ISC/19/ALBWG-01/01

Summary of results for the North Pacific albacore tuna (*Thunnus alalunga*) management strategy evaluation [1]

Desiree Tommasi, Steven L. H. Teo

NOAA Fisheries
Southwest Fisheries Science Center
8901 La Jolla Shores Drive
La Jolla, CA 92037, USA

Email: Desiree.Tommasi@noaa.gov

[1]This working paper was submitted to the ISC Albacore Working Group Intercessional Workshop, 26 February - 5 March 2019, held at the NRIFSF/FRA, Shimizu, Shizuoka, JAPAN. Document not to be cited without the author's permission.

Abstract

A management strategy evaluation framework was developed for North Pacific albacore tuna (NPALB, *Thunnus alalunga*) to assess the performance of alternative candidate alternative management strategies and reference points for NPALB given uncertainty. Harvest strategies with Total Allowable Effort (TAE) control performed better than ones with Total Allowable Catch (TAC) control across all performance metrics because they could quickly adjust catches in response to changes in biomass between assessment periods. HS3 showed more variability than HS1 in catch between years because of the steeper changes in catch required once the threshold reference point was crossed. For the same target reference point (TRP), harvest control rules (HCRs) with a higher limit reference point (LRP) performed poorer. They showed a higher probability of the LRP being breached, lower odds of catches being higher than the historical period, and a higher probability of decreases in catch from one year to the next being higher than 30%. Across TRPs, there was no single best-performing HCR for all performance metrics (PMs). Trade-offs were evident between conservation and economic indicators. With a lower fishing intensity TRP, the population was maintained at a higher level, requiring less management intervention and resulting in lower catch variability between years. However, this stability came at a cost to overall catch.

Introduction

Management strategy evaluation (MSE) is process whereby the robustness to uncertainty of a set of management harvest rules given some performance metrics of interest to stakeholders, are assessed using a computer simulation. The two Regional Fisheries Management Organizations (RFMOs) tasked with managing the NPALB stock, namely the Western and Central Pacific Fisheries Commission of the Northern Committee (WCPFC NC) and the Inter American Tropical Tuna Commission (IATTC), agreed for the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean (ISC) Albacore Working Group to start developing an MSE framework for NPALB. While a limit reference point (LRP) of 20%$SSB_{CURRENT,F=0}$ has been established for NPALB, no formal harvest strategy or target reference point (TRP) exists. The aim of this MSE process was to examine the performance of candidate alternative management strategies and associated reference points for NPALB given uncertainty. Here we summarize the results of the first round of analyses from the NPALB MSE effort.

Methods

For a detailed overview of the modeling structure, conditioning of the operating models (OMs), and description of the harvest strategies and management objectives the reader is referred to ISC (2018). Briefly, the MSE framework includes a set of OMs, which are mathematical representation of the true dynamics of the population of interest. Data is generated with error from the OM and is input to the estimation model (EM, i.e. the assessment model). Estimates of stock status are generated with the estimation and input into the management model, which sets a TAC or TAE. The TAC or TAE plus an implementation error is then fed back into the OM. The implementation error is always positive, varies randomly between 5 and 20%, and is the same for all fisheries.

One uses a set of OMs, rather than a single one to capture the range of uncertainty in the system. The uncertainties to be considered in this first round of NPALB MSE were agreed upon and prioritized in

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October 2017 (ISC 2017). This first set of operating models only considered uncertainties in the factors considered as highest priority by the ISC: 1) recruitment – autocorrelation and steepness, 2) natural mortality, 3) growth, and 4) juvenile movement (via time varying selectivity for the Eastern Pacific Ocean (EPO) fleet). OMs were developed to capture the above uncertainties. Each OM is associated with a scenario. Given the long run times, time constraints on MSE development, and similarities in terms of stock productivity between scenarios, in May 2018 the ISC ALBWG proposed a reduced set of five scenarios and 11 harvest control rules (HCRs) to be tested (ISC 2018). See Table 1 for a list of parameter specifications for the five OMs used to characterize parameter uncertainty. The five OMs showed a wide range in potential stock productivity trends (Fig. 1). In addition to the five uncertainty scenarios mentioned above, two potential future fishing effort scenarios prioritized in October 2017 were developed: 1) shift of south Pacific fishing effort to the north Pacific – new entrant to fishery but catch is known to the assessment and under HCR – ramp in catch, 2) Shift of south Pacific fishing effort to the north Pacific – new entrant to fishery but catch is known to the assessment and under HCR – step change in catch. These two fishing scenarios and scenario 7 were treated as robustness (less plausible) scenarios. Scenario 7 was a high productivity trial with a much higher biomass and lower fishing intensity as compared to the base case (Fig. 1). Here results are presented across the four reference scenarios, but their robustness to the other scenarios was also examined.

Table 2 displays the list of the 11 finalized HCRs with their associated reference points. These HCRs were tested in the MSE framework as part of both harvest strategy 1 (HS1) and HS3, and with TAC and TAE as output control. Differences between HS1 and HS3 lie in the management action implemented when SSB is between the threshold and LRP, with HS3 using a steeper but gradual decline in fishing intensity (F) from threshold to LRP, and HS1 using a more gentle decline which results in a sharp change in F once the LRP is breached (Fig. 2). HS2 was based on the IATTC's tropical tuna HS. See ISC (2018) for a detailed description of HS2.

Results

Performance Metric 1

Performance metric 1 (PM1) is a measure of management objective 1, *maintain spawning biomass above the limit reference point*. It is dependent on both the value of spawning biomass as well as the level of the limit reference point (LRP).

The largest changes in SSB were associated with changes in the target reference point (TRP) rather than the threshold or LRP, with higher target fishing intensity (e.g. HCRs 13 and 15 with TRP F30) displaying the lowest SSB (Fig. 1). In terms of SSB, the performance of HS1 and HS3 was comparable (Fig. 3). For both HS1 and HS3, TAE-based rules maintained a higher SSB than TAC-based ones as they could respond to random changes in biomass between assessment periods. The TAE rules based on effort levels from 2002-2004 (HCRs 16, 17, and 18) showed an intermediate performance between TRP F40 and TRP F30 and similar to HS2 (Fig. 3). Unlike other HCRs, their performance varied across uncertainty scenarios, with poorer performance in the low productivity scenarios (e.g. scenario 6), where maintaining constant effort levels from 2002-2004 implied a high fishing intensity (Fig. 4).

Changes in PM1, the ratio of SSB to the LRP, were associated with the above trends in SSB, as well as the LRP value. For the same LRP, the observed drop in PM1 from low to high TRP (TRP F50 to TRP F30) (Fig. 5) was due to the decrease in SSB. Also, TAE-based rules performed better in terms on PM1 as they maintained a higher overall biomass. For all TAE-based rules the odds of SSB being higher than the

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LRP during any year of the simulation were almost certain. However, TAC-based rule breached the LRP at times (Fig. 5), with the odds of SSB being higher than the LRP falling to highly likely for TAC-based HCR7 and HCR13 (Fig. 6). These were the HCRs with the highest LPR for the F40 and F30 LRPs, respectively. Hence, given the same TRP, PM1 was lowest for the HCR with the highest LRP.

Performance Metric 2

Performance metric 2 (PM2) is a measure of management objective 2, *maintain total biomass, with reasonable variability, around the historical average depletion of total biomass*. It was measured as the ratio of depletion of total biomass across the 30 years of simulation to minimum historical (2006-2010) depletion. As for variability in SSB, the largest differences in PM2 were due to variation in TRP, with the highest target fishing intensity (TRP F30) showing the lower PM2 (Fig. 7). As for SSB, TAE-based rules performed better than TAC-based ones in terms of PM2. HCRs 1, 4 and 6, the TRP F50 TAE-based rules of HS1 and HS3, were the only ones showing the odds of depletion being higher than the minimum historical depletion as better than even (Fig. 8). All TAC-based rules and HS2 had even odds of depletion being higher than the minimum historical.

Performance Metric 3

This MSE was not designed to define an allocation scheme for the fleets involved, and at the Vancouver MSE Workshop (ISC 2017) it was decided to maintain an allocation constant for the entire simulation at the average historical allocation for the period of 1999-2015. Therefore, PM3, *maintain harvest ratio by fishery*, is not well assessed by this MSE exercise, with differences in PM3 between HCRs being minimal because all use the same average allocation. The value of PM3, measured as the average harvest ratio over the 30 years simulation over the minimum or maximum historical (2006-2015) harvest ratio, shown here for the EPO fleet relative to the minimum historical harvest ratio (Fig. 9) was rather a reflection of the difference in harvest ratio for a specific fishery from the 1999-2015 allocation used in the simulation versus the 2006-2015 value used in defining PM3. The only change in PM3 occurred under the two fishing effort scenarios. With the arrival of a new fishery, the catch allocation to the other fleets had to be reduced (Fig. 10).

Performance Metric 4

Objective 4 was to *maintain catches above average historical catch*. For all HS, the largest changes in PM4 were due to variation in TRP, with higher catches relative to the historical average at higher fishing intensities (TRP F30) (Fig. 11). However, there was a trade-off between increased catch and increased catch variability with catches being less variable for TRP F50 (Fig. 11). Also, for the same LRP, TRP, and threshold reference point, catches in HS1 were less variable than in HS3 (Fig. 11), as, once the threshold point was breached, HS3 forced a steeper change in fishing intensity. Trends in both mean catch and catch variability were reflected in the odds of catch being greater than the historical average. Odds were highest for HS2, and HCR 12 and 15 for HS1 TAC-based, and HCR 15 and 18 for HS1 and HS3 TAE-based (Fig. 12).

PM4 was also computed by fleet (see Fig. 13 for an EPO example). Here trends are a reflection of TRP as above but also of the difference in harvest ratio from the historical period of comparison used in PM3 (1981-2010) and the harvest ratios used in the MSE (1999-2015). Differences across HCRs, however, were largely a reflection of the trends in overall catch described above with catch being higher but more variable at a higher fishing intensity (Fig. 13).

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Performance Metric 5

PM5, the % change in TAC between years (separate for increases vs. decreases), is outlined in Fig. 14 (for decreases). To compute this metric we first removed the instances when the fishery closed and TAC=0, as these are represented in another metric (% years fishery closed, Fig. 15), we then separated increases vs. decreases in TAC. Unlike other performance metrics, there were no large differences in PM5 between TRPs. The largest difference in PM5 was observed between TAC and TAE-based rules, with the latter showing smaller changes in TAC between years, as biomass was maintained at a higher level and management interventions were less frequent (Fig. 14). Indeed, while all TAE-based rules showed the odds of a decrease in catch between years to be “almost certain”, the odds varied across HCRs for TAC-based rules, with HCR 7, 13, and 15 being the worst performing (Fig. 15). For the TAC-based rules, HS3 showed larger decreases in TAC between years (Fig. 14) and lower odds of decreases in TAC between years being less than 30% (Fig. 15). However, HS3 showed less fishery closures. This is most apparent by looking at results from scenario 6, which had the most instances of fisheries closures (Fig. 16). For TAE based rules, the fishery was closed more often in HCR 7, 13, 16, and 17 because of the higher LRPs relative to the target biomass level (Fig. 17).

Performance Metric 6

Management objective 6, maintain F at the target value with reasonable variability, was measured as the ratio of the TRP to the observed F in each year of the simulation. All HCRs except for HS2 had PM6 < 1 as the implementation error was forced to always be positive (i.e. catches were always higher than what was set by management) (Fig. 18). HS2 was the only rule where if the current F was lower than the F-based TRP, the F was allowed to exceed the TRP. PM6 was lowest for HCRs with the lowest TRP, with the odds of TRP being higher than the actual F being even only for TRP F30 (Fig. 16). Trends in PM6 are due to a combination of implementation and estimation (i.e. assessment) error. Given the decreasing biomass level and higher catches from TRP F50 to TRP F30 HCRs, the same implementation error is more likely to bring TRP F30 HCRs below the reference point, forcing F to move back towards TRP. TRP F50 HCRs can instead allow for more implementation error, leading the current F further away from Ftarget before a management action is triggered.

Discussion

The MSE results demonstrated that TAE-based harvest strategies performed better than TAC based ones. This is exemplified in Fig. 19, which provides an overview of results for HCR 13 for HS1 and HS3 as well as HS2. The TAC based rules underperformed TAE ones across all performance indicators (see Table 3 for a description of the performance indicators used in Fig. 19 to 24). The largest difference occurred for PM5, represented in Fig. 19 as the odds of a decrease in catch between years being less than 30%. Given the 3 years assessment frequency, in a TAC-based rule the TAC is maintained constant over a 3-year period. Hence, if biomass is reduced because of random, biologically driven variability, fishing intensity can increase and drive the population below the threshold and limit reference points more often, requiring more management intervention. This resulted in TAC-based rules having higher catch variability and being closed more often.

Among the TAC-based rules, HS1 and HS3 were comparable across PMs except for PM5. HS3 showed more variability in catch between years (Fig. 19) because of the steeper changes in catch required once the threshold reference point was crossed. However, the more drastic reductions in catch resulted in a lower frequency of fishery closures (Fig. 16).

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Among TAC-based rules, for the same TRP, those with a higher LRP performed poorer in terms of PM1, PM4, and PM5. Fig. 20 demonstrates that, for HS1 HCRs with an F40 TRP, HCR 7, the HCR with an LRP of 20%$SSB_{CURRENT,F=0}$, had the lowest odds of catch being higher than the historical average, of changes in TAC between years being < 30%, and of the fishery not requiring a drastic management action.

Across TRPs, there was no single best-performing HCR for all PMs. Trade-offs were evident between PM2, PM4, and PM5. Fig. 21 shows results for HS1 TAC-based HCRs with an LRP of 14% $SSB_{CURRENT,F=0}$, but different TRPs. HCR6 (TRP F50) performs best in terms of PM2, p(depletion), and PM5, p(catch decrease < 30%). With a lower fishing intensity, the population was maintained at a higher level, requiring less management intervention and resulting in lower catch variability between years. However, this stability comes at a cost to overall catch, with PM4, p(catch), being lowest for HCR6 (Fig. 21). By contrast, increasing fishing intensity from HCR12 (TRP F40) to HCR15 (TRP F30) did not result in an increase in PM4 (Fig. 21). This is because the higher fishing intensity of HCR15 could not compensate for the lower biomass and higher frequency of management intervention leading to high catch variability and a higher probability of catch being less than the historical average as compared to HCR12. In conclusion, for TAC-based rules, the best performing HCRs overall were HCR4, HCR6, HCR10 and HCR12. HCR10 and HCR12 (TRP F40) performed best in terms of PM4, while HCR4 and HCR6 performed better in terms of PM2.

If the current LRP of 20%$SSB_{CURRENT,F=0}$ were to be maintained, the best performing TAC-based HCR would be HCR1. In this case, the probability of catch being higher than the historical average was comparable to HCR7, the only other TAC-based rule with an LRP of SSB20% as, under the high LRP, the F40 HCR7 rule experienced more frequent management intervention, leading to more closures and higher catch variability (Fig. 22).

The best performing TAC-based HCRs here highlighted were robust to both the ramp in catch and the pulse in catch fishing scenarios. Table 4 outlines the PMs for the base case and effort scenarios for HS3, demonstrating that for most performance metrics the HCRs do similarly well in the scenarios as in the base case. This is because the catch from the new "South Pacific" fishery is known and subject to management, and thus any increase in catch is quickly reduced to maintain fishing intensity around the TRP, resulting in a similar performance across PMs. PM3 was obviously an exception, as the arrival of a new fishery implies that the catch allocation to the other fleets has to be reduced (Fig. 10). PM5 was also an exception, with the probability of a change in TAC between years being less than 30% being lowest for the pulse in catch scenario (Table 3) because of the drastic reduction in catch required following the first time step to bring fishing intensity back to the TRP.

TAE-based rules were more effective at maintaining SSB around the specified TRP and SSB rarely fell below the LRP. Nevertheless, the fishery was closed for some time steps in HCRs 7, 13, 16, and 17 (Fig. 17), because of the combination of high LRP and lower biomass level compared to TRP F50 rules. Differences between TAE-based HCRs were most evident for PM2 and PM4. For instance, given a LRP of 14%$SSB_{CURRENT,F=0}$, HCR4 (TRP F50) performed best in terms of PM2, p(depletion), but worst in terms of PM4, p(catch) (Fig. 23). No single HCR performed best in terms of PM4, p(catch), but HCR10 (TRP F40) was the second best in terms of PM2 (Fig. 23). The F40 HCR was thus better able to meet the conservation performance metric than the F30 one, without compromising economic performance.

A trade-off between conservation and economic goals was evident also for HCRs with an LRP of 20%$SSB_{CURRENT,F=0}$, with HCR1 (TRP F50) performing better in terms of PM2 but more poorly in terms

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of PM4 (Fig. 21). However, given the higher likelihood for management intervention and fishery closure (Fig. 17), and higher catch variability (Fig. 11) for HCR7 and HCR16, HCR1 would be the best performing HCR if the current 20%$SSB_{CURRENT,F=0}$ LRP would be maintained. In conclusion, the best performing TAE-based HCRs were HCR1, HCR4, HCR6, HCR10, HCR12, and HCR15, with the first three performing best with regards to PM2 and the last three performing best in terms of PM4.

While interpreting the results of this analysis, it is important to keep in mind some of the limitations of the current MSE modelling framework. As previously mentioned with regards to PM3 allocation is kept constant throughout the simulation. Implementation of a more dynamic allocation scheme would require further consultation with managers. Secondly, effort is not modeled explicitly, rather the TAC or TAE is translated directly to a fishing mortality. We also assume that effort control is as effective as catch control and implemented effectively across all fisheries, both NPALB targeting and non-targeting. Development of a fishing effort sub-model, in conjunction with social scientists, would allow for the testing of how the proposed HCRs might be implemented via realistic effort or catch control management measures. Third, we assume that the there is one pan-Pacific stock, and that the Japanese adult long line CPUE is a good index of SSB for this population. It is well known that availability to the EPO varies between years, and that EPO CPUE is not always consistent with the main CPUE index. In the absence of a mechanistic understanding of what drives migration to the EPO, random errors in time-varying age selectivity were employed to simulate variability in availability to the EPO fleet. Further work could include the development of an area specific OM to better capture uncertainty in migration rates and stock structure, and their relationship to availability in the EPO. Finally, the OM of this MSE is based on the most recent assessment, which starts in 1993. Some data inconsistencies between pre and post 1990s make it hard to develop a model that satisfactorily fits data from both periods. Thus, the MSE results are most applicable to recent conditions. Nevertheless, inclusion of Scenario 6, with a large $L_{infinity}$ parameter for the growth function, more similar to what growth patterns were like in the early period, was an attempt to include some of this uncertainty.

References

ISC 2017. Report of the albacore working group workshop.

ISC 2018. Progress report on Management Strategy Evaluation for North Pacific albacore.

Tables

Table 1. List of the five operating models (OMs) representing different uncertainty scenarios and their parameter specifications. H refers to steepness, G to growth, and M to natural mortality. A value of 1 for a parameter means a base case value, a value of 2 a lower value than base, and a value of 3 a higher value than base. See Table 4 in ISC (2018) for a detailed list of actual steepness, growth, and natural mortality values for each operating model. OM No. 3 here corresponds to OM No. 22 in Table 4 in ISC (2018), OM No. 4 to OM No. 25, OM No. 6 to OM No. 26, and OM 7 to OM No. 27.

OM No.	h	G	M	Age selectivity	Recruitment autocorrelation
Base/1	1	1	1	Time varying	0.42

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3	3	2	1	Base	Base
4	3	3	1	Base	Base
6	3	3	2	Base	Base
7	3	3	3	Base	Base

Table 2. List of harvest control rules for harvest strategies 1. and 3 Ftarget is an indicator of fishing intensity based on SPR. SPR is the SSB per recruit that would result from the current year's pattern and intensity of fishing mortality relative to the unfished stock. A fishing intensity at an Ftarget of F50 would result in 50% of the SSB per recruit relative to the unfished state. A fishing intensity at an Ftarget of 30 implies a higher fishing intensity, and would result in 30% of the SSB per recruit relative to the unfished state. F0204 uses a fishing intensity corresponding to the average fishing intensity from 2002 to 2004. For the base case, this is equivalent to F42. SSB-based reference points refer to the specified percentage of dynamic virgin (unfished) SSB. Dynamic virgin SSB fluctuates depending on changes in recruitment.

Harvest Strategy	**Output Control**	**HCR**	$\mathbf{F_{TARGET}}$	$\mathbf{SSB_{THRESHOLD}}$	$\mathbf{SSB_{LIMIT}}$
1 or 3	TAC or TAE	1	F50	30	20
1 or 3	TAC or TAE	4	F50	20	14
1 or 3	TAC or TAE	6	F50	14	7.7
1 or 3	TAC or TAE	7	F40	30	20
1 or 3	TAC or TAE	10	F40	20	14
1 or 3	TAC or TAE	12	F40	14	7.7
1 or 3	TAC or TAE	13	F30	20	14
1 or 3	TAC or TAE	15	F30	14	7.7
1 or 3	TAC or TAE	16	F0204	30	20
1 or 3	TAC or TAE	17	F0204	20	14
1 or 3	TAC or TAE	18	F0204	14	7.7

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Table 3. List of proposed performance indicators.

Management Objective	Label	Performance Indicator
1. Maintain SSB above the limit reference point (LRP)	p(no drastic management action)	Probability that SSB in any given year of the MSE forward simulation is above the LRP
2. Maintain depletion of total biomass around historical average depletion	p(depletion)	Probability that depletion in any given year of the MSE forward simulation is above minimum historical (2006-2015) depletion
4. Maintain catches above average historical catch	p(catch)	Probability that catch in any given year of the MSE forward simulation is above average historical (1981-2010) catch
5. Change in total allowable catch between years should be relatively gradual	p(catch decrease < 30%)	Probability that a decrease in TAC between years is < 30%. Calculated excluding years TAC=0.
6. Maintain fishing intensity (F) at the target value with reasonable variability	F_{TARGET}/F	F_{TARGET}/F

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Table 4. Performance metrics for the base case (B, scenario 1) and the pulse in catch (P) and ramp in catch (R) fishing scenarios for the best performing HCRs in HS3 with TAC control. For details on the definition of performance indicators, refer to Table 3.

	PM1			PM2			PM4			PM5			PM6		
HCR	B	P	R	B	P	R	B	P	R	B	P	R	B	P	R
1	1	1	1	0.63	0.62	0.63	0.70	0.72	0.72	0.70	0.54	0.68	0.9	0.9	0.9
4	1	1	1	0.59	0.58	0.59	0.72	0.74	0.76	0.91	0.63	0.90	0.9	0.9	0.9
6	1	1	1	0.63	0.62	0.63	0.76	0.77	0.78	0.93	0.63	0.92	0.9	0.9	0.9
10	1	1	1	0.50	0.49	0.50	0.80	0.81	0.79	0.75	0.64	0.67	1	0.9	0.9
12	1	1	1	0.52	0.50	0.50	0.85	0.87	0.87	0.92	0.73	0.91	1	0.9	0.9

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Figures

Figure 1. Example harvest control rule (HCR) for harvest strategy 1 (HS1) and HS3.

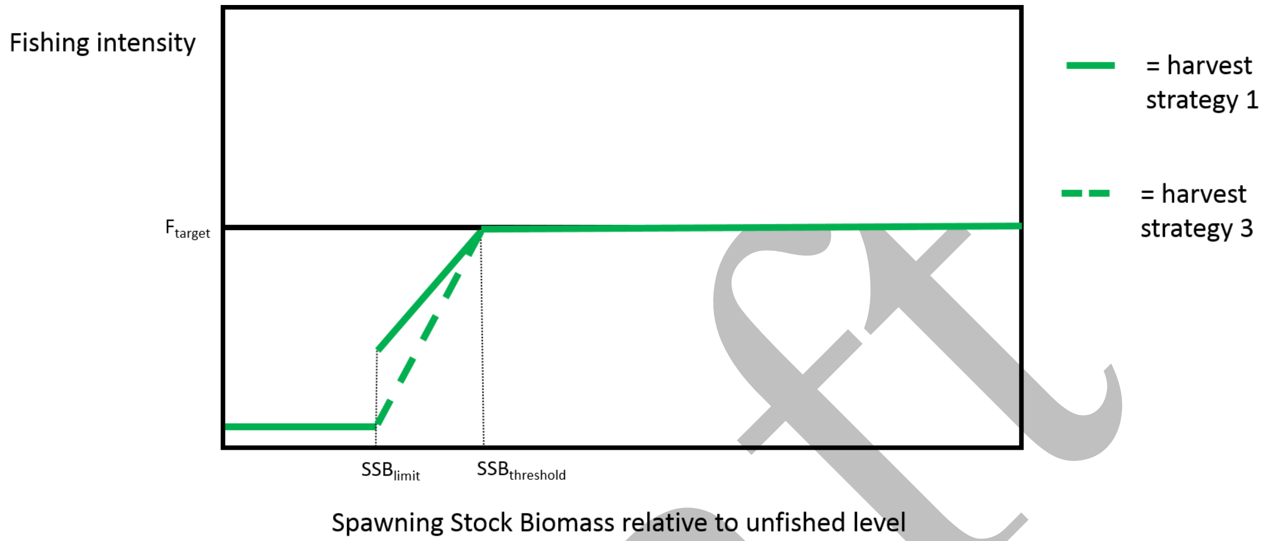

Figure 2. Trends in fishing intensity (1-SPR) and female spawning stock biomass (SSB) for the five operating models used in the first round of MSE. 1-SPR is the reduction in female SSB per recruit due to fishing and is used to describe the overall fishing intensity on the stock.

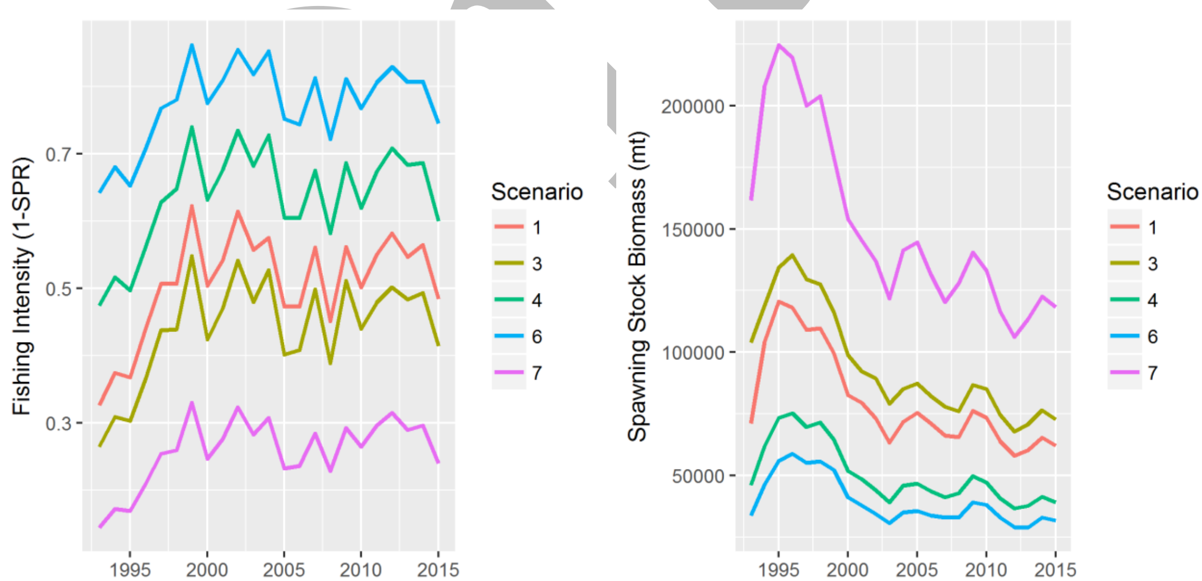

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Figure 3. Median and 5th and 95th quantiles of SSB for the 30 year simulation across all runs and reference scenarios for all the harvest strategies and harvest control rules tested.

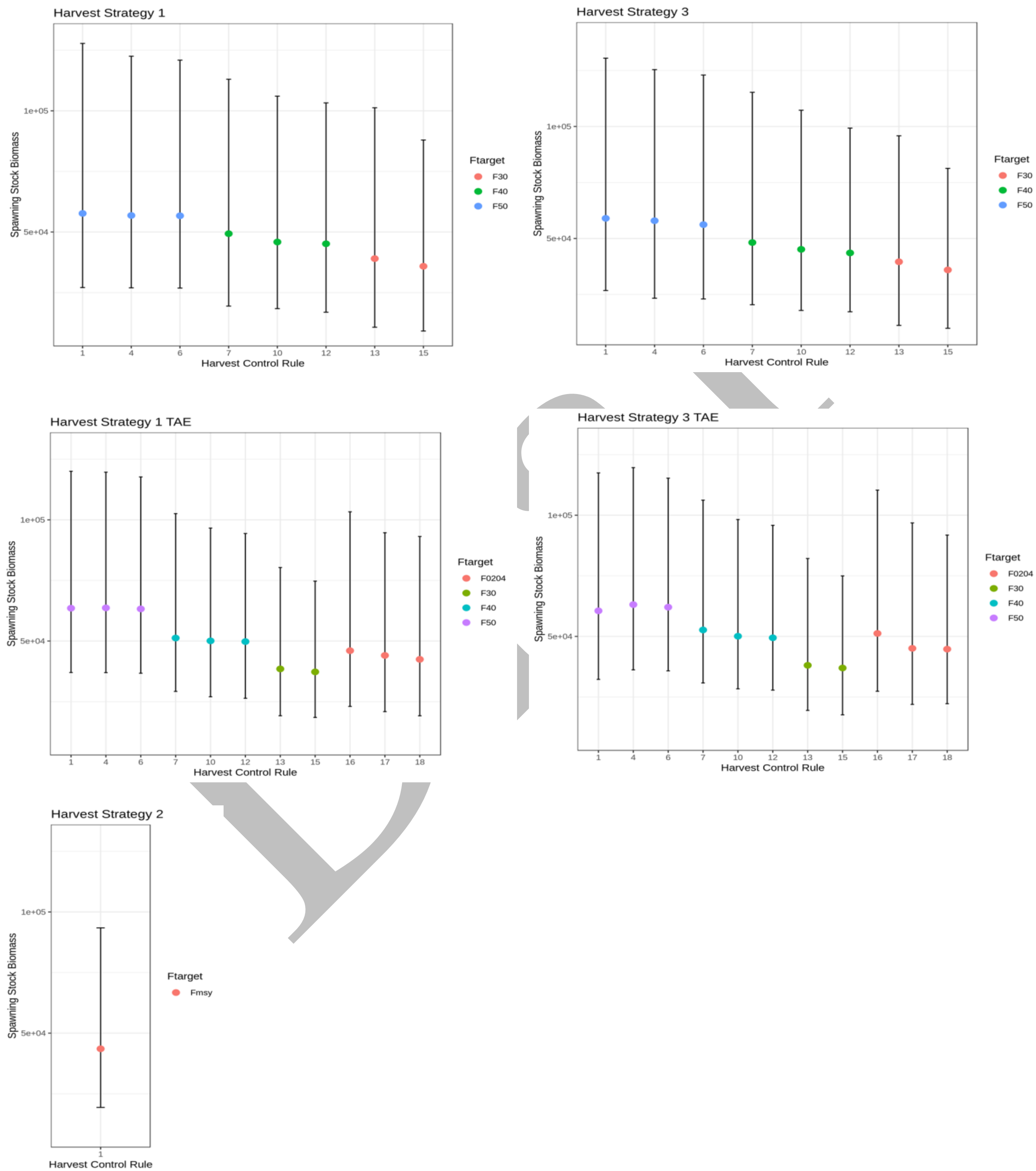

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Figure 4. Median and 5th and 95th quantiles of SSB for the 30 year simulation across all runs for each reference scenarios for harvest strategies 1 TAE.

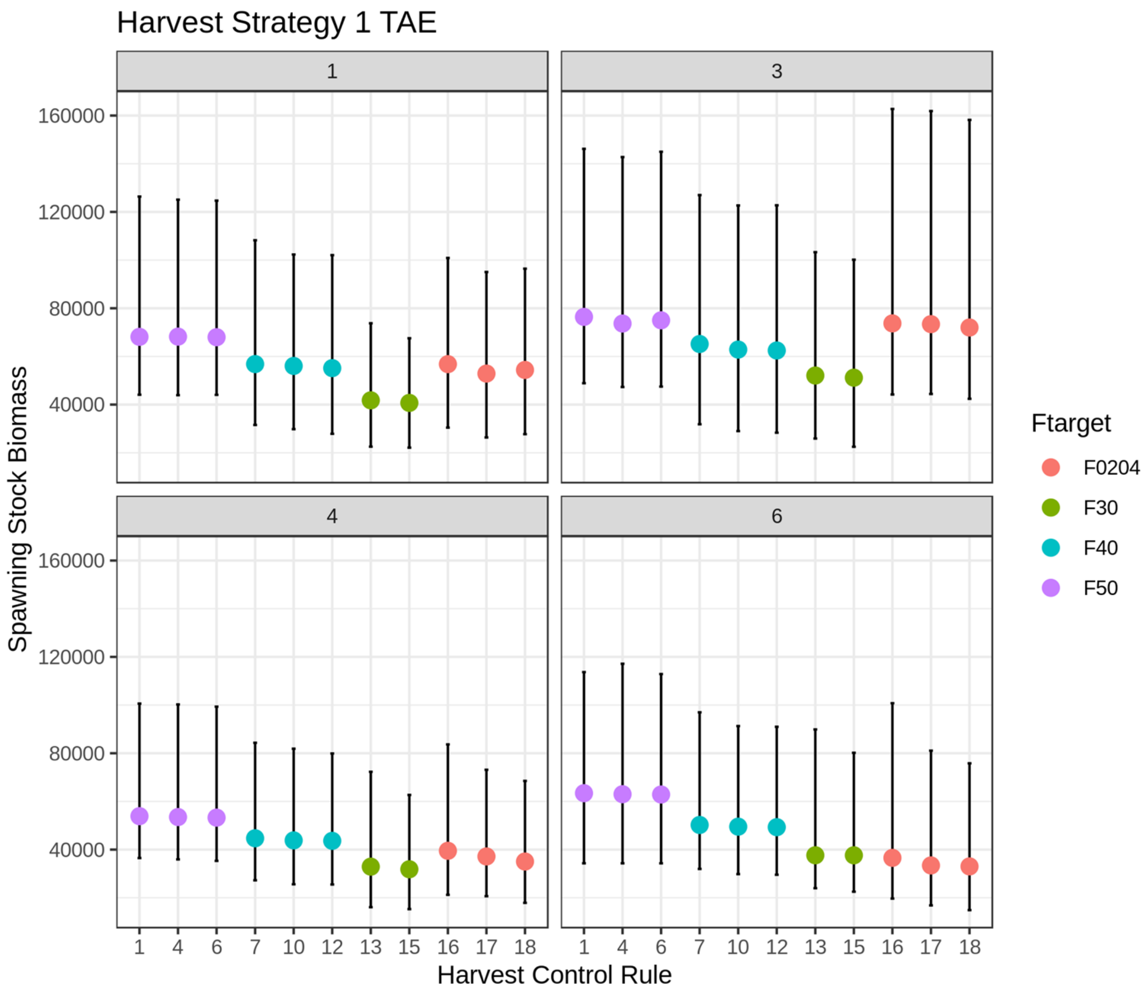

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Figure 5. Median and 5th and 95th quantiles of PM1 for the 30 year simulation across all runs and reference scenarios for all the harvest strategies and harvest control rules tested.

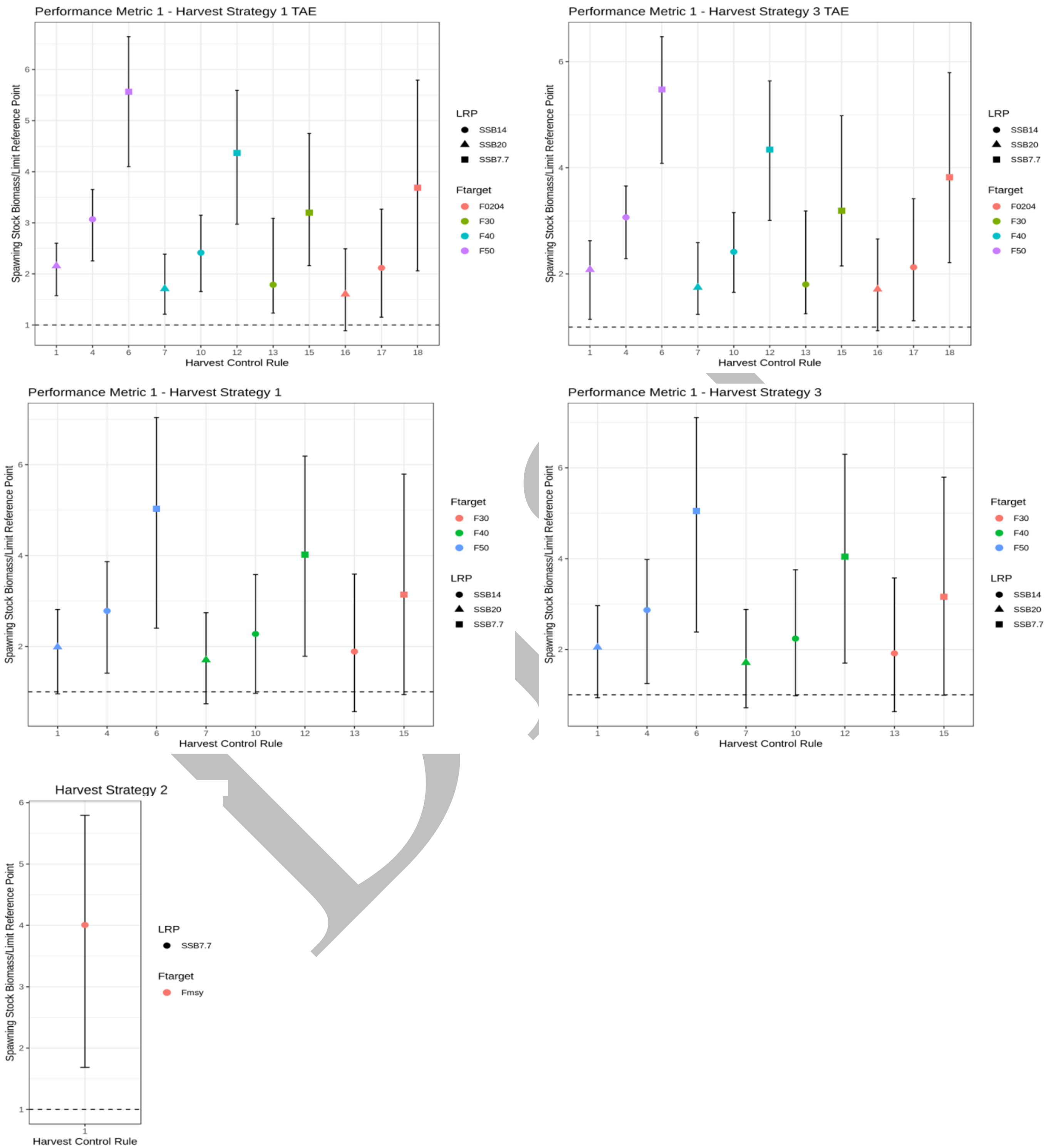

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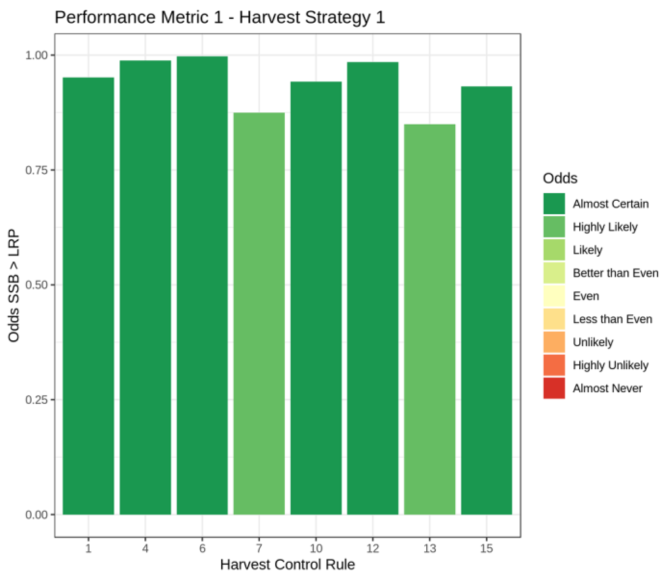
Figure 6. Probability in any given year of the simulation of SSB being greater than the limit reference point for TAC-based HS1 and HS3.



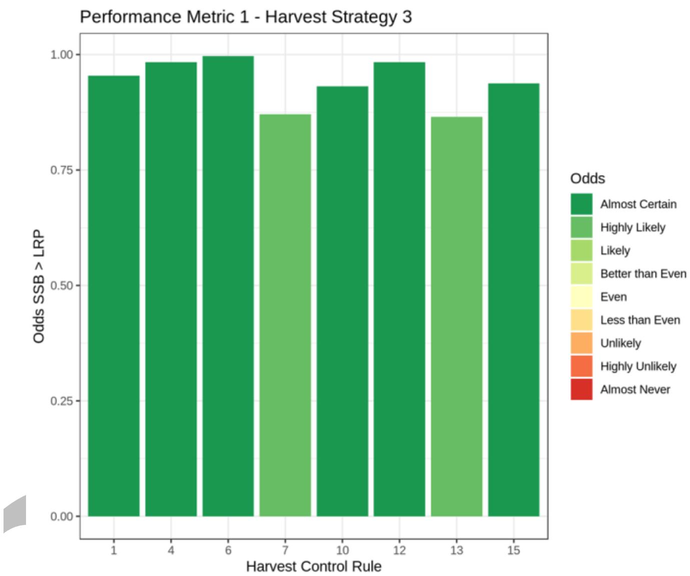


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Figure 7. Median and 5th and 95th quantiles of PM2 for the 30 year simulation across all runs and reference scenarios for all the harvest strategies and harvest control rules tested. Minimum historical depletion was computed across the years 2006-2010.

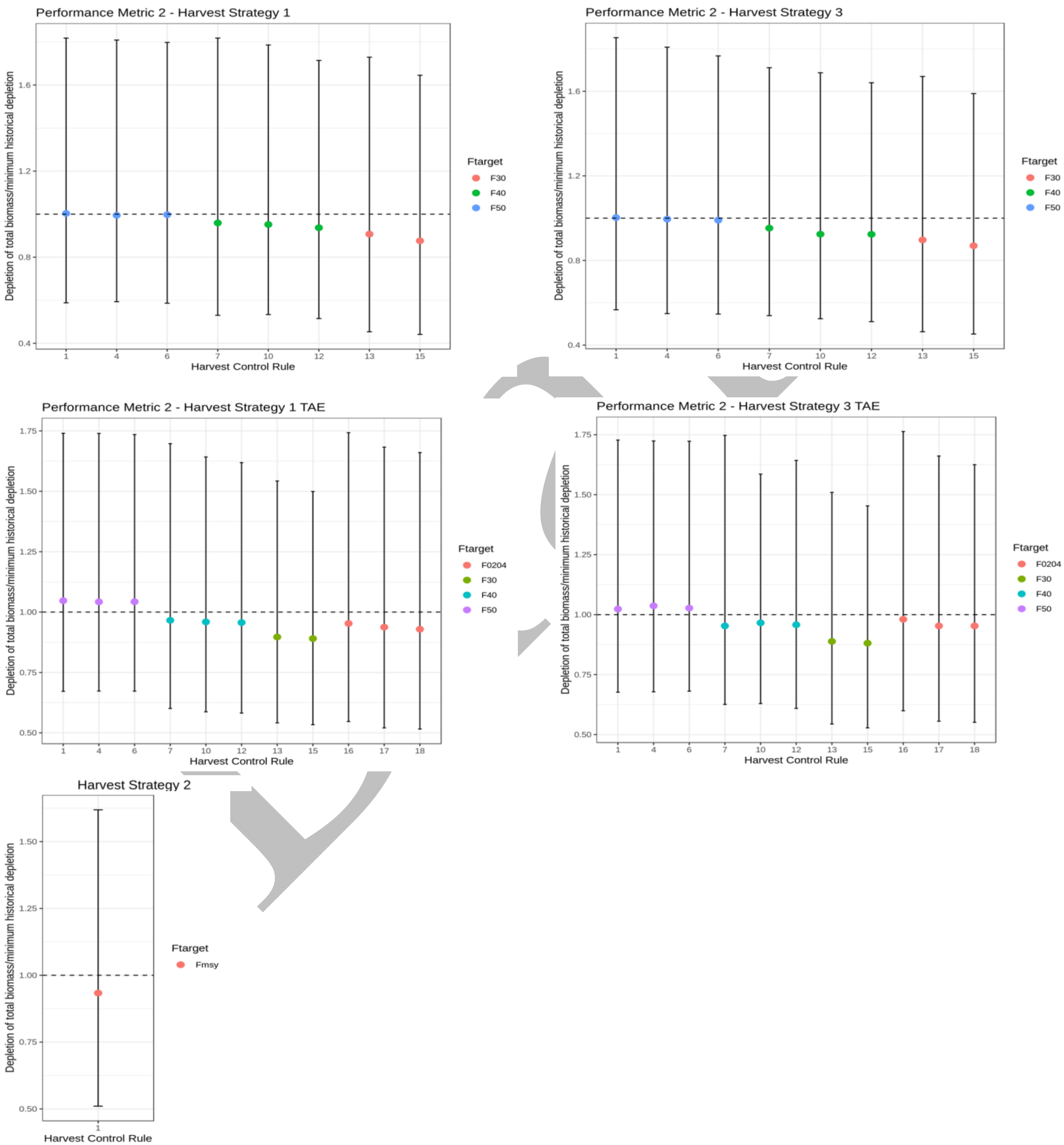

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Figure 8. Probability in any given year of the simulation of total biomass depletion being greater than the minimum historical (2006-2010) depletion for TAE-based HCR 1 and 3.

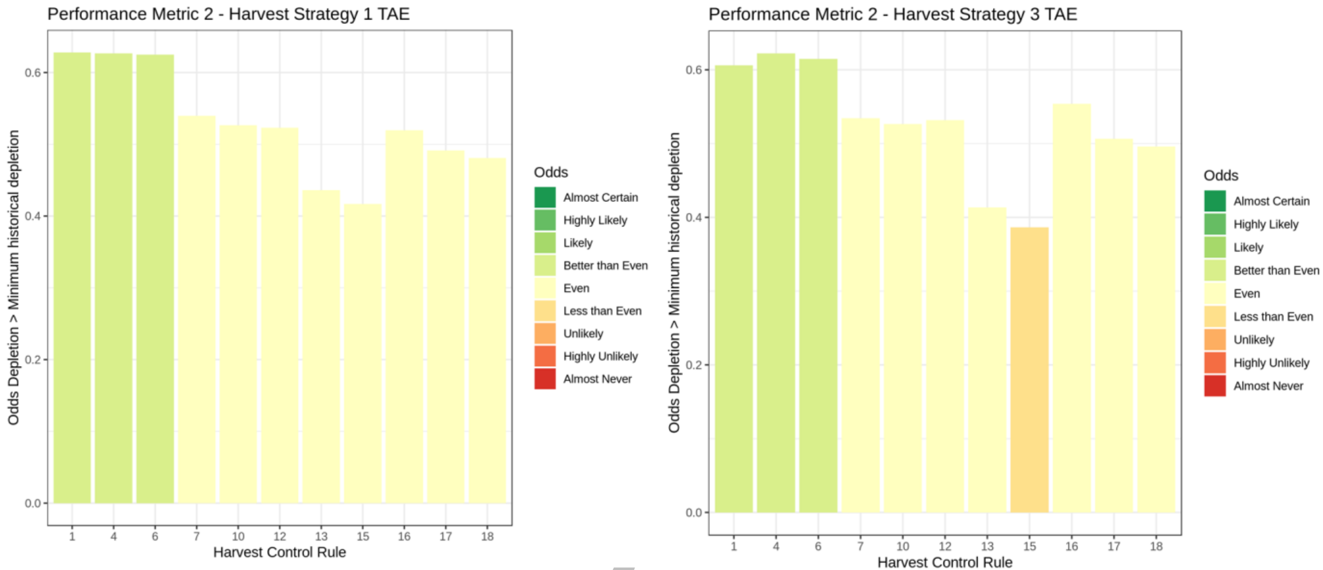

Figure 9. Median and 5th and 95th quantiles of the harvest ratio for the EPO fleet for the 30 year simulation across all runs for each reference scenarios for harvest strategies 1 TAE. The dotted lines represent the maximum and minimum harvest ratio for this fleet for the period of 2006-2010.

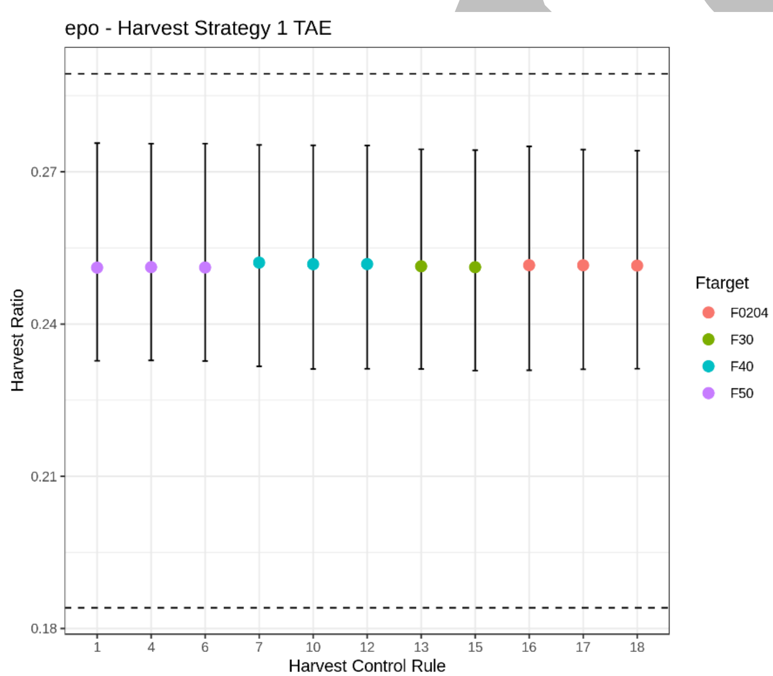

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Figure 10. Median and 5th and 95th quantiles of the harvest ratio for the EPO fleet for the 30 year simulation across the base case (scenario 1) and the ramp in catch and pulse in catch scenarios for harvest strategies 1 TAE. The dotted lines represent the maximum and minimum harvest ratio for this fleet for the period of 2006-2010. For the pulse in catch scenario, only data from the first time step of the simulation when the pulse occurred is shown.

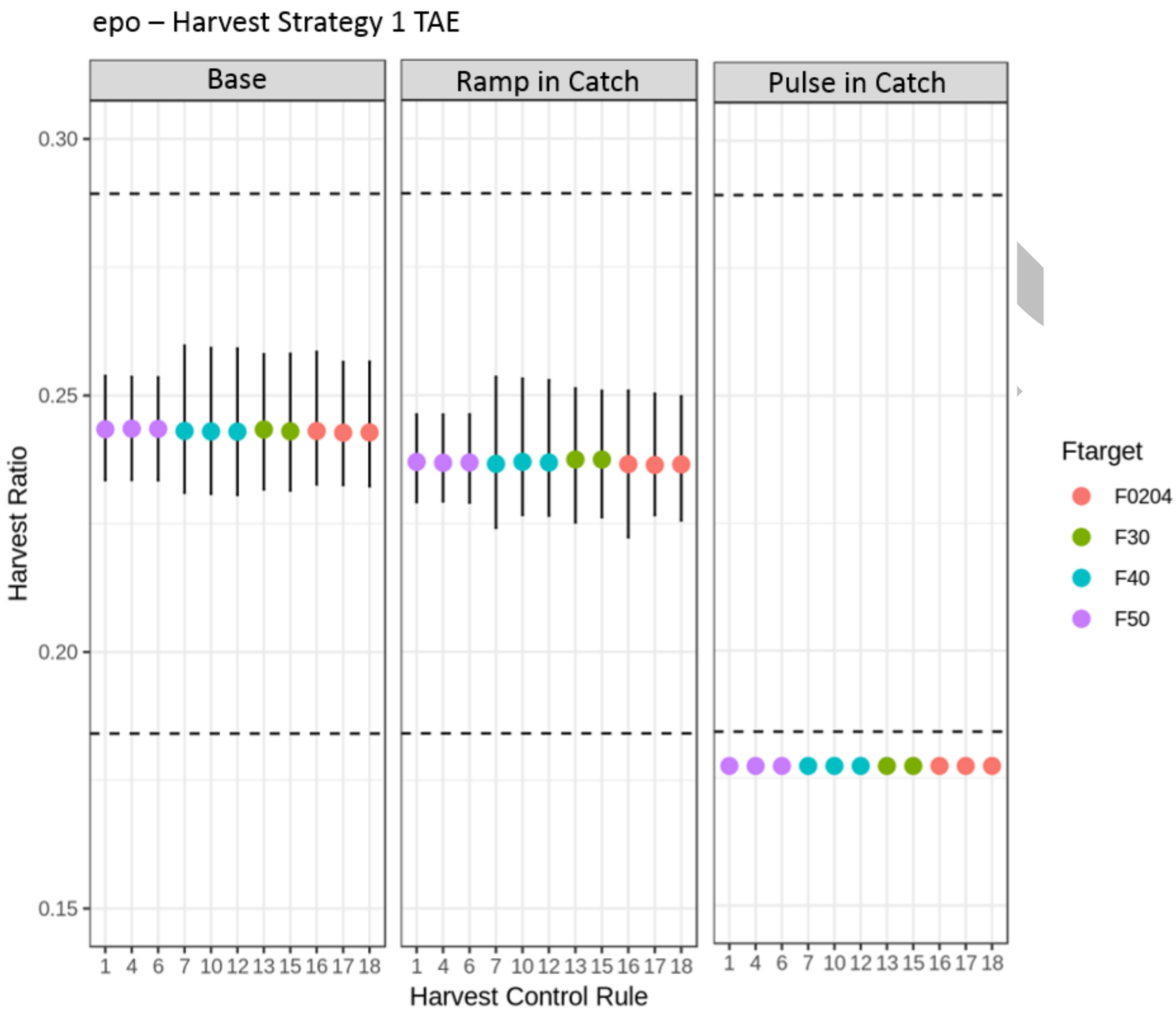

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Figure 11. Median and 5th and 95th quantiles of PM4 for the 30 year simulation across all runs and reference scenarios for all the harvest strategies and harvest control rules tested. Historical mean catch was computed across the years 1981-2010.

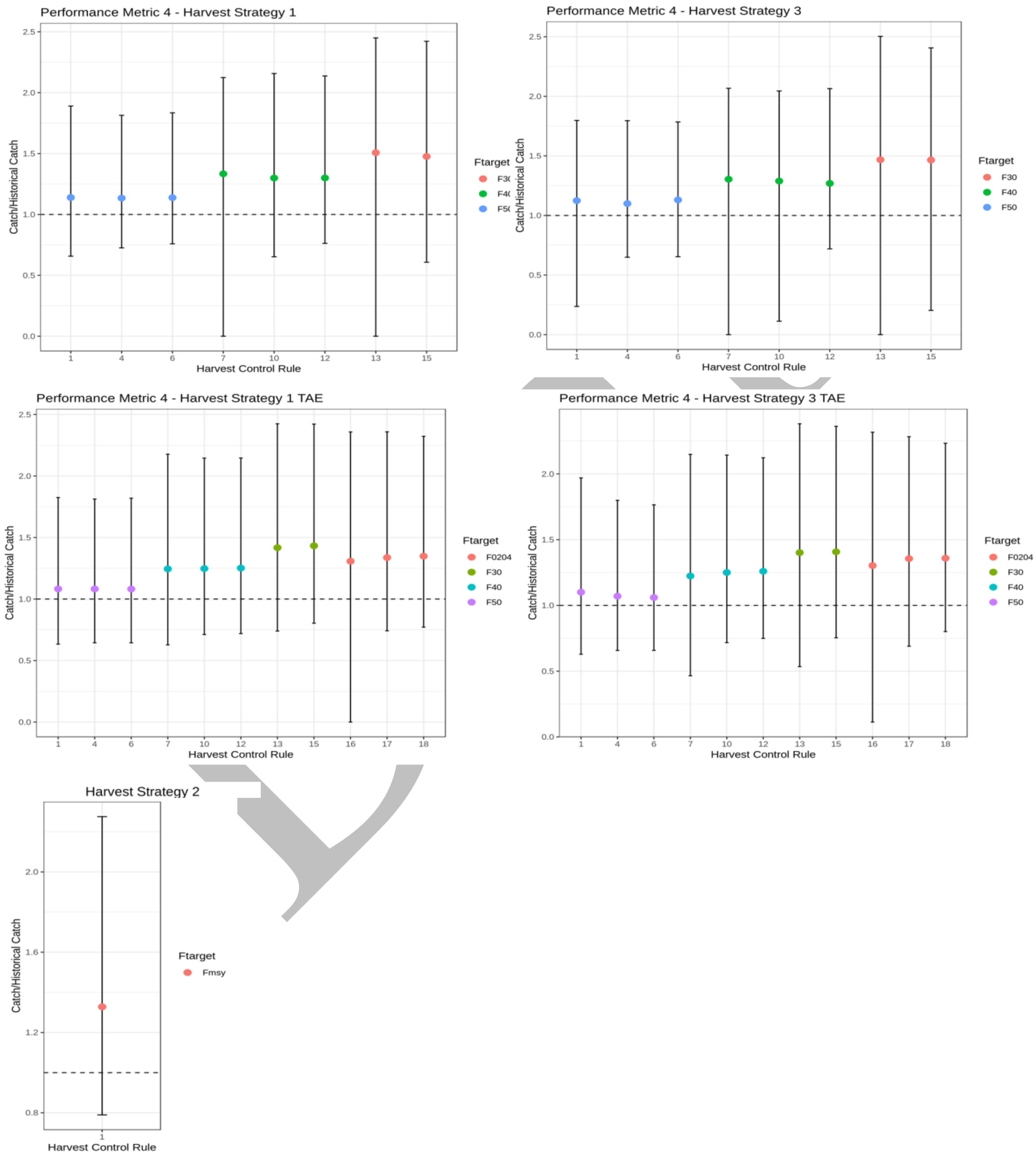

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Figure 12. Probability in any given year of the simulation of total catch being greater than the average historical (1981-2010) catch for each harvest strategy across all reference scenarios.

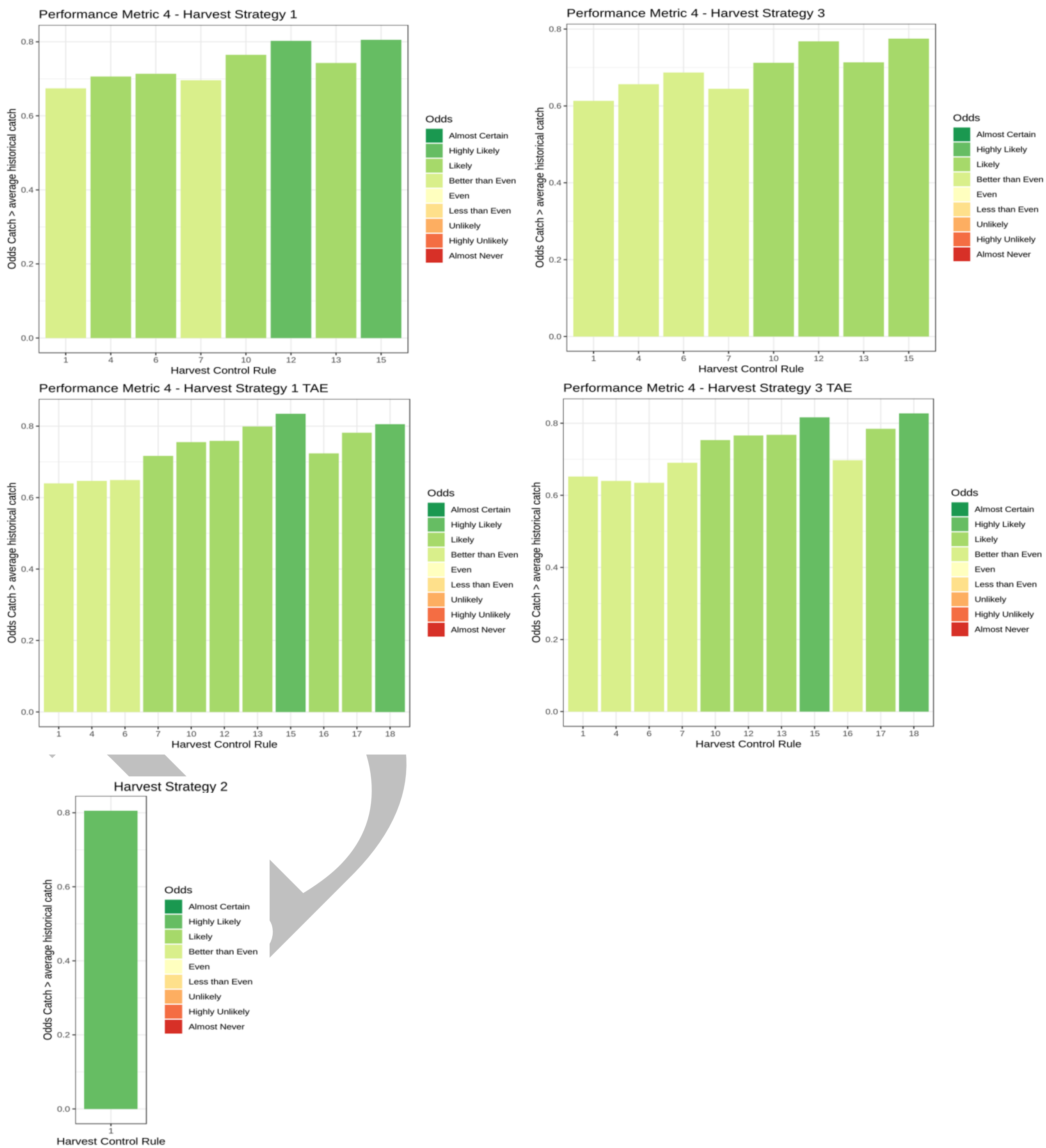

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Figure 13. Same as Figure 11, but for the EPO flee

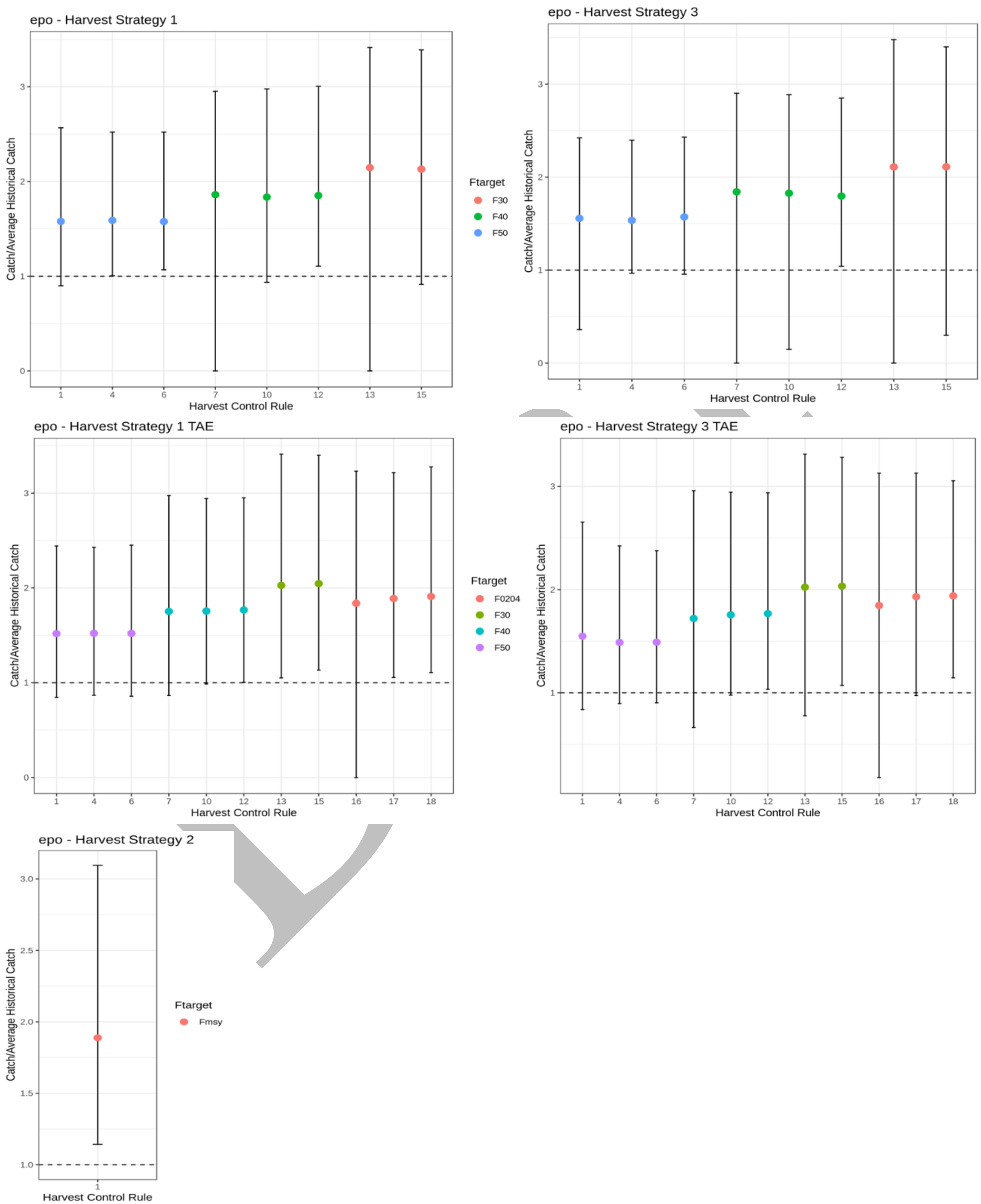

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Figure 14. Median and 5th and 95th quantiles of PM5 for the % decrease in TAC between years for the 30 year simulation across all runs and reference scenarios for all the harvest strategies and harvest control rules tested.

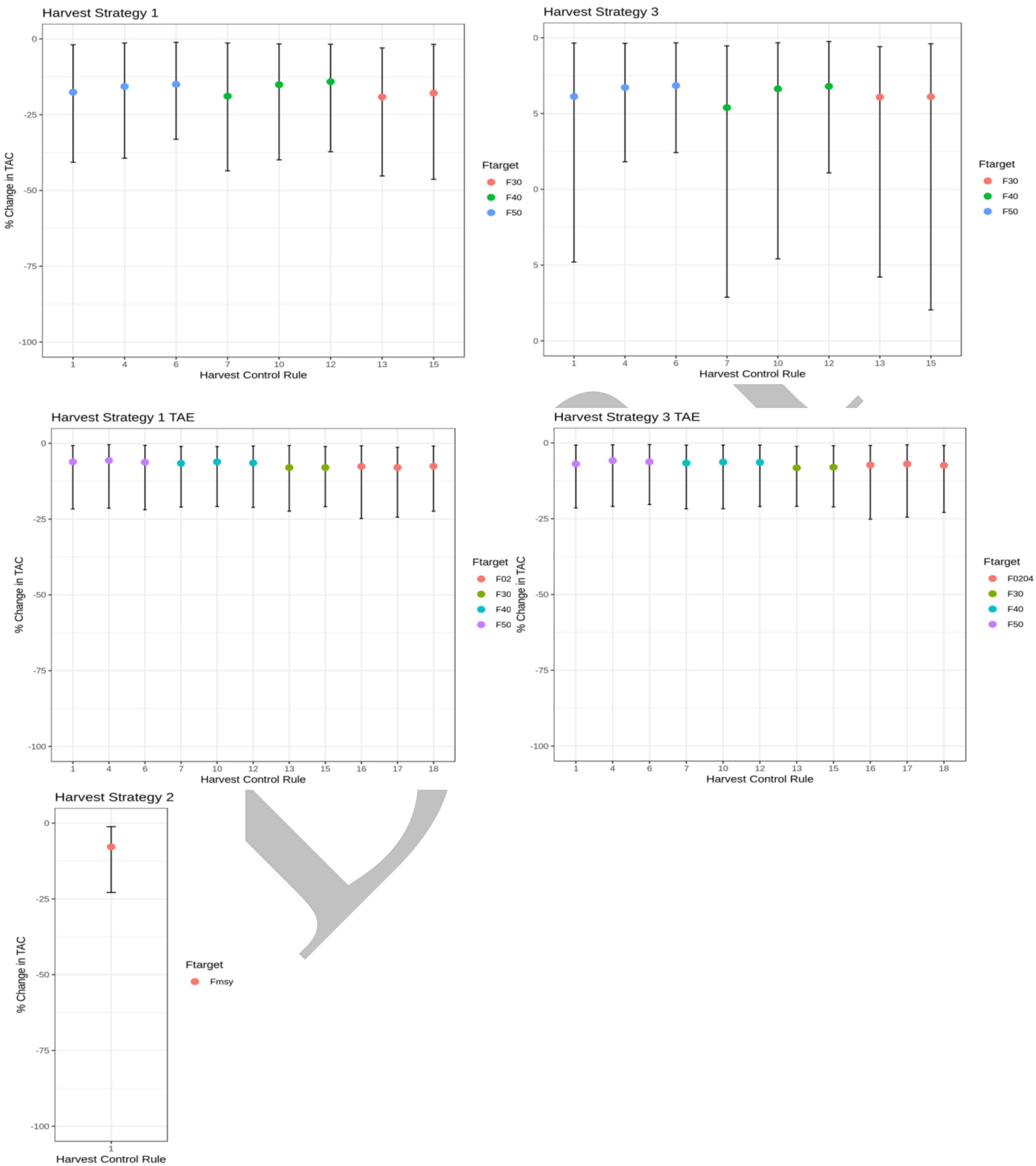

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Figure 15. Probability of a decrease in TAC between years being less than 30% for TAC-based HS1 and HS3 across all reference scenarios.

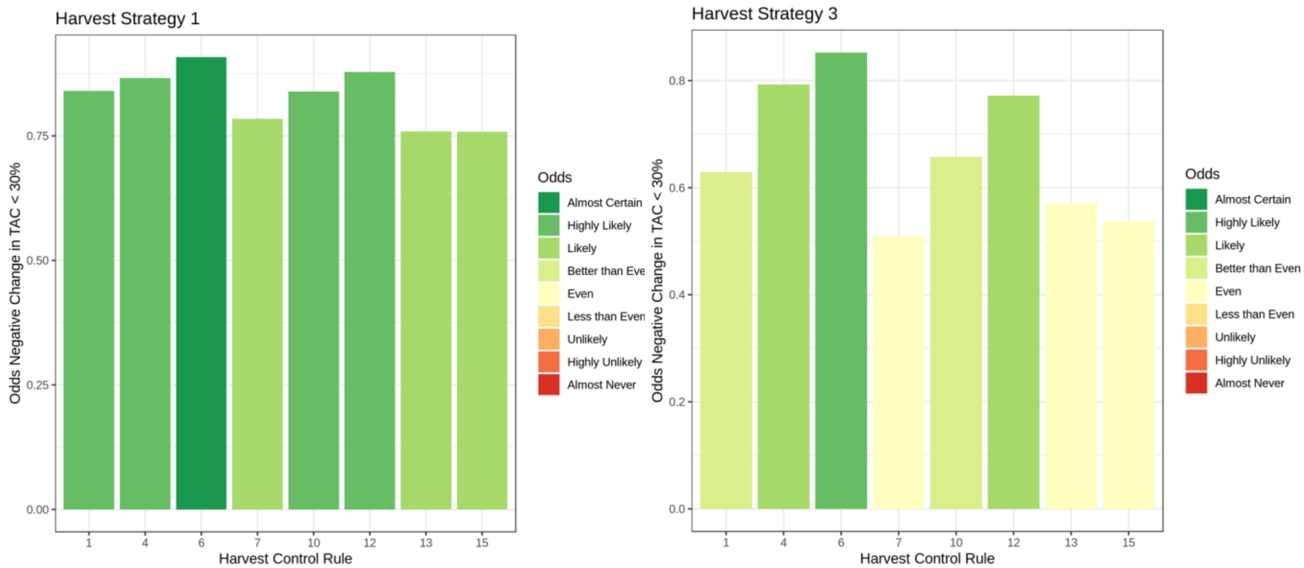

Figure 16. Median and 5th and 95th quantiles of the % of years the fishery was closed in the 30 year simulation across all runs for reference scenario 6 for HS1 and HS3.

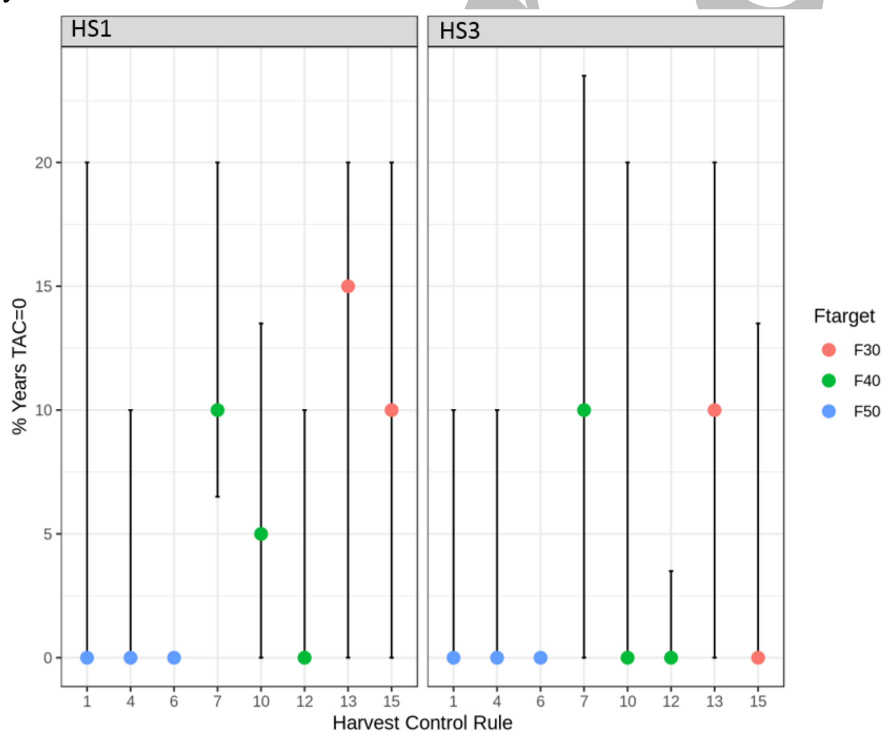

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Figure 17. Median and 5th and 95th quantiles of the % of years the fishery was closed in the 30 year simulation across all runs and reference scenarios for TAE-based rules for HS1 and HS3. The fishery was never closed under HS2, so it is not shown here.

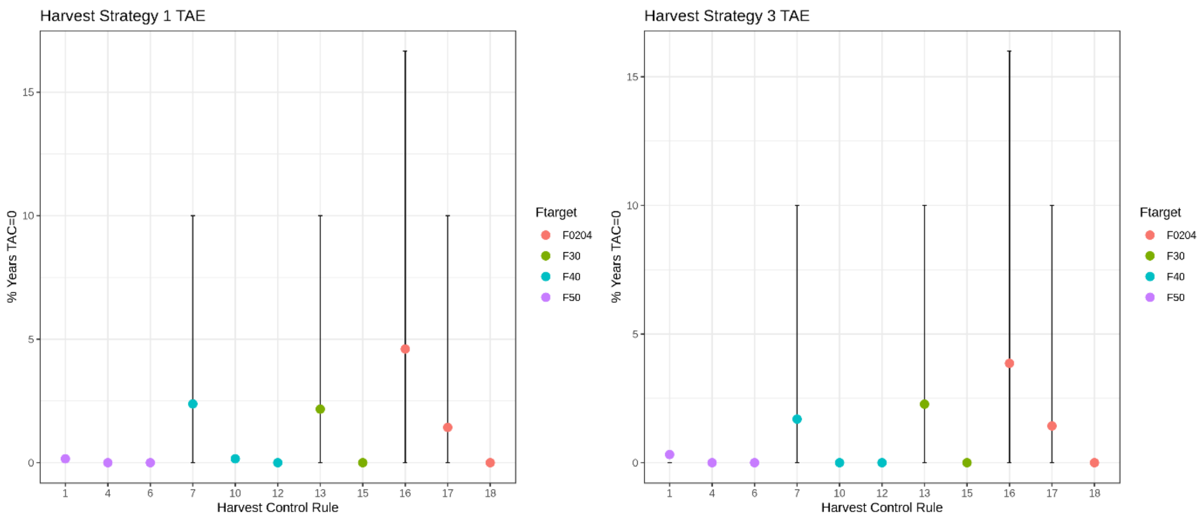

Figure 18. Median and 5th and 95th quantiles of PM6, the ratio of the F-based target reference point (TRP) to the current F in each year of the 30 year simulation across all runs and reference scenarios for HS1-TAC and HS2.

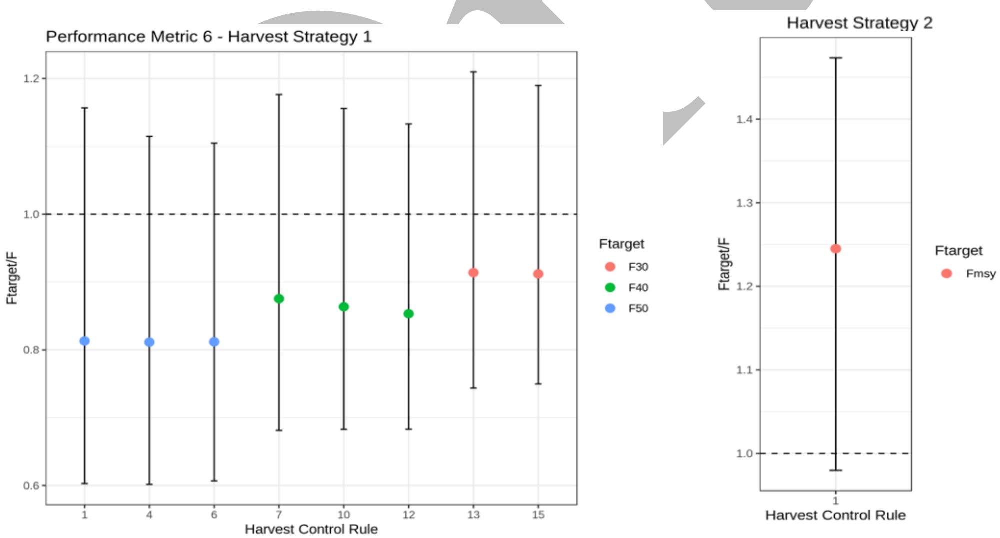

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Figure 19. Cobweb plot depicting performance indicators for TAC-based and TAE-based HCR13 for HS1 and HS3, and HS2 (IATTC rule). Values close to the outer web signify a more positive outcome for that performance indicator. Refer to Table 3 for a description of the performance indicators.

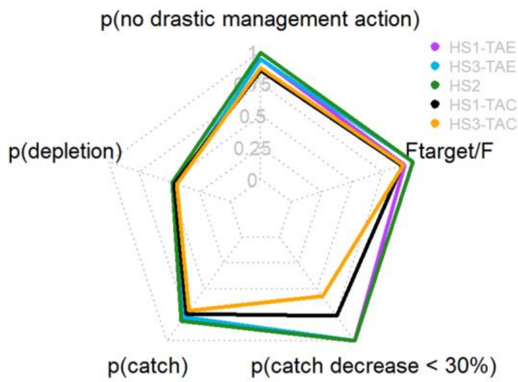

Figure 20. Cobweb plot depicting performance indicators for TAC-based HCR7, HCR10, and HCR12 for HS1. All use a TRP of F40. Values close to the outer web signify a more positive outcome for that performance indicator. Refer to Table 3 for a description of the performance indicators.

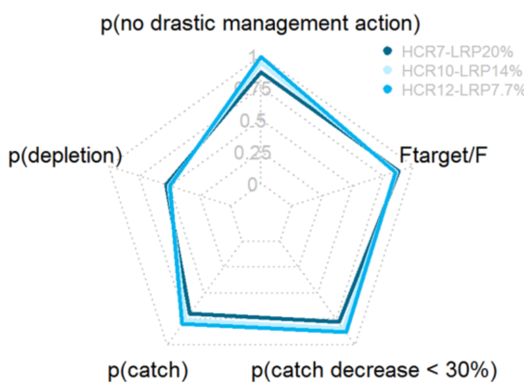

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Figure 21. Cobweb plot depicting performance indicators for TAC-based HCR6, HCR12, and HCR15 for HS1. All use an LRP of 14%$SSB_{CURRENT,F=0}$. Values close to the outer web signify a more positive outcome for that performance indicator. Refer to Table 3 for a description of the performance indicators.

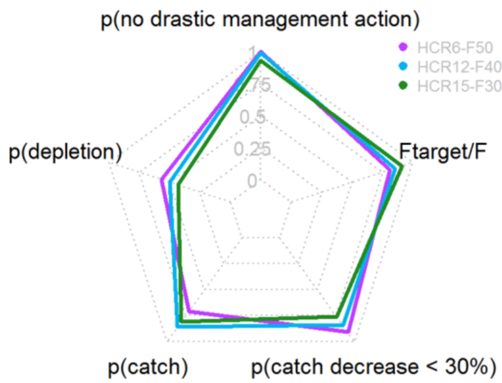

Figure 22. Cobweb plot depicting performance indicators for TAC-based HCR1, and HCR7 for HS1. All use an LRP of 20%$SSB_{CURRENT,F=0}$. Values close to the outer web signify a more positive outcome for that performance indicator. Refer to Table 3 for a description of the performance indicators.

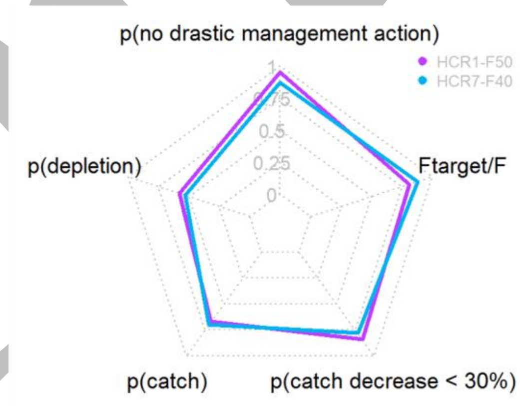

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Figure 23. Cobweb plot depicting performance indicators for TAE-based HCR4, HCR10, HCR13, and HCR17 for HS1. All use an LRP of 14%$SSB_{CURRENT,F=0}$. Values close to the outer web signify a more positive outcome for that performance indicator. Refer to Table 3 for a description of the performance indicators.

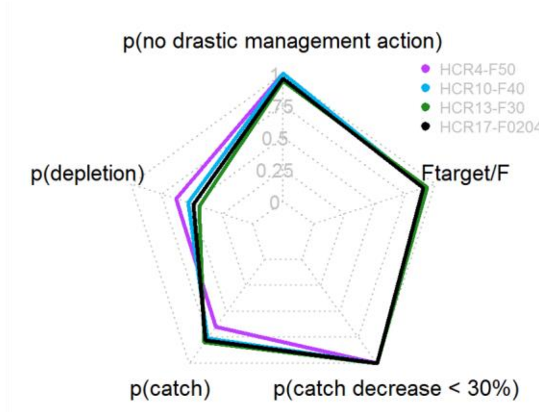
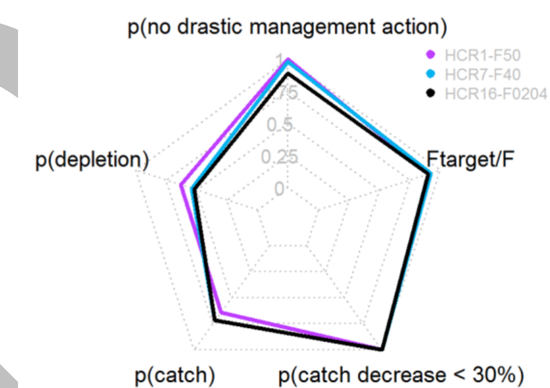


Figure 24. Cobweb plot depicting performance indicators for TAE-based HCR1, HCR7, and HCR16 for HS1. All use an LRP of 20%$SSB_{CURRENT,F=0}$. Values close to the outer web signify a more positive outcome for that performance indicator. Refer to Table 3 for a description of the performance indicators.



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