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Report of the First North Pacific Albacore Management Strategy Evaluation (ISC19 – ANNEX 12)

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REPORT FOR THE FIRST NORTH PACIFIC ALBACORE MANAGEMENT STRATEGY EVALUATION

July 2019

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Annex 12

REPORT FOR THE FIRST NORTH PACIFIC ALBACORE MANAGEMENT STRATEGY EVALUATION

ALBACORE MANAGEMENT STRATEGY EVALUATION WORKSHOP
International Scientific Committee for Tuna and Tuna-Like Species in the North Pacific Ocean

March 5-7, 2019
Yokohama, Japan

1. EXECUTIVE SUMMARY

Goal of 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. The Western and Central Pacific Fisheries Commission (WCPFC) established a limit reference point (LRP) of $20\%SSB_{CURRENT, F=0}$ (SSB: Female Spawning Stock Biomass) for North Pacific albacore (NPALB). 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 strategies and associated reference points for NPALB. Performance was evaluated based on management objectives pre-agreed upon with managers and stakeholders.

Management Objectives and Performance Indicators
The management objectives for this MSE were: 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, however, be noted that management objective #3 (maintain historical harvest ratios of each fishery) was not evaluated for this round of MSE because there were no allocation rules specific to each fishery. Instead, harvest ratios of each fishery were maintained at the average of 1999 – 2015 into the future. The ALBWG represented these management objectives, except #3, into quantitative performance metrics (Table ES1). These performance metrics were used to quantitatively evaluate the performance of the harvest strategies tested relative to the management objectives.

Table ES1. List of proposed performance indicators. Management objective #3 was not included because it could not be evaluated in this round of MSE.

Management Objective	Label	Performance Indicator
1. Maintain SSB above the limit reference point (LRP)	Odds of no fishery closure	Probability that SSB in any given year of the MSE forward simulation is above the LRP
2. Maintain depletion of total biomass around historical average depletion	Relative Total Biomass	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	Relative Total Catch	Probability that catch in any given year of the MSE forward simulation is above average historical (1981-2010) catch
5. Change in total allowable catch between years should be relatively gradual	Catch Stability	Probability that a decrease in TAC is <30% between consecutive assessment periods (once every 3 years), excluding years where TAC=0.
6. Maintain fishing intensity (F) at the target value with reasonable variability	F_{TARGET}/F	F_{TARGET}/F

Harvest Strategies and Harvest Control Rules

Three harvest strategies were evaluated in the first round of the NPALB MSE. Within each harvest strategy, different levels of total allowable harvest are set by a harvest control rule 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 is implemented as either Total Allowable Catch (TAC) or Total Allowable Effort (TAE). Figure ES1 depicts example harvest control rules (HCRs) that specify management actions for two of the three harvest strategies tested: Harvest Strategy 1 (HS1) and Harvest Strategy 3 (HS3). If spawning stock biomass (SSB) is above the threshold reference point ($SSB_{threshold}$), then the level of fishing intensity (F; calculated in terms of spawning potential ratio; see Reference Points section) is set by the target reference point (TRP) (F_{target} in Figure 1) for both HS1 and HS3. If SSB is below the threshold reference point but above the limit reference point (LRP; SSB_{limit}), the level of F is reduced to below the TRP, for both HS1 and HS3. However, as shown by the steeper drop in F for HS3 (dotted line) in Fig. ES1, this reduction is steeper for HS3 than HS1. 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 severe management actions that could occur when the LRP is breached. If SSB falls below the LRP, the F is drastically reduced for both HS1 and HS3, which in this first MSE round is assumed to go to 0 and all fisheries that catch NPALB are closed. For each harvest strategy, different values of TRPs, threshold reference points, LRPs, and rebuilding plans (i.e. management actions when SSB is below the LRP) can be tested.

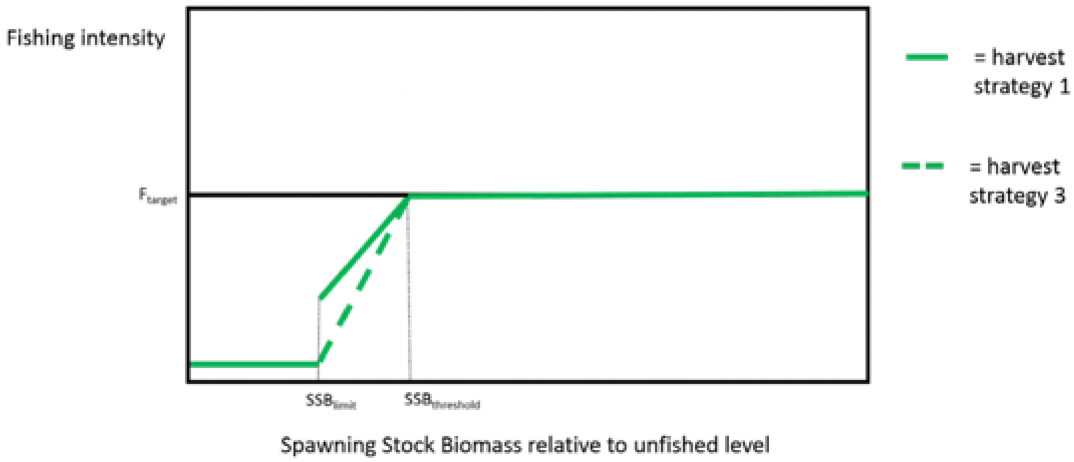

Figure ES1. Example harvest control rule (HCR) for Harvest Strategy 1 and 3. For HS1 and HS3, 11 harvest control rules with different combinations of TRPs, threshold reference points, and LRPs were tested. These are listed in Table ES2. For HS1 and HS3 output control occurs either via a Total Allowable Catch (TAC) or a Total Allowable Effort (TAE).

Table ES2. List of harvest control rules for harvest strategies 1 and 3. 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. A TRP of F40 would result in the SSB fluctuating around 40% of the unfished SSB. A TRP of F30 implies a higher fishing intensity, and would result in a SSB of around 30% of the unfished SSB. F0204 is a fishing intensity corresponding to the average fishing intensity from 2002 to 2004. The threshold and limit reference points are SSB-based and refer to the specified percentage of unfished SSB. The unfished SSB fluctuates depending on changes in recruitment.

Harvest Strategy	Output Control	Harvest Control Rule Label	Target reference point (F_{target})	Threshold reference point ($SSB_{threshold}$)	Limit reference point (SSB_{limit})
1 or 3	TAC or TAE	1	F50	30%	20%
1 or 3	TAC or TAE	4	F50	20%	14%
1 or 3	TAC or TAE	6	F50	14%	7.7%
1 or 3	TAC or TAE	7	F40	30%	20%
1 or 3	TAC or TAE	10	F40	20%	14%
1 or 3	TAC or TAE	12	F40	14%	7.7%
1 or 3	TAC or TAE	13	F30	20%	14%
1 or 3	TAC or TAE	15	F30	14%	7.7%
1 or 3	TAE	16	F0204	30%	20%
1 or 3	TAE	17	F0204	20%	14%
1 or 3	TAE	18	F0204	14%	7.7%

Harvest Strategy 2 (HS2) is based on the IATTC's Resolution C-16-02, which is aimed at tropical tunas. This harvest strategy is TAE based and has no $SSB_{threshold}$ (i.e. a biomass-based threshold reference point). Instead of gradually reducing F upon breaching $SSB_{threshold}$, management measures are established if the probability that the current SSB is below the biomass-based LRP is greater than 10% or if the probability that the current fishing intensity exceeds the F-based LRP (F_{limit}) is greater than 10%. Similar to HS1 and HS3, all fisheries that catch NPALB are assumed to be closed if the LRP is breached in this first MSE round. For HS2, the biomass-based LRP is $SSB_{0.5r0}$ and F-based LRP (F_{limit}) is $F_{0.5r0}$. This is the SSB or F corresponding to the SSB that leads to a 50% reduction in the unfished recruitment level given a steepness value of 0.75. For NPALB, this corresponds to an SSB that is approximately 7.7% of the unfished biomass. Hence, we refer to these LRPs as SSB7.7% and F7.7. For HS2, if SSB is above the LRP, management actions only occur if the current F is above the TRP (F_{MSY}), whereby F is set to the TRP. For NPALB, F_{MSY} corresponds to an F that would produce approximately 14% of the unfished SSB. Otherwise, the current F is maintained. This is different from HS1 and HS3, where if SSB is above $SSB_{threshold}$, F is always set to the TRP (i.e. F_{target}), no matter the current F.

Reference Points

A TRP refers to a desired state that management wants to achieve. The TRPs for all three harvest strategies evaluated during this round of 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. For HS1 and HS3, the level of total harvest given four TRPs: F50, F40, F30, and F0204 were evaluated. F40 represents a 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 F30 leads to a SSB that is around 30% of unfished SSB per recruit (i.e., a fishing intensity of 0.7 removing about 70% of the SSB). A TRP of F30 means fishing harder than F40, so the level of biomass desired is lower. F0204 corresponds to the average F from 2002-2004 (F42 for the base case). For HS2, the TRP is F_{MSY}. In the MSE, the level of total harvest was affected primarily by the TRP.

According to the latest assessment in 2017, the average F for 2012-2014 was about F50. This is close to the average over the past 20 years, which was F51 (Fig. ES2). Since 1993, F has never reached F30 and only exceeded F40 in 1999 (Fig. ES2).

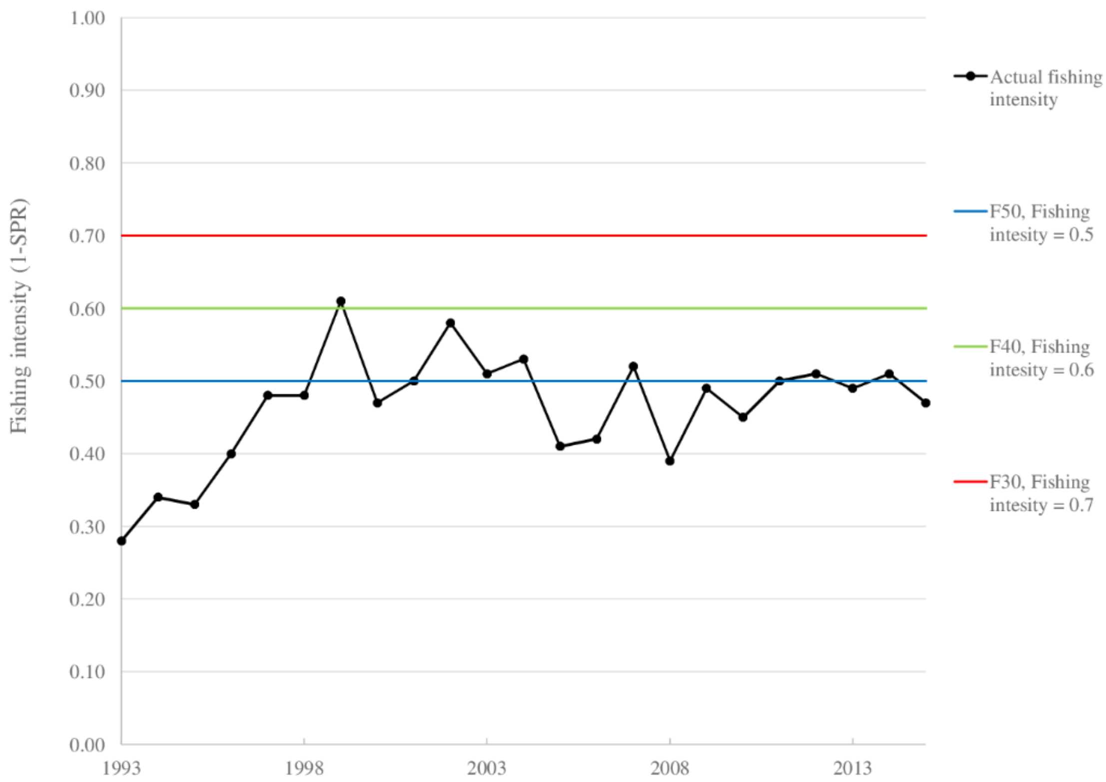

Figure ES2. Past trend in fishing intensity (1-SPR) from the 2017 NPALB stock assessment model. The fishing intensity associated with the three target reference points used in the MSE is also shown. Higher fishing intensity implies lower spawning potential as fraction of unfished (SPR).

For HS1 and HS3, three different threshold reference points were evaluated: SSB30%, SSB20%, and SSB14% (Table 2), which were associated with three respective LRPs: SSB20%, SSB14%, and SSB7.7% (Table ES2). For example, SSB30% roughly means that the reference point is at 30% of unfished SSB. The actual reference point in terms of tons will change depending on the level of estimated recruitment. HS2 had no threshold reference point, only a SSB-based LRP of SSB7.7%, and an F-based LRP of F7.7.

Overview of MSE Framework

To test the performance of each harvest strategy given the set of management objectives, the MSE had to simulate the biological, fisheries, and management processes acting on the NPALB stock. When modelling the "future" processes, the MSE simulation is run forward in time for a period of 30 years (Fig. ES3). At each time step of the 30-year simulation, an operating model (OM) simulates the true population dynamics of the NPALB and the fisheries operating on it given the catch set by the candidate HCR. Before the "future" simulation starts, a "conditioning" process is undertaken to determine if the OM is a realistic representation of the stock by "conditioning" the OM on historical data (Fig. ES3; See section 3.1 and 3.1.1 for details). If the OM can adequately recreate past trends in catch, CPUE, and size composition data, it is used to simulate the population dynamics of stock forward in time. 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) and input in a simulated stock assessment model (i.e. the estimation model or EM) (Fig. ES3). As in the real world, the stock assessment model estimates the current population levels and fishing intensity as well as reference points. A management model then sets a total allowable catch (TAC) or effort (TAE) based on the specific harvest control rule being tested (Fig. ES3). The harvest control rule specifies a management action to be taken (or not), based on the condition of the simulated albacore population relative to reference points. The TAC or TAE is then split into catch by fishery using the 1999-2015 average allocation and input into the OM with some implementation error for simulation of population dynamics in the next time step.

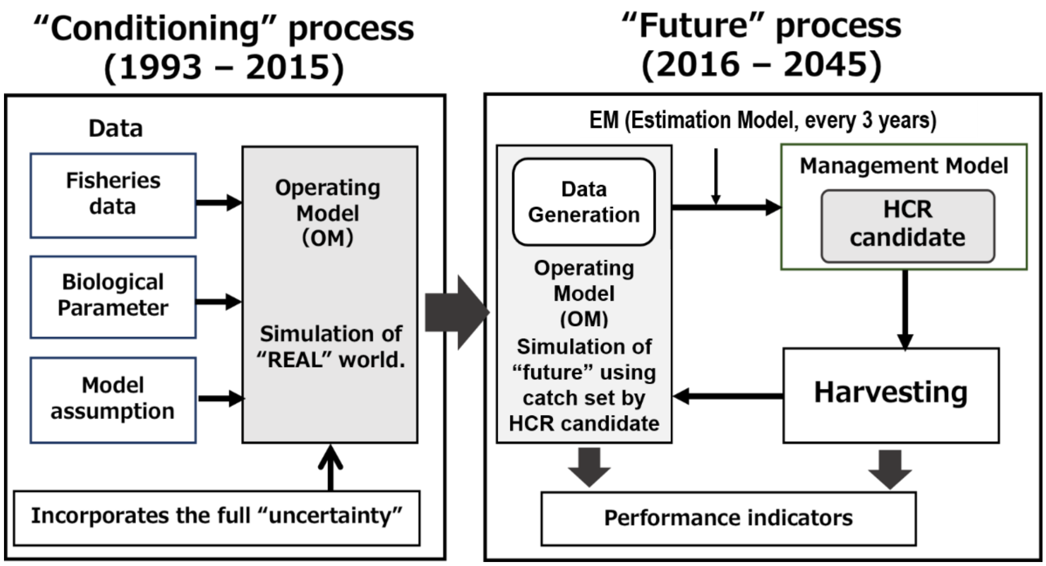

Figure ES1. Overview of North Pacific albacore management strategy evaluation framework.

Uncertainties considered

The computer simulations allowed for testing the harvest strategies under different "what if" scenarios for stock productivity, recruitment variability, availability to the Eastern Pacific Ocean (EPO) fishery, observation error, assessment error, or 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.

Five scenarios were developed to represent the range of uncertainty in stock productivity. They required different operating model (OM) structures in terms of the parametrization of biological factors such as growth or natural mortality (See section 3.1 and 3.1.1 for details).

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, in the OM, the age selectivity for the EPO fleet was made time-varying using additive random walk deviations for ages one to four. For each HS/HCR/productivity scenario combination, 45 iterations with different random trajectories in recruitment and EPO age selectivity were run.

In addition to the five stock productivity scenarios, two potential future fishing effort scenarios prioritized during the 3rd ISC ALB MSE Workshop were developed:

1) Shift of south Pacific fishing effort to the north Pacific – new entrant to fishery but catch is known to the assessment and under HCR – ramp in catch
2) Shift of south Pacific fishing effort to the north Pacific – new entrant to fishery but catch is known to the assessment and under HCR – step change in catch

Operating Models and Conditioning Process

All the OMs consisted of a population dynamics model of NPALB with a fishery model component relating the modeled dynamics to catch, catch-per-unit-effort (CPUE), and size composition data. To capture the uncertainty in stock productivity, the MSE simulation included a set of different operating models (OMs). The base case OM (Scenario 1) structure was similar to the latest stock assessment model (SAM) in 2017. One difference consisted of the addition of a new CPUE based juvenile index, which was based on the Japanese longline fishery targeting juvenile albacore. Growth in the SAM and base case OM both follow sex-specific von Bertalanffy growth functions. However, the SAM in 2017 used fixed growth parameters that were obtained externally, whereas the OM used growth parameters that were estimated internally during the conditioning phase by fitting to age-length data, in addition to length composition data from the catch. Finally, unlike the SAM, recruitment deviations in the OM were autocorrelated and age selectivity for the EPO fleet was time varying. Following the 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+.

Consideration of uncertainties in growth, natural mortality, and steepness was deemed important by the ALBWG, and three different levels for these parameters were tested: 1) base case value, 2) lower than base, and 3) higher than base. This led to 27 different OMs being developed from all the possible combinations of growth, natural mortality, and steepness.

To determine if these OMs were realistic representation of the stock, these models were "conditioned" on historical data (1993-2015) by fitting the simulated data over the historical period to observed catch, CPUE, and length composition data using maximum likelihood. Nine out of the 27 OMs failed to converge and five produced unrealistic SSB estimates and were not considered further. Given the long run times, time constraints on MSE development, and similarities in terms of stock productivity trends between scenarios, the ALBWG proposed a reduced set of five scenarios to be tested. See Table ES3 for a list of parameter specifications for the five OMs used to characterize uncertainty in stock productivity. The five scenarios showed a wide range in potential stock productivity trends (Fig. ES4). Scenario 7 was a high productivity trial with a much higher biomass and lower fishing intensity as compared to the base case (Fig. ES4) and was treated as a robustness (less plausible) scenario. Most figures present results across the four reference scenarios (Scenarios 1, 3, 4, 6).

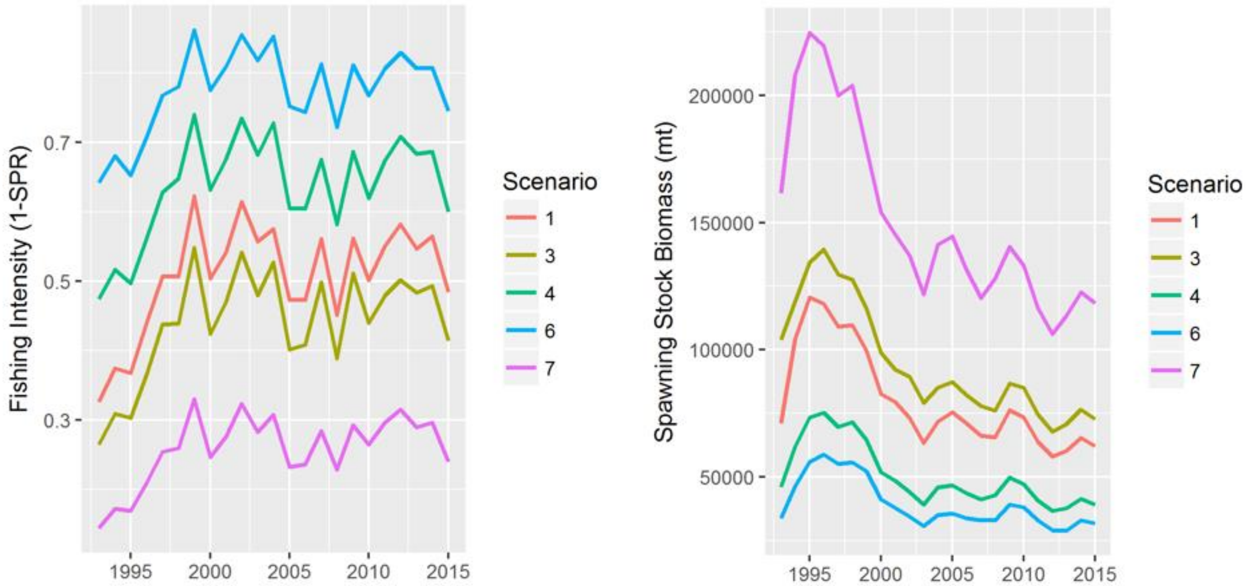

Figure ES4. Trends in fishing intensity (1-SPR) and female spawning stock biomass (SSB) for the five operating models used in the first round of MSE. 1-SPR is the reduction in female SSB per recruit due to fishing and is used to describe the overall fishing intensity on the stock.

Table ES3. List of the five operating models (OMs) representing different uncertainty scenarios and their parameter specifications. H refers to steepness, G to growth, and M to natural mortality. The OMs are ordered from the one simulating the most productive NPALB population to the least productive.

OM No.	h	G	M	Age selectivity	Recruitment autocorrelation
7	high	high	high	Time varying	0.42
3	high	low	medium	Time varying	0.42
Base/1	medium	medium	medium	Time varying	0.42
4	high	high	medium	Time varying	0.42
6	high	high	low	Time varying	0.42

Data Generation

Catch, CPUE, and size composition data with error was generated from the OM using the Stock Synthesis data generation routine and subsequently used as inputs into the simulated stock assessment (i.e. the estimation model). The data generation routine created a data set of 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), and 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.

Estimation Model

The estimation model (EM) was the simulated stock assessment model in the MSE simulation. It had the same structure as the 2017 SAM but it employed the new juvenile abundance index and the same growth parameters as the base case OM. The EM was used to determine the current SSB and fishing intensity and reference points to be used in the harvest control rule to determine the TAC or TAE. Integration of the EM in the MSE framework allowed for consideration of the stock assessment error.

Implementation Error

An implementation error was added to the TAC or TAE to account for the fact that the realized catch can differ from that set by the TAC or TAE. The NPALB stock has not been subjected to TACs or TAEs, and assumptions therefore had to be made about the implementation error. The implementation error was assumed to be always positive, varied randomly between 5 and 20%, and was the same for all fisheries.

Results

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

1. *A lower fishing intensity TRP (i.e. F50), maintains the population at a higher level than F40 and F30, requiring less management intervention and resulting in lower catch variability between years. However, lower fishing intensity results in lower overall catch.*

There was a clear trade-off between relative total biomass and relative catch. HCRs with F50 (HCRs 1, 4, and 6; blue bars in Fig. ES5) had the highest relative total biomass but lowest relative catch, given the same LRP (Compare Fig. ES5a and ES5b). For the same LRP, a TRP of F50 also had the lowest odds of a fishery closure (Fig. ES5c) and the highest catch stability (Fig. ES5d).

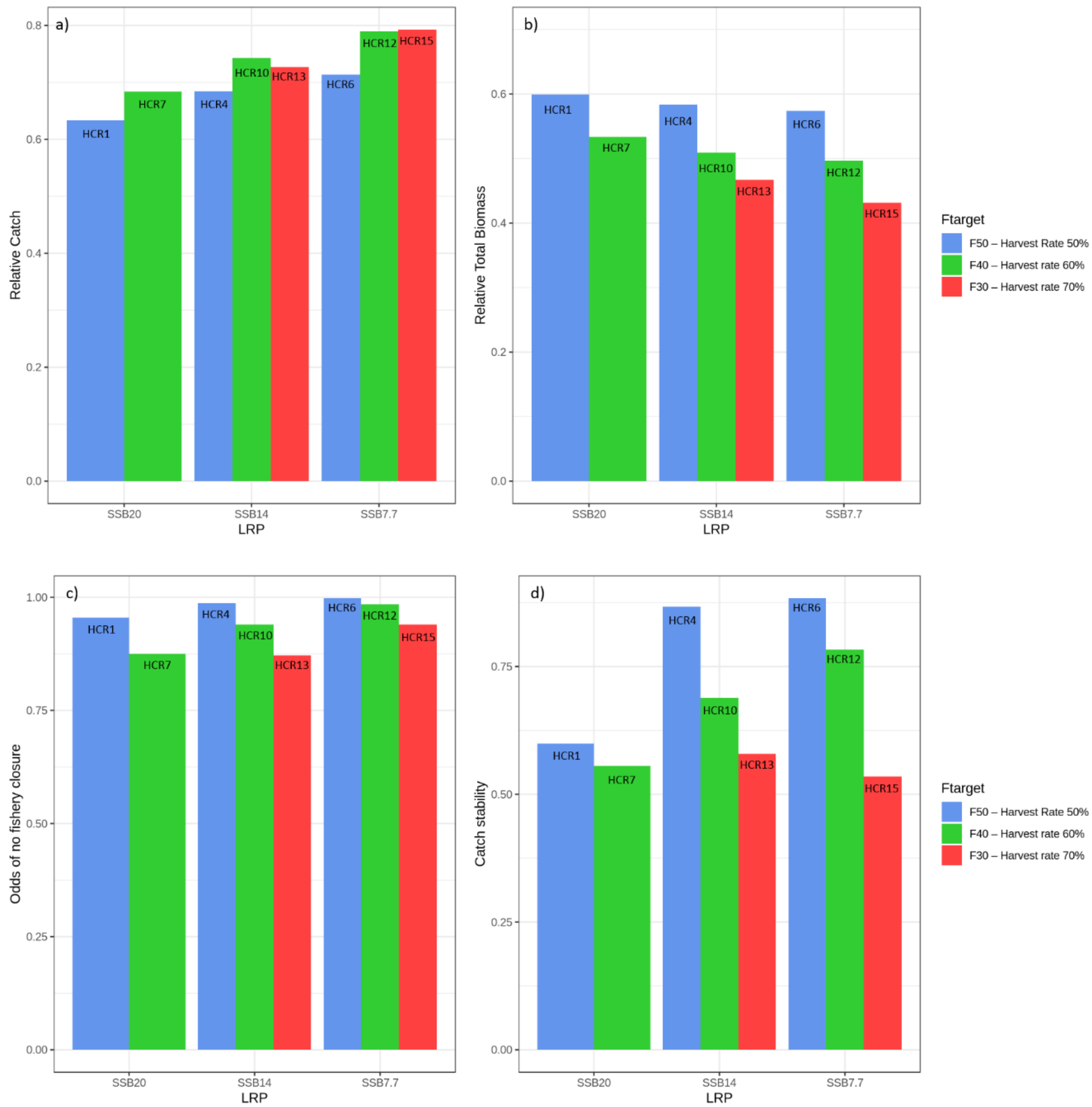

Figure ES5. Comparison of the *relative catch*, *relative total biomass*, *odds of no fishery closures*, and *catch stability* performance metrics across limit reference points (LRP) for all the harvest control rules (HCRs) tested in Harvest Strategy 3 with TAC (total allowable catch) control. Performance metrics were computed across all runs of the four reference scenarios. *Relative catch* is defined as the odds of catch in any given year of the MSE forward simulation being above average historical (1981-2010) catch. *Relative total biomass* is defined as the odds of depletion in any given year of the MSE forward simulation being above minimum historical (2006-2015) depletion. *Odds of no fishery closure* is the probability that SSB in any given year of the MSE forward simulation is above the LRP. *Catch stability* is defined as the probability that a decrease in TAC is <30% between consecutive assessment periods (once every 3 years), excluding years where TAC=0.

2. *HCRs with a TRP of F40 have less closures and higher catch stability as compared to a TRP of F30, resulting in comparable or higher catch despite lower fishing intensity.*

The trade-off between more catch and less biomass was as evident when comparing TRPs of F40 against F30. HCRs with a TRP of F40 performed as well or better than a TRP of F30 not only in terms of relative biomass (green vs. red bars in Fig. ES5b), fishery closures (green vs. red bars in Fig. ES5c), and catch stability (green vs. red bars in Fig. ES5d), but also for relative catch (green vs. red bars in Fig. ES5a). For the same LRP, relative catch of HCRs with a TRP of F40, was comparable to that of HCRs with a TRP of F30 (green vs. red bars in Fig. ES5a). Improved catch stability and lower management intervention led to higher or comparable odds of projected catch being more than average historical catch for a TRP of F40 as compared to F30, even if the F was lower.

3. *An LRP and threshold reference point closer to the TRP results in a higher frequency of management interventions, fishery closures and lower catch stability.*

A LRP closer to the desired target biomass set by the F-based TRP is more likely to be breached. This leads to lower catch stability and higher probability of fishery closures for HCRs with an LRP set at 20% of unfished SSB (SSB20%). Fig. ES6 shows that for HCRs with the same F40 TRP, HCR 7, the one with the highest LRP of SSB20%, had the lowest relative catch, lowest catch stability, and lowest odds of no fishery closure.

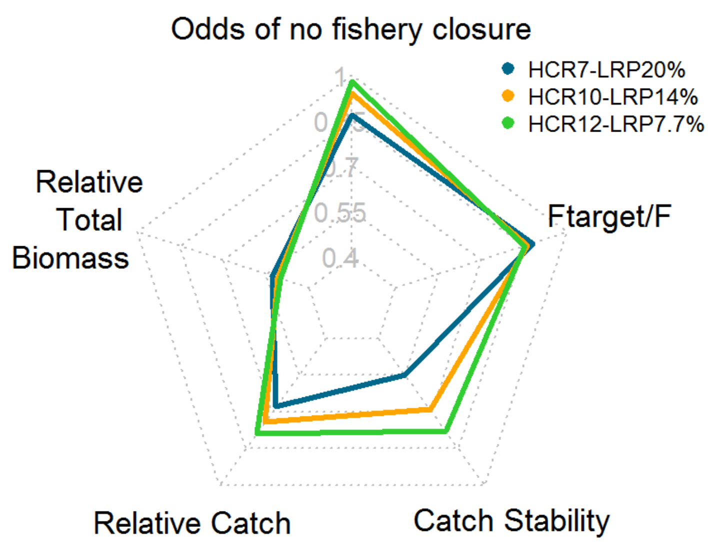

Figure ES6. Cobweb plot depicting performance indicators for TAC-based HCR7, HCR10, and HCR12 for HS3 across all runs and reference scenarios. All use a TRP of F40. Values close to the outer web signify a more positive outcome for that performance indicator (i.e., further out is better). Refer to Table 1 for a description of the performance indicators. *Relative catch* is defined as the odds of catch in any given year of the MSE forward simulation being above average historical (1981-2010) catch. *Relative total biomass* is defined as the odds of depletion in any given year of the MSE forward simulation being above minimum historical (2006-2015) depletion. *Odds of no fishery* *closure* is the probability that SSB in any given year of the MSE forward simulation is above the LRP. *Catch stability* is defined as the probability that a decrease in TAC is <30% between consecutive assessment periods (once every 3 years), excluding years where TAC=0. *Ftarget/F* is the ratio of the F specified by the TRP to the actual fishing intensity in the operating model (OM).

4. *HS3 showed lower catch stability than HS1, but had less fishery closures.*

Harvest Strategy 3 showed less stability in catch between years (Fig. ES7) because steeper changes in TAC or TAE were required once the threshold reference point was crossed. However, these steeper reductions in TAC or TAE resulted in a slightly lower frequency of fishery closures because the probability of breaching the LRP was lower (Fig. ES7).

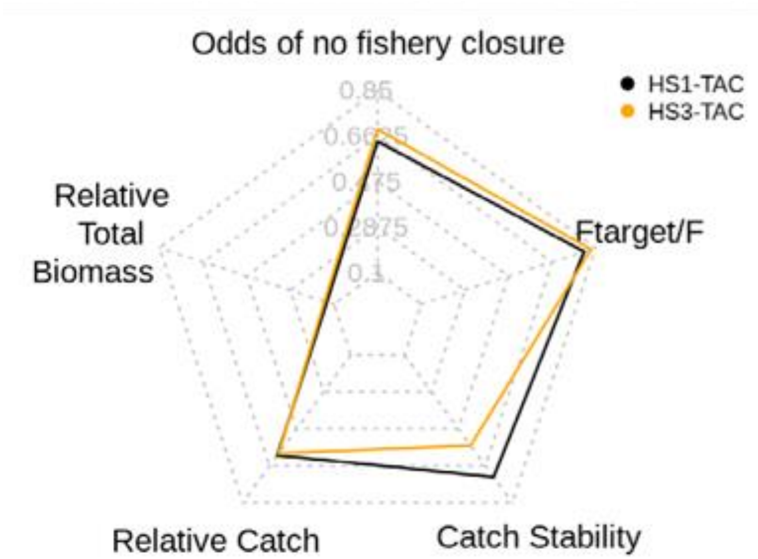

Figure ES7. Cobweb plot depicting performance indicators for TAC-based HCR13 for HS1 and HS3 for all runs in the lowest productivity scenario (Scenario 6). Scenario 6 was chosen as it was the scenario with the most fisheries closures and hence best depicted the trade-off between higher catch variability and lower fisheries closures. Values close to the outer web signify a more positive outcome for that performance indicator. *Relative catch* is defined as the odds of catch in any given year of the MSE forward simulation being above average historical (1981-2010) catch. *Relative total biomass* is defined as the odds of depletion in any given year of the MSE forward simulation being above minimum historical (2006-2015) depletion. *Odds of no fishery closure* is the probability that SSB in any given year of the MSE forward simulation is above the LRP. *Catch stability* is defined as the probability that a decrease in TAC is <30% between consecutive assessment periods (once every 3 years), excluding years where TAC=0. *Ftarget/F* is the ratio of the F specified by the TRP to the actual fishing intensity in the operating model (OM).

5. *Harvest strategies with Total Allowable Effort (TAE) had a lower frequency of fisheries closures and higher catch stability than ones with Total Allowable Catch (TAC) control.*

Fig. ES8 provides an overview of results for HCR 13 for HS1 with both a TAC and TAE output control. The TAC based rules underperformed TAE ones across most performance indicators. The largest difference occurred for catch stability. Given the 3 years assessment frequency, in a TAC-based rule the TAC is maintained constant over a 3-year period. Hence, if biomass is reduced because of random, biologically driven variability, fishing intensity can increase and drive the population below the threshold and limit reference points more often, requiring more management intervention. This resulted in TAC-based rules having lower catch stability and being closed more often. However, it should be noted that potential difficulties in measuring and implementing TAEs relative to TACs in the real world were not evaluated for this MSE.

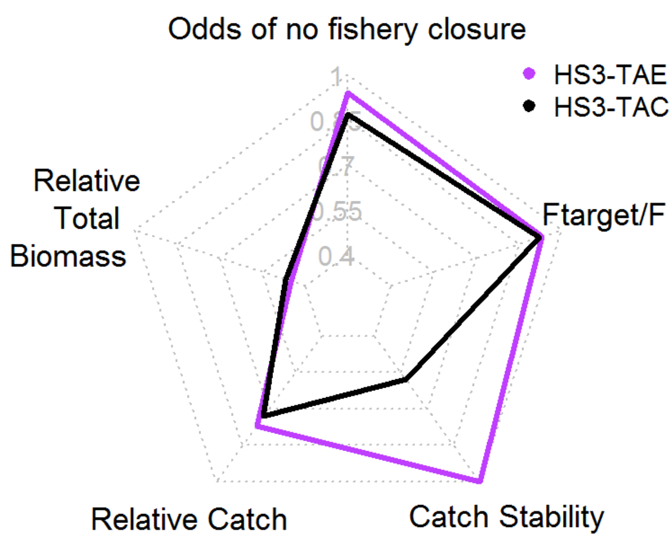

Figure ES8. Cobweb plot depicting performance indicators for TAC-based and TAE-based HCR13 for HS3 for all runs and reference scenarios. Values close to the outer web signify a more positive outcome for that performance indicator. *Relative catch* is defined as the odds of catch in any given year of the MSE forward simulation being above average historical (1981-2010) catch. *Relative total biomass* is defined as the odds of depletion in any given year of the MSE forward simulation being above minimum historical (2006-2015) depletion. *Odds of no fishery closure* is the probability that SSB in any given year of the MSE forward simulation is above the LRP. *Catch stability* is defined as the probability that a decrease in TAC is <30% between consecutive assessment periods (once every 3 years), excluding years where TAC=0. *Ftarget/F* is the ratio of the F specified by the TRP to the actual fishing intensity in the operating model (OM).

For HS1 and HS3, a TRP of F0204, which was only used with TAE control, performed most similarly to F30. For the same LRP, a TRP of F0204 had lower catch stability and more fishery closures than TRPs of F40 or F50 (Fig. ES9). Relative catch, while higher than F50, was comparable to that of F40 and F30 (Fig. ES9). HS2 had a LRP of SSB7.7% and performed similarly to F0204 and F30. It had lower catch stability and relative total biomass than F40 or F50, but higher relative catch (Fig. ES9).

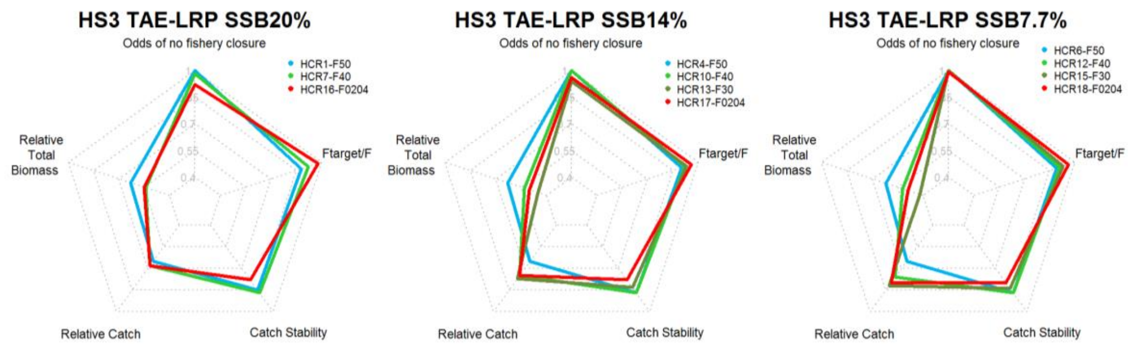

Figure ES9. Cobweb plot depicting performance indicators for TAE-based HCRs for HS3 grouped by LRP for all runs and reference scenarios. Values close to the outer web signify a more positive outcome for that performance indicator. Note that because catch variability between consecutive assessment periods was rarely greater than 30% for all TAE-based rules, to better contrast HCRs here catch stability is defined as the probability that a decrease in catch between consecutive assessment periods is <15%. *Relative catch* is defined as the odds of catch in any given year of the MSE forward simulation being above average historical (1981-2010) catch. *Relative total biomass* is defined as the odds of depletion in any given year of the MSE forward simulation being above minimum historical (2006-2015) depletion. *Odds of no fishery closure* is the probability that SSB in any given year of the MSE forward simulation is above the LRP. *Catch stability* is defined as the probability that a decrease in TAC is <15% between consecutive assessment periods (once every 3 years), excluding years where TAC=0. *Ftarget/F* is the ratio of the F specified by the TRP to the actual fishing intensity in the operating model (OM).

Key Limitations

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

- Effort is modeled as fishing intensity rather than being modeled explicitly as the number of fishing days or number of hooks. However, in the real world, managers would manage effort as the number of hooks or the number of fishing days rather than fishing intensity. If TAE control was to be implemented, more work would be needed to quantify how fishing intensity would be translated into effort in terms of number of fishing days and number of hooks.
- Given the uncertainty in the relationship between fishing intensity in the MSE and real world effort in number of fishing days and number of hooks, effort control may be more effective in the simulation than in the real world and is assumed to be as effective as TAC control, which may not be realistic.
- It is assumed that effort or catch control is implemented equally effectively across all fisheries, including both NPALB targeting and non-targeting (e.g. surface fleets vs. longline).
- 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.

- In the simulations for HS1 and HS3, if the fishing intensity is lower than the target reference point, the simulated fishing intensity is increased to the target level when setting the TAC or TAE. This assumes no limitations in the capacity of the NPALB fleets.
- Given the lack of computer and personnel resources, only one rebuilding plan (fishery is closed) was tested. Further work could examine other rebuilding measures proposed by managers and stakeholders at the 3rd MSE workshop in Vancouver during 2017.
- Given the lack of computer and personnel resources, when determining stock status, only the probability of SSB being higher than the LRP or threshold reference point at a 50% level was tested. Further work could examine other probabilities proposed at the 3rd MSE workshop in Vancouver during 2017.
- 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 an area specific model 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 to1966. 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.

Recommendations from the 4th ISC ALB MSE Workshop

Participants of the 4th ISC ALB MSE Workshop reviewed the results here presented and brought forward a series of recommendations (ISC 2019), summarized below.

Presentation of MSE Results

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".
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.
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.

Management Objectives

4. Managers and stakeholders should prioritize, rank, or weight the management objectives to assist decision making and help resolve tradeoffs in management objectives.

5. Management Objective #6 was considered of relatively low priority by managers and stakeholders in evaluating candidate reference points and harvest control rules.
6. 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.
7. 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.

<u>Candidate harvest strategies, reference points and harvest control rules</u>

8. The 2nd round of MSE should focus on Harvest Strategy 3 using the specific reference points and harvest control rules listed in Table ES4.
9. 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.
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.
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 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.
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.

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.
17. Implementation error distribution should include both positive and negative errors.

<u>MSE Workplan</u>

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 tradeoffs and potential performance of candidate reference points 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.
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.
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.

<u>Others</u>

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.
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.
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.

Changes for 2nd round of MSE analysis

Following recommendations from the 4th ISC ALB MSE Workshop, the ALBWG proposed to focus the second round of MSE analysis on the HCRs presented in Table ES4. These are based on HS3 and TRPs of F50 and F40 with different combinations of LRPs and threshold reference points. Furthermore, when $SSB > SSB_{threshold}$, an additional option of no harvest control will be examined in addition to F=TRP (Table ES4).

Table ES4. List of control-type, candidate target, threshold, and limit reference points to be evaluated for the 2nd round of NPALB MSE. Mixed control-type indicates that surface fleets (i.e., Japan pole-and-line, and EPO surface) are under Total Allowable Effort (TAE) control while all other fleets are under Total Allowable Catch (TAC) control.

Control	Harvest Control Rule Label	Target reference point (F_{target})	Threshold reference point ($SSB_{threshold}$)	Limit reference point (SSB_{limit})	Action if SSB > $SSB_{threshold}$
All Fleets under TAC	1	F50	30%	20%	
All Fleets under TAC	2	F50	30%	14%	
All Fleets under TAC	3	F50	30%	7.7%	
All Fleets under TAC	4	F50	20%	14%	
All Fleets under TAC	5	F50	20%	7.7%	
All Fleets under TAC	6	F40	20%	14%	
All Fleets under TAC	7	F40	20%	7.7%	
All Fleets under TAC	8	F40	14%	7.7%	
All Fleets under TAE	9	F40	30%	20%	F = TRP or No harvest control (F sampled from historical distribution)
All Fleets under TAE	10	F50	30%	14%	
All Fleets under TAE	11	F50	30%	7.7%	
All Fleets under TAE	12	F50	20%	14%	
All Fleets under TAE	13	F50	20%	7.7%	
All Fleets under TAE	14	F40	20%	14%	
All Fleets under TAE	15	F40	20%	7.7%	
All Fleets under TAE	16	F40	14%	7.7%	
Mixed	17	F50	30%	20%	
Mixed	18	F50	30%	14%	
Mixed	19	F50	30%	7.7%	
Mixed	20	F50	20%	14%	
Mixed	21	F50	20%	7.7%	
Mixed	22	F40	20%	14%	
Mixed	23	F40	20%	7.7%	
Mixed	24	F40	14%	7.7%	

Also, additional management actions when SSB < LRP will be examined. More specifically, the management model will be modified to include 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 SSB20% or SSB14% these levels will be 0.5 and 0.25 of the fishing intensity or catch at the LRP. For HCRs with an LRP of 7.7% these levels will be 0.25 of the fishing intensity or catch at the LRP or a fishery closure. The fishing intensity or catch at the LRP were defined at the third ISC MSE Workshop in Vancouver, Canada (ISC 2017). Figure ES10 represents the eight different combination of reference points listed in Table ES4 for each control type. Each combination of reference points is associated with the two minimum levels of fishing intensity, for a total of 16 HCRs.

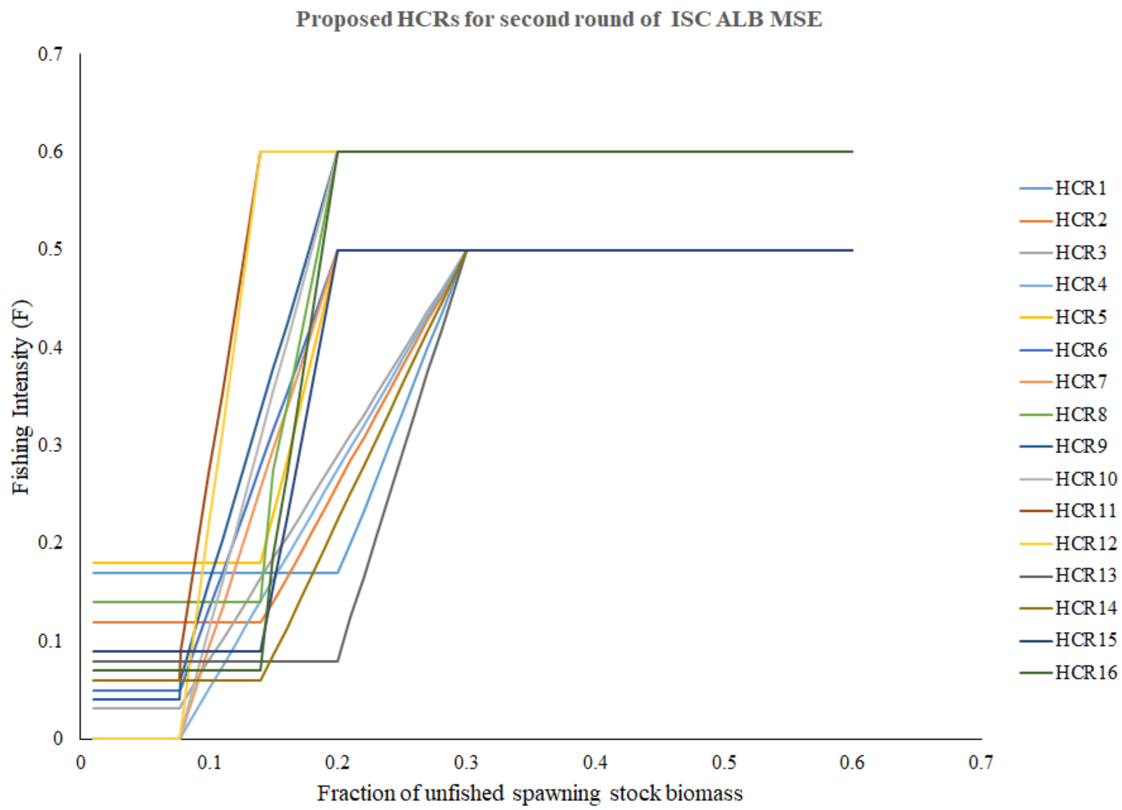

Figure ES10. Harvest control rules (HCRs) proposed for the second round of MSE during the 4th ISC ALB MSE workshop showing the different combinations of target reference points (F50 and F40), threshold reference points (SSB30%, SSB20%, SSB14%), limit reference points (SSB20%, SSB14%, SSB7.7%), and minimum levels of fishing intensity when spawning stock biomass is below the limit reference point.

In terms of the MSE modelling framework, the following changes are going to be undertaken:

- The TAC or TAE will be capped to a level of fishing intensity or mortality not exceeding maximum levels over the period of 1997-2015.
- Implementation error will be bidirectional (i.e., fleets can fish at, less or more than the TAE or TAC).
- Additional options will be added to the management model to simulate no harvest control if $SSB \geq SSB_{THRESHOLD}$.
- Stricter risk levels (80% for HCRs with an LRP of SSB20%; 90% for HCRs with an LRP of SSB14% or SSB7%) in evaluation of risk of breaching candidate LRPs will be used. This risk will be calculated using the current NPALB future projection software.

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 mangers and stakeholders under a range of uncertainties. It serves as a tool for mangers 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 this first round of 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 mangers 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 third 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 (section 2.6). Within each harvest strategy, different levels of harvest were set by a harvest control rule 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). For HS1 and HS3, 8 harvest control rules (HCRs) with TAC control and 11 HCRs with TAE control were evaluated. For HS2 only one HCR with TAE control was examined. Results from this first MSE analysis for NPALB, which compared performance of the 39 HS/HCRs/output control combinations under different uncertainty scenarios, were presented to managers and stakeholders at the 4th ISC NPALB MSE Workshop in

Yokohama, Japan. This report provides a detailed overview of the NPALB MSE framework and presents those results in detail.
To provide a context for the MSE framework here presented, Section 2 contains background information on the biology, fisheries, and management of NPALB, as well as management objectives and performance indicators, reference points, candidate harvest strategies and harvest control rules, and uncertainties considered in this MSE. Section 3 illustrates the MSE framework. There are two phases in the development of an MSE (Fig. ES3). In a first, "conditioning" process (section 3.1) a set of operating models are developed that simulate the *true* population dynamics of the NPALB and the fisheries operating on it. Multiple operating models are built to account for uncertainty in the biology, environment, and fisheries (See section 2.7 and 3.1 for details). In this phase, the realism of each OM is evaluated by "conditioning" it on historical data (section 3.1). If the OM can adequately recreate past trends in catch, CPUE, and size composition data, it is used to simulate the population dynamics of stock forward in time (section 3.2). Section 4 highlights the results of this first round of MSE.

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. 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. Pole-and-line catches in the 2000s exhibited greater year-to-year variability than catches by the other gear types since they are influenced by target switching between skipjack (*Katsuwonus pelamis*) and albacore by some vessels on the fishing grounds off the east coast of Japan (Kiyofuji and Uosaki 2010). 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 NPLAB, 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 breeched (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 $20\%SSB_{CURRENT,\,F=0}$ (SSB: Female Spawning Stock Biomass) (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 (WCPC 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.

According to the 2017 NPALB stock assessment (ALBWG 2017), the NPALB stock is not likely in an overfished condition relative to the LRP (20%$SSB_{CURRENT, F=0}$) adopted by the WCPFC NC, with current SSB estimated to be at approximately 47% of unfished SSB. Although no F-based reference points have been adopted by the RFMOs to evaluate overfishing, current fishing intensity during 2012-2014, calculated as 1-SPR, was lower than potential F-based reference points identified nor NPALB, except for $F_{50\%}$.

3.4. Management Objectives and Performance Indicators

The management objectives used to evaluate the performance of the different candidate harvest strategies were identified and agreed upon by mangers and stakeholders in a series of MSE workshops organized by ISC (see Introduction). The management objectives are outlined in Table 1 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 management objective #3 (maintain historical harvest ratios of each fishery) was not evaluated for this round of MSE because there were no allocation rules specific to each fishery. Instead, harvest ratios of each fishery were maintained at the average of 1999 – 2015 into the future.

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. An initial set of performance metrics and example output for each metric were proposed at the 3rd ISC MSE Workshop by the ALBWG and are outlined in Table 1. In order to ease the presentation of results, a smaller, final list of performance metrics were agreed upon by the ALBWG (Table 2) and most figures and results are based on this set. Appendix Tables present results for all the metrics proposed, including the initial set (Table 1).

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), LRPs, or threshold reference points. A TRP refers to a desired state that management wants to achieve. The TRPs for all the three harvest strategies 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 F30 leads to a SSB that is around 30% of unfished SSB per recruit (i.e., a fishing intensity of 0.7 removing about 70% of the SSB). A TRP of F30 means fishing harder than F40, so the level of biomass desired is lower.

The reference points to be used in the HCRs for the harvest strategies tested were selected by managers and stakeholders at the 3rd MSE Workshop in Vancouver, Canada (ISC 2017). For Harvest Strategy 1 (HS1) and Harvest Strategy 3 (HS3), three different TRPs of F50, F40, and F30 were evaluated for HCRs with TAC-based control. Rules with TAE-based control examined an additional TRP of F0204. F0204 corresponds to the average F from 2002-2004 (F42 for the base case operating model). Note that the SPR associated with this TRP changes depending on the operating model used. For the same level of catch, a model assuming a less productive stock would estimate a higher fishing intensity (Fig. 6). Therefore, different operating models have a different estimate for F0204. For Harvest Strategy 2 (HS2), the TRP is F_{MSY}. F_{MSY} corresponds to F14.

According to the latest assessment in 2017, the average F for 2012-2014 was about F50. This is close to the average over the past 20 years, which was F51 (Fig. ES2). Since 1993, F has never reached F30 and only exceeded F40 in 1999 (Fig. ES2).
LRPs are biomass or fishing intensity levels to be avoided. Generally, LRPs refer to a biomass or fishing intensity leading to a biomass 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%$SSBcurrent_{F=0}$, 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 biomass. These three LRPs of SSB20%, SSB14%, and SSB7.7% were all examined in HS1 and HS3. For all LRPs, the percentage refers to the percentage of dynamic unfished SSB, so SSB20% is equivalent to 20%$SSBcurrent_{F=0}$. HS2 has both a biomass and an F based LRPs set to SSB7.7% and F7.7, respectively.

In addition to TRPs and LRPs, HCRs for HS1 and HS3 use a threshold reference point (Section 2.6). This reference point is based on SSB as a fraction of unfished 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 adjusted. 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. HCRs in HS1 and HS3 test three different $SSB_{threshold}$ levels (SSB30%, SSB20%, and SSB14%).

3.6. Candidate Harvest Strategies and Harvest Control Rules

Three candidate harvest strategies were selected during the 3rd ISC NPALB MSE Workshop. A harvest strategy is a management framework used to determine a harvest for the stock. It specifies how data is collected, how the status of the stock is estimated, and a HCR. In empirical MSEs, the estimate of stock status informing the HCR is derived directly from the input data (e.g. a CPUE index). By contrast, the input for model-based MSEs comes from stock assessment estimates and the HCR then translates the assessment output into a management action. In this MSE, all harvest strategies are model-based. 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 assessment relative to reference points. The management action is implemented as either Total Allowable Catch (TAC) or Total Allowable Effort (TAE). The data inputs, and assessment model are consistent across the harvest strategies tested. The only difference stems from the shape of the HCRs used in each harvest strategies, as is detailed below.

3.6.1. Harvest Strategy 1

Figure ES1 depicts an example of HCRs that specify management actions for two of the three harvest strategies tested (HS1 and HS3). For HS1, if current SSB is at or above the $SSB_{threshold}$ reference point, the TACs or TAEs are set to maintain a fishing impact at the TRP (Fig. 1). In the simulation, this is done by calculating an exploitation rate (total catch as fraction of total biomass at the beginning of the year) leading to a fishing intensity (1-SPR) equal to the TRP. If current SSB is below $SSB_{threshold}$ with a 0.5 probability, but above the LRP, the F is gradually diminished (Fig. 1). The reduction in fishing intensity is based on a proportional reduction of the exploitation rate associated with the TRP using the fraction $SSB_{current}/SSB_{threshold}$, so that Exploitation rate = Exploitation rate at the TRP* $SSB_{current}/SSB_{threshold}$. If $SSB_{current}$ is below the LRP with a 0.5 probability the fishery is closed (F=0). For each harvest strategy, different HCRs with varying values of TRPs, threshold reference points, and LRPs can be tested. For HS1, 8 TAC-based harvest control rules and 11 TAE-based HCRs with different combinations of TRPs, threshold reference points, and LRPs were tested (Table ES2).

3.6.2. Harvest Strategy 2

HS2 is based on IATTC's Resolution C-16-02, which is aimed at tropical tunas. This harvest strategy is TAE based and has no $SSB_{threshold}$. Instead of gradually reducing the fishing intensity upon breaching $SSB_{threshold}$, management measures are established if the probability that the current SSB is below the biomass-based LRP is greater than 10% or if the probability that the current fishing intensity exceeds the F-based LRP (F_{limit}) is greater than 10%. Similar to HS1 and HS3, all fisheries that catch NPALB are assumed to be closed if the LRP is breached. For HS2, the biomass-based LRP is $SSB_{0.5r0}$ and the F-based LRP (F_{limit}) is $F_{0.5r0}$. This is the SSB or F corresponding to a biomass that leads to a 50% reduction in the unfished recruitment level given a steepness value of 0.75, and corresponds to an SSB that is approximately 7.7% of the unfished SSB. Hence, we refer to these LRPs as SSB7.7% and F7.7. For HS2, if SSB is above the LRP, management actions only occur if the current F is above the TRP (F_{MSY}), whereby F is set to the TRP. For NPALB, F_{MSY} corresponds to an F that would produce approximately 14% of the unfished SSB. Otherwise, the current F is maintained. This is different from HS1 and HS3, where if SSB is above $SSB_{threshold}$, F is always set to the TRP, no matter the current F.

3.6.3. Harvest Strategy 3

HS3 is the same as HS1 except that the proportional reduction in F when $SSB_{current}$ is below $SSB_{threshold}$ but above the LRP occurs at a faster rate, decreasing linearly until when $SSB_{current}$ is below the LRP and the fishery is closed (Fig. 1). Like HS1, there are 8 TAC-based HCRs and 11 TAE-based HCRs, given the same potential combinations of reference points as HS1, that were examined (Table ES2).

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 (Table 3). 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
4) Juvenile movement (via time-varying age selectivity), which was a medium priority (Table 3).

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 3.1).

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 latest stock assessment model starting in 1993 and the sensitivity run starting in 1966 from the latest stock assessment was examined.

Recruitment estimates from 1993 were not significantly autocorrelated at any lag (Fig. 2). By contrast, estimates of recruitment deviations from 1966 showed a significant autocorrelation of 0.42 at lag 1 (Fig. 3). 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 multiannual 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 4).

Uncertainty in recruitment variability and time-varying age selectivity for the EPO fleet are measures of process uncertainty. For each HS/HCR/productivity scenario combination, 45 iterations with different random trajectories in recruitment and EPO age selectivity were run.

In addition to parameter and process uncertainty, two potential future fishing effort scenarios put forward during the 3rd ISC ALB MSE Workshop were developed:

- Shift of south Pacific fishing effort to the north Pacific – new entrant to fishery but catch is known to the assessment and under HCR – ramp in catch
- Shift of south Pacific fishing effort to the north Pacific – new entrant to fishery but catch is known to the assessment and under HCR – step change in catch

To implement these scenarios, the South Pacific albacore (SPALB) catch by country based on WCPFC Year book 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 future effort scenario 1, the total SPALB catch is divided by 30 years and the NPALB catch is gradually increased every year by 2400 mt. For future effort scenario 2, the total SPALB catch is introduced as a step change during the first time step of the simulation. For both fishing effort scenarios, the new catch is associated with a new longline fishery operating in area 4, whose selectivity is mirrored to that of the Area 4 Japanese longline fleet. Inclusion of a new entry required modification to the allocation scheme used in other scenarios and based on average 1999-2015 allocation. In future effort scenario 1, the allocation was left unchanged and increase in catch of the new entrant was implemented via an additional implementation error of 2400 mt for this fleet at each time step. In future effort scenario 2, to force the step change during the first time step of the MSE, 45% of the total NPALB was allocated to the new entrant, and allocation to the other fisheries was reduced equally across the other fleets by the same amount. Note, however, that initial total catch was increased from the 95,000 mt used in the other scenarios to 167,000 mt (95,000 + 72,000) so that actual catch by fishery did not vary. Following the step change and inclusion of the fleet into the management framework, allocation to the new fleet was arbitrarily set to 5% and the allocation to the other fleets was reduced by 5%.

The ALBWG also recommended inclusion of assessment error by running an estimation model based on the current stock assessment in the MSE framework (see Section 3.2.2), and of an implementation error (see Section 3.2.3).

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. 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, it is difficult to select one “true” OM model. Therefore, to capture the range of uncertainty in the system (see Section 2.7) 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, it is determined if the OMs can reasonably represent past trends in catch, catch per unit effort (CPUE), and size composition data. The conditioning process followed a series of steps:

1. Growth was estimated using maximum likelihood methods by running each of the OMs while fitting to the conditional age-at-length data (sections 3.1.1.2.1.2 and 3.1.1.3.1), in addition to the length compositions, abundance indices, and catch.
2. Growth parameters were fixed to those estimated in step 1, and a second set of parameters was estimated for each OM using maximum likelihood methods, namely the log of recruitment at virgin biomass, ln(R_0), recruitment deviations, selectivities, and catchabilities.
3. Model fits of each OM were analyzed by assessing model convergence, fits to the abundance indices, size composition data, and catch data, as well as trends in estimated SSB and fishing intensity (1-SPR).
4. Model parameters were fixed to values estimated in Step 2. During the "Future Process" phase, the conditioned OMs are used to simulate trends in the population under a range of different management models (i.e. different harvest strategies and harvest control rules). This closed-loop forward simulation is described in section 3.2.

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. 4). 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 4). 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 3). 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 4). 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 4). 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 4).

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 long line 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 5.

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 (Table 4) 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 (section 3.1.1.2.1.2).

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 downweighted by multiplying the likelihood of these data by 0.1.
-

Key parameters for the base case OM are outlined in Table 6.

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 6).

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).

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.

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.

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 6 for actual natural mortality values.

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 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.

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 (SS*B*0) corresponding to *R*0, and was assumed to follow a lognormal distribution with standard deviation σR (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 (σR) 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, *R1*, were estimated during the conditioning phase. During the forward simulation $\ln(R_0)$ and *R1* 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 σR and an autocorrelation, ρ_R, of 0.42 (section) according to:

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

Steepness of the stock-recruitment relationship (h) was defined as the fraction of recruitment from a virgin population (R0), when the spawning stock biomass is 20% of its unfished level ($SSB0$). 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).

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.

Fishery Dynamics

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 7.

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 7). 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 6).

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 7). 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.

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.

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*).

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).

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.

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 25th percentile and 75th 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 25th and 75th 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.

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.

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 (Table 8 and 9). 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 work flow to estimate the growth parameters of the alternative OMs listed in Table 9 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 at 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.

Results of Conditioning Process and Final Set of Operating Models

The 27 OMs (Table 8 and 9) 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 (Table 9) and were therefore not considered further. OMs with the high natural mortality parametrization produced unrealistic spawning biomass (SSB) estimates unless growth option 3 (large L_{inf}) was used concurrently (Fig. 5). These OMs were also excluded from the final set of OMs. OM no. 4 (Table 8) produced an extremely low SSB estimate (Fig. 5) and was also not considered further. 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 5 OMs (Fig. 6 and Table 8). 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. In particular, no OM in the final set had a low steepness value. Scenarios 1, 3, 4, and 6 were treated as the reference set, whereas scenario 7 was considered a robustness (less plausible) scenario. Scenario 7 was a high productivity trial with a much higher biomass and lower fishing intensity as compared to the base case (Fig. 6). Results (Section 4) are presented across the four reference scenarios, and robustness to Scenario 7 is 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. Each of the OMs was projected forward in time from 2016 to 2045, a period of 30 years, which corresponds to 2 lifespans of NPALB (Fig. ES3).

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 3.2.1) and input into a simulated stock assessment model (i.e. the estimation model or EM, Section 3.2.2) (Fig. ES3). 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 model, which is comprised of a HCR with specific reference points (See Section 2.6 for a list of the rules being compared) (Fig. ES3). A total allowable catch (TAC) or total allowable effort (TAE) is set according to the HCR, based on the condition of the simulated albacore population relative to reference points.

For each HCR, the exploitation rate (biomass at the beginning of the year/total catch per year) that produces the fishing intensity (1-SPR) specified by the TRP in the HCR is computed. For TAC-based rules, this exploitation rate is multiplied by the current total biomass to obtain a catch. The TAC is then split into a fishery-specific catch using the 1999-2015 average catch ratios and input into the OM with some implementation error (Section 3.2.3) for simulation of population dynamics in the next time step. The same TAC is kept constant for the following three years of simulation, until the next assessment period. For TAE-based rules, the same process is followed to determine a catch to input into the OM. However, it is the exploitation rate, rather than the catch, that is kept constant for the following three years of simulation, so that the actual catch varies depending on fluctuations in total biomass. 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, 8, and 9 show examples of CPUE time series and size composition data generated for a model run.

4.2.2. Estimation Model

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}), terminal year fishing intensity (F_{LATEST}) and reference points are produced by the EM and input into the HCR being evaluated to set a TAC or TAE.

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 feedbacks 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 10 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 HS3. Relative error was computed as:

$$(\text{EMvalue}-\text{OMvalue})/\text{OMvalue}$$

A negative value therefore implies that the EM is underestimating the quantity of interest. The median is a reflection of the bias in the errors, while the standard deviation reflects the error variability. Patterns of errors in the LRP and TRP were consistent across HCRs (Table 10). Estimates of the LRP and TRP were precise (low σ) across all scenarios. However, bias in the LRP and TRP changed across scenarios. Bias in the LRP was low for most scenarios except 6 and 7. Bias in the LRP was negative for scenario 6 (Table 10), implying the EM estimated a lower LRP than the OM, thus management action would be delayed as compared to an EM with no assessment error. By contrast, bias for scenario 7 was large and positive (Table 10). Therefore, this scenario would be associated with an earlier than necessary management action. The estimated TRP was only biased for scenario 7, with the TRP being ~20% higher than in the OM. In this case, the assessment error leads to estimation of a TRP that is too high, therefore potentially endangering the stock.

Estimates of terminal SSB and F were much less precise (high σ) than LRP and TRP estimates across all scenarios (Table 10). Variability in F was consistent across scenarios and HCRs, ranging from 0.10 to 0.15. However, variability in SSB error varied substantially across HCRs and scenarios. For all HCRs, scenarios 1 and 3 showed the lowest variability in SSB (0.3 to 0.7), followed by scenarios 4 and 7 (0.4 to 1), with scenario 6 having the highest (0.6 to 1.3, Table 10). HCRs 1, 4 and 6, which had a TRP of F50 had the lowest variability in SSB, while HCR 15, with the highest fishing intensity TRP, had the most. Patterns in terminal SSB bias also varied across HCRs with bias increasing from HCR1 to HCR15 for scenarios 1 and 3 (~ 0 to -0.15), but being reduced from HCR1 to HCR15 for scenarios 4, 6, and 7. Bias in terminal year fishing intensity (1-SPR) was consistently low across all HCRs for scenarios 1, 3, and 7, but was underestimated in scenarios 4 and 6. Similarly to bias in terminal SSB, bias in fishing intensity was reduced in HCRs 13 and 15 as compared to other HCRs, dropping from -0.1 and -0.2 to -0.05 and -0.1 (Table 10). Clearly there were feedbacks between the HCRs, status of the stock, data quality (more closure imply more years with missing data), and the assessment error of various quantities important to management, suggesting integration of a full stock assessment to account for this patterns was necessary.

4.2.3. Implementation Error

Before the catch determined by the HCR is introduced into the OM, each fishery-specific catch is modified by an implementation error. We assume that the actual catch always exceeds the amount set by the HCR. The catch set by the HCR is multiplied by a random implementation error ranging from 5% to 20% and set to $1.05 + \text{abs}(N(0, \sigma = 0.05))$.

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 45 iterations and the four reference scenarios. However, results for each scenario are reported in the Appendix Tables. Also note that all the performance metrics are based from 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 robustness scenario 7 and fishing effort scenarios are reported in the Appendix Tables. Overall, the performance of harvest strategies and HCRs relative to one another was robust to scenario 7 and both the ramp in catch and the pulse in catch fishing scenarios, with the HCRs performing similarly across performance metrics in the robustness and fishing scenarios as the results across reference scenarios (Appendix Tables). For the fishing effort scenarios, this is because the catch from the new “South Pacific” fishery is known and subject to management, and thus any increase in catch was quickly reduced to maintain fishing intensity around the TRP, resulting in a similar performance across PMs as the reference scenarios. The few cases that show different patterns in HCR ranking for a specific performance metric for the effort scenario or scenario 7 as compared to the reference set are highlighted in the appropriate results section below.

Results for each performance metric separately are highlighted first. Then, tradeoffs across performance metrics and harvest strategies and HCRs are illustrated.

5.1. Performance Metric 1

Performance Metric 1 (PM1) is a measure of the performance of candidate HSs and HCRs with respect to management objective 1, *maintain spawning biomass above the limit reference point* (Table 1). It is based on the ratio of SSB for each projected year over the SSB-based LRP. PM1 was defined as the probability that SSB in any given year of the MSE forward simulation is above the LRP and represents the *odds of no fishery closure* because the fishery is closed when the LRP is breached in this MSE. Changes in PM1 between strategies and HCRs are dependent on both the value of SSB as well as the level of the LRP.

For all HSs, the largest differences in SSB were associated with differences in the TRP rather than the threshold or LRP. HCRs with higher target fishing intensity (e.g. HCRs 13 and 15 with TRP F30) resulted in lower SSB (Fig. 11). This pattern was consistent across harvest strategies and control types (Fig. 11). In terms of SSB, the performance of HS1 and HS3 was comparable (Fig. 11). For both HS1 and HS3, TAE-based rules maintained a higher SSB than TAC-based ones for TRPs of F50 and F40 (Fig. 11). This may have been associated to the ability of TAE-based rules to respond to random changes in biomass between assessment periods. TAE rules also showed less variability in SSB (Fig. 11). The TAE rules based on effort levels from 2002-2004 (HCRs 16, 17, and 18) showed an intermediate performance between TRP F40 and TRP F30 and similar to HS2 (Fig. 11). Unlike other HCRs, the performance of HCRs 16, 17 and 18 varied across uncertainty scenarios, with poorer performance in the low productivity scenarios (e.g. scenario 6) because maintaining constant effort levels from 2002-2004 in low productivity scenario implied a high fishing intensity (Fig. 12).

Differences in the ratios of SSB to the LRP were similarly associated with differences in the TRP but were also influenced by the LRP value. For the same LRP, the SSB to LRP ratio decreases as the TRP changes from a low to high fishing intensity (TRP F50 to TRP F30) (Fig. 13) because SSB decreases (Fig. 11). TAE-based rules with TRPs of F50 and F40 had higher SSB to LRP ratios and showed less variability (Fig. 13) because they maintained a higher and less variable SSB (Fig. 10). Similar to the SSB results, the TAE rules based on effort levels from 2002-2004 (HCRs 16, 17, and 18) showed an intermediate performance in the SSB to LRP ratio, somewhere between TRP F40 and TRP F30 and similar to HS2 (Fig. 13). Variation in the ratio of SSB to the LRP across HCRs was not only affected by the TRP, but also by the LRP. For the same TRP, HCRs with the highest LRP had relatively poor performance (Fig. 13).

A high PM1 is dependent on maintaining the ratio of SSB to the LRP to be higher than 1 (dotted line in Fig. 13) because this means that the SSB is above the LRP and no drastic management action (i.e. fishery closure) is required. HCRs with even the 5th quantiles of the SSB to LRP ratio above 1 had the highest PM1 (i.e. the highest probability of SSB being greater than the LRP) (Fig. 13 and 14). For both HS1 and HS3 with TAC-based rules, it was the HCRs with the highest TRPs of F30 (HCRs 13 and 15) and HCRs 1, 7, and 10 that showed poorest performance for PM1 (Fig. 14). These HCRs had the highest risks of the SSB being below the LRP and thus incurring the severe management action of closing the fishery, with HS3 showing slightly better performance for PM1 than HS1 (Fig. 14). For all TAE-based rules, the odds of no fishery closure were almost certain (probability ≥ 0.99), except for HCRs 7, 13, 16, and 17 (Fig. 14). In summary, for the same LRP, performance for PM1 was highest for the lowest TRP (e.g. F50). For the same TRP, PM1 performance was highest for the

HCRs with the lower LRP.

5.2. Performance Metric 2

Performance metric 2 (PM2) is a measure of the performance of candidate HSs and HCRs with respect to management objective 2, *maintain total biomass, with reasonable variability, around the historical average depletion of total biomass* (Table 1). Depletion is defined as the total biomass as a fraction of unfished total biomass. Therefore, a higher depletion implies a higher relative total biomass. PM2 was defined as the probability that depletion in any given year of the MSE forward simulation is above minimum historical depletion from 2006-2015, which was 0.61.
As with variability in SSB, the largest differences in total depletion were due to variation in the TRP, with the highest target fishing intensity (TRP F30) showing the lower depletion (Fig. 15). For the same TRP, a higher LRP (e.g., SSB20% vs SSB14%) was associated with a higher depletion (i.e., higher relative total biomass) (Fig. 15). However, differences in depletion due to changes in LRP were not as marked as differences due to TRP (Fig. 15). HCRs with the lowest TRP (F50) were the only ones showing depletion levels comparable to or higher than historical minimum depletion (Fig. 15). Depletion levels were comparable between HS1 and HS3 (Fig. 15). HS2 performed similarly to HCRs with an F0204 TRP, with median depletion levels between those of HCRs with a TRP of F40 and F30 (Fig. 15). Similar to PM1, TAE-based rules with TRPs of F50 and F40 performed better than TAC-based ones in terms of depletion (Fig. 15), and TAE- based rules had less variable depletion.

Trends in PM2 across harvest strategies and HCRs mirrored those in total depletion. Performance was similar between HS1 and HS3, but HS2 performed poorer than HS1 and HS3 rules with TRPs of F40 or F50. HCRs with the highest TRP (F30) performed poorest (Fig. 16). HCRs with a F0204 TRP performed better than TRPs of F30, but worse than TRPs of F50 (Fig. 16). For the same TRP, HCRs with the lowest LRP performed worst (Fig. 6). Finally, TAE-rules generally performed better than TAC-rules in terms of PM2 (Fig. 16).

Unlike results for the reference scenarios, the best performing HS and HCRs for robustness scenario 7 were HS2 and HCRs with a TRP of F0204 (Fig. 30). This is because scenario 7 had the highest productivity and thus the TRP based on 2002-2004 levels of effort had the lowest fishing intensity of any scenario (~F70), leading to a high total depletion and high PM2 performance. HS2 was the only strategy that did not increase fishing intensity to the TRP, if historical fishing intensity was lower. The initial TAC at the beginning of the simulation was set at 95,000 mt across scenarios. For scenario 7, this corresponded to an harvest rate of ~30%, which, in HS2, was maintained unless a random low recruitment event brought fishing intensity below the TRP, leading to an improved performance of HS2 for scenario 7 as compared to the reference set.

5.3. Performance Metric 3

This MSE was not designed with an allocation scheme 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 1), 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 minimum historical (2006-2015) harvest ratio, was a reflection of the difference in harvest ratio from the 1999-2015 used to set the allocation in the simulation versus the 2006-2015 value used in defining PM3. As an example, PM3 for the EPO fleet is shown in Figure 26.

The only change in PM3 occurred under the two fishing effort scenarios. With the arrival of a new fishery, the catch allocation to the other fleets had to be reduced (Fig. 27).

5.4. Performance Metric 4

Management objective 4 was to *maintain catches above average historical catch* (Table 1). Performance Metric 4 (PM4), relative total catch, was defined as the probability 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. 17).

Trends in median catch were comparable between HS1 and HS3 (Fig. 18). Median catch was highest for HCRs with the highest TRP of F30, and lowest for the lowest TRP of F50 (Fig. 18). HS2 performed better in terms of median catch than HS1 or HS3 rules with TRPs of F40 or F50 (Fig. 18). Median catch was slightly higher for TAC-based rules as compared to TAEs but TAC-based rules also resulted in the highest catch variability (Fig. 18). There was a trade-off between increased catch and increased catch variability with catches being more variable for HCRs with a TRP of F30 (Fig. 18). This is because higher TRPs, like F30, resulted in lower SSBs (Fig. 11) and required more management actions, which resulted in more variable catch. Catch variability was also higher for HS3 than HS1 (Fig. 18) because HS3 required steeper changes in fishing intensity once the threshold reference point was crossed (Fig. 1). For the same TRP, median catch was comparable across LRPs but catch variability increased with a higher LRP because the probability of breaching the LRP increased, which resulted in more management interventions (Fig. 18). It should be noted that median catch was greater than average historical (1981-2010) catch (i.e. ratio of catch/historical is > 1, dotted line in Fig. 18) for all HCRs.

The performance of a candidate HCR with respect to PM4 was dependent on both median catch and catch variability. A higher median catch would lead to a higher probability of catch being above historical, but a higher variability in catch would lead to that probability being lower. For all HS, the largest differences in PM4 were due to differences in TRP, where HCRs with a low TRP of F50 having lower PM4 (Fig. 19). However, differences in PM4 between F40 and F30 were not as evident. For TAC rules, median catch was higher with a TRP of F30 relative to F40 but this was not enough to offset the increase in catch variability, leading to HCRs with a TRP of F40 having comparable or better PM4 performance than HCRs with a TRP of F30 and the same LRP (Fig. 19). Catch for TAE rules was not as variable as for TAC rules because of overall less management intervention, so the offset in PM4 for HCRs with a TRP of F40 relative to F30 was not as apparent (Fig. 19). However, differences in PM4 between HCRs with F40 and F30 were less than differences between F40 and F50, suggesting that even for TAE-based rules, PM4 does not scale linearly with median catch given the effect of increased catch variability at a higher TRP. HS3 generally performed poorer than HS1 for PM4 due to the higher catch variability (Fig. 18 and Fig. 19). HS2 performance was poorer than that of HS1 or HS3, with a F30 TRP and the same LRP of SSB7.7% (Fig. 19). For the same TRP, PM4 was generally higher for rules with a lower LRP (Fig. 19). For robustness scenario 7, PM4 performance was generally higher than the reference scenarios and differences in PM4 between TRPs were less marked (Fig. 31). Scenario 7 has the most productive scenario and therefore the lowest historical fishing intensity, which was rarely higher than F70 (Fig. ES4). Thus, under scenario 7 even a TRP of F50 implies much higher catches than historically observed. Similar to the reference sets, rules with a higher TRP have higher median catch, but lower catch variability. However, in scenario 7, the lower catch variability and reduced management intervention for TRP50 can offset the increase in median catch associated with even TRP30, resulting in comparable performance for PM4 across all TRPs.

PM4 was also computed by fishery (see Fig. 20 for an example for the Japanese pole-and-line fishery and Table 11 for results for all fisheries). Here fishery is defined by flag and gear with the exception of the EPO fishery which includes both the Canadian and US surface fleets. Differences in PM4 across HS and HCRs were similar to those highlighted for overall relative catch, with relative catch by fishery being higher at higher fishing intensity. Variation in PM4 across fisheries was a reflection of the difference in catch ratios from the historical period used in PM4 (1981-2010) to the period over which the allocation used in the MSE was computed (1999-2015) (compare left and right panels in Fig. 21). For instance, there was a large increase in the catch ratio of China and Vanuatu in the more recent period (1999-2015) as compared to 1981-2010 (Fig. 21), so the probability of catch being higher than historical was highest for these fisheries (Table 11). By contrast, catch ratios for Korea were drastically reduced from 1981-2010 to 1999-2015 (Fig. 21), so the probability of catch being higher for the Korean fishery was zero for all HCRs (Table 11). However, even for the Korean fleet, catch was always higher than the lower 25% of historical (1981-2010) catches (i.e. PM4 25 in Table 11 is 1).

5.5. Performance Metric 5

Performance Metric 5 (PM5) is a measure of management objective 5, *change in total allowable catch between years should be relatively gradual* (i.e., catch stability). To compute PM5, the percentage change in TAC between consecutive assessment periods (once every 3 years), excluding years where TAC=0, was first computed. PM5 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 TAE rules, the catch associated with the TAE was used rather than a 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. Results for positive changes in catch are reported in Table A5).

The largest difference in the median decrease in TAC between assessment periods was between TAC and TAE-based rules, with the latter showing smaller decreases in TAC (Fig. 22). This may have been due to biomass being maintained at a higher level and management interventions being less frequent with TAE-based rules. Differences in the median decrease in TAC across TRP or LRP were not large, but the variability increased at higher TRPs and higher LRPs (Fig. 22). Variability in decreases in TAC was also highest for HS3 as compared to HS1 for TAC-based rules (Fig. 22). This was associated with the steeper decrease in fishing intensity required by HS3 once the threshold reference point is crossed (Fig. 1).

Performance with respect to PM5 (i.e., catch stability) is dependent on both the median decrease in TAC and its variability. For TAC-based rules, PM5 performance was highest for HCRs with the lowest TRP (i.e. F50, Fig. 23), given the same LRP. For TRPs F50 and F40, catch stability was highest for HCRs with the lowest LRP (Fig. 22) because management actions were more infrequent. Also, PM5 performance was better for HS1 as compared to HS3 because HS3 included a steeper decrease in fishing once the $SSB_{threshold}$ reference point was crossed (Fig. 23). There were no differences in PM5 between TAE rules as decreases in catch were never larger than 30%. However, if PM5 for TAE-based rules was instead defined as the probability of a decrease in catch between consecutive assessment periods being <15%, rather than 30%, catch stability was lowest for HS2 and HCRs with the TRP of F30 or F0204 (Fig. 24).

In the scenario where albacore fishing effort was shifted from the South Pacific to the North Pacific in a step change (Section 2.7), performance of PM5 was poorer than the reference scenarios (Fig. 32) because of the drastic reduction in catch required following the first time step to bring fishing intensity back to the TRP. This reduction in catch was highest for HCRs with the lowest TRP. Thus, unlike for the reference set, catch stability was highest for the HCRs with higher TRP because of the large decrease in in catch required in the first time step.

5.6. Performance Metric 6

Management objective 6 was to *maintain F at the target value with reasonable variability*. Performance Metric 6 was used to measure the performance of HSs and 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 than the F was higher than the TRP (i.e. a higher fishing intensity than that set by the TRP).

All HCRs except for HS2 had PM6 less than 1 (Fig. 25). This was because HS2 was the only strategy where, if the current F was lower than the F-based TRP, the F was allowed to continue to be lower than the TRP. For HS1 and HS3, fishing was always set to the TRP, so fishing intensity was always at least as high as set by the TRP. Moreover, as the implementation error was forced to always be positive (i.e. catches were always higher than what was set by management), the actual F was always higher than the TRP for HS1 and HS3, leading to a PM6 of less than 1.

PM6 was highest for HCRs with the highest TRP (i.e. for F30 as compared to F50, Fig. 25). This is because a higher TRP was associated with a lower SSB (Fig. 11) and more frequent management intervention, which decreases F to be below the TRP. By contrast, the F for HCRs with a higher TRP could fluctuate more widely due to implementation error before a management action was triggered, leading the F further away from the TRP.

While the relative rank of HCRs was similar for the robustness scenario 7 as for the reference set, with rules with a higher TRP performing better, PM6 for TAC rules under scenario 7 was higher than 1, unlike the reference set (Fig. 33). This is because of the large positive bias in the estimated LRP for scenario 7 (Table 10) as compared to the OM. A larger LRP estimate implies that management actions occur sooner than what would be warranted from the "true" stock status, leading to overall lower fishing intensity as compared to the TRP. The population is therefore maintained at a higher biomass, with a lower fishing intensity.

5.7. Tradeoffs between Performance Metrics

There was no single best-performing HCR for all management objectives. Trade-offs were evident between performance metrics. Fig. 28 shows performance of all TAC-based HCRs for HS1 and HS3 across all metrics. Lines closer to the outer margin (value of 1) indicate better performance. For each LRP, a higher TRP (e.g. F30) performed better in terms of relative catch (PM4) but poorer in terms of relative total biomass (PM2), odds of no fishery closure (PM1), and catch stability (PM3). With a lower fishing intensity TRP, the population was maintained at a higher level, requiring less management intervention and resulting in lower catch variability between years. However, this stability comes at a cost to overall catch, with PM4 being lowest for HCRs with a TRP of F50 (Fig. 28).

However, the increase in relative catch for HCRs with a higher TRP was at times marginal relative to the decreases in other metrics. For rules with an LRP of SSB20%, differences in relative catch between HCR1 (F50) and HCR7 (F40) were smaller than those in relative total biomass or in the odds of a fishery closure (Fig. 28). Thus, if the current LRP of SSB20% were to be maintained, the best performing TAC-based HCR may be one with a TRP of F50 (Fig. 28). Likewise, for an LRP of SSB14%, differences in relative catch were not as marked as differences in odds of no fishery closure or catch stability (Fig. 28). For instance, HCR10 (TRP F40) performed comparably to HCR13 (TRP F30) in terms of relative catch, but had higher catch stability and lower odds of a fishery closure (Fig. 28). A similar pattern was evident for HCRs with a LRP of SSB 7.7%, with HCR12 (F40) showing comparable relative catch to HCR15 (F30), but higher catch stability, odds of no fishery closure, and relative total biomass (Fig. 28). This is because the higher fishing intensity set by the HCR15 TRP could not compensate for the lower biomass and higher frequency of management intervention leading to high catch variability and a higher probability of catch being less than the historical average as compared to HCR12. In conclusion, for TAC-based rules, the best performing HCRs overall were HCR1, HCR4, HCR6, HCR10 and HCR12. HCR10 and HCR12 (TRP F40) performed best in terms of PM4, while HCR1, HCR4 and HCR6 performed better in terms of PM1, PM2, and PM5.

A trade-off between relative catch and relative biomass, catch stability, and odds of no fishery closure was evident also for TAE-based HCRs (Fig. 29). For HCRs with an LRP of SSB20%, relative total biomass (PM2) was highest for HCR1 (F50), but HCR1 was associated with the lowest relative catch (Fig. 29). Relative catch was comparable between HCR7 (F40) and HCR16 (F0204), whose TRP averaged across scenarios would correspond to ~F34. It is interesting to note, however, that the decrease in relative catch for HCR1 (F50) under HS3 was marginal. HS3 rules were associated with more variable catch than HS1 rules because of the steeper decline in fishing required once the threshold reference point was crossed (Fig. 1). Thus, the higher catch variability of HCR7 and HCR16 reduced relative catch to level more comparable to HCR1 (F50) under HS3 as compared to HS1, and the tradeoff between relative catch and relative total biomass was less evident. Catch stability and odds of no fishery closure were comparable for HCR1 and HCR7 (F40), and lowest for HCR16 (F0204). Thus, if the current LRP of SSB20% were to be maintained, the best performing TAE-based HCR may be one with a TRP of F50 for HS3 (Fig. 29).

Similarly, for TAE-based HCRs with a LRP of SSB14%, HCR4, with the lowest TRP (F50) performed best in terms of relative biomass (PM2), but worst in terms of relative catch (PM4) (Fig. 29). However, while performance of PM2 decreased linearly with increasing TRP, the relationship between TRP and PM4 was non-linear, with all HCRs with a TRP higher than F50 performing comparably well (Fig. 29). Due to the lower catch stability and higher odds of fishery closure at higher TRPs, relative catch between HCR10 (F40) and HCR13 (F30) was comparable. The same trends were apparent for HCRs with an LRP of SSB7.7%, whereby the F40 HCR (HCR12) was better able to meet the conservation performance metric, PM2, than the F30 HCR (HCR15), without compromising economic performance (Fig. 29). HS2 performed well in terms of PM4 and PM1, but its performance was intermediate for PM2, and low for PM5. In conclusion, for TAE-based rules, the best performing HCRs overall were HCR1, HCR4, HCR6, in terms of PM2, and HCR10, HCR12, and HCR15 in terms of PM4. Performance in terms of PM1 and PM5 was comparable among these 6 HCRs.

6. CONCLUSIONS

A MSE framework was developed for NPALB to assess the performance of alternative management strategies and reference points given uncertainty. Harvest strategies with TAE control performed better than ones with TAC control in terms of PM1 (odds of no fishery closures) and PM5 (catch stability). With TAE control, catches adjusted quickly, without management interventions, in response to changes in biomass between assessment periods. HS3 showed more variability than HS1 in catch between years because of the steeper changes in TAC or TAE required once the threshold reference point was crossed, but had a lower probability of fishery closures. HCRs with an LRP and threshold reference point closer to the TRP resulted in a higher frequency of management interventions, fishery closures and lower catch stability. Across TRPs, there was no single best-performing HCR for all performance metrics (PMs). Trade-offs were evident between relative catch and relative biomass, catch stability, and odds of no fishery closure. HCRs with the lowest fishing intensity TRP (F50), maintained the population at a higher level than those with the highest fishing intensity TRP (F30), requiring less management intervention and resulting in lower catch variability between years but had the lowest catches. However, rules with an intermediate TRP of F40 had comparable or higher relative catch than F30 rules despite lower fishing intensity because of fewer closures and higher catch stability. Comparing TAE-based HCRs with the same LRP, HS2 performed poorer than HS1 or HS3 rules with a TRP of F40 and F50, in terms of PM2 (relative total biomass) and PM5 (catch stability), but better in terms of PM4 (relative catch), and PM6 (Ftarget/F). It is important to note that these results are subject to the limitations of the MSE framework outlined in the following section.

7. KEY LIMITATIONS

The ISC ALBWG recognized the following limitations of the current MSE modelling framework.

- Effort is modeled as fishing intensity rather than being modeled explicitly as the number of fishing days or number of hooks. However, in the real world, managers would manage effort as the number of hooks or the number of fishing days rather than fishing intensity. If TAE control was to be implemented, more work would be needed to quantify how fishing intensity would be translated into effort in terms of number of fishing days and number of hooks.
- Given the uncertainty in the relationship between fishing intensity in the MSE and real world effort in number of fishing days and number of hooks, effort control may be more effective in the simulation than in the real world and is assumed to be as effective as TAC control, which may not be realistic.
- It is assumed that effort or catch control is implemented equally effectively across all fisheries, including both NPALB targeting and non-targeting (e.g. surface fleets vs. longline).
- 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.
- In the simulations for HS1 and HS3, if the fishing intensity is lower than the target reference point, the simulated fishing intensity is increased to the target level when setting the TAC or TAE. This assumes no limitations in the capacity of the NPALB fleets.
- Given the lack of computer and personnel resources, only one rebuilding plan (fishery is closed) was tested. Further work could examine other rebuilding measures proposed by managers and stakeholders at the 3rd MSE workshop in Vancouver during 2017.
- Given the lack of computer and personnel resources, when determining stock status, only the probability of SSB being higher than the LRP or threshold reference point at a 50% level was tested. Further work could examine other probabilities proposed at the 3rd MSE workshop in Vancouver during 2017.
- 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 an area specific model 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.

8. RECOMMENDATIONS FROM THE 4TH ISC ALB MSE WORKSHOP

Following presentation of the MSE results highlighted in this report at the 4th ISC ALB MSE workshop, managers and stakeholders brought forward the following recommendations. These recommendations are also listed in the 4th ISC ALB MSE workshop report (ISC 2019).

Presentation of MSE Results

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".
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.
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.

Management Objectives

4. Managers and stakeholders should prioritize, rank, or weight the management objectives to assist decision making and help resolve tradeoffs in management objectives.
5. Management Objective #6 was considered of relatively low priority by managers and stakeholders in evaluating candidate reference points and harvest control rules.
6. 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.
7. 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.

Candidate harvest strategies, reference points and harvest control rules

8. The 2nd round of MSE should focus on Harvest Strategy 3 (Fig. 6) using the specific reference points and harvest control rules listed in Table ES4.
9. 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.

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.
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 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.
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.
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.
17. Implementation error distribution should include both positive and negative errors.

<u>MSE Workplan</u>

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 tradeoffs and potential performance of candidate reference points 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.
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.

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.

Others

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.
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.
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.

9. PROPOSED CHANGES FOR 2ND ROUND OF MSE ANALYSIS

Following the recommendations of the 4th ISC ALB MSE workshop, the ISC ALBWG will be carrying out a second round of MSE, comparing the HCRs, all from HS3, listed in Table ES4 with the management action listed in Table 12. The management model will be modified to include two additional levels of minimum TAC or TAE when the LRP is breached as specified in Table 12. For HCRs with LRPs of SSB20% or SSB14% these levels will be 0.5 and 0.25 of the fishing intensity or catch at the LRP. For HCRs with an LRP of 7.7% these levels will be 0.25 of the fishing intensity or catch at the LRP or a fishery closure. The fishing intensity or catch at the LRP were defined at the third ISC MSE Workshop in Vancouver, Canada (ISC 2017) and details of their calculation are presented in Table 12. As their value depends on the TRP, $SSB_{threshold}$, and LRP, they vary across HCRs as depicted in Figure ES10. Figure ES10 represents the eight different combination of reference points listed in Table ES4 for each control type. Each combination of reference points is associated with the two minimum levels of fishing intensity, for a total of 16 HCRs.

Performance of the HCRs highlighted in Table 12 will be evaluated across all five uncertainty scenarios used in the first round of MSE (Table ES3), and, if time allows, two additional potential fishing effort scenarios presented in Table 13.

Furthermore, changes to the operating model and MSE framework listed in Table 14 will be undertaken in the second round of MSE to address some of the recommendations identified at the 4th ISC ALB MSE workshop.

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11. 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. SSB_{LIMIT}) or fishing intensity-based (e.g. F_{LIMIT}).
- **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.
- **$SSB_{CURRENT,F=0}$ or $SSB_{X\%}$** – 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. SSB_{TARGET}) or fishing intensity-based (e.g. F_{TARGET}).

- **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.

12. TABLES

Table 1. Updated management objectives for the North Pacific albacore tuna, October 2017. $SSB_{CURRENT, F=0}$ refers to dynamic virgin (unfished) spawning stock biomass and fluctuates depending on changes in recruitment. $SSB_{0.5R0}$ is the spawning biomass that leads to a 50% reduction in the virgin recruitment level given a steepness value of 0.75. 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. For objective 2, depletion refers to the ratio of the latest projected total stock biomass and the unfished total stock biomass.

Management Objective[A]	Quantity	Proposed Performance Indicators[B, C, D]	Example Output[B]
1. Maintain spawning biomass above the limit reference point	Limit reference points tested: • $20\%SSB_{CURRENT, F=0}$ • $14\%SSB_{CURRENT, F=0}$ • $SSB_{0.5R0}$, where h = 0.75	• SSB for each projected year / SSB-based LRP	• % of runs in which ratio ≥1 for 29/30, 27/30, 24/30; • Each run = 30 years
2. Maintain total biomass, with reasonable variability, around the historical average depletion of total biomass	• Historical depletion is estimated as the-depletion level of total biomass for 2006-2015	• Depletion of projected total biomass over 30 yrs /minimum historical depletion of total biomass (minimum of 2006 - 2015)	• % of runs in which ratio ≥1 for 29/30, 27/30, 24/30; • Each run = 30 years
3. Maintain harvest ratios by fishery (fraction of fishing impact with respect to SSB) at historical average	• Historical harvest ratio by fishery estimated as the average of 2006 – 2015 • Historical variability in harvest ratio estimated from 2006 – 2015	• Harvest ratio (H) by fishery (i) for each year is calculated as $(1\text{-}SPR_i)/1\text{-}SPR_{total}$ • Projected harvest ratio by fishery over 30 yrs >= minimum historical harvest ratio by fishery (minimum of 2006 - 2015) and <= maximum historical harvest ratio by fishery (maximum of 2006 - 2015)	• % of runs within minimum and maximum for 29/30, 27/30, 24/30; • Each run = 30 years
4. Maintain catches by fishery above average historical catch	• Average catch by fishery over the 30 year period, 1981-2010	• Total catch of each projected year / average total historical catch (1981 – 2010) • Catch by fishery of each projected year / average historical catch of the fishery (1981 – 2010)	• % of runs in which ratio ≥1 for 29/30, 27/30, 22/30, 15/30; • Each run = 30 years;

Management Objective[A]	Quantity	Proposed Performance Indicators[B, C, D]	Example Output[B]
		• Projected catch by fisheries over 30 yrs /lower 25% of historical catch (1981 - 2010) • Projected catch by fisheries over 30 yrs /upper 25% of historical catch (1981 - 2010)	
5. If a change in total allowable effort and/or total allowable catch occurs, the rate of change should be relatively gradual		• % change in TAE and/or TAC between years (separate increases vs decreases)	• Median ± 5 and 95% percentiles of maximum % change in TAE and/or TAC for all years over all runs • Median ± 5 and 95% percentiles of % of projected years where change (0-15%, 15-30%, >30%) in TAE and/or TAC for all years over all runs
6. Maintain F at the target value with reasonable variability	Various potential target values previously suggested by NC	• F-ratio-target = F-based TRP/ F of each projected year	• Median ± 5 and 95% percentiles of median of F-ratio-target over all runs • Median ± 5 and 95% percentiles of 10%, 95% of F-ratio-target over all runs

<table>
<tr><th>Management Objective[A]</th><th>Quantity</th><th>Proposed Performance Indicators[B, C, D]</th><th>Example Output[B]</th></tr>
<tr><td colspan="4">The objectives shown below were suggested as ideas requiring further work to implement. They are shown here as an indication of future direction.</td></tr>
<tr><td colspan="4">I. Maximize economic returns of existing fisheries
II. Maintain interests of artisanal, subsistence and small-scale fishers, including limiting the regulatory impact on these fisheries</td></tr>
<tr><td colspan="4">NOTES
A - Objectives 1-6 for the first round of MSE were reviewed and agreed upon by the 3rd MSE Workshop participants, October 17-19, 2017.
B - Performance indicators and example output proposed by the Albacore Working Group
C - Performance indicators are configured so that higher estimated values mean better performance and lower estimated values means poorer performance, i.e., they have consistent directionality to reduce confusion in interpreting results. The exception to this practice is the first indicator (% change due to HCR between years) for objective 5 for which there is no directionality.
D - Definition of each fishery for fishery-specific performance indicators should be based on flag and gear.</td></tr>
</table>

Table 2. List of proposed performance indicators. Management objective #3 was not included because it could not be evaluated in this round of MSE.

Management Objective	Label	Performance Indicator
1. Maintain SSB above the limit reference point (LRP)	Odds of no fishery closure	Probability that SSB in any given year of the MSE forward simulation is above the LRP
2. Maintain depletion of total biomass around historical average depletion	Relative Total Biomass	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	Relative Total Catch	Probability that catch in any given year of the MSE forward simulation is above average historical (1981-2010) catch
5. Change in total allowable catch between years should be relatively gradual	Catch Stability	Probability that a decrease in TAC is <30% between consecutive assessment periods (once every 3 years), excluding years where TAC=0.
6. Maintain fishing intensity (F) at the target value with reasonable variability	F_{TARGET}/F	F_{TARGET}/F

Table 3. Uncertainties for OM conditioning and its progress.

		Progress
High Priority		
Recruitment	autocorrelation and various values of steepness	Done
Natural Mortality	various values of M	Done
Growth	Various values of growth parameters	Done
Medium Priority		
Age selectivity	time-varying age selectivity	Done
Recruitment	linked to environmental indices	in progress
Natural mortality	Sex-specificity	in progress
Catchability	time varying implementation error	in progress
Low Priority		
Growth	time-varying growth	in progress
Catchability	time varying catchability of indices	in progress
Size selectivity	time varying selectivity	in progress

Table 4. 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 indicates 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 5. 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 6. 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 7. 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 6.

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 8. List of the 27 operating models (OMs) representing different uncertainty scenarios and their parameter specifications. H refers to steepness, G to growth, and M to natural mortality. A value of 1 for a parameter means a base case value, a value of 2 a lower value than base, and a value of 3 a higher value than base. See Table 9 for a detailed list of actual steepness, growth, and natural mortality values for each operating model. Five out of the 27 models were selected to run a full MSE simulation with after thorough review by the ALBWG and those are denoted by an asterisk with the uncertainty scenario label used in the forward simulation also specified.

OM No.	h	G	M	Age selectivity	Recruitment autocorrelation	Convergence
Base* = Scenario 1	1	1	1	Time varying	0.42	
2	1	1	2	Base	Base	
3	1	1	3	Base	Base	No
4	1	2	1	Base	Base	
5	1	2	2	Base	Base	No
6	1	2	3	Base	Base	
7	1	3	1	Base	Base	No
8	1	3	2	Base	Base	
9	1	3	3	Base	Base	No
10	2	1	1	Base	Base	
11	2	1	2	Base	Base	No
12	2	1	3	Base	Base	
13	2	2	1	Base	Base	
14	2	2	2	Base	Base	No
15	2	2	3	Base	Base	
16	2	3	1	Base	Base	No
17	2	3	2	Base	Base	No
18	2	3	3	Base	Base	
19	3	1	1	Base	Base	
20	3	1	2	Base	Base	
21	3	1	3	Base	Base	
22* = Scenario 3	3	2	1	Base	Base	
23	3	2	2	Base	Base	No
24	3	2	3	Base	Base	
25* = Scenario 4	3	3	1	Base	Base	
26* = Scenario 6	3	3	2	Base	Base	
27* = Scenario 7	3	3	3	Base	Base	

Table 9. Steepness, growth and natural mortality parameter specifications for alternative operating models (OMs). See Table 6 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+	Mm 3+
Base	0.90	108.91	0.2836	45.06	0.1187	-0.4179	0.0393	1.36	0.56	0.45	0.48	0.39
2	0.90	110.72	0.2641	45.75	0.1018	-0.3465	0.0310	1.01	0.42	0.33	0.36	0.29
3	0.90	108.28	0.2904	44.55	0.1309	-0.4727	0.0373	1.84	0.76	0.61	0.66	0.53
4	0.90	100.38	0.3803	42.90	0.2106	-0.7657	0.0896	1.36	0.56	0.45	0.48	0.39
5	0.90	101.31	0.3721	43.60	0.1944	-0.7065	0.0812	1.01	0.42	0.33	0.36	0.29
6	0.90	99.32	0.3977	42.36	0.2109	-0.7685	0.0853	1.84	0.76	0.61	0.66	0.53
7	0.90	117.44	0.2204	46.54	0.0455	-0.1516	0.0162	1.36	0.56	0.45	0.48	0.39
8	0.90	120.14	0.2110	45.92	0.0524	-0.1762	0.0120	1.01	0.42	0.33	0.36	0.29
9	0.90	117.25	0.2157	45.96	0.0657	-0.2400	0.0151	1.84	0.76	0.61	0.66	0.53
10	0.70	108.86	0.2842	45.02	0.1193	-0.4202	0.0395	1.36	0.56	0.45	0.48	0.39
11	0.70	109.54	0.2755	45.53	0.1124	-0.3871	0.0356	1.01	0.42	0.33	0.36	0.29
12	0.70	108.34	0.2898	44.56	0.1305	-0.4705	0.0367	1.84	0.76	0.61	0.66	0.53
13	0.70	100.43	0.3748	43.38	0.1681	-0.6481	0.0784	1.36	0.56	0.45	0.48	0.39
14	0.70	101.42	0.3721	43.55	0.1893	-0.6872	0.0793	1.01	0.42	0.33	0.36	0.29
15	0.70	99.36	0.3961	42.35	0.2143	-0.7811	0.0863	1.84	0.76	0.61	0.66	0.53
16	0.70	117.29	0.2248	45.63	0.0721	-0.2547	0.0139	1.36	0.56	0.45	0.48	0.39
17	0.70	117.65	0.2216	46.63	0.0479	-0.1461	0.0141	1.01	0.42	0.33	0.36	0.29
18	0.70	117.33	0.2155	45.92	0.0621	-0.2280	0.0152	1.84	0.76	0.61	0.66	0.53
19	0.97	108.88	0.2841	45.07	0.1190	-0.4191	0.0394	1.36	0.56	0.45	0.48	0.39
20	0.97	110.38	0.2677	45.70	0.1051	-0.3605	0.0329	1.01	0.42	0.33	0.36	0.29
21	0.97	108.28	0.2904	44.55	0.1309	-0.4729	0.0374	1.84	0.76	0.61	0.66	0.53
22	0.97	100.38	0.3826	43.03	0.2013	-0.7283	0.0848	1.36	0.56	0.45	0.48	0.39
23	0.97	101.24	0.3638	44.02	0.1642	-0.6217	0.0714	1.01	0.42	0.33	0.36	0.29
24	0.97	99.32	0.3978	45.96	0.2113	-0.7700	0.0859	1.84	0.76	0.61	0.66	0.53
25	0.97	117.38	0.2238	45.67	0.0691	-0.2458	0.0137	1.36	0.56	0.45	0.48	0.39
26	0.97	119.53	0.2055	47.10	0.0220	-0.0670	0.0110	1.01	0.42	0.33	0.36	0.29
27	0.97	117.24	0.2158	45.96	0.0657	-0.2400	0.0151	1.84	0.76	0.61	0.66	0.53

Table 10. 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.

HCR1								
	SSB		LRP		TRP		F	
Scenario	Median	σ	Median	σ	Median	σ	Median	σ
1	-0.06	0.34	-0.01	0.02	0.00	0.01	0.00	0.14
3	-0.02	0.33	0.08	0.03	-0.06	0.01	0.04	0.14
4	0.15	0.48	0.05	0.03	0.05	0.01	-0.12	0.13
6	0.35	0.61	-0.19	0.08	0.06	0.01	-0.25	0.15
7	0.31	0.46	0.50	0.09	0.19	0.03	0.05	0.12
HCR4								
	SSB		LRP		TRP		F	
Scenario	Median	σ	Median	σ	Median	σ	Median	σ
1	-0.06	0.32	-0.01	0.02	0.00	0.01	0.00	0.13
3	-0.01	0.33	0.10	0.03	-0.06	0.01	0.02	0.15
4	0.13	0.46	0.04	0.03	0.05	0.01	-0.11	0.12
6	0.41	0.59	-0.20	0.08	0.06	0.01	-0.26	0.12
7	0.36	0.43	0.53	0.08	0.19	0.02	0.04	0.12
HCR6								
	SSB		LRP		TRP		F	
Scenario	Median	σ	Median	σ	Median	σ	Median	σ
1	-0.03	0.33	-0.01	0.02	0.00	0.01	-0.01	0.14
3	-0.04	0.32	0.08	0.03	-0.06	0.01	0.05	0.14
4	0.21	0.48	0.06	0.03	0.05	0.01	-0.13	0.11
6	0.41	0.66	-0.20	0.08	0.05	0.01	-0.27	0.12
7	0.35	0.41	0.50	0.08	0.19	0.03	0.06	0.12
HCR7								
	SSB		LRP		TRP		F	
Scenario	Median	σ	Median	σ	Median	σ	Median	σ
1	-0.09	0.38	0.00	0.02	-0.01	0.02	0.00	0.13
3	-0.13	0.40	0.08	0.03	-0.06	0.01	0.04	0.13
4	0.08	0.53	0.06	0.03	0.04	0.02	-0.09	0.12
6	0.23	0.69	-0.20	0.08	0.03	0.01	-0.20	0.15

Scenario	SSB Median	SSB σ	LRP Median	LRP σ	TRP Median	TRP σ	F Median	F σ
7	0.29	0.44	0.49	0.09	0.21	0.03	0.07	0.11
HCR10								
	SSB		LRP		TRP		F	
Scenario	Median	σ	Median	σ	Median	σ	Median	σ
1	-0.09	0.40	0.00	0.02	-0.01	0.02	0.00	0.12
3	-0.08	0.45	0.10	0.03	-0.06	0.01	0.04	0.15
4	0.10	0.62	0.06	0.04	0.04	0.02	-0.11	0.12
6	0.31	0.70	-0.22	0.08	0.03	0.01	-0.21	0.14
7	0.28	0.52	0.52	0.10	0.21	0.03	0.06	0.11
HCR12								
	SSB		LRP		TRP		F	
Scenario	Median	σ	Median	σ	Median	σ	Median	σ
1	-0.07	0.41	-0.01	0.02	0.00	0.02	0.00	0.12
3	-0.07	0.38	0.10	0.03	-0.06	0.01	0.03	0.12
4	0.13	0.62	0.05	0.03	0.04	0.02	-0.09	0.10
6	0.30	0.90	-0.23	0.08	0.02	0.01	-0.20	0.13
7	0.32	0.49	0.53	0.09	0.22	0.03	0.06	0.09
HCR13								
	SSB		LRP		TRP		F	
Scenario	Median	σ	Median	σ	Median	σ	Median	σ
1	-0.15	0.50	0.00	0.02	0.00	0.03	0.02	0.12
3	-0.19	0.45	0.10	0.04	-0.06	0.02	0.06	0.11
4	-0.01	0.56	0.05	0.05	0.04	0.03	-0.05	0.11
6	-0.02	0.74	-0.27	0.08	0.00	0.02	-0.10	0.16
7	0.20	0.58	0.50	0.10	0.24	0.05	0.08	0.13
HCR15								
	SSB		LRP		TRP		F	
Scenario	Median	σ	Median	σ	Median	σ	Median	σ
1	-0.12	0.69	0.00	0.02	0.00	0.03	0.01	0.12
3	-0.15	0.50	0.12	0.04	-0.06	0.02	0.04	0.11
4	0.08	0.98	0.05	0.05	0.04	0.03	-0.06	0.14
6	0.06	1.27	-0.28	0.08	0.00	0.02	-0.12	0.15
7	0.23	0.46	0.55	0.11	0.23	0.03	0.08	0.08

Table 11. Results of performance metric 4 (PM4), the probability in any given year of the simulation of catch for each fishery being greater than the average historical (1981-2010) catch for each fishery for each harvest strategy (HS) and harvest control rule (HCR) across all reference scenarios. EPO is the Eastern Pacific Ocean Canadian and American surface fleet, JPLL is the Japanese longline fleet, JPPL is the Japanese pole and line fleet, USLL is the US longline fleet, TWLL is the Chinese Taipei longline fleet, KRLL is the Korean longline fleet, CHLL is the Chinese longline fleet, and VNLL is the Vanuatu longline fleet. PM4 25 is the probability in any given year of the simulation of catch for each fishery being greater than the lower 25% of the historical (1981-2010) catch for each fishery; PM4 75 is the probability in any given year of the simulation of catch for each fishery being greater than the upper 75% of the historical (1981-2010) catch for each fishery.

			EPO			JPLL			JPPL			USLL		
Output Control	HS	HCR	PM4	PM4 25	PM 4 75	PM4	PM4 25	PM4 75	PM4	PM4 25	PM4 75	PM4	PM4 25	PM4 75
TAC	1	1	0.89	1.00	0.79	0.53	0.98	0.05	0.73	0.99	0.36	0.65	1.00	0.60
TAC	1	4	0.92	1.00	0.82	0.56	0.98	0.05	0.77	1.00	0.40	0.68	1.00	0.65
TAC	1	6	0.93	1.00	0.82	0.57	0.98	0.06	0.78	1.00	0.41	0.69	1.00	0.65
TAC	1	7	0.85	1.00	0.91	0.62	0.99	0.20	0.74	1.00	0.61	0.70	1.00	0.80
TAC	1	10	0.92	1.00	0.93	0.68	0.99	0.28	0.82	1.00	0.68	0.77	1.00	0.85
TAC	1	12	0.95	1.00	0.94	0.72	0.99	0.32	0.86	1.00	0.72	0.82	1.00	0.88
TAC	1	13	0.87	1.00	0.97	0.69	1.00	0.49	0.78	1.00	0.82	0.77	1.00	0.94
TAC	1	15	0.92	1.00	0.97	0.76	1.00	0.57	0.85	1.00	0.85	0.84	1.00	0.95
TAC	3	1	0.84	1.00	0.72	0.48	0.96	0.02	0.66	0.99	0.26	0.59	1.00	0.50
TAC	3	4	0.89	1.00	0.76	0.51	0.96	0.04	0.72	0.99	0.33	0.63	1.00	0.56
TAC	3	6	0.92	1.00	0.80	0.54	0.98	0.05	0.75	1.00	0.36	0.66	1.00	0.61
TAC	3	7	0.80	1.00	0.89	0.57	0.99	0.09	0.68	1.00	0.49	0.64	1.00	0.75
TAC	3	10	0.87	1.00	0.93	0.63	1.00	0.16	0.76	1.00	0.63	0.72	1.00	0.86
TAC	3	12	0.93	1.00	0.93	0.67	0.99	0.22	0.83	1.00	0.66	0.78	1.00	0.87
TAC	3	13	0.84	1.00	0.95	0.66	0.99	0.42	0.75	1.00	0.77	0.74	1.00	0.91
TAC	3	15	0.90	1.00	0.96	0.73	0.99	0.52	0.82	1.00	0.83	0.81	1.00	0.94
TAE	1	1	0.87	1.00	0.68	0.49	0.92	0.07	0.69	0.97	0.33	0.59	1.00	0.50
TAE	1	4	0.88	1.00	0.69	0.49	0.92	0.07	0.69	0.97	0.33	0.60	1.00	0.50
TAE	1	6	0.88	1.00	0.69	0.50	0.93	0.07	0.70	0.97	0.34	0.60	1.00	0.51
TAE	1	7	0.88	1.00	0.85	0.62	0.96	0.25	0.76	0.98	0.58	0.70	1.00	0.73

TAE	1	10	0.91	1.00	0.86	0.66	0.96	0.29	0.80	0.98	0.62	0.73	1.00	0.76
TAE	1	12	0.91	1.00	0.86	0.66	0.97	0.29	0.80	0.98	0.62	0.74	1.00	0.77
TAE	1	13	0.92	1.00	0.95	0.73	0.99	0.50	0.84	1.00	0.79	0.80	1.00	0.90
TAE	1	15	0.95	1.00	0.95	0.77	0.99	0.53	0.87	0.99	0.81	0.83	1.00	0.90
TAE	1	16	0.87	1.00	0.91	0.65	0.98	0.31	0.77	0.99	0.69	0.72	1.00	0.83
TAE	1	17	0.92	1.00	0.93	0.70	0.99	0.40	0.83	1.00	0.74	0.78	1.00	0.87
TAE	1	18	0.93	1.00	0.94	0.73	0.99	0.42	0.85	1.00	0.77	0.80	1.00	0.90
TAE	3	1	0.85	1.00	0.85	0.53	0.90	0.14	0.69	0.95	0.42	0.62	1.00	0.57
TAE	3	4	0.88	1.00	0.88	0.49	0.94	0.04	0.69	0.98	0.30	0.59	1.00	0.50
TAE	3	6	0.88	1.00	0.88	0.48	0.94	0.04	0.68	0.98	0.29	0.58	1.00	0.48
TAE	3	7	0.85	1.00	0.85	0.60	0.97	0.19	0.73	0.99	0.56	0.67	1.00	0.72
TAE	3	10	0.91	1.00	0.91	0.65	0.97	0.28	0.80	0.99	0.62	0.73	1.00	0.76
TAE	3	12	0.92	1.00	0.92	0.67	0.97	0.29	0.81	0.99	0.64	0.74	1.00	0.77
TAE	3	13	0.90	1.00	0.90	0.70	0.99	0.44	0.81	1.00	0.77	0.78	1.00	0.89
TAE	3	15	0.94	1.00	0.94	0.75	0.99	0.49	0.86	1.00	0.79	0.82	1.00	0.90
TAE	3	16	0.84	1.00	0.84	0.62	0.99	0.21	0.74	1.00	0.67	0.69	1.00	0.84
TAE	3	17	0.92	1.00	0.92	0.71	1.00	0.37	0.83	1.00	0.80	0.78	1.00	0.92
TAE	3	18	0.95	1.00	0.95	0.74	1.00	0.41	0.88	1.00	0.81	0.82	1.00	0.93
TAE	2	1	0.94	1.00	0.95	0.72	0.99	0.37	0.86	1.00	0.76	0.80	1.00	0.90
			TWLL			KRLL			CHLL			VNLL		
Output Control	HS	HCR	PM4	PM4 25	PM 4 75	PM4	PM4 25	PM4 75	PM4	PM4 25	PM4 75	PM4	PM4 25	PM4 75
TAC	1	1	0.82	1.00	0.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	1	4	0.86	1.00	0.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	1	6	0.87	1.00	0.01	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	1	7	0.80	1.00	0.07	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	1	10	0.88	1.00	0.13	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	1	12	0.92	1.00	0.16	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	1	13	0.84	1.00	0.33	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	1	15	0.91	1.00	0.44	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	3	1	0.75	1.00	0.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00

TAC	3	4	0.81	1.00	0.01	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	3	6	0.84	1.00	0.01	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	3	7	0.75	1.00	0.02	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	3	10	0.83	1.00	0.04	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	3	12	0.90	1.00	0.08	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	3	13	0.81	1.00	0.27	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAC	3	15	0.88	1.00	0.40	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	1	1	0.75	1.00	0.02	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.99
TAE	1	4	0.76	1.00	0.02	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.99
TAE	1	6	0.76	1.00	0.02	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.99
TAE	1	7	0.80	1.00	0.13	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.99
TAE	1	10	0.84	1.00	0.17	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.99
TAE	1	12	0.84	1.00	0.18	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	1	13	0.88	1.00	0.38	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	1	15	0.90	1.00	0.43	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	1	16	0.81	1.00	0.17	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	1	17	0.86	1.00	0.25	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	1	18	0.88	1.00	0.28	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	3	1	0.75	1.00	0.08	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	0.98
TAE	3	4	0.76	1.00	0.01	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	3	6	0.76	1.00	0.01	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	3	7	0.78	1.00	0.09	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	3	10	0.83	1.00	0.17	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	3	12	0.85	1.00	0.18	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	3	13	0.85	1.00	0.32	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	3	15	0.89	1.00	0.38	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	3	16	0.79	1.00	0.07	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	3	17	0.87	1.00	0.19	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	3	18	0.90	1.00	0.24	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00
TAE	2	1	0.89	1.00	0.22	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00

Table 12. 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 corresponds to Table 3 in the Report of the 4th ISC ALB MSE workshop (ISC 2019).

Stock Status	Candidate Harvest Control Rules
$SSB \geq SSB_{THRESHOLD}$	No TAE or TAC control $TAE = E(F_{TARGET})$ $TAC = B_{LATEST} * F_{TARGET}$
$SSB < SSB_{THRESHOLD}$, $> SSB_{LIMIT}$	$TAE = TAE_{MIN} + [E(F_{TARGET}) – TAE_{MIN}] * (SSB - SSB_{LIMIT}) / (SSB_{THRESHOLD} – SSB_{LIMIT})$, or TAE_{MIN}, whichever is greater $TAC = TAC_{MIN} + [(B_{LATEST} * F_{TARGET}) – TAC_{MIN}] * (SSB – SSB_{LIMIT}) / (SSB_{THRESHOLD} – SSB_{LIMIT})$, 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 $TAC=0.25 * C_{SSBLIM}$ $E_{SSBLIM} = E(F_{TARGET}) * SSB_{LIMIT} / SSB_{THRESHOLD}$ $C_{SSBLIM} = B_{LATEST} * F_{TARGET} * SSB_{LIMIT} / SSB_{THRESHOLD}$
$Prob(SSB > SSB_{LIMIT})$	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%
Rebuilding plan when $SSB \leq SSB_{LIMIT}$	To be determined in future MSE rounds. Previously identified candidates for rebuilding plan: $TAE = E(F(Prob. (SSB > SSB_{TARGET}) > 50\%))$ in 2 generations $TAC = B * F(Prob. (SSB > SSB_{TARGET}) > 50\%)$ in 2 generations

Additional Assumptions	
Assessment periodicity	Once every 3 years
Allocation	Average of 1999-2015

Table 13. List of potential future fishery effort scenarios to be evaluated for the 2nd round of NPALB MSE. These future fishery effort scenarios are of medium priority and may be evaluated with a subset of model runs if there are time constraints. This Table corresponds to Table 5 in the Report of the 4th ISC ALB MSE workshop (ISC 2019).

Potential future fishery effort scenarios
1) Increased effort & catches in the north Pacific – new entrant to fishery but catch is known to the assessment and under HCR – ramp in catch of 2,400 t per year up to 50,000 t
2) Increased effort & catches in the north Pacific – new entrant to fishery but catch is not known to the assessment and is not under HCR – ramp in catch of 2,400 t per year up to 50,000 t

Table 14. Proposed changes to the operating model for the 2nd round of NPALB MSE. This Table corresponds to Table 1 in the Report of the 4th ISC ALB MSE workshop (ISC 2019).

Model Process	**1st MSE Round**	**2nd MSE Round**
Available Fishing Effort	All fleets assumed to fish at the TAE or TAC, with an implementation error. This is assumed to be true even if TAE or TAC is greater than achieved historically by the fleets	Maximum fishing intensity or mortality for each year is based on a random draw from the estimated distribution of historical fishing intensity or mortality for 1997-2015. e.g., Max(F) ~ Normal[$F_{1997\text{-}2015}$, SD($F_{1997\text{-}2015}$)]. The fishing intensity or mortality could be fleet-specific or non-fleet-specific. If TAC or TAE is greater than historical maximum catch or effort, catch/effort are based on Max(F). If Max(F) is greater than TAE or TAC, fleets assumed to fish at TAE or TAC with an implementation error. The ISC ALBWG will attempt to model the historical relationship between catch, effort, and fishing intensity to explore the potential feasibility of modelling TAE control in terms of effort as number of vessels or number of fishing days for the surface fleets in the second round of MSE.
Implementation Error	Positive implementation error only (i.e., fleets are assumed to only fish at or more than the TAE or TAC).	Bidirectional implementation error (i.e., fleets can fish at, less or more than the TAE or TAC).
Harvest controls when SSB ≥ $SSB_{THRESHOLD}$	Fleets assumed to be under TAE or TAC control, based on F_{TARGET}.	Additional option to be evaluated where fleets are not under harvest control, if SSB ≥ $SSB_{THRESHOLD}$.
Harvest controls when SSB ≤ SSB_{LIMIT}	TAC = 0 or TAE =0	Evaluate additional options listed in Table 12.
Computation of Prob(SSB > SSB_{LIMIT})	Computed using the maximum likelihood estimate of SSB and its standard deviation as estimated by	Use the current NPALB future projection software to calculate the Prob(SSB > SSB_{LIMIT}) over the next

	the EM (i.e. simulated stock assessment)	10 years using current fishing conditions.

13. FIGURES

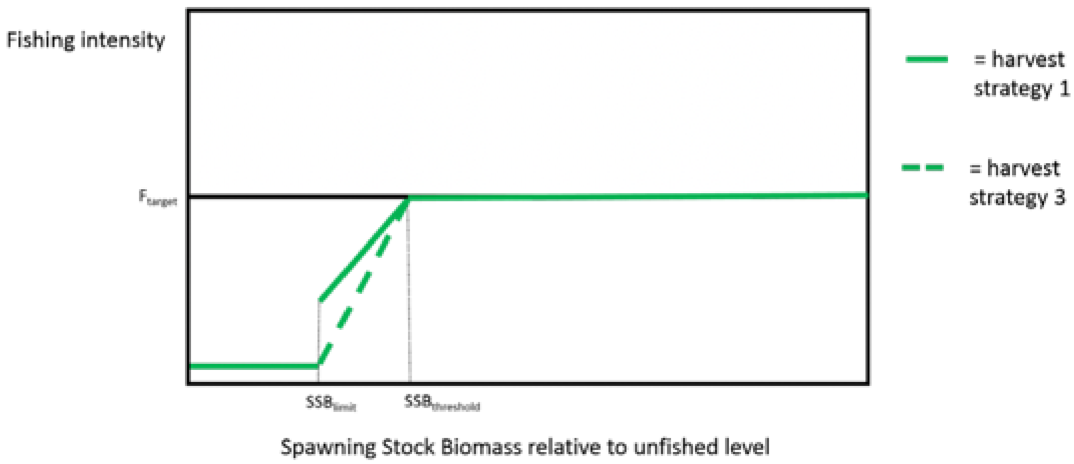

Figure 1. Example harvest control rule (HCR) for Harvest Strategy 1 and 3.

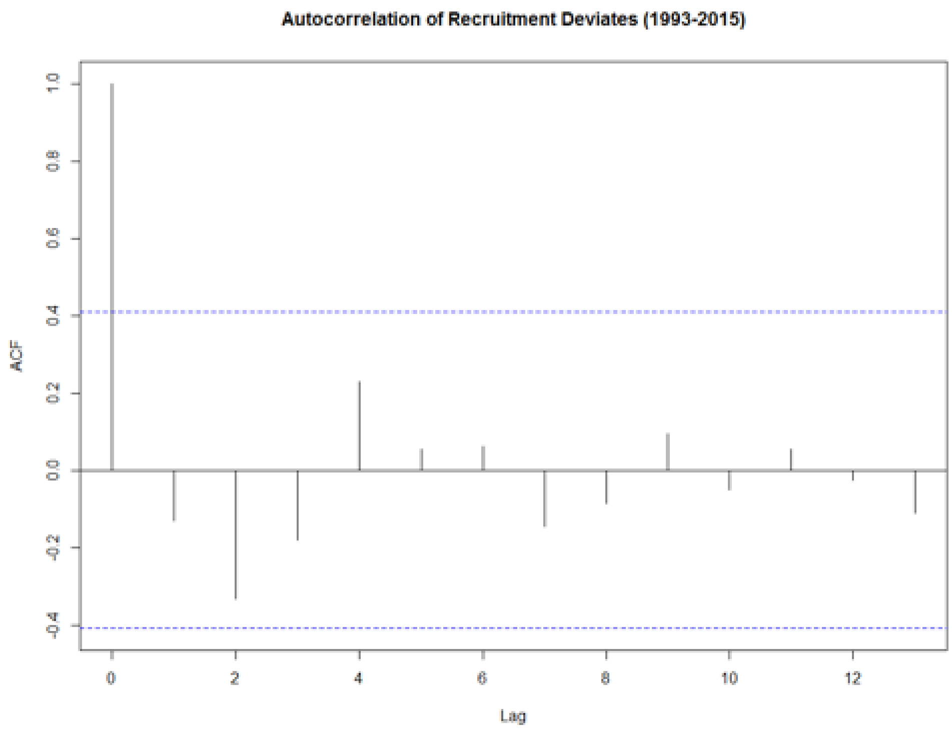

Figure 2. Autocorrelation from lag 0 to lag 13 of recruitment deviates from the 2015 stock assessment base model starting in 1993.

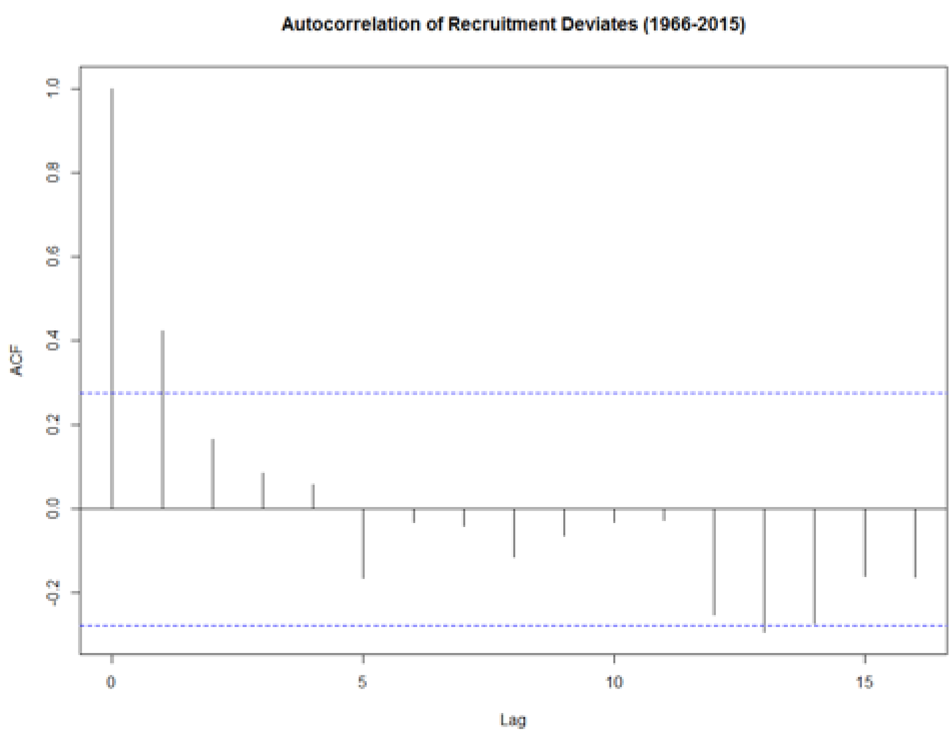

Figure 3. Autocorrelation from lag 0 to lag 16 of recruitment deviates from the 2015 stock assessment sensitivity model run starting in 1966.

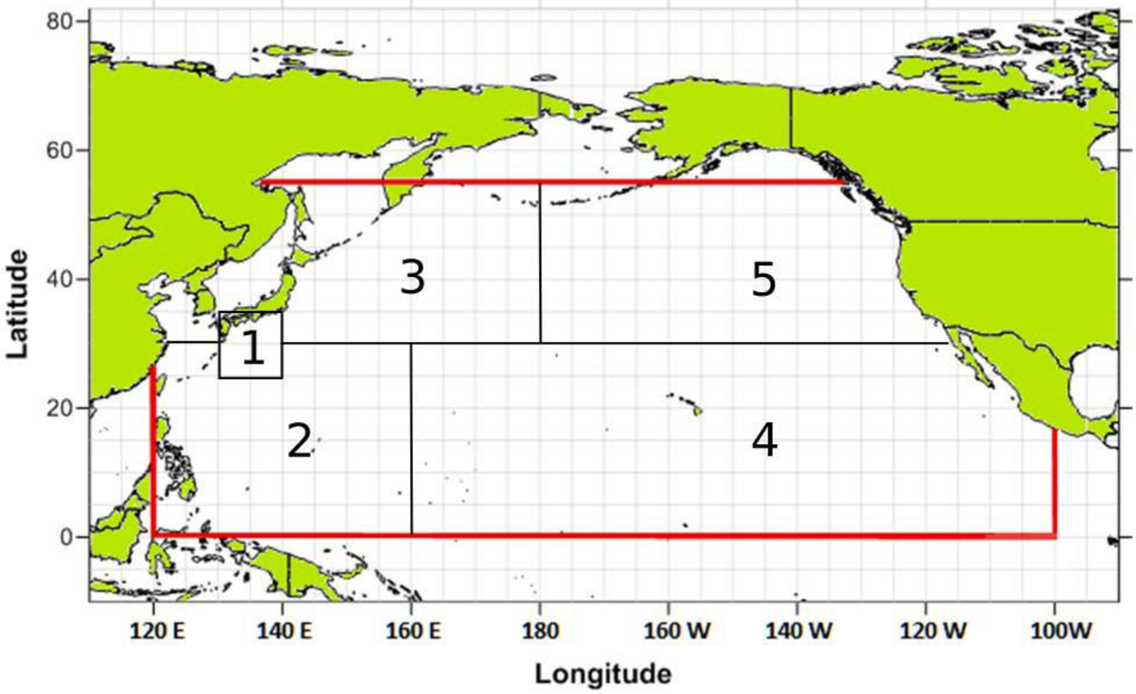

Figure 4. Spatial domain (red box) of the north Pacific albacore stock (*Thunnus alalunga*) in the 2017 stock assessment. Fishery definitions were based on five fishing areas (black boxes and numbers) defined from cluster analyses of size composition data.

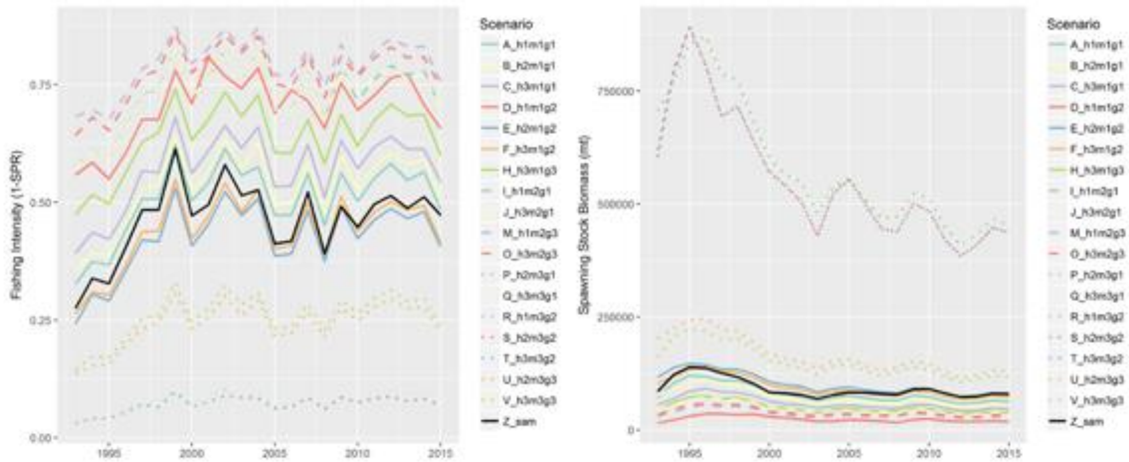

Figure 5. Trends in fishing intensity (1-SPR) and female spawning stock biomass (SSB) of the 18 out 27 OMs that converged during the conditioning process. 1-SPR is the reduction in female SSB per recruit due to fishing and is used to describe the overall fishing intensity on the NPALB. Refer to Tables 7 and 8 for a list of the specific steepness (h), natural mortality (m), and growth (g) parameters of each model.

Figure 6. Trends in fishing intensity (1-SPR) and female spawning stock biomass (SSB) for the five operating models used in the first round of MSE. 1-SPR is the reduction in female SSB per recruit due to fishing and is used to describe the overall fishing intensity on the stock. Refer to Tables 7 and 8 for a list of the specific steepness (h), natural mortality (m), and growth (g) parameters of scenario.

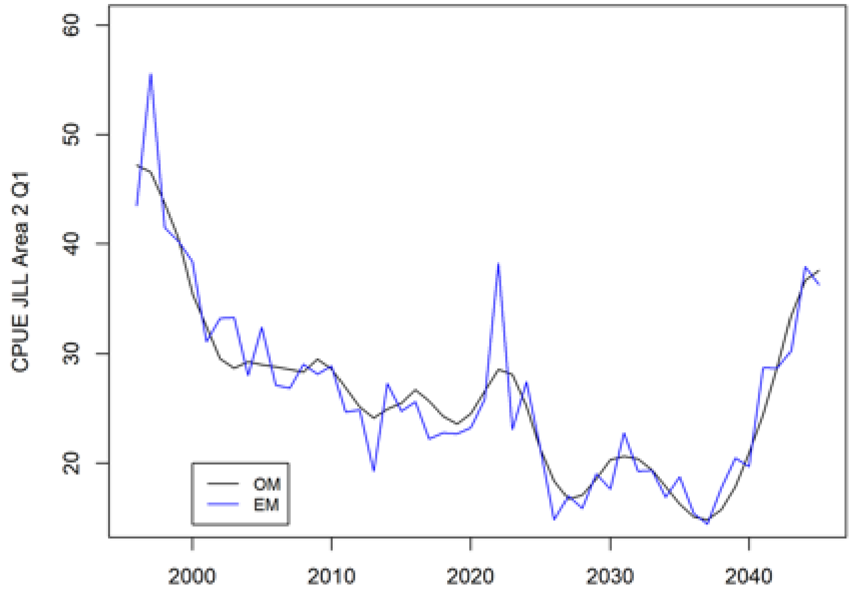

Figure 7. True S1 (Japanese longline operating in Area 2, quarter 1) CPUE time series from the operating model (OM, black line) and CPUE with error input into the estimation model (EM, blue line) taken from a random MSE simulation.

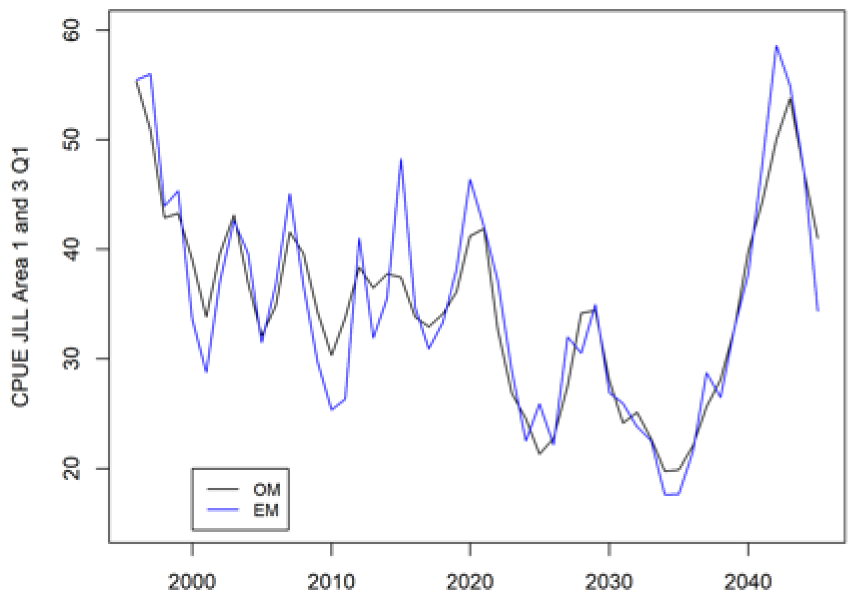

Figure 8. True S2 (Japanese longline operating in Areas 1 and 3, quarter 1) CPUE time series from the operating model (OM, black line) and CPUE with error input into the estimation model (EM, blue line) taken from a random MSE simulation.

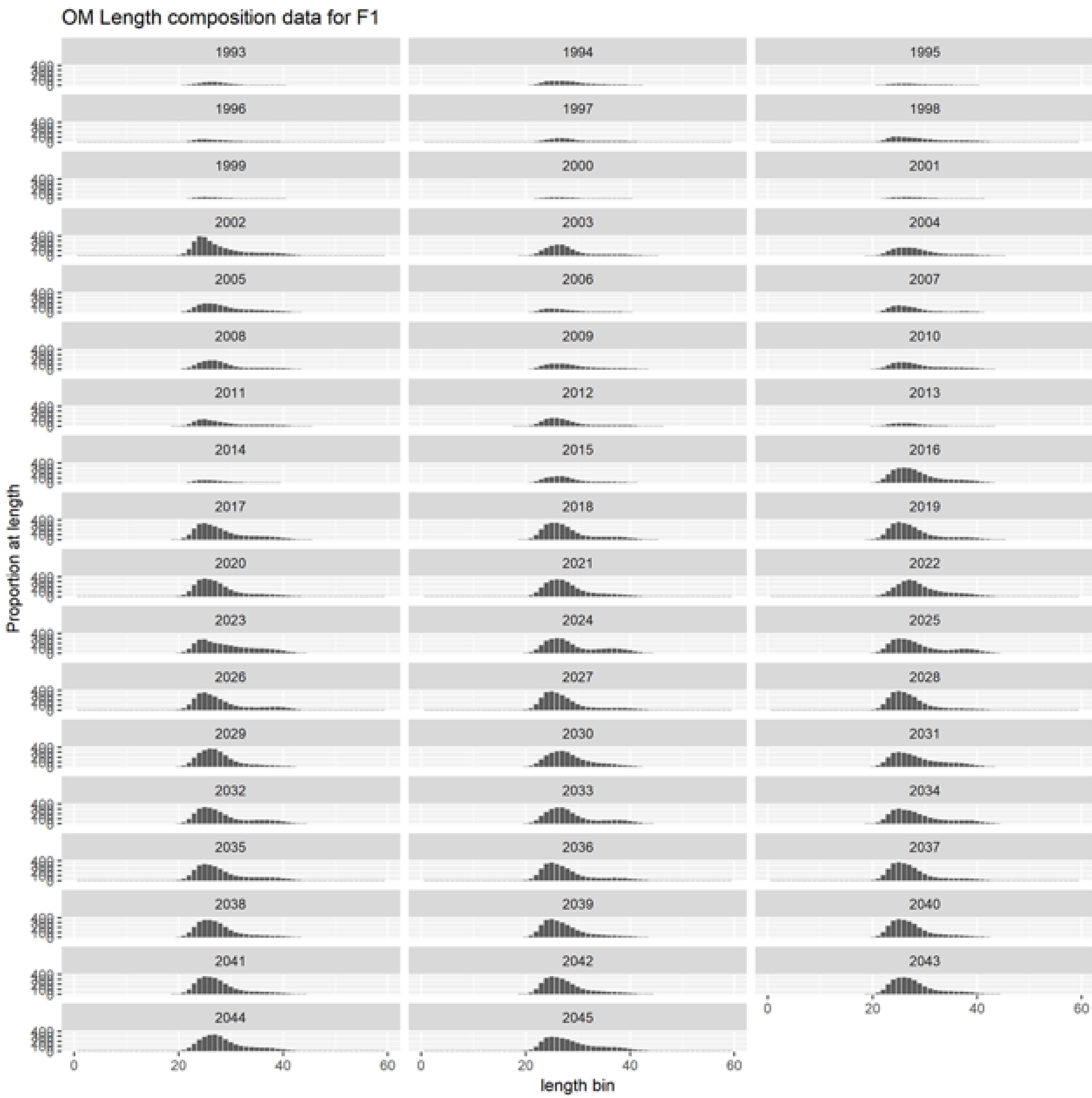

Figure 9. True size composition data from the operating model (OM, above) for the F1 fisheries (Japanese longline operating in Areas 1 and 3 in quarter 1) taken from a random MSE simulation.

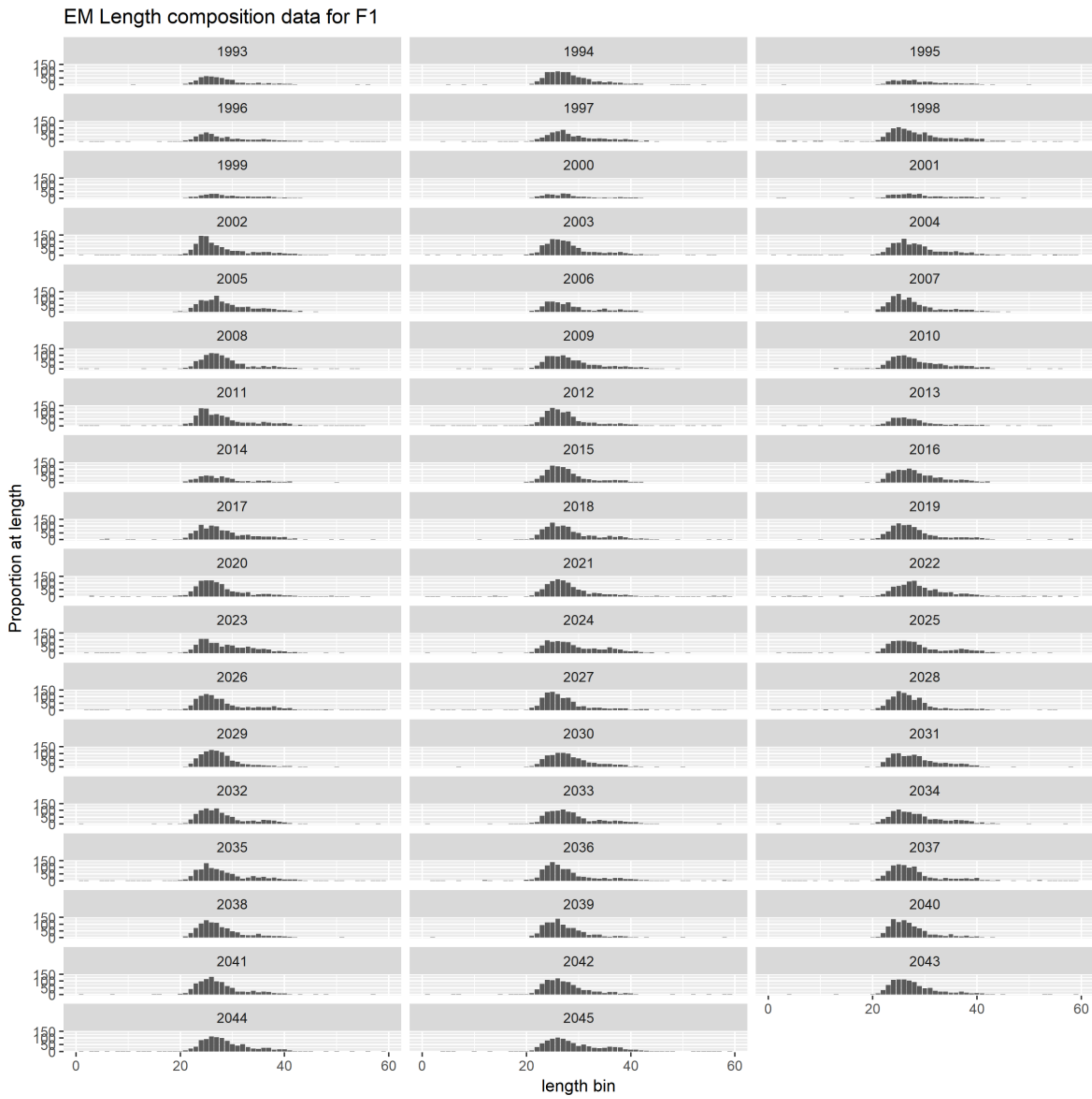

Figure 10. Size composition data with error input into the estimation model (EM, below) for the F1 fisheries (Japanese longline operating in Areas 1 and 3 in quarter 1) taken from the same MSE simulation used to obtain the operating model (OM) size composition data shown in Figure 8.

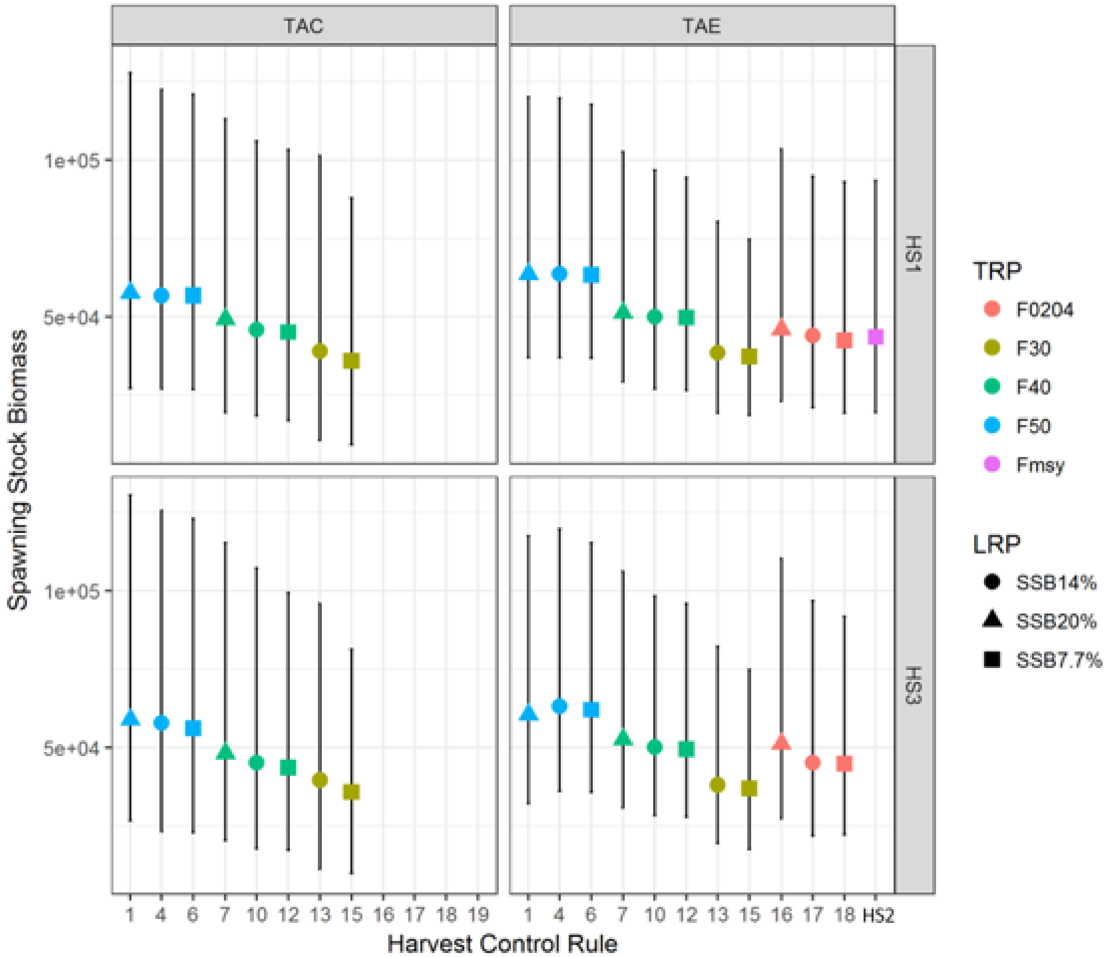

Figure 11. Median and 5th and 95th quantiles of female spawning stock biomass (SSB) for the 30-year simulation across all runs and reference scenarios for all the harvest strategies (HS) and harvest control rules (HCRs) tested. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

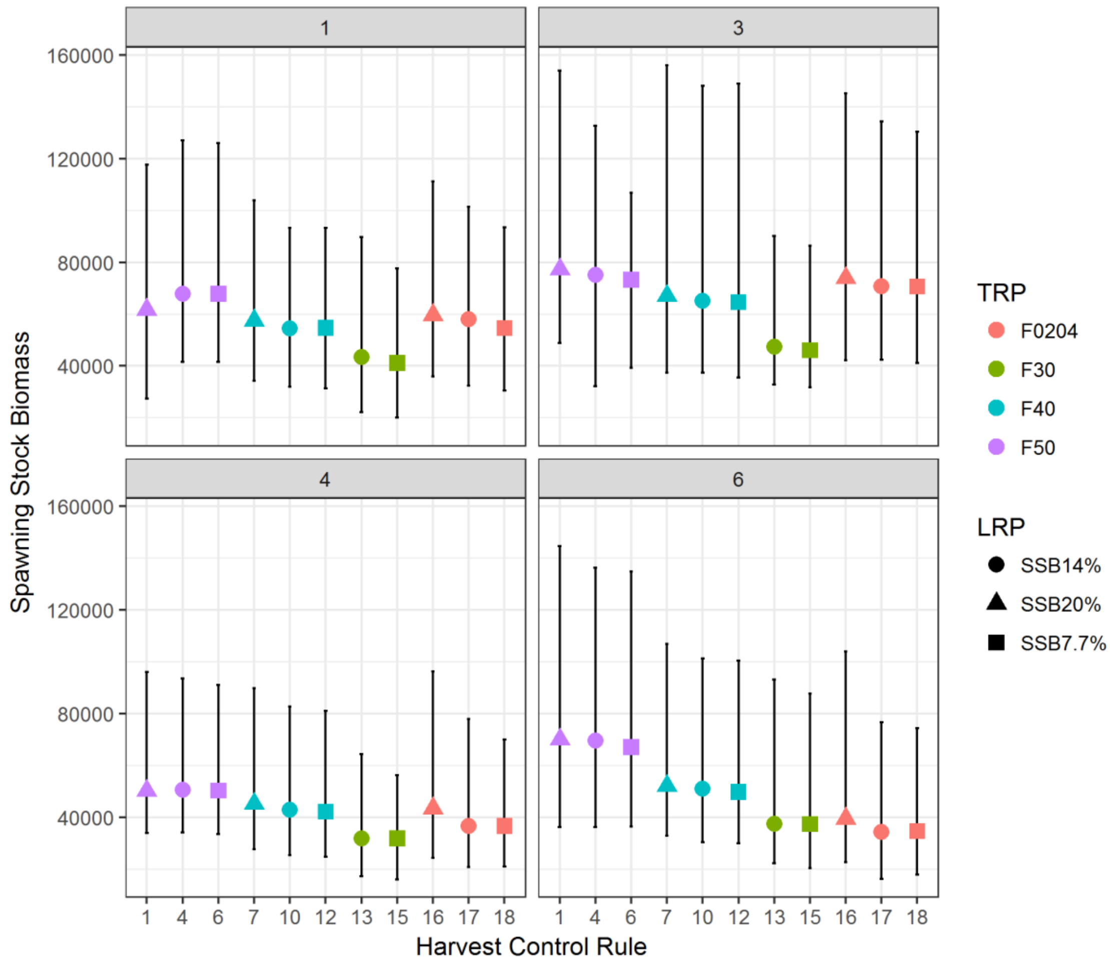

Figure 12. Median and 5th and 95th quantiles of female spawning stock biomass (SSB) for the 30-year simulation across all iterations for each reference scenarios for harvest strategy 3 TAE.

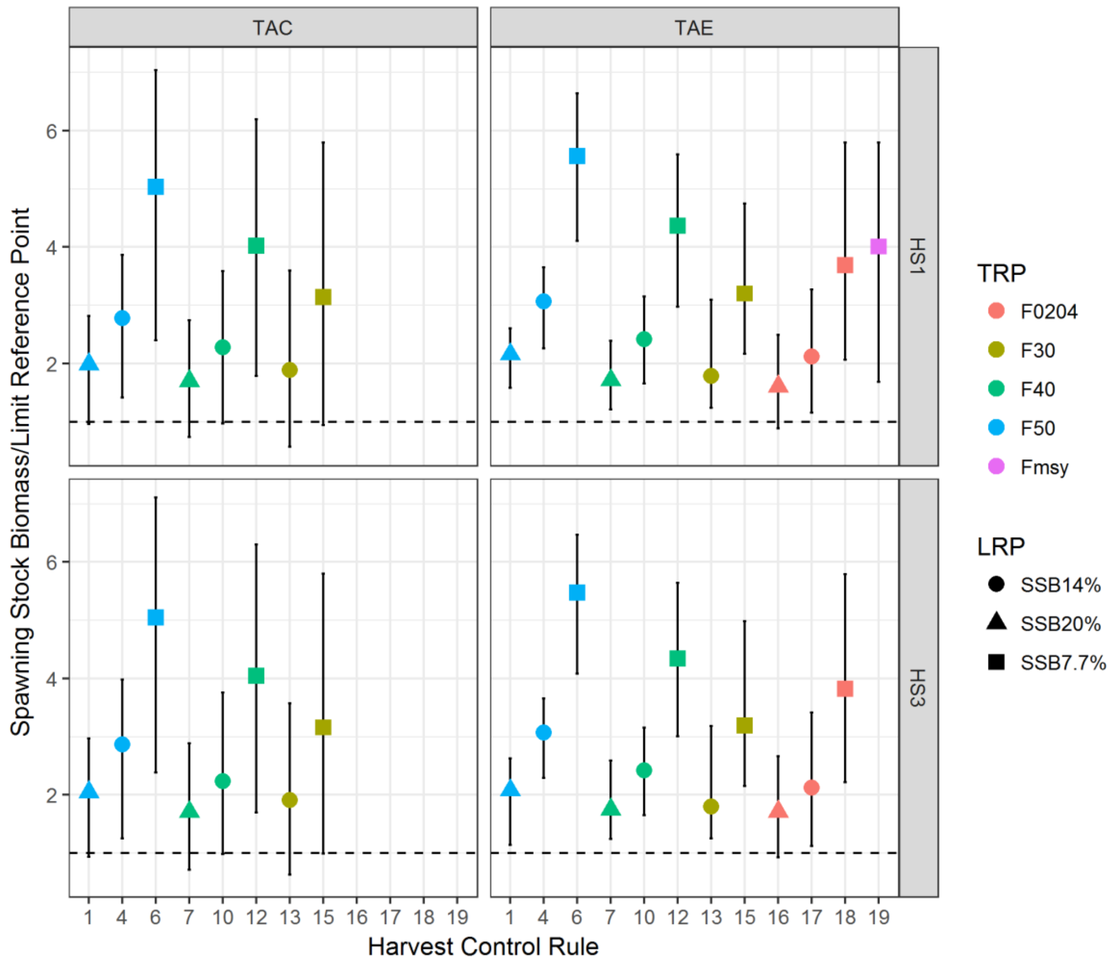

Figure 13. Median and 5th and 95th quantiles of the ratio of female spawning stock biomass (SSB) over the limit reference point (LRP) for the 30-year simulation across all runs and reference scenarios for all the harvest strategies (HS) and harvest control rules (HCRs) tested. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

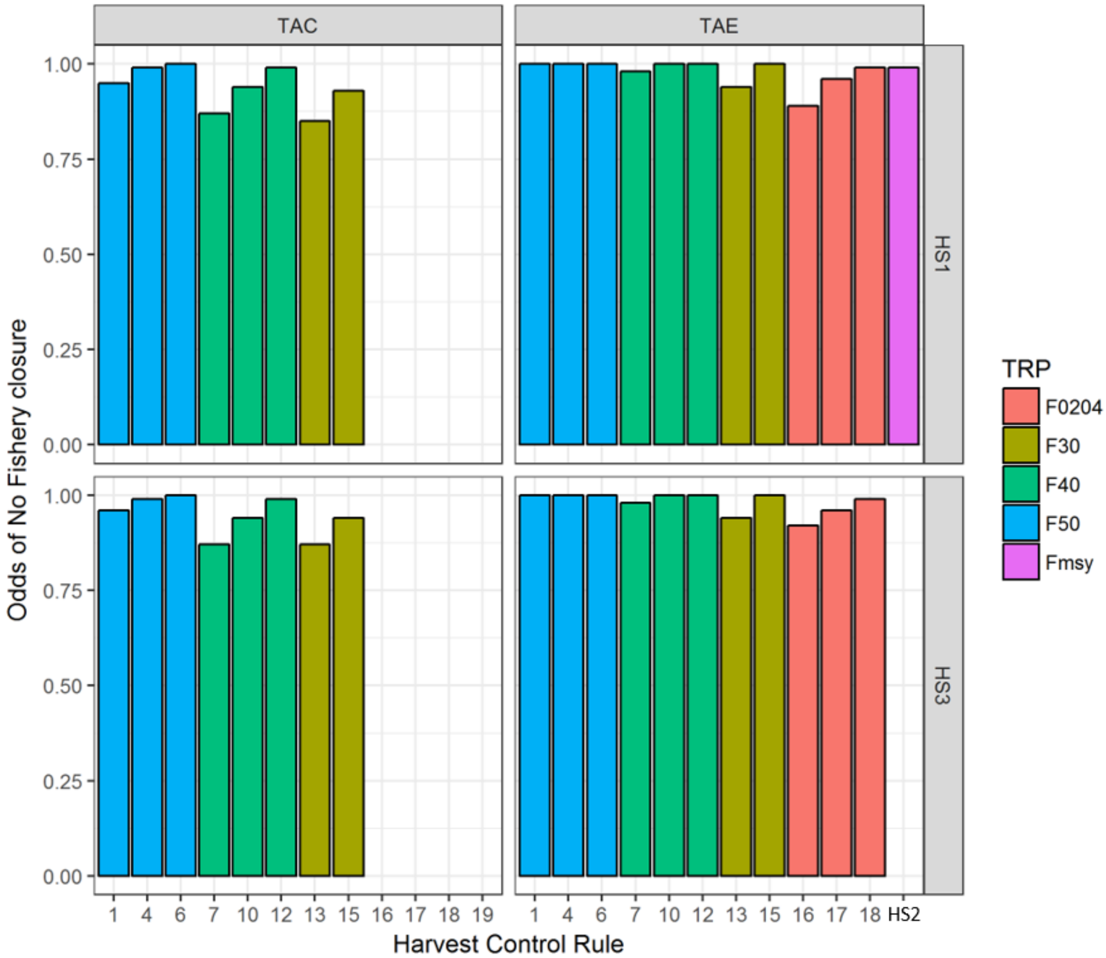

Figure 14. Plot of performance metric 1, the probability in any given year of the simulation of spawning stock biomass (SSB) being greater than the limit reference point (LRP), for all the harvest strategies (HS) and harvest control rules (HCRs) across all reference scenarios. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

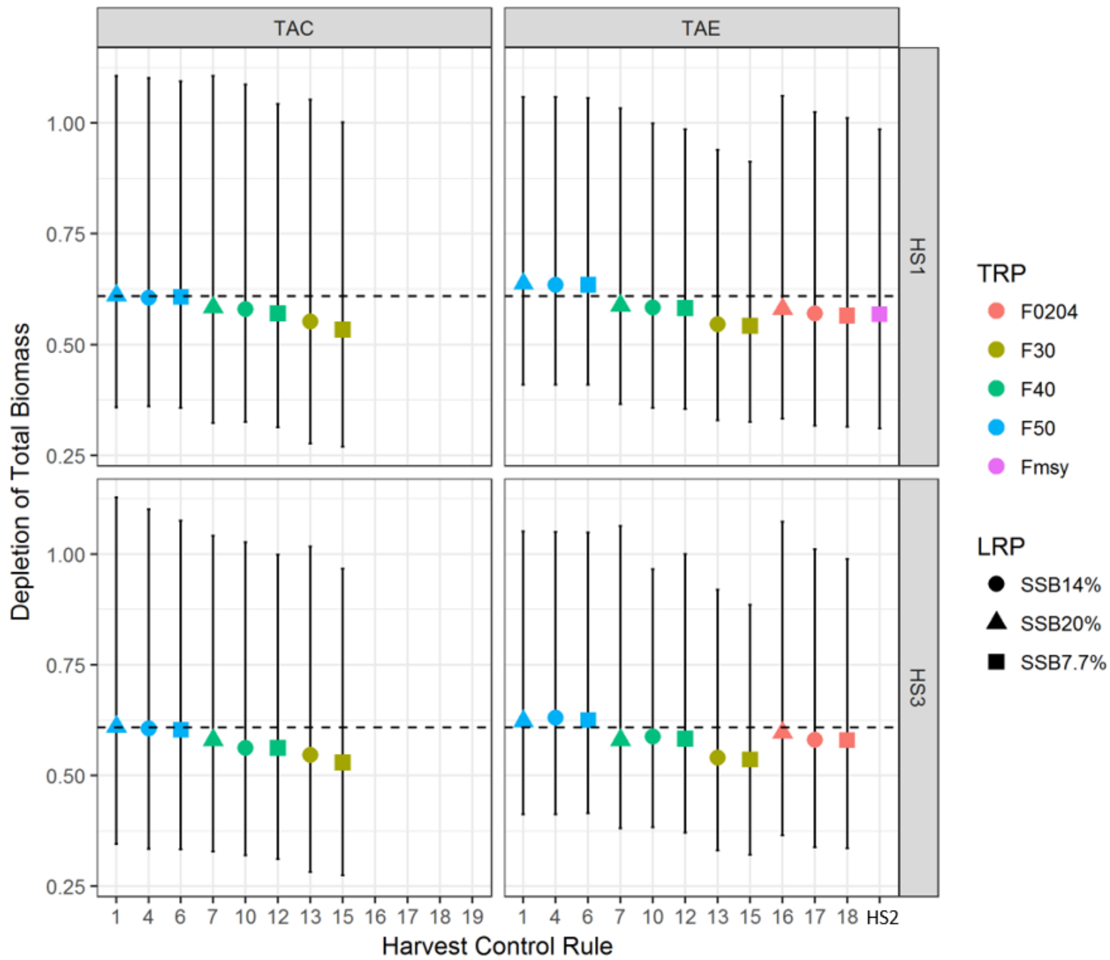

Figure 15. Median and 5th and 95th quantiles of total biomass depletion (total biomass as fraction of unfished) for the 30-year simulation across all runs and reference scenarios for all the harvest strategies (HS) and harvest control rules (HCRs) tested. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

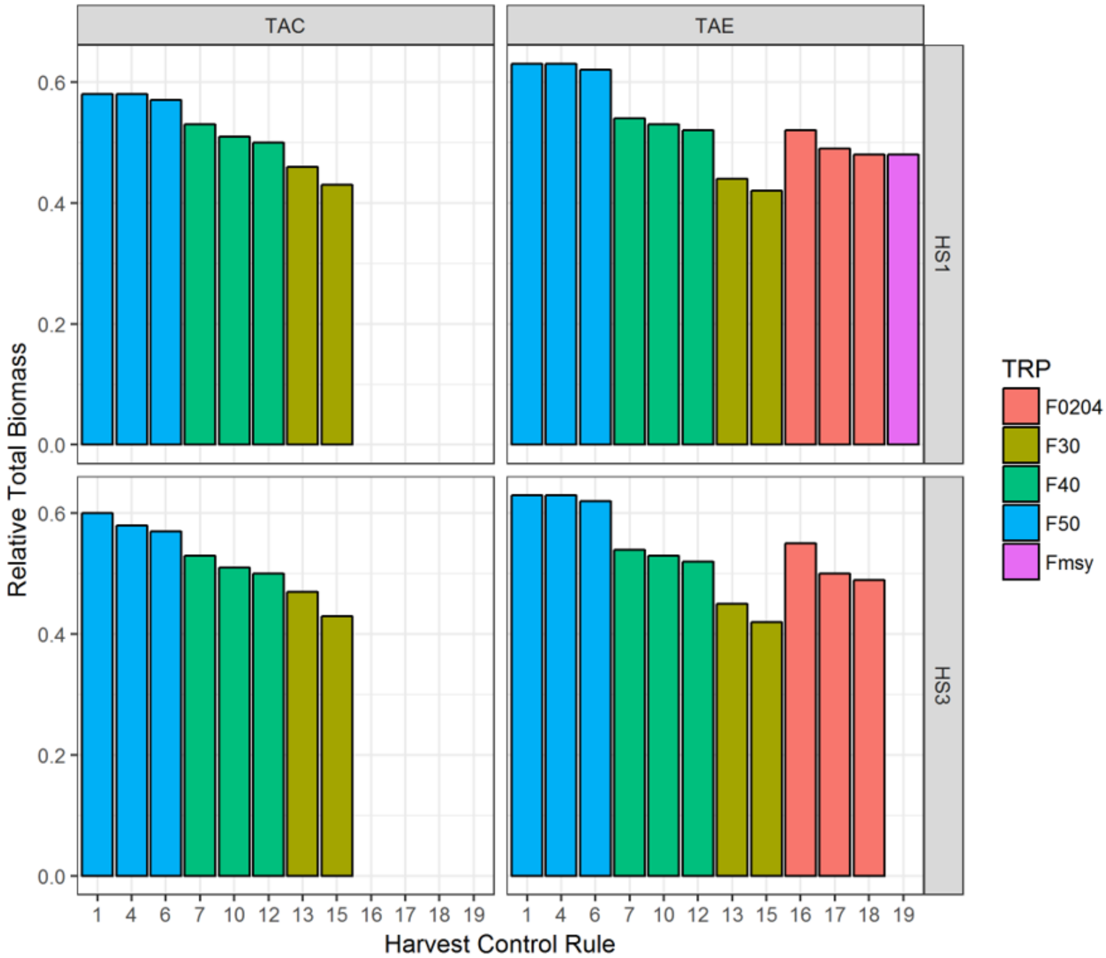

Figure 16. Plot of performance metric 2, relative total biomass, defined as the probability in any given year of the simulation of total biomass depletion being greater than historical (2006-2015) total biomass depletion, for all the harvest strategies (HS) and harvest control rules (HCRs) across all reference scenarios. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

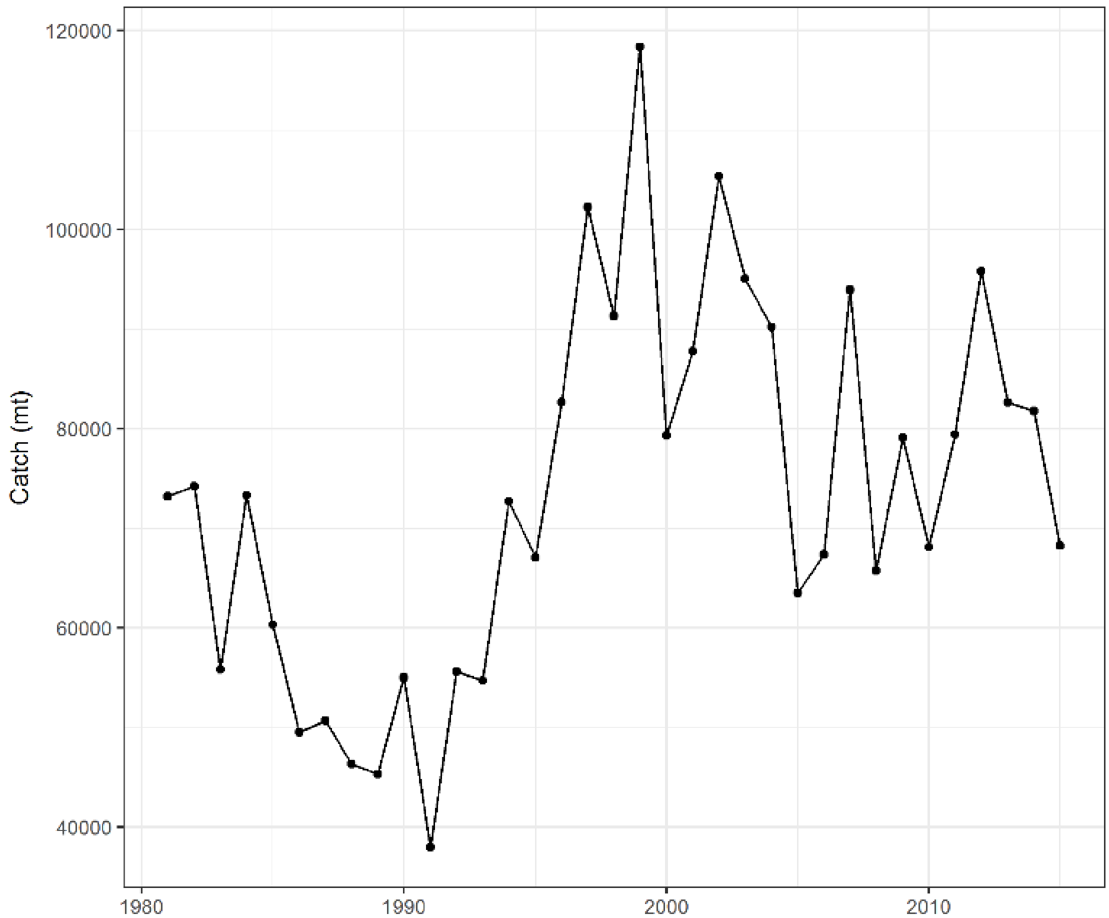

Figure 17. Trends in total NPALB catch from 1981-2015.

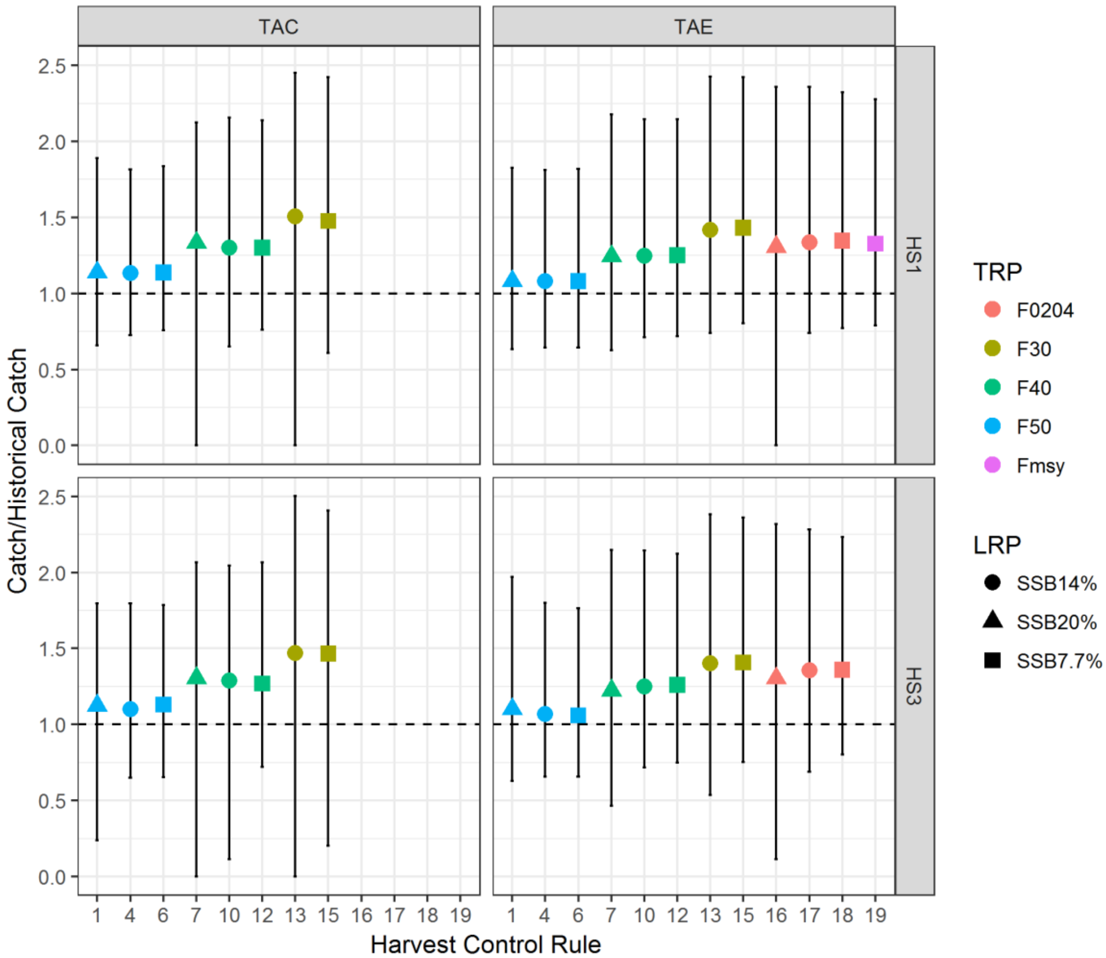

Figure 18. Median and 5th and 95th quantiles of the ratio of catch in any given year of the simulation over historical (1981-2010) catch for the 30-year simulation across all runs and reference scenarios for all the harvest strategies (HS) and harvest control rules (HCRs). Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

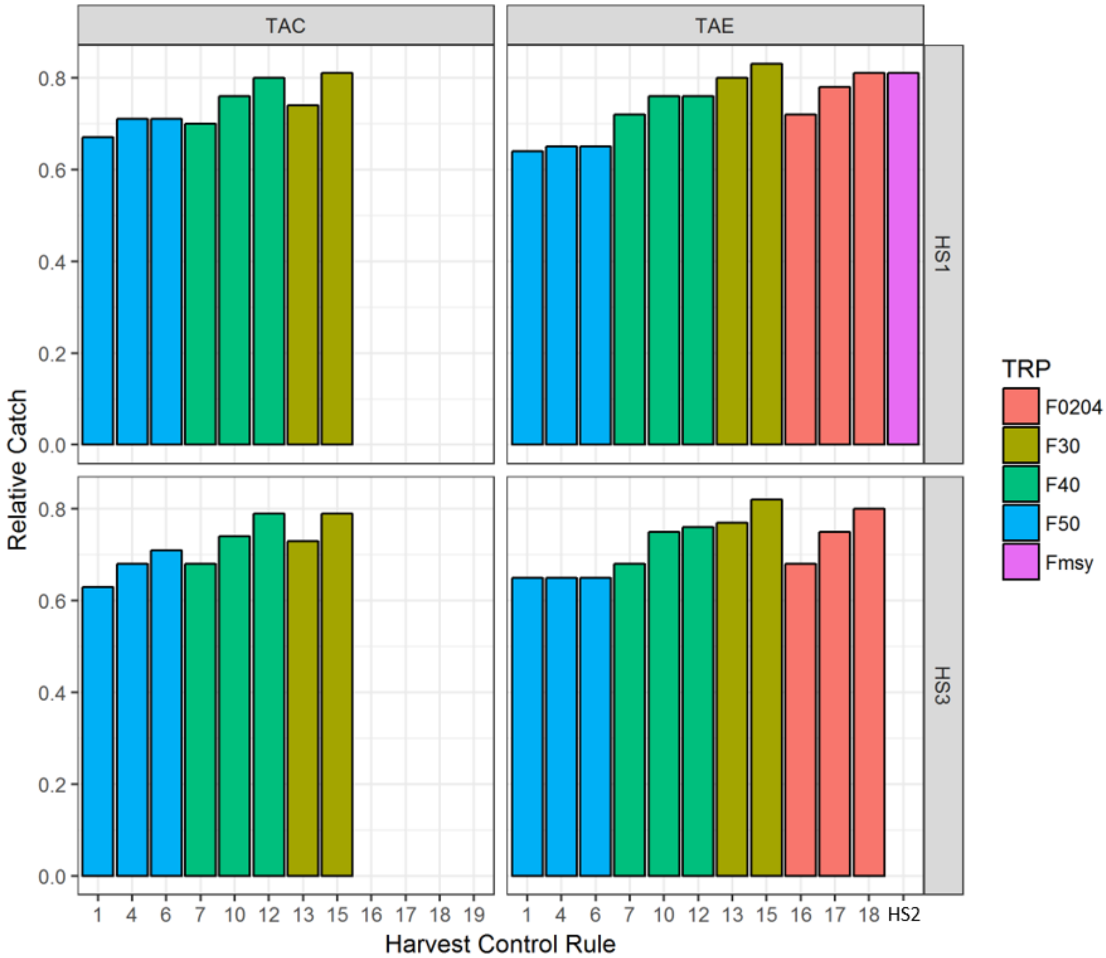

Figure 19. Plot of performance metric 4, relative catch, defined as the probability in any given year of the simulation of catch being greater than historical (1981-2010) catch, for all the harvest strategies (HS) and harvest control rules (HCRs) across all reference scenarios. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

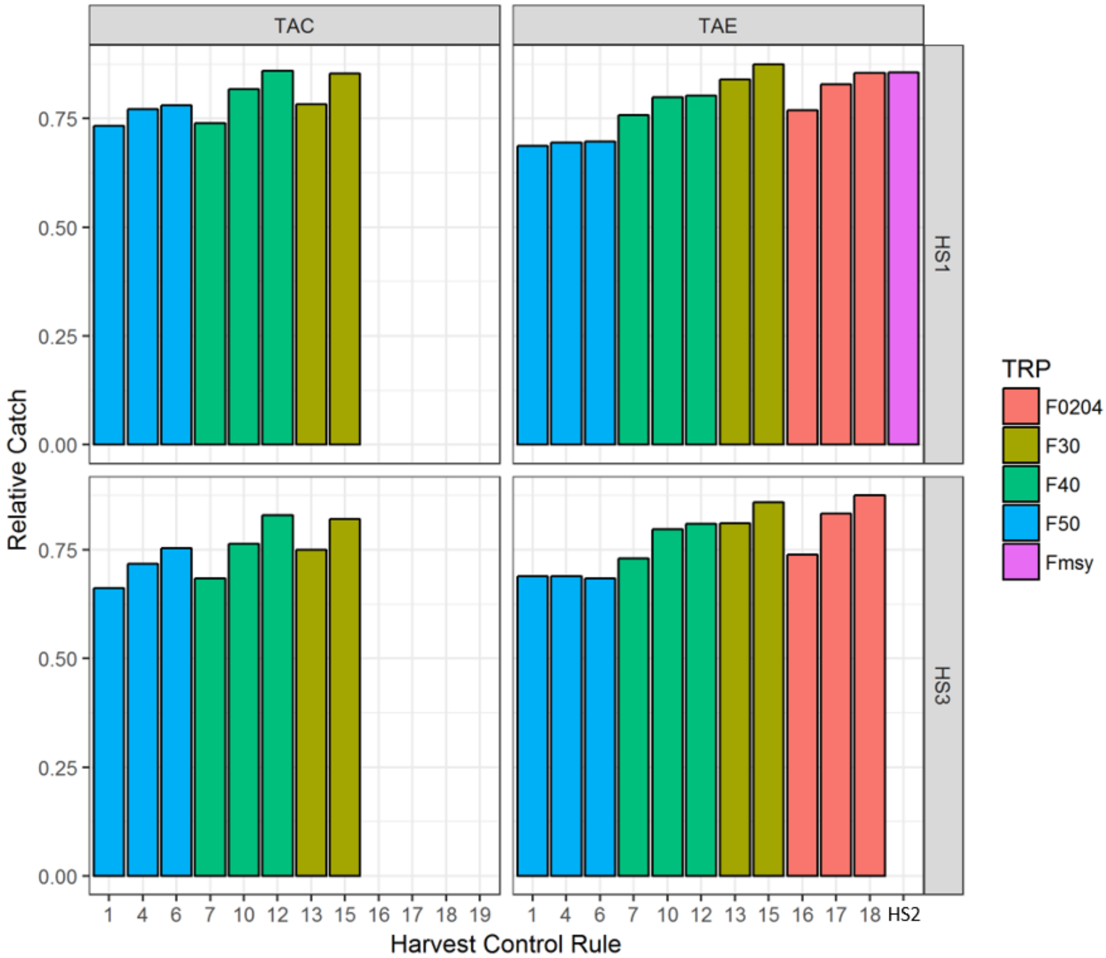

Figure 20. Plot of performance metric 4, relative catch, defined as the probability in any given year of the simulation of catch of the Japanese pole-and-line fisheries being greater than historical (1981-2010) Japanese pole-and-line catch, for all the harvest strategies (HS) and harvest control rules (HCRs) across all reference scenarios. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

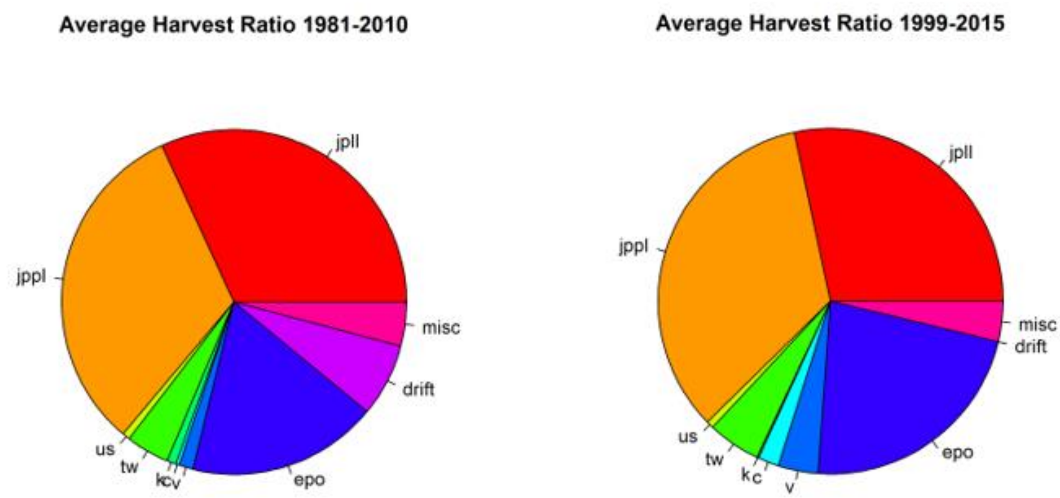

Figure 21. Catch ratios by fishery averaged over 1981-2000 (left panel) and 1999-2015 (right panel). DRIFT refers to the driftnet fishery, EPO to the Canadian and US surface fleet operating in the Eastern Pacific Ocean, V to the Vanuatu longline fleet, C to the Chinese longline fleet, K to the Korean 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.

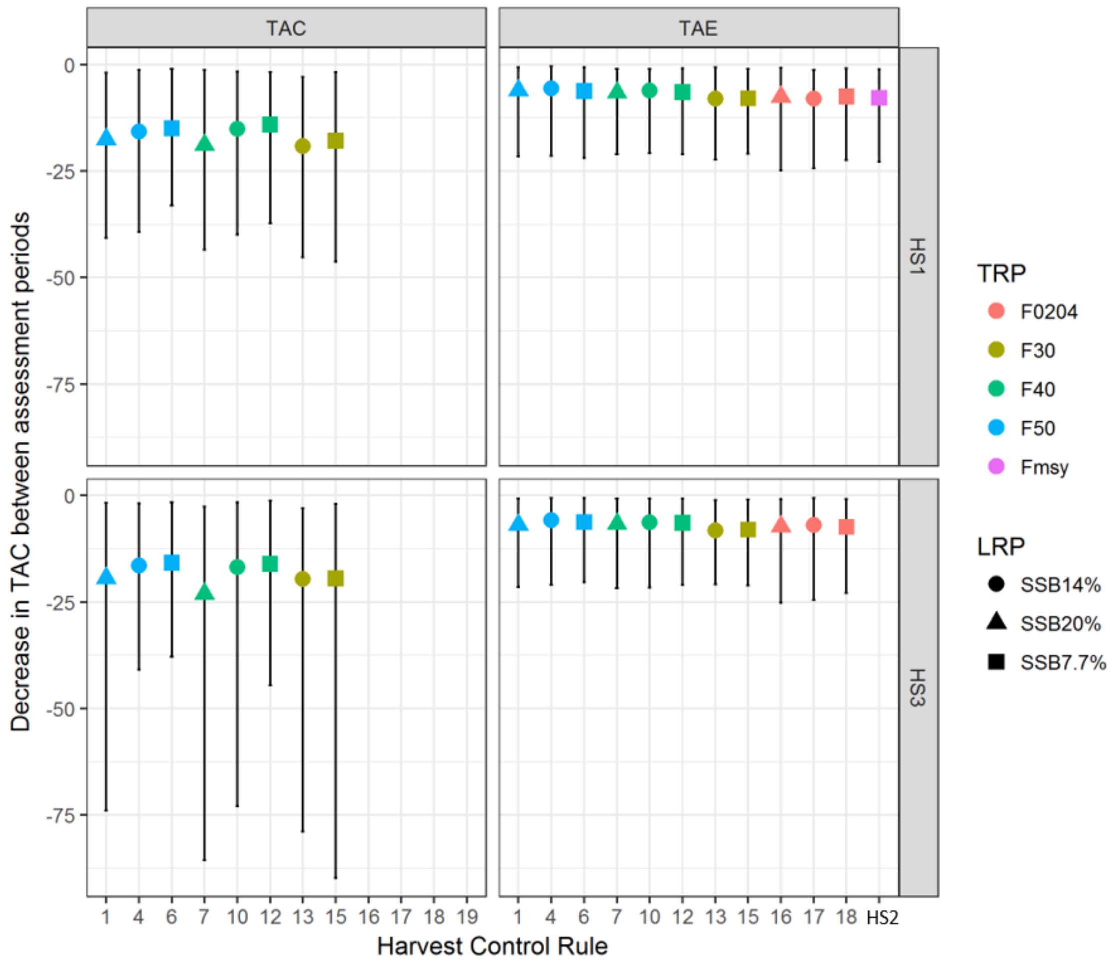

Figure 22. Median and 5th and 95th quantiles of the decrease in TAC (or catch for TAE rules) between assessment periods excluding years where TAC=0 for the 30-year simulation across all runs and reference scenarios for all the harvest strategies (HS) and harvest control rules (HCRs) across all reference scenarios. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

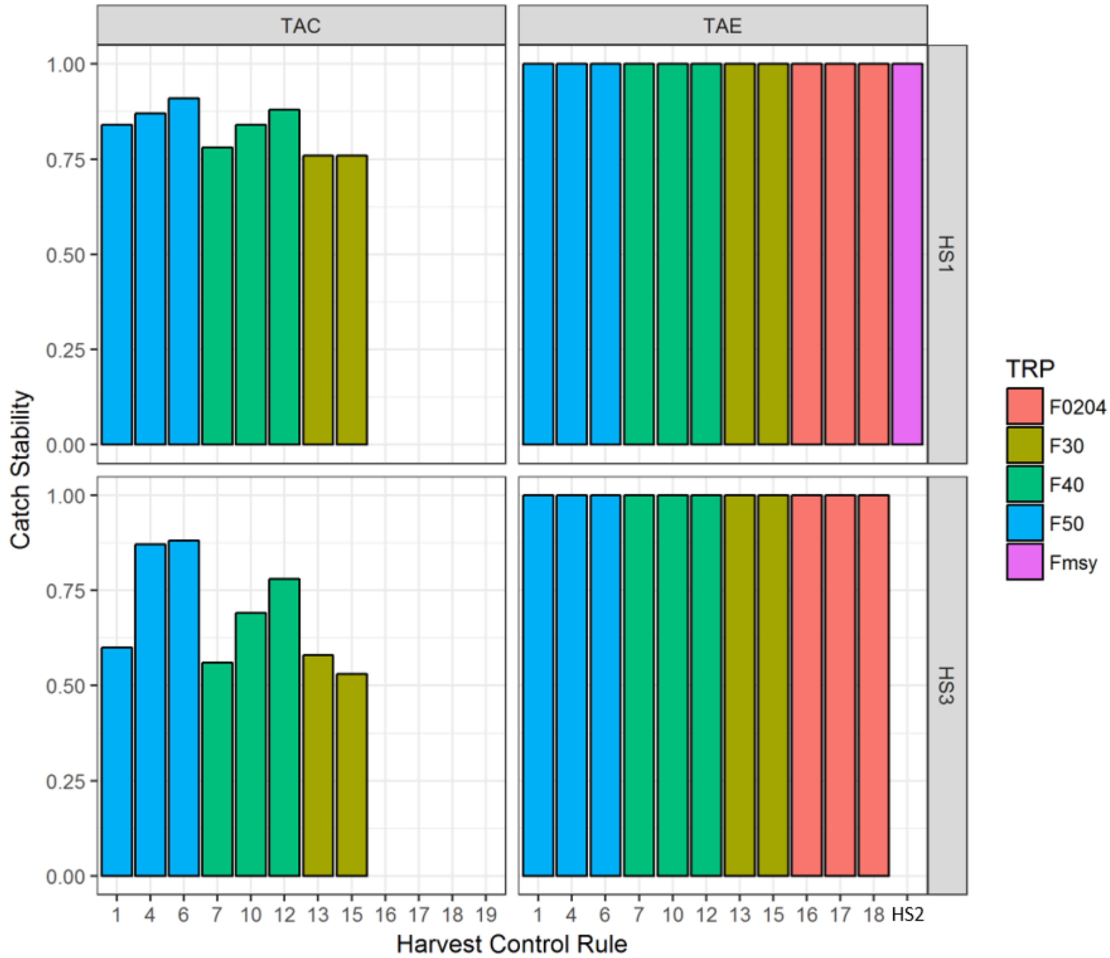

Figure 23. Plot of performance metric 5, catch stability, defined as the probability of a decrease in TAC (or catch for TAE rules) between assessment periods excluding years where TAC or TAE =0 being <30%, for all the harvest strategies (HS) and harvest control rules (HCRs) across all reference scenarios. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

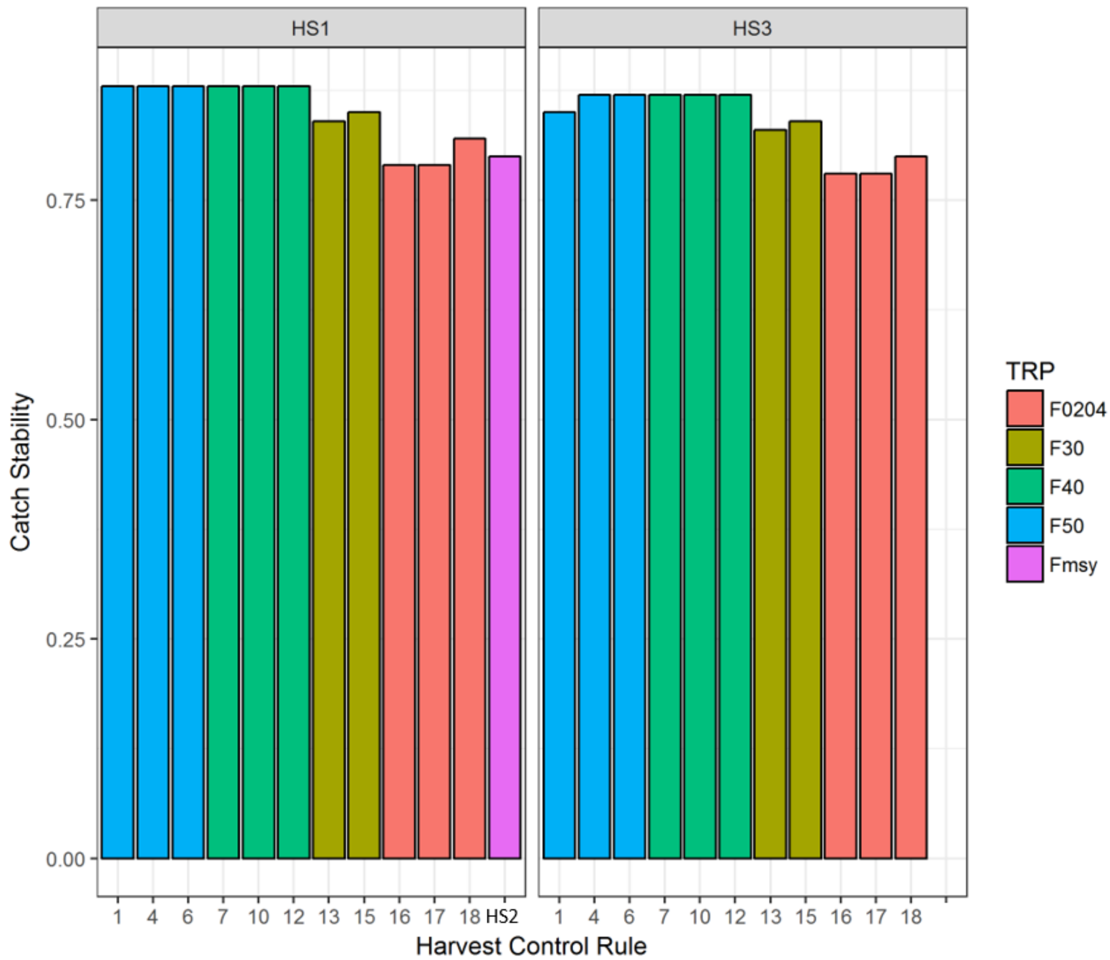

Figure 24. Plot of catch stability defined as the probability of a decrease in catch between assessment periods excluding years where catch=0 being <15%, for all the harvest strategies (HS) and harvest control rules (HCRs) with TAE output control across all reference scenarios. Left panels shows results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

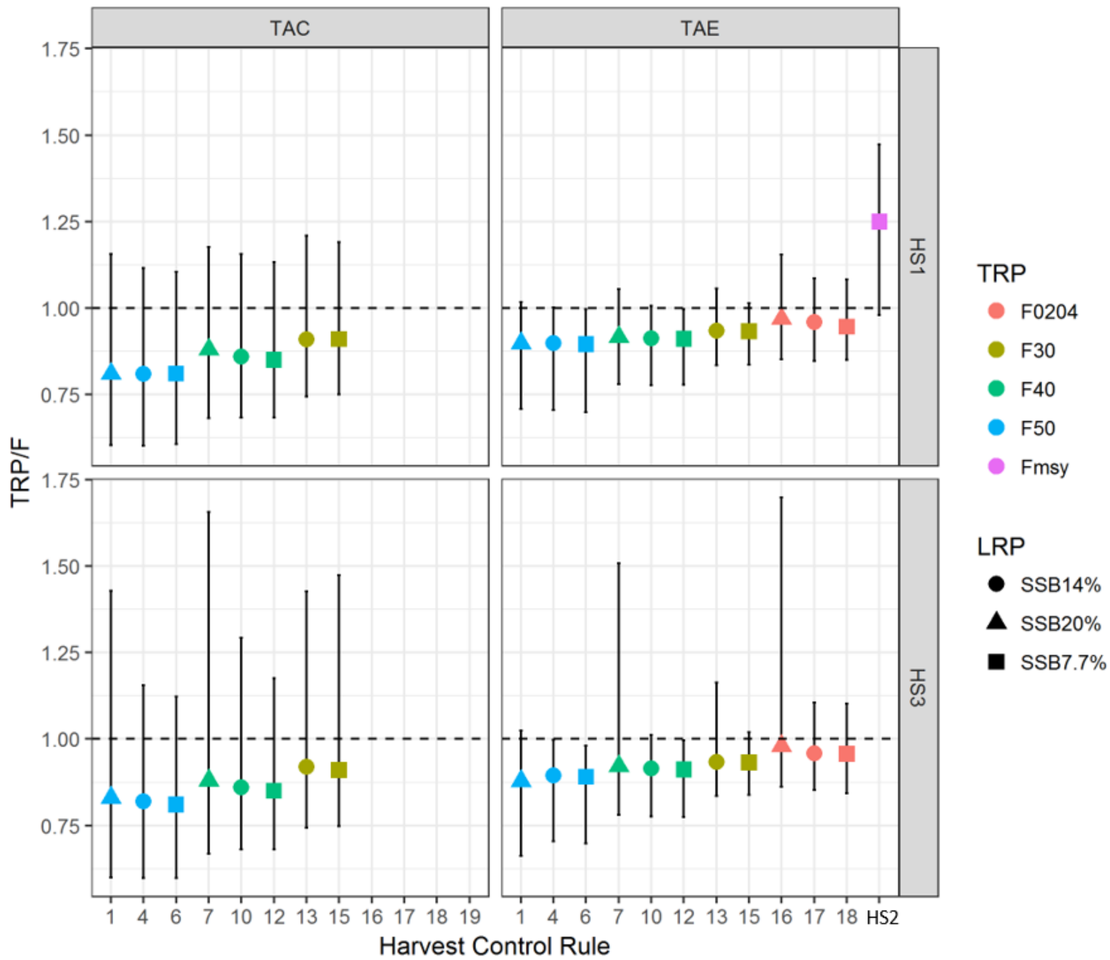

Figure 25. Median and 5th and 95th quantiles of the PM6, the ratio of the target reference point (TRP) to the fishing intensity (F) in any given year of the 30-year simulation across all reference scenarios for all the harvest strategies (HS) and harvest control rules (HCRs) tested. F and TRP are based 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. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

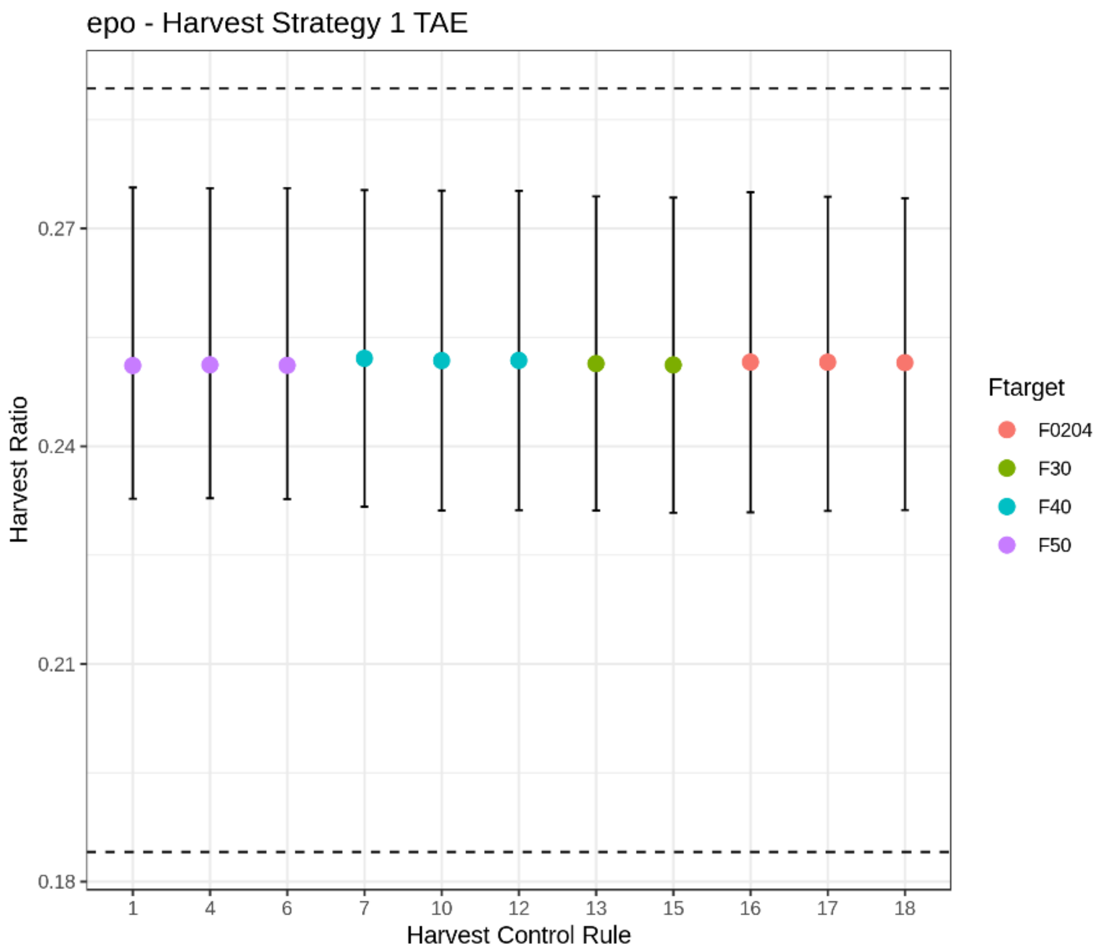

Figure 26. Median and 5th and 95th quantiles of the harvest ratio for the EPO fleet for the 30 year simulation across all reference scenarios for harvest strategies 1 TAE. The dotted lines represent the maximum and minimum harvest ratio for this fleet for the period of 2006-2010.

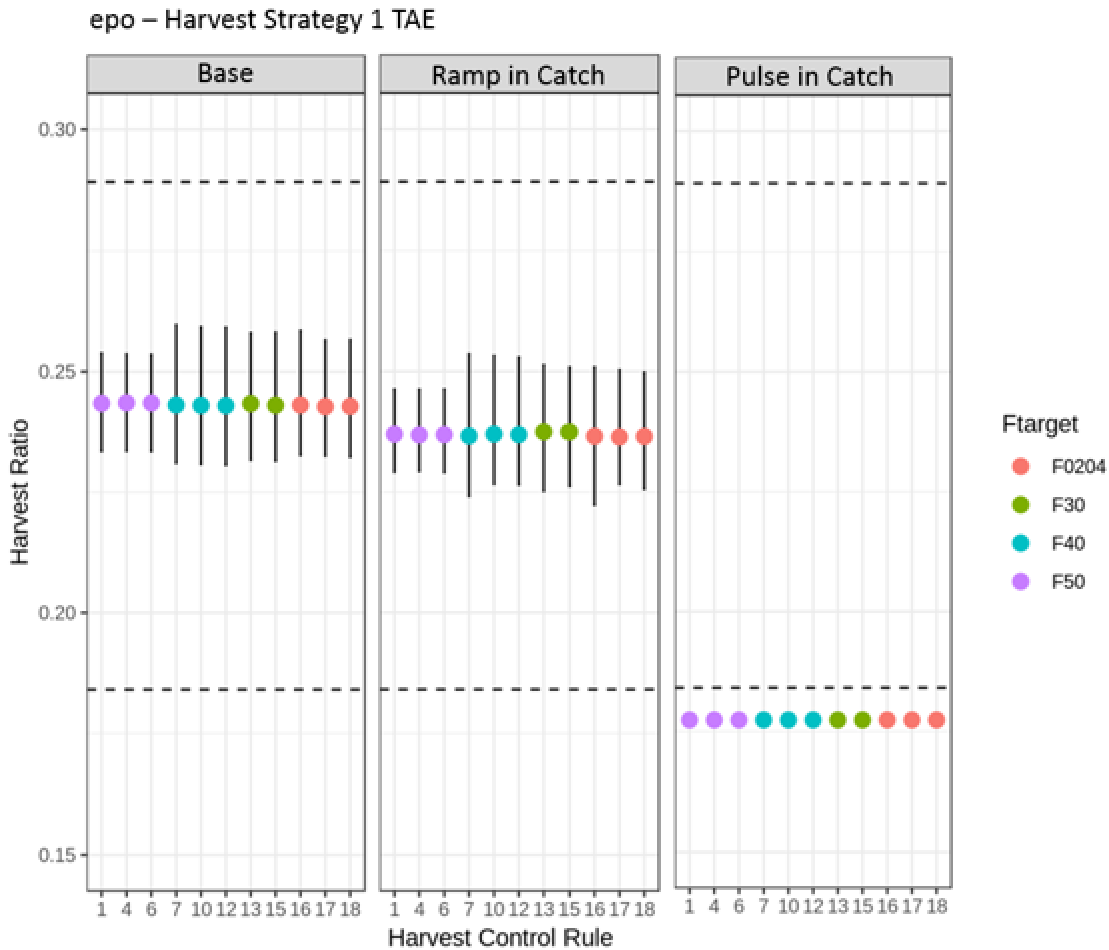

Figure 27. Median and 5th and 95th quantiles of the harvest ratio for the EPO fleet for the 30 year simulation across the base case (scenario 1) and the ramp in catch and pulse in catch scenarios for harvest strategies 1 TAE. The dotted lines represent the maximum and minimum harvest ratio for this fleet for the period of 2006-2010. For the pulse in catch scenario, only data from the first time step of the simulation when the pulse occurred is shown.

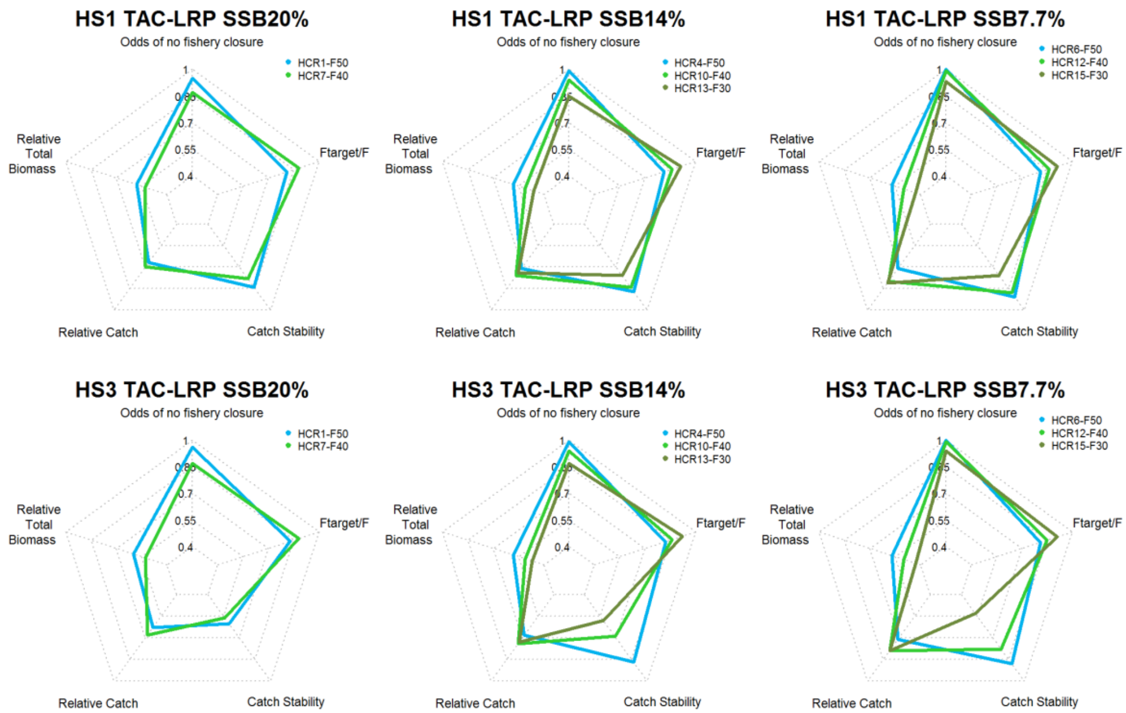

Figure 28. Cobweb plot depicting performance indicators for TAC-based HCRs for HS1 and HS3 grouped by LRP for all runs and reference scenarios. Values close to the outer web signify a more positive outcome for that performance indicator. *Relative catch* is defined as the odds of catch in any given year of the MSE forward simulation being above average historical (1981-2010) catch. *Relative total biomass* is defined as the odds of depletion in any given year of the MSE forward simulation being above minimum historical (2006-2015) depletion. *Odds of no fishery closure* is the probability that SSB in any given year of the MSE forward simulation is above the LRP. *Catch stability* is defined as the probability that a decrease in TAC is <15% between consecutive assessment periods (once every 3 years), excluding years where TAC=0. *Ftarget/F* is the ratio of the F specified by the TRP to the actual fishing intensity in the operating model (OM).

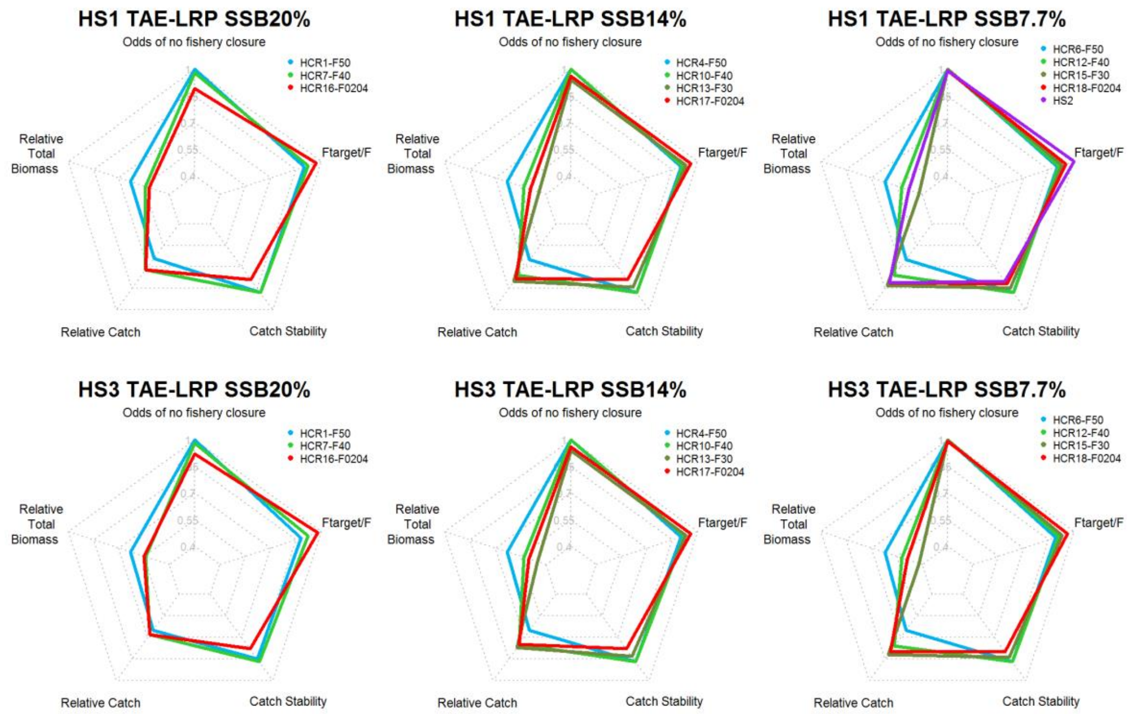

Figure 29. Cobweb plot depicting performance indicators for TAE-based harvest control rules (HCRs) for all harvest strategies, grouped by LRP, for all runs and reference scenarios. Values close to the outer web signify a more positive outcome for that performance indicator. Note that because catch variability between consecutive assessment periods was rarely greater than 30% for all TAE-based rules, to better contrast HCRs here catch stability is defined as the probability that a decrease in catch between consecutive assessment periods is <15%. *Relative catch* is defined as the odds of catch in any given year of the MSE forward simulation being above average historical (1981-2010) catch. *Relative total biomass* is defined as the odds of depletion in any given year of the MSE forward simulation being above minimum historical (2006-2015) depletion. *Odds of no fishery closure* is the probability that SSB in any given year of the MSE forward simulation is above the LRP. *Catch stability* is defined as the probability that a decrease in TAC is <15% between consecutive assessment periods (once every 3 years), excluding years where TAC=0. *Ftarget/F* is the ratio of the F specified by the TRP to the actual fishing intensity in the operating model (OM). *Ftarget/F* was greater than 1 for HS2, but is reported here as 1.

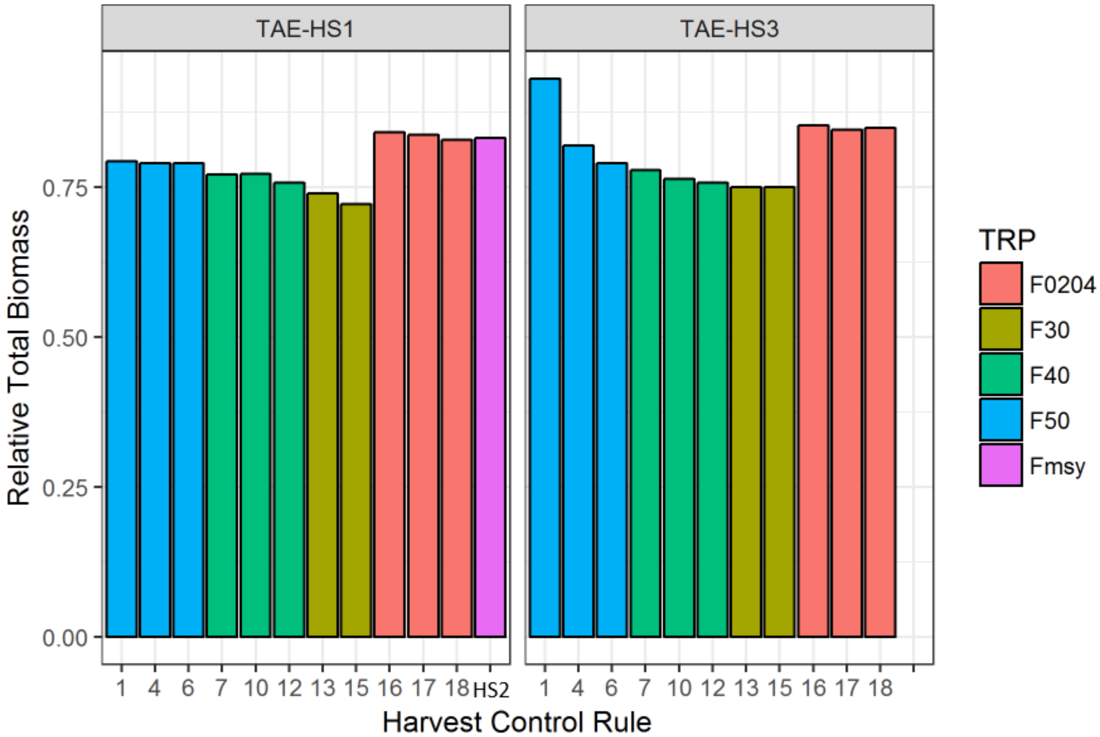

Figure 30. Plot of performance metric 2, relative total biomass, defined as the probability in any given year of the simulation of total biomass depletion being greater than historical (2006-2015) total biomass depletion, for all the harvest strategies (HS) and harvest control rules (HCRs) with TAE control for scenario 7. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

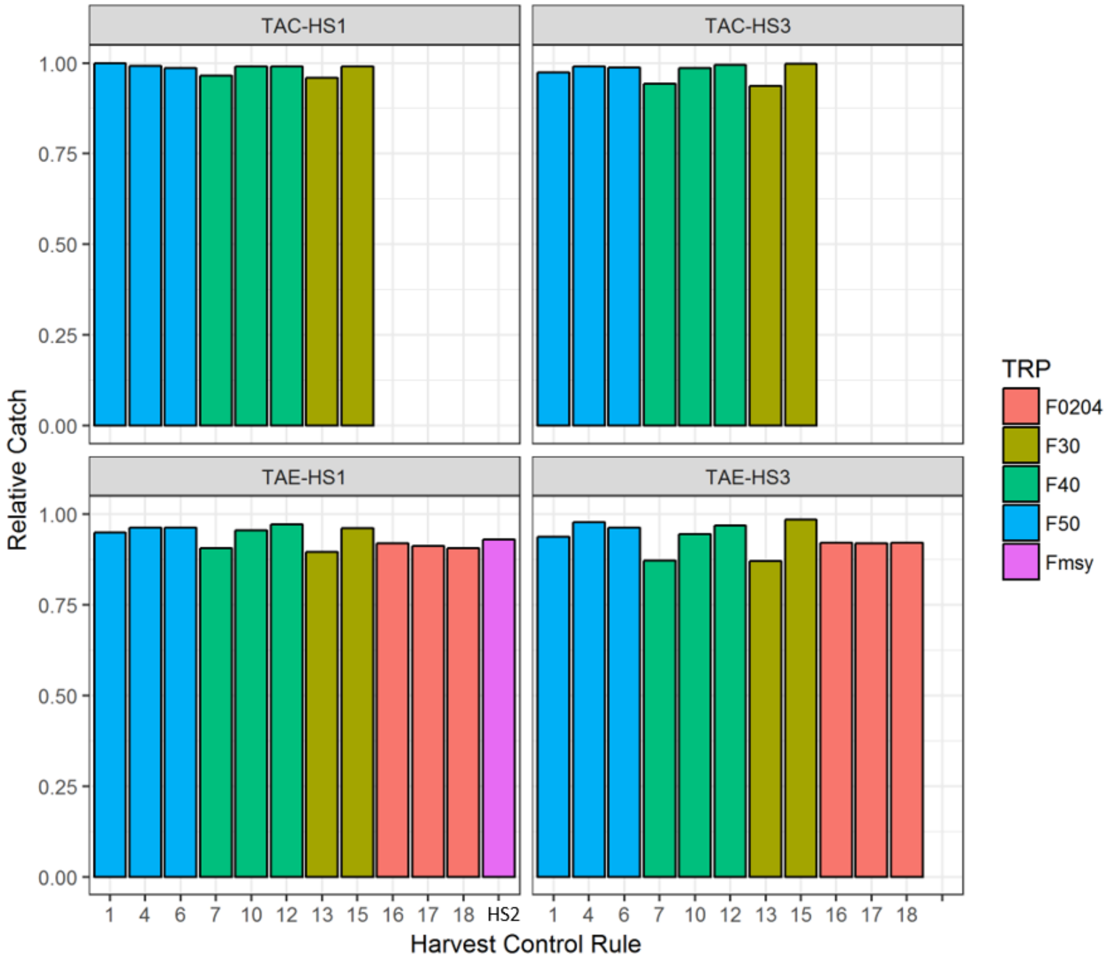

Figure 31. Plot of performance metric 4, relative catch, defined as the probability in any given year of the simulation of catch being greater than historical (1981-2010) catch, for all the harvest strategies (HS) and harvest control rules (HCRs) across scenario 7. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

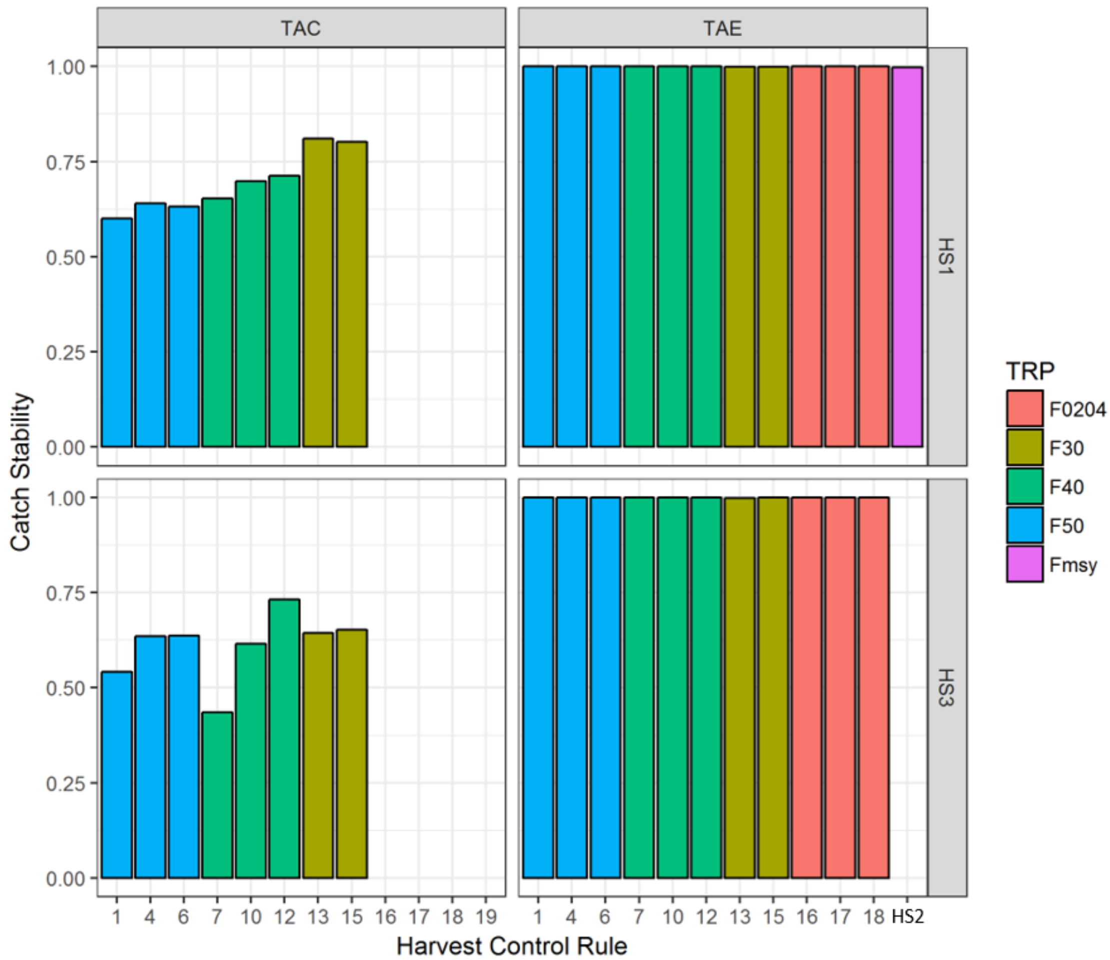

Figure 32. Plot of performance metric 5, catch stability, defined as the probability of a decrease in TAC (or catch for TAE rules) between assessment periods excluding years where TAC or TAE =0 being <30%, for all the harvest strategies (HS) and harvest control rules (HCRs) across the fishing effort scenario with an initial pulse in catch. Left panels shows results for HCRs with TAC as output control, while the right panels for TAE control. Top panels show results for HS1 and bottom panels for HS3. Note that for ease of comparison results of HS2, which only has one HCR, are plotted together with HS1.

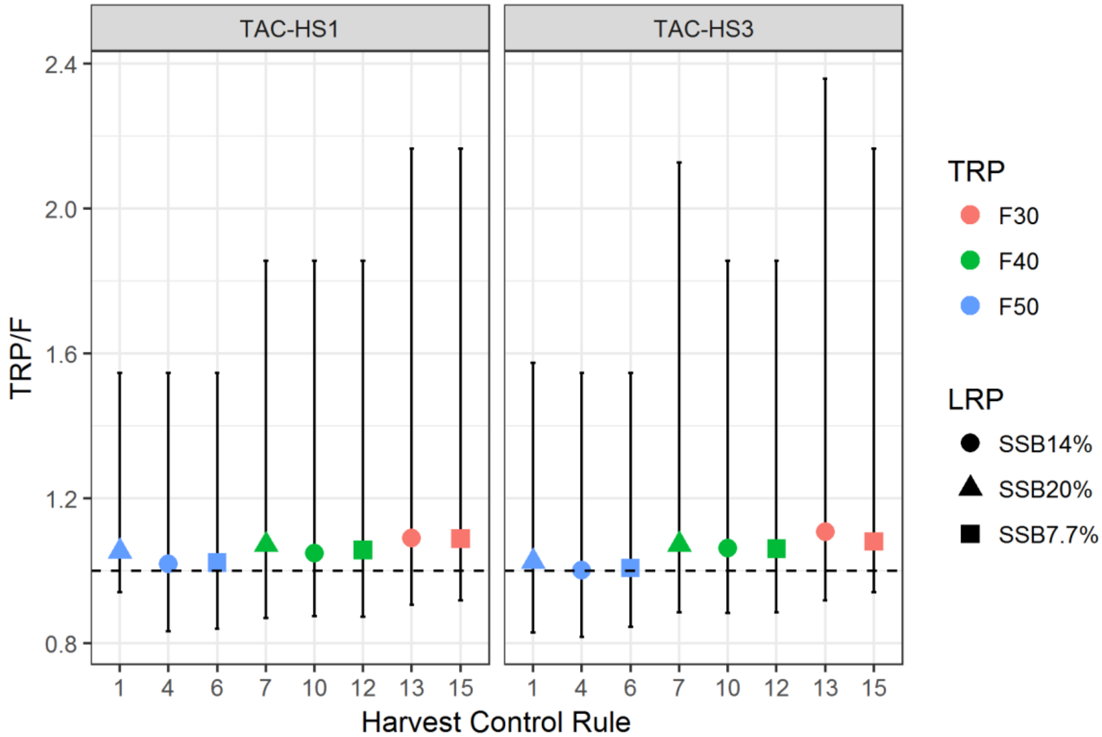

Figure 33. Median and 5th and 95th quantiles of PM6, the ratio of the target reference point (TRP) to the fishing intensity (F) in any given year of the 30-year simulation across scenario 7 for all the TAC-control harvest strategies (HS) and harvest control rules (HCRs) tested. F and TRP are based on 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.

14. APPENDIX

Table A1. Performance of indicators relative to management objective 1 for each harvest strategy and harvest control rule across all iterations for each uncertainty scenario and the two fishing effort scenarios (pulse and ramp). HS refers to harvest strategy, HCR to harvest control rule, SCN to scenario, SSB to female spawning biomass, LRP to limit reference point, p29 to the % of runs in which ratio of SSB/LRP is ≥1 for 29 out of the 30 years of simulation, p27 to the % of runs in which ratio of SSB/LRP is ≥1 for 27 out of the 30 years of simulation, p24 to the % of runs in which ratio of SSB/LRP is ≥1 for 24 out of the 30 years of simulation, PM1 refers to performance metric 1, the probability that SSB is higher than the LRP in any given year of the simulation.

Control	HS	HCR	SCN	Median SSB over all years and runs	Median SSB/LRP over all years and runs	p29	p27	p24	PM1
TAC	HS1	1	1	6.7	2.2	100	100	100	1.00
TAC	HS1	1	3	7.1	2.5	100	100	100	1.00
TAC	HS1	1	4	4.7	1.8	92	100	100	0.97
TAC	HS1	1	6	4.3	1.3	0	0	29	0.76
TAC	HS1	1	7	9.8	2.7	100	100	100	1.00
TAC	HS1	1	pulse	6.1	2.2	100	100	100	1.00
TAC	HS1	1	ramp	6.5	2.2	100	100	100	1.00
TAC	HS1	4	1	6.7	3.2	100	100	100	1.00
TAC	HS1	4	3	7.1	3.5	100	100	100	1.00
TAC	HS1	4	4	4.6	2.5	100	100	100	1.00
TAC	HS1	4	6	4.4	1.9	79	93	100	0.93
TAC	HS1	4	7	10.5	3.8	100	100	100	1.00
TAC	HS1	4	pulse	5.9	3.0	100	100	100	1.00
TAC	HS1	4	ramp	6.3	3.1	100	100	100	1.00
TAC	HS1	6	1	6.6	5.7	100	100	100	1.00
TAC	HS1	6	3	7.1	6.4	100	100	100	1.00
TAC	HS1	6	4	4.6	4.6	100	100	100	1.00
TAC	HS1	6	6	4.0	3.0	93	100	100	0.98
TAC	HS1	6	7	10.4	6.8	100	100	100	1.00
TAC	HS1	6	pulse	6.1	5.5	100	100	100	1.00
TAC	HS1	6	ramp	6.4	5.5	100	100	100	1.00
TAC	HS1	7	1	5.8	1.9	90	100	100	0.98
TAC	HS1	7	3	7.0	2.2	100	100	100	1.00
TAC	HS1	7	4	4.2	1.6	25	71	100	0.88
TAC	HS1	7	6	3.7	1.0	0	0	0	0.65
TAC	HS1	7	7	9.3	2.3	98	100	100	0.99
TAC	HS1	7	pulse	5.4	1.8	92	100	100	0.98

TAC	HS1	7	ramp	5.4	1.8	100	100	100	1.00
TAC	HS1	10	1	5.6	2.7	100	100	100	1.00
TAC	HS1	10	3	6.9	2.9	100	100	100	1.00
TAC	HS1	10	4	3.9	2.1	67	96	100	0.95
TAC	HS1	10	6	3.4	1.4	7	36	57	0.78
TAC	HS1	10	7	9.1	3.2	100	100	100	1.00
TAC	HS1	10	pulse	5.2	2.5	97	100	100	1.00
TAC	HS1	10	ramp	5.4	2.5	100	100	100	1.00
TAC	HS1	12	1	5.6	4.7	100	100	100	1.00
TAC	HS1	12	3	6.8	5.3	100	100	100	1.00
TAC	HS1	12	4	3.9	3.8	100	100	100	0.99
TAC	HS1	12	6	3.4	2.6	50	86	100	0.93
TAC	HS1	12	7	9.1	5.8	100	100	100	1.00
TAC	HS1	12	pulse	5.0	4.4	100	100	100	1.00
TAC	HS1	12	ramp	5.4	4.6	100	100	100	1.00
TAC	HS1	13	1	4.9	2.2	70	90	100	0.94
TAC	HS1	13	3	5.2	2.6	100	100	100	0.99
TAC	HS1	13	4	3.6	1.9	13	42	92	0.85
TAC	HS1	13	6	2.9	1.2	0	0	0	0.65
TAC	HS1	13	7	7.6	2.8	90	100	100	0.97
TAC	HS1	13	pulse	4.4	2.1	61	92	100	0.94
TAC	HS1	13	ramp	4.3	1.9	100	100	100	0.97
TAC	HS1	15	1	4.6	3.6	95	100	100	0.99
TAC	HS1	15	3	4.9	4.2	100	100	100	1.00
TAC	HS1	15	4	3.5	3.1	63	96	100	0.94
TAC	HS1	15	6	2.7	1.9	0	7	71	0.83
TAC	HS1	15	7	11.0	4.9	100	100	100	0.99
TAC	HS1	15	pulse	3.5	3.6	98	100	100	0.99
TAC	HS1	15	ramp	5.1	3.5	97	100	100	0.99
TAC	HS3	1	1	6.7	2.2	100	100	100	1.00
TAC	HS3	1	3	7.8	2.5	100	100	100	1.00
TAC	HS3	1	4	4.8	1.9	100	100	100	0.97
TAC	HS3	1	6	4.6	1.4	0	0	0	0.77
TAC	HS3	1	7	10.3	2.6	100	100	100	1.00
TAC	HS3	1	pulse	6.3	2.2	100	100	100	1.00
TAC	HS3	1	ramp	6.6	2.2	100	100	100	1.00
TAC	HS3	4	1	6.7	3.2	100	100	100	1.00
TAC	HS3	4	3	7.7	3.5	100	100	100	1.00
TAC	HS3	4	4	4.6	2.6	100	100	100	0.99
TAC	HS3	4	6	4.0	1.7	36	64	93	0.86
TAC	HS3	4	7	9.9	3.7	100	100	100	1.00

TAC	HS3	4	pulse	6.1	3.1	100	100	100	1.00
TAC	HS3	4	ramp	6.2	3.0	100	100	100	1.00
TAC	HS3	6	1	6.6	5.7	100	100	100	1.00
TAC	HS3	6	3	7.7	6.5	100	100	100	1.00
TAC	HS3	6	4	4.6	4.5	100	100	100	1.00
TAC	HS3	6	6	4.2	3.2	86	100	100	0.97
TAC	HS3	6	7	10.0	6.7	100	100	100	1.00
TAC	HS3	6	pulse	6.1	5.5	100	100	100	1.00
TAC	HS3	6	ramp	6.5	5.6	100	100	100	1.00
TAC	HS3	7	1	5.7	2.0	95	100	100	0.98
TAC	HS3	7	3	7.3	2.4	100	100	100	0.99
TAC	HS3	7	4	4.3	1.6	29	67	100	0.89
TAC	HS3	7	6	3.5	1.0	0	0	0	0.64
TAC	HS3	7	7	9.4	2.4	96	100	100	0.99
TAC	HS3	7	pulse	5.5	1.9	95	100	100	0.98
TAC	HS3	7	ramp	5.8	1.9	100	100	100	0.99
TAC	HS3	10	1	5.4	2.6	100	100	100	1.00
TAC	HS3	10	3	7.0	3.1	100	100	100	1.00
TAC	HS3	10	4	4.0	2.2	71	96	100	0.94
TAC	HS3	10	6	3.3	1.3	0	21	57	0.76
TAC	HS3	10	7	9.2	3.2	100	100	100	1.00
TAC	HS3	10	pulse	5.3	2.5	100	100	100	1.00
TAC	HS3	10	ramp	5.5	2.6	100	100	100	1.00
TAC	HS3	12	1	5.3	4.7	100	100	100	1.00
TAC	HS3	12	3	7.0	5.5	100	100	100	1.00
TAC	HS3	12	4	3.9	4.0	96	100	100	0.99
TAC	HS3	12	6	3.2	2.5	57	86	100	0.93
TAC	HS3	12	7	9.0	5.8	100	100	100	1.00
TAC	HS3	12	pulse	5.0	4.4	100	100	100	1.00
TAC	HS3	12	ramp	5.4	4.6	100	100	100	1.00
TAC	HS3	13	1	5.1	2.2	60	95	100	0.95
TAC	HS3	13	3	5.2	2.5	80	100	100	0.99
TAC	HS3	13	4	3.5	1.9	0	42	92	0.86
TAC	HS3	13	6	3.1	1.3	7	7	14	0.69
TAC	HS3	13	7	8.1	2.9	95	100	100	0.97
TAC	HS3	13	pulse	4.4	2.1	63	97	100	0.94
TAC	HS3	13	ramp	4.5	2.1	100	100	100	0.96
TAC	HS3	15	1	4.7	3.7	100	100	100	0.99
TAC	HS3	15	3	5.0	4.3	100	100	100	0.99
TAC	HS3	15	4	3.3	3.1	58	96	100	0.94
TAC	HS3	15	6	2.8	2.1	0	21	86	0.86

TAC	HS3	15	7	7.0	4.7	100	100	100	0.99
TAC	HS3	15	pulse	4.4	3.6	100	100	100	0.99
TAC	HS3	15	ramp	4.3	3.5	100	100	100	0.98
TAE	HS1	1	1	6.8	2.2	100	100	100	1.00
TAE	HS1	1	3	7.6	2.5	100	100	100	1.00
TAE	HS1	1	4	5.4	2.1	100	100	100	1.00
TAE	HS1	1	6	6.3	1.9	100	100	100	0.99
TAE	HS1	1	7	8.9	2.3	100	100	100	1.00
TAE	HS1	1	pulse	6.4	2.2	100	100	100	1.00
TAE	HS1	1	ramp	6.7	2.2	100	100	100	1.00
TAE	HS1	4	1	6.8	3.2	100	100	100	1.00
TAE	HS1	4	3	7.4	3.5	100	100	100	1.00
TAE	HS1	4	4	5.4	3.0	100	100	100	1.00
TAE	HS1	4	6	6.3	2.7	100	100	100	1.00
TAE	HS1	4	7	8.8	3.3	100	100	100	1.00
TAE	HS1	4	pulse	6.3	3.1	100	100	100	1.00
TAE	HS1	4	ramp	6.5	3.1	100	100	100	1.00
TAE	HS1	6	1	6.8	5.8	100	100	100	1.00
TAE	HS1	6	3	7.5	6.5	100	100	100	1.00
TAE	HS1	6	4	5.3	5.4	100	100	100	1.00
TAE	HS1	6	6	6.3	4.9	100	100	100	1.00
TAE	HS1	6	7	8.7	6.0	100	100	100	1.00
TAE	HS1	6	pulse	6.3	5.7	100	100	100	1.00
TAE	HS1	6	ramp	6.5	5.7	100	100	100	1.00
TAE	HS1	7	1	5.7	1.8	100	100	100	1.00
TAE	HS1	7	3	6.5	2.1	100	100	100	1.00
TAE	HS1	7	4	4.5	1.7	100	100	100	0.98
TAE	HS1	7	6	5.0	1.5	79	100	100	0.95
TAE	HS1	7	7	7.8	2.0	100	100	100	0.97
TAE	HS1	7	pulse	5.4	1.8	100	100	100	1.00
TAE	HS1	7	ramp	5.4	1.8	100	100	100	0.99
TAE	HS1	10	1	5.6	2.6	100	100	100	1.00
TAE	HS1	10	3	6.3	2.9	100	100	100	1.00
TAE	HS1	10	4	4.4	2.3	100	100	100	1.00
TAE	HS1	10	6	5.0	2.2	100	100	100	1.00
TAE	HS1	10	7	7.3	2.7	100	100	100	0.99
TAE	HS1	10	pulse	5.3	2.5	100	100	100	1.00
TAE	HS1	10	ramp	5.3	2.5	100	100	100	1.00
TAE	HS1	12	1	5.5	4.6	100	100	100	1.00
TAE	HS1	12	3	6.2	5.3	100	100	100	1.00
TAE	HS1	12	4	4.4	4.3	100	100	100	1.00

TAE	HS1	12	6	4.9	3.9	100	100	100	1.00
TAE	HS1	12	7	7.1	4.8	100	100	100	1.00
TAE	HS1	12	pulse	5.3	4.6	100	100	100	1.00
TAE	HS1	12	ramp	5.3	4.5	100	100	100	1.00
TAE	HS1	13	1	4.2	1.9	100	100	100	0.97
TAE	HS1	13	3	5.2	2.3	100	100	100	0.99
TAE	HS1	13	4	3.3	1.8	88	100	100	0.93
TAE	HS1	13	6	3.8	1.5	86	93	100	0.95
TAE	HS1	13	7	6.3	2.2	100	100	100	0.94
TAE	HS1	13	pulse	4.1	1.9	100	100	100	0.97
TAE	HS1	13	ramp	4.0	1.8	95	100	100	0.95
TAE	HS1	15	1	4.1	3.3	100	100	100	1.00
TAE	HS1	15	3	5.1	4.0	100	100	100	1.00
TAE	HS1	15	4	3.2	3.1	100	100	100	1.00
TAE	HS1	15	6	3.8	2.8	100	100	100	1.00
TAE	HS1	15	7	5.6	3.7	100	100	100	0.97
TAE	HS1	15	pulse	4.0	3.3	100	100	100	1.00
TAE	HS1	15	ramp	3.9	3.2	100	100	100	1.00
TAE	HS1	16	1	5.7	1.8	100	100	100	1.00
TAE	HS1	16	3	7.4	2.3	100	100	100	1.00
TAE	HS1	16	4	3.9	1.5	71	96	100	0.90
TAE	HS1	16	6	3.7	1.0	0	0	0	0.64
TAE	HS1	16	7	11.4	3.1	100	100	100	1.00
TAE	HS1	16	pulse	5.5	1.8	100	100	100	1.00
TAE	HS1	16	ramp	5.4	1.8	97	100	100	0.99
TAE	HS1	17	1	5.3	2.5	100	100	100	1.00
TAE	HS1	17	3	7.3	3.3	100	100	100	1.00
TAE	HS1	17	4	3.7	2.0	100	100	100	1.00
TAE	HS1	17	6	3.3	1.4	29	43	93	0.81
TAE	HS1	17	7	11.4	4.5	100	100	100	1.00
TAE	HS1	17	pulse	5.3	2.5	100	100	100	1.00
TAE	HS1	17	ramp	5.4	2.5	100	100	100	1.00
TAE	HS1	18	1	5.4	4.6	100	100	100	1.00
TAE	HS1	18	3	7.2	5.8	100	100	100	1.00
TAE	HS1	18	4	3.5	3.4	100	100	100	1.00
TAE	HS1	18	6	3.3	2.4	100	100	100	0.99
TAE	HS1	18	7	11.3	8.2	100	100	100	1.00
TAE	HS1	18	pulse	5.4	4.6	100	100	100	1.00
TAE	HS1	18	ramp	5.3	4.4	100	100	100	1.00
TAE	HS2	19	1	5.3	4.5	100	100	100	1.00
TAE	HS2	1	3	7.0	5.8	100	100	100	1.00

TAE	HS2	1	4	3.9	3.9	100	100	100	1.00
TAE	HS2	1	6	3.0	2.2	93	100	100	0.97
TAE	HS2	1	7	4.3	7.9	100	100	100	1.00
TAE	HS2	1	pulse	7.2	2.9	100	100	100	0.98
TAE	HS2	1	ramp	4.3	4.2	100	100	100	1.00
TAE	HS3	1	1	6.2	2.1	75	90	100	0.96
TAE	HS3	1	3	7.7	2.5	100	100	100	1.00
TAE	HS3	1	4	5.0	2.0	100	100	100	1.00
TAE	HS3	1	6	7.0	2.0	100	100	100	0.99
TAE	HS3	1	7	9.0	2.3	100	100	100	1.00
TAE	HS3	1	pulse	6.3	2.2	100	100	100	1.00
TAE	HS3	1	ramp	6.6	2.2	100	100	100	1.00
TAE	HS3	4	1	6.8	3.2	100	100	100	1.00
TAE	HS3	4	3	7.5	3.6	100	100	100	1.00
TAE	HS3	4	4	5.1	2.9	100	100	100	1.00
TAE	HS3	4	6	7.0	2.8	100	100	100	1.00
TAE	HS3	4	7	8.8	3.2	100	100	100	1.00
TAE	HS3	4	pulse	6.4	3.1	100	100	100	1.00
TAE	HS3	4	ramp	6.4	3.1	100	100	100	1.00
TAE	HS3	6	1	6.8	5.8	100	100	100	1.00
TAE	HS3	6	3	7.3	6.4	100	100	100	1.00
TAE	HS3	6	4	5.0	5.3	100	100	100	1.00
TAE	HS3	6	6	6.7	4.9	100	100	100	1.00
TAE	HS3	6	7	8.7	6.0	100	100	100	1.00
TAE	HS3	6	pulse	6.3	5.7	100	100	100	1.00
TAE	HS3	6	ramp	6.4	5.7	100	100	100	1.00
TAE	HS3	7	1	5.8	1.9	100	100	100	1.00
TAE	HS3	7	3	6.7	2.2	100	100	100	1.00
TAE	HS3	7	4	4.5	1.7	100	100	100	0.98
TAE	HS3	7	6	5.2	1.5	79	100	100	0.94
TAE	HS3	7	7	8.1	2.1	100	100	100	0.98
TAE	HS3	7	pulse	5.5	1.8	100	100	100	0.99
TAE	HS3	7	ramp	5.7	1.8	97	100	100	0.99
TAE	HS3	10	1	5.4	2.6	100	100	100	1.00
TAE	HS3	10	3	6.5	3.0	100	100	100	1.00
TAE	HS3	10	4	4.3	2.3	100	100	100	1.00
TAE	HS3	10	6	5.1	2.2	100	100	100	1.00
TAE	HS3	10	7	7.4	2.7	100	100	100	0.99
TAE	HS3	10	pulse	5.3	2.5	100	100	100	1.00
TAE	HS3	10	ramp	5.3	2.5	100	100	100	1.00
TAE	HS3	12	1	5.5	4.7	100	100	100	1.00

TAE	HS3	12	3	6.5	5.2	100	100	100	1.00
TAE	HS3	12	4	4.2	4.2	100	100	100	1.00
TAE	HS3	12	6	5.0	3.9	100	100	100	1.00
TAE	HS3	12	7	7.1	4.8	100	100	100	1.00
TAE	HS3	12	pulse	5.4	4.6	100	100	100	1.00
TAE	HS3	12	ramp	5.3	4.5	100	100	100	1.00
TAE	HS3	13	1	4.3	1.9	100	100	100	0.96
TAE	HS3	13	3	4.7	2.2	100	100	100	0.98
TAE	HS3	13	4	3.2	1.7	92	100	100	0.93
TAE	HS3	13	6	3.7	1.5	71	100	100	0.93
TAE	HS3	13	7	6.6	2.4	100	100	100	0.95
TAE	HS3	13	pulse	4.3	1.9	100	100	100	0.97
TAE	HS3	13	ramp	4.3	1.9	95	100	100	0.95
TAE	HS3	15	1	4.1	3.3	100	100	100	1.00
TAE	HS3	15	3	4.6	4.0	100	100	100	1.00
TAE	HS3	15	4	3.2	3.1	100	100	100	1.00
TAE	HS3	15	6	3.7	2.8	100	100	100	1.00
TAE	HS3	15	7	5.6	3.7	100	100	100	0.97
TAE	HS3	15	pulse	4.0	3.3	100	100	100	1.00
TAE	HS3	15	ramp	3.9	3.2	100	100	100	0.99
TAE	HS3	16	1	6.0	1.9	100	100	100	1.00
TAE	HS3	16	3	7.4	2.3	100	100	100	1.00
TAE	HS3	16	4	4.3	1.6	79	100	100	0.93
TAE	HS3	16	6	4.0	1.1	0	0	0	0.71
TAE	HS3	16	pulse	11.3	3.1	100	100	100	1.00
TAE	HS3	16	ramp	5.6	1.9	100	100	100	0.99
TAE	HS3	16	11	5.7	1.9	97	100	100	1.00
TAE	HS3	17	1	5.8	2.6	100	100	100	1.00
TAE	HS3	17	3	7.1	3.3	100	100	100	1.00
TAE	HS3	17	4	3.7	1.9	96	100	100	0.98
TAE	HS3	17	6	3.4	1.4	14	43	93	0.81
TAE	HS3	17	7	11.4	4.5	100	100	100	1.00
TAE	HS3	17	pulse	5.5	2.6	100	100	100	1.00
TAE	HS3	17	ramp	5.3	2.5	100	100	100	1.00
TAE	HS3	18	1	5.5	4.5	100	100	100	1.00
TAE	HS3	18	3	7.1	5.9	100	100	100	1.00
TAE	HS3	18	4	3.7	3.6	100	100	100	1.00
TAE	HS3	18	6	3.5	2.6	100	100	100	1.00
TAE	HS3	18	7	11.4	8.2	100	100	100	1.00
TAE	HS3	18	pulse	5.3	4.6	100	100	100	1.00
TAE	HS3	18	ramp	5.3	4.4	100	100	100	1.00

Table A2. Performance of indicators relative to management objective 2 for each harvest strategy and harvest control rule across all iterations for each uncertainty scenario and the two fishing effort scenarios (pulse and ramp). HS refers to harvest strategy, HCR to harvest control rule, SCN to scenario, Total Biomass Depletion to the total biomass as a fraction of unfished total biomass, p29 to the % of runs in which ratio of Total Biomass Depletion/Minimum Historical Total Biomass Depletion is ≥1 for 29 out of the 30 years of simulation, p27 to the % of runs in which the ratio is ≥1 for 27 out of the 30 years of simulation, p24 to the % of runs in which the ratio is ≥1 for 24 out of the 30 years of simulation, PM2 refers to performance metric 2, the probability that total biomass depletion is higher than the minimum historical (2006-2015) total biomass depletion in any given year of the simulation.

Control	HS	HCR	SCN	Median Total Biomass Depletion over all years and runs	Median Total Biomass Depletion/ Minimum Historical Total Biomass Depletion over all years and runs	p29	p27	p24	PM2
TAC	HS1	1	1	0.64	1.0	10	15	15	0.65
TAC	HS1	1	3	0.66	1.0	0	0	20	0.64
TAC	HS1	1	4	0.64	1.0	0	13	17	0.64
TAC	HS1	1	6	0.48	1.0	0	0	7	0.36
TAC	HS1	1	7	0.77	1.3	0	0	0	0.93
TAC	HS1	1	pulse	0.62	1.0	0	0	0	0.62
TAC	HS1	1	ramp	0.62	1.0	0	0	0	0.62
TAC	HS1	4	1	0.63	1.0	10	10	15	0.64
TAC	HS1	4	3	0.66	1.0	0	0	20	0.63
TAC	HS1	4	4	0.64	1.0	0	8	17	0.63
TAC	HS1	4	6	0.48	0.9	0	0	7	0.35
TAC	HS1	4	7	0.80	1.3	0	0	0	0.83
TAC	HS1	4	pulse	0.61	1.0	0	0	0	0.59
TAC	HS1	4	ramp	0.61	1.0	0	0	0	0.60
TAC	HS1	6	1	0.63	1.1	10	10	15	0.64
TAC	HS1	6	3	0.66	1.1	0	0	20	0.63
TAC	HS1	6	4	0.64	1.1	0	8	17	0.63
TAC	HS1	6	6	0.46	1.1	0	0	7	0.33
TAC	HS1	6	7	0.79	1.3	0	0	0	0.81
TAC	HS1	6	pulse	0.62	1.0	0	0	0	0.62
TAC	HS1	6	ramp	0.61	1.0	0	0	0	0.61
TAC	HS1	7	1	0.60	1.1	5	5	10	0.59
TAC	HS1	7	3	0.66	1.1	20	20	20	0.65
TAC	HS1	7	4	0.59	1.0	0	4	4	0.58

TAC	HS1	7	6	0.46	1.0	0	0	0	0.30
TAC	HS1	7	7	0.79	1.3	0	0	0	0.80
TAC	HS1	7	pulse	0.60	1.0	0	0	0	0.55
TAC	HS1	7	ramp	0.59	1.0	0	0	0	0.53
TAC	HS1	10	1	0.60	1.1	5	5	5	0.57
TAC	HS1	10	3	0.66	1.0	20	20	20	0.64
TAC	HS1	10	4	0.59	1.0	0	4	4	0.55
TAC	HS1	10	6	0.43	1.0	0	0	0	0.25
TAC	HS1	10	7	0.79	1.3	0	0	0	0.79
TAC	HS1	10	pulse	0.60	1.0	0	0	0	0.53
TAC	HS1	10	ramp	0.59	1.0	0	0	0	0.52
TAC	HS1	12	1	0.60	1.0	5	5	5	0.56
TAC	HS1	12	3	0.65	1.0	20	20	20	0.64
TAC	HS1	12	4	0.58	1.0	0	4	4	0.54
TAC	HS1	12	6	0.43	0.9	0	0	0	0.24
TAC	HS1	12	7	0.79	1.3	0	0	0	0.79
TAC	HS1	12	pulse	0.59	1.0	0	0	0	0.52
TAC	HS1	12	ramp	0.60	1.0	0	0	0	0.52
TAC	HS1	13	1	0.58	0.8	5	5	5	0.52
TAC	HS1	13	3	0.60	0.8	0	0	0	0.55
TAC	HS1	13	4	0.58	0.8	0	0	4	0.53
TAC	HS1	13	6	0.40	0.8	0	0	0	0.15
TAC	HS1	13	7	0.77	1.3	0	0	0	0.76
TAC	HS1	13	pulse	0.57	0.9	0	0	0	0.47
TAC	HS1	13	ramp	0.55	0.9	0	0	0	0.39
TAC	HS1	15	1	0.58	0.7	0	5	5	0.49
TAC	HS1	15	3	0.59	0.7	0	0	0	0.53
TAC	HS1	15	4	0.58	0.7	0	0	4	0.51
TAC	HS1	15	6	0.40	0.7	0	0	0	0.10
TAC	HS1	15	7	0.76	1.2	0	0	0	0.76
TAC	HS1	15	pulse	0.55	0.9	0	0	0	0.43
TAC	HS1	15	ramp	0.55	0.9	0	0	0	0.43
TAC	HS3	1	1	0.64	1.1	10	15	20	0.63
TAC	HS3	1	3	0.75	1.0	20	20	40	0.75
TAC	HS3	1	4	0.62	1.0	0	8	13	0.61
TAC	HS3	1	6	0.49	1.0	0	0	0	0.38
TAC	HS3	1	7	0.80	1.3	0	0	0	0.81
TAC	HS3	1	pulse	0.63	1.0	0	0	0	0.62
TAC	HS3	1	ramp	0.63	1.0	0	0	0	0.63
TAC	HS3	4	1	0.63	0.9	0	10	20	0.59
TAC	HS3	4	3	0.74	0.9	20	20	40	0.74

TAC	HS3	4	4	0.62	1.0	0	4	13	0.60
TAC	HS3	4	6	0.47	1.0	0	0	0	0.36
TAC	HS3	4	7	0.79	1.3	0	0	0	0.80
TAC	HS3	4	pulse	0.62	1.0	0	0	0	0.58
TAC	HS3	4	ramp	0.61	1.0	0	0	0	0.59
TAC	HS3	6	1	0.62	1.2	10	10	20	0.63
TAC	HS3	6	3	0.74	1.2	20	20	40	0.74
TAC	HS3	6	4	0.61	1.2	0	4	8	0.59
TAC	HS3	6	6	0.47	1.2	0	0	0	0.34
TAC	HS3	6	7	0.79	1.3	0	0	0	0.80
TAC	HS3	6	pulse	0.62	1.0	0	0	0	0.62
TAC	HS3	6	ramp	0.62	1.0	0	0	0	0.63
TAC	HS3	7	1	0.58	1.1	0	0	0	0.51
TAC	HS3	7	3	0.70	1.1	0	60	60	0.72
TAC	HS3	7	4	0.59	1.0	0	4	4	0.58
TAC	HS3	7	6	0.43	1.0	0	0	0	0.28
TAC	HS3	7	7	0.79	1.3	0	0	0	0.80
TAC	HS3	7	pulse	0.60	1.0	0	0	0	0.55
TAC	HS3	7	ramp	0.60	1.0	0	0	0	0.57
TAC	HS3	10	1	0.57	1.0	0	0	0	0.50
TAC	HS3	10	3	0.69	1.0	0	20	60	0.70
TAC	HS3	10	4	0.58	1.0	0	4	4	0.55
TAC	HS3	10	6	0.42	1.0	0	0	0	0.25
TAC	HS3	10	7	0.79	1.3	0	0	0	0.80
TAC	HS3	10	pulse	0.60	1.0	0	0	0	0.49
TAC	HS3	10	ramp	0.60	1.0	0	0	0	0.50
TAC	HS3	12	1	0.57	1.0	0	0	0	0.52
TAC	HS3	12	3	0.68	1.0	0	20	40	0.69
TAC	HS3	12	4	0.59	1.0	0	4	4	0.54
TAC	HS3	12	6	0.42	0.9	0	0	0	0.22
TAC	HS3	12	7	0.79	1.3	0	0	0	0.81
TAC	HS3	12	pulse	0.58	0.9	0	0	0	0.50
TAC	HS3	12	ramp	0.60	1.0	0	0	0	0.50
TAC	HS3	13	1	0.59	0.8	0	5	5	0.53
TAC	HS3	13	3	0.61	0.8	0	0	0	0.53
TAC	HS3	13	4	0.58	0.8	0	4	4	0.50
TAC	HS3	13	6	0.41	0.7	0	0	0	0.15
TAC	HS3	13	7	0.78	1.3	0	0	0	0.76
TAC	HS3	13	pulse	0.56	0.9	0	0	0	0.47
TAC	HS3	13	ramp	0.56	0.9	0	0	0	0.42
TAC	HS3	15	1	0.58	0.7	0	5	5	0.49

TAC	HS3	15	3	0.60	0.7	0	0	0	0.51
TAC	HS3	15	4	0.56	0.7	0	0	4	0.46
TAC	HS3	15	6	0.40	0.6	0	0	0	0.09
TAC	HS3	15	7	0.74	1.2	0	0	0	0.77
TAC	HS3	15	pulse	0.57	0.9	0	0	0	0.47
TAC	HS3	15	ramp	0.55	0.9	0	0	0	0.43
TAE	HS1	1	1	0.67	1.1	5	20	25	0.69
TAE	HS1	1	3	0.69	1.1	20	20	60	0.72
TAE	HS1	1	4	0.65	1.1	0	17	17	0.67
TAE	HS1	1	6	0.54	0.9	0	0	0	0.39
TAE	HS1	1	7	0.79	1.3	0	0	0	0.79
TAE	HS1	1	pulse	0.63	1.0	0	0	0	0.62
TAE	HS1	1	ramp	0.64	1.1	0	0	0	0.66
TAE	HS1	4	1	0.67	1.1	5	15	25	0.69
TAE	HS1	4	3	0.68	1.1	0	20	60	0.71
TAE	HS1	4	4	0.65	1.1	0	17	17	0.67
TAE	HS1	4	6	0.54	0.9	0	0	0	0.39
TAE	HS1	4	7	0.78	1.3	0	0	0	0.79
TAE	HS1	4	pulse	0.63	1.0	0	0	0	0.62
TAE	HS1	4	ramp	0.62	1.0	0	0	0	0.62
TAE	HS1	6	1	0.67	1.1	5	15	25	0.69
TAE	HS1	6	3	0.68	1.1	0	20	40	0.72
TAE	HS1	6	4	0.65	1.1	0	13	17	0.67
TAE	HS1	6	6	0.54	0.9	0	0	0	0.38
TAE	HS1	6	7	0.78	1.3	0	0	0	0.79
TAE	HS1	6	pulse	0.63	1.0	0	0	0	0.62
TAE	HS1	6	ramp	0.62	1.0	0	0	0	0.62
TAE	HS1	7	1	0.61	1.0	5	5	5	0.59
TAE	HS1	7	3	0.66	1.1	0	20	20	0.64
TAE	HS1	7	4	0.60	1.0	0	4	4	0.59
TAE	HS1	7	6	0.50	0.8	0	0	0	0.30
TAE	HS1	7	7	0.77	1.3	0	0	0	0.77
TAE	HS1	7	pulse	0.60	1.0	0	0	0	0.55
TAE	HS1	7	ramp	0.60	1.0	0	0	0	0.54
TAE	HS1	10	1	0.61	1.0	5	5	5	0.58
TAE	HS1	10	3	0.65	1.1	0	0	20	0.62
TAE	HS1	10	4	0.59	1.0	0	4	4	0.58
TAE	HS1	10	6	0.49	0.8	0	0	0	0.29
TAE	HS1	10	7	0.76	1.2	0	0	0	0.77
TAE	HS1	10	pulse	0.60	1.0	0	0	0	0.54
TAE	HS1	10	ramp	0.59	1.0	0	0	0	0.51

TAE	HS1	12	1	0.60	1.0	5	5	5	0.58
TAE	HS1	12	3	0.65	1.1	0	0	20	0.62
TAE	HS1	12	4	0.60	1.0	0	4	4	0.57
TAE	HS1	12	6	0.49	0.8	0	0	0	0.29
TAE	HS1	12	7	0.76	1.2	0	0	0	0.76
TAE	HS1	12	pulse	0.60	1.0	0	0	0	0.54
TAE	HS1	12	ramp	0.59	1.0	0	0	0	0.52
TAE	HS1	13	1	0.55	0.9	0	0	0	0.41
TAE	HS1	13	3	0.64	1.0	20	20	20	0.60
TAE	HS1	13	4	0.56	0.9	0	4	4	0.48
TAE	HS1	13	6	0.47	0.8	0	0	0	0.29
TAE	HS1	13	7	0.74	1.2	0	0	0	0.74
TAE	HS1	13	pulse	0.55	0.9	0	0	0	0.41
TAE	HS1	13	ramp	0.56	0.9	0	0	0	0.38
TAE	HS1	15	1	0.55	0.9	0	0	0	0.38
TAE	HS1	15	3	0.64	1.0	20	20	20	0.59
TAE	HS1	15	4	0.56	0.9	0	4	4	0.46
TAE	HS1	15	6	0.47	0.8	0	0	0	0.28
TAE	HS1	15	7	0.73	1.2	0	0	0	0.72
TAE	HS1	15	pulse	0.54	0.9	0	0	0	0.37
TAE	HS1	15	ramp	0.54	0.9	0	0	0	0.40
TAE	HS1	16	1	0.60	1.0	5	5	5	0.56
TAE	HS1	16	3	0.71	1.2	20	20	40	0.73
TAE	HS1	16	4	0.58	1.0	0	4	4	0.55
TAE	HS1	16	6	0.45	0.7	0	0	0	0.32
TAE	HS1	16	7	0.82	1.3	0	0	0	0.84
TAE	HS1	16	pulse	0.60	1.0	0	0	0	0.55
TAE	HS1	16	ramp	0.60	1.0	0	0	0	0.53
TAE	HS1	17	1	0.60	1.0	5	5	5	0.53
TAE	HS1	17	3	0.70	1.2	20	20	40	0.73
TAE	HS1	17	4	0.58	1.0	0	4	4	0.52
TAE	HS1	17	6	0.43	0.7	0	0	0	0.24
TAE	HS1	17	7	0.81	1.3	0	0	0	0.84
TAE	HS1	17	pulse	0.59	1.0	0	0	0	0.51
TAE	HS1	17	ramp	0.60	1.0	0	0	0	0.52
TAE	HS1	18	1	0.60	1.0	5	5	5	0.54
TAE	HS1	18	3	0.69	1.1	20	20	40	0.73
TAE	HS1	18	4	0.57	0.9	0	4	4	0.49
TAE	HS1	18	6	0.43	0.7	0	0	0	0.23
TAE	HS1	18	7	0.81	1.3	0	0	0	0.83
TAE	HS1	18	pulse	0.59	1.0	0	0	0	0.52

TAE	HS1	18	ramp	0.59	1.0	0	0	0	0.51
TAE	HS2	1	1	0.59	1.0	5	5	5	0.53
TAE	HS2	1	3	0.69	1.1	20	40	40	0.68
TAE	HS2	1	4	0.59	1.0	0	4	4	0.55
TAE	HS2	1	6	0.42	0.7	0	0	0	0.15
TAE	HS2	1	7	0.79	1.3	0	0	0	0.83
TAE	HS2	1	pulse	0.53	0.9	0	0	0	0.35
TAE	HS2	1	ramp	0.58	1.0	0	0	0	0.48
TAE	HS3	1	1	0.61	1.0	5	10	10	0.61
TAE	HS3	1	3	0.69	1.1	20	20	40	0.72
TAE	HS3	1	4	0.62	1.0	4	8	13	0.61
TAE	HS3	1	6	0.61	1.0	0	7	7	0.56
TAE	HS3	1	7	0.77	1.3	0	0	0	0.93
TAE	HS3	1	pulse	0.62	1.0	0	0	0	0.61
TAE	HS3	1	ramp	0.63	1.0	0	0	0	0.62
TAE	HS3	4	1	0.67	1.1	5	15	20	0.68
TAE	HS3	4	3	0.69	1.1	0	0	20	0.65
TAE	HS3	4	4	0.62	1.0	0	8	13	0.60
TAE	HS3	4	6	0.60	1.0	0	7	7	0.55
TAE	HS3	4	7	0.79	1.3	0	0	0	0.82
TAE	HS3	4	pulse	0.64	1.1	0	0	0	0.65
TAE	HS3	4	ramp	0.62	1.0	0	0	0	0.60
TAE	HS3	6	1	0.67	1.1	5	15	20	0.68
TAE	HS3	6	3	0.66	1.1	0	0	0	0.54
TAE	HS3	6	4	0.61	1.0	0	8	13	0.60
TAE	HS3	6	6	0.60	1.0	0	7	7	0.55
TAE	HS3	6	7	0.78	1.3	0	0	0	0.79
TAE	HS3	6	pulse	0.62	1.0	0	0	0	0.62
TAE	HS3	6	ramp	0.62	1.0	0	0	0	0.60
TAE	HS3	7	1	0.60	1.0	0	0	0	0.57
TAE	HS3	7	3	0.68	1.1	20	20	40	0.69
TAE	HS3	7	4	0.60	1.0	0	4	4	0.60
TAE	HS3	7	6	0.44	0.7	0	0	0	0.21
TAE	HS3	7	7	0.78	1.3	0	0	0	0.78
TAE	HS3	7	pulse	0.60	1.0	0	0	0	0.54
TAE	HS3	7	ramp	0.60	1.0	0	0	0	0.56
TAE	HS3	10	1	0.59	1.0	0	5	5	0.49
TAE	HS3	10	3	0.67	1.1	20	20	40	0.68
TAE	HS3	10	4	0.59	1.0	0	4	4	0.58
TAE	HS3	10	6	0.52	0.9	0	0	0	0.38
TAE	HS3	10	7	0.76	1.3	0	0	0	0.76

TAE	HS3	10	pulse	0.59	1.0	0	0	0	0.53
TAE	HS3	10	ramp	0.60	1.0	0	0	0	0.52
TAE	HS3	12	1	0.60	1.0	0	0	0	0.54
TAE	HS3	12	3	0.66	1.1	20	20	40	0.67
TAE	HS3	12	4	0.59	1.0	0	4	4	0.57
TAE	HS3	12	6	0.51	0.8	0	0	0	0.37
TAE	HS3	12	7	0.76	1.2	0	0	0	0.76
TAE	HS3	12	pulse	0.60	1.0	0	0	0	0.53
TAE	HS3	12	ramp	0.59	1.0	0	0	0	0.50
TAE	HS3	13	1	0.57	0.9	5	5	5	0.49
TAE	HS3	13	3	0.56	0.9	0	0	0	0.48
TAE	HS3	13	4	0.54	0.9	0	0	0	0.38
TAE	HS3	13	6	0.47	0.8	0	0	0	0.31
TAE	HS3	13	7	0.75	1.2	0	0	0	0.75
TAE	HS3	13	pulse	0.56	0.9	0	0	0	0.45
TAE	HS3	13	ramp	0.56	0.9	0	0	0	0.40
TAE	HS3	15	1	0.56	0.9	5	5	5	0.45
TAE	HS3	15	3	0.56	0.9	0	0	0	0.46
TAE	HS3	15	4	0.54	0.9	0	0	0	0.36
TAE	HS3	15	6	0.47	0.8	0	0	0	0.30
TAE	HS3	15	7	0.71	1.2	0	0	0	0.75
TAE	HS3	15	pulse	0.55	0.9	0	0	0	0.40
TAE	HS3	15	ramp	0.54	0.9	0	0	0	0.36
TAE	HS3	16	1	0.63	1.0	0	5	10	0.61
TAE	HS3	16	3	0.72	1.2	0	0	40	0.74
TAE	HS3	16	4	0.59	1.0	0	4	8	0.58
TAE	HS3	16	6	0.47	0.8	0	0	0	0.35
TAE	HS3	16	7	0.79	1.3	0	0	0	0.85
TAE	HS3	16	pulse	0.60	1.0	0	0	0	0.55
TAE	HS3	16	ramp	0.60	1.0	0	0	0	0.56
TAE	HS3	17	1	0.62	1.0	0	5	5	0.59
TAE	HS3	17	3	0.71	1.2	0	0	60	0.74
TAE	HS3	17	4	0.58	1.0	0	4	4	0.53
TAE	HS3	17	6	0.45	0.7	0	0	0	0.26
TAE	HS3	17	7	0.81	1.3	0	0	0	0.84
TAE	HS3	17	pulse	0.60	1.0	0	0	0	0.53
TAE	HS3	17	ramp	0.59	1.0	0	0	0	0.50
TAE	HS3	18	1	0.60	1.0	0	5	5	0.56
TAE	HS3	18	3	0.71	1.2	0	0	40	0.73
TAE	HS3	18	4	0.58	1.0	0	4	4	0.52
TAE	HS3	18	6	0.44	0.7	0	0	0	0.25

TAE	HS3	18	7	0.82	1.4	0	0	0	0.85
TAE	HS3	18	pulse	0.59	1.0	0	0	0	0.52
TAE	HS3	18	ramp	0.59	1.0	0	0	0	0.52

Table A3. Performance of indicators relative to management objective 4 for each harvest strategy and harvest control rule across all iterations for each uncertainty scenario and the two fishing effort scenarios (pulse and ramp). HS refers to harvest strategy, HCR to harvest control rule, SCN to scenario, p29 to the % of runs in which ratio of Catch/Average Historical Catch is ≥1 for 29 out of the 30 years of simulation, p27 to the % of runs in which the ratio is ≥1 for 27 out of the 30 years of simulation, p24 to the % of runs in which the ratio is ≥1 for 24 out of the 30 years of simulation, p15 to the % of runs in which the ratio is ≥1 for 15 out of the 30 years of simulation PM4 refers to performance metric 4, the probability that catch is higher than the average historical (1981-2010) catch in any given year of the simulation.

Control	HS	HCR	SCN	Media nCatch (mt) over all years and runs	Median Catch/Average historical catch over all years and runs	p29	p27	p22	p15	PM4
TAC	HS1	1	1	82939	1.2	15	15	25	75	0.72
TAC	HS1	1	3	85974	1.2	0	20	40	100	0.77
TAC	HS1	1	4	81887	1.1	13	17	38	71	0.67
TAC	HS1	1	6	76908	1.1	0	7	7	21	0.60
TAC	HS1	1	7	147482	2.0	100	100	100	100	1.00
TAC	HS1	1	pulse	80505	1.1	7	17	41	80	0.70
TAC	HS1	1	ramp	83916	1.2	13	34	58	95	0.74
TAC	HS1	4	1	82836	1.1	10	15	25	65	0.74
TAC	HS1	4	3	92105	1.3	0	20	40	100	0.79
TAC	HS1	4	4	80821	1.1	8	17	38	67	0.71
TAC	HS1	4	6	79676	1.1	7	7	7	14	0.63
TAC	HS1	4	7	165760	2.3	100	100	100	100	0.99
TAC	HS1	4	pulse	81511	1.1	8	18	44	90	0.72
TAC	HS1	4	ramp	84461	1.2	16	38	59	95	0.74
TAC	HS1	6	1	82726	1.1	10	15	25	75	0.74
TAC	HS1	6	3	88475	1.2	0	20	40	100	0.78
TAC	HS1	6	4	80736	1.1	8	17	38	67	0.71
TAC	HS1	6	6	78500	1.1	7	7	7	21	0.66
TAC	HS1	6	7	160349	2.2	100	100	100	100	0.99
TAC	HS1	6	pulse	81996	1.1	11	21	47	87	0.72
TAC	HS1	6	ramp	83095	1.2	17	39	56	90	0.75
TAC	HS1	7	1	99455	1.4	5	10	30	45	0.75
TAC	HS1	7	3	109437	1.5	20	20	20	100	0.83
TAC	HS1	7	4	94524	1.3	4	4	33	54	0.67
TAC	HS1	7	6	88127	1.2	0	0	0	7	0.61

TAC	HS1	7	7	190546	2.6	60	100	100	100	0.96
TAC	HS1	7	pulse	94816	1.3	21	58	87	100	0.74
TAC	HS1	7	ramp	98739	1.4	32	74	84	95	0.86
TAC	HS1	10	1	98455	1.4	5	5	30	50	0.82
TAC	HS1	10	3	110212	1.5	20	20	20	100	0.90
TAC	HS1	10	4	91727	1.3	4	4	25	50	0.74
TAC	HS1	10	6	84096	1.2	0	0	0	7	0.67
TAC	HS1	10	7	196048	2.7	97	100	100	100	0.99
TAC	HS1	10	pulse	96567	1.3	42	66	84	95	0.83
TAC	HS1	10	ramp	100263	1.4	44	66	91	97	0.86
TAC	HS1	12	1	98501	1.4	5	5	30	45	0.86
TAC	HS1	12	3	109175	1.5	20	20	20	100	0.89
TAC	HS1	12	4	91560	1.3	4	4	21	50	0.80
TAC	HS1	12	6	85147	1.2	0	0	0	0	0.70
TAC	HS1	12	7	194693	2.7	100	100	100	100	0.99
TAC	HS1	12	pulse	97481	1.4	50	78	85	98	0.85
TAC	HS1	12	ramp	99087	1.4	57	71	83	100	0.87
TAC	HS1	13	1	115211	1.6	5	5	15	55	0.79
TAC	HS1	13	3	121908	1.7	0	0	0	80	0.88
TAC	HS1	13	4	107691	1.5	4	4	13	50	0.74
TAC	HS1	13	6	92845	1.3	0	0	0	0	0.62
TAC	HS1	13	7	214653	3.0	50	97	99	100	0.96
TAC	HS1	13	pulse	112464	1.6	24	66	97	100	0.80
TAC	HS1	13	ramp	116407	1.6	64	100	100	100	0.94
TAC	HS1	15	1	114510	1.6	5	5	10	50	0.88
TAC	HS1	15	3	124447	1.7	0	0	0	60	0.91
TAC	HS1	15	4	106962	1.5	4	4	8	50	0.79
TAC	HS1	15	6	92395	1.3	0	0	0	0	0.68
TAC	HS1	15	7	213342	3.0	97	100	100	100	0.99
TAC	HS1	15	pulse	109591	1.5	56	77	98	100	0.88
TAC	HS1	15	ramp	112087	1.6	68	82	94	97	0.89
TAC	HS3	1	1	82577	1.1	0	40	60	85	0.70
TAC	HS3	1	3	98227	1.4	40	80	100	100	0.82
TAC	HS3	1	4	76708	1.1	4	17	33	67	0.57
TAC	HS3	1	6	77316	1.1	7	14	36	57	0.54
TAC	HS3	1	7	160603	2.2	72	97	100	100	0.97
TAC	HS3	1	pulse	81415	1.1	10	33	60	90	0.72
TAC	HS3	1	ramp	81403	1.1	17	38	66	90	0.72
TAC	HS3	4	1	81331	1.1	25	35	60	95	0.72
TAC	HS3	4	3	99077	1.4	60	80	80	100	0.86
TAC	HS3	4	4	77314	1.1	4	25	33	63	0.62

TAC	HS3	4	6	74777	1.0	0	7	29	57	0.56
TAC	HS3	4	7	158595	2.2	97	100	100	100	0.99
TAC	HS3	4	pulse	81458	1.1	19	29	52	83	0.74
TAC	HS3	4	ramp	82572	1.1	18	33	54	92	0.76
TAC	HS3	6	1	83871	1.2	25	45	65	100	0.76
TAC	HS3	6	3	98391	1.4	60	80	80	100	0.84
TAC	HS3	6	4	77257	1.1	8	25	38	67	0.67
TAC	HS3	6	6	75306	1.0	0	7	21	64	0.58
TAC	HS3	6	7	158924	2.2	100	100	100	100	0.99
TAC	HS3	6	pulse	82242	1.1	20	35	50	95	0.77
TAC	HS3	6	ramp	83688	1.2	29	38	55	93	0.78
TAC	HS3	7	1	93965	1.3	0	35	80	100	0.66
TAC	HS3	7	3	115759	1.6	20	60	80	100	0.77
TAC	HS3	7	4	93899	1.3	0	17	63	100	0.64
TAC	HS3	7	6	90082	1.3	0	7	36	100	0.58
TAC	HS3	7	7	188313	2.6	44	84	100	100	0.94
TAC	HS3	7	pulse	94254	1.3	5	46	77	100	0.70
TAC	HS3	7	ramp	100187	1.4	9	41	86	100	0.75
TAC	HS3	10	1	93998	1.3	5	25	85	95	0.80
TAC	HS3	10	3	112867	1.6	60	80	100	100	0.88
TAC	HS3	10	4	94316	1.3	8	46	75	100	0.70
TAC	HS3	10	6	83328	1.2	0	0	57	100	0.63
TAC	HS3	10	7	193155	2.7	82	96	100	100	0.99
TAC	HS3	10	pulse	97849	1.4	33	67	86	100	0.81
TAC	HS3	10	ramp	99170	1.4	35	71	88	100	0.79
TAC	HS3	12	1	92577	1.3	25	55	70	95	0.85
TAC	HS3	12	3	112006	1.6	80	80	100	100	0.92
TAC	HS3	12	4	89677	1.2	21	50	71	96	0.77
TAC	HS3	12	6	84571	1.2	0	14	43	100	0.68
TAC	HS3	12	7	194475	2.7	100	100	100	100	0.99
TAC	HS3	12	pulse	95770	1.3	46	64	85	97	0.87
TAC	HS3	12	ramp	98306	1.4	54	74	79	100	0.87
TAC	HS3	13	1	112506	1.6	10	45	90	100	0.77
TAC	HS3	13	3	116075	1.6	20	100	100	100	0.82
TAC	HS3	13	4	105492	1.5	0	33	88	100	0.71
TAC	HS3	13	6	86208	1.2	0	7	50	100	0.60
TAC	HS3	13	7	221604	3.1	27	82	100	100	0.94
TAC	HS3	13	pulse	111835	1.6	9	57	86	100	0.76
TAC	HS3	13	ramp	113905	1.6	31	69	100	100	0.86
TAC	HS3	15	1	112073	1.6	45	75	95	100	0.85
TAC	HS3	15	3	123313	1.7	40	100	100	100	0.86

TAC	HS3	15	4	105984	1.5	13	58	88	100	0.76
TAC	HS3	15	6	87702	1.2	0	43	71	93	0.66
TAC	HS3	15	7	206774	2.9	94	100	100	100	1.00
TAC	HS3	15	pulse	113888	1.6	50	81	100	100	0.86
TAC	HS3	15	ramp	111528	1.5	41	77	100	100	0.85
TAE	HS1	1	1	88282	1.2	15	40	65	100	0.78
TAE	HS1	1	3	93350	1.3	20	60	80	100	0.82
TAE	HS1	1	4	76123	1.1	4	4	33	67	0.62
TAE	HS1	1	6	61701	0.9	0	0	0	21	0.35
TAE	HS1	1	7	168659	2.3	86	100	100	100	0.95
TAE	HS1	1	pulse	84506	1.2	11	27	51	95	0.73
TAE	HS1	1	ramp	87469	1.2	16	39	65	100	0.77
TAE	HS1	4	1	88023	1.2	30	45	65	100	0.79
TAE	HS1	4	3	95104	1.3	40	60	80	100	0.84
TAE	HS1	4	4	75763	1.1	4	4	33	71	0.62
TAE	HS1	4	6	61147	0.8	0	0	0	21	0.36
TAE	HS1	4	7	170470	2.4	99	99	100	100	0.96
TAE	HS1	4	pulse	85312	1.2	15	28	55	95	0.74
TAE	HS1	4	ramp	85597	1.2	21	34	58	97	0.76
TAE	HS1	6	1	88573	1.2	25	40	65	100	0.80
TAE	HS1	6	3	94561	1.3	60	60	80	100	0.84
TAE	HS1	6	4	75713	1.1	4	8	38	71	0.63
TAE	HS1	6	6	61209	0.8	0	0	0	14	0.37
TAE	HS1	6	7	170636	2.4	99	100	100	100	0.96
TAE	HS1	6	pulse	85691	1.2	17	34	57	94	0.75
TAE	HS1	6	ramp	86344	1.2	19	36	61	94	0.76
TAE	HS1	7	1	102023	1.4	35	50	90	95	0.80
TAE	HS1	7	3	110335	1.5	60	80	80	100	0.79
TAE	HS1	7	4	88224	1.2	8	29	50	100	0.72
TAE	HS1	7	6	71121	1.0	0	0	14	50	0.52
TAE	HS1	7	7	191529	2.7	40	84	100	100	0.91
TAE	HS1	7	pulse	98202	1.4	33	51	82	100	0.80
TAE	HS1	7	ramp	99272	1.4	30	48	86	100	0.80
TAE	HS1	10	1	102905	1.4	50	70	85	95	0.85
TAE	HS1	10	3	108820	1.5	80	80	80	100	0.86
TAE	HS1	10	4	88829	1.2	13	29	71	100	0.77
TAE	HS1	10	6	71838	1.0	0	0	7	50	0.54
TAE	HS1	10	7	197193	2.7	81	99	100	100	0.96
TAE	HS1	10	pulse	99759	1.4	39	65	84	97	0.84
TAE	HS1	10	ramp	99056	1.4	43	58	93	98	0.84
TAE	HS1	12	1	102476	1.4	55	70	85	100	0.85

TAE	HS1	12	3	110963	1.5	80	80	80	100	0.86
TAE	HS1	12	4	89085	1.2	8	33	67	100	0.78
TAE	HS1	12	6	71515	1.0	0	0	7	50	0.54
TAE	HS1	12	7	199976	2.8	100	100	100	100	0.97
TAE	HS1	12	pulse	100988	1.4	41	56	88	100	0.85
TAE	HS1	12	ramp	100285	1.4	46	63	88	98	0.86
TAE	HS1	13	1	111164	1.5	60	75	95	100	0.87
TAE	HS1	13	3	134518	1.9	80	80	80	100	0.90
TAE	HS1	13	4	96845	1.3	21	46	79	100	0.76
TAE	HS1	13	6	86644	1.2	7	7	43	93	0.73
TAE	HS1	13	7	217234	3.0	19	77	99	100	0.90
TAE	HS1	13	pulse	109150	1.5	45	61	95	100	0.84
TAE	HS1	13	ramp	110510	1.5	46	59	97	100	0.83
TAE	HS1	15	1	111345	1.5	75	90	100	100	0.92
TAE	HS1	15	3	133270	1.8	80	80	80	100	0.91
TAE	HS1	15	4	98840	1.4	25	63	88	96	0.82
TAE	HS1	15	6	87303	1.2	7	7	43	100	0.74
TAE	HS1	15	7	224689	3.1	81	100	100	100	0.96
TAE	HS1	15	pulse	109247	1.5	55	68	97	97	0.88
TAE	HS1	15	ramp	111623	1.5	66	76	100	100	0.89
TAE	HS1	16	1	98177	1.4	25	45	85	100	0.78
TAE	HS1	16	3	107947	1.5	60	80	100	100	0.87
TAE	HS1	16	4	92740	1.3	8	33	71	100	0.71
TAE	HS1	16	6	83583	1.2	0	0	36	86	0.64
TAE	HS1	16	7	120053	1.7	84	95	98	100	0.92
TAE	HS1	16	pulse	98320	1.4	32	51	84	97	0.80
TAE	HS1	16	ramp	99534	1.4	25	44	81	100	0.78
TAE	HS1	17	1	101607	1.4	40	55	90	95	0.83
TAE	HS1	17	3	108079	1.5	40	100	100	100	0.87
TAE	HS1	17	4	93586	1.3	21	46	75	100	0.78
TAE	HS1	17	6	86448	1.2	14	14	43	93	0.70
TAE	HS1	17	7	117511	1.6	79	90	98	100	0.91
TAE	HS1	17	pulse	97896	1.4	49	64	85	97	0.83
TAE	HS1	17	ramp	100199	1.4	44	62	82	97	0.84
TAE	HS1	18	1	99830	1.4	40	60	80	95	0.83
TAE	HS1	18	3	110723	1.5	60	100	100	100	0.88
TAE	HS1	18	4	96605	1.3	38	63	92	96	0.81
TAE	HS1	18	6	87427	1.2	14	14	43	93	0.73
TAE	HS1	18	7	116454	1.6	73	90	100	100	0.91
TAE	HS1	18	pulse	99162	1.4	41	59	85	100	0.85
TAE	HS1	18	ramp	100847	1.4	50	60	90	98	0.85

TAE	HS2	1	1	101297	1.4	5	5	15	40	0.85
TAE	HS2	1	3	113023	1.6	40	40	80	80	0.88
TAE	HS2	1	4	93112	1.3	4	4	21	46	0.79
TAE	HS2	1	6	88335	1.2	0	0	0	7	0.74
TAE	HS2	1	7	119906	1.7	86	100	100	100	0.93
TAE	HS2	1	pulse	115161	1.6	43	60	91	100	0.84
TAE	HS2	1	ramp	103282	1.4	45	64	88	100	0.87
TAE	HS3	1	1	98945	1.4	30	60	75	95	0.80
TAE	HS3	1	3	93061	1.3	40	60	60	100	0.80
TAE	HS3	1	4	72836	1.0	4	4	13	63	0.53
TAE	HS3	1	6	66190	0.9	7	7	7	21	0.50
TAE	HS3	1	7	168971	2.3	72	97	100	100	0.94
TAE	HS3	1	pulse	83125	1.2	11	17	56	92	0.72
TAE	HS3	1	ramp	85981	1.2	13	31	56	95	0.73
TAE	HS3	4	1	88684	1.2	20	45	60	100	0.78
TAE	HS3	4	3	93925	1.3	0	20	60	80	0.76
TAE	HS3	4	4	72720	1.0	4	4	17	58	0.55
TAE	HS3	4	6	67281	0.9	7	7	7	21	0.51
TAE	HS3	4	7	177063	2.5	83	100	100	100	0.98
TAE	HS3	4	pulse	87133	1.2	18	32	63	97	0.77
TAE	HS3	4	ramp	84582	1.2	13	32	68	94	0.75
TAE	HS3	6	1	88780	1.2	20	40	60	95	0.78
TAE	HS3	6	3	89619	1.2	0	0	0	100	0.72
TAE	HS3	6	4	72703	1.0	4	4	17	54	0.56
TAE	HS3	6	6	68194	0.9	7	7	7	43	0.52
TAE	HS3	6	7	171254	2.4	99	100	100	100	0.96
TAE	HS3	6	pulse	84650	1.2	12	21	55	97	0.74
TAE	HS3	6	ramp	84554	1.2	14	35	59	97	0.75
TAE	HS3	7	1	96027	1.3	20	30	85	100	0.76
TAE	HS3	7	3	111070	1.5	0	60	100	100	0.78
TAE	HS3	7	4	87068	1.2	4	17	38	100	0.68
TAE	HS3	7	6	74055	1.0	0	0	21	71	0.56
TAE	HS3	7	7	186856	2.6	10	49	100	100	0.87
TAE	HS3	7	pulse	96147	1.3	11	34	79	100	0.74
TAE	HS3	7	ramp	98536	1.4	9	34	80	100	0.73
TAE	HS3	10	1	98514	1.4	55	60	90	100	0.85
TAE	HS3	10	3	113382	1.6	60	80	100	100	0.84
TAE	HS3	10	4	88388	1.2	13	29	63	100	0.76
TAE	HS3	10	6	73504	1.0	0	0	7	64	0.59
TAE	HS3	10	7	195667	2.7	70	94	100	100	0.95
TAE	HS3	10	pulse	98641	1.4	37	54	85	98	0.83

TAE	HS3	10	ramp	100310	1.4	44	58	89	97	0.84
TAE	HS3	12	1	98708	1.4	60	65	90	100	0.87
TAE	HS3	12	3	113651	1.6	80	80	80	100	0.86
TAE	HS3	12	4	88734	1.2	13	29	63	100	0.77
TAE	HS3	12	6	74084	1.0	0	0	7	71	0.59
TAE	HS3	12	7	198468	2.8	99	100	100	100	0.97
TAE	HS3	12	pulse	100680	1.4	46	64	87	97	0.85
TAE	HS3	12	ramp	100094	1.4	47	64	83	97	0.86
TAE	HS3	13	1	114283	1.6	35	55	95	100	0.81
TAE	HS3	13	3	119488	1.7	60	60	100	100	0.89
TAE	HS3	13	4	93839	1.3	25	33	83	100	0.75
TAE	HS3	13	6	85837	1.2	14	14	36	93	0.70
TAE	HS3	13	7	212132	2.9	7	49	100	100	0.87
TAE	HS3	13	pulse	110313	1.5	20	54	95	100	0.80
TAE	HS3	13	ramp	111347	1.5	17	49	93	100	0.80
TAE	HS3	15	1	114248	1.6	70	80	95	95	0.87
TAE	HS3	15	3	120222	1.7	60	80	100	100	0.92
TAE	HS3	15	4	94994	1.3	33	54	79	96	0.82
TAE	HS3	15	6	83955	1.2	14	14	36	93	0.72
TAE	HS3	15	7	229806	3.2	50	100	100	100	0.99
TAE	HS3	15	pulse	110382	1.5	54	66	95	98	0.87
TAE	HS3	15	ramp	110606	1.5	50	68	98	98	0.87
TAE	HS3	16	1	100995	1.4	25	40	100	100	0.78
TAE	HS3	16	3	107533	1.5	40	60	100	100	0.82
TAE	HS3	16	4	88248	1.2	0	4	38	100	0.67
TAE	HS3	16	6	83227	1.2	0	0	7	93	0.61
TAE	HS3	16	7	121061	1.7	90	97	100	100	0.92
TAE	HS3	16	pulse	95787	1.3	13	26	69	97	0.74
TAE	HS3	16	ramp	96397	1.3	15	33	74	100	0.75
TAE	HS3	17	1	103420	1.4	40	65	100	100	0.85
TAE	HS3	17	3	108361	1.5	40	100	100	100	0.89
TAE	HS3	17	4	96203	1.3	8	46	83	100	0.77
TAE	HS3	17	6	86755	1.2	7	7	50	93	0.69
TAE	HS3	17	7	116984	1.6	83	94	100	100	0.92
TAE	HS3	17	pulse	96336	1.3	32	49	78	97	0.81
TAE	HS3	17	ramp	100631	1.4	40	60	85	100	0.83
TAE	HS3	18	1	105613	1.5	55	70	95	100	0.89
TAE	HS3	18	3	109215	1.5	60	80	100	100	0.90
TAE	HS3	18	4	95520	1.3	21	50	88	100	0.82
TAE	HS3	18	6	89367	1.2	21	21	50	93	0.73
TAE	HS3	18	7	118095	1.6	88	94	100	100	0.92

TAE	HS3	18	pulse	98427	1.4	45	55	79	100	0.84
TAE	HS3	18	ramp	101302	1.4	52	62	90	100	0.86

Table A4. Performance of indicators relative to management objective 5 for each harvest strategy and harvest control rule across all iterations for each uncertainty scenario and the two fishing effort scenarios (pulse and ramp). HS refers to harvest strategy, HCR to harvest control rule, PM5 to performance metric 5, the probability that a decrease in TAC (or catch for TAE rules) is <30% between consecutive assessment periods (once every 3 years), excluding years where TAC (or catch for TAE rules) = 0.

Control	HS	HCR	SCN	Median Relative Decrease in TAC between years across all runs (%)	Median Maximum Relative Decrease in TAC between years across all runs (%)	Median of % of years where decrease in TAC is 0-15%	Median of % of years where decrease in TAC is 16-30%	Median of % of years where decrease in TAC is >30%	PM5
TAC	HS1	1	1	-15	-26	55	40	0	0.92
TAC	HS1	1	3	-14	-31	60	25	20	0.92
TAC	HS1	1	4	-19	-33	37	40	17	0.94
TAC	HS1	1	6	-22	-37	33	33	25	0.89
TAC	HS1	1	7	-9	-18	75	25	0	1.00
TAC	HS1	1	pulse	-19	-57	40	25	25	0.60
TAC	HS1	1	ramp	-16	-28	45	40	0	0.89
TAC	HS1	4	1	-16	-27	50	50	0	0.91
TAC	HS1	4	3	-8	-33	67	0	25	0.93
TAC	HS1	4	4	-14	-29	50	33	0	0.82
TAC	HS1	4	6	-21	-43	45	25	25	0.79
TAC	HS1	4	7	-12	-24	60	33	0	0.95
TAC	HS1	4	pulse	-17	-58	40	33	25	0.64
TAC	HS1	4	ramp	-13	-28	60	40	0	0.92
TAC	HS1	6	1	-14	-26	60	40	0	0.84
TAC	HS1	6	3	-13	-31	33	33	33	0.90
TAC	HS1	6	4	-15	-29	45	50	0	0.88
TAC	HS1	6	6	-16	-30	40	40	0	0.78
TAC	HS1	6	7	-11	-25	60	33	0	0.94
TAC	HS1	6	pulse	-16	-58	40	25	23	0.63
TAC	HS1	6	ramp	-14	-25	50	40	0	0.95
TAC	HS1	7	1	-15	-27	50	37	0	0.84
TAC	HS1	7	3	-19	-28	33	50	0	0.96
TAC	HS1	7	4	-19	-32	42	50	25	0.83
TAC	HS1	7	6	-25	-41	25	29	42	0.91
TAC	HS1	7	7	-16	-32	45	33	20	0.83

TAC	HS1	7	pulse	-21	-46	33	29	33	0.65
TAC	HS1	7	ramp	-16	-28	33	40	0	0.92
TAC	HS1	10	1	-12	-29	50	25	13	0.84
TAC	HS1	10	3	-19	-28	25	50	0	0.89
TAC	HS1	10	4	-15	-32	50	25	25	0.92
TAC	HS1	10	6	-18	-32	42	33	25	0.80
TAC	HS1	10	7	-13	-28	60	25	0	0.92
TAC	HS1	10	pulse	-20	-43	37	33	25	0.70
TAC	HS1	10	ramp	-13	-26	55	25	0	0.89
TAC	HS1	12	1	-14	-25	50	50	0	0.81
TAC	HS1	12	3	-13	-27	50	50	0	0.86
TAC	HS1	12	4	-13	-30	60	29	0	0.70
TAC	HS1	12	6	-16	-36	45	33	18	0.69
TAC	HS1	12	7	-16	-28	45	40	0	0.91
TAC	HS1	12	pulse	-18	-44	40	25	25	0.71
TAC	HS1	12	ramp	-13	-26	50	33	0	0.91
TAC	HS1	13	1	-15	-30	33	33	13	0.73
TAC	HS1	13	3	-22	-33	50	33	25	0.74
TAC	HS1	13	4	-20	-35	10	33	29	0.85
TAC	HS1	13	6	-22	-34	33	42	23	0.60
TAC	HS1	13	7	-17	-33	40	37	25	0.81
TAC	HS1	13	pulse	-19	-32	45	40	25	0.81
TAC	HS1	13	ramp	-15	-27	60	40	0	0.96
TAC	HS1	15	1	-16	-31	50	25	10	0.78
TAC	HS1	15	3	-11	-23	50	33	0	0.82
TAC	HS1	15	4	-19	-40	33	33	25	0.73
TAC	HS1	15	6	-19	-31	37	33	20	0.76
TAC	HS1	15	7	-14	-32	50	25	20	0.85
TAC	HS1	15	pulse	-18	-34	50	33	20	0.80
TAC	HS1	15	ramp	-15	-29	45	40	0	0.82
TAC	HS3	1	1	-18	-35	50	37	25	0.70
TAC	HS3	1	3	-18	-34	50	33	20	0.91
TAC	HS3	1	4	-21	-35	40	33	23	0.93
TAC	HS3	1	6	-21	-47	33	37	29	0.58
TAC	HS3	1	7	-13	-26	55	33	0	0.78
TAC	HS3	1	pulse	-21	-57	33	25	33	0.54
TAC	HS3	1	ramp	-18	-32	40	40	20	0.68
TAC	HS3	4	1	-13	-25	60	33	0	0.91
TAC	HS3	4	3	-14	-25	50	50	0	0.83
TAC	HS3	4	4	-19	-33	40	40	20	0.58
TAC	HS3	4	6	-18	-29	37	55	0	0.61

TAC	HS3	4	7	-13	-24	55	25	0	0.93
TAC	HS3	4	pulse	-16	-57	50	23	25	0.63
TAC	HS3	4	ramp	-18	-26	40	50	0	0.90
TAC	HS3	6	1	-14	-26	50	40	0	0.93
TAC	HS3	6	3	-8	-26	60	33	0	0.97
TAC	HS3	6	4	-18	-30	40	40	8	0.95
TAC	HS3	6	6	-17	-40	40	40	20	0.47
TAC	HS3	6	7	-13	-25	50	33	0	0.96
TAC	HS3	6	pulse	-17	-55	40	25	25	0.63
TAC	HS3	6	ramp	-16	-25	50	50	0	0.92
TAC	HS3	7	1	-19	-46	45	25	33	0.86
TAC	HS3	7	3	-23	-63	33	33	33	0.83
TAC	HS3	7	4	-24	-50	25	25	37	0.63
TAC	HS3	7	6	-27	-62	33	25	45	0.61
TAC	HS3	7	7	-17	-59	50	33	25	0.60
TAC	HS3	7	pulse	-28	-58	25	25	50	0.44
TAC	HS3	7	ramp	-21	-74	25	40	25	0.49
TAC	HS3	10	1	-16	-34	45	37	20	0.75
TAC	HS3	10	3	-16	-31	50	40	25	0.74
TAC	HS3	10	4	-19	-43	33	33	25	0.86
TAC	HS3	10	6	-14	-45	50	33	20	0.51
TAC	HS3	10	7	-14	-25	60	25	0	0.80
TAC	HS3	10	pulse	-22	-42	40	20	33	0.64
TAC	HS3	10	ramp	-13	-30	60	25	10	0.67
TAC	HS3	12	1	-14	-31	50	33	17	0.92
TAC	HS3	12	3	-21	-34	33	50	25	0.87
TAC	HS3	12	4	-13	-30	50	25	8	0.58
TAC	HS3	12	6	-23	-46	25	42	25	0.48
TAC	HS3	12	7	-14	-26	50	33	0	0.90
TAC	HS3	12	pulse	-16	-44	40	25	20	0.73
TAC	HS3	12	ramp	-12	-27	60	25	0	0.91
TAC	HS3	13	1	-20	-39	40	33	25	0.57
TAC	HS3	13	3	-7	-45	67	17	33	0.69
TAC	HS3	13	4	-20	-39	50	27	33	0.72
TAC	HS3	13	6	-21	-39	33	45	33	0.43
TAC	HS3	13	7	-21	-43	33	37	29	0.53
TAC	HS3	13	pulse	-21	-38	33	33	20	0.64
TAC	HS3	13	ramp	-21	-52	40	25	25	0.56
TAC	HS3	15	1	-19	-37	37	37	25	0.65
TAC	HS3	15	3	-12	-62	50	17	25	0.58
TAC	HS3	15	4	-27	-49	25	25	37	0.51

TAC	HS3	15	6	-18	-55	33	27	29	0.52
TAC	HS3	15	7	-14	-26	55	33	0	0.86
TAC	HS3	15	pulse	-21	-37	27	50	23	0.65
TAC	HS3	15	ramp	-18	-39	45	29	33	0.63
TAE	HS1	1	1	-6	-14	100	0	0	1.00
TAE	HS1	1	3	-5	-19	80	20	0	1.00
TAE	HS1	1	4	-6	-15	85	15	0	1.00
TAE	HS1	1	6	-6	-18	83	17	0	1.00
TAE	HS1	1	7	-7	-15	100	0	0	1.00
TAE	HS1	1	pulse	-6	-14	100	0	0	1.00
TAE	HS1	1	ramp	-6	-14	100	0	0	1.00
TAE	HS1	4	1	-6	-15	92	8	0	1.00
TAE	HS1	4	3	-5	-19	80	20	0	1.00
TAE	HS1	4	4	-6	-15	93	7	0	1.00
TAE	HS1	4	6	-5	-17	85	15	0	1.00
TAE	HS1	4	7	-7	-15	100	0	0	1.00
TAE	HS1	4	pulse	-6	-14	100	0	0	1.00
TAE	HS1	4	ramp	-6	-15	100	0	0	1.00
TAE	HS1	6	1	-6	-15	100	0	0	1.00
TAE	HS1	6	3	-5	-19	80	20	0	1.00
TAE	HS1	6	4	-6	-16	82	18	0	1.00
TAE	HS1	6	6	-5	-17	85	15	0	1.00
TAE	HS1	6	7	-7	-15	100	0	0	1.00
TAE	HS1	6	pulse	-6	-15	100	0	0	1.00
TAE	HS1	6	ramp	-7	-15	93	0	0	1.00
TAE	HS1	7	1	-6	-15	93	7	0	1.00
TAE	HS1	7	3	-9	-15	100	0	0	1.00
TAE	HS1	7	4	-7	-17	83	17	0	1.00
TAE	HS1	7	6	-7	-18	82	18	0	1.00
TAE	HS1	7	7	-7	-16	83	17	0	1.00
TAE	HS1	7	pulse	-7	-16	80	20	0	1.00
TAE	HS1	7	ramp	-7	-16	83	15	0	1.00
TAE	HS1	10	1	-7	-15	93	7	0	1.00
TAE	HS1	10	3	-7	-15	100	0	0	1.00
TAE	HS1	10	4	-6	-17	83	17	0	1.00
TAE	HS1	10	6	-5	-18	83	17	0	1.00
TAE	HS1	10	7	-8	-16	83	17	0	1.00
TAE	HS1	10	pulse	-7	-15	100	0	0	1.00
TAE	HS1	10	ramp	-7	-16	80	18	0	1.00
TAE	HS1	12	1	-7	-14	100	0	0	1.00
TAE	HS1	12	3	-7	-15	80	20	0	1.00

TAE	HS1	12	4	-6	-17	82	17	0	1.00
TAE	HS1	12	6	-6	-19	83	17	0	1.00
TAE	HS1	12	7	-7	-15	86	7	0	1.00
TAE	HS1	12	pulse	-7	-15	85	7	0	1.00
TAE	HS1	12	ramp	-7	-16	80	20	0	1.00
TAE	HS1	13	1	-7	-17	83	17	0	1.00
TAE	HS1	13	3	-9	-14	100	0	0	1.00
TAE	HS1	13	4	-8	-19	80	20	0	1.00
TAE	HS1	13	6	-8	-16	83	17	0	1.00
TAE	HS1	13	7	-8	-17	80	20	0	1.00
TAE	HS1	13	pulse	-9	-17	80	20	0	1.00
TAE	HS1	13	ramp	-8	-18	80	20	0	1.00
TAE	HS1	15	1	-8	-17	82	10	0	1.00
TAE	HS1	15	3	-8	-14	100	0	0	1.00
TAE	HS1	15	4	-8	-18	80	20	0	1.00
TAE	HS1	15	6	-8	-17	85	15	0	1.00
TAE	HS1	15	7	-8	-16	80	18	0	1.00
TAE	HS1	15	pulse	-8	-17	80	20	0	1.00
TAE	HS1	15	ramp	-8	-17	80	20	0	1.00
TAE	HS1	16	1	-7	-17	82	18	0	1.00
TAE	HS1	16	3	-6	-15	100	0	0	1.00
TAE	HS1	16	4	-8	-18	82	17	0	1.00
TAE	HS1	16	6	-9	-23	78	20	0	1.00
TAE	HS1	16	7	-7	-13	100	0	0	1.00
TAE	HS1	16	pulse	-7	-16	83	14	0	1.00
TAE	HS1	16	ramp	-7	-17	80	20	0	1.00
TAE	HS1	17	1	-7	-16	80	20	0	1.00
TAE	HS1	17	3	-6	-15	100	0	0	1.00
TAE	HS1	17	4	-8	-17	80	20	0	1.00
TAE	HS1	17	6	-10	-19	80	18	0	1.00
TAE	HS1	17	7	-7	-14	100	0	0	1.00
TAE	HS1	17	pulse	-7	-15	100	0	0	1.00
TAE	HS1	17	ramp	-7	-15	93	0	0	1.00
TAE	HS1	18	1	-7	-16	83	17	0	1.00
TAE	HS1	18	3	-6	-15	100	0	0	0.99
TAE	HS1	18	4	-7	-18	83	17	0	0.99
TAE	HS1	18	6	-10	-18	82	18	0	1.00
TAE	HS1	18	7	-7	-15	100	0	0	1.00
TAE	HS1	18	pulse	-7	-16	80	17	0	1.00
TAE	HS1	18	ramp	-7	-17	80	20	0	1.00
TAE	HS2	1	1	-7	-16	93	7	0	1.00

TAE	HS2	1	3	-5	-13	100	0	0	1.00
TAE	HS2	1	4	-7	-17	83	17	0	1.00
TAE	HS2	1	6	-10	-21	73	27	0	0.99
TAE	HS2	1	7	-7	-14	100	0	0	1.00
TAE	HS2	1	pulse	-9	-19	80	20	0	1.00
TAE	HS2	1	ramp	-7	-15	83	0	0	1.00
TAE	HS3	1	1	-8	-15	90	0	0	1.00
TAE	HS3	1	3	-4	-14	100	0	0	1.00
TAE	HS3	1	4	-6	-16	80	20	0	1.00
TAE	HS3	1	6	-7	-13	100	0	0	1.00
TAE	HS3	1	7	-7	-15	100	0	0	1.00
TAE	HS3	1	pulse	-6	-13	100	0	0	1.00
TAE	HS3	1	ramp	-7	-14	100	0	0	1.00
TAE	HS3	4	1	-5	-13	100	0	0	1.00
TAE	HS3	4	3	-7	-13	100	0	0	1.00
TAE	HS3	4	4	-7	-15	92	0	0	1.00
TAE	HS3	4	6	-5	-14	100	0	0	1.00
TAE	HS3	4	7	-6	-15	92	8	0	1.00
TAE	HS3	4	pulse	-6	-14	100	0	0	1.00
TAE	HS3	4	ramp	-7	-15	100	0	0	1.00
TAE	HS3	6	1	-6	-13	100	0	0	1.00
TAE	HS3	6	3	-5	-16	60	40	0	1.00
TAE	HS3	6	4	-6	-17	80	18	0	1.00
TAE	HS3	6	6	-6	-14	100	0	0	1.00
TAE	HS3	6	7	-7	-15	93	0	0	1.00
TAE	HS3	6	pulse	-6	-14	100	0	0	1.00
TAE	HS3	6	ramp	-6	-15	100	0	0	1.00
TAE	HS3	7	1	-6	-17	85	15	0	1.00
TAE	HS3	7	3	-8	-17	80	20	0	1.00
TAE	HS3	7	4	-7	-16	86	14	0	1.00
TAE	HS3	7	6	-8	-17	83	17	0	1.00
TAE	HS3	7	7	-8	-16	80	20	0	1.00
TAE	HS3	7	pulse	-7	-17	80	17	0	1.00
TAE	HS3	7	ramp	-7	-17	80	20	0	1.00
TAE	HS3	10	1	-6	-15	93	7	0	1.00
TAE	HS3	10	3	-6	-16	80	20	0	1.00
TAE	HS3	10	4	-6	-18	85	15	0	1.00
TAE	HS3	10	6	-7	-16	93	7	0	1.00
TAE	HS3	10	7	-7	-15	83	15	0	1.00
TAE	HS3	10	pulse	-7	-16	80	17	0	1.00
TAE	HS3	10	ramp	-7	-15	82	18	0	1.00

TAE	HS3	12	1	-6	-16	85	15	0	1.00
TAE	HS3	12	3	-7	-17	83	17	0	1.00
TAE	HS3	12	4	-7	-15	93	7	0	1.00
TAE	HS3	12	6	-6	-17	86	14	0	1.00
TAE	HS3	12	7	-8	-15	85	7	0	1.00
TAE	HS3	12	pulse	-7	-16	83	17	0	1.00
TAE	HS3	12	ramp	-7	-14	100	0	0	1.00
TAE	HS3	13	1	-8	-18	80	18	0	1.00
TAE	HS3	13	3	-8	-14	100	0	0	1.00
TAE	HS3	13	4	-9	-17	80	20	0	1.00
TAE	HS3	13	6	-8	-16	85	15	0	1.00
TAE	HS3	13	7	-9	-18	80	20	0	1.00
TAE	HS3	13	pulse	-8	-18	80	20	0	1.00
TAE	HS3	13	ramp	-9	-19	80	20	0	1.00
TAE	HS3	15	1	-8	-17	80	20	0	1.00
TAE	HS3	15	3	-8	-15	100	0	0	1.00
TAE	HS3	15	4	-8	-17	78	23	0	1.00
TAE	HS3	15	6	-8	-16	85	15	0	1.00
TAE	HS3	15	7	-9	-16	88	13	0	1.00
TAE	HS3	15	pulse	-8	-17	80	20	0	1.00
TAE	HS3	15	ramp	-9	-18	80	20	0	1.00
TAE	HS3	16	1	-7	-16	92	0	0	1.00
TAE	HS3	16	3	-6	-12	100	0	0	1.00
TAE	HS3	16	4	-7	-19	83	17	0	1.00
TAE	HS3	16	6	-9	-20	83	17	0	0.99
TAE	HS3	16	7	-6	-13	100	0	0	1.00
TAE	HS3	16	pulse	-7	-17	80	17	0	1.00
TAE	HS3	16	ramp	-7	-16	83	17	0	1.00
TAE	HS3	17	1	-6	-15	100	0	0	1.00
TAE	HS3	17	3	-5	-11	100	0	0	1.00
TAE	HS3	17	4	-7	-17	83	17	0	1.00
TAE	HS3	17	6	-8	-19	83	17	0	1.00
TAE	HS3	17	7	-7	-14	100	0	0	1.00
TAE	HS3	17	pulse	-7	-16	80	17	0	1.00
TAE	HS3	17	ramp	-7	-16	82	17	0	1.00
TAE	HS3	18	1	-7	-15	92	0	0	1.00
TAE	HS3	18	3	-5	-12	100	0	0	1.00
TAE	HS3	18	4	-8	-17	80	20	0	1.00
TAE	HS3	18	6	-8	-19	80	18	0	1.00
TAE	HS3	18	7	-6	-13	100	0	0	1.00
TAE	HS3	18	pulse	-8	-16	82	17	0	1.00

TAE	HS3	18	ramp	-7	-16	85	7	0	1.00

Table A5. Same as Table A4 but for increases in TAC (or catch for TAE rules) between years.

Control	HS	HCR	SCN	Median Relative Increase in TAC between years across all runs (%)	Median Maximum Relative Increase in TAC between years across all runs (%)	Median of % of years where increase in TAC is 0-15%	Median of % of years where increase in TAC is 16-30%	Median of % of years where increase in TAC is >30%	PM5
TAC	HS1	1	1	12	43	50	25	25	0.66
TAC	HS1	1	3	14	41	50	20	20	0.72
TAC	HS1	1	4	23	53	33	23	33	0.67
TAC	HS1	1	6	15	53	42	27	33	0.67
TAC	HS1	1	7	12	82	60	0	25	0.55
TAC	HS1	1	pulse	20	45	40	25	25	0.58
TAC	HS1	1	ramp	17	42	40	25	25	0.60
TAC	HS1	4	1	14	41	50	25	20	0.65
TAC	HS1	4	3	11	36	50	17	20	0.68
TAC	HS1	4	4	20	44	45	25	25	0.50
TAC	HS1	4	6	22	53	40	18	33	0.43
TAC	HS1	4	7	21	91	40	20	40	0.42
TAC	HS1	4	pulse	17	40	40	25	25	0.68
TAC	HS1	4	ramp	16	41	40	25	25	0.63
TAC	HS1	6	1	17	39	40	29	25	0.74
TAC	HS1	6	3	11	29	50	33	0	0.81
TAC	HS1	6	4	18	43	40	25	25	0.87
TAC	HS1	6	6	18	54	40	25	29	0.44
TAC	HS1	6	7	21	92	40	17	40	0.43
TAC	HS1	6	pulse	18	42	40	25	25	0.65
TAC	HS1	6	ramp	15	40	50	25	25	0.67
TAC	HS1	7	1	16	39	50	23	23	0.80
TAC	HS1	7	3	23	61	33	40	40	0.66
TAC	HS1	7	4	19	49	37	29	33	0.53
TAC	HS1	7	6	23	70	33	25	37	0.39
TAC	HS1	7	7	25	151	40	18	50	0.34
TAC	HS1	7	pulse	14	41	50	18	33	0.63
TAC	HS1	7	ramp	15	49	50	20	20	0.63
TAC	HS1	10	1	14	41	59	20	20	0.47
TAC	HS1	10	3	11	35	80	14	17	0.58
TAC	HS1	10	4	17	57	45	23	33	0.63

TAC	HS1	10	6	18	54	29	25	37	0.56
TAC	HS1	10	7	21	149	40	20	40	0.37
TAC	HS1	10	pulse	17	42	50	25	29	0.57
TAC	HS1	10	ramp	15	47	50	23	25	0.63
TAC	HS1	12	1	17	42	40	40	20	0.54
TAC	HS1	12	3	15	29	50	0	0	0.54
TAC	HS1	12	4	16	55	50	25	25	0.46
TAC	HS1	12	6	23	63	33	33	33	0.43
TAC	HS1	12	7	20	154	40	20	40	0.37
TAC	HS1	12	pulse	16	44	45	20	33	0.65
TAC	HS1	12	ramp	15	44	50	25	25	0.64
TAC	HS1	13	1	29	49	25	23	45	0.51
TAC	HS1	13	3	16	50	50	17	40	0.50
TAC	HS1	13	4	27	63	25	29	50	0.57
TAC	HS1	13	6	23	56	33	33	42	0.45
TAC	HS1	13	7	33	222	25	20	50	0.29
TAC	HS1	13	pulse	20	45	33	0	33	0.55
TAC	HS1	13	ramp	26	46	25	25	40	0.60
TAC	HS1	15	1	28	60	29	20	37	0.52
TAC	HS1	15	3	30	53	40	20	60	0.51
TAC	HS1	15	4	25	68	20	37	45	0.45
TAC	HS1	15	6	22	45	37	40	25	0.54
TAC	HS1	15	7	24	215	40	0	50	0.33
TAC	HS1	15	pulse	23	52	33	25	33	0.47
TAC	HS1	15	ramp	24	53	25	27	33	0.50
TAC	HS3	1	1	17	50	55	23	25	0.44
TAC	HS3	1	3	18	92	33	25	33	0.53
TAC	HS3	1	4	25	56	33	20	45	0.73
TAC	HS3	1	6	25	136	37	0	50	0.41
TAC	HS3	1	7	21	88	40	20	45	0.41
TAC	HS3	1	pulse	18	56	50	25	25	0.42
TAC	HS3	1	ramp	17	59	50	25	33	0.44
TAC	HS3	4	1	15	30	45	25	10	0.47
TAC	HS3	4	3	16	29	50	25	0	0.49
TAC	HS3	4	4	20	48	45	23	40	0.45
TAC	HS3	4	6	18	47	38	20	25	0.41
TAC	HS3	4	7	20	103	40	20	37	0.43
TAC	HS3	4	pulse	15	40	50	20	25	0.66
TAC	HS3	4	ramp	14	36	50	25	20	0.54
TAC	HS3	6	1	14	39	50	20	20	0.50
TAC	HS3	6	3	20	32	25	25	25	0.69

TAC	HS3	6	4	20	46	37	25	25	0.62
TAC	HS3	6	6	27	56	10	27	45	0.38
TAC	HS3	6	7	18	96	40	20	31	0.45
TAC	HS3	6	pulse	17	41	45	25	25	0.70
TAC	HS3	6	ramp	15	38	54	25	20	0.72
TAC	HS3	7	1	20	125	45	20	37	0.50
TAC	HS3	7	3	20	164	40	20	40	0.62
TAC	HS3	7	4	20	88	33	23	37	0.42
TAC	HS3	7	6	26	110	33	29	50	0.39
TAC	HS3	7	7	38	161	25	0	60	0.39
TAC	HS3	7	pulse	29	148	25	20	50	0.43
TAC	HS3	7	ramp	21	264	40	20	40	0.42
TAC	HS3	10	1	15	55	50	20	25	0.40
TAC	HS3	10	3	22	70	50	29	25	0.45
TAC	HS3	10	4	19	66	42	25	33	0.59
TAC	HS3	10	6	22	71	23	29	37	0.43
TAC	HS3	10	7	24	151	37	20	40	0.37
TAC	HS3	10	pulse	21	62	33	25	33	0.46
TAC	HS3	10	ramp	15	75	50	20	25	0.44
TAC	HS3	12	1	14	45	55	20	20	0.42
TAC	HS3	12	3	20	46	33	40	33	0.52
TAC	HS3	12	4	19	40	37	20	33	0.45
TAC	HS3	12	6	24	112	40	20	40	0.43
TAC	HS3	12	7	21	154	50	20	33	0.37
TAC	HS3	12	pulse	15	36	50	25	25	0.60
TAC	HS3	12	ramp	15	43	50	25	20	0.56
TAC	HS3	13	1	29	67	25	25	50	0.39
TAC	HS3	13	3	13	105	33	0	50	0.43
TAC	HS3	13	4	28	66	25	25	50	0.42
TAC	HS3	13	6	39	132	25	8	63	0.39
TAC	HS3	13	7	46	223	25	20	63	0.38
TAC	HS3	13	pulse	24	60	33	0	50	0.41
TAC	HS3	13	ramp	32	131	25	25	50	0.38
TAC	HS3	15	1	27	79	25	25	33	0.40
TAC	HS3	15	3	32	108	33	20	50	0.43
TAC	HS3	15	4	31	112	25	18	50	0.42
TAC	HS3	15	6	33	81	0	23	71	0.42
TAC	HS3	15	7	21	229	37	21	33	0.33
TAC	HS3	15	pulse	20	66	33	20	37	0.42
TAC	HS3	15	ramp	29	68	25	23	50	0.42
TAE	HS1	1	1	7	19	35	0	0	0.97

TAE	HS1	1	3	7	16	40	0	0	0.97
TAE	HS1	1	4	6	14	35	0	0	0.97
TAE	HS1	1	6	5	14	30	0	0	0.98
TAE	HS1	1	7	8	24	75	17	0	0.92
TAE	HS1	1	pulse	7	18	80	0	0	0.98
TAE	HS1	1	ramp	7	18	80	17	0	0.98
TAE	HS1	4	1	7	19	30	0	0	0.97
TAE	HS1	4	3	7	18	30	0	0	0.97
TAE	HS1	4	4	7	14	30	0	0	0.99
TAE	HS1	4	6	6	14	35	0	0	0.99
TAE	HS1	4	7	8	24	75	17	0	0.92
TAE	HS1	4	pulse	6	17	85	0	0	0.99
TAE	HS1	4	ramp	7	15	100	0	0	0.99
TAE	HS1	6	1	7	19	30	0	0	0.99
TAE	HS1	6	3	7	18	30	0	0	0.99
TAE	HS1	6	4	6	15	35	0	0	0.99
TAE	HS1	6	6	5	15	30	0	0	0.96
TAE	HS1	6	7	8	24	75	17	0	0.92
TAE	HS1	6	pulse	6	15	100	0	0	0.99
TAE	HS1	6	ramp	7	18	80	0	0	0.99
TAE	HS1	7	1	8	17	30	5	0	0.96
TAE	HS1	7	3	8	26	30	10	0	0.96
TAE	HS1	7	4	6	10	30	0	0	0.93
TAE	HS1	7	6	6	17	30	5	0	0.94
TAE	HS1	7	7	9	24	71	20	0	0.92
TAE	HS1	7	pulse	7	14	100	0	0	0.99
TAE	HS1	7	ramp	7	16	80	0	0	0.99
TAE	HS1	10	1	7	20	30	5	0	0.94
TAE	HS1	10	3	7	26	30	10	0	0.93
TAE	HS1	10	4	7	13	30	0	0	0.93
TAE	HS1	10	6	6	16	40	5	0	0.96
TAE	HS1	10	7	9	25	75	17	0	0.90
TAE	HS1	10	pulse	7	18	80	17	0	0.98
TAE	HS1	10	ramp	7	18	80	8	0	0.98
TAE	HS1	12	1	8	21	40	5	0	0.97
TAE	HS1	12	3	8	25	30	10	0	0.96
TAE	HS1	12	4	6	13	30	0	0	0.98
TAE	HS1	12	6	6	15	30	0	0	0.98
TAE	HS1	12	7	9	26	75	20	0	0.90
TAE	HS1	12	pulse	7	19	75	17	0	0.97
TAE	HS1	12	ramp	7	18	83	0	0	0.98

TAE	HS1	13	1	7	16	35	5	0	0.98
TAE	HS1	13	3	7	29	30	10	0	0.99
TAE	HS1	13	4	8	15	30	0	0	0.99
TAE	HS1	13	6	7	12	30	0	0	0.99
TAE	HS1	13	7	10	24	67	25	0	0.90
TAE	HS1	13	pulse	7	18	75	20	0	0.98
TAE	HS1	13	ramp	7	17	75	0	0	0.98
TAE	HS1	15	1	7	16	25	0	0	0.97
TAE	HS1	15	3	7	29	30	10	0	0.95
TAE	HS1	15	4	8	19	25	5	0	0.97
TAE	HS1	15	6	6	15	30	0	0	0.97
TAE	HS1	15	7	9	26	75	20	0	0.89
TAE	HS1	15	pulse	7	18	80	0	0	0.97
TAE	HS1	15	ramp	8	18	75	18	0	0.97
TAE	HS1	16	1	8	17	30	10	0	0.96
TAE	HS1	16	3	9	25	35	0	0	0.99
TAE	HS1	16	4	7	17	35	0	0	0.99
TAE	HS1	16	6	9	18	35	5	0	0.99
TAE	HS1	16	7	7	22	75	17	0	0.94
TAE	HS1	16	pulse	7	15	83	0	0	0.99
TAE	HS1	16	ramp	7	16	92	0	0	0.98
TAE	HS1	17	1	7	18	30	10	0	0.99
TAE	HS1	17	3	8	23	30	0	0	0.99
TAE	HS1	17	4	6	18	30	5	0	0.99
TAE	HS1	17	6	6	18	25	0	0	0.99
TAE	HS1	17	7	8	22	75	17	0	0.94
TAE	HS1	17	pulse	6	15	83	0	0	0.98
TAE	HS1	17	ramp	7	16	82	0	0	0.99
TAE	HS1	18	1	8	18	25	10	0	0.99
TAE	HS1	18	3	9	23	20	10	0	0.97
TAE	HS1	18	4	7	17	30	5	0	0.98
TAE	HS1	18	6	6	23	30	5	0	0.96
TAE	HS1	18	7	8	22	75	17	0	0.92
TAE	HS1	18	pulse	6	19	80	0	0	0.98
TAE	HS1	18	ramp	7	17	80	0	0	0.98
TAE	HS2	1	1	8	21	75	0	0	0.97
TAE	HS2	1	3	6	15	100	0	0	0.96
TAE	HS2	1	4	7	19	75	0	0	0.97
TAE	HS2	1	6	6	12	100	0	0	0.98
TAE	HS2	1	7	7	23	75	17	0	0.94
TAE	HS2	1	pulse	8	21	75	20	0	0.95

TAE	HS2	1	ramp	7	15	100	0	0	0.98
TAE	HS3	1	1	-8	-15	78	0	0	1.00
TAE	HS3	1	3	-4	-14	100	0	0	1.00
TAE	HS3	1	4	-6	-16	100	0	0	1.00
TAE	HS3	1	6	-7	-13	93	0	0	1.00
TAE	HS3	1	7	8	23	75	17	0	0.93
TAE	HS3	1	pulse	7	14	92	0	0	0.99
TAE	HS3	1	ramp	6	15	100	0	0	0.99
TAE	HS3	4	1	-5	-13	80	0	0	1.00
TAE	HS3	4	3	-7	-13	60	25	20	1.00
TAE	HS3	4	4	-7	-15	90	0	0	1.00
TAE	HS3	4	6	-5	-14	80	18	0	1.00
TAE	HS3	4	7	9	16	75	25	0	0.98
TAE	HS3	4	pulse	6	18	82	0	0	0.99
TAE	HS3	4	ramp	6	18	83	0	0	0.99
TAE	HS3	6	1	-6	-13	80	0	0	1.00
TAE	HS3	6	3	-5	-16	100	0	0	1.00
TAE	HS3	6	4	-6	-17	100	0	0	1.00
TAE	HS3	6	6	-6	-14	79	17	0	1.00
TAE	HS3	6	7	8	24	75	17	0	0.92
TAE	HS3	6	pulse	6	15	86	0	0	0.99
TAE	HS3	6	ramp	6	15	100	0	0	0.99
TAE	HS3	7	1	-6	-17	90	0	0	1.00
TAE	HS3	7	3	-8	-17	67	0	0	1.00
TAE	HS3	7	4	-7	-16	100	0	0	1.00
TAE	HS3	7	6	-8	-17	82	8	0	1.00
TAE	HS3	7	7	10	24	67	18	0	0.91
TAE	HS3	7	pulse	8	18	80	0	0	0.98
TAE	HS3	7	ramp	8	16	83	0	0	0.98
TAE	HS3	10	1	-6	-15	80	10	0	1.00
TAE	HS3	10	3	-6	-16	67	20	0	1.00
TAE	HS3	10	4	-6	-18	100	0	0	1.00
TAE	HS3	10	6	-7	-16	82	0	0	1.00
TAE	HS3	10	7	9	24	71	20	0	0.90
TAE	HS3	10	pulse	7	16	83	0	0	0.98
TAE	HS3	10	ramp	7	15	82	0	0	0.99
TAE	HS3	12	1	-6	-16	80	8	0	1.00
TAE	HS3	12	3	-7	-17	67	20	0	1.00
TAE	HS3	12	4	-7	-15	80	10	0	1.00
TAE	HS3	12	6	-6	-17	92	0	0	1.00
TAE	HS3	12	7	9	26	75	20	0	0.90

TAE	HS3	12	pulse	7	16	80	0	0	0.99
TAE	HS3	12	ramp	7	16	80	0	0	0.99
TAE	HS3	13	1	-8	-18	75	0	0	1.00
TAE	HS3	13	3	-8	-14	75	25	0	1.00
TAE	HS3	13	4	-9	-17	80	0	0	1.00
TAE	HS3	13	6	-8	-16	90	0	0	1.00
TAE	HS3	13	7	9	25	67	25	0	0.90
TAE	HS3	13	pulse	7	18	80	0	0	0.98
TAE	HS3	13	ramp	8	18	80	17	0	0.98
TAE	HS3	15	1	-8	-17	78	0	0	1.00
TAE	HS3	15	3	-8	-15	75	0	0	1.00
TAE	HS3	15	4	-8	-17	75	0	0	1.00
TAE	HS3	15	6	-8	-16	78	0	0	1.00
TAE	HS3	15	7	5	18	90	10	0	1.00
TAE	HS3	15	pulse	7	18	80	20	0	0.97
TAE	HS3	15	ramp	8	18	75	20	0	0.98
TAE	HS3	16	1	-7	-16	90	0	0	1.00
TAE	HS3	16	3	-6	-12	75	0	0	1.00
TAE	HS3	16	4	-7	-19	75	10	0	1.00
TAE	HS3	16	6	-9	-20	58	33	0	0.99
TAE	HS3	16	7	7	21	75	17	0	0.97
TAE	HS3	16	pulse	8	18	75	20	0	0.97
TAE	HS3	16	ramp	7	16	80	0	0	0.98
TAE	HS3	17	1	-6	-15	82	0	0	1.00
TAE	HS3	17	3	-5	-11	75	0	0	1.00
TAE	HS3	17	4	-7	-17	75	10	0	1.00
TAE	HS3	17	6	-8	-19	83	17	0	1.00
TAE	HS3	17	7	8	22	75	0	0	0.94
TAE	HS3	17	pulse	7	17	83	0	0	0.98
TAE	HS3	17	ramp	7	15	82	0	0	0.98
TAE	HS3	18	1	-7	-15	80	0	0	1.00
TAE	HS3	18	3	-5	-12	75	0	0	1.00
TAE	HS3	18	4	-8	-17	88	0	0	1.00
TAE	HS3	18	6	-8	-19	80	0	0	1.00
TAE	HS3	18	7	8	22	75	17	0	0.94
TAE	HS3	18	pulse	7	19	75	17	0	0.98
TAE	HS3	18	ramp	7	19	80	8	0	0.98

Table A6. Performance of indicators relative to management objective 6 for each harvest strategy and harvest control rule across all iterations for each uncertainty scenario and the two fishing effort scenarios (pulse and ramp). HS refers to harvest strategy, HCR to harvest control rule, TRP to target reference points, F to fishing insity measured as 1-SPR, where 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. PM6 refers to performance metric 6, the median of the TRP/F ratio over all runs.

Control	HS	HCR	SCN	Median of the lowest 10% of the TRP/F ratio over all runs	Median of the lowest 95% of the TRP/F ratio over all runs	PM6
TAC	HS1	1	1	0.74	0.92	0.93
TAC	HS1	1	3	0.73	0.96	0.97
TAC	HS1	1	4	0.64	0.77	0.78
TAC	HS1	1	6	0.57	0.67	0.67
TAC	HS1	1	7	0.94	1.05	1.05
TAC	HS1	1	pulse	0.71	0.91	0.92
TAC	HS1	1	ramp	0.74	0.89	0.90
TAC	HS1	4	1	0.74	0.92	0.93
TAC	HS1	4	3	0.72	0.96	0.97
TAC	HS1	4	4	0.64	0.77	0.78
TAC	HS1	4	6	0.57	0.68	0.68
TAC	HS1	4	7	0.83	1.01	1.02
TAC	HS1	4	pulse	0.70	0.90	0.91
TAC	HS1	4	ramp	0.72	0.88	0.89
TAC	HS1	6	1	0.73	0.91	0.92
TAC	HS1	6	3	0.73	0.96	0.96
TAC	HS1	6	4	0.65	0.78	0.79
TAC	HS1	6	6	0.57	0.66	0.67
TAC	HS1	6	7	0.84	1.02	1.02
TAC	HS1	6	pulse	0.70	0.91	0.91
TAC	HS1	6	ramp	0.73	0.88	0.89
TAC	HS1	7	1	0.77	0.96	0.96
TAC	HS1	7	3	0.82	1.01	1.03
TAC	HS1	7	4	0.70	0.84	0.84
TAC	HS1	7	6	0.63	0.72	0.72
TAC	HS1	7	7	0.87	1.06	1.07
TAC	HS1	7	pulse	0.78	0.93	0.94
TAC	HS1	7	ramp	0.80	0.94	0.95
TAC	HS1	10	1	0.78	0.96	0.96
TAC	HS1	10	3	0.84	1.00	1.01
TAC	HS1	10	4	0.71	0.83	0.83

TAC	HS1	10	6	0.65	0.73	0.73
TAC	HS1	10	7	0.88	1.04	1.05
TAC	HS1	10	pulse	0.77	0.91	0.92
TAC	HS1	10	ramp	0.78	0.93	0.93
TAC	HS1	12	1	0.78	0.94	0.95
TAC	HS1	12	3	0.81	0.99	1.01
TAC	HS1	12	4	0.71	0.83	0.83
TAC	HS1	12	6	0.64	0.73	0.73
TAC	HS1	12	7	0.87	1.05	1.06
TAC	HS1	12	pulse	0.77	0.90	0.91
TAC	HS1	12	ramp	0.77	0.92	0.93
TAC	HS1	13	1	0.82	0.96	0.97
TAC	HS1	13	3	0.86	1.02	1.02
TAC	HS1	13	4	0.76	0.89	0.89
TAC	HS1	13	6	0.71	0.79	0.80
TAC	HS1	13	7	0.91	1.08	1.09
TAC	HS1	13	pulse	0.83	0.96	0.96
TAC	HS1	13	ramp	0.86	0.95	0.96
TAC	HS1	15	1	0.82	0.96	0.96
TAC	HS1	15	3	0.86	0.99	1.00
TAC	HS1	15	4	0.77	0.89	0.89
TAC	HS1	15	6	0.72	0.80	0.81
TAC	HS1	15	7	0.92	1.08	1.09
TAC	HS1	15	pulse	0.84	0.96	0.96
TAC	HS1	15	ramp	0.83	0.95	0.95
TAC	HS3	1	1	0.72	0.93	0.93
TAC	HS3	1	3	0.76	0.97	1.01
TAC	HS3	1	4	0.64	0.80	0.80
TAC	HS3	1	6	0.56	0.67	0.68
TAC	HS3	1	7	0.83	1.02	1.03
TAC	HS3	1	pulse	0.70	0.91	0.92
TAC	HS3	1	ramp	0.74	0.90	0.91
TAC	HS3	4	1	0.74	0.91	0.92
TAC	HS3	4	3	0.76	0.96	0.98
TAC	HS3	4	4	0.65	0.79	0.80
TAC	HS3	4	6	0.56	0.66	0.67
TAC	HS3	4	7	0.82	0.99	1.00
TAC	HS3	4	pulse	0.70	0.91	0.92
TAC	HS3	4	ramp	0.72	0.88	0.89
TAC	HS3	6	1	0.72	0.91	0.91
TAC	HS3	6	3	0.76	0.95	0.96

TAC	HS3	6	4	0.64	0.77	0.78
TAC	HS3	6	6	0.55	0.67	0.68
TAC	HS3	6	7	0.84	1.00	1.01
TAC	HS3	6	pulse	0.71	0.90	0.91
TAC	HS3	6	ramp	0.73	0.89	0.90
TAC	HS3	7	1	0.76	0.95	0.96
TAC	HS3	7	3	0.79	1.07	1.07
TAC	HS3	7	4	0.70	0.84	0.84
TAC	HS3	7	6	0.63	0.72	0.72
TAC	HS3	7	7	0.89	1.06	1.07
TAC	HS3	7	pulse	0.78	0.93	0.94
TAC	HS3	7	ramp	0.80	0.95	0.96
TAC	HS3	10	1	0.77	0.94	0.95
TAC	HS3	10	3	0.79	1.02	1.03
TAC	HS3	10	4	0.70	0.83	0.83
TAC	HS3	10	6	0.64	0.72	0.72
TAC	HS3	10	7	0.88	1.05	1.06
TAC	HS3	10	pulse	0.77	0.91	0.92
TAC	HS3	10	ramp	0.78	0.94	0.94
TAC	HS3	12	1	0.76	0.94	0.95
TAC	HS3	12	3	0.77	1.03	1.03
TAC	HS3	12	4	0.71	0.84	0.84
TAC	HS3	12	6	0.63	0.73	0.73
TAC	HS3	12	7	0.88	1.06	1.06
TAC	HS3	12	pulse	0.78	0.90	0.91
TAC	HS3	12	ramp	0.77	0.92	0.93
TAC	HS3	13	1	0.82	0.96	0.97
TAC	HS3	13	3	0.85	1.02	1.03
TAC	HS3	13	4	0.77	0.88	0.89
TAC	HS3	13	6	0.71	0.83	0.83
TAC	HS3	13	7	0.92	1.09	1.11
TAC	HS3	13	pulse	0.83	0.96	0.96
TAC	HS3	13	ramp	0.85	0.95	0.96
TAC	HS3	15	1	0.83	0.97	0.97
TAC	HS3	15	3	0.84	1.02	1.02
TAC	HS3	15	4	0.77	0.88	0.88
TAC	HS3	15	6	0.72	0.82	0.82
TAC	HS3	15	7	0.94	1.08	1.08
TAC	HS3	15	pulse	0.84	0.96	0.96
TAC	HS3	15	ramp	0.83	0.94	0.95
TAE	HS1	1	1	0.82	0.93	0.93

TAE	HS1	1	3	0.82	0.97	0.98
TAE	HS1	1	4	0.71	0.87	0.88
TAE	HS1	1	6	0.61	0.85	0.86
TAE	HS1	1	7	0.83	0.90	0.91
TAE	HS1	1	pulse	0.79	0.92	0.93
TAE	HS1	1	ramp	0.82	0.91	0.91
TAE	HS1	4	1	0.83	0.93	0.93
TAE	HS1	4	3	0.82	0.97	0.97
TAE	HS1	4	4	0.70	0.87	0.87
TAE	HS1	4	6	0.61	0.85	0.85
TAE	HS1	4	7	0.83	0.90	0.90
TAE	HS1	4	pulse	0.77	0.92	0.92
TAE	HS1	4	ramp	0.82	0.90	0.91
TAE	HS1	6	1	0.82	0.92	0.93
TAE	HS1	6	3	0.81	0.98	0.98
TAE	HS1	6	4	0.70	0.87	0.87
TAE	HS1	6	6	0.62	0.85	0.85
TAE	HS1	6	7	0.83	0.90	0.90
TAE	HS1	6	pulse	0.77	0.92	0.92
TAE	HS1	6	ramp	0.80	0.90	0.91
TAE	HS1	7	1	0.84	0.94	0.94
TAE	HS1	7	3	0.85	0.99	0.99
TAE	HS1	7	4	0.79	0.89	0.89
TAE	HS1	7	6	0.72	0.87	0.88
TAE	HS1	7	7	0.87	0.95	0.95
TAE	HS1	7	pulse	0.85	0.93	0.94
TAE	HS1	7	ramp	0.84	0.93	0.93
TAE	HS1	10	1	0.85	0.94	0.94
TAE	HS1	10	3	0.86	0.99	0.99
TAE	HS1	10	4	0.78	0.89	0.89
TAE	HS1	10	6	0.72	0.87	0.88
TAE	HS1	10	7	0.86	0.93	0.94
TAE	HS1	10	pulse	0.85	0.93	0.93
TAE	HS1	10	ramp	0.84	0.92	0.92
TAE	HS1	12	1	0.84	0.94	0.94
TAE	HS1	12	3	0.85	0.99	0.99
TAE	HS1	12	4	0.78	0.89	0.89
TAE	HS1	12	6	0.72	0.87	0.87
TAE	HS1	12	7	0.86	0.93	0.93
TAE	HS1	12	pulse	0.85	0.93	0.93
TAE	HS1	12	ramp	0.84	0.92	0.92

TAE	HS1	13	1	0.89	0.95	0.95
TAE	HS1	13	3	0.92	0.99	0.99
TAE	HS1	13	4	0.84	0.91	0.91
TAE	HS1	13	6	0.80	0.91	0.91
TAE	HS1	13	7	0.89	0.97	0.98
TAE	HS1	13	pulse	0.89	0.95	0.95
TAE	HS1	13	ramp	0.88	0.94	0.94
TAE	HS1	15	1	0.89	0.95	0.95
TAE	HS1	15	3	0.94	0.99	0.99
TAE	HS1	15	4	0.84	0.91	0.91
TAE	HS1	15	6	0.80	0.91	0.91
TAE	HS1	15	7	0.89	0.96	0.96
TAE	HS1	15	pulse	0.89	0.94	0.95
TAE	HS1	15	ramp	0.88	0.93	0.94
TAE	HS1	16	1	0.83	0.92	0.93
TAE	HS1	16	3	0.80	0.92	0.93
TAE	HS1	16	4	0.88	0.99	0.99
TAE	HS1	16	6	0.92	1.05	1.05
TAE	HS1	16	7	0.69	0.76	0.77
TAE	HS1	16	pulse	0.84	0.92	0.92
TAE	HS1	16	ramp	0.82	0.91	0.91
TAE	HS1	17	1	0.82	0.90	0.90
TAE	HS1	17	3	0.80	0.92	0.93
TAE	HS1	17	4	0.88	0.99	0.99
TAE	HS1	17	6	0.92	1.03	1.04
TAE	HS1	17	7	0.68	0.78	0.78
TAE	HS1	17	pulse	0.83	0.90	0.91
TAE	HS1	17	ramp	0.82	0.90	0.90
TAE	HS1	18	1	0.83	0.92	0.92
TAE	HS1	18	3	0.79	0.90	0.90
TAE	HS1	18	4	0.87	0.95	0.95
TAE	HS1	18	6	0.93	1.04	1.04
TAE	HS1	18	7	0.70	0.78	0.78
TAE	HS1	18	pulse	0.84	0.91	0.91
TAE	HS1	18	ramp	0.82	0.90	0.90
TAE	HS2	1	1	1.19	1.32	1.32
TAE	HS2	1	3	1.28	1.49	1.50
TAE	HS2	1	4	1.08	1.21	1.21
TAE	HS2	1	6	0.93	1.02	1.03
TAE	HS2	1	7	1.92	2.13	2.14
TAE	HS2	1	pulse	1.01	1.11	1.11

TAE	HS2	1	ramp	1.17	1.28	1.28
TAE	HS3	1	1	0.64	0.85	0.87
TAE	HS3	1	3	0.86	0.98	0.99
TAE	HS3	1	4	0.70	0.87	0.87
TAE	HS3	1	6	0.64	0.85	0.86
TAE	HS3	1	7	0.83	0.91	0.91
TAE	HS3	1	pulse	0.77	0.92	0.92
TAE	HS3	1	ramp	0.80	0.91	0.91
TAE	HS3	4	1	0.81	0.92	0.93
TAE	HS3	4	3	0.82	0.97	0.98
TAE	HS3	4	4	0.70	0.87	0.87
TAE	HS3	4	6	0.65	0.85	0.86
TAE	HS3	4	7	0.83	0.89	0.90
TAE	HS3	4	pulse	0.78	0.92	0.93
TAE	HS3	4	ramp	0.81	0.90	0.90
TAE	HS3	6	1	0.80	0.92	0.93
TAE	HS3	6	3	0.81	0.97	0.98
TAE	HS3	6	4	0.70	0.87	0.87
TAE	HS3	6	6	0.62	0.85	0.85
TAE	HS3	6	7	0.83	0.90	0.90
TAE	HS3	6	pulse	0.77	0.92	0.92
TAE	HS3	6	ramp	0.81	0.91	0.91
TAE	HS3	7	1	0.86	0.94	0.95
TAE	HS3	7	3	0.86	0.99	1.00
TAE	HS3	7	4	0.78	0.89	0.90
TAE	HS3	7	6	0.72	0.88	0.89
TAE	HS3	7	7	0.87	0.95	0.96
TAE	HS3	7	pulse	0.85	0.94	0.94
TAE	HS3	7	ramp	0.84	0.93	0.93
TAE	HS3	10	1	0.86	0.94	0.94
TAE	HS3	10	3	0.89	0.99	0.99
TAE	HS3	10	4	0.78	0.89	0.89
TAE	HS3	10	6	0.72	0.88	0.88
TAE	HS3	10	7	0.86	0.93	0.94
TAE	HS3	10	pulse	0.85	0.93	0.93
TAE	HS3	10	ramp	0.84	0.92	0.92
TAE	HS3	12	1	0.85	0.94	0.94
TAE	HS3	12	3	0.89	0.98	0.99
TAE	HS3	12	4	0.77	0.89	0.89
TAE	HS3	12	6	0.72	0.87	0.88
TAE	HS3	12	7	0.86	0.93	0.93

TAE	HS3	12	pulse	0.85	0.93	0.93
TAE	HS3	12	ramp	0.84	0.92	0.92
TAE	HS3	13	1	0.88	0.95	0.95
TAE	HS3	13	3	0.90	0.99	0.99
TAE	HS3	13	4	0.84	0.91	0.91
TAE	HS3	13	6	0.80	0.91	0.91
TAE	HS3	13	7	0.89	0.97	0.98
TAE	HS3	13	pulse	0.90	0.95	0.95
TAE	HS3	13	ramp	0.88	0.94	0.94
TAE	HS3	15	1	0.88	0.95	0.95
TAE	HS3	15	3	0.91	0.99	0.99
TAE	HS3	15	4	0.84	0.91	0.91
TAE	HS3	15	6	0.80	0.91	0.91
TAE	HS3	15	7	0.90	0.96	0.96
TAE	HS3	15	pulse	0.89	0.94	0.95
TAE	HS3	15	ramp	0.87	0.93	0.94
TAE	HS3	16	1	0.85	0.94	0.94
TAE	HS3	16	3	0.79	0.90	0.91
TAE	HS3	16	4	0.88	0.99	1.00
TAE	HS3	16	6	0.93	1.05	1.05
TAE	HS3	16	7	0.68	0.76	0.76
TAE	HS3	16	pulse	0.83	0.93	0.93
TAE	HS3	16	ramp	0.84	0.93	0.94
TAE	HS3	17	1	0.84	0.92	0.93
TAE	HS3	17	3	0.79	0.92	0.92
TAE	HS3	17	4	0.87	0.97	0.97
TAE	HS3	17	6	0.92	1.03	1.03
TAE	HS3	17	7	0.70	0.79	0.79
TAE	HS3	17	pulse	0.85	0.93	0.93
TAE	HS3	17	ramp	0.83	0.90	0.91
TAE	HS3	18	1	0.82	0.91	0.91
TAE	HS3	18	3	0.79	0.91	0.91
TAE	HS3	18	4	0.88	0.97	0.98
TAE	HS3	18	6	0.95	1.06	1.06
TAE	HS3	18	7	0.70	0.78	0.78
TAE	HS3	18	pulse	0.84	0.91	0.91
TAE	HS3	18	ramp	0.82	0.90	0.90