the F_{TARGET} reference point associated with each HCR. The dotted line identifies the total catch limit set by the WCPFC's CMM 23-02 plus IATTC's Resolution C-21-05, effective in 2024, plus EPO recreational catches for calendar year 2023. The dashed line identifies the total catch limit set by the WCPFC's CMM 24-01 plus IATTC's Resolution C-24-02, effective in 2025, plus EPO recreational catches for calendar year 2023. For the IATTC's resolution, catch limits were based on half of the biennial TAC.

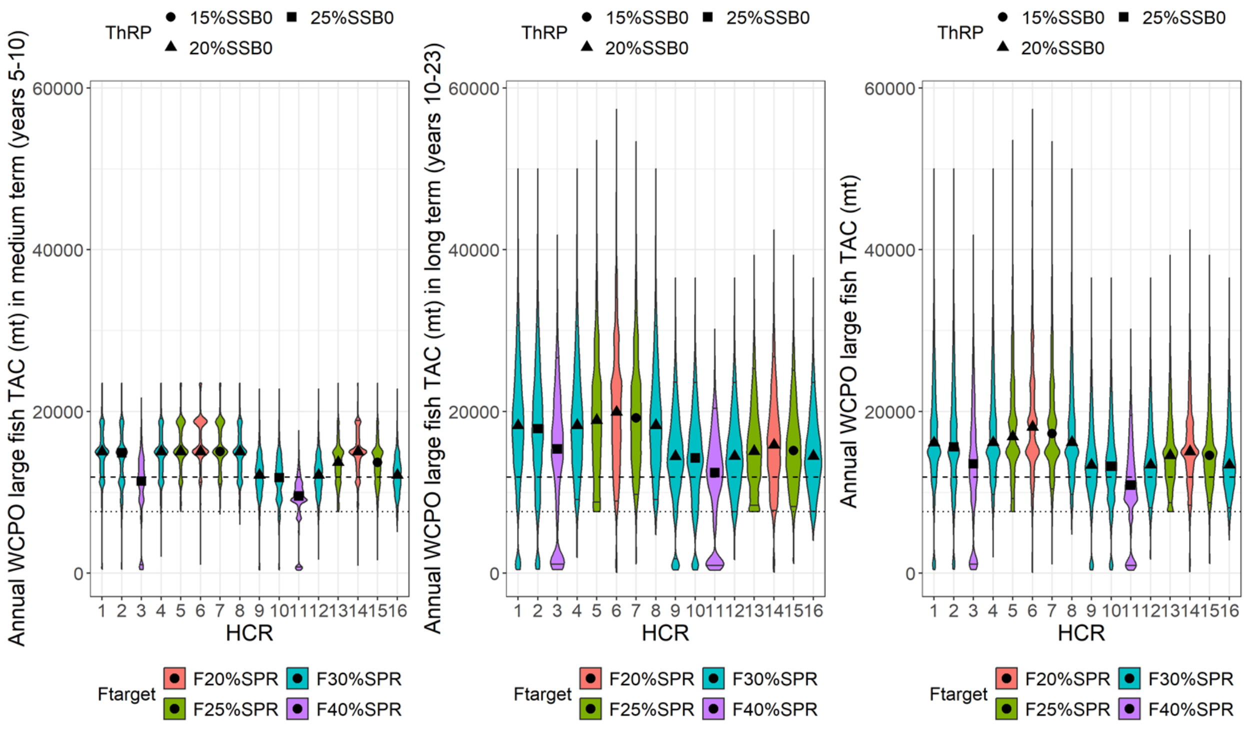

Figure ES8. Violin plots showing the probability density of the TAC for the Western Central Pacific Ocean (WCPO) large fish fleets for each harvest control rule (HCR) across all iterations, reference scenarios, and simulation years in the medium term (first panel), long term (second panel), and annually (third panel). The medium term shows the annual catch distribution over years 5 to 10 of the simulation, the long term over years 10 to 23 of the simulation. The marker inside each violin plot is the median medium term, long term, or annual TAC and horizontal solid lines within each violin represent the 5^{th} to 95^{th} quantile range. The ThRP is the first control point for each HCR and stands for Threshold reference point. Colors represent the F_{TARGET} reference point associated with each HCR. The dotted line identifies the catch limit for large fish set by the WCPFC's CMM 23-02, effective in 2024. The dashed line identifies the catch limit for large fish set by the WCPFC's CMM 24-01, effective in 2025.

Figure ES9. Violin plots showing the probability density of the TAC for the Western Central Pacific Ocean (WCPO) small fish fleets for each harvest control rule (HCR) across all iterations, reference scenarios, and simulation years in the medium term (first panel), long term (second panel), and annually (third panel). The medium term shows the annual catch distribution over years 5 to 10 of the simulation, the long term over years 10 to 23 of the simulation. The marker inside each violin plot is the median medium term, long term, or annual TAC and horizontal solid lines within each violin represent the 5th to 95th quantile range. The ThRP is the first control point for each HCR and stands for Threshold reference point. Colors represent the F_{TARGET} reference point associated with each HCR. The dotted line identifies the catch limit for small fish set by the WCPFC's CMM 23-02, effective in 2024. The dashed line identifies the catch limit for small fish set by the WCPFC's CMM 24-01, effective in 2025.

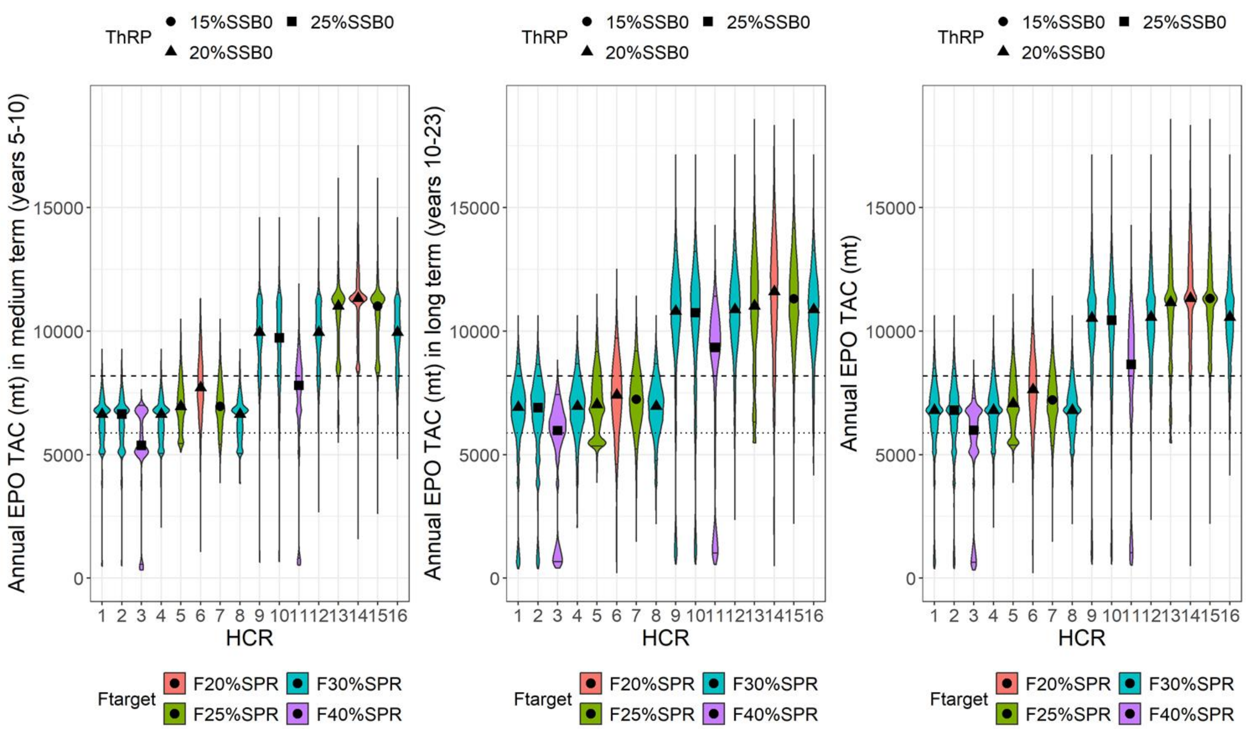

Figure ES10. Violin plots showing the probability density of the TAC for the Eastern Pacific Ocean (EPO) fleets for each harvest control rule (HCR) across all iterations, reference scenarios, and simulation years in the medium term (first panel), long term (second panel), and annually (third panel). The medium term shows the annual catch distribution over years 5 to 10 of the simulation, the long term over years 10 to 23 of the simulation. The marker inside each violin plot is the median medium term, long term, or annual TAC and horizontal solid lines within each violin represent the 5th to 95th quantile range. The ThRP is the first control point for each HCR and stands for Threshold reference point. Colors represent the F_{TARGET} reference point associated with each HCR. The dotted line identifies the catch limit for the EPO set by IATTC's Resolution C-21-05, effective in 2024, plus EPO recreational catches for calendar year 2023. The dashed line identifies the catch limit set by IATTC's Resolution C-24-02, effective in 2025, plus EPO recreational catches for calendar year 2023. Catch limits were based on the half of the biennial TAC. Note that in the MSE, the EPO TAC includes recreational fleets.

3. *Catch in the medium and long term for all HCRs are expected to be higher than the current catch limit, except for HCRs 3 and 11 in the medium term. However, the expected TAC trends differ among fleets, with only the WCPO large fish fleet and the EPO with a 70:30 impact ratio increasing above current catch limits.*

While median catch increased with a higher F_{TARGET}, median catches of all HCRs, except for HCRs 3 and 11 in the medium term and across all years, reached higher levels than the current catch limit (Fig. ES7). All HCRs had a long term catch higher than the current catch limit (Fig. ES7). Across all HCRs, the increase in catch above the current catch limit was due to increases in the WCPO large fish TAC (Figs. ES8, ES9, and ES10). The WCPO large fish TAC was always higher than the current catch limits for all HCRs, except for HCRs 3 and 11 in the medium term and for HCR 11 across all years (Fig. ES8). The WCPO small fish TAC was always smaller than the current catch limits for all HCRs (Fig. ES9). The EPO TAC was larger only for HCRs 9 to 16, which had a higher EPO fisheries impact (Fig. ES10). In the MSE, allocation of catch across the different fleet segments is set by the relative allocation of fishing mortality across fleets, which is set to the 2015-2022 baseline agreed upon by the JWG. These patterns are also affected by the fact that as the population biomass grows throughout the simulation, more biomass accumulates in older age classes, while average numbers of recruits and juveniles targeted by the WCPO small fish fleet segment and EPO may remain more stable. Furthermore, the TAC is dependent on estimates of numbers at age from the terminal year, which for young age classes are uncertain due to the lack of a recruitment or juvenile index. Thus, the estimation model tends to always estimate current recruitment to the average of the stock-recruitment function, leading to relatively low and stable small fish TACs.

4. *HCRs 1, 2, 3, 9, 10, and 11, had more instances of drastic (>25%) declines in catches due to severe management intervention resulting from breaching their respective LRP more often than other HCRs.*

HCRs 1, 2, 3, 9, 10, and 11 have longer lower tails in the annual catch violin plots in Fig. ES7, implying more instances of very low catch values. This is a result of more instances of severe management intervention due to their higher LRPs, which are breached more often than other HCRs. Indeed, worm plots of total TAC show that these HCRs have more instances where TAC declines dramatically (Fig. ES12) and these HCRs have the lowest 5th quantiles of TAC (Figs. ES7 and ES11).

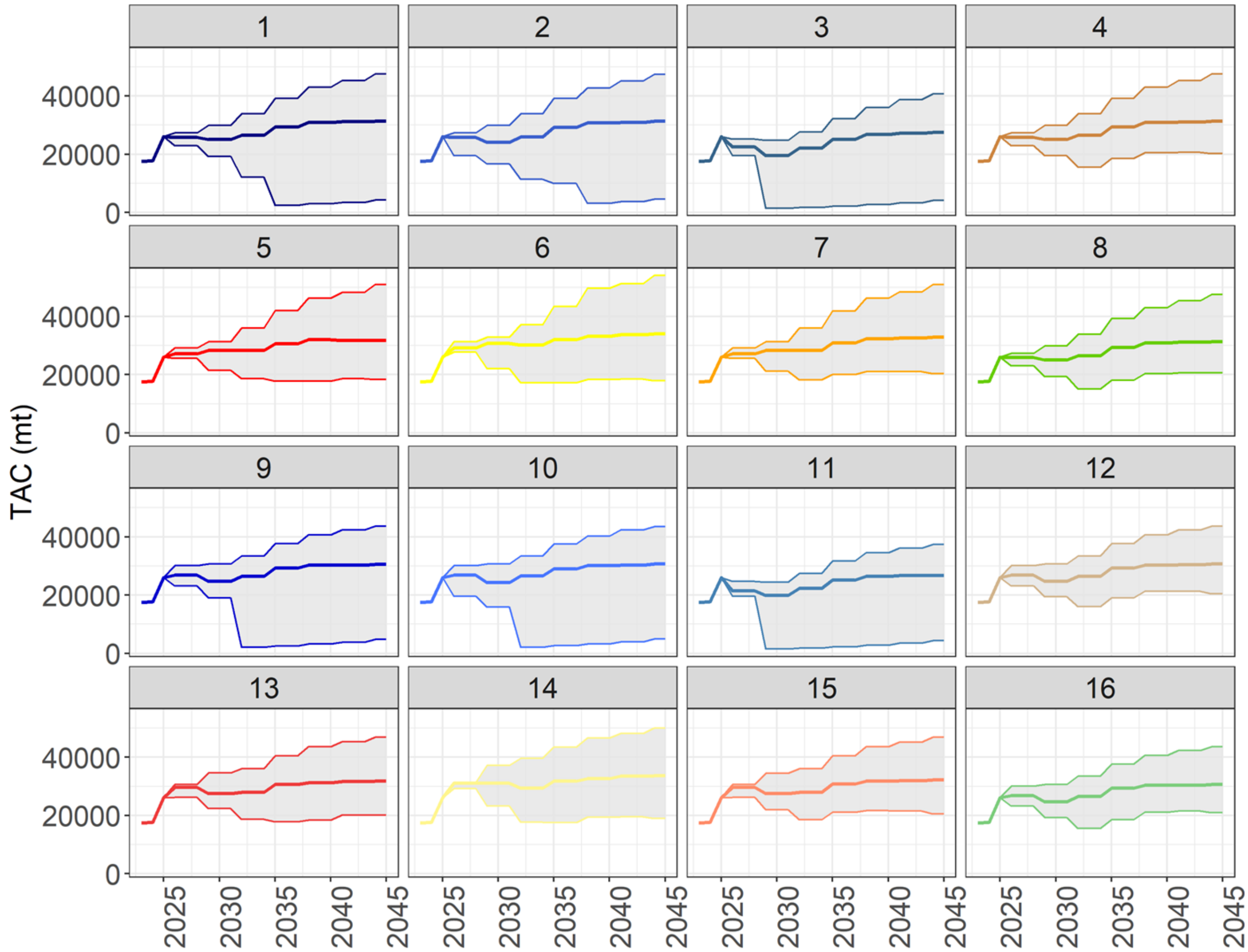

Figure E11 Trends in median total allowable catch (TAC) set by each harvest control rule (HCR) under all iterations and reference scenarios by harvest control rule (HCR). The grey shading represents trends in the 5th to 95th quantiles of TAC.

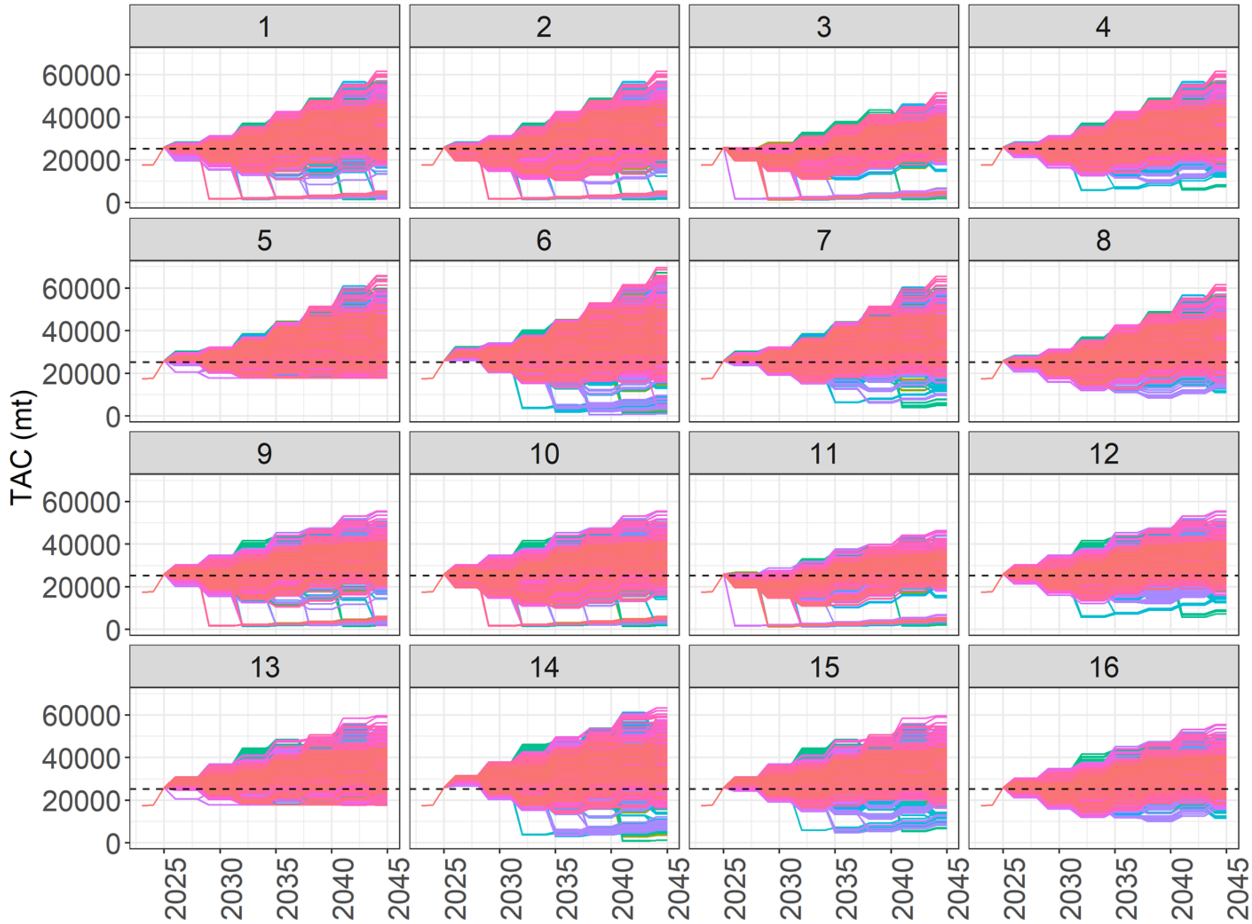

Figure ES12. Worm plots of the total allowable catch (TAC) set by each harvest control rule (HCR) for individual runs for each HCR and all reference scenarios. Each panel presents the results for the labeled HCR. Trajectories represent separate iterations differing in simulated random recruitment deviates. The dashed line represents the current catch limit set by the WCPFC's CMM 24-01 and IATTC's Resolution C-24-02, plus EPO recreational catches for calendar year 2023. For the IATTC's resolution, catch limits were based on half of the biennial TAC..

5. *HCRs with a first control point (i.e., ThRP) closer to the target SSB (SSB associated with their F_{TARGET}) had lower catch stability.*

HCRs 2, 5, 6, 10, 13, and 14 have a first control point that is closer to the target SSB than other HCRs (Table ES2). This leads to more frequent large reductions in fishing intensity and lower stability (Figs. ES13, ES14, Table ES4). HCRs 3 and 11 have the largest differences between their first control point and the SSB associated with their F_{TARGET} and have the highest catch stability when SSB is at or above the LRP (Figs. ES13, ES14, Table ES4). However, due to the built-in 25% limit on TAC change in each HCR, all HCRs met the stability objective.

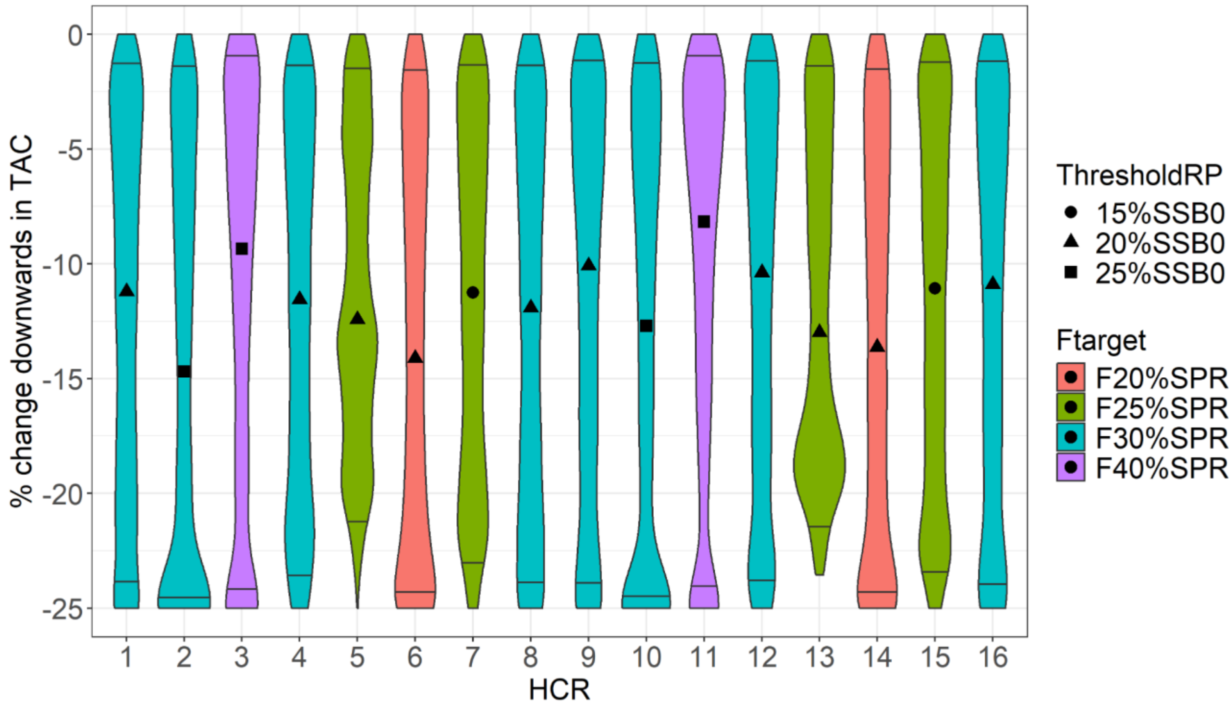

Figure E13. Violin plots showing the probability density of downward changes in TAC between management periods when SSB≥LRP for each harvest control rule (HCR) across all iterations, reference scenarios, and simulation years. The marker inside each violin plot is the median downward change in TAC and horizontal solid lines within each violin represent the 5^{th} to 95^{th} quantile range.

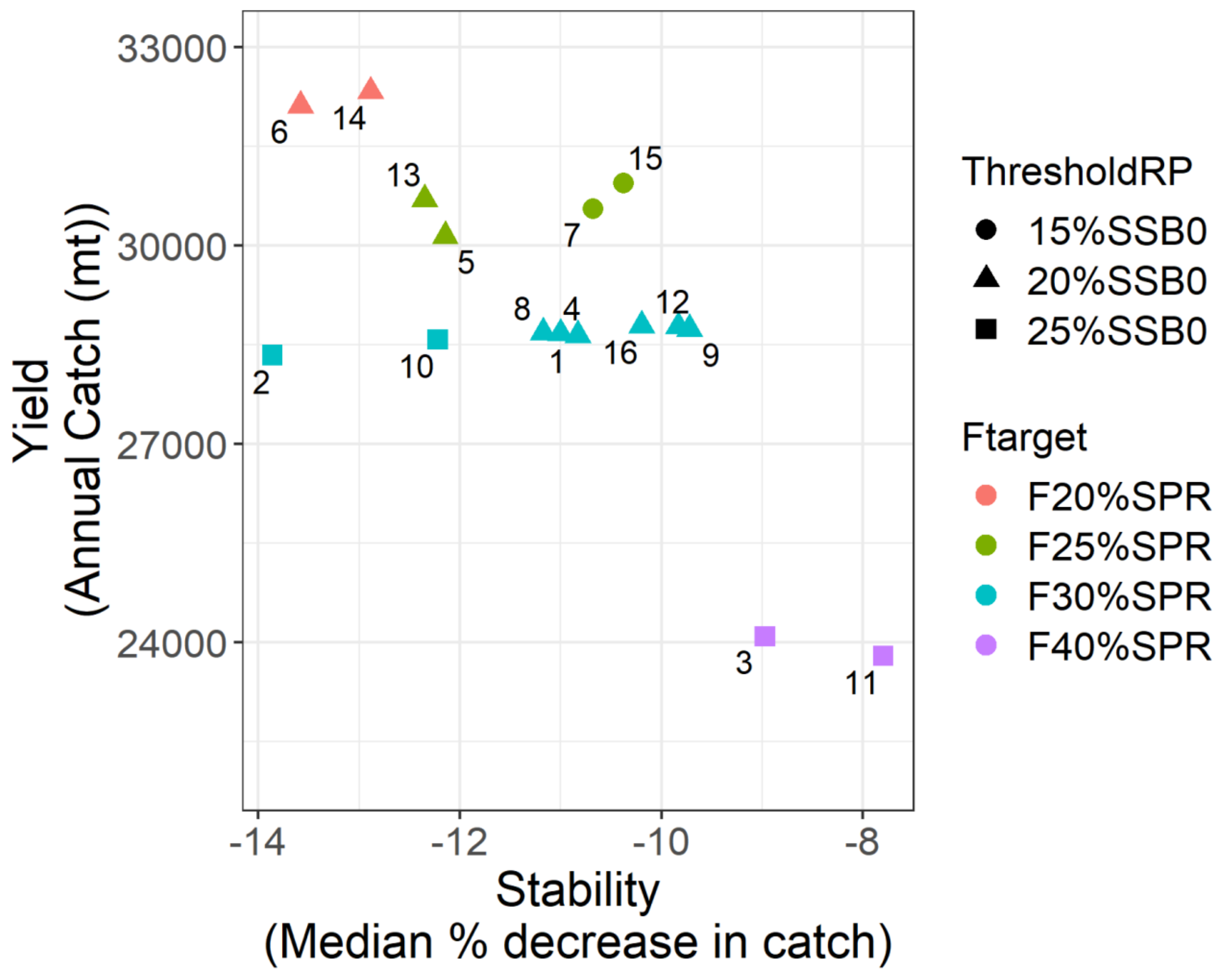

Figure E14 Median annual total catch versus the median decrease in catch between management periods. Each HCR is labeled and represented by a symbol colored according to their F_{TARGET}. The ThresholdRP is the first control point for each HCR and stands for Threshold reference point.

6. *All HCRs met the status objective of maintaining fishing mortality at or below the F_{TARGET} with at least 50% probability.*

Despite uncertainties in stock productivity, recruitment variability, observation, estimation, and implementation, all HCRs met the status objective and maintained fishing mortality at or below the F_{TARGET} with at least 50% probability (Fig. ES15, Table ES4). For all HCRs, this probability was higher than 50% because the EM estimated fishing mortality as being lower than in the OMs, leading to a median F that was lower than the F_{TARGET} for all HCRs. The probability was highest for HCRs 1, 2, 3, 9, 10, and 11 because they had a higher LRP, resulting in drastic management interventions occurring more often. Once F fell to these low levels, it was slow to increase due to the 25% limit in TAC changes between management periods, even if biomass rebuilt quickly, leading to median F being lower.

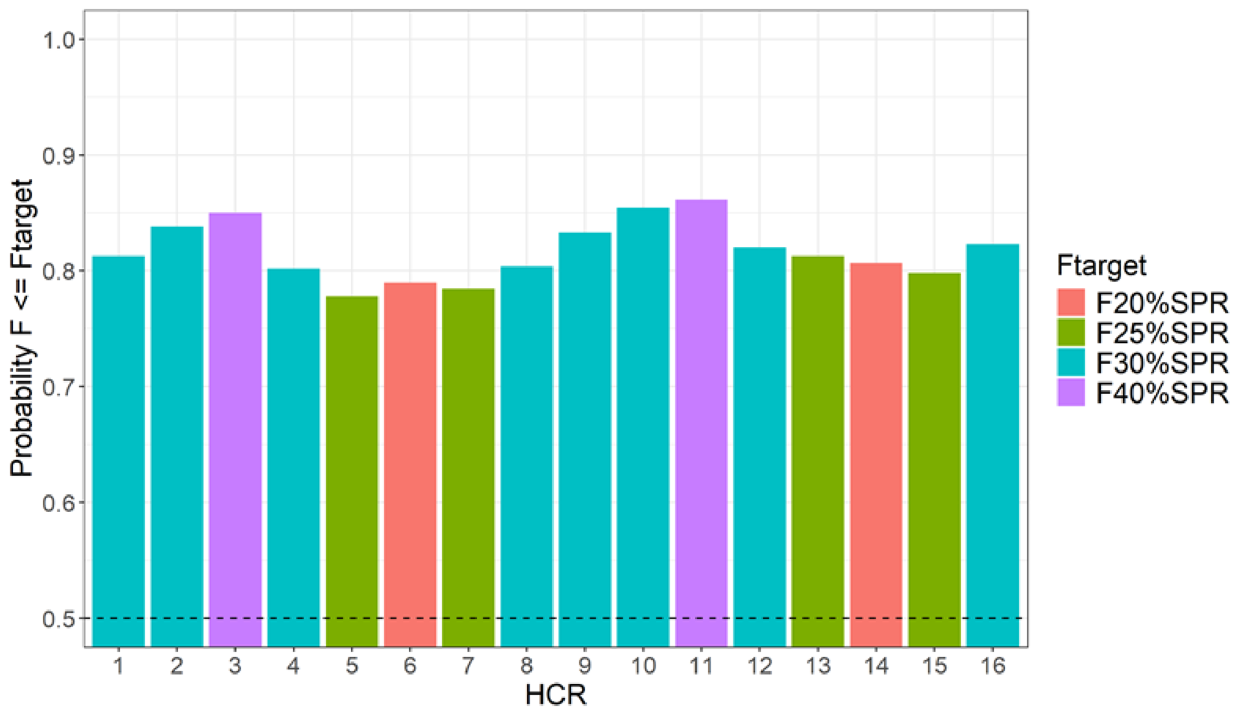

Figure ES15. Plot of the first status performance metric, the probability, for each harvest control rule (HCR), of fishing mortality (F, 1-SPR) being less or equal to the F_{TARGET} across all reference scenarios, iterations, and simulation years. The horizontal dotted line represents a 50% probability.

7. *The different fisheries impact ratios only affected yield metrics but other performance metrics remain almost unchanged.*

HCRs 1 to 8 maintained the current WCPO:EPO fisheries impact ratio (about 80:20), while HCRs 9 to 16 were tuned to meet a 70:30 ratio. We would then expect higher yield for EPO fleets and lower yields for WCPO fleets under HCRs 9 to 16 (Figs. ES7, ES8, and ES9). All other metrics remained quite similar (Table ES4). Other performance metrics remained almost unchanged as shown in various tables and figures.

Table ES4. Performance indicators for each harvest control rule (HCR) across all iterations, evaluation years, and operating models. SSB refers to spawning stock biomass, LRP to limit reference point, SSB_0 refers to unfished spawning stock biomass, F refers to fishing mortality measured as 1-SPR where SPR is spawning potential ratio, TAC refers to total allowable catch, WCPO refers to Western Central Pacific Ocean and EPO refers to Eastern Pacific Ocean. Note that to ensure that for all indicators a higher value is better, here we reversed the performance metrics showed in Figures ES2 and ES3 to be the probability of SSB≥LRP and of $SSB \geq 20\%SSB_{F=0}$ instead of the probability of SSB<LRP and $SSB < 20\%SSB_{F=0}$. The % change upwards in TAC (% change TAC +) was set to negative so that high values are better. The % change downwards does not include years when SSB is below LRP as provided by the management objective. The value including when SSB is below LRP is provided in the main body of the report. The 2026 TAC is the total TAC and for each fleet segment that could be applied in 2026 if each of the HCR would be adopted. It is calculated based on biomass status estimated by EM. Color shadings reflect the range of each column. Highest levels have dark green, lowest light yellow, and different shades of green to yellow are in between.

Performance Indicators

Reference Set

	Prob SSB => LRP	Prob SSB => 20%SSBo	Prob F <= Ftarget	Prob SSB => SSBtarget	% change TAC +	% change TAC -	EPO Impact	Median annual catch	Median year 5-10 average catch	Median year 11-23 average catch	Median WCPO large fish annual TAC	Median WCPO small fish annual TAC	Median EPO annual TAC	2026 TAC	2026 TAC WCPO large fish	2026 TAC WCPO small fish	2026 TAC EPO
1	93	86	81	62	-14	-11	23	28644	28253	31229	16119	4088	6794	25868	14836	4512	6520
2	93	87	84	64	-16	-14	23	28339	27764	31198	15621	4064	6794	25868	14836	4512	6520
3	90	90	85	55	-17	-9	24	24091	22238	27860	13529	3344	5984	24366	14836	3844	5686
4	99	86	80	61	-13	-11	23	28671	28253	31229	16170	4097	6794	25868	14836	4512	6520
5	100	81	78	66	-13	-12	22	30141	30409	31978	16885	4612	7069	27485	14836	5161	7488
6	99	76	79	76	-13	-14	22	32115	32195	32731	18074	5057	7631	29437	14836	5939	8662
7	100	82	78	67	-13	-11	23	30552	30409	32166	17251	4551	7206	27485	14836	5161	7488
8	100	86	80	61	-13	-11	23	28686	28253	31229	16178	4095	6794	25868	14836	4512	6520
9	93	86	83	62	-13	-10	32	28739	27454	30160	13367	3722	10524	27942	14073	4392	9476
10	93	87	85	64	-16	-12	32	28579	27281	30105	13239	3722	10442	27942	14073	4392	9476
11	91	91	86	55	-16	-8	32	23796	22371	26720	10900	3023	8650	23653	10724	3844	9085
12	99	86	82	61	-12	-10	33	28776	27454	30160	13396	3722	10563	27942	14073	4392	9476
13	100	82	81	68	-13	-12	30	30697	30119	31190	14561	4160	11163	29323	14836	5010	9476
14	99	76	81	76	-15	-13	31	32326	33075	31719	15040	4591	11323	30061	14836	5749	9476
15	100	81	80	66	-12	-10	32	30944	30119	31395	14555	4106	11323	29323	14836	5010	9476
16	100	86	82	61	-12	-10	33	28789	27454	30258	13396	3722	10562	27942	14073	4392	9476

8. *Under robustness tests, all HCRs were robust to discard and effort-creep uncertainty, but performance deteriorated under extreme drops (40%) in recruitment over a 10 year period.*

Under robustness tests where HCRs faced more unlikely but still possible situations, the performance naturally deteriorated as they were placed in more extreme conditions. Nonetheless, all the HCRs were fairly robust to the "doubling of the discard" scenario and the "effort-creep" scenario. However, although the degree was different among HCRs, all HCRs had difficulty in dealing with the "recruitment drop" scenario. This is expected because the MPs only respond to the assessed terminal SSB. Since PBF fully mature at 5 years of age and the abundance trend was informed only by the longline CPUE index, which informs the relative biomass of age 7 and older, it takes several years for the EM to detect a decline in SSB from the recruitment drop and for the MPs to initiate a significant reduction in catches. In the meantime, small fish catches remain an important component of the fishing mortality. Once the EM eventually detected the decrease of SSB, F was curtailed, and SSB ultimately rebuilt back to target levels (TBC) . It is therefore important to carefully monitor a recruitment index and also SSB through regular assessments to timely detect if a chronic decline of recruitment occurs and to consider appropriate exceptional circumstances provisions to swiftly deal with such a situation. For more details see the main body of the report.

Key Limitations

- Fleet selectivity was assumed to be constant at the current average of 2015-2022 levels throughout the simulation. If fleet operations and targeting behavior changes in the future so that the size composition of catch of specific fleets differs widely from what was simulated, results from this analysis may no longer be applicable.
- The operating models were conditioned on data from 1983 onwards, thus the management procedures tested here are robust to uncertainty in productivity that was bound by those historical observations. If future population dynamics strongly diverge from the past, results from this analysis may no longer be applicable.