IPHC Secretariat MSE Program of Work (2022–2023) and an update on progress

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PURPOSE

To provide the Scientific Review Board (SRB) with an update of progress on the Management Strategy Evaluation (MSE) program of work for 2022–2023.

1 INTRODUCTION

The current interim management procedure (MP) at the International Pacific Halibut Commission (IPHC) is shown in Figure 1.

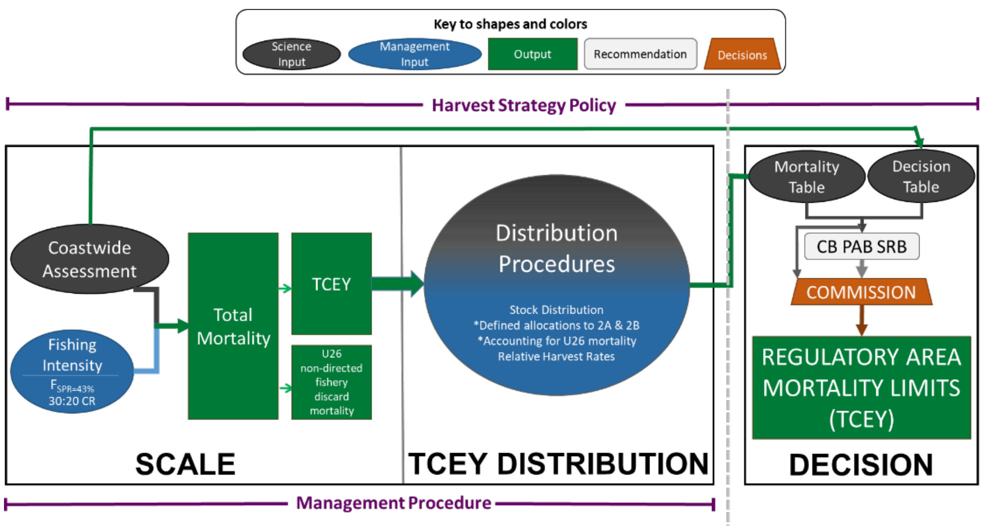

Figure 1. Illustration of the Commission interim IPHC harvest strategy policy (reflecting paragraph ID002 in IPHC-2020-CR-007) showing the coastwide scale and TCEY distribution components that comprise the management procedure. Items with an asterisk are interim agreements in place through 2022. The decision component is the Commission decision-making procedure, which considers inputs from many sources.

The Management Strategy Evaluation (MSE) at the IPHC completed an evaluation in 2021 of management procedures (MPs) relative to the coastwide scale and distribution of the Total Constant Exploitation Yield (TCEY) to IPHC Regulatory Areas for the Pacific halibut fishery using a recently developed closed-loop simulation framework. The development of this closed-loop simulation framework supports the evaluation of the trade-offs between fisheries management scenarios. Descriptions of the MPs evaluated and simulation results are presented in Hicks et al. (2021). Additional tasks were identified at the 11th Special Session of the IPHC (IPHC-2021-SS011-R) to supplement and extend this analysis for future evaluation (Table 1). Document IPHC-2021-MSE-02 contains details of the current MSE Program of Work.

Table 1. Tasks recommended by the Commission at SS011 (IPHC-2021-SS011-R para 7) for inclusion in the IPHC Secretariat MSE Program of Work for 2021–2023.

ID	Category	Task	Deliverable
F.1	Framework	Develop migration scenarios	Develop OMs with alternative migration scenarios
F.2	Framework	Implementation variability	Incorporate additional sources of implementation variability in the framework
F.3	Framework	Develop more realistic simulations of estimation error	Improve the estimation model to more adequately mimic the ensemble stock assessment
F.5	Framework	Develop alternative OMs	Code alternative OMs in addition to the one already under evaluation.
M.1	MPs	Size limits	Identification, evaluation of size limits
M.3	MPs	Multi-year assessments	Evaluation of multi-year assessments
E.3	Evaluation	Presentation of results	Develop methods and outputs that are useful for presenting outcomes to stakeholders and Commissioners

This document provides updates on the progress for the framework related tasks and the MP related tasks. Potential improvements to the evaluation and presentation of results are provided in this document and work will continue in 2022 with input from the MSAB.

2 Closed-Loop Simulation Framework

The closed-loop framework (Figure 2) with a multi-area operating model (OM) and three options for examining estimation error was initially described in Hicks et al. (2020b). Technical details are updated as needed in IPHC-2022-MSE-01 on the IPHC MSE webpage. Improvements to the framework have been made in accordance with this program of work and a new OM has been developed.

2.1 Development of a new Operating Model

The IPHC stock assessment (Stewart & Hicks 2022) consists of four stock synthesis models integrated into an ensemble to provide probabilistic management advice accounting for observation, process, and structural uncertainty. A similar approach was taken when developing the models for the closed-loop simulation framework along with some other specifications to improve the efficiency when conditioning models and running simulations.

2.1.1 General specifications of the OM

The emerging understanding of Pacific halibut diversity across the geographic range of its stock indicates that IPHC Regulatory Areas should be only considered as management units and do not represent relevant sub-populations (Seitz et al. 2017). Therefore, four Biological Regions (Figure 3) were defined with boundaries that matched some of the IPHC Regulatory Area boundaries (see Hicks et al 2020b for more description). The OM is a multi-regional model with population dynamics modelled within and between each Biological Region, and fisheries mostly operating at the IPHC Regulatory Area scale. Multiple fisheries within a Biological Region may have different selectivity and retention patterns to mimic differences similar to that of areas-as-fleets approach. Thirty-three fisheries were defined for five general sectors consistent with the definitions in the recent IPHC stock assessment:

- **directed commercial** representing the O32 mortality from the directed commercial fisheries including O32 discard mortality (from lost gear or regulatory compliance);
- **directed commercial discard** representing the U32 discard mortality from the directed commercial fisheries, comprised of Pacific halibut discarded due to the minimum size limit;
- **non-directed commercial discard** representing the mortality from incidentally caught Pacific halibut in non-directed commercial fisheries;
- **recreational** representing recreational landings (including landings from commercial leasing) and recreational discard mortality; and
- **subsistence** representing non-commercial, customary, and traditional use of Pacific halibut for direct personal, family, or community consumption or sharing as food, or customary trade.

Additionally, there are four modelled surveys, one for each Biological Region.

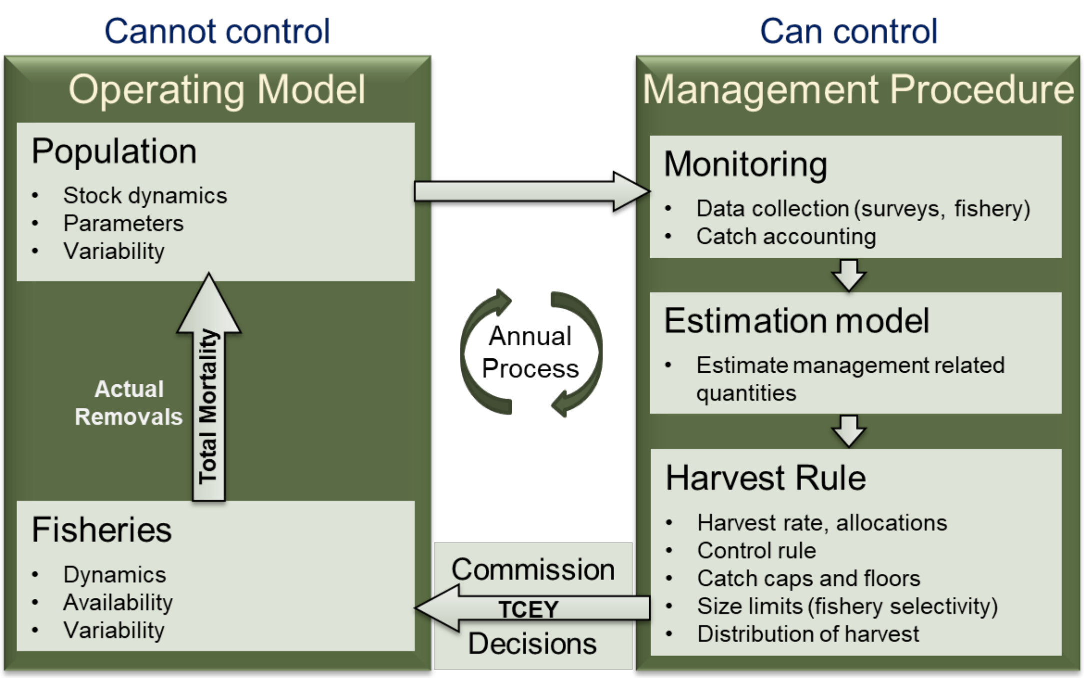

Figure 2. Illustration of the closed-loop simulation framework with the operating model (OM) and the Management Procedure (MP). This is the annual process on a yearly timescale.

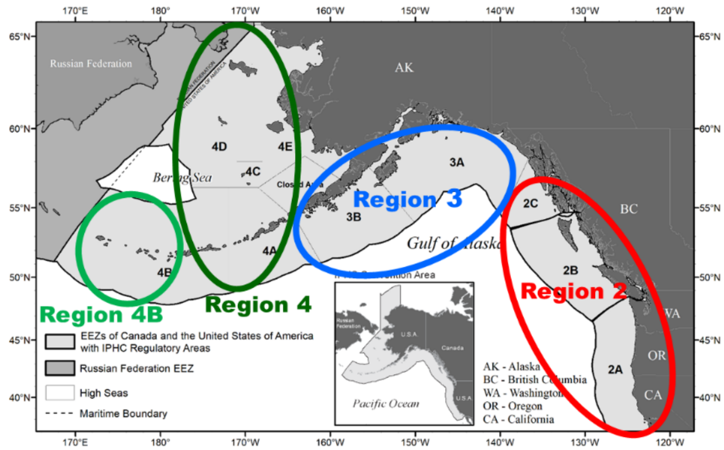

Figure 3. IPHC Regulatory Areas, Biological Regions, and the Pacific halibut geographical range within the territorial waters of Canada and the United States of America.

Two of the four models in the IPHC stock assessment (Stewart & Hicks 2022) consider a long time-series of observations beginning in 1888. One model specifies coastwide fisheries (called the coastwide (CW) long model) and the other model specifies four regions in an areas-as-fleets approach (called the areas-as-fleets (AAF) long model). The previous MSE OM also started in 1888 and simulated the entire time-series up to recent years before starting the forward simulations. However, the early portion of the time-series is challenging to model due to relatively little data, some significant catches in Biological Region 2, and the potential for unknown differences in population dynamics (e.g. movement between Biological Regions) compared to recent periods. To reduce the technical complexity and focus on information contained in the richer data set in the later period, the 2022 OM models were started in 1958. In order to allow for flexible starting conditions, 30 years of initial recruitment and an average fishing mortality were estimated for each fleet. This initialized the models after a bottleneck of potentially high fishing mortality in the 1930's that is confounded with the estimation of movement, yet allowed for a sufficient period of time to burn-in the population such that projections began with at an appropriate state. The period from 1958 to the present includes major changes in fishery catches, weight-at-age in the population, and population size.

2.1.2 Conditioning the OM and incorporating variability

The OM was parameterised and conditioned using two methods, resulting in two models to be integrated into a single OM. The first model was parameterised from and conditioned to results from the long AAF stock assessment model. The second model was parameterised from and conditioned using results from the long CW stock assessment model. Because these two OM models started in 1958, they are called the medium AAF (medAAF) and medium CW (medCW) models.

Many parameters used in the OM models were drawn from the corresponding stock assessment model. Natural mortality was fixed in each model, separately for males and females. Maturity, mean weight-at-age, recruitment deviations, the relationship between R_0 and the Pacific Decadal Oscillation (PDO), selectivity, and fishing mortality were fixed at the values from the stock assessment.

Parameters estimated during conditioning included

- R_0: initial average recruitment for the low PDO period;
- multinomial logit parameters for recruitment distribution among Biological Regions: there are 6 parameters, 3 defining the proportion among Biological Regions and 3 adjusting those parameters in high PDO years to change the distribution of age-0 recruits;
- a multiplier on initial fishing mortality: increased or decreased the initial fishing mortality input to initialize the population;
- movement from Biological Region 4 to Biological Region 3 (5 parameters) and movement from Biological Region 3 to Biological Region 2 (5 parameters), which were estimated for low PDO and high PDO periods (thus 20 total parameters).

There is considerable confounding between the recruitment distribution and movement parameters (which was evident during the conditioning process), thus some parameters for movement between Biological Regions were fixed at values estimated from previous analyses (see Figure 3 in Hicks et al 2020). The previous OM estimated considerably higher movement rates-at-age from region 2 back to region 3, which was unexpected. Fixing movement from 2 to 3 at values estimated directly from data resulted in more stable estimation with similar outputs.

The models were conditioned to five general sources of information:

- Historical spawning biomass estimated from the corresponding stock assessment. For example, the medAAF model was conditioned to the spawning biomass estimates from 1958 to 1992 from the 2021 long AAF stock assessment model.
- Recent ensemble spawning biomass from the corresponding spatial structure of the stock assessment. For example, the medCW model was conditioned to the spawning biomass estimates from 1993 to 2021 from the integration of the 2021 long CW and short CW stock assessment models.
- Fishery Independent Setline Survey (FISS) indices of abundance for each Biological Region.
- FISS estimates of proportions-at-age for each Biological Region. This component was downweighted compared to other components.
- Proportion of all-sizes weight-per-unit-effort (WPUE) in each Biological Region from the space-time model analysis of FISS observations. This is also called stock distribution and was given the highest weight as this is an important component for the OMs to mimic.

The conditioning was heavily weighted to the stock distribution and spawning biomass components. The goal was to have models adequately predicting stock distribution and spawning biomass in recent years, with some variability.

Even though many parameters were fixed when conditioning the models, variability was propagated from the estimated as well as some fixed parameters. Variances and covariances of parameters estimated in the conditioning process were estimated from the inverse of the Hessian. However, due to multicollinearity and difficulty in finding optimal solutions when all parameters were estimated[1], some parameters were fixed to estimate the Hessian and then supplied a small variance. Variability and correlations for some parameters fixed in the conditioning process were estimated from the stock assessment. This included natural mortality for each sex, recruitment deviations, and steepness (the long stock assessment models were run with a broad prior on steepness only to determine variability in steepness through estimation of the Hessian). The covariance matrices from the conditioning and assessment models were combined without accounting for correlation in parameters between the two sources, but correlations between parameters were accounted for within each source.

The combined covariance matrix was used to sample from a truncated multivariate normal distribution to provide replicate parameter sets for each OM model, providing multiple trajectories from 1958 through 2021 for each model. Bounds were enforced on some parameters, hence the truncated multivariate normal distribution. For example, steepness was bounded between 0.6 and 0.98, probability parameters associated with movement parameterizations were bounded between 0 and 1, and the natural log of recruitment deviations were bounded between -4 and 4. In a few uncommon cases, the standard deviation of a parameter had to be reduced because it was often exceeding a bound (e.g. probability parameters near zero). Parameter sets that resulted in unrealistically low population sizes or extremely poor fits to stock distribution or spawning biomass were rejected. The likelihood thresholds were arbitrarily based on visual fits to the data and investigation of outputs at various likelihood values. This is required because some correlations between parameters are not accounted for that could result in unrealistic combinations.

2.1.3 OM results and outputs

The two OM models showed important structural differences in terms of movement rates-at-age, recruitment distribution, and historical spawning biomass trends. The long AAF and long CW stock assessment models, which are the basis for conditioning each OM model, estimate significantly different historical spawning biomass trajectories before the early 2000s and subtle differences in recent trajectories (Figure 4). These differences are attributable to the very different assumptions about how the stock was distributed and connected via movement in relation to historical fishing mortality, and it is important to capture these differences through movement in the OM.

The two OM models (medAAF and medCW) generally captured these trends in spawning biomass (Figure 5). The uncertainty in the OM also spanned the 2021 ensemble stock assessment uncertainty, except for the low spawning biomass values prior to 2007. Recent spawning biomass was similar between the OM and the stock assessment, with the OM exceeding the upper quantiles of spawning biomass slightly.

[1] The function ‘optim’ was used in R with abrupt penalties enforced when spawning biomass was predicted below a small inconceivable value or when parameters were out of pre-specified bounds.

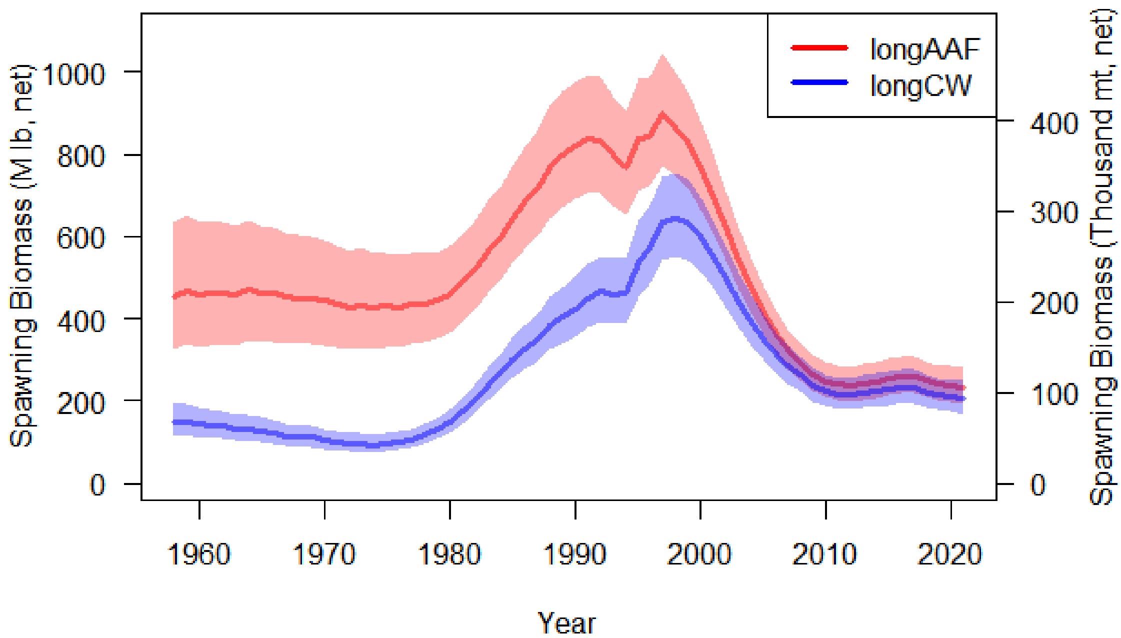

Figure 4. Estimated spawning biomass trajectories from 1958 to 2021 from the 2021 long AAF and long CW stock assessment models (Stewart & Hicks 2022).

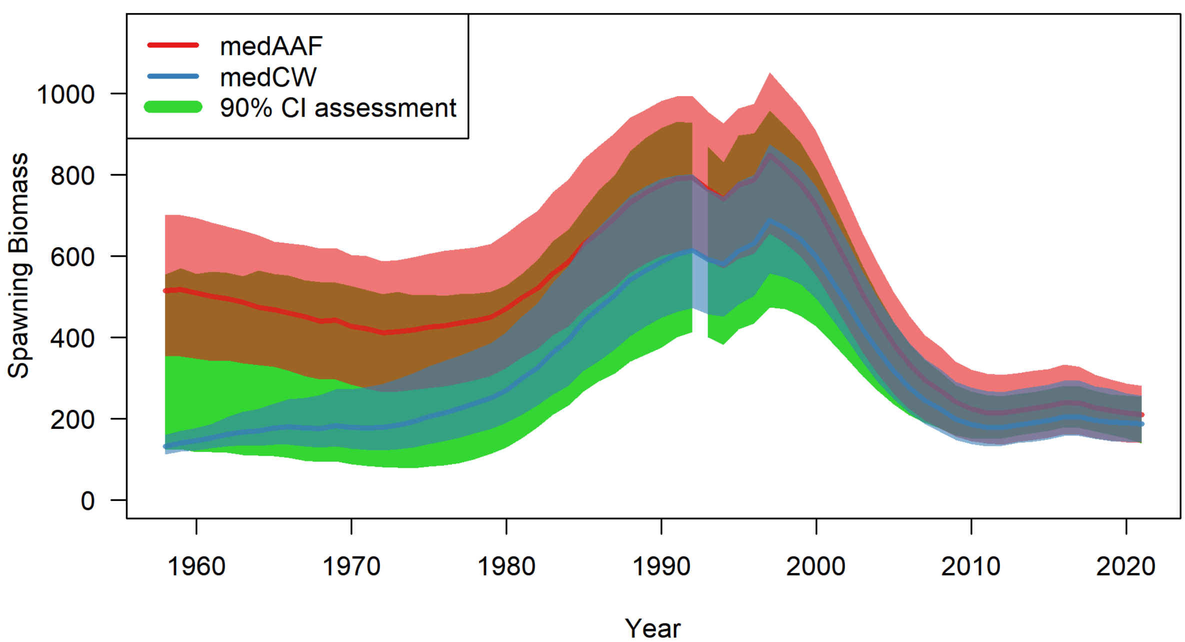

Figure 5. Median, 5th, and 95th quantiles for the medAAF OM model (red) and the medCW OM model (blue). The region between the 5th and 95th quantiles from the 2021 ensemble stock assessment are shown shaded in green.

Stock distribution was fit well by both OM models (Figure 6) and showed very similar patterns of lack of fit for both models in some years. Specifically, the earliest years in Biological Region 4 were overfit by the OM, and recent years overfit in Biological Region 3 corresponding with a slight underfitting in region 4. Both OMs predicted a faster increase in Biological Region 3 since 2018 than the data, but matched closely with the proportion of biomass observed in 2021.

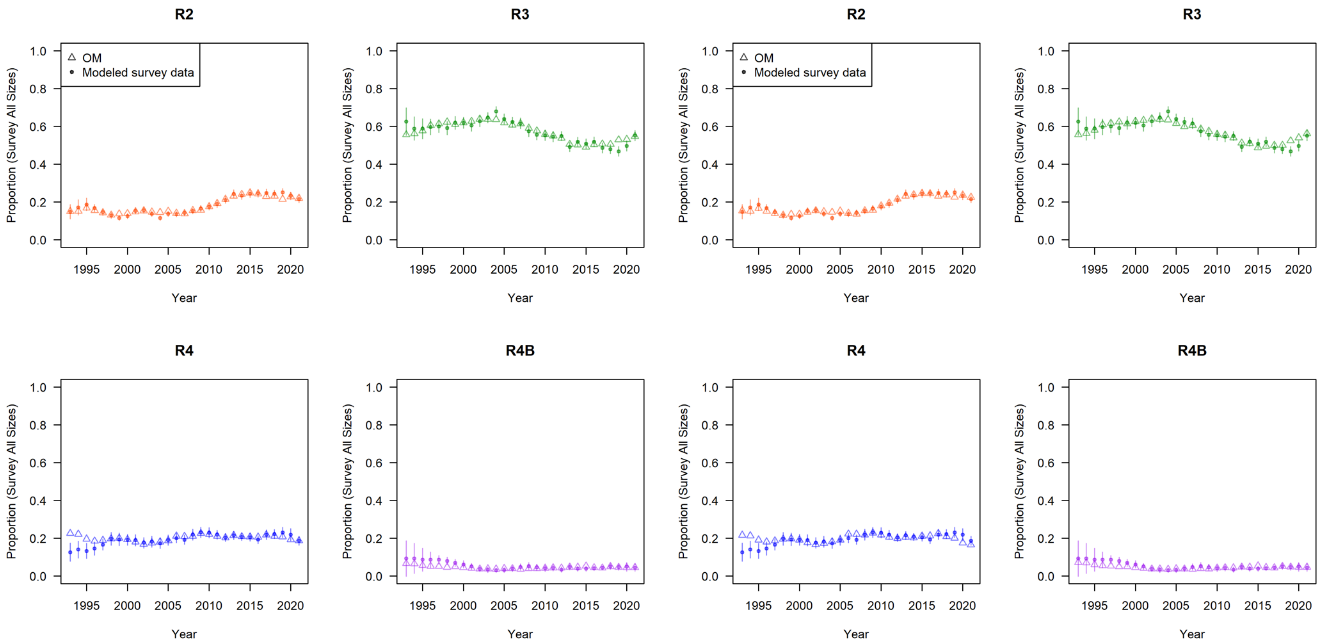

Figure 6. Fits to stock distribution across Biological Regions for each OM model (medAAF on the left and medCW on the right).

Distributions used for sex-specific natural mortality (*M*) and steepness were similar for the two models (Figure 7 and Figure 8). Female natural mortality did not encompass the value of 0.15, which was value fixed at in the two 2021 short stock assessment models, and an improvement to the OM may be to include models with lower *M* values. However, preliminary results from the development of the 2022 stock assessment (see IPHC-2022-SRB020-07) suggest that *M* may be estimated in the short AAF model, and the resulting value is greater than 0.15.

The distribution of age-0 recruits showed a high proportion going to Biological Region 4 in both low and high PDO regimes. Sadorus et al. (2020) found that recruits were more likely to end up in the Bering Sea in “warm years” for most spawning areas in the Gulf of Alaska. Furthermore, “cold years” were likely to have less dispersal to the west in the Bering Sea and “warm years” were more likely to have more dispersal to the northwest from spawning in the Western Gulf of Alaska. The medCW showed a higher proportion of recruits going to Biological Region 4 in high PDO years, but the medAAF model showed a slightly smaller proportion (Figure 9). The variability in the medCW model was smaller than in the medAAF model.

Movement rates between Biological Regions 3 and 2, and Biological Regions 4 and 3 were different between the two OMs (Figure 10). Both models generally showed high movement rates around ages 4 and 5 and slight differences between low and high PDO periods. Movement of fish younger than age 4 was very small from Biological Region 4 to 3 for both models and regimes, but there are few observations of fish younger than age 6 and a number of different movement rates of very young fish in combination with ages 4–7 could achieve similar results.

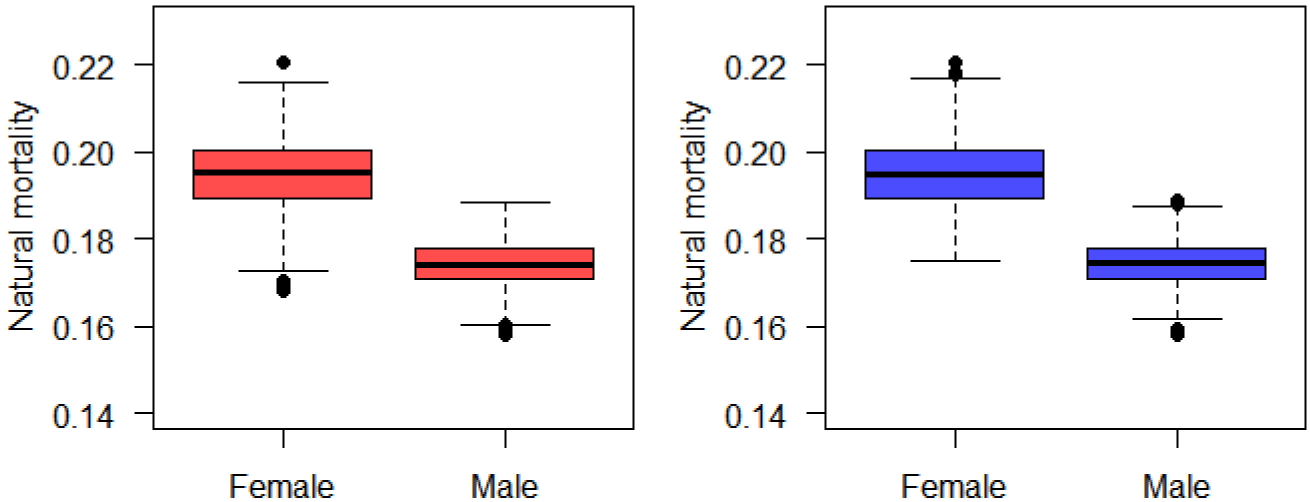

Figure 7. Natural mortality (*M*) distributions used to create multiple trajectories of the medAAF (left) and medCW (right) models.

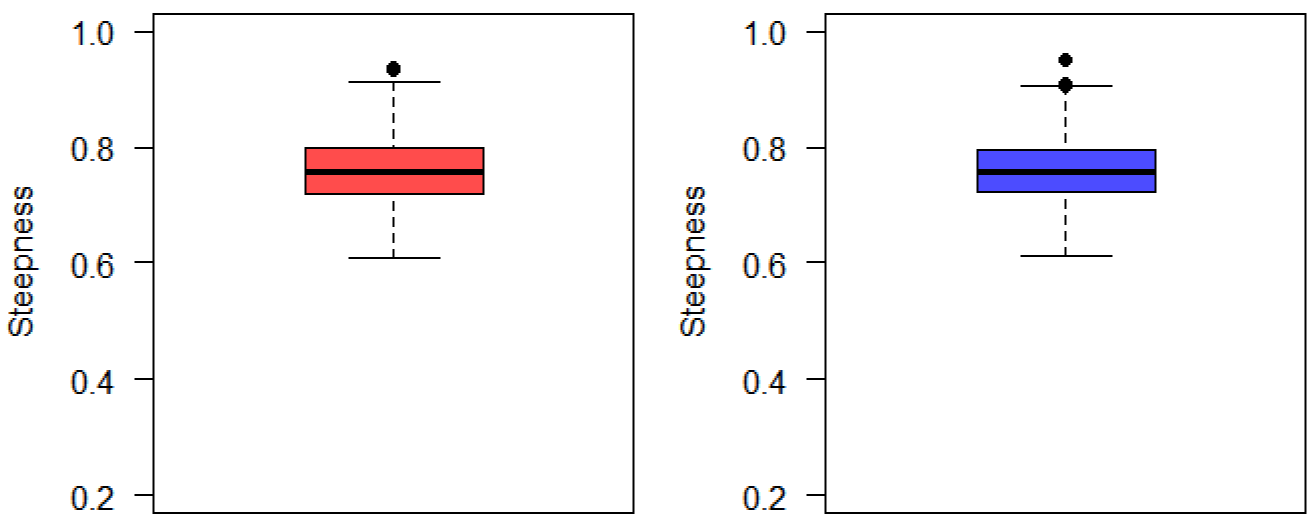

Figure 8. Steepness distributions used to create multiple trajectories in the medAAF (left) and medCW (right) models.

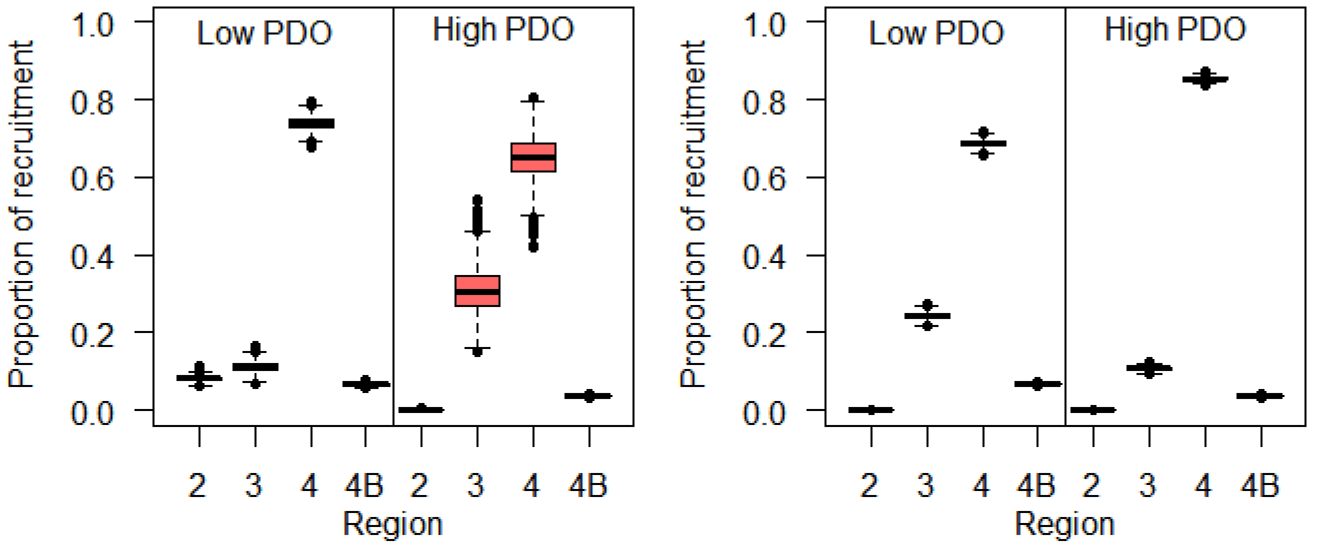

Figure 9. Proportion of recruits in each Biological Region for low and high PDO regimes for the medAAF model (left) and the medCW model (right).

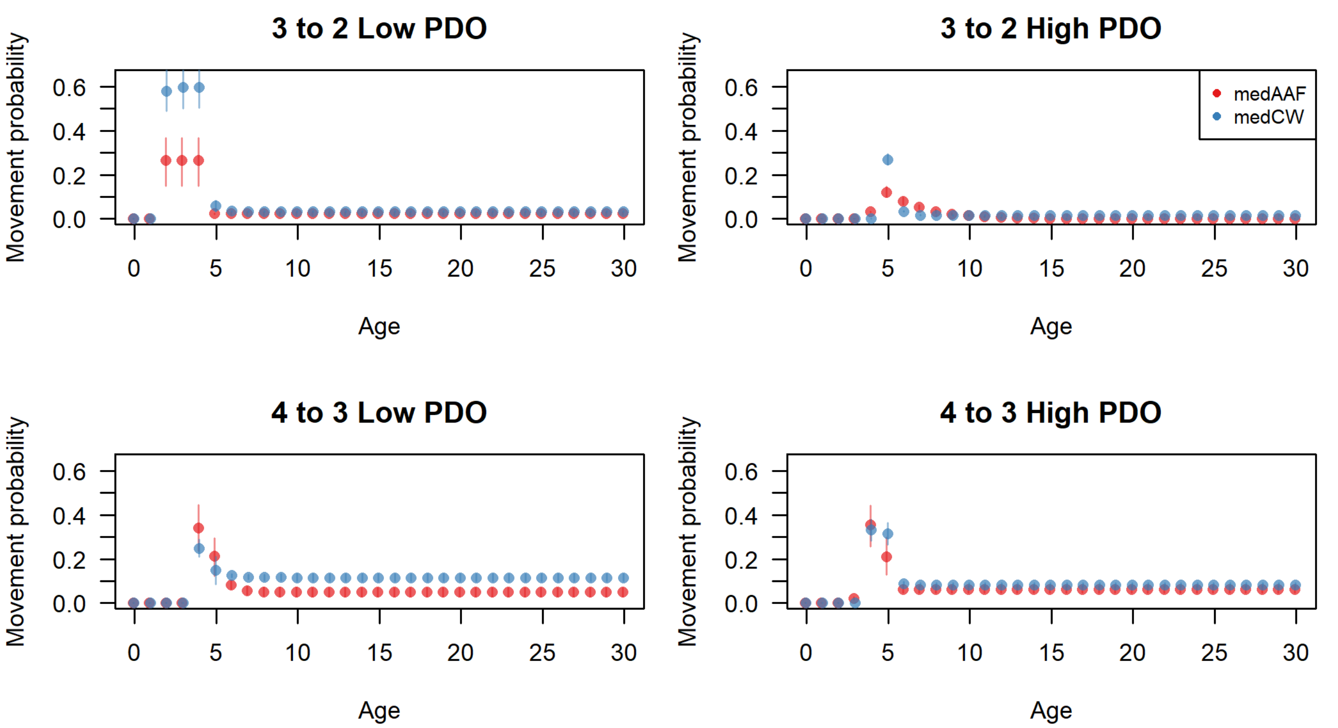

Figure 10. Probability of movement-at-age from Biological Region 3 to region 2 (top) and region 4 to region 3 (bottom) in low PDO (left) and high PDO (right) regimes for the two OM models.

2.2 Projections

The conditioned OM with multiple trajectories is the base of setting up the replicate projections. After which, they are left untouched as the closed-loop simulation projects forward in time using various management procedures (MPs). The simulation of weight-at-age, selectivity/retention deviations, and the environmental regime do not depend on the population dynamics and can be created ahead of time to save time in the simulations. Any of these processes could be dependent on the size of the population, or a certain demographic, and included in the simulation process.

2.2.1 Projected Weight-at-age

Historical weight-at-age varies substantially, and the projections capture that variation using an ARIMA(2,1,0) process that includes deviations from the previous two years. It is important to simulate time-varying weight-at-age because it is an influential contributor to the yield and scale of the Pacific halibut stock. This variability incorporates autocorrelation in a straightforward manner, is determined from past observations, and allows for slight departures between regions and fisheries. The method used to simulate weight-at-age is described in Hicks et al. (2020a) and the 2021 technical document (IPHC-2021-MSE-01).

2.2.2 Modeling discards

Pacific halibut have shown highly variable size- and weight-at-age over time. Studies on growth and analysis of length data continue, but recent population modelling of Pacific halibut has converted numbers-at-age to biomass using observed weight-at-age relationships directly, instead of using intermediate length-at-age calculations. The OM follows the direct weight-at-age method to avoid modelling the complexities of changing length-at-age relationships over time. However, this means that defining size-based quantities, such as needed for size limits or U26/O32 metrics, for example, must be approximated.

A size limit has been in place for directed commercial Pacific halibut fisheries for many decades (Myhre 1973), creating discard mortality which needs to be included in the population modelling. The historical period of the OM follows the same approach as the stock assessment by modelling observed directed discard mortality as a separate fleet. This approach is useful because it uses direct observations (or best estimates) of mortality, can use a separate mean weight-at-age vector which is likely to differ from the landings, and may be a better approach when discards are not directly related to the landings. However, the MSE Program of Work includes the investigation of size limits, and a separate fleet for modelling unknown discard mortality is not as convenient for long-term simulations under variable demographics.

We took the approach of using an age-based retention curve along with age-based selectivity to simulate future landings and discards. The OM does not model length-at-age, thus age-based processes, such as selectivity, must be modelled with deviations included to account for changes in size that may affect the age-based process (Stewart & Martell 2014). Therefore, an approximation must be made to determine retention given changes in size (i.e. weight-at-age).

Using recently reanalysed length-weight relationships (Webster & Stewart 2022) we determined the mean length-at-age given the projected population weight-at-age. Additionally, length-at-age from FISS samples were used to determine an average coefficient of variation (CV) for the variability of length-at-age for each sex separately (0.16 and 0.11 for females and males, respectively). Calculating the proportion of the length-at-age distribution greater than the size limit (1–CDF) provides the probability of retention-at-age (Figure 11).

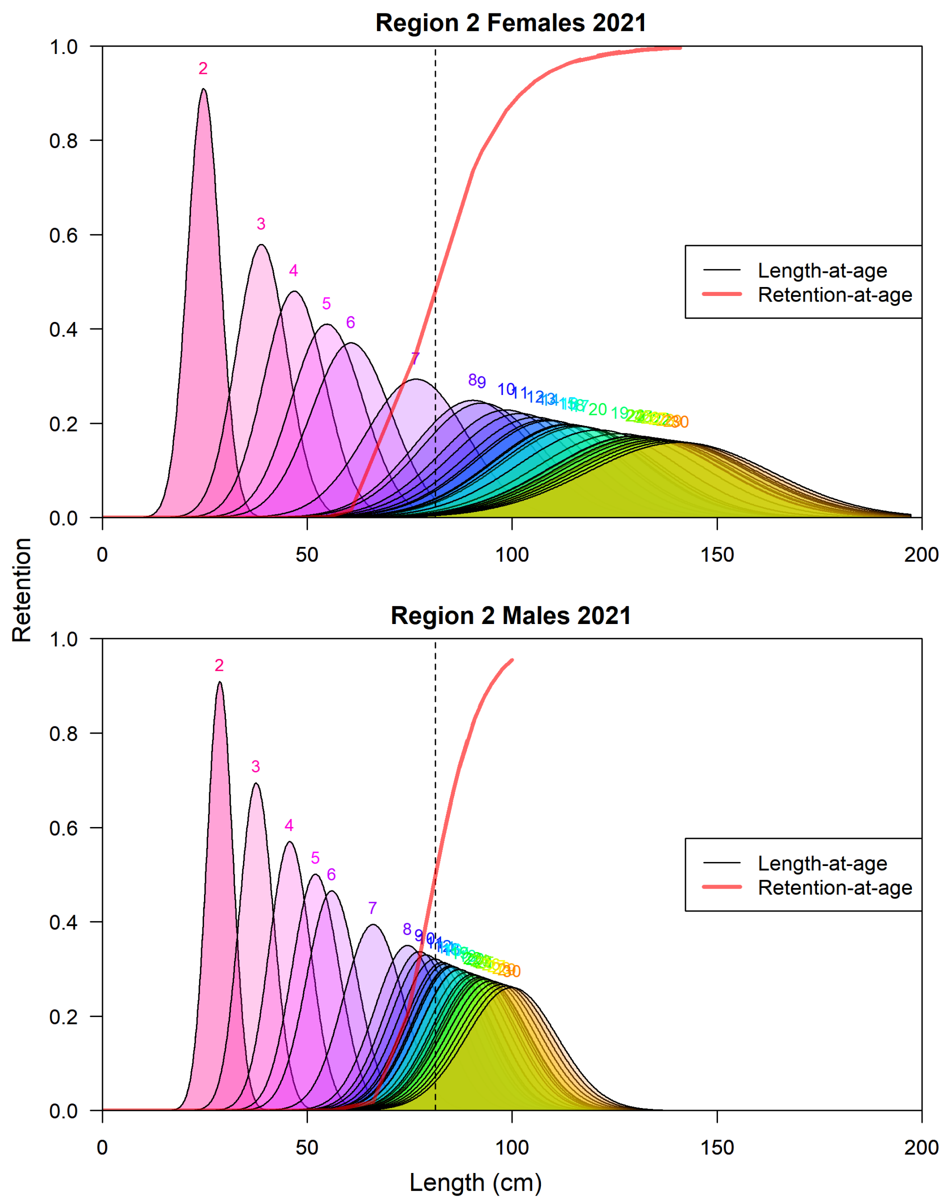

Figure 11. Distributions of length-at-age for females (top) and males (bottom) in Biological Region 2 determined from mean weight-at-age in 2021, length-weight relationships, and coefficients of variation equal to 0.16 and 0.11 for females and males, respectively. The dashed vertical lines represent a size limit at 81.3 cm. The red line is a retention-at-age curve based on the proportion of fish above 81.3 cm in each distribution (noting that the red line does not correspond to the x-axis, but instead the age represented by the peak of each distribution).

Retention-at-age, combined with selectivity-at-age, can separate landings and discards in the OM. However, selectivity in this context encompasses discarded and retained fish, which is not determined in the stock assessment. Fortunately, landings are the product of selectivity-at-age and retention-at-age, which is called ‘keep-at-age’ here, and the directed commercial fisheries model only landings, thus use keep-at-age. Dividing keep-at-age (from directed commercial fleets) by retention-at-age (from length-at-age distributions and length-weight relationships) determines selectivity-at-age for a fleet that models retention (landings) and discards. O32 discards are a small component of the directed commercial fleet that can be accounted for by reducing the asymptote of the retention curve.

The above method was used to determine selectivity and retention curves for new fleets in the OM that replaces the directed commercial and discard fleets, modelling them as one and accounting for any size limit. The keep curve at young ages was sensitive to small values of retention, and the resulting keep curve was often unrealistically jagged. Therefore the following assumptions were enforced:

- Retention was forced to be zero at ages 5 and under to avoid spikes in selectivity at young ages.
- The retention curve was parameterized to a double logistic formulation before calculating selectivity to smooth it and prepare it for use in the OM.
- The selectivity was parameterized as an asymptotic double normal to smooth the curve and prepare it for use in the OM.

All the curves in this process are shown in Figure 12 for 2021.

To ground-truth this method and determine if any adjustments should be made to the calculated selectivity, the U32 discards were predicted in the OM for the directed commercial fleets in each IPHC Regulatory Area for the years 2010 to 2021, and the peak parameter was adjusted until the predicted discards matched the observed U32 discards. This was done individually for each year because misfitting the discards in one year changes the dynamics in subsequent years. It was also performed separately for each OM model. Only one parameter could be chosen for the adjustment because only one observation is being fitted. The ascending limb was not fit, although estimated ascending limb deviations from the stock assessment are more correlated with weight-at-age than peak devations. However, the peak parameter may be a good choice since the temporal variability in size-at-age is generally consistent across younger age classes.

The adjustment to the peak parameter of the asymptotic double normal selectivity curve differed for each IPHC Regulatory Area and ranged from an adjustment of near 8 years younger to an adjustment of near 4 years older, depending on the year and area (Figure 13). The adjustments for each OM model were similar. Even though the years differed substantially, the general patterns were similar within a Biological Region and are intuitive. First, there was a general trend of shifting selectivity to younger ages. Additionally, IPHC Biological Region 3 often sees a lot of undersized Pacific halibut, and the adjustment was towards the youngest fish in both IPHC Regulatory Areas 3A and 3B. This may be because the fishery is unable to avoid these small fish as well as in other IPHC Regulatory Areas. The range of adjustments in each IPHC

Regulatory Areas could be natural variability as well as a result of uncertainty in the discards entered into the model.

Similarly, an adjustment to the asymptote of the retention curve was estimated using O32 discards (using a grid approach over specific values to save time). This adjustment ranged from near 0 to a deviate slightly more than 0.05 applied to lower the asymptote. Triangle distributions were roughly fit to the estimated adjustments, as shown in Figure 14, and were the same for each OM model. Since regulatory discards and lost gear are not directly related to an evaluation of size limits, and these are added into the directed commercial fishery landings in the stock assessment, it is undecided whether this adjustment should be applied, or if O32 discards should simply be included in the retained mortality to reduce complexity. If included, the deviation to the retention asymptote will be sampled from the triangle distributions shown in Figure 14.

This method was used to parameterize a directed commercial retention fleet in the OM for each IPHC Regulatory Area. Eight additional fleets, duplicating the directed commercial and directed discard fleets, were added to each OM model and parameterized with selectivity and retention using the methods above. The median values for each OM model and IPHC Regulatory Area from the ground-truthing exercise (Figure 13) were used to determine the base selectivity for these directed commercial retention fleets. The projections, starting in 2022, assigned directed commercial fishing retained mortality to these fleets and zero fishing mortality was assigned to the original directed commercial and directed discard fleets. Directed commercial discards are therefore a result of the OM and not directly needed as an input. This allows for the MP to account for directed commercial discards using the methods currently in practice, whereas realized directed commercial discards may differ from what was assumed when setting mortality limits. The greatest benefit of this formulation is that any size limit can be consistently evaluated, and appropriately linked to changing weight-at-age.

A benefit of modelling landings and discards separately is that separate mean weight-at-age vectors could be used for each mortality type, effectively accounting for potentially smaller sized fish at each age being discarded. This benefit was maintained in the OM directed commercial retention fleets by allowing for different mean weight-at-age vectors in the kept and discard components of the fishing mortality.

2.2.2.1 Selectivity and retention deviations

When projecting the population and fisheries, mean weight-at-age is dynamic, thus the retention and selectivity curves must be recalculated based on current mean weight-at-age. The stock assessment applies annual deviations to the peak and ascending limb parameters of selectivity to account for temporal changes in mean weight-at-age; the annual recalculation of retention and selectivity mimics this process. Deviations are applied to the peak parameter based on a random draw from distributions representing the range of adjustments observed in Figure 13. Deviations, drawn from the triangle distributions shown in Figure 14 are applied to the retention asymptote to account for O32 discards.

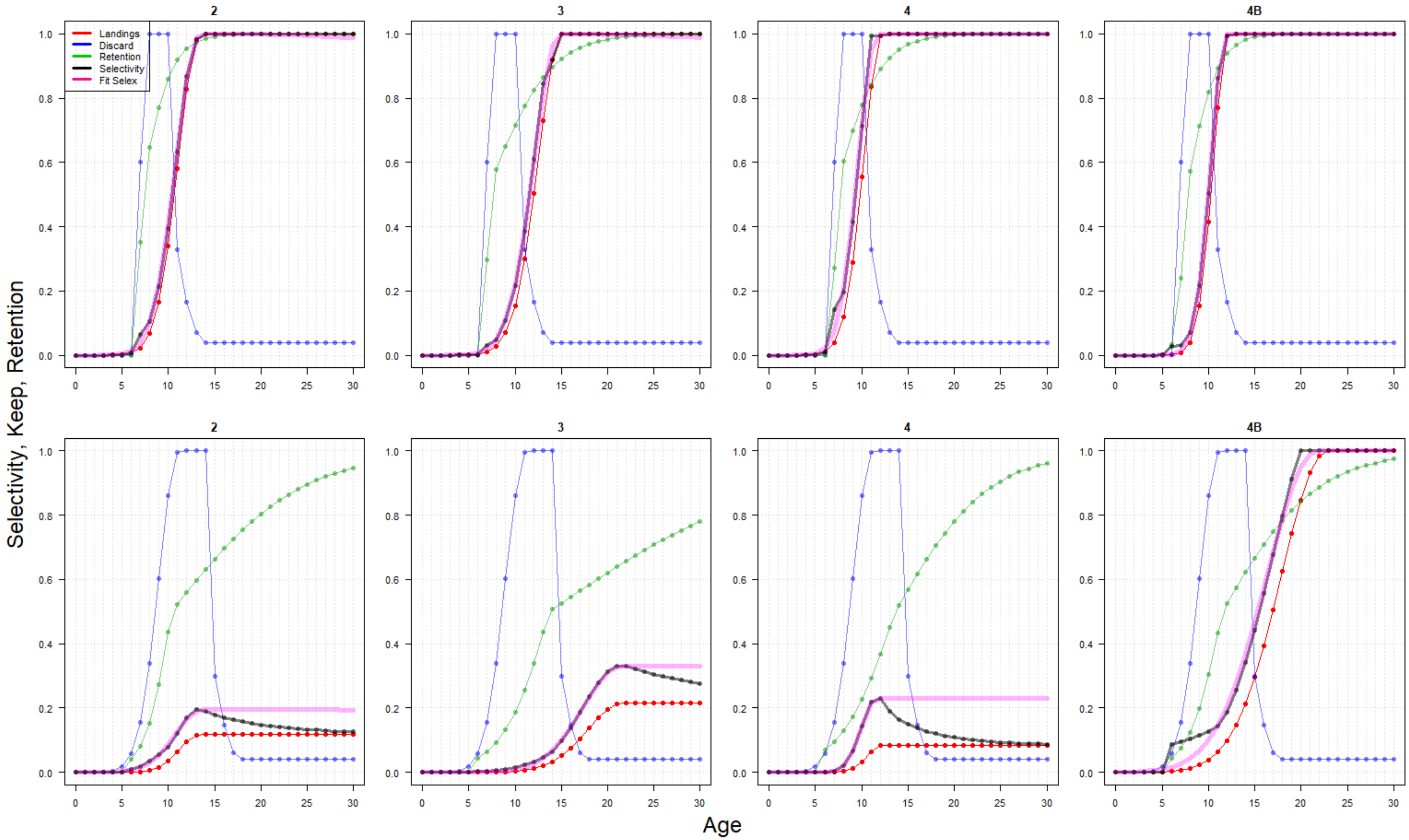

Figure 12. Selectivity, retention, and keep curves for each Biological Region (columns) and sex (rows, females in the top panels, males on the bottom panels) calculated using values from 2021. Landings is the keep curve for the directed commercial fleet as entered in the OM (red curve with dots). Discard (blue) is the selectivity curve for directed discard mortality as entered in the OM. Retention (green) is the double logistic parameterization of the retention calculated from weight-at-age, length-at-weight, and length-at-age relationships. Selectivity (black) is the selectivity-at-age determined from keep and retention. The selectivity curve fitted to selectivity using a asymptotic double normal parameterization is shown in pink.

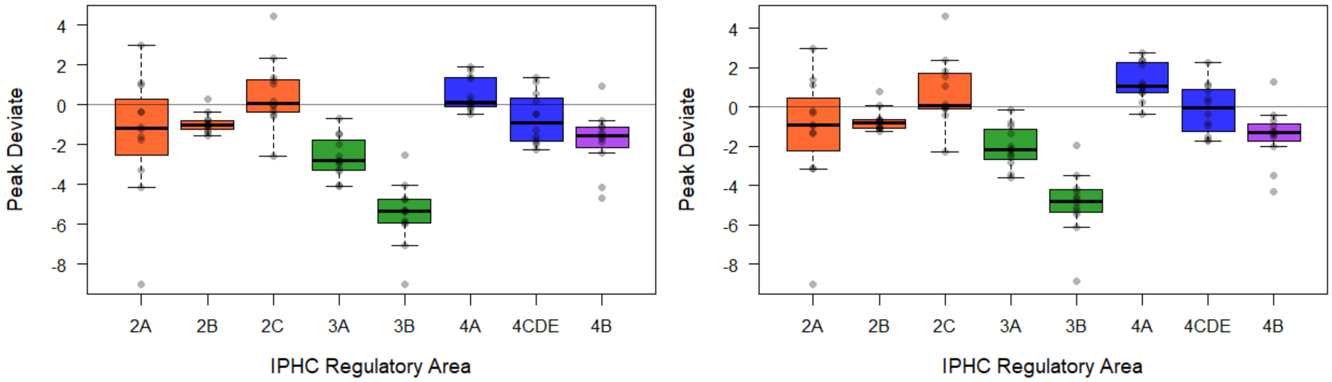

Figure 13. Estimated deviations (in age) from the peak parameter for selectivity for the medAAF (left) and medCW (right) OM models and IPHC Regulatory Area across the years 2010 to 2021. Colors are associated with each Biological Region. Dots indicate each individual year.

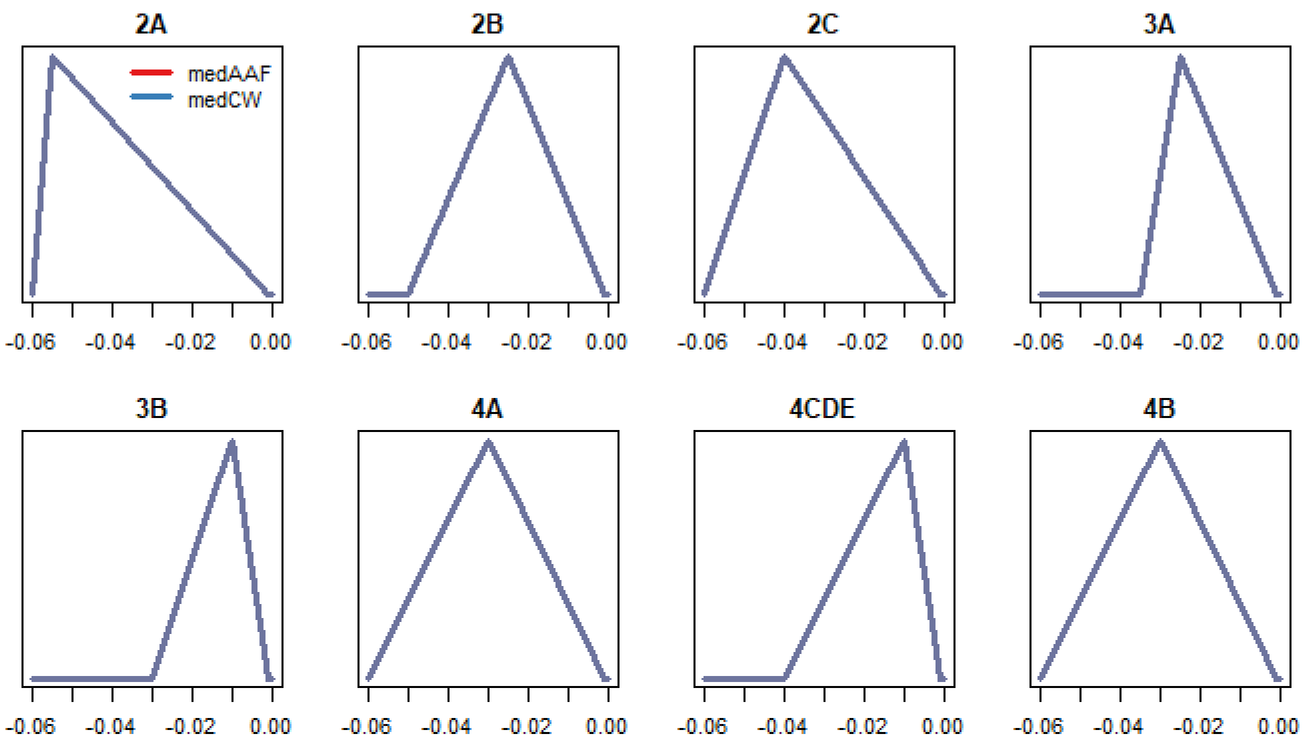

Figure 14. Triangle distributions used to draw random deviates for the retention asymptote. The distributions are the same for each OM model.

2.2.3 Implementation variability and uncertainty

Implementation variability is defined as the deviation of the fishing mortality from the mortality limit determined from an MP. It can be thought of as what actually (or is believed to have) happened compared to the limits that were set. It is useful to define four different fishing mortalities that are subject to different types of implementation variability.

- **MP mortality limit**: This is the mortality limit determined from the management procedure which is calculated from a defined method without ambiguity and is repeatable.
- **Adopted mortality limit**: This is the mortality limit set by the Commission after reviewing all inputs from the stock assessment, subsidiary bodies, and public. It is determined in the "decision" step of Figure 1.
- **Estimated fishing mortality**: This is the perceived mortality after fishing occurs that is determined from landings, at-sea samples, discard mortality rates, and any other observations used in catch accounting. It may also be determined from methods or assumptions that do not use direct observations of catches or landings (e.g. effort). These estimates have sampling uncertainty and are used in estimation models, such as the stock assessment.
- **Actual fishing mortality**: This is the mortality that actually occurred from fishing activities. It is unknown in reality but is used in the OM which simulates the Pacific halibut population. Estimated fishing mortality may affect actual fishing mortality in cases where in-season management uses estimates of fishing mortality to determine if fisheries should be closed or opened.

These four types of mortality are hierarchically related to each other as shown in Figure 15. There are multiple pathways for modelling estimated and actual fishing mortalities. For example, estimated fishing mortality may modelled as a function of the adopted mortality limit or as a function of the actual fishing mortality. Actual fishing mortality may be modelled as a function of the adopted mortality limit or as a function of the estimated fishing mortality. These pathways may differ for different sectors.

We have identified three types of implementation variability that define these relationships. If there is no implementation variability, then all four types of fishing mortality are equal to each other.

1. **Decision-making** variability is the difference between the MP mortality limits and the adopted mortality limits set by the Commission.
2. **Realized** variability is the difference between the adopted mortality limits set by the Commission and the actual mortality resulting from fishing.
3. **Perceived** variability is the variation that determines the estimated fishing mortality, which can differ importantly from actual mortality and the adopted mortality.

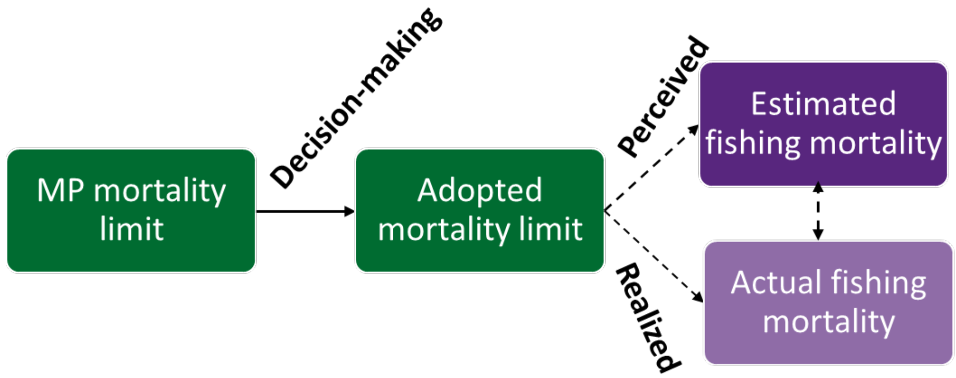

Figure 15. The hierarchy between four fishing mortality types (boxes: green indicates known quantities, light purple indicates unknown, and dark purple indicates observed with error) and where implementation variability occurs (black text). Dashed lines indicate that the estimated and actual fishing mortalities could be modelled from different pathways (e.g., estimated fishing mortality is a function of the adopted mortality limit or a function of the actual fishing mortality). The OM calculates estimated and actual fishing mortality, and uses each of these quantities in different parts of the simulation process.

Variability is defined as the inherent heterogeneity in the data or population, which cannot be reduced. On the other hand, uncertainty is defined as the incomplete understanding of the data, estimate, or process. Uncertainty can be reduced to zero with increased sampling. With these definitions, we refer to historical variations in implementation of mortality limits as implementation variability, and the future simulation of potential variations in the implementation of mortality limits as implementation uncertainty. Variability has already happened in the past and can be determined and not changed, whereas future simulations are uncertain about the variations, thus simulate a range of possible deviations.

To identify reasonable methods to simulate implementation uncertainty in the MSE, we considered some possible hypotheses and looked at historical implementation variability. First, decision-making uncertainty can be applied to the MP mortality limit ($TCEY_t$) as a multiplier.

$$\widetilde{TCEY}_t = TCEY_t \varepsilon_I$$

where $\widetilde{TCEY}_t$ is the adopted mortality and ε_I is the multiplier. Using observations from 2014 to 2021 of the MP mortality limit determined from the interim management procedure and the adopted mortality limits set by the Commission for that year and IPHC Regulatory Area, the multipliers are shown in Figure 16. These years were chosen because they used a relatively consistent management procedure, although as noted in the following paragraphs from Annual Meeting reports, explicit use of SPR was added in 2017, additional agreements were added in 2019 and 2020, and the reference SPR changed from 46% to 43% in 2021.

> ***IPHC-2017-AM093–R* (para. 29) NOTING** *that the IPHC Secretariat and the IPHC Scientific Review Board (SRB) have demonstrated that Ebio is outdated and inconsistent with current assessment results, and that numerous elements of the current harvest policy*

*are reliant on Ebio, and that the Commission has agreed that the current harvest policy is considered to be outdated (IPHC–2016–IM092–R, items 21, 22), the Commission **RECOMMENDED** IPHC–2017–AM093–R Page 8 of 61 that reference to all elements of the current harvest policy reliant on Ebio, as well as the use of the Blue line, be eliminated subsequent to the close of the 93rd Session of the Commission. The "status quo SPR" (F46%) may serve as an interim "hand rail" that allows all participants to gauge this and future years' catch limit discussions in comparison to previous years.*

***IPHC-2020-AM096-R* (para. 97)** *The Commission **ADOPTED**: a)[…]; and b) a fixed TCEY for IPHC Regulatory Area 2A of 1.65 million pounds is intended to apply for a period from 2019-2022, subject to any substantive conservation concerns; and c) a share-based allocation for IPHC Regulatory Area 2B. The share will be defined based on a weighted average that assigns 30% weight to the current interim management procedure's target TCEY distribution and 70% on 2B's recent historical average share of 20%. This formula for defining IPHC Regulatory Areas 2B's annual allocation is intended to apply for a period of 2019 to 2022. For 2020, this equates to a share of 18.2% before accounting for U26; and […]*

***IPHC-2020-CR-007* (ID002).** *The Commission **RECOMMENDED** a reference SPR fishing intensity of 43% with a 30:20 control rule be used as an updated interim harvest policy consistent with MSE results pending delivery of the final MSE results at AM097 […]*

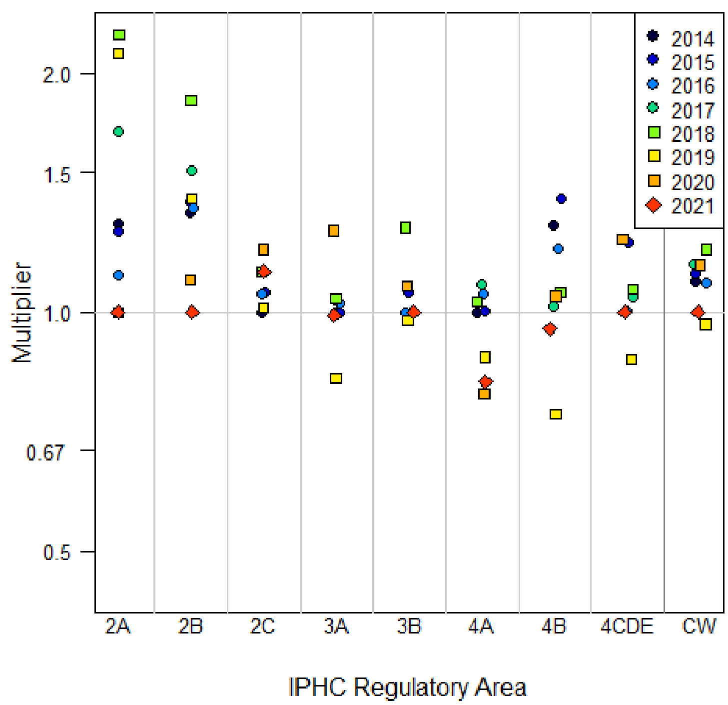

Figure 16. Multipliers for the difference between MP mortality limits and adopted mortality limits from 2014 to 2021. "CW" refers to coastwide.

This investigation of past decisions can inform the development of methods to simulate decision-making uncertainty. To further aid in the development, six potential decision-making response hypotheses were identified from discussions with the SRB and Management Strategy Advisory Board (MSAB), as well as from past observations.

1) When the TCEY is high the Commission may be less inclined to increase the coastwide TCEY above the MP TCEY (the multipliers become closer to 1).
2) When the TCEY is decreasing from the previous year, the multiplier is typically above 1, whereas when the TCEY is increasing, it is typically around 1. The SRB made a recommendation related to this scenario.

   SRB019–Rec.06 (para. 35) ***NOTING*** *the inclusion of uncertainty stemming from implementation* ***uncertainty****, the SRB* ***RECOMMENDED*** *that the IPHC Secretariat develop, for presentation at SRB020, alternative scenarios that represent implementation* ***bias****, i.e. the potential for quota reductions called for by the management procedure to be less likely implemented than quota increases.*

3) When the stock status is less than 30%, the Commission may deviate (increased fishing intensity/higher TCEY) from the MP. An extreme example is that they may decide to not set the TCEY to zero when the relative spawning biomass is less than 20%, as defined by the interim control rule.
4) When coastwide stock status is above 30% (trigger point of CR) the multiplier may be increasingly greater than one as the TCEY becomes lower or is below some threshold.
5) When the decision table from the assessment indicates a lower risk of stock decline or falling below 30% RSB, the multiplier may become increasingly greater than 1.
6) When there is an agreement for an IPHC Regulatory Area, the implementation variability is much less, or near 1.0 for these areas.

2.2.3.1 Method to simulate decision-making uncertainty

The multiplier to simulate decision-making uncertainty is drawn from a lognormal distribution with correlation between multipliers for each IPHC Regulatory Area. The mean ($\boldsymbol{\mu_\varepsilon}$) and standard deviation ($\boldsymbol{\sigma_\varepsilon}$) of that distribution are modified as follows depending on the TCEY from the MP.

$$\boldsymbol{\mu_\varepsilon} \text{ or } \boldsymbol{\sigma_\varepsilon} = \begin{cases} \boldsymbol{\bar{x}} \text{ or } \boldsymbol{s} & TCEY < TCEY_{low} \\ \boldsymbol{a} + \boldsymbol{b} * TCEY & TCEY_{low} \le TCEY \le TCEY_{high} \\ \mathbf{1.0} \text{ or } \boldsymbol{s}/\mathbf{2} & TCEY > TCEY_{high} \end{cases}$$

Using IPHC Regulatory Area 2A as an example (without a TCEY agreement in place), with a coastwide $TCEY_{low}$ of 30 Mlbs and a coastwide $TCEY_{high}$ equal to 60 Mlbs, the distribution of simulated multipliers gets closer to 1 as the TCEY increases (Figure 17).

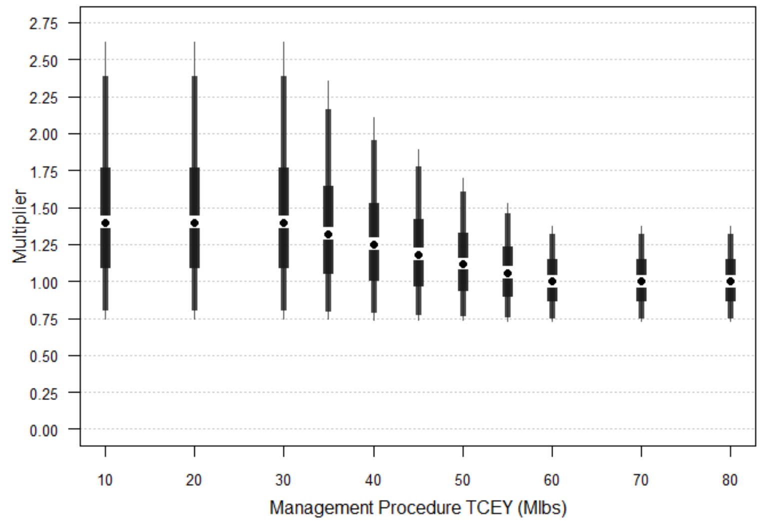

Figure 17. Simulated multipliers for IPHC Regulatory 2A at different values of the coastwide TCEY (without the recent agreement on the 2A TCEY). The thickest portion of the vertical bar represents the 25th and 75th percentiles, followed by the 5th and 95th percentiles, and then the 2.5th and 97.5th percentiles.

This method directly addresses hypotheses 1 and 4, and could be easily modified to address 2, 3, and 6. Hypothesis 5 could be approximated with additional investigation and modification.

Actual decision-making variability is likely more complex than this simple method. In fact, some IPHC Regulatory Areas show a consistent adopted TCEY over a range of MP TCEYs (e.g., 4B in Figure 18). However, the goal of including decision-making uncertainty in the MSE simulations isn't to exactly simulate what the pattern is, but to identify the effect of decision-making uncertainty and identify MPs that are robust to a plausible amount of uncertainty. Therefore, simulations will be done with and without decision-making uncertainty to identify MPs that are robust to this uncertainty. Various modifications may be made to decision-making uncertainty to explore sensitivity to various hypotheses. For example, different offsets depending on the trend in the population or TCEY, as suggested by the SRB (SRB019–Rec.06, para. 35).

2.2.3.2 Methods to simulate realized and perceived implementation uncertainty

Realized uncertainty is currently implemented in the OM by simulating a range of actual non-directed discard mortality, recreational mortality, and subsistence mortality. These are likely the largest sources of realized variability in the Pacific halibut fisheries, which is relatively small compared to many fisheries.

Perceived uncertainty is currently not simulated in the OM but will be considered as work progresses.

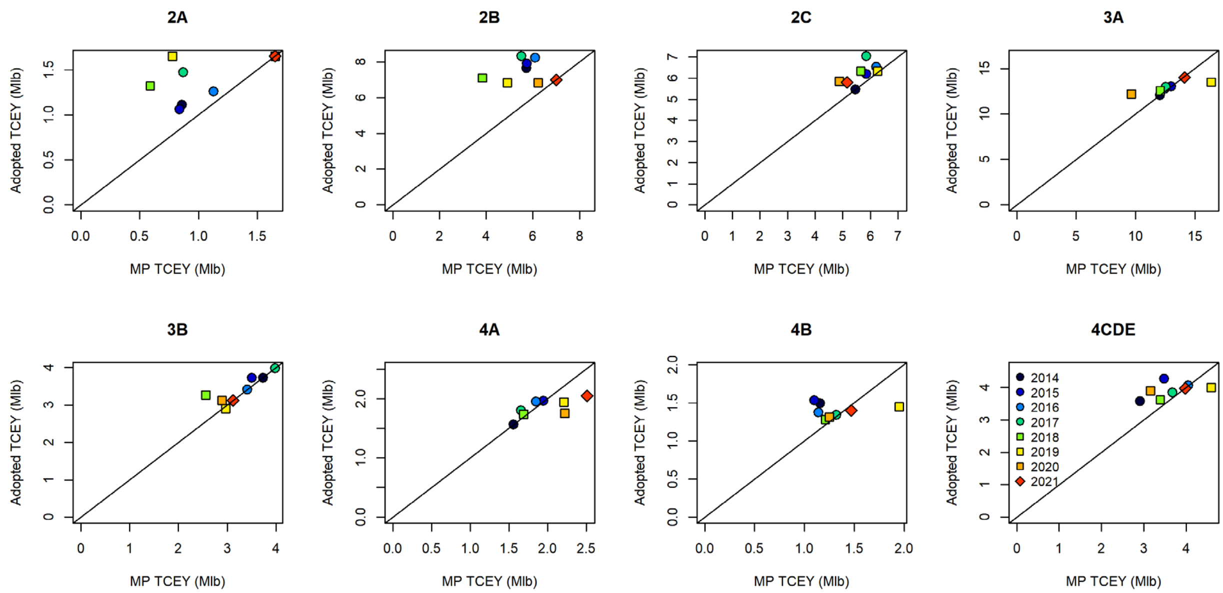

Figure 18. Adopted TCEYs plotted against MP TCEYs for each IPHC Regulatory Area and years 2014 to 2021.

2.2.4 Projections with no fishing mortality

Projections with the OM incorporating parameter variability and projection variability produced a wide range of spawning biomass trajectories. Figure 19 shows fifty projected trajectories without fishing, variable weight-at-age, and an environmental regime switching on average every 30 years. An individual trajectory may cover a wide range of spawning biomass values in this 90-year period. The variability looks like it has reached its full range after 30 years, but there is still cyclic behavior which is due to the long period of the environmental regime.

Figure 20 shows the percentage of time that the simulated PDO is in a positive phase. With a thirty-year average time remaining in a phase, a 90 year projection has little opportunity to show a mixing of negative and positive phases. There is very little probability of a positive phase approximately 40 years in the projections and almost very high probability of a positive phase approximately 60 years in the projections (noting that there is something incorrect in the simulation with an almost instantaneous return to a positive phase around 2075). Longer simulations would provide better mixing while retaining the long period of a single phase, but at the expense of very long simulation times. To better characterize the uncertainty of the environmental effect on recruitment while retaining the cumulative effects on the population of potentially long periods of a single phase, the average period of a phase was reduced to 20 year and the slope of the logistic function defining the probabilities based on the period of the current phase was made shallower (Figure 21). This is also justified by a recent potentially short negative phase (Figure 52 in IPHC-2022-SA-02). Additionally, the environmental regime will be modelled external to the C++ operating model code to save simulation time, allow for the exact same pattern across MP simulations, and ensure that the environmental regime behaves as expected (Figure 22).

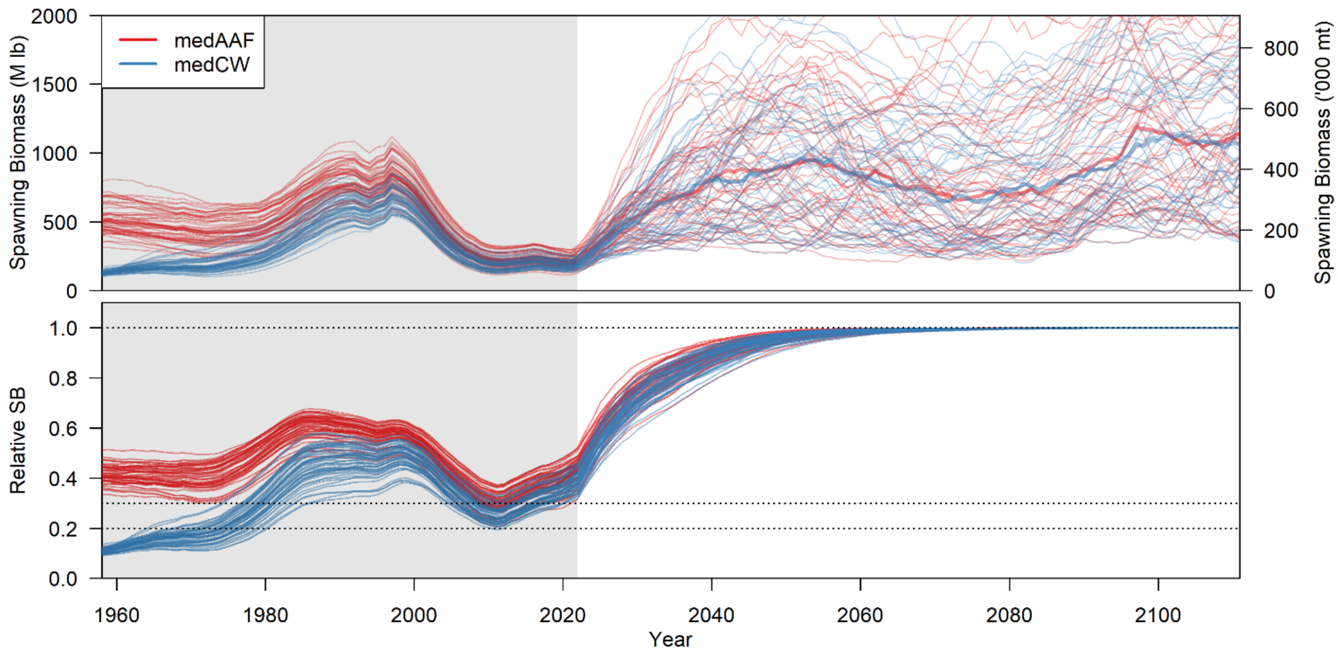

Figure 19: Fifty projections of spawning biomass and median spawning biomass (top) and relative spawning biomass (bottom) for 90 years without fishing mortality for each OM model. An environmental regime is simulated with an average period of 30 years before switching to the opposite regime.

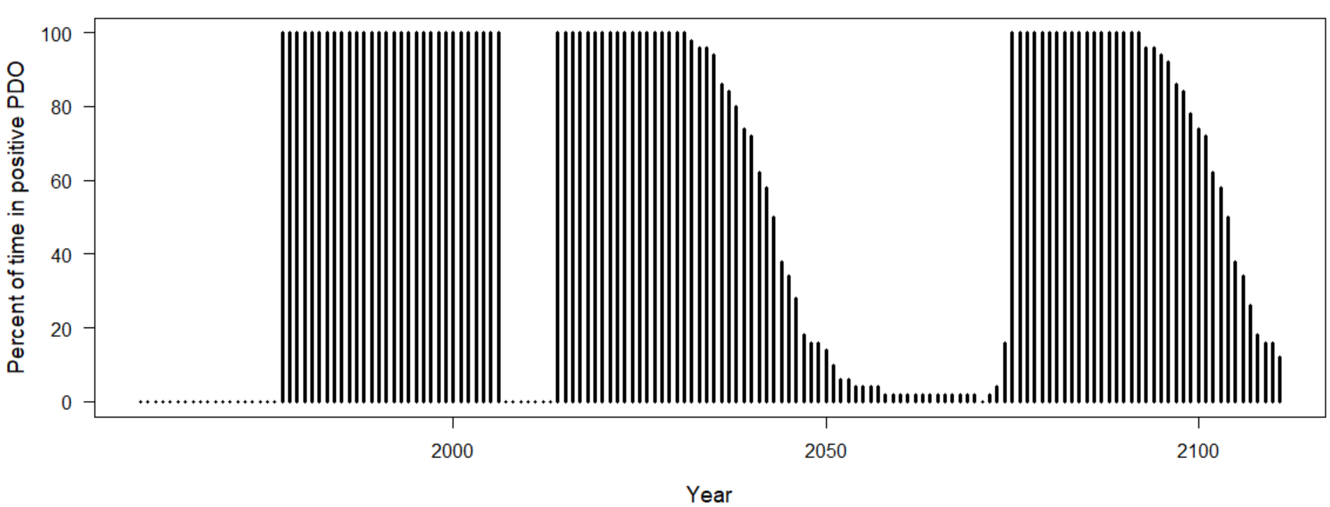

Figure 20. Percent of simulations where the PDO is in a positive phase. Simulations start in 2022 and the PDO phase is fixed before then.

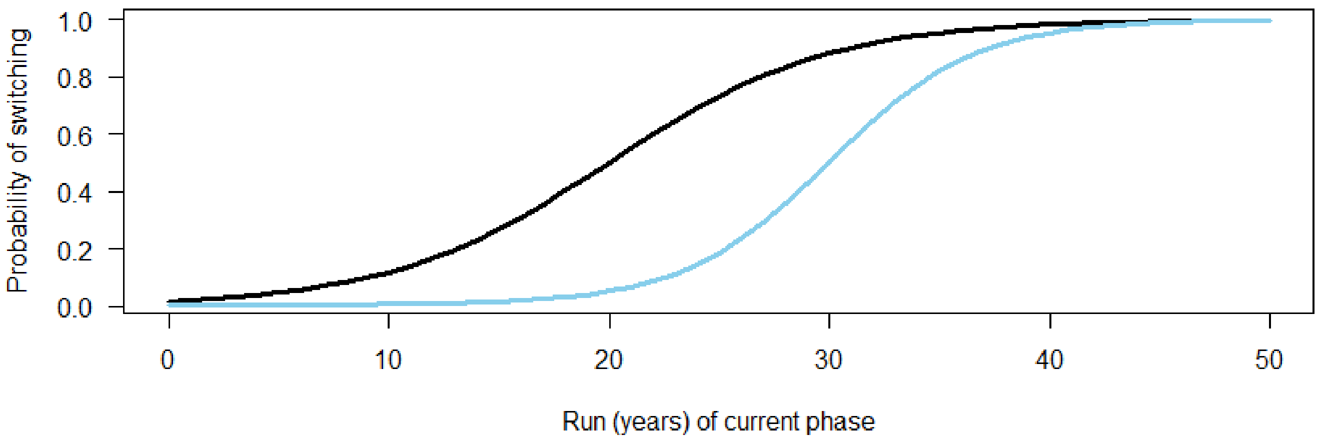

Figure 21. Modelled probability of the environmental regime switching to the opposite regime based on the number of years (run) of the current regime. The blue line is the parameterization used in Figure 20 and the black line is the proposed new parameterization to ensure adequate uncertainty in the phases.

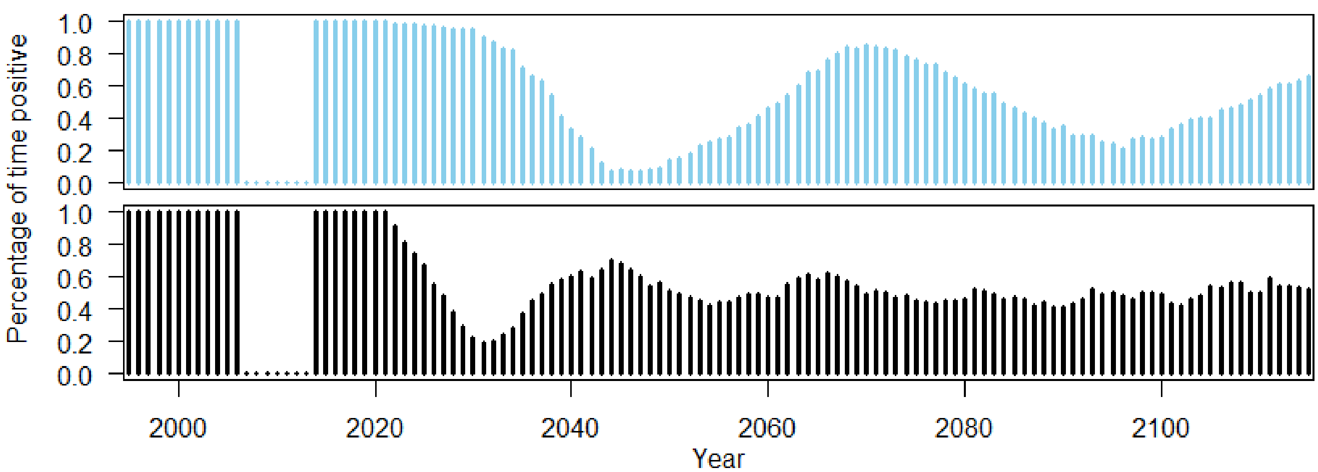

Figure 22. Percentage of simulations that the simulated PDO was positive for two parameterizations of the probability that the PDO switches. The top and bottom plots correspond to Figure 21. The top has a 0.5 probability of change at 30 years while the bottom plot is 20 years. The slope and y intercept of the logistic function is 0.3 and 0.005 in the top plot and 0.2 and 0.0 in the bottom plot.

2.3 Runs and Scenarios

The primary closed-loop simulations will consist of integrating the two OM models with equal weight by simulating an equal number of trajectories/projections from each model. The results from the full set of projections will be used to calculate the performance metrics. Implementation variability will be the symmetric method described above. Additional scenarios may be evaluated that include OM models with lower M values, different assumptions of migration, or different scenarios of implementation error.

3 MANAGEMENT PROCEDURES

Two categories of MPs were prioritised in the MSE Program of Work for 2021–2023. One was the investigation of size limits (M.1) and the other was to investigate multi-year stock assessments (i.e. not conducting the stock assessment annually; M.3). Due to improvements in the MSE framework and changes in the OM, select MPs from the set evaluated in 2021 may need to be reanalysed.

3.1 Size limits

Since 1973, IPHC has restricted the directed commercial fishery for Pacific halibut with a 32 inch (81.3 cm) minimum size limit, although other forms of size limits have been in place since 1940 (Myhre 1973). Many investigations of size limits have been completed since then including IPHC (1960), Clark & Parma (1995), Parma (1999), Valero & Hare (2012), Martell et al. (2015a), Martell et al. (2015b), Stewart & Hicks (2018), and Stewart et al (2021). Most of these analyses have focused on short-term effects or effects on reference points. The novelty of this analysis using the MSE framework will be to examine long-term effects of different size limits in relation to defined conservation and fishery objectives. Additionally, long-term changes to the stock and fishery distribution as well as changes in productivity will be examined.

The Commission requested that three size limits be investigated: 32 inches, 26 inches, and no size limit.

> **IPHC-2022-AM098-R, para. 61**: *The Commission RECALLED SS011-Rec.01 and REQUESTED that the current size limit (32 inches), a 26 inch size limit, and no size limit be investigated. to understand the long-term effects of a change in the size limit.*

As noted in Section 2.2.2, even though some approximations need to be made, any size limit can be investigated. Additional size limits will be added if necessary to gain a better understanding of the trade-offs.

It is uncertain how selectivity of the directed commercial fisheries may change with the implementation of a different size limit than the current 32 inches. Fisheries may choose to target smaller fish to increase efficiency, they may maintain current practices, or they may target larger fish if that provides improved economic gains. Some sensitivities to changes in selectivity may be investigated.

An important concept to bring into the evaluation of size limits is market considerations. Stewart et al. (2021) used the ratio between the U32 price and O32 price for Pacific halibut to determine what ratio is necessary for the fishery to break even economically. It is unknown what prices will be for U32 Pacific halibut if a size limit was removed, but the FISS has recently begun selling U32 fish, which may be an indicator for future market conditions of small fish. Regardless, a performance metric related to economics will be important to consider in this evaluation.

3.2 Multi-year assessments

Management procedures with multi-year assessments incorporate a process where the stock assessment occurs at intervals longer than annually. The mortality limits in a year with the stock assessment can be determined as in previously defined MPs, but in years without a stock assessment, the mortality limits would need an alternative approach. This may be as simple as maintaining the same mortality limits for each IPHC Regulatory Area in years with no stock assessment, or as complicated as invoking an alternative MP that does not require a stock assessment (such as an empirical-based MP relying only on data/observations). Potential MPs for years without an assessment that may be evaluated include the following.

a. The same TCEY from the previous year for each IPHC Regulatory Area.
b. Setting multi-year TCEYs using projections from the stock assessment.
c. Updating the distribution of the TCEY in non-assessment years using FISS results and/or other data sources, but maintaining the same coastwide TCEY.
d. Updating the coastwide TCEY in non-assessment years using FISS results and/or other data sources, and then distributing the coastwide TCEY using a distribution procedure.
e. Updating the TCEY within each IPHC Regulatory Area separately using FISS results and/or other data sources, resulting in a change to the coastwide TCEY.

The Commission requested that the Secretariat investigate biennial assessments and potentially longer intervals as time allows. Specific approaches for non-assessment years will be developed by the Secretariat.

> **IPHC-2022-AM098-R, para 64**: *The Commission REQUESTED that multi-year management procedures include the following concepts:*
>
> > *a) The stock assessment occurs biennially (and possibly triennial if time in 2022 allows) and no changes would occur to the FISS (i.e. remains annual);*
> >
> > *b) The TCEY within IPHC Regulatory Areas for non-assessment years:*
> >
> > > *i. remains the same as defined in the previous assessment year, or*
> > >
> > > *ii. changes within IPHC Regulatory Areas using simple empirical rules, to be developed by the IPHC Secretariat, that incorporate FISS data.*

An alternative approach that would not require a stock assessment for setting mortality limits in any year would be to adopt an empirical-based MP as the method for setting annual mortality limits. The stock assessment would be used at a defined interval to verify that management is effective and to potentially tune the MSE OM and existing MP (Cox and Kronlund 2008). Any of the MPs mentioned in this section, empirical- or model-based or a hybrid of the two, can be evaluated using the current MSE framework, and the evaluation of multi-year assessments with an empirical rule will be a useful path to evaluating an annual empirical MP without a stock assessment.

The Commission has realized that there are some benefits to multi-year assessments, including time for development/improvement of the stock assessment, the potential to address additional topics at meetings in years without a stock assessment, and the potential for increased collaboration across branches within the IPHC Secretariat. However, there may be some costs associated with multi-year assessments. For example, detailed harvest advice will not be available every year.

It is also important to consider costs and benefits associated with an annual assessment. In particular, the annual preparation of a stock assessment occupies many staff in terms of preparing and providing data in a timely manner, writing documents to support associated data and analyses, conducting the stock assessment, preparing the stock assessment document and presentations, and participating in public outreach associated with a new stock assessment.

The Commission has asked the SRB to assist the Secretariat in identifying potential costs and benefits of not conducting an annual stock assessment.

> **IPHC-2022-AM098-R, para 63:** *The Commission REQUESTED that the IPHC Secretariat work with the SRB and others as necessary to identify potential costs and benefits of not conducting an annual stock assessment. This will include a prioritized list of work items that could be accomplished in its place.*

It may be premature to begin identifying detailed costs and benefits of multi-year assessments until an evaluation has been done to determine whether or not multi-year assessments may meet the Commission objectives already defined. An evaluation of multi-year assessments using Commission conservation and fishery objectives will be presented at SRB021, after which a discussion of detailed costs and benefits would be informative.

3.3 Modelling distribution

The fisheries in the OM are specified by IPHC Regulatory Area because many of the Commission objectives used to evaluate MPs are specific to IPHC Regulatory Areas and the OM is spatially structured by Biological Region. This makes it necessary to distribute the TCEY across the fisheries to appropriately remove biomass from each Biological Region and allow for the calculation of necessary performance metrics. Distribution procedures have been evaluated (Hicks et al. 2021), but a specific MP has not been implemented. Even though distribution procedures are not currently being evaluated and there is no specific agreement on a single distribution procedure, they are part of the MP and need to be included in the simulations. Therefore, the Commission has recommended five different distribution procedures representing a practicable range to provide a robust analysis of size limits and multi-year assessments.

> **IPHC-2022-SS012-R, para 11**: *The Commission RECOMMENDED the following five distribution procedures to be used in the management strategy evaluation of size limits and multi-year assessments, noting that these distribution procedures are for analytical purposes only and are not endorsed by both parties, thus would be reviewed in the future if the Commission wishes to evaluate them for implementation.*
>
> > *a) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3A, relative harvest rates of 0.75 for IPHC Regulatory Areas 3B-4, and no application of the current interim agreements for 2A and 2B;*

b) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3A, relative harvest rates of 0.75 for IPHC Regulatory Areas 3B-4, and current interim agreements for 2A and 2B;

c) Baseline based on recent year O32 FISS results with 1.65 Mlbs to 2A and 20% of the coastwide TCEY to 2B;

d) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3, 4A, and 4CDE, a relative harvest rate of 0.75 for IPHC Regulatory Area 4B, and no agreements for 2A and 2B;

e) Baseline based on recent year O32 FISS results, relative harvest rates of 1.0 for IPHC Regulatory Areas 2-3, 4A, and 4CDE, a relative harvest rate of 0.75 for IPHC Regulatory Area 4B, and current interim agreements for IPHC Regulatory Areas 2A and 2B

3.4 MP combinations

It is easy in any MSE to specify a large set of runs due to the combination of many MP elements. Given that the simulation time for a single MP may be days, it is useful to identify a small set of runs that will provide insight into the performance of each element of the MP of interest. The three components presented above have multiple elements which will be combined as shown in Table 2 to form the primary set of twenty-five MPs. For each MP, an SPR of 43% will be used.

A secondary set of MPs will be developed based on the performance of the primary set. This may include crossing size limits with biennial assessments, investigating alternative SPR values, and incorporating various forms of implementation variability. This secondary set will not be a full factorial, but instead a specific investigation of relevant factors, and to refine the best performing MPs relative to stock and fishery objectives.

Furthermore, a set of sensitivities will be done using alternative scenarios such as different migration hypotheses, different assumptions about natural mortality, and shifts in selectivity to mimic changes in fishery practices. These will be performed on a small set of the best performing MPs.

EVALUATION

The twenty-five MPs in Table 2 will be integrated across the distribution procedures, resulting in the five MPs in Table 3. Therefore, performance metrics will only be reported for the five MPs in Table 3 and distribution will be considered an uncertainty in this evaluation.

The methods to evaluate simulation results and present those for decision-making are always being improved. Current tasks specifically include updates to the MSE Explorer tool, improving the ranking procedure to identify best performing management procedures, determining new methods to identify best performing management procedures, and providing new types of plots and tables that effectively communicate the results. This task will benefit from interactions with stakeholders and management agencies, which may include MSAB meetings.

Table 2. Primary MPs to be evaluated. The multi-year assessment specifies the frequency of the stock assessment and the procedure for years without a stock assessment. The distribution procedure corresponds to the letter in IPHC-2022-SS012-R, para 11 and quoted in this text.

#	MP ID	Multi-year assessment	Size Limit (inches)	Distribution
1	MP-A32a	Annual	32	a
2	MP-A32b	Annual	32	b
3	MP-A32c	Annual	32	c
4	MP-A32d	Annual	32	d
5	MP-A32e	Annual	32	e
6	MP-Bc32a	Biennial, constant TCEY	32	a
7	MP-Bc32b	Biennial, constant TCEY	32	b
8	MP-Bc32c	Biennial, constant TCEY	32	c
9	MP-Bc32d	Biennial, constant TCEY	32	d
10	MP-Bc32e	Biennial, constant TCEY	32	e
11	MP-Be32a	Biennial, empirical rule	32	a
12	MP-Be32b	Biennial, empirical rule	32	b
13	MP-Be32c	Biennial, empirical rule	32	c
14	MP-Be32d	Biennial, empirical rule	32	d
15	MP-Be32e	Biennial, empirical rule	32	e
16	MP-A26a	Annual	26	a
17	MP-A26b	Annual	26	b
18	MP-A26c	Annual	26	c
19	MP-A26d	Annual	26	d
20	MP-A26e	Annual	26	e
21	MP-A0a	Annual	0	a
22	MP-A0b	Annual	0	b
23	MP-A0c	Annual	0	c
24	MP-A0d	Annual	0	d
25	MP-A0e	Annual	0	e

Table 3. Primary MPs to be evaluated. The multi-year assessment specifies the frequency of the stock assessment and the procedure for years without a stock assessment.

MP ID	Multi-year assessment	Size Limit (inches)
MP-A32	Annual	32
MP-Bc32	Biennial, constant TCEY	32
MP-Be32	Biennial, empirical rule	32
MP-A26	Annual	26
MP-A0	Annual	0

RECOMMENDATION/S

That the SRB

a) **NOTE** paper IPHC-2022-SRB020-06 Rev_1 describing improvements to the closed-loop simulation framework, methods to simulate implementation variability, two types of management procedures to simulate and evaluate in 2022, and potential areas of improvement to the evaluation process.

b) **NOTE** two new population models conditioned using assumptions and outputs from the two long models from the recent stock assessment will be integrated and used as an OM.

c) **NOTE** that improvements to the closed-loop simulation framework allow for a more direct method of evaluating size limits without specifically modelling a growth curve.

d) **NOTE** the methods for simulating implementation error based on past management outcomes.

e) **NOTE** that there are costs and benefits to not conducting annual stock assessments, which may affect research opportunities.

f) **NOTE** that five primary MPs investigating three size-limits, and annual and biennial assessments will be evaluated in 2022, with five distribution procedures treated as uncertainty. Sensitivities will be performed using the best performing MPs.

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APPENDICES

Appendix A: Supplementary material

APPENDICES

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In addition to this document, an MSE technical document is available electronically. This is document IPHC-2022-MSE-01 and is available on the IPHC MSE page (https://www.iphc.int/management/science-and-research/management-strategy-evaluation).