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EXECUTIVE SUMMARY *(DRAFT)*

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). The WCPFC-NC and IATTC PBF Joint Working Group (JWG) was started to coordinate PBF management between these two RFMOs. Fishing records date back to the 1800s, and the stock has experienced high fishing pressure, with spawning stock biomass (SSB) falling to 2% of the 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%$SSB_{F=0}$. These management measures were successful, with SSB surpassing the second rebuilding target in 2021.

Now that the stock has rebuilt to the second rebuilding target of 20%$SSB_{F=0}$, the RFMOs have tasked the ISC PBF working group (WG) with developing a management strategy evaluation (MSE) to inform the development of a long-term management procedure (MP) for PBF. MSE is a process that evaluates the tradeoffs and performance of candidate MPs under a range of uncertainties using computer simulations. Testing MPs in an MSE allows for the ruling out of those MPs that do not perform adequately in computer simulations 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 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 the performance of 16 candidate management procedures, relative to the set of management objectives and performance metrics agreed-upon by the RFMOs given uncertainties, using a closed loop computer simulation. The closed loop simulation recreates the real-world management process, from data collection, assessment of stock status, and management procedure implementation (Fig. ES1).

An MP 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 MPs in this MSE only differ in terms of the HCRs and associated control points used. As in the real world, estimates of the condition of the PBF stock relative to control points are calculated via a simulated stock assessment, referred to as the estimation model (EM). For this MSE, the EM 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 were 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 would occur in the real world. Data on catch, size composition, and the index of abundance are generated, with observation errors, from operating models (OMs), which are mathematical representations of the possible true dynamics of the stock and fisheries (Fig. ES1). These observations are then fed into the simulated stock assessment (i.e., the EM). As in the real world, the results from the simulated assessment are then used to inform the 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 the PBF stock (Fig. ES1). At the end of the 23-year long simulation, output from the OMs is used to compute performance metrics to assess the performance relative to the set of management objectives of each of the candidate HCRs.

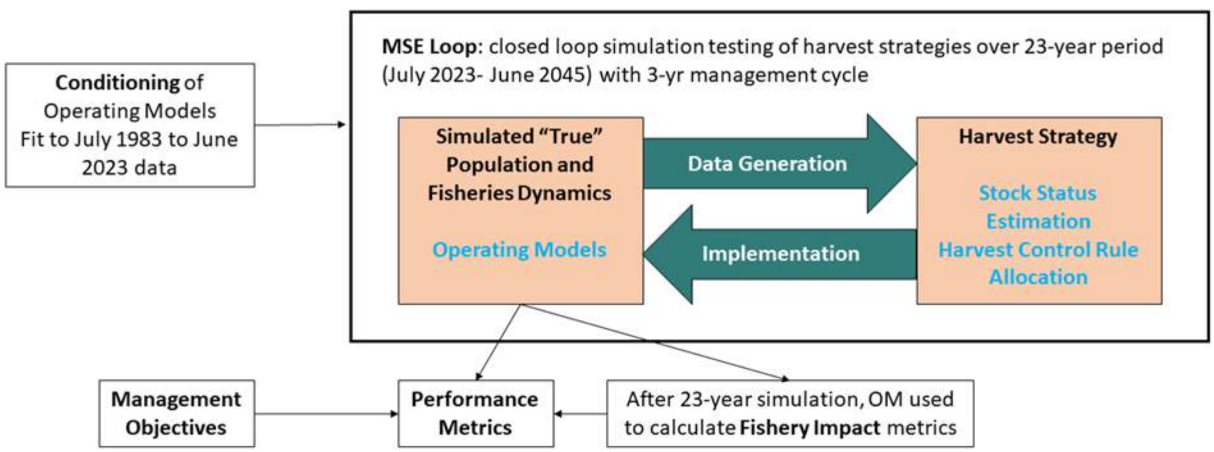

Figure ES1. Overview of the PBF MSE closed-loop simulation framework showing the MSE feedback loop where data are sampled with error from the operating models and fed into the management procedure, which includes a simulated assessment, which determines stock status and informs the harvest control rule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

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 JWG meetings. These are outlined in Table ES1. Performance indicators were used to quantitatively evaluate the performance of the HCRs tested relative to the management objectives.

Harvest Control Rules

The HCRs and reference points considered in this MSE (Table ES2) were put forward by the JWG. The HCRs specify a management action based on SSB 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 EM. 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 calculated based on the EM but outside 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 are available. The potential TACs are listed in Table ES4.

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%.

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. An F_{TARGET} of FSPR40% is associated with a fishing mortality that would leave 40% of the SSB per recruit 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 LRP, 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 from 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

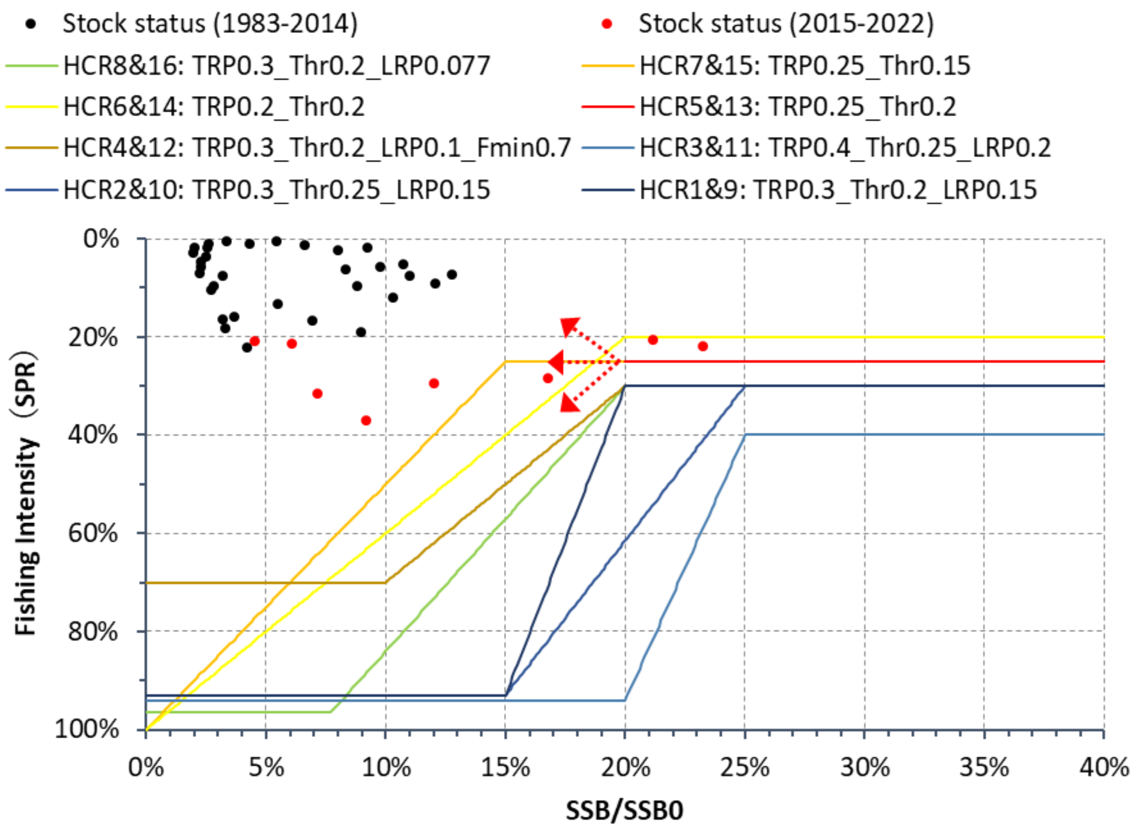

Figure ES2. Candidate HCR evaluated in the PBF MSE. Fishing intensity is an indicator of fishing mortality based on SPR. SPR is the spawning potential ratio that would result from the current year's pattern and intensity of fishing mortality relative to the unfished stock. SSB/SSB0 is SSB relative to 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 to the one applied in 2015-2022, is used 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 that HCRs 9 to 16 are not represented as they are identical in shape to HCRs 1 to 8.

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 assessments. 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. 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. Figure ES2 outlines, for each HCR, the allowed F 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, the allowed F is reduced, except for HCR 5 and 13, 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 F as estimated by the latest stock assessment has never been at a 40%SPR level, even when the stricter management measures were in place (Fig. ES2).

It is important to note that the LRPs and TRPs in the HCRs serve both as control points of management actions and as measuring sticks to evaluate performance. However, control points can differ 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.

Uncertainties considered

MSE recreates the real-world management process to ensure that management procedures will work even in the presence of errors in the observations, assessment, and implementation. The PBF MSE framework therefore adds realistic error to the data used in the simulated stock assessments (i.e., the EMs). As in the real world, the MSE framework also runs the EM every three years and estimates stock status with this data to ensure that estimation error is considered. The MSE also simulates a realistic lag between the availability of data used in the assessment and the implementation of management actions. For instance, the first EM in the MSE uses data up to fishing year 2023 (i.e., up to June 2024) to set a TAC that is applied starting in calendar year 2026. TACs are 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 includes an implementation error by adding 1.2% higher catch than set by the HCR to EPO recreational fleets, 5% higher to the WCPO fleets except for the Japanese troll for penning fleet, which is set at 100% higher 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 addressed by developing 20 different OMs, each representing an equally plausible "true" version of the system. In developing the potential OMs, the ISC PBF WG reviewed potential sources of uncertainty for the PBF stock and identified natural mortality, growth, and the steepness parameter as the most influential sources of uncertainty. The PBF WG then diagnosed plausible ranges for these parameters and developed population dynamics models using the resulting parameter combinations. Models that passed a series of quantitative diagnostic tests to ensure they were plausible and could reasonably replicate past 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 statuses (Fig. ES3). All results and performance metrics are calculated across this entire reference set.

In addition to the reference set, the PBF WG also developed 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 longline fleet on which the main index of abundance is based; and 3) about a 40% 10-year long drop in recruitment, starting from 2042. These robustness OMs were constructed by modifying OM1, which has the same settings 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 stable, the MSE also considered process uncertainty in recruitment. This was done by, for each OM, sampling recruitment deviations from a normal distribution with a mean of 0 and standard deviation σ_R=0.6 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 had an extremely high estimation error (> 1000% absolute relative error) or produced unrealistically low estimated SSB (less than 1 fish) that were not seen in the OMs 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 81 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**	**OM #**	**M_{2+}**	**L_2**	**h**
1	0.25	118.57	0.999	12	0.25	118.57	0.99
2	0.25	118	0.91	13	0.25	119	0.99
3	0.193	118.57	0.97	14	0.25	118	0.97
4	0.193	118	0.999	15	0.25	119	0.97
5	0.193	118	0.99	16	0.25	118	0.95
6	0.193	118.57	0.99	17	0.25	118.57	0.95
7	0.193	119	0.99	18	0.25	119	0.95
9	0.25	118	0.999	19	0.25	118	0.93
10	0.25	119	0.999	20	0.25	118.57	0.93
11	0.25	118	0.99	21	0.25	119	0.93

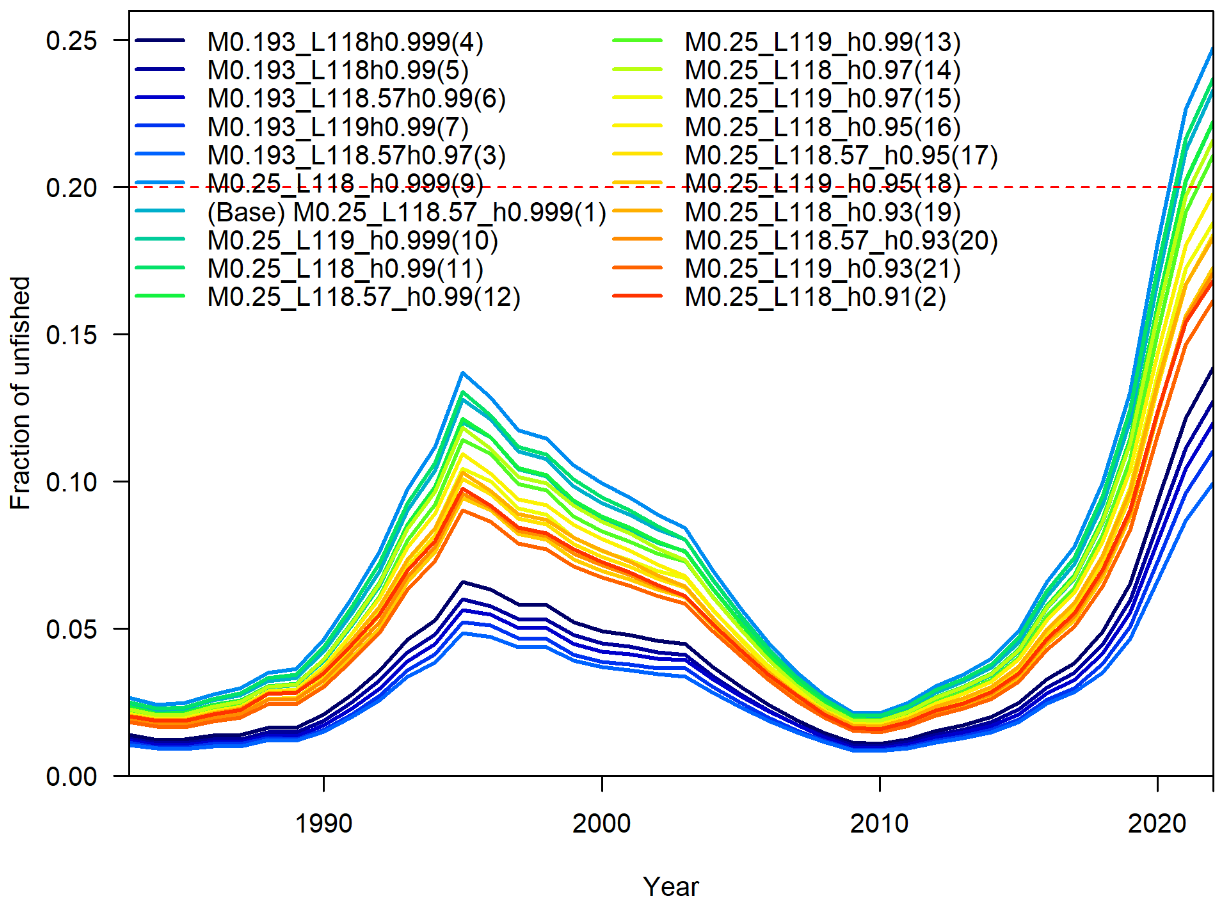

Figure ES3. Historical trajectory of the relative spawning stock biomass estimated from each of the 20 operating models (OMs) in the reference set representing different productivity scenarios and their parameter specifications. The dashed line indicates the rebuilding target at 20%$SSB_{F=0}$. The models were considered equally plausible and given equal weight in the calculation of performance metrics. M refers to natural mortality for age 2 and older fish, L refers to the length at age 3, and h refers to steepness. The OM number in parentheses refers to **Table ES2**. OM 1 has the same parameter specifications as the current base case stock assessment for Pacific bluefin tuna.

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 targets (Fig. ES4).*

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 a 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. ES5 and ES6, Table ES4). Furthermore, all HCRs except 6 and 14, had a less than 20% probability of SSB being below the second rebuilding target of 20%$SSB_{F=0}$ (Fig. ES7, Table ES4). Also, under all HCRs, median SSB increased from initial conditions to levels above their respective targets (Fig. ES4).

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 $SSB_{F=0}$).

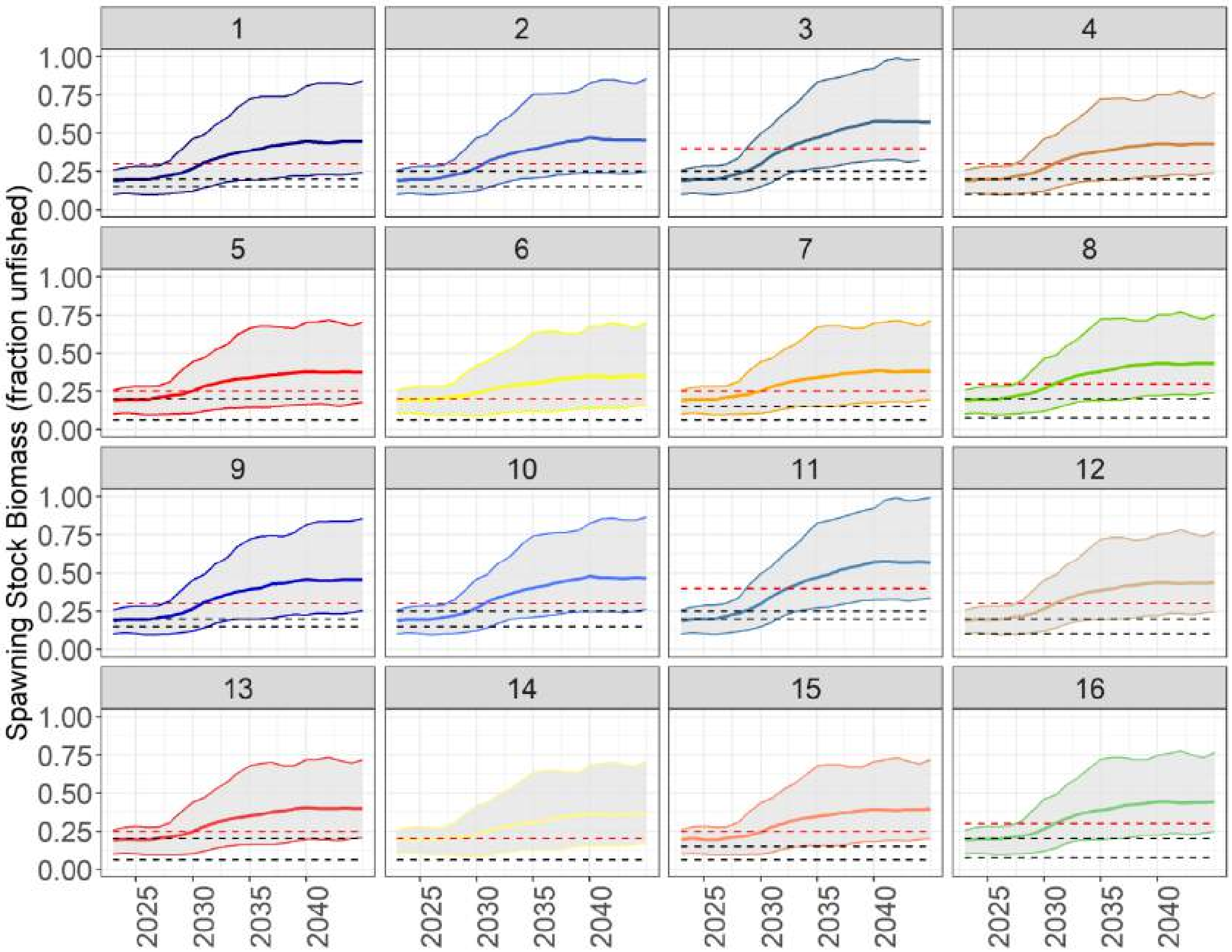

Figure ES4. Trends in median relative spawning stock biomass (SSB/unfished SSB, thick solid color lines) from the operating models under all iterations and reference scenarios by harvest control rule (HCR). The grey shading represents trends in the 5th to 95th quantile range. The lowest black dotted line represents the lowest control point for each HCR, and the highest black dotted line represents 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 lowest dashed line marks the LRP specified by the JWG to assess performance.

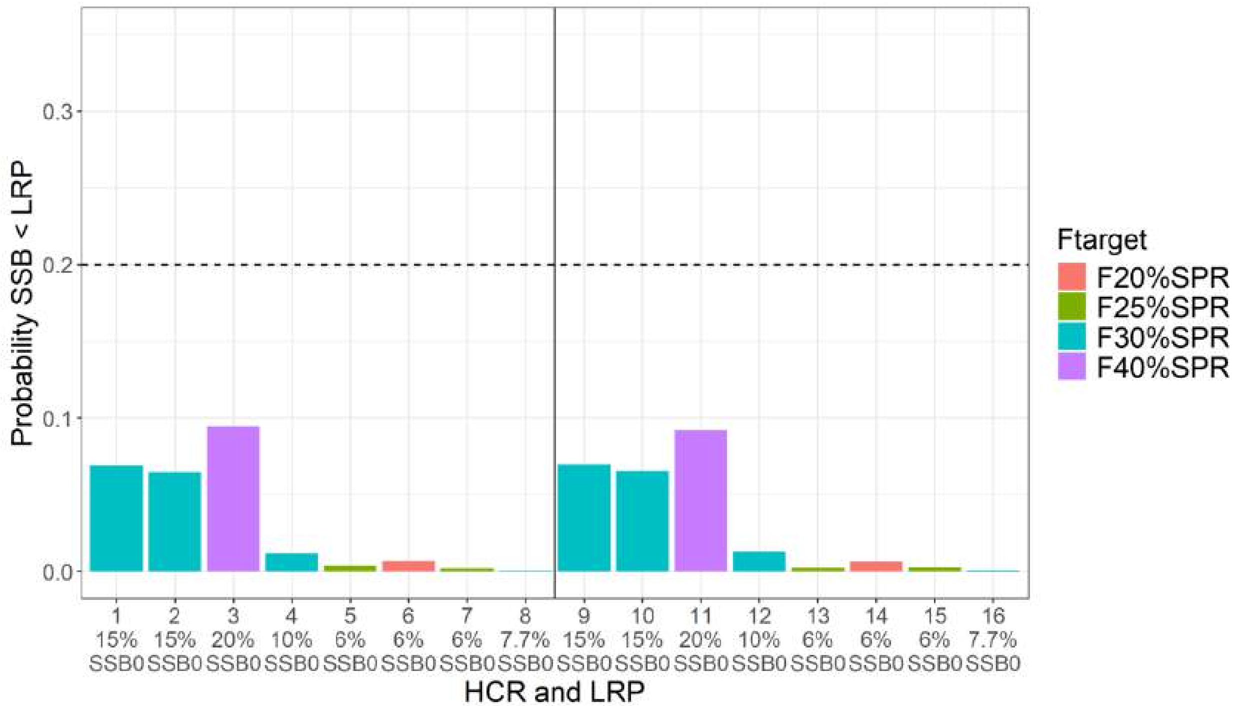

Figure ES5. Probability, for each harvest control rule (HCR), of spawning stock biomass (SSB) being below the limit reference point (LRP) specified by each HCR across all reference scenarios, iterations, and simulation years. Colors represent the F_{TARGET} reference point associated with each HCR. The x-axis shows both the HCR number and the LRP relative biomass level associated with each HCR. The vertical solid line separates HCRs 9 to 16, which are tuned to an EPO:WCPO impact ratio of 30:70 but are otherwise the same as HCRs 1 to 8. EPO stands for Eastern Pacific Ocean and WCPO for Western Central Pacific Ocean.

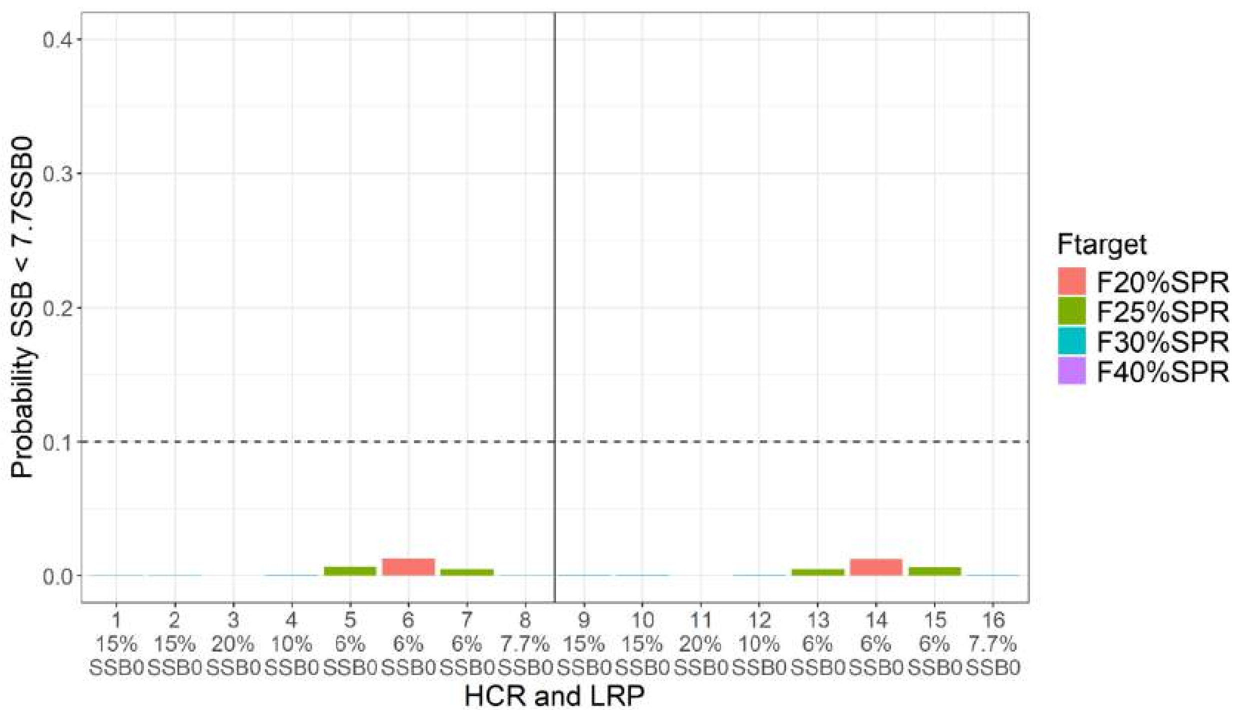

Figure ES6. Probability, for each harvest control rule (HCR), of spawning stock biomass (SSB) being less than 7.7%$SSB_{F=0}$ across all reference scenarios, iterations, and simulation years. The x-axis shows both the HCR number and the LRP relative biomass level associated with each HCR. Colors represent the F_{TARGET} reference point associated with each HCR. The horizontal dotted line represents a 10% probability. The vertical solid line separates HCRs 9 to 16, which are tuned to an EPO:WCPO impact ratio of 30:70 but are otherwise the same as HCRs 1 to 8. EPO stands for Eastern Pacific Ocean and WCPO for Western Central Pacific Ocean.

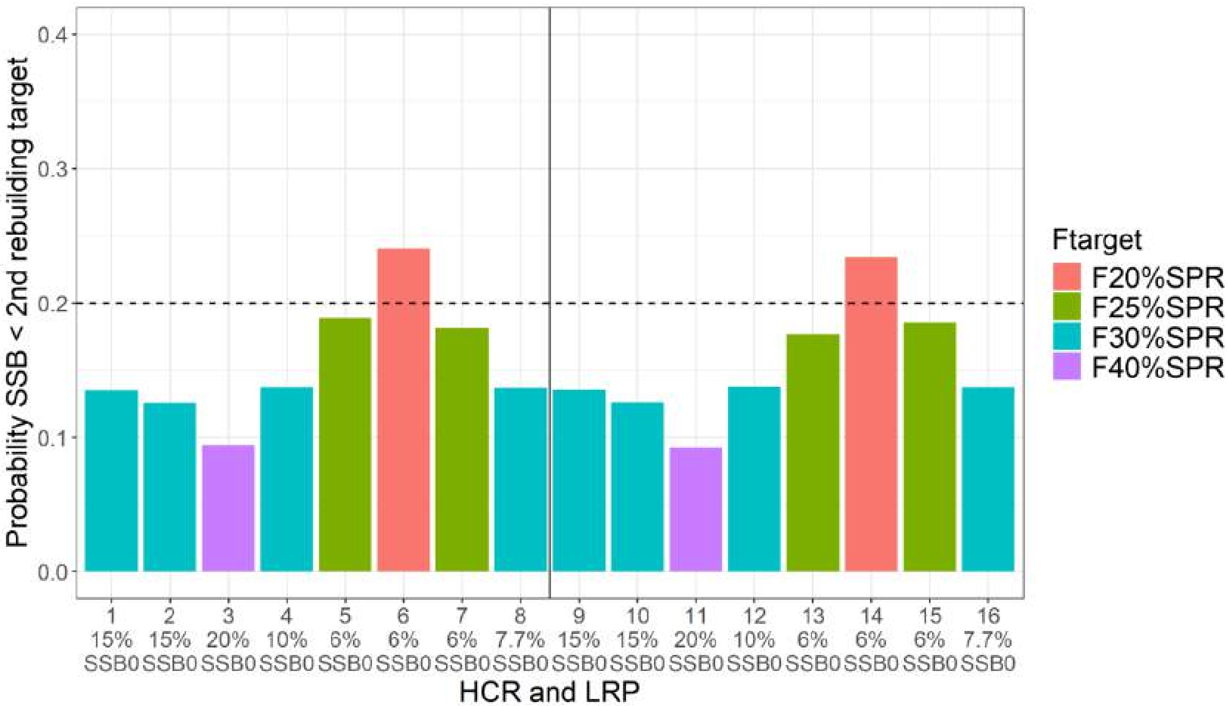

Figure ES7. Probability, for each harvest control rule (HCR), of spawning stock biomass (SSB) being less than 20%$SSB_{F=0}$ across all reference scenarios, iterations, and simulation years. The x-axis shows both the HCR number and the LRP relative biomass level associated with each HCR. Colors represent the F_{TARGET} reference point associated with each HCR. The horizontal dotted line represents a 20% probability. The vertical solid line separates HCRs 9 to 16, which are tuned to an EPO:WCPO impact ratio of 30:70 but are otherwise the same as HCRs 1 to 8. EPO stands for Eastern Pacific Ocean and WCPO for Western Central Pacific Ocean.

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 or above the second rebuilding target of 20%$SSB_{F=0}$, but this came at the cost of lower yields (Fig. ES8), 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. ES9, ES10, ES11, and ES12, Table ES4). HCRs with the same F_{TARGET} perform 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.

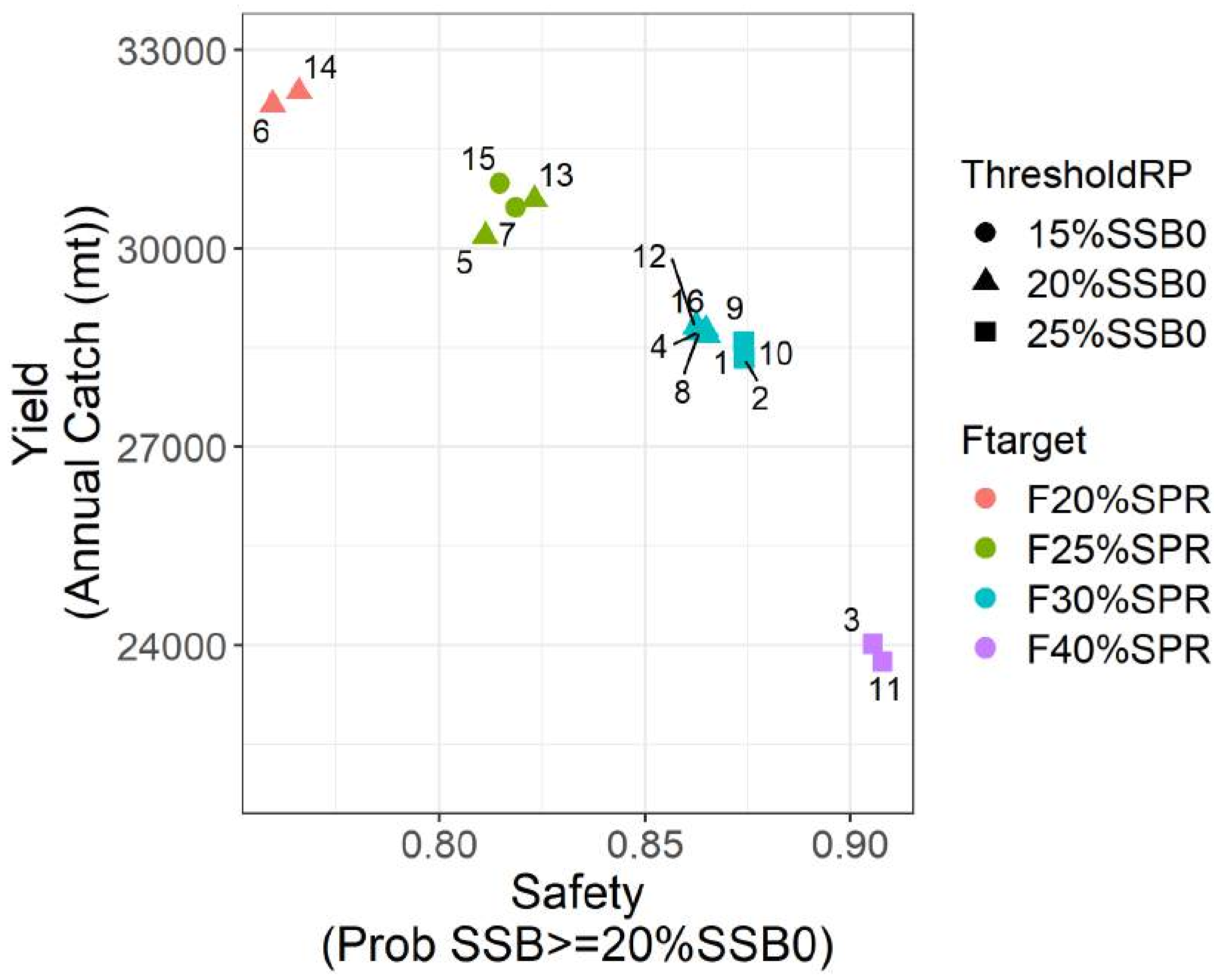

Figure ES8. Median annual total catch versus the probability of spawning stock biomass (SSB) being at or above the second rebuilding target of 20%$SSB_{F=0}$. Note that to ensure that for both measures a higher value is better, here we reversed the second performance metric shown in Fig. ES5 to be the probability of SSB≥20%$SSB_{F=0}$ instead of the probability of SSB<20%$SSB_{F=0}$. Each HCR is labeled and colored according to their F_{TARGET}. Each symbol represents a different ThresholdRP, which is the first control point for each HCR and stands for Threshold Reference Point.

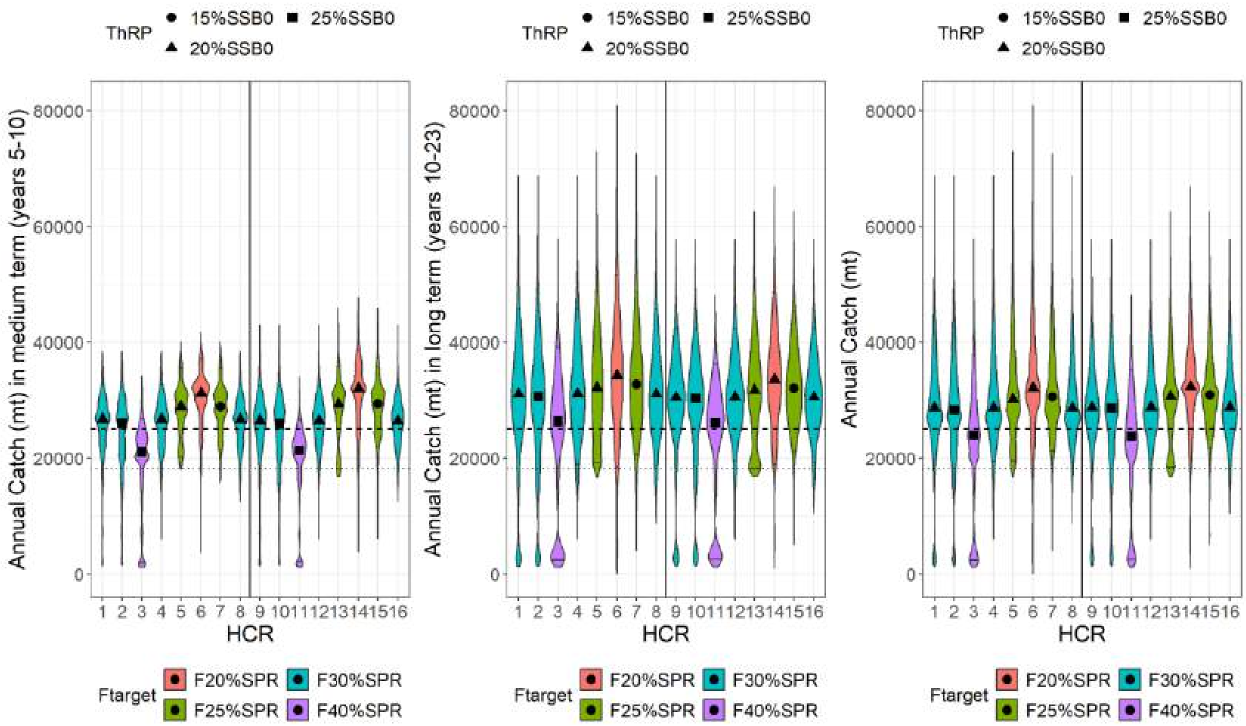

Figure ES9. Violin plots showing the probability density of total annual catch (including discards and the EPO recreational fleet) for each harvest control rule (HCR) across all iterations, reference scenarios, and simulation years in the medium term (first panel), long term (second panel), and all years (third panel). The medium term shows the annual catch distribution over years 5 to 10 of the simulation, while the long term shows the distribution over years 10 to 23 of the simulation. Colors represent the F_{TARGET} reference point associated with each HCR. The marker inside each violin plot is the median value for the medium term, long term, or annual catch, and horizontal solid lines within each violin represent the 5th to 95th quantile range. The shape of each marker represents the ThresholdRP (ThRP), which is the first control point for each HCR and stands for Threshold Reference Point. 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 the 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 the calendar year 2023. For the IATTC's resolution, catch limits were based on half of the biennial TAC. The vertical solid line separates HCRs 9 to 16, which are tuned to an EPO:WCPO impact ratio of 30:70 but are otherwise the same as HCRs 1 to 8. EPO stands for Eastern Pacific Ocean and WCPO for Western Central Pacific Ocean.

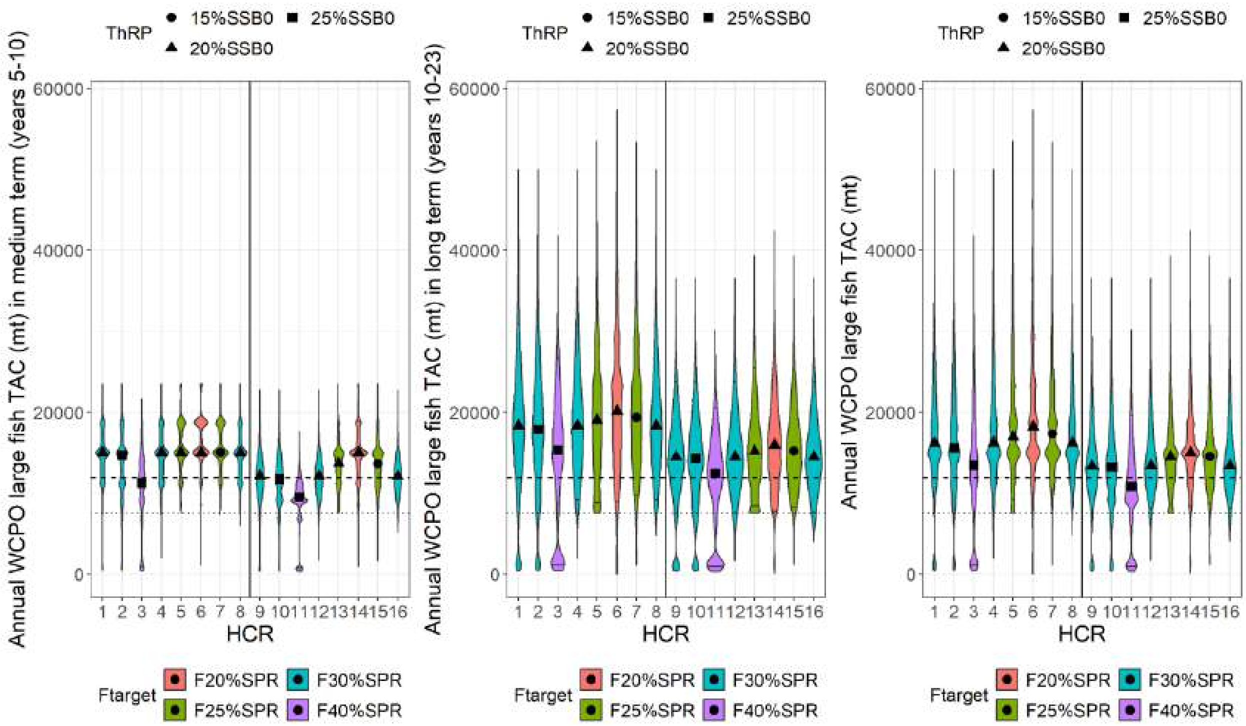

Figure ES10. Violin plots showing the probability density of the TAC for the Western Central Pacific Ocean (WCPO) large fish fleets for each harvest control rule (HCR) across all iterations, reference scenarios, and simulation years in the medium term (first panel), long term (second panel), and annually (third panel). The medium term shows the annual catch distribution over years 5 to 10 of the simulation, while the long term shows the distribution over years 10 to 23 of the simulation. Colors represent the F_{TARGET} reference point associated with each HCR. The marker inside each violin plot is the median value for the medium term, long term, or annual TAC, and horizontal solid lines within each violin represent the 5th to 95th quantile range. The shape of each marker represents the ThresholdRP (ThRP), which is the first control point for each HCR and stands for Threshold Reference Point. 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. The vertical solid line separates HCRs 9 to 16, which are tuned to an EPO:WCPO impact ratio of 30:70 but are otherwise the same as HCRs 1 to 8. EPO stands for Eastern Pacific Ocean.

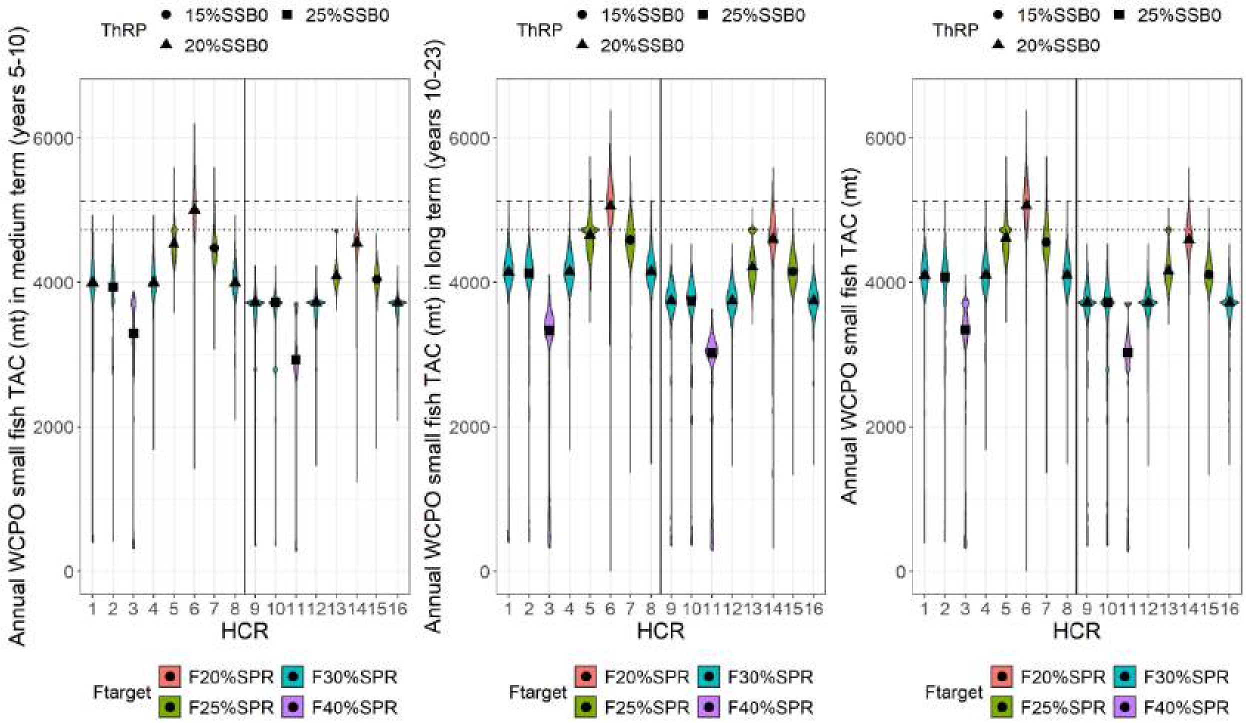

Figure ES11. Violin plots showing the probability density of the TAC for the Western Central Pacific Ocean (WCPO) small fish fleets for each harvest control rule (HCR) across all iterations, reference scenarios, and simulation years in the medium term (first panel), long term (second panel), and annually (third panel). The medium term shows the annual catch distribution over years 5 to 10 of the simulation, while the long term shows the distribution over years 10 to 23 of the simulation. Colors represent the F_{TARGET} reference point associated with each HCR. The marker inside each violin plot is the median value for the medium term, long term, or annual TAC, and horizontal solid lines within each violin represent the 5th to 95th quantile range. The shape of each marker represents the ThresholdRP (ThRP), which is the first control point for each HCR and stands for Threshold Reference Point. 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. The vertical solid line separates HCRs 9 to 16, which are tuned to an EPO:WCPO impact ratio of 30:70 but are otherwise the same as HCRs 1 to 8. EPO stands for Eastern Pacific Ocean.

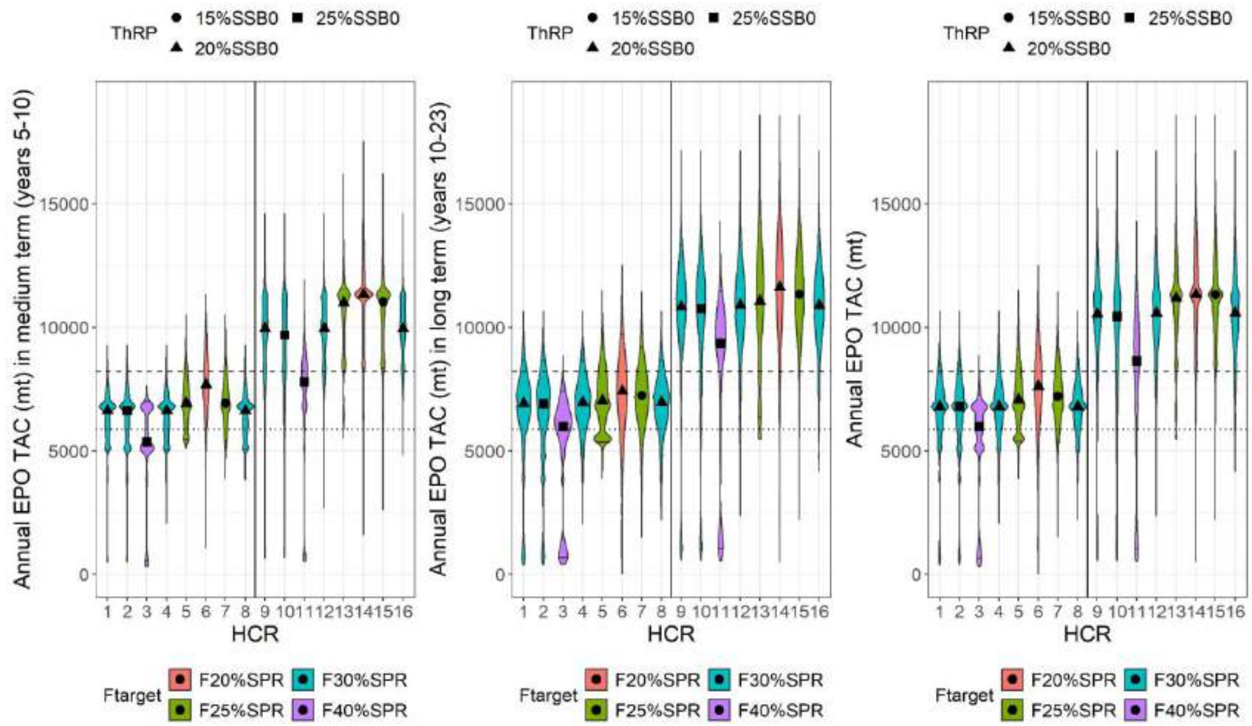

Figure ES12. Violin plots showing the probability density of the TAC for the Eastern Pacific Ocean (EPO) fleets for each harvest control rule (HCR) across all iterations, reference scenarios, and simulation years in the medium term (first panel), long term (second panel), and annually (third panel). The medium term shows the annual catch distribution over years 5 to 10 of the simulation, while the long term shows the distribution over years 10 to 23 of the simulation. Colors represent the F_{TARGET} reference point associated with each HCR. The marker inside each violin plot is the median value for the medium term, long term, or annual TAC and horizontal solid lines within each violin represent the 5th to 95th quantile range. The shape of each marker represents the ThresholdRP (ThRP), which is the first control point for each HCR and stands for Threshold Reference Point. 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 the 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 the 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. The vertical solid line separates HCRs 9 to 16, which are tuned to an EPO:WCPO impact ratio of 30:70, but are otherwise the same as HCRs 1 to 8. WCPO stands for Western Central Pacific Ocean.

3. Catch in the medium and long term for all HCRs is 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 fleet under a 70:30 impact ratio increasing above current catch limits.

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. ES9). All HCRs had a long term catch higher than the current catch limit (Fig. ES9). Across all HCRs, the increase in catch was due to increases in the WCPO large fish TAC, although the EPO TAC can be increased under a 70:30 impact ratio (Figs. ES10, ES11, and

ES12). 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. ES10). The WCPO small fish TAC was always smaller than the current catch limits for all HCRs (Fig. ES11). The EPO TAC was larger only for HCRs 9 to 16, which had a higher EPO fisheries impact, with HCR 11 in the medium term being an exception (Fig. ES12). 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. ES9, 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. ES13) and these HCRs have the lowest 5th quantiles of TAC (Figs. ES9 and ES14).

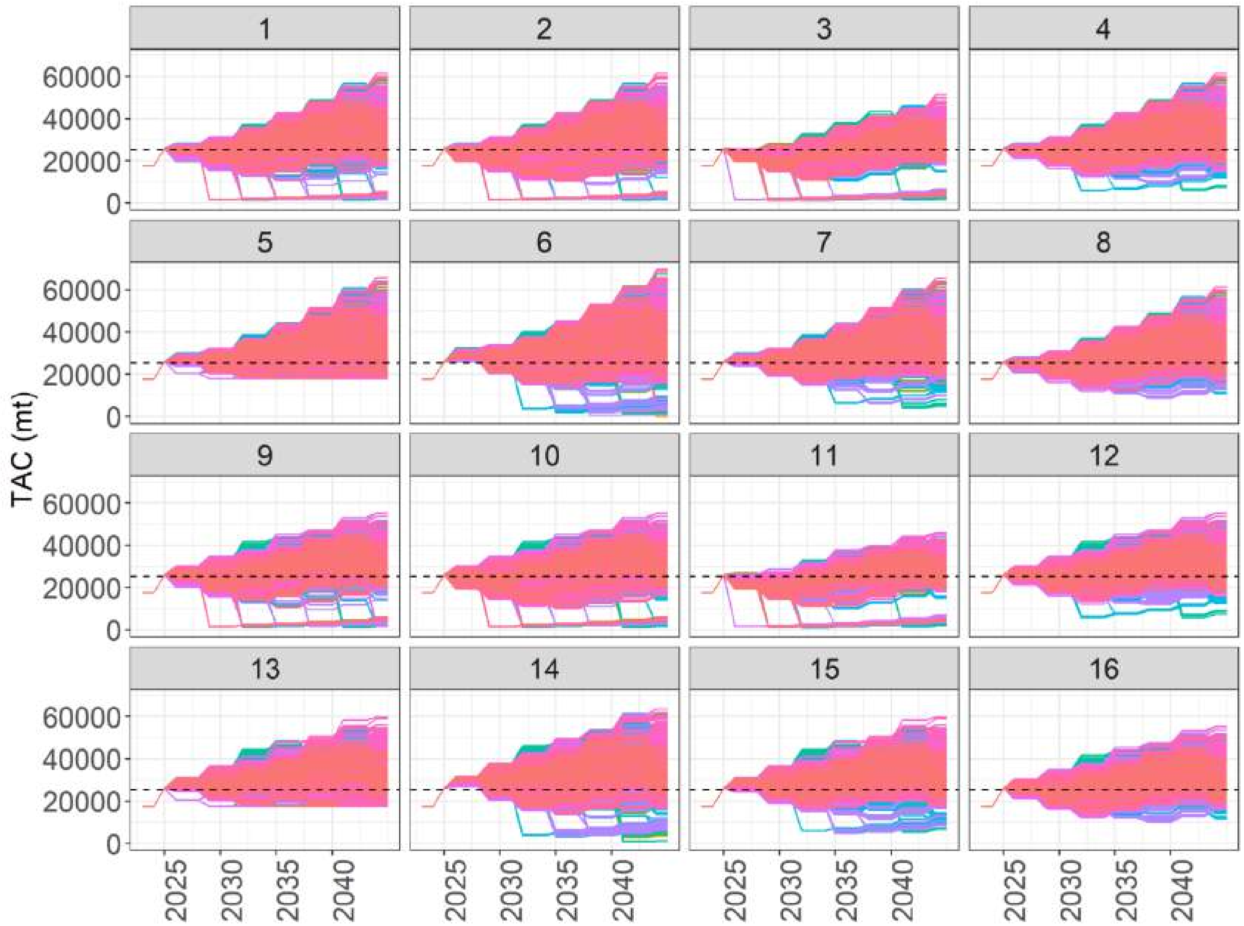

Figure ES13. Worm plots of the total allowable catch (TAC) set by each harvest control rule (HCR) for individual runs across all reference scenarios. Each panel presents the results for the labeled HCR. Trajectories represent separate iterations differing in simulated random recruitment deviates. The 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 the calendar year 2023. For the IATTC's resolution, catch limits were based on half of the biennial TAC.

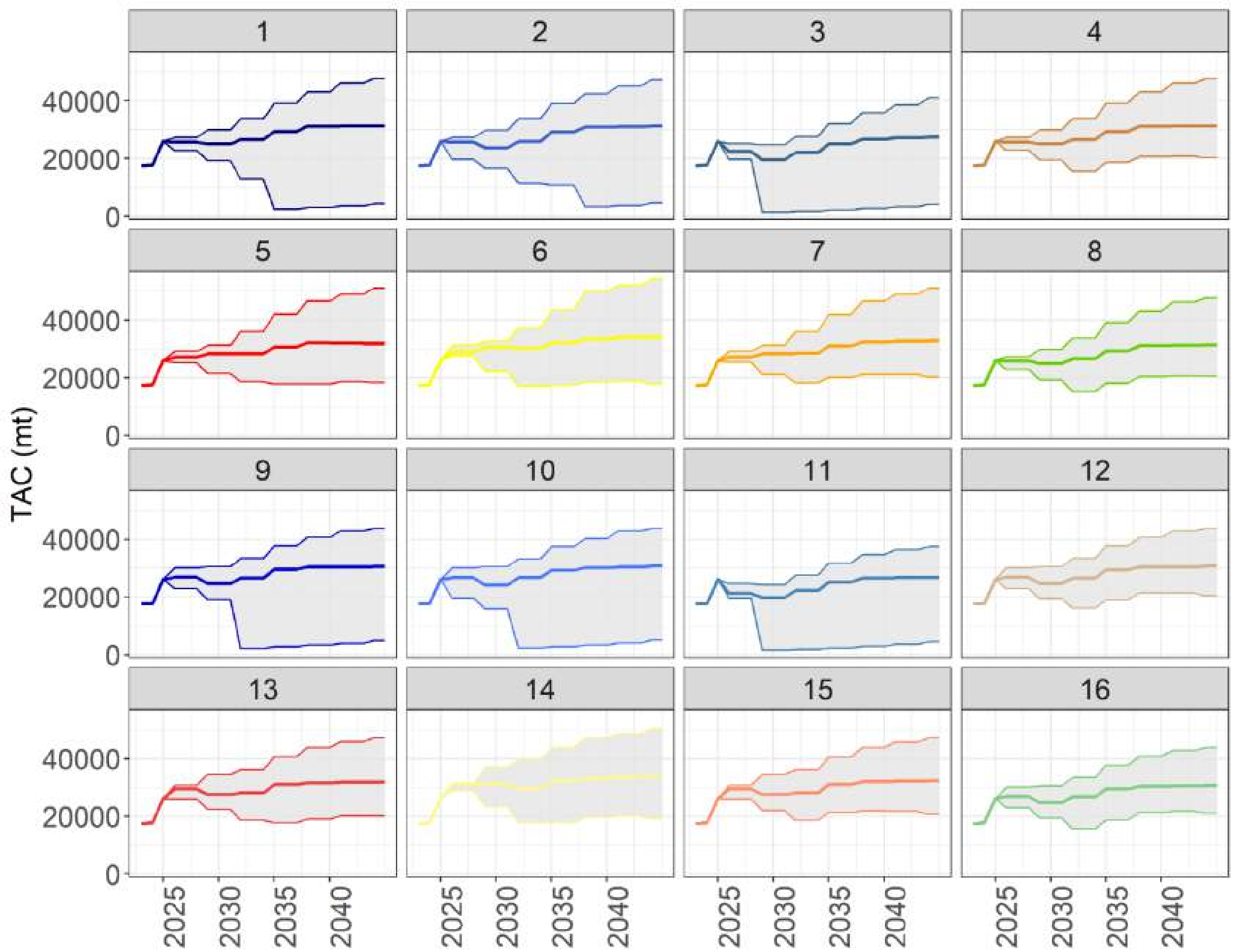

Figure ES14. Trends in median total allowable catch (TAC) set by each harvest control rule (HCR) under all iterations and reference scenarios. The grey shading represents trends in the 5th to 95th quantiles of TAC.

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 F and lower stability (Figs. ES15, ES16, 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. ES15, ES16, Table ES4). Nonetheless, due to the built-in 25% limit on TAC change in each HCR, all HCRs met the stability objective.

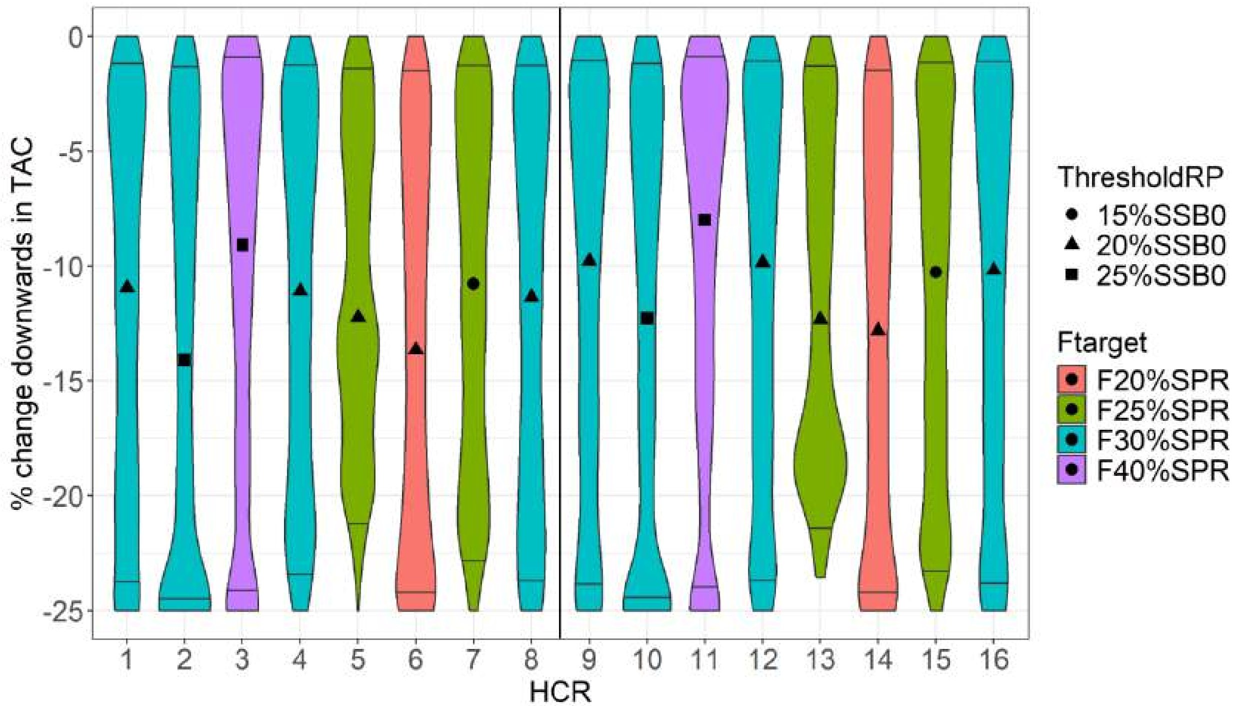

Figure ES15. Violin plots showing the probability density of downward changes in TAC between management periods when SSB≥LRP for each harvest control rule (HCR) across all iterations, reference scenarios, and simulation years. Each HCR is colored according to their F_{TARGET}. The marker inside each violin plot is the median downward change in TAC, and horizontal solid lines within each violin represent the 5th to 95th quantile range. Each symbol represents a different ThresholdRP, which is the first control point for each HCR and stands for Threshold Reference Point. The vertical solid line separates HCRs 9 to 16, which are tuned to an EPO:WCPO impact ratio of 30:70, but are otherwise the same as HCRs 1 to 8. EPO stands for Eastern Pacific Ocean and WCPO for Western Central Pacific Ocean.

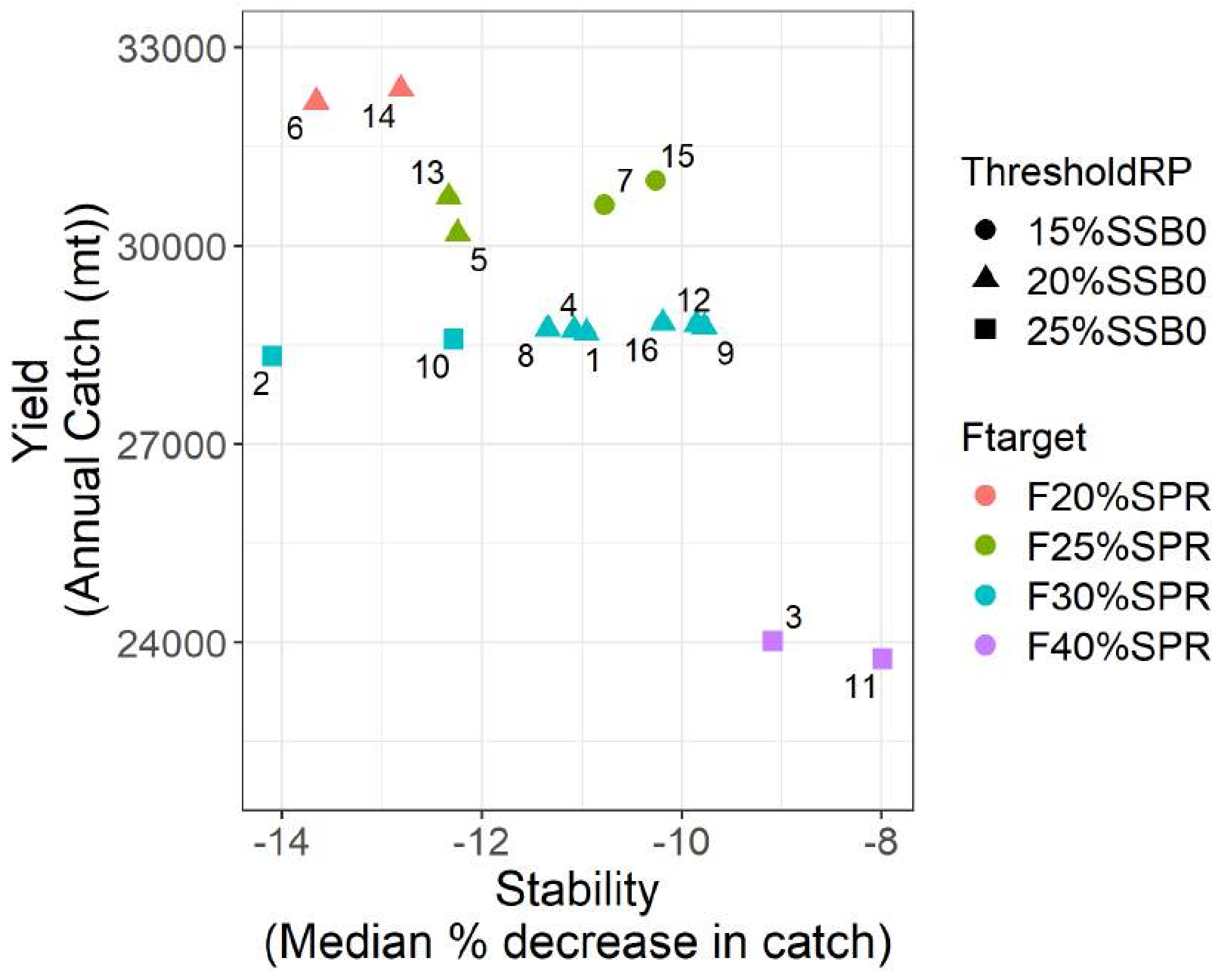

Figure ES16. Median annual total catch versus the median decrease in catch between management periods. Each HCR is labeled colored according to their F_{TARGET}. Each symbol represents a different ThresholdRP, which is the first control point for each HCR and stands for Threshold Reference Point.

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. ES17, 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.

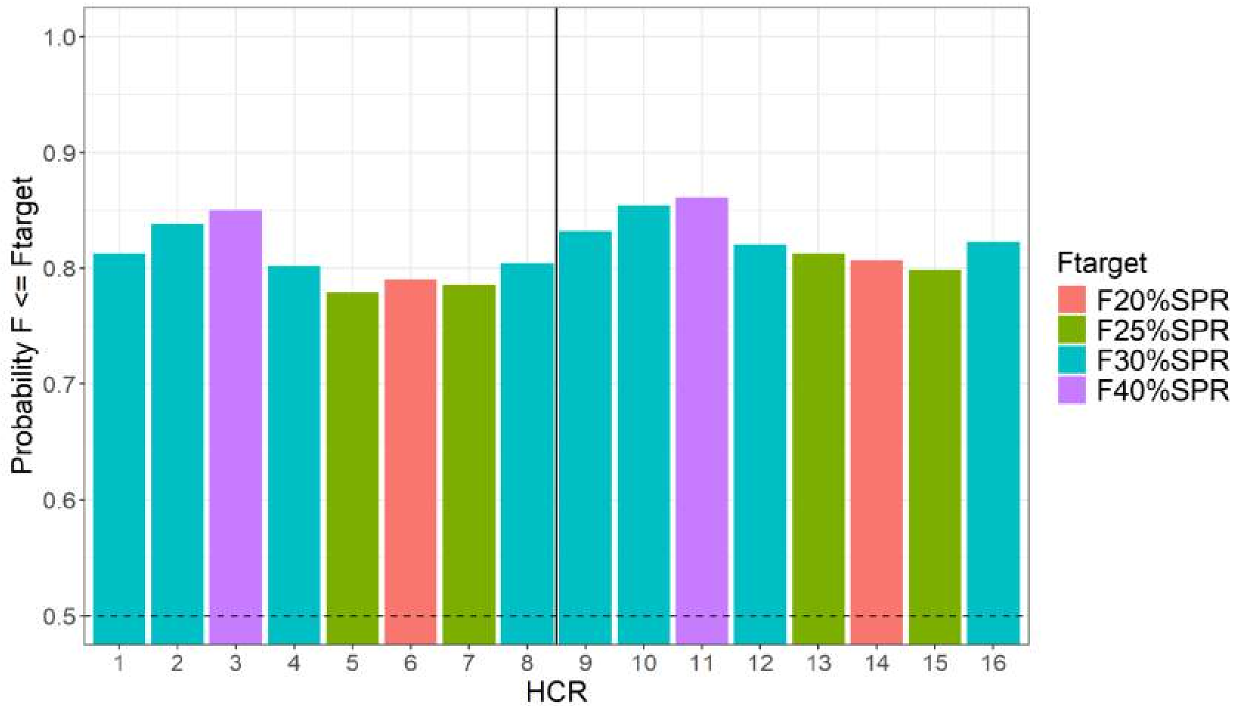

Figure ES17. Plot of the first status performance metric, the probability, for each harvest control rule (HCR), of fishing mortality (F, 1-SPR) being less or equal to the F_{TARGET} across all reference scenarios, iterations, and simulation years. Each HCR is colored according to their F_{TARGET}. The horizontal dotted line represents a 50% probability. The vertical solid line separates HCRs 9 to 16, which are tuned to an EPO:WCPO impact ratio of 30:70 but are otherwise the same as HCRs 1 to 8. EPO stands for Eastern Pacific Ocean and WCPO for Western Central Pacific Ocean.

7. *The different fisheries impact ratios only affected yield metrics but other performance metrics remained 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 yields 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.

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 HCRs were fairly robust to the "doubling of the discards" 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 in SSB, F was curtailed, and median SSB ultimately rebuilt to target levels for all HCRs. It is therefore important to carefully monitor the recruitment and also SSB through regular assessments to detect in a timely manner if a chronic decline in recruitment has occurred 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 change 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 bounded by those historical observations. If future population dynamics strongly diverge from the past, results from this analysis may no longer be applicable.

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 ES5 and ES7 to be the probability of SSB≥LRP and of SSB≥20%$SSB_{F=0}$. The % change upwards in TAC (% change TAC +) was set to negative so that high values (smaller -) are better. The % change downwards does not include years when SSB is below LRP as provided by the management objective. The value including years when SSB is below LRP is provided in the main body of the report. The 2026 TAC is the total TAC and the TAC 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. As there is no optimal impact, the EPO impact column does not have a color.

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 years 5-10 annual catch	Median years 11-23 annual 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	87	81	62	-14	-11	23	28685	26744	31094	16174	4093	6794	25868	14836	4512	6520
2	94	87	84	64	-15	-14	23	28330	26054	30691	15618	4069	6794	25868	14836	4512	6520
3	91	91	85	56	-17	-9	24	24026	21135	26361	13472	3346	5971	24366	14836	3844	5686
4	99	86	80	61	-13	-11	23	28722	26745	31124	16221	4102	6794	25868	14836	4512	6520
5	100	81	78	66	-13	-12	22	30183	28894	32227	16965	4617	7054	27485	14836	5161	7488
6	99	76	79	76	-14	-14	22	32174	31286	34249	18243	5063	7609	29437	14836	5939	8662
7	100	82	79	67	-13	-11	23	30616	28940	32814	17330	4557	7192	27485	14836	5161	7488
8	100	86	80	61	-14	-11	23	28741	26746	31127	16222	4101	6794	25868	14836	4512	6520
9	93	86	83	63	-13	-10	32	28773	26503	30537	13378	3722	10528	27942	14073	4392	9476
10	93	87	85	65	-16	-12	32	28582	25973	30368	13242	3722	10433	27942	14073	4392	9476
11	91	91	86	56	-16	-8	32	23748	21378	26147	10877	3023	8632	23653	10724	3844	9085
12	99	86	82	62	-12	-10	33	28812	26505	30572	13414	3722	10568	27942	14073	4392	9476
13	100	82	81	68	-13	-12	30	30735	29380	31768	14567	4160	11175	29323	14836	5010	9476
14	99	77	81	77	-15	-13	31	32369	32077	33617	15040	4592	11323	30061	14836	5749	9476
15	100	81	80	67	-12	-10	32	30988	29413	32137	14567	4108	11323	29323	14836	5010	9476
16	100	86	82	62	-12	-10	33	28826	26507	30582	13413	3722	10565	27942	14073	4392	9476