Revised Method to Tune the Relative Fishing Mortality in the Pacific Bluefin tuna MSE for the Requested Proportional Fishery Impact

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February 2024

Working document submitted to the ISC Pacific bluefin tuna Working Group, International Scientific Committee for Tuna and Tuna-Like Species in the North Pacific Ocean (ISC), from 29 February to 8 March 2024, Kaohsiung Taiwan.

Summary
The model-based harvest control rules currently being examined by the Pacific bluefin (PBF) management strategy evaluation (MSE) aim to set catch limits that would, over the long-term, reach a specified target fishing intensity. The target fishing intensity is set based on a specified percentage of spawning biomass per recruit (SPR). Since fleets have specific selectivities and target different ages of the PBF population, the proportional fishery impact associated with a specific management measure depends on the relative exploitation pattern across fleets (i.e. allocation). The relative exploitation pattern across fleets also affects the overall catch limit required to reach the desired F_{target}. Thus, in the MSE management module, the relative exploitation pattern needs to be specified for the calculation of the catch limit that will result in the specified F_{target}. While the PBF Joint Working Group (JWG) did not specify an allocation by fleet, it did identify one of the management objectives of the MSE as maintaining an equitable balance between WCPO and EPO proportional fishery impact and proposed two potential WCPO:EPO proportional fishery impact scenarios of 80:20 and 70:30. Tommasi and Lee (2023) illustrated a method to find the relative exploitation pattern across fleets to be input into the PBF MSE that leads to the F_{target} and EPO/WCPO relative fishing impact specified by managers. We modify that method to ensure that while the relative EPO/WCPO fishing impact changes, the relative fishing intensity within the EPO or WCPO stays the same as the 2017-2019 baseline.

Introduction
The two Regional Fisheries Management Organizations (RFMOs) tasked with managing the Pacific Bluefin tuna (PBF) stock, namely the Western and Central Pacific Fisheries Commission of the Northern Committee (WCPFC NC) and the Inter American Tropical Tuna Commission (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 operational management objectives and performance metrics with which to evaluate performance of potential management strategies for Pacific Bluefin tuna (WCPFC 2023a). One of the yield objectives was to "Maintain an equitable balance in proportional fishery impact between the Western Central Pacific Ocean (WCPO) and Eastern Pacific Ocean (EPO)". Derivation of performance metrics for this objective necessitates calculation of proportional fishery impact by EPO and WCPO and by fishery (Table 1).
Fishery impact examines the effect of a particular fishery group (e.g. by gear or region)

on spawning stock biomass (SSB). It is computed by simulating what the SSB would have been in the absence of catches from that fishery group and depends not only on the amount of catch of that fishery group but also on the size composition of that catch. For instance, catching juvenile fish would have a larger impact on SSB than catching the same amount of mature fish as those fish are removed before they reach their full growth potential or reproduce (Wang et al. 2009). Proportional fishery impact is the fishery impact of a particular group relative to the impact of all the fisheries combined and has become a quantity routinely computed and presented to managers in the PBF stock assessment (ISC 2022).

Tommasi et al. 2023 detailed how a proportional fishery impact metric is calculated from output of the PBF MSE and presented preliminary results of the fishery impact metric for the 1a harvest strategy initially proposed by the JWG for PBF (JWG 2022). Since the initial harvest strategies proposed by the JWG did not provide specifications regarding the allocation of that fishing intensity, Tommasi et al. 2023 carried out their analysis by assuming that the current (2017-2019) relative fishing pattern across fleets, a measure of allocation, would be maintained. That is, the harvest strategy algorithm identified the fishing mortality required to achieve the F_{target} assuming that the relative apical fishing mortality across fleets was maintained at 2017-2019 average levels. This relative fishing mortality pattern resulted in a median relative fishing impact between the EPO and WCPO across all the iterations and HCRs for harvest strategy 1a of 18% for the EPO and 82% for the WCPO.

In the latest round of JWG discussions, it was requested that a final set of 12 HCRs be evaluated in the PBF MSE with allocations tuned to reach a WCPO:EPO fishery impact ratio of 70:30 or 80:20 in the terminal year of the evaluation period (WCPFC 2023b). In the current PBF MSE framework, this would require specification in the MSE of the apical fishing mortality across fleets that would lead to the desired impact ratios. Therefore, there is a need to develop a method to find the relative fishing mortality pattern leading to a specified impact ratio. Tommasi and Lee 2023 presented a a methodology that allows determination of what the relative apical fishing mortality across fleet should be to meet a pre-determined impact ratio between the EPO and WCPO. However, in this method the increase (or decrease) in fishing intensity was not allocated to fleets within the EPO (or WCPO) proportionally to their 2017-2019 levels. Here we modify the method of Tommasi and Lee 2023 to ensure the increase (or decrease) in fishing intensity is applied proportionally across fleets within the EPO and WCPO groups.

This tool enables the PBF WG to select, a priori, a relative fishing mortality pattern across fleets to input into the MSE framework that would achieve a requested fishery impact ratio.

Table 1. List of operational management objectives and performance metrics for Pacific Bluefin tuna for the yield category from WCPFC 2023a. SSB refers to female spawning stock biomass.

Category	Operational Management Objective	Performance Metric
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	

Methods

We used the same empirical approach outlined in Tommasi and Lee 2023 to relate fishery impact to the relative apical fishing mortality across fleets (relative F). We run a set of simulations for a single HCR with progressively different EPO/WCPO relative Fs to assess the effect of changes in relative F on the proportional EPO/WCPO fishery impact metric. We run the simulation for the first of the final set of HCRs proposed by the JWG (WCPFC 2023b). We chose to run only one HCR as Tommasi et al. 2023 showed that the relative impact metric was consistent across different HCRs as it was dependent on the specified relative F. This HCR has a limit reference point of 15% $SSB_{F=0}$, a threshold reference point of 20% $SSB_{F=0}$, and a target reference point (TRP) of F30. The TRP is an indicator of fishing intensity based on spawning potential ratio (SPR). SPR 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 in the long run would produce 30% of the spawning potential in an unfished state.

The simulations were run using the PBF MSE framework presented in Tommasi and Lee (2022), updated by Tommasi et al. 2023a and Tommasi et al. 2023b, and available at https://github.com/detommas/PBF_MSE. 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. Since Tommasi et al. 2023 showed that the median EPO impact was 18% when using the 2017-2019 relative F, the EPO relative F would need to be increased to reach one of the requested WCPO:EPO fishery impact ratios of 80:20 or 70:30. We therefore ran a sequence of 12 simulations where the EPO relative F, expressed in %, was increased by increments of 0.5 or 1% from 2017-2019 levels (and the WCPO relative F was decreased by the same amount) up to an increase of 8% (Table 2).

The relative F ($relF_{f,s,t}$ where f = fleet, s = season, and t = year) in Stock Synthesis (SS) and in the MSE framework is equal to

$$relF_{f,s,t} = \frac{F'_{f,s,t}}{\sum_{f,s} F'_{f,s,t}} \quad (1)$$

where F' is the apical F (maximum value across ages) for fleet f in season s and year t (e.g. average of apical F during 2017-2019 by each fleet and season). It indicates the proportion for a specific fleet and season of the total apical F. To find the TAC per fleet and season that would meet the F_{target}, the MSE algorithm uses the SS forecast calculation. The SS forecast first searches for the F multiplier that achieves the F_{target} given the specified relative F and selectivity and biological parameters. The F multiplier is multiplied by the $relF_{f,s,r}$ to obtain the apical F for each fleet, year, and season ($F'_{f,s,t}$). Then, the catch per fleet and season that would occur while fishing at the F_{target} given terminal year numbers at age are computed (see Tommasi et al. 2023b for details). For the base simulation we specify in the operating model SS forecast file that the $relF_{f,s,t}$ to be used in the forecast calculations be the $relF_{f,s,t}$ averaged over 2017-2019. For all the other simulations, we specify in the SS forecast file to set the forecast $relF_{f,s,t}$ to use user-specified values added to the forecast file.

The user-specified $relF_{f,s,t}$ where computed by adding the increases specified in Table 2 to the 2017-2019 $relF_{f,s,t}$ of the EPO fleets and subtracting it from the WCPO fleets. Note that the $relF_{f,s,t}$ add to 100% and so an increase in EPO $relF_{f,s,t}$ had to be matched by a decrease in in WCPO $relF_{f,s,t}$. To ensure that the increase (or decrease) in relative F within the EPO (or WCPO) was proportional to the relative fishing intensity in 2017-2019 (i.e. the fleet with a larger 2017-2019 relative F would receive more of the increase), the specified increase (or decrease) was split across all the fleets based on their 2017-2019 contribution to EPO or WCPO total relative F. For instance, if the relative F of fleet 2 in season 1 was 13% of the total WCPO relative F, then it would be assigned 13% of the increase. Thus, for example, for a total WCPO 3% decrease in relative F, the fleet and season specific relative F to input into the forecast file is calculated as:

$Forecast\_relF_{f,s} = (relF_{WCPO,2017\text{-}2019} - 0.03)*(relF_{f,1}/ relF_{WCPO,2017\text{-}2019})$

The corresponding 3% in EPO relative F, would result in a fleet and season specific relative F of:

$Forecast\_relF_{f,s}= (relF_{EPO,2017\text{-}2019} + 0.03)*(relF_{f,1}/ relF_{EPO,2017\text{-}2019})$

Table 2. Increase in EPO relative F from the 2017-2019 levels for each of the 12 simulations run in the analysis. EPO relative F is the EPO proportion of the total apical F in %.

Simulation #	**Increase in EPO relative F in % from 2017-2019 levels**
Base	0
1	0.5
2	1
3	1.5
4	2
5	3
6	4
7	4.5
8	5
9	6
10	6.5
11	7
12	8

Once the runs were completed, for each of the 12x100 runs we computed the EPO/WCPO proportional fishery impact following the algorithm described in Tommasi et al. 2023. In

R version 4.1.3 we fit a polynomial regression with a quadratic term to the relative F and proportional fishery impact output, following the formula below where *x* is the relative F and *y* is the proportional fishery impact.

$$y = a + bx + cx^2 \qquad (2)$$

We then use the estimated relationship to compute, as an example, what increase in EPO relative F would be needed to be to obtain a proportional fishery impact ratio of 30/70 and compare PBF MSE performance metrics under that scenario to the base case. Proportional fishery impact is calculated for the terminal year of the evaluation period as specified in the performance metrics table from the JWG (WCPFC 2023a). Furthermore, while the simulation is run for 24 years, the evaluation period is taken as the last 21 years. This is because catch for the first three years of the simulation is set to the CMM catch limits and thus the HCR only starts being applied from the fourth year onwards (Tommasi and Lee 2022). All performance metrics are calculated over the entire evaluation period except for the status metric which was computed over the last 10 years of the simulation to ensure that F would be at or below F_{target} with 50% probability even once the stock was rebuilt to the F_{target}.

Results

The polynomial fitted the output data well (Fig. 1). The R^2 was 0.96, and the F statistic was significant with 1,297 degrees of freedom and a p-value less than $2e^{-16}$. The model coefficients are presented in Table 3.

Table 3. Estimated coefficients for the polynomial regression in Equation 1.

	Regression Coefficients		
	a	***b***	***c***
Estimate	0.18	0.0269	-0.0006
Standard Error	0.0007	0.00046	0.00006

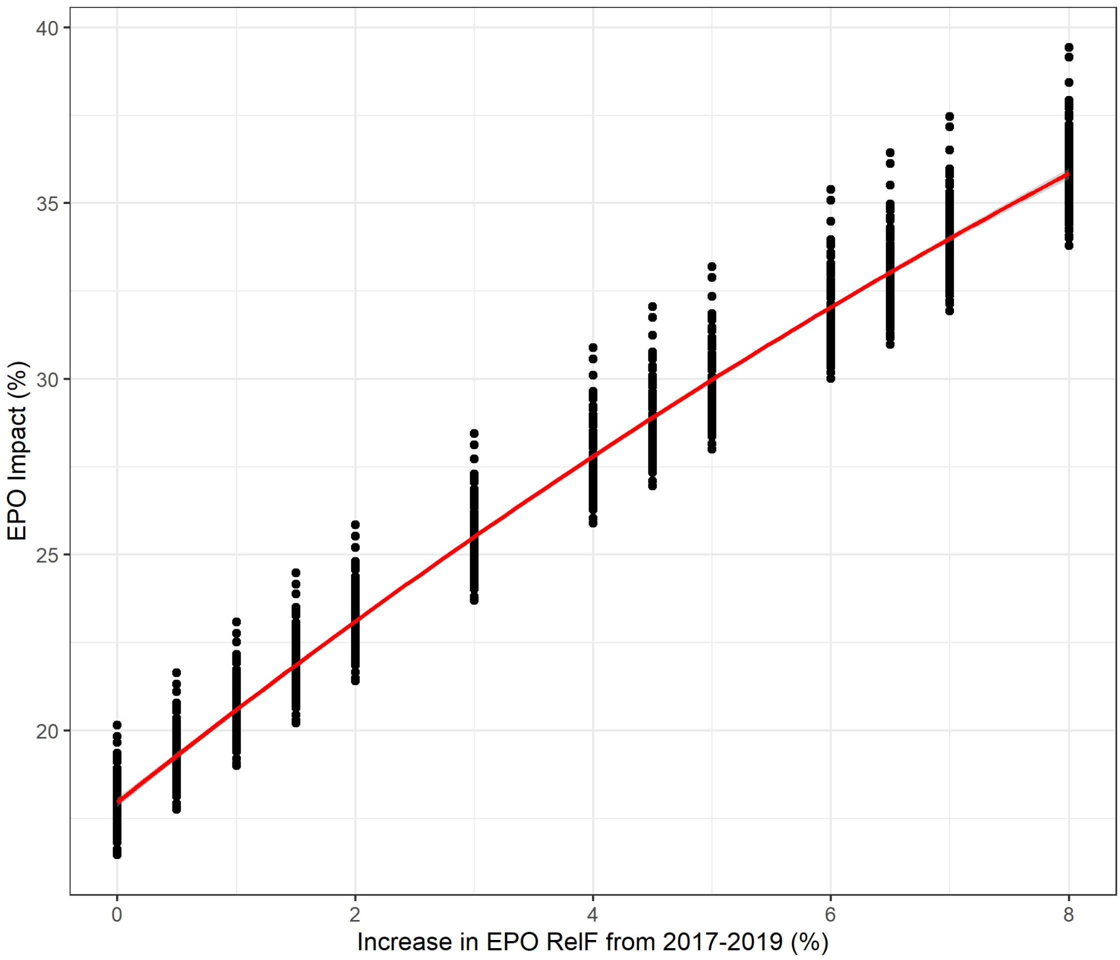

Figure 1. EPO relative F increase from 2017-2019 average levels and associated proportional EPO Fishery impact for the 12x100 simulations and the 100 base case runs (black dots). The red line is the best fit polynomial regression.

Using the estimated coefficients, the relative F impact associated with an EPO proportional impact of 30 is 5.03%. Indeed, the median proportional EPO fishery impact of the run with a 5% increase in EPO relative F was around 30% (Fig. 2).

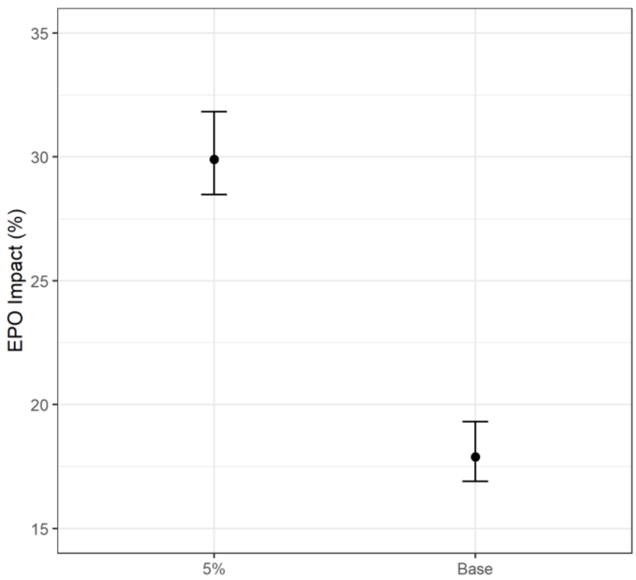

Figure 2. Median and 5th-95th quantile range for proportional EPO fishery impact in the last year of the simulation across all the base case simulations and the simulations with an increase of 5% in EPO relative F.

To assess the impact of a change in relative F on the MSE performance metrics other than the proportional fishery impact, we compared output from the 5% simulation to that of the base simulation. Relative median SSB and its variability over the simulation period and iterations was similar between the two simulations (Fig. 3). Both simulations met management objective #1, that there should be a less than 20% probability of the stock falling below the limit reference point, here 15% $SSB_{F=0}$. In both cases there was a 0% probability that the stock was below the limit reference point.

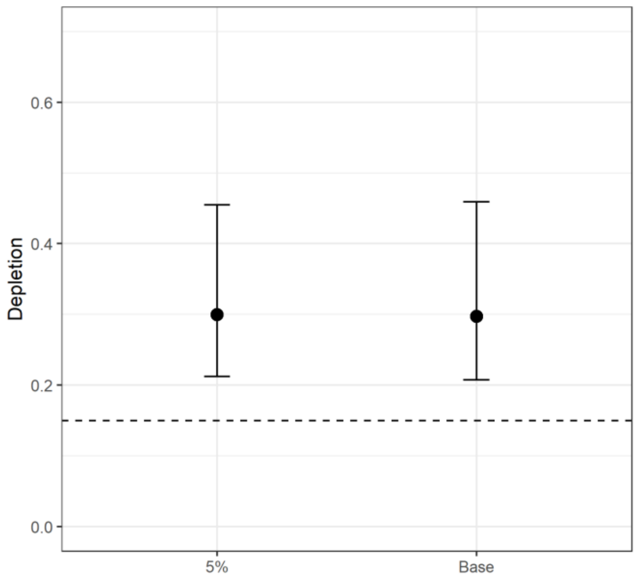

Figure 3. Median and 5th-95th quantile range for depletion, the ratio of spawning stock biomass (SSB) and the unfished spawning stock biomass ($SSB_{F=0}$) across the evaluation period for the base case simulations and the simulations with an increase of 5% in EPO relative F. The dotted horizontal line reflects the limit reference points of 15% $SSB_{F=0}$ used in the HCR tested.

Both simulations also met the status performance metric of the probability of F being at or below the F_{target} with a probability of at least 50% and had similar median fishing intensity, measured as 1-SPR (Fig. 4 and 5).

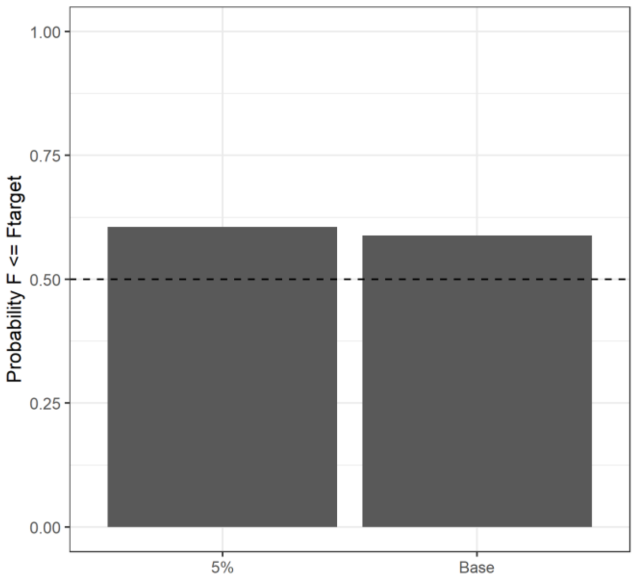

Figure 4. Probability of fishing intensity being less or equal to the target reference point (F_{target}) across the last 10 years of the simulation for the base case simulations and the simulations with an increase of 5% in EPO relative F. The dotted horizontal line reflects the 50% probability of F being above the F_{taget}.

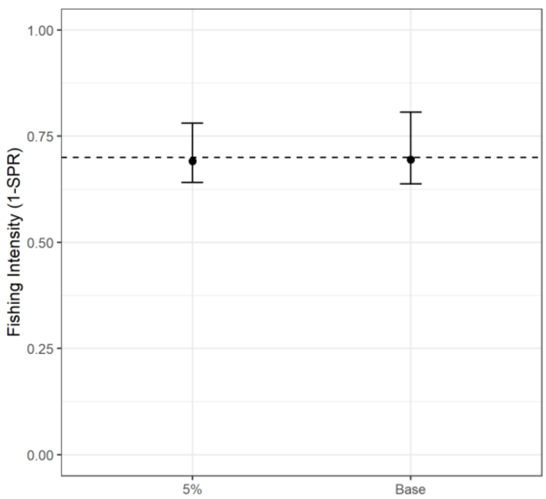

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Figure 5. Median and 5th-95th quantile range for fishing intensity (1-SPR) for the base case simulation across the last 10 years of the simulation for the base case simulations and the simulations with an increase of 5% in EPO relative F. The dotted horizontal line reflects the F_{taget} of F30, which corresponds to a fishing intensity (1-SPR) of 0.70.

Both simulations had a similar median % change downwards in catch between management periods of less than 25% across the entire simulation period and iterations (Fig. 6).

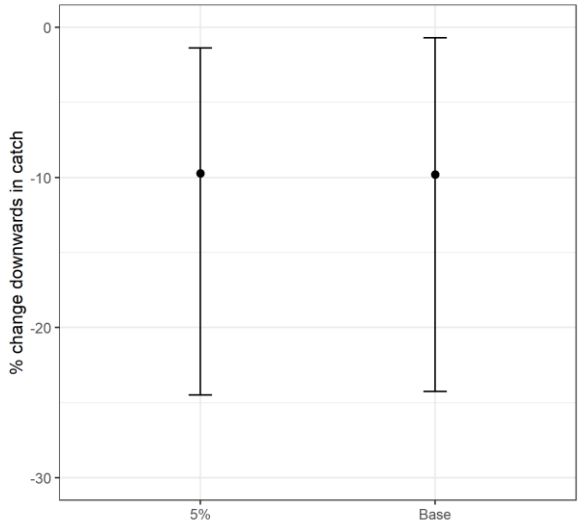

Figure 6. Median and 5th-95th quantile range of the % decrease in catch between management periods across the evaluation period for the 100 base case simulations and 100 simulations with an increase of 3.56% in EPO relative F.

The largest difference in performance metrics was for the yield metric of maximizing yield over the medium (5-10 years) and long (10-24 years) terms, as well as average annual catch yield from the fishery. Median annual, medium-term, and long-term catch was highest for the 5% increase simulation for all catch performance metrics (Fig. 7).

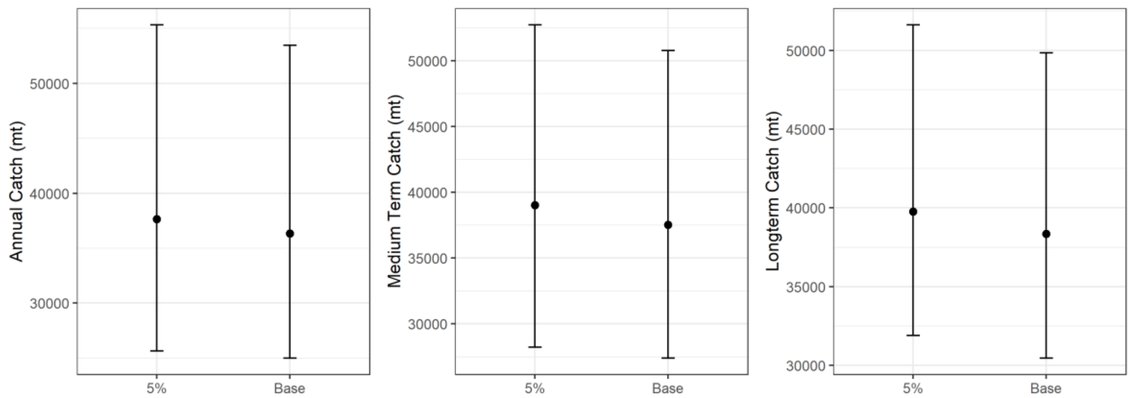

Figure 7. Median and 5th-95th quantile range for annual catch (left panel), medium term catch (middle panel), and long term catch (right panel) across the evaluation period for the base case simulations and the simulations with an increase of 5% in EPO relative F.

As expected, all EPO catch performance metrics were higher and WCPO catch metrics lower for the 5% increase simulation (Fig. 8 and 9).

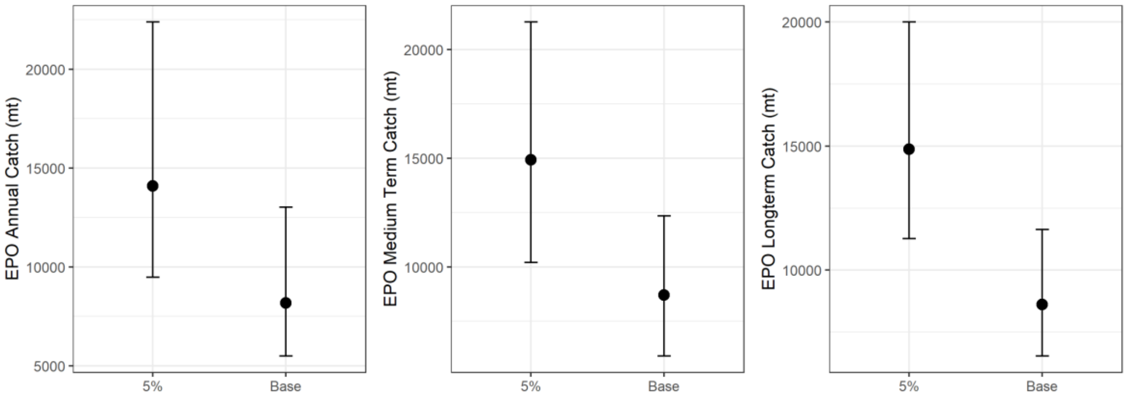

Figure 8. Median and 5th-95th quantile range for Eastern Pacific Ocean (EPO) annual catch (left panel), medium term catch (middle panel), and long term catch (right panel) for the base case simulations and the simulations with an increase of 5% in EPO relative F.

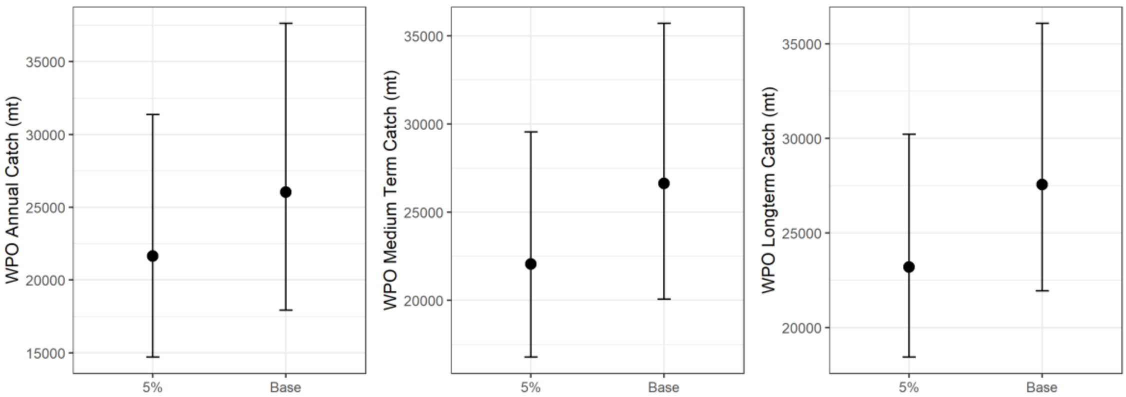

Figure 9. Median and 5th-95th quantile range for Western and Central Pacific (WPO) annual catch (left panel), medium term catch (middle panel), and long term catch (right panel) for the base case simulations and the simulations with an increase of 5% in EPO relative F.

However, within the EPO or WCPO the relative catch across fleets remained the same between the two relative F scenarios (Fig. 10 and 11).

Figure 10. Catch ratios within the Eastern Pacific Ocean (EPO) fleets over the simulation period. F30 is the EPO discard fleets and its catches are quite low relative to the other EPO fleets.

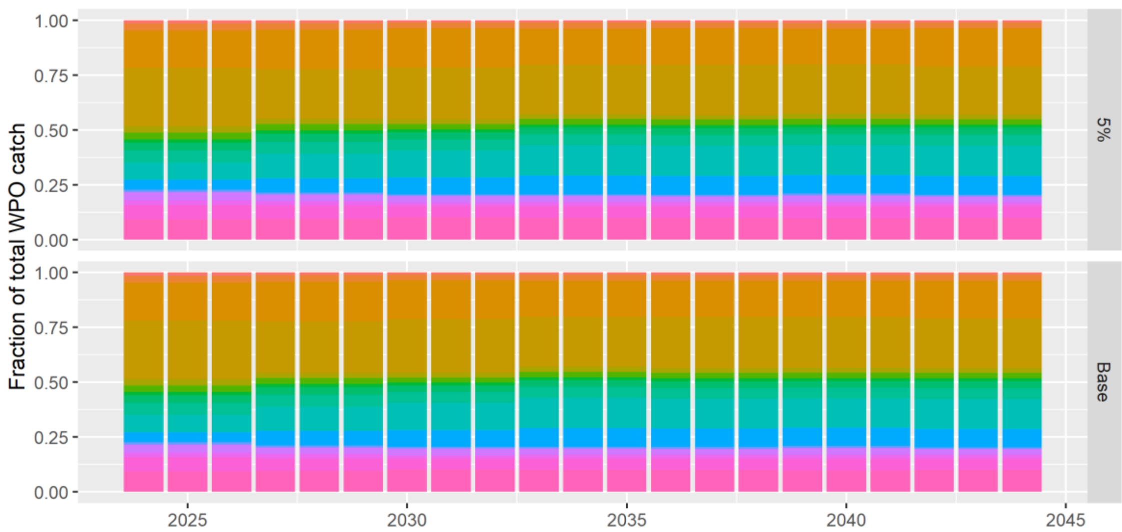

Figure 11. Catch ratios within the Western and Central Pacific Ocean (WPO) fleets over the simulation period. The different colors represent the 20 different WPO fleets.

Discussion

This analysis revises the method proposed by Tommasi and Lee 2023 to ensure that the increase for EPO catch (or decrease for WCPO) associated with a change in proportional EPO/WCPO impact is spread equitably within the EPO or WCPO fleets. We demonstrate that the relative catch of EPO or WCPO fleets does not change across

the two impact scenarios, showing that the revision ensures that the increase (or decrease) is applied proportionally across fleets based on their recent (2017-2019) catches. As for the previous method, we are also able to find the relative F to be input in the MSE management module to ensure that the management measure generates the desired proportional fishery impact. As in Tommasi and Lee (2023) the safety and status performance metrics, which are dependent on the HCR rather than the relative F across fleets, were comparable across impact scenarios, as was the stability metric.
Also, as expected and shown in Tommasi and Lee (2023), following an increase in EPO relative F and a corresponding decrease in WCPO relative F, EPO catch increased and WCPO catch decreased. Furthermore, since the EPO and WCPO fleets have different selectivities, with an increase in EPO relative F, the overall catch also increased as the higher spawning potential allowed for a higher catch under the same F_{target}.

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