INTER-AMERICAN TROPICAL TUNA COMMISSION

SCIENTIFIC ADVISORY COMMITTEE

12TH MEETING

(by videoconference)

10-14 May 2021

DOCUMENT SAC-12 INF-C

REPORT OF THE NORTH PACIFIC ALBACORE TUNA MANAGEMENT STRATEGY EVALUATION

This preliminary report is subject to change after review by the ISC21 Plenary in July 2021

Foreward to the North Pacific Albacore Management Strategy Evaluation Report

Management strategy evaluation (MSE) is a process used to evaluate the consequences of alternative harvest strategies against pre-defined fishery and conservation objectives for a stock, taking into account uncertainties in environmental, biological and management systems and the likelihood that harvest strategies are able to achieve the chosen objectives. MSE has the advantage of revealing the trade-offs among a range of possible management decisions to managers and stakeholders and delineate assessment challenges to scientists. Conducting an MSE requires more active particpation by scientists, managers and stakeholders than in a standard stock assessment process.

The Western and Central Pacific Fisheries Commission Northern Committee (WCPFC-NC) and the Inter-American Tropical Tuna Commission (IATTC) endorsed an MSE process by the Albacore Working Group (ALBWG) of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific (ISC) to refine the interim harvest strategy currently in place for North Pacific Albacore tuna and adopt a target reference point (TRP). The MSE results for North Pacific Albacore Tuna presented in this report, coupled with the results of runs from previous iterations in this process, represent a substantial amount of information for WCPFC-NC and IATTC member countries and managers on which to base decisions concerning harvest strategy for this stock.

The North Pacific Albacore Tuna MSE process was strongly supported by the United States, who provided a scientist to develop and run the operating models and produce the results. This support is greatly appreciated by the ISC. However, the capacity available to conduct MSE processes is limited in most countries given the quantitative skills and simulation experience needed to be successful. Future iterations of this MSE are not planned by the ISC because the current results need to be fully assimilated by managers and stakeholders.

March 2021
John Holmes

John Holmes
Chair,
International Scientific Committee for Tuna and Tuna-like Species in the North Pacific Ocean

Division Manager
Stock Assessment and Research Division, Pacific Biological Station
Fisheries and Oceans Canada / 3190 Hammond Bay Road, Nanaimo, BC, V9T 6N7, Canada
John.Holmes@dfo-mpo.gc.ca / Phone: +1-250-756-7145; Cell: +1-250-667-1758

Table of Contents

1 Executive Summary

History and Goal of NPALB Management Strategy Evaluation

Management strategy evaluation (MSE) is a process that, given management objectives conveyed by stakeholders and managers, uses computer simulations to assess the performance of candidate harvest strategies under uncertainty (Fig. ES1). The Western and Central Pacific Fisheries Commission (WCPFC) established a limit reference point (LRP) of 20%SSB0_d (SSB: Female Spawning Stock Biomass) for North Pacific albacore (NPALB). The LRP is based on dynamic unfished SSB (SSB0_d) and fluctuates depending on changes in recruitment. In addition, the Inter American Tropical Tuna Commission (IATTC) and WCPFC also adopted measures in 2005 that restricted NPALB fishing effort to below "current" (current is undefined but assumed to be the average of 2002–2004) levels. However, no formal harvest strategy or target reference point (TRP) has been established. The goal of this MSE was to examine the performance of alternative harvest control rules and associated reference points for NPALB. Performance was evaluated based on management objectives pre-agreed upon with managers and stakeholders. Management objectives and performance metrics were finalized in October 2017, at the 3rd ISC NPALB MSE Workshop in Vancouver, Canada, where candidate reference points and harvest control rules for testing were also agreed upon (ISC 2017). The ALBWG then started developing the MSE framework and running the first simulations, but due to limited computing resources and long running times it was not feasible to run all the proposed harvest control rules (HCRs) by the 4th ISC NPALB MSE Workshop in February 2019 in Yokohama, Japan (ISC 2019). Following presentation of the initial set of results from the first round of NPALB MSE managers and stakeholders at the 4th MSE Workshop recommended removal from further consideration of two candidate harvest strategies and TRPs and assessment of performance of additional candidate harvest control rules focused on the best performing TRPs, F40 and F50. Those are the simulations here presented. Managers and stakeholders also recommended changes to the MSE framework to improve the realism of the simulations. Those changes are described below. This latest round of simulations evaluated all the HCRs and associated reference points proposed at the 4th MSE Workshop and represents the final set of MSE analyses in support of development of a harvest strategy for NPALB.

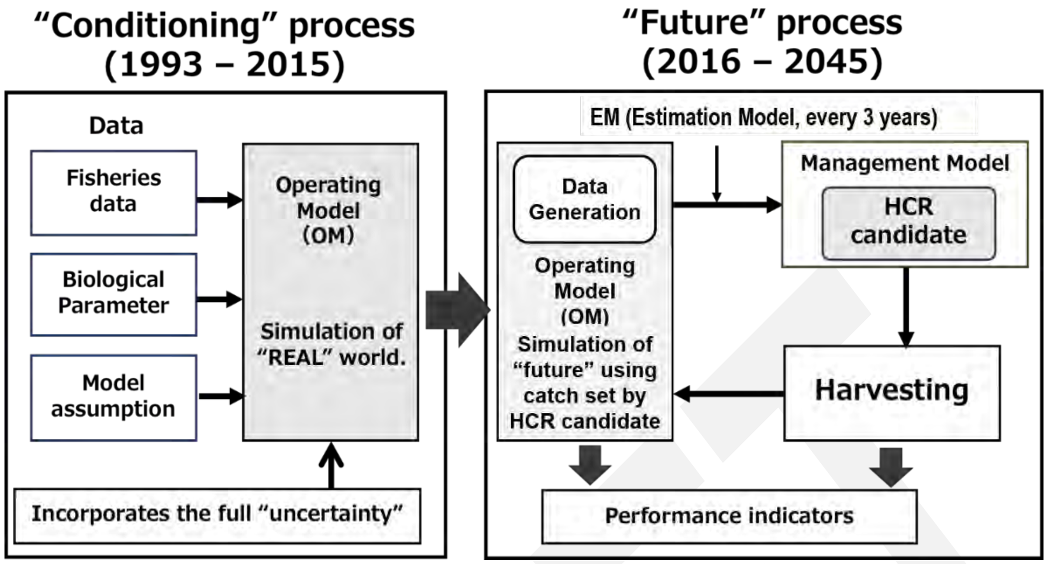


Figure ES1. Overview of North Pacific albacore management strategy evaluation framework. Details of the MSE framework and models can be found in Section 4.

Major changes from MSE Round 1 Report

Following recommendations from the 4th ISC ALB MSE Workshop, five major changes to the MSE framework algorithm were undertaken for the 2nd Round of MSE.

1. The 1st MSE framework put no limitations on the capacity of the NPALB fleets, with fishing intensity (F, 1-SPR) increasing to levels higher than what has historically been observed to meet the target fishing intensity reference point (TRP) when setting the Total Allowable Catch (TAC) or Total Allowable effort (TAE). This limitation was addressed by, when SSB was greater than $SSB_{threshold}$, setting a TAC or TAE based on a F randomly sampled from the time series of historical (1997-2015) Fs rather than setting the F equal to the TRP. This approach was used for uncertainty scenarios 1 and 3, which estimated Fs during the historical period as being on average lower than either of the candidate TRPs.
2. A new management option of mixed control was implemented in the code. Managers and stakeholders suggested that it may be impractical to manage non-targeting longline fleets by TAE, but still wanted to explore the option for the albacore targeting surface fleets. Under mixed control, longline fleets are subject to a TAC, whereas surface fleets are managed with a TAE.
3. The new MSE framework also generates bidirectional implementation errors (i.e., fleets can fish at, less or more than the TAE or TAC) rather than strictly positive ones as in the 1st round of MSE.
4. The MSE code was modified to enable use of stricter risk levels (80% for HCRs with an LRP of 20%SSB0_d; 90% for HCRs with an LRP of 14% SSB0_d or 7.7%SSB0_d) in evaluation of the risk of breaching candidate limit reference point (LRP) in the MSE management module. This risk was calculated using the NPALB future projection software developed for the 2017 NPALB stock assessment.
5. The MSE management module was modified to allow for examination of two additional levels of minimum TAC or TAE when the LRP is breached in addition to TAC or TAE =

0. For HCRs with LRPs of 20% SSB0_d or 14% SSB0_d these levels are 0.5 and 0.25 of the fishing intensity or catch at the LRP. For HCRs with an LRP of 7.7% SSB0_d these levels are 0.25 of the fishing intensity or catch at the LRP or a fishery closure.

Management Objectives and Performance Indicators

The management objectives for this MSE were: 1) maintain SSB above the limit reference point; 2) maintain depletion of total biomass around historical average depletion; 3) maintain historical harvest ratios of each fishery; 4) maintain catches above average historical catch; 5) change in total allowable catch between years should be relatively gradual; and 6) maintain fishing intensity at the target value with reasonable variability. Note that management objectives were not ranked according to importance. It should also be noted that management objective #3 (maintain historical harvest ratios of each fishery) was not evaluated because there were no allocation rules specific to each fishery. Instead, harvest ratios of each fishery were assumed to be maintained at the average of 1999–2015 according to the agreement at the 3rd ISC NPALB MSE Workshop. Thus, performance relative to management objective #3 does not vary between HCRs. The ALBWG represented these management objectives, except #3, as quantitative performance indicators (Table ES1). These performance indicators were used to quantitatively evaluate the performance of the harvest strategies tested relative to the management objectives. In addition, other general metrics like the mean and variability of SSB, depletion, and catch were also provided for reference (Appendix Tables).

Table ES1. List of management objectives, performance indicators, and corresponding labels for figures and tables. Management objective #3 was not included because this management objective was not evaluated in this MSE. SSB refers to female spawning stock biomass, LRP to limit reference point, SSB0 to unfished female spawning stock biomass. Unless specified as "equilibrium SSB0", the SSB0 is dynamic (i.e., equal to SSB0_d) and fluctuates depending on changes in recruitment. Depletion refers to the ratio of current total biomass to unfished equilibrium total biomass and is a measure of relative biomass. Management objectives are not ranked according to importance.

Management Objective	**Label**	**Performance Indicator**
1. Maintain SSB above the limit reference point	Odds of not breaching the LRP	Probability that SSB in any given year of the MSE forward simulation is above the LRP
	Odds SSB > 20%SSB0	Probability that SSB in any given year of the MSE forward simulation is above the 20% of dynamic unfished SSB.
	Odds SSB > 7.7%SSB0	Probability that SSB in any given year of the MSE forward simulation is above 7.7% of dynamic unfished SSB.
	Odds SSB > equilibrium 7.7%SSB0	Probability that SSB in any given year of the MSE forward simulation is above the 7.7% of equilibrium unfished SSB.

2. Maintain depletion of total biomass around historical average depletion	Odds depletion > minimum historical	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	Odds catch >historical	Probability that catch in any given year of the MSE forward simulation is above average historical (1981-2010) catch.
	Odds medium term catch > historical	Probability that catch averaged over years 7-13 of the simulation is above average historical (1981-2010) catch.
	Odds long term catch > historical	Probability that catch averaged over years 20-30 of the simulation is above average historical (1981-2010) catch.
5. Change in total allowable catch between years should be relatively gradual	Catch stability	Probability that a decrease in TAC (or catch for mixed control) is <30% between consecutive assessment periods (once every 3 years), excluding years where TAC=0.
	Odds of no management action	Probability of SSB > $SSB_{threshold}$
6. Maintain fishing intensity (F) at the target value with reasonable variability	F_{target}/F	F_{target}/F

Harvest Control Rules

Each harvest control rule (HCR) specifies a management action to be taken (or not), based on the estimated condition of the simulated albacore population relative to reference points. The management action is implemented as either Total Allowable Catch (TAC) or Mixed Control. Figure ES2 depicts how fishing intensity (F; calculated in terms of spawning potential ratio) varies according to changes in spawning stock biomass (SSB) relative to unfished SSB for each of the 16 HCRs tested. For each HCR, if SSB is above $SSB_{threshold}$, then the level of fishing intensity is set to the TRP or is sampled from the historical time series of fishing intensities ($F_{historical}$), if the TRP is greater than $F_{historical}$. If SSB is below $SSB_{threshold}$ but above the limit reference point (LRP), the level of F is reduced to below the TRP. The reason for an HCR to initiate management action at $SSB_{threshold}$ rather than the LRP is to reduce the chances of ever breaching the LRP and avoid severe management actions that could occur when the LRP is breached. If SSB falls below the LRP, the F is maintained at a low level until SSB is rebuilt above the LRP. This minimum F (F_{min}) is a fraction of the F or catch associated with the LRP (TAE_{min} or TAC_{min}). Note that F_{min} is a function of the TRP, LRP, and $SSB_{threshold}$, and as such it varies between HCRs (Fig. ES2). We tested 16 harvest control rules with different combinations of TRPs, $SSB_{threshold}$, and LRPs (Fig. ES2). These are listed in Table ES2 and detailed in Table 2 of the main report.

Figure ES2. Harvest control rules (HCRs) tested in the second round of MSE for NPALB. Vertical dotted grey lines indicate the limit or threshold reference points listed in Table ES2.

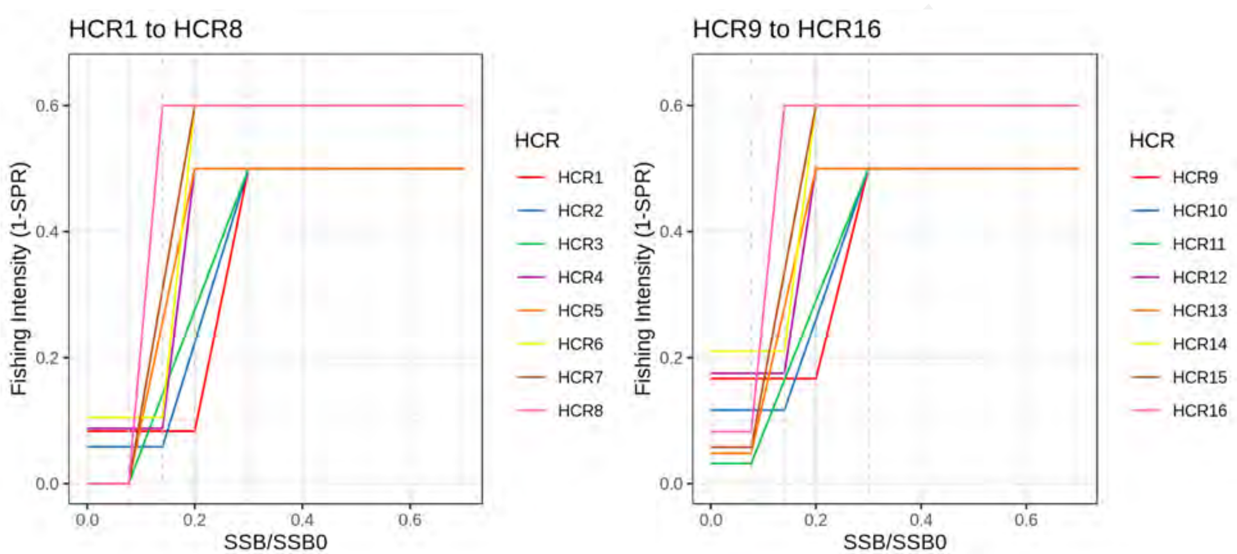


Table ES2. List of harvest control rules (HCRs). The TRP is an indicator of fishing intensity based on SPR. SPR is the female spawning stock biomass (SSB) per recruit that would result from the current year's pattern and intensity of fishing mortality relative to the unfished stock. A TRP of F50 would result in the SSB fluctuating around 50% of the unfished SSB. A TRP of F40 implies a higher fishing intensity (i.e., 1-SPR of 0.6) and would result in a SSB of around 40% of the unfished SSB. The threshold and limit reference points, $SSB_{threshold}$ and LRP, are SSB-based and refer to the specified percentage of unfished SSB. The unfished SSB is dynamic and fluctuates depending on changes in recruitment. The fraction used to calculate TACmin or TAEmin refers to the fraction of the catch or F associated with the LRP.

HCR	Target reference point (TRP)	Threshold reference point ($SSB_{threshold}$)	Limit reference point (LRP)	Prob SSB > LRP	Fraction used to calculate TAC_{min} or TAE_{min}
1	F50	30%	20%	0.8	0.25
2	F50	30%	14%	0.9	0.25
3	F50	30%	7.7%	0.9	0
4	F50	20%	14%	0.9	0.25
5	F50	20%	7.7%	0.9	0

6	F40	20%	14%	0.9	0.25
7	F40	20%	7.7%	0.9	0
8	F40	14%	7.7%	0.9	0
9	F50	30%	20%	0.8	0.5
10	F50	30%	14%	0.9	0.5
11	F50	30%	7.7%	0.9	0.25
12	F50	20%	14%	0.9	0.5
13	F50	20%	7.7%	0.9	0.25
14	F40	20%	14%	0.9	0.5
15	F40	20%	7.7%	0.9	0.25
16	F40	14%	7.7%	0.9	0.25

Uncertainties considered

The MSE computer simulations allowed for testing candidate HCRs under different "what if" scenarios for stock productivity, recruitment variability, availability to the Eastern Pacific Ocean (EPO) fishery, observation error, assessment error, and management implementation error to make sure that the proposed harvest strategies could meet management goals in the real world. These "what if" scenarios were based on the ALBWG's best estimate of the uncertainty or were specified by the managers and stakeholders. Four scenarios were developed to represent the range of uncertainty in stock productivity (Table ES3). They required different operating model (OM) structures in terms of the parametrization of biological factors such as growth or natural mortality. Other productivity scenarios were also evaluated during the first round of the MSE but were found to overlap with these four scenarios here and produce similar results to the scenarios included here. Therefore, this round of the MSE only included these four scenarios to save time and effort. NPALB recruitment can vary greatly between years due to unknown environmental factors, even when SSB remains the same. To account for uncertainty in recruitment, recruitment deviations in the OM were sampled from a distribution with σ_R=0.5 and an autocorrelation of 0.42. The autocorrelation implies that a good recruitment year was more likely to be followed by another good recruitment event, giving rise to good and bad recruitment cycles. There is also uncertainty in the number of juveniles migrating to the EPO every year. To account for changes in the availability of specific age classes to the EPO fishery between years, the age selectivity for the EPO fleet in the OM was made time-varying using additive random walk deviations for ages one to four. For each HCR/productivity scenario combination, 70 iterations with different random trajectories in recruitment and EPO age selectivity were run.

In addition to the four stock productivity scenarios, a potential future fishing effort scenario prioritized during the 4th ISC ALB MSE Workshop was developed and consisted of a shift of south Pacific fishing effort to the north Pacific modeled as a ramp in catch from a new entrant to the fishery with catch not known to the assessment and not under HCR control.

Table ES3. List of the four operating models (OMs) representing different productivity scenarios and their parameter specifications. H refers to steepness, G to growth, and M to natural mortality. The OMs are ordered from the one simulating the most productive NPALB population to the least productive. Model fit during the OM conditioning phase is provided as the negative log-likelihood (NLL) of each model (i.e., lower is better). Biological plausibility of each OM is also provided, based on the expert opinion of the ALBWG.

OM No.	h	G	M	Age selectivity	Recruitment autocorrelation	OM Model Fit (NLL)	Biological Plausibility
3	high	low	medium	Time varying	0.42	358.12	Medium
Base/1	medium	medium	medium	Time varying	0.42	348.11	High
4	high	high	medium	Time varying	0.42	363.05	Medium
6	high	high	Low	Time varying	0.42	364.25	Low

Results

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

1. *Under both TAC and mixed control, all harvest control rules (HCRs) were able to maintain the stock above the WCPFC's limit reference point (20% SSB0_d), the IATTC limit reference point used for tropical tunas (7.7%SSB0), and the LRP specified by each HCR with high probability (>0.8), when simulation outcomes across all reference scenarios where considered.*

The NPALB stock is in good condition and even when considering the range of uncertainties in stock productivity, recruitment variability, availability to the EPO surface fleet, observation, assessment, and implementation error, all HCRs had highly likely odds (>0.8) of SSB being above the 20% SSB0_d *LRP,* the 7.7% SSB0_d LRP, and their respective LRP (Table ES4 and ES5) under both TAC and mixed control.

Table ES4. Performance of indicators for each harvest control rule under mixed control across all iterations and uncertainty scenarios. HCR refers to harvest control rule, LRP to limit reference point, $SSB_{threshold}$ to the threshold reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. The LRP and $SSB_{threshold}$ are SSB-based and refer to the specified fraction of SSB0. Unless specified as equilibrium SSB0, the unfished SSB is dynamic and fluctuates depending on changes in recruitment. See Table ES1 for a detailed definition of performance indicators. Colors represent risk categories and associated risk levels as defined in the legend. Some HCRs have F_{target}/F of >1 because on average, the Fs for those HCRs are below the F_{target}.

Mixed Control
Across Reference Scenarios

hcr	TRP	LRP	SSB threshold	Odds of Not Breaching the LRP	Odds SSB > 20% SSBo	Odds SSB > Equilibrium 7.7% SSBo	Odds SSB > 7.7% SSBo	Odds Depletion > Minimum Historical	Odds Mean Annual Catch > Historical	Odds Mean Medium Term Catch > Historical Catch	Odds Mean Long Term Catch > Historical Catch	Catch Stability	Odds No Management Action	Ftarget/F
1	F50	0.20	0.30	0.98	0.98	0.96	1.00	0.75	0.59	0.59	0.67	0.99	0.88	0.92
2	F50	0.14	0.30	0.99	0.97	0.96	1.00	0.74	0.60	0.59	0.68	1.00	0.87	0.92
3	F50	0.08	0.30	1.00	0.98	0.96	1.00	0.74	0.59	0.58	0.68	1.00	0.88	0.92
4	F50	0.14	0.20	0.99	0.98	0.96	1.00	0.74	0.60	0.59	0.68	1.00	0.98	0.92
5	F50	0.08	0.20	1.00	0.98	0.96	1.00	0.75	0.60	0.59	0.68	1.00	0.98	0.92
6	F40	0.14	0.20	0.97	0.93	0.93	0.99	0.72	0.69	0.68	0.77	1.00	0.93	1.04
7	F40	0.08	0.20	0.99	0.92	0.93	0.99	0.72	0.69	0.68	0.77	0.99	0.92	1.04
8	F40	0.08	0.14	0.99	0.92	0.93	0.99	0.72	0.69	0.68	0.77	1.00	0.97	1.04
9	F50	0.20	0.30	0.98	0.98	0.96	1.00	0.74	0.60	0.59	0.68	1.00	0.88	0.92
10	F50	0.14	0.30	0.99	0.98	0.96	1.00	0.74	0.60	0.58	0.68	1.00	0.88	0.92
11	F50	0.08	0.30	1.00	0.98	0.96	1.00	0.75	0.60	0.59	0.68	1.00	0.88	0.92
12	F50	0.14	0.20	0.99	0.98	0.96	1.00	0.75	0.60	0.59	0.69	1.00	0.98	0.92
13	F50	0.08	0.20	1.00	0.98	0.96	1.00	0.75	0.60	0.59	0.68	1.00	0.98	0.92
14	F40	0.14	0.20	0.97	0.92	0.93	0.99	0.72	0.69	0.68	0.77	1.00	0.92	1.04
15	F40	0.08	0.20	0.99	0.93	0.93	0.99	0.72	0.69	0.68	0.77	1.00	0.93	1.04
16	F40	0.08	0.14	0.99	0.93	0.93	0.99	0.72	0.69	0.68	0.77	1.00	0.97	1.04

Odds

- Almost Certain - 0.9-<1
- Highly Likely - 0.8-0.89
- Likely - 0.7-0.79
- Better than Even - 0.6-0.69
- Even - 0.4-0.59
- Less than Even - 0.3-0.39
- Unlikely - 0.2-0.29
- Highly Unlikely - 0.1-0.19
- Almost Never - >0-0.09

Table ES5. Performance of indicators for each harvest control rule under TAC control across all iterations and uncertainty scenarios. HCR refers to harvest control rule, LRP to limit reference point, $SSB_{threshold}$ to the threshold reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. The LRP and $SSB_{threshold}$ are SSB-based and refer to the specified fraction of SSB0. Unless specified as equilibrium SSB0, the unfished SSB is dynamic and fluctuates depending on changes in recruitment. See Table ES1 for a detailed definition of performance indicators. Colors represent risk categories as defined in the caption and legend for Table ES4. Some HCRs have F_{target}/F of >1 because on average, the Fs for those HCRs are below the F_{target}.

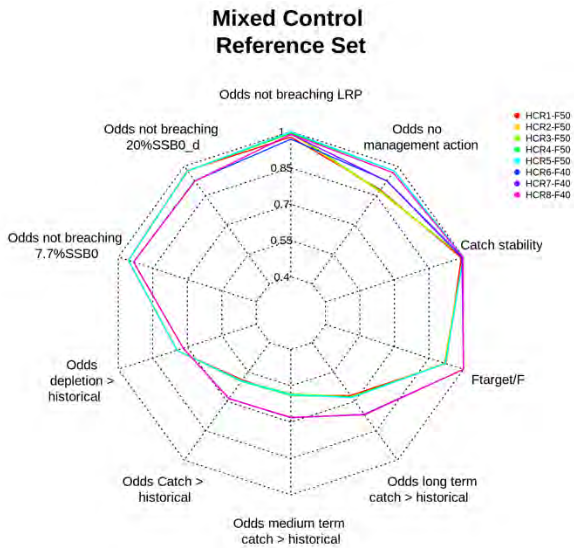
TAC Control
Across Reference Scenarios

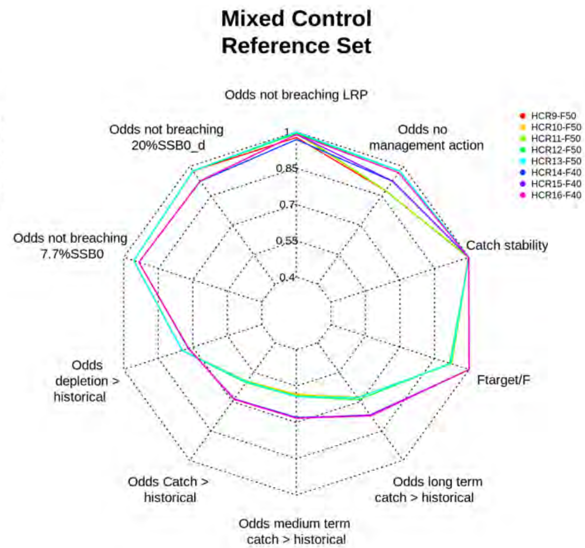
hcr	TRP	LRP	SSB threshold	Odds of Not Breaching the LRP	Odds SSB > 20% SSBo	Odds SSB > Equilibrium 7.7% SSBo	Odds SSB > 7.7% SSBo	Odds Depletion > Minimum Historical	Odds Mean Annual Catch > Historical	Odds Mean Medium Term Catch > Historical Catch	Odds Mean Long Term Catch > Historical Catch	Catch Stability	Odds No Management Action	Ftarget/F
1	F50	0.20	0.30	0.92	0.92	0.92	0.99	0.70	0.63	0.64	0.68	0.70	0.77	0.88
2	F50	0.14	0.30	0.96	0.92	0.92	0.98	0.70	0.62	0.64	0.68	0.72	0.77	0.89
3	F50	0.08	0.30	0.98	0.91	0.92	0.98	0.70	0.62	0.64	0.67	0.75	0.76	0.89
4	F50	0.14	0.20	0.96	0.91	0.92	0.98	0.70	0.63	0.65	0.68	0.78	0.91	0.88
5	F50	0.08	0.20	0.98	0.91	0.92	0.98	0.69	0.65	0.67	0.71	0.82	0.91	0.87
6	F40	0.14	0.20	0.93	0.87	0.90	0.97	0.68	0.64	0.61	0.73	0.63	0.87	1.06
7	F40	0.08	0.20	0.97	0.88	0.90	0.97	0.68	0.66	0.63	0.75	0.66	0.88	1.05
8	F40	0.08	0.14	0.96	0.86	0.90	0.96	0.67	0.67	0.63	0.75	0.70	0.92	1.02
9	F50	0.20	0.30	0.91	0.91	0.92	0.98	0.70	0.63	0.66	0.68	0.75	0.76	0.89
10	F50	0.14	0.30	0.96	0.92	0.92	0.99	0.70	0.62	0.64	0.69	0.74	0.77	0.89
11	F50	0.08	0.30	0.99	0.92	0.92	0.99	0.70	0.63	0.67	0.69	0.79	0.77	0.89
12	F50	0.14	0.20	0.96	0.91	0.92	0.98	0.70	0.64	0.66	0.70	0.82	0.91	0.88
13	F50	0.08	0.20	0.98	0.91	0.92	0.98	0.69	0.65	0.66	0.71	0.82	0.91	0.87
14	F40	0.14	0.20	0.92	0.86	0.90	0.96	0.67	0.65	0.63	0.73	0.67	0.86	1.02
15	F40	0.08	0.20	0.97	0.87	0.90	0.97	0.67	0.66	0.64	0.74	0.67	0.87	1.01
16	F40	0.08	0.14	0.96	0.86	0.90	0.96	0.67	0.66	0.65	0.75	0.71	0.92	1.03

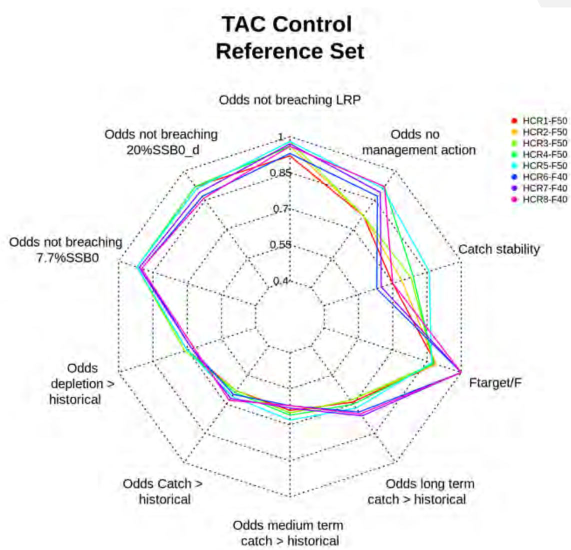
2. *Under mixed control, there was a tradeoff between the odds of biomass being above the 20%SSB0_d LRP and catch metrics.*

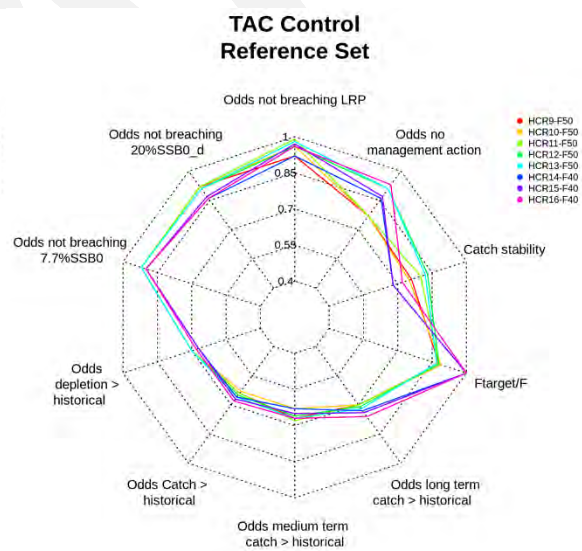
Mixed control maintained higher and less variable stock biomass than TAC control as the catches of surface fleets under effort control responded quickly to changes in biomass and their catch levels were not impacted by assessment errors in biomass estimates. It was rare for SSB to fall below $SSB_{threshold}$ and for a management action to be triggered. For scenarios 1 and 3, there was no difference in performance as F was largely the same across HCRs because SSB was largely above $SSB_{threshold}$ and F was therefore sampled from historical F in that case. Thus, when simulation outcomes across all reference scenarios were considered, the tradeoff was less apparent than for the low productivity scenario (Fig. ES3 and ES4). Across reference scenarios, HCRs with a TRP of F40 maintained higher odds of catch being above average historical catch than F50 rules, and comparable catch stability and odds of relative biomass being above minimum historical (Fig. ES3). While the odds of SSB being above the 20%SSB0_d LRP were lower for F40 rules than for F50 rules, they remained above 0.8 (Fig. ES2). Under the low productivity scenario, there was more contrast in the performance of F50 and F40 with regards to both biomass and catch metrics (Fig. ES4). The odds of SSB being above the 20%SSB0_d LRP or the equilibrium 7.7%SSB0 LRP, and of relative biomass being above minimum historical were higher for F50 rules, but this came at the cost of a decrease in the odds of annual, medium term, or long term catch being above historical (Fig. ES4).

Figure ES3 Cobweb plot depicting performance indicators for HCRs 1-8 (left) and HCRs 9-16 (right) under mixed control (top) and TAC control (bottom) for all runs across reference scenarios. 20%SSB0_d corresponds to 20% of the unfished dynamic SSB and corresponds to the current WCPFC limit reference point (LRP). 7.7%SSB0 refers to 7.7% of unfished equilibrium SSB and is the LRP used by IATTC for tropical tunas. Values close to the outer web signify a more positive outcome for that performance indicator. See Table ES1 for a definition of the performance indicators. See Table ES1 for a definition of the performance indicators. Detail of each HCR are provided for reference. In the table, TRP refers to target reference point, $SSB_{threshold}$ to threshold reference point, and LRP to limit reference point.









HCR	TRP	$SSB_{threshold}$	LRP	Prob SSB > LRP	TAC_{min} or TAE_{min} Fraction
1	F50	30%	20%	0.8	0.25
2	F50	30%	14%	0.9	0.25
3	F50	30%	7.7%	0.9	0
4	F50	20%	14%	0.9	0.25
5	F50	20%	7.7%	0.9	0
6	F40	20%	14%	0.9	0.25
7	F40	20%	7.7%	0.9	0
8	F40	14%	7.7%	0.9	0

HCR	TRP	$SSB_{threshold}$	LRP	Prob SSB > LRP	TAC_{min} or TAE_{min} Fraction
9	F50	30%	20%	0.8	0.5
10	F50	30%	14%	0.9	0.5
11	F50	30%	7.7%	0.9	0.25
12	F50	20%	14%	0.9	0.5
13	F50	20%	7.7%	0.9	0.25
14	F40	20%	14%	0.9	0.5
15	F40	20%	7.7%	0.9	0.25
16	F40	14%	7.7%	0.9	0.25

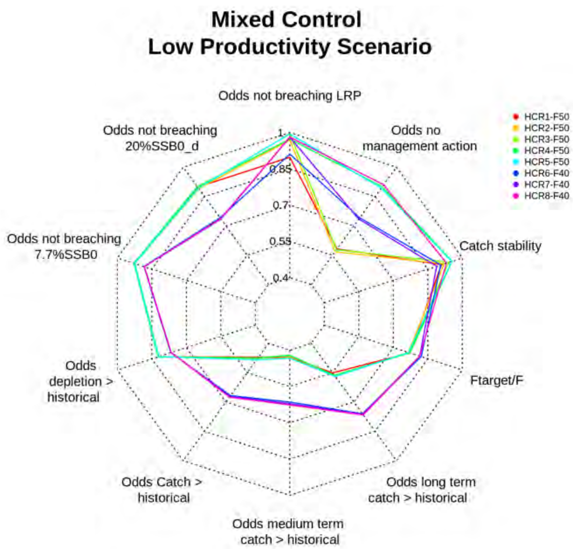
3. *Under TAC control, median catch is higher for F40 HCRs, but also more variable, than F50 HCRs. The tradeoff between catch and catch variability leads to the odds of catch being above historical being comparable between F50 and F40 HCRs.*

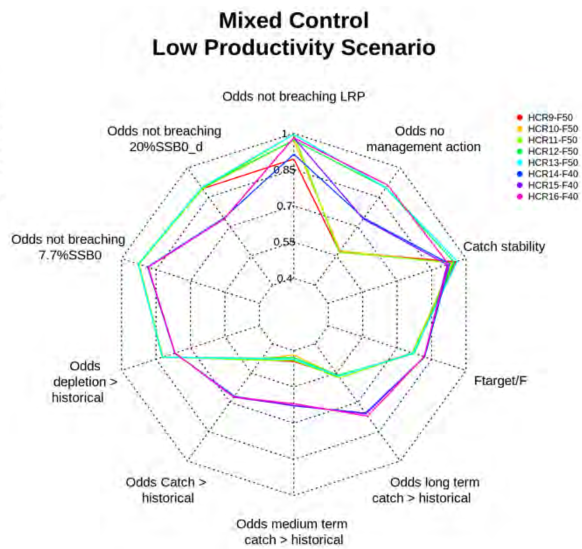
Across all reference scenarios, the largest difference in performance between HCRs under TAC control was for catch stability. F50 HCRs, particularly those with a $SSB_{threshold}$ of 20% SSB0_d (HCR4, HCR5, HCR12, and HCR13) have higher odds of decreases in catch between assessment periods being less than 30% than F40 HCRs and comparable performance in terms of the odds of different catch metrics being above historical, the odds of SSB being above different LRP metrics, and of depletion (i.e., total biomass relative to unfished levels) being above historical (Fig. ES3). Across reference scenarios, both F40 and F50 HCRs achieved comparable results in terms of biomass and catch metrics but the process for achieving the results was different. The higher fishing intensity of F40 HCRs leads to higher catches but a faster reduction of biomass to a lower level, and a more variable TAC. In contrast, for the same $SSB_{threshold}$ and LRP (e.g., compare HCR5 with HCR7 in Fig. ES3), an F50 TRP maintains biomass at a higher level and catches are lower but more consistent, leading to lower management intervention and comparable odds of catch being above historical. The same tradeoff between catch and catch variability is apparent for the low productivity scenario (Fig. ES4). Here the lower fishing intensity is also associated with a lower risk of breaching the 20% SSB0_d LRP and higher medium term catch (Fig. ES4), even if F was lower, because less drastic management intervention was required.

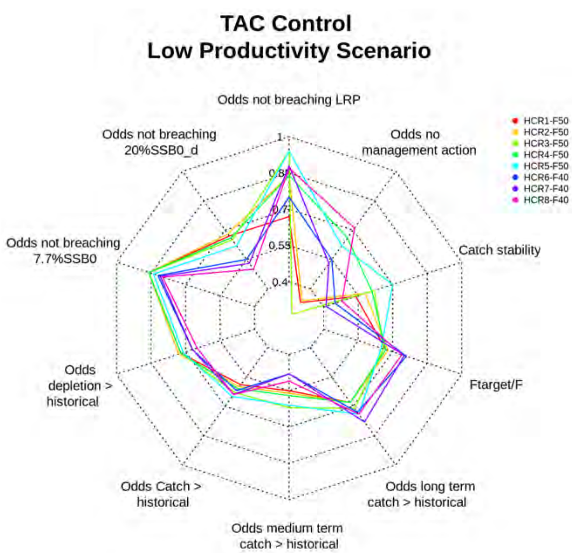
4. *HCRs with the LRP and $SSB_{threshold}$ reference points closer to the SSB associated with F_{target} resulted in a higher frequency of management interventions.*

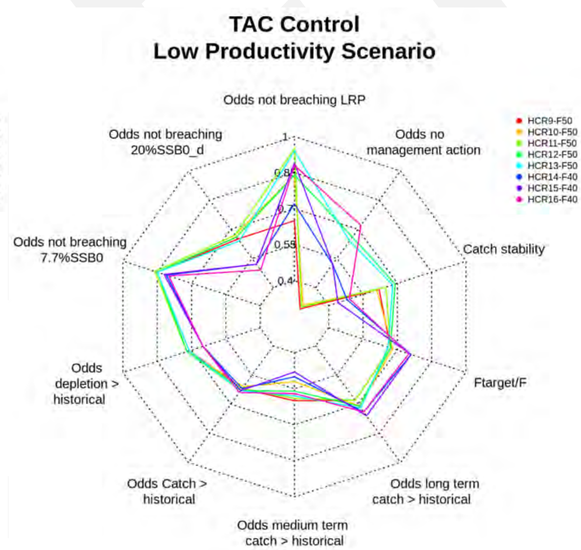
Among the F50 HCRs, the HCRs with the higher $SSB_{threshold}$ of 30% SSB0_d (i.e., HCR1 to HCR3 and HCR9 to HCR11) had higher odds of management intervention (Fig. ES2 and ES3). Similarly, for F40 HCRs, the HCRs with the higher 20% SSB0_d $SSB_{threshold}$ (i.e., HCR6, HCR7, HCR14, and HCR15) had higher odds of management intervention (Fig. ES2 and ES3). Higher odds of management intervention, however, were not associated with improved performance in biomass metrics either across reference scenarios or for the low productivity scenario (Fig. ES3 and ES4). Variability in performance in both biomass and catch metrics was instead largely driven by the TRP.

Figure ES4 Cobweb plot depicting performance indicators for HCRs 1-8 (left) and HCRs 9-16 (right) under mixed control (top) and TAC control (bottom) for all runs for the low productivity scenario. 20%SSB0_d corresponds to 20% of the unfished dynamic SSB and corresponds to the current WCPFC limit reference point (LRP). 7.7%SSB0 refers to 7.7% of unfished equilibrium SSB and is the LRP used by IATTC for tropical tunas. Values close to the outer web signify a more positive outcome for that performance indicator. See Table ES1 for a definition of the performance indicators. See Table ES1 for a definition of the performance indicators. Detail of each HCR are provided for reference. In the table, TRP refers to target reference point, $SSB_{threshold}$ to threshold reference point, and LRP to limit reference point.









HCR	TRP	$SSB_{threshold}$	LRP	Prob SSB > LRP	TAC_{min} or TAE_{min} Fraction
1	F50	30%	20%	0.8	0.25
2	F50	30%	14%	0.9	0.25
3	F50	30%	7.7%	0.9	0
4	F50	20%	14%	0.9	0.25
5	F50	20%	7.7%	0.9	0
6	F40	20%	14%	0.9	0.25
7	F40	20%	7.7%	0.9	0
8	F40	14%	7.7%	0.9	0

HCR	TRP	$SSB_{threshold}$	LRP	Prob SSB > LRP	TAC_{min} or TAE_{min} Fraction
9	F50	30%	20%	0.8	0.5
10	F50	30%	14%	0.9	0.5
11	F50	30%	7.7%	0.9	0.25
12	F50	20%	14%	0.9	0.5
13	F50	20%	7.7%	0.9	0.25
14	F40	20%	14%	0.9	0.5
15	F40	20%	7.7%	0.9	0.25
16	F40	14%	7.7%	0.9	0.25

5. *Both mixed and TAC control are able to maintain the stock above the WCPFC's limit reference point (20% SSB0_d) and the IATTC limit reference point used for tropical tunas (7.7%SSB0) with high probability (>0.8), even with increasing catches from an unknown, unmanaged fleet. However, this comes at the expense of reduced catches for the managed fleets.*

Results from the robustness scenario, where catches of an unknown, unmanaged fleet increase overtime up to 50,000 mt, demonstrate that the current NPALB stock would be resilient to an increase in unreported catches if under mixed or TAC control and if the TRP is at or below F40. Indeed, the odds of SSB being above the LRP or other conservation limits are highly likely (> 0.8) (Table ES6 and ES7). This is because the estimation model (i.e., simulated stock assessment) correctly detects the decrease in biomass from the abundance indices and composition data despite observation error. As the TAC and TAE of the managed fleets are dependent on stock biomass, they are reduced over time and catches of the managed fleets diminish. Thus, maintenance of stock biomass comes at the cost of decreased catches for the managed fleets (Table ES6 and ES7).

Table ES6. Performance of indicators for each harvest control rule under mixed control for the unknown fleet robustness scenario. Larger values indicate better performance. HCR refers to harvest control rule, LRP to limit reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. Unless specified as equilibrium SSB0, the SSB0 is dynamic (i.e., SSB0_d) and fluctuates depending on changes in recruitment. See table ES1 for a detailed definition of performance indicators. Colors represent risk categories as defined in the caption and legend for Table ES4.

Mixed Control

Unknown Fleet Robustness Scenario

hcr	TRP	LRP	SSB threshold	Odds of Not Breaching the LRP	Odds SSB > 20% SSBo	Odds SSB > Equilibrium 7.7% SSBo	Odds SSB > 7.7% SSBo	Odds Depletion > Minimum Historical	Odds Mean Annual Catch > Historical	Odds Mean Medium Term Catch > Historical Catch	Odds Mean Long Term Catch > Historical Catch	Catch Stability	Odds No Management Action	Ftarget/F
9	F50	0.20	0.30	0.98	0.98	0.95	1	0.62	0.43	0.53	0.30	0.78	0.78	0.80
10	F50	0.14	0.30	1.00	0.97	0.95	1	0.62	0.44	0.54	0.31	0.79	0.77	0.79
11	F50	0.08	0.30	1.00	0.98	0.95	1	0.62	0.44	0.53	0.32	0.85	0.77	0.79
12	F50	0.14	0.20	1.00	0.97	0.95	1	0.61	0.45	0.55	0.34	0.94	0.97	0.78
13	F50	0.08	0.20	1.00	0.97	0.95	1	0.61	0.45	0.54	0.34	0.94	0.97	0.78
14	F40	0.14	0.20	1.00	0.97	0.95	1	0.61	0.45	0.53	0.36	0.96	0.97	0.94
15	F40	0.08	0.20	1.00	0.97	0.95	1	0.61	0.46	0.55	0.35	0.92	0.97	0.94
16	F40	0.08	0.14	1.00	0.97	0.95	1	0.62	0.45	0.54	0.35	0.97	1.00	0.94

Table ES7. Performance of indicators for each harvest control rule under TAC control for the unknown fleet robustness scenario with no restrictions on the fleet capacity (i.e., F of managed fleets could increase up to the TRP). Larger values indicate better performance. HCR refers to harvest control rule, LRP to limit reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. Unless specified as equilibrium SSB0, the SSB0 is dynamic (i.e., SSB0_d) and fluctuates depending on changes in recruitment. See table ES1 for a detailed definition of performance indicators. Colors represent risk categories as defined in the caption and legend for Table ES4.

TAC Control

Unknown Fleet Robustness Scenario

hcr	TRP	LRP	SSB threshold	Odds of Not Breaching the LRP	Odds SSB > 20% SSBo	Odds SSB > Equilibrium 7.7% SSBo	Odds SSB > 7.7% SSBo	Odds Depletion > Minimum Historical	Odds Mean Annual Catch > Historical	Odds Mean Medium Term Catch > Historical Catch	Odds Mean Longterm Term Catch > Historical Catch	Catch Stability	Odds No Management Action	Ftarget/F
9	F50	0.20	0.30	0.95	0.95	0.93	1.00	0.61	0.36	0.37	0.21	0.54	0.70	0.78
12	F50	0.14	0.20	0.99	0.94	0.92	1.00	0.61	0.36	0.43	0.19	0.66	0.94	0.77
14	F40	0.14	0.20	0.96	0.86	0.91	0.99	0.56	0.52	0.48	0.41	0.47	0.86	0.86
16	F40	0.08	0.14	0.99	0.86	0.90	0.99	0.56	0.53	0.54	0.42	0.59	0.96	0.86

Key Limitations

The ALBWG examined the MSE models in detail and identified the following key limitations.

- The uncertainty in the relationship between the measure of effort in the MSE (i.e., exploitation rate that generates the F specified by the HCR) and real-world effort in number of fishing days for the EPO surface fleet increases at smaller effort levels. Therefore, at very low annual exploitation rates, implementation error for the EPO fleet under mixed control may be greater in the real world than the implementation error assumed in the MSE simulation. However, impact of this underestimation of implementation error for the EPO on MSE results is likely low as such low values comprised only 5% of all the simulated exploitation rates.

- It is assumed that catch control is implemented equally effectively across all fisheries, including both NPALB targeting and non-targeting (e.g., surface fleets vs. longline). This may not be true in the real world but there is no prior experience or information on implementation error of catch control between albacore targeting and non-targeting fisheries.

- Allocation is assumed to be constant at the average of 1999-2015 levels throughout the simulation. This formulation prevents an assessment of management objective 3, *maintain harvest ratios by fishery*, as the harvest ratios are kept constant by design. Testing of different allocation schemes would require input from managers as to what those allocation rules might be.

- NPALB is a highly migratory species whose movement rates to given areas in the North Pacific are highly variable. This affects availability to the fisheries operating in those areas. However, the simulations do not explicitly model these movement processes and instead only approximate the availability to various fleets. Further work could include the development of area specific operating models to better capture uncertainty in migration rates, and their relationship to availability.

- The simulations are conditioned on data from 1993 onwards, although available data dates back to 1966. Therefore, the simulations may not include the full range of uncertainty in the population dynamics of NPALB. Thus, the MSE results are most applicable to recent conditions. Nevertheless, inclusion of the lowest productivity scenario (Scenario 6) was an attempt to accommodate some of this uncertainty.

2 Introduction

Management strategy evaluation (MSE) is a process that uses a closed, feedback-loop computer simulation to assess how effective a candidate harvest strategy is at achieving management objectives put forward by managers and stakeholders under a range of uncertainties. It serves as a tool for managers and stakeholders to test the performance of and select between a set of candidate harvest strategies given specific management objectives.

Two Regional Fisheries Management Organizations (RFMOs) are tasked with managing the North Pacific albacore tuna (NPALB) stock: the Northern Committee of the Western and Central Pacific Fisheries Commission (WCPFC NC), and the Inter American Tropical Tuna Commission (IATTC). To refine the interim harvest strategy currently in place for NPALB and adopt a target reference point (TRP), the WCPFC NC and IATTC endorsed development of an MSE by the Albacore Working Group (ALBWG) of the International Scientific Committee for Tuna and Tuna-like Species in the North Pacific (ISC) (WCPFC 2017). The goal of the MSE work was to examine the performance of candidate harvest strategies and associated reference points for NPALB under uncertainty. Performance was evaluated based on management objectives pre-agreed upon with managers and stakeholders.

Engagement with managers and stakeholders for this MSE process started in April 2015 during the 1st ISC NPALB MSE Workshop in Yokohama, Japan. Fishery managers, industry representatives, NGOs, and scientists were introduced to the concept of MSE and discussed the objectives, benefits, and requirements of a potential MSE (ISC 2015). The 2nd ISC NPALB MSE Workshop was held in May 2016 in Yokohama, Japan. Stakeholders and scientists identified management objectives and performance metrics to be evaluated in the MSE (ISC 2016). In October 2017, the 3rd ISC MSE Workshop was held in Vancouver, Canada. Management objectives and performance metrics were finalized and candidate reference points and harvest control rules for testing were agreed upon (ISC 2017). In April 2017, the main MSE analyst for this work was hired and started developing the MSE framework. Following initial runs it became clear that, given the long run times required for the MSE analysis and limited computing resources, not all the harvest control rules and uncertainty scenarios proposed at the Vancouver workshop could be completed in time for the 4th ISC NPALB MSE Workshop planned for February 2019. Thus, at the ISC ALBWG Meeting in May 2018 in La Jolla, USA, a reduced set of harvest control rules and uncertainty scenarios for a first MSE round of analysis was agreed upon.

Three harvest strategies (HS1, HS2, and HS3) were evaluated in the first round of the NPALB MSE. Within each harvest strategy, different levels of harvest were set by a harvest control rule (HCR) that specifies a management action to be taken (or not), based on the condition of the simulated albacore population relative to reference points. The management action was implemented as either Total Allowable Catch (TAC) or Total Allowable Effort (TAE). Results from this first MSE analysis for NPALB, which compared performance of the 39 HS/HCRs/management control combinations under different uncertainty scenarios, were presented to managers and stakeholders at the 4th ISC NPALB MSE Workshop. It was suggested that the two worst performing HS, HS1 and HS2, as well as the worst performing reference points be removed from further consideration. Managers and stakeholders also recommended further analysis of the performance of an additional set of HS3 HCRs focused on candidate TRPs F40 and F50 and listed in Table ES2. Furthermore, they suggested that an evaluation of HCRs under a mixed control management setting, where surface fisheries (i.e., Japan pole-and-line and EPO surface) are managed by TAE and all other fisheries are managed by TAC, be carried out. Managers and stakeholders also recommended that a stricter risk level of 90% be used when evaluating the risk of breaching the candidate LRPs of 7.7% SSB0_d and 14% SSB0_d (i.e., the LRP is breached if the probability of being above the limit reference point drops below 90%), and of 80% for the 20% SSB0_d LRP, and that this risk level be calculated by using the future projection software over a period of 10 years as is done during the stock assessment. Finally, it was suggested that the levels of fishing intensity should be limited by the historical (1997–2015) levels achieved by the NPALB fisheries. All recommendations from the 4th ISC NPALB MSE Workshop and how they were addressed are listed in Table 1.

This report provides a detailed overview of the NPALB MSE framework, including changes undertaken to meet recommendations of the 4th ISC NPALB MSE Workshop (Section 3), and assesses performance of the HCRs listed in Table ES2 with respect to the NPALB management objectives (Section 4). This latest round of simulations evaluated all the HCRs and associated reference points proposed at the 4th MSE Workshop and represents the final set of MSE analyses in support of development of a harvest strategy for NPALB. Section 2 contains background information on the biology, fisheries, and management of NPALB, as well as management objectives and performance indicators, reference points, and candidate harvest control rules, and uncertainties considered in this new set of MSE simulations.

3 Background

3.1 Biology

Albacore tuna in the Pacific Ocean consist of the north Pacific stock (focus of this MSE) and the south Pacific stock. The discreteness of these stocks is supported by fishery data [lower catch rates in equatorial regions; Suzuki et al. (1977)], tagging data [there are no south Pacific Ocean recoveries of fish tagged in the north Pacific Ocean; Ramon and Bailey (1996)], ecological data [albacore larvae are rare in samples from equatorial waters; Ueyanagi (1969)], and genetic data [showing differentiation between north and south Pacific albacore; Takagi et al. (2001)]. Thus, north Pacific albacore is assumed to be a discrete, reproductively isolated stock, with no internal sub-group structure within the stock.

Albacore are batch spawners, shedding hydrated oocytes, in separate spawning events, directly into the sea where fertilization occurs. Spawning frequency is estimated to be 1.7 d in the western Pacific Ocean (Chen et al. 2010), and batch fecundity ranges between 0.17 and 2.6 million eggs (Ueyanagi 1957, Otsu and Uchida 1959, Chen et al. 2010). Female albacore mature at lengths ranging from 83 cm fork length (FL) in the western Pacific Ocean (Chen et al. 2010) to 90 cm FL in the central Pacific Ocean (Ueyanagi 1957), and 93 cm FL north of Hawaii (Otsu and Uchida 1959).

Spawning occurs in tropical and sub-tropical waters between Hawaii (155°W) and the east coast of Taiwan and the Philippines (120°E) and between 10 and 25°N latitudes at depths exceeding 90 m (Ueyanagi 1957, 1969, Otsu and Uchida 1959, Yoshida 1966, Chen et al. 2010). Although spawning probably occurs over an extended period from March through September in the western and central Pacific Oceans, recent evidence based on a histological assessments of gonadal status and maturity (Chen et al. 2010) shows that spawning peaks in the March-April period in the western Pacific Ocean, which is consistent with evidence from larval sampling surveys in the same region (Nishikawa et al. 1985). In contrast, studies of albacore reproductive biology in the central Pacific Ocean have concluded that there was a probable peak spawning period between June and August (Ueyanagi 1957, Otsu and Uchida 1959), but these studies are based on indirect observation methods, are more than 50 years old, and have not been updated using modern histological techniques (e.g., see Chen et al. 2010).

Growth of albacore tuna is commonly modeled by a von Bertalanffy growth function, with rapid growth in immature fish followed by a slowing of growth rates at maturity and through the adult period. Growth in the first year of life is uncertain since these young fish are rarely captured in any of the active fisheries in the North Pacific Ocean. However, juvenile albacore recruit into intensive surface fisheries in both the eastern and western Pacific Oceans at age-2 and as a result, much better size-at-age and growth information is available. Early growth models combined both sexes because sex-specific fishery data were not collected, although it was known that adult males attained a larger size than females (Otsu and Uchida 1959, Yoshida 1966, Otsu and Sumida 1968). Chen et al. (2012) provided clear evidence of sexually dimorphic growth functions for males and females after they reach sexual maturity and reported that males attained a larger size and older age than females (114 cm FL and 14 years vs. 103.5 cm FL and 10 years, respectively).

A re-examination of the age and growth data compiled by Wells et al. (2013), some of which were used as conditional age-at-length data in the 2011 assessment, showed that for those individuals in which sex was recorded, there was clear evidence of sexually dimorphic growth between males and females (Xu et al. 2014). Given the clear evidence of sexual dimorphism in the growth and longevity of north Pacific albacore, the ALBWG used sex-specific male and female von Bertalanffy growth functions, as in the 2017 assessment.

North Pacific albacore are highly migratory, and these movements are influenced by oceanic conditions (e.g., Polovina et al. 2001, Zainuddin et al. 2006, 2008). The majority of the migrating population is believed to be composed of juvenile fish (i.e., immature animals that are less than 5 years old and 85 cm FL), which generally inhabit surface waters (0-50 m) in the Pacific Ocean. Some juvenile albacore undertake trans-Pacific movements from west to the east and display seasonal movements between the eastern or western and central Pacific Ocean (Ichinokawa et al. 2008, Childers et al. 2011). The trans-Pacific movements track the position of the transition zone chlorophyll front (Polovina et al. 2001, Zainuddin et al. 2006, 2008) and increase when large meanders in the Kuroshio current occur, increasing albacore prey availability in the transition zone (Kimura et al. 1997, Watanabe et al. 2004). Westward movements of juveniles tend to be more frequent than eastward movements (Ichinokawa et al. 2008), corresponding to the recruitment of juvenile fish into fisheries in the western and eastern Pacific Ocean and are followed by a gradual movement of older juveniles and mature fish to low latitude spawning grounds in the western and central Pacific Ocean. This pattern may be complicated by sex-specific movements of large adult fish, which may be predominately male, to areas south of 20°N. The significance of sex-related movements on the population dynamics of this stock is uncertain at present.

3.2 Fisheries

Albacore tuna is a valuable species with a long history of exploitation in the North Pacific Ocean (e.g., Clemens 1961). The total reported catch of north Pacific albacore for all nations combined peaked at a 126,175 metric tonnes (t) in 1976 and then declined to a lowest observed catch in the time series (37,274 t) in 1991. Following this low point, total catch recovered to a second peak of 119,297 t by 1999. Total catch declined through the 2000s to a low of 63,654 t in 2005 and has recovered slightly, fluctuating between 69,000 and 93,000 t in recent years (2010-2015). Average catch over the operating model conditioning period (1993-2015) was 82,724 t. Over 2011-2015, Japanese fisheries accounted for 61.9% of the annual total harvest on average, followed by fisheries from the United States (16.9%), Canada (5.4%), China (4.3%), Chinese-Taipei (3.9%), Korea (0.1%), and Mexico (<0.1%). During the same five year period, non-ISC countries, primarily Vanuatu, harvested an average of 7.3% of the total annual catch.

The main gears deployed to harvest albacore in the North Pacific Ocean are longline, and troll and pole-and-line. Surface fisheries capture smaller, juvenile fish, and include the USA and Canada troll and pole-and-line fisheries and Japanese pole-and-line fisheries. Over the operating model conditioning period (1993 – 2015), surface fisheries have harvested approximately 53.6% of the north Pacific albacore catch. The surface fleets generally target albacore, but some Japanese pole-and-line vessels operating off the east coast of Japan switch targets between skipjack (*Katsuwonus pelamis*) and albacore (Kiyofuji and Uosaki 2010). Longline fisheries, which fish deeper in the water column and tend to capture larger, mature albacore, were responsible for harvesting about 41.7% of the albacore during the same period, with major fleets from Japan, USA, Chinese-Taipei, and recently China and Vanuatu. Most Japanese longline vessels operate offshore, target bigeye and catch larger, adult albacore. However, there exists a Japanese longline coastal fleet that targets juvenile albacore near southern coastal Japan (Ijima and Satoh 2014). By contrast, no longline vessel from the USA targets albacore directly. The USA shallow-set longline operates in the northern central/eastern Pacific and targets swordfish, but also catches juvenile and subadult albacore (Teo 2017). The USA deep-set longline vessels target bigeye, and at times also catch adult albacore (Teo 2017). Chinese-Taipei longline operations initially targeted albacore and were focused in subtropical waters (Chen and Cheng 2016). Operations then expanded to tropical waters starting in 2000 and catches of albacore decreased as yellowfin and bigeye became target species (Chen and Cheng 2016). High gillnet catches of albacore in the 1980s reflect data from high seas driftnet fisheries, which began in 1978 and ceased operating in 1993 as a result of United Nations General Assembly Resolution 44/225, which put in place a moratorium on the use of high seas driftnets (Uosaki et al. 2011).

3.3 Management

Two RFMOs (WCPFC NC and IATTC) are tasked with managing the NPALB stock. While there is no formal harvest control rule or target reference point for NPALB, the WCPFC adopted an *Interim Harvest Strategy for North Pacific Albacore* in December 2017, as recommended by the WCPFC NC (WCPFC 2017). The *Interim Harvest Strategy* specifies a broad, interim management objective for the fishery, a limit reference point (LRP), and a decision rule when the LRP is breached (WCPFC 2017). The interim management objective is "*to maintain the biomass, with reasonable variability, around its current level in order to allow recent exploitation levels to continue and with a low risk of breaching the LRP*" (WCPFC 2017). The LRP is established at 20% SSB0_d (SSB0_d: dynamic unfished SSB) (WCPFC 2017). The decision rule states that "*in the event that, based on information from ISC, the spawning stock size decreases below the LRP at any time, NC will, at its next regular session or intersessionally if warranted, adopt a reasonable timeline, but no longer than 10 years, for rebuilding the spawning stock to at least the LRP and recommend a Conservation and Management Measure (CMM) that can be expected to achieve such rebuilding within that timeline*" (WCPFC 2017).

In addition to the *Interim Harvest Strategy*, the IATTC and WCPFC also adopted conservation and management measures in 2005 that restricted NPALB fishing effort to below "current" (current is undefined but assumed to be the average of 2002 – 2004) levels (WCPFC 2005 WCPFC CMM 2005-03, IATTC RESOLUTION C-05-02). Each nation is required to "*take necessary measures to ensure that the level of fishing effort for NPALB is not increased beyond current levels*", but no specific management actions are specified.

The IATTC adopted an interim harvest control rule for tropical tunas in 2016 (Resolution C16-02), which although not applicable for NPALB, was taken into account when choosing potential candidate HCRs and performance metrics in this MSE.

According to the 2020 NPALB stock assessment (ALBWG 2020), the NPALB stock is not likely in an overfished condition relative to the LRP (20%SSB0_d) adopted by the WCPFC NC, with current SSB estimated to be at approximately 46% of SSB0_d. Although no F-based reference points have been adopted by the RFMOs, current fishing intensity (2015-2017), calculated as 1-SPR, was 0.50. This is the same fishing intensity as for the candidate TRP of F50 and lower than the 0.60 fishing intensity associated with the candidate F40 TRP, the 2002-2004 fishing intensity, or F_{msy}. The $F_{2002\text{-}2004}$ is a fishing intensity of 0.58 according to the base case NPALB MSE operating model, while F_{msy} is 0.86.

3.4 Management Objectives and Performance Indicators

The overarching objective for NPALB management is to maintain the viability and sustainability of the current NPALB stock and fisheries. However, more specific management objectives were identified and agreed upon by managers and stakeholders in a series of MSE workshops organized by ISC (see Introduction) and used to evaluate the performance of the different candidate harvest control rules. The management objectives are outlined in Table ES1 and summarized here: 1) maintain historical spawning biomass; 2) maintain historical total biomass; 3) maintain historical harvest ratios of each fishery; 4) maintain catches above historical average;

5) minimize changes in management over time; and 6) maintain fishing impact around the target value. It should be noted that it was agreed at the 3rd ISC NPALB MSE Workshop that harvest ratios of each fishery be maintained at the average of 1999-2015 in the MSE simulation and to not have allocation rules specific to each fishery. Thus, management objective 3 (maintain historical harvest ratios of each fishery) did not differ among the candidate HCRs and could not be evaluated. The objectives were not ranked in order of importance during the MSE workshops.

To quantitatively evaluate the performance of the harvest strategies tested relative to the management objectives, the ALBWG represented these management objectives into quantitative performance metrics. The final list of performance metrics associated with each objective agreed upon by the ALBWG are presented in Table ES1. Most of the figures and results are based on this set.

3.5 Reference Points

Reference points are benchmarks with which estimates of biomass or fishing intensity are compared to. Reference points are generally associated with a harvest control rule (HCR), which specifies a management action given the state of the stock relative to the reference point. Reference points are defined in this MSE as either target reference points (TRPs), limit reference points (LRPs), or threshold reference points.

A TRP refers to a desired state that management wants to achieve. The TRPs for all the HCRs evaluated in this MSE are based on fishing intensity (F). Fishing intensity is defined as 1-SPR, where SPR is the spawning potential ratio, or the SSB per recruit relative to the unfished population. The TRPs are labeled as Fx, where x refers to an SPR value. For instance, F40 represents an F that leads to a SSB per recruit that fluctuates around 40% of the unfished (i.e., removing about 60% of the SSB). In contrast, a TRP of F50 leads to a SSB that is around 50% of unfished SSB per recruit (i.e., a fishing intensity of 0.5 removing about 50% of the SSB). A TRP of F40 means fishing harder than F50, so the average level of SSB desired is lower.

The TRPs used in this last round of MSE simulations were F40 and F50, as recommended by managers and stakeholders at the 4th MSE Workshop in Yokohama, Japan, following results from the first round of NPALB MSE, which tested a wider range of TRPs (ISC 2019). According to the 2017 stock assessment, the current F (2012-2014) was 0.51, while the current F from the 2020 stock assessment was 0.50. This is close to the average F over the conditioning period of 1993-2015 from the base case OM, which was 0.51 (Fig. 1). In the base case MSE operating model, fishing intensity has only exceeded F40 in 1999 and 2002 (Fig. 1). However, note that the estimates of SPR and associated fishing intensity (defined as 1-SPR) change depending on the operating model (OM) used. For the same level of catch, a model assuming a less productive stock would estimate a higher fishing intensity. Therefore, different operating models have different estimates of historical fishing intensity levels. OM4 and OM6, which simulated less productive populations, had average historical fishing intensities greater than either candidate TRP, at 0.63 and 0.69, respectively (Fig. 1). By contrast, OM3, which simulated a more productive population had an average historical fishing intensity lower than the base case model at 0.44 (Fig. 1).

LRPs are biomass or fishing intensity levels to be avoided. Generally, LRPs refer to a biomass or fishing intensity leading to a biomass level below which recruitment would be endangered. Therefore, if biomass falls below an LRP, a harvest control rule would require drastic reductions in harvest. Since steepness of NPALB is not well known, WCPFC treats NPALB as a Level 2 stock, which requires the LRP be based on an x% of the unfished spawning stock biomass (SSB). To be consistent with the Annex II of the UN Fish Stocks Agreement (UNFSA) and recent WCPFC decisions on LRPs for the three tropical tuna species and South Pacific albacore, the LRP for NPALB was established in 2017 as 20% of the dynamic unfished SSB (20% SSB0_d, WCPFC 2017). Dynamic unfished SSB fluctuates depending on changes in recruitment. For Level 1 stocks with a reliable estimate of steepness, WCPFC considers B_{MSY} as the LRP. For NPALB, B_{MSY} would correspond to approximately 14% of unfished SSB. By contrast, IATTC defines the LRP of tropical tunas as $SSB_{0.5r0}$ or $F_{0.5r0}$. This is the SSB or F corresponding to a biomass that leads to a 50% reduction in the unfished recruitment level given a conservative steepness value of 0.75. This corresponds to an SSB that is approximately 7.7% of the unfished equilibrium biomass. In the HCRs under consideration three LRPs of 20%SSB0_d, 14% SSB0_d, and 7.7% SSB0_d were examined. For all LRPs, the percentage refers to the percentage of dynamic unfished SSB (SSB0_d). However, in terms of performance metrics we compare the odds of SSB being greater than 7.7% of both dynamic SSB0 (7.7% SSB0_d) and equilibrium SSB_0 (7.7% SSB0_d).

In addition to TRPs and LRPs, HCRs use a threshold reference point (Section 2.6). This reference point is based on SSB as a fraction of unfished dynamic SSB and will be referred to as $SSB_{threshold}$ throughout the report. $SSB_{threshold}$ acts as control point below which fishing intensity starts to be reduced. The reason for an HCR to initiate management action at $SSB_{threshold}$ rather than the LRP is to reduce the chances of ever reaching the LRP and to avoid the severe management actions that could occur when the LRP is breached. The HCRs considered three different $SSB_{threshold}$ levels: 30%SSB0_d, 20%SSB0_d, and 14%SSB0_d.

3.6 Candidate Harvest Control Rules

Candidate harvest control rules (HCRs) were suggested by managers and stakeholders during the 4th ISC NPALB MSE Workshop. The MSE for NPALB is model-based, meaning that the input to the HCR (i.e. current SSB and reference points) is derived, as in the current NPALB management system, from a stock assessment. In the MSE, the stock assessment is represented by an estimation model (EM). The HCR then translates the EM (i.e., assessment) output into a management action. As is happening under the current management framework, a stock assessment is conducted every three years in this MSE to estimate the status of the stock. The HCR then specifies a management action to be taken (or not) based on the condition of the albacore population as estimated by the EM (i.e., assessment) relative to reference points. The management action is implemented as either mixed control or Total Allowable Catch (TAC). Under mixed control, surface fisheries (Eastern Pacific Ocean troll and pole-and-line and Japanese pole-and-line) are managed via effort control while longline fisheries are managed via a TAC.

Figure ES2 depicts, for each of the HCRs under consideration, the management actions (i.e. changes fishing intensity) associated with a specific estimate of stock status (SSB relative to unfished SSB). Specific equations detailing how TAC and TAE change in relation to changes in SSB are provided in Table 2, but we provide a synopsis here. If current SSB (SSB_{latest}) is at or above the $SSB_{threshold}$ the level of fishing intensity is set to the TRP or is sampled from the historical time series of fishing intensities ($F_{historical}$) if the TRP is greater than $F_{historical}$. The MSE management module (Section 4.2.3) then uses Stock Synthesis benchmark calculations to find the exploitation rate (H_{target}, total catch as fraction of total biomass at the beginning of the year) that would produce a fishing intensity (1-SPR) equal to the TRP or $F_{historical}$. The exploitation rate is the TAE in the MSE simulation. If $SSB_{current}$ is below $SSB_{threshold}$ with a 0.5 probability, but above the LRP with a probability of 0.9 for 7.7%SSB0_d and 14%SSB0_d, and a probability of 0.8 for 20%SSB0_d, the F (or H) is reduced to below the TRP (or H_{target}). In this case, the F (or H) is reduced proportionally based on the following fraction: ($SSB_{current}$-LRP)/($SSB_{threshold}$ - LRP). If SSB falls below the LRP, the F is drastically reduced and maintained constant at a low level until SSB is rebuilt above the LRP. This minimum F (F_{min}) is a fraction (T_{min}) of the F associated with the LRP as defined in Table 2. Note that F_{min} is a function of the TRP, LRP, and $SSB_{threshold}$, and as such it varies between HCRs (Fig. ES1). In the MSE framework the F_{min} is translated to a H_{min} by using H_{target}, rather than the TRP, in the computation of F_{min}. We tested 16 harvest control rules with different combinations of TRP, $SSB_{threshold}$, LRP, and T_{min}, as described in Table ES2.

For TAC control, the TAC associated with the specified fishing intensity is found by multiplying the exploitation rate H by the current total biomass. Thus, while the exploitation rate and fishing intensity stay constant when SSB is above $SSB_{threshold}$ or below the LRP, the TAC changes with the biomass, eventually decreasing to 0 when the biomass is 0 (Fig. 2). We use Fig. 2 to exemplify the relationship between stock status and TAC as well as the different rate of change in TAC between F40 and F50 HCRs, when SSB is above $SSB_{threshold}$. The F40 HCRs show a steeper change in TAC as biomass changes, but a higher TAC for the same SSB/SSB0. We note, however, that the TAC levels are approximate. In the MSE simulation the algorithm considers the current age structure of the population (defined by selectivities and the relative impact of different fleets) to find the current total stock biomass and define a TAC. For generating the figure, total biomass at each SSB/SSB0 was obtained by multiplying the SSB/SSB0 ratio by the unfished total biomass (B_0), assuming that the population has a constant age structure that is the same as that under unfished conditions. B_0 was that of the base case OM over the conditioning period.

3.7 Uncertainties Considered in MSE Process

MSE allows for testing the harvest strategies under different "what if" scenarios in terms of biology, fishery dynamics, assessment error, observation error, or implementation error. This is done to test the ability of each harvest strategy under consideration to meet management objectives given uncertainty.

At the 3rd ISC MSE WS in October 2017, the ALBWG put forward and prioritized a list of uncertainties deemed most influential to NPALB. Given the long run time to complete a single

MSE simulation and the limited time to complete the work, this first MSE considered uncertainties in the factors agreed to be of highest priority by the ALBWG:

1) Recruitment - autocorrelation and various values of steepness parameter
2) Natural mortality - various values of natural mortality parameters
3) Growth-various values of growth parameters

and in 4) juvenile movement (via time-varying age selectivity), which was a medium priority.

Uncertainty in steepness, natural mortality and growth reflect uncertainty in stock productivity and are referred to as parameter uncertainty. Implementation of these uncertainties in the MSE framework required use of different operating model (OM) structures in terms of the parametrization of the specified biological factors (See section 4.1).

NPALB recruitment can vary greatly between years due to unknown environmental factors, even when SSB remains the same. To account for uncertainty in future recruitment, recruitment deviations in the forward projection of the OM were sampled from a distribution with σ_R=0.5. The ALBWG also determined that recruitment deviations in the OM should be autocorrelated. The autocorrelation implies that a good recruitment year was more likely to be followed by another good recruitment event, giving rise to good and bad recruitment cycles. To select the amount of autocorrelation, the autocorrelation of recruitment deviates from the 2017 stock assessment model starting in 1993 and the sensitivity run starting in 1966 from the 2017 stock assessment was examined.

Recruitment estimates from 1993 were not significantly autocorrelated at any lag (Fig. 3). By contrast, estimates of recruitment deviations from 1966 showed a significant autocorrelation of 0.42 at lag 1 (Fig. 4). It is interesting that interannual variability appears to be higher, and hence autocorrelation lower, in recent years. As the reason for including autocorrelated recruitment errors in the OM was to ensure that the proposed harvest control rules (HCRs) are robust to the unknown effect of multiyear environmental trends on recruitment, future recruitment deviations in the OM were generated assuming an autocorrelation of 0.42 as in the model that starts in 1966.

Albacore movement and, in particular, juvenile migration rates to the eastern Pacific Ocean (EPO) vary between years. To represent uncertainties in the availability of specific age classes to the EPO fishery between years, the OM has a time varying selectivity for the EPO surface fleet, which targets juveniles. As in the stock assessment, age selectivity for the three juvenile targeting surface fisheries F16, F17, and F27 was set as a free parameter from ages 1-5. In addition, the age-selectivity of the EPO fleet was made time varying in the OM using additive random walk deviations for ages 1-4 (Table 3).

Uncertainty in recruitment variability and time-varying age selectivity for the EPO fleet are measures of process uncertainty. For each HCR/productivity scenario combination, 70 iterations with different random trajectories in recruitment and EPO age selectivity were run. An analysis, presented at the August 2020 ALBWG meeting (ISC 2020) was carried to assess the impact of iteration number on the rank order of HCRs for each performance metric (PM) and the value of each PM. It was found that 45 iterations were adequate to distinguish the broad patterns of HCR performance highlighted in the report for the first round of MSE. Small differences in the value of performance indicators (<0.001) were apparent and these could lead to different PM rankings, but with >55 iterations even rankings are consistent. The ALBWG agreed that 70 iterations were adequate (ISC 2020).

In addition to parameter and process uncertainty, a potential future fishing effort scenario prioritized during the 4th ISC ALB MSE Workshop where an unmanaged new fishery is removing an increasing amount of unreported catch was developed. It consisted in a shift of south Pacific fishing effort to the north Pacific modeled as a ramp in catch from an unmanaged new entrant to the fishery with catch not known to the assessment and not under HCR control. To implement this scenario, the South Pacific albacore (SPALB) catch by country based on WCPFC Yearbook 2016 was examined. Since 2001 nine countries, namely Japan, Chinese Taipei, China, French Polynesia, Fiji, Korea, New Zealand, United States, and Vanuatu have fished SPALB. Average catch from 2001 to 2016 was approximately 72,000 mt. For the future effort scenario, the NPALB catch is gradually increased every year by 2500 mt until a maximum catch of 50,000 mt per year is reached for the unknown ghost fleet. The new catch is associated with a new longline fishery operating in area 4, whose selectivity is mirrored to that of the F25 longline fleet. While the OM (i.e., true state of nature) accounted for these catches, the EM (i.e. assessment model) that informed management did not.

4 MSE Framework Description

4.1 Operating Models

In an MSE, the operating model (OM) is a mathematical representation of the "true" dynamics of the stock and the fisheries operating on it. However, it is difficult to select one "true" OM model because of uncertainty in our understanding of biological processes, the effects of environmental variability on stock productivity and distribution, and their interplay with fisheries dynamics. Therefore, to capture the range of uncertainty in the system (see Section 3.7), a set of OMs representing potential versions of the "true" stock and the fisheries operating on it are developed. All the OMs consist of a population dynamics model of NPALB with a fishery model component relating the modeled dynamics to catch, CPUE, and size composition data. Like the stock assessment, the OMs are developed using the Stock Synthesis modelling platform (Methot and Wetzel 2013).

4.1.1 Conditioning process

To determine if the OMs are realistic representations of the stock, these models are "conditioned" on historical data. During the "conditioning" process, model parameters are estimated given observed fishery-specific catches, size composition, and abundance indices and it is determined if the OMs can reasonably represent past trends in catch, catch per unit effort (CPUE), and size composition data. If an OM cannot reasonably represent these historical data, the OM is discarded and not used for the MSE. The conditioning phase also allows the OM to have estimated model parameters that are consistent with historical observations, given the OM structure. All OMs in this MSE were found to be able to represent historical observations of catch, CPUE, and size composition. However, the OMs had different levels of biological plausibility and model fit to the data (Table ES3).

During the forward simulation in the "Future Process" phase OM model parameters are fixed to the values estimated during the conditioning process, and trends in the population under a range of different management models (i.e., different harvest control rules) are assessed. This closed-loop forward simulation is described in section 4.2.

The conditioning process was carried out during the first round of MSE (ISC 2020) and was not repeated for this latest round of simulations. However, the overview of the conditioning data and process and specifications of the base case model and the final set of operating models from the first round of MSE report is provided also here for context.

4.1.1.1 Data used for conditioning

As in the 2017 NPALB stock assessment, three types of data were used in the conditioning of the OMs: fishery-specific catches, size composition, and abundance indices. These data were compiled from 1993 through 2015. Catch and size composition data were compiled into quarters (Jan–Mar, Apr–Jun, Jul–Sep, Oct–Dec) and a quarterly time step was used for the OMs.

The geographic area of the OMs is the Pacific Ocean from 0° to 55°N, and from 120°E to 100°W (Fig. 5). This area includes all of the known catches of north Pacific albacore from 1993 through 2015. The base case model is not spatially explicit, but fisheries were defined using multiple criteria, including fishing area, and therefore implicitly included spatial inferences (Table 3). Analyses of fishing operations and size composition data from Japanese and US longline vessels in the north Pacific showed that there were five areas with relatively consistent size distributions of albacore (Ochi et al. 2016, Teo 2016) (Fig 5). These five fishing areas were used to define fisheries in OMs.

Fishery definitions were the same as in the 2017 stock assessment. Twenty-nine (29) fisheries were defined on the basis of gear, fishing area, season, and unit of catch (numbers or weight), and all catch and effort data were allocated to these fisheries (Table 3). The aim was to define relatively homogeneous fisheries with greater differences in selectivity and catchability between fisheries than temporal changes in these parameters within fisheries. This approach allowed the ALBWG to use differences in selectivity between fisheries as proxies for movement between fishing areas (Hurtado-Ferro et al. 2014, Waterhouse et al. 2014) since movement information is not available. These fisheries consisted primarily of 23 longline fisheries from Japan (F1 – F15), USA (F19 & F20), Chinese-Taipei (F21 & F22), Korea (F23), China (F24 & F25), and Vanuatu (F26) (Table 3). There were also three pole-and-line fisheries from Japan (F16 – F18), and the surface gears (primarily troll and pole-and-line) from Canada, Mexico, and the USA, which were combined into a single surface gear fishery (F27). In addition, drift net catches from Japan, Korea, and Chinese-Taipei were combined into a single fishery (F28), which was important in the past but less so during the modeling period; and catch from all other miscellaneous gears (e.g., purse-seine) from Japan and Chinese-Taipei were combined into a single miscellaneous fishery (F29). Estimates of total catch in each fishery were compiled by calendar quarter for

1993-2015. Catch was reported and compiled in original units consisting of weight or 1000s of fish (Table 3).

For the conditioning of the OM, the abundance index from the Japanese longline fishery in Area 2 and Quarter 1 (S1; 1996 - 2015) was used as the index of adult albacore abundance (Ochi et al. 2017), as in the 2017 stock assessment. This index is an appropriate index for adult albacore in the north Pacific because the majority of the adult albacore population in the north Pacific Ocean is thought be in the western Pacific, especially Area 2. In addition, the S1 index had good contrast and ASPM analysis run for the 2017 stock assessment showed that an ASPM was able to fit well to the index, which the ALBWG interpreted as an indication that the S1 index was informative on both population trend and scale. The OMs were also conditioned to a new CPUE-based juvenile index not yet ready for the 2017 assessment. It was made available by Dr. D. Ochi in February 2018 and was based on the Japanese longline fishery that operates in Areas 1 and 3 in quarter 1, targeting juvenile/sub adult albacore (S2; 1996 - 2015). Before inclusion in the OM, the consistency of the new index with the original assessment was evaluated by comparing the fit to the adult CPUE index and size composition data of a model with and without the new juvenile CPUE index. The fit to the adult index was actually slightly improved, showing an RMSE of 0.158 with the juvenile index and of 0.164 without. The fit to the size composition was only slightly degraded with the minimum likelihood increasing to 412.4 with the juvenile index from 408.9 without. This suggested that the new juvenile index was consistent with the adult one, and it was therefore used in the conditioning process. Standardized annual values and input coefficients of variation (CVs) for the S1 and S2 indices used for conditioning are shown in Table 4.

Quarterly length composition data from 1993 through 2015 were used in the conditioning process. Length data for 15 of the 29 fisheries in the base case model were compiled into 2-cm size bins, ranging from 26 to 142 cm fork length. The length frequency observations were the estimated catch-at-size (i.e., size compositions were raised to the catch) for the 15 fisheries with size composition data and these size composition data were fitted during the conditioning process. The majority of albacore length composition data were collected through port sampling or on-board sampling by vessel crews or observers. Length data for the Japanese longline (F1 – F4; F9 – F10; F13; & F15) and pole-and-line fisheries (F16 – F18) were measured to the nearest cm at the landing ports or onboard fishing vessels from which catch-at-size data were derived (Ijima et al. 2017). Fork lengths of albacore in the EPO surface fishery (F27) were compiled from port samples of the USA troll and pole-and-line fisheries (Teo 2017b). Although length composition data were available for the Canadian component of this fishery (2008-present), these data were not used because the USA and Canada components of the fishery overlap greatly in their fishing areas and size composition plots of both fisheries are very similar so the data from the USA component were thus considered representative of the entire fishery. Length compositions for the US longline fishery were collected by observers (Teo 2017c). Albacore lengths for the Taiwanese longline fishery (F21) were measured onboard fishing vessels and compiled for 1995 to 2015 by the Overseas Fisheries Development Council (OFDC) of Chinese-Taipei (Chen and Cheng 2017). Length composition data prior to 2003 were not considered representative of catches by this fishery because they were sampled from a restricted geographic area and a shorter annual period than the spatial and temporal scope at which the fishery was operating (ALBWG 2014). Thus, only the 2003-2015 length data were considered representative of the catch and used in the conditioning process.

Conditional age-at-length data were available from the growth studies of Chen et al. (2012) and Wells et al. (2013), for a total of 759 samples. All data for the Chen et al. (2012) study were sex-specific and sampled from the catches of Chinese-Taipei longline vessels (F21 and F22) operating in the Western and Central Pacific over 2001-2006 and Japanese pole-and-line vessels (F17) operating in the Western and Central Pacific over 2006-2008. Samples from the Wells et al. (2013) study were from Japanese longline vessels from 1997-2012 operating in the Western Pacific (F1), US longline vessels operating in the Central Pacific (F20) over 1990-2011, and the US surface fleet operating in the Eastern Pacific Ocean (F27) over 2007-2010. Only 26% of the Wells et al. data were sex-specific. Conditional age-at-length data were not fitted during the final conditioning of the OMs but were used during the estimation of the growth parameters.

4.1.1.2 Base Case Operating Model Structure

The base case OM structure was similar to the 2017 stock assessment model (SAM) for NPALB and uses the Stock Synthesis software version 3.24ab (Methot and Wetzel 2013). Differences consisted in the addition of a new S2 juvenile index (section 3.1.11), methods for estimation of growth parameters (section 3.1.1.2.1.2), autocorrelation in recruitment deviations (section 2.7), and time varying age selectivity for the EPO surface fleet (F27) (section2.7).

The following model structural features are common to both the 2017 NPALB SAM, the base case OM, and the alternative OMs:

- One area model
- 29 fisheries
- Spawning season is quarter 2
- Spawner-recruit relationship is Beverton-Holt
- Model start year is 1993
- Length composition data from the Japanese longline Area 2 fisheries, the Japanese longline area 4 fisheries, and the US longline fishery are down weighted by multiplying the likelihood of these data by 0.1.

Key parameters for the base case OM are outlined in Table 5.

4.1.1.2.1 Biological and Demographic Assumptions

Growth parameters are the only fixed life-history parameters that vary in the base case OM as compared to the 2017 stock assessment model (Table 5).

4.1.1.2.2 Maximum Age

The maximum age bin in the model was 15 years based on the maximum observed age (Wells et al. 2013). This bin served as the accumulator for all older ages. To avoid potential biases associated with the approximation of dynamics in the accumulator age, the maximum longevity was set at an age sufficient to result in near zero fish in this age bin (≈ 1 percent of an unfished cohort).

4.1.1.2.3 Growth

As with the 2017 stock assessment, growth in the base case OM follows the von Bertalanffy growth function and growth curves are sex-specific. However, the specific growth parameters differed between the base case OM and the 2017 assessment. The assessment fixed the growth parameters to values obtained by Xu et al. (2014). Xu et al. (2014) collated age at length data from the Chen at al. 2012 and Wells et al. 2013 studies, and growth parameter estimates were computed by assuming that each length observation was a random sample for a given age. However, given gear selectivity and fish movement, this may not have been the case. Hence, for the OM, growth parameters were first estimated within the stock assessment model by fitting to age-length data in addition to length composition data from the catch. Note that while the model estimates growth parameters for females, the model estimates exponential offset parameters for males. For instance, the asymptotic length, L_{inf}, for males is calculated as: female L_{inf}*exp(L_{inf} offset parameter). During estimation of the growth parameters, a range of different likelihood weights for the age-length data were tested, and a 0.6 weight was chosen as the best trade-off between a good fit to the CPUE index, as compared to the SAM, and information from the age-length data.

However, fitting to age-at length data not only informs growth parameter estimates but also stock status estimates. Therefore, during the final conditioning of the base case OM, the growth parameters were fixed at those estimated when fitting to the age at length data, and the model was not fit to the age at length data. To summarize, growth parameters were estimated following these steps:

1. Estimate growth data given the age at length data with a weight of 0.6

2. Run the OM model with no age at length data and with the growth parameters fixed at what was estimated in step 1.

4.1.1.2.4 Weight at length

Non sex-specific weight-length relationships are used to convert catch-at-length to weight-at-length data. A previous study (Watanabe et al. 2006) reported that there were seasonal differences in the relationship between weight (kg) and fork length (cm) of north Pacific albacore. As in the 2017 stock assessment, these non sex-specific seasonal weight-at-length relationships were used in the OMs.

4.1.1.2.5 Natural Mortality

Following the 2017 stock assessment and best-available biological knowledge for this stock, the OMs have an age-specific natural mortality (M) for ages 0 to 2, and a sex-specific, constant M for ages 3+. The base case OM set M to the median of the M distribution derived from the meta-analyses of empirical relationships between adult M and life history parameters described in Teo (2017a) and Kinney and Teo (2016), as was done for the 2017 stock assessment. See Table 5 for actual natural mortality values.

4.1.1.2.6 Sex specificity

A sex-specific (two sex) model was used for the OMs because of known differences in growth of female and male albacore (Chen et al. 2012, Xu et al. 2014) and natural mortality (Kinney and Teo 2016, Teo 2017a). In addition, males predominate in longline catches of large, mature albacore sampled scientifically, while juveniles <85 cm generally have a sex ratio of 1:1 (Ashida et al. 2016). However, there are currently no data on the sex of individual fish caught by commercial fisheries. As described above, sex-specific growth curves and natural mortality were used in the base case model. However, the OMs did not include sex-specific selectivity, and sex ratio at birth was assumed to be 1:1.

4.1.1.2.7 Recruitment and reproduction

As in the 2017 stock assessments, spawning and recruitment was assumed in all OMs to occur in the second quarter of the year (Q2) based on recent histological assessments of gonadal status and maturity from the western Pacific Ocean (Chen et al. 2010, Ashida et al. 2016). Although historical circumstantial evidence supported spawning in the central Pacific Ocean near Hawaii through the third quarter of the year (e.g., Otsu and Uchida 1959), there is no recent confirmation of this spawning segment, and so the ALBWG did not consider spawning season as a high priority uncertainty to be tested at this stage. Ashida et al. (2016) also recently estimated the length at 50% maturity for female north Pacific albacore at 86 cm, which was approximately the expected length at age-5. Based on this finding, the ALBWG assumed that 50% of the albacore at age-5 were mature and that all fish age-6+ were mature. This maturity ogive has been used in NPALB assessments since 2006.

A standard Beverton-Holt stock recruitment relationship was used in the OMs. The expected annual recruitment was a function of spawning biomass with steepness (h), virgin recruitment (R_0), and unfished equilibrium spawning biomass (SSB_0) corresponding to R_0, and was assumed to follow a lognormal distribution with standard deviation σ_R (Methot 2000, Methot and Wetzel 2013). Annual recruitment deviations were estimated based on the information available in the data and the central tendency that penalizes the log (recruitment) deviations. A log-bias adjustment factor was used to assure that the estimated log-normally distributed recruitments were mean unbiased (Methot and Taylor 2011).

Recruitment variability (σ_R) was fixed to approximate the expected variability of 0.5. The log of R_0, $\ln(R_0)$, annual recruitment deviates, and the offset for the initial recruitment relative to virgin recruitment, R_1, were estimated during the conditioning phase. During the forward simulation $\ln(R_0)$ and R_1 in the OMs were fixed to the values estimated during the conditioning process, while future recruitment deviates (d) were sampled from a normal distribution with mean 0 and standard deviation of σ_R and an autocorrelation, ρ_R, of 0.42 (Section 3.7) according to:

$d_y = \rho_R * d_{y-1} + \text{sqrt}(1- \rho_R^2) * \varepsilon_y$, where $\varepsilon_y = N(0, \sigma R^2)$

Steepness of the stock-recruitment relationship (h) was defined as the fraction of recruitment from a virgin population (R_0), when the spawning stock biomass is 20% of its unfished level (SSB_0). For the base case OM, the ALBWG assumed a steepness value of 0.9, which is intermediate between the range of values reported by two independent estimates of steepness for north Pacific albacore (Brodziak et al. 2011, Iwata et al. 2011), based on the life history approach of Mangel et al. (2010).

4.1.1.3 Initial conditions

The operating model must assume something about the period prior to the start of the conditioning period. Initial conditions were estimated (where possible) assuming equilibrium catch. The equilibrium catch is the catch taken from a fish stock when it is in equilibrium with fishery removals and natural mortality balanced by stable recruitment and growth. The initial fishing mortality rates in the operating model that remove these equilibrium catches were estimated to allow the model to start at an appropriate depletion level. Initial fishing mortality rates were estimated for the F21 (Taiwanese longline in Areas 3 & 5) because it captures a wide size range of albacore, but the initial fishing mortality rates were not fitted to historical catches prior to 1993. This approach allowed the model to start in 1993 at a depletion level that was consistent with the adult abundance index and size composition data without being overly constrained. In addition, the model included estimation of 10 recruitment deviations prior to 1993 to develop a non-equilibrium age structure at the start of the model time frame.

4.1.1.3.1 Fishery Dynamics

4.1.1.3.1.1 Selectivity

Selectivity curves were fishery-specific and assumed to be a function of only size for all but three fisheries. Preliminary model runs for the 2017 stock assessment indicated that size composition data of the Japanese pole-and-line fisheries in Area 3 (F16 and F17) and the EPO surface fishery (F27) had very strong modes corresponding to juvenile age classes and could not be adequately fit using only size selectivity curves. Therefore, the selectivity curves of F16, F17, and F27 were assumed to be a product of size and age. The age-based selectivity was applied to surface fisheries operating north of 30°N and is intended to capture differences in the availability of juvenile fish to the fishing gear based on movement patterns which may vary between seasons and years.

Selectivity curves were estimated for all fisheries with representative size composition data while selectivity curves for fisheries without representative size composition data were assumed to be the same as fisheries with similar operating characteristics (season, area, gear) and estimated selectivity curves. If specific fisheries had changes in fishery operations or exhibited changes in size composition data consistent with changes in movement patterns, then selectivity was allowed to vary with time to account for these changes. Highlights of the parameterization of the selectivity curves are briefly described below but more details can be found in Table 6.

Like in the 2017 stock assessment, selectivity curves for longline fisheries and the Japanese pole-and-line fishery in Area 2 (F18) were assumed to be dome-shaped and were modeled using either double-normal functions (F2, F4, F9, F10, F15, F18, F19, F20, and F21) or spline functions (F1, F3, and F13) (Table 6). The double-normal selectivity functions were configured to use four parameters: 1) peak, which is the initial length at which albacore were fully selected; 2) width of the plateau at the top; 3) width of the ascending limb of the curve; and 4) width of the descending limb of the curve. If the estimated width of the plateau at the top was negligible and tended to hit the lower bounds, then that parameter was fixed at a small value. The spline selectivity functions were configured to be three knot splines. The first and third knots were generally located near the edges of the respective size compositions, while the second knot was typically located near the midpoint between the first and third knot. The values of two of the three knots were estimated relative to the value of the third knot, which was fixed at an arbitrary value. The gradients before the first knot and after the third knot were also estimated.

Selectivity curves of the Japanese pole-and-line fisheries in Area 3 (F16 and F17) and the EPO surface fishery (F27) were assumed to be a product of size and age because the 2017 stock assessment found that their size composition data exhibited very strong modes corresponding to juvenile age classes. Indeed, in the 2017 stock assessment, the interactions between the age and size selectivity resulted in substantially improved fits to their size composition data. The size selectivity curves for these fisheries were assumed to be dome-shaped and were modeled using double normal functions, which were configured as described above. The age selectivity of the juvenile age-classes (age-1 through age-5) of these three fisheries were estimated as free parameters. Albacore movement and, in particular, juvenile migration rates to the eastern Pacific Ocean (EPO) vary between years. To represent uncertainties in juvenile migration rates over time and variability in the availability to the EPO fishery between years, the OMs have a time varying selectivity for the EPO surface fleet, which targets juveniles. The age-selectivity of the EPO fleet was made time varying in the OM using additive random walk deviations for ages 1-4 (Table 5).

The selectivity curves for fisheries lacking representative size composition data (F5, F6, F7, F8, F11, F12, F14, F22, F23, F24, F25, F26, F28, and F29) were assumed to be the same as (i.e., mirrored to) closely related fisheries or fisheries operating in the same area (Table 6). For example, the selectivity of F5 was assumed to be the same as F1 because F5 was identical to F1 except for their catch units.

Selectivity curves for relative abundance indices were assumed to be the same as the fishery from which each respective index was derived. Size selectivity for the S1 index was assumed to be the same as the F9 longline fishery. Selectivity for the juvenile S2 index was similarly assumed to be the same as the F1 longline fishery.

4.1.1.3.1.2 Catchability

Catchability, q, was assumed to be constant over time for each index. It was estimated (solved analytically) during the conditioning process, assuming the abundance index was proportional to vulnerable biomass with a scaling factor of q. It was then kept constant at the value estimated during conditioning for the forward simulation.

4.1.1.3.1.3 Data Observation Models

During conditioning, the OMs fitted three data components: 1) total catch, 2) relative abundance indices, and 3) size composition data. The observed total catches were assumed to be unbiased and relatively precise and were fitted assuming a lognormal error distribution with standard error (SE) of 0.05. An unacceptably poor fit to catch occurred if a model removed <99% of the observed total catch from any fishery.

The relative abundance indices were assumed to have lognormally distributed errors with SE in log space, which is approximately equivalent to CV (SE/estimate) in natural space. The estimated CVs of each index are in Table 5. However, the reported CVs for the abundance indices only capture observation errors within the standardization model and do not reflect process errors that are inherent in the link between the unobserved vulnerable population and observed abundance indices. Similar to the stock assessment, the ALBWG initially assumed during conditioning process that the minimum average CV for any index was 0.2 and indices with average CV <0.2 were scaled to CV=0.2 by adding a constant while indices with CV >0.2 were left unmodified. Therefore, a constant of 0.101854 was added to the CVs of the S1 index in the base case model, and 0.075 to the CV of the juvenile S2 index.

The size composition data were assumed to have multinomial error distributions with the error variance determined by the effective sample size (*effN*).

4.1.1.3.1.4 Data Weighting

Statistical stock assessment models used as OMs fit a variety of data components, including abundance indices and size composition data. The results of these models can depend substantially on the relative weighting between different data components (Francis 2011). In the OMs, different components were weighted in the same way as the 2017 stock assessment.

Relative abundance indices were prioritized on the principle that relative abundance indices should be fitted well and that other data components such as size composition data should not induce poor fits to the abundance indices because abundance indices are a direct measure of population trends and scale (Francis 2011). Preliminary models for the 2017 stock assessment indicated that the size composition data from several of the longline fisheries (F9, F10, F13, F19 and F20) degraded the fit of the S1 abundance index. The weightings to the size composition data from these five fisheries were down-weighted by multiplying the likelihoods of these data by 0.1 (i.e., lambda = 0.1).

4.1.1.4 Model Structure of alternative Operating Models

Alternative OM structures were developed to consider uncertainties in natural mortality, steepness, and growth (Section 2.7). As the base case OM, alternative OMs have autocorrelated recruitment deviations and time varying age selectivity for the EPO fishery. The only differences in model structure from the base case OM are in the values of natural mortality, steepness, and growth. We provide below a description of how these alternative parameter values were selected.

4.1.1.4.1 Natural Mortality

Similar to the base case, the alternative OMs have an age-specific natural mortality (M) for ages 0 to 2, and a sex-specific, constant M for ages 3+. The SAM and base case OM set M to the median of the M distribution derived from the meta-analyses of empirical relationships between adult M and life history parameters described in Teo (2017a) and Kinney and Teo (2016). To capture the uncertainty in M, the 25^{th} percentile and 75^{th} percentile of that same distribution were taken as alternative values of age 3+ M: 0.29 and 0.53 for males, and 0.36 to 0.66 for females. Following Teo (2017a) and Kinney and Teo (2016), the 25^{th} and 75^{th} percentiles for M for ages 0 to 2 were calculated by assuming M for younger ages to be size dependent and using the

Lorenzen method to calculate age-specifc M for ages 0 to 2 from the 25th or 75th percentiles of the male age 3+ M distribution.

4.1.1.4.2 Recruitment Steepness

The base case uses a steepness of 0.90. Alternative values of steepness were derived from Brodziak et al. (2011), which used Mangel's simulation method (Mangel et al. 2010) to estimate probable values of steepness given information on growth, maturity, weight at age, natural mortality, and reproductive ecology. Alternative values of steepness that were considered were the 5th percentile of the lowest Brodziak et al. (2011) estimate of mean steepness, 0.70, and the 95th of the highest estimate, 0.97.

4.1.1.4.3 Growth

The combination of three different steepness values and three different sets of M parameters, produces nine potential OMs, including the base case model. Similar to the base case, growth parameters for each of these alternative OMs were estimated using age at length data.

The asymptotic length, L_{inf}, was considered the most uncertain growth parameter by the ALBWG. Therefore, to consider uncertainty in growth, 18 additional OMs were developed that used the 5th or 95th percentiles of the female L_{inf} parameter estimated for each of the nine potential OMs. In these additional 18 OMs, the other growth parameters were estimated while keeping the female L_{inf} parameter fixed at the 5th or 95th percentiles values. The modelling workflow to estimate the growth parameters of the alternative OMs is outlined in more detail below:

1. Estimate growth data given the age at length data with a weight of 0.6 for each steepness and mortality combination

2. Run the model with no age at length data and with the growth parameters fixed a t what was estimated in step 1. These are the g1 values used in the base case.

3. Compute the 5th or 95th percentile of the female L_{inf} given the standard deviation of the L_{inf} parameter estimated in step 1

4. Run the model again with the female L_{inf} fixed at the value in step 3 to estimate the other growth parameters using the age at length data

5. Run the model with no age at length data and with the growth parameters fixed at what was estimated in step 4. These are the g2 (5th percentile) or g3 (95th percentile) cases.

4.1.1.5 Results of Conditioning Process and Final Set of Operating Models

27 OMs were conditioned on observations from 1993-2015 by fitting the simulated historical data to observed catch, CPUE, and length composition data using maximum likelihood. Nine out of the 27 OMs failed to converge and were therefore not considered further. Others produced

unrealistic spawning biomass (SSB) estimates and were also excluded from the final set of OMs. Finally, given the long run times and time constraints on MSE development, the ALBWG decided in May 2018 to refine the set of OMs further by discarding OMs that produced similar trends in spawning potential ratio (SPR), SSB, and depletion, leaving a final set of 4 reference set OMs, referred to as uncertainty scenarios 1 (Base case), 3 (OM3), 4 (OM4), and 6 (OM6) (Fig. 1, Table ES3, Table 7) that was used in this latest round of simulations. These final scenarios do not include the full set of growth, natural mortality, and steepness combinations but do reflect a range of uncertainty in stock productivity. To assess HCR performance across a broad range of uncertainties, results (Section 4) are presented across the four reference scenarios. However, to highlight differences in performance of the HCRs results are also highlighted separately for the low productivity scenario (OM6), which had more instances of SSB breaching the reference points. Results from the robustness fishing effort scenario (Section 5.8) are also examined separately.

4.2 "Future" Process

Once the "conditioning" process was completed, the OMs were projected forward in time in a closed loop simulation with feedback between the population dynamics and management actions. For HCR, each of the four OMs was projected forward in time from 2016 to 2045, a period of 30 years, which corresponds to 2 lifespans of NPALB, for 70 different iterations to account for process uncertainty in recruitment and the EPO fleet age selectivity (Section 3.7).

An MSE aims to simulate a realistic management process, which includes data collection, an estimation of stock status given the observed data using a stock assessment, and a management decision given the stock status estimate. At each time step of the 30-year simulation, the operating model (OM) simulated the "true" population dynamics of the NPALB and the fisheries operating on it given the catch or effort set by a candidate HCR. Catch, CPUE, and size composition data with error are sampled from the OM every three years (based on the current 3-year stock assessment frequency, Section 4.2.1) and input into a simulated stock assessment model (i.e., the estimation model or EM, Section 4.2.2) (Fig. ES4). As in the real world, the stock assessment model estimates the current population levels and fishing intensity as well as reference points. Estimates of stock status and reference points are then supplied to a management module, which is comprised of a HCR with specific reference points (Table ES2). Fleet-specific catches derived from a total allowable catch (TAC) or total allowable effort (TAE) are set in the management module (Section 4.2.3) and input into the OM with some implementation error (Section 4.2.4) for simulation of population dynamics in the next time step. We describe below in more detail, components of the forward closed loop simulation.

4.2.1 Data Generation

Catch, CPUE, and size composition data are generated using the Stock Synthesis data generation routine (Methot and Wetzel 2013). First, the new catch data given the TAC or TAE is added to the operating model data files and dummy data is put in for the two CPUE indices and the size composition data. The data generation routine then creates a new data set of random observations using the same variance properties (standard error of fleet specific catch, standard error of the

CPUE indices, and effective sample size of the size composition data), error structure (lognormal for catch and CPUE, multinomial for the size composition data) assumed during the conditioning phase and the expected value for each datum. The new data with observation error is then inputted into the EM, while data without error is added to the OM data file. Figures 6, 7, and 8 show examples of CPUE time series and size composition data generated for a model run.

4.2.2 Estimation Model and Simulated Assessment Error

The estimation model has the same model structure of the 2017 stock assessment model; it does not assume recruitment deviations are autocorrelated and does not employ time varying age selectivity for the EPO fishery. However, as the base case OM, it employs the new juvenile abundance index and the growth parameters are the same as the base case OM. Estimates of terminal year female SSB (SSB_{latest}) and reference points are produced by the EM and input into the HCR being evaluated to set a TAC or TAE (Section 4.2.3). The biomass based $SSB_{threshold}$ and LRP reference points are based on dynamic unfished SSB (SSB0_d), while the TRP is based on fishing intensity defined as 1-SPR.

Integration of the complete stock assessment model into the MSE framework allows the MSE to test a harvest strategy that closely mimics the management system that is currently in place, which relies on stock assessment output. It also enables for an estimation of the full assessment error given errors in the input data, potential misspecification in the assessment model, and complex feedback between the state of the stock and the assessment error (Wiedenmann et al. 2015). However, as the stock assessment has to estimate 80+ parameters at each assessment time step, including the full assessment significantly increases the run times of the MSE simulation.

Table 8 shows the median and standard deviation of the relative error between the OM and EM estimates of the quantities informing the HCR across all the runs for TAC control. Relative error was computed as:

$(Value_{OM}\text{-}Value_{EM})/Value_{OM}$

The relative error was computed on the log-transformed values for SSB_{latest} and SSB0_d. A negative value implies that the EM is overestimating the quantity of interest. The median relative error is a reflection of the bias in the errors, while the standard deviation reflects the error variability. We examine assessment error for each of the reference scenarios and between HCRs.

For all scenarios, errors in SSB0_d and TRP were the most precise and least biased (Table 8). Given the SSB_{latest} log-transformation, F, for all scenarios, consistently had the largest and most variable relative error. Scenario 1 had a relative mean error for all management inputs that was less than 10%, the lowest of all scenarios. There was no bias in TRP or SSB0_d. Errors in SSB_{latest}, SSB0_d, and the TRP were consistent across HCRs, while errors in F were the most variable with the EM estimating a 2-6% lower terminal F than the OM on average depending on the HCR (Table 8). SSB_{latest} was overestimated by 1% on the log-scale. By contrast, scenario 3 underestimated SSB_{latest} by 1% and overestimated F by 9-13% (Table 8). There was no bias in SSB0_d, but the TRP was underestimated by 6%. Like scenario 1, scenario 4 overestimated SSB_{latest}, which was 4% higher than the OM. Under scenario 4, the EM underestimated F by 12-

19%. Both SSB0_d and the TRP were overestimated, by 1 and 5% respectively. Scenario 6 had the largest relative errors, with F being underestimated by 22-31% depending on the HCR. SSB_{latest} and the TRP were overestimated by 5%, while SSB0_d was underestimated by 2% (Table 8).

Assessment error varied by scenario, but in some cases also by HCR. Clearly there were feedbacks between the HCRs, status of the stock, data quality, and the assessment error of various quantities important to management, suggesting integration of the full stock assessment in the MSE to account for this pattern and ensure candidate HCRs would be robust to assessment error was necessary.

4.2.3 Management Module

The management module consists of the HCR, which defines the management action to be taken given current SSB conditions (SSB_{latest}) as estimated by the EM relative to the reference points $SSB_{threshold}$ and the LRP. Reference points are also estimated by the EM. The management module algorithm follows the following steps:

1. The TRP, based on F (1-SPR), is determined by the HCR.
2. For scenarios 1 and 3, which estimate historical Fs lower than the TRP, a $F_{historical}$ is sampled at random from the time series of historical Fs.
3. The Stock Synthesis benchmark calculations is used to find the exploitation rate (H_{target}, biomass at the beginning of the year/total catch per year) that would produce F_{target}.and $F_{historical}$, these are H_{target} and $H_{historical}$
4. Assess if SSB_{latest} is above $SSB_{threshold}$ with a probability of 0.50 by comparing SSB current to the mean estimate of $SSB_{threshold.}$ Both are input from the EM.
5. If SSB is greater than $SSB_{threshold}$ F is set to $F_{historical}$ (scenarios 1 and 3) or F_{target} (scenarios 4 and 6), and H to $H_{historical}$ (scenarios 1 and 3) or H_{target} (scenarios 4 and 6).
6. If SSB is less than $SSB_{threshold}$ but higher than the LRP with a probability of >0.8 (for 20%SSB0_d) or >0.9 (14%SSB0_d, 7.7%SSB0_d), where probabilities are calculated with the projection software (Section 4.2.4), the F and H are reduced relative to F_{target} and H_{target} according to equations in Table 2.
7. If SSB is less than the LRP the F_{min} and H_{min} are calculated from the reference points according to Table 2.
8. Under TAC control, the TAC is calculated from multiplying the exploitation rate H with the total biomass estimated from the EM.
9. The TAC is split across fleets using the allocation (mean 1999-2015 catch ratios) agreed upon by managers and stakeholders during the 3rd MSE workshop. The fleet specific TAC is kept constant for three years until the next simulated assessment.
10. Under TAE control, the exploitation rate H is split among the fleets using the pre-agreed upon allocation (mean 1999-2015 catch ratios). Catch is derived from multiplying the exploitation rate H with the total biomass estimated from the OM. The fleet specific TAE is kept constant for three years until the next simulated assessment.
11. Under mixed control, the fleet-specific TAC of longline fleets is kept constant for three years, while for the surface fleets, the H remains constant between assessment periods. Therefore, unlike for the longline fleets, the catch of the surface fleets varies between years depending on the biomass from the OM.

To exemplify how the MSE management module works, we contrast two runs for HCR7 under mixed control in Fig. 9 and Fig. 10. HCR7 is characterized by a TRP of F40, a $SSB_{threshold}$ of 20%SSB0_d and a LRP of 7.7%SSB0_d. The two runs share the same iteration (#60), so they experience the same recruitment variability (Fig. 11). However, they are taken from two different potential ‘states of nature’. Fig. 9 shows trends in indicators of interest for the 30-year MSE simulation under scenario 1 (base case), while Fig. 10 shows the same under scenario 4, a less productive albacore population. Trends in both the ‘true’ SSB from the OM and the ‘estimated’ SSB from the EM (i.e., what a manager would see as estimated by the simulated assessment) are shown. As explained above (Section 4.2.2), the ‘estimated’ SSB from the EM may be quite different from the ‘true’ SSB due to assessment error, especially when the assumed productivity parameters in the assessment are incorrect (Fig. 9 & 10). The exploitation rate and fishing intensity shown are also from the EM. The fishing intensity and ratio of SSB to dynamic unfished SSB from each run are plotted over the HCR to exemplify any management actions taken (Fig. 9 and 10).

Under scenario 1, SSB remains above the reference points (Fig. 9) despite the large drop in recruitment (Fig. 11) and hence no management action was required (all dots on the bottom right panel of Fig. 9 are above $SSB_{threshold}$). Hence, during every assessment time step, the F was sampled at random from historical fishing intensities and translated into an exploitation rate. Since average $F_{historical}$ is 0.51, lower than the 0.60 fishing intensity set by the F40 target, fishing intensity remains below the F40 target (Fig. 9). Stock assessment error was small for scenario 1 and thus trends in estimated SSB closely match those from the OM (Fig. 9, top panels).

Under scenario 4, the population is less productive and starts off at a lower biomass (compare top-left panel in Fig. 9 and Fig. 10). However, note that because of assessment error, the SSB is overestimated by the EM and managers assume that the population is in a better condition than the ‘true’ population from the OM (Fig. 10). Nevertheless, following the decline in recruitment, SSB from the EM is also estimated to fall below $SSB_{threshold}$ and a management action is triggered resulting in a decline in exploitation rate, catch, and fishing intensity. SSB recovers quickly following management intervention. Also note that SSB does not decline as early as catches. This is because catch of the surface fleets, which target juvenile albacore, respond first to drops in recruitment than SSB, which only includes biomass of mature fish (age 5+). Finally, under scenario 4, $F_{historical}$ averages at 0.63, which is higher than the 0.60 fishing intensity associated with the F40 scenario, so when SSB is greater than $SSB_{threshold}$, F is set at F_{target}, rather than $F_{historical}$ and fishing intensity fluctuates around F40 (Fig. 10) rather than $F_{historical}$ as under scenario 1 (Fig. 9).

4.2.4 Calculation of probabilities of SSB being above the limit reference point

The updated MSE framework used in this latest round of analyses integrates the NPALB projection software (Ijima et al. 2016) within the MSE framework to calculate the probability of SSB being greater than the LRP. In the first round of MSE, this probability was assessed using the asymptotic uncertainty estimate of terminal year SSB. However, since the projection software is used in NPALB assessments to provide conservation information, at the 4^{th} NPALB

MSE workshop managers and stakeholders recommended the use of the NPALB projection software (ISC 2019).

The projection software projects the simulation forward in time over a 10 year period after the terminal year of assessment under random recruitment variability and a constant fishing mortality corresponding to the average fishing mortality over the three years prior to the terminal year of the assessment. For an assessment ending in 2015, the constant F used in the projection would be the average fishing mortality from 2012 to 2014. The projection uses terminal year biology and selectivities. The version of the projection software used in the MSE is that used in the 2017 NPALB stock assessment (Ijima et al. 2016).

In the MSE framework, at each assessment time step, the algorithm runs the projection software as part of the management module immediately after the estimation model (i.e, the simulated assessment model) to calculate the probability of SSB being greater than the LRP. The projection software first generates 500 potential initial populations by multiplying the estimated proportions at age and sex from the EM with a range of 500 potential total biomass sampled from the estimated distribution of total biomass from the EM. This accounts for uncertainty in initial population size in the projection. Each of these 500 initial populations are subsequently projected forward in time 1000 different times under different random recruitment deviations. Thus, the projection also takes into consideration uncertainty in future recruitment. A total of 500x1000 = 500,000 projections are therefore run at each assessment time step within the MSE framework.

The projection software was updated for the 2020 NPALB assessment and is expected to evolve over time. Therefore, it was of interest to assess if the results of the MSE are robust to the changes in projection software as well as projection method (asymptotic uncertainty estimate vs. projection software). To do so, we took an example HCR and scenario combination and, for a total of 550 events (55 iterations and 10 assessment times in each simulation), the probability of SSB being greater than the LRP was calculated using: 1) the asymptotic uncertainty estimate of terminal year SSB from the EM as in the first round of MSE, 2) the projection software used with the 2017 assessment as is currently done in the MSE, and 3) the projection software used with the 2020 assessment. For the latter method, the 2020 version of the projection software had to be modified to read in SS3.24 input files rather than the SS3.30 files it was developed for. The 2020 projection software version, unlike the 2017 version, calculates uncertainty in initial numbers at age not from the uncertainty in the terminal year total biomass estimate, but using a multivariate normal distribution consistent with the estimated terminal year N-at-age and its variance-covariance matrix (Ijima et al. 2020). Therefore, for each of these 550 EM had to be re-run with a new SS control file that specified that variance estimates for numbers at age needed to be generated.

Output showed that the MSE results were relatively robust to using either version of the projection software or the asymptotic uncertainty estimates from the EM. The 2017 and 2020 projection software detected a similar number of events when SSB was lower than the LRP with a 10% probability, 32 and 36, respectively. All the 17 events when SSB was less than the LRP with 10% probability detected by the asymptotic uncertainty method were also detected by the projection methods. The projection methods likely detected additional events when the LRP was breached compared to asymptotic uncertainty method because the projection software considers uncertainty in both initial abundance and recruitment. The asymptotic uncertainty method only considers uncertainty in terminal SSB. It is also important to stress that output from the projection and asymptotic uncertainty method assess different metrics, and would therefore be expected to differ somewhat. The first assesses future stock status (i.e., probability of future SSB being above the LRP) given current fishing intensity, while the latter assesses current stock status (i.e., probability of current SSB being above the LRP).

4.2.5 Implementation Error

Before the catch determined by the HCR is introduced into the OM, each fishery-specific catch is modified by a bidirectional implementation error. The catch set by the HCR is multiplied by a random implementation error ranging from 5% to 20% and set to $1.05 + N(0, \sigma = 0.05)$.
The implementation error accounts for errors in reporting, problems with compliance, errors in management (e.g., deviation of actual management regulation from HCR recommendation), or unforeseen changes in fisher behavior. Errors and uncertainties in translating the model-based effort metric to real-world effort metrics (Section 4.2.6), such as number of fishing days, would also be accounted for in the implementation error.

4.2.6 Relationship between real-world effort measures and simulated effort for the surface fleets

TAE in the MSE simulation was modeled as the exploitation rate (H) for the overall NPALB fleet derived from the SPR-based fishing intensity (F) specified by each HCR. Under mixed control, TAE for the surface fleets (EPO troll and pole-and-line and Japanese pole-and-line) was derived from this overall TAE using the agreed-upon allocation based on average historical (1999-2015) catch ratios. In the real-world TAE would be enforced by regulating the number of vessels or number of fishing days specific to each country and gear-type. Realism of the effectiveness of the simulated effort control relies on an ability to scale a specified decline in TAE to a decline in effort in terms, for instance, of fishing days. To aid managers and stakeholders in interpreting results of the mixed control simulations, we derive a statistical relationship between annual exploitation rate over the OM conditioning period (1993-2015) and annual effort in number of fishing days for the surface fleets. This analysis serves a dual purpose. It is used to 1) determine the error associated with translating TAE to an actual effort measure that would be regulated to assess if the implementation error in the MSE is adequate to account for this uncertainty, and 2) showcase a potential method for translating the model-based TAE to real-world effort. We note, however, that this methodology could be refined further outside the MSE process in collaboration with managers.

According to the Cobb-Douglas equation $C=aE^bB^c$ where C is catch, E is effort, and B is biomass. If we assume that b and c are equal to 1 and set the exploitation rate $H=C/B$, $H=aE$ or $E=1/aH$. This relationship can be linearized to $\log E=\log 1/a+\log H$. For the EPO fleet, a linear model of annually averaged log-transformed effort with log-transformed H from 1993-2015 was developed. As in the MSE management module, H was calculated as the overall H (total catch per year/total biomass at the beginning of the year) multiplied by the EPO catch ratio. As this was an historical analysis, instead of using the agreed-upon allocation as the catch ratio, the year-specific observed catch ratio was used. Changes in H were able to account for some of the variability in effort, and the model had an R^2 of 0.52. However, model residuals were not homogenous and decreased with fitted values (Fig. 12). Therefore, a second generalized linear model was developed (Fig. 13) that allowed for a decrease in residual spread with log-transformed H by setting $var(\varepsilon_i)=\sigma^2 e^{2\delta logH_i}$ where i is year. Spread of standardized residuals was less heterogeneous and AIC decreased from 39.7 to 9.8. Error around the fit averaged 12% of fitted values and ranged from 10 to 29%. The 29% error was associated with the lowest fitted value. In Figure 14, we exemplify how this method could be used to relate the exploitation rate from the estimation model to a measure of real-world effort data for the EPO fleet using the same HCR.

The same model was fit to the JPPL annual effort and H over 1993-2015. However, for the JPPL fleet, which switches targets between skipjack and albacore tuna, overall effort was scaled by the proportion of albacore in the catch (ratio of albacore to skipjack and albacore catches) prior to analysis to generate a measure of ‘albacore’ only effort. The JPPL model had an R^2 of 0.76 and showed no pattern in residuals against the fitted values (Fig. 15 and Fig. 16). Standard errors around the fitted value ranged from 5 to 13% with a mean of 7%.
This analysis demonstrates that effort scales with exploitation rate for the surface fleets and suggests that an implementation error between 5 and 20% is a reasonable approximation. Implementation error for the EPO fleet might be higher (~30%) at very low TAE values (< 0.015, Fig. 13), but those were rarely simulated, accounting for only 5% of all the simulated H for the EPO. It also should be noted that while error for the JPPL fleet was relatively small, the actual precision of TAE control for the JPPL fleet would depend on the variability of target switching and the ability of managers to determine the proportion of albacore in the catch.

5 Results

Results were voluminous, and some synopsis was required to convey the important findings clearly. Results for each performance metric were summarized across the 70 iterations and the four reference scenarios under mixed and TAC control. Results for the low productivity scenario, OM6, are also highlighted here to further underscore differences in performance among HCRs. However, results for all performance metrics by scenario can be found in the Appendix Tables. Tommasi and Teo (2020) assessed the relationship between the fishing mortality for each fleet and effort as the number of hooks (longline fleets) or number of fishing days (surface fleet). The analysis found no strong correlation between fishing mortality and effort for most of the longline fleets. Thus, MSE runs where all fleets are under TAE control would show overly optimistic results as the MSE assumes that fishing mortality can be effectively managed by changes in effort. This assumption does not appear realistic for most of the longline fleets, likely as albacore is not their main target species. In light of these results, results for TAE control are not highlighted here, but can be found in the Appendix Tables. Note that the EM did not converge for some iterations, and the simulation could not be completed for those iterations (Table 9). In those cases, to ensure HCRs were compared across the same recruitment patterns, performance was assessed over the same set of converged iterations.

The changes to the MSE framework recommended by the 4th ISC NPALB MSE workshop and carried out for this last round of simulations to simulate a more realistic fishery, namely ensuring that fishing intensity is not set over historical levels achieved by the NPALB fisheries and TAE control for the surface fleets, resulted in reduced contrast between HCRs as compared to results from the first round of MSE. This is because, for all HCRs irrespective of their TRP, fishing intensity was set equal to $F_{historical}$ for scenarios 1 and 3 when SSB was greater than $SSB_{threshold}$, which was the most common state for all runs. Also, mixed control maintains a higher biomass than TAC control as catch of the surface fleets responds quickly to changes in available biomass and is not impacted by assessment errors in biomass and this further reduces the need for management intervention.

Also note that all the performance metrics are based on output of the OM. While the EM is used in the simulation to inform management action, performance is based on the effects of such management on the "true" population and fisheries simulated in the OM. Results for each performance metric separately are highlighted first. Then, tradeoffs across performance metrics and HCRs are illustrated.

5.1 Management Objective 1

Performance of the different HCRs with respect to management objective 1, *maintain spawning biomass above the limit reference point* (Table ES1), was measured using four performance metrics. All these metrics are based on the ratio of SSB for each projected year over a LRP and compute the probability that SSB in any given year of the MSE forward simulation is above the specified LRP. The LRP used in the comparison differs with each performance metric. PM1a, *the odds of not breaching the LRP*, uses the LRP specific to the HCR under consideration and thus its LRP varies by HCR according to Table ES2. PM1a is a measure of the probability of drastic management intervention. By contrast, all other metrics use a LRP that remains consistent across HCRs notwithstanding the actual LRP associated with each specific rule. PM1b is defined as the probability that SSB in any given year of the MSE forward simulation is above the LRP adopted by the WCPFC, 20%SSB0_d. PM1c compares SSB to IATTC's LRP used for tropical tunas, 7.7% of equilibrium unfished SSB (7.7%SSB0), while PM1d uses 7.7% of dynamic SSB0 (7.7%SSB0_d). For PM1a, changes in performance between HCRs are dependent on both the value of SSB as well as the LRP, but for the other measures variability across HCRs is largely dependent on changes in SSB. We first provide an overview of changes in SSB across HCRs and management control types and then compare changes in the performance metrics themselves.

When looking at the individual trajectories in SSB across the 30-year simulation (i.e., individual lines in Fig. 17), we see a lot of variability in SSB over time between trajectories due to recruitment variability, and between different reference scenarios due to different assumptions about the productivity of the population and associated initial conditions. Under mixed control, only a few lines, largely associated with the low productivity scenario, fall below the 20%SSB0_d LRP (Fig. 17). HCRs with the higher TRP fishing intensity of F40 (HCR6 to HCR8 and HCR14 to HCR16) have relatively more lines below this threshold (Fig. 17). Indeed, the proportion of years with SSB below the 20%SSB0_d LRP was higher for the F40 HCRs (Fig. 18). TAC control also shows a pattern of a higher proportion of years with SSB below the 20% SSB0_d LRP for F40 rules (Fig. 19), and a higher number of runs below the 20%SSB0_d LRP than mixed control (Fig. 18 and 19). For both control types, HCRs with F40 TRPs (HCR6 to HCR8 and HCR14 to HCR16) resulted in lower and more variable SSB than HCRs with F50 TRPs (Fig. 21). A TRP of F40 aims to produce, on average and over the long term, SSB levels that are 40% of unfished SSB (SSB0), while F50 is associated with a long term average of 50%

SSB0. Indeed, trends in the mean and 5th and 95th quantiles of SSB over time across all the runs and scenarios demonstrate that F50 rules built SSB to a higher level than F40 rules and had lower variability (Fig. 22 and 23). This was associated with higher odds of SSB being above the 20%SSB0_d and 7.7%SSB0 LRPs (Fig. 24). This pattern was consistent across control types, but TAC control built SSB to a target level more slowly than mixed control (Fig.22 and 23) and had overall lower PM1b and PM1c performance metrics (Fig. 24).

The MSE simulation started in 2016 following 2015 initial conditions defined by the end of the conditioning period. When averaged across all reference scenarios, SSB at the start of the simulation was 36% of SSB_0. Given these initial conditions, on average, all HCRs were able to maintain a high enough biomass so that, even with high recruitment variability, all HCRs showed at least highly likely (probability >0.80) odds of SSB being above 20%SSB0_d, 7.7%SSB0, 7.7%SSB0_d, or their specified LRP in any given year of the simulation (Fig. 24 to 25). It was particularly rare for SSB to breach the 7.7%SSB0_d LRP and differences in performance between HCRs were less pronounced for PM1d (Fig. 25).

Differences in performance of PM1a, *odds of SSB being above the LRP specified in each HCR*, were largely due to differences in the TRP, but were also influenced by the LRP. For the same LRP, PM1a was lower for F40 rules (Fig. 25). While for the same TRP, HCRs with the highest LRP had relatively poorer performance for PM1a (Fig. 25). Nevertheless, odds of SSB being greater than the LRP were almost certain (>0.9) for all HCRs and control types (Fig. 25). Examination of the proportion of years below the LRP specific to each HCR (Fig. 26 and 27) also demonstrates that HCRs were largely effective at maintaining biomass above their respective LRP. For both control types, HCR1 and HCR9, which had the highest LRP (20%SSB0_d), also had the highest proportion of years below the LRP, followed by HCR6 and HCR14, which had the highest LRP, 14%SSB0_d, of the F40 rules.

Results for the low productivity scenario (OM6), which starts at a lower initial biomass and simulates a less productive population, can be used to further contrast the effectiveness of different HCRs in meeting Management Objective 1. All HCRs were able to increase biomass from the low initial conditions. However, the biomass increase was to a lower level under F40 rules given the higher TRP, and the biomass increase was slower for TAC control (Fig. 28 and 29). Also note that, the 'true' SSB (i.e., from the OM) builds to a lower level than across the set of reference scenarios because the EM in the low productivity scenario has larger assessment errors and tends to overestimate the SSB (compare Fig. 28 and Fig. 22). This in turn leads to higher TACs and TAEs being set than should be the case and increases the odds of SSB being below LRPs across all HCRs. Under the low productivity scenario, HCRs with F40 TRPs have poorer performances for PM1b (i.e., odds of SSB being above the 20%SSB0_d LRP are lower) and PM1c (i.e., odds of SSB being above the 7.7%SSB0 LRP are lower) compared with the HCRs with F50 TRPs (Fig. 30). Nevertheless, under mixed control, HCRs were able to maintain high odds (>0.8) of SSB being above their LRP even under the low productivity scenario (Fig. 31). Under low productivity scenario and TAC control, the best performing HCRs for PM1a were those with a F50 TRP and the lowest LRP (i.e., HCR4, HCR5, HCR12, and HCR13).

5.2 Management Objective 2

Management objective 2, *maintain total biomass, with reasonable variability, around the historical average depletion of total biomass*, was measured by PM2, *the odds of depletion in* *any given year of the MSE forward simulation being above minimum historical (2006-2015) depletion* (Table ES1). Depletion is defined as the total biomass as a fraction of unfished total biomass. Therefore, a higher depletion implies a higher relative total biomass. The level of minimum historical depletion varied by OM. It was 0.59 for OM1, 0.63 for OM3, 0.55 for OM4, and 0.40 for OM6.

As with variability in SSB, the largest differences in total depletion were due to variation in the TRP. HCRs with the highest target fishing intensity, TRP F40, show lower depletion relative to the minimum historical (Fig. 32). This pattern was consistent for both mixed and TAC control, but, as with SSB, depletion was on average lower under TAC control (Fig. 32). All HCRs reached a median depletion level higher than minimum historical under both control types (Fig. 32). The odds of depletion being above the historical minimum (i.e., PM2) were better than even (odds >60%) under TAC control, and likely (odds >70%) under mixed control (Fig. 33). The pattern of HCRs with the F50 TRP being associated with a higher PM2, was also evident in the results for the low productivity scenario (Table 10 and Table 11).

5.3 Management Objective 3

This MSE was not designed to test different allocation schemes for the fleets involved. Instead, it was decided at the Vancouver MSE Workshop (ISC 2017) to maintain the fleet allocation for the entire simulation at a constant level set at the average historical allocation for 1999-2015. Differences in management objective 3, *maintain harvest ratio by fishery* (Table ES1), across harvest strategies and HCRs were therefore minimal because the same average allocation is maintained throughout the 30-year simulation. Rather, the value of Performance Metric 3 (PM3), measured as the average harvest ratio over the 30 years simulation over the mean historical (2006-2015) harvest ratio, was a reflection of the difference in harvest ratio from the 1999-2015 value used to set the allocation in the simulation versus the 2006-2015 level used in defining PM3 (Fig. 34). For fleets whose harvest ratio was increased from 1999 to 2006, like the Vanuatu longline fleet, the PM3 was smaller. In contrast, the fleets that saw a decrease in their share of total catches, like the Korean longline fleet, the PM3 was larger (Table 12). Also note that under mixed control, the catch of the TAE controlled fleets (i.e., surface fleets) are dependent on the 'true' biomass but the catch of the TAC controlled fleets (i.e., longline) are dependent on the 'estimated' biomass from the EM (i.e., assessment model). Therefore, when the EM overestimates the 'estimated' biomass for scenarios 1, 4, and 6, the harvest ratios of surface fleets are lower than that of longline fleets. This results in the PM3 being lower for surface fleets under mixed control relative to TAC control, whereas the reverse is true for longline fleets. (Table 12).

5.4 Management Objective 4

Management objective 4 was to *maintain catches above average historical catch* (Table ES1). Three performance metrics were developed to assess management objective 4. Performance Metric 4a (PM4a), was defined as the *odds that catch in any given year of the MSE forward simulation was above average historical (1981-2010) catch*. Average historical catch for 1981-2010 was 72,050 mt, which includes the period of low catch in the late 1980's-early 1990's (Fig. 35). Average catch over the conditioning period of 1993-2015 was actually higher at 83,067 mt.

PM4b was the *odds that medium term catch (catch averaged over years 7-13 of each simulation run) was over average historical catch*, while PM4c was the *odds that long term catch (catch averaged over the last 10 years of each simulation run) was higher than average historical catch*.

Unlike SSB or depletion, median catch was highest for HCRs with TRPs of F40 under both TAC and mixed control (Fig. 36). In the MSE simulation, initial catches were set at 95,000 mt, which is greater than the historical average, and catches decreased initially as the simulation started for both control types but built up over the course of the simulation (Fig. 37 and 38). Therefore, for both control types, catch was highest over the long term (Fig. 37 and 38) and long term catch (i.e., PM4c) had the highest odds of being above the historical average. Catch was higher, but more variable under TAC control (Fig. 36).

While median catch of F40 rules was higher on average than F50 rules, the catch of F40 HCRs was more variable than F50 rules with the same $SSB_{threshold}$ and LRP (e.g., compare HCR4 vs. HCR6, HCR5 vs HCR7, HCR12 vs. HCR14, HCR13 vs. HCR15) (Fig. 36). Overall, catch variability was highest for F50 rules with the highest $SSB_{threshold}$ (HCR 1 to HCR3, and HCR9 to HCR11) and for F40 rules (Fig. 36). Indeed, individual trajectories of catch over time show a larger number of steep drops in catch for HCR1 to HCR3 and HCR9 to HCR11 and F40 HCRs (HCR6 to HCR8 and HCR14 to HCR16) (Fig. 39 and 40). Amongst these HCRs, catch with a higher TAC_{min} had lower catch variability (e.g., compare HCR6 vs. HCR14, Fig. 39 and 40). Thus, unlike for biomass based metrics, TAC_{min} had an impact on catch variability, with a higher TAC_{min} resulting in a lower catch variability as the change in TRP, and hence catch, required by a drop in biomass was more gradual than for the same rules with a lower TAC_{min} (Fig. 1). For F50 rules, $SSB_{threshold}$ also had an impact on catch variability, with higher $SSB_{threshold}$ being associated with a higher catch variability (e.g., compare HCR3 vs. HCR5, Fig. 39 and 40) because of more frequent management intervention.

The performance of a candidate HCR with respect to the catch performance metrics (PM4a to PM4c) was dependent on both median catch and catch variability. A higher median catch leads to a higher probability of catch being above historical, but higher variability in catch can decrease the odds of catch being above historical. Under mixed control odds of SSB falling below the $SSB_{threshold}$ or LRP were low across reference scenarios (Table ES4) and hence, the probability of management action was low. The largest differences in catch performance metrics (PM4a to PM4c) were due to differences in median catch, which were largely due to difference in the TRP. Therefore, under mixed control, HCRs with the lower TRP of F50 had lower catch metrics compared to the HCRs with F40 as the TRP (PM4c) (Fig. 41).

Under TAC control, however, differences in PM4a and PM4b across were comparable across HCRs and reference scenarios (Fig. 41). The higher variability in catch of the F40 rules offset their higher average catch and led to relatively comparable odds of catch being above historical in any given year of the simulation (PM4a) (Fig. 41) or over the medium term (PM4b) (Fig. 41). Initial catch was reduced more gradually under F40 rules and given recruitment variability, more drastic reductions in catch were required over the medium term to bring SSB above reference points (Fig. 38). Thus, for TAC control, improved performance of F40 rules over F50 rules for catch metrics was only evident when looking at long term catch (Fig. 41).

Similarly, under the low productivity scenario and TAC control, there was no evidence of improved performance for PM4a and PM4b for HCRs with a F40 TRP. For TAC rules, median catch was higher with a TRP of F40 relative to F50 (Fig. 42). However, this was not enough to offset the increase in catch variability, leading to HCRs with a TRP of F50 having better performance for PM4b than HCRs with a TRP of F40 (Fig. 43). Changes in median catch over time for the low productivity scenario show that catches under F50 were gradually reduced over time to meet the TRP (Fig. 44). In contrast, median catches for F40 rules initially increased only before starting to decline later into the simulation, and the rate of reduction was much steeper than for F50 rules (Fig. 44). Thus, under the low productivity scenario, the odds of catch being higher than average historical over the medium term were actually higher for F50 rules (Fig. 42). Nevertheless, the odds of long term catch being higher than average historical catch (PM4c) remained higher for F40 rules (Fig. 43). Thus, for TAC rules, catches were higher on average, but this came at the cost of higher catch variability, and a steeper reduction in catch over the medium term. Under mixed control, biomass rebuilt faster (Fig. 28 and 29) as catches of the surface fleets varied in between assessment, responding to changes in available biomass and were not overestimated. Thus, even for F40 rules, no drastic management action was required mid way through the simulation (Fig. 45), leading to the odds of catch in any year of the simulation (PM4a), over the medium term (PM4b), and over the long term (PM4c) being higher than average historical catches (Table 11).

5.5 Management Objective 5

Management objective 5, *change in total allowable catch between years should be relatively gradual* was assessed using performance metric 5a (PM5a), *catch stability*. To compute PM5a, the percentage change in TAC between consecutive assessment periods (once every 3 years), excluding years where TAC=0 was first assessed. PM5a was then calculated as *the probability of a decrease in TAC being <30% between consecutive assessment periods* (once every 3 years), excluding years where TAC=0. Note that for mixed control, the catch was used rather than the TAC. Here, we focus the results on the decreases in TAC (or catch) between years as a drop in TAC is more concerning to stakeholders.

PM5a levels depend on both the frequency of management intervention as well as the degree of change in fishing intensity from the TRP, and hence TAC or catch, required when SSB falls below SSB reference points. Importantly, we also measured the frequency of management intervention with PM5b, *the odds of no management intervention*, which was calculated as the probability of biomass falling below the $SSB_{threshold}$. Odds of no management intervention were higher for mixed control rules. However, for both control types, performance of PM5b was lowest for those HCRs with the highest $SSB_{threshold}$ (30%), HCR1 to HCR3 and HCR9 to HCR11. The highest PM5b performance differed for different TRPs, with HCR4, HCR5, HCR12, and HCR13 performing best for F50 rules, while HCR8 and HCR16 performed best for F40 rules (Fig. 46). Although some F40 rules (HCR6, HCR7, HCR14 and HCR15) had the same $SSB_{threshold}$ and LRP as the best performing F50 HCRS, their PM5b performance was only intermediate because their lower TRP led to lower average biomass and increased odds of falling below the $SSB_{threshold}$ (Fig. 46).

Under TAC control, the F50 HCRs with the best performing PM5b (HCR4, HCR5, HCR12, and HCR13) also had the lowest median decrease in TAC (Fig. 47) and higher TAC stability (Fig. 48). However, the relative performance in catch and TAC stability of the other HCRs was reversed as compared to PM5b performance, with all F40 HCRs performing poorer in terms of catch stability than F50 HCRs (Fig. 48). F40 rules had the highest median decrease in TAC between assessments (Fig. 47) and the most variable decreases in TAC (see interquartile range in Fig. 47). Thus, while management was more frequent under rules with a SSB threshold of 30%, the TRP level had a stronger effect on determining catch stability. Under a F50 TRP, the change in TAC was more gradual, resulting in higher catch stability. The same pattern of lower performance in terms of catch stability for F40 rules was apparent for the low productivity scenario (Table 11).

Under mixed control, biomass was maintained at a higher level and PM5b performance was better than for TAC control (Fig. 46). Median decrease in catch between assessments was comparable across HCRs and TRPs (Fig. 46), albeit HCR4, HCR5, HCR12, and HCR13 showed the lowest variability in decreases in catch (see interquartile range in Fig. 46). All HCRs showed almost certain (>90%) odds of a decrease in catch between assessment periods being less than 30% (Fig. 47), even under the low productivity scenario (Table 10 and 11). Differences among HCRs start to become more evident when considering the odds of a decrease in catch being less than 20%, with HCR4, HCR5, HCR12, and HCR13 performing best, which were the same best performing HCRs under TAC control (Fig. 49).

5.6 Management Objective 6

Management objective 6 was to *maintain F at the target value with reasonable variability*. Performance Metric 6 (PM6) was used to measure the performance of HCRs with respect to this management objective and was calculated as *the ratio of the TRP to the F in each year of the simulation*, where the F and TRP are based on 1-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. Trends in PM6 are due to a combination of implementation and estimation (i.e. assessment) error. A PM6 less than 1 implies that the F was higher than the TRP (i.e. a higher fishing intensity than that set by the TRP).

Across all reference scenarios and for both control types, PM6 was highest for F40 rules (Fig. 50). For scenarios 1 and 3 most runs had SSB greater than $SSB_{threshold}$ and the fishing intensity was therefore randomly selected from the historical fishing intensity which averaged 0.51 for scenario 1 and 0.44 for scenario 3. These fishing intensities were smaller than the fishing intensity of 0.60 associated with an F40 target, leading to a F_{target}/F greater than 1. This is exemplified by Fig. 51 showing individual run trajectories of F over time for scenario 1 under mixed control being clustered around the historical F_{target} of 0.51 for all HCRs irrespective of F_{target}.

For both control types, PM6 for F40 rules was higher than for F50 rules even under the low productivity scenario (Table 11). While F was higher on average for F40 rules, F40 HCRs had more drastic management interventions, as shown for TAC control in Fig. 52 by the large drops in F apparent for F40 HCRs (HCR6 to HCR8 and HCR14 to HCR 16). These drastic reductions in F led to PM6 being higher for F40 rules, even if F was higher on average. With mixed control, reductions in F were less frequent and less drastic than under TAC control, but F40 HCRs showed more instances of reductions in F away from the average as compared to F50 rules (Fig. 53).

5.7 Tradeoffs between Performance Metrics

Under mixed control, there was no single best-performing HCR for all management objectives. Trade-offs were evident between performance metrics. Fig. ES2 shows performance of all HCRs across all reference scenarios for all metrics under mixed control. Lines closer to the outer margin (value of 1) indicate better performance. HCRs with a TRP of F40 performed better in terms of catch metrics (PM4a to PM4c) but poorer in terms of biomass metrics (PM2, PM1b, PM1c). Nevertheless, odds of not breaching the 20%SSB0_d or 7.7%SSB0 LRPs remained highly likely (>80%) even for F40 HCRs. While the odds of no management action were lowest (i.e. poorest PM5b performance) for F40 and F50 rules with their respective highest $SSB_{threshold}$ (20%SSB0_d, for F40 rules; 30%SSB0_d, for F50 rules), the odds of not breaching the LRP (PM1a) or catch stability (PM5a) were comparable among HCRs.

The same tradeoffs between catch and biomass metrics were evident for the low productivity scenario under mixed control (Fig. ES3). However, differences in performance between HCRs with regards to the odds of not breaching the LRP became more distinct. HCR1 and HCR9, the only ones with a 20%SSB0_d LRP, and HCR6 and HCR14, the only F40 HCRs with a 14% SSB0_d LRP, showed lower odds of not breaching those LRPs and therefore resulted in more occurrences of drastic management interventions (i.e. poorer performance in PM1a) (Fig. ES3). The increase in management intervention, however, was not associated with improvement in biomass metrics relative to other HCRs that had the same TRP (Fig. ES3).

By contrast, under TAC control, the tradeoff between lower TRP (F50), higher biomass and lower catch metrics was not as evident. F50 HCRs performed better in terms of the odds of not breaching the 20%SSB0_d and had a comparable performance to the F40 HCRs for two out of the three catch metrics (Fig.ES). F50 HCRs also had higher catch stability. Under TAC control, the higher catch variability of F40 rules led to the odds in annual catch (PM4a) or medium term catch (PM4b) being comparable to F50 rules despite the higher fishing intensity. Among F50 rules HCR1 and HCR9 had lower odds of not breaching the LRP (poorer PM1a), lower odds of no management intervention (poorer PM5b), and also lower catch stability (poorer PM5a). HCR2, HCR3, HCR10, and HCR11 showed lower odds of no management intervention (poorer PM5b) and lower catch stability (poorer PM5a) than other F50 HCRs. F50 HCRs with a 20%SSB0_d threshold (HCR4, HCR5, HCR12, and HCR13) performed best among the F50 HCRs under TAC control by having comparable biomass metrics (PM1a-d, PM2), higher catch stability (better PM5a), and higher catch (better PM4a-c). The same HCRs were also the best performing F50 HCRs in the low productivity scenario (Fig. ES3). Due to their higher catch stability, they also performed as well as F40 HCRs in terms of the odds of catch in any year of the simulation (PM4a) and medium-term catch (PM4b) being above historical, despite better performance in terms of biomass metrics (PM1a-d, PM2) (Fig. ES2, Table 11).

5.8 Unknown fleet robustness scenario

Results from this robustness scenario demonstrate that given current biomass estimates and fishing intensities as estimated by the base case reference scenario, the NPALB stock is quite resilient to a gradual increase in catches up to 50,000 mt over a period of 20 years from an unknown fleet that is not subject to management. Under mixed control, catches of the unknown fleet increase until 2035 when the 50,000 mt are reached (Fig. 54). By contrast, catches of the managed fleets remain relatively constant on average until 2035 when they start decreasing (Fig. 55). Trends in total median fishing intensity peak in 2035, just below a fishing intensity of 0.70, and then start decreasing as the catches of the managed fleets start to decline (Fig. 56). The latter ten years of the simulation are characterized by increased management intervention as illustrated by the increased variability in catches during that period, particularly for the F50 HCRs, HCR9 to HCR13 (larger quantile spread in Fig. 55). By contrast, median SSB declines earlier in the simulation with the unchecked increase in catches and then stabilizes around 2035 at a lower level than for the reference scenarios (compare Fig. 57 and Fig. 22). Note that this robustness scenario was run on the base case, scenario 1, and therefore, if SSB was above $SSB_{threshold}$, fishing intensity was sampled from the historical fishing intensity, which averaged at 0.51. Because of the relatively high status of the NPALB population and the assumption of no increases in the fleet capacity/effort of the managed fleet (i.e., F is sampled from historical), the increase in unknown fleet catch is not enough to bring the population below management thresholds, even $SSB_{threshold}$, and differences in performance between F50 and F40 rules are not apparent (Table ES1). Biomass and catch metrics are comparable between HCRs, and differences in performance in terms of catch stability and the odds of no management intervention can be ascribed to the higher $SSB_{threshold}$ (30%SSB0_d) of HCR9 to HCR11 rather than differences in the TRP. Improved performance of F40 rules in terms of PM6, Ftarget/F is due to F being set at $F_{historical}$ over most of the simulations, even for F40 rules, leading to a higher Ftarget/F ratio than F50 HCRs. Both the odds of depletion being above historical and the odds of various catch metrics being above historical were lower than for the reference scenarios, with the largest change for the catch metrics (Table 13). The drop in performance relative to the catch metrics under the robustness scenario as compared to the reference scenarios is largely due to a drop in catches associated with the decline in biomass, and, in the latter years of the simulation, management intervention.

The EM (i.e., simulated stock assessment), even without data from the unmanaged fleet, was able to correctly detect the decrease in biomass despite observation error. However, in the absence of increases in reported catches, it ascribed the change to a drop in recruitment, with mean recruitment across all runs being 1.99×10^5 for the OM ("true recruitment") but 1.67×10^5 for the EM ("estimated" recruitment from the simulated assessment). Thus, catch declined over time for both longline and surface fleets. Longline catches declined because their catches were subject to a TAC which declined as the estimated biomass from the simulated assessment. The catches of the surface fleets declined because their catches were a function of TAE and declining available "true" biomass. These results appear to suggest that, assuming that there are no increases in fleet capacity or effort of the managed fleets (i.e., F of managed fleets does not increase over historical levels) and no hyperstability of the abundance indices, management via mixed control using any of the HCRs here considered would aid in reducing the impact of the increased fishing pressure on the stock. This is in contrast to an unmanaged situation where fleets might maintain their current catch levels (e.g., by increasing effort), despite decreasing biomass as they are not subject to a TAC or TAE.

To better assess the impact of the different TRPs, some additional runs were carried for the robustness scenario for some HCRs (HCR9, HCR12, HCR14, HCR16) under TAC control, with no restrictions on the fleet capacity (i.e., F of managed fleets could increase up to the TRP) and a faster increase in the catches of the unknown fleet (50,000 mt in 10 years). In this simulation the fisheries are able to meet the F40 TRP if SSB is greater than $SSB_{threshold}$. Having TAC control implies that between assessment periods also surface fleets are assumed to meet their TAC notwithstanding changes in available biomass. This is different from mixed control where the catch of surface fleets is dependent on the available biomass (i.e., biomass from the OM). In this scenario, the catch of the unknown fleet increases sharply until ~2027 (Fig. 58). Median catch of the managed fleets decreases sharply over the same period and then stabilizes at a lower level (Fig. 59). Median SSB for this robustness scenario declines initially with increased unreported catches and then stabilizes to a lower level than for the reference scenarios (Fig. 60 vs. Fig. 23). Note that catches for the F50 rules (HCR9 and HCR12) start off at a lower level because of their lower fishing intensity and thus biomass decline more moderately (Fig. 60) and there is no drastic decline in catch later in the simulation (Fig. 59). HCR9 and HCR14 have the highest catch variability (interquartile spread in Fig. 59) as management action is required in some runs once biomass declines. Indeed, the odds of management action are highest for HCR9 and HCR14 (Table 14). HCR9 has the highest $SSB_{threshold}$ at 30%SSB0_d and thus management action is triggered more often. The higher rate of management intervention for HCR9, however, does not lead to better performance as compared to HCR12, which has the same TRP but a lower $SSB_{threshold}$ of 20%SSB0_d. Biomass metrics perform similarly but catch over the medium term and catch stability are lower for HCR9 because of increased management intervention (Table 14). Similarly, the two F40 HCRs, HCR14 and HCR16, perform similarly to each other in terms of biomass and most catch metrics, despite the higher management intervention of HCR14, which leads to lower catch stability and lower medium term catch (Table 14). The largest differences in performance are associated with the TRP. The lower fishing intensity TRP, F50, leads to higher odds of depletion (i.e., relative total biomass) being above historical and of SSB being above 20%SSB0_d, but this comes at the cost of catch metrics, where the odds of catch over the long term being above historical are twice as high for F40 rules. Furthermore, odds of SSB being above the LRP, or 20%SSB0_d, or 7.7%SSB0 are greater than 0.8 for both F50 and F40 HCRs. For the same $SSB_{threshold}$ and LRP (compare HCR12 with HCR14). F40 rules have lower catch stability because the F40 TRP results in higher fishing intensity, which leads to a lower biomass and higher probability of breaching the reference points. Catch stability of HCR16 is also lower than HCR12 (both with F40 TRPs), despite low management intervention. These additional analyses support the results above, namely that, given the good current condition of the stock and maintenance of fishing intensities below F40, the population can be resilient to an increase in unreported catch under TAC management. This is because the estimation model is able to detect the decline in biomass, even without data from the unmanaged fleet, and the TAC of managed fleets therefore also declines. Because the catch of the unmanaged fleet is unreported, however, management actions cannot increase biomass back to historical levels and catch for the managed fleets remains lower than in the reference scenarios.

6 Key Limitations and Meta-rules

The ALBWG examined the MSE models in detail and identified the following key limitations.

- The uncertainty in the relationship between the measure of effort in the MSE (i.e., exploitation rate that generates the F specified by the HCR) and real-world effort in number of fishing days for the EPO surface fleet increases at smaller effort levels. Therefore, at very low annual exploitation rates, implementation error for the EPO fleet under mixed control may be greater in the real world than the implementation error assumed in the MSE simulation. However, impact of this underestimation of implementation error for the EPO on MSE results is likely low as such low values comprised only 5% of all the simulated exploitation rates.

- It is assumed that catch control is implemented equally effectively across all fisheries, including both NPALB targeting and non-targeting (e.g., surface fleets vs. longline). This may not be true in the real world but there is no prior experience or information on implementation error of catch control between albacore targeting and non-targeting fisheries.

- Allocation is assumed to be constant at the average of 1999-2015 levels throughout the simulation. This formulation prevents an assessment of management objective 3, *maintain harvest ratios by fishery*, as the harvest ratios are kept constant by design. Testing of different allocation schemes would require input from managers as to what those allocation rules might be.

- NPALB is a highly migratory species whose movement rates to given areas in the North Pacific are highly variable. This affects availability to the fisheries operating in those areas. However, the simulations do not explicitly model these movement processes and instead only approximate the availability to various fleets. Further work could include the development of area specific operating models to better capture uncertainty in migration rates, and their relationship to availability.

- The simulations are conditioned on data from 1993 onwards, although available data dates back to 1966. Therefore, the simulations may not include the full range of uncertainty in the population dynamics of NPALB. Thus, the MSE results are most applicable to recent conditions. Nevertheless, inclusion of the lowest productivity scenario (Scenario 6) was an attempt to accommodate some of this uncertainty.

If one of the HCRs presented here were to be adopted as part of a management procedure for NPALB, meta-rules may be put in place (e.g., Preece et al. 2015 for Pacific southern bluefin tuna) to define situations outside the range for which robustness of the HCRs was evaluated and for which a different management action than specified by the adopted HCR may be taken.

Definition of such exceptional circumstances should consider the limitations above and could consider: 1) if the population dynamics are significantly different from those specified in the range of OMs used in evaluating the HCRs, 2) if the fleets or fishing operations have changed substantially, 3) if input data to the estimation model have been altered, and 4) if, once a TAC or TAE is place, total removals or effort differ significantly (i.e. more than what was specified by the implementation error) from what is recommended by the HCR. While the results presented here in support of the development of a harvest strategy for NPALB are considered final under current conditions, should the above circumstances arise, the MSE framework should be reviewed and revised.

7 References

ALBWG. 2014. Stock assessment of albacore tuna in the north Pacific Ocean in 2014Available at: http://isc.ac.affrc.go.jp/pdf/ISC14pdf/Annex%2011-%20NPALB%20Stock%20Assessment%20Report_revsied%2029Aug14.pdf

ALBWG 2017. Stock assessment of albacore tuna in the North Pacific Ocean in 2017. Available at http://isc.fra.go.jp/pdf/ISC17/ISC17_Annex12-Stock_Assessment_of_Albacore_Tuna_in_the_North_Pacific_Ocean_in_2017.pdf

ALBWG 2020. Stock assessment of albacore tuna in the North Pacific Ocean in 2020. Available at http://isc.fra.go.jp/pdf/ISC20/ISC20_ANNEX12_Stock_Assessment_Report_for_Albacore_Tuna_in_NorthPacific.pdf

Ashida, H., Gosho, T., and Kiyofuji, H. 2016. Sex ratio, spawning season, spawning fraction and size at maturity of North Pacific albacore (*Thunnus alalunga*) caught in subtropical western North Pacific. ISC/16/ALBWG-02/05. Work. Doc. Submitt. to ISC Albacore Work. Gr. Meet. 8 - 14 November, 2016, Pacific Biol. Station. Nanaimo, BC, Canada.

Brodziak, J., Lee, H.H., and Mangel, M. 2011. Probable values of stock-recruitment steepness for north Pacific albacore tuna. ISC/11/ALBWG/11. Work. Pap. Submitt. to ISC Albacore Work. Gr. Stock Assess. Work. 4-11 June 2011, Natl. Res. Inst. Far Sea Seas Fish. Shimizu, Japan.

Chen, C.-Y., and Cheng, F.-C. 2017. Length distributions of albacore catch made by Taiwanese albacore-targeting longline fishery in the Pacific Ocean north of 25N, 2003-2015. ISC/17/ALBWG/02. Work. Doc. Submitt. to ISC Albacore Work. Gr. Meet. 11-19 April 2017, Southwest Fish. Sci. Center, La Jolla, California, USA.

Chen, K.-S., Crone, P.R., and Hsu, C.-C. 2010. Reproductive biology of albacore *Thunnus alalunga*. J. Fish Biol. **77**(1): 119–136. doi:10.1111/j.1095-8649.2010.02662.x.

Chen, K.-S., Shimose, T., Tanabe, T., Chen, C.-Y., and Hsu, C.-C. 2012. Age and growth of albacore *Thunnus alalunga* in the North Pacific Ocean. J. Fish Biol. **80**(6): 2328–44. doi:10.1111/j.1095-8649.2012.03292.x.

Clemens, H.B. 1961. The migration, age, and growth of Pacific albacore (*Thunnus germo*), 1951-1958. Fish Bull. Calif. Dep. Fish Game **115**: 1–128.

Francis, R.I.C.C. 2011. Data weighting in statistical fisheries stock assessment models. Can. J. Fish. Aquat. Sci. **68**: 1124–1138. doi:10.1139/F2011-025.

Hurtado-Ferro, F., Punt, A.E., and Hill, K.T. 2014. Use of multiple selectivity patterns as a proxy for spatial structure. Fish. Res. **158**: 102–115. doi:10.1016/j.fishres.2013.10.001.

Ichinokawa, M., Coan, A.L., and Takeuchi, Y. 2008. Transoceanic migration rates of young North Pacific albacore, *Thunnus alalunga*, from conventional tagging data. Can. J. Fish. Aquat. Sci. **65**(8): 1681–1691. doi:10.1139/F08-095.

Ijima, H., Ochi, D., and Kiyofuji, H. 2017. Estimation for Japanese catch at length data of North Pacific albacore tuna (Thunnus alalunga). ISC/17/ALBWG/04. Work. Doc. Submitt. to ISC Albacore Work. Gr. Meet. 11-19 April 2017, Southwest Fish. Sci. Center, La Jolla, California, USA.

ISC 2015. Report of the 1st ISC ALB MSE Workshop

ISC 2016. Report of the 2nd ISC ALB MSE Workshop

ISC 2017. Report of the 3rd ISC ALB MSE Workshop

ISC 2018. Progress report on Management Strategy Evaluation for North Pacific albacore. Available from https://www.wcpfc.int/node/31907

ISC 2019. Report of the 4th ISC ALB MSE Workshop.

ISC 2020. Report of the albacore working group workshop, 31 Aug – 3 and 8 Sep 2020.

Ijima, H., Sakai, O., Akita, T., and Kiyofuji, H. 2016. New future projection program for North Pacific albacore tuna (Thunnus alalunga): considering two-sex-age-structured population dynamics. ISC/16/ALBWG-02/06. Work. Doc. Submitt. To ISC Albacore Work. Gr. Meet. 8-14 November 2016, Pacific Biol. Station, Nanaimo, BC, Canada.

Ijima, H. 2020. The test run of future projection for North Pacific albacore stock using the SSfuture C++ and the multivariate normal distribution. ISC/20/ALBWG-01/03. Working document submitted to the ISC Albacore Working Group Meeting, 6-15 April 2020, by Webinar.

Iwata, S., Sugimoto, H., and Takeuchi, Y. 2011. Calculation of the steepness for the north Pacific albacore. ISC/11/ALBWG/18. Work. Pap. Submitt. to ISC Albacore Work. Gr. Stock Assess. Work. 4-11 June 2011, Natl. Res. Inst. Far Sea Seas Fish. Shimizu, Japan.

Kimura, S., Nakai, M., and Sugimoto, T. 1997. Migration of albacore, *Thunnus alalunga*, in the North Pacific Ocean in relation to large oceanic phenomena. Fish. Oceanogr. **6**(2): 51–57. doi:10.1046/j.1365-2419.1997.00029.x.

Kinney, M.J., and Teo, S.L.H. 2016. Meta-analysis of north Pacific albacore tuna natural mortality. ISC/16/ALBWG-02/07. Nanaimo, British Columbia, Canada.

Kiyofuji, H., and Uosaki, K. 2010. Revision of standardized CPUE for albacore caught by the Japanese pole and line fisheries in the northwestern North Pacific albacore. ISC/10-3/ALBWG/07. Work. Pap. Present. ISC Albacore Work. Gr. Work. 12-19 Oct. 2010, Southwest Fish. Sci. Center, NOAA, La Jolla, USA.

Lorenzen, K. 1996. The relationship between body weight and natural mortality in juvenile and adult fish: A comparison of natural ecosystems and aquaculture. J. Fish Biol. 49: 627–647. doi:10.1111/j.1095-8649.1996.tb00060.x.

Mangel, M., Brodziak, J., and DiNardo, G. 2010. Reproductive ecology and scientific inference of steepness: A fundamental metric of population dynamics and strategic fisheries management. doi:10.1111/j.1467-2979.2009.00345.x.

Methot, R.D. 2000. Technical Description of the Stock Synthesis Assessment Program. NOAA Tech. Memo. NMFS-NWFSC-43. Northwest Fisheries Science Center, Seattle, Washington.

Methot, R.D., and Taylor, I.G. 2011. Adjusting for bias due to variability of estimated recruitments in fishery assessment models. Can. J. Fish. Aquat. Sci. **68**(10): 1744–1760. doi:10.1139/f2011-092

Methot, R.D., and Wetzel, C.R. 2013. Stock synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fish. Res. **142**: 86–99. Elsevier B.V. doi:10.1016/j.fishres.2012.10.012.

Nishikawa, Y., Honma, M., Ueyanagi, S., and KikawaS. 1985. Average distribution of larvae of oceanic species of scrombroid fishes, 1956–1981. Far Seas Fish. Res. Lab. , Shimizu, S Ser. 12.

Ochi, D., Ijima, H., Kinoshita, J., and Kiyofuji, H. 2016. New fisheries definition from Japanese longline North Pacific albacore size data. ISC/16/ALBWG-02/03. Work. Doc. Submitt. to ISC Albacore Work. Gr. Meet. 8 - 14 November, 2016, Pacific Biol. Station. Nanaimo, BC, Canada.

Ochi, D., Ijima, H., and Kiyofuji, H. 2017. Abundance indices of albacore caught by Japanese longline vessels in the North Pacific during 1976-2015. ISC/17/ALBWG/01. Work. Doc. Submitt. to ISC Albacore Work. Gr. Meet. 11-19 April 2017, Southwest Fish. Sci. Center, La Jolla, California, USA.

Otsu, T., and Sumida, R.F. 1968. Distribution, apparent abundance, and size composition of albacore (*Thunnus alalunga*) taken in the longline fishery based in American Samoa, 1954-65. Fish. Bull. **67**(1): 47–67.

Otsu, T., and Uchida, R.N. 1959. Sexual maturity and spawning of albacore in the Pacific Ocean. Fish. Bull. **59**(148): 287–305.

Polovina, J.J., Howell, E., Kobayashi, D.R., and Seki, M.P. 2001. The transition zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. Prog. Oceanogr. **49**(1–4): 469–483. doi:10.1016/S0079-6611(01)00036-2.

Preece, A.L., Davies, C.R., Hillary, R.M. 2017. Meta-rules and exceptional circumstances considerations. CCSBT-ESC/1709/15.

Ramon, D., and Bailey, K. 1996. Spawning seasonality of albacore, *Thunnus alalunga*, in the South Pacific ocean. Fish. Bull. **94**(4): 725–733.

Suzuki, Z., Warashina, Y., and Kishida, M. 1977. The comparison of catches by regular and deep tuna longline gears in the western and central equatorial Pacific. Bull. Far Seas Fish. Lab. **15**: 51–89.

Takagi, M., Okamura, T., Chow, S., and Taniguchi, N. 2001. Preliminary study of albacore (*Thunnus alalunga*) stock differentiation inferred from microsatellite DNA analysis. Fish. Bull. **99**(4): 697–701.

Teo, S.L.H. 2016. Spatiotemporal definitionsof the US albacore longline fleets in the north Pacific for the 2017 assessment. ISC/16/ALBWG-02/08. Work. Doc. Submitt. to ISC Albacore Work. Gr. Meet. 8 - 14 November, 2016, Pacific Biol. Station. Nanaimo, BC, Canada.

Teo, S.L.H. 2017a. Meta-analysis of north Pacific albacore tuna natural mortality: an update. ISC/17/ALBWG/07. Work. Doc. Submitt. to ISC Albacore Work. Gr. Meet. 11-19 April 2017, Southwest Fish. Sci. Center, La Jolla, California, USA.

Teo, S.L.H. 2017b. Catch and size composition time series of the US and Mexico surface fishery for the 2017 north Pacific albacore tuna assessment. ISC/17/ALBWG/08. Work. Doc. Submitt. to ISC Albacore Work. Gr. Meet. 11-19 April 2017, Southwest Fish. Sci. Center, La Jolla, California, USA.

Teo, S.L.H. 2017c. Catch and size composition time series of the US pelagic longline fleets for the 2017 north Pacific albacore tuna assessment. ISC/17/ALBWG/10. Work. Doc. Submitt. to ISC Albacore Work. Gr. Meet. 11-19 April 2017, Southwest Fish. Sci. Center, La Jolla, California, USA.

Tommasi, D., Teo, S.L.H. 2020. Relationship between the effort of longline and surface fleets in the North Pacific and Albacore Fishing Mortality. ISC/20/ALBWG-01/5. Work. Doc. Submitt. to ISC Albacore Work. Gr. Meet. 6-15 April 2020, held virtually.

Ueyanagi, S. 1957. Spawning of the albacore in the Western Pacific. Rep. Nankai Reg. Fish. Res. Lab. **6**: 113–124.

Ueyanagi, S. 1969. Observations on the distribution of tuna larvae in the Indo-Pacific Ocean with emphasis on the delineation of the spawning areas of albacore, Thunnus alalunga. Bull. Far Seas Fish. Lab. **2**: 177–256.

Uosaki, K., Kiyofuji, H., and Matsumoto, T. 2011. Review of Japanese albacore fisheries as of 2011. ISC/11/ALBWG/13. Work. Pap. Submitt. to ISC Albacore Work. Gr. Stock Assess. Work. 4-11 June 2011, Natl. Res. Inst. Far Sea Seas Fish. Shimizu, Japan.

Watanabe, H., Kubodera, T., Masuda, S., and Kawahara, S. 2004. Feeding habits of albacore *Thunnus alalunga* in the transition region of the central North Pacific. Fish. Sci. **70**: 573–579. doi:10.1111/j.1444-2906.2004.00843.x.

Watanabe, K., Uosaki, K., Kokubo, T., Crone, P.R., Coan, A.L., and Hsu, C.C. 2006. Revised practical solutions of application issues of length-weight relationship for the North Pacific albacore with respect to stock assessment. ISC/06/ALBWG/14. Rep. ISC Albacore Work. Gr. Work. 28 Novemb. - 5 December, 2006.

Waterhouse, L., Sampson, D.B., Maunder, M., and Semmens, B.X. 2014. Using areas-as-fleets selectivity to model spatial fishing: Asymptotic curves are unlikely under equilibrium conditions. Fish. Res. **158**: 15–25. doi:10.1016/j.fishres.2014.01.009.

WCPFC 2017. Interim Harvest Strategy for North Pacific Albacore tuna. WCPFC14 Summary Report Attachment I

Wells, R.J.D., Kohin, S., Teo, S.L.H., Snodgrass, O.E., and Uosaki, K. 2013. Age and growth of North Pacific albacore (*Thunnus alalunga*): Implications for stock assessment. Fish. Res. **147**: 55–62. Elsevier B.V. doi:10.1016/j.fishres.2013.05.001.

Xu, Y., Sippel, T., Teo, S.L.H., Piner, K., Chen, K., and Wells, R.J. 2014. A comparison study of North Pacific albacore (*Thunnus alalunga*) age and growth among various sources 1. (April 2014).

Yoshida, H.O. 1966. Early life history and spawning of the albacore, *Thunnus alalunga*, in hawaiian waters. Fish. Bull. **67**(2): 205–211. Available from http://fishbull.noaa.gov/67-2/yoshida.pdf.

Zainuddin, M., Kiyofuji, H., Saitoh, K., and Saitoh, S.I. 2006. Using multi-sensor satellite remote sensing and catch data to detect ocean hot spots for albacore (*Thunnus alalunga*) in the northwestern North Pacific. Deep. Res. Part II Top. Stud. Oceanogr. **53**(3–4): 419–431. doi:10.1016/j.dsr2.2006.01.007.

Zainuddin, M., Saitoh, K., and Saitoh, S.-I. 2008. Albacore (*Thunnus alalunga*) fishing ground in relation to oceanographic conditions in the western North Pacific Ocean using remotely sensed satellite data. Fish. Oceanogr. **17**(2): 61–73. doi:10.1111/j.1365-2419.2008.00461.x.

8 Glossary

- **Depletion -** can be defined as spawning biomass depletion or total biomass depletion. It shows what fraction of unfished biomass (spawning or total) the current biomass is. It is calculated as the ratio of the current to unfished biomass (spawning or total).
- **Estimation Model (EM)** – An analytical model that takes data generated with error by the operating model (e.g. catch, abundance index) and produces an estimate of stock status. This often mirrors a stock assessment model.
- **Fishing intensity** – a harvest rate 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 of F30 would result in 30% of the SSB per recruit relative to the unfished state. This is approximately equivalent to a harvest rate of 70%.
- **Harvest control rule (HCR)** - Pre-agreed upon set of rules that specify a management action (e.g. setting the total allowable catch or location/timing of closures) based on a comparison of the status of the system to specific reference points.
- **Harvest strategy (or management strategy)** - a framework for deciding which fisheries management actions (such as setting a TAC) will achieve stated management objectives. It specifies (1) what harvest control rule will be applied, (2) how stock status estimates will be calculated (e.g. via a stock assessment), and (3) how catch or effort will be monitored.
- **Limit reference point (LRP)** – A benchmark current stock status is compared to and that should not be exceeded with a high probability. It can be biomass-based (e.g. SSBLIMIT) or fishing intensity-based (e.g. FLIMIT).
- **Management Objectives** – High-level goals of a management plan (e.g. prevent overfishing or promote profitability of the fishery).
- **Management Strategy Evaluation (MSE)** – a simulation-based analysis to evaluate trade-offs achieved by alternative harvest (or management) strategies and to asses the consequences of uncertainty in achieving management objectives
- **Operating Model (OM)** – Mathematical representation of plausible versions of the true dynamics of the system under consideration. These are conditioned on historical data. Generally, multiple OMs are required to represent the range of uncertainty in different factors. OMs can range in complexity (e.g. from single species to ecosystems models) depending on the management objectives and management strategies being evaluated.
- **Performance metrics** - Quantitative indicators that are used to evaluate each HCR and serve as a quantitative representation of the management objectives.
- **Spawning potential ratio (SPR)** – the ratio of female spawning stock biomass per recruit under fishing to female spawning stock biomass per recruit under unfished conditions.
- **SSB** – female spawning stock biomass.
- **SSB0_d** – unfished spawning stock biomass that fluctuates with changes in recruitment. Also referred to as dynamic unfished spawning stock biomass.

- **Target reference point (TRP) -** A benchmark which a current stock levels is compared to. It represents a desired state that management intends to achieve. It can be biomass-based (e.g. SSBTARGET) or fishing intensity-based (e.g. FTARGET).
- **Threshold reference point** – A benchmark current stock status is compared to. Its value is between that of a target and limit reference point. It represents a control point below which a management action is undertaken to bring the stock back to a target state.

9 Tables

Table 1. Managers and stakeholders' recommendations following the 1st round of ISC NPALB MSE and how they were addressed. Note that colors in left column are categorized as presentation of results (blue), Management objective (orange), candidate harvest strategies, reference points and harvest control rules (green), workplan (purple) and others (yellow), respectively. Table was from (ISC 2020).

	Recommendation	Progress
1	The ALBWG should be more explicit in the labelling of performance indicators and specify if an indicator is based on a probability. For example, for Management Objective #2, the performance indicator labelled "Relative total biomass" was actually the probability of the depletion of total biomass being over the minimum historical depletion and could instead be labelled "probability of total biomass > minimum historical".	Performance Indicators for Management Objectives #2 was replaced to "Odds depletion > historical" and for #4 was replaced to "Odds catch > historical", respectively.
2	Performance indicators using relative total or spawning biomass are likely to be better understood than indicators using probabilities. Separate plots of the mean or median of the relative biomasses coupled with plots of the variability of those relative biomasses may be preferable to a single plot of probabilities. Comparison with historical levels could be done by including indications of the historical levels to be compared.	Use of 'worm' plots to show individual simulation runs for various time series plots, in addition to violin plots with the median and 95% confidence intervals with pie charts to show proportions of different outcomes.
3	The ALBWG should provide guidance on how to interpret fishing intensity in terms of implications to fleet management. For example, it would be useful for managers to be shown the changes in fishing intensity relative to current fishing intensity.	Additional analyses were conducted and presented by the MSE specialist. (**See http://isc.fra.go.jp/pdf/ALB/ISC20_ALB_1/ISC20-ALBWG01-05.pdf**).

<table>
<tr><td>4</td><td>Managers and stakeholders should prioritize, rank, or weight the management objectives to assist decision making and help resolve trade-offs in management objectives.</td><td>It was recommended that this be discussed during the MSE WS in early 2021 for managers and stakeholders.</td></tr>
<tr><td>5</td><td>Management Objective #6 was considered of relatively low priority by managers and stakeholders in evaluating candidate reference points and harvest control rules.</td><td>Results relevant to management objective 6 are still be presented in this round of MSE report.</td></tr>
<tr><td>6</td><td>The ALBWG should try to obtain the necessary expertise to evaluate the Management Objective of “Maximizing the economic returns of existing fisheries”. However, this would be a longer-term goal beyond the 2nd round of MSE.</td><td>The WG noted that CPUE could be as an economic proxy, however, in the current OMs and EMs, there are only standardized CPUE and there may be some work necessary to project the nominal CPUE for various fleets. No clear decision was made by the WG on whether to include CPUE to evaluate this objective as a performance indicator at this stage.</td></tr>
<tr><td>7</td><td>As the MSE process continues, it should be emphasized that the overarching objective running through all the management objectives of the MSE is to maintain the viability and sustainability of the current NPALB stock and fisheries.</td><td>Now emphasized in the final report for the 2nd round of MSE.</td></tr>
<tr><td>8</td><td>The 2nd round of MSE should focus on Harvest Strategy 3 using the specific reference points and harvest control rules listed in Table 4 (in summary report: http://isc.fra.go.jp/pdf/ISC19/ISC19_ANNEX12_Report_First_North_Pacific_Albacore_MSE.pdf).</td><td rowspan="2">• These recommendations were reflected in the development of the modeling framework for the 2nd round of MSE.
• MSE specialist has been working on HS3 and TRPs of F40 and F50 with different combinations of LRPs and threshold reference points (See Table ES2).
• Three LRPs (20%SSB0_d, 14%SSB0_d, and 7.7%SSB0_d) requested by the managers and stakeholders were also evaluated for further consideration of LRPS.</td></tr>
<tr><td>9</td><td>Harvest Strategy 1 should be removed from further consideration because it performed poorer in terms of Management Objective #1 relative to Harvest Strategy 3, and it was considered undesirable to have a discontinuity in fishing intensity once the limit reference point was breached. In addition, participants of the 3rd MSE Workshop intended to evaluate Harvest Strategy 3 rather than Harvest Strategy 1.</td></tr>
</table>

10	Harvest Strategy 2 should be removed from further consideration because the absence of a threshold reference point required a large drop in fishing intensity once the limit reference point was breached and it performed poorer than Harvest Strategy 3 with F50 or F40 in terms of Management Objective #2.	
11	The candidate target reference point of F30 should be removed from further consideration because it was the worst performing in terms of Management Objectives #1, 2, and 5, and had a similar performance to F40 for Management Objective #4.	
12	The candidate target reference point of F0204 should be removed from further consideration because the actual fishing intensity of this reference point varied substantially between productivity scenarios. It also performed poorer than TRP40 and TRP50 for Management Objectives #1, 2, and 5.	
13	A stricter risk level of 90% (rather than 50%) should be used when evaluating the risk of breaching the candidate limit reference points of SSB7.7% and SSB14% (i.e., the LRP is breached if the probability of being above the limit reference point drops below 90%). Given that the candidate limit reference point of SSB20% is relatively conservative, a risk level of 80% was considered appropriate for that reference point. This risk level should be calculated in the same way as is currently done in NPALB stock assessments, by using future projection software over a period of 10 years and calculating the probability of breaching the limit reference point.	• New HCRs tested in 2nd round of MSE use a 90% or 80% risk level of breaching candidate LRP. • Code was modified to calculate the probability of breaching the LRP using the projection software (2017 SA version) rather than the MLE estimate from EM output as in the 1st round of MSE. • The projection software is run for 10 years with 1,000 iterations within the MSE loop. The uncertainties in the projection software are derived from recruitment variability and initial N at age based on the CV of SSB.
14	In addition to harvest control rules where all fisheries are managed by total allowable effort (TAE) or total allowable catch (TAC), there should be an evaluation of harvest control	Code was modified to include a mixed TAC/TAE option as follows.

	rules where surface fisheries (i.e., Japan pole-and-line and EPO surface) are managed by TAE and all other fisheries are managed by TAC.	✓ Compute the overall TAC using the fishing intensity (1-SPR) according the status of the SSB relative to the reference points (as per TAC rule). ✓ The TAC is split across fleets according to the pre-agreed upon allocation (1999-2015 catch ratios) and is kept constant between assessments for the non–surface fleets. ✓ For the EPO surface fleet and the Japanese pole-and-line fleets the exploitation rate is kept constant between assessments, but the catch varies given the biomass from the OM.
15	The levels of fishing intensity should be limited by the historical (1997 – 2015) levels (or distributions of historical fishing intensity levels) achieved by the NPALB fisheries. However, if these levels of fishing intensity are not high enough to compare performance of threshold and limit reference points, low productivity scenario should be used in the operating models to evaluate these reference points, where appropriate.	Code was modified to set F as a random F sampled from historical Fs rather than F
16	A future fishing effort scenario where an unmanaged new fishery is removing an increasing amount of unreported catch should be evaluated to understand how large amounts of unreported catch may affect the performance of the harvest control rules.	Code was developed to include this as a robustness scenario. The new fishery has the characteristics of the F25 fleet operating in area 2 and 4.
17	Implementation error distribution should include both positive and negative errors.	Both positive and negative errors were included as 1.05 + N(0, σ=0.05).
18	The ISC ALBWG should continue working on the MSE process for a 2nd round because the results presented at the 4th ISC ALB MSE Workshop were useful for understanding the trade-offs and potential performance of candidate reference points	• Three LRPs (20%SSB0_d, 14%SSB0_d, and 7.7%SSB0_d) requested by the managers and stakeholders were also evaluated for further consideration of LRPS.

	and harvest control rules. However, some candidate reference points and harvest control rules developed at the 3rd MSE Workshop were not evaluated in time due to computer resource limitations. Therefore, the workshop participants developed a focused list of candidate reference points and harvest control rules to be examined for the 2nd round of MSE.	● This will be discussed at the 2nd round of MSE WS.
19	Pending approval by the ISC Plenary and resolving potential conflicts with the workload of the ALBWG, results of the 2nd round of MSE should be presented at the 5th ISC ALB MSE Workshop as soon as possible, and no later than late 2020.	It may be a good idea to distribute the preliminary report to the WS participants prior to the WS even though the ISC Plenary has not reviewed it. **The WG thought it was a good idea and recommended doing so as long as the ISC Plenary agrees. The WG Chair agreed to ask the ISC Chair about this matter in the near future.**
20	Given the timeline and previous computer resource limitations, it is important that improved computer resources be available for the 2nd round of ISC ALB MSE.	Some additional resources at NOAA were available until early 2020. Results were completed by late 2020 as planned.
21	The adequacy of 45 replicates per "run" (i.e., each OM-MP combination) should be examined to a) determine if the rank order of each run for each performance indicator was stable as more replicates are added; and b) determine if and how the value of each performance indicator varied with increasing numbers of replicates.	● **The WG recommended using broader risk classes based on the Table 4 from the 2nd ISC NPALB MSE workshop (attachment 5 in http://isc.fra.go.jp/pdf/ISC16/ISC16_Annex_08_Report_of_the_ALBWG(Apr2016).pdf) to group performance metrics based on probabilities.** For metrics not based on probabilities, it is suggested that the metric be split in classes prior to ranking. ● **The WG also agreed with the presenter that the 70 iterations for the 2nd round of MSE was adequate.** If certain iterations of the runs did not converge, the same set of converged iterations should be used to compare the candidate HCRs , noting which HCRs failed to complete the 70 iterations.

22	The relationship between how effort is modelled in the MSE operating models (i.e., fishing intensity) and effort in the real world should be examined by the ALBWG and included in the future round of MSE to help managers and stakeholders, if possible.	MSE fishing intensity was compared to real world effort.
23	Economic expertise, even though now is not available for the ALBWG, may be needed for future round of MSE since economic aspects are important incentives for the fishery industry.	This is related to Rec. #6.

Table 2. Details of candidate harvest controls at specific SSB relative to SSB reference points to be evaluated for the 2nd round of NPALB MSE. This Table was modified from Table 3 in the Report of the 4th ISC ALB MSE workshop (ISC 2019).

Stock Status	Candidate Harvest Control Rules
$SSB \geq SSB_{THRESHOLD}$	If $F_{TARGET} > F_{HISTORICAL}$, $TAE = H_{HISTORICAL}$ = H to produce $F_{HISTORICAL}$, $TAC = B_{LATEST} * H_{HISTORICAL}$ else $TAE = H_{TARGET}$ = H to produce F_{TARGET} $TAC = B_{LATEST} * H_{TARGET}$
$SSB_{LIMIT} < SSB < SSB_{THRESHOLD}$	$TAE = TAE_{MIN} + [H_{TARGET} - TAE_{MIN}] * (SSB - SSB_{LIMIT}) / (SSB_{THRESHOLD} - SSB_{LIMIT})$, or TAE_{MIN}, whichever is greater $TAC = TAC_{MIN} + [(B_{LATEST} * H_{TARGET}) - TAC_{MIN}] * (SSB - SSB_{LIMIT}) / (SSB_{THRESHOLD} - SSB_{LIMIT})$, or TAC_{MIN}, whichever is greater TAE_{MIN} and TAC_{MIN} are the TAEs and TACs when $SSB \leq SSB_{LIMIT}$, without the rebuilding plan (see below)
$SSB \leq SSB_{LIMIT}$	For LRPs (B_{LIMIT}) with $20\%SSB_{CURRENT, F=0}$, or $14\%SSB_{CURRENT, F=0}$ $TAE=0.25 * E_{SSBLIM}$ $TAE=0.5 * E_{SSBLIM}$ $TAC=0.25 * C_{SSBLIM}$ $TAC=0.5 * C_{SSBLIM}$ For LRPs (B_{LIMIT}) with $7.7\%SSB_{CURRENT, F=0}$ TAE=0 $TAE=0.25 * E_{SSBLIM}$ TAC=0 $TAC=0.25 * C_{SSBLIM}$ $E_{SSBLIM} = H_{TARGET} * SSB_{LIMIT} / SSB_{THRESHOLD}$ $C_{SSBLIM} = B_{LATEST} * H_{TARGET} * SSB_{LIMIT} / SSB_{THRESHOLD}$

Prob($SSB > SSB_{LIMIT}$)	For LRPs (B_{LIMIT}) with 20%$SSB_{CURRENT,\ F=0}$ Prob($SSB > SSB_{LIMIT}$) = 80% For LRPs (B_{LIMIT}) with 14%$SSB_{CURRENT,\ F=0}$, or 7.7%$SSB_{CURRENT,\ F=0}$ Prob($SSB>SSB_{LIMIT}$) = 90%
Prob($SSB > SSB_{THRESHOLD}$)	50%
Additional Assumptions	
Assessment periodicity	Once every 3 years
Allocation	Average of 1999-2015

Table 3. Fishery definitions for the operating and estimation models of the NPALB MSE. Availability of size and abundance index data is indicated in the notes. Notes indicate the size or index data fitted during conditioning. Two letter country codes are used in the fishery name: JP = Japan; US = United States of America; TW = Chinese-Taipei; KR = Korea; and VU = Vanuatu.

ID	Fishery name	Area	Primary gear	Quarter	Catch unit	Notes
F1	F1_JPLL_A13_Q1_wt	1 & 3	Longline	1	Tonnes	Size, Index
F2	F2_JPLL_A13_Q2_wt	1 & 3	Longline	2	Tonnes	Size
F3	F3_JPLL_A13_Q3_wt	1 & 3	Longline	3	Tonnes	Size
F4	F4_JPLL_A13_Q4_wt	1 & 3	Longline	4	Tonnes	Size
F5	F5_JPLL_A13_Q1_num	1 & 3	Longline	1	1000s	
F6	F6_JPLL_A13_Q2_num	1 & 3	Longline	2	1000s	
F7	F7_JPLL_A13_Q3_num	1 & 3	Longline	3	1000s	
F8	F8_JPLL_A13_Q4_num	1 & 3	Longline	4	1000s	
F9	F9_JPLL_A2_Q1_wt	2	Longline	1	Tonnes	Size, Index
F10	F10_JPLL_A2_Q234_wt	2	Longline	2, 3 & 4	Tonnes	Size

F11	F11_JPLL_A2_Q1_num	2	Longline	1	1000s	
F12	F12_JPLL_A2_Q234_num	2	Longline	2, 3 & 4	1000s	
F13	F13_JPLL_A4_wt	4	Longline	All	Tonnes	Size
F14	F14_JPLL_A4_num	4	Longline	All	1000s	
F15	F15_JPLL_A5_num	5	Longline	All	1000s	Size
F16	F16_JPPL_A3_Q12	3	Pole & line	1 & 2	Tonnes	Size
F17	F17_JPPL_A3_Q34	3	Pole & line	3 & 4	Tonnes	Size
F18	F18_JPPL_A2	2	Pole & line	All	Tonnes	Size
F19	F19_USLL_A35	3 & 5	Longline	All	Tonnes	Size
F20	F20_USLL_A24	2 & 4	Longline	All	Tonnes	Size
F21	F21_TWLL_A35	3 & 5	Longline	All	Tonnes	Size
F22	F22_TWLL_A24	2 & 4	Longline	All	Tonnes	
F23	F23_KRLL	All	Longline	All	Tonnes	
F24	F24_CNLL_A35	3 & 5	Longline	All	Tonnes	
F25	F25_CNLL_A24	2 & 4	Longline	All	Tonnes	
F26	F26_VULL	All	Longline	All	Tonnes	
F27	F27_EPOSF	3 & 5	Surface	All	Tonnes	
F28	F28_JPKRTW_DN	All	Drift net	All	Tonnes	
F29	F29_JPTW_MISC	All	Misc	All	Tonnes	

Table 4. Standardized values and input coefficients of variation (CVs) of north Pacific albacore annual abundance indices used for conditioning the operating models (OMs). Units are number of fish. Quarter refers to annual quarters in which the majority of catch was made in the underlying fishery, where 1 = Jan-Mar.

	S1 - Japanese longline in Area 2, Quarter 1		**S2 - Japanese longline in Area 1 and 3, Quarter 1**	
Year	**CPUE**	**CV**	**CPUE**	**CV**
1996	36.91	0.10	51.22	0.12
1997	41.25	0.10	76.52	0.12
1998	43.41	0.10	65.06	0.13
1999	33.32	0.10	47.03	0.12
2000	45.08	0.10	47.92	0.13
2001	40.53	0.10	30.25	0.13
2002	26.93	0.10	49.30	0.13
2003	29.67	0.09	56.74	0.12
2004	21.45	0.10	27.98	0.13
2005	28.82	0.10	28.05	0.13
2006	30.95	0.09	32.27	0.13
2007	27.43	0.09	42.54	0.13
2008	28.62	0.10	26.87	0.12
2009	28.86	0.10	29.50	0.12
2010	34.11	0.09	30.64	0.13
2011	26.40	0.10	27.34	0.13
2012	27.20	0.10	45.04	0.12
2013	25.97	0.11	30.21	0.12
2014	19.47	0.10	31.48	0.12
2015	33.74	0.10	45.01	0.12

Table 5. Key life history parameters and model structures for the base case OM. Fixed parameters different from the 2017 stock assessment are highlighted in italics. Parameters

estimated during the conditioning process are highlighted in bold. These also differ from the 2017 stock assessment. Note that in the forward simulation during the MSE "Future Process" all OM parameters are fixed.

Parameter	
Female asymptotic length (L_{inf})	*108.91 cm*
Female growth rate (k)	*0.2836 y^{-1}*
Female length at age-1 (L_1)	*45.06 cm*
Male L_{inf} Offset	*0.1187*
Male L_1 Offset	*0.0393*
Male k Offset	*-0.4179*
CV of L_1	0.06
CV of L_{inf}	0.04
Weight at length in kg for Q1	$8.7*10^{-5}L(cm)^{2.67}$ kg
Weight at length in kg for Q2	$3.9*10^{-5}L(cm)^{2.84}$ kg
Weight at length in kg for Q3	$2.1*10^{-5}L(cm)^{2.99}$ kg
Weight at length in kg for Q4	$2.8*10^{-5}L(cm)^{2.92}$ kg
Maturity	50% at age 5, 100% at age 6^+
Steepness (h)	0.9
Log of recruitment at virgin biomass ln(R_0)	**12.25**
Recruitment variability	0.5
Natural mortality age-0 (M0)	1.36 y^{-1}
Natural mortality age-1 (M1)	0.56 y^{-1}
Natural mortality age-2 (M2)	0.45 y^{-1}
Female natural mortality age-3+ (Mf3+)	0.48 y^{-1}
Male natural mortality age-3+ (Mm3+)	0.39 y^{-1}
Selectivity parameters	**See Table 6**
Standard deviation of age 1 age selectivity deviations for F27	**0.60**
Standard deviation of age 2 age selectivity deviations for F27	**0.90**
Standard deviation of age 3 age selectivity deviations for F27	**0.90**

Standard deviation of age 4 age selectivity deviations for F27	**0.80**
Catchability for S1 index	**0.005**
Catchability for S2 index	**0.001**

Table 6. Selectivity parameters used in the base case OM. The optional initial and final parameters for all double-normal selectivity curves were fixed at -999 and ignored by the model. The value for the first knot for all spline selectivity curves were fixed at 0 and values for the second and third knot were estimated relative to that. Knot locations in cm are indicated in parentheses in the years column. Fisheries without an estimated selectivity were assumed to have size selectivity identical to other fisheries (mirrored selectivity). Age selectivity was modeled as estimated free parameters for ages-1 to 5, with all other ages fixed at a negligible low value (-9). Note that for F27 yearly deviations in the age selectivity parameters for ages 1-4 were also estimated. The standard deviations for those age selectivity deviations are shown in Table 5.

Size selectivity only – double normal					
Fishery	Years	Parm 1 Size at peak	Parm 2 Plateau width	Parm 3 Ascending slope	Parm 4 Descending slope
F2	1993-2015	79.94	-9	3.82	4.56
F4	1993-2015	106.84	-1.12	5.63	2.87
F9	1993-2015	110.67	-9	5.63	3.24
F10	1993-2015	106.44	-9	4.67	3.60
F15	1993-2015	102.32	0.08	5.94	-0.47
F18	1993-2015	92.12	-9	4.12	2.31
F19	1993-2004	101.93	-0.53	6.12	1.19
	2005-2015	99.51	-6.81	5.92	6.10
F20	1993-2004	122.98	-6.20	5.42	-0.51
	2005-2015	124.08	0.09	5.60	4.29
F21	1993-2015	90.98	1.06	5.32	4.07
Size selectivity only – 3-knot spline					
Fishery	Years (knot locations in cm)	Gradient Low	Gradient High	Value at 2nd knot	Value at 3rd knot

F1	1993-2015 (60, 90, 130)	1.25	-1.60	8.11	-7.17
F3	1993-2015 (70, 95, 120)	0.69	-0.54	4.82	3.79
F13	1993-2015 (60, 90, 140)	0.17	-1.16	6.50	-3.93

Size selectivity only - mirrored

Fishery	Fishery mirrored to
F5	F1
F6	F2
F7	F3
F8	F4
F11	F9
F12	F10
F14, F22, F23, F25	F13
F24, F26	F26
F28, F29	F16

Size and age selectivity

Size selectivity – double normal

Fishery	Years	Parm 1 Size at peak	Parm 2 Plateau width	Parm 3 Ascending slope	Parm 4 Descending slope
F16	1993-2015	70.42	-9	4.42	4.70
F17	1993-2015	75.18	-9	4.98	4.04
F27	1993-2015	65.53	495	3.38	4.00

Age selectivity – free parameters for ages 1 to 5

Fishery	Years	Age 1	Age 2	Age 3	Age 4	Age 5
F16	1993-2015	4.04	-7.81	-8.95	-4.76	-4.59
F17	1993-2015	-0.16	-3.94	-4.63	-3.60	7.22
F27	1993-2015	9.28	-2.17	-0.93	-3.34	-2.82

Table 7. Steepness, growth and natural mortality parameter specifications for the operating models (OMs). See Table 5 for definitions of parameter symbols.

OM No.	h	L_{inf}	k	L_1	L_{inf} offset	k offset	L_1 offset	M0	M1	M2	Mf 3+	Mm3 +
1	0.90	108.91	0.2836	45.06	0.1187	-0.4179	0.0393	1.36	0.56	0.45	0.48	0.39
3	0.97	100.38	0.3826	43.03	0.2013	-0.7283	0.0848	1.36	0.56	0.45	0.48	0.39
4	0.97	117.38	0.2238	45.67	0.0691	-0.2458	0.0137	1.36	0.56	0.45	0.48	0.39
6	0.97	119.53	0.2055	47.10	0.0220	-0.0670	0.0110	1.01	0.42	0.33	0.36	0.29

Table 8. Median and standard deviation (σ) in the relative error of management relevant metrics estimated by the estimation model (EM, the simulated stock assessment) for different uncertainty scenarios and harvest control rules (HCRs) for harvest strategy 3. Spawning stock biomass (SSB) refers to the terminal year female SSB. The limit reference point (LRP) is computed as a fraction of dynamic unfished SSB, where the unfished SSB fluctuates depending on changes in recruitment. The target reference point (TRP) 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. F is the terminal year fishing intensity, computed as 1-SPR. Relative error was computed as: $(Value_{OM}-Value_{EM})/Value_{OM}$. The relative error was computed on the log-transformed values for SSB_{latest} and $SSB_{current,F=0}$. A negative value implies that the EM is overestimating the quantity of interest.

Scenario	HCR	SSB_{latest}		F		$SSB_{current,F=0}$		TRP	
		Mean	sd	Mean	sd	Mean	sd	Mean	sd
1	1	-0.01	0.01	0.04	0.07	0.00	0.005	0.00	0.02
	2	-0.01	0.01	0.05	0.07	0.00	0.004	0.00	0.02
	3	-0.01	0.01	0.05	0.08	0.00	0.005	0.00	0.02
	4	-0.01	0.01	0.04	0.07	0.00	0.005	0.00	0.02
	5	-0.01	0.01	0.04	0.08	0.00	0.005	0.00	0.02
	6	-0.01	0.01	0.04	0.07	0.00	0.004	0.00	0.02
	7	-0.01	0.01	0.02	0.07	0.00	0.004	0.00	0.02
	8	-0.01	0.01	0.04	0.07	0.00	0.005	0.00	0.02
	9	-0.01	0.01	0.04	0.07	0.00	0.005	0.00	0.02
	10	-0.01	0.01	0.05	0.08	0.00	0.005	0.00	0.02
	11	-0.01	0.01	0.06	0.07	0.00	0.005	0.00	0.02

	12	-0.01	0.01	0.04	0.07	0.00	0.004	0.00	0.02
	13	-0.01	0.01	0.04	0.08	0.00	0.005	0.00	0.02
	14	-0.01	0.01	0.04	0.07	0.00	0.004	0.00	0.03
	15	-0.01	0.01	0.04	0.07	0.00	0.004	0.00	0.02
	16	-0.01	0.01	0.03	0.07	0.00	0.004	0.00	0.02

Scenario	HCR	SSB_{latest}		F		$SSB_{current,F=0}$		TRP	
		Mean	sd	Mean	sd	Mean	sd	Mean	sd
3	1	0.01	0.01	-0.12	0.10	0.00	0.005	0.06	0.01
	2	0.01	0.01	-0.12	0.12	0.00	0.006	0.06	0.01
	3	0.01	0.01	-0.12	0.11	0.00	0.006	0.06	0.01
	4	0.01	0.01	-0.12	0.11	0.00	0.006	0.06	0.01
	5	0.01	0.01	-0.10	0.10	0.00	0.006	0.06	0.01
	6	0.01	0.01	-0.09	0.10	-0.01	0.005	0.06	0.01
	7	0.01	0.01	-0.10	0.10	0.00	0.005	0.06	0.02
	8	0.01	0.01	-0.10	0.09	0.00	0.005	0.06	0.01
	9	0.01	0.01	-0.11	0.10	0.00	0.005	0.06	0.01
	10	0.01	0.01	-0.11	0.12	0.00	0.006	0.06	0.01

	11	0.01	0.01	-0.12	0.11	0.00	0.005	0.06	0.01
	12	0.01	0.01	-0.13	0.11	0.00	0.006	0.06	0.01
	13	0.01	0.01	-0.11	0.11	0.00	0.006	0.06	0.01
	14	0.01	0.01	-0.10	0.10	0.00	0.005	0.06	0.02
	15	0.01	0.01	-0.10	0.11	-0.01	0.006	0.06	0.01
	16	0.01	0.01	-0.10	0.10	-0.01	0.005	0.06	0.01

Scenario	HCR	SSB_{latest}		F		$SSB_{current,F=0}$		TRP	
		Mean	sd	Mean	sd	Mean	sd	Mean	sd
4	1	-0.04	0.02	0.18	0.07	-0.01	0.006	-0.05	0.02
	2	-0.04	0.02	0.18	0.07	-0.01	0.005	-0.05	0.02
	3	-0.04	0.02	0.17	0.07	-0.01	0.006	-0.05	0.02
	4	-0.04	0.02	0.17	0.07	-0.01	0.006	-0.05	0.02
	5	-0.04	0.02	0.18	0.07	-0.01	0.005	-0.05	0.02
	6	-0.03	0.02	0.13	0.07	-0.01	0.006	-0.05	0.02
	7	-0.03	0.02	0.12	0.07	-0.01	0.006	-0.06	0.02
	8	-0.03	0.02	0.12	0.07	-0.01	0.006	-0.06	0.02
	9	-0.04	0.02	0.18	0.06	-0.01	0.005	-0.05	0.02

	10	-0.04	0.02	0.18	0.07	-0.01	0.006	-0.05	0.01
	11	-0.04	0.02	0.17	0.07	-0.01	0.005	-0.05	0.02
	12	-0.04	0.02	0.18	0.07	-0.01	0.006	-0.05	0.02
	13	-0.04	0.02	0.19	0.07	-0.01	0.006	-0.05	0.02
	14	-0.03	0.02	0.13	0.07	-0.01	0.005	-0.06	0.02
	15	-0.03	0.02	0.13	0.07	-0.01	0.005	-0.06	0.02
	16	-0.03	0.02	0.13	0.08	-0.01	0.006	-0.06	0.02

Scenario	HCR	SSB_{latest}		F		$SSB_{current,F=0}$		TRP	
		Mean	sd	Mean	sd	Mean	sd	Mean	sd
6	1	-0.05	0.03	0.30	0.08	0.01	0.011	-0.05	0.02
	2	-0.05	0.03	0.30	0.08	0.01	0.011	-0.05	0.02
	3	-0.05	0.03	0.30	0.07	0.01	0.010	-0.05	0.02
	4	-0.05	0.04	0.29	0.08	0.01	0.011	-0.05	0.02
	5	-0.05	0.03	0.30	0.08	0.01	0.010	-0.04	0.02
	6	-0.04	0.07	0.23	0.10	0.02	0.012	-0.02	0.02
	7	-0.04	0.03	0.22	0.09	0.02	0.011	-0.03	0.02
	8	-0.04	0.03	0.22	0.09	0.02	0.011	-0.02	0.02

	9	-0.05	0.03	0.31	0.07	0.01	0.010	-0.05	0.02
	10	-0.05	0.03	0.30	0.08	0.01	0.011	-0.05	0.02
	11	-0.05	0.03	0.30	0.07	0.01	0.010	-0.05	0.02
	12	-0.05	0.03	0.29	0.07	0.01	0.010	-0.05	0.02
	13	-0.05	0.03	0.30	0.08	0.01	0.011	-0.05	0.02
	14	-0.04	0.05	0.22	0.12	0.02	0.012	-0.02	0.02
	15	-0.04	0.04	0.23	0.10	0.02	0.012	-0.02	0.02
	16	-0.04	0.05	0.22	0.10	0.02	0.012	-0.02	0.02

Table 9. List of completed 30-year iterations for each HCR, scenario, and management control combination.

HCR	Scenario 1	Scenario 3	Scenario 4	Scenario 6
	Mixed Control			
1	70	70	70	70
2	67	70	70	70
3	70	70	70	70
4	70	70	70	70
5	70	70	70	70
6	70	70	70	70
7	70	70	70	70
8	70	70	70	70
9	70	70	70	70
10	70	70	70	70
11	70	70	70	70
12	70	68	70	70
13	70	70	70	70
14	70	70	69	70
15	70	70	70	69
16	70	70	70	70
	TAC Control			
1	70	70	70	70
2	70	70	70	69
3	70	70	70	70
4	70	70	70	70
5	70	70	70	70
6	60	70	66	62
7	59	70	70	56

8	59	70	69	60
9	70	70	70	69
10	70	70	70	69
11	70	70	70	69
12	70	70	69	69
13	70	70	70	69
14	52	70	69	64
15	56	70	69	58
16	60	70	67	61

Table 10. Performance of indicators for each harvest control rule under mixed control for the low productivity scenario, OM6. Larger values indicate better performance. HCR refers to harvest control rule, LRP to limit reference point, $SSB_{threshold}$ to the threshold reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. The LRP and $SSB_{threshold}$ are SSB-based and refer to the specified fraction of SSB0. Unless specified as equilibrium SSB0, the unfished SSB is dynamic and fluctuates depending on changes in recruitment. See Table ES1 for a detailed definition of performance indicators.Colors represent risk categories as defined in the caption and legend for Table ES4.

Mixed Control

Low Productivity Scenario

hcr	scn	TRP	LRP	SSBthreshold	Odds of Not Breaching the LRP	Odds SSB > 20% SSBo	Odds SSB > Equilibrium 7.7% SSBo	Odds SSB > 7.7% SSBo	Odds Depletion > Minimum Historical	Odds Mean Annual Catch > Historical	Odds Mean Medium Term Catch > Historical Catch	Odds Mean Long Term Catch > Historical Catch	Catch Stability	Odds No Management Action	Ftarget/F
1	6	F50	0.200	0.30	0.90	0.90	0.93	1.00	0.82	0.47	0.43	0.55	1.00	0.58	0.77
2	6	F50	0.140	0.30	0.97	0.89	0.92	0.99	0.82	0.48	0.43	0.57	1.00	0.57	0.77
3	6	F50	0.077	0.30	0.99	0.89	0.93	0.99	0.82	0.47	0.42	0.56	1.00	0.58	0.77
4	6	F50	0.140	0.20	0.97	0.90	0.93	1.00	0.82	0.48	0.42	0.56	1.00	0.90	0.77
5	6	F50	0.077	0.20	0.99	0.89	0.92	0.99	0.82	0.49	0.43	0.57	1.00	0.89	0.77
6	6	F40	0.140	0.20	0.91	0.74	0.88	0.98	0.77	0.67	0.61	0.76	0.99	0.74	0.82
7	6	F40	0.077	0.20	0.98	0.74	0.88	0.98	0.77	0.67	0.62	0.76	0.99	0.74	0.81
8	6	F40	0.077	0.14	0.98	0.74	0.88	0.98	0.77	0.68	0.63	0.77	1.00	0.91	0.82
9	6	F50	0.200	0.30	0.89	0.89	0.92	0.99	0.82	0.48	0.45	0.57	1.00	0.57	0.77
10	6	F50	0.140	0.30	0.97	0.90	0.93	0.99	0.82	0.48	0.42	0.57	1.00	0.58	0.77
11	6	F50	0.077	0.30	0.99	0.89	0.92	0.99	0.82	0.48	0.44	0.58	1.00	0.57	0.76
12	6	F50	0.140	0.20	0.97	0.90	0.93	1.00	0.82	0.47	0.43	0.56	1.00	0.90	0.77
13	6	F50	0.077	0.20	1.00	0.90	0.93	1.00	0.82	0.48	0.44	0.57	1.00	0.90	0.77
14	6	F40	0.140	0.20	0.91	0.74	0.89	0.98	0.77	0.67	0.63	0.75	1.00	0.74	0.82
15	6	F40	0.077	0.20	0.98	0.74	0.88	0.98	0.77	0.67	0.63	0.76	1.00	0.74	0.82
16	6	F40	0.077	0.14	0.98	0.74	0.88	0.98	0.77	0.67	0.62	0.77	1.00	0.91	0.82

Table 11. Performance of indicators for each harvest control rule under TAC control for the low productivity scenario, OM6. Larger values indicate better performance. HCR refers to harvest control rule, LRP to limit reference point, $SSB_{threshold}$ to the threshold reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. The LRP and $SSB_{threshold}$ are SSB-based and refer to the specified fraction of SSB0. Unless specified as equilibrium SSB0, the unfished SSB is dynamic and fluctuates depending on changes in recruitment. See Table ES1 for a detailed definition of performance indicators.Colors represent risk categories as defined in the caption and legend for Table ES4.

TAC Control

Low Productivity Scenario

hcr	scn	TRP	LRP	SSBthreshold	Odds of Not Breaching the LRP	Odds SSB > 20% SSBo	Odds SSB > Equilibrium 7.7% SSBo	Odds SSB > 7.7% SSBo	Odds Depletion > Minimum Historical	Odds Mean Annual Catch > Historical	Odds Mean Medium Term Catch > Historical Catch	Odds Mean Long Term Catch > Historical Catch	Catch Stability	Odds No Management Action	Ftarget/F
1	6	F50	0.200	0.30	0.66	0.66	0.85	0.94	0.71	0.59	0.58	0.63	0.54	0.31	0.67
2	6	F50	0.140	0.30	0.83	0.66	0.85	0.94	0.71	0.59	0.57	0.63	0.55	0.31	0.67
3	6	F50	0.077	0.30	0.94	0.64	0.85	0.94	0.70	0.61	0.64	0.64	0.59	0.27	0.66
4	6	F50	0.140	0.20	0.83	0.65	0.85	0.94	0.70	0.60	0.59	0.63	0.62	0.65	0.66
5	6	F50	0.077	0.20	0.93	0.62	0.84	0.93	0.69	0.63	0.62	0.69	0.63	0.62	0.65
6	6	F40	0.140	0.20	0.74	0.54	0.81	0.89	0.66	0.61	0.49	0.71	0.45	0.54	0.75
7	6	F40	0.077	0.20	0.88	0.53	0.81	0.88	0.66	0.63	0.48	0.73	0.43	0.53	0.76
8	6	F40	0.077	0.14	0.87	0.49	0.79	0.87	0.64	0.63	0.54	0.72	0.48	0.70	0.74
9	6	F50	0.200	0.30	0.64	0.64	0.85	0.94	0.70	0.61	0.64	0.64	0.60	0.28	0.66
10	6	F50	0.140	0.30	0.83	0.66	0.86	0.94	0.71	0.59	0.55	0.65	0.57	0.30	0.67
11	6	F50	0.077	0.30	0.95	0.66	0.86	0.95	0.71	0.61	0.62	0.66	0.66	0.28	0.67
12	6	F50	0.140	0.20	0.83	0.65	0.85	0.94	0.71	0.62	0.59	0.67	0.66	0.65	0.66
13	6	F50	0.077	0.20	0.94	0.63	0.85	0.94	0.70	0.62	0.60	0.66	0.66	0.63	0.66
14	6	F40	0.140	0.20	0.73	0.52	0.81	0.88	0.64	0.62	0.51	0.71	0.47	0.52	0.75
15	6	F40	0.077	0.20	0.89	0.52	0.81	0.89	0.65	0.62	0.48	0.71	0.45	0.52	0.76
16	6	F40	0.077	0.14	0.88	0.49	0.80	0.88	0.64	0.63	0.54	0.71	0.49	0.71	0.75

Table 12. Results for performance metric 3, the average harvest ratio over the 30 years simulation over the mean historical (2006-2015) harvest ratio by harvest control rule, fleet, and management control type.

	Mixed control							
HCR	EPO	JPPL	JPLL	USLL	TWLL	KRLL	CHLL	VNLL
1	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
2	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
3	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
4	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
5	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
6	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
7	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
8	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
9	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
10	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
11	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
12	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
13	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
14	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
15	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38
16	1.22	0.97	1.03	1.17	1.41	0.26	6.97	3.38

	TAC control							
HCR	EPO	JPPL	JPLL	USLL	TWLL	KRLL	CHLL	VNLL
1	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
2	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
3	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
4	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
5	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
6	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
7	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
8	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
9	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
10	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
11	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
12	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
13	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
14	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
15	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00
16	1.33	1.09	0.91	1.01	1.27	0.23	6.06	3.00

Table 13. Performance of indicators for each harvest control rule under mixed control for the unknown fleet robustness scenario. Larger values indicate better performance. HCR refers to harvest control rule, LRP to limit reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. Unless specified as equilibrium SSB0, the SSB0 is dynamic (i.e., SSB0_d) and fluctuates depending on changes in recruitment. See table ES1 for a detailed definition of performance indicators. Colors represent risk categories as defined in the caption and legend for Table ES4.

Mixed Control
Unknown Fleet Robustness Scenario

hcr	TRP	LRP	SSB threshold	Odds of Not Breaching the LRP	Odds SSB > 20% SSBo	Odds SSB > Equilibrium 7.7% SSBo	Odds SSB > 7.7% SSBo	Odds Depletion > Minimum Historical	Odds Mean Annual Catch > Historical	Odds Mean Medium Term Catch > Historical Catch	Odds Mean Long Term Catch > Historical Catch	Catch Stability	Odds No Management Action	Ftarget/F
9	F50	0.20	0.30	0.98	0.98	0.95	1	0.62	0.43	0.53	0.30	0.78	0.78	0.80
10	F50	0.14	0.30	1.00	0.97	0.95	1	0.62	0.44	0.54	0.31	0.79	0.77	0.79
11	F50	0.08	0.30	1.00	0.98	0.95	1	0.62	0.44	0.53	0.32	0.85	0.77	0.79
12	F50	0.14	0.20	1.00	0.97	0.95	1	0.61	0.45	0.55	0.34	0.94	0.97	0.78
13	F50	0.08	0.20	1.00	0.97	0.95	1	0.61	0.45	0.54	0.34	0.94	0.97	0.78
14	F40	0.14	0.20	1.00	0.97	0.95	1	0.61	0.45	0.53	0.36	0.96	0.97	0.94
15	F40	0.08	0.20	1.00	0.97	0.95	1	0.61	0.46	0.55	0.35	0.92	0.97	0.94
16	F40	0.08	0.14	1.00	0.97	0.95	1	0.62	0.45	0.54	0.35	0.97	1.00	0.94

Table 14. Performance of indicators for each harvest control rule under TAC control for the unknown fleet robustness scenario. Larger values indicate better performance. HCR refers to harvest control rule, LRP to limit reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. Unless specified as equilibrium SSB0, the SSB0 is dynamic (i.e., SSB0_d) and fluctuates depending on changes in recruitment. See table ES1 for a detailed definition of performance indicators. Colors represent risk categories as defined in the caption and legend for Table ES4.

TAC Control
Unknown Fleet Robustness Scenario

hcr	TRP	LRP	SSB threshold	Odds of Not Breaching the LRP	Odds SSB > 20% SSBo	Odds SSB > Equilibrium 7.7% SSBo	Odds SSB > 7.7% SSBo	Odds Depletion > Minimum Historical	Odds Mean Annual Catch > Historical	Odds Mean Medium Term Catch > Historical Catch	Odds Mean Longterm Term Catch > Historical Catch	Catch Stability	Odds No Management Action	Ftarget/F
9	F50	0.20	0.30	0.95	0.95	0.93	1.00	0.61	0.36	0.37	0.21	0.54	0.70	0.78
12	F50	0.14	0.20	0.99	0.94	0.92	1.00	0.61	0.36	0.43	0.19	0.66	0.94	0.77
14	F40	0.14	0.20	0.96	0.86	0.91	0.99	0.56	0.52	0.48	0.41	0.47	0.86	0.86
16	F40	0.08	0.14	0.99	0.86	0.90	0.99	0.56	0.53	0.54	0.42	0.59	0.96	0.86

10 Figures

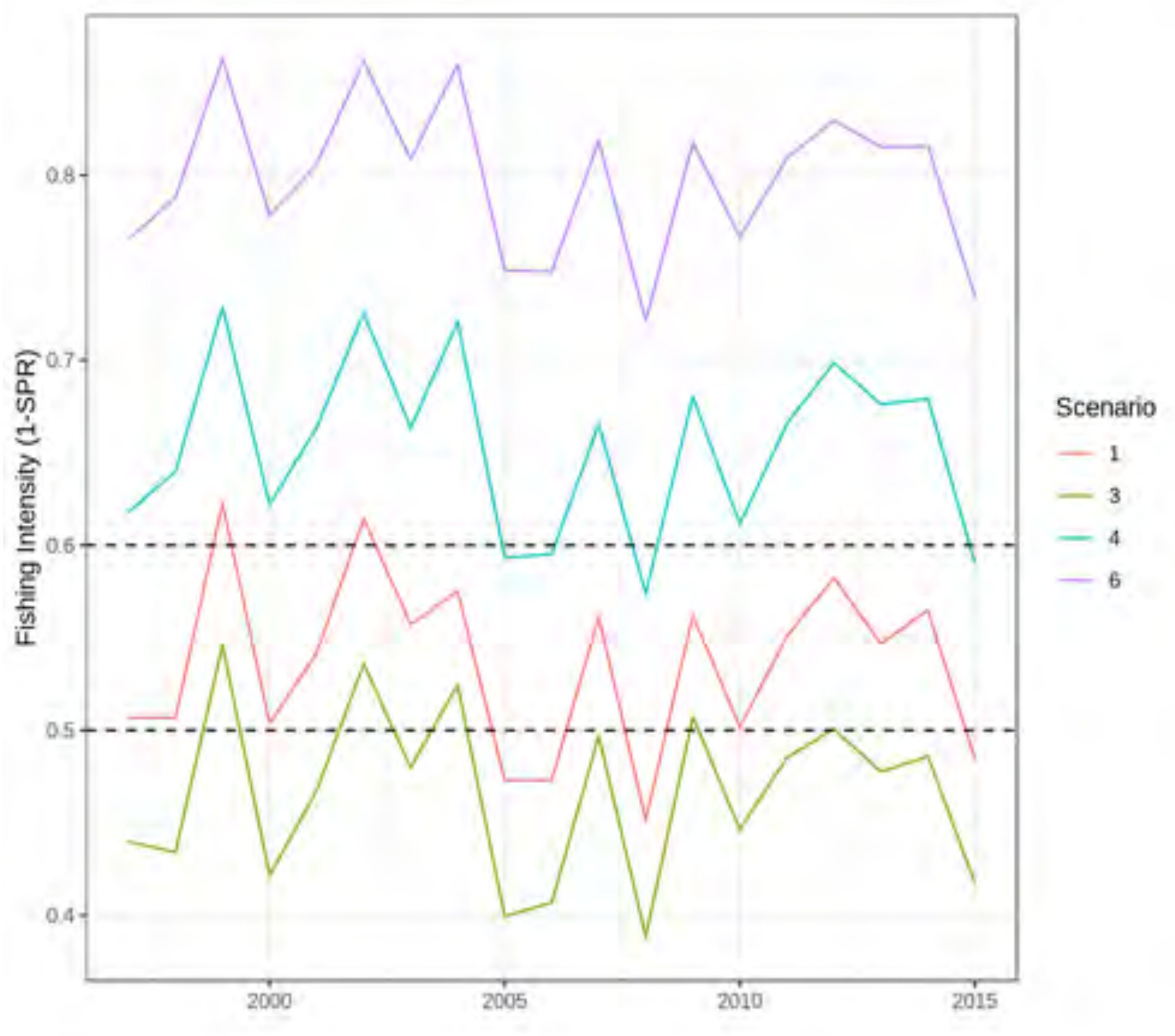


Figure 1. Trends in fishing intensity (1-SPR) for the four operating models used in the reference set. 1-SPR is the reduction in female SSB per recruit due to fishing and is used to describe the overall fishing intensity on the stock. The dotted lines represent the fishing intensity associated with each of the target reference points (TRP) under consideration, 0.6 for the F40 TRP and 0.5 for the F50 TRP.

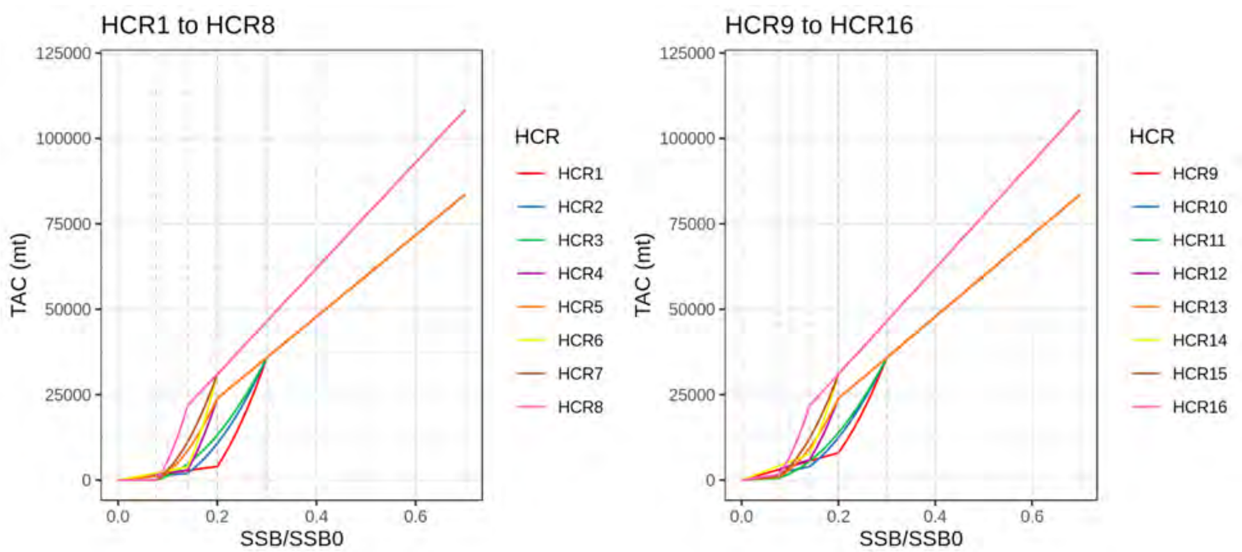


Figure 2. Changes in TAC associated with the harvest control rules (HCRs) tested in the second round of MSE for NPALB and represented in Fig. ES1. Note that the TAC levels are approximate and will depend on the age structure of the population, selectivities and relative fishing intensity between fleets of the simulation run under consideration. Note that catches in the MSE simulation were capped to 120,000 mt, the maximum over the historical period.

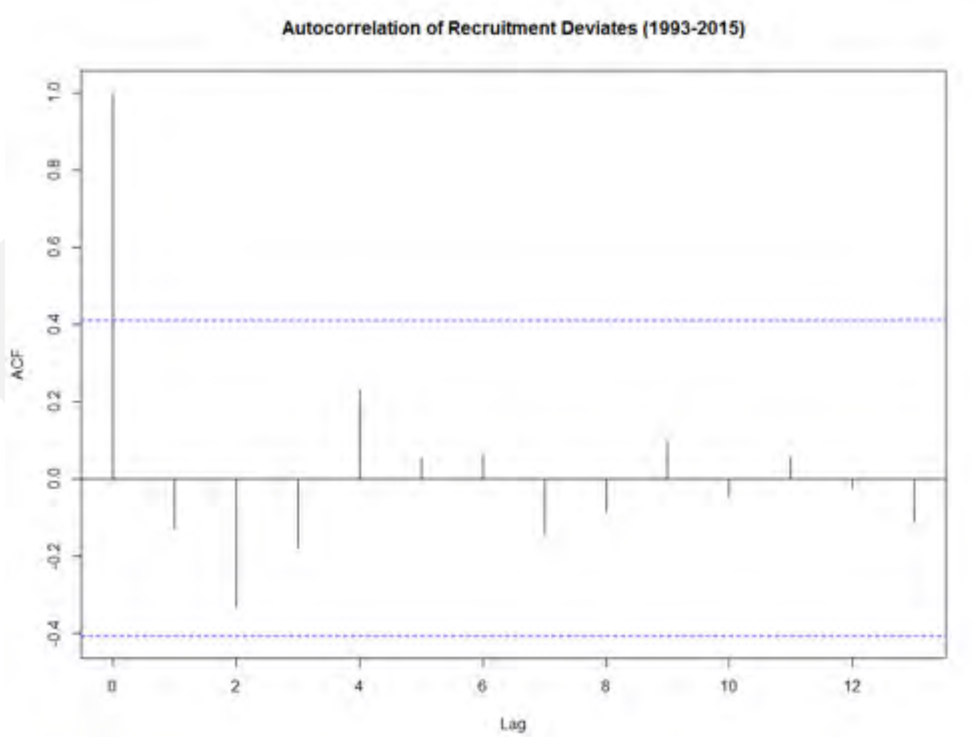


Figure 3. Autocorrelation from lag 0 to lag 13 of recruitment deviates from the 2015 stock assessment base model starting in 1993.

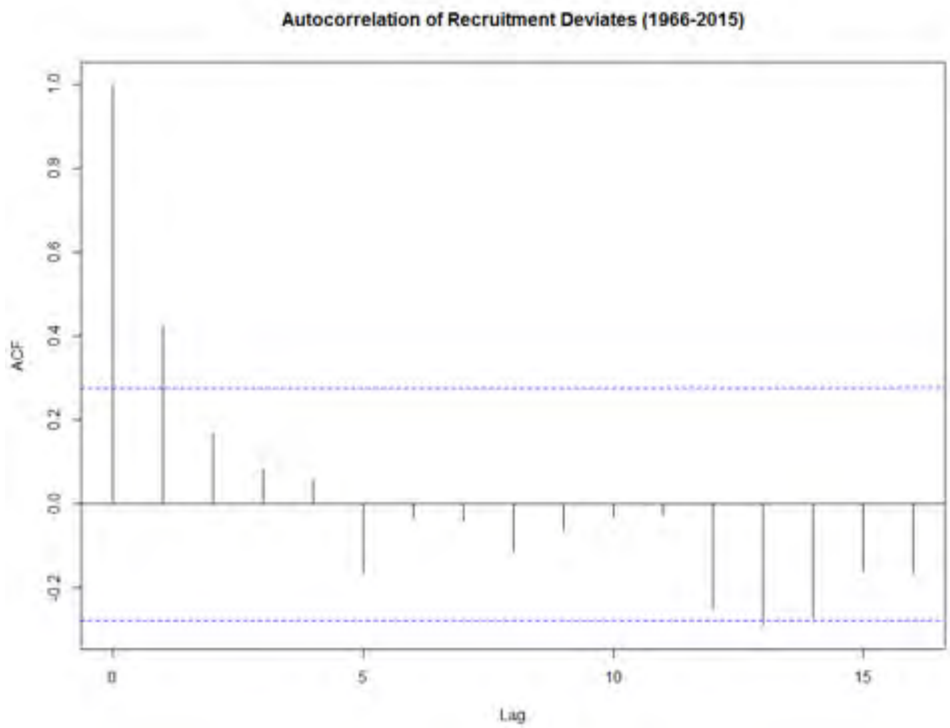


Figure 4. Autocorrelation from lag 0 to lag 16 of recruitment deviates from the 2015 stock assessment sensitivity model run starting in 1966.

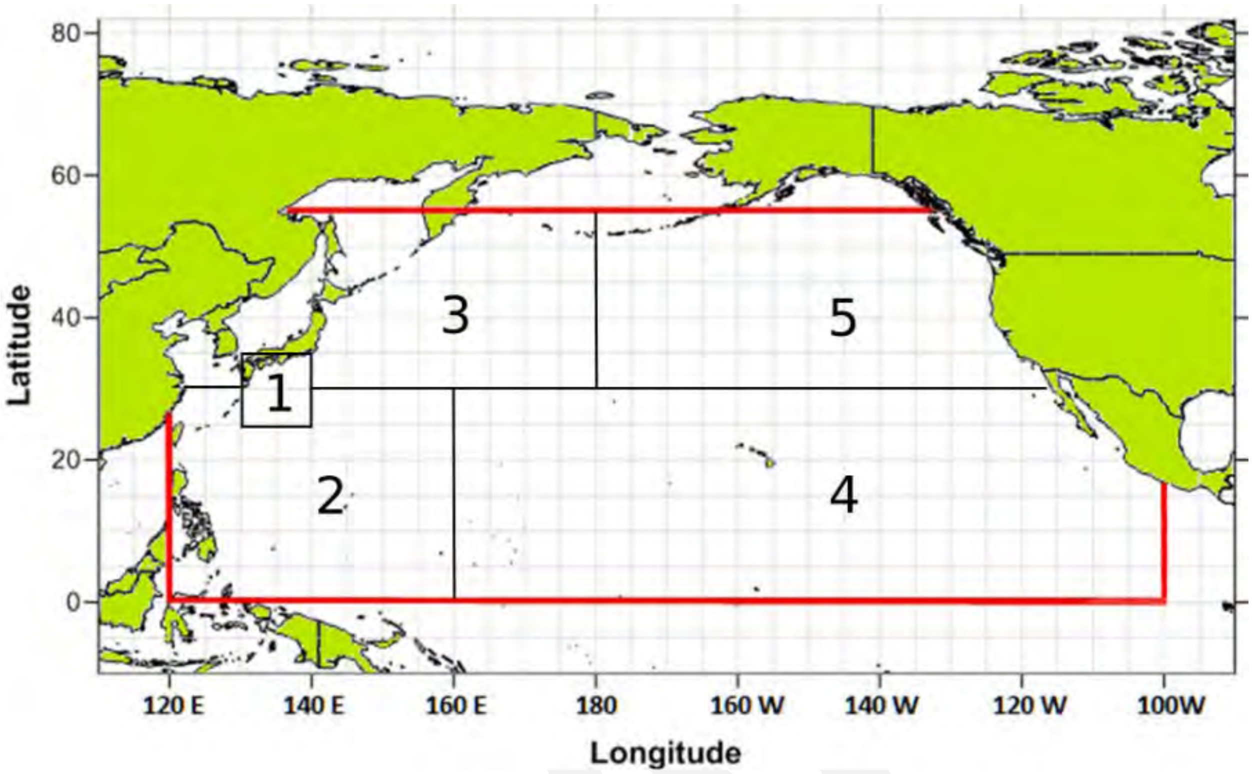


Figure 5. Spatial domain (red box) of the north Pacific albacore stock (*Thunnus alalunga*) in the 2017 stock assessment. Fishery definitions were based on five fishing areas (black boxes and numbers) defined from cluster analyses of size composition data.

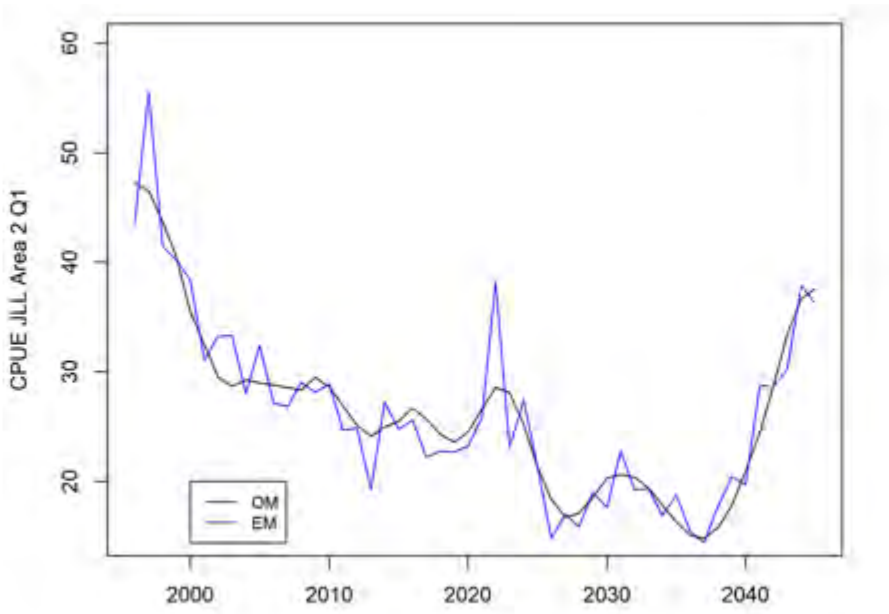


Figure 6. True S1 (Japanese longline operating in Area 2, quarter 1) CPUE time series from the operating model (OM, black line) and CPUE with error input into the estimation model (EM, blue line) taken from a random MSE simulation.

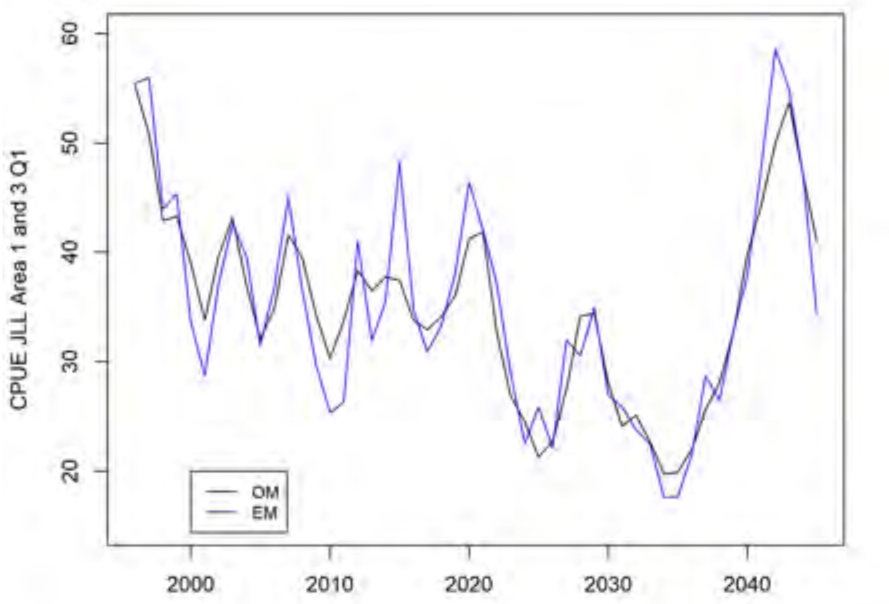


Figure 7. An example from a random MSE simulation of a "true" S2 (Japanese longline operating in Areas 1 and 3, quarter 1) CPUE time series from the operating model (OM, black line) and the corresponding CPUE time series with error that were used as data inputs in the estimation model (EM, blue line).

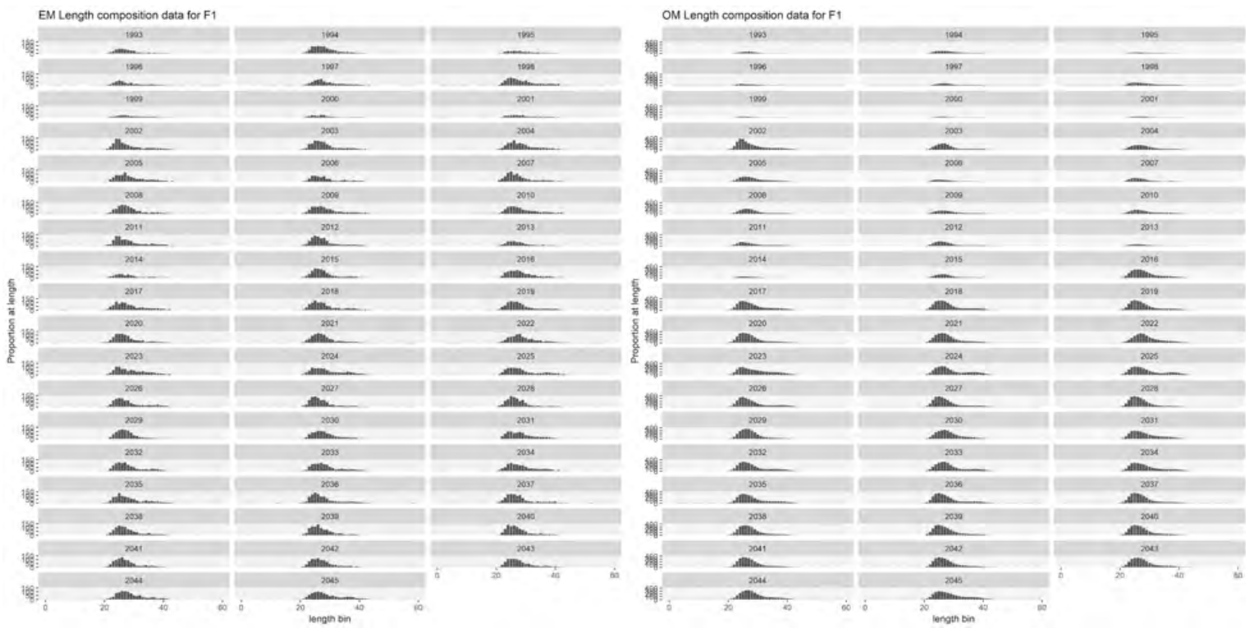


Figure 8. An example from a random MSE simulation of size composition data with error used as data inputs in the estimation model (EM, left) and the "true" size composition data from the operating model (OM, right) for the F1 fisheries (Japanese longline operating in Areas 1 and 3 in quarter 1.

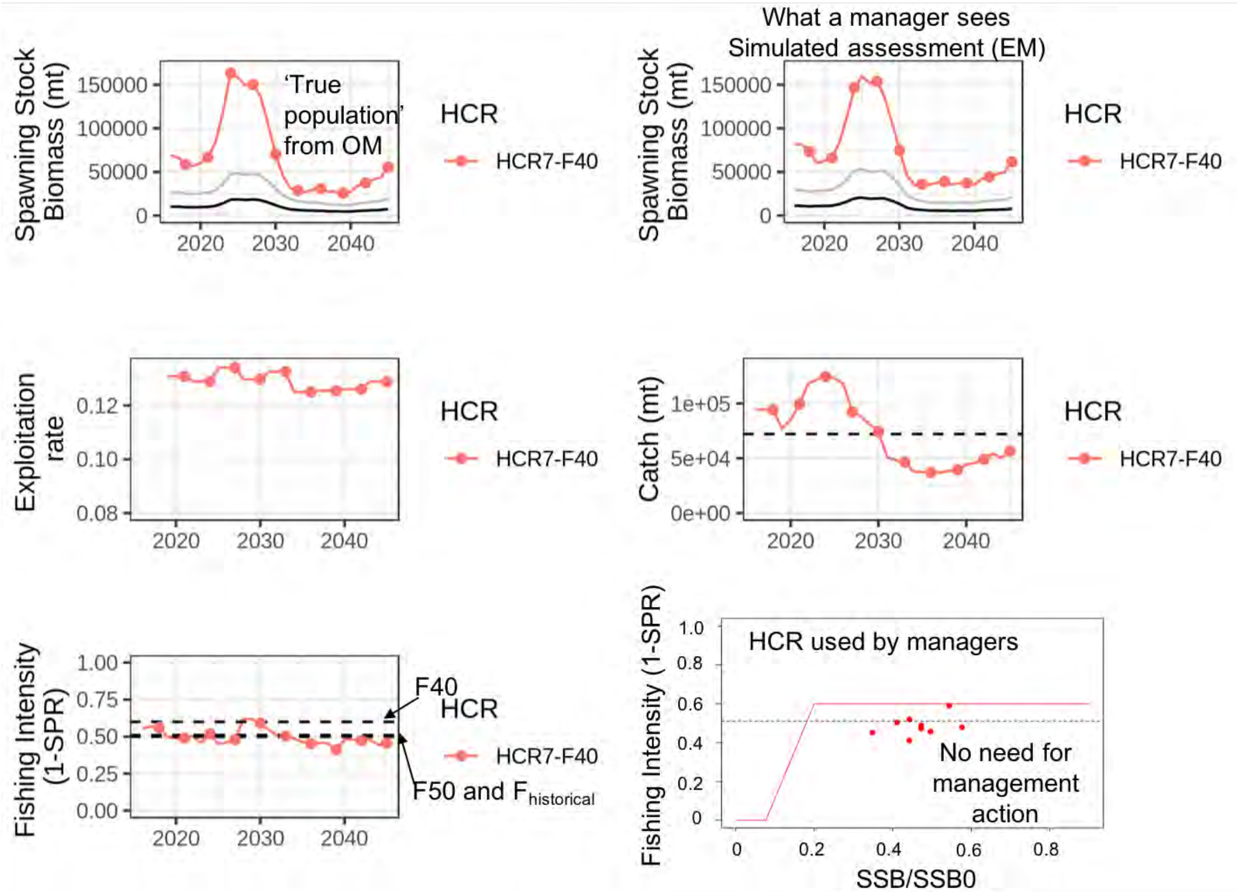


Figure 9. Trends in the 'true' female spawning stock biomass (SSB) from the operating model (OM), estimated SSB from the estimation model (EM), catch, exploitation rate from the EM, and fishing intensity from the EM from the MSE forward simulation of iteration #60, scenario 1, and HCR7. Also shown is the HCR with the fishing intensity and relative biomass as estimated by the EM overlaid. The grey line in the top panels refers to the $SSB_{threshold}$ reference point and the black line to the limit reference point. The dotted line in the catch panel is the average historical catch and the dotted line in the HCR plot is the average historical fishing intensity for scenario 1.

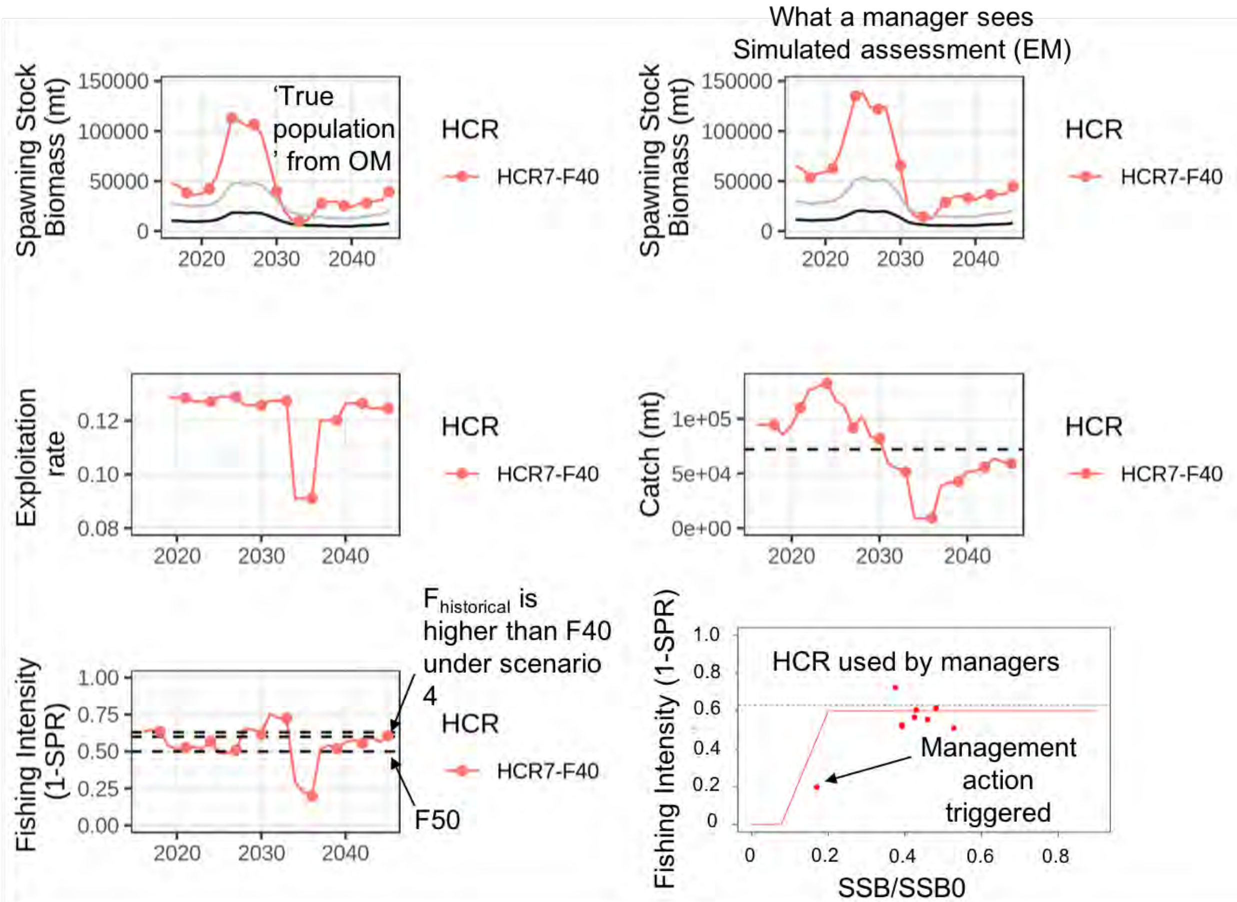


Figure 10. Trends in the 'true' female spawning stock biomass (SSB) from the operating model (OM), estimated SSB from the estimation model (EM), catch, exploitation rate from the EM, and fishing intensity from the EM from the MSE forward simulation of iteration #60, scenario 4, and HCR7. Also shown is the HCR with the fishing intensity and relative biomass as estimated by the EM overlaid. The grey line in the top panels refers to the $SSB_{threshold}$ reference point and the black line to the limit reference point. The dotted line in the catch panel is the average historical catch and the dotted line in the HCR plot is the average historical fishing intensity for scenario 4.

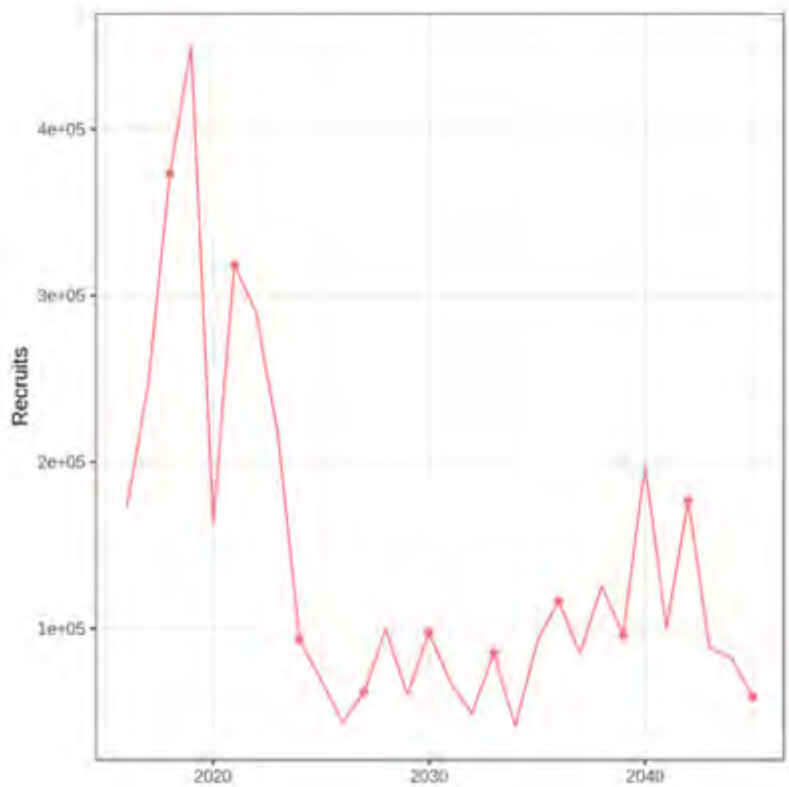


Figure 11. Trends in recruitment from the operating model (OM) for iteration #60.

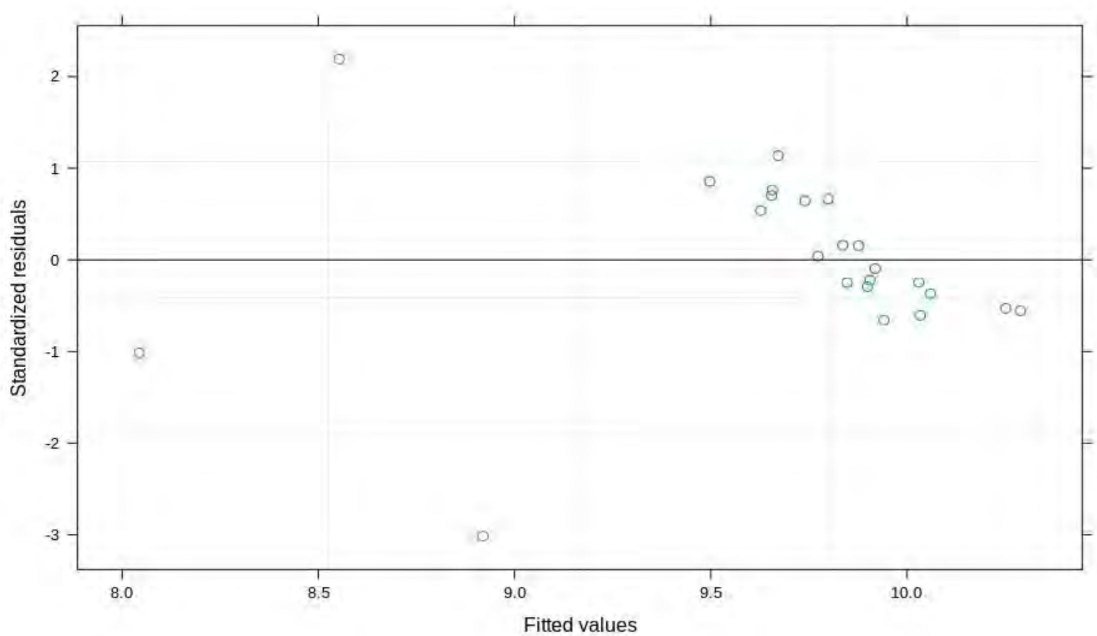


Figure 12. Standardized residuals against fitted values for the linear model of log-transformed effort and log-transformed exploitation rate for the Eastern Pacific Ocean surface fleet.

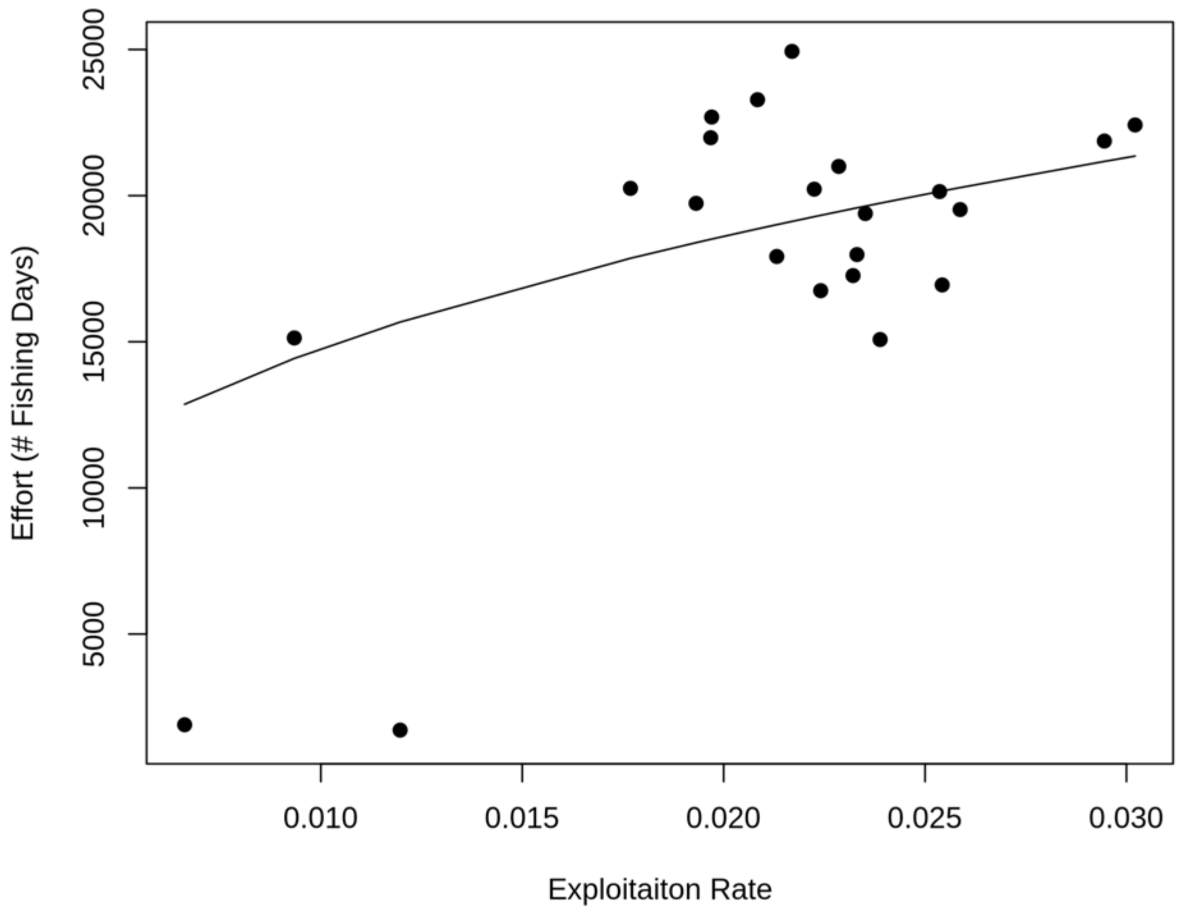


Figure 13. Observed log-transformed effort (number of fishing days) against exploitation rate for the Eastern Pacific Ocean surface fleet (circles) and fitted relationship.

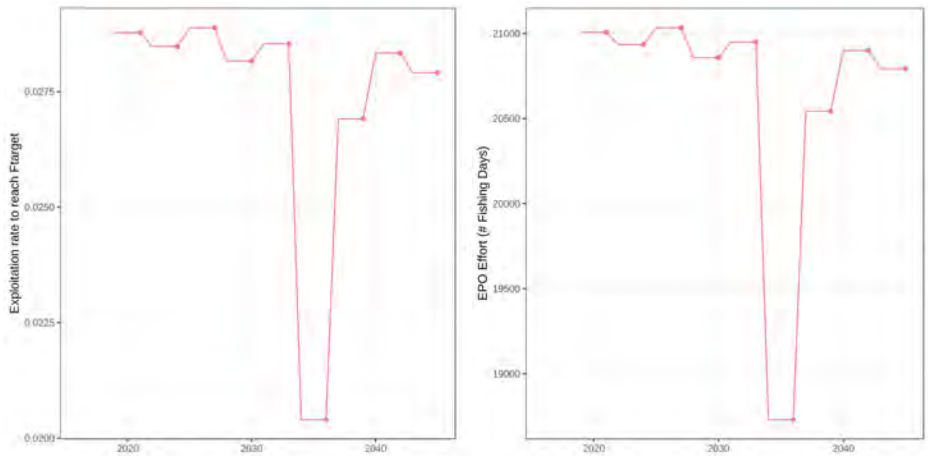


Figure 14. Trends in exploitation rate for the Eastern Pacific Ocean from HCR7, iteration #60, scenario 4, translated into a measure of effort in number of fishing days.

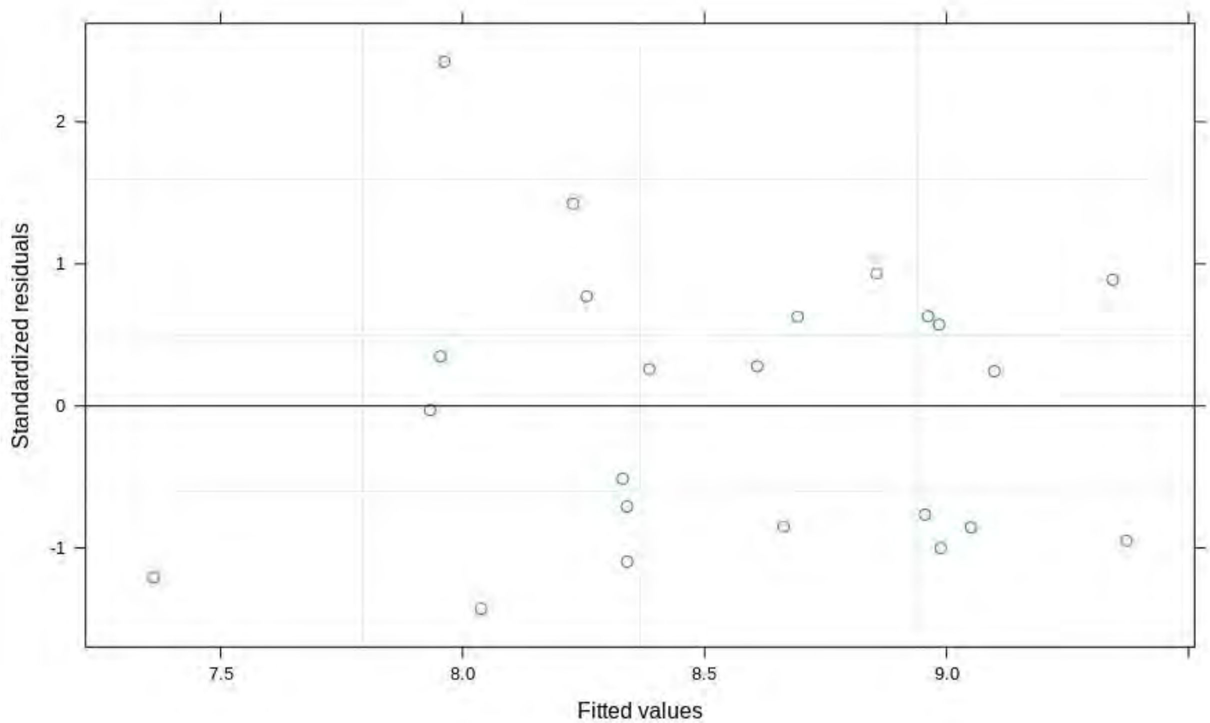


Figure 15. Standardized residuals against fitted values for the linear model of log-transformed effort and log-transformed exploitation rate for the Japanese pole-and-line fishery.

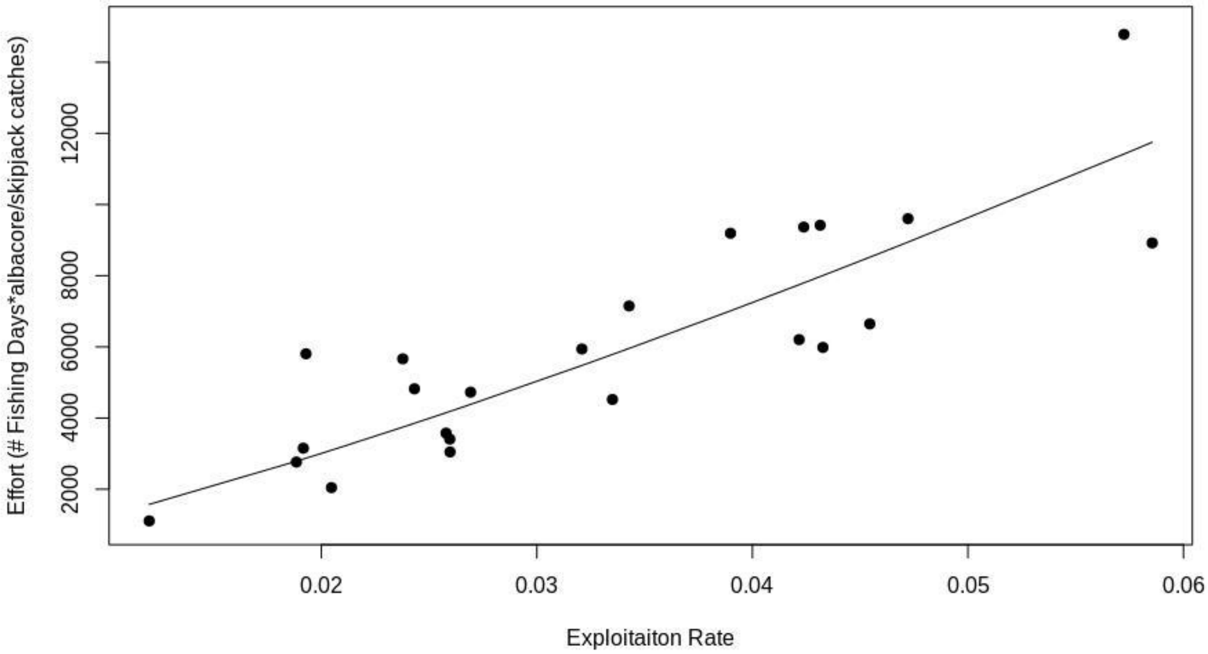


Figure 16. Observed log-transformed effort (number of fishing days) against exploitation rate for the Japanese pole-and-line fishery (circles) and fitted relationship.

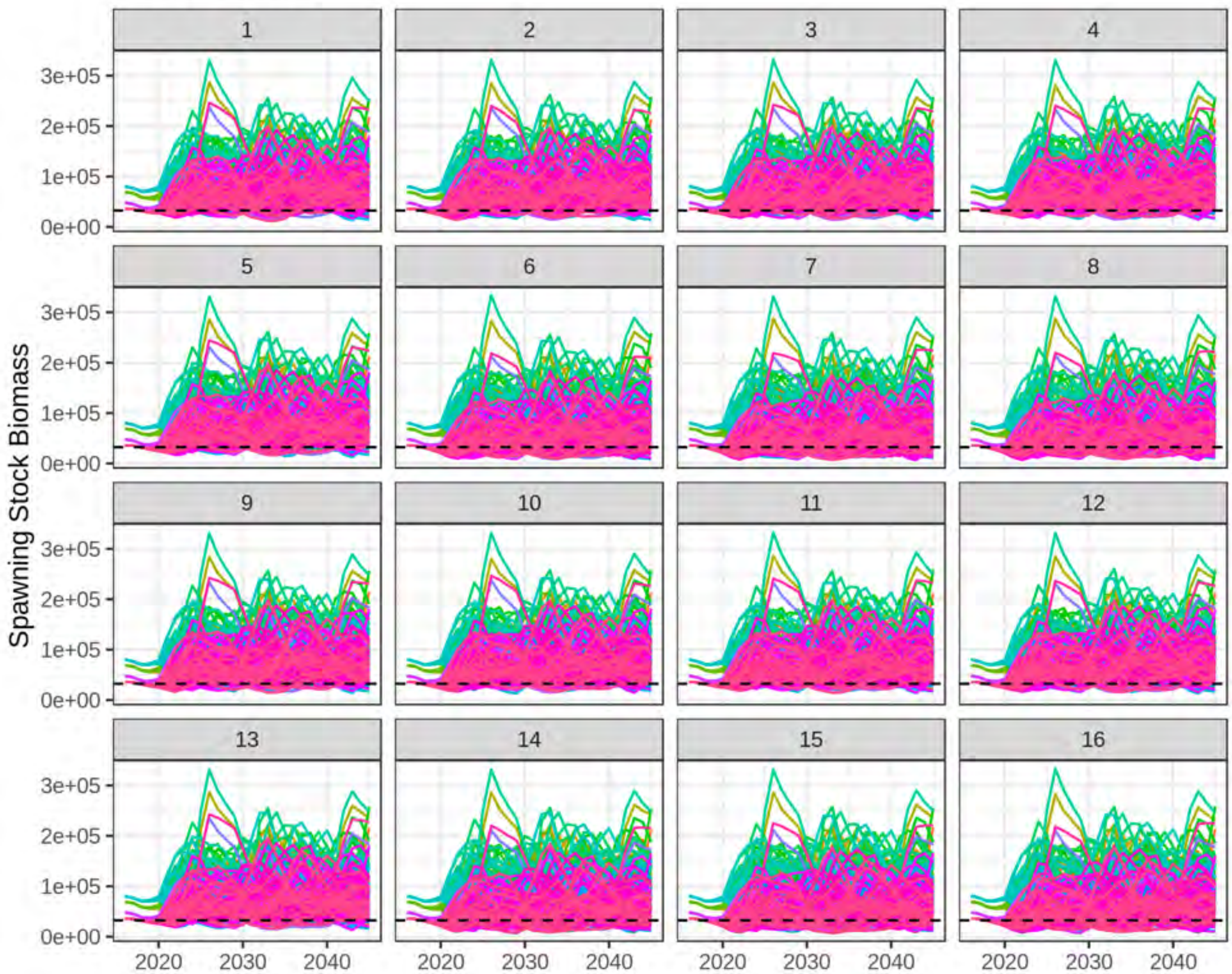


Figure 17. Worm plots of female spawning stock biomass (SSB) for individual runs for the **mixed control** simulation and for each harvest control rule (HCR) for **all reference scenarios**. Each panel presents the results for the labeled HCR. Each colored line represents a separate iteration differing in simulated random recruitment deviates, EPO age-based selectivity deviates, and implementation error. Note that runs for each of the four different scenarios have different starting conditions due to different parameterizations of mortality and growth. The dotted line represents the 20%SSB0_d limit reference point.

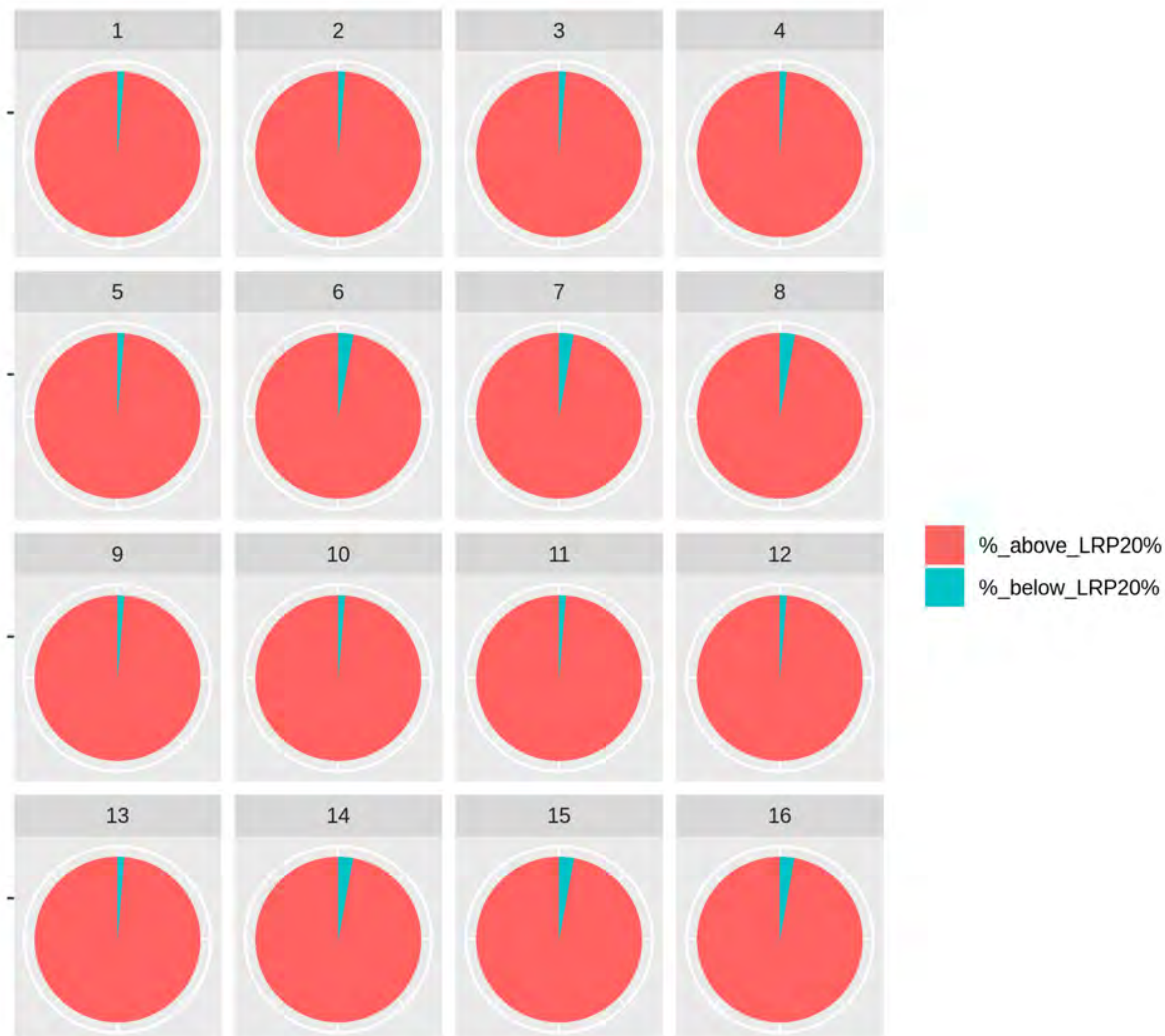


Figure 18. Pie charts showing, for each harvest control rule (HCR) under **mixed control** and **across reference scenarios**, the % of years across all iterations above or below the 20%SSB0_d limit reference point (LRP).

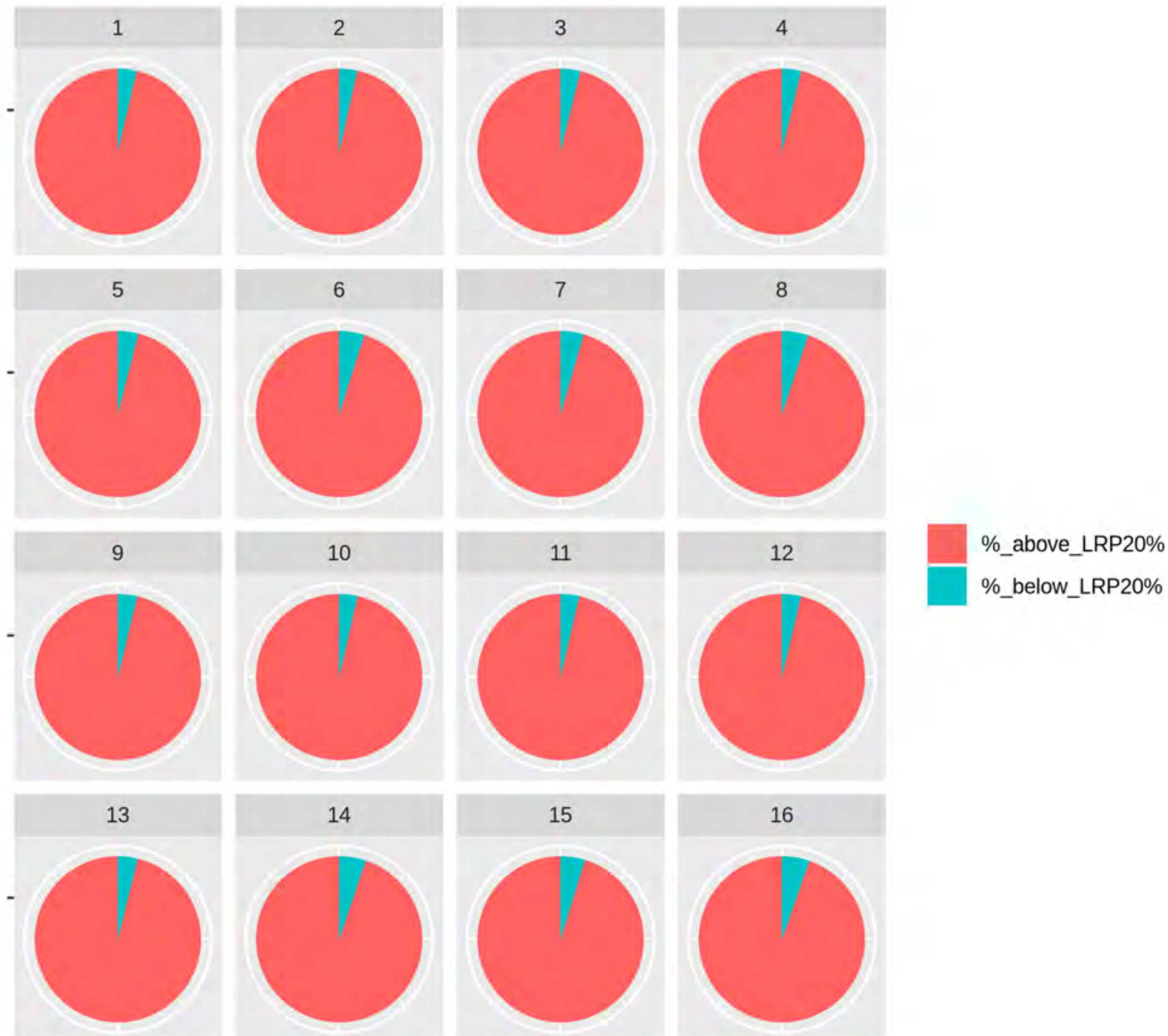


Figure 19. Pie charts showing, for each harvest control rule (HCR) under **TAC control** and **across reference scenarios**, the % of years across all iterations above or below the 20%SSB0_d limit reference point (LRP).

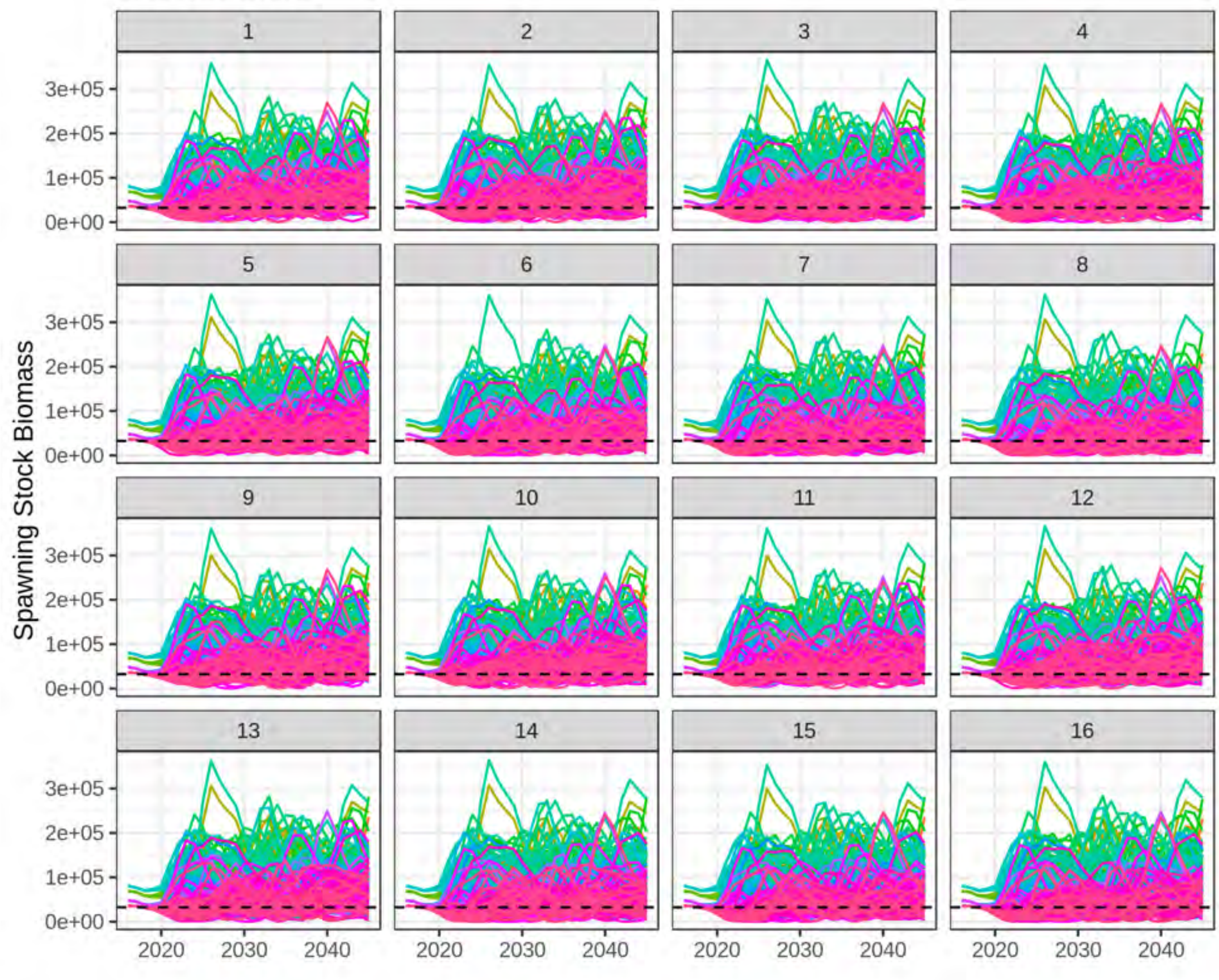


Figure 20. Worm plots of female spawning stock biomass (SSB) for individual runs for the **TAC control** simulation and for each harvest control rule (HCR) for **all reference scenarios**. Each panel presents the results for the labeled HCR. Trajectories represent separate iterations differing in simulated random recruitment deviates, EPO age-based selectivity deviates, and implementation error. Note that runs for each of the four different scenarios have different starting conditions due to different parameterizations of mortality and growth. The dotted line represents the 20%SSB0_d limit reference point.

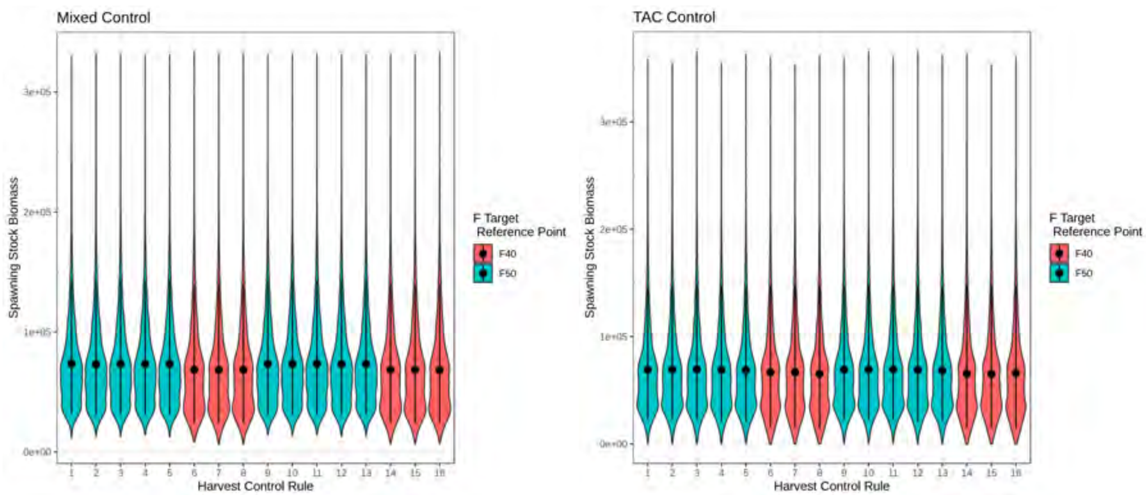


Figure 21. Violin plot showing the probability density of female spawning stock biomass (SSB) for each harvest control rule (HCR) for the 30-year simulation across all iterations and reference scenarios. The marker inside each violin plots is the median SSB and vertical bars represent the 5th to 95th quantile range. Results on the left are for mixed control and on the right for TAC control.

Figure 22. Trends in median female spawning stock biomass (SSB, black line) across all iterations and **all reference scenarios** for each harvest control rule (HCR) under **mixed control**. The green shading represents trends in the 5th to 95th quantiles of SSB. The median limit reference point (LRP) associated with each HCR across all iterations and reference scenarios is also shown (red line). The red shading represents trends in the 5th to 95th quantiles of the LRP.

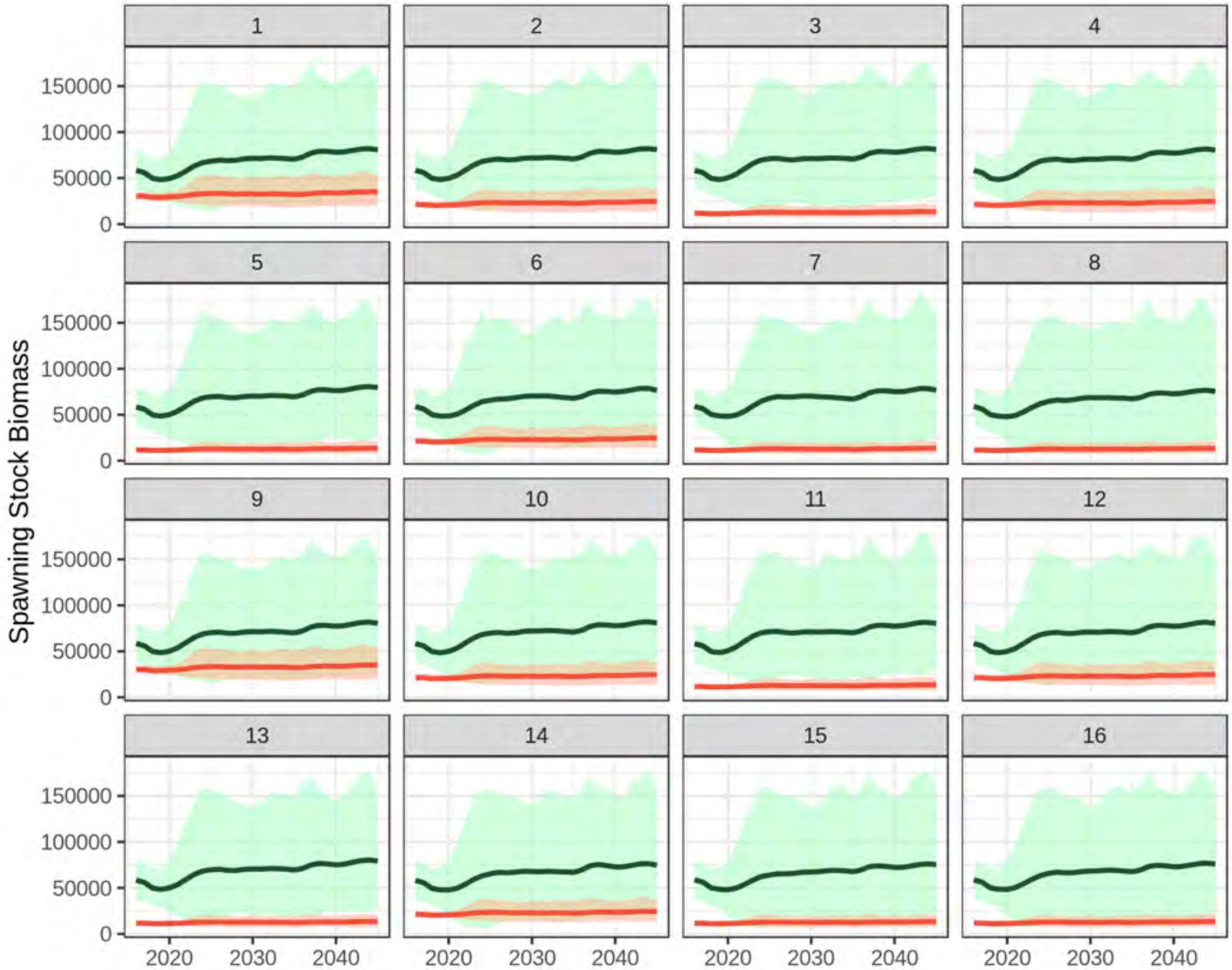


Figure 23. Trends in median female spawning stock biomass (SSB, black line) across all iterations and **all reference scenarios** for each harvest control rule (HCR) under **TAC control**. The green shading represents trends in the 5th to 95th quantiles of SSB. The median limit reference point (LRP) associated with each HCR across all iterations and reference scenarios is also shown (red line). The red shading represents trends in the 5th to 95th quantiles of the LRP.

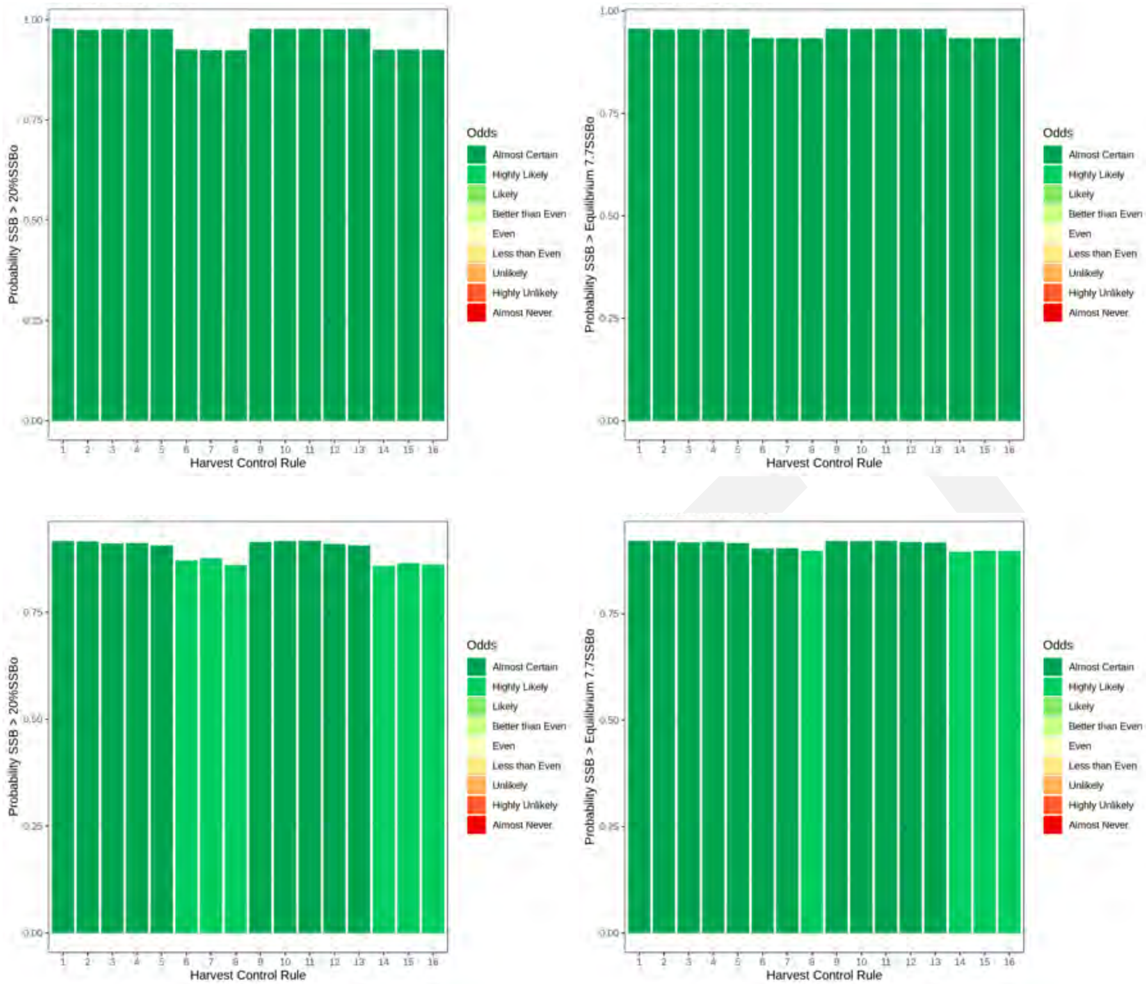


Figure 24. Plot of performance metric PM1b (left panel), the odds in any given year of the simulation of spawning stock biomass (SSB) being greater than the 20%SSB0_d limit reference point (LRP), and PM1c (right panel), the odds in any given year of the simulation of SSB being greater than the 7.7%SSB_0 LRP, for each harvest control rule (HCR) across all reference scenarios. The top panels show results for mixed control, while the bottom panels for TAC control.

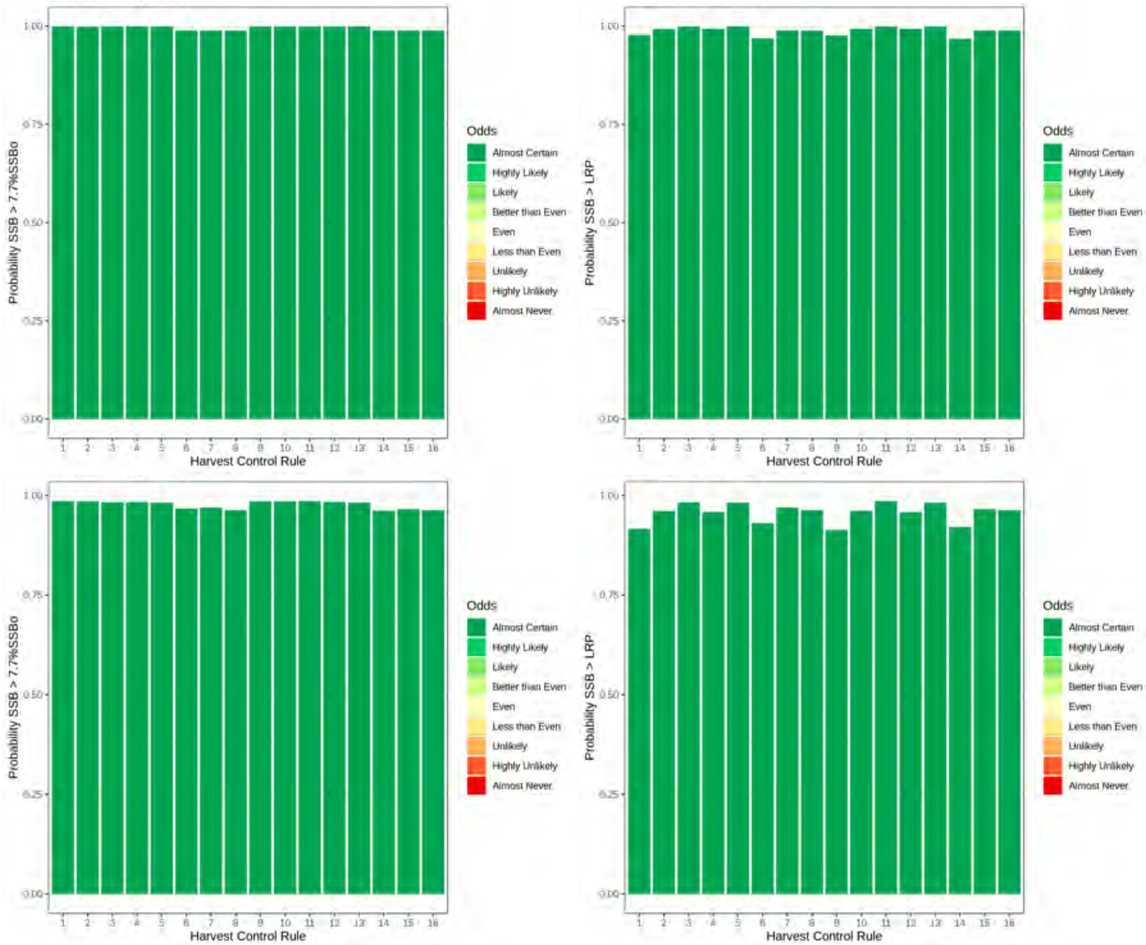


Figure 25. For each harvest control rule (HCR) and across all reference scenarios, plot of performance metric PM1d (left panel), the odds in any given year of the simulation of spawning stock biomass (SSB) being greater than the 7.7%SSB0_d limit reference point (LRP), and PM1a (right panel), the odds in any given year of the simulation of SSB being greater than the LRP as specified in each HCR, The top panels show results for mixed control, while the bottom panels for TAC control.

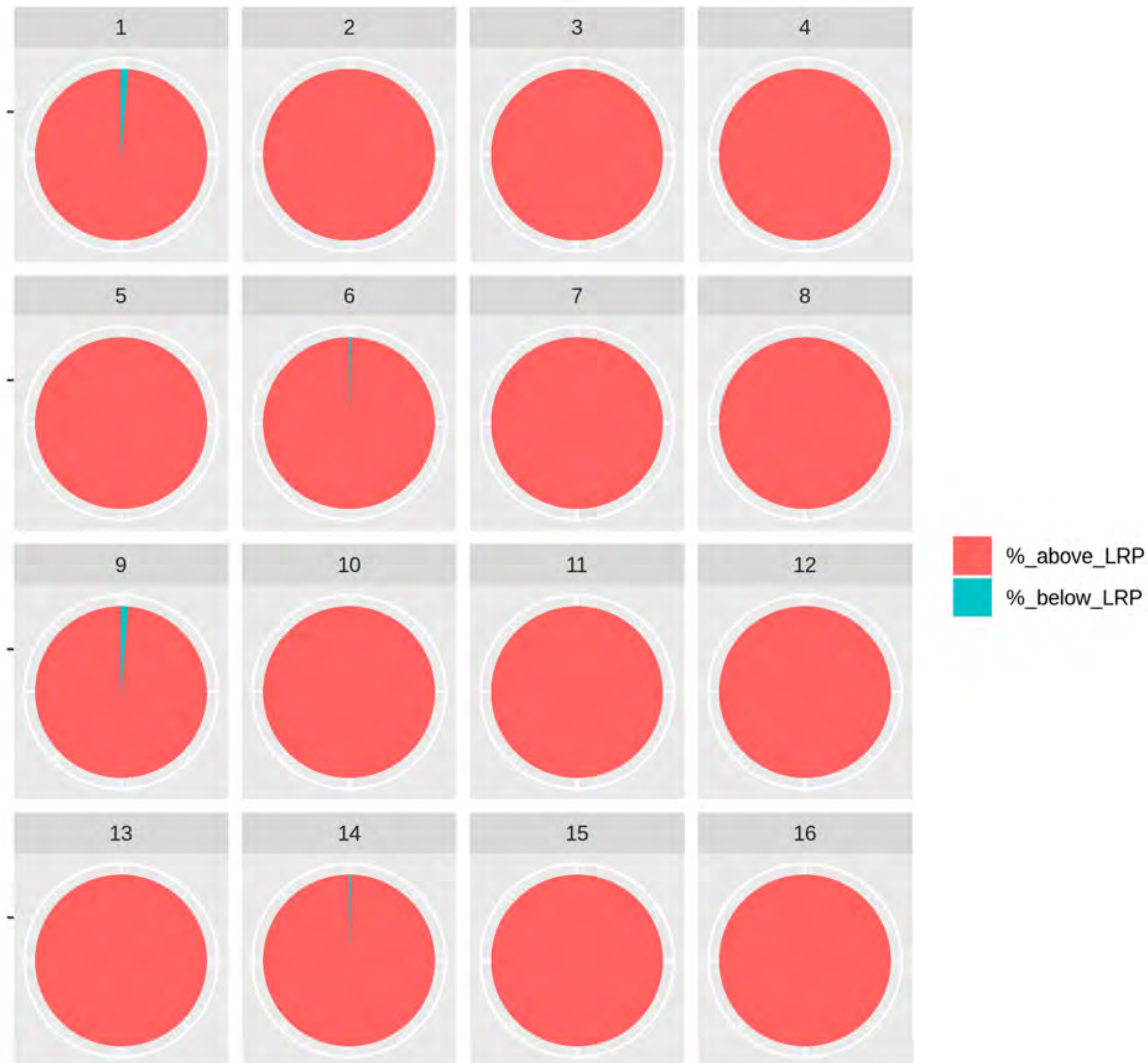


Figure 26. Pie charts showing, for each harvest control rule (HCR) under **mixed control** and **across reference scenarios**, the % of years across all iterations above or below the limit reference point (LRP) associated with each HCR.

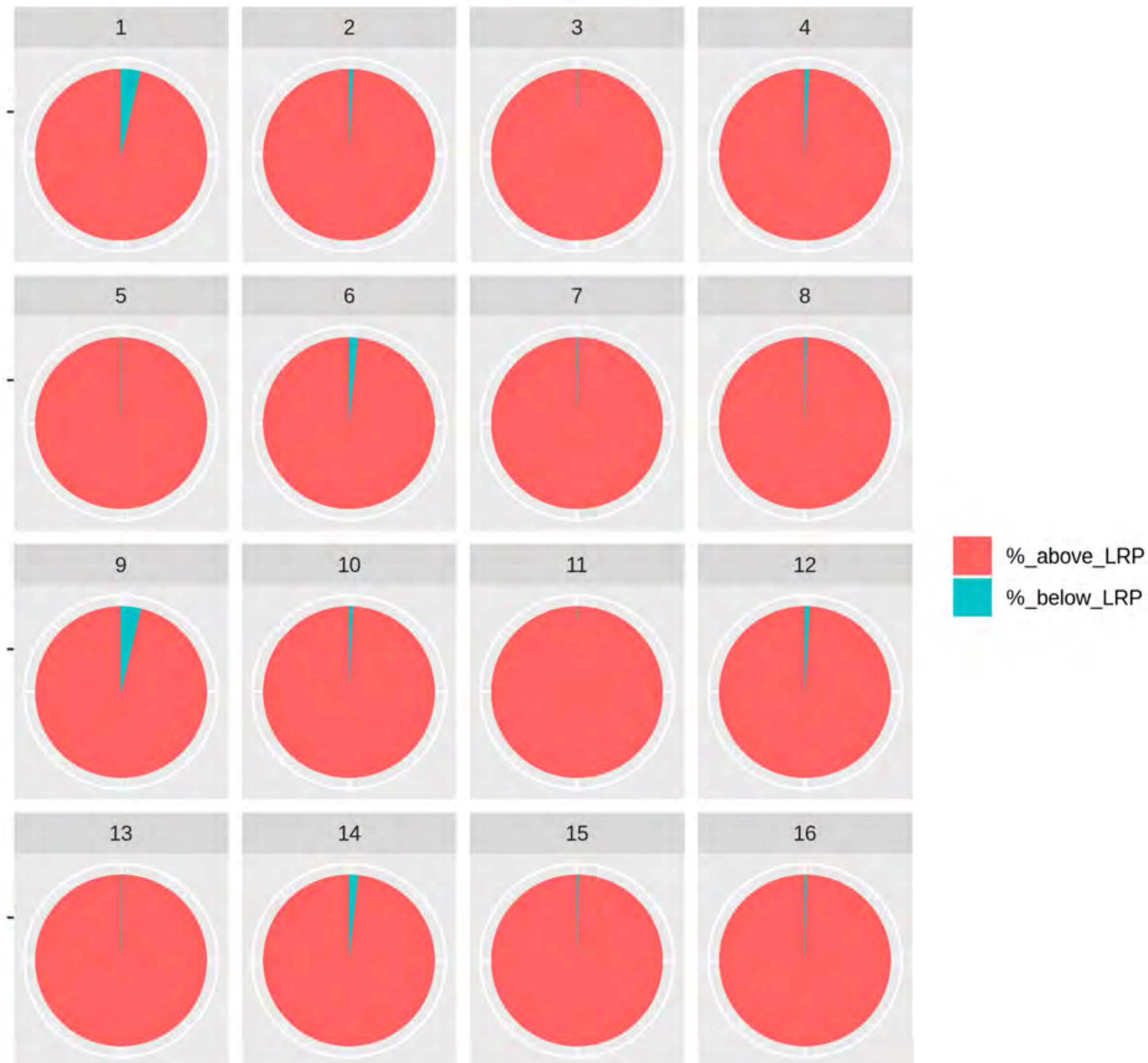


Figure 27. Pie charts showing, for each harvest control rule (HCR) under **TAC control** and **across reference scenarios**, the % of years across all iterations above or below the limit reference point (LRP) associated with each HCR.

Figure 28. Trends in median female spawning stock biomass (SSB, black line) across all iterations for the **low productivity scenario** (OM6) and for each harvest control rule (HCR) under **mixed control**. The green shading represents trends in the 5th to 95th quantiles of SSB. The median limit reference point (LRP) associated with each HCR across all iterations and OM6 is also shown (red line). The red shading represents trends in the 5th to 95th quantiles of the LRP.

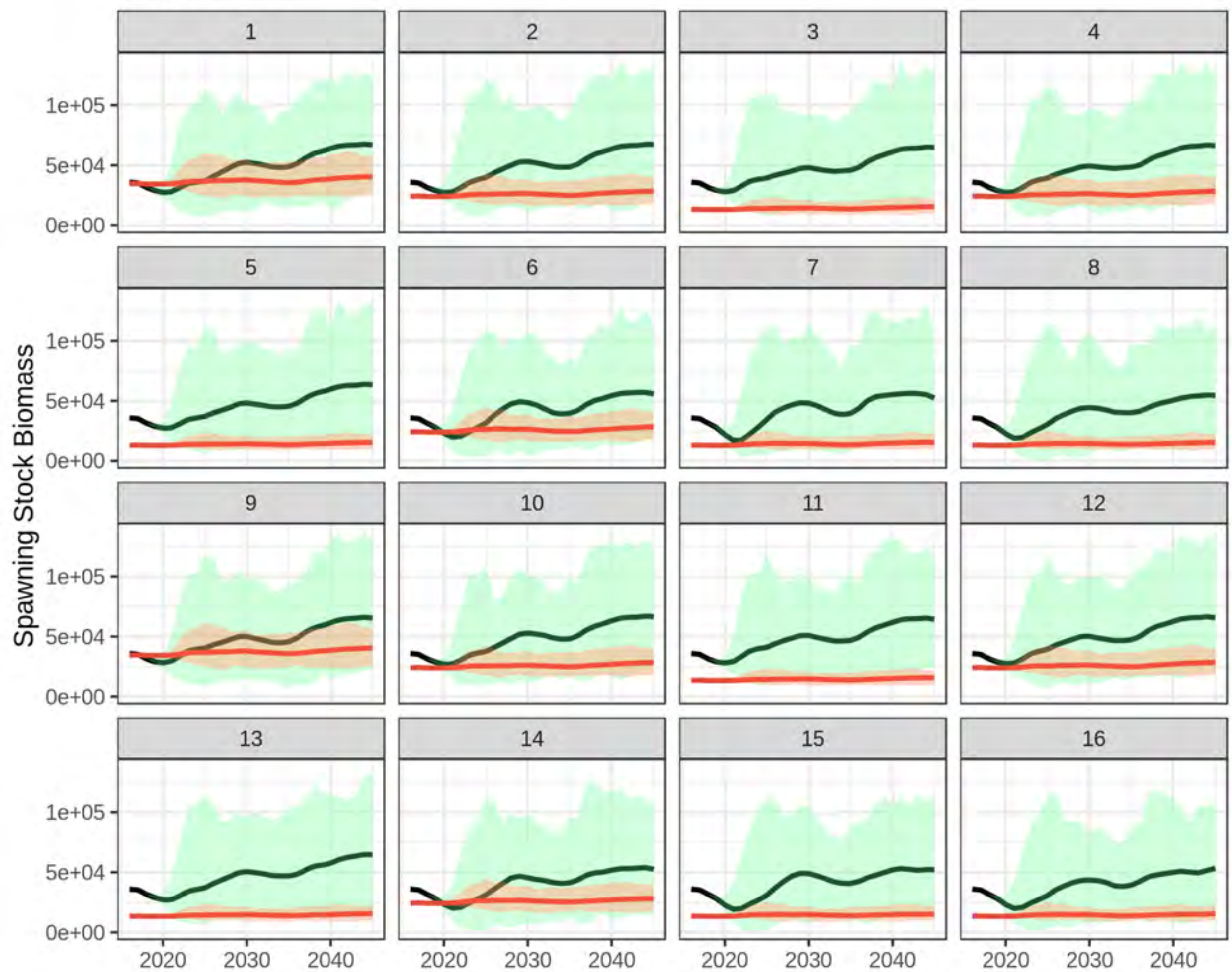


Figure 29. Trends in median female spawning stock biomass (SSB, black line) across all iterations for the **low productivity scenario** (OM6) and for each harvest control rule (HCR) under **TAC control**. The green shading represents trends in the 5th to 95th quantiles of SSB. The median limit reference point (LRP) associated with each HCR across all iterations and OM6 is also shown (red line). The red shading represents trends in the 5th to 95th quantiles of the LRP.

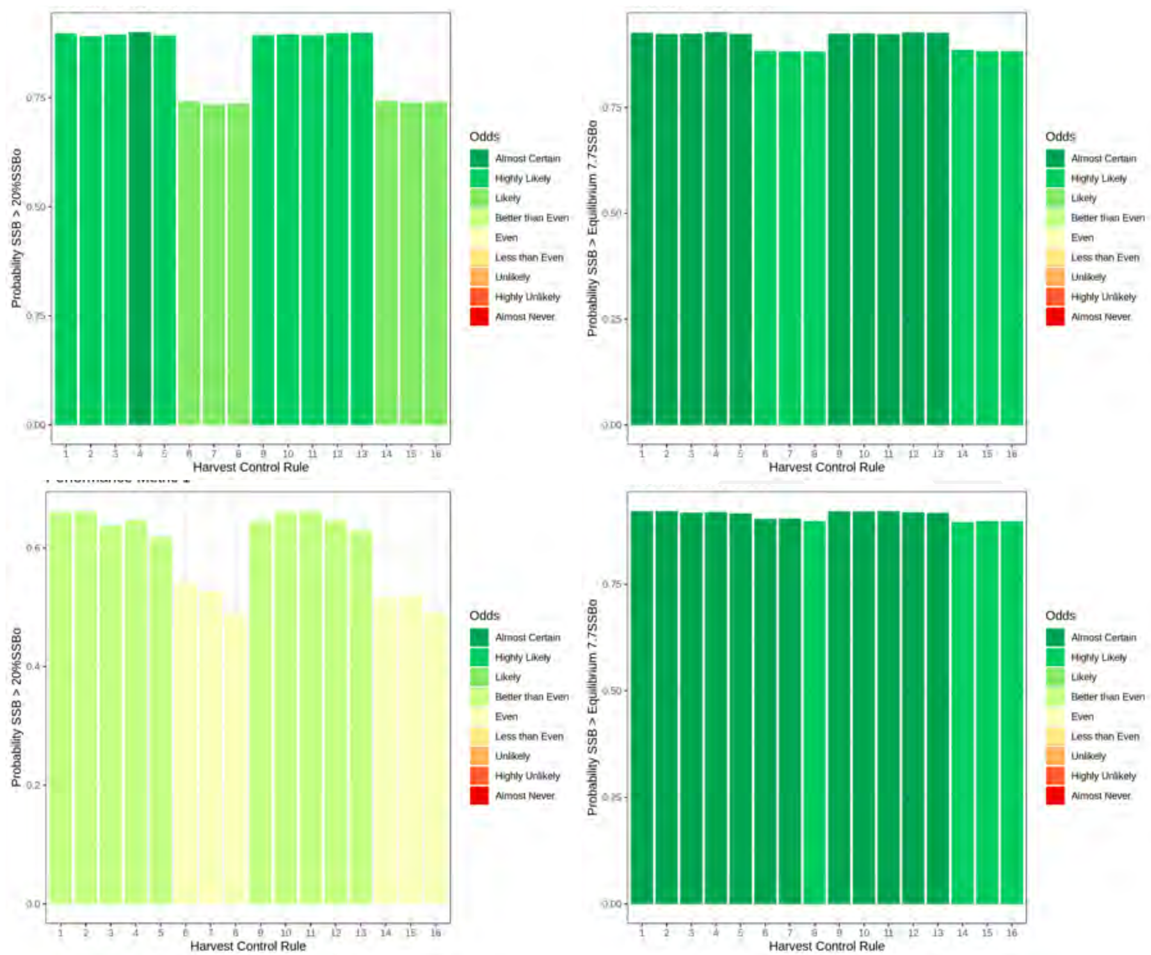


Figure 30. Plot of performance metric PM1b (left panel), the odds in any given year of the simulation of spawning stock biomass (SSB) being greater than the 20%SSB0_d limit reference point (LRP), and PM1c (right panel), the odds in any given year of the simulation of SSB being greater than the 7.7%SSB_0 LRP, for each harvest control rule (HCR) for the **low productivity scenario** (OM6). The top panels show results for mixed control, while the bottom panels for TAC control.

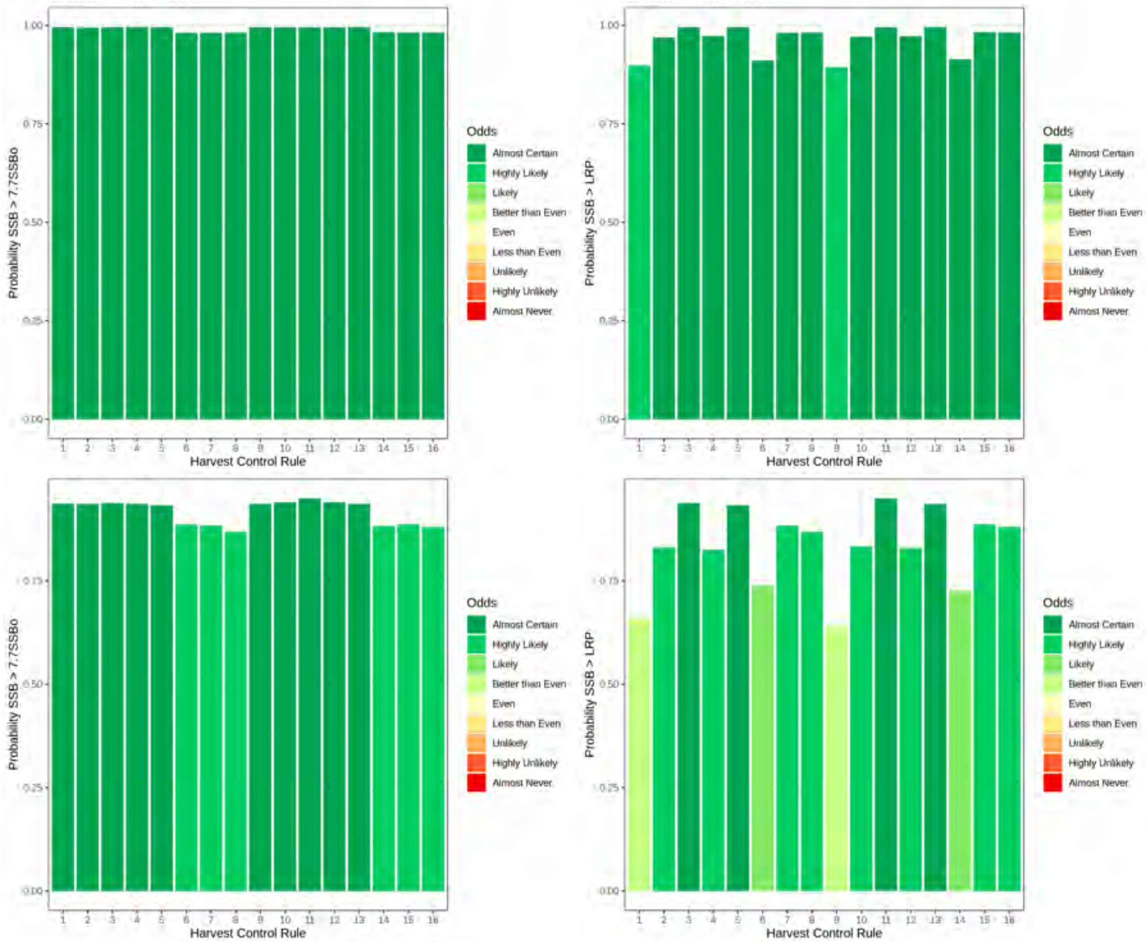


Figure 31. For each harvest control rule (HCR) and the **low productivity scenario** (OM6), plot of performance metric PM1d (left panel), the odds in any given year of the simulation of spawning stock biomass (SSB) being greater than the 7.7%SSB0_d limit reference point (LRP), and PM1a (right panel), the odds in any given year of the simulation of SSB being greater than the LRP as specified in each HCR, The top panels show results for mixed control, while the bottom panels for TAC control.

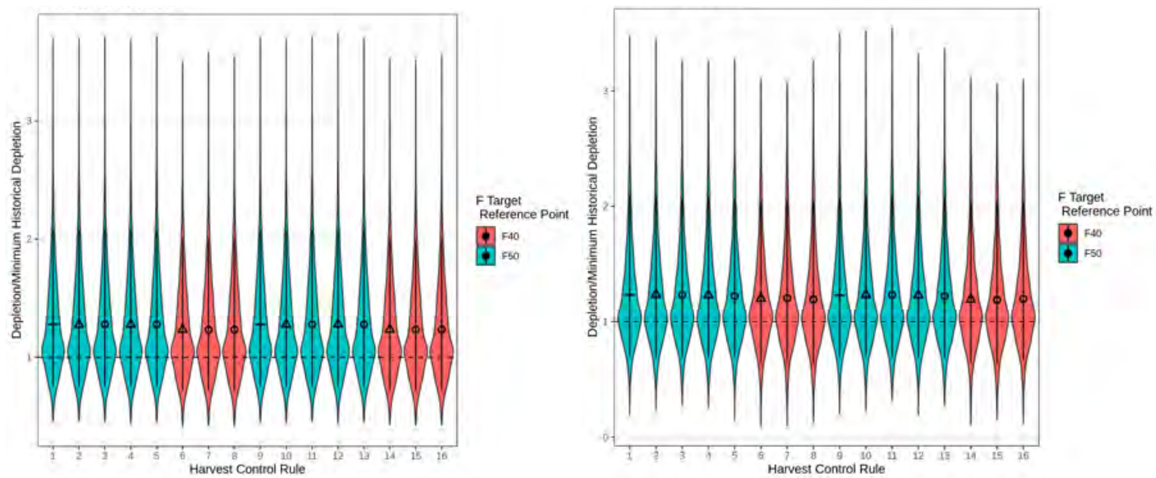


Figure 32. Violin plot showing the probability density of total biomass depletion (total biomass as fraction of unfished) relative to minimum historical (2006-2015) depletion for each harvest control rule (HCR) for the 30-year simulation across all iterations and **all reference scenarios**. The marker inside each violin plot is the median SSB and vertical bars represent the 5^{th} to 95^{th} quantile range. The + marker represents the 20%SSB0_d limit reference point (LRP), the ▵ the 14%SSB0_d, and ○ the 7.7%SSB0_d. Results for mixed control are on the left and for TAC control on the right.

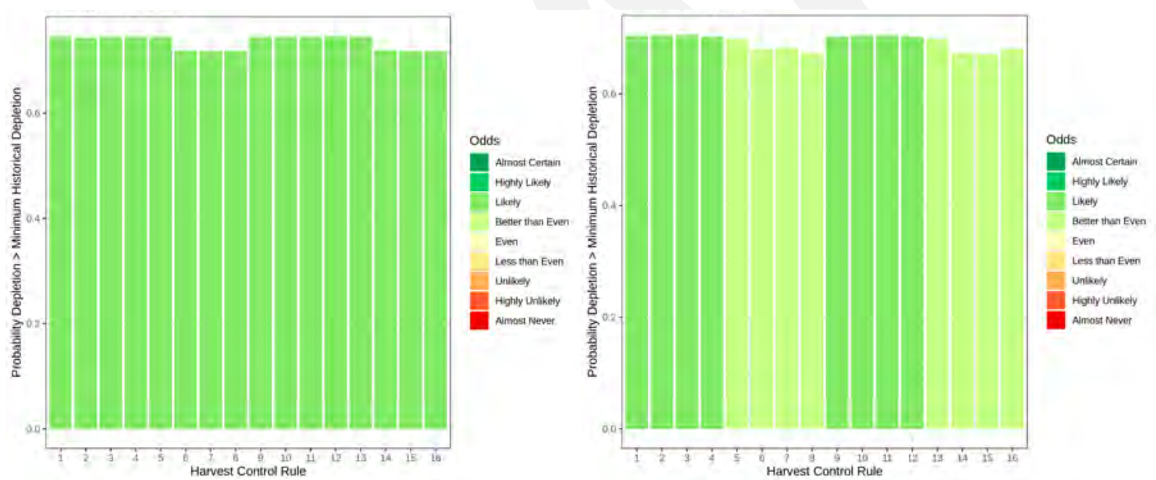
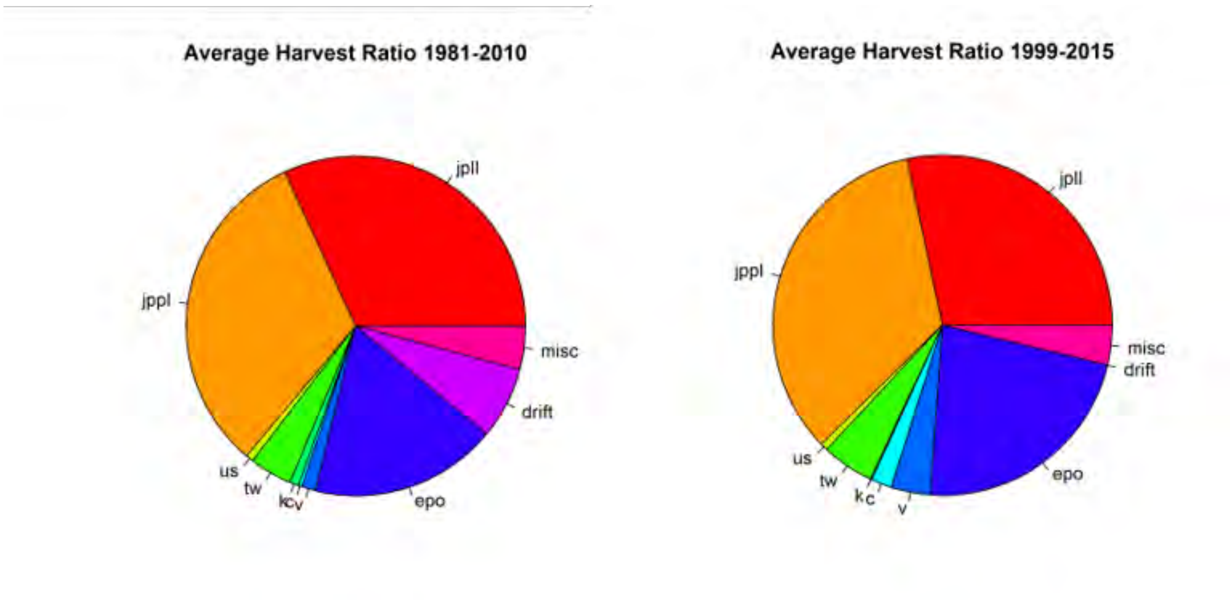


Figure 33. For each harvest control rule (HCR) and across **all reference scenarios**, plot of performance metric PM2, the odds in any given year of the simulation of depletion (total biomass as fraction of unfished) being greater than minimum historical (2006-2015) depletion. The left panel shows results for mixed control, while the right panel for TAC control.



wee

Figure 34. Catch ratios by fishery averaged over 1981-2000 (left panel) and 1999-2015 (right panel). DRIFT refers to the driftnet fishery, EPO to the Canadian and US surface fleet operating in the Eastern Pacific Ocean, V to the Vanuatu longline fleet, C to the Chinese longline fleet, K to the Korean longline fleet, TW to the Chinese Taipei longline fleet, US to the US longline fleet, JPPL to the Japanese pole-and-line fleet, JPLL to the Japanese longline fleet, and MISC to any remaining fleet.

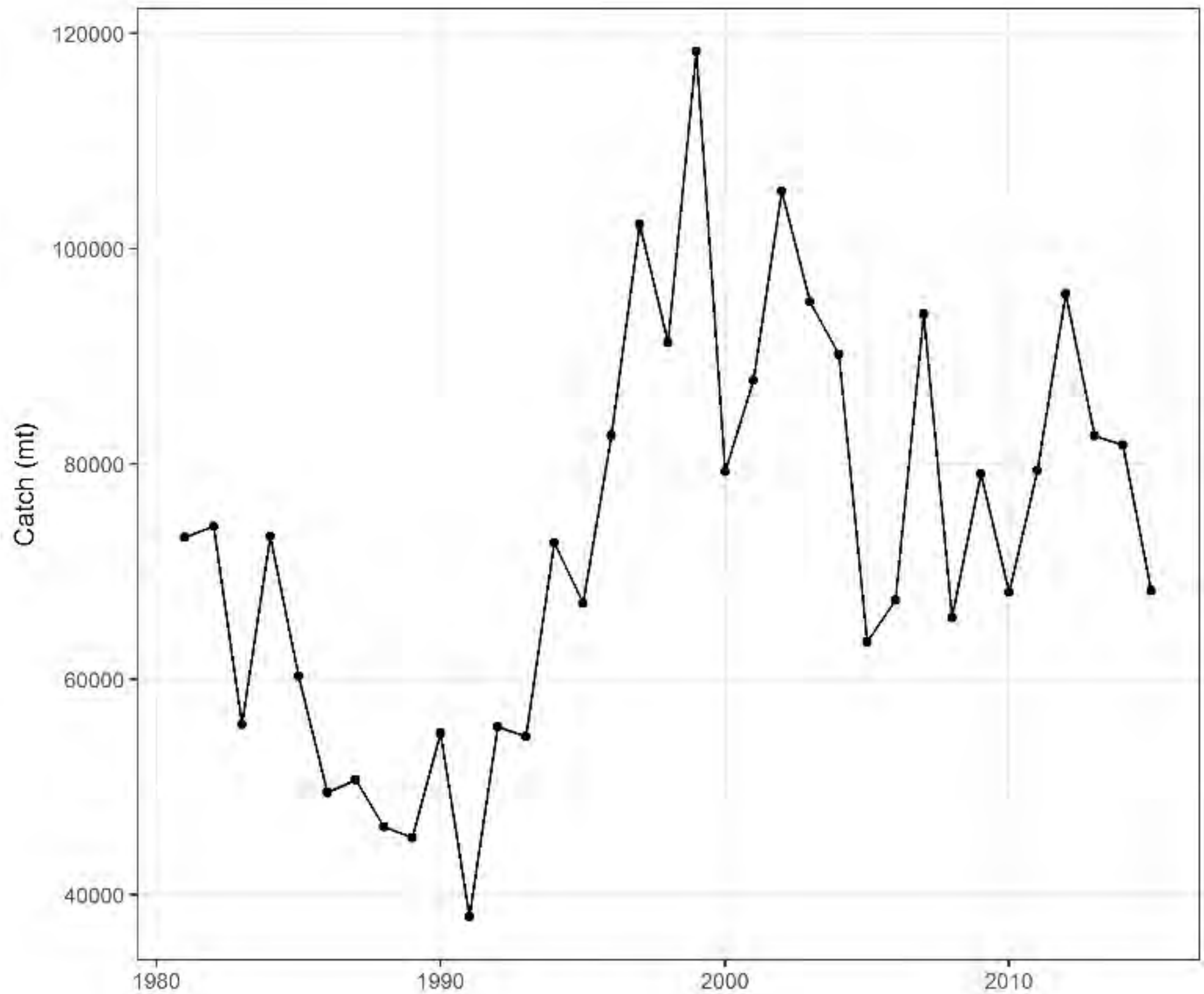


Figure 35. Trends in total NPALB catch from 1981-2015.

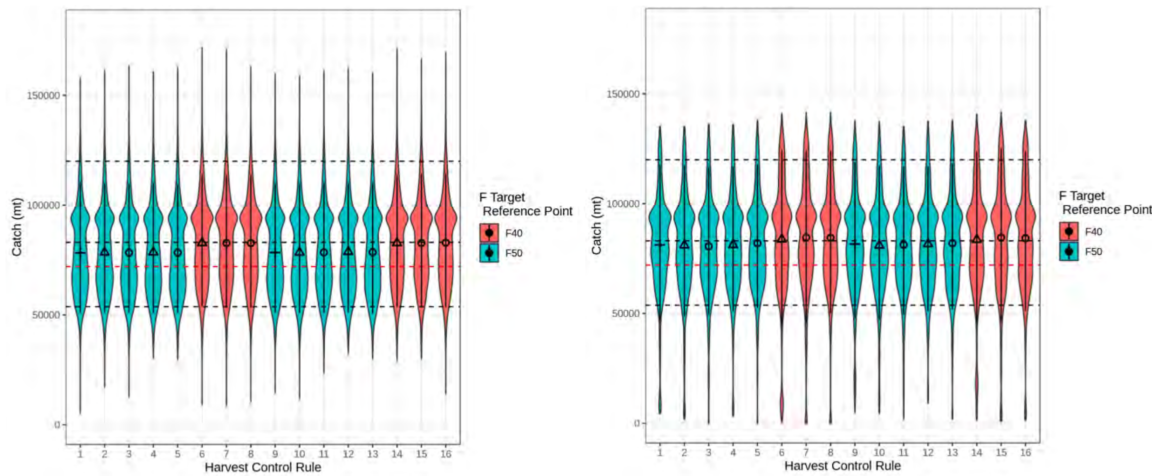


Figure 36. Violin plot showing the probability density of catch for each harvest control rule (HCR) for the 30-year simulation across all iterations and **all reference scenarios**. The marker inside each violin plots is the median catch and vertical bars represent the 5th to 95th quantile range. The + marker represents the 20%SSB0_d limit reference point (LRP), the ▵ the 14%SSB0_d, and ○ the 7.7%SSB0_d. The red dotted line represents the mean historical (1981-2010) catch. The black dotted lines represent, from top to bottom, maximum, mean, and minimum catch over the conditioning period of 1993-2015. Results for mixed control are on the left and for TAC control on the right.

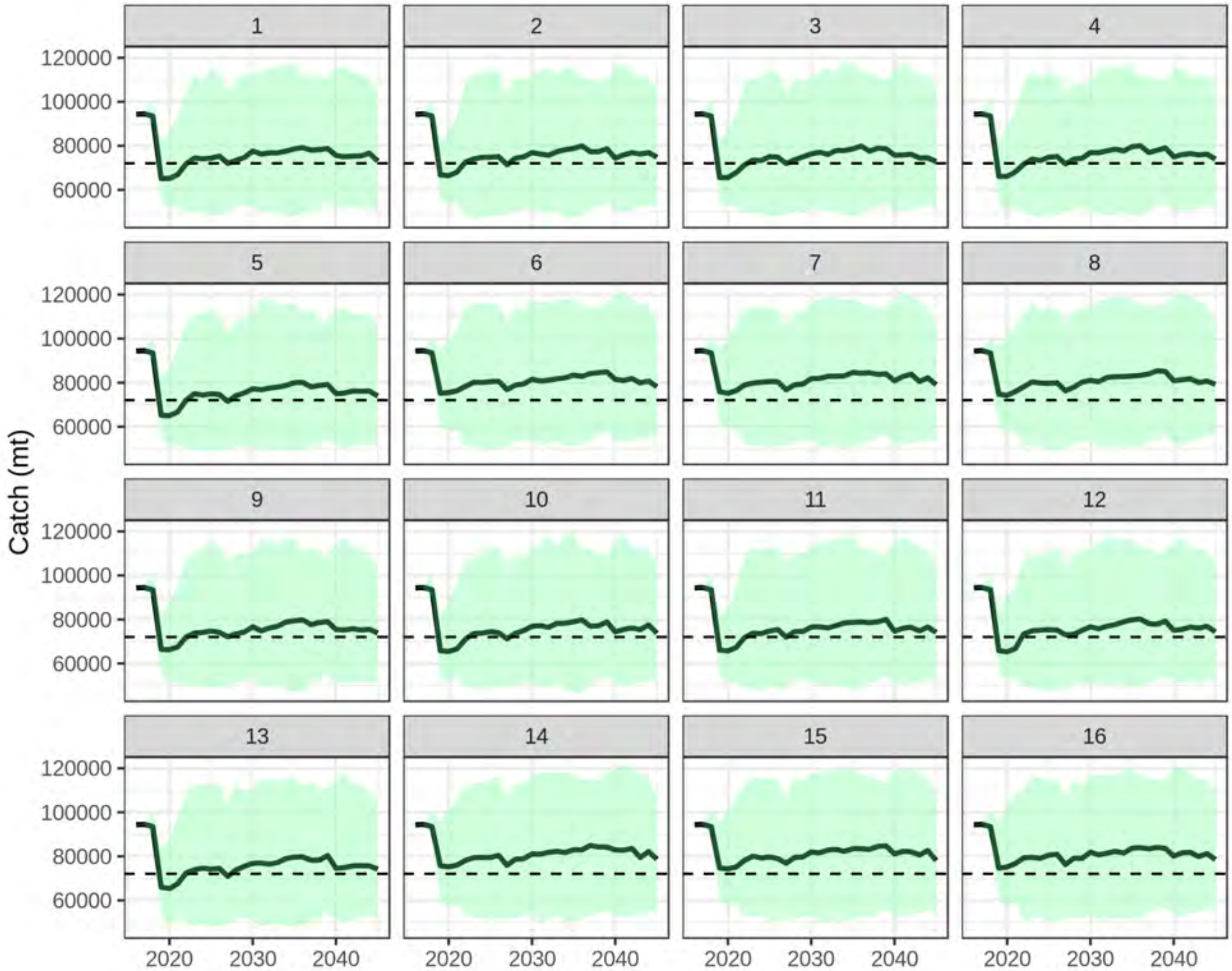


Figure 37. Trends in median catch across all iterations and **all reference set scenarios** for each harvest control rule (HCR) under **mixed control**. The green shading represents trends in the 5th to 95th quantiles of catch. The dotted line is the mean historical (1981-2010) catch.

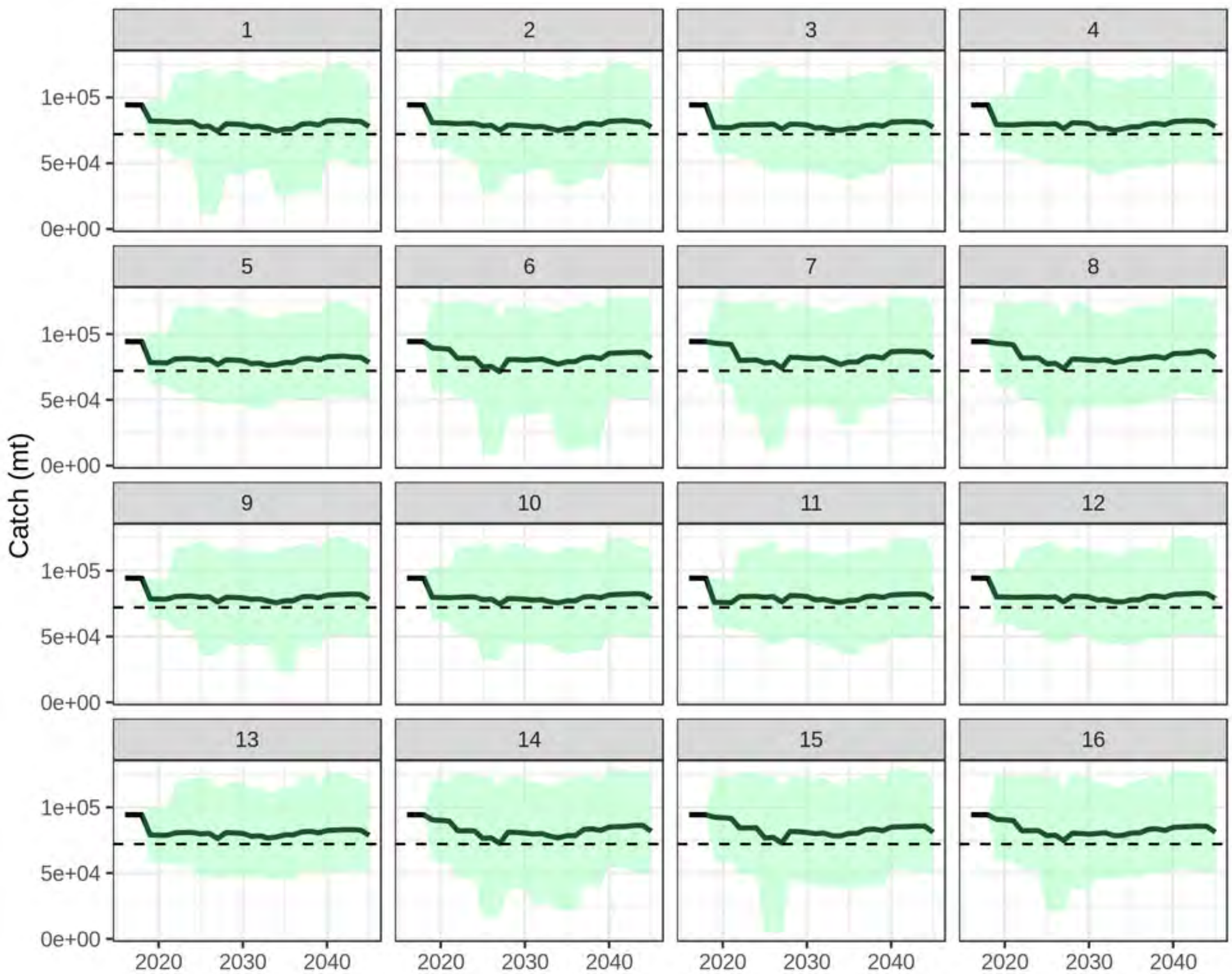


Figure 38. Trends in median catch across all iterations and **all reference scenarios** for each harvest control rule (HCR) under **TAC control**. The green shading represents trends in the 5th to 95th quantiles of catch. The dotted line is the mean historical (1981-2010) catch.

Figure 39. Worm plots of catch for individual runs for the **mixed control** simulation and for each harvest control rule (HCR) for **all reference scenarios**. Each panel presents the results for the labeled HCR. Trajectories represent separate iterations differing in simulated random recruitment deviates, EPO age-based selectivity deviates, and implementation error. The dotted line represents the mean historical (1981-2010) catch.

Figure 40. Worm plots of catch for individual runs for the **TAC control** simulation and for each harvest control rule (HCR) for **all reference scenarios**. Each panel presents the results for the labeled HCR. Trajectories represent separate iterations differing in simulated random recruitment deviates, EPO age-based selectivity deviates, and implementation error. The dotted line represents the mean historical (1981-2010) catch.

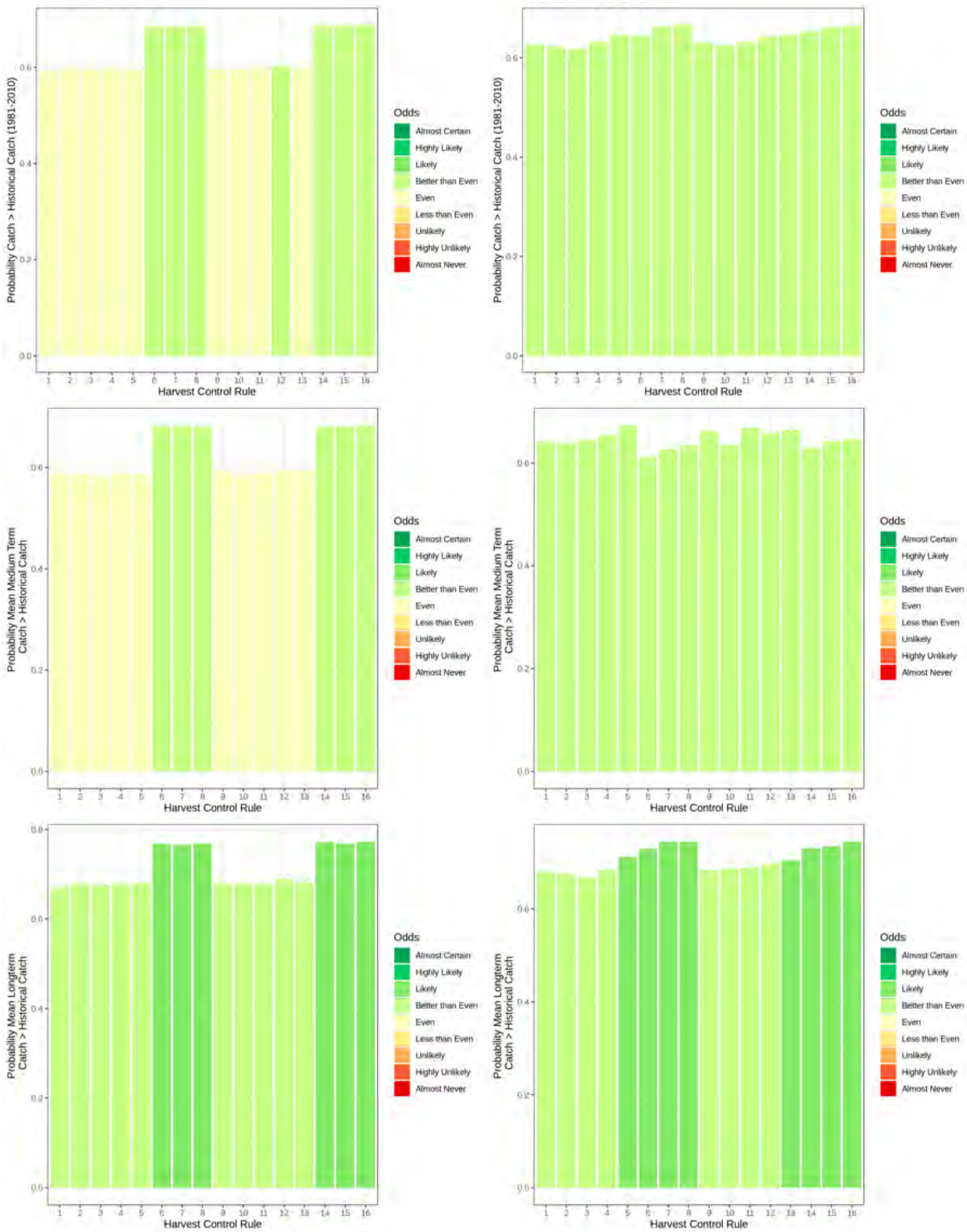


Figure 41. For each harvest control rule (HCR) and **across reference scenarios**, plot of performance metric PM4a, the odds of catch in any given year of the simulation being greater than historical, PM4b, the odds of medium term (years 7 to 13) catch being greater than historical, and PM4c, the odds of long term (years 20 to 30) catch being greater than historical. The left panels show results for mixed control, while the right panels for TAC control.

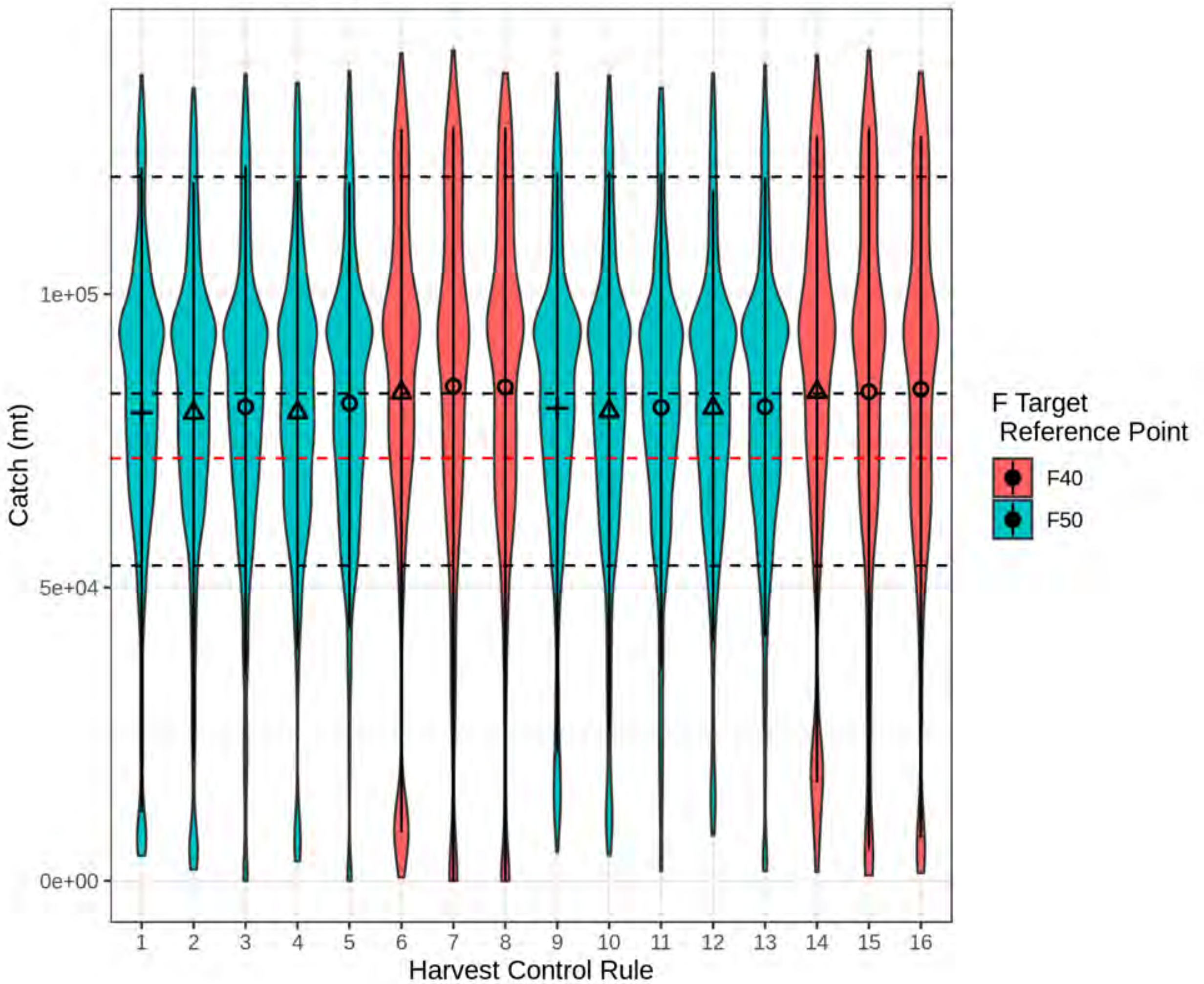


Figure 42. Violin plot showing the probability density of catch for each harvest control rule (HCR) for the 30-year simulation across all iterations and all **reference scenarios under TAC control**. The marker inside each violin plots is the median catch and vertical bars represent the 5th to 95th quantile range. The + marker represents the 20%SSB0_d limit reference point (LRP), the ▵ the 14%SSB0_d, and ○ the 7.7%SSB0_d. The red dotted line represents the mean historical (1981-2010) catch. The black dotted lines represent, from top to bottom, maximum, mean, and minimum catch over the conditioning period of 1993-2015.

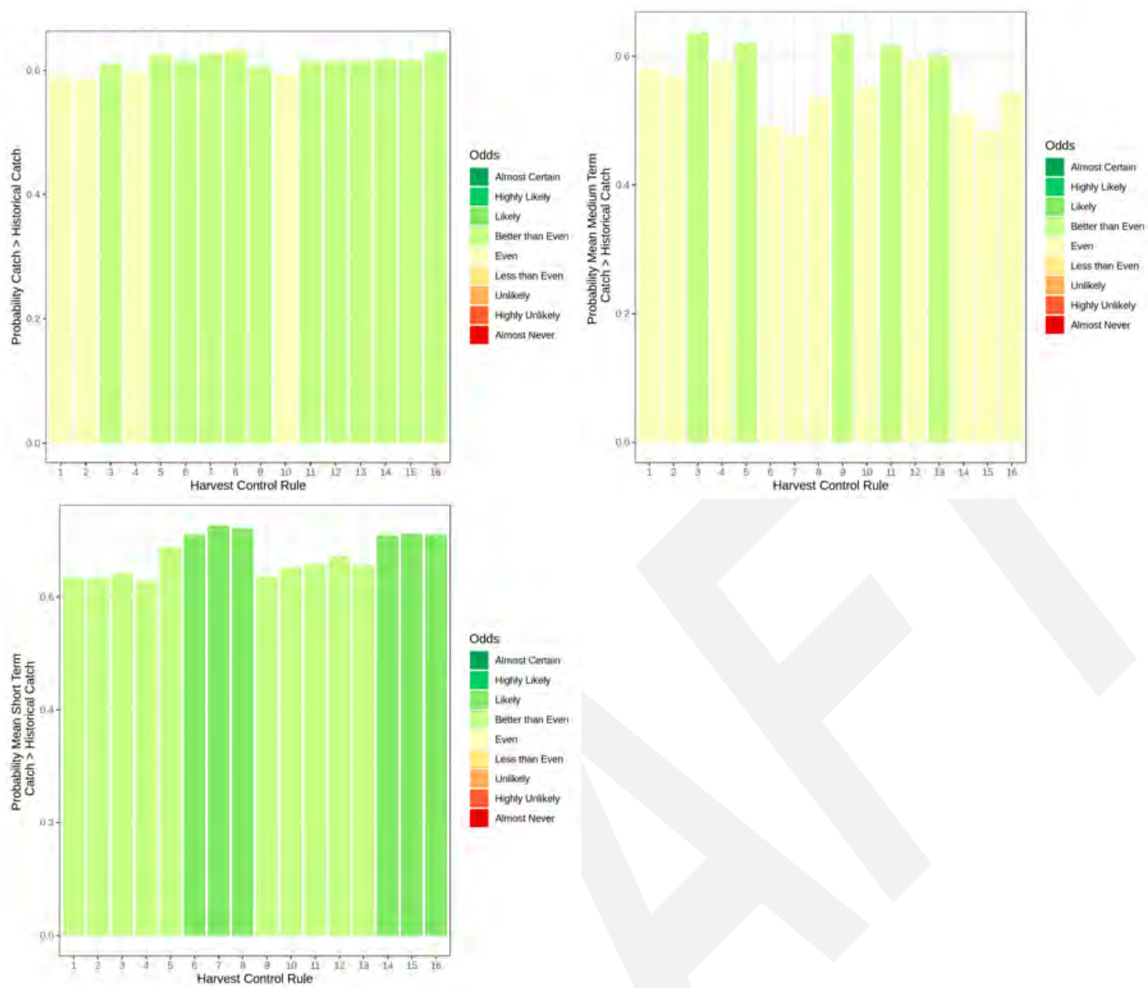


Figure 43. For each harvest control rule (HCR) for the **low productivity scenario** under **TAC control**, plot of performance metric PM4a, the odds of catch in any given year of the simulation being greater than historical, PM4b, the odds of medium term (years 7 to 13) catch being greater than historical, and PM4c, the odds of long term (years 20 to 30) catch being greater than historical.

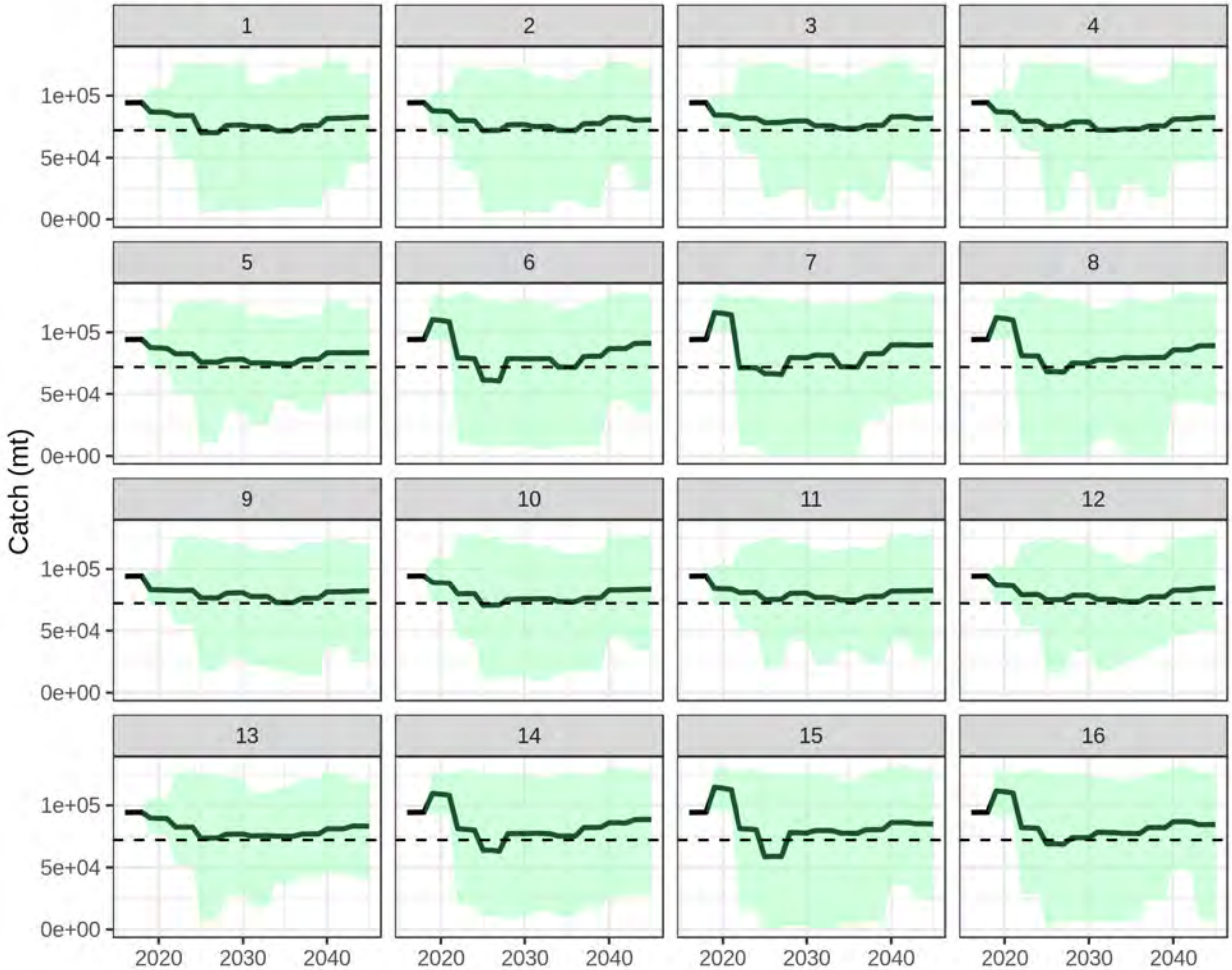


Figure 44. Trends in median catch across all iterations for the **low productivity scenario** for each harvest control rule (HCR) under **TAC control**. The green shading represents trends in the 5th to 95th quantiles of catch. The dotted line is the mean historical (1981-2010) catch.

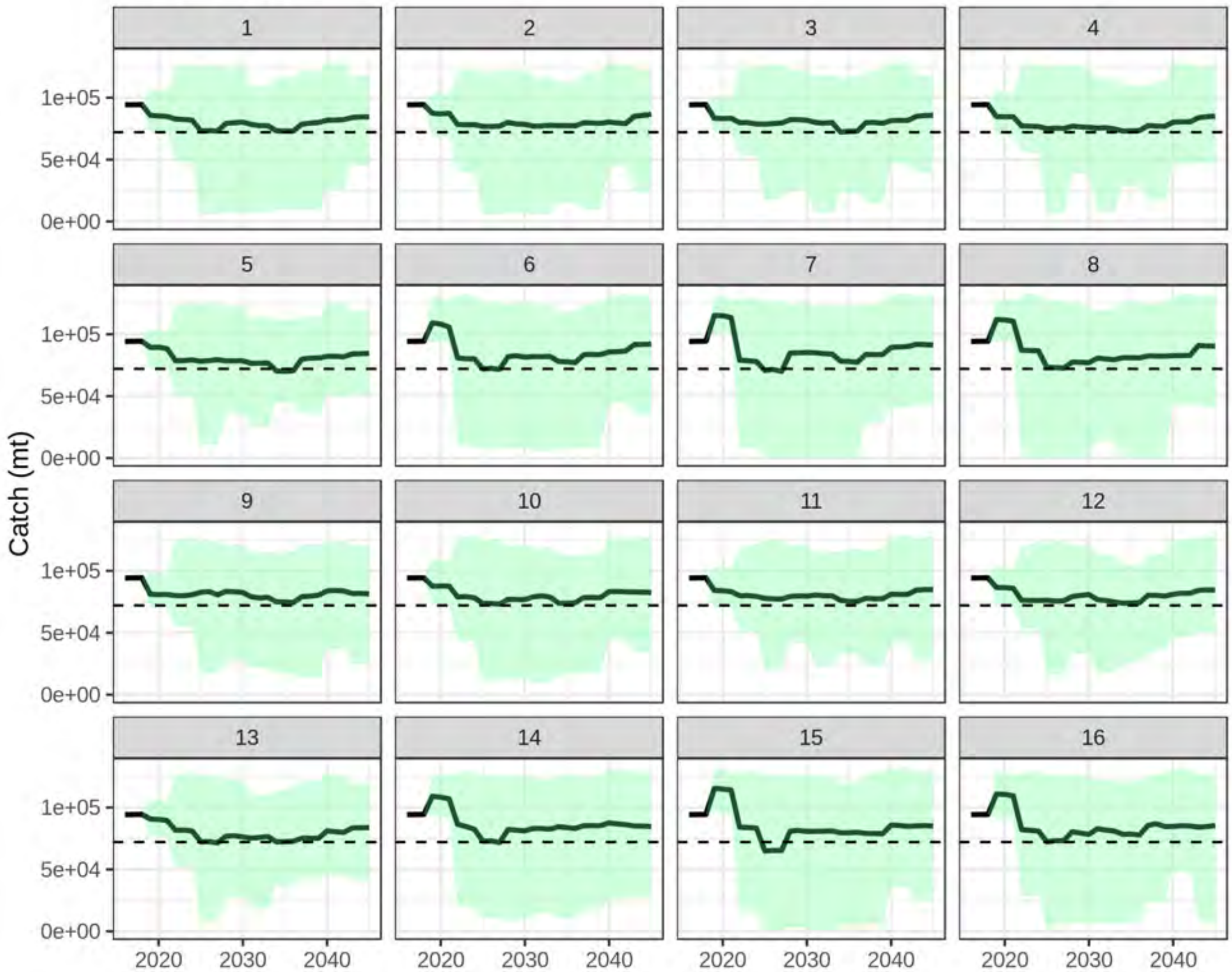
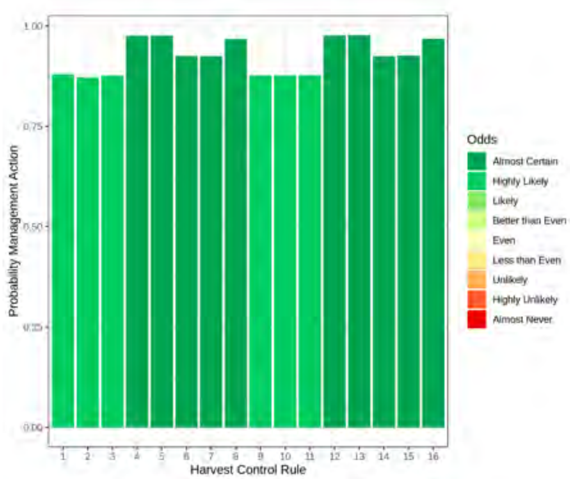


Figure 45. Trends in median catch across all iterations for the **low productivity scenario** for each harvest control rule (HCR) under **mixed control**. The green shading represents trends in the 5^{th} to 95^{th} quantiles of catch. The dotted line is the mean historical (1981-2010) catch.



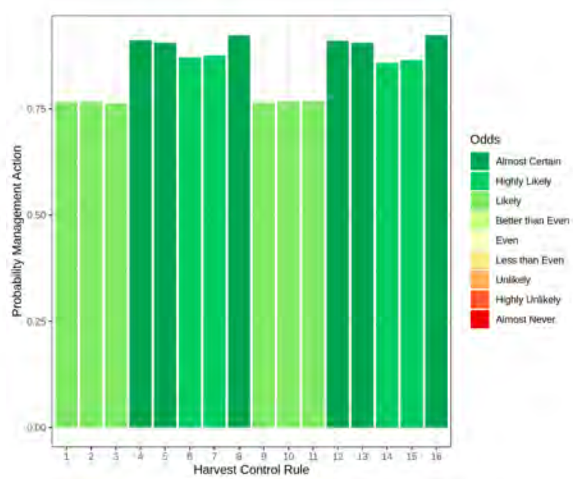


Figure 46. For each harvest control rule (HCR) and across **all reference scenarios**, plot of performance metric PM5b, the odds of no management intervention. The left panel shows results for mixed control, while the right panel for TAC control.

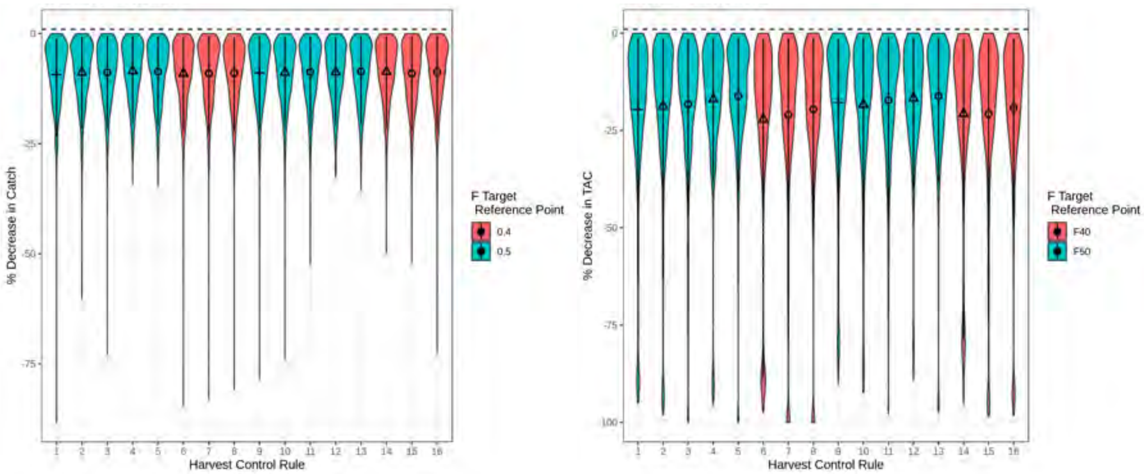


Figure 47. Violin plot showing the probability density of decreases in catch between assessment periods for the 30-year simulation across all iterations and **all reference scenarios**. The marker inside each violin plots is the median decrease in catch and vertical bars represent the 5th to 95th quantile range. The + marker represents the 20%SSB0_d limit reference point (LRP), the ▵ the 14%SSB0_d, and ○ the 7.7%SSB0_d. The left panel shows results for mixed control, while the right panel for TAC control.

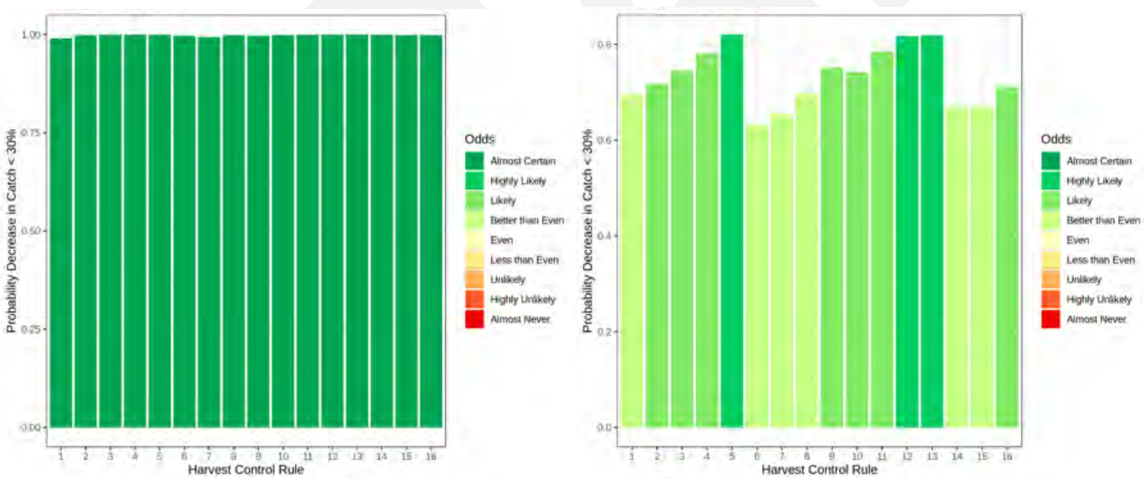


Figure 48. For each harvest control rule (HCR) and across **all reference scenarios**, plot of performance metric PM5a, catch stability, the odds of a decrease in TAC (or catch for mixed control) between assessment periods being less than 30%. The left panel shows results for mixed control, while the right panel for TAC control.

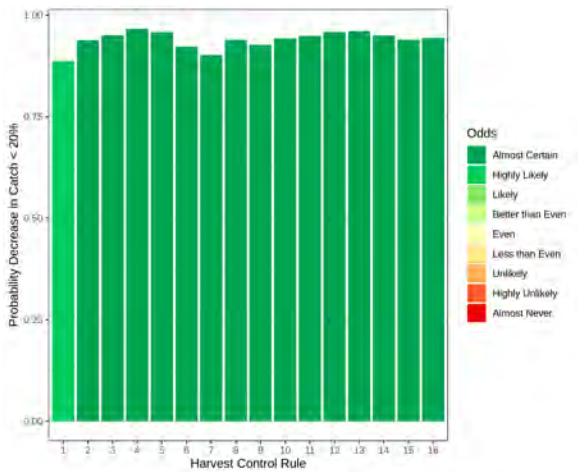


Figure 49. For each harvest control rule (HCR) under **mixed control** and across **all reference scenarios**, plot of the odds of a decrease in catch between assessment periods being less than 20%.

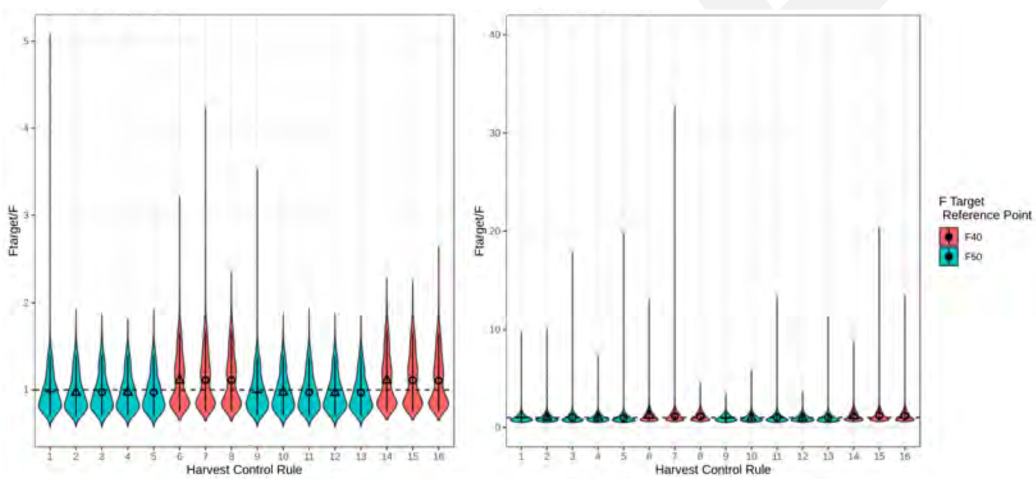


Figure 50. For each harvest control rule (HCR) and across **all reference scenarios**, plot of performance metric PM6, the ratio of the fishing intensity target reference point (F_{target}) over the fishing intensity in any year of the 30-year simulation. The left panel shows results for mixed control, while the right panel for TAC control.

Figure 51. Worm plots of fishing intensity (F, 1-SPR) for individual runs for the **mixed control** simulation and for each harvest control rule (HCR) for the **base case scenario, OM1**. Each panel presents the results for the labeled HCR. Trajectories represent separate iterations differing in simulated random recruitment deviates, EPO age-based selectivity deviates, and implementation error. The dotted line represents the 'current' (2015-2017) F estimated by the 2020 stock assessment, the solid black line represents the 'current' (2012-2014) F estimated by the 2017 stock assessment and the mean F estimated over the conditioning period (1993-2015) for OM1, both 0.51.

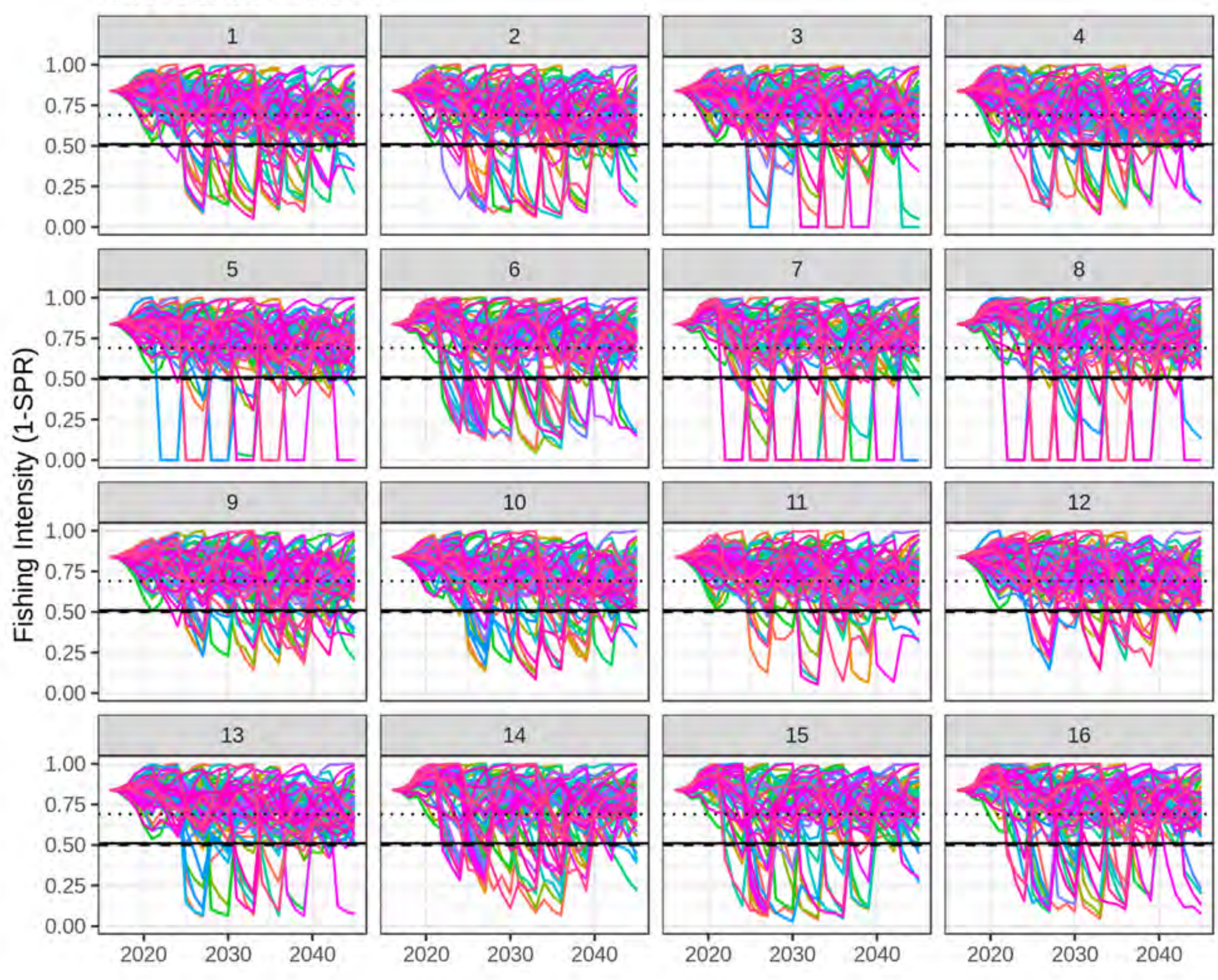


Figure 52. Worm plots of fishing intensity (F, 1-SPR) for individual runs for the **TAC control** simulation and for each harvest control rule (HCR) for the **low productivity scenario, OM6**. Each panel presents the results for the labeled HCR. Trajectories represent separate iterations differing in simulated random recruitment deviates, EPO age-based selectivity deviates, and implementation error. The dash line represents the ‘current’ (2015-2017) F estimated by the 2020 stock assessment, the solid black line represents the ‘current’ (2012-2014) F estimated by the 2017 stock assessment and the dotted line the mean F estimated over the conditioning period (1993-2015) for OM6.

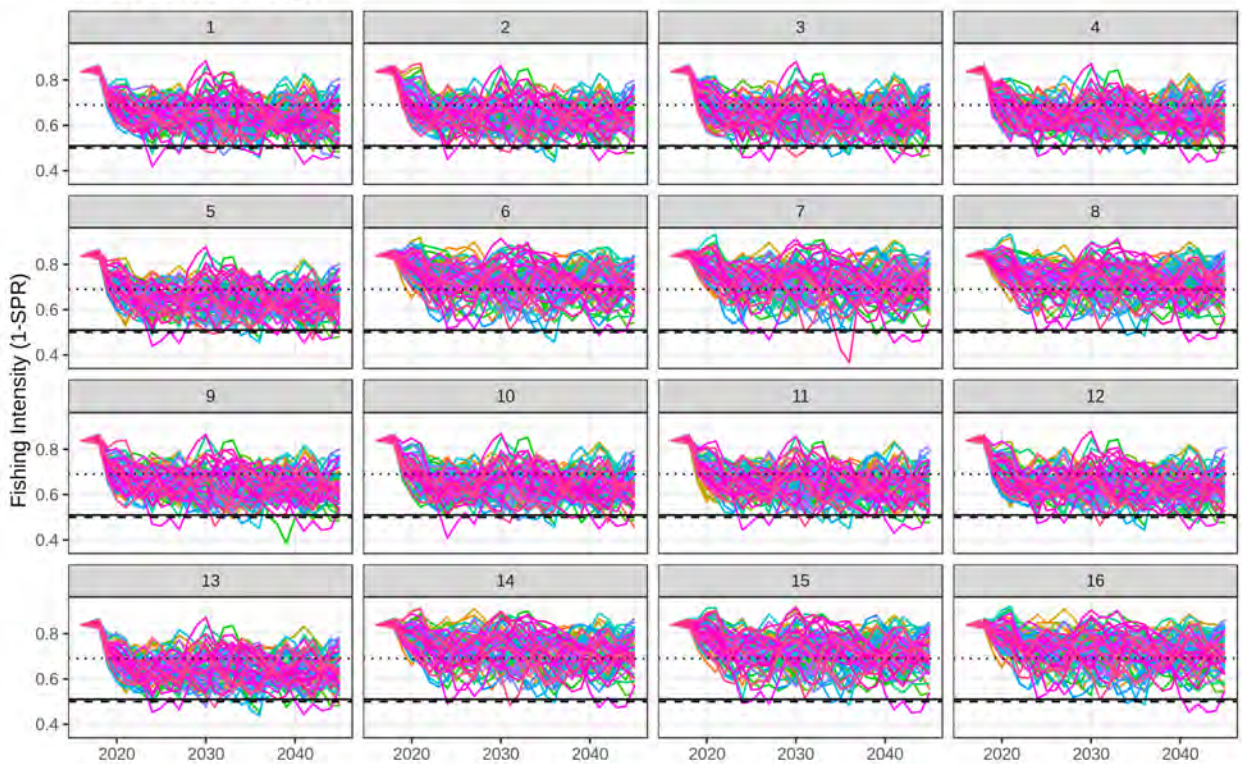


Figure 53. Worm plots of fishing intensity (F, 1-SPR) for individual runs for the **mixed control** simulation and for each harvest control rule (HCR) for the **low productivity scenario, OM6**. Each panel presents the results for the labeled HCR. Trajectories represent separate iterations differing in simulated random recruitment deviates, EPO age-based selectivity deviates, and implementation error. The dash line represents the 'current' (2015-2017) F estimated by the 2020 stock assessment, the solid black line represents the 'current' (2012-2014) F estimated by the 2017 stock assessment and the dotted line the mean F estimated over the conditioning period (1993-2015) for OM6.

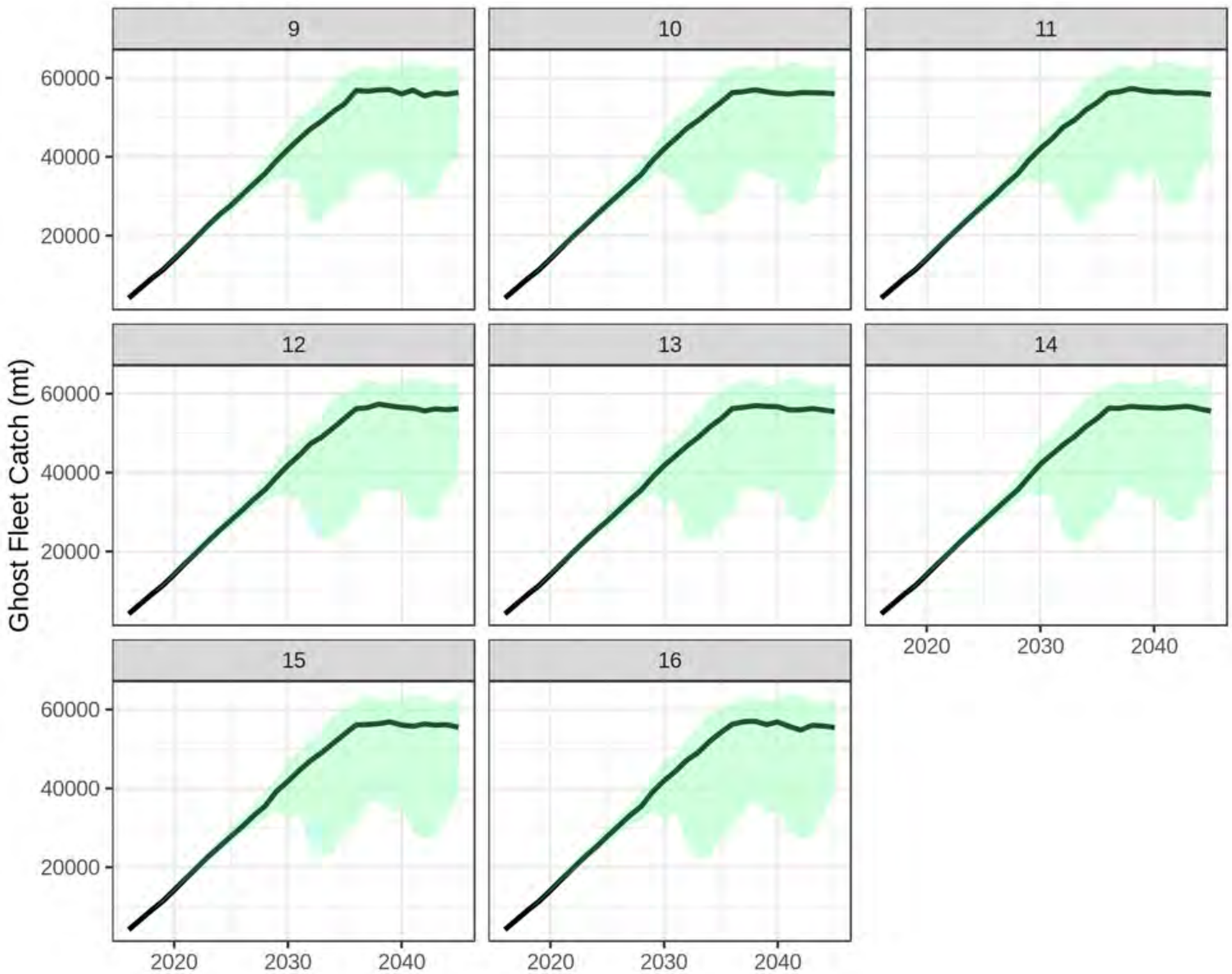


Figure 54. Trends in median catch for the unknown fleet in the **robustness scenario** by harvest control rule (HCR) under **mixed control**. The green shading represents trends in the 5th to 95th quantiles of catch.

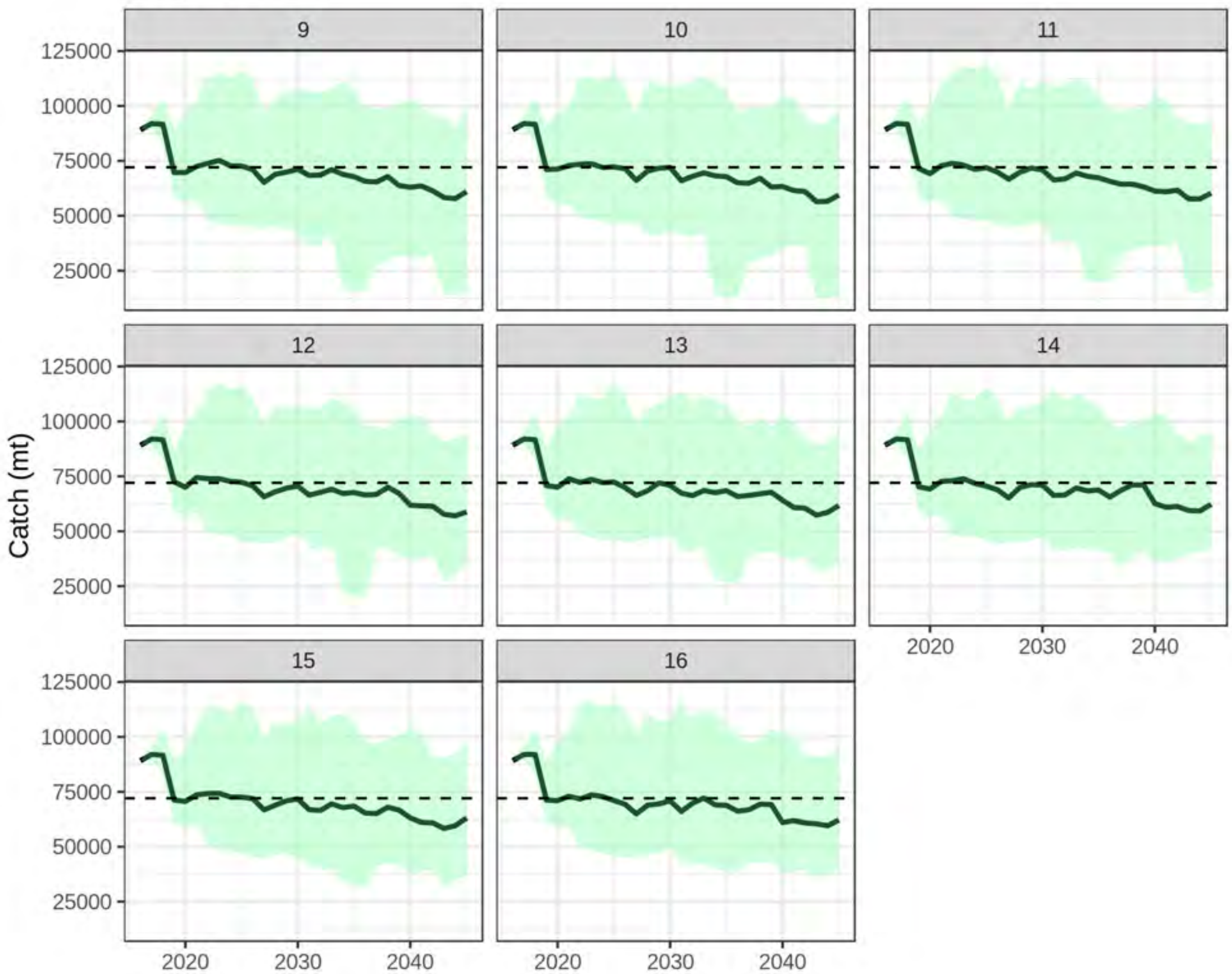


Figure 55. Trends in median catch for the managed fleets under the **unknown fleet robustness scenario** by harvest control rule (HCR) under **mixed control**. The green shading represents trends in the 5th to 95th quantiles of catch.

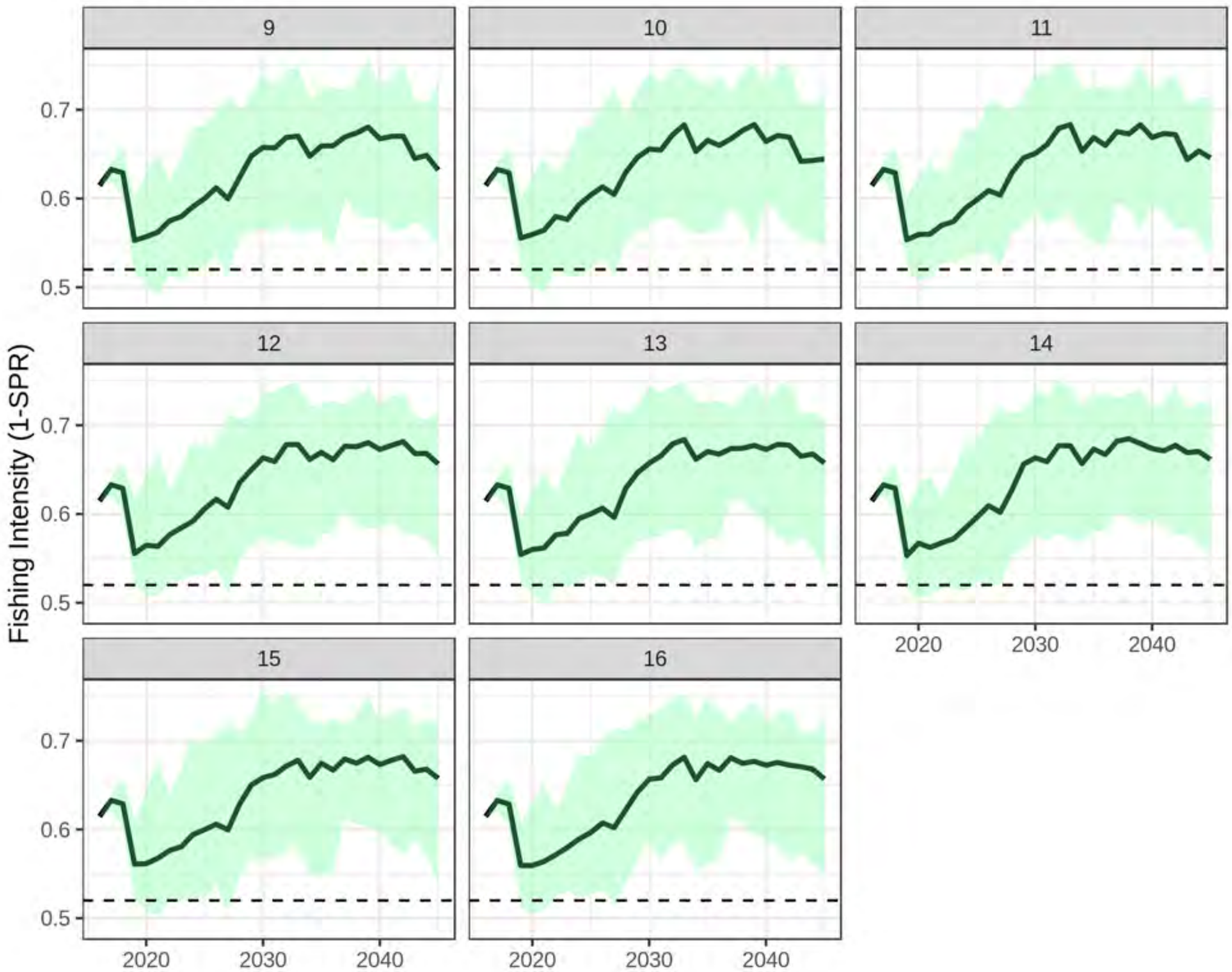


Figure 56. Trends in median fishing intensity under the **unknown fleet robustness scenario** by harvest control rule (HCR) under **mixed control**. The green shading represents trends in the 5th to 95th quantiles of catch.

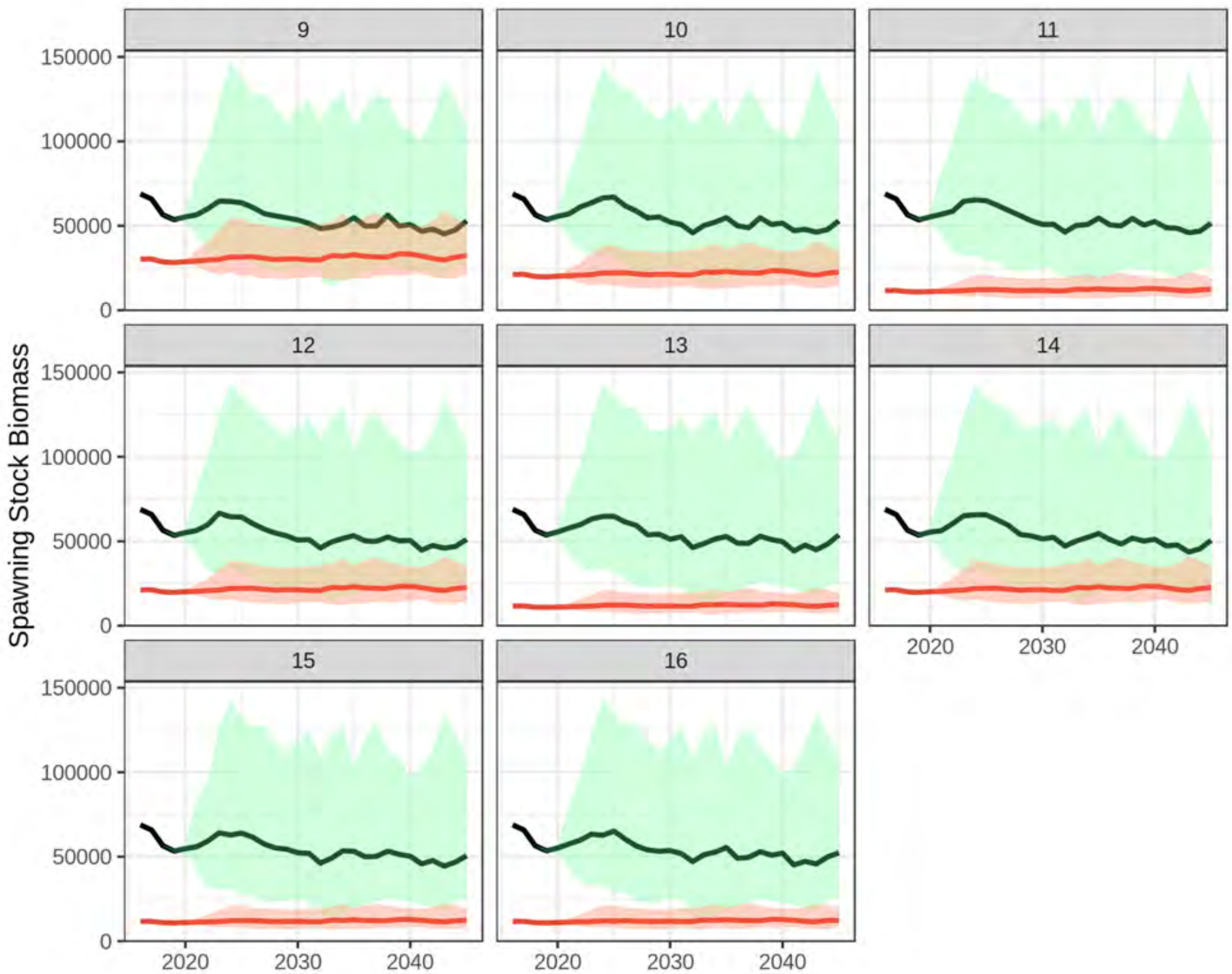


Figure 57. Trends in median female spawning stock biomass under the **unknown fleet robustness scenario** by harvest control rule (HCR) under **mixed control**. The green shading represents trends in the 5th to 95th quantiles of catch.

Figure 58. Trends in median catch for the unknown fleet in the **robustness scenario** by harvest control rule (HCR) under **TAC control**. The green shading represents trends in the 5th to 95th quantiles of catch.

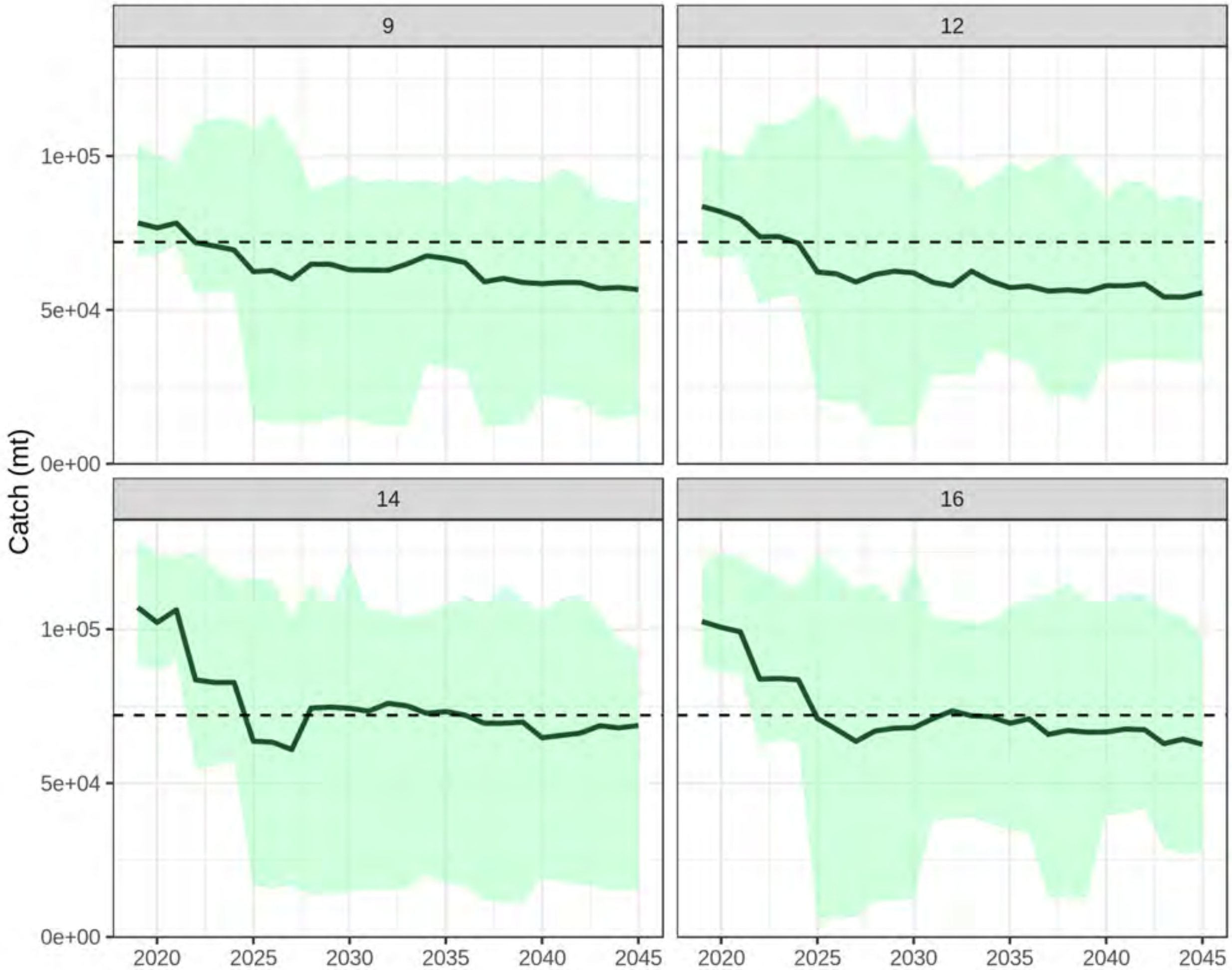


Figure 59. Trends in median catch for the managed fleets under the **unknown fleet robustness scenario** by harvest control rule (HCR) under **TAC control**. The green shading represents trends in the 5th to 95th quantiles of catch.

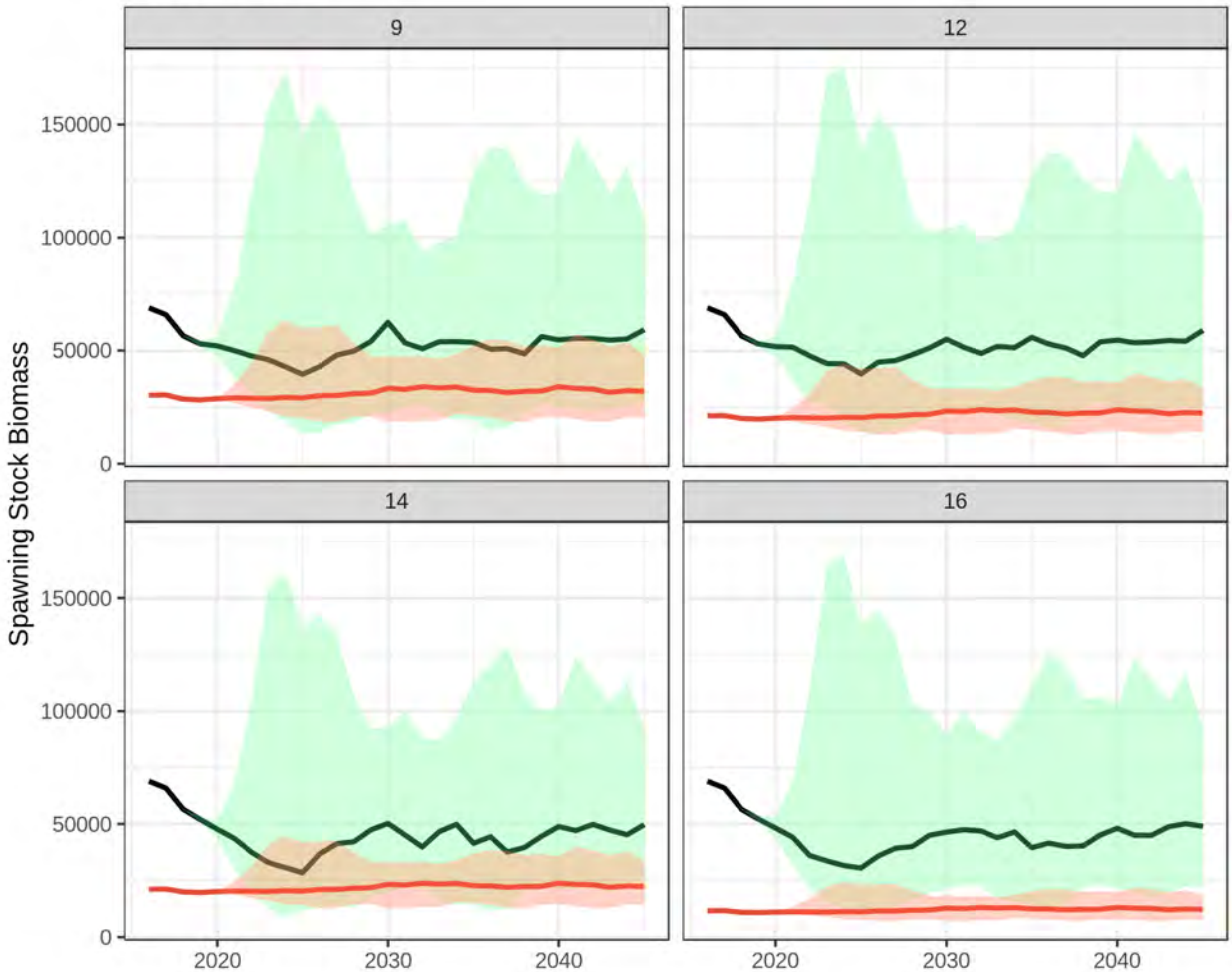


Figure 60. Trends in median female spawning stock biomass under the **unknown fleet robustness scenario** by harvest control rule (HCR) under **mixed control**. The green shading represents trends in the 5th to 95th quantiles of catch.

11 Appendix Tables

Table A1. Performance of additional general metrics for each harvest control rule under **mixed control** across all iterations and **across reference scenario**. HCR refers to harvest control rule, LRP to limit reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. Unless specified as equilibrium SSB0, the unfished SSB is dynamic and fluctuates depending on changes in recruitment.

Mixed Control
Across Reference Scenarios

hcr	TRP	LRP	SSBthreshold	Average SSB (mt)	SSB Variation (mt)	Average Depletion of Total Biomass	Depletion of Total Biomass Variation	Average Catch (mt)	Catch Variation (mt)	Mean Medium Term Catch (mt)	Medium Term Catch Variation (mt)	Mean Long Term Catch (mt)	Long Term Catch Variation (mt)	Mean % Decrease in TAC between assessment periods	% Decrease in TAC between assessment periods Variation
1	F50	0.200	0.30	73836	35768	0.69	0.23	76468	19194	75859	16919	78472	14608	-9.3	8.8
2	F50	0.140	0.30	73228	35768	0.68	0.23	76697	18823	75852	17176	78693	14324	-8.8	7.2
3	F50	0.077	0.30	73719	35938	0.69	0.23	76587	18925	75673	17197	78655	14464	-8.8	6.8
4	F50	0.140	0.20	73563	35810	0.69	0.23	76776	18890	75885	17020	78789	14483	-8.5	6.3
5	F50	0.077	0.20	73671	35897	0.69	0.23	76629	18868	75717	16883	78788	14353	-8.7	6.6
6	F40	0.140	0.20	68382	37093	0.67	0.23	81510	19495	80347	17581	82994	14937	-9.1	7.7
7	F40	0.077	0.20	68354	37228	0.67	0.23	81442	19486	80291	17422	82851	14882	-9.1	8.5
8	F40	0.077	0.14	68376	37239	0.67	0.23	81456	19386	80212	17463	83008	14923	-8.9	7.2
9	F50	0.200	0.30	73606	35798	0.69	0.23	76703	19021	76048	17140	78729	14329	-8.9	7.6
10	F50	0.140	0.30	73651	35790	0.69	0.23	76681	19004	75615	16930	78784	14502	-8.8	7.1
11	F50	0.077	0.30	73617	35724	0.69	0.23	76736	18978	75870	17026	78834	14567	-8.7	6.9
12	F50	0.140	0.20	73415	35682	0.69	0.23	76997	18937	76116	17159	79132	14291	-8.8	6.5
13	F50	0.077	0.20	73547	35671	0.69	0.23	76843	19043	76117	17151	78905	14611	-8.6	6.5
14	F40	0.140	0.20	68463	37124	0.67	0.23	81483	19416	80169	17444	83088	14811	-8.7	6.9
15	F40	0.077	0.20	68457	37144	0.67	0.23	81487	19410	80251	17421	83013	14953	-9.1	7.1
16	F40	0.077	0.14	68280	37078	0.67	0.23	81628	19439	80416	17558	83125	14781	-8.7	7.1

Table A2. Performance of additional general metrics for each harvest control rule under **TAC control** across all iterations and **across reference scenario**. HCR refers to harvest control rule, LRP to limit reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. Unless specified as equilibrium SSB0, the unfished SSB is dynamic and fluctuates depending on changes in recruitment.

TAC Control

Across Reference Scenarios

hcr	TRP	LRP	SSBthreshold	Average SSB (mt)	SSB Variation (mt)	Average Depletion of Total Biomass	Depletion of Total Biomass Variation	Average Catch (mt)	Catch Variation (mt)	Mean Medium Term Catch (mt)	Medium Term Catch Variation (mt)	Mean Long Term Catch (mt)	Long Term Catch Variation (mt)	Mean % Decrease in TAC between assessment periods	% Decrease in TAC between assessment periods Variation
1	F50	0.200	0.30	68912	39671	0.66	0.25	79461	22803	79145	19486	79291	15341	-19.6	20.2
2	F50	0.140	0.30	69280	40008	0.66	0.25	79144	22695	78814	19068	79250	15835	-18.7	19.6
3	F50	0.077	0.30	69440	40629	0.66	0.25	78519	21612	78881	18433	78760	15493	-18.3	17.8
4	F50	0.140	0.20	68848	39950	0.66	0.25	79295	21426	79447	18697	79509	15608	-17.0	16.7
5	F50	0.077	0.20	68314	40225	0.66	0.25	79867	20781	80280	18311	80351	14813	-16.1	15.2
6	F40	0.140	0.20	66745	41727	0.65	0.25	81750	26432	78188	21619	82356	16843	-22.1	23.6
7	F40	0.077	0.20	66834	41835	0.66	0.25	82750	25371	79065	21853	82788	16282	-21.0	22.4
8	F40	0.077	0.14	65332	41682	0.65	0.25	82685	24641	79303	21073	82972	16562	-19.5	20.3
9	F50	0.200	0.30	69079	40005	0.66	0.25	79348	21944	79654	18107	79521	15683	-17.8	17.9
10	F50	0.140	0.30	69316	40049	0.66	0.25	79083	22084	78492	18658	79584	15477	-18.4	17.8
11	F50	0.077	0.30	69291	39950	0.66	0.25	79195	21135	79769	17775	79634	15357	-17.2	16.1
12	F50	0.140	0.20	68832	40161	0.66	0.25	79692	20907	79494	18357	79955	15249	-16.7	14.6
13	F50	0.077	0.20	68257	39966	0.66	0.25	79987	21192	79852	18339	80573	15792	-16.1	15.2
14	F40	0.140	0.20	65524	42118	0.65	0.25	82017	25436	79019	21152	82346	16740	-20.7	21.1
15	F40	0.077	0.20	65302	41621	0.65	0.25	82693	25476	80146	22184	82544	16687	-20.7	21.1
16	F40	0.077	0.14	65935	42188	0.65	0.25	82392	24310	79847	20678	82635	16057	-19.2	19.4

Table A3. Performance of additional general metrics for each harvest control rule under **mixed control** across all iterations for **each reference scenario**. HCR refers to harvest control rule, LRP to limit reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. Unless specified as equilibrium SSB0, the unfished SSB is dynamic and fluctuates depending on changes in recruitment.

Mixed Control
By Scenario

hcr	scn	TRP	LRP	SSBthreshold	Average SSB (mt)	SSB Variation (mt)	Average Depletion of Total Biomass	Depletion of Total Biomass Variation	Average Catch (mt)	Catch Variation (mt)	Mean Medium Term Catch (mt)	Medium Term Catch Variation (mt)	Mean Long Term Catch (mt)	Long Term Catch Variation (mt)	Mean % Decrease in TAC between assessment periods	% Decrease in TAC between assessment periods Variation
1	1	F50	0.200	0.30	78041	32079	0.70	0.22	82172	20166	81311	18062	83938	15427	-9.3	7.4
2	1	F50	0.140	0.30	77171	31570	0.70	0.22	81845	20016	81267	18110	83353	15192	-8.7	7.2
3	1	F50	0.077	0.30	77574	31865	0.70	0.22	82691	20251	81689	18000	84451	15624	-8.7	6.4
4	1	F50	0.140	0.20	78056	32110	0.70	0.22	82159	19946	81101	17872	83996	15172	-8.8	6.3
5	1	F50	0.077	0.20	78413	32010	0.70	0.22	81853	20299	80876	17984	83896	15447	-8.7	6.7
6	1	F40	0.140	0.20	78025	32062	0.70	0.22	82209	20169	81009	18046	84110	15487	-8.9	6.5
7	1	F40	0.077	0.20	77848	32128	0.70	0.22	82374	19980	81266	17759	84196	15236	-8.5	6.7
8	1	F40	0.077	0.14	77985	32014	0.70	0.22	82279	20227	81203	18258	84157	15387	-9.2	6.6
9	1	F50	0.200	0.30	78074	32167	0.70	0.22	82096	20163	81159	17848	83814	15169	-9.2	7.6
10	1	F50	0.140	0.30	77962	32006	0.70	0.22	82305	20171	80992	17797	84252	15418	-8.7	6.5
11	1	F50	0.077	0.30	78342	31968	0.70	0.22	81876	20338	80690	18107	83844	15731	-8.9	7.3
12	1	F50	0.140	0.20	77736	32013	0.70	0.22	82553	20202	81519	17916	84489	15278	-9.1	6.1
13	1	F50	0.077	0.20	78102	31917	0.70	0.22	82149	20326	80938	18304	84114	15734	-8.8	6.6
14	1	F40	0.140	0.20	77774	32030	0.70	0.22	82469	20070	81147	17851	84289	15377	-8.4	6.6
15	1	F40	0.077	0.20	78104	32134	0.70	0.22	82139	20159	80730	17627	84234	15349	-9.4	6.6
16	1	F40	0.077	0.14	78004	32041	0.70	0.22	82309	20253	81033	18115	84315	15389	-8.7	6.4
1	3	F50	0.200	0.30	96661	36960	0.77	0.23	76158	19084	75927	17287	78023	14253	-8.3	6.2
2	3	F50	0.140	0.30	96563	36939	0.77	0.23	76260	18980	75905	17524	78106	14289	-8.2	6.2
3	3	F50	0.077	0.30	97078	37130	0.77	0.23	75540	18808	75453	17340	77209	14150	-7.9	5.8

Mixed Control

By Scenario

4	3	F50	0.140	0.20	96623	36924	0.77	0.23	76172	19044	75961	17397	77897	14459	-8.1	6.0
5	3	F50	0.077	0.20	96727	37106	0.77	0.23	76027	18875	75844	17313	77789	14049	-8.3	6.1
6	3	F40	0.140	0.20	96428	36926	0.77	0.23	76488	19049	76426	17527	78127	14259	-8.0	6.1
7	3	F40	0.077	0.20	96661	37125	0.77	0.23	76129	18811	75895	17058	77950	14026	-8.0	6.3
8	3	F40	0.077	0.14	96832	37044	0.77	0.23	75920	19045	75618	17346	77812	14367	-8.1	6.3
9	3	F50	0.200	0.30	96374	37021	0.77	0.23	76494	19021	76441	17560	78160	14012	-8.4	6.9
10	3	F50	0.140	0.30	96540	36849	0.77	0.23	76320	19226	76170	17647	78063	14410	-8.1	5.9
11	3	F50	0.077	0.30	96291	36811	0.77	0.23	76638	19265	76688	17695	78213	14480	-8.6	6.2
12	3	F50	0.140	0.20	96775	36765	0.78	0.23	76938	18813	76544	17096	78987	13724	-8.0	5.9
13	3	F50	0.077	0.20	96296	36807	0.77	0.23	76643	19243	76596	17690	78215	14579	-8.2	6.2
14	3	F40	0.140	0.20	96866	36959	0.77	0.23	75883	19100	75845	17732	77806	14278	-7.8	5.6
15	3	F40	0.077	0.20	96524	36916	0.77	0.23	76373	19015	76129	17474	78120	14309	-7.9	6.2
16	3	F40	0.077	0.14	96243	36935	0.77	0.23	76742	19073	76701	17374	78410	14246	-8.3	6.1
1	4	F50	0.200	0.30	58279	26889	0.70	0.22	76668	19356	76609	16412	78245	14391	-10.2	12.6
2	4	F50	0.140	0.30	57616	26911	0.69	0.22	77526	18450	77027	16326	79292	14171	-8.8	8.0
3	4	F50	0.077	0.30	57998	27125	0.70	0.22	77097	18459	76352	16757	78983	13997	-9.1	8.0
4	4	F50	0.140	0.20	57383	26995	0.69	0.22	77720	18355	77245	16574	79200	14244	-8.4	6.1
5	4	F50	0.077	0.20	57888	26981	0.70	0.22	77191	18333	76467	16373	79201	13802	-8.7	6.8
6	4	F40	0.140	0.20	48367	24614	0.66	0.22	88157	20101	87428	17303	88633	15305	-9.9	9.4
7	4	F40	0.077	0.20	48618	24907	0.66	0.22	87807	20360	87224	17480	87889	15571	-10.2	10.9
8	4	F40	0.077	0.14	48391	24875	0.66	0.22	88116	19591	87094	16987	88654	15097	-9.4	8.0
9	4	F50	0.200	0.30	58137	26918	0.70	0.22	76917	18881	76547	16902	78828	14201	-9.6	9.1
10	4	F50	0.140	0.30	58111	27201	0.70	0.22	76916	18389	76188	16084	78678	13928	-9.6	8.4

Mixed Control

By Scenario

11	4	F50	0.077	0.30	58069	26845	0.70	0.22	77021	18522	76115	16683	78879	14223	-8.7	7.0
12	4	F50	0.140	0.20	57549	26891	0.69	0.22	77496	18430	76991	16894	79093	14001	-8.9	7.1
13	4	F50	0.077	0.20	57606	26826	0.69	0.22	77485	18402	77203	16373	79223	14234	-9.1	6.6
14	4	F40	0.140	0.20	48386	24676	0.66	0.21	88383	19505	86815	17278	89205	14192	-9.2	7.7
15	4	F40	0.077	0.20	48506	24741	0.66	0.22	87956	19879	87130	17430	88341	15197	-9.5	7.6
16	4	F40	0.077	0.14	48355	24712	0.66	0.22	88096	19969	87265	17636	88342	15107	-8.8	7.9
1	6	F50	0.200	0.30	62362	32989	0.57	0.19	70872	16267	69588	13869	73683	12679	-9.4	7.9
2	6	F50	0.140	0.30	61733	32956	0.57	0.19	71376	16246	69439	14871	74220	12365	-9.6	7.4
3	6	F50	0.077	0.30	62227	33136	0.57	0.19	71023	16095	69197	14508	73979	12133	-9.4	6.8
4	6	F50	0.140	0.20	62192	32628	0.57	0.19	71053	16356	69233	14146	74065	12446	-8.5	6.8
5	6	F50	0.077	0.20	61657	32844	0.57	0.19	71444	16284	69681	14027	74267	12572	-8.9	6.6
6	6	F40	0.140	0.20	50706	30245	0.53	0.18	79184	16484	76524	15357	81104	12792	-9.4	8.1
7	6	F40	0.077	0.20	50288	30115	0.53	0.18	79459	16681	76778	15283	81369	13038	-9.4	8.7
8	6	F40	0.077	0.14	50295	30061	0.53	0.18	79507	16391	76932	15133	81411	12872	-9.0	7.4
9	6	F50	0.200	0.30	61838	32883	0.57	0.19	71305	16264	70048	14557	74116	12406	-8.4	6.8
10	6	F50	0.140	0.30	61991	32909	0.57	0.19	71185	16385	69110	14112	74142	12580	-8.9	7.2
11	6	F50	0.077	0.30	61765	33016	0.57	0.19	71408	16077	69988	13911	74400	12360	-8.6	7.2
12	6	F50	0.140	0.20	62269	32743	0.57	0.19	70999	16310	69421	14686	73955	12300	-9.1	6.7
13	6	F50	0.077	0.20	62184	32808	0.57	0.19	71095	16349	69729	14388	74066	12193	-8.5	6.5
14	6	F40	0.140	0.20	50538	29834	0.53	0.18	79298	16625	76963	14972	81140	13190	-9.2	7.4
15	6	F40	0.077	0.20	50436	30113	0.53	0.18	79451	16444	76967	15167	81331	13217	-9.4	7.6
16	6	F40	0.077	0.14	50517	30163	0.53	0.18	79366	16370	76665	15143	81434	12684	-9.0	7.7

Table A4. Performance of additional general metrics for each harvest control rule under **TAC control** across all iterations for **each reference scenario**. HCR refers to harvest control rule, LRP to limit reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. Unless specified as equilibrium SSB0, the unfished SSB is dynamic and fluctuates depending on changes in recruitment.

TAC Control

By Scenario

hcr	scn	TRP	LRP	SSBthreshold	Average SSB (mt)	SSB Variation (mt)	Average Depletion of Total Biomass	Depletion of Total Biomass Variation	Average Catch (mt)	Catch Variation (mt)	Mean Medium Term Catch (mt)	Medium Term Catch Variation (mt)	Mean Long Term Catch (mt)	Long Term Catch Variation (mt)	Mean % Decrease in TAC between assessment periods	% Decrease in TAC between assessment periods Variation
1	1	F50	0.200	0.30	76718	35257	0.70	0.23	83168	21510	84324	17863	82900	15969	-17.5	17.0
2	1	F50	0.140	0.30	75763	35030	0.69	0.23	84505	21393	84232	18148	84820	16568	-16.2	14.1
3	1	F50	0.077	0.30	77733	35863	0.70	0.23	82345	19508	83187	16180	83338	15413	-14.8	11.4
4	1	F50	0.140	0.20	76205	34971	0.69	0.23	84110	19782	83478	17501	85303	16060	-14.6	11.3
5	1	F50	0.077	0.20	76577	35634	0.70	0.23	83569	19477	84971	16667	84601	14999	-14.2	10.6
6	1	F40	0.140	0.20	77244	34208	0.70	0.22	83482	19665	83875	16200	85128	15594	-14.8	10.7
7	1	F40	0.077	0.20	78427	36074	0.71	0.24	84309	19145	84547	16829	85430	15365	-13.8	10.6
8	1	F40	0.077	0.14	74949	33737	0.69	0.22	84416	19293	82007	16538	85952	14705	-14.4	10.6
9	1	F50	0.200	0.30	77175	35250	0.70	0.23	82811	20477	82838	17089	83631	15756	-15.8	13.9
10	1	F50	0.140	0.30	77630	35586	0.70	0.23	82482	20546	82087	17168	83851	15748	-15.9	13.6
11	1	F50	0.077	0.30	76798	35132	0.70	0.23	83464	19902	85337	15821	84665	15506	-14.9	12.4
12	1	F50	0.140	0.20	75801	35111	0.69	0.23	84467	19739	84549	16630	85253	15768	-14.7	10.5
13	1	F50	0.077	0.20	76288	34766	0.69	0.23	84150	20012	84112	17039	85932	16112	-14.3	10.4
14	1	F40	0.140	0.20	76424	35783	0.70	0.23	84286	19045	84056	17212	84975	14760	-15.0	9.9
15	1	F40	0.077	0.20	73281	35634	0.68	0.24	86132	20223	86207	17927	85917	16430	-15.1	10.4
16	1	F40	0.077	0.14	77464	35447	0.70	0.23	84270	18853	83480	17077	86168	13968	-13.8	10.0
1	3	F50	0.200	0.30	96987	41014	0.77	0.24	75511	17001	75572	15143	75964	13001	-13.6	9.9
2	3	F50	0.140	0.30	98804	41171	0.78	0.24	72800	16129	73318	14235	73596	12433	-13.0	9.4
3	3	F50	0.077	0.30	99853	41442	0.78	0.25	71454	15650	71537	12995	73020	12468	-12.9	8.5

TAC Control
By Scenario

4	3	F50	0.140	0.20	98364	40876	0.78	0.24	73497	16915	74729	15410	74419	12737	-13.1	9.2
5	3	F50	0.077	0.20	98084	40951	0.78	0.24	73968	16633	74434	14050	75323	12926	-12.6	9.7
6	3	F40	0.140	0.20	99185	41613	0.78	0.25	72354	16363	73787	14338	73494	11895	-13.1	9.4
7	3	F40	0.077	0.20	97587	41066	0.78	0.24	74558	16597	75298	15062	74845	12175	-13.8	9.9
8	3	F40	0.077	0.14	98676	41296	0.78	0.24	73114	16045	73692	13976	74211	12470	-12.9	9.3
9	3	F50	0.200	0.30	98032	40890	0.78	0.24	74099	16807	74745	14909	75090	13447	-12.7	9.6
10	3	F50	0.140	0.30	97899	41304	0.78	0.25	74124	16454	75215	13760	74758	12743	-13.6	9.6
11	3	F50	0.077	0.30	98531	41345	0.78	0.25	73244	16155	74128	13988	74636	12285	-12.7	9.4
12	3	F50	0.140	0.20	98536	41214	0.78	0.25	73289	16648	74244	15219	74345	12629	-13.0	9.2
13	3	F50	0.077	0.20	98540	41026	0.78	0.24	73306	16934	74157	14274	74892	13081	-13.0	9.3
14	3	F40	0.140	0.20	99390	41460	0.78	0.25	72142	15957	71842	14121	73574	11956	-12.9	9.1
15	3	F40	0.077	0.20	98689	41105	0.78	0.24	73028	15974	74079	14275	73829	12211	-12.3	8.7
16	3	F40	0.077	0.14	99235	41579	0.78	0.25	72297	15500	73411	13344	73293	12050	-12.8	8.7
1	4	F50	0.200	0.30	54005	29363	0.67	0.23	80972	23278	79785	19561	80595	15078	-20.6	21.6
2	4	F50	0.140	0.30	53893	29107	0.67	0.23	81119	22806	81684	18370	80749	15081	-19.8	21.0
3	4	F50	0.077	0.30	53857	29730	0.67	0.23	80984	22134	80841	18938	80383	15053	-20.3	19.7
4	4	F50	0.140	0.20	53577	29448	0.67	0.23	81317	21248	82085	16880	80779	14770	-17.4	16.7
5	4	F50	0.077	0.20	53092	29390	0.67	0.23	81976	20197	82562	16920	81843	14442	-15.5	12.9
6	4	F40	0.140	0.20	46594	28568	0.64	0.23	89896	28562	84036	22877	89220	16941	-27.1	26.5
7	4	F40	0.077	0.20	46706	29081	0.64	0.23	89266	26360	85058	22378	87946	15659	-23.5	23.5
8	4	F40	0.077	0.14	45689	28405	0.64	0.23	90586	24425	86663	19567	89175	16111	-20.4	18.3
9	4	F50	0.200	0.30	53660	29063	0.67	0.23	81427	22461	81536	17654	81382	15292	-18.9	18.9
10	4	F50	0.140	0.30	53740	29602	0.67	0.23	81289	22422	81434	17538	81032	15038	-18.5	18.3

TAC Control
By Scenario

11	4	F50	0.077	0.30	54043	29451	0.67	0.23	80874	21736	81379	18033	80325	15207	-19.6	17.2
12	4	F50	0.140	0.20	53123	29388	0.67	0.23	81969	21024	81994	18177	81217	14999	-18.1	15.0
13	4	F50	0.077	0.20	51980	29007	0.66	0.23	83165	20626	83304	17123	82669	15234	-15.9	13.6
14	4	F40	0.140	0.20	46306	28555	0.64	0.23	90229	25727	88262	20530	89167	16622	-22.6	21.7
15	4	F40	0.077	0.20	45928	28404	0.64	0.23	90139	25367	89120	20792	89067	16214	-22.9	21.6
16	4	F40	0.077	0.14	45342	28277	0.63	0.23	91024	24156	87657	20351	89563	14731	-20.3	19.1
1	6	F50	0.200	0.30	47938	31592	0.50	0.19	78192	27457	76899	23632	77704	16478	-27.3	26.7
2	6	F50	0.140	0.30	48362	32328	0.51	0.20	78137	27433	75983	22941	77815	17019	-26.3	27.0
3	6	F50	0.077	0.30	46315	30753	0.50	0.19	79294	26122	79958	22495	78298	17129	-24.7	24.1
4	6	F50	0.140	0.20	47244	31614	0.50	0.20	78259	25418	77497	23127	77535	16757	-22.8	23.9
5	6	F50	0.077	0.20	45504	30927	0.50	0.19	79956	24723	79152	23036	79635	15489	-22.2	22.6
6	6	F40	0.140	0.20	41412	30361	0.47	0.19	82012	34498	71430	28064	82375	18587	-33.7	32.3
7	6	F40	0.077	0.20	41337	30900	0.48	0.20	83202	34549	70506	28691	83484	18961	-35.5	32.6
8	6	F40	0.077	0.14	39565	30661	0.47	0.20	83061	32831	74727	29434	83130	18873	-31.9	31.4
9	6	F50	0.200	0.30	47134	31926	0.50	0.20	79052	26067	79493	21524	77961	17005	-24.1	24.1
10	6	F50	0.140	0.30	47685	31136	0.50	0.19	78427	26790	75185	23992	78681	16962	-25.9	24.3
11	6	F50	0.077	0.30	47478	30863	0.50	0.19	79197	24572	78212	20961	78901	16721	-21.5	20.9
12	6	F50	0.140	0.20	47338	31771	0.50	0.20	79068	23937	77191	21454	79010	15631	-21.6	20.1
13	6	F50	0.077	0.20	45900	30137	0.50	0.19	79316	24785	77806	22529	78772	16625	-21.1	22.3
14	6	F40	0.140	0.20	40344	29777	0.47	0.19	82119	33296	72809	26072	82452	18881	-32.0	29.8
15	6	F40	0.077	0.20	40351	29277	0.47	0.19	82178	34255	70940	28952	82046	17894	-34.0	30.1
16	6	F40	0.077	0.14	39000	28930	0.46	0.19	82648	32124	75081	27047	82272	18407	-30.8	28.1

Table A5. Performance of indicators for each harvest control rule under **mixed control** across all iterations for **each reference scenario**. HCR refers to harvest control rule, LRP to limit reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. Unless specified as equilibrium SSB0, the unfished SSB is dynamic and fluctuates depending on changes in recruitment. See table ES1 for a detailed definition of performance indicators.

Mixed Control

By Scenario

hcr	scn	TRP	LRP	SSBthreshold	Odds of Not Breaching the LRP	Odds SSB > 20% SSBo	Odds SSB > Equilibrium 7.7% SSBo	Odds SSB > 7.7% SSBo	Odds Depletion > Minimum Historical	Odds Mean Annual Catch > Historical	Odds Mean Medium Term Catch > Historical Catch	Odds Mean Long Term Catch > Historical Catch	Catch Stability	Odds No Management Action	Ftarget/F
1	1	F50	0.200	0.30	1.00	1.00	0.98	1.00	0.69	0.69	0.70	0.78	1.00	1.00	0.99
2	1	F50	0.140	0.30	1.00	1.00	0.98	1.00	0.69	0.69	0.69	0.77	1.00	1.00	0.98
3	1	F50	0.077	0.30	1.00	1.00	0.98	1.00	0.69	0.70	0.70	0.79	1.00	1.00	0.99
4	1	F50	0.140	0.20	1.00	1.00	0.98	1.00	0.69	0.69	0.69	0.78	1.00	1.00	0.99
5	1	F50	0.077	0.20	1.00	1.00	0.98	1.00	0.69	0.69	0.69	0.78	1.00	1.00	1.00
6	1	F40	0.140	0.20	1.00	1.00	0.98	1.00	0.69	0.69	0.69	0.78	1.00	1.00	1.19
7	1	F40	0.077	0.20	1.00	1.00	0.98	1.00	0.69	0.70	0.70	0.79	1.00	1.00	1.19
8	1	F40	0.077	0.14	1.00	1.00	0.98	1.00	0.69	0.69	0.69	0.78	1.00	1.00	1.19
9	1	F50	0.200	0.30	1.00	1.00	0.98	1.00	0.69	0.69	0.70	0.78	1.00	1.00	0.99
10	1	F50	0.140	0.30	1.00	1.00	0.98	1.00	0.69	0.69	0.69	0.79	1.00	1.00	0.99
11	1	F50	0.077	0.30	1.00	1.00	0.98	1.00	0.69	0.69	0.68	0.77	1.00	1.00	1.00
12	1	F50	0.140	0.20	1.00	1.00	0.98	1.00	0.69	0.70	0.70	0.79	1.00	1.00	0.99
13	1	F50	0.077	0.20	1.00	1.00	0.98	1.00	0.69	0.69	0.69	0.78	1.00	1.00	1.00
14	1	F40	0.140	0.20	1.00	1.00	0.98	1.00	0.69	0.70	0.69	0.79	1.00	1.00	1.19
15	1	F40	0.077	0.20	1.00	1.00	0.98	1.00	0.69	0.69	0.69	0.79	1.00	1.00	1.19
16	1	F40	0.077	0.14	1.00	1.00	0.98	1.00	0.69	0.69	0.69	0.79	1.00	1.00	1.19
1	3	F50	0.200	0.30	1.00	1.00	0.99	1.00	0.73	0.59	0.59	0.66	1.00	1.00	1.25
2	3	F50	0.140	0.30	1.00	1.00	0.99	1.00	0.73	0.59	0.59	0.66	1.00	1.00	1.25
3	3	F50	0.077	0.30	1.00	1.00	0.99	1.00	0.73	0.57	0.58	0.64	1.00	1.00	1.26

Mixed Control

By Scenario

4	3	F50	0.140	0.20	1.00	1.00	0.99	1.00	0.73	0.59	0.59	0.66	1.00	1.00	1.25
5	3	F50	0.077	0.20	1.00	1.00	0.99	1.00	0.73	0.58	0.59	0.66	1.00	1.00	1.25
6	3	F40	0.140	0.20	1.00	1.00	0.99	1.00	0.73	0.59	0.60	0.66	1.00	1.00	1.50
7	3	F40	0.077	0.20	1.00	1.00	0.99	1.00	0.73	0.59	0.59	0.66	1.00	1.00	1.49
8	3	F40	0.077	0.14	1.00	1.00	0.99	1.00	0.73	0.58	0.58	0.66	1.00	1.00	1.51
9	3	F50	0.200	0.30	1.00	1.00	0.99	1.00	0.72	0.59	0.60	0.67	1.00	1.00	1.25
10	3	F50	0.140	0.30	1.00	1.00	0.99	1.00	0.73	0.59	0.59	0.66	1.00	1.00	1.25
11	3	F50	0.077	0.30	1.00	1.00	0.99	1.00	0.72	0.59	0.60	0.66	1.00	1.00	1.24
12	3	F50	0.140	0.20	1.00	1.00	0.99	1.00	0.73	0.60	0.60	0.69	1.00	1.00	1.24
13	3	F50	0.077	0.20	1.00	1.00	0.99	1.00	0.73	0.59	0.60	0.66	1.00	1.00	1.24
14	3	F40	0.140	0.20	1.00	1.00	0.99	1.00	0.73	0.58	0.58	0.66	1.00	1.00	1.51
15	3	F40	0.077	0.20	1.00	1.00	0.99	1.00	0.73	0.59	0.59	0.66	1.00	1.00	1.50
16	3	F40	0.077	0.14	1.00	1.00	0.99	1.00	0.72	0.60	0.61	0.67	1.00	1.00	1.49
1	4	F50	0.200	0.30	1.00	1.00	0.96	1.00	0.74	0.59	0.61	0.67	0.94	0.90	0.85
2	4	F50	0.140	0.30	1.00	1.00	0.96	1.00	0.74	0.62	0.62	0.70	1.00	0.89	0.84
3	4	F50	0.077	0.30	1.00	1.00	0.96	1.00	0.74	0.61	0.60	0.69	1.00	0.90	0.85
4	4	F50	0.140	0.20	1.00	0.99	0.96	1.00	0.74	0.62	0.62	0.69	1.00	0.99	0.84
5	4	F50	0.077	0.20	1.00	1.00	0.96	1.00	0.74	0.61	0.61	0.70	1.00	1.00	0.85
6	4	F40	0.140	0.20	0.99	0.96	0.94	1.00	0.69	0.79	0.81	0.86	0.98	0.96	0.89
7	4	F40	0.077	0.20	1.00	0.96	0.93	1.00	0.69	0.78	0.81	0.85	0.97	0.96	0.89
8	4	F40	0.077	0.14	1.00	0.96	0.93	1.00	0.68	0.79	0.81	0.86	0.99	0.99	0.89
9	4	F50	0.200	0.30	1.00	1.00	0.96	1.00	0.74	0.60	0.60	0.68	0.99	0.90	0.86
10	4	F50	0.140	0.30	1.00	1.00	0.96	1.00	0.74	0.60	0.60	0.68	0.99	0.90	0.85

Mixed Control

By Scenario

11	4	F50	0.077	0.30	1.00	1.00	0.96	1.00	0.74	0.61	0.60	0.68	1.00	0.90	0.85
12	4	F50	0.140	0.20	1.00	0.99	0.96	1.00	0.74	0.62	0.61	0.69	1.00	0.99	0.85
13	4	F50	0.077	0.20	1.00	1.00	0.96	1.00	0.74	0.62	0.62	0.69	1.00	1.00	0.85
14	4	F40	0.140	0.20	0.99	0.96	0.93	1.00	0.69	0.80	0.80	0.89	1.00	0.96	0.89
15	4	F40	0.077	0.20	1.00	0.96	0.93	1.00	0.69	0.79	0.81	0.86	1.00	0.96	0.89
16	4	F40	0.077	0.14	1.00	0.96	0.93	1.00	0.68	0.79	0.81	0.86	1.00	0.99	0.89
1	6	F50	0.200	0.30	0.90	0.90	0.93	1.00	0.82	0.47	0.43	0.55	1.00	0.58	0.77
2	6	F50	0.140	0.30	0.97	0.89	0.92	0.99	0.82	0.48	0.43	0.57	1.00	0.57	0.77
3	6	F50	0.077	0.30	0.99	0.89	0.93	0.99	0.82	0.47	0.42	0.56	1.00	0.58	0.77
4	6	F50	0.140	0.20	0.97	0.90	0.93	1.00	0.82	0.48	0.42	0.56	1.00	0.90	0.77
5	6	F50	0.077	0.20	0.99	0.89	0.92	0.99	0.82	0.49	0.43	0.57	1.00	0.89	0.77
6	6	F40	0.140	0.20	0.91	0.74	0.88	0.98	0.77	0.67	0.61	0.76	0.99	0.74	0.82
7	6	F40	0.077	0.20	0.98	0.74	0.88	0.98	0.77	0.67	0.62	0.76	0.99	0.74	0.81
8	6	F40	0.077	0.14	0.98	0.74	0.88	0.98	0.77	0.68	0.63	0.77	1.00	0.91	0.82
9	6	F50	0.200	0.30	0.89	0.89	0.92	0.99	0.82	0.48	0.45	0.57	1.00	0.57	0.77
10	6	F50	0.140	0.30	0.97	0.90	0.93	0.99	0.82	0.48	0.42	0.57	1.00	0.58	0.77
11	6	F50	0.077	0.30	0.99	0.89	0.92	0.99	0.82	0.48	0.44	0.58	1.00	0.57	0.76
12	6	F50	0.140	0.20	0.97	0.90	0.93	1.00	0.82	0.47	0.43	0.56	1.00	0.90	0.77
13	6	F50	0.077	0.20	1.00	0.90	0.93	1.00	0.82	0.48	0.44	0.57	1.00	0.90	0.77
14	6	F40	0.140	0.20	0.91	0.74	0.89	0.98	0.77	0.67	0.63	0.75	1.00	0.74	0.82
15	6	F40	0.077	0.20	0.98	0.74	0.88	0.98	0.77	0.67	0.63	0.76	1.00	0.74	0.82
16	6	F40	0.077	0.14	0.98	0.74	0.88	0.98	0.77	0.67	0.62	0.77	1.00	0.91	0.82

Table A6. Performance of indicators for each harvest control rule under **TAC control** across all iterations for **each reference scenario**. HCR refers to harvest control rule, LRP to limit reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. Unless specified as equilibrium SSB0, the unfished SSB is dynamic and fluctuates depending on changes in recruitment. See table ES1 for a detailed definition of performance indicators.

TAC Control

By Scenario

hcr	scn	TRP	LRP	SSBthreshold	Odds of Not Breaching the LRP	Odds SSB > 20% SSBo	Odds SSB > Equilibrium 7.7% SSBo	Odds SSB > 7.7% SSBo	Odds Depletion > Minimum Historical	Odds Mean Annual Catch > Historical	Odds Mean Medium Term Catch > Historical Catch	Odds Mean Long Term Catch > Historical Catch	Catch Stability	Odds No Management Action	Ftarget/F
1	1	F50	0.200	0.30	1.00	1.00	0.97	1.00	0.67	0.70	0.75	0.75	0.77	0.97	0.95
2	1	F50	0.140	0.30	1.00	1.00	0.96	1.00	0.67	0.72	0.75	0.78	0.84	0.97	0.94
3	1	F50	0.077	0.30	1.00	1.00	0.97	1.00	0.68	0.70	0.75	0.77	0.91	0.98	0.97
4	1	F50	0.140	0.20	1.00	1.00	0.97	1.00	0.67	0.73	0.74	0.80	0.91	1.00	0.95
5	1	F50	0.077	0.20	1.00	1.00	0.96	1.00	0.67	0.72	0.78	0.80	0.93	1.00	0.95
6	1	F40	0.140	0.20	1.00	1.00	0.97	1.00	0.68	0.72	0.77	0.80	0.92	1.00	1.16
7	1	F40	0.077	0.20	1.00	1.00	0.97	1.00	0.69	0.74	0.77	0.81	0.94	1.00	1.15
8	1	F40	0.077	0.14	1.00	1.00	0.97	1.00	0.67	0.74	0.73	0.83	0.93	1.00	1.13
9	1	F50	0.200	0.30	1.00	1.00	0.97	1.00	0.68	0.70	0.74	0.77	0.85	0.98	0.96
10	1	F50	0.140	0.30	1.00	1.00	0.97	1.00	0.68	0.69	0.72	0.77	0.85	0.98	0.97
11	1	F50	0.077	0.30	1.00	1.00	0.97	1.00	0.67	0.72	0.80	0.79	0.89	0.98	0.96
12	1	F50	0.140	0.20	1.00	1.00	0.96	1.00	0.67	0.74	0.77	0.80	0.93	1.00	0.94
13	1	F50	0.077	0.20	1.00	1.00	0.97	1.00	0.67	0.73	0.76	0.81	0.94	1.00	0.95
14	1	F40	0.140	0.20	1.00	1.00	0.96	1.00	0.68	0.74	0.76	0.81	0.94	1.00	1.14
15	1	F40	0.077	0.20	1.00	1.00	0.96	1.00	0.65	0.76	0.79	0.80	0.92	1.00	1.10
16	1	F40	0.077	0.14	1.00	1.00	0.97	1.00	0.69	0.74	0.75	0.84	0.95	1.00	1.14
1	3	F50	0.200	0.30	1.00	1.00	0.98	1.00	0.72	0.58	0.59	0.62	0.95	1.00	1.24
2	3	F50	0.140	0.30	1.00	1.00	0.98	1.00	0.73	0.52	0.54	0.55	0.97	1.00	1.29
3	3	F50	0.077	0.30	1.00	1.00	0.98	1.00	0.73	0.48	0.48	0.53	0.98	1.00	1.31

TAC Control

By Scenario

4	3	F50	0.140	0.20	1.00	1.00	0.98	1.00	0.73	0.53	0.57	0.57	0.97	1.00	1.28
5	3	F50	0.077	0.20	1.00	1.00	0.98	1.00	0.72	0.55	0.57	0.60	0.96	1.00	1.27
6	3	F40	0.140	0.20	1.00	1.00	0.98	1.00	0.73	0.51	0.55	0.55	0.96	1.00	1.54
7	3	F40	0.077	0.20	1.00	1.00	0.98	1.00	0.72	0.56	0.59	0.59	0.95	1.00	1.50
8	3	F40	0.077	0.14	1.00	1.00	0.98	1.00	0.73	0.53	0.55	0.57	0.97	1.00	1.54
9	3	F50	0.200	0.30	1.00	1.00	0.98	1.00	0.72	0.55	0.57	0.59	0.96	1.00	1.26
10	3	F50	0.140	0.30	1.00	1.00	0.98	1.00	0.72	0.55	0.59	0.58	0.96	1.00	1.26
11	3	F50	0.077	0.30	1.00	1.00	0.98	1.00	0.73	0.53	0.56	0.58	0.97	1.00	1.27
12	3	F50	0.140	0.20	1.00	1.00	0.98	1.00	0.73	0.53	0.56	0.57	0.97	1.00	1.27
13	3	F50	0.077	0.20	1.00	1.00	0.98	1.00	0.73	0.53	0.56	0.59	0.97	1.00	1.27
14	3	F40	0.140	0.20	1.00	1.00	0.98	1.00	0.73	0.50	0.49	0.55	0.97	1.00	1.55
15	3	F40	0.077	0.20	1.00	1.00	0.98	1.00	0.73	0.52	0.56	0.56	0.98	1.00	1.53
16	3	F40	0.077	0.14	1.00	1.00	0.98	1.00	0.73	0.51	0.54	0.54	0.98	1.00	1.54
1	4	F50	0.200	0.30	0.95	0.95	0.93	1.00	0.69	0.65	0.65	0.71	0.67	0.74	0.79
2	4	F50	0.140	0.30	0.99	0.95	0.93	1.00	0.69	0.65	0.70	0.72	0.69	0.74	0.80
3	4	F50	0.077	0.30	1.00	0.95	0.92	1.00	0.69	0.66	0.68	0.71	0.69	0.73	0.80
4	4	F50	0.140	0.20	0.99	0.95	0.93	1.00	0.69	0.67	0.72	0.72	0.77	0.95	0.79
5	4	F50	0.077	0.20	1.00	0.95	0.92	1.00	0.69	0.69	0.73	0.75	0.87	0.95	0.78
6	4	F40	0.140	0.20	0.94	0.84	0.89	0.98	0.65	0.73	0.70	0.84	0.54	0.84	0.85
7	4	F40	0.077	0.20	0.98	0.84	0.89	0.98	0.65	0.74	0.72	0.84	0.61	0.84	0.85
8	4	F40	0.077	0.14	0.98	0.84	0.89	0.98	0.64	0.78	0.77	0.86	0.70	0.94	0.85
9	4	F50	0.200	0.30	0.95	0.95	0.93	1.00	0.69	0.66	0.70	0.73	0.72	0.74	0.79
10	4	F50	0.140	0.30	0.99	0.95	0.93	1.00	0.69	0.66	0.70	0.72	0.73	0.73	0.79

TAC Control

By Scenario

11	4	F50	0.077	0.30	1.00	0.95	0.93	1.00	0.69	0.66	0.70	0.71	0.73	0.74	0.80
12	4	F50	0.140	0.20	0.99	0.94	0.92	1.00	0.69	0.68	0.71	0.73	0.79	0.94	0.79
13	4	F50	0.077	0.20	1.00	0.94	0.92	1.00	0.68	0.70	0.74	0.76	0.85	0.94	0.77
14	4	F40	0.140	0.20	0.94	0.85	0.89	0.99	0.65	0.76	0.79	0.85	0.63	0.85	0.85
15	4	F40	0.077	0.20	0.99	0.84	0.89	0.99	0.64	0.76	0.79	0.85	0.63	0.84	0.85
16	4	F40	0.077	0.14	0.98	0.83	0.89	0.98	0.64	0.78	0.78	0.88	0.70	0.94	0.85
1	6	F50	0.200	0.30	0.66	0.66	0.85	0.94	0.71	0.59	0.58	0.63	0.54	0.31	0.67
2	6	F50	0.140	0.30	0.83	0.66	0.85	0.94	0.71	0.59	0.57	0.63	0.55	0.31	0.67
3	6	F50	0.077	0.30	0.94	0.64	0.85	0.94	0.70	0.61	0.64	0.64	0.59	0.27	0.66
4	6	F50	0.140	0.20	0.83	0.65	0.85	0.94	0.70	0.60	0.59	0.63	0.62	0.65	0.66
5	6	F50	0.077	0.20	0.93	0.62	0.84	0.93	0.69	0.63	0.62	0.69	0.63	0.62	0.65
6	6	F40	0.140	0.20	0.74	0.54	0.81	0.89	0.66	0.61	0.49	0.71	0.45	0.54	0.75
7	6	F40	0.077	0.20	0.88	0.53	0.81	0.88	0.66	0.63	0.48	0.73	0.43	0.53	0.76
8	6	F40	0.077	0.14	0.87	0.49	0.79	0.87	0.64	0.63	0.54	0.72	0.48	0.70	0.74
9	6	F50	0.200	0.30	0.64	0.64	0.85	0.94	0.70	0.61	0.64	0.64	0.60	0.28	0.66
10	6	F50	0.140	0.30	0.83	0.66	0.86	0.94	0.71	0.59	0.55	0.65	0.57	0.30	0.67
11	6	F50	0.077	0.30	0.95	0.66	0.86	0.95	0.71	0.61	0.62	0.66	0.66	0.28	0.67
12	6	F50	0.140	0.20	0.83	0.65	0.85	0.94	0.71	0.62	0.59	0.67	0.66	0.65	0.66
13	6	F50	0.077	0.20	0.94	0.63	0.85	0.94	0.70	0.62	0.60	0.66	0.66	0.63	0.66
14	6	F40	0.140	0.20	0.73	0.52	0.81	0.88	0.64	0.62	0.51	0.71	0.47	0.52	0.75
15	6	F40	0.077	0.20	0.89	0.52	0.81	0.89	0.65	0.62	0.48	0.71	0.45	0.52	0.76
16	6	F40	0.077	0.14	0.88	0.49	0.80	0.88	0.64	0.63	0.54	0.71	0.49	0.71	0.75

Table A7. Performance of indicators for each harvest control rule under **TAE control** across all iterations for **each reference scenario**. HCR refers to harvest control rule, LRP to limit reference point, SSB to female spawning biomass, SSB0 to unfished female spawning stock biomass. Unless specified as equilibrium SSB0, the unfished SSB is dynamic and fluctuates depending on changes in recruitment. See table ES1 for a detailed definition of performance indicators.

TAE Control

By Scenario

hcr	scn	TRP	LRP	SSBthreshold	Odds of Not Breaching the LRP	Odds SSB > 20% SSBo	Odds SSB > Equilibrium 7.7% SSBo	Odds SSB > 7.7% SSBo	Odds Depletion > Minimum Historical	Odds Mean Annual Catch > Historical	Odds Mean Medium Term Catch > Historical Catch	Odds Mean Long Term Catch > Historical Catch	Catch Stability	Odds No Management Action	Ftarget/F
1	1	F50	0.200	0.30	1.00	1.00	0.98	1	0.70	0.66	0.66	0.75	0.96	1.00	1.01
2	1	F50	0.140	0.30	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.01
3	1	F50	0.077	0.30	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.01
4	1	F50	0.140	0.20	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.01
5	1	F50	0.077	0.20	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.01
6	1	F40	0.140	0.20	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.21
7	1	F40	0.077	0.20	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.21
8	1	F40	0.077	0.14	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.21
9	1	F50	0.200	0.30	1.00	1.00	0.98	1	0.70	0.66	0.66	0.75	0.98	1.00	1.01
10	1	F50	0.140	0.30	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.01
11	1	F50	0.077	0.30	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.01
12	1	F50	0.140	0.20	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.01
13	1	F50	0.077	0.20	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.01
14	1	F40	0.140	0.20	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.21
15	1	F40	0.077	0.20	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.21
16	1	F40	0.077	0.14	1.00	1.00	0.98	1	0.70	0.66	0.66	0.76	0.98	1.00	1.21
1	3	F50	0.200	0.30	1.00	1.00	0.99	1	0.72	0.64	0.65	0.74	0.97	1.00	1.20
2	3	F50	0.140	0.30	1.00	1.00	0.99	1	0.72	0.65	0.65	0.74	0.98	1.00	1.20
3	3	F50	0.077	0.30	1.00	1.00	0.99	1	0.72	0.65	0.65	0.74	0.98	1.00	1.20

TAE Control

By Scenario

4	3	F50	0.140	0.20	1.00	1.00	0.99	1	0.72	0.65	0.65	0.74	0.98	1.00	1.20
5	3	F50	0.077	0.20	1.00	1.00	0.99	1	0.72	0.65	0.65	0.74	1.00	1.00	1.19
6	3	F40	0.140	0.20	1.00	1.00	0.99	1	0.72	0.64	0.65	0.74	1.00	1.00	1.43
7	3	F40	0.077	0.20	1.00	1.00	0.99	1	0.72	0.64	0.65	0.74	1.00	1.00	1.43
8	3	F40	0.077	0.14	1.00	1.00	0.99	1	0.72	0.65	0.65	0.74	0.98	1.00	1.44
9	3	F50	0.200	0.30	1.00	1.00	0.99	1	0.72	0.64	0.65	0.74	0.96	1.00	1.20
10	3	F50	0.140	0.30	1.00	1.00	0.99	1	0.72	0.65	0.65	0.74	0.98	1.00	1.20
11	3	F50	0.077	0.30	1.00	1.00	0.99	1	0.72	0.65	0.65	0.74	0.98	1.00	1.20
12	3	F50	0.140	0.20	1.00	1.00	0.99	1	0.72	0.65	0.65	0.74	0.98	1.00	1.20
13	3	F50	0.077	0.20	1.00	1.00	0.99	1	0.72	0.65	0.65	0.74	0.98	1.00	1.20
14	3	F40	0.140	0.20	1.00	1.00	0.99	1	0.72	0.65	0.65	0.74	0.98	1.00	1.44
15	3	F40	0.077	0.20	1.00	1.00	0.99	1	0.72	0.64	0.65	0.73	0.98	1.00	1.44
16	3	F40	0.077	0.14	1.00	1.00	0.99	1	0.72	0.65	0.65	0.74	0.98	1.00	1.44
1	4	F50	0.200	0.30	1.00	1.00	0.98	1	0.76	0.50	0.49	0.57	0.97	0.97	0.93
2	4	F50	0.140	0.30	1.00	1.00	0.98	1	0.76	0.50	0.49	0.57	0.97	0.97	0.93
3	4	F50	0.077	0.30	1.00	1.00	0.98	1	0.76	0.50	0.49	0.57	0.98	0.97	0.93
4	4	F50	0.140	0.20	1.00	1.00	0.98	1	0.76	0.50	0.49	0.58	0.98	1.00	0.93
5	4	F50	0.077	0.20	1.00	1.00	0.98	1	0.76	0.50	0.49	0.58	0.98	1.00	0.93
6	4	F40	0.140	0.20	1.00	1.00	0.96	1	0.70	0.71	0.73	0.81	0.97	1.00	0.94
7	4	F40	0.077	0.20	1.00	1.00	0.96	1	0.70	0.72	0.73	0.81	0.97	1.00	0.94
8	4	F40	0.077	0.14	1.00	1.00	0.96	1	0.70	0.72	0.73	0.81	0.98	1.00	0.94
9	4	F50	0.200	0.30	1.00	1.00	0.98	1	0.76	0.50	0.49	0.57	0.97	0.97	0.93
10	4	F50	0.140	0.30	1.00	1.00	0.98	1	0.76	0.50	0.49	0.58	0.98	0.97	0.93

TAE Control

By Scenario

11	4	F50	0.077	0.30	1.00	1.00	0.98	1	0.76	0.50	0.49	0.57	0.98	0.97	0.93
12	4	F50	0.140	0.20	1.00	1.00	0.98	1	0.76	0.50	0.49	0.58	0.98	1.00	0.93
13	4	F50	0.077	0.20	1.00	1.00	0.98	1	0.76	0.50	0.49	0.58	0.98	1.00	0.93
14	4	F40	0.140	0.20	1.00	1.00	0.96	1	0.70	0.71	0.73	0.81	0.98	1.00	0.94
15	4	F40	0.077	0.20	1.00	1.00	0.96	1	0.70	0.72	0.73	0.81	0.97	1.00	0.94
16	4	F40	0.077	0.14	1.00	1.00	0.96	1	0.70	0.72	0.73	0.81	0.98	1.00	0.94
1	6	F50	0.200	0.30	0.97	0.97	0.96	1	0.87	0.26	0.19	0.29	0.99	0.82	0.93
2	6	F50	0.140	0.30	0.99	0.97	0.96	1	0.87	0.26	0.18	0.29	0.99	0.82	0.93
3	6	F50	0.077	0.30	1.00	0.97	0.96	1	0.87	0.26	0.18	0.29	0.99	0.82	0.93
4	6	F50	0.140	0.20	0.99	0.97	0.96	1	0.87	0.27	0.19	0.30	0.99	0.97	0.93
5	6	F50	0.077	0.20	1.00	0.97	0.96	1	0.87	0.26	0.19	0.29	0.99	0.97	0.93
6	6	F40	0.140	0.20	0.99	0.94	0.96	1	0.83	0.47	0.44	0.57	0.98	0.94	0.95
7	6	F40	0.077	0.20	1.00	0.94	0.96	1	0.83	0.47	0.44	0.57	0.98	0.94	0.95
8	6	F40	0.077	0.14	1.00	0.94	0.96	1	0.83	0.47	0.44	0.57	0.98	0.99	0.94
9	6	F50	0.200	0.30	0.97	0.97	0.96	1	0.87	0.26	0.19	0.29	0.98	0.82	0.93
10	6	F50	0.140	0.30	0.99	0.97	0.96	1	0.87	0.26	0.19	0.29	0.99	0.82	0.93
11	6	F50	0.077	0.30	1.00	0.97	0.96	1	0.87	0.26	0.19	0.29	0.99	0.82	0.93
12	6	F50	0.140	0.20	0.99	0.97	0.96	1	0.87	0.26	0.19	0.29	0.99	0.97	0.93
13	6	F50	0.077	0.20	1.00	0.97	0.96	1	0.87	0.26	0.19	0.29	0.99	0.97	0.93
14	6	F40	0.140	0.20	0.99	0.94	0.96	1	0.83	0.47	0.44	0.57	0.98	0.94	0.95
15	6	F40	0.077	0.20	1.00	0.94	0.96	1	0.83	0.47	0.44	0.57	0.98	0.94	0.95
16	6	F40	0.077	0.14	1.00	0.94	0.96	1	0.83	0.47	0.44	0.57	0.98	0.99	0.95