Implementation of New Candidate Harvest Control Rules in the Management Strategy Evaluation for Pacific Bluefin Tuna

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Summary

Here we describe changes made to the Pacific Bluefin tuna (PBF) Management Strategy Evaluation code to allow for testing of the new candidate harvest control rules (HCRs) proposed at the 8th Meeting of the Inter American Tropical Tuna Commission (IATTC) and Western and Central Pacific Fisheries Commission of the Northern Committee (WCPFC NC) Joint Working Group (JWG) on PBF management. Preliminary results show that, in simulations with no assessment error and under one base case scenario, all HCRs are able to rebuild biomass and maintain fishing intensity at their specified target levels.

Introduction

The two Regional Fisheries Management Organizations (RFMOs) tasked with managing the PBF stock, WCPFC NC and IATTC, requested, via the JWG, that the ISC PBF working group develop an MSE to help inform development of a long-term management strategy for PBF once the stock is rebuilt to the second rebuilding target of 20%SSB0 (JWG 2022). As part of the MSE process the JWG finalized a list of candidate HCRs to evaluate in the MSE (WCPFC 2023).

HCRs specify a management action to be taken based on a comparison of the status of the system to specific control points. These control points can be the same as the reference points specified in the safety and status management objectives for a stock. Such reference points can be a limit reference point (LRP), which is a benchmark current stock status is compared to that should not be exceeded with a high probability, or a target reference point (TRP), which is a state management wants to achieve. Some HCRs also have an intermediate control point between the LRP and TRP often defined as a threshold reference point (ThRP), which represents a stock level below which a management action is initiated to bring the stock back to a target state. Reference points can be based on either biomass or fishing intensity.

All the PBF HCRs proposed by the JWG are characterized by a fishing intensity control point (Table 1). This F_{target} is an indicator of fishing intensity based on SPR. SPR (spawning potential ratio) is 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. For example, an F_{target} of FSPR30% is associated with a fishing intensity that would produce 30% of the spawning potential in an unfished state.

Table 1. Characteristics and reference points for the candidate HCRs to be evaluated in the PBF MSE.

HCR Number	F_{target}	SSB Control Point 1 (ThRP)	SSB Control Point 2 (LRP)	Number of SSB control points	F_{min}
1	FSPR30%	$20\%SSB_{F=0}$	$15\%SSB_{F=0}$	2	$10\%F_{target}$
2	FSPR30%	$25\%SSB_{F=0}$	$15\%SSB_{F=0}$	2	$10\%F_{target}$
3	FSPR40%	$20\%SSB_{F=0}$	$15\%SSB_{F=0}$	2	$10\%F_{target}$
4	FSPR40%	$25\%SSB_{F=0}$	$15\%SSB_{F=0}$	2	$10\%F_{target}$
5	FSPR40%	$25\%SSB_{F=0}$	$20\%SSB_{F=0}$	2	$10\%F_{target}$
6	FSPR30%	$20\%SSB_{F=0}$	$10\%SSB_{F=0}$	2	FSPR70%
7	FSPR25%	$20\%SSB_{F=0}$	$10\%SSB_{F=0}$	2	FSPR50%
8	FSPR30%	$20\%SSB_{F=0}$	Median SSB 1952-2014	2	CMM limits
9	FSPR20%	$20\%SSB_{F=0}$	NA	1	NA
10	FSPR25%	$15\%SSB_{F=0}$	NA	1	NA
11	FSPR30%	$15\%SSB_{F=0}$	$7.7\%SSB_{F=0}$	2	$5\%F_{target}$
12	FSPR30%	$20\%SSB_{F=0}$	$7.7\%SSB_{F=0}$	2	$5\%F_{target}$

Each of the candidate HCRs has also 1 or 2 additional control points based on spawning stock biomass (SSB, Table 1). In the one control point rules, HCR9 and HCR10, the fishing intensity is decreased from the F_{target} rate when SSB is lower than the biomass-based control point and there is a linear transition in fishing intensity between the biomass-based control point (or ThRP) and the origin (Fig. 1). In the other HCRs there is also a decline in fishing intensity from F_{target} if SSB falls below the ThRP, but the decline is down to the second control point, rather than the origin, and a minimum fishing intensity (F_{min}) is applied when SSB is at or below this lower biomass-based control point (Fig. 1). Among these two control points HCRs, HCR8 is a bit different from the others as an F_{min} was not specified by the JWG. Instead, when SSB breaches the lower control point, the catch limits from the WCPFC CMM2020-02 and IATTC Resolution C-18-01 are applied. This means that the actual F_{min} can vary depending on the actual biomass when the catch limit is applied, with F increasing as the stock declines given the constant catch limit. In Figure 1 we used an F_{min} of $10\%F_{target}$ for HCR8 as an example, but note that this would vary in the actual simulation.

The aim of this paper is to detail how these newly proposed HCRs have been implemented in the PBF MSE code and assess if they behaved as expected in a simulation with a perfect assessment.
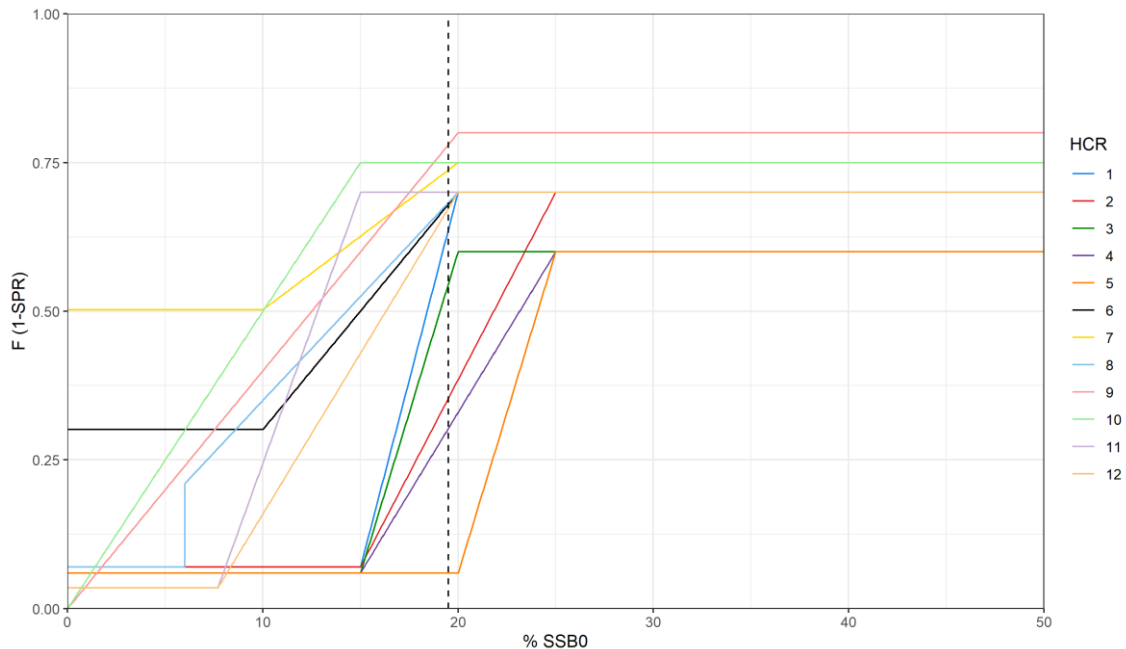

Figure 1. Candidate HCRs to be evaluated in the PBF MSE. The dotted line represents SSB as a fraction of unfished SSB when the HCRs are first applied in the MSE simulation. Note that HCR8 here has an F_{min} of $10\%F_{target}$, but the actual F_{min} in the simulation depends on the biomass of the stock when the catch limit is applied.

Methods

The preliminary PBF MSE framework (Fig. 2) was outlined in Tommasi and Lee (2022), and Tommasi et al. 2023 and is available at https://github.com/detommas/PBF_MSE. In this analysis, the MSE is run with no assessment model error (i.e. no estimation model) to reduce run times, and each simulation was run for 24 years and 100 different iterations to account for recruitment process uncertainty. As described in Tommasi and Lee (2022), the PBF MSE uses a modified version of the short 2022 Stock Synthesis (SS) PBF stock assessment model (Fukuda et al. 2022) as the base case operating model (OM). The OM has been conditioned using historical data and is run with no estimation using parameters set in the .par file during the forward simulation. In the full MSE simulation, data from the OM would be sampled with error and fed into the estimation model (EM), i.e. the simulated stock assessment model. However, here we assume there is a perfect estimation with no observation or assessment error. Thus, management quantities, such as reference

points and current biomass, are input into the HCRs directly from the OM rather than the EM. Catches in the OM .dat file are updated every three years as set by the TAC determined by the HCR. Thus, in the 24-year simulations a TAC is set eight times. However, the catch for the first three years of the simulation is set to the CMM catch limits (see Tommasi and Lee 2022) and thus the HCRs starts being applied over the last 21 years of the simulation.
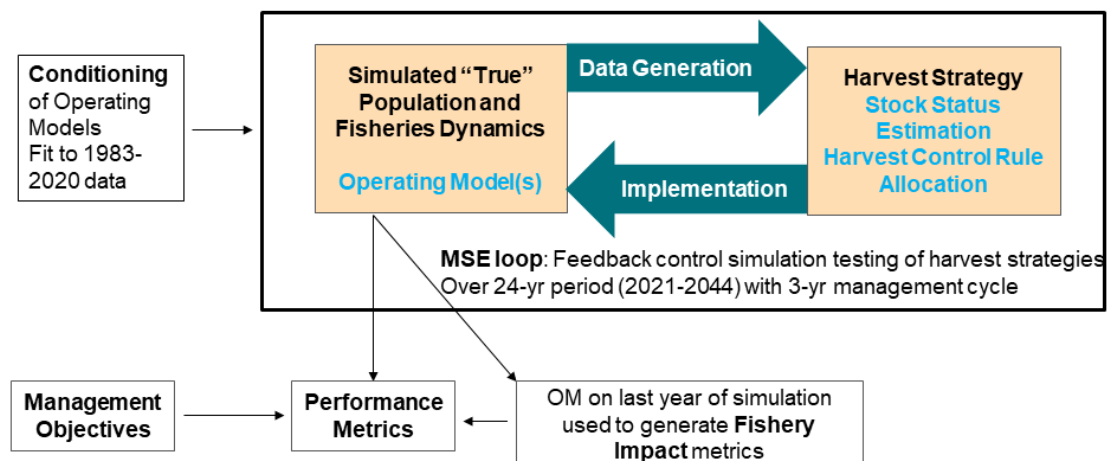
Figure 2. Overview of preliminary PBF MSE framework. Note that for this initial analysis the MSE loop was run assuming no error in data, assessment, or implementation.

HCRs 1 to 7 and 11 to 12 are coded as the type 1a HCRs in Tommasi et al. 2023. They are run in parallel using the code *PBF_MSE_prll_hs1_hcr1to71112.R* available at https://github.com/detommas/PBF_MSE/blob/main/PBF_MSE/Rcode/PBF_MSE_prll_ hs1_hcr1to71112.R. Here, the user specifies the harvest strategy (line 47), HCR (line 49), and scenario (line 51) being run. The harvest strategy specifies the shape of the HCR. All the HCRs with two control points are specified as harvest strategy 1. The scenario refers to the OM being used, i.e. the uncertainty scenario. In this analysis, we use the base case OM, which corresponds to scenario 1. In the call to the function *PBF_MSE_hs1_for.R* (line 68) the control points, i.e. the SSB-based control points, and the F_{min}, need to be specified for each HCR. Note that the *PBF_MSE_hs1_for.R* code expects the F_{min} to be input as fraction of the F_{target}, but for HCRs 6 and 7 it was specified directly as FSPR70% and FSPR50%, respectively. We calculated what fraction of their F_{target}, FSPR30% and FSPR25%, these fishing intensities correspond to, by first defining the F_{target} and specified minimum F in terms of fishing intensity (1-SPR):

HCR6 F_{target} (1-SPR) = (1-0.3) = 0.7   HCR7 F_{target} (1-SPR) = (1-0.25) = 0.75

HCR6 Minimum F (1-SPR) = (1-0.7) = 0.3 HCR7 Minimum F (1-SPR) = (1-0.5) = 0.5

HCR6 F_{min} = Minimum F/F_{target} = 0.3/0.7 = 0.43 = 43%F_{target}

HCR7 F_{min} = Minimum F/F_{target} = 0.5/0.75 = 0.67 = 67%F_{target}

In the PBF MSE framework, each HCR has an associated forecast file, where the F_{target} is specified, see example forecast file at https://github.com/detommas/PBF_MSE/tree/main/PBF_MSE/1/15 (see Tommasi and Lee 2022). The forecast file also specifies the relative apical fishing mortality for each fleet and season (RelF$_{t,f,s}$ where t = a year or multi- year period, f = fleet and s = season) to be used. The RelF$_{t,f,s}$= F'$_{t,f,s}$/(sum of F'$_{t,f,s}$ for all fleets and seasons) where F' is the apical (i.e. fully selected) fishing mortality for a specific season, fleet, and year or averaged over a multi-year period. The RelF$_{t,f,s}$ determines how the TAC is allocated across fleets. A user can choose to do this by specifying the year(s) over which to compute the RelF$_{t,f,s}$ or by entering a RelF$_{t,f,s}$ to be used directly in the forecast file. The example uses the average from 2017-2019.

The MSE framework uses the Stock Synthesis forecast algorithm to find the F multiplier that would reach the F_{target} given a specified relative F, selectivity and biology. Here the forecast file uses the 2017-2019 average selectivity and the 2002-2004 biology. The function *HCR1a_pbf_byfleet_f.R* available at https://github.com/detommas/PBF_MSE/blob/main/PBF_MSE/Rcode/R_funs/HCR1a_ pbf_byfleet_f.R determines how the F multiplier corresponding to the F_{target} should be changed depending on stock status, i.e. the level of terminal year SSB relative to the ThRP and LRP control points (lines 46 to 52) for HCRs 1to 7 and 11 and 12 (Table 2).

Table 2. Details of candidate harvest controls at specific current spawning stock biomass (SSB$_{current}$) relative to SSB reference points proposed for the PBF MSE. ThRP is the SSB based threshold reference point, LRP is the SSB-based limit reference point, and Fmult$_{target}$ is the F multiplier associated with the target reference point. Fmult$_{min}$ is the fraction of the Fmult$_{target}$ as defined by F_{min} in Table 1.

Stock Status	HCR	F multiplier
SSB$_{current}$ ≥ ThRP	All	Fmult = Fmult$_{target}$

	1:7, 11, 12	$Fmult = (Fmult_{target} - Fmult_{min})*(SSB_{current} - LRP)/(ThRP-LRP) + Fmult_{min}$
$LRP < SSB_{current} < ThRP$	8	$Fmult = (Fmult_{target}/ThRP)*SSB_{current}$
$SSB_{current} < ThRP$	9, 10	$Fmult = (Fmult_{target}/ThRP)*SSB_{current}$
$SSB_{current} \leq LRP$	1:7, 11, 12	$Fmult = Fmult_{min}$
	8	No Fmult, managed by constant catch set by CMM

Given this F multiplier, terminal year numbers at age, natural mortality at age, age selectivity per fleet, and weight at age, the function catch_calc_f.R available at https://github.com/detommas/PBF_MSE/blob/main/PBF_MSE/Rcode/R_funs/catch_calc_f.R calculates the TAC per fleet that would meet the F_{target} to be input as catch in the next time step of the OM. First, the F multiplier is multiplied by the $RelF_{f,s}$ specified in the forecast file to find the apical F for each fleet and season ($F'_{f,s}$) to be used in the forecast:

$F'_{f,s} = Fmult * RelF_{f,s}$

These apical Fs are multiplied by the age selectivity per fleet and season ($Sel_{f,s}$) to obtain the fishing mortality per fleet and season ($F_{f,s}$). The function extracts the $Sel_{f,s}$ from the OM (as no EM was run in this simulation) report file and averages the age selectivity for the years specified.

$F_{f,s} = F'_{f,s} * Sel_{f,s}$

The total fishing mortality for each season is also found by summing the $F_{f,s}$ across fleets and this is added to the natural mortality to find the total mortality for each season.

Then the starting numbers at age for the forecast season 1 ($Nfor_{1,a}$) are calculated from the terminal year numbers at age in season 1 ($Nty_{1,a}$) and the Z at age (Zty_a, natural plus fishing mortality) extracted from the OM report file, according to:

for ages 1 to A-1 where A is the oldest age, $Nfor_{1,a} = Nty_{1,a-1}*exp(-Zty_{a-1})$

for age A, $Nfor_{1,A} = Nty_{1,A-1}*exp(-Zty_{A-1}) + Nty_{1,A}*exp(-Zty_A)$

for age 0, $Nfor_{1,0}$ = Recruits from terminal year season 4

The catch by fleet at age for forecast season 1 ($C_{1,f,a}$), is calculated as:

$$C_{1,f,a} = F_{1,f,a}/Z_a * Nfor_{1,a}*(1-exp(-0.25*Z_a))$$

This is then multiplied by the weight at age and summed across ages to obtain the TAC by fleet for season 1 that is input back into the OM for the next time step. Note that we multiply Z_a by 0.25 as this is the season duration since there are four seasons in a year in the PBF OM.

The numbers at age for forecast seasons 2 to 4 ($Nfor_{s,a}$) are calculated from the mortality and numbers at age in the previous seasons:

$$Nfor_{s,a} = Nfor_{s-1,a}*exp(-0.25*Z_a)$$

In each season, the catch at age and TAC is calculated using the Baranov catch equation as shown above for season 1. The code was checked to make sure it reproduced the numbers at age in the OM Report file for the forecast year season 1 and subsequent seasons when fished at the Fmult corresponding to the F_{target}, which is what Stock Synthesis uses to generate numbers at age in the forecast.

HCRs 9 and 10 are run using the code *PBF_MSE_prll_hs2_hcr9_10.R* available at https://github.com/detommas/PBF_MSE/blob/main/PBF_MSE/Rcode/PBF_MSE_prll_hs2_hcr9_10.R. As described for the HCRs above, the user specifies here the harvest strategy (line 47), HCR (line 49), and scenario (line 51) being run. The harvest strategy for these HCRs with one control points is 2. As above, since we are using the base case OM, the scenario is 1. In the call to the function *PBF_MSE_hs2_910_for.R* (line 67) the control point, i.e. the ThRP needs to be specified for each HCR. Note that while an LRP corresponding to the median SSB from 1952 to 2014 was specified for these HCRs in order to calculate performance metrics, it is not used as a control point. As for the other HCRs, the F_{target} is set in the forecast file. The function *HCR2_pbf_byfleet_f.R* available at https://github.com/detommas/PBF_MSE/blob/main/PBF_MSE/Rcode/R_funs/HCR2_pbf_byfleet_f.R determines how the F multiplier corresponding to the F_{target} should be changed depending on stock status, which is the level of terminal year SSB relative to the ThRP control point (lines 48 to 52) for HCRs 9 and 10 (Table 2). The same catch_calc_f.R described above is then called to calculate the TAC by fleet and season given the F multiplier.

HCR 8 is run using the code *PBF_MSE_prll_hs1_hcr8.R* available at https://github.com/detommas/PBF_MSE/blob/main/PBF_MSE/Rcode/PBF_MSE_prll_hs1_hcr8.R. As described for the other HCRs, the user specifies here the harvest strategy (line 47), HCR (line 49), and scenario (line 52) being run. The harvest strategy for HCR8 is 1 as it uses two control points. As above, the scenario is 1 as we are using the base case OM. In the call to the function *PBF_MSE_hs1_hcr8_for.R* the ThRP needs to be specified. Note that for this HCR the JWG specified an second, lower control point corresponding to the median SSB from 1952 to 2014. Thus, we extracted what the median SSB from 1952 to 2014 was using output from the 2022 PBF stock assessment (ISC 2022) and specify this level, 40724.6 mt, corresponding to 6% $SSB_{F=0}$, in *PBF_MSE_hs1_hcr8_for.R* during the call to the *HCR8_pbf_byfleet_f.R* function. Unlike for HCRs 1 to 7, 11, and 12 no F_{min} is specified as the JWG detailed that this HCR would be managed by setting the TAC at the CMM when SSB was below the LRP (Table 2). We used the 2022 stock assessment projections based on the CMM to set this minimum TAC: 4475 mt to WPO small fish, 7860 mt to WPO large fish, and 3995 mt to the EPO (ISC 2022). These catches were split among the different fleets using the average 2017-2019 catch ratios and the fleet designations listed in Table 2 of Tommasi and Lee 2022. Note that while the CMM specifies large and small fish catches for the WPO, some WPO fleets are mixed (catch both small and large fish). Their share of the total WPO catch is small (6%). It was assumed that 3% of the small fish WPO catch and 3% of the large fish catch would go to these fleets for a total of 370 mt to the mixed fleet, 4341 to the small, and 7624 to the large. As for the other HCRs, the F_{target} is set in the forecast file. The function *HCR8_pbf_byfleet_f.R*. available at https://github.com/detommas/PBF_MSE/blob/main/PBF_MSE/Rcode/R_funs/HCR8_pbf_byfleet_f.R determines how the F multiplier corresponding to the F_{target} should be changed depending on stock status, i.e. the level of terminal year SSB relative to the ThRP and LRP control points (lines 46 to 121) for HCR8 (Table 2). Since a minimum F cannot be specified for this HCR, the decrease in F as SSB falls below the ThRP was based on a line going from a point at the ThRP/F_{target} to the origin, as for HCR 9 and 10, rather than a line going from a point at the ThRP/F_{target} to the LRP/F_{min} (Fig. 1). When SSB is above the LRP, the same catch_calc_f.R described above is called to calculate the TAC by fleet and season given the F multiplier. However, when SSB is at or below the LRP, the F multiplier is not used and the TAC by fleet and season to be input into the OM is set at the CMM levels.

The output of the simulation for each HCR was plotted in R version 4.1.3 to assess trends

in SSB, relative SSB, fishing intensity, catch and recruitment and ensure the HCRs were working as intended. The code read_output_pbfMSE.R available at https://github.com/detommas/PBF_MSE/blob/main/PBF_MSE/Rcode/read_outpt_pbfMSE.R was used once the MSE simulation was completed to collate the output.txt file produced by each iteration into one large text file containing, for each HCR, output from all the iterations. This output files for each HCR were then read by the HCR_check_plots.R code available at https://github.com/detommas/PBF_MSE/blob/main/PBF_MSE/Rcode/HCR_check_plots.R to compute the plots shown here.

Results

While SSB trends were specific to the recruitment patterns associated with each different iteration (Fig. 3), on average all HCRs rebuilt SSB to the SSB levels associated with the their specific F_{target} (Fig. 4). For example, median relative SSB across all the iterations for HCRs 1, 2, 6, 8, 11, and 12, which have an F_{target} of FSPR30%, was rebuilt to a level of about $30\%SSB_{F=0}$ by the end of the MSE simulation (Fig. 4). All HCRs were also able to maintain SSB above their specific lower biomass control points and the probability of SSB being at or below these "LRPs" was less than 20% for all HCRs. However, some HCRs breached the second rebuilding target of $20\%SSB_{F=0}$ more often than others (Fig. 3) depending on if this rebuilding target was closer to the SSB associated with their F_{target} or their lowest SSB-based control point. For example, HCR5 uses $20\%SSB_{F=0}$ as a limit (Table 1), and thus no iteration breaches this SSB level (Fig. 3). By contrast, HCR 9 uses $20\%SSB_{F=0}$ as a target and ThRP (Table 1) and thus more iterations and simulation years have SSB below this level than for HCR5 (Fig. 3).
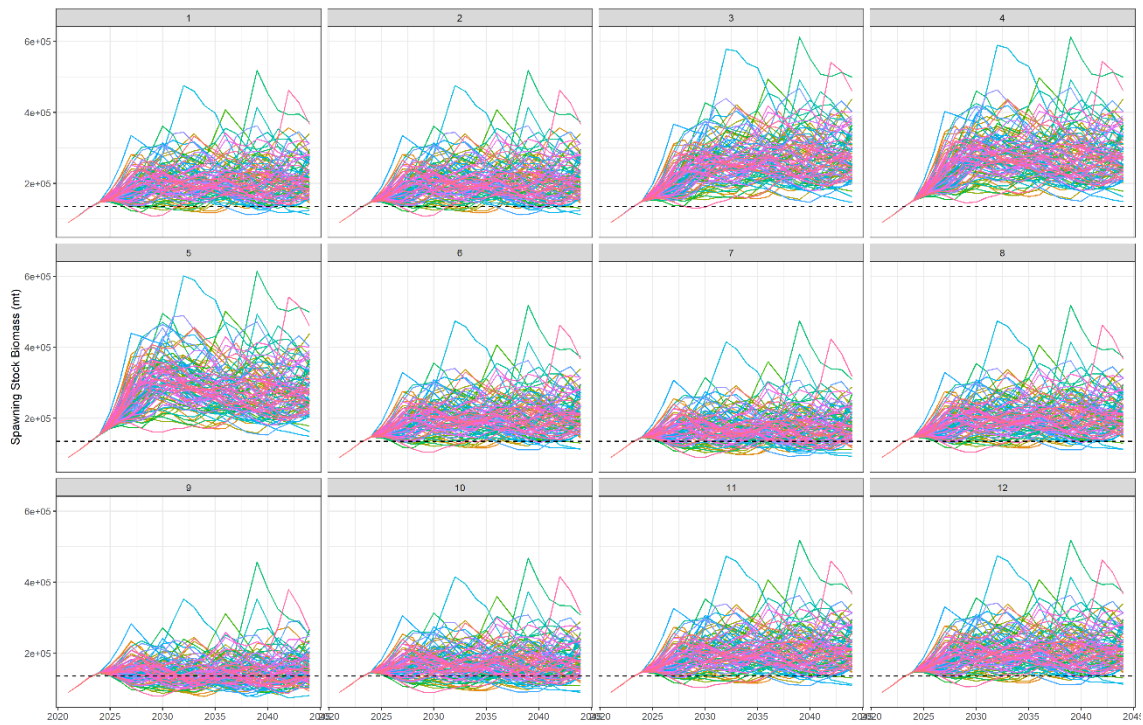
Figure 3. Worm plots of spawning stock biomass (SSB) for the 100 individual runs for each harvest control rule (HCR). Each panel presents the results for the labeled HCR. Trajectories represent separate iterations differing in simulated random recruitment deviates. The dotted line represents the 20%SSB$_{F=0}$ rebuilding target.
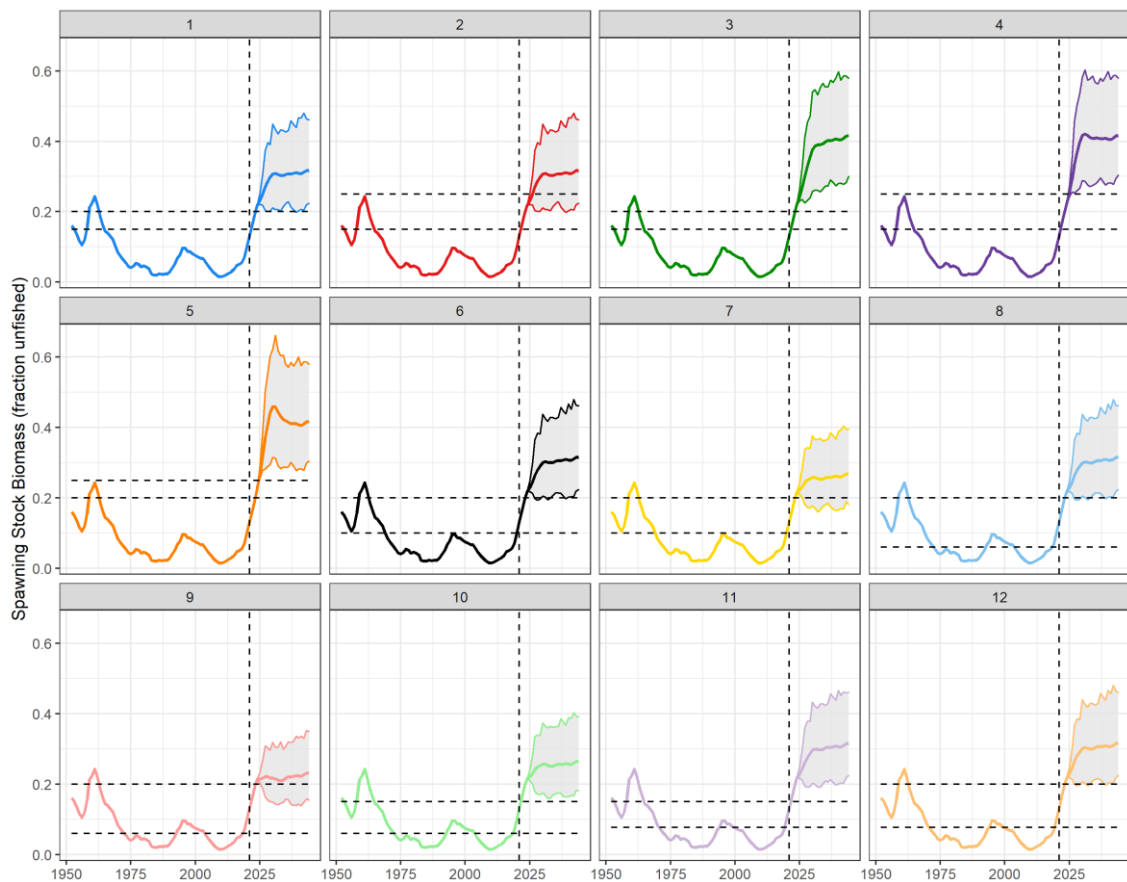
Figure 4. Historical trends in spawning stock biomass (SSB) from the 2022 Pacific bluefin tuna (PBF) stock assessment (ISC 2022) and median SSB (thick color lines) across all iterations for each harvest control rule (HCR) from the PBF MSE. The vertical dotted line marks the end of the historical estimates and start of the MSE simulation output. For the MSE output, the grey shading represents trends in the 5th to 95th quantiles of SSB. The threshold and limit reference points associated with each HCR are shown as horizontal dotted lines.

All HCRs were able to maintain fishing intensity (1-SPR) around the F_{target} except for an early rebuilding period where, as dictated by each HCR, fishing intensity was lower than F_{target} since SSB was below the control points specified by each HCR (Fig. 5). HCR5 has the highest second biomass-based control point of 20%$SSB_{F=0}$ and was the only HCR with an SSB lower than its lowest biomass-based control point at the start of the simulation (Fig. 4). This led to the most drastic decrease in fishing intensity across HCRs (Fig. 5) and also to a rapid increase in SSB, with SSB overshooting the SSB level associated with its F_{target} (Fig. 4). Note that the fishing intensity bounces around the F_{target} with a see-saw pattern (Fig. 5) as, with no assessment or observation error there is perfect

knowledge of terminal year biomass, recruits, and biological parameters. Thus, the TAC always leads to the target fishing intensity the year following the assessment. However, as that TAC is maintained for the two following years notwithstanding changes in recruitment dynamics, it starts drifting away from the F_{target} in a way specific to the recruitment pattern in each iteration, and it's brought back to the target level after the next assessment time step. HCR9, which had a ThRP of $20\%SSB_{F=0}$ matching the SSB that would be associated with its F_{target} of FSPR20% had more drastic management intervention (i.e. SSB breached the ThRP more often, necessitating a decrease in fishing intensity from the F_{target}). This resulted in a median fishing intensity that was slightly lower than the F_{target} (Fig. 5) as well as higher catch variability than other HCRs (Fig. 6, grey shading).

Figure 5. Historical trends in fishing intensity (F, 1-SPR) from the 2022 Pacific bluefin tuna (PBF) stock assessment (ISC 2022) and median F (thick color line) across all iterations for each harvest control rule (HCR) from the PBF MSE. The vertical dotted line marks the end of the historical estimates and start of the MSE simulation output. For the MSE output, the grey shading represents trends in the 5th to 95th quantiles of F. The target

reference point associated with each HCR is shown as a horizontal dotted line.

The catch trends also demonstrate expected differences between HCRs, with HCR4 and HCR5 being the only rules having an initial decline in catch (Fig. 6) due to their higher biomass reference points relative to starting conditions (Fig. 4), which necessitated a more drastic initial drop in fishing intensity than other HCRs (Fig. 5). Trends in median catch were a result of patterns in biomass and fishing intensity. Once median SSB stabilized after the initial rebuilding to the level associated with the F_{target} of each HCR (Fig. 4), median catch was relatively stable (Fig. 6). Median catch at the end of the simulation was lowest for the HCRs with the lowest target fishing intensity, HCRs 3, 4, and 5 (Table 1, Fig. 6). These HCRs have an F_{target} of FSPR40% and thus a fishing intensity of 0.60 (1-SPR). Median catch at the end of the simulation for the other HCRs was similar at around 40,000 mt (Fig. 6) despite the F_{target} ranging from FSPR20% to FSPR30% across these HCRs (Table 1). FSPR30% HCRs (HCRs 1, 2, 6, 8, 11, 12) had higher median SSB than HCRs 7, 9, and 10, which had F_{target} of FSPR25% FSPR20% FSPR25%, respectively (Fig. 4). The higher fishing intensity of these HCRs could not make up for the loss in catch due to the lower biomass as compared to the FSPR30% HCRs.
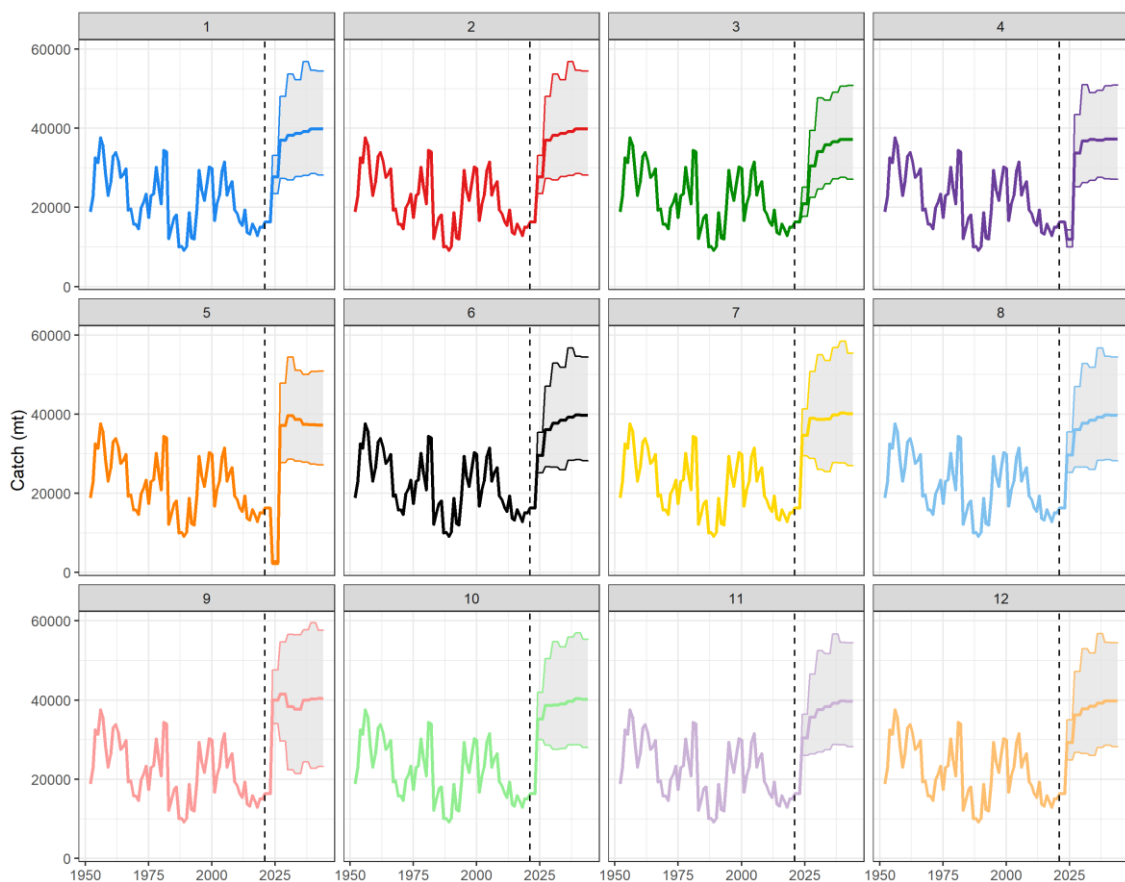
Figure 6. Historical trends in catch from the 2022 Pacific bluefin tuna (PBF) stock assessment (ISC 2022) and median catch (thick color line) across all iterations for each harvest control rule (HCR) from the PBF MSE. The vertical dotted line marks the end of the historical estimates and start of the MSE simulation output. For the MSE output, the grey shading represents trends in the 5th to 95th quantiles of catch.

By design, the recruitment variability covered the range of recruitment observed over the historical period and was the same for all HCRs (Fig. 7) so that their relative performance under the same conditions could be compared.
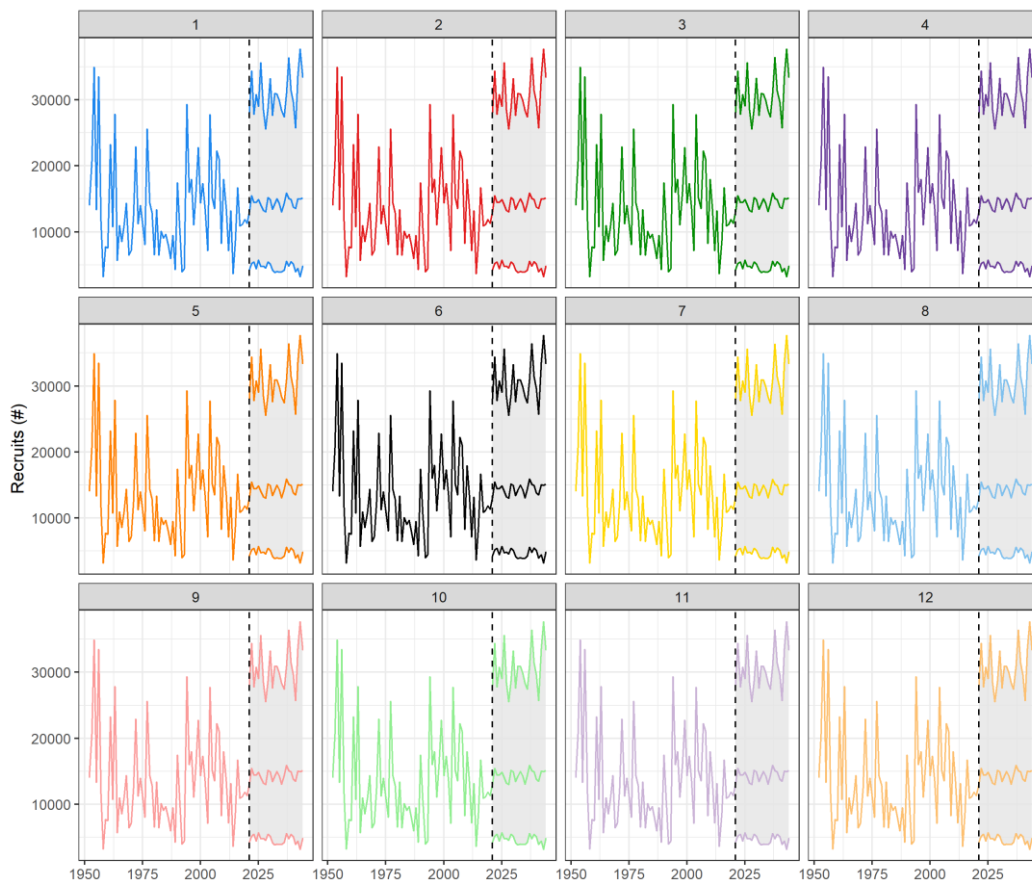
Figure 7. Historical trends in recruitment from the 2022 Pacific bluefin tuna (PBF) stock assessment (ISC 2022) and median recruitment across all iterations for each harvest control rule (HCR) from the PBF MSE. The vertical dotted line marks the end of the historical estimates and start of the MSE simulation output. For the MSE output, the grey shading represents trends in the 5th to 95th recruitment quantiles.

Discussion

We detail and provide links to the R code showing how the twelve candidate HCRs proposed by the JWG are implemented in the current PBF MSE framework. It is hoped that this will facilitate review and testing of the PBF MSE code by the PBF WG before the running of the final MSE simulations in 2024 and 2025. We also have outlined how, in the absence of an F-based F_{min} for HCR8, the authors had to make an assumption regarding the slope of the HCR from the F_{target} and ThRP down to the lowest biomass-based control, point. This affects the resulting TAC when SSB is between the two biomass-based control points. Thus, final implementation of this HCR in the PBF MSE framework needs to be discussed among the PBF WG.

In this perfect information simulation with random recruitment deviations, all HCRs work as expected. Median long-term levels of relative SSB and fishing intensity matched those that would be associated with the F_{target} of each HCR. Starting from a depleted SSB that was below the SSB associated with each of the F_{target} levels, each HCR rebuilt SSB to the level associated with the F_{target} and maintained fishing intensity around the F_{target} once SSB was rebuilt.

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